



COSINE Experiment

current status and prospect

Hyun Su Lee

Center for Underground Physics (CUP)

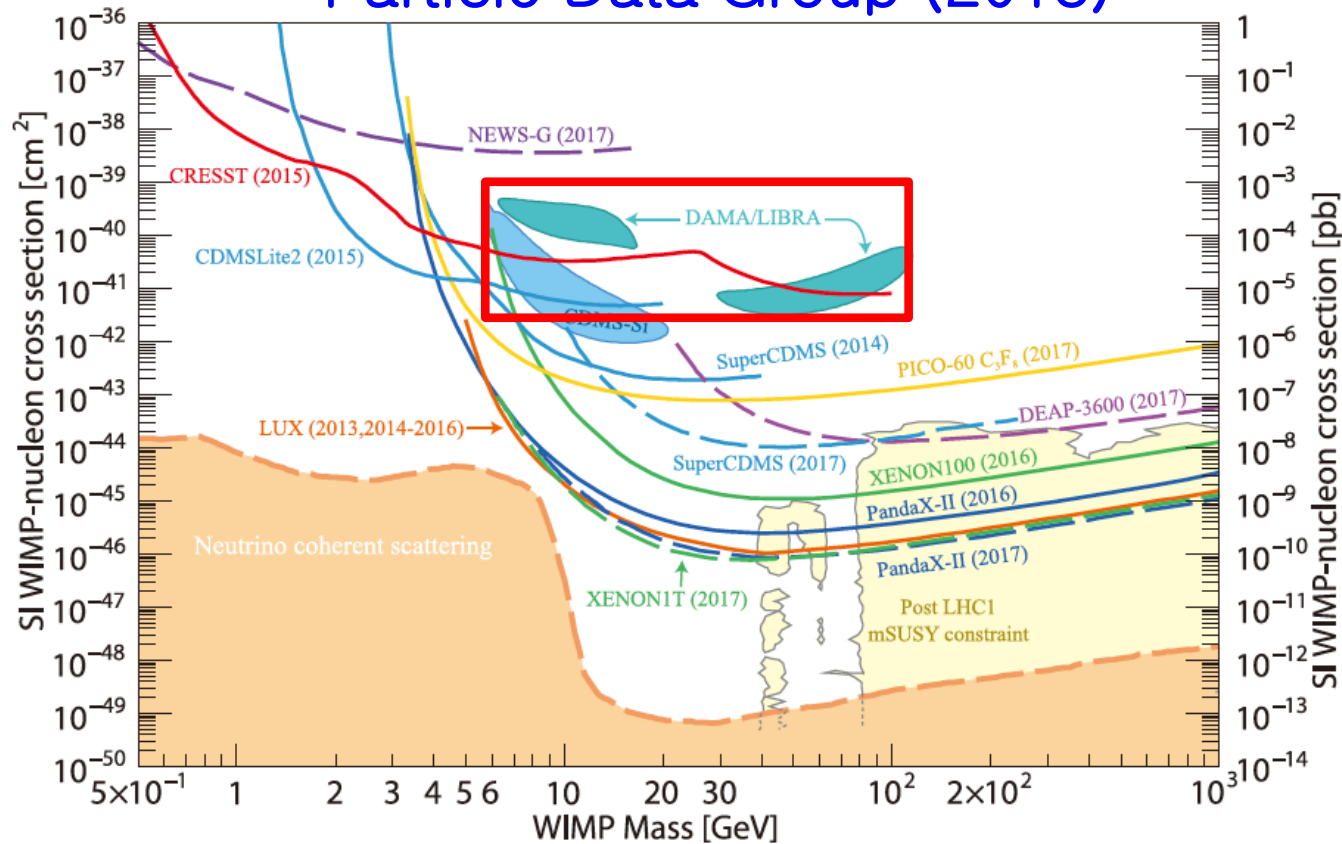
Institute for Basic Science (IBS)

Long-term Strategy of High Energy Physics in Korea

September 20-21, 2019

Current status of direct dark matter searches

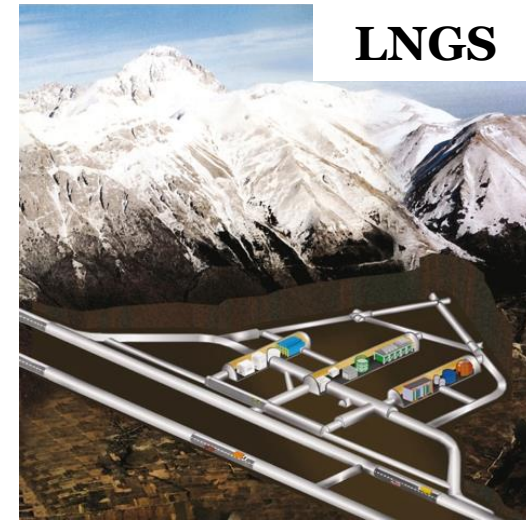
Particle Data Group (2018)



- Well progressed for high mass search to 10^{-46} cm² @ 50 GeV
- Exploring low-mass dark matter
- **Unresolved signal from DAMA**

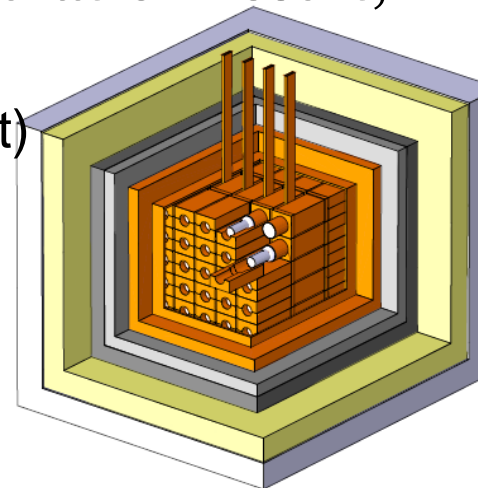
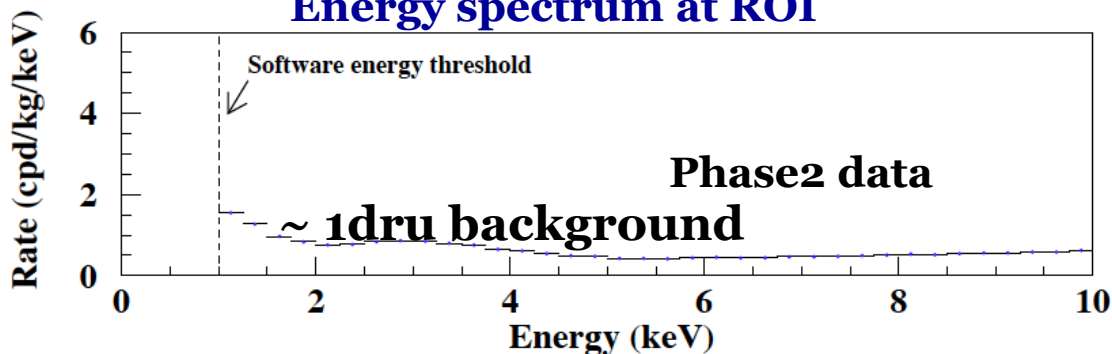
DAMA/LIBRA experiment

- 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 NPE/keV



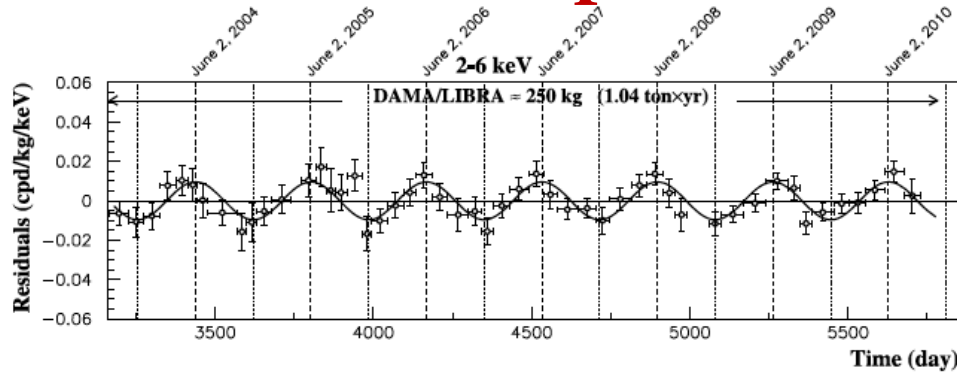
- DAMA/NaI (100 kg, 1996~2003) **First modulation result, PLB 424, 195 (1998)**
- DAMA/LIBRA-phase1 (250 kg, 2003-2010)
- DAMA/LIBRA-phase2 (250 kg, 2010~current)

Energy spectrum at ROI



Annual modulation signal from DAMA/LIBRA

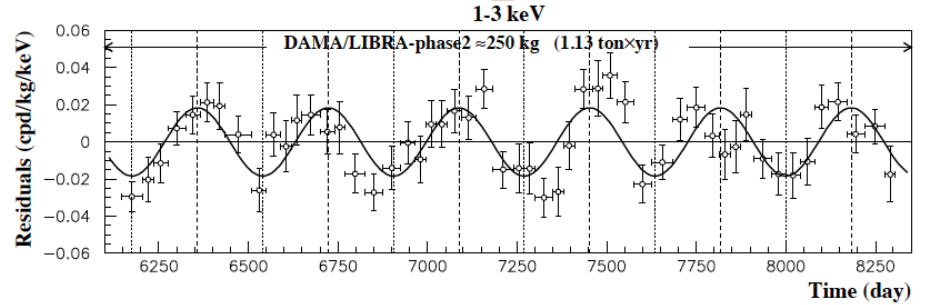
Phase1 experiment



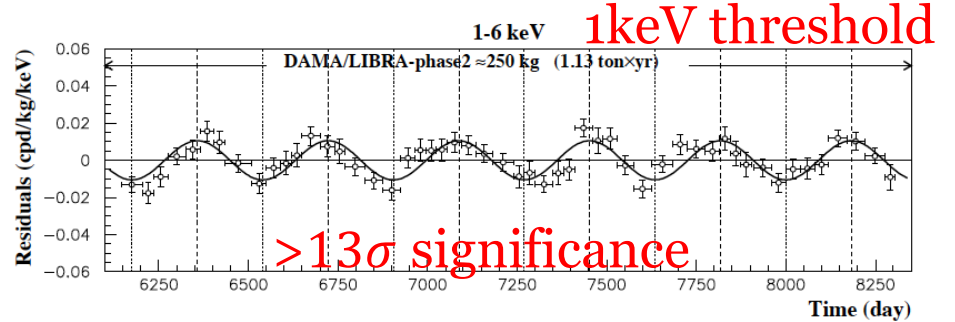
Eur. Phys. J. C 73:2648 (2013)

2keV threshold

Phase2 experiment



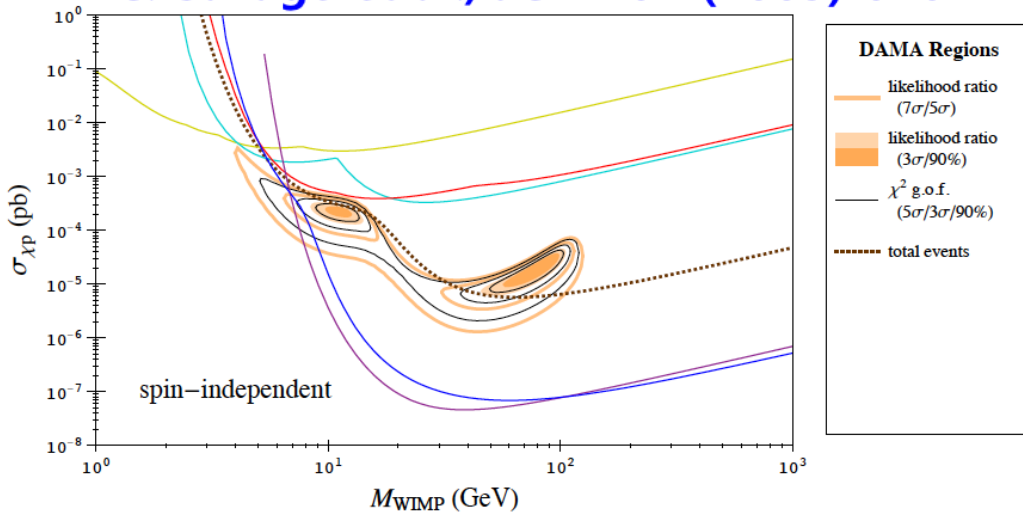
Nucl. Phys. At. Energy 19, 307 (2018)



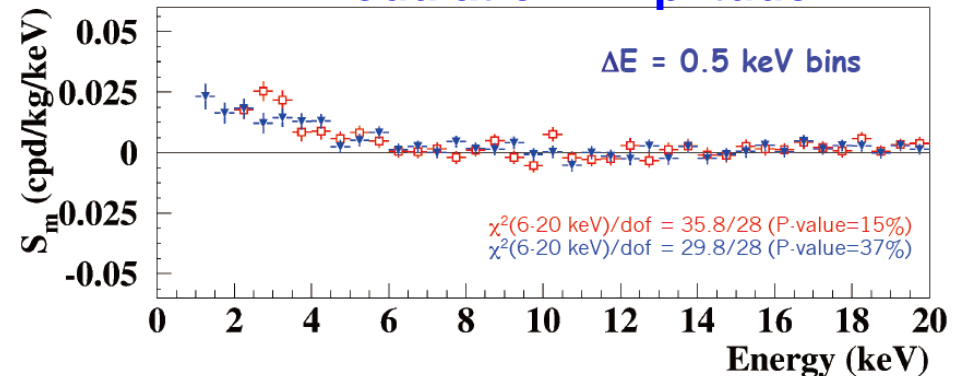
1keV threshold

>13σ significance

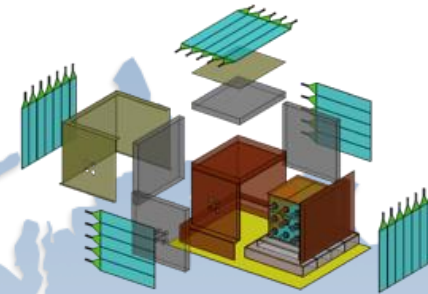
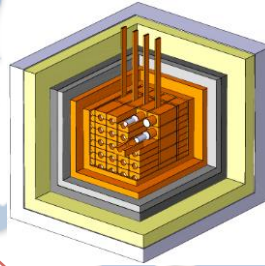
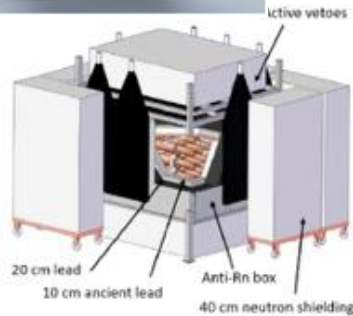
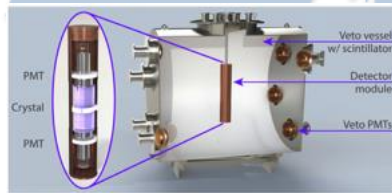
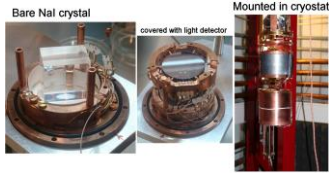
C. Savage *et al.*, JCAP 04 (2009) 010



Modulation Amplitude



Global NaI(Tl) efforts



COSINUS
@ LNGS

DAMA
@ LNGS

SABRE
@ LNGS

KIMS/COSINE
@ Yangyang

Background ~ 3 dru

In Data-taking
since Sept/2016

PICO-LON
@ Kamioka

ANAIS
@ Canfranc

In Data-taking
since Aug/2017

SABRE
@ Stawell

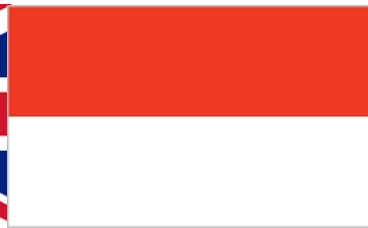
COSINE, SABRE, PICO-LON are developing low background NaI(Tl) crystals

DM-Ice @ South Pole



COSINE collaboration (Since 2015)

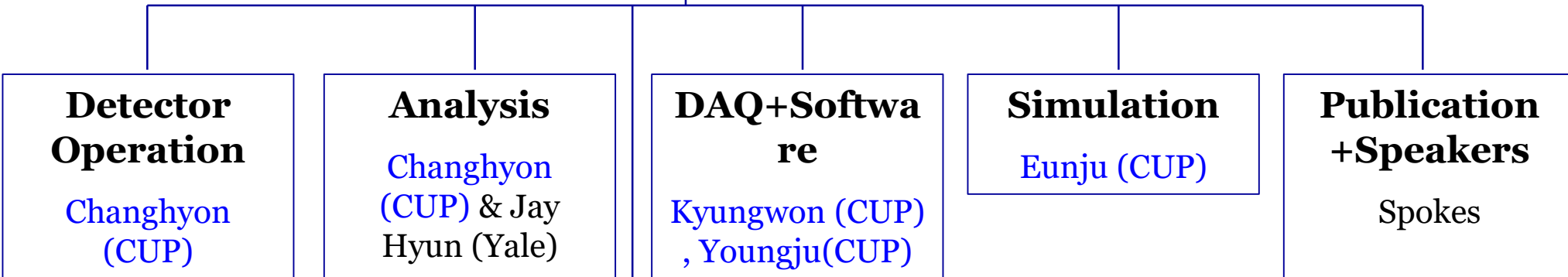
KIMS and **DM-Ice** joint effort to search for dark matter interactions in NaI(Tl) scintillating crystals.
(Goal to test **DAMA/LIBRA** experiment)



COSINE organization

Spokesperson
Reina (Yale) & Hyunsu (CUP)

Collaboration Council
Yeongduk (CUP), Hongjoo (KNU), SunKee (SNU), Neil (Sheffield), Liang (Urbana-Champagne)



COSINE-200 R&D (Hyunsu)
Purification (KunA), Crystal growing (Sejin), Detector encapsulation (Changhyon) + others



COSINE-100 detectors

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

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

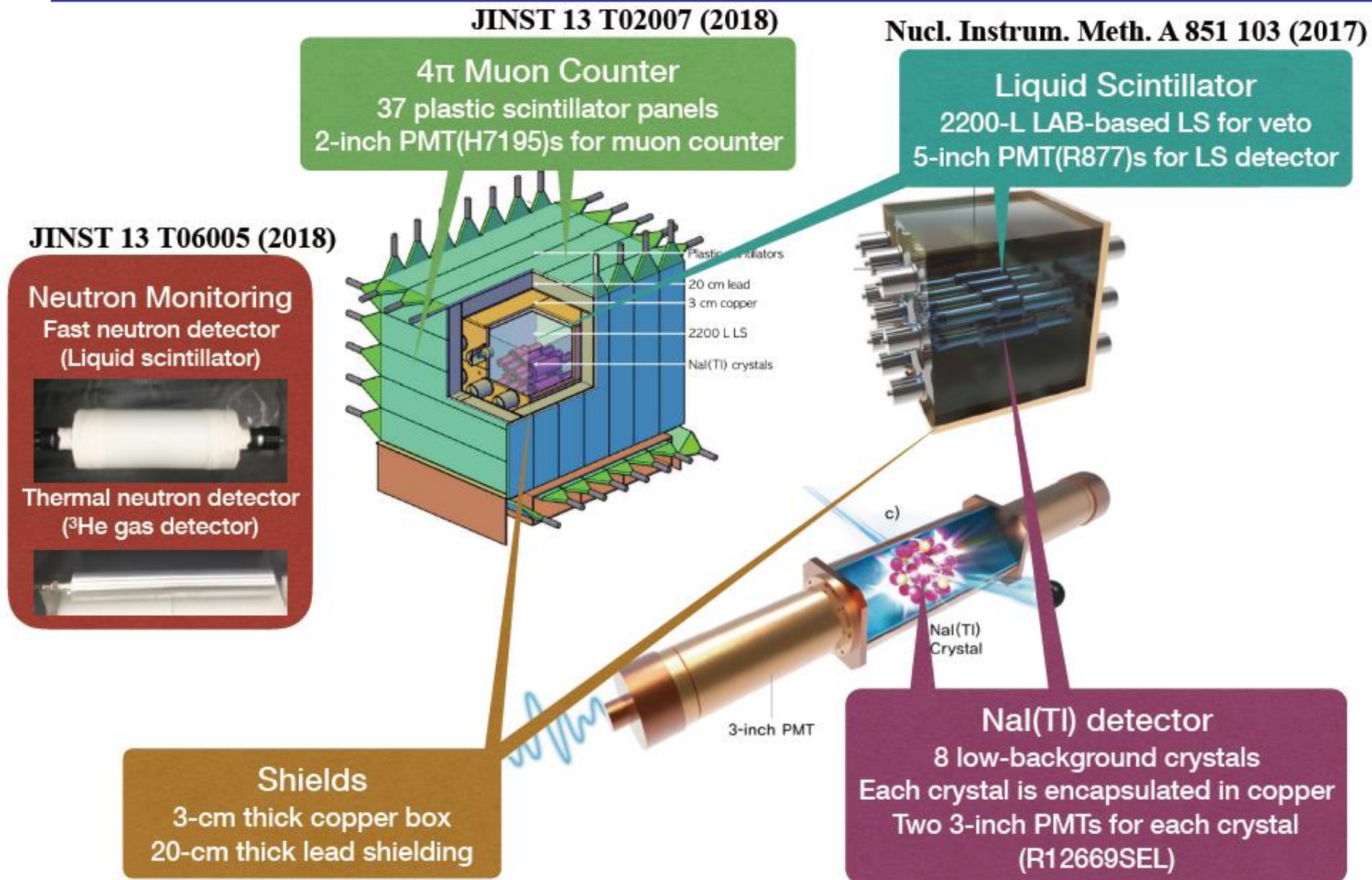
JINST 13 (2018) P09006

JINST 13 (2018) T02007

JINST 13 (2018) T06005

Physics run since Sept/2016

COSINE-100 detector configuration



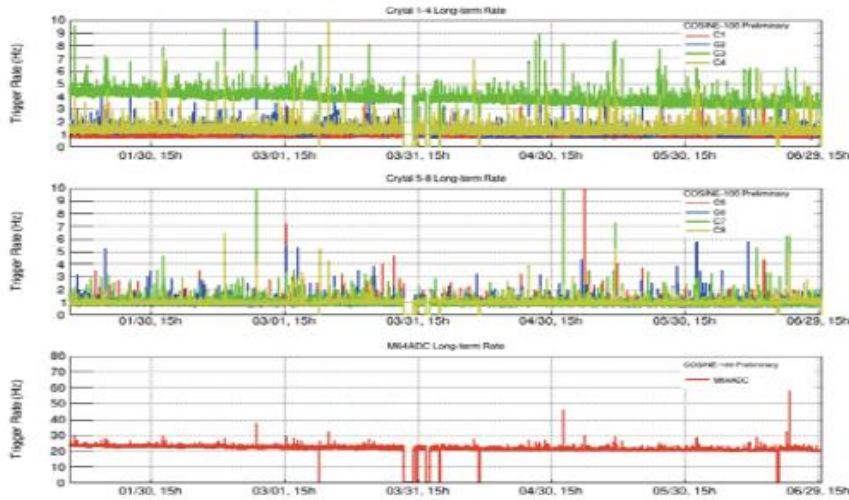
Costs

Items	price
Crystals	10 (5)
3" PMTs	0.5 (0.2)
Shielding	2
Lead	4.5
Copper	0.5
LS	0.2
5" PMTs	0.3
Muon	1
2" PMTs	0.4
DAQ	0.5
High Voltage	0.3
Total	20.2억원

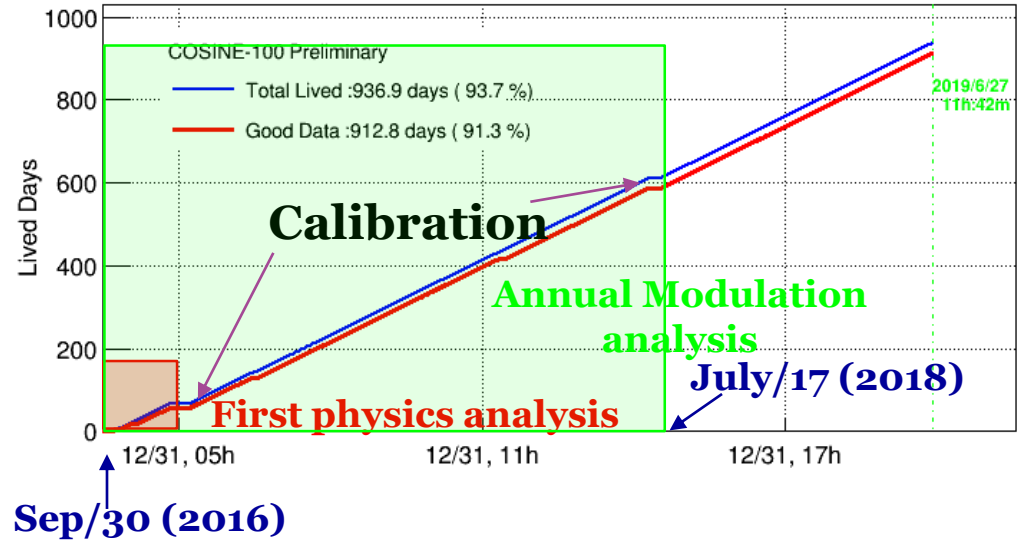
**Contribution from
Yale ~ 5.2**

Unit : 0.1 billion KRW (1억원)

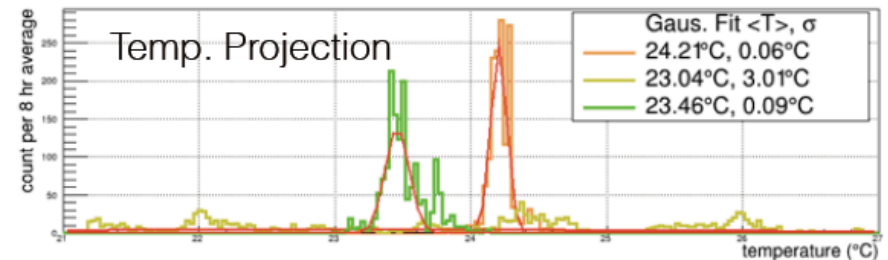
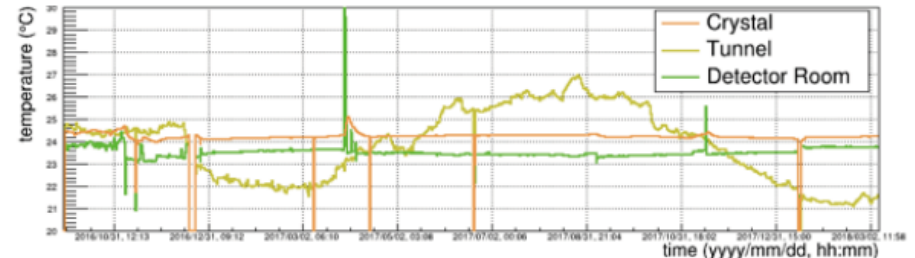
COSINE-100 operation



COSINE-100 exposure

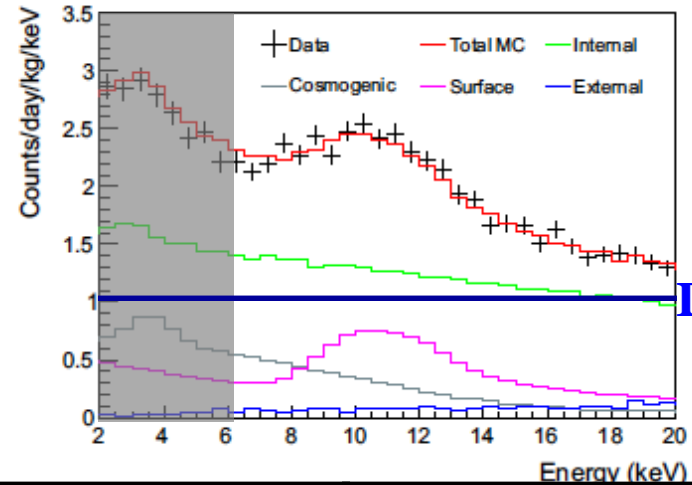
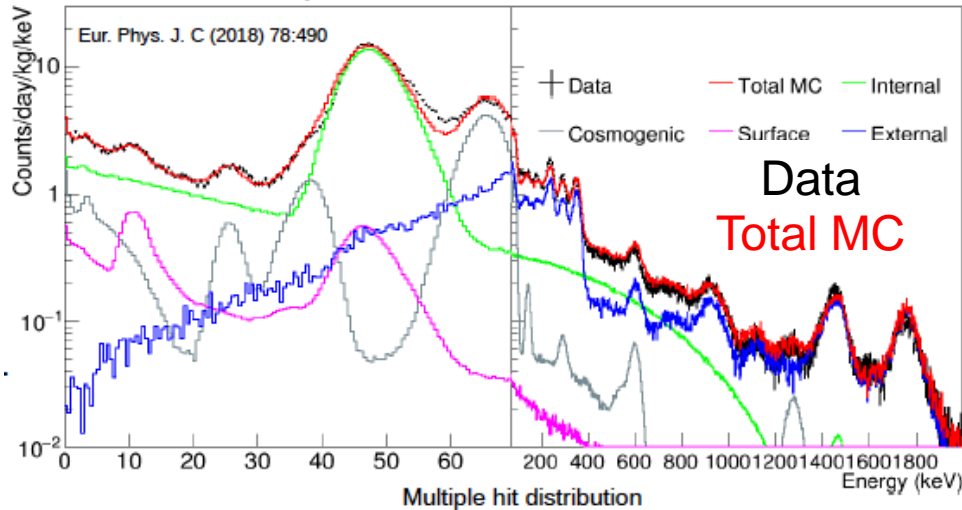


- **Stable physics run**
 - ❖ >90% physics data
 - ❖ >95% good runs
- Operating more than 2.8 years
 - ❖ **2.5 years good data**



Background understanding

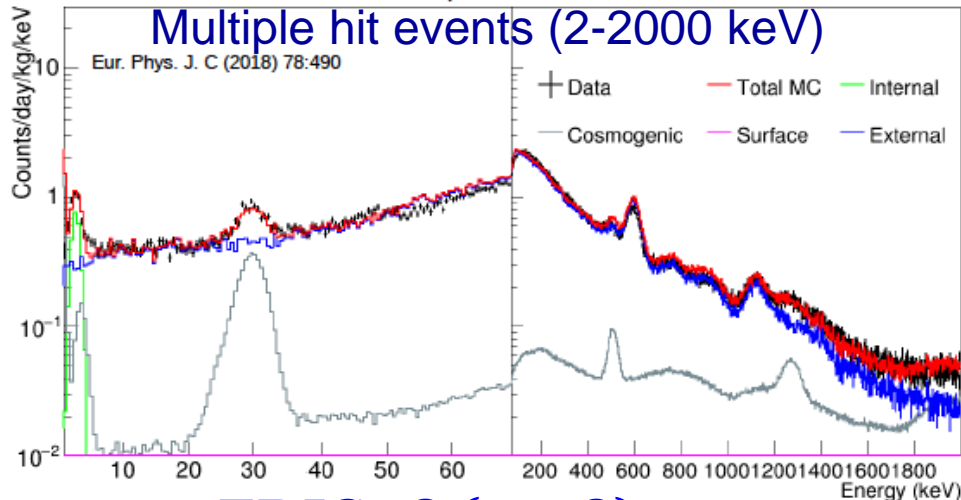
Single hit event (6-2000 keV)



DAMA

Multiple hit distribution

Multiple hit events (2-2000 keV)



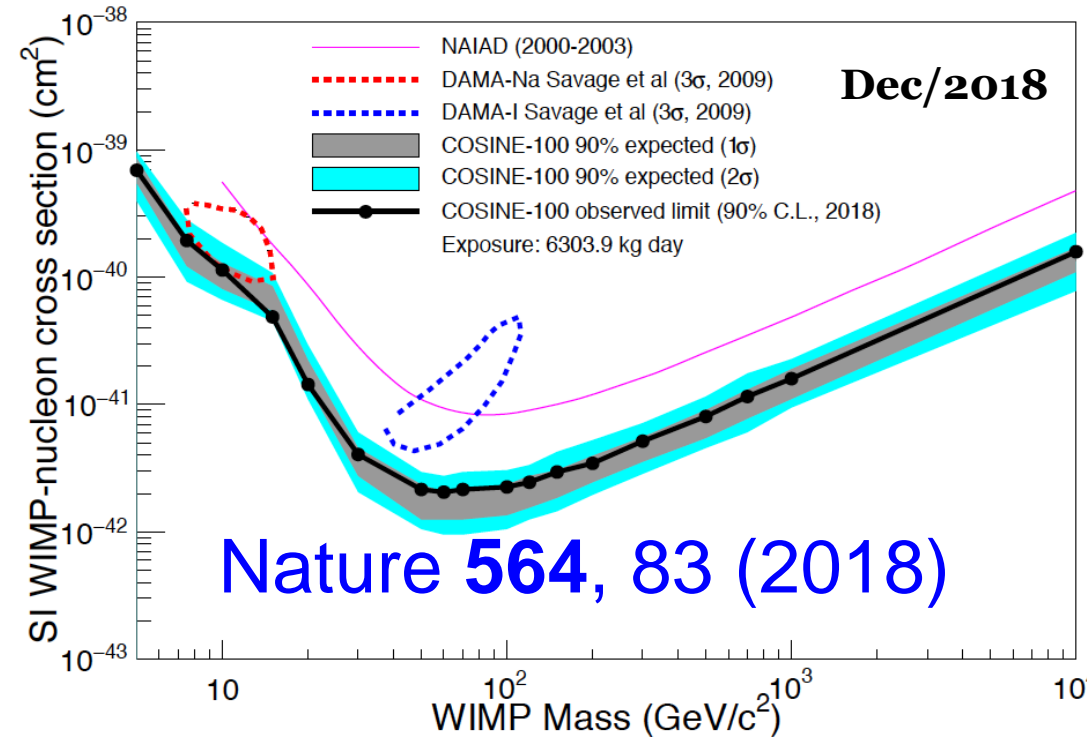
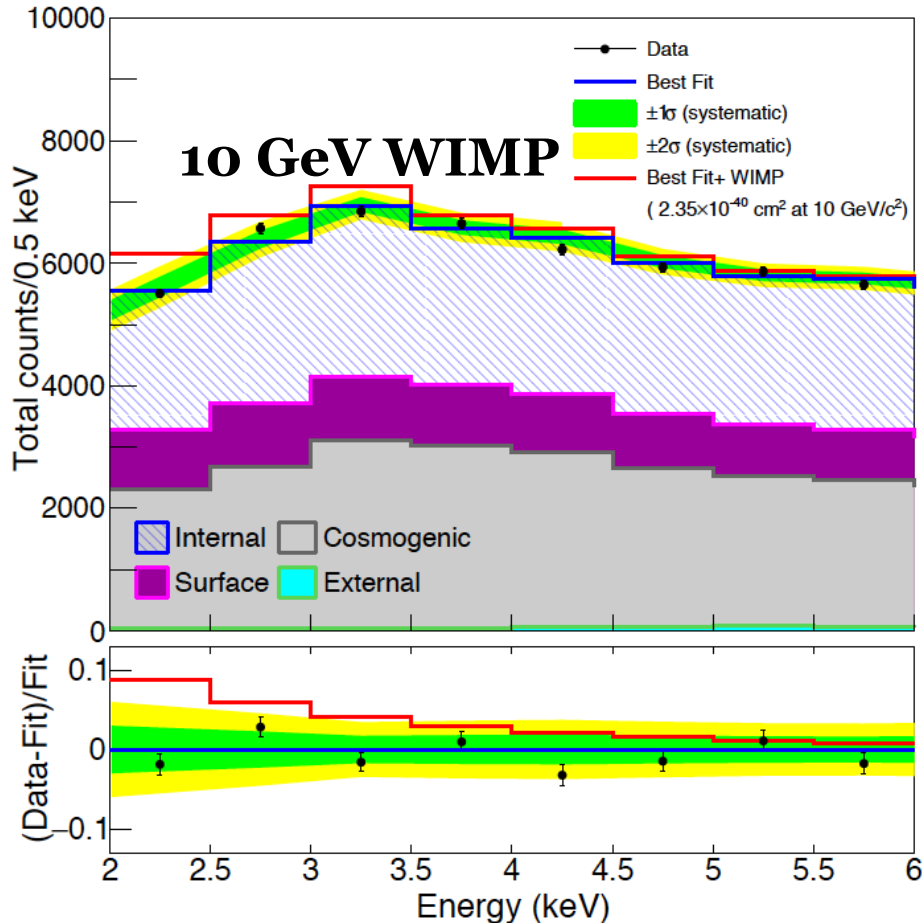
EPJC 78 (2018) 490

Unique in COSINE

Components	Background 2-6 keV (dru)
Internal ^{210}Pb	1.50 +/- 0.07
Internal ^{40}K	0.05 +/- 0.01
Surface ^{210}Pb	0.38 +/- 0.21
^3H (Cosmogenic)	0.58 +/- 0.54
^{109}Cd (Cosmogenic)	0.09 +/- 0.09
Other cosmogenic	0.05 +/- 0.03
External	0.03 +/- 0.02
Total expected	2.70 +/- 0.59
Data	2.64 +/- 0.05

First physics result (two month data)

Precise background understanding & signal fit



COSINE-100 **excludes** DAMA/LIBRA-phase1's interpretation with the **SI-WIMP** interaction in Standard Halo Model

Consistent with other null experiments

First time with same NaI(Tl)

Inelastic boosted dark matter search (two month)

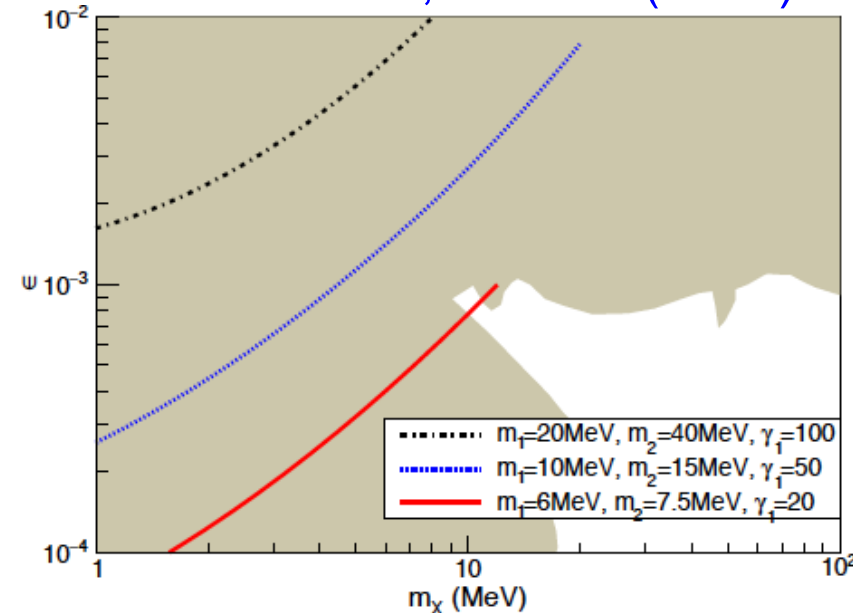
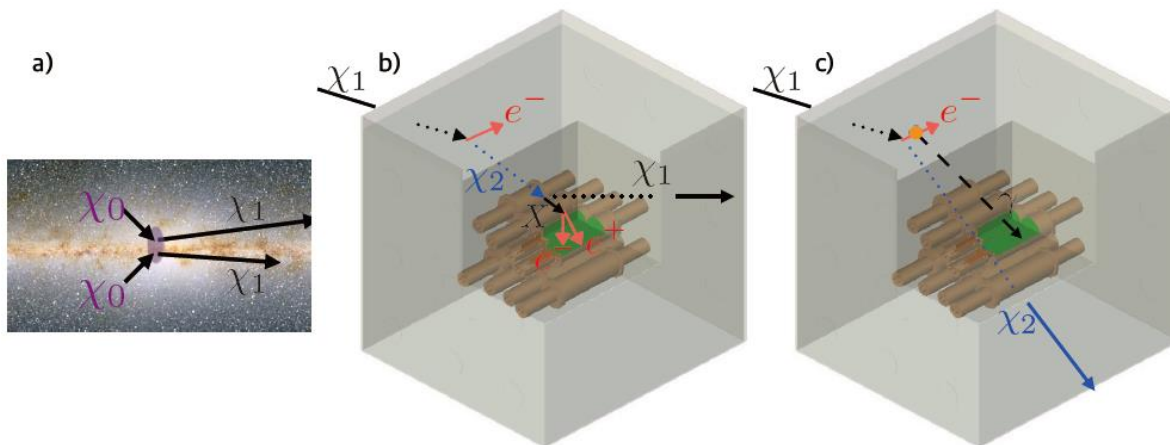
PHYSICAL REVIEW LETTERS **122**, 131802 (2019)

Editors' Suggestion

April/2019

First Direct Search for Inelastic Boosted Dark Matter with COSINE-100

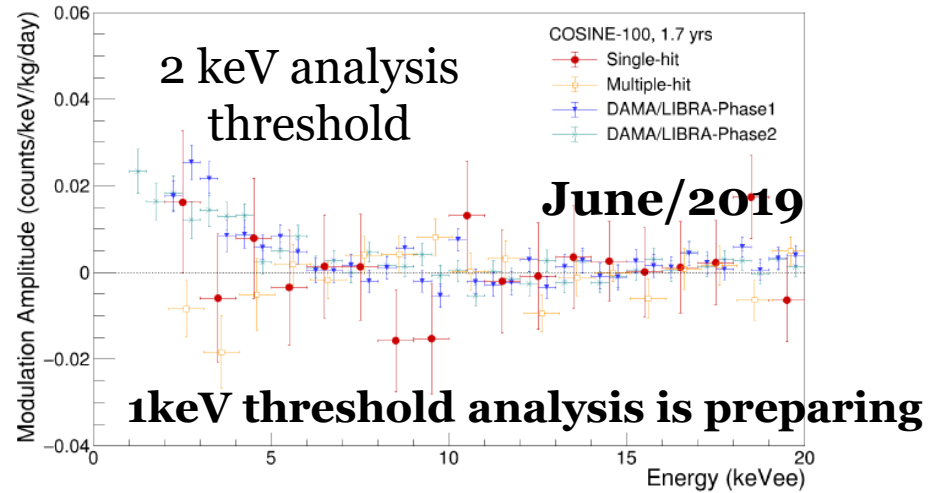
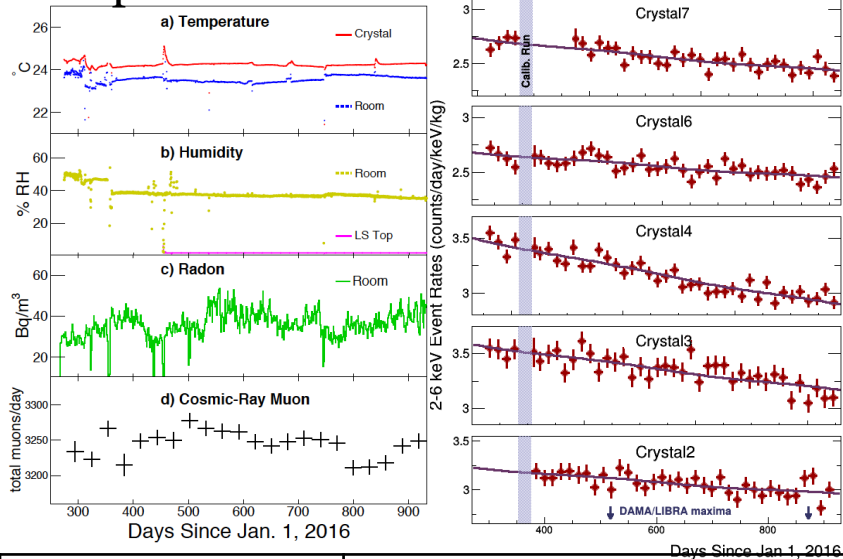
PRL 122, 131802 (2019)



Effectively ton scale detector taking advantages of **2 ton liquid scintillator**

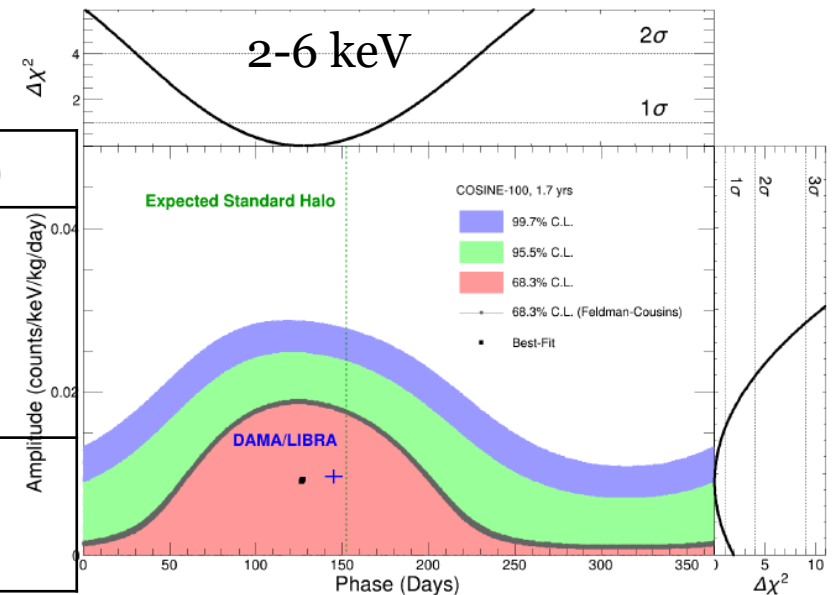
Annual modulation result with COSINE-100 (1.7 years)

Oct/21 (2016) ~ Jul/18 (2018), 1.7 year
Environmental parameters



PRL 122, 131802 (2019)

Config	Amplitude (2-6 keV)	Phase (days)
COSINE-100	0.0083 ± 0.0068	152.5 (fixed)
ANAIS <small>PRL 122, 131801 (2019)</small>	-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



Publication summary (2014 - 2019)

Nature	1
PRL	2
JHEP	3
JCAP	1
PRD	1
EPJC	4
AP	4
NIMA	2
JINST	4
JRNC	1
IEEE	1
Total	24

2014	2
2015	3
2016	3
2017	2
2018	8
2019	6+(?)
Total	24

Ph.D students

Three Ph.D Theses so far
SNU, Sejong, Bangdung

Current Ph.D students

IBS-UST	2
Sejong	1
SNU	1 (+1)
KNU	1
SKKU	1
Korea	1
Yale	2
Sheffield	1
Sao Paulo	2 (+3)
Total	11 (+5)

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

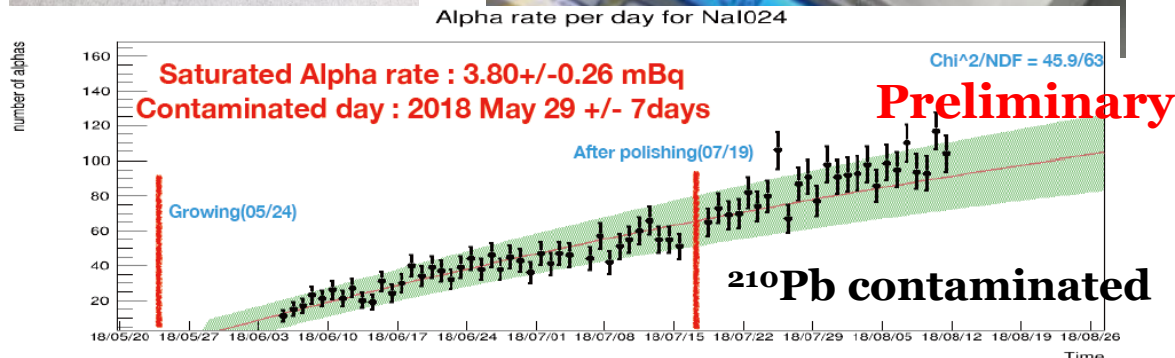
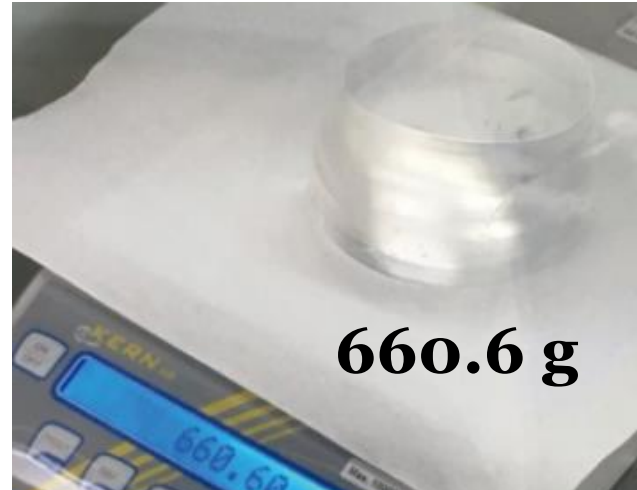
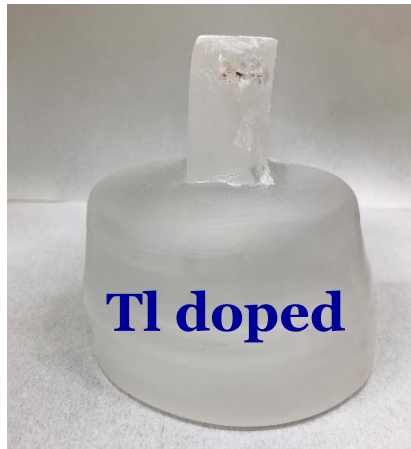
K.A. Shin et al., J. Rad. Nucl. Chem. 317, 1329 (2018)

	K (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



COSINE-200 crystal development

May/2018



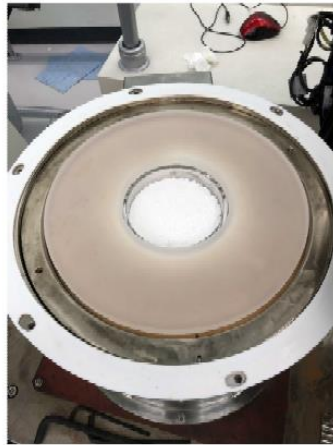
Goal : less than 0.1 mBq/kg

- Demonstrated quick detector assembly and underground measurements!!
- Good optical quality
- If we reduce ^{210}Pb contamination, we can reach to DAMA level (1dru)

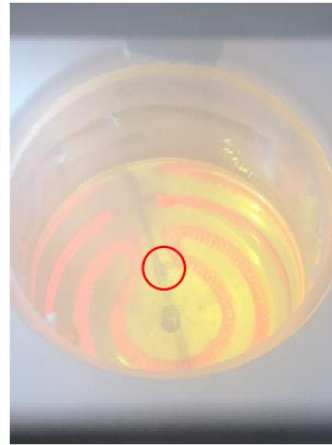
COSINE-200 crystal development

Aug/2019

Pure NaI



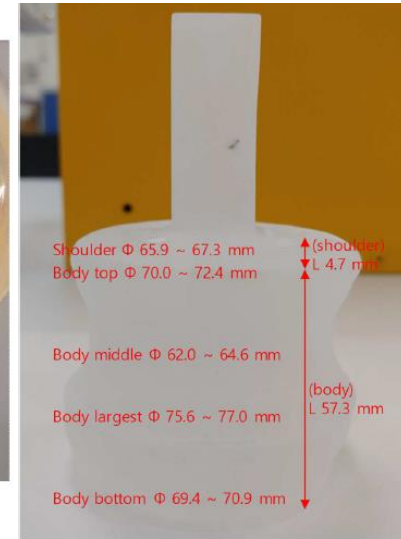
<Quartz cover>



<Impurity>



<Body growth>



ICP-MS measurement

	K (ppb)	Pb (ppt)	U (ppt)	Th (ppt)
Powder	<14	<300	<5.2	<4.6
Aug/2018	300	9000	<5.2	<4.6
Mar/2019	100	17000	<4.3	<2.6
Aug/2019	100	<240	<4.3	<2.6

Tl doped



To understand ^{210}Pb , we need underground measurement

Competitors



SABRE

Arrived at LNGS on August 6, 2019

First crystals

Total Alpha : 0.4 mBq/kg

0.4 ppt ^{238}U

0.2 ppt ^{232}Th



3.5 kg

PICO-LON

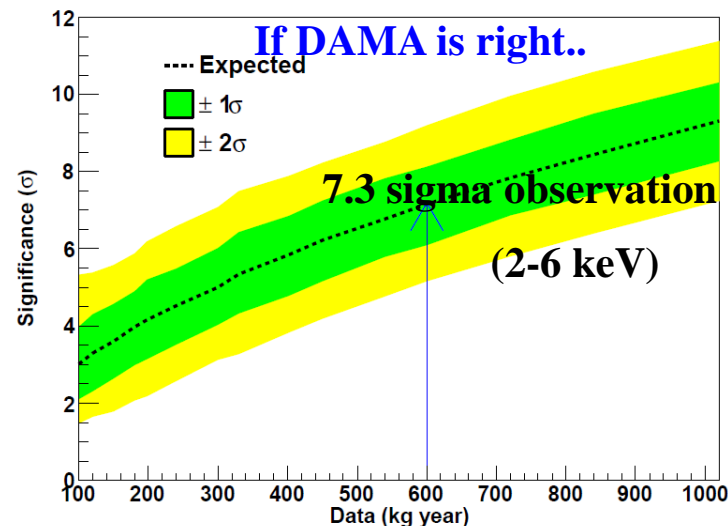
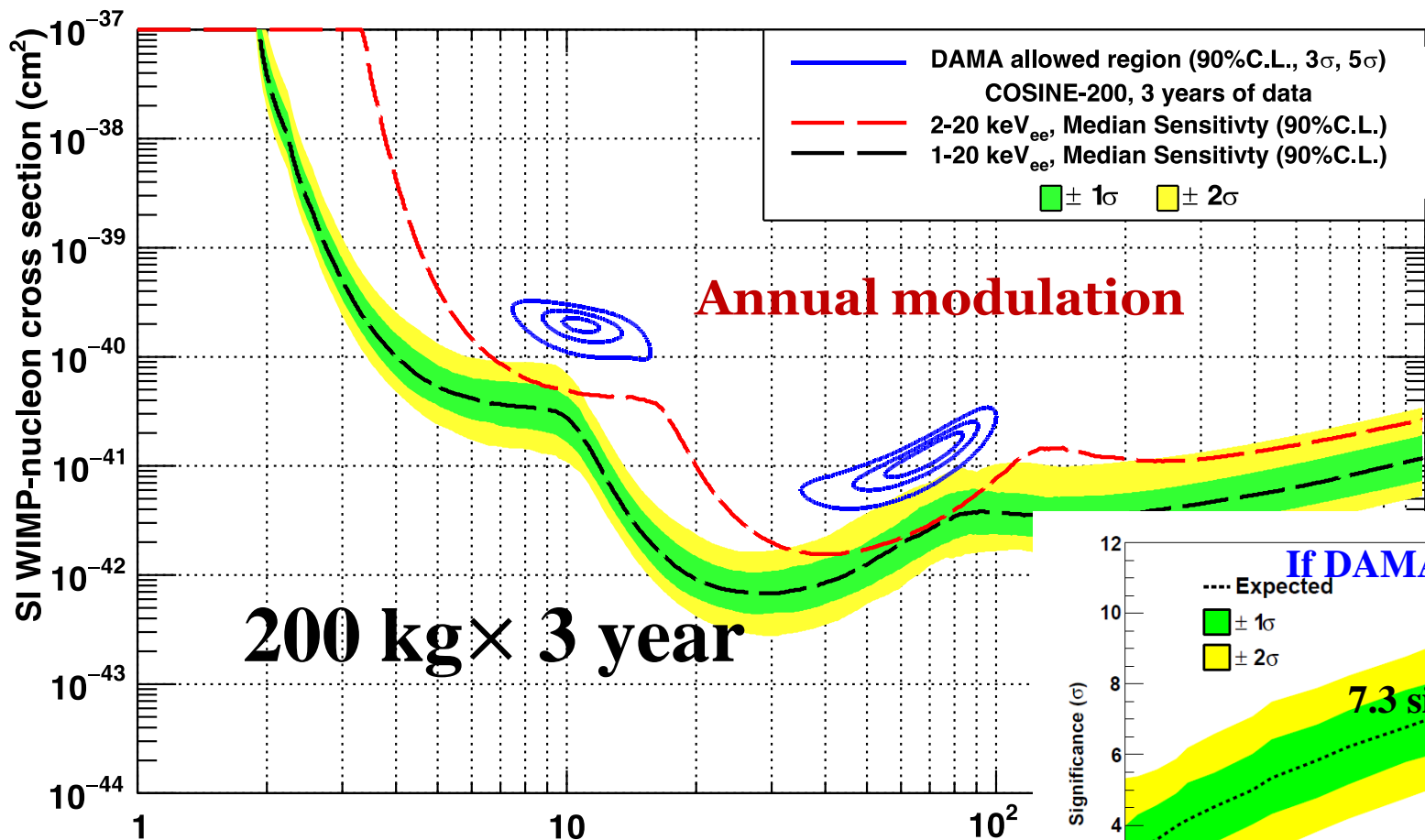


RI	Ingot26 (2015)	Ingot37 (2016)	Ingot71 (2018)	Ingot76 (2019)	Goal
Size	3" ϕ X3"	4" ϕ X3#	3" ϕ X3"	5" ϕ X4"(*)	5" ϕ X5"
^{40}K (ppb)	2630	120	<20	<20	<20
^{232}Th (ppt)	0.4 \pm 0.5	3.7 \pm 0.5	1.7 \pm 0.2	--	<4
^{238}U (ppt)	4.7 \pm 0.3	5.9 \pm 0.3	9.7 \pm 0.8	4.4 \pm 0.2	<10
^{210}Pb ($\mu\text{Bq/kg}$)	30 \pm 7	2300	1076	~560	<50
Method	Resin for Pb	126+cation resin	double re-crystallizat ion	Pb resin + double re-crystallizat ion	
		Factory moved.			

COSINE is frontier in low-background NaI crystal (CUP has all technologies)

COSINE-200 sensitivity (similar for all future project)

- 1 counts/kg/keV/day background (same as DAMA/LIBRA)



Model independent comparison of the modulation amplitude at 2-6 keV will be performed

COSINE-200 costs (2021~)

- Current COSINE-100 shield is designed for 200 kg experiment
- We just need to replace all crystals
- COSINE-200 may start around **2020-2021**
- **Yale won NSF funding** for COSINE experiment since 2019 fall

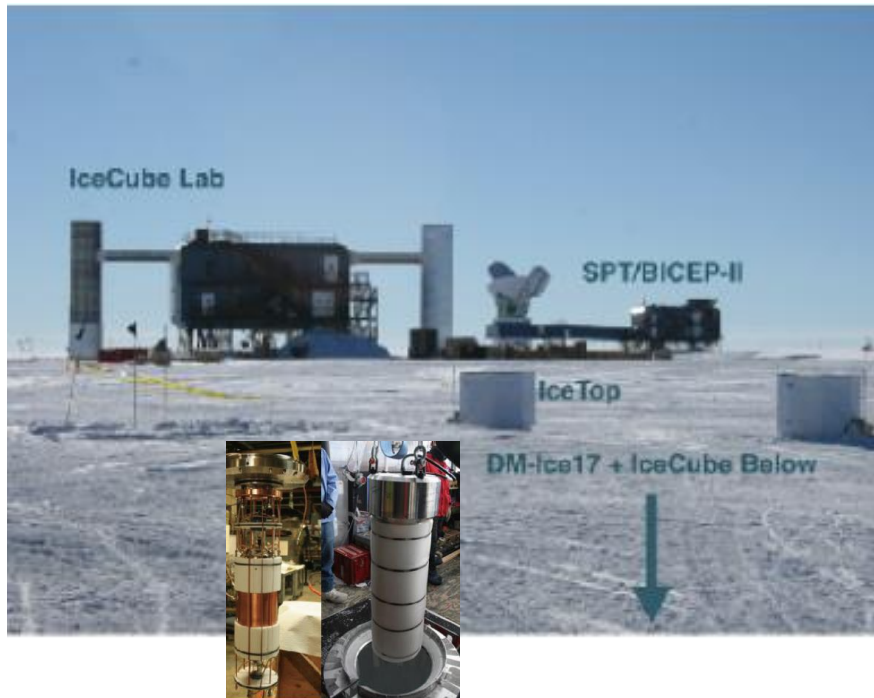
Items	price
Crystals	2
3" PMTs	0.5
Shielding	-
Lead	-
Copper	-
LS	0.2
5" PMTs	-
Muon	-
2" PMTs	-
DAQ	0.5
High Voltage	0.3
Total	3.5 억원

Already 2.3 억원 was spent

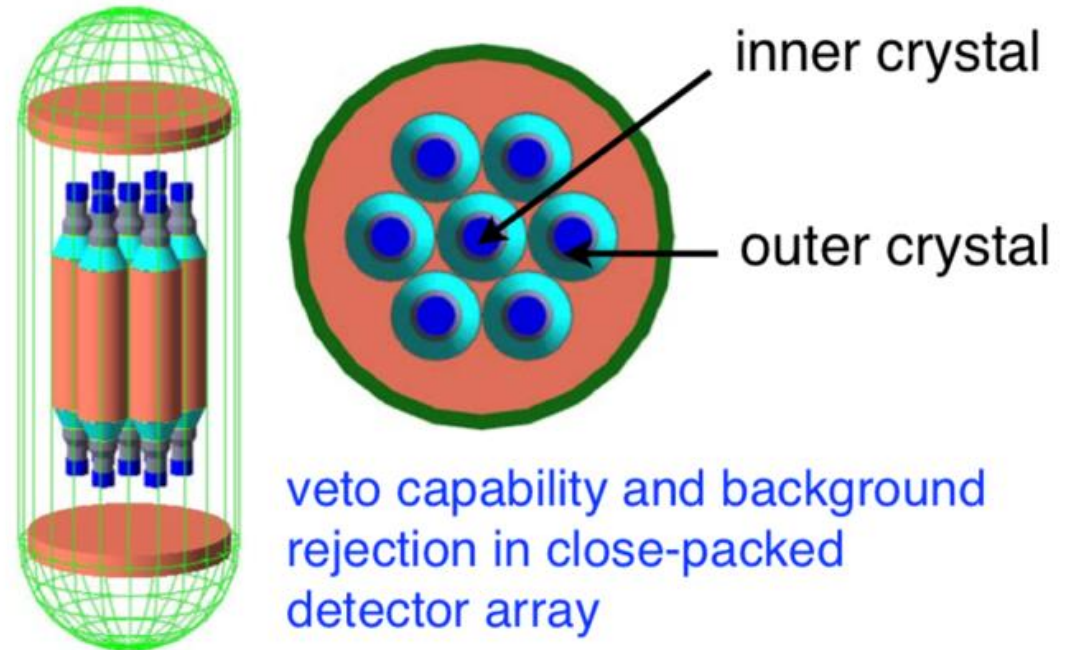
1.2 억원 will be supplied (2020~2021)

COSINE-200 in the South Pole (2023?)

- If we observe similar modulation as DAMA
 - ❖ Southern hemisphere experiment is needed
- South Pole has good option at 2022-2023 with IceCube upgrade
 - ❖ We can provide low-background NaI(Tl) detectors



Close-Packed Detector Array



COSINE-200 in Gran Sasso (?)

- If we do not see similar modulation as DAMA/LIBRA
 - ❖ It may be local environmental (or scientific?) issue
 - ❖ It seems to be required to do same experiment in same place

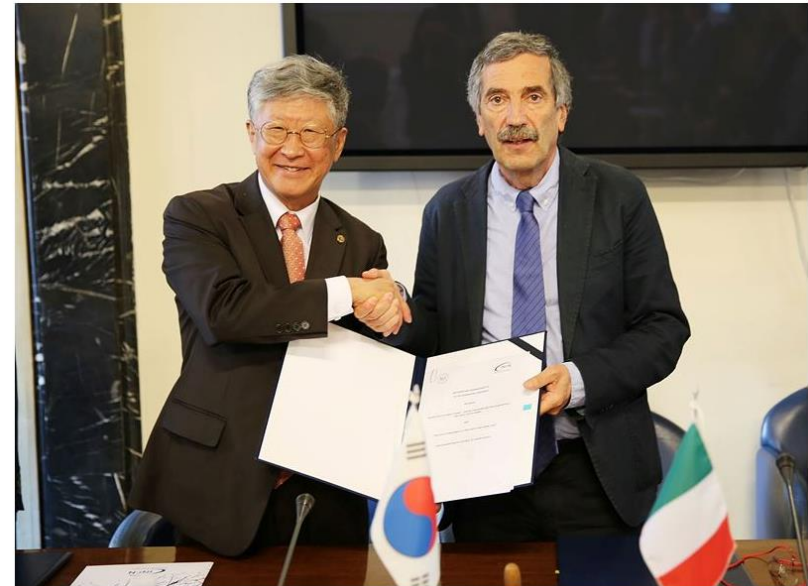
SABRE in Gran Sasso



MOU between IBS and INFN

한국-이탈리아 손잡고 우주의 비밀 풀다

IBS, 이탈리아 국립핵물리연구소(INFN)와 업무협약(MOU) 체결



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SABRE in Gran Sasso



COSINUS

COHERENT

DAMA-1ton

MOU between IBS and INFN

한국-이탈리아 손잡고 우주의 비밀 풀다

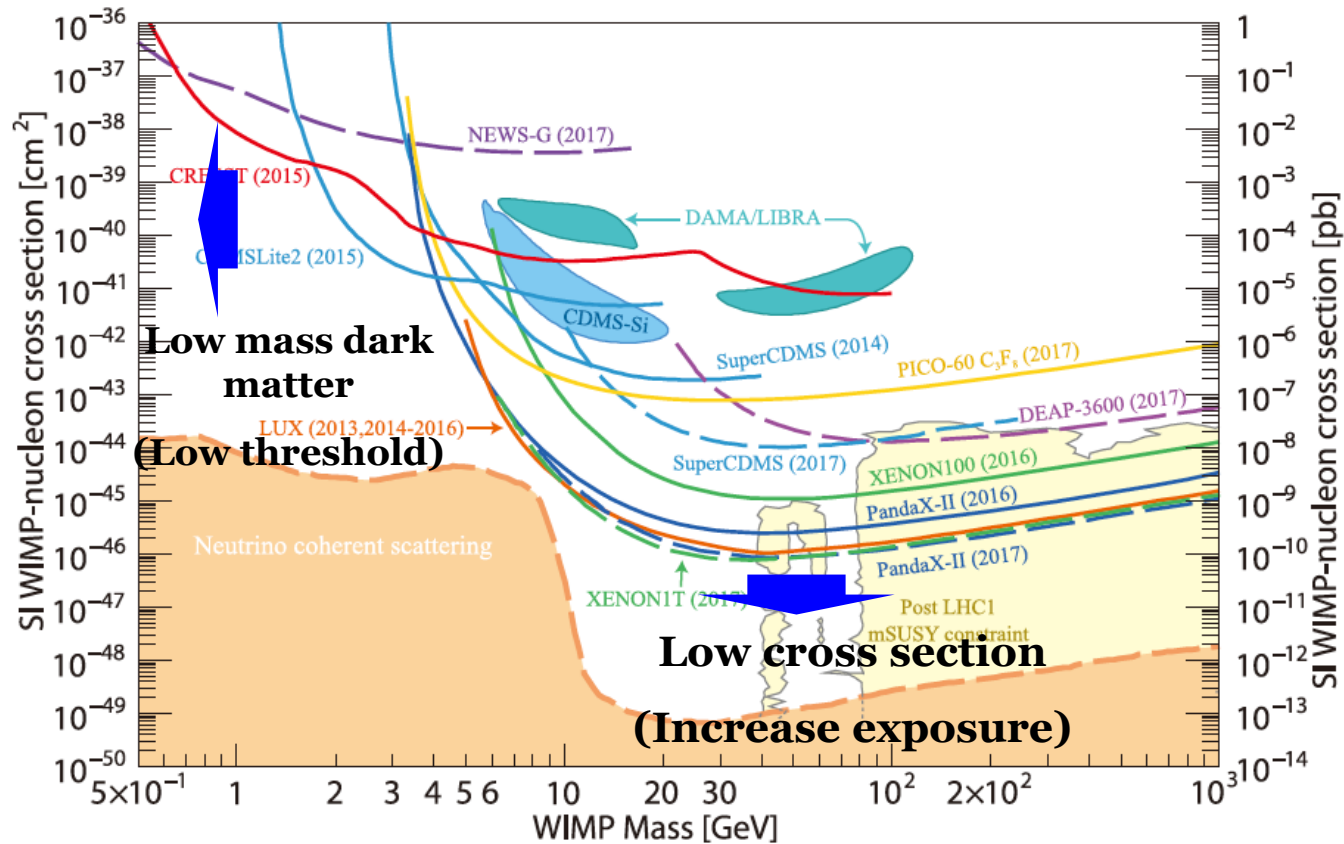
IBS, 이탈리아 국립핵물리연구소(INFN)와 업무협약(MOU) 체결



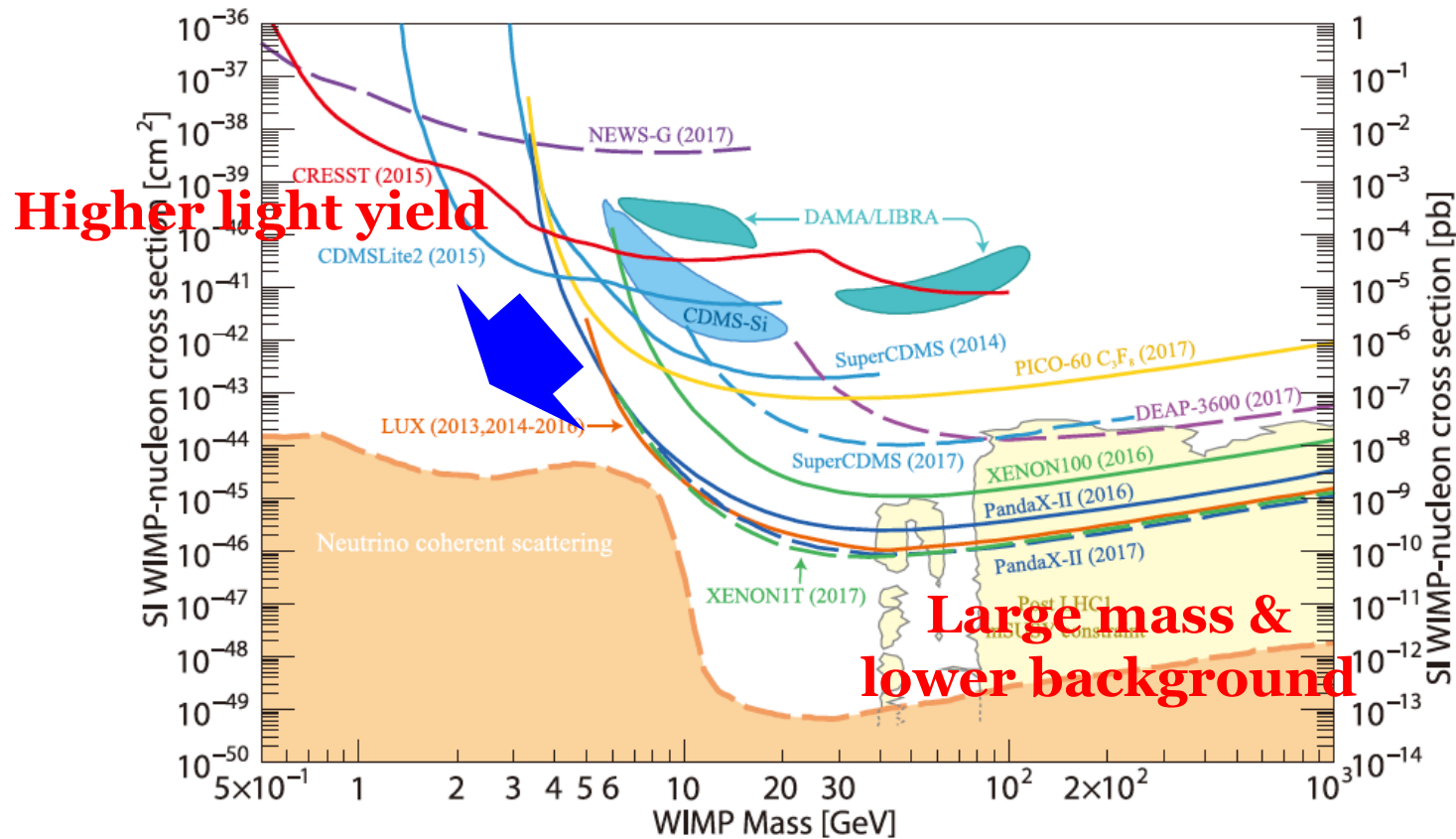
**Low-background NaI has large interests
from community**



General direction for dark matter detector



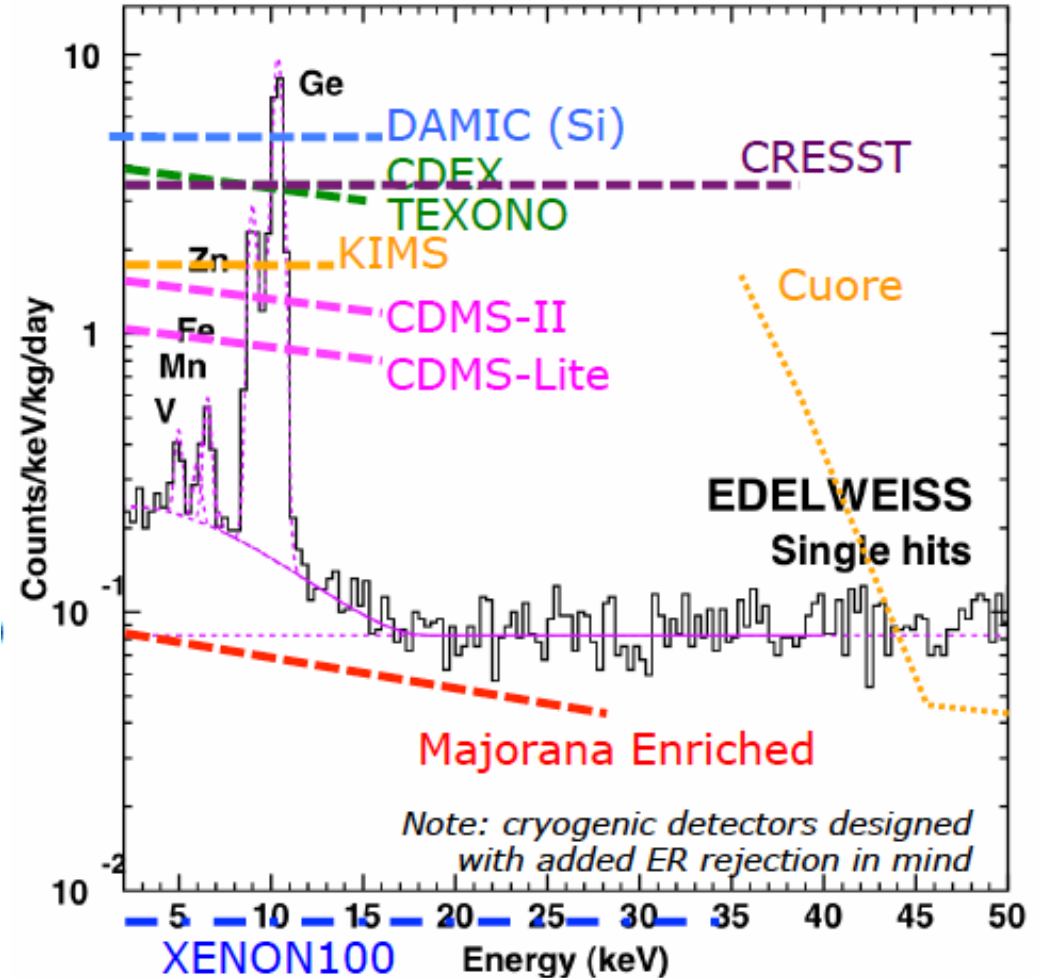
NaI(Tl) for dark matter detector



- NaI(Tl) is easy to scale up with affordable background & cost
- Affordably low energy threshold

0.1 dru background?

- Cosmogenic
 - ❖ ^{22}Na , ^3H may be issue
 - ❖ **Our own growing** make much less contribution
 - ❖ May consider **underground crystal growing lab**
- Internal background
 - ❖ Further development of **powder purification & crystal growing**
- External background
 - ❖ At low energy, it is already low enough. Can consider **crystal capsuled with LS**
 - ❑ May consider **larger LS thickness** between PMT to crystal

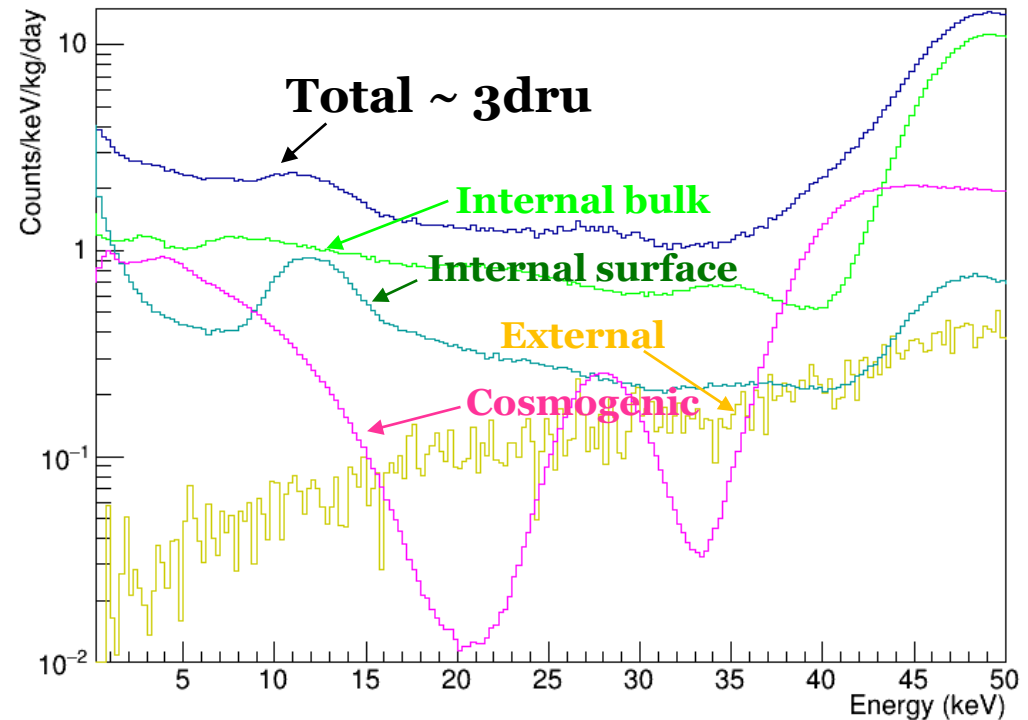


Jules Gascon (IDM2016)

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Current COSINE crystal



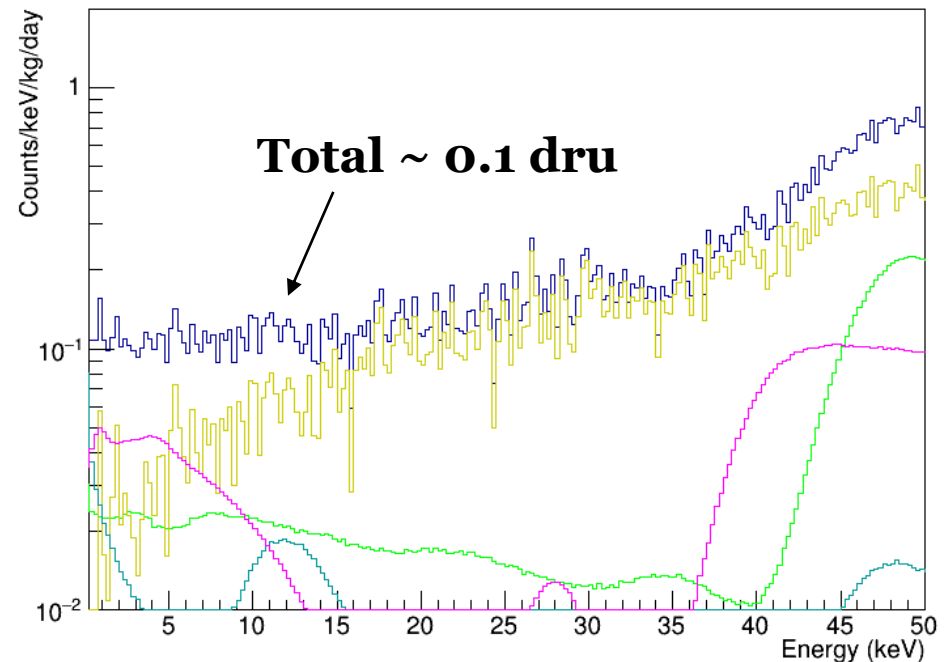
0.1 dru background?

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Internal (1/30)

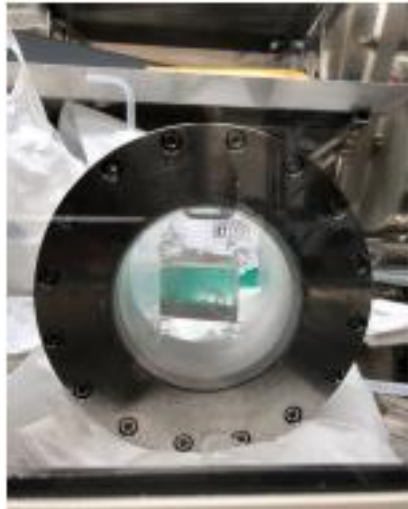
cosmogenic (1/20)

Background reduced crystal

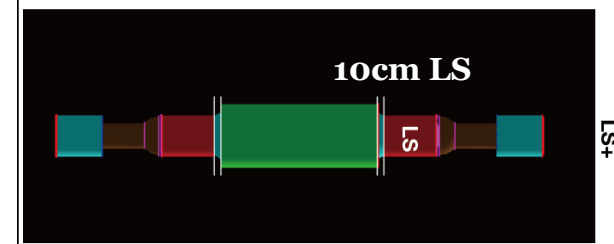
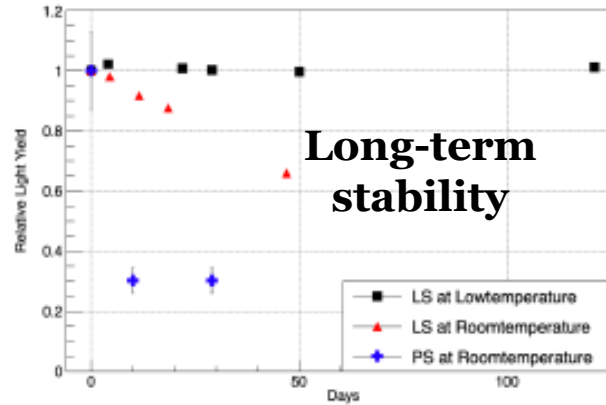


Further lower background

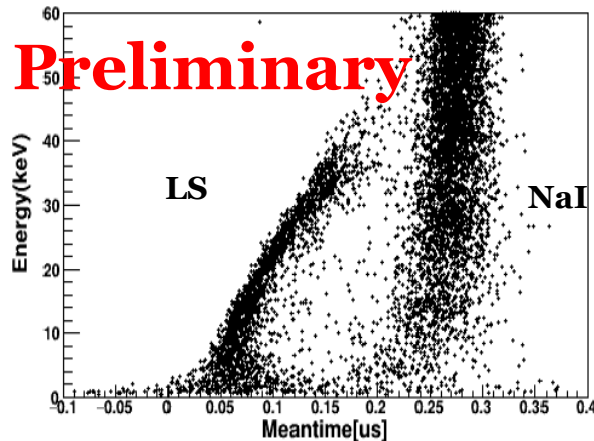
- External background can be rejected if we put active tagging (liquid scintillator) between PMT and crystal



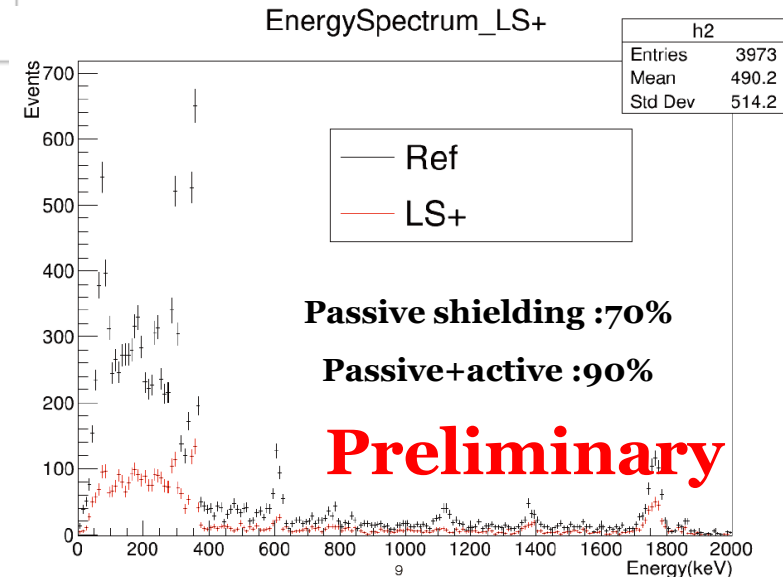
arXiv:1908.04022



Meantime distribution of NaI014 (SET54)



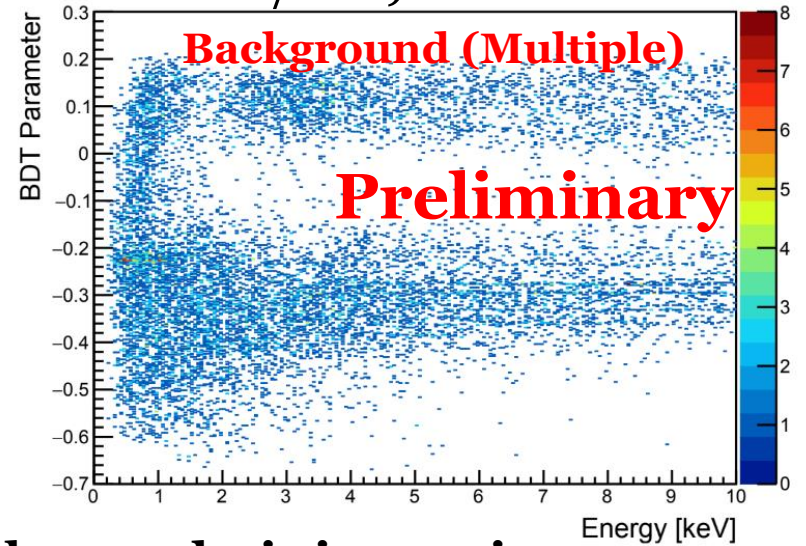
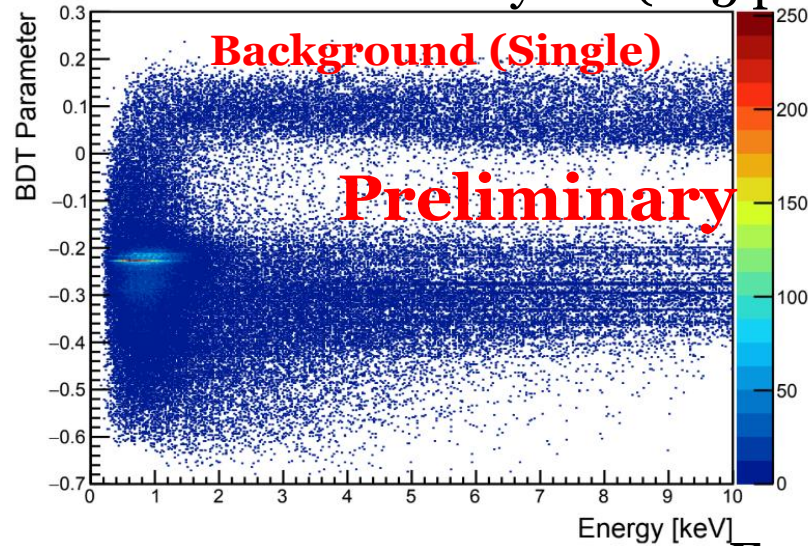
This design can tag surface recoil events!!



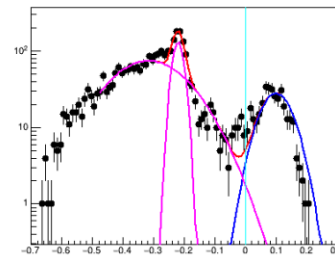
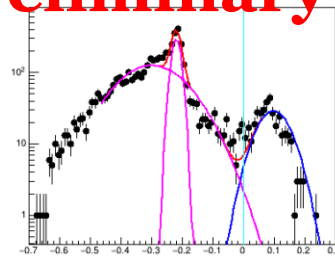
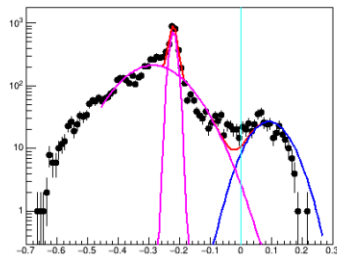
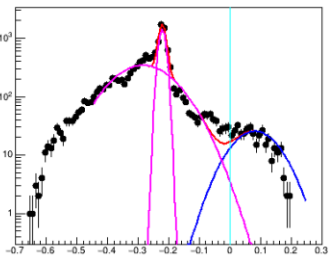
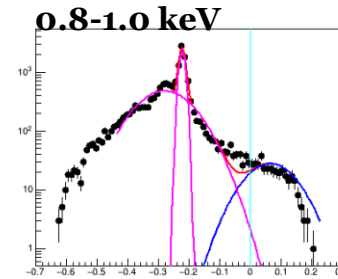
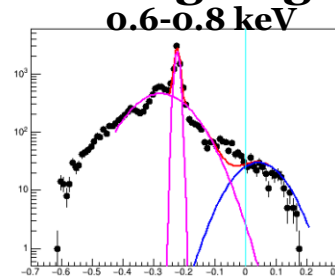
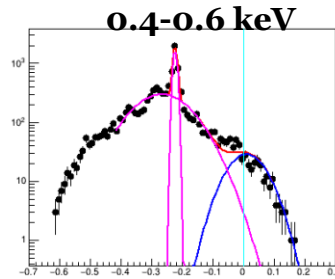
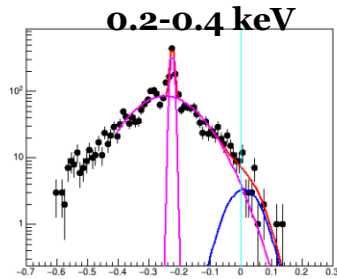
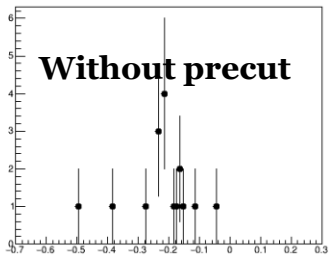
Con: Higher analysis threshold

Low energy threshold with multivariable analysis

One of COSINE-100 crystal (~ 15 photoelectrons/keV)



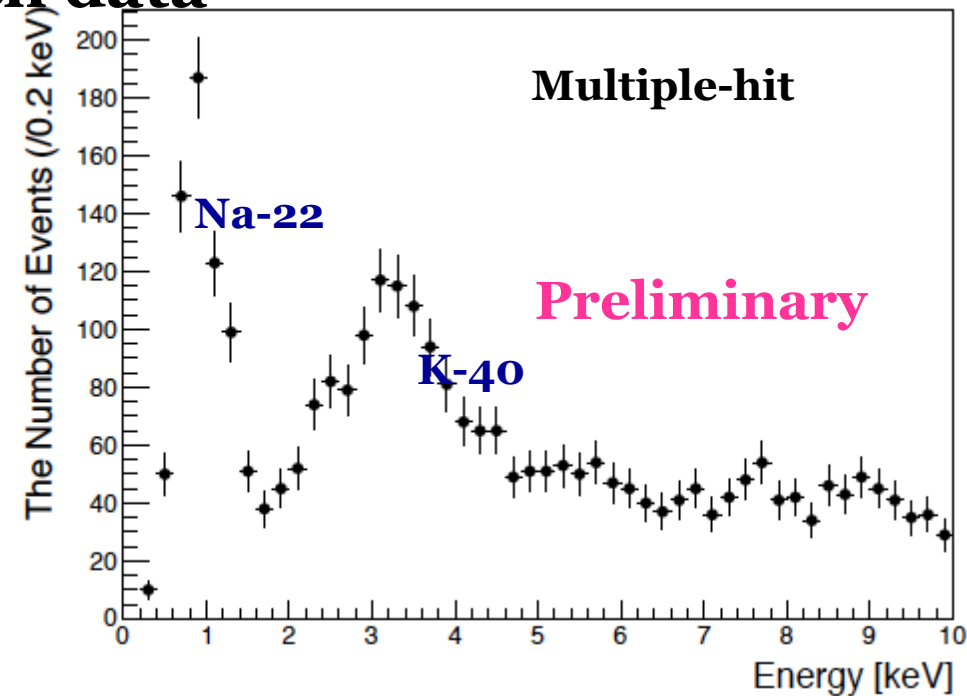
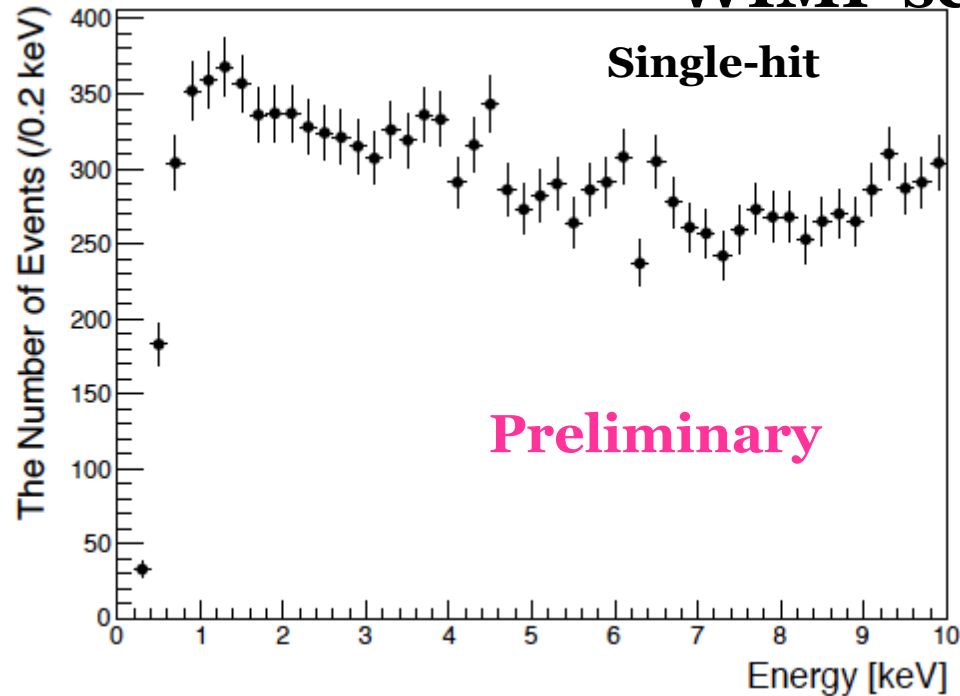
Further analysis is ongoing



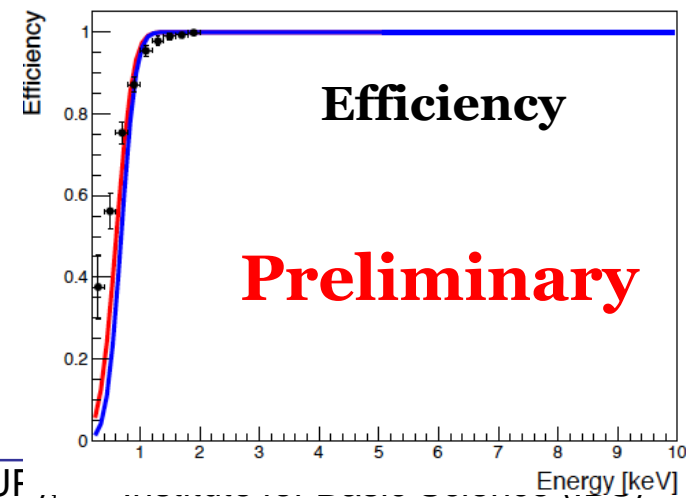
Preliminary

Low energy threshold from COSINE-100 detector

WIMP search data



- 0.4 keV (6 NPE) threshold
 - ❖ Efficiency is about 20%
 - ❖ We may reduce to ~ 4 NPE
- Try to use Deep Learning

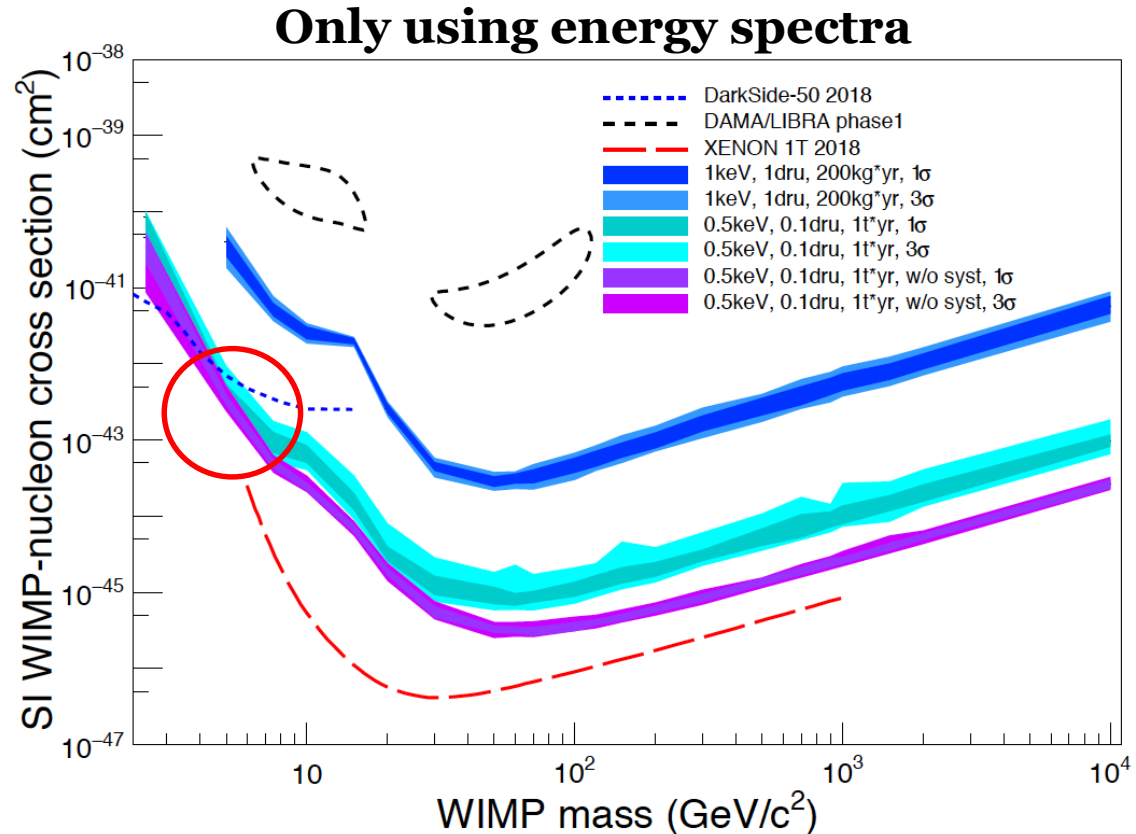


COSINE-1ton experiment ? (2025~)

- 0.1 dru background, 0.5 keV threshold, 1 ton year exposure

COSINE-200 will be precursor for COSINE-1ton

Items	price
Crystals	10
3" PMTs	5
Shielding	5
Lead	15
LS	1
5" PMTs	0.5
Muon	2
2" PMTs	1
DAQ	1
High Voltage	1
Total	~40 억원

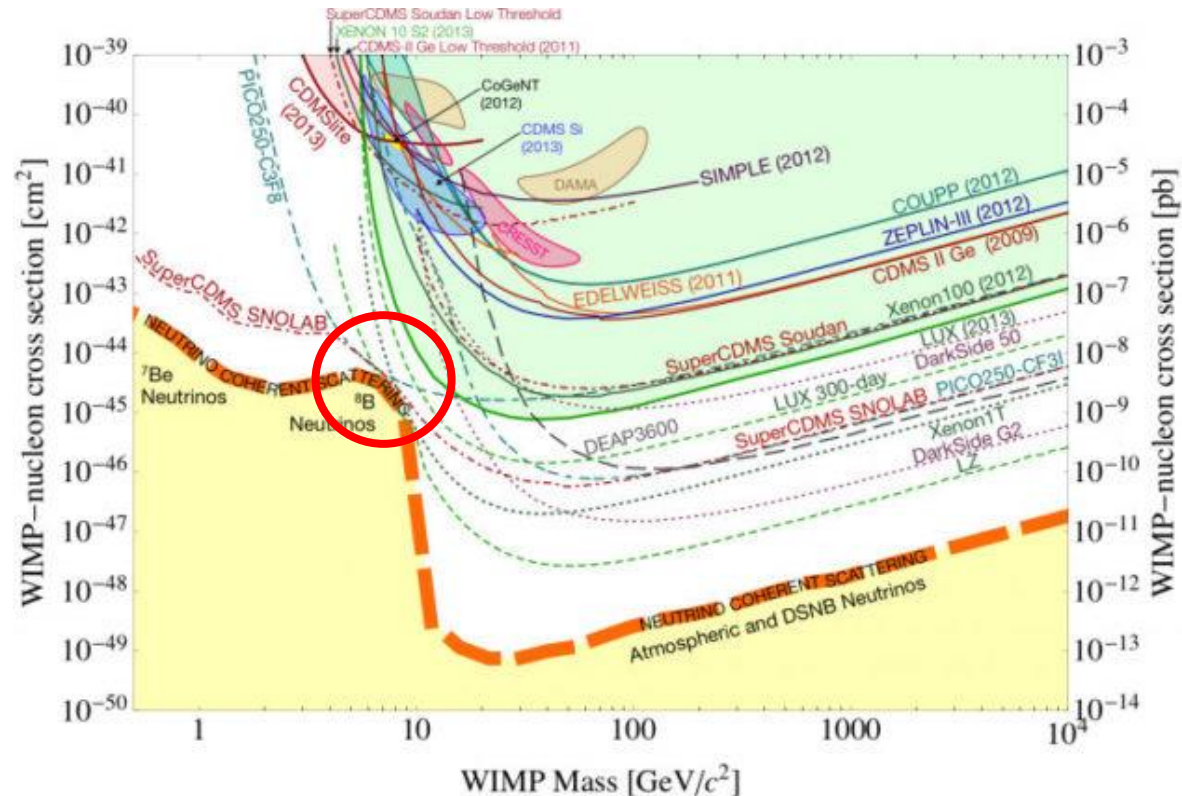


It can be reduced to half if we reuse all materials of COSINE-200

COSINE-1ton experiment ? (2025~)

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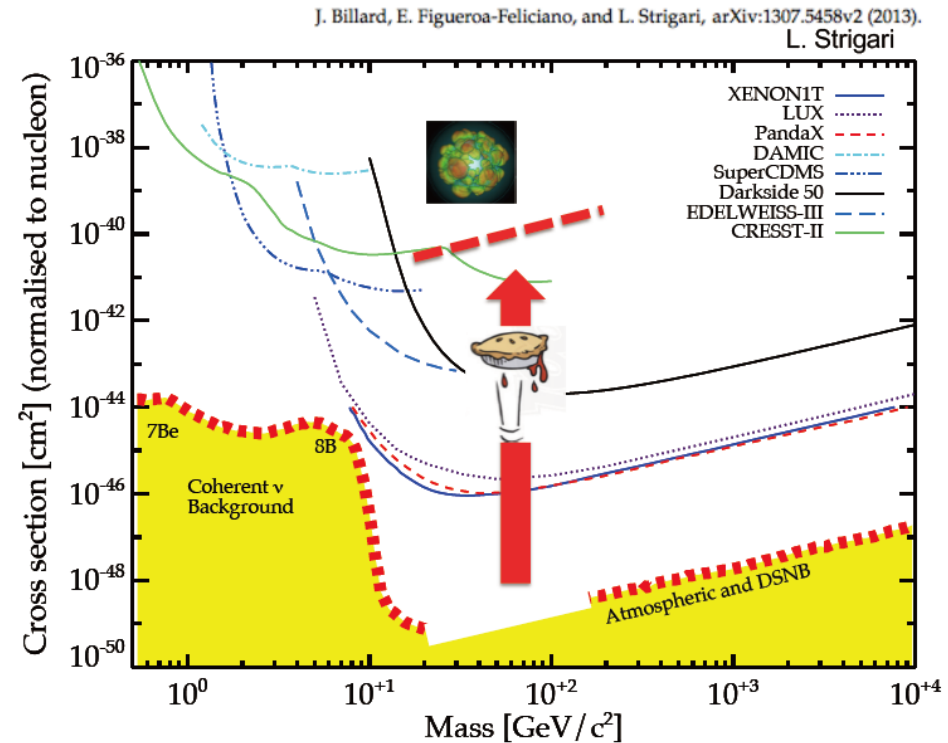


Good detector to study ⁸B solar neutrino

COSINE-1ton experiment ? (2025~)

- 0.1 dru background, 0.5 keV threshold, 1 ton year exposure

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Crystals	10
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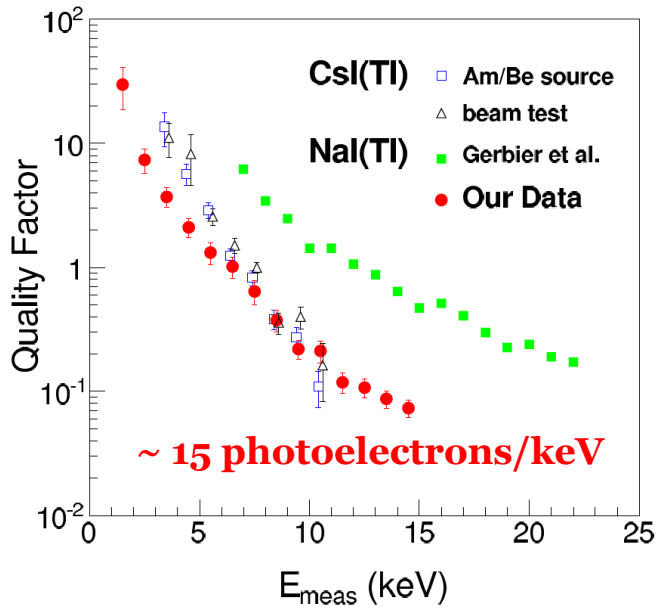
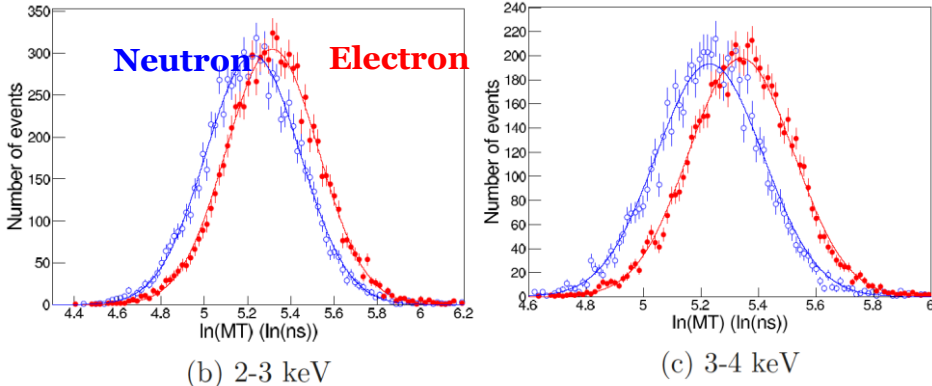


SN burst @ 10 kpc
Supernovae neutrino

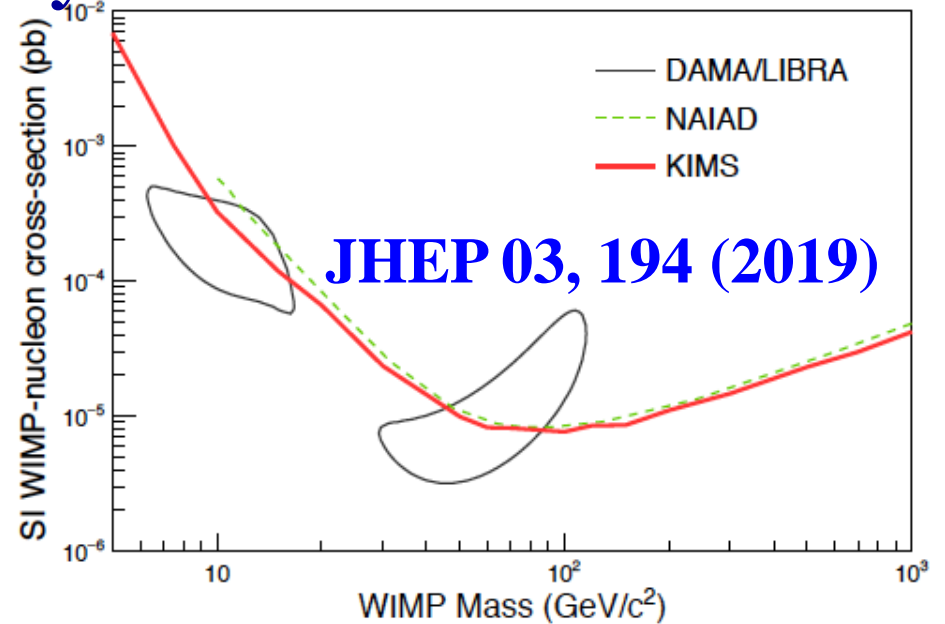
Pulse shape discrimination

JHEP 08, 093 (2015)

Nuclear recoil discrimination



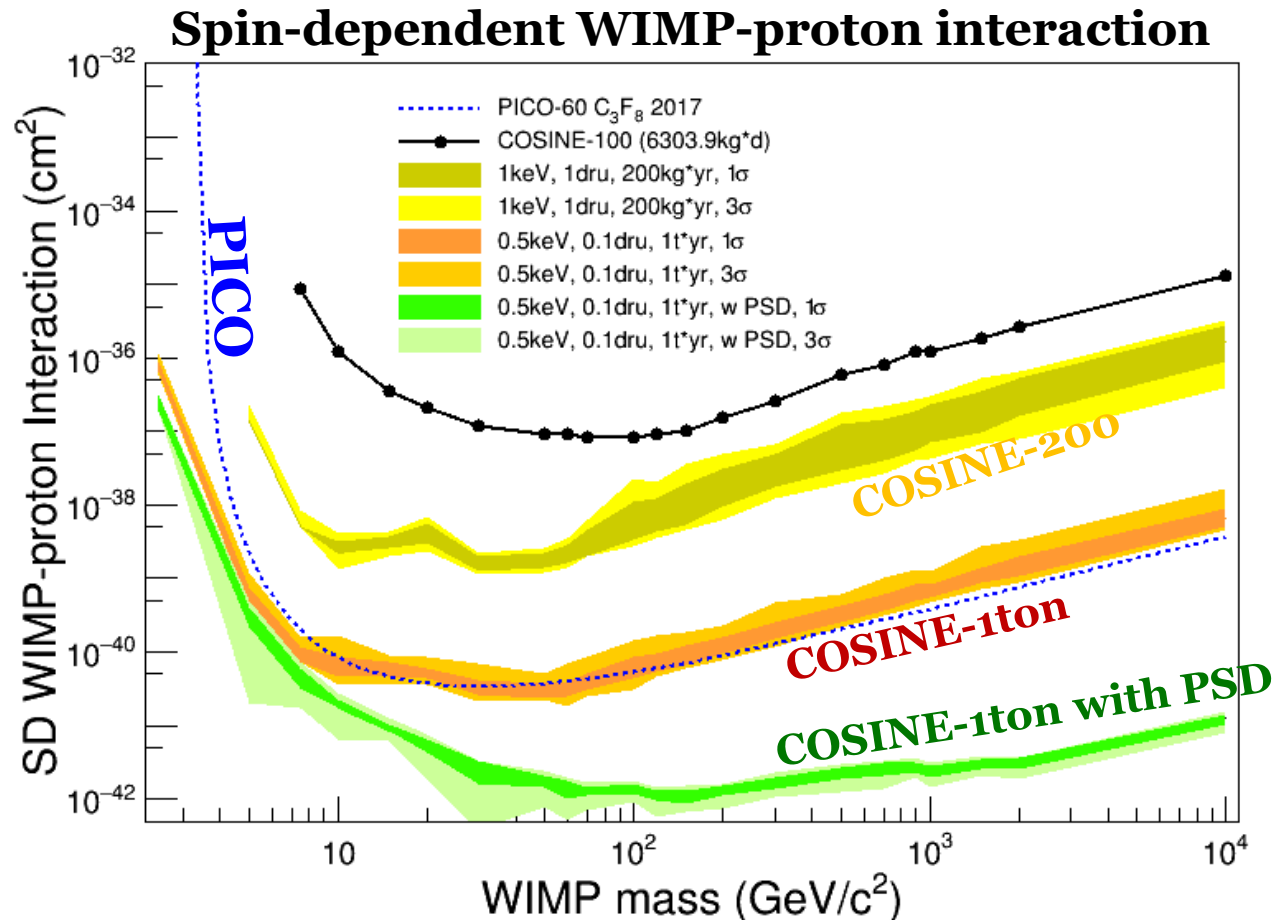
Physics results with R&D data



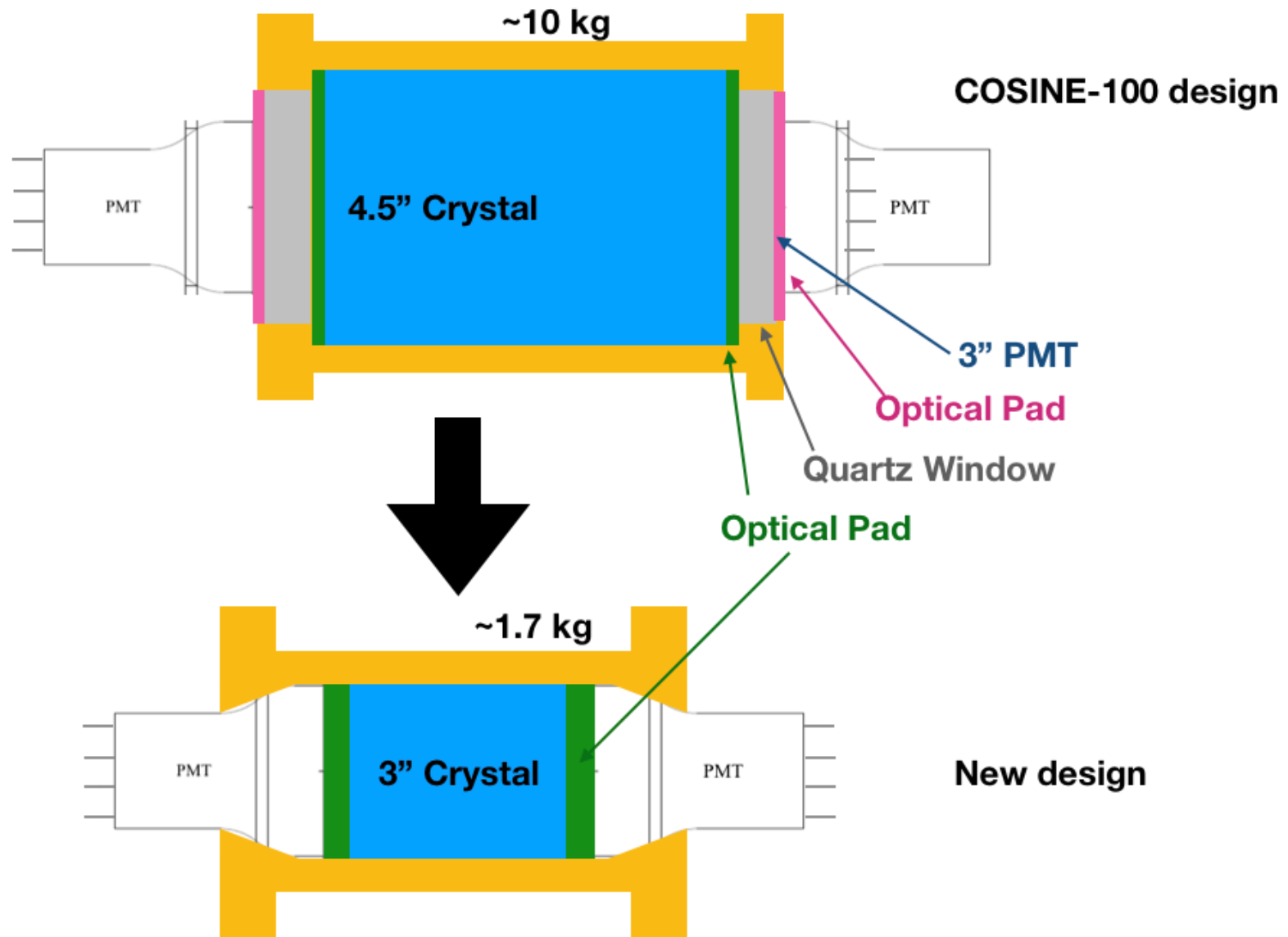
Improving PSD performance with neural network is ongoing

COSINE-1ton for spin-dependent interaction

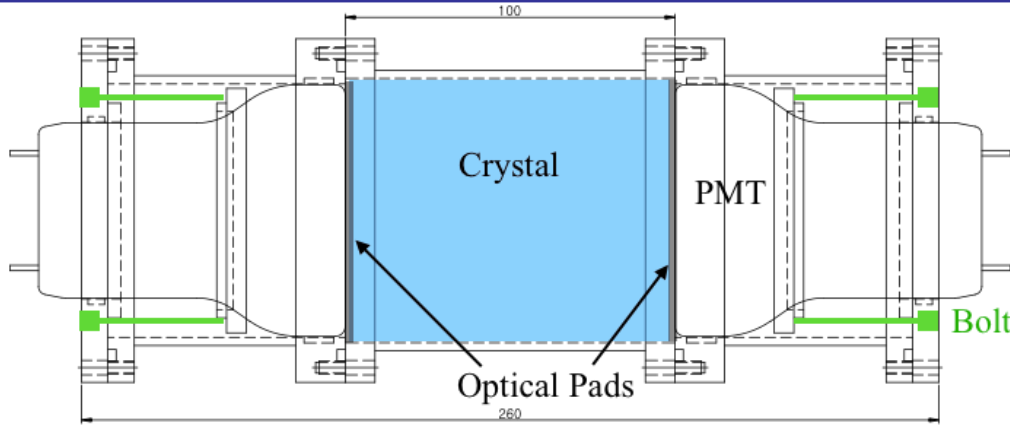
- Both Na ($Z=11$) and I ($Z=53$) are proton spin-odd
 - ❖ Sensitive detector for spin-dependent WIMP-proton interaction
 - ❖ Most of dark matter detector has proton even element



Optimize crystal encapsulation for high light yield



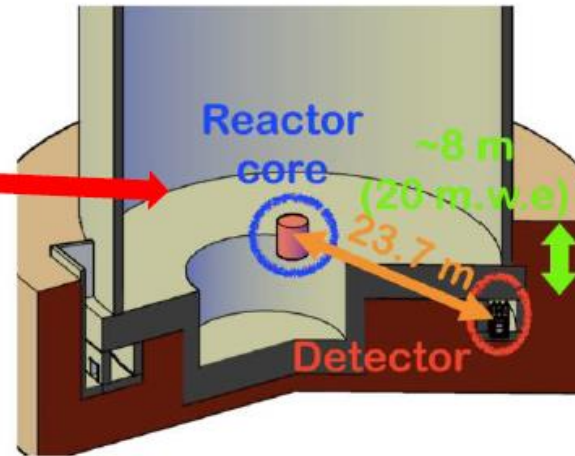
Assembly



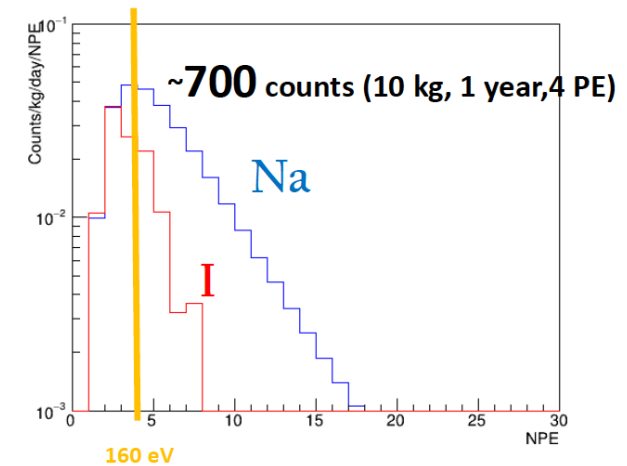
- 25 NPE/keV would be possible

❖ ~0.25 keV energy threshold

NEON : Neutrino Elastic-scattering Observation with NaI(Tl)



Expected Signals (LY : 25 PE/keV)



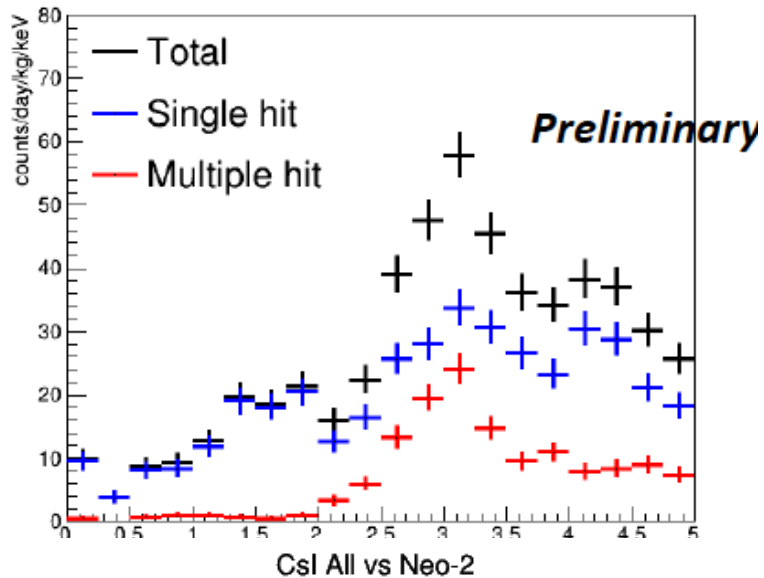
Tendon Gallery of Hanbit Nuclear Power Plant (Yeonggwang)

- Use same place of NEOS experiment
- Put ~ 10 kg commercial NaI(Tl) detectors
 - ❖ Largest mass between similar experiments at reactor

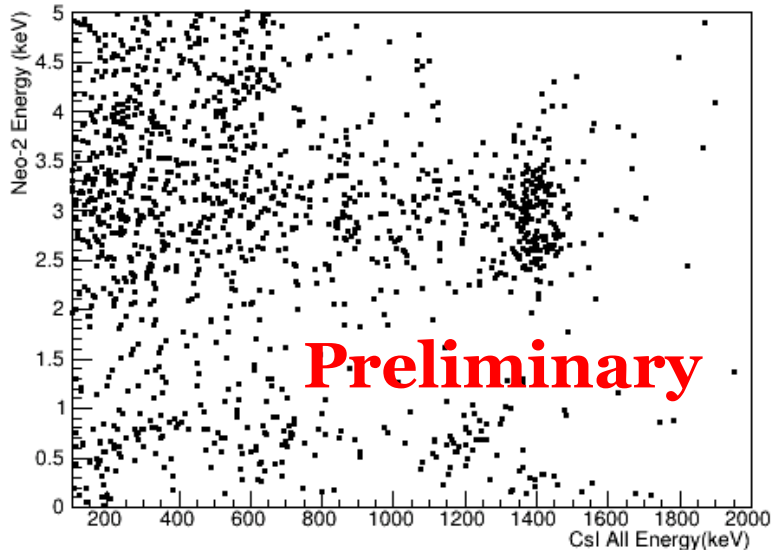
Background of commercial crystals

Underground measurement

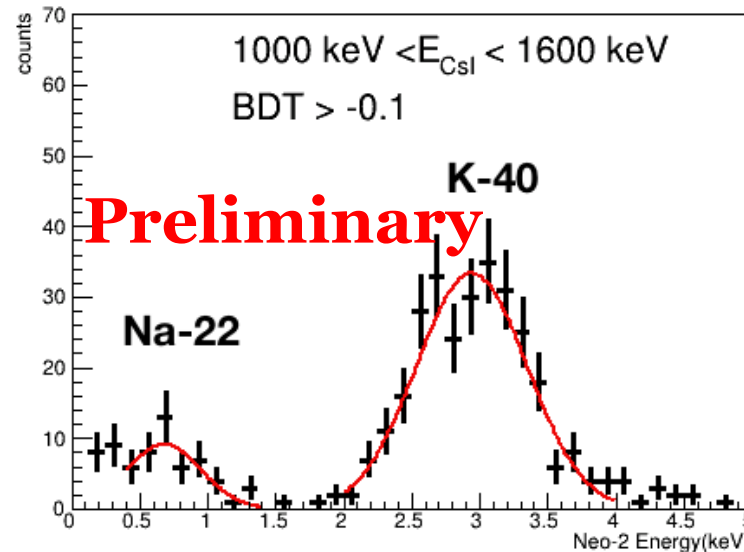
NEO-02 Energy Spectrum (Zoom)



- Commercial crystals
- ~ 10 dru background
 - ❖ COSINE crystal is 3 dru
- Low threshold below 0.5 keV
- Further studies are ongoing



Neo-2 High Energy Coincidence

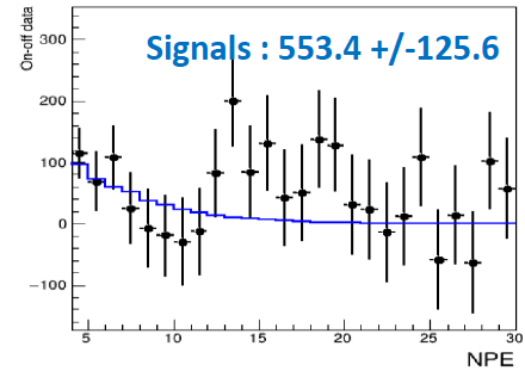
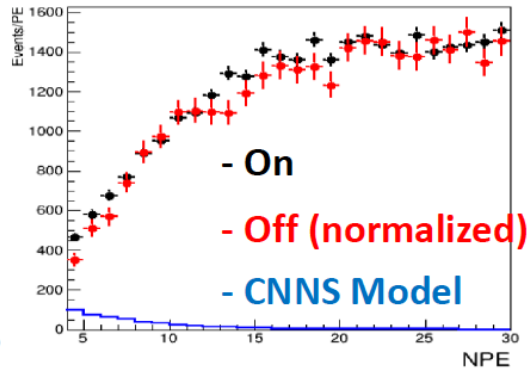


Sensitivity

• Input parameters

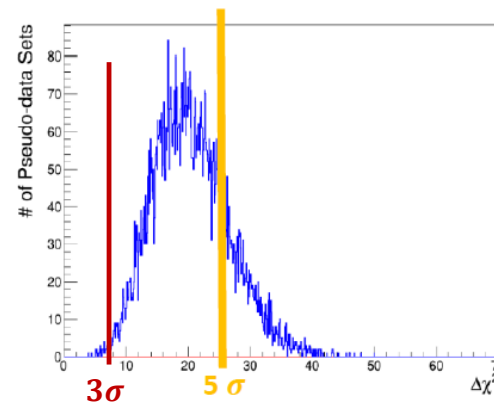
- Flat background ~ 10 dru
- Total mass ~ 10 kg
- Reactor on data ~ 365 days
- Reactor off data ~ 100 days
- Light yields = 25 PE/keV
- Threshold ≥ 4 PE

One example of Pseudo experiment



On - Off data

1000 Pseudo experiments $\Delta\chi^2$ distribution



Estimate $\Delta\chi^2 = \chi^2 (\text{null}) - \chi^2 (\text{best fit})$

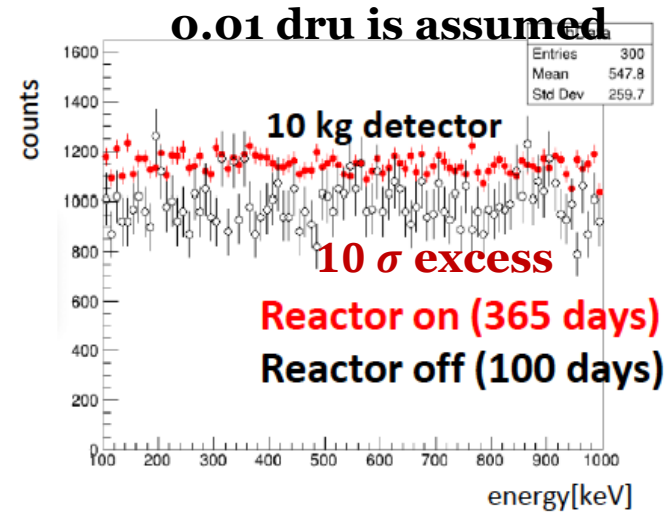
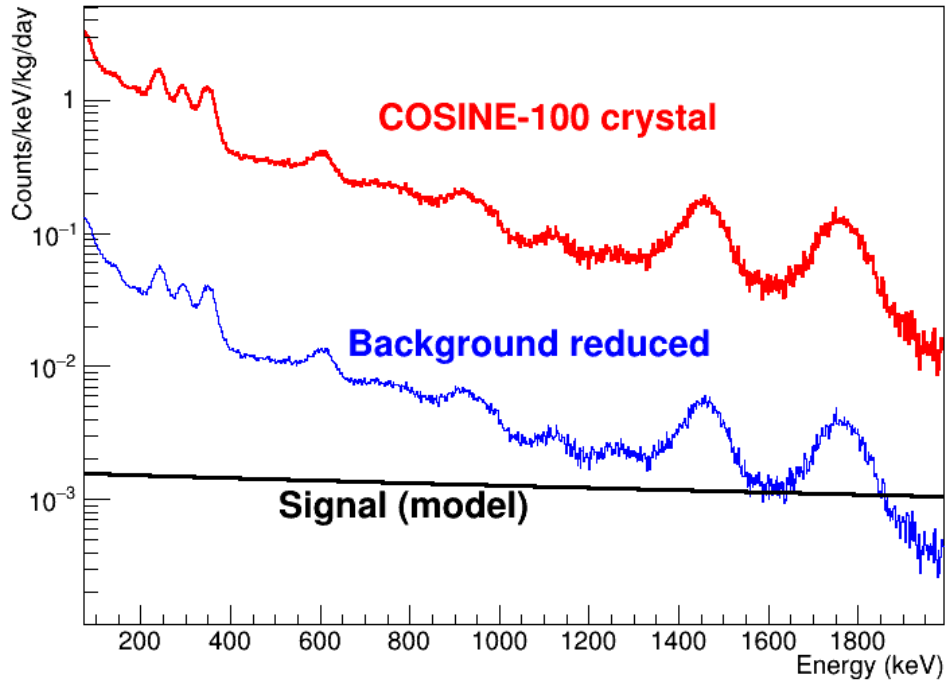
Significance : $4.5 \pm 0.7 \sigma$

Strategy & costs

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

- NEON-pilot (~2021) ~ **1억원** (+**2억원 already spent**)
 - ~ 10 kg commercial quality crystals (Expect ~10 dru background)
 - We will install detector by the end of this year **> 3 σ evidence**
 - Goal : demonstration of detector performance and some hints of CNNS signals
- NEON-phase1 (~2023) ~ **+1억원 (crystal +5억원) Recycle COSINE-100 crystal?**
 - ~ 50 kg COSINE-100 quality crystals (~3 dru background)
 - Goal : observation of CNNS from reactor **> 5 σ observation**
- NEON-phase2 (~2025) ~ **+2억원 Can use COSINE-200 crystals**
 - ~100 kg further purified crystals (< 1 dru background) **> 10 σ**
 - Goal : precision measurement and explore new physics interaction

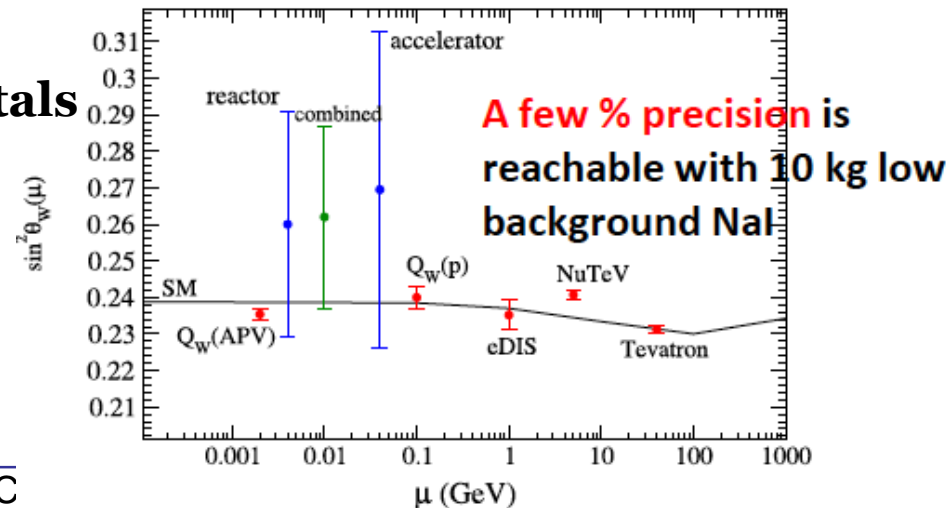
$\bar{\nu}_e - e$ scattering at below 3 MeV



10 kg 1 year can have ~10,000 signal events
Phys. Lett. B 761 (2016) 450

Good opportunity with low background crystals

Neutrino magnetic moment?



Summary

- Primary goal of COSINE experiment is to prove (disprove) DAMA annual modulation
 - ❖ COSINE-100 has produced interesting understanding for this purpose
 - ❖ COSINE-200 will make final conclusion
- NaI(Tl) detector R&D for COSINE-200 is well progressed
- Beyond DAMA modulation has been studied and a few interesting directions are available
 - ❖ Spin-dependent WIMP-proton interaction
 - ❖ Coherent neutrino scattering

Backup

COSINE-100 construction

Dec. 2015



Jan. 2016



Feb. 2016



Mar. 2016

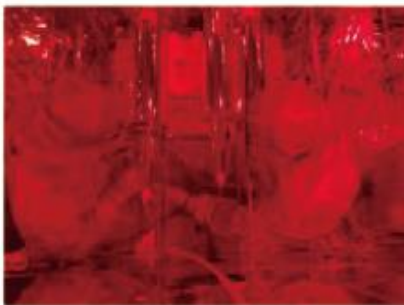
Apr. 2016



May. 2016

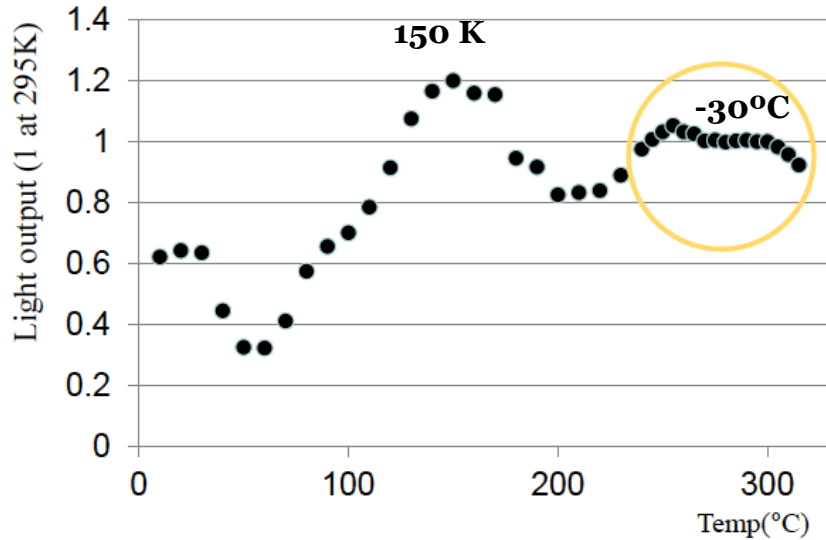
Jun. 2016

Sep. 2016



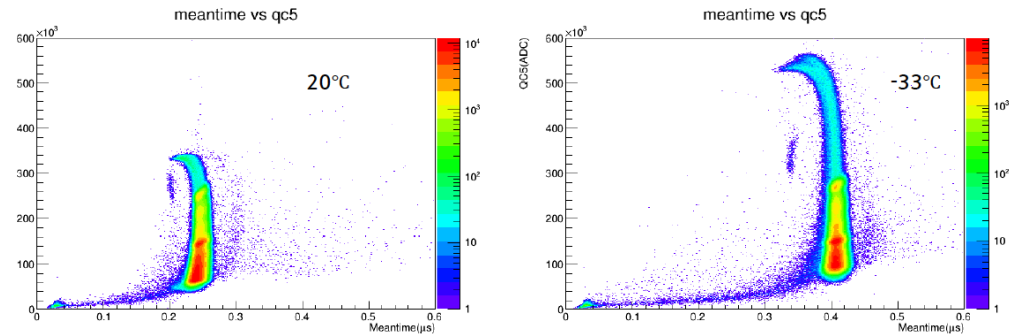
Light yield with different temperature

NaI(Tl) light output



Test setup for 150K

))



- We observe ~20% increase of light yield
- In addition, alpha quenching is increased ~ 20%
- Total 40% increase (?)

Nal(Tl) crystals

Pro

- High light output
 - ❖ 40,000 photons/MeV
 - ❖ >60,000 photons/MeV?
- Easy to grow
 - ❖ Cheap
 - ❖ Large size
- The most widely used scintillator

Con

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



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

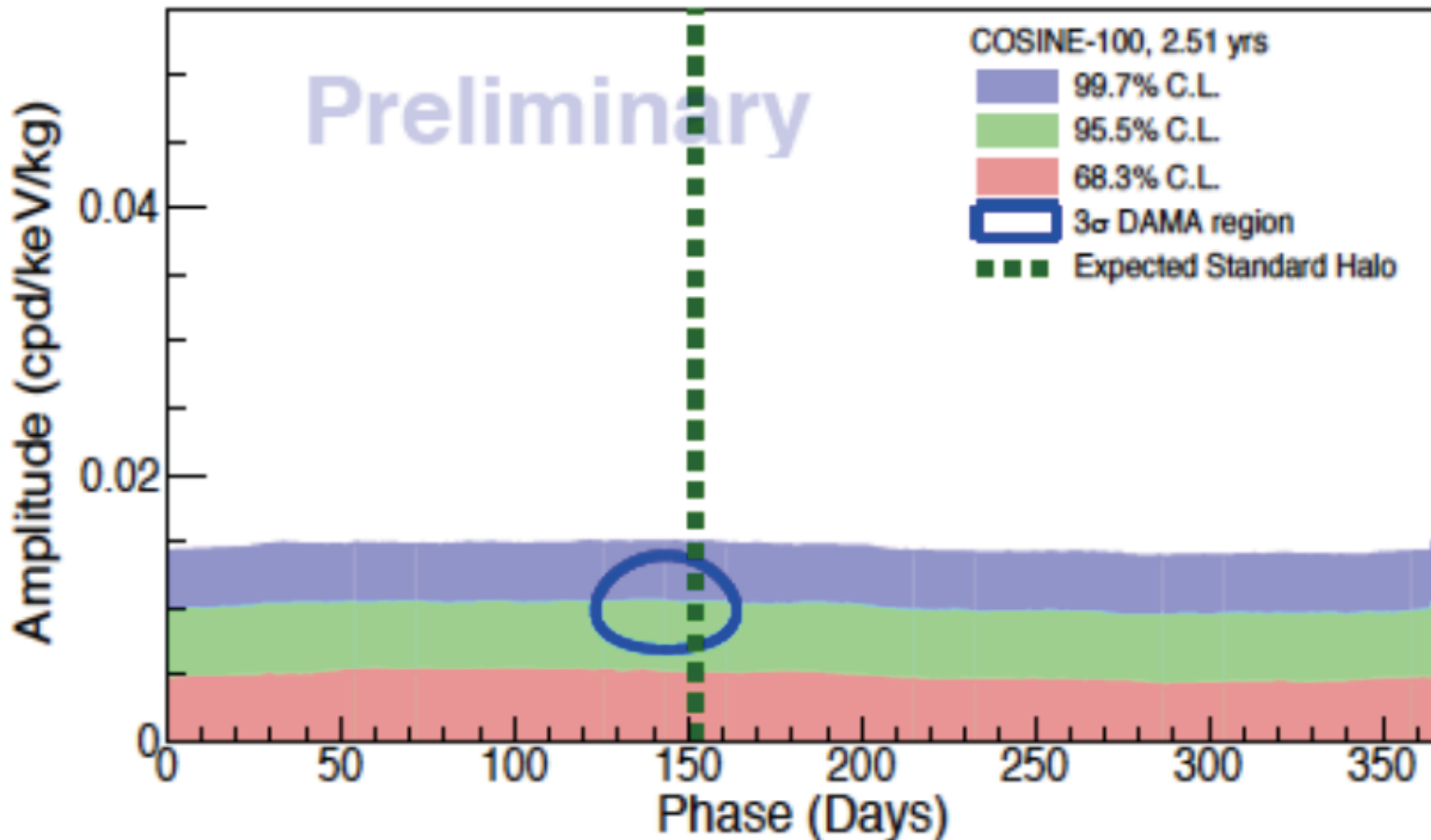


Properties	From Saint-Gobain
Density [g/cm ³]	3.67
Melting point [K]	924
Thermal expansion coefficient [C ⁻¹]	47.4 x 10 ⁻⁶
Cleavage plane	<100>
Hardness (Mho)	2
Hygroscopic	yes
Wavelength of emission max [nm]	415
Refractive index @ emission max.	1.85
Primary decay time [ns]	250
Light yield [photons/keV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

SET3 Predicted Sensitivity Assuming no modulation case

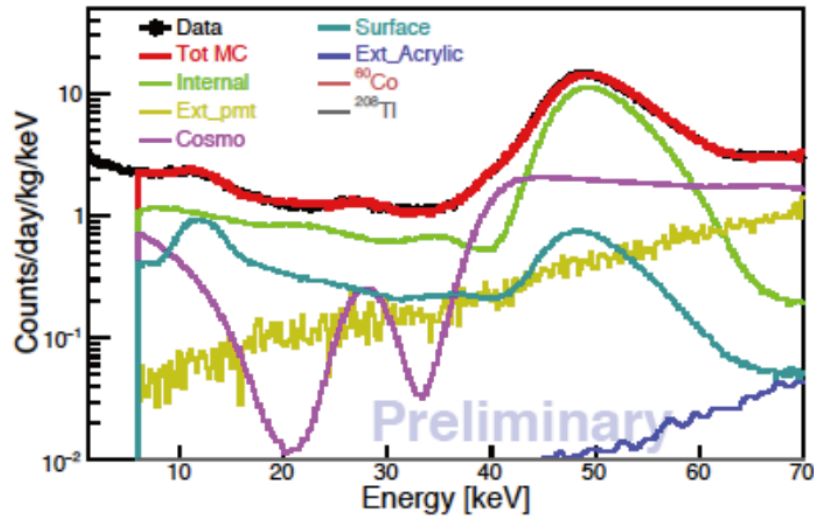
~ 3 years data

~ This winter

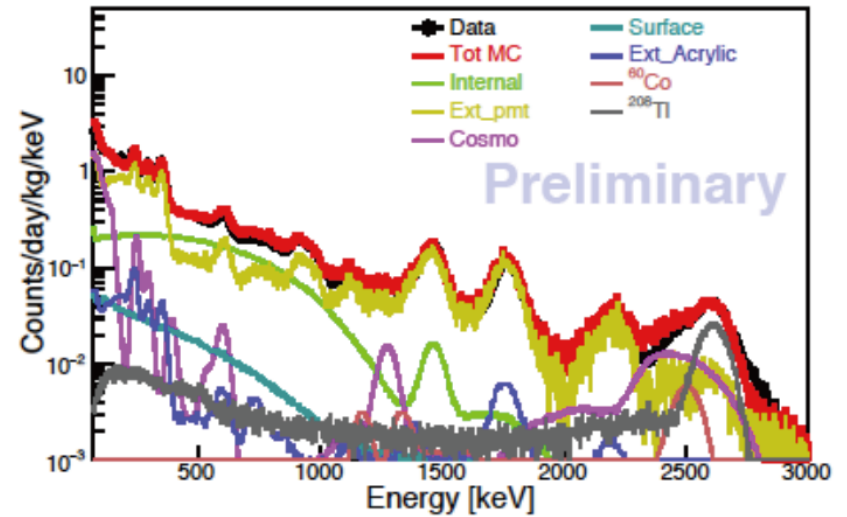


Improving Background Understanding

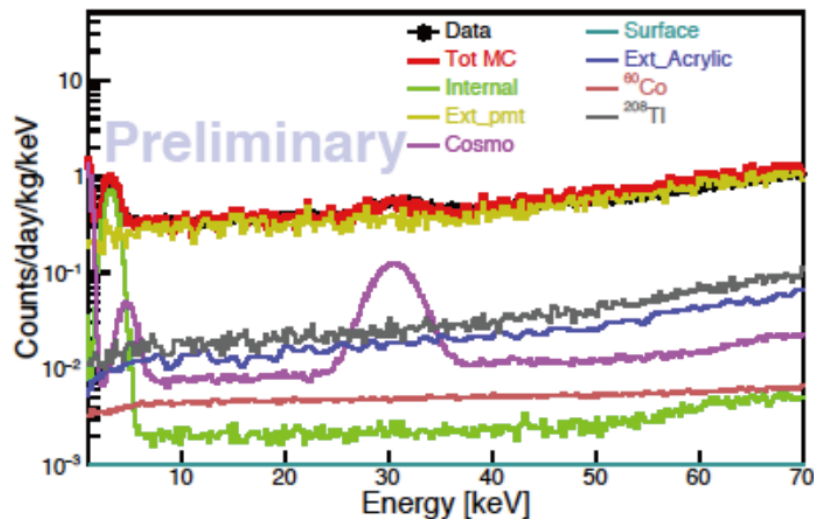
Background modeling for C6 [High gain, Single Hit]



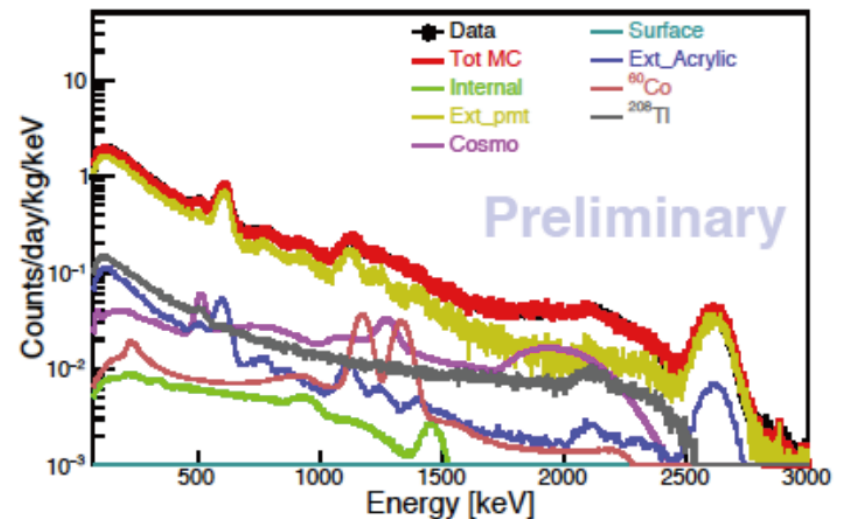
Background modeling for C6 [Low gain, Single Hit]



Background modeling for C6 [High gain, Multiple Hit]



Background modeling for C6 [Low gain, Multiple Hit]



with 1 keV threshold