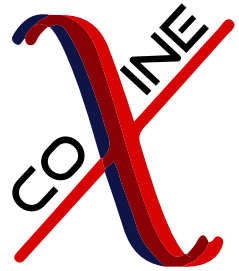
NaI 검출기를 이용한 암흑물질 및 중성미자 연구



이현수

기초과학연구원

지하실험연구단

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

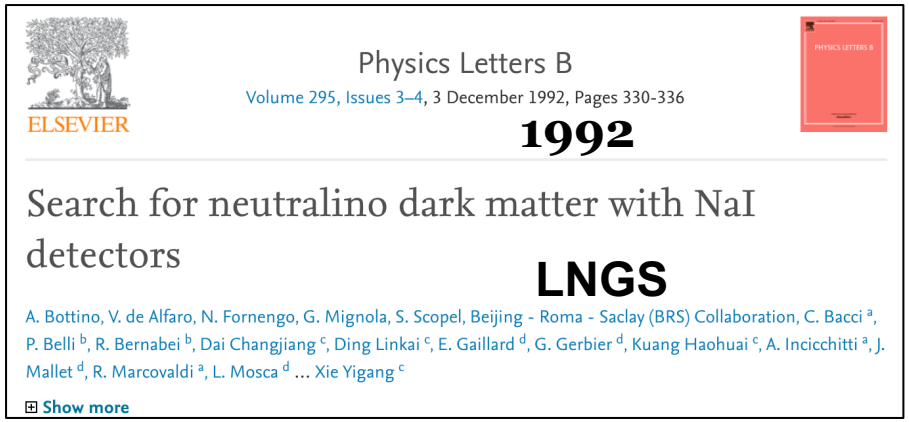
The first 32 inch diameter NaI(Tl) crystal. Pictured from left to right are Dr. Swinehart, Ed Jablon, Joe Knaus and Marko Sfilgoi.

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

Con

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

NaI(Tl) for rare event searches : Dark Matter



ELSEVIER

Physics Letters B

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

1992

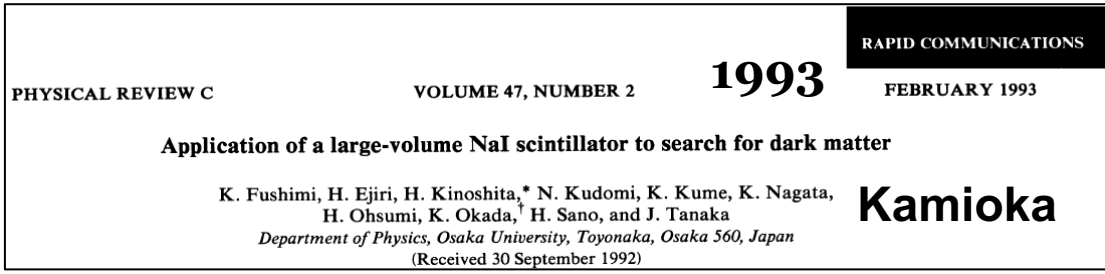
Search for neutralino dark matter with NaI detectors

LNGS

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

Show more

DAMA/LIBRA



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

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

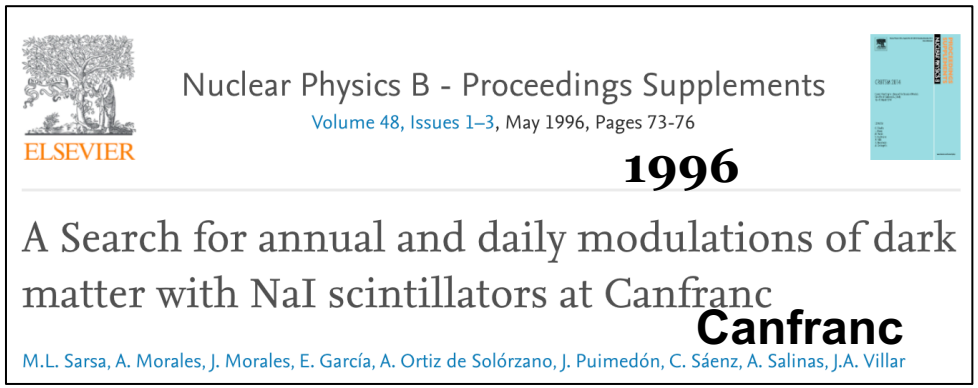
K. Fushimi, H. Ejiri, H. Kinoshita,* N. Kudomi, K. Kume, K. Nagata, H. Ohsumi, K. Okada,† H. Sano, and J. Tanaka

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

(Received 30 September 1992)

Kamioka

PICO-LON



ELSEVIER

Nuclear Physics B - Proceedings Supplements

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

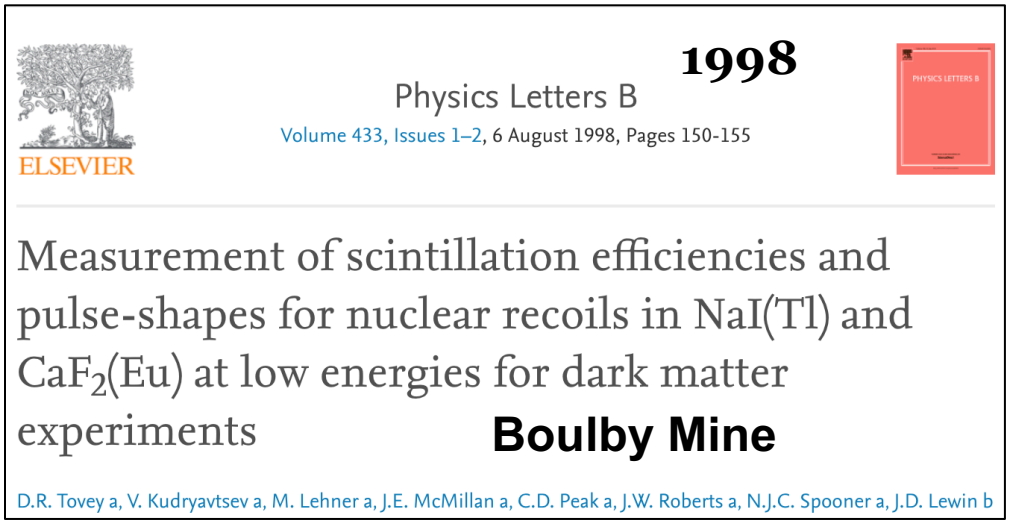
1996

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

ANAIS



ELSEVIER

1998

Physics Letters B

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

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

Boulby Mine

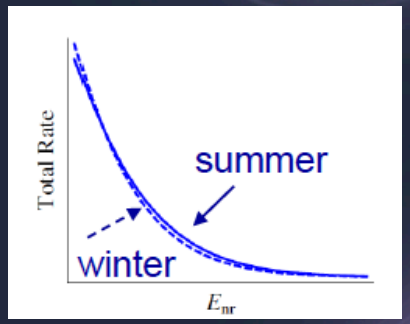
D.R. Tovey a, V. Kudryavtsev a, M. Lehner a, J.E. McMillan a, C.D. Peak a, J.W. Roberts a, N.J.C. Spooner a, J.D. Lewin b

COSINE

Annual modulation of dark matter

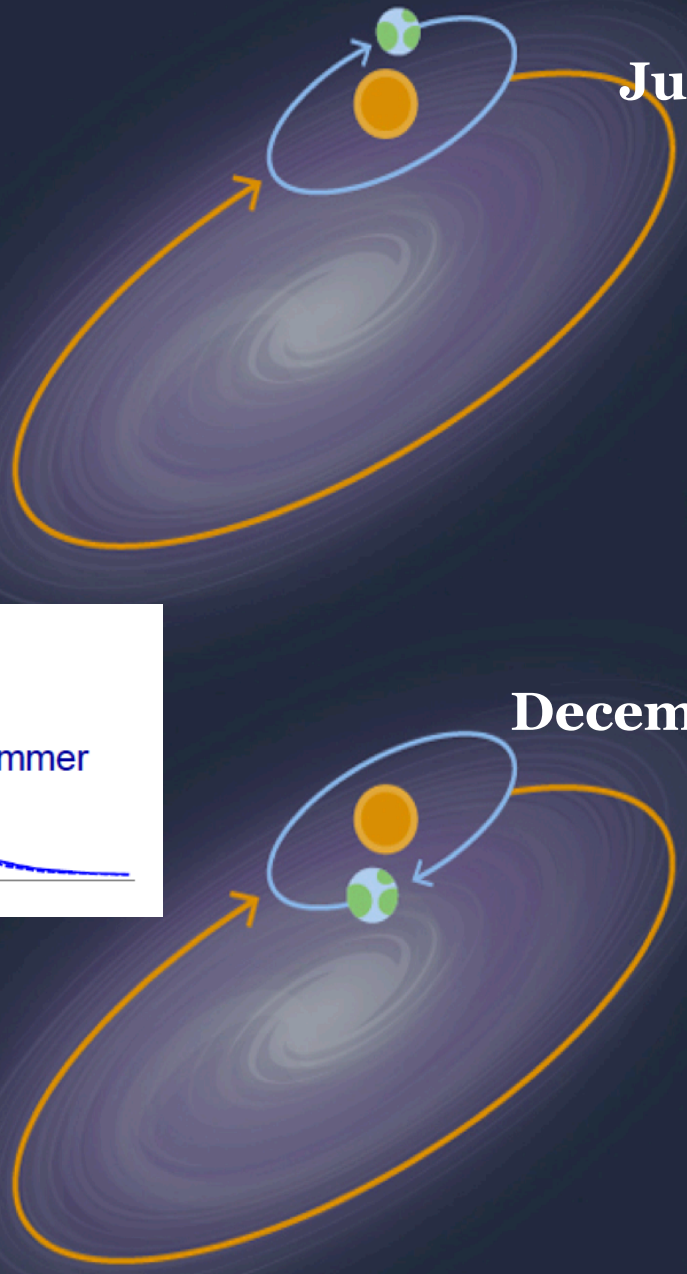
The Highs

In June, Earth moves at its fastest speed through the dark matter halo.



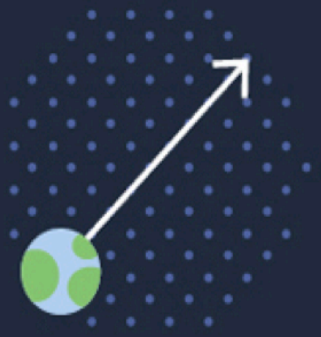
The Lows

In December, Earth moves at its slowest speed.

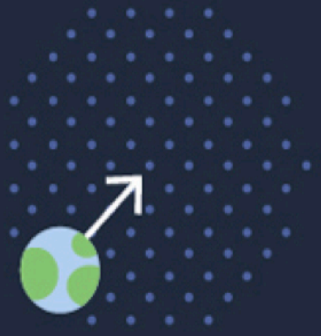


Sun and Earth move in the same relative direction

Earth and sun orbits are opposed



Earth passes through many dark matter particles

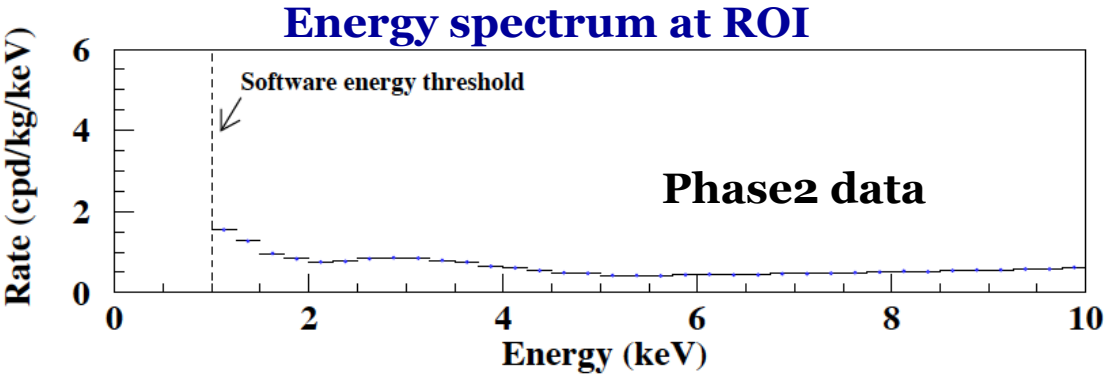


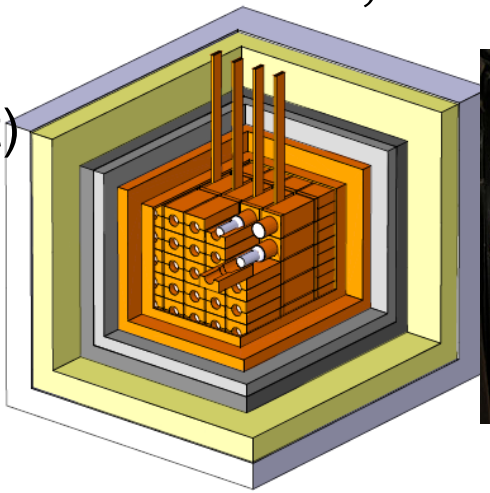
Earth encounters fewer particles

DAMA/LIBRA experiment

- Located at LNGS, Italy
- 25 x 9.70 kg NaI(Tl) detectors ~ 250 kg
- Search for the annual modulation signal
- Crystals grown by Saint-Gobain
  - Extensive R&D for low-background crystals
  - 0.85 ~ 1.3 counts/keV/kg/day (dru) background
- Light yield of 5~10 PE/keV

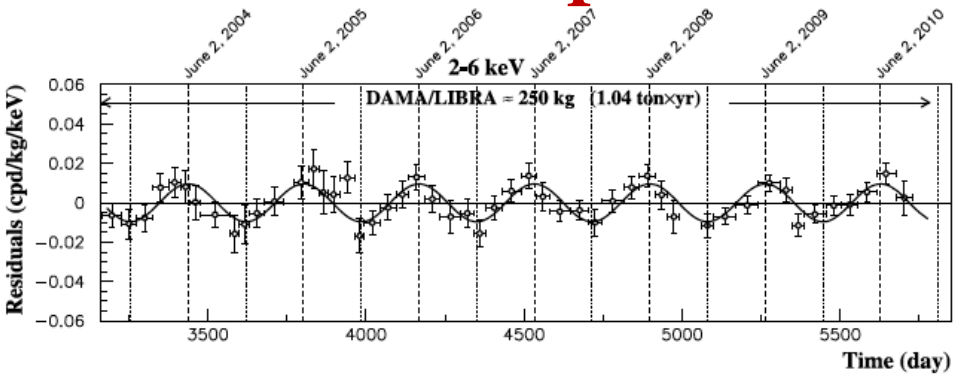
- DAMA/NaI (100 kg, 1996~2003) **First modulation result, PLB 424, 195 (1998)**
- DAMA/LIBRA-phase1 (250 kg, 2003-2010)
- DAMA/LIBRA-phase2 (250 kg, 2010~current)





Annual modulation signal from DAMA/LIBRA

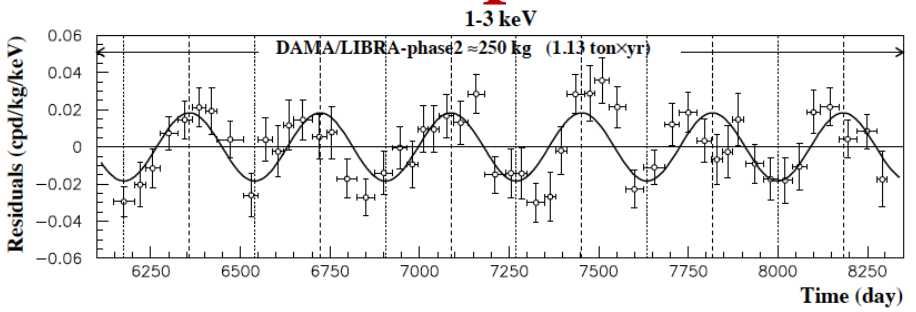
Phase1 experiment



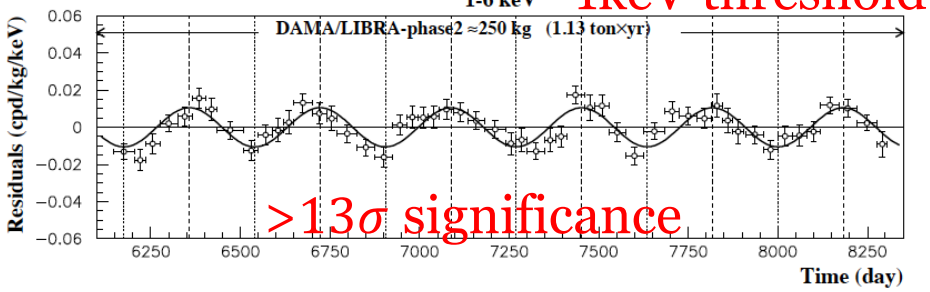
Eur. Phys. J. C 73:2648 (2013)

2keV threshold

Phase2 experiment



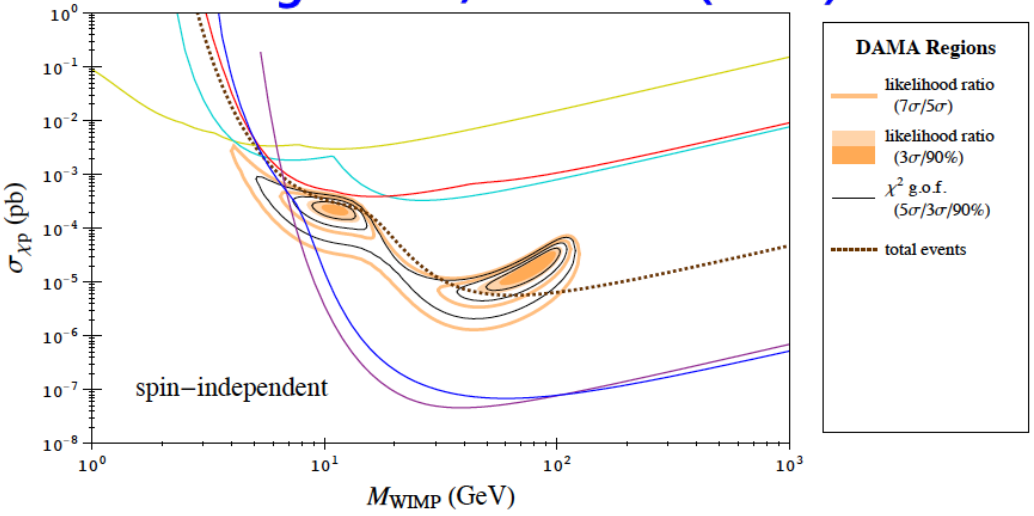
Nucl. Phys. At. Energy 19, 307 (2018)



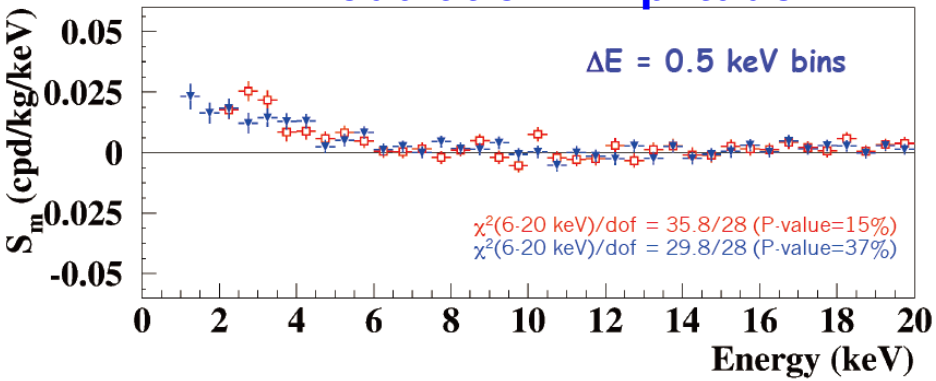
1keV threshold

>13σ significance

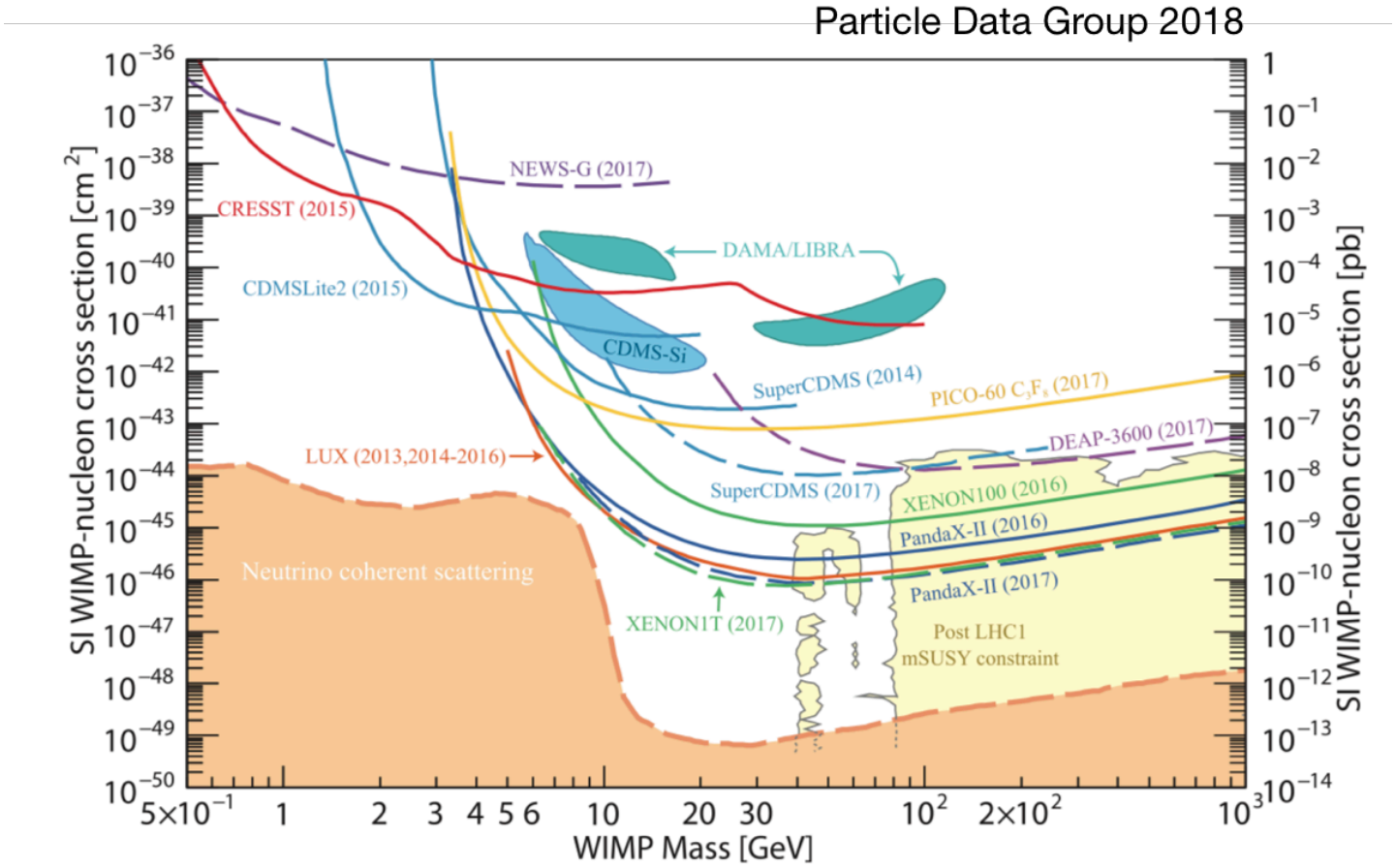
C. Savage *et al.*, JCAP 04 (2009) 010



Modulation Amplitude

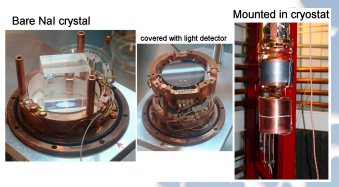


However…

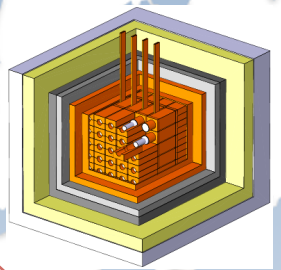


- Is NaI special for certain types of dark matter?
- Modulation signals vs time-averaged limits?
- Environmental effects? **Better to have another NaI experiments**

Global NaI(Tl) efforts

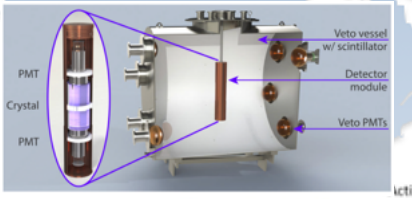


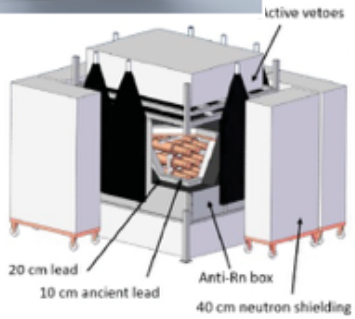
COSINUS @ LNGS



DAMA @ LNGS

SABRE @ LNGS

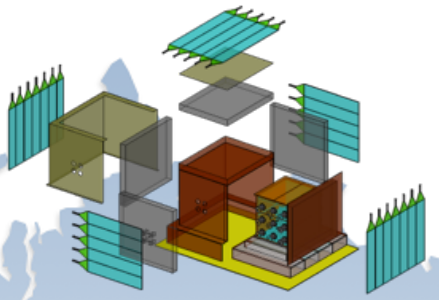




ANAIS @Canfranc

In Data-taking

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



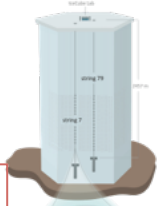
KIMS/COSINE @ Yangyang

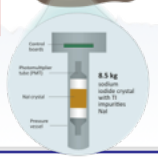
In Data-taking

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

PICO-LON @ Kamioka

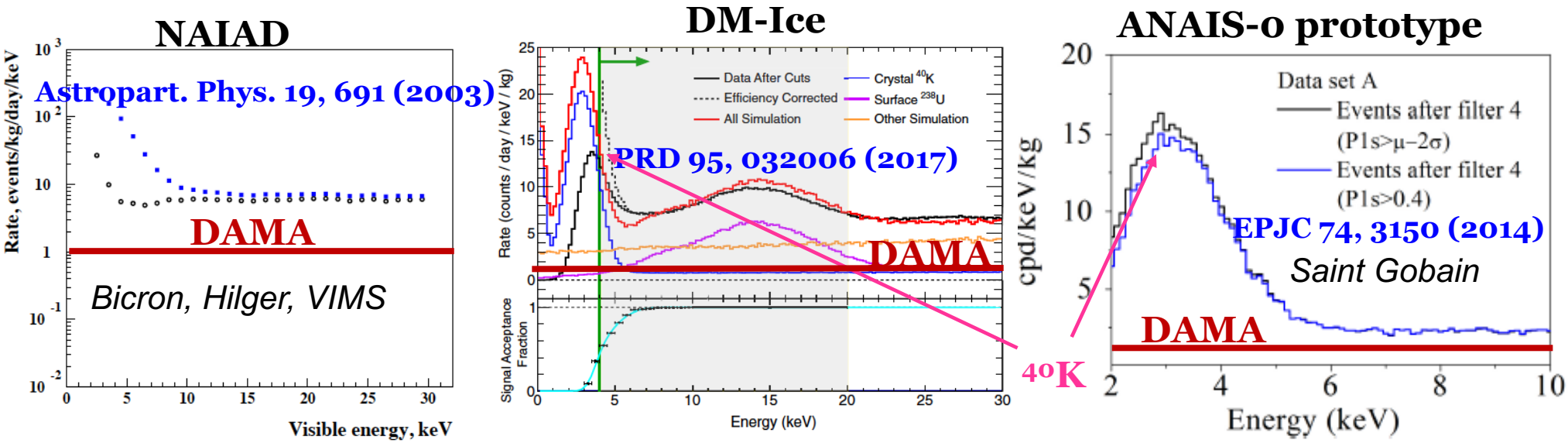
SABRE @ Stawell





DM-Ice @ South Pole

Why it is so hard to reproduce DAMA?

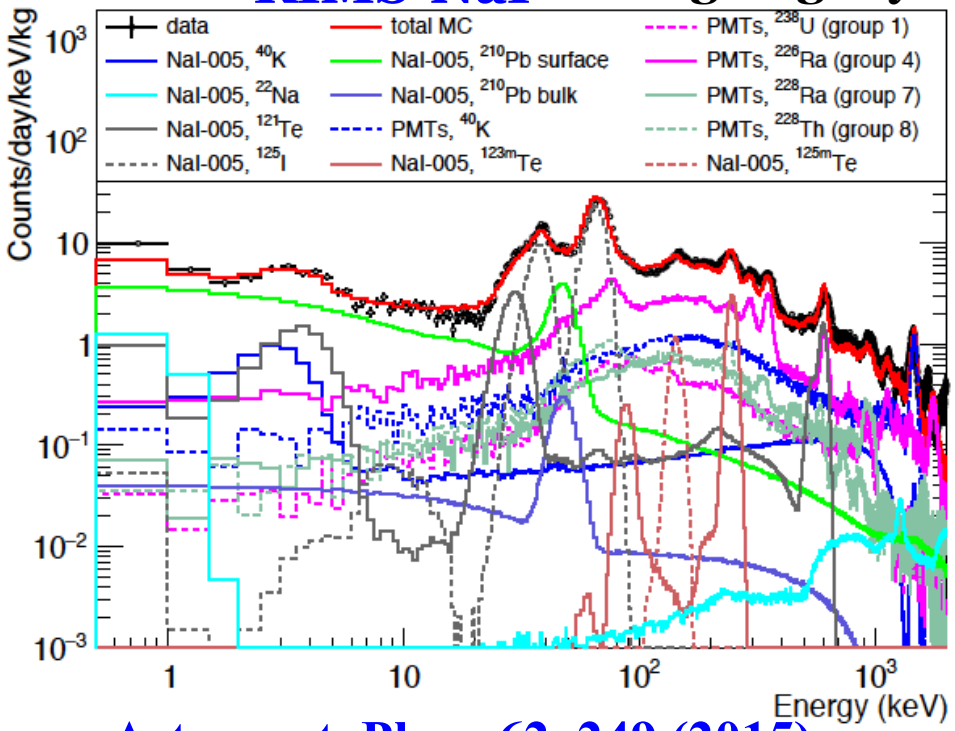


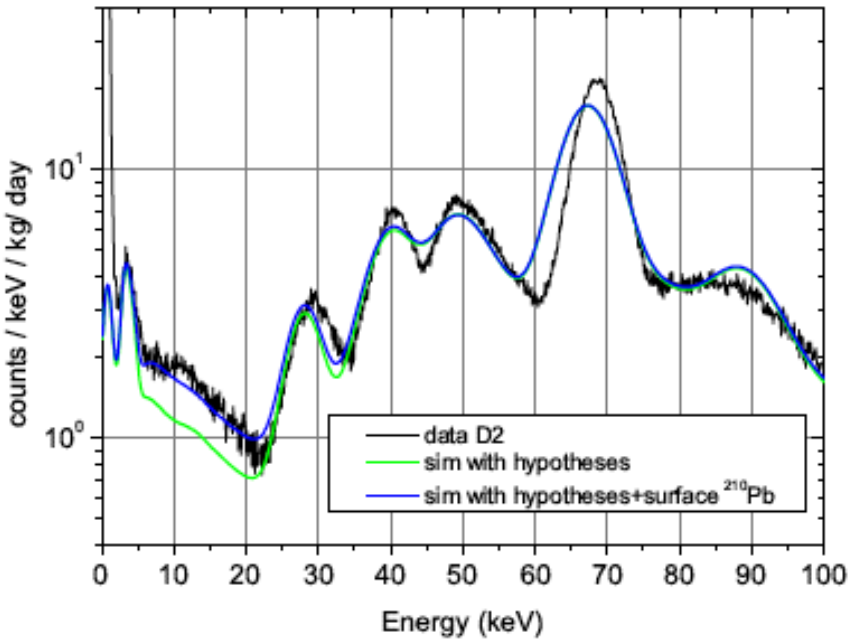
- No other experiments achieve the low-background rate of NaI(Tl)
- Saint-Gobain lost the technique for low-background NaI(Tl) crystals
  - Confidential contraction between DAMA and Saint-Gobain was finished already

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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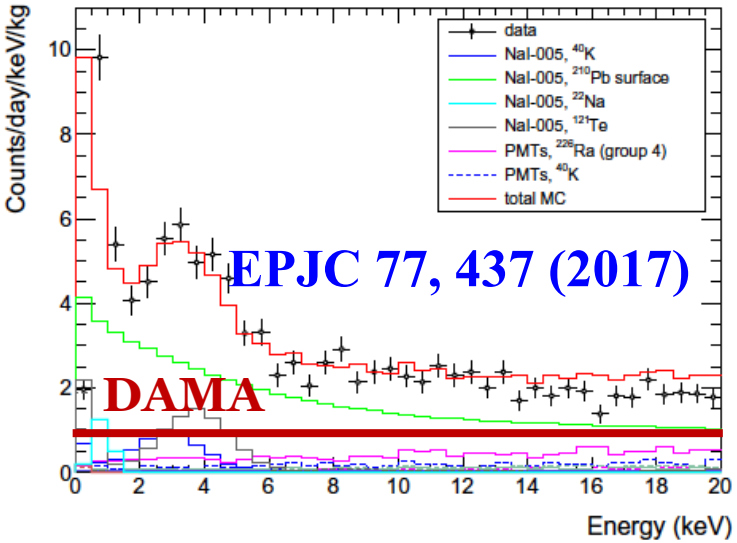
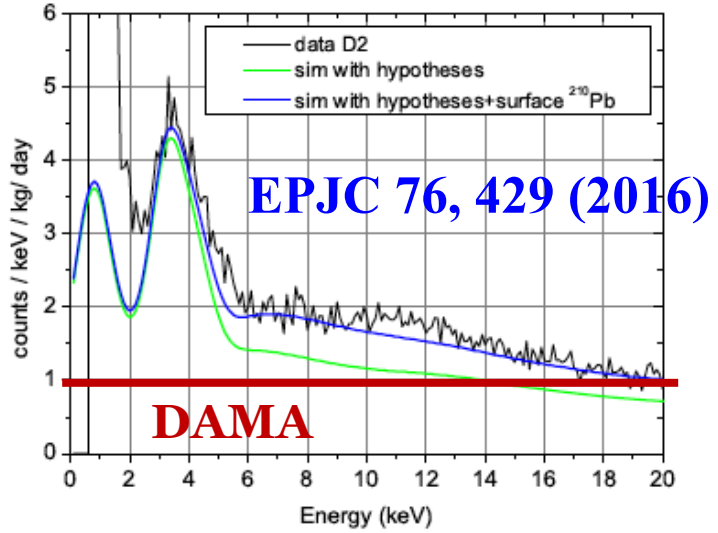




COSINE-100 **ANAIS-112**

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**)

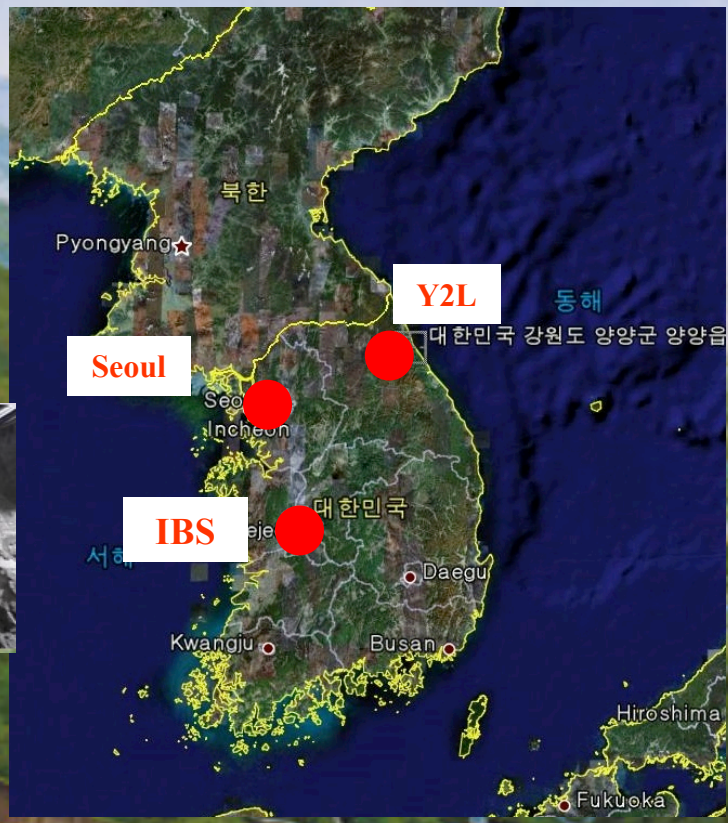
YangYang(Y2L) Underground Laboratory

(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 detector configuration

arXiv:2005.13672 JINST 13 T02007 (2018)

Nucl. Instrum. Meth. A 851 103 (2017)

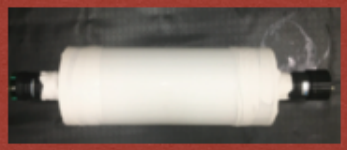
4π Muon Counter
37 plastic scintillator panels
2-inch PMT(H7195)s for muon counter

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

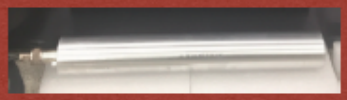
arXiv:2004.03463

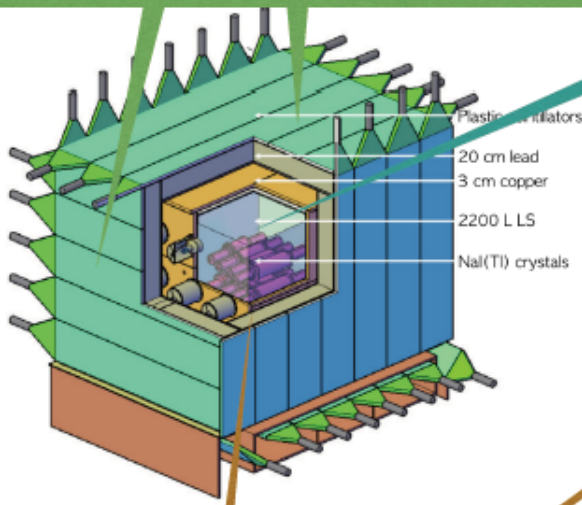
JINST 13 T06005 (2018)

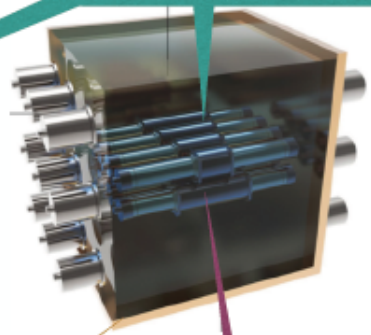
Neutron Monitoring
Fast neutron detector
(Liquid scintillator)

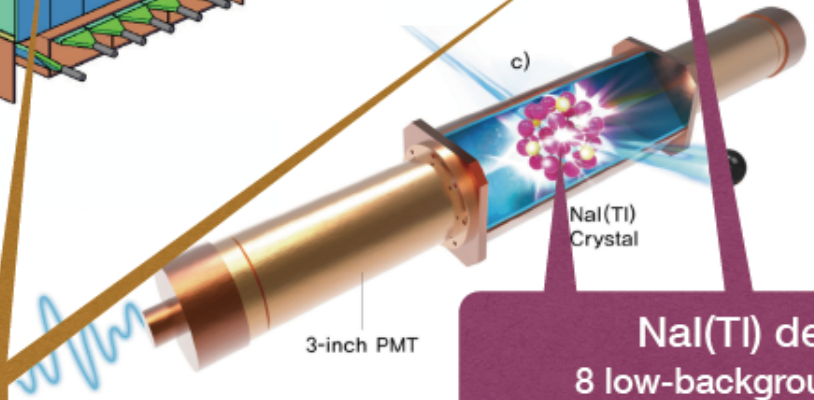


Thermal neutron detector
(^{3}He gas detector)







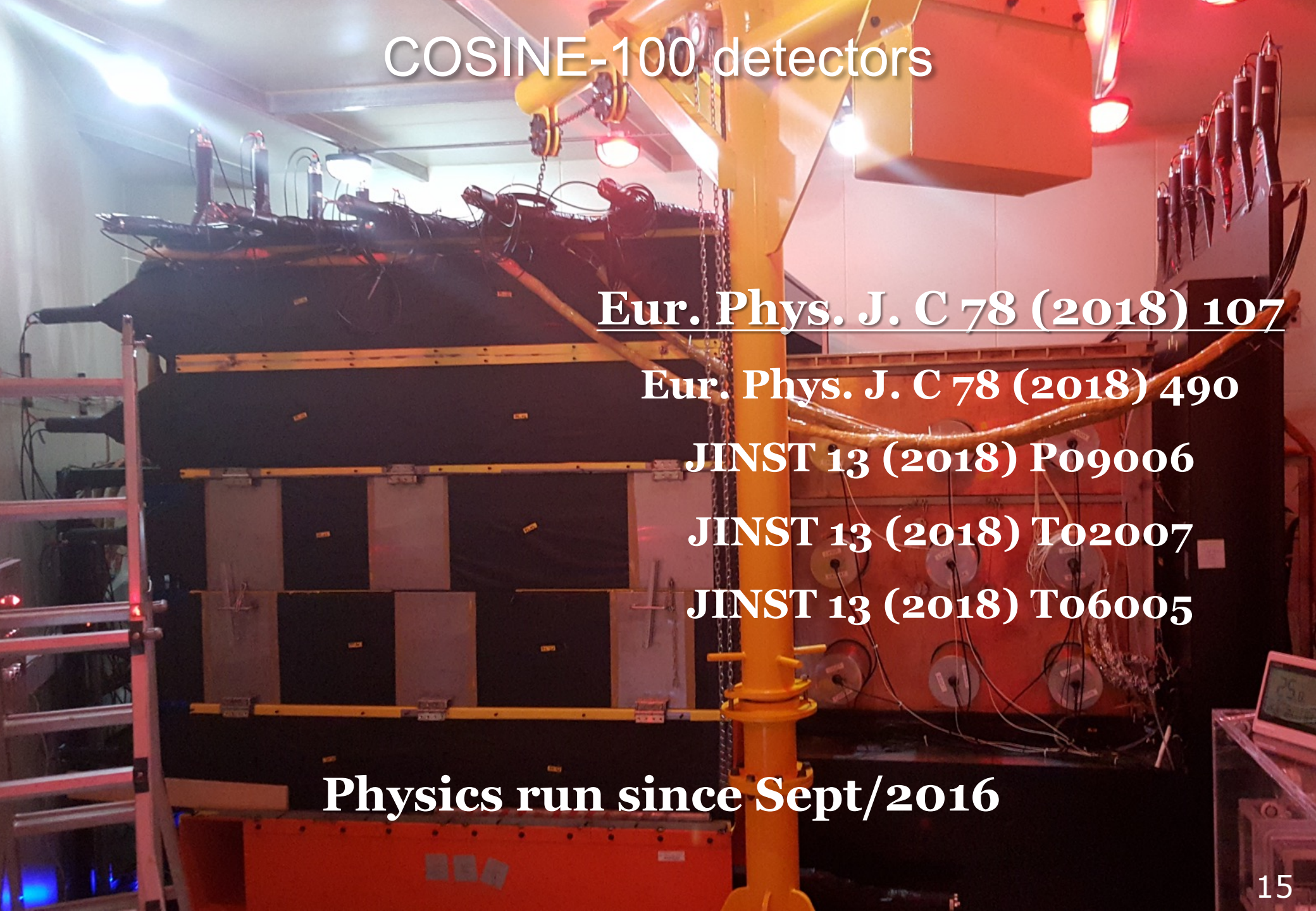


Shields
3-cm thick copper box
20-cm thick lead shielding

NaI(Tl) detector
8 low-background crystals
Each crystal is encapsulated in copper
Two 3-inch PMTs for each crystal
(R12669SEL)

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

COSINE-100 detectors



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

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

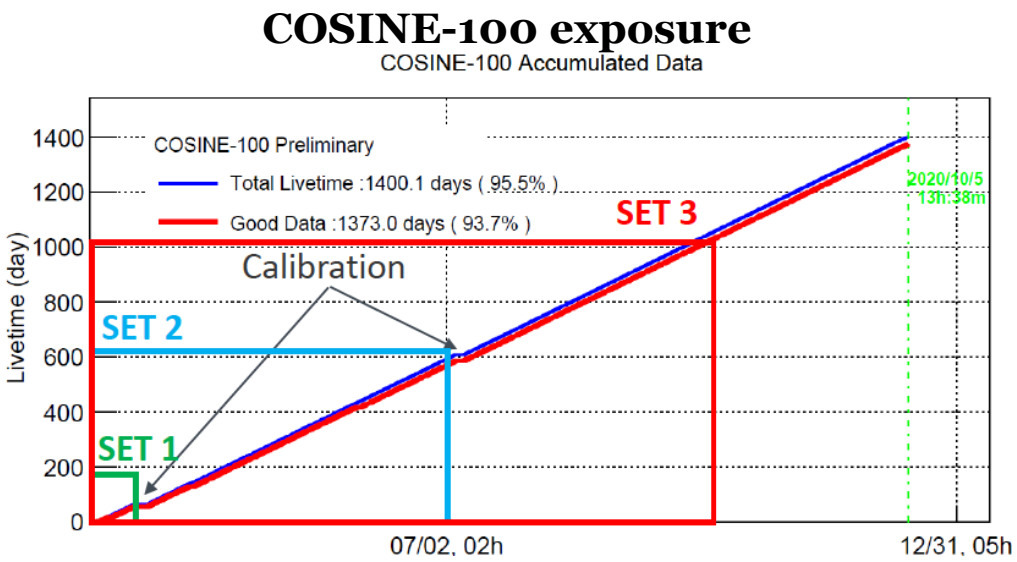
JINST 13 (2018) P09006

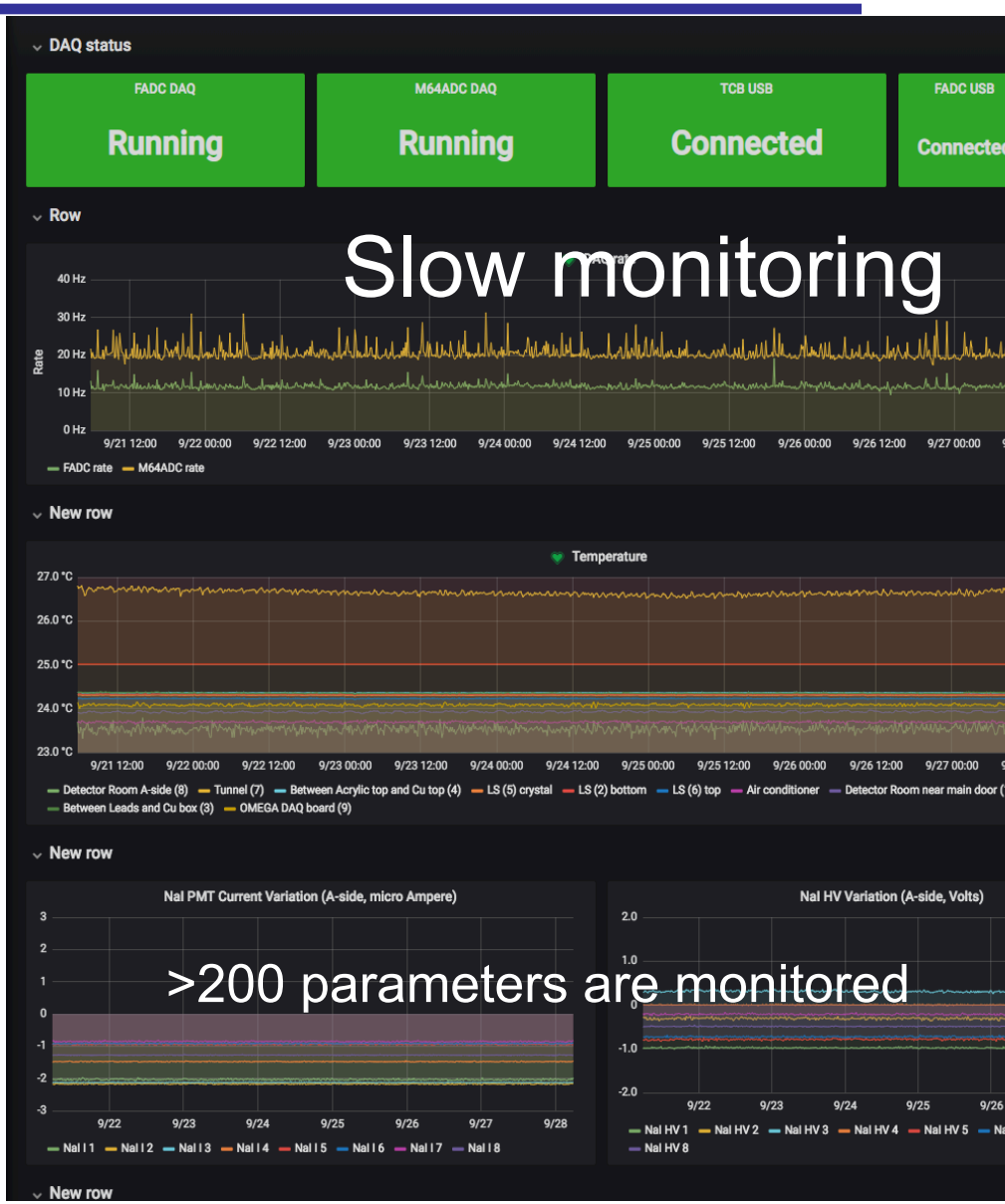
JINST 13 (2018) T02007

JINST 13 (2018) T06005

Physics run since Sept/2016

COSINE-100 operation

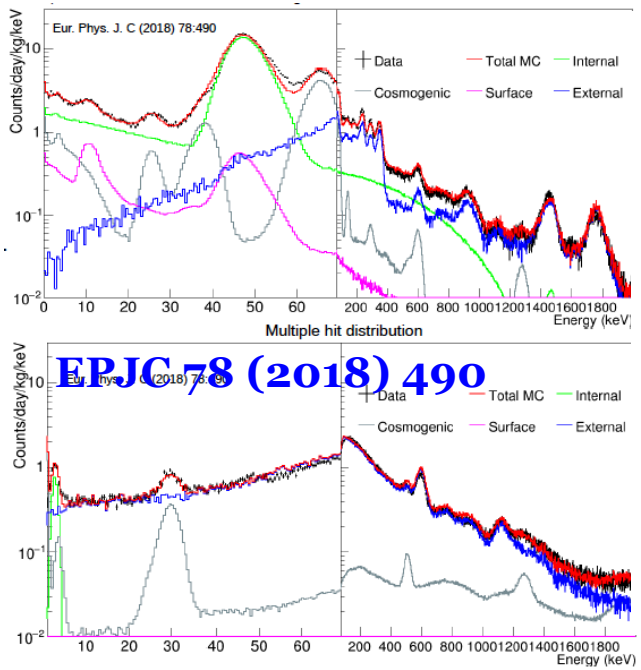




- Stable physics run
  - ❖ >95% physics data
  - ❖ >93% good runs
- In operation for > 4 years
  - ❖ ~ 4 years good data

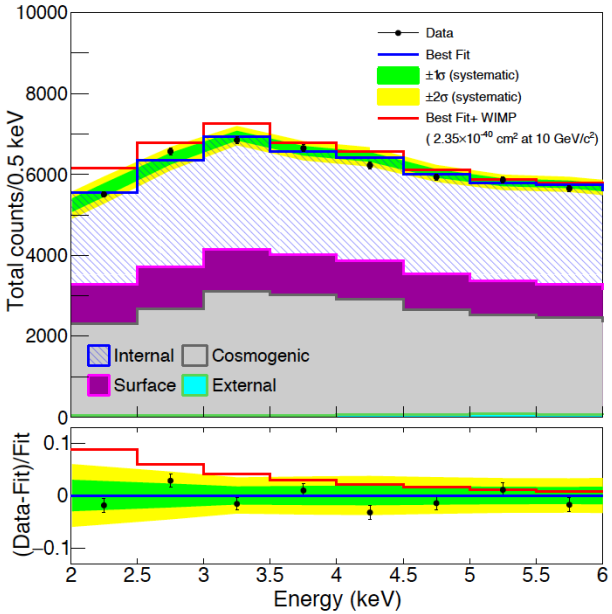
COSINE-100 Physics results (2 keV threshold)

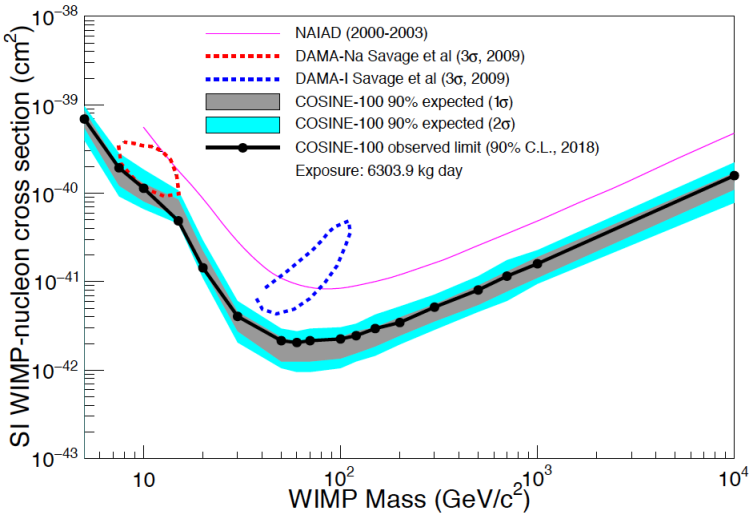
Background modeling (59.5 days)



EPJC 78 (2018) 490

WIMP Search (59.5 days)

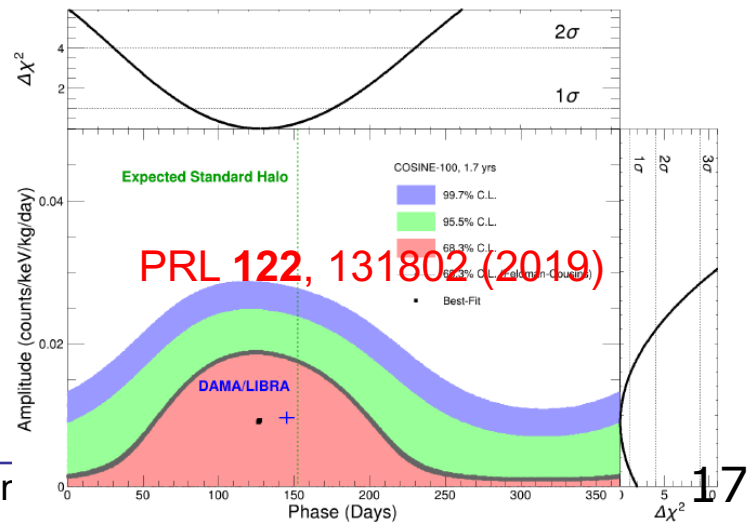




Nature **564**, 83 (2018)

Annual Modulation analysis (**1.7** years)

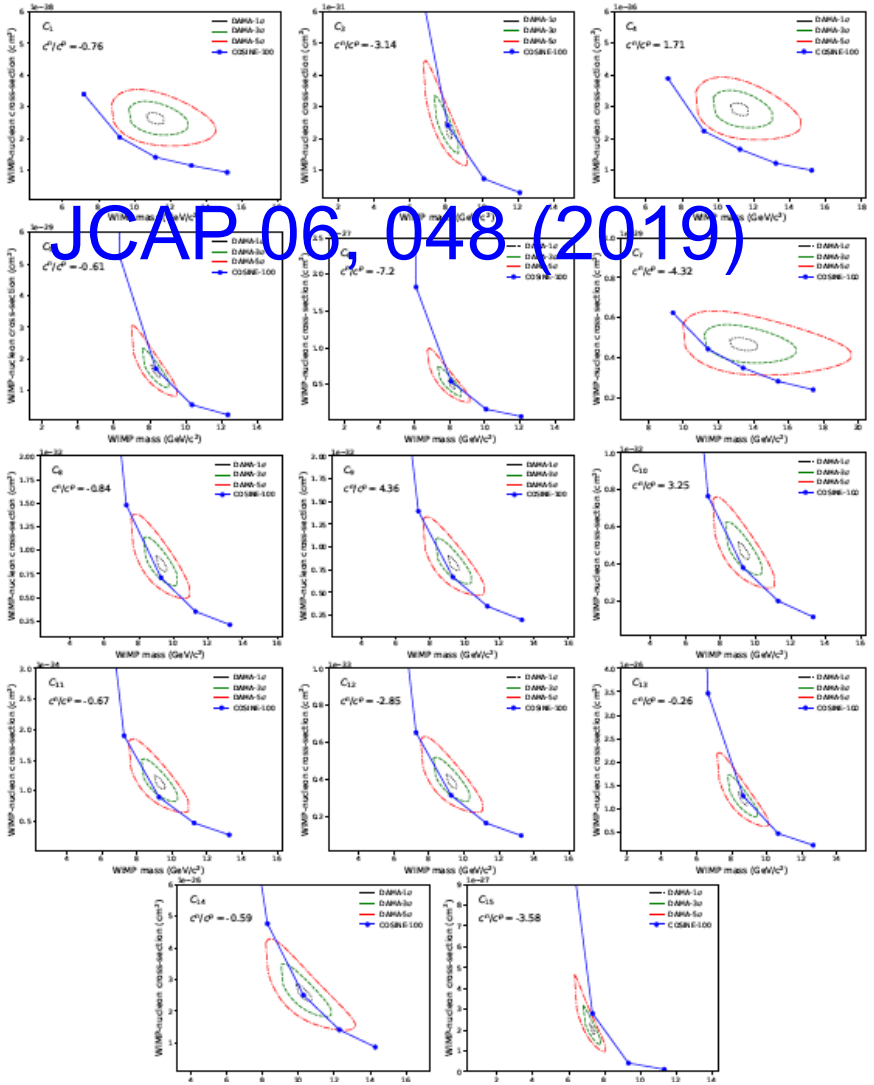
Config	Amplitude (2-6 keV)	Phase (days)
COSINE-100	$\mathbf{0.0083 \pm 0.0068}$	**152.5 (fixed)**
ANAIS	-0.0044 ± 0.0058	152.5 (fixed)
DAMA	0.0095 ± 0.0008	152.5 (fixed)
COSINE-100	0.0092 ± 0.0067	127 ± 46
DAMA	0.0096 ± 0.0008	145 ± 5



PRL **122**, 131802 (2019)

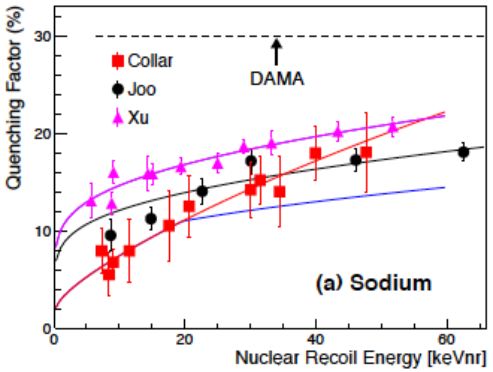
Other interpretations

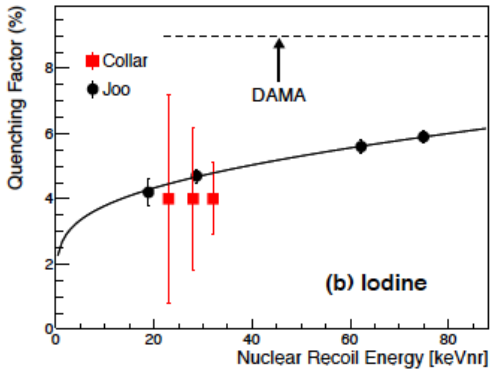
Test 15 Effective Field Theory operators



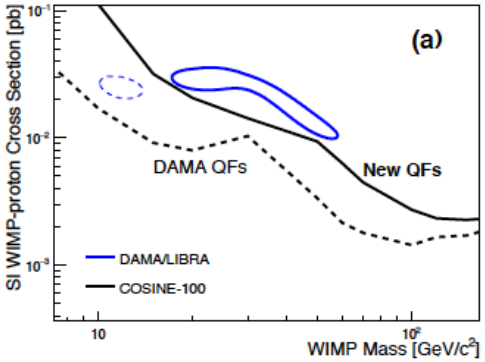
JCAP 06, 048 (2019)

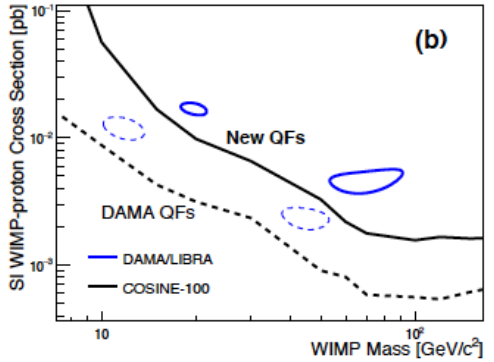
Quenching factors & DAMA/LIBRA phase1+phase2





JCAP 11, 008 (2019)



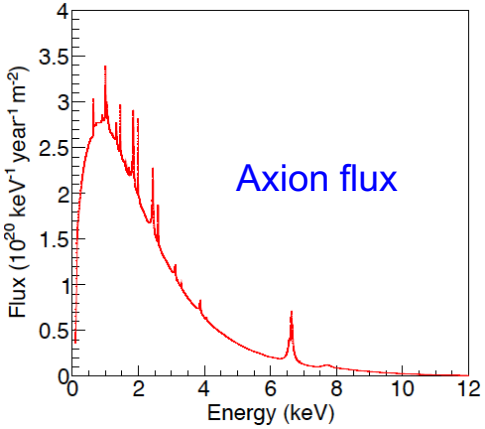


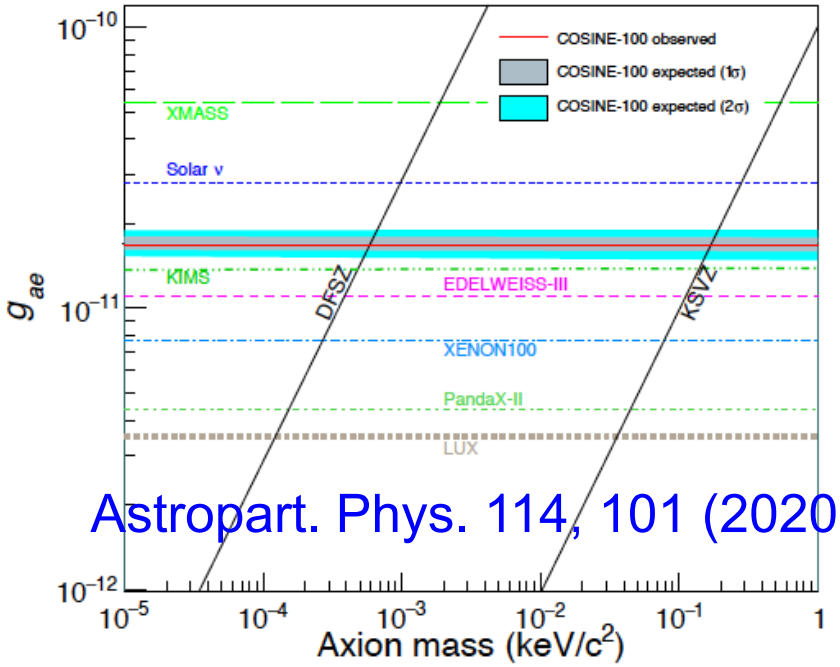
Isospin violating interaction

Best fit region of DAMA was not fully covered yet

Other DM candidates

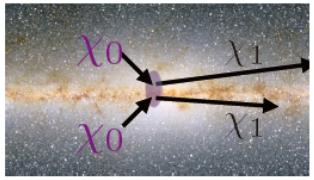
Solar Axion

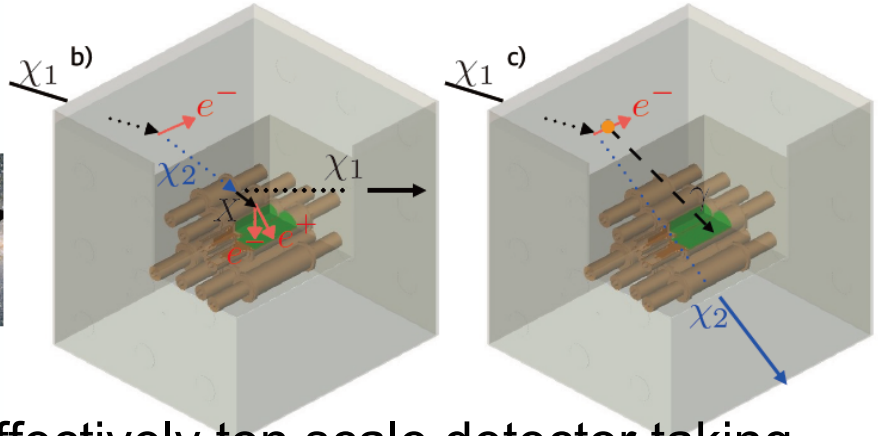




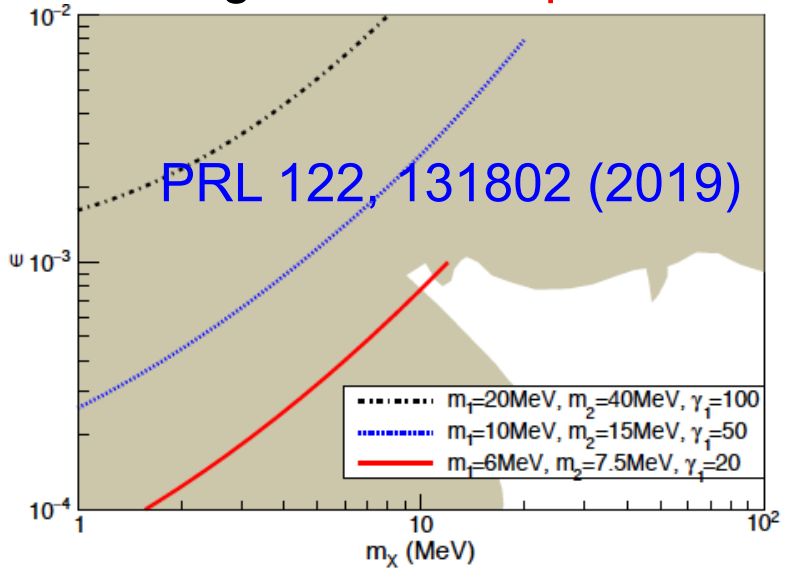
Astropart. Phys. 114, 101 (2020)

Inelastic boosted dark matter





Effectively ton scale detector taking advantage of 2 ton liquid scintillator

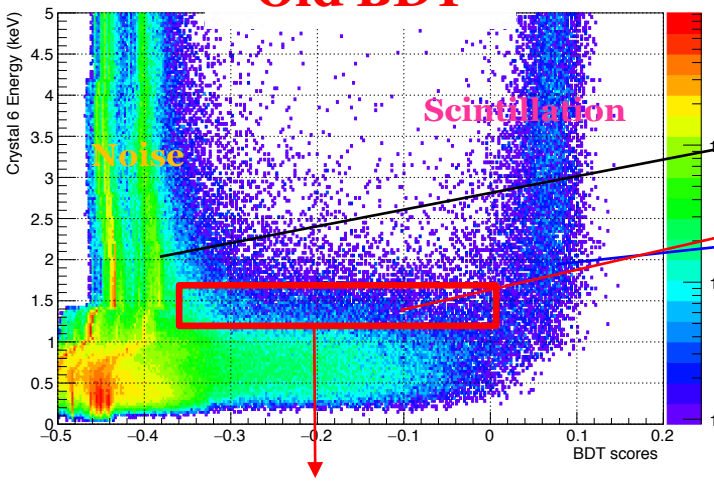


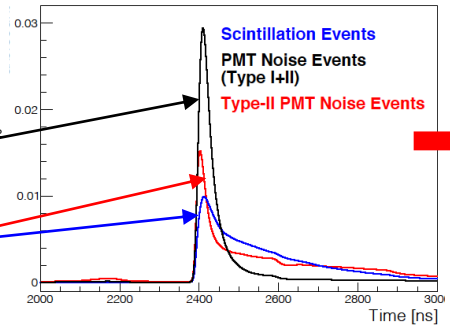
Lowering energy threshold

Reduced threshold from 2 keV to 1 keV with better noise control

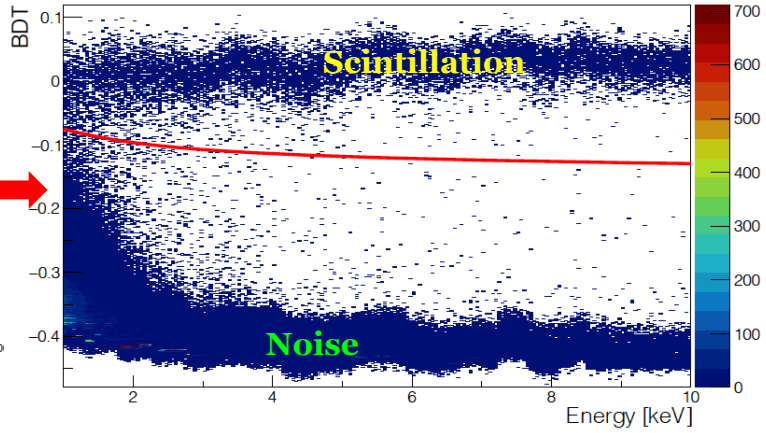
Use ~ two years data

Old BDT

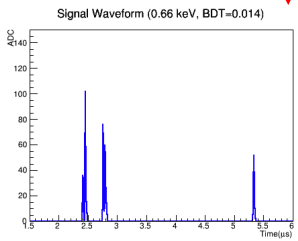


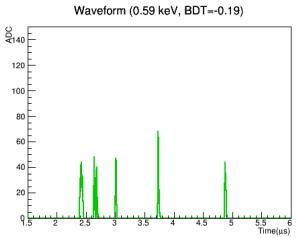


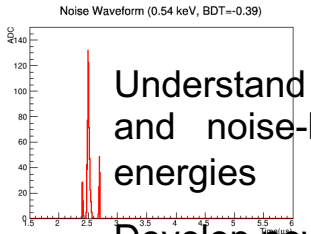
New BDT



arXiv:2005.13784



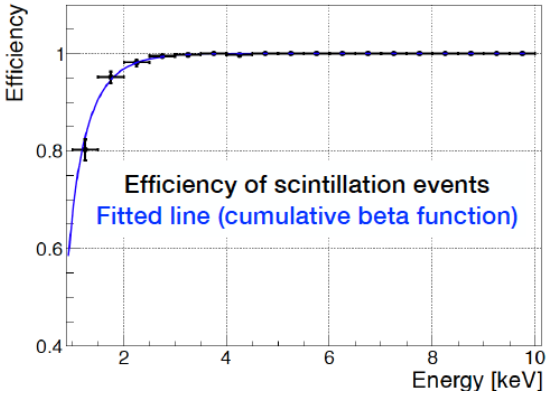




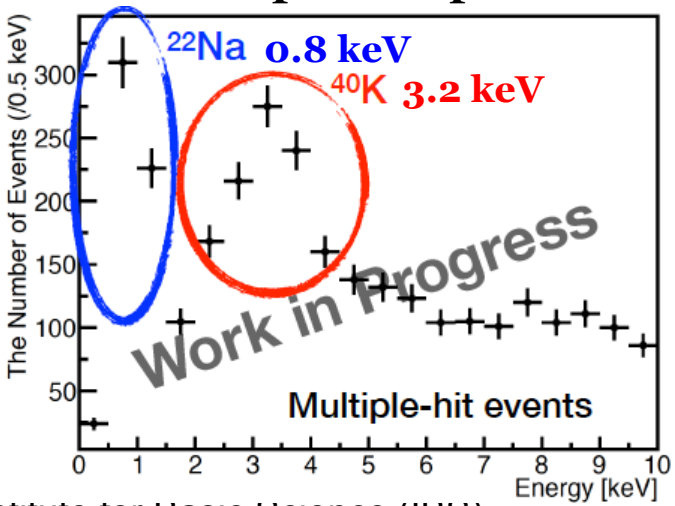
Understand signal-like events and noise-like events at low energies

Develop new parameter for BDT

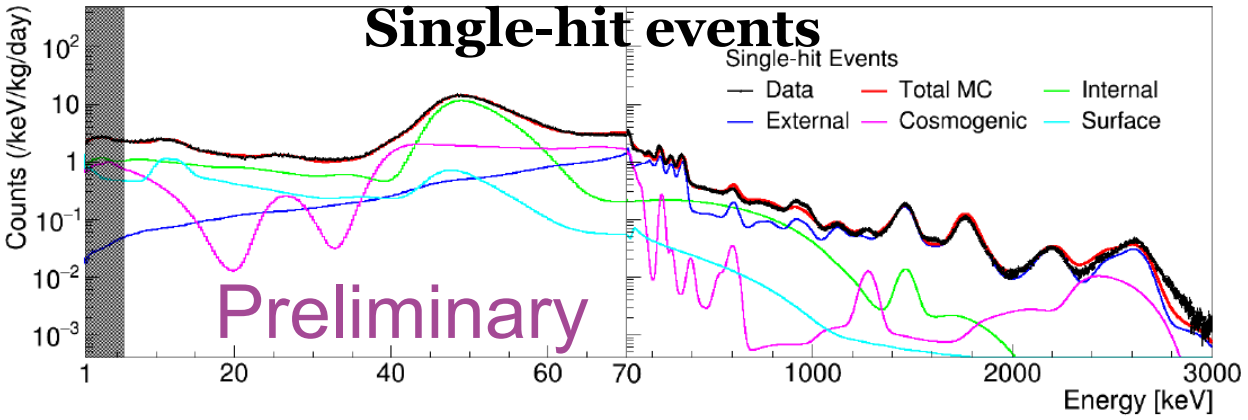
Selection Efficiency

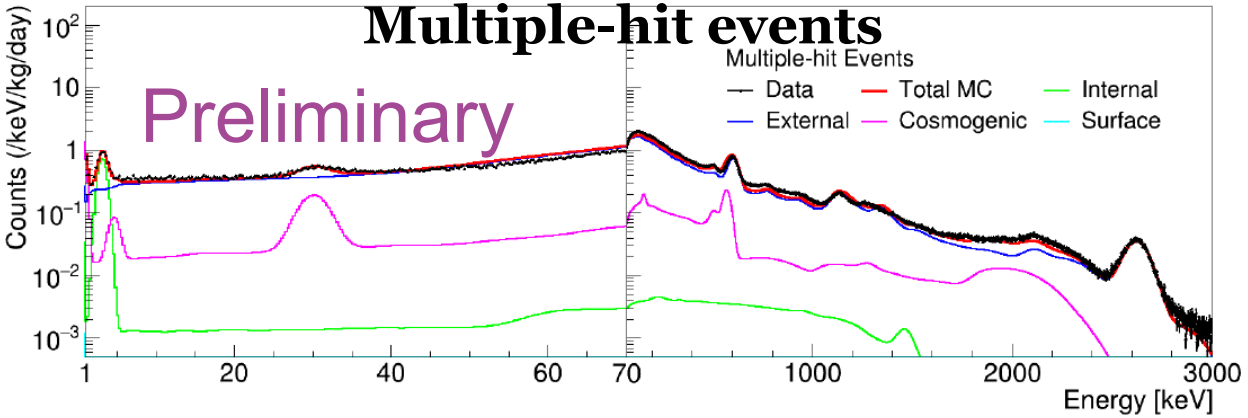


Multiple-hit spectrum



Background modeling (1.7 years)

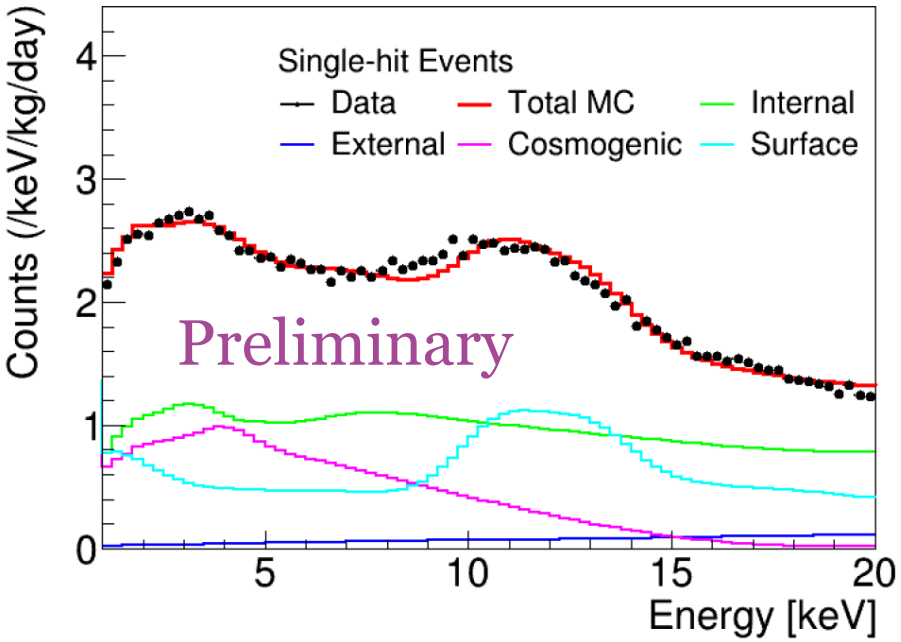




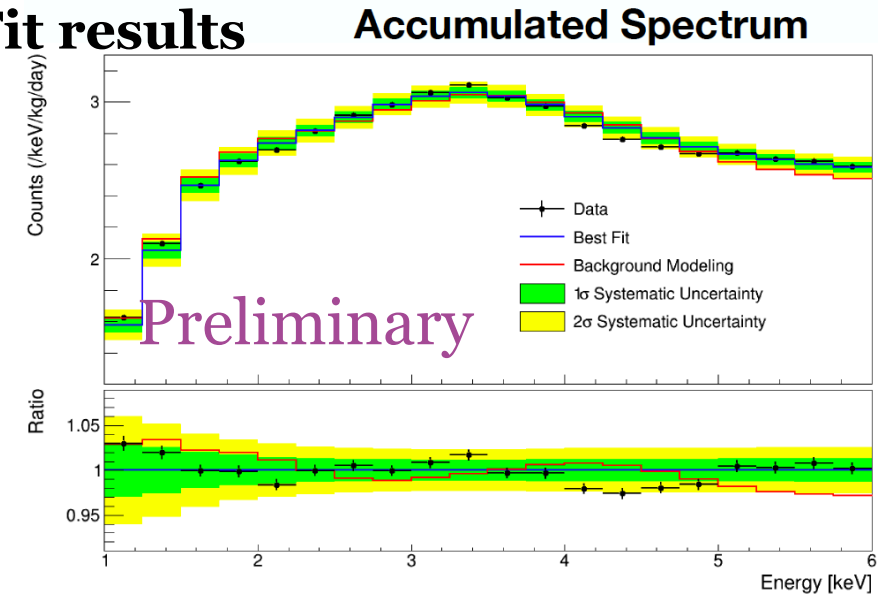
- Improved background modeling
  - ^{129}I, rock-gamma (^{208}Tl) are added
  - Better modeling of surface ^{210}Pb using contaminated crystal (Astropart. Phys. 126 (2021) 102528)

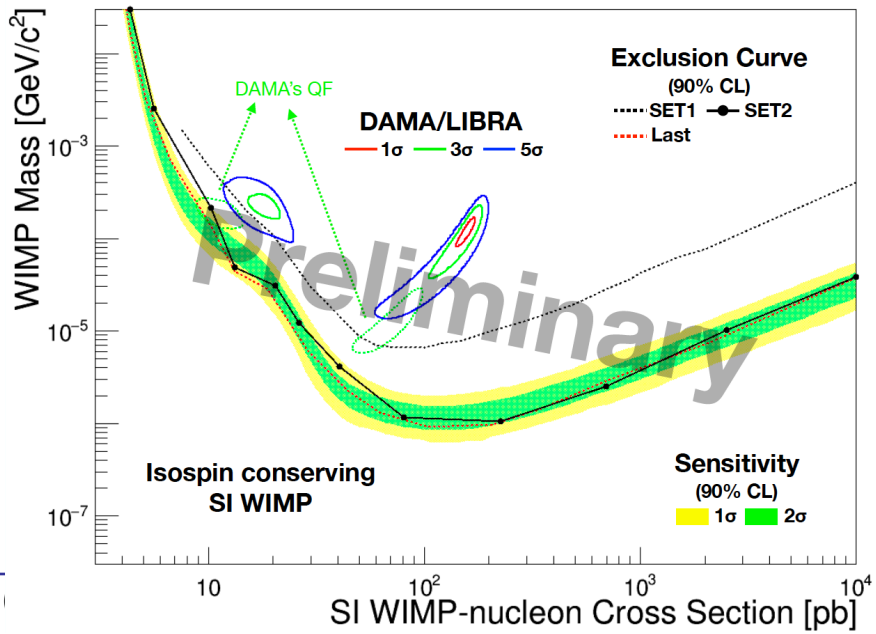
WIMP Search results (1.7 years)

Low energy signal region



Fit results





~ an order of magnitude better results than the previous result

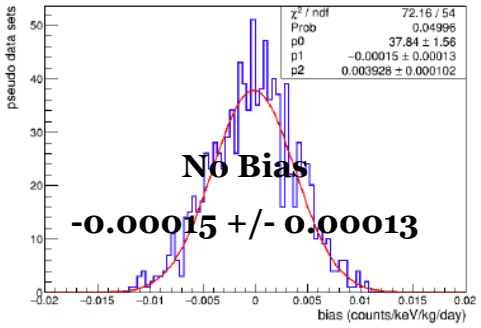
Other interpretation is ongoing

Annual Modulation Analysis

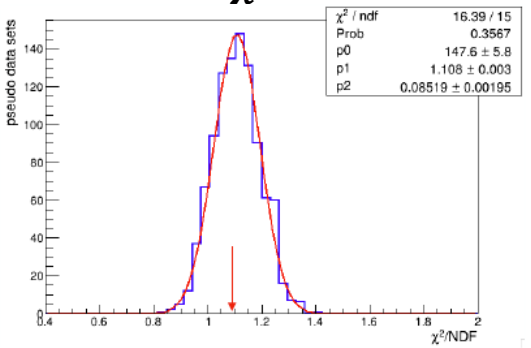
- More data ~ 3 years
- 1keV energy threshold
- Improved event selection
- Improved background modeling
- Develop Bayesian toolkits
- Realistic pseudo experiments for testing machinery

1,000 Pseudo experiments

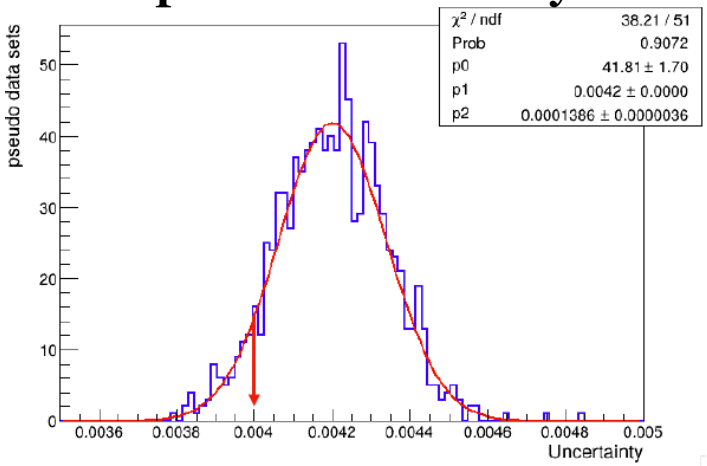
Bias

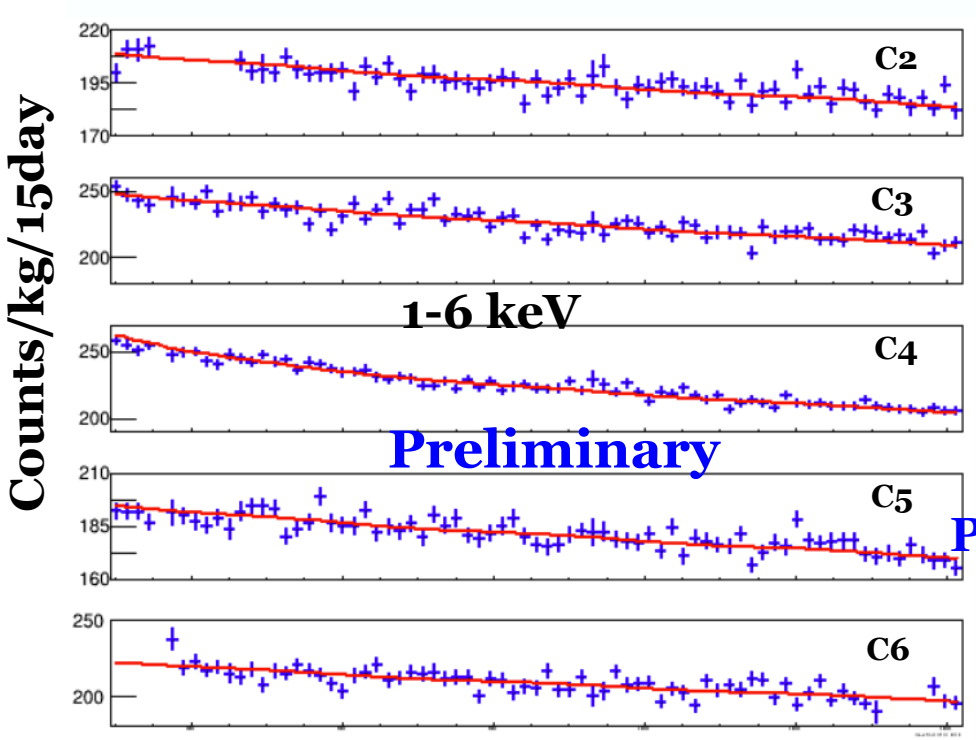


χ^2



Expected Uncertainty





Preliminary result : 0.0061+/-0.0040 dru

DAMA/LIBRA : 0.0106+/-0.0011 dru

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

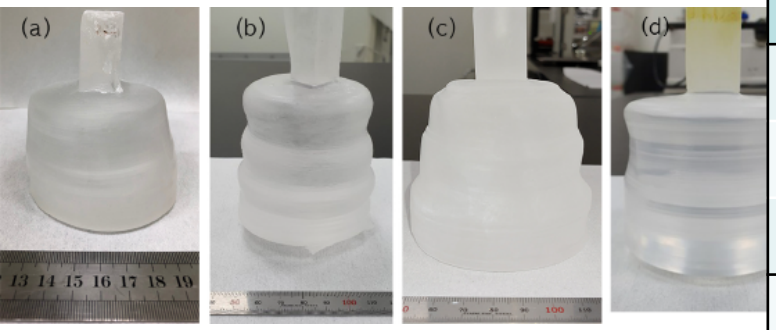
K.A. Shin et al., J. Rad. Nucl. Chem. 317, 1329 (2018)

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

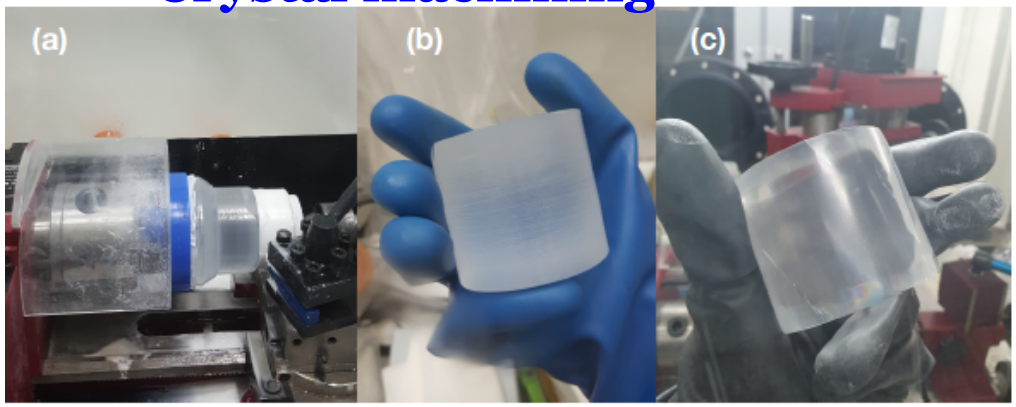
Our grown crystals

Crystal ingots



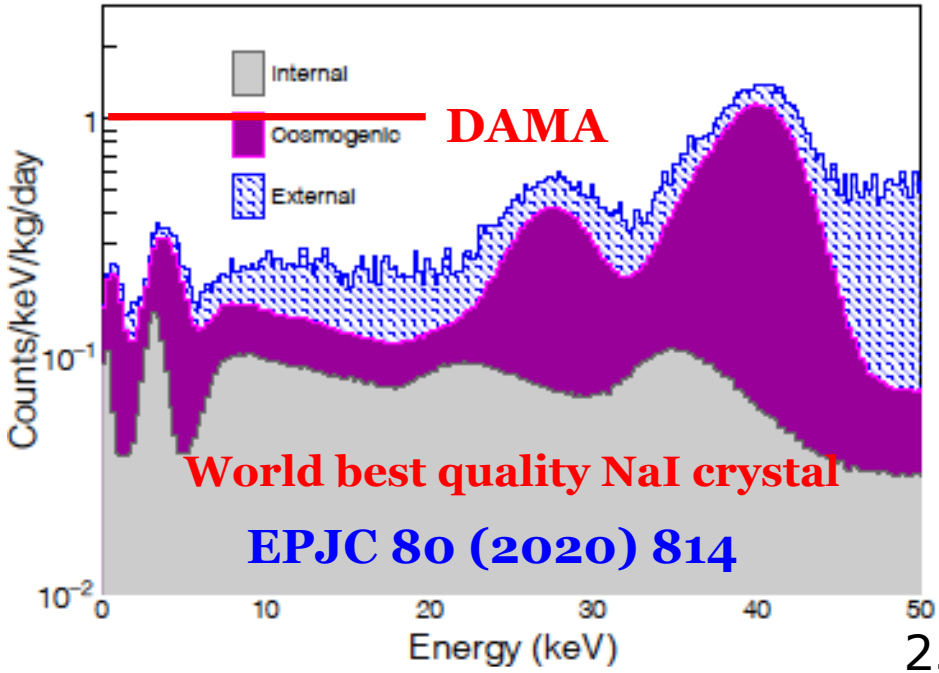
	K (ppb)	^{210}Pb (mBq/kg)	^{238}U (μBq/kg)	^{232}Th(μBq/k
Powder	5	-	<20	<20
Aug/2018	684	3.8+/-0.3	26+/-7	<6
Sept/2019	**8**	**0.01+/-0.02**	**11+/-4**	**7+/-2**
DAMA	<20	0.01~0.03	8.7~124	2~31

Crystal machining



Detector assembly

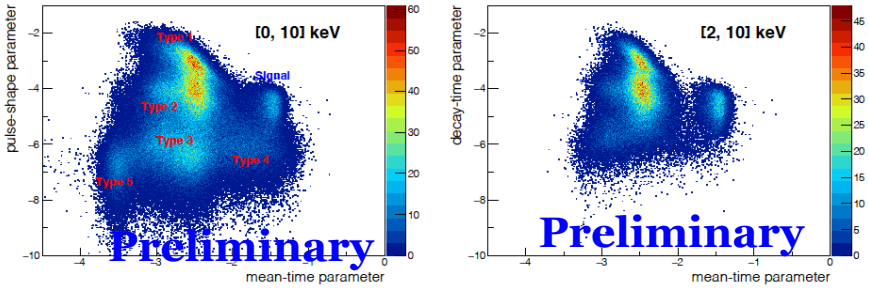
Expected background

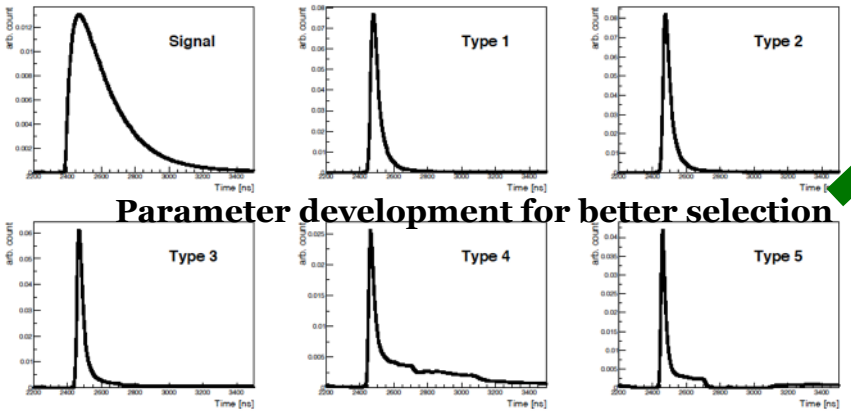


A proof of principle for low background NaI

Low-threshold NaI(TI) detectors

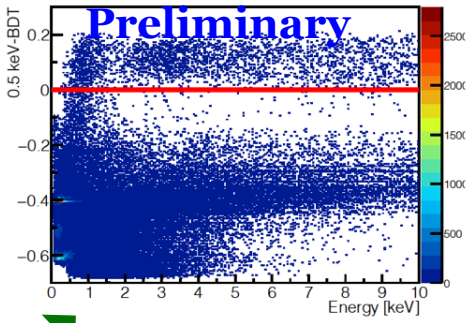
New parameters for BDT





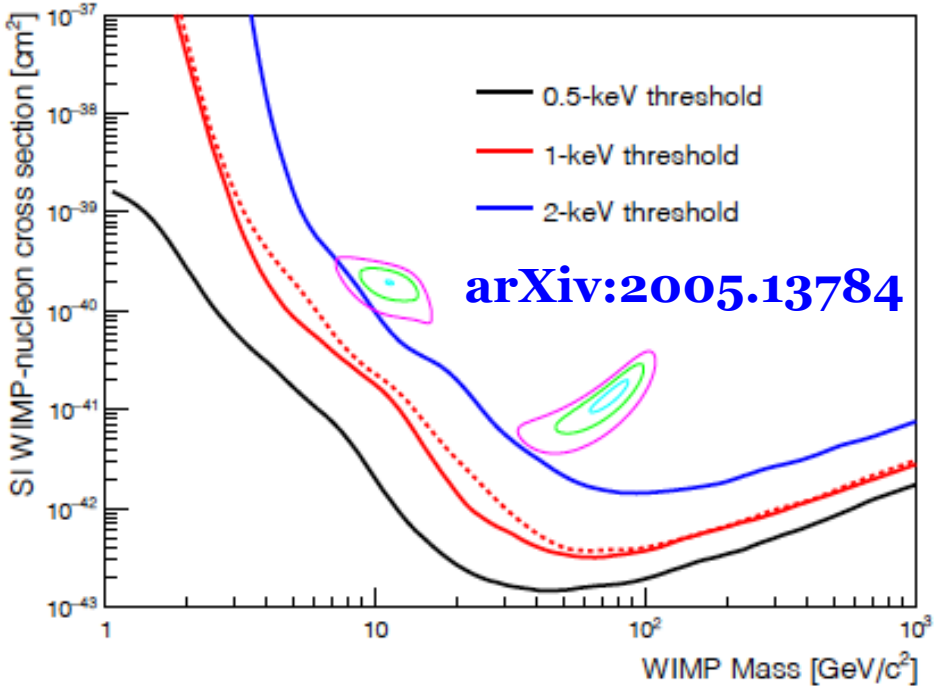
Parameter development for better selection

Goal : 0.5 keV threshold with COSINE-100

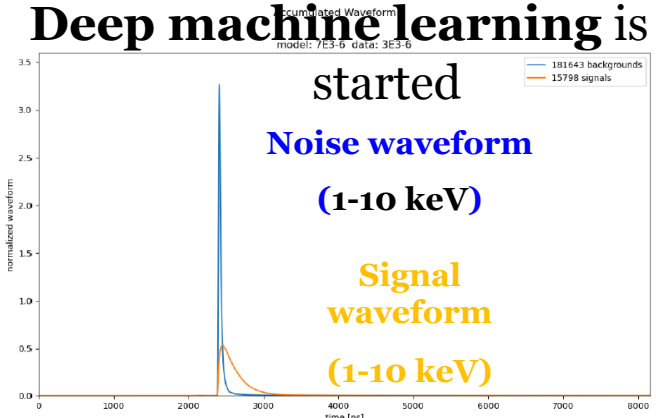


Multiple-hit

~ 0.4 keV (6 NPE) threshold achievable!!

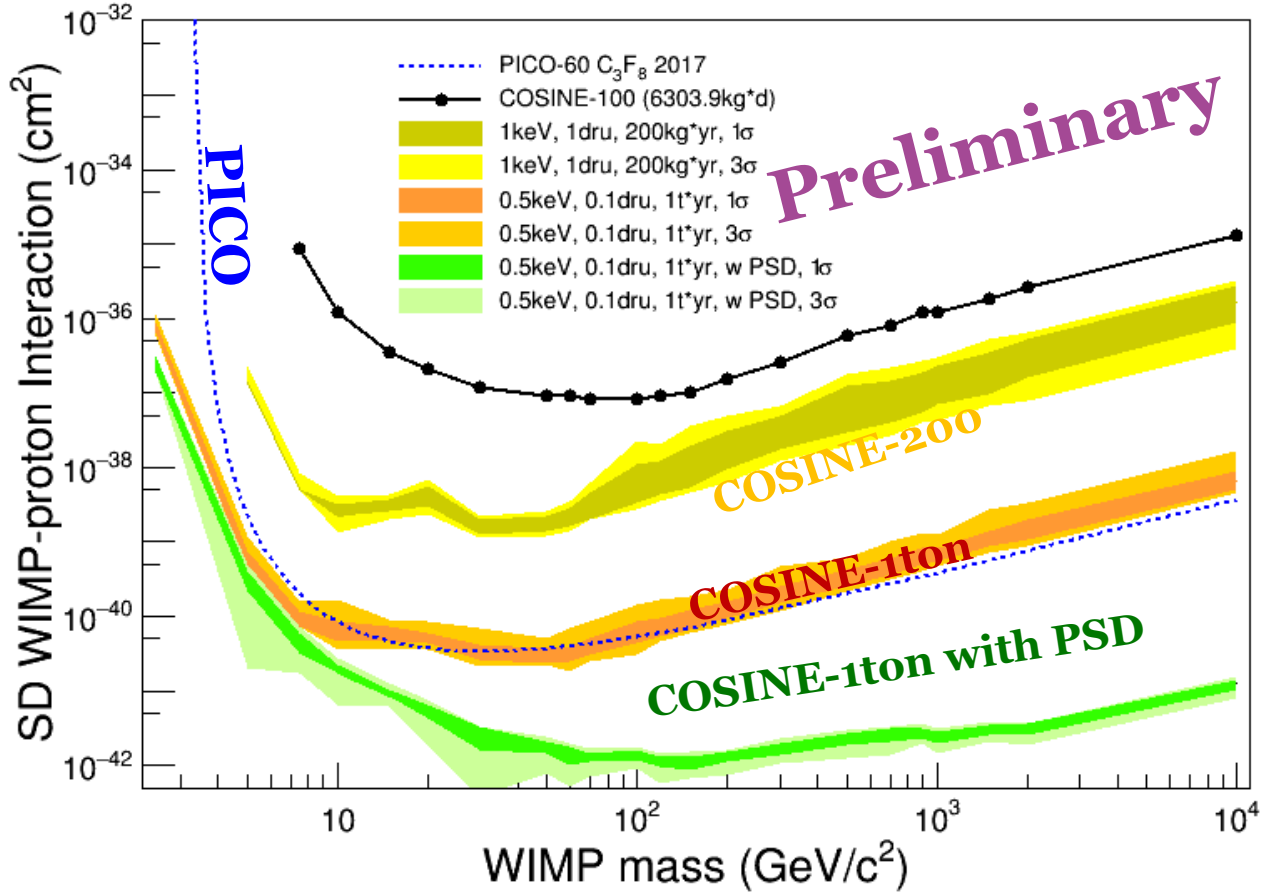


Deep machine learning is also started

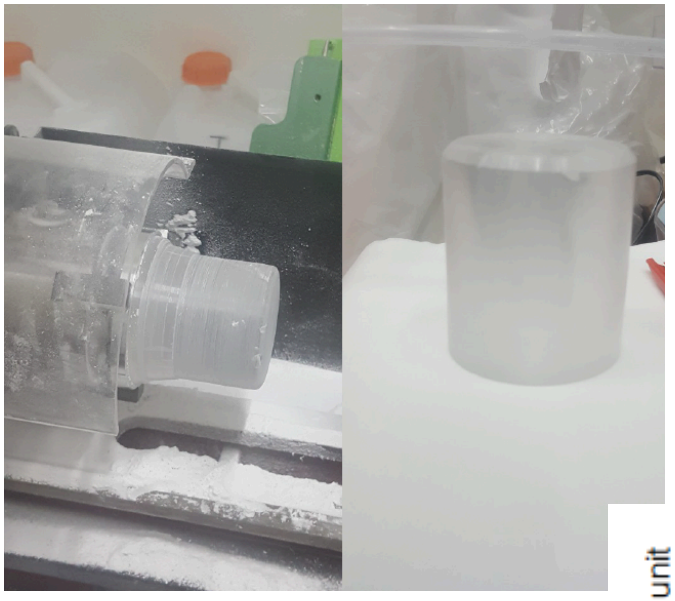


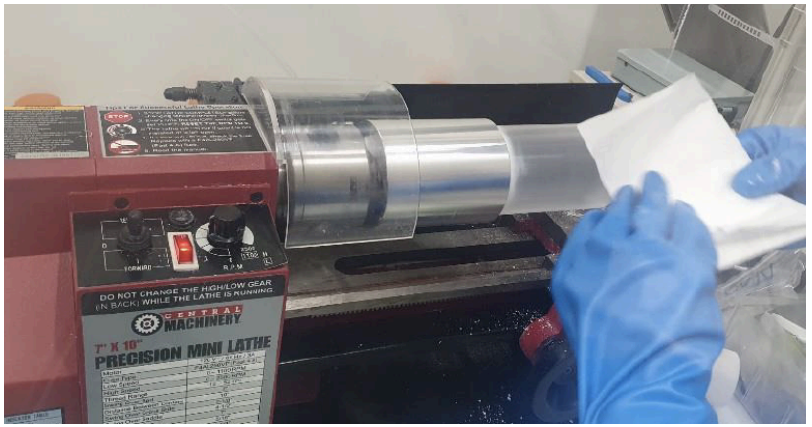
NaI(Tl) for spin-dependent interactions

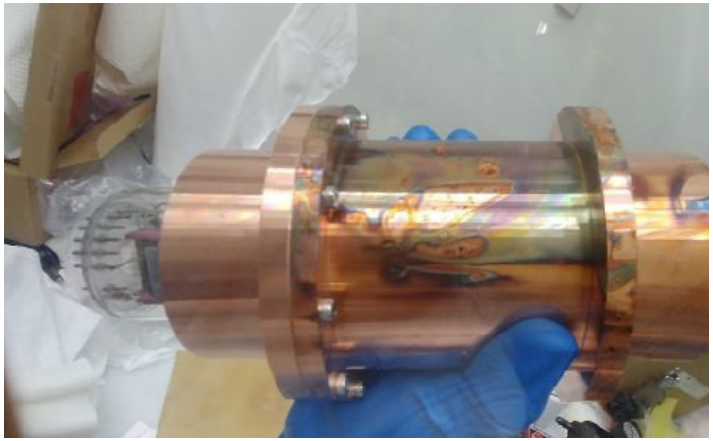
- Unique **proton odd target (Na = 11, I = 57)**
  - ❖ Good for spin-dependent interactions
  - ❖ A world best detector for spin-dependent interaction is possible



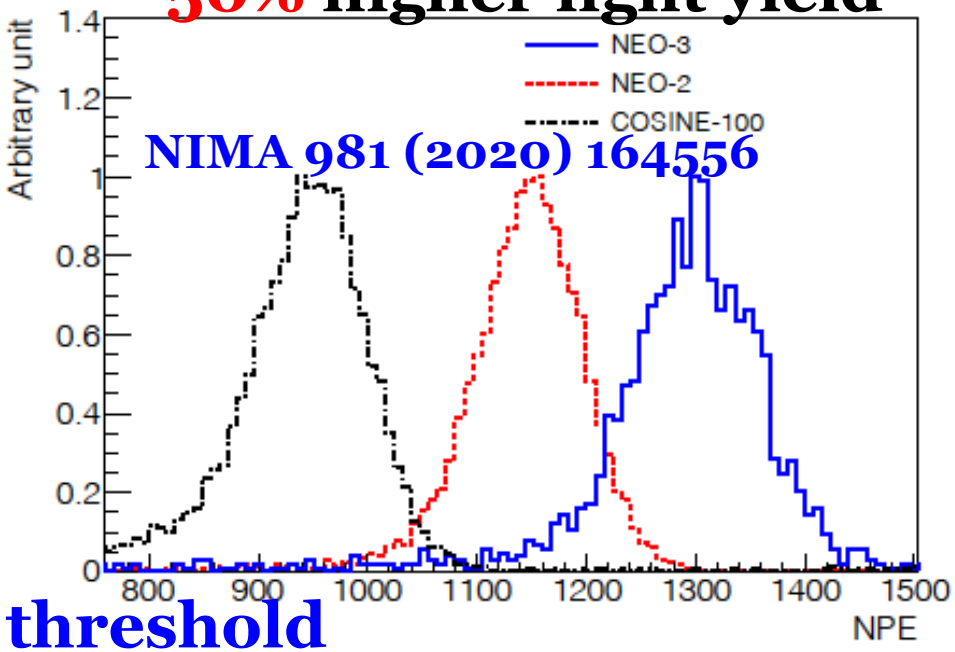
Detector assembly for high light yield (low threshold)







~50% higher light yield



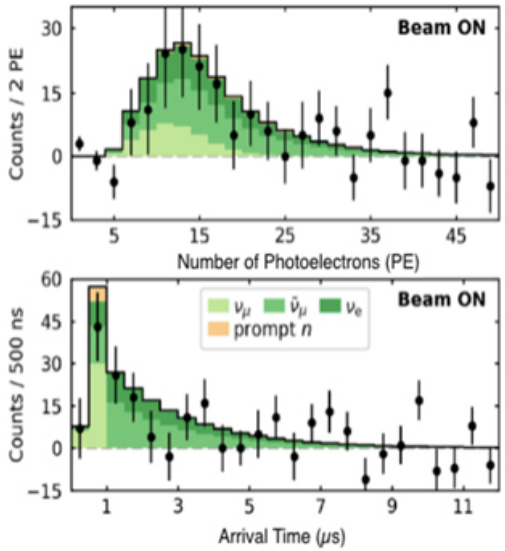
NIMA 981 (2020) 164556

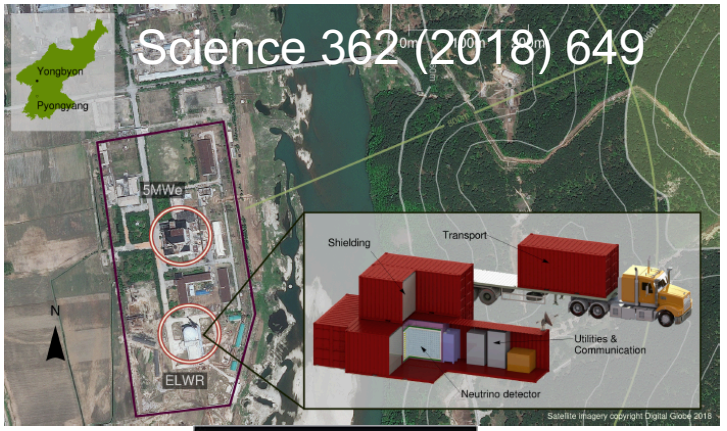
~22 NPE/keV => 0.25 keV threshold

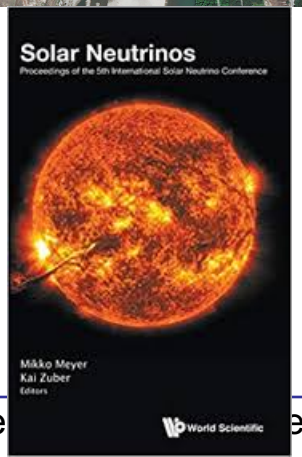
Possibility to detect CEνNS in reactor

- 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

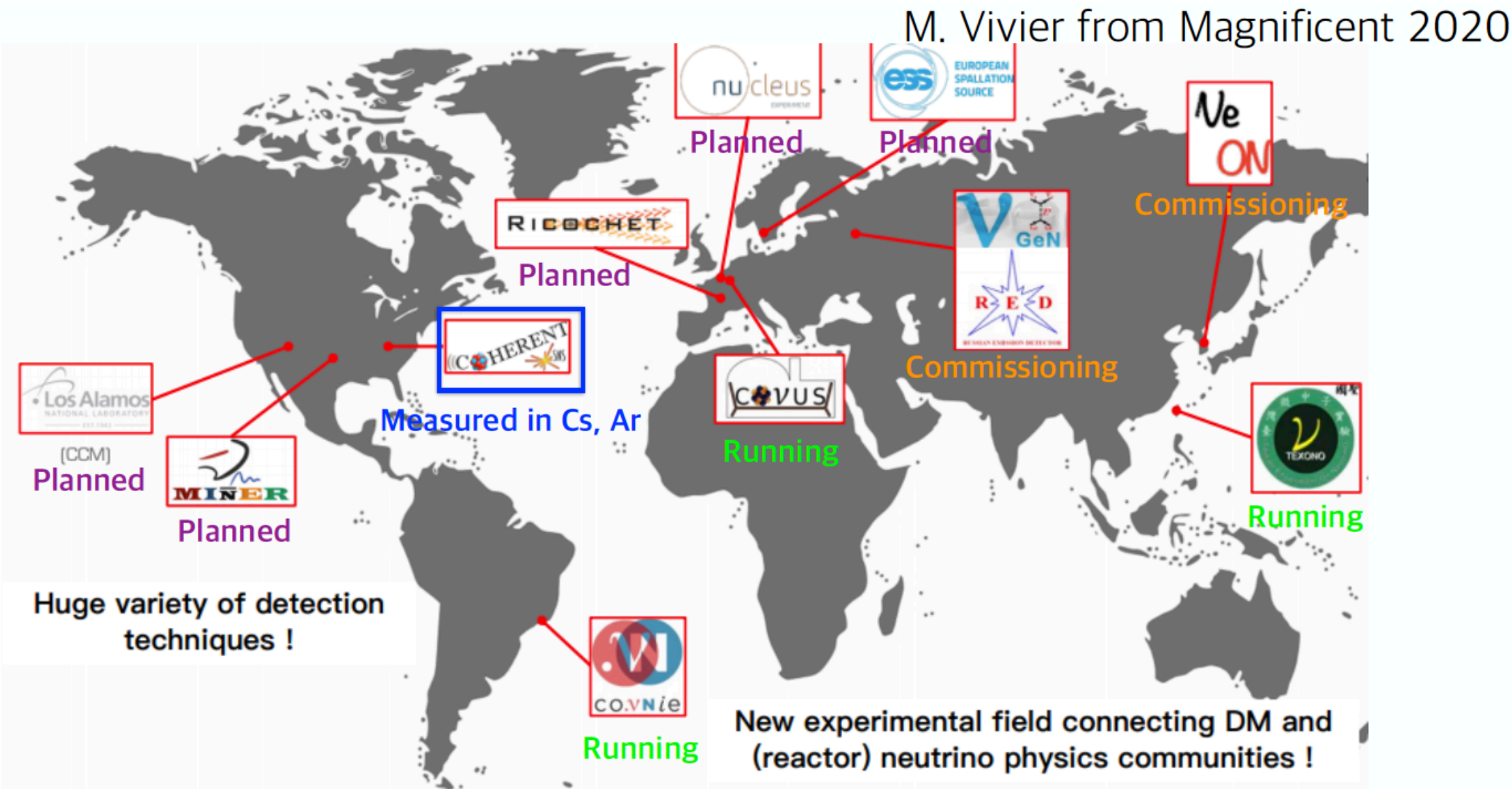
Science **357**, 1123 (2017)







Worldwide efforts for CEνNS



NEON Collaboration

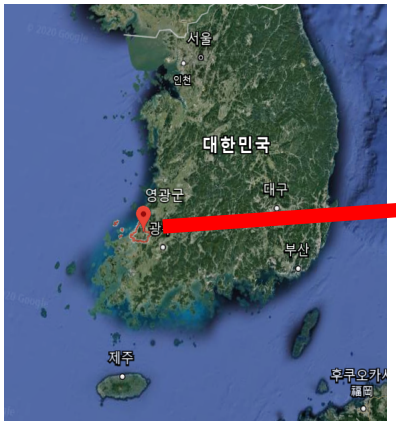
~ 15 people who are all active members of COSINE-100 and/or NEOS

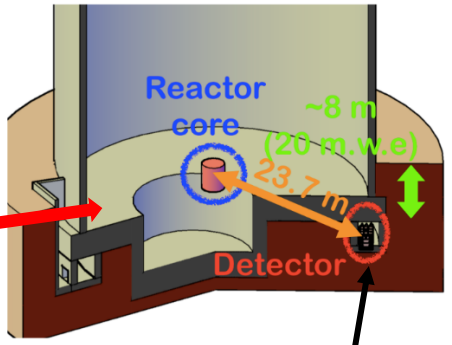
Aim to observe CEνNS from reactor $\bar{\nu}_e$ using NaI(Tl) detector

Can take an advantage of COSINE-100 and NEOS experiences

Reactor & NEON detector

Tendon Gallery of Hanbit Nuclear Power Plant (Yeonggwang)



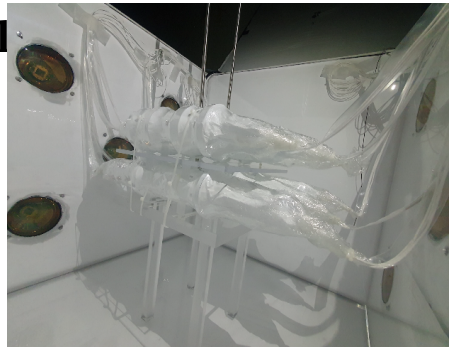


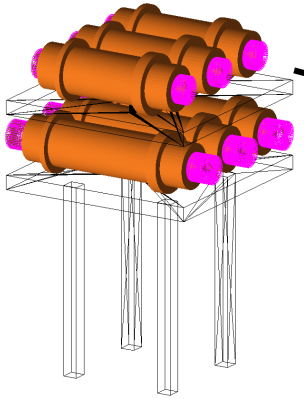
All commercial NaI(Tl) crystal

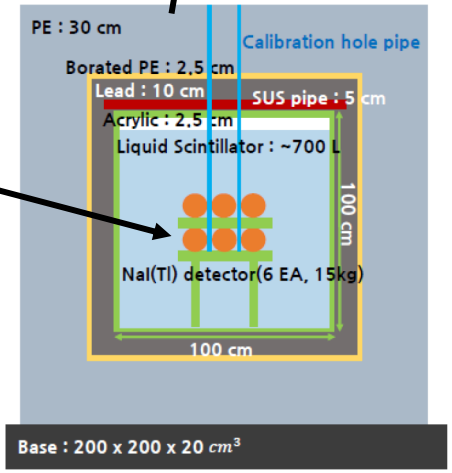
Total 15 kg

3 units of 3”x4”

3 units of 3”x8”







Construction of the NEON detector (Nov/2020)

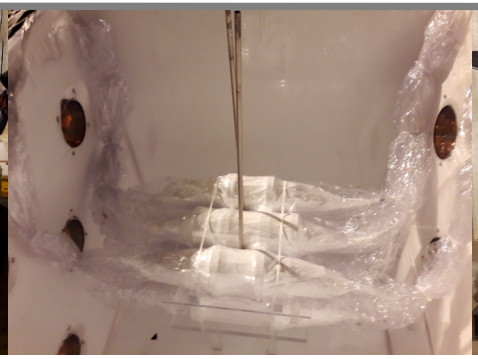
Nov/12



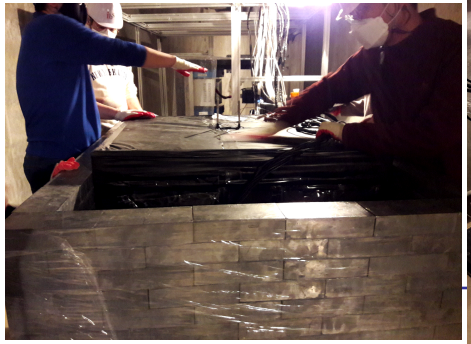
Nov/13


Nov/19


Nov/20




Nov/26



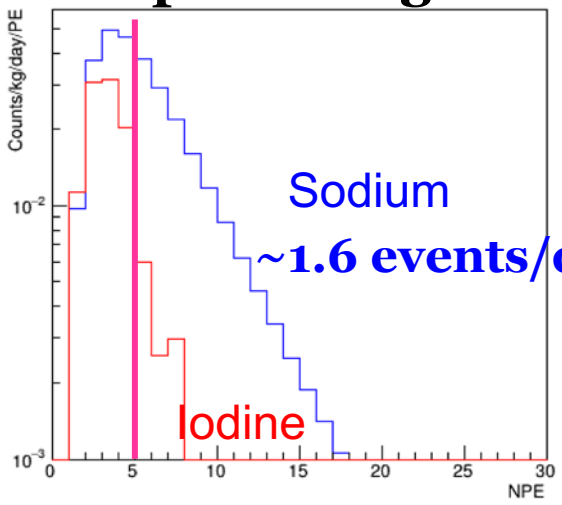

Dec/7/2020

Start Physics Run!!

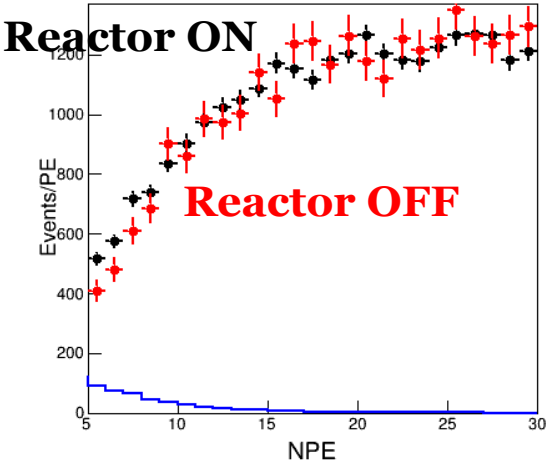
Sensitivity

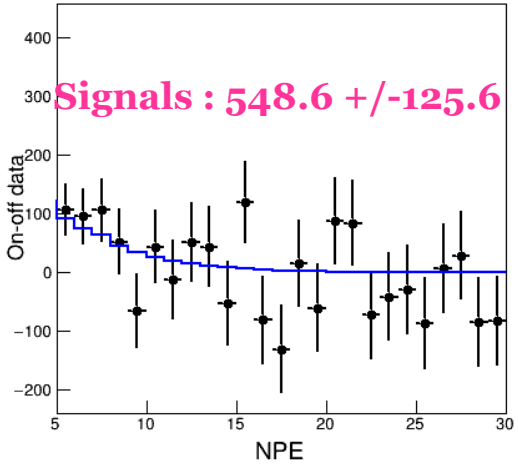
- Flat background ~5 dru
- Detector mass = 15 kg
- Reactor on data = **365 days**
- Reactor off data = **100 days**
- Light yield = 22 NPE/keV
- Trigger and selection efficiency
- Threshold = 5 NPE

Expected Signals

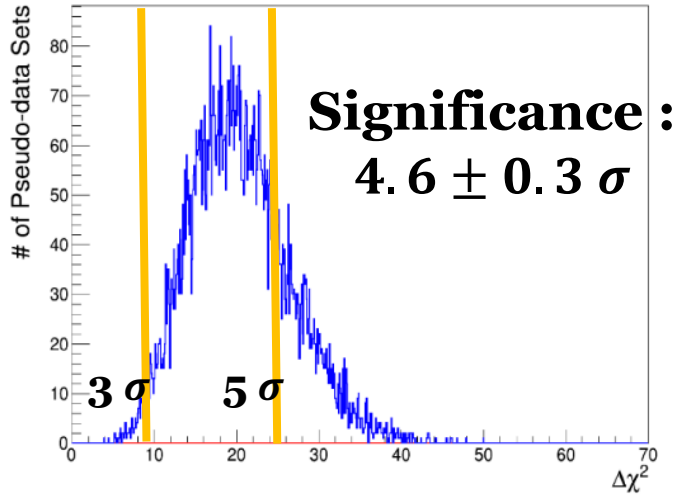


Single pseudo experiment





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

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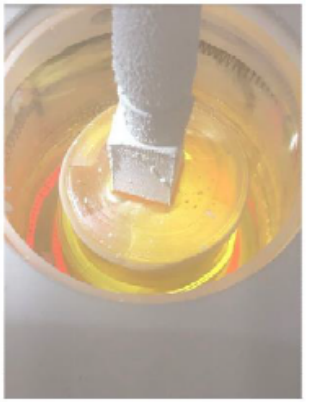


<Body growth>

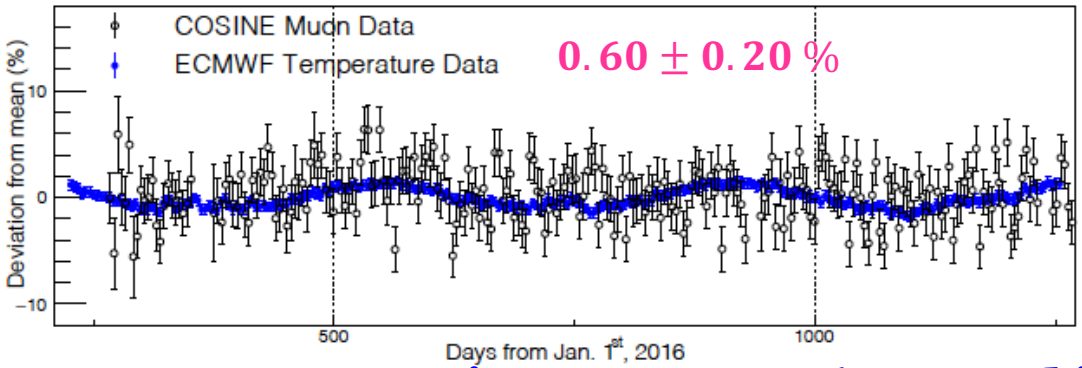
Summary & Conclusion

- NaI(Tl) crystals have been developed for dark matter search experiments in Korea
  - ❖ Revisit DAMA experiments
- 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 search : Spin-dependent WIMP-proton interaction
  - ❖ Coherent elastic neutrino nucleus scattering
    - ❑ Good chance for the first observation from reactor anti-neutrino

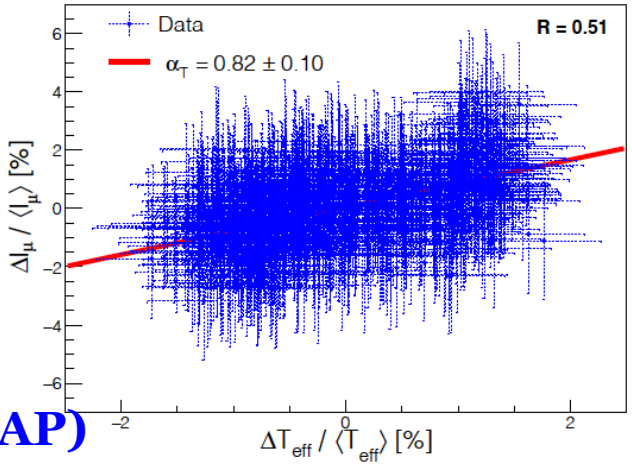
Stay tuned for more exciting results to come from COSINE and NEON experiments!

Muon modulation (3 years data)

Annual modulation of muon rate

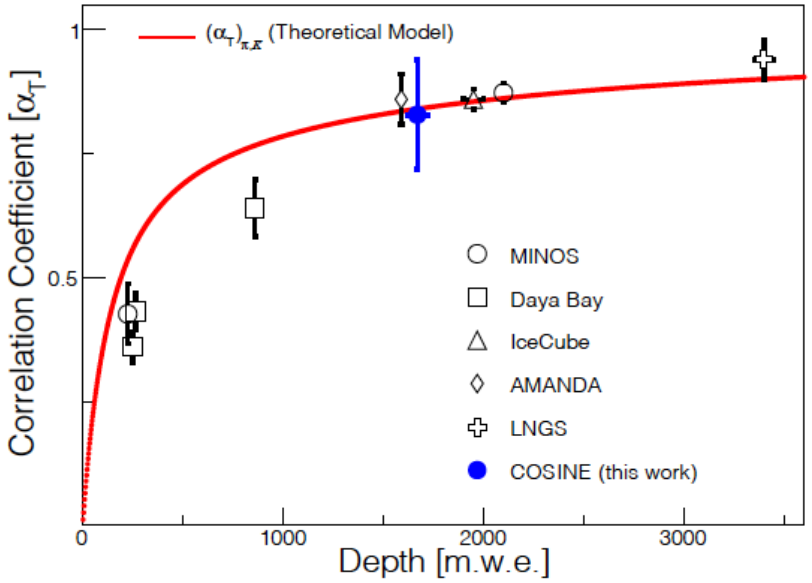


Correlation with T_{eff}



arXiv:2005.13672 (accepted in JCAP)

Annual modulation of muon rate



Diurnal modulation