Status of COSINE experiment

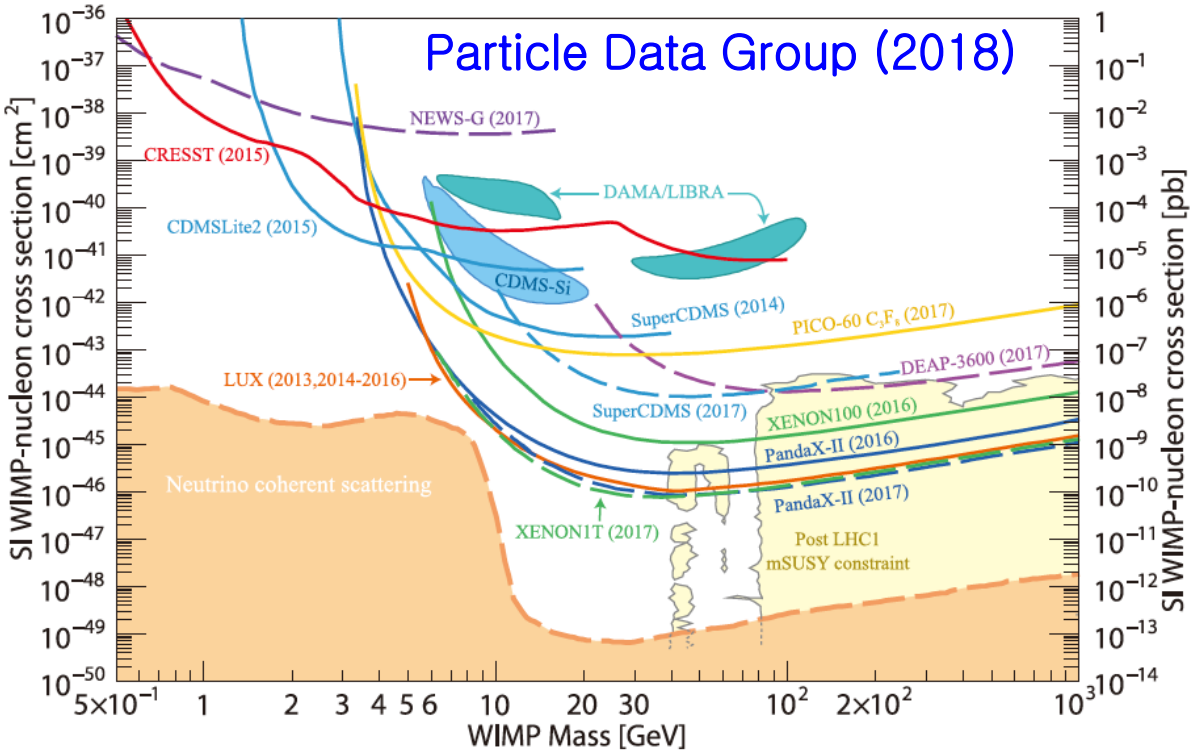
Hyun Su Lee

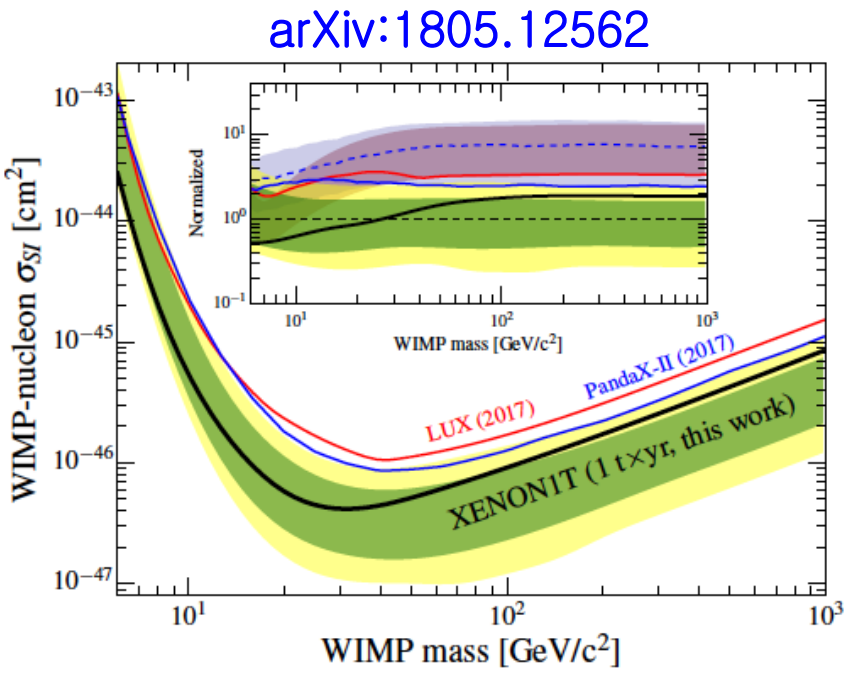
Center for Underground Physics (CUP)

Institute for Basic Science (IBS)

On behalf of the COSINE Collaboration

Current status of direct dark matter searches





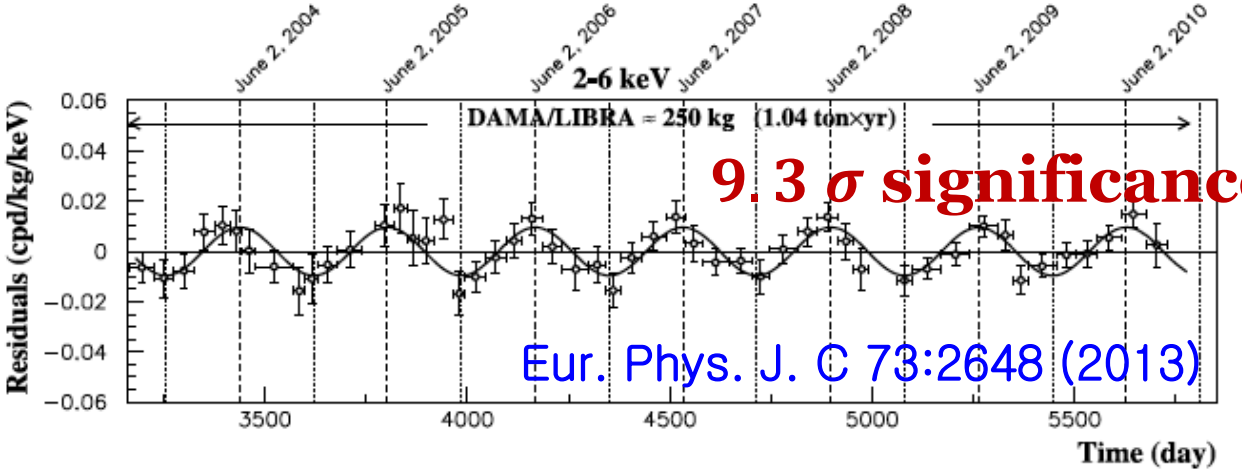
- No sign of WIMP dark matter down to 4×10^{-47}cm^2 @ 30 GeV
- Exploring low-mass dark matter
- Unresolved signal from DAMA

Observation of dark matter annual modulation signal (?)

DAMA/LIBRA experiment

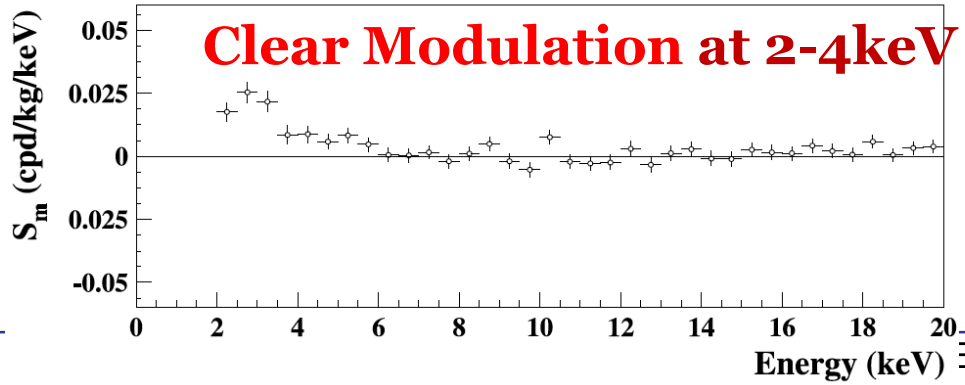
- Annual Modulation Searches with an array of NaI(Tl) crystals

Claimed an observation of the dark matter



9.3 σ significance

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



DAMA/LIBRA phase 1

1.33 ton-year

Observation of dark matter annual modulation signal (?)

DAMA/LIBRA experiment

- Annual Modulation Searches with an array of NaI(Tl) crystals

Claimed an observation of the dark matter

First model independent results from DAMA/LIBRA–phase2

New result from DAMA/LIBRA

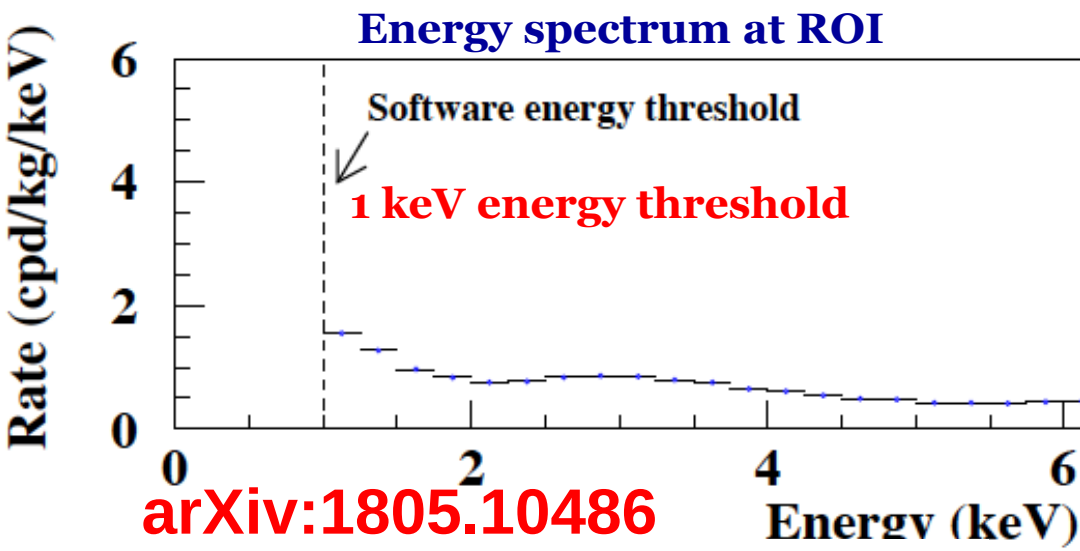
R. Bernabei[a,b], P. Belli[a,b], A. Bussolotti[b], F. Cappella[c,d], V. Caracciolo[e], R. Cerulli[a,b], C.J. Dai[f], A. d'Angelo[c,d], A. Di Marco[b], H.L. He[f], A. Incicchitti[c,d], X.H. Ma[f], A. Mattei[d], V. Merlo[a,b], F. Montecchia[b,g], X.D. Sheng[f], Z.P. Ye[f,h]

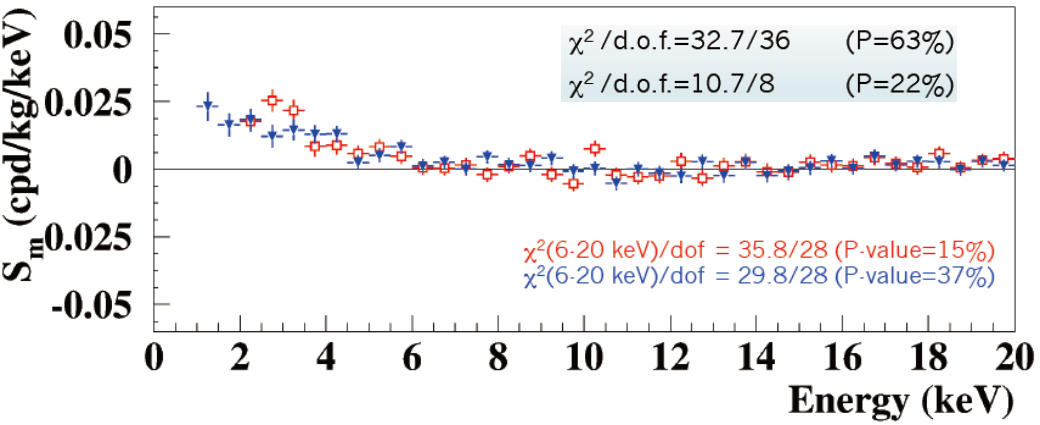
arXiv:1805.10486

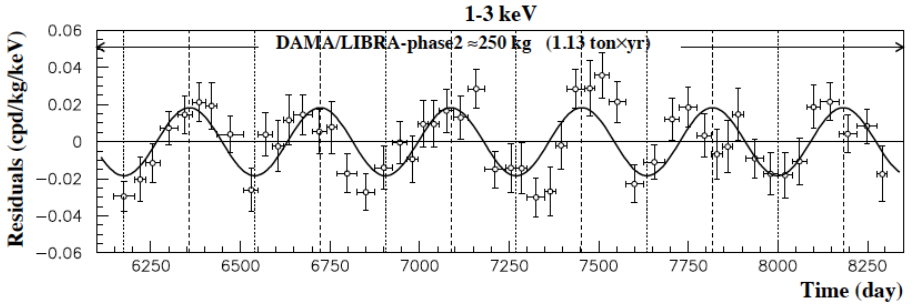
e 1

DAMA/LIBRA phase 2

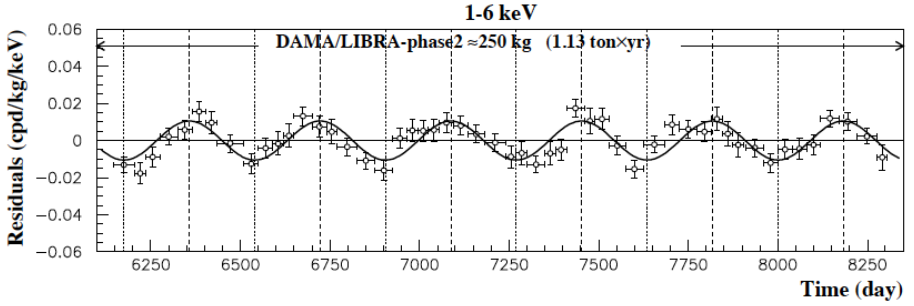
- Energy threshold reached to 1 keV with better PMTs
- Still there is modulation
- Significance
  - ❖ 1-6 keV : **9.5 σ** (phase 2)
  - ❖ 2-6 keV : **12.9 σ** (phase 1+2)
- Increased modulation amplitude below 2keV



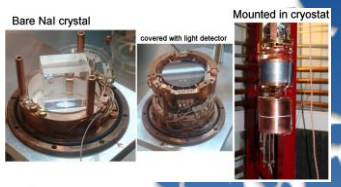




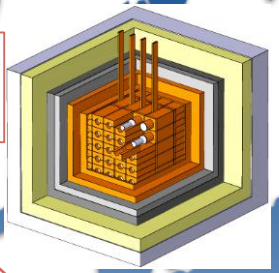
Modulation amplitude



Global NaI(Tl) efforts

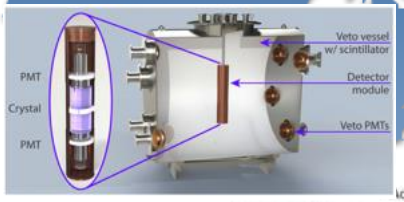


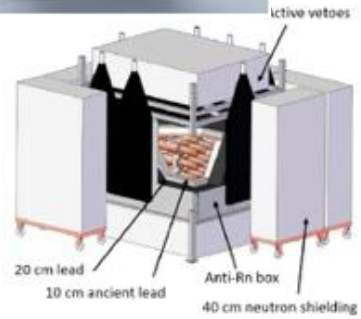
COSINUS
@ Modane



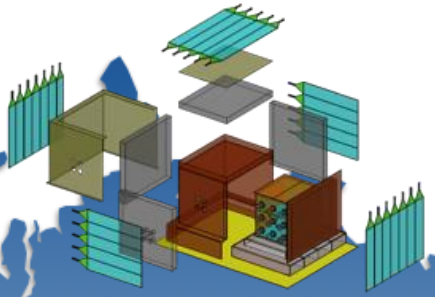
DAMA
@ LNGS

SABRE
@ LNGS



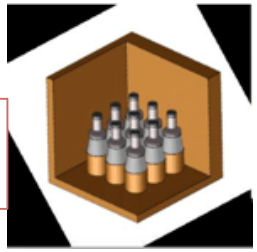


KIMS/**COSINE**
@ Yangyang

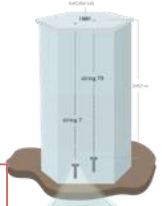


ANAIS
@Canfranc

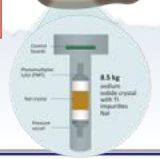
PICO-LON
@ Kamioka



SABRE
@ Stawell

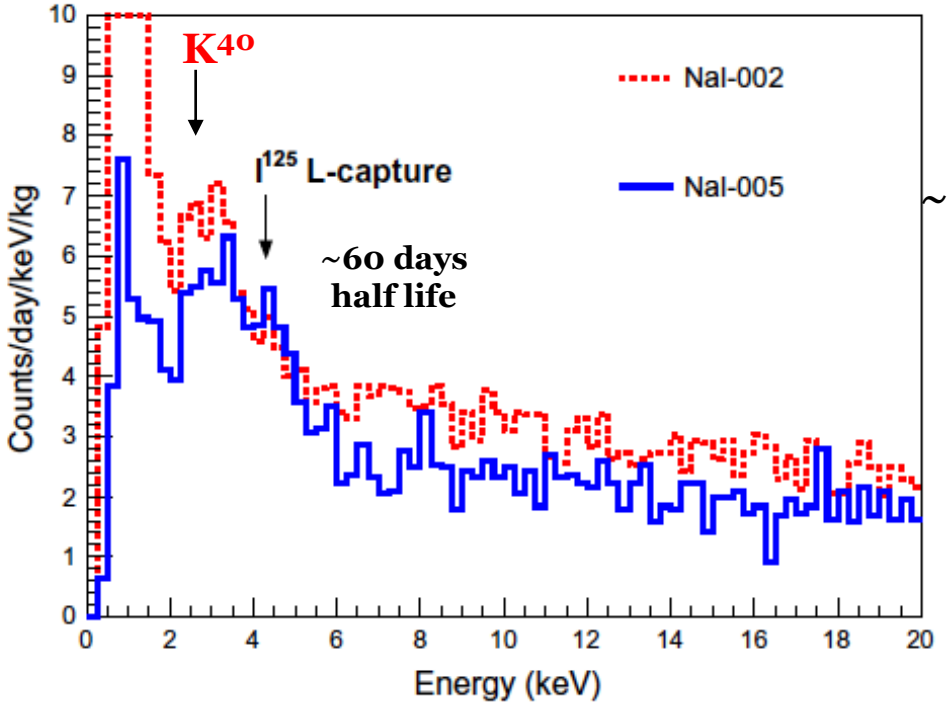


DM-Ice @ South Pole



NaI(Tl) crystal developments by KIMS (since 2013)

K.W.Kim et al., Astropart. Phys. 62, 249 (2015)
P. Adhikari et al., EPJC 76, 185 (2016)
G.Adhikari et al., EPJC 77, 437 (2017)



~ 2keV energy threshold

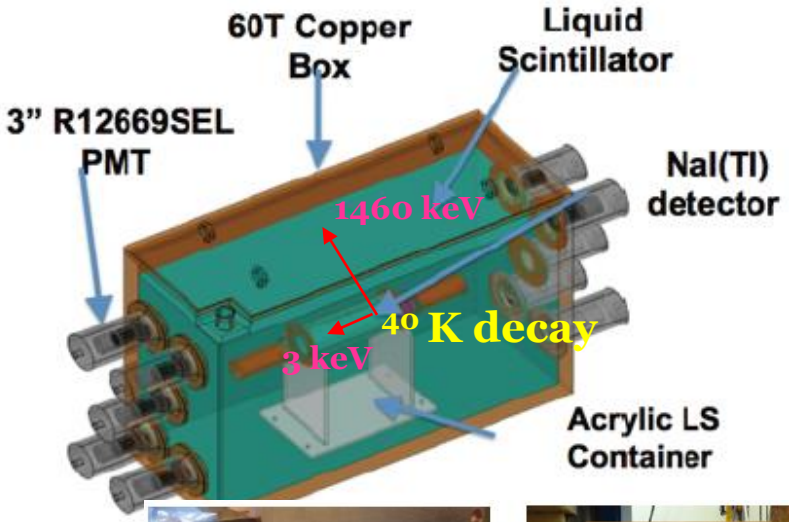
~ 2 dru background @ 6keV

^{40}K and ^{210}Pb are main background at low energy

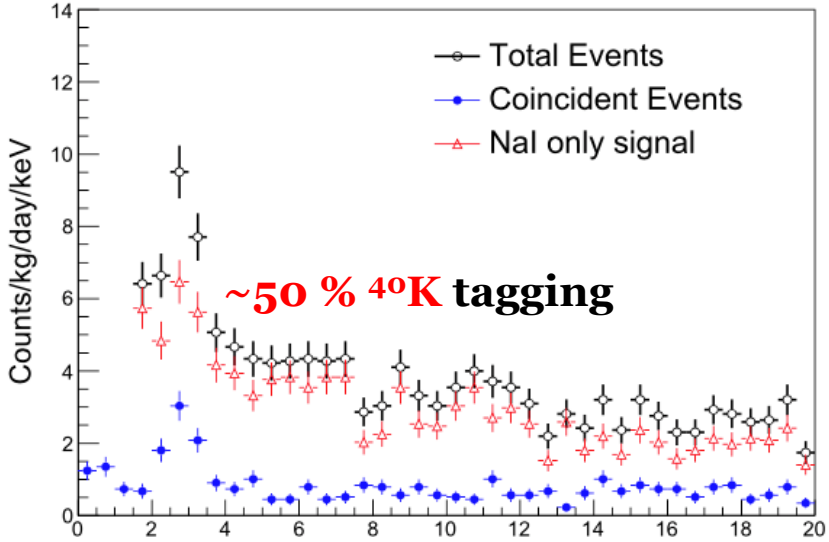
- Understanding internal background very well
- We achieved ~2 counts/kg/day/keV level at 6keV
- Continue to reduce background of the crystal

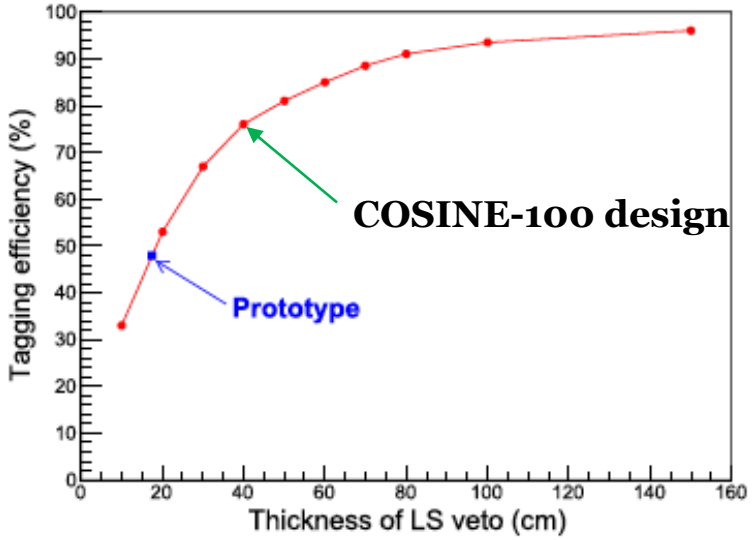
Internal ^{40}K and external background reduction

- Active veto with liquid scintillator **J.S. Park *et al.*, NIMA, 851 (2017) 103**



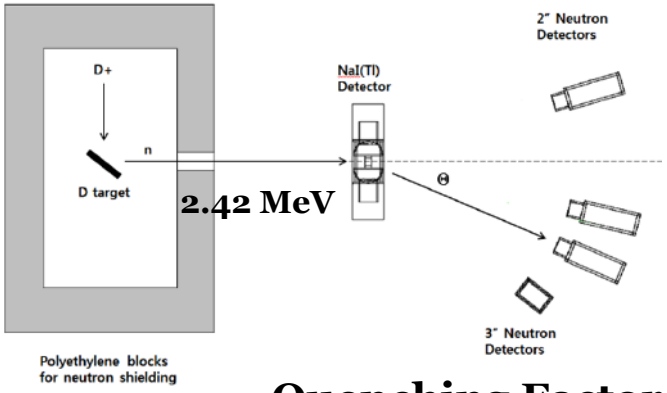
Prototype design for single crystal



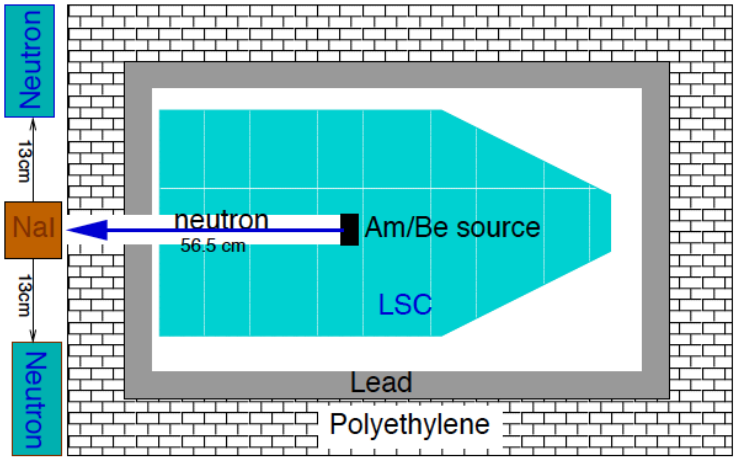


Nuclear recoil data

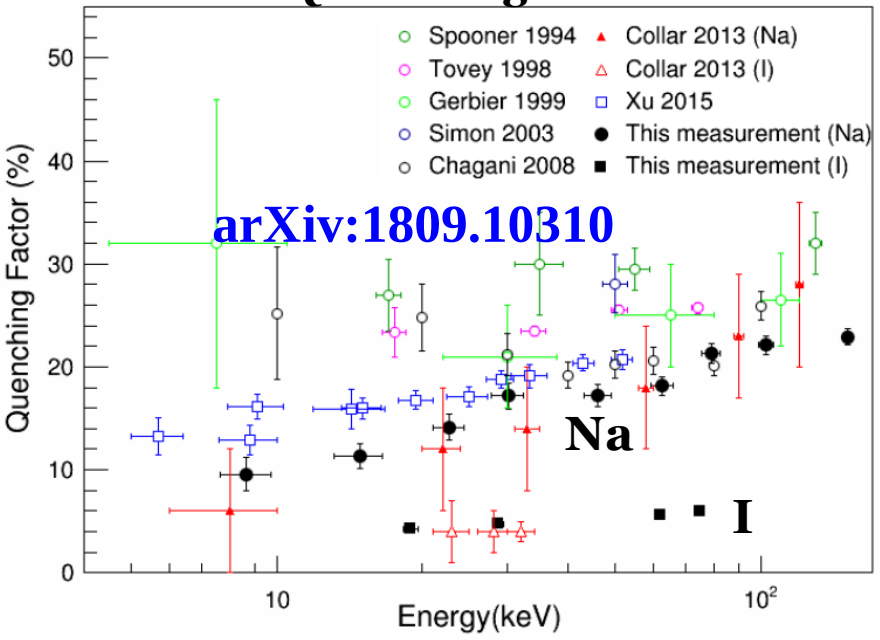
D-D neutron generator



Am/Be source

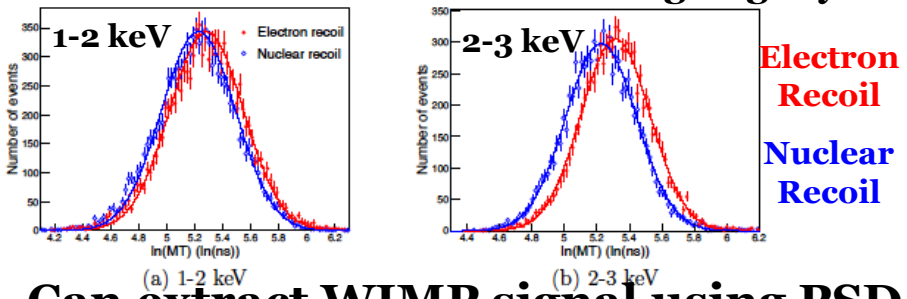


Quenching Factor

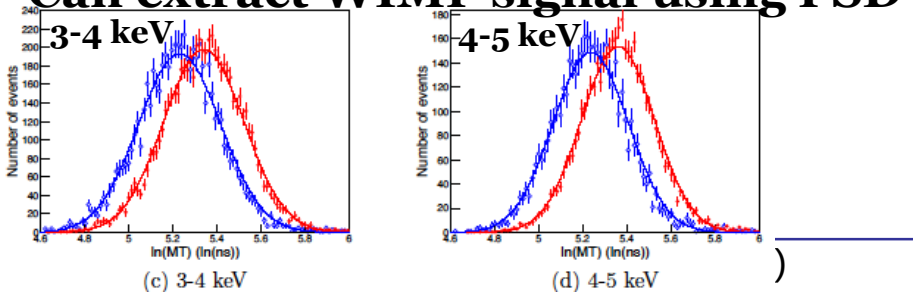


H.S. Lee *et al.*, JHEP 08 (2015) 093

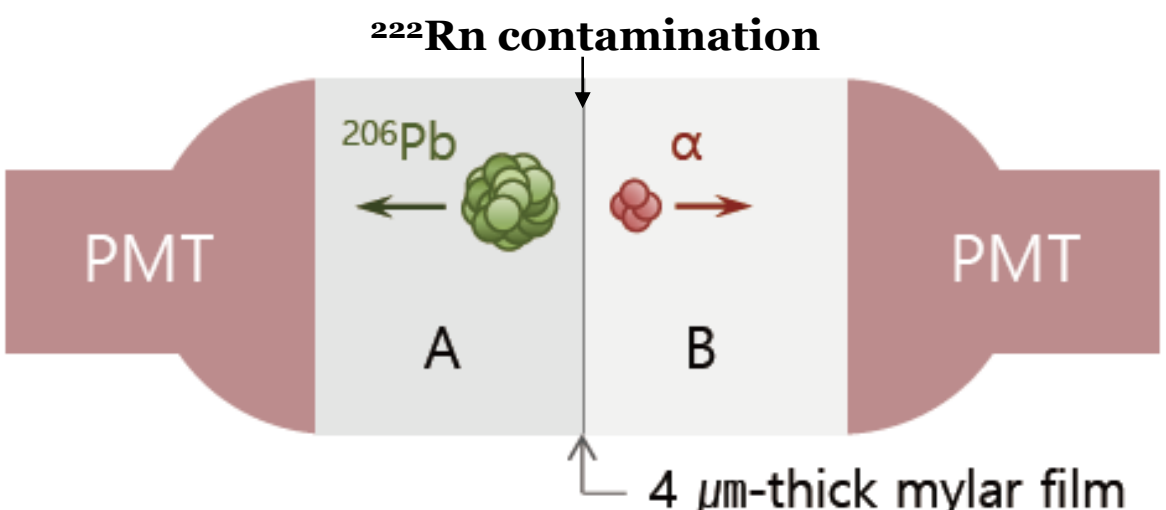
Good discrimination due to high light yield !!



Can extract WIMP signal using PSD

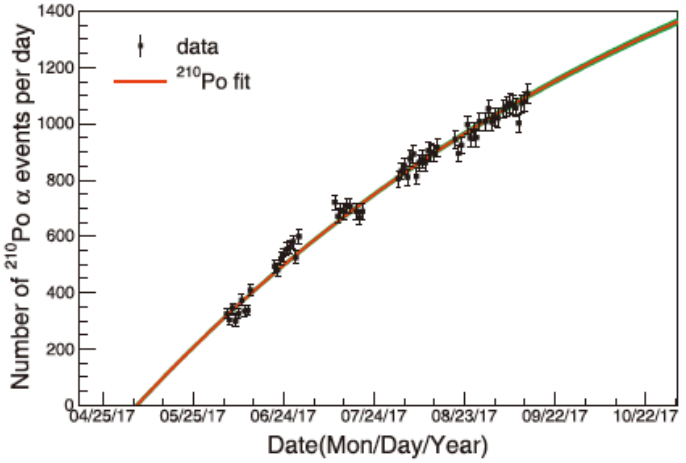


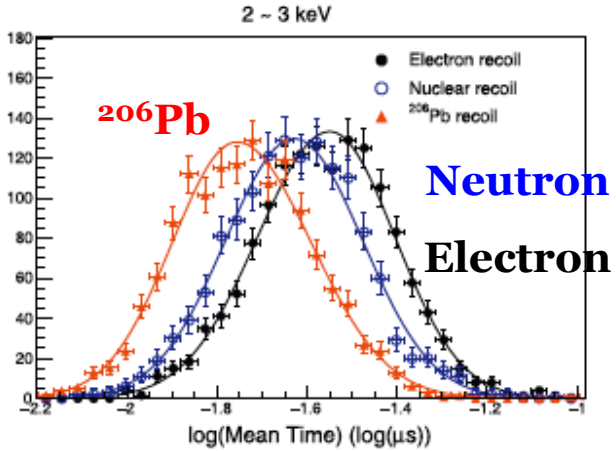
Surface ^{206}Pb recoil measurement

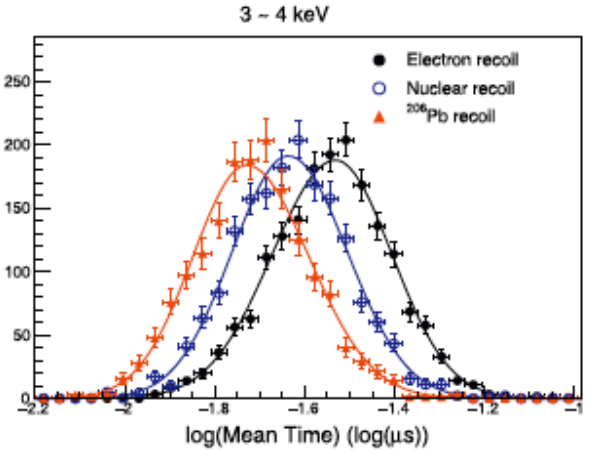


K.W. Kim *et al.*, Astropart. Phys. 102 (2018) 51

^{210}Po has been increased



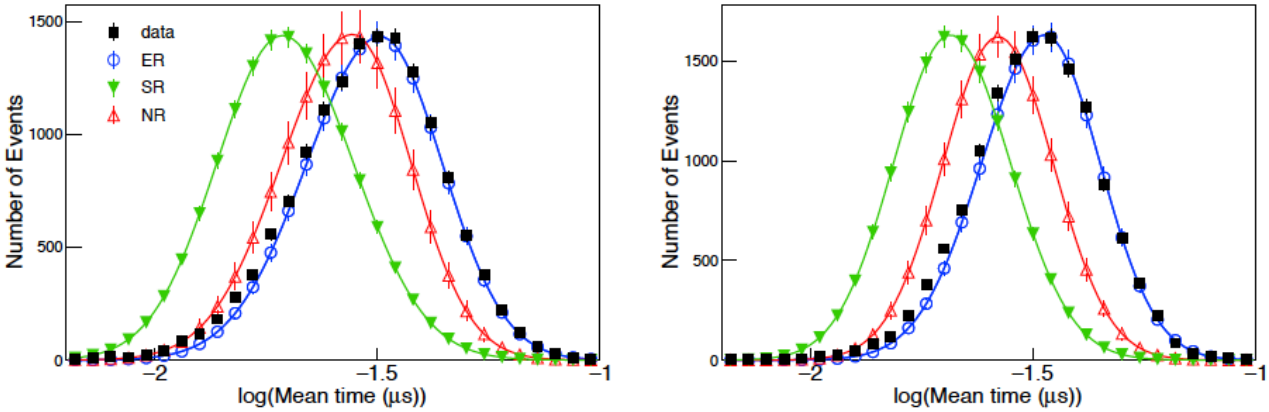




- Surface ^{206}Pb recoils are much faster than typical NaI nuclear recoils
- We will use those shapes to extract WIMP signals

Nuclear recoil event extraction using pulse shape discrimination

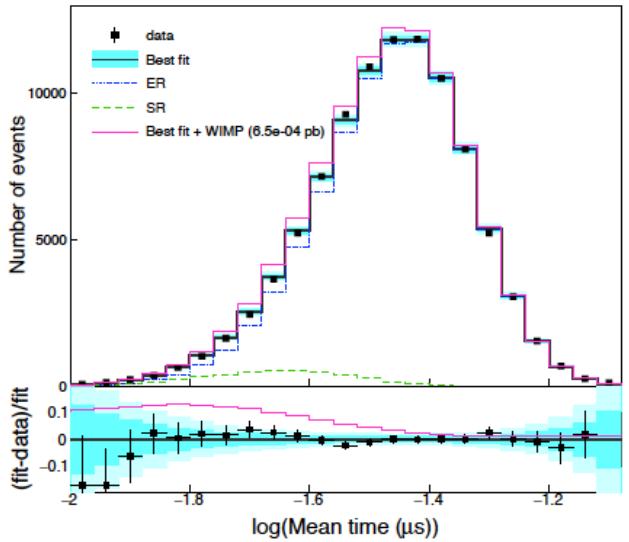
- 2967.4 kg days exposure from KIMS-NaI R&D (two crystals)



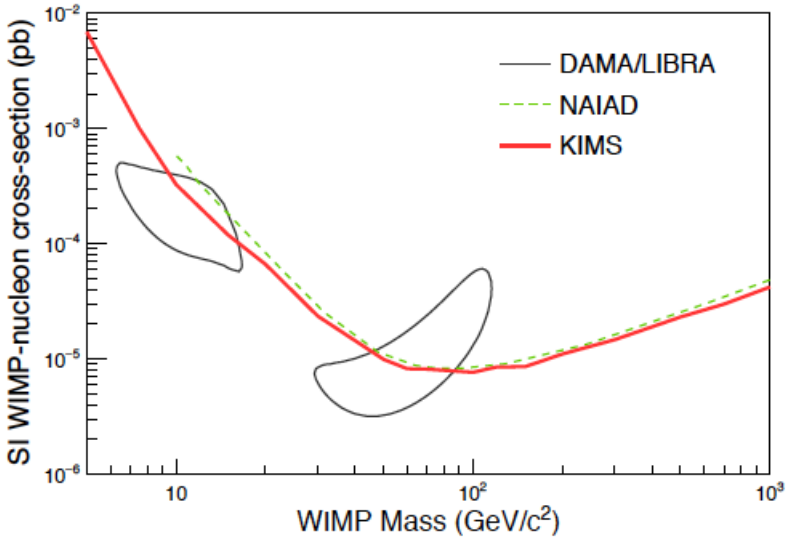
(a) 2–3 keV (b) 3–4 keV

K.W. Kim *et al.*, arXiv:1806.06499

Fit results (2-8 keV)

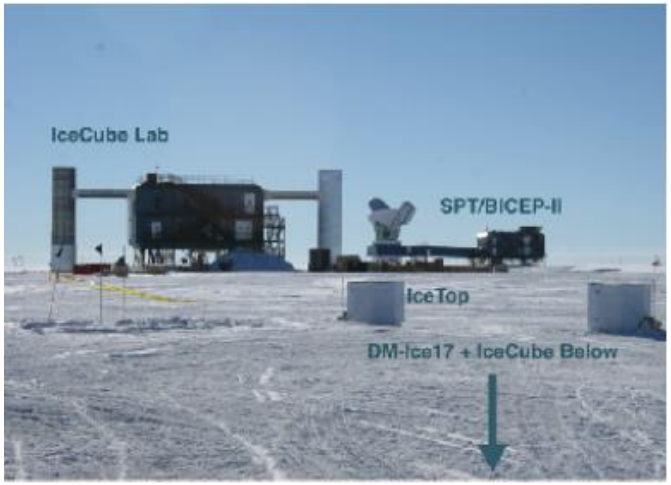


Spin Independent WIMP-nucleon interaction



DM-Ice17

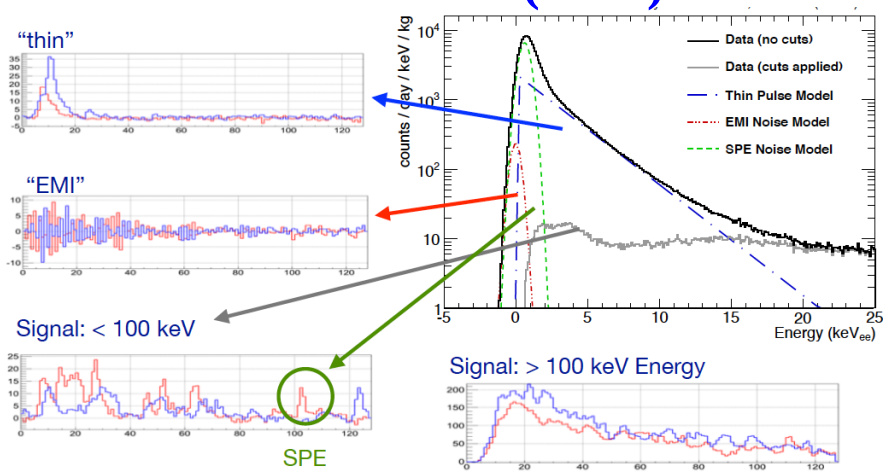
- DM-Ice17 in South pole (Jun.2011 – Jan.2015)



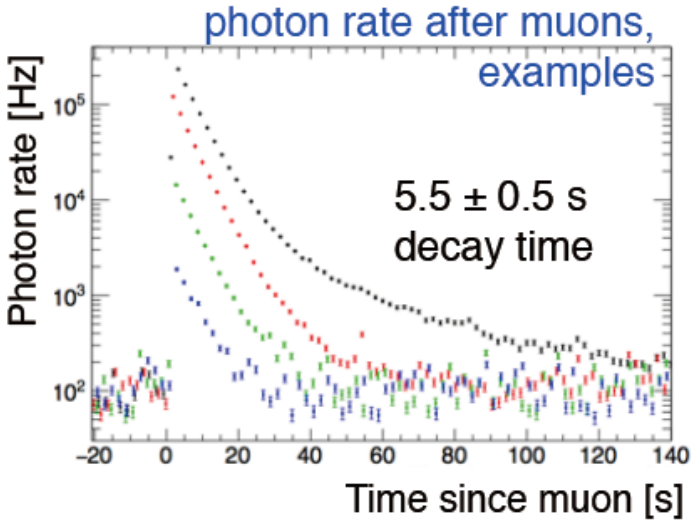
Two 8.47 kg crystal

2200 m.w.e overburden

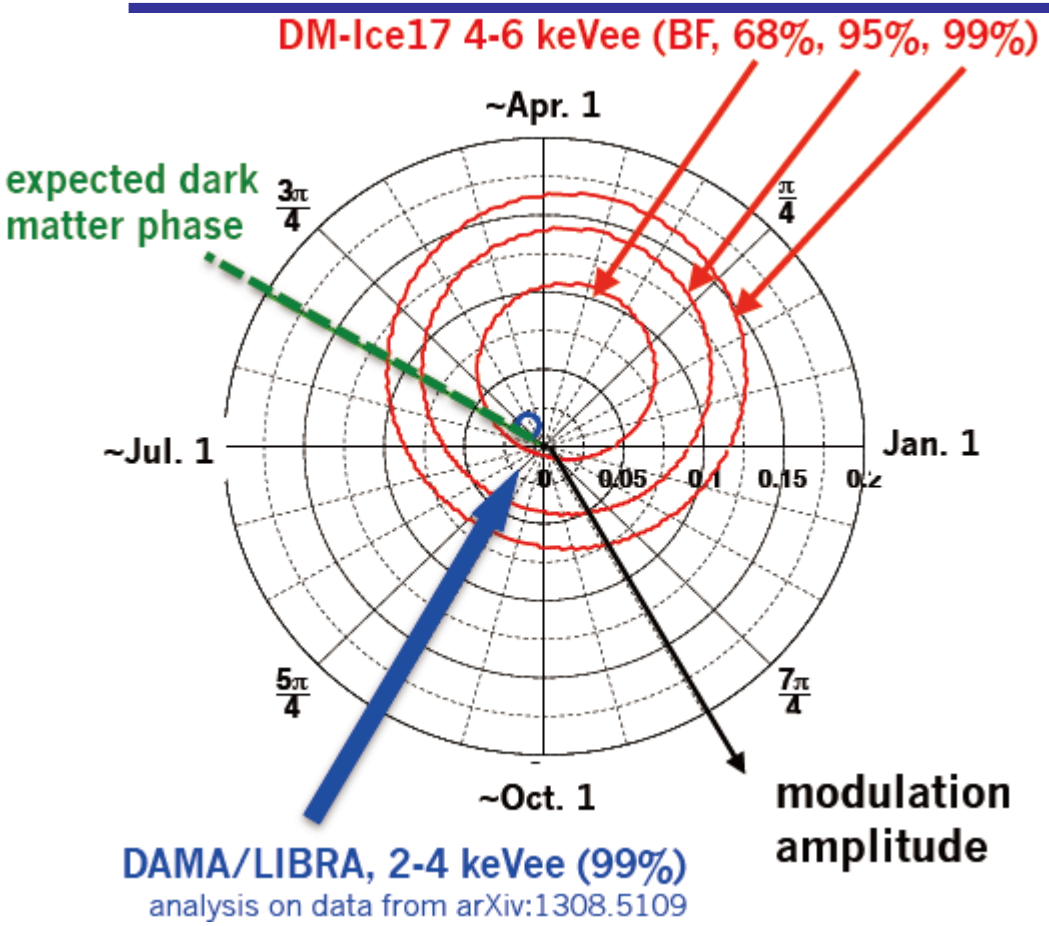
PRD 90 092005 (2014)

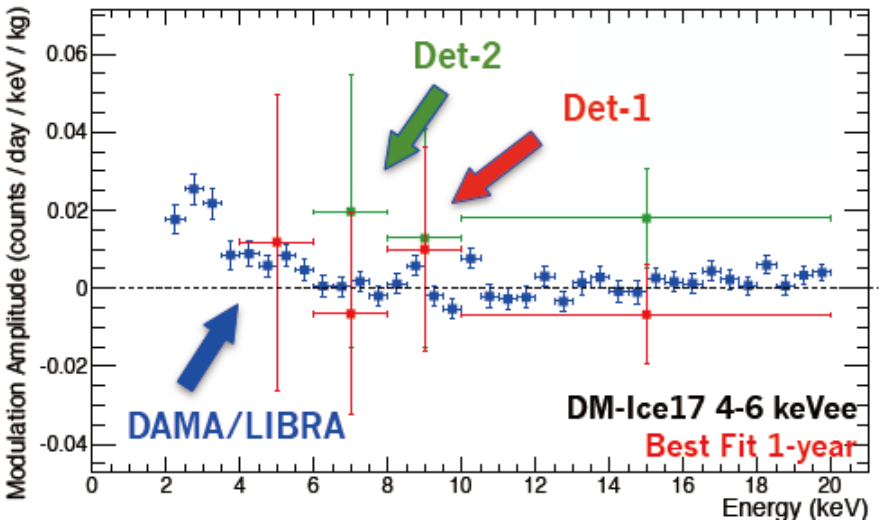


PRD 93 042001 (2016)



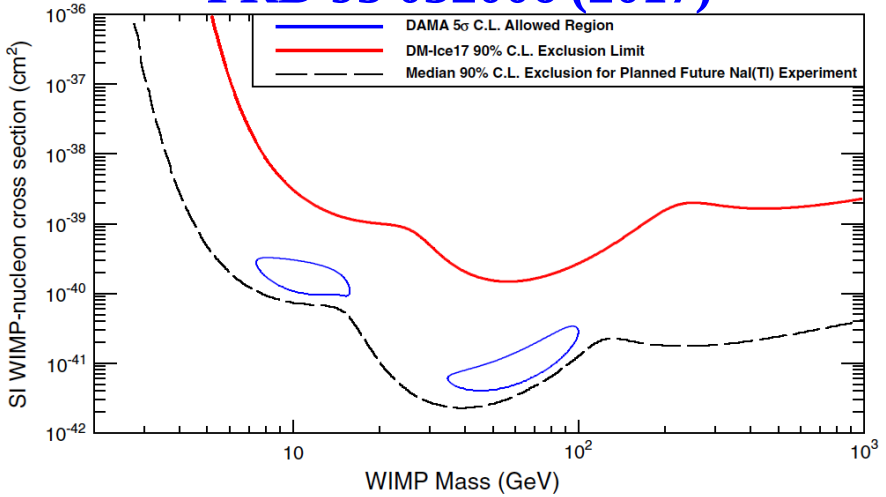
Annual modulation study with DM-Ice17





Proof of principle

PRD 95 032006 (2017)



- Continue to develop low background NaI(Tl) crystals

COSINE Project (Since 2015)

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

YangYang(Y2L) Underground Laboratory

(Upper Dam) YangYang Pumped Storage Power Plant

Center for Underground Physics

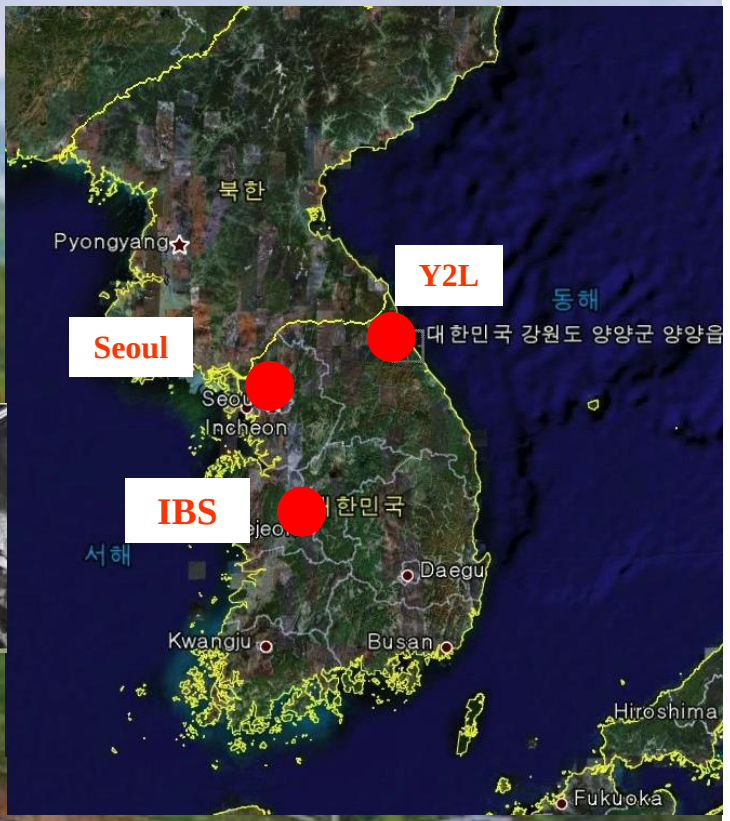
IBS (Institute for Basic Science)

1000m

700m

(Power Plant)

양양양수발전소



(Lower Dam)

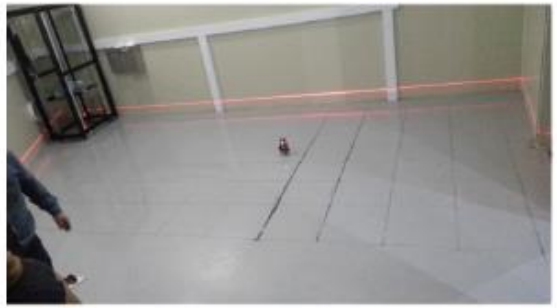
KIMS (Dark Matter Search)

AMoRE (Double Beta Decay Experiment)

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

COSINE-100 Construction

Dec. 2015 Jan. 2016 Feb. 2016




Mar. 2016 Apr. 2016




May. 2016 Jun. 2016 Sep. 2016

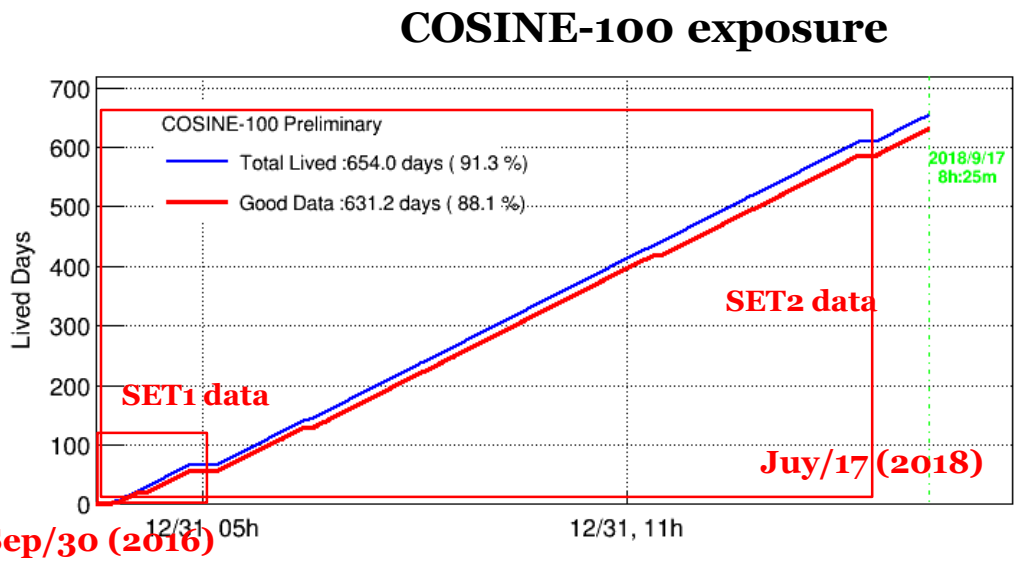



COSINE-100 detectors

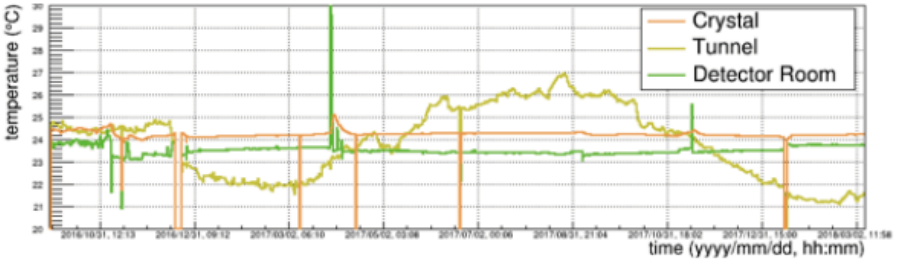
Physics run started since Sept/2016

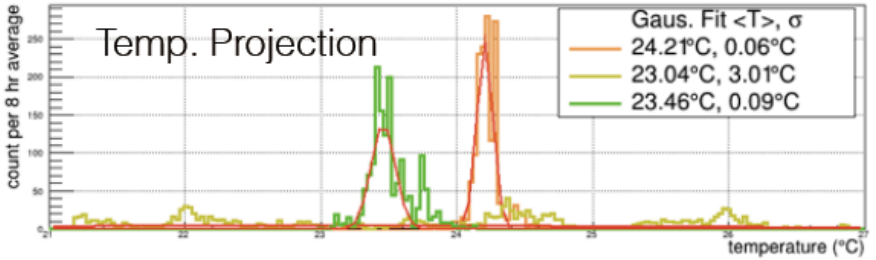
Eur. Phys. J. C 78 (2018) 107

COSINE-100 operation

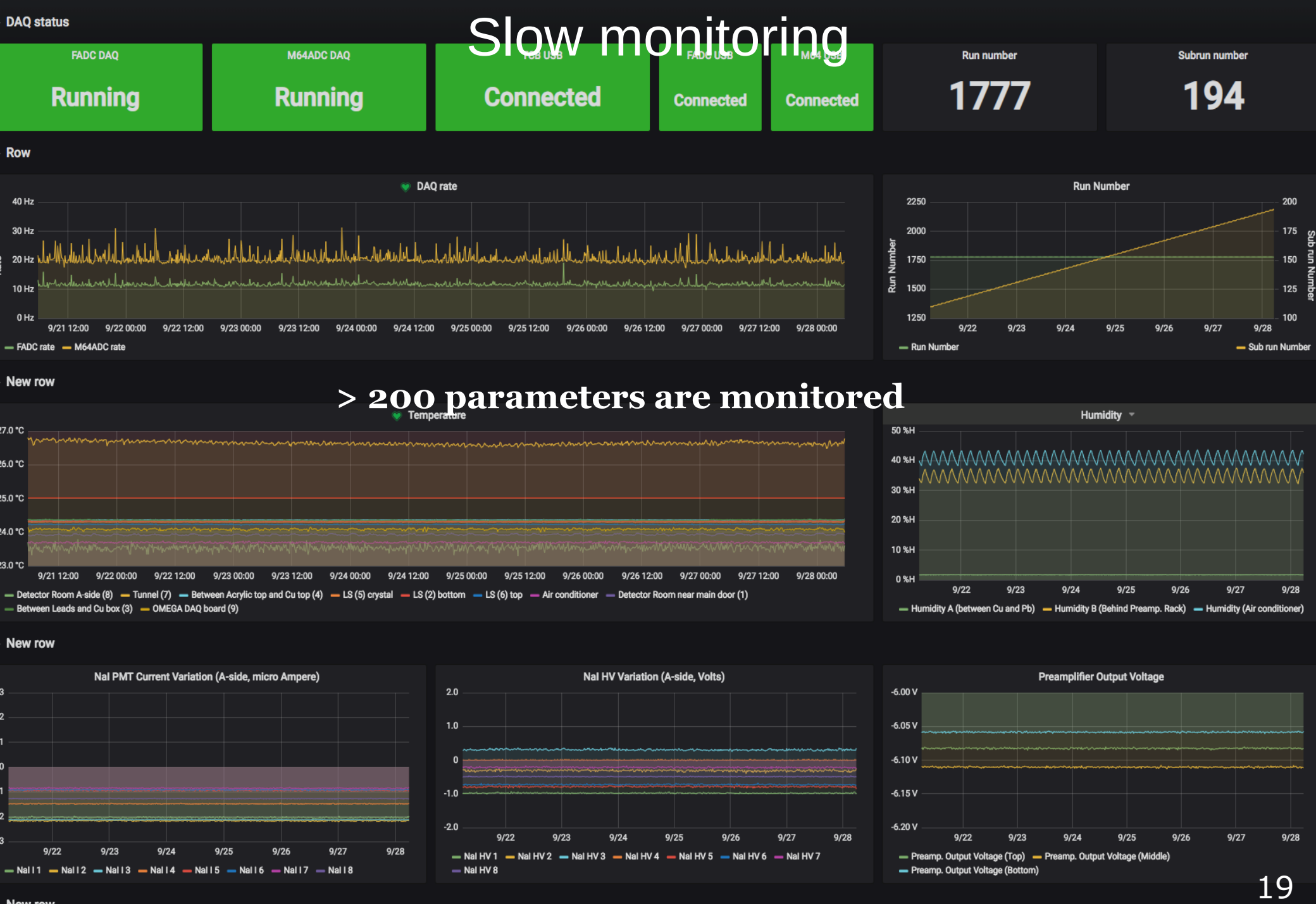


- Stable physics run
  - More than 90% live time!! Most of data are marked as good quality data
- Operating about 2 years





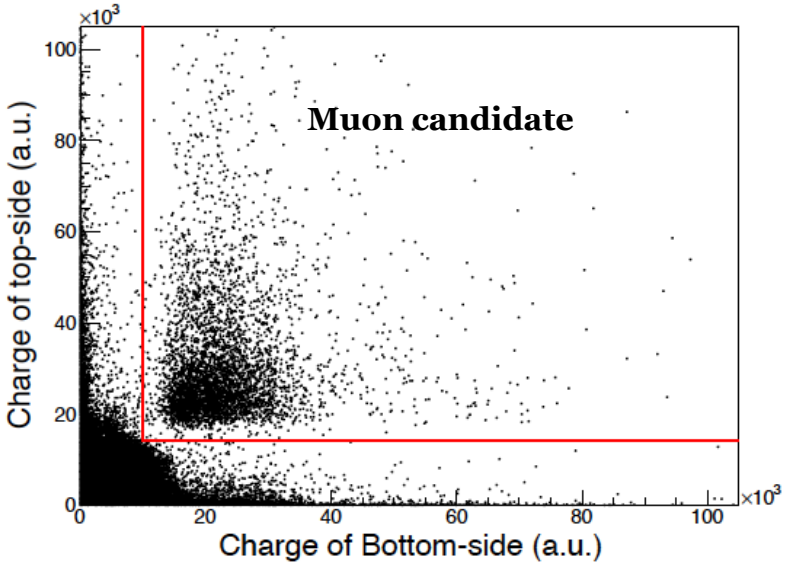
Slow monitoring

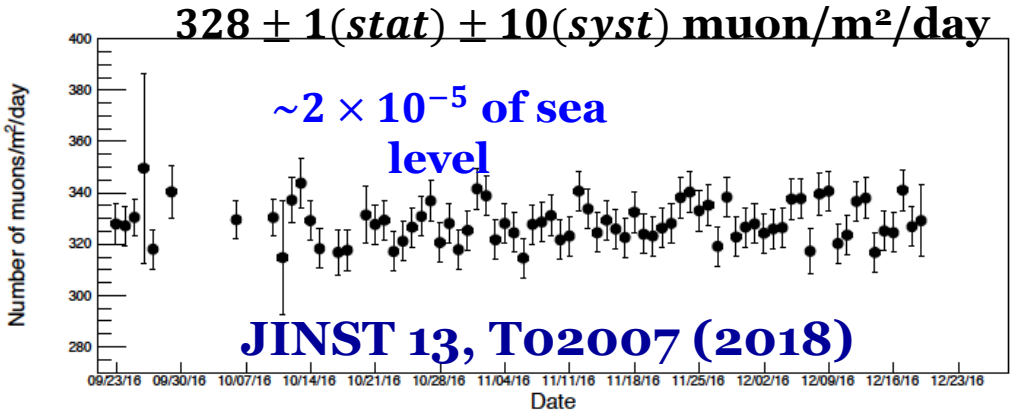


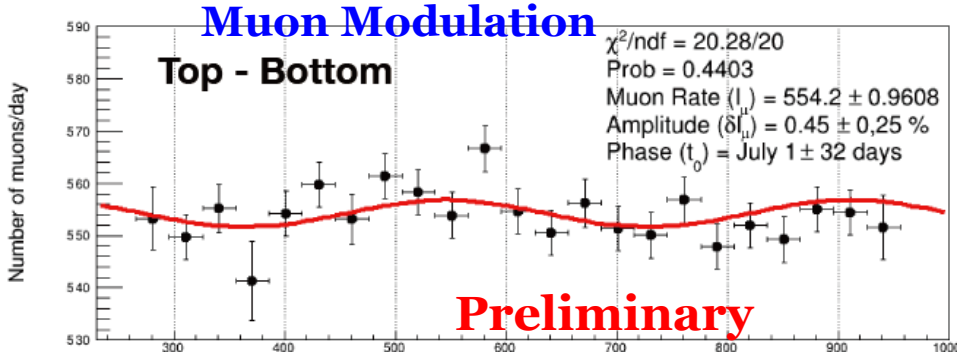
> 200 parameters are monitored

Muon detector

- Outer muon veto consists of 37 plastic scintillator panels



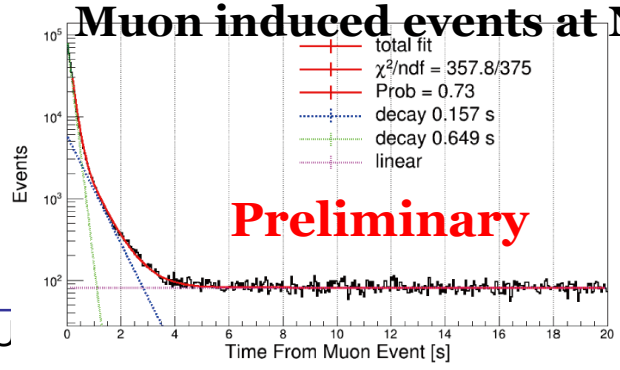




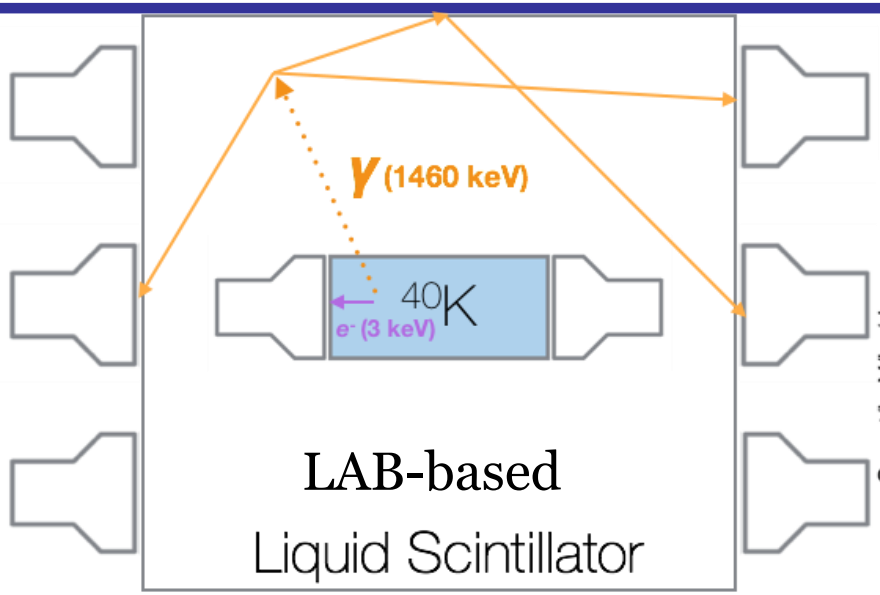
Muon flux has been monitored stably

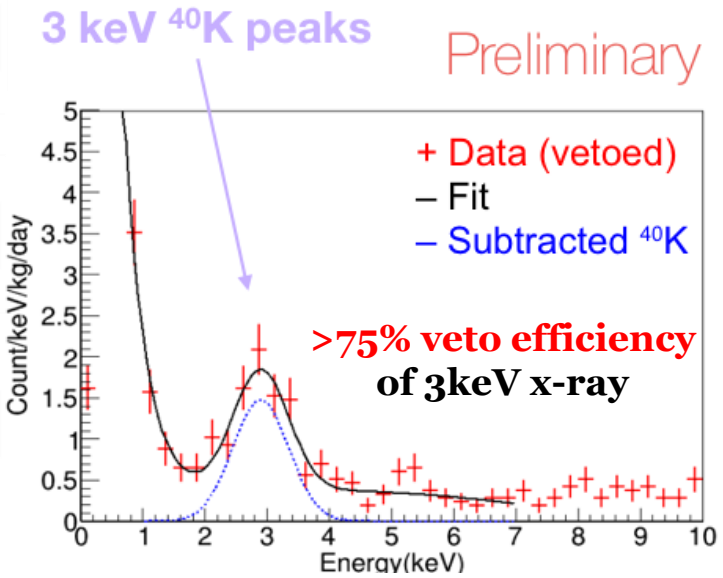
Vetoing of muon correlated events in NaI(Tl) crystals was implemented

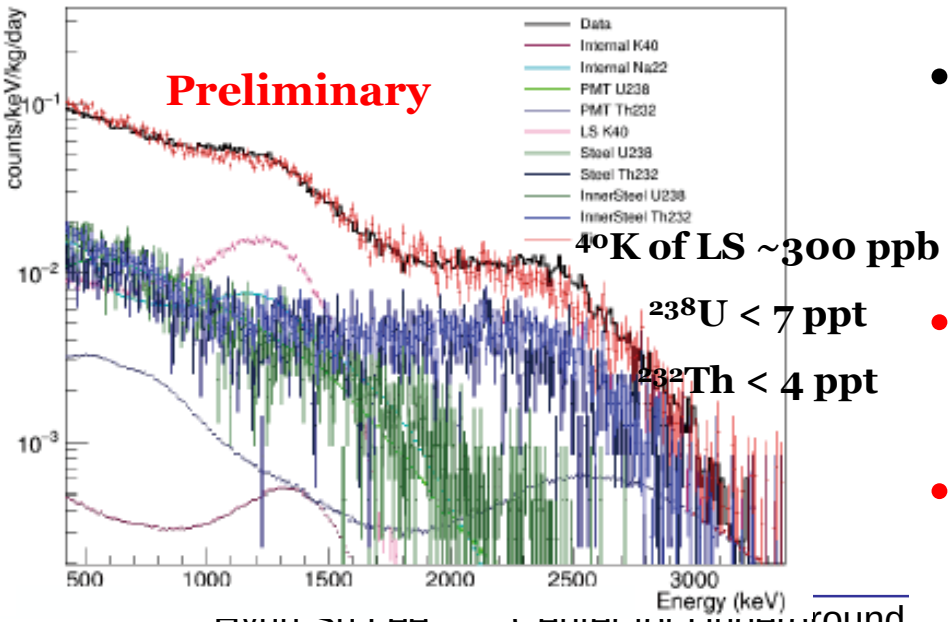
Study on muon induced events with NaI(Tl) and liquid scintillator is ongoing



Liquid scintillator veto system

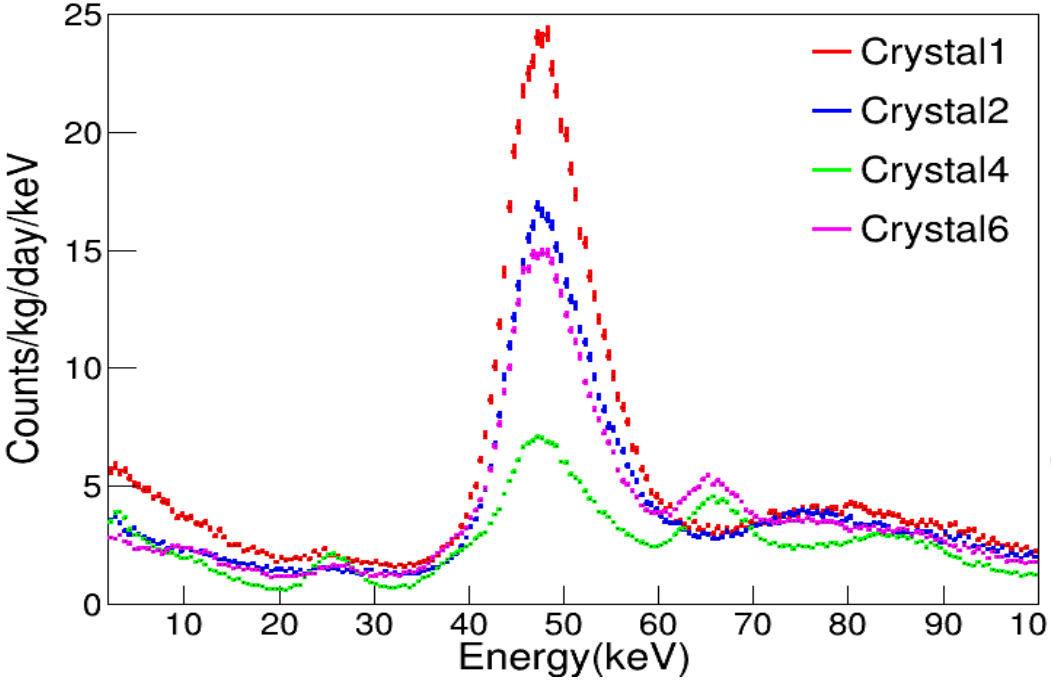


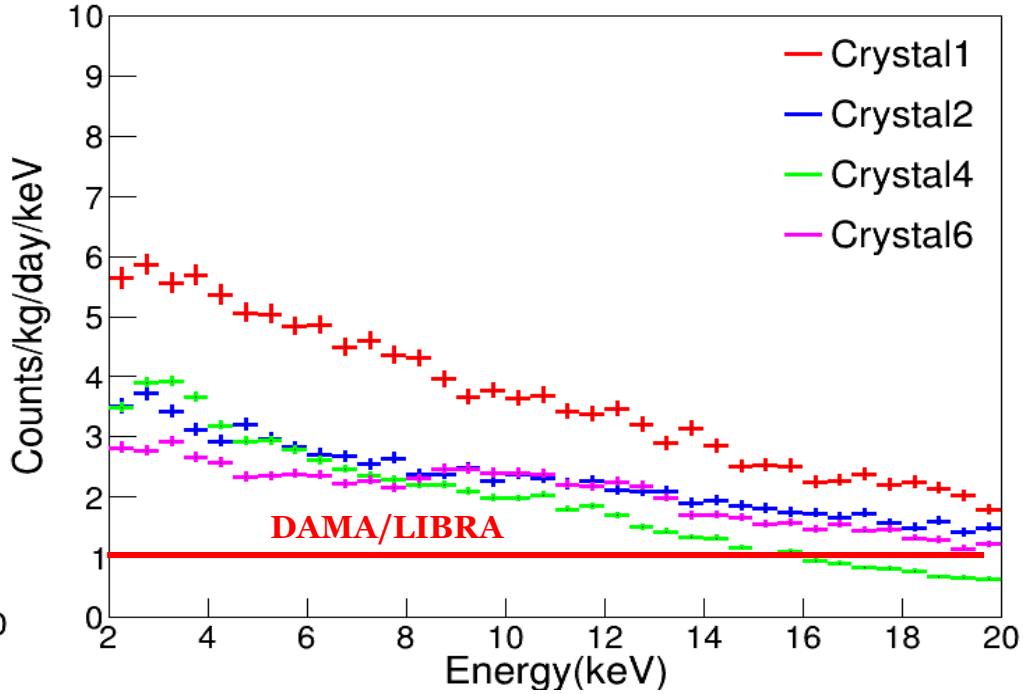




- Tagging rate of ^{40}K is well understood with Geant4-based simulation
- Internal background of LS is well understood and low enough
- 20 keV tagging threshold is achieved

Crystal data (initial two month – SET1)

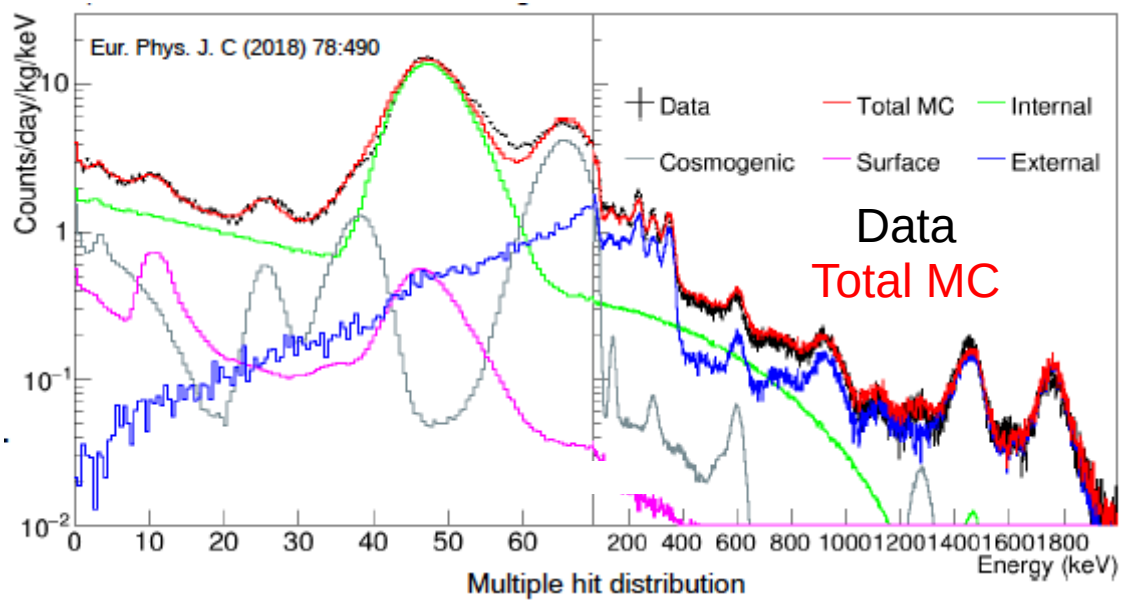




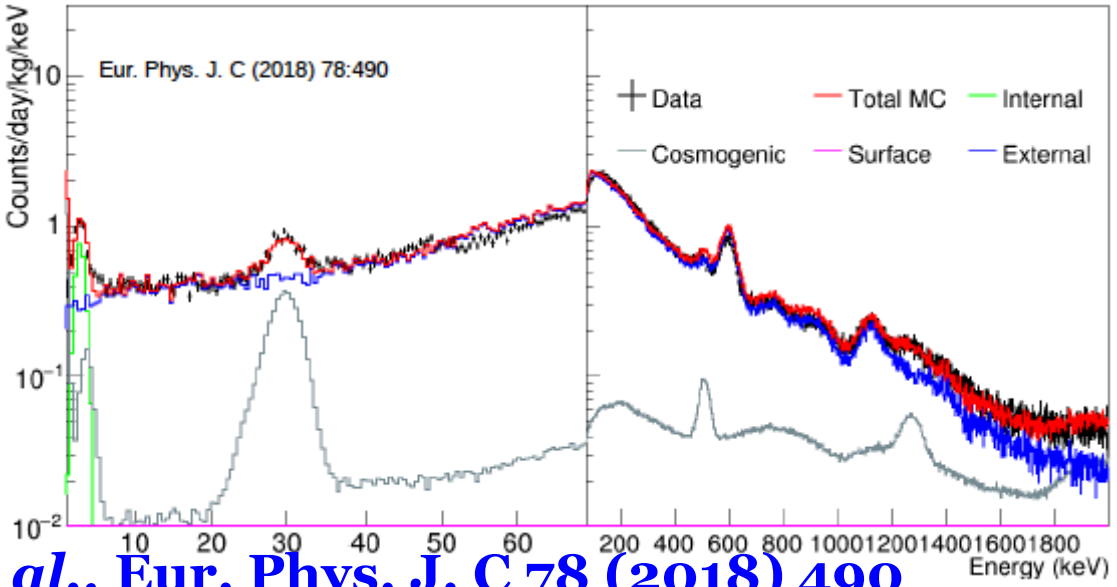
- **Background levels** from 2 to 4 dru (counts/kg/day/keV)
  - ❖ Higher than DAMA/LIBRA crystals
  - ❖ Efficiency corrected spectra

Background understanding

Single hit event
(6-2000 keV)

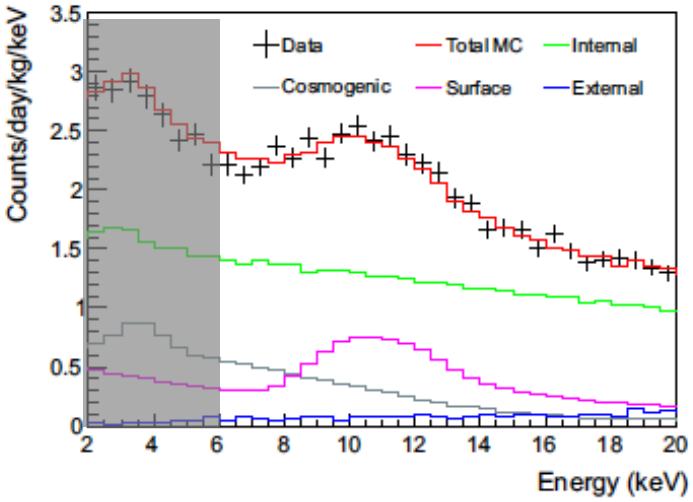


Multiple hit events
(2-2000 keV)



P. Adhikari *et al.*, Eur. Phys. J. C 78 (2018) 490

Expected background (2-6 keV)



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
^{3}H (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**

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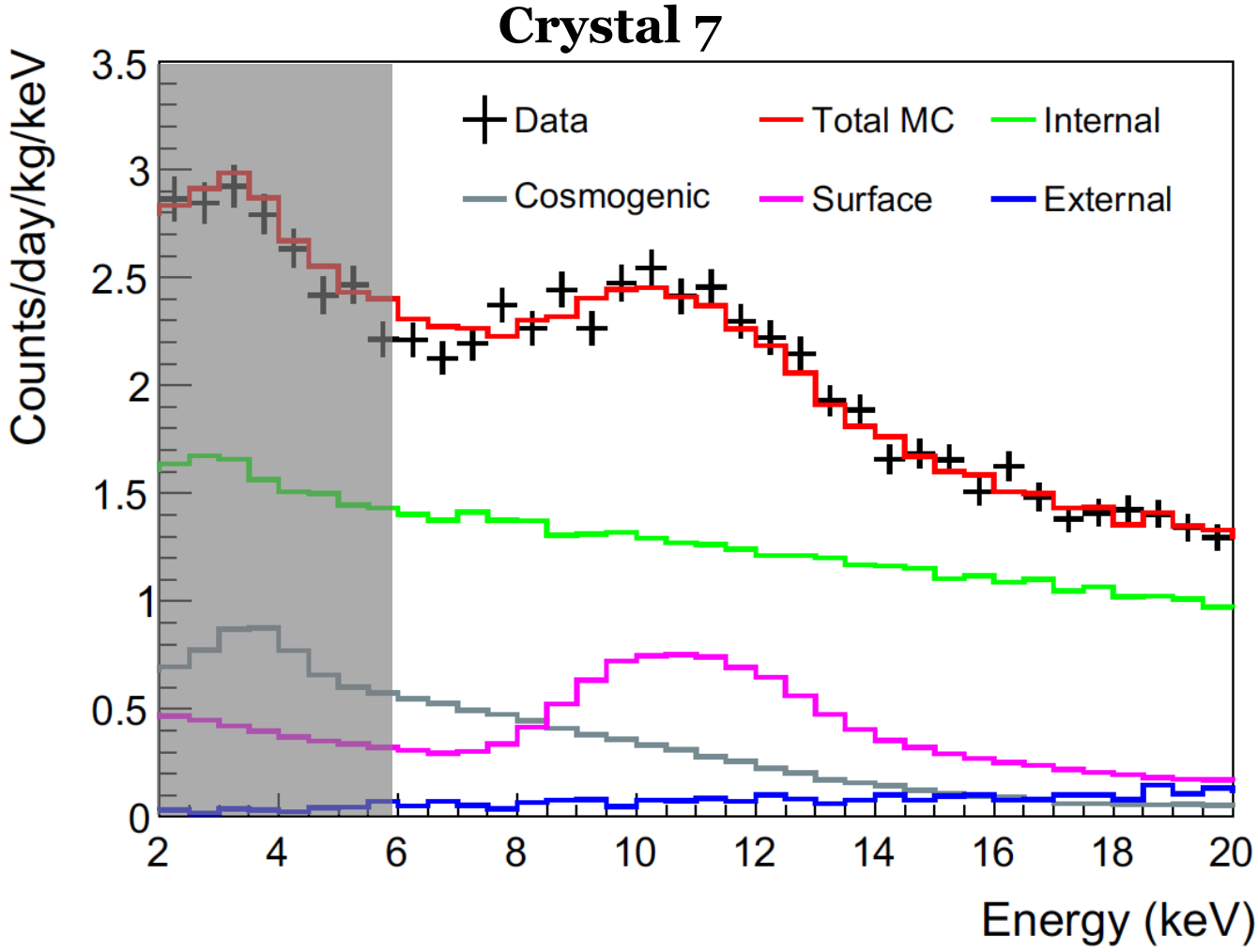
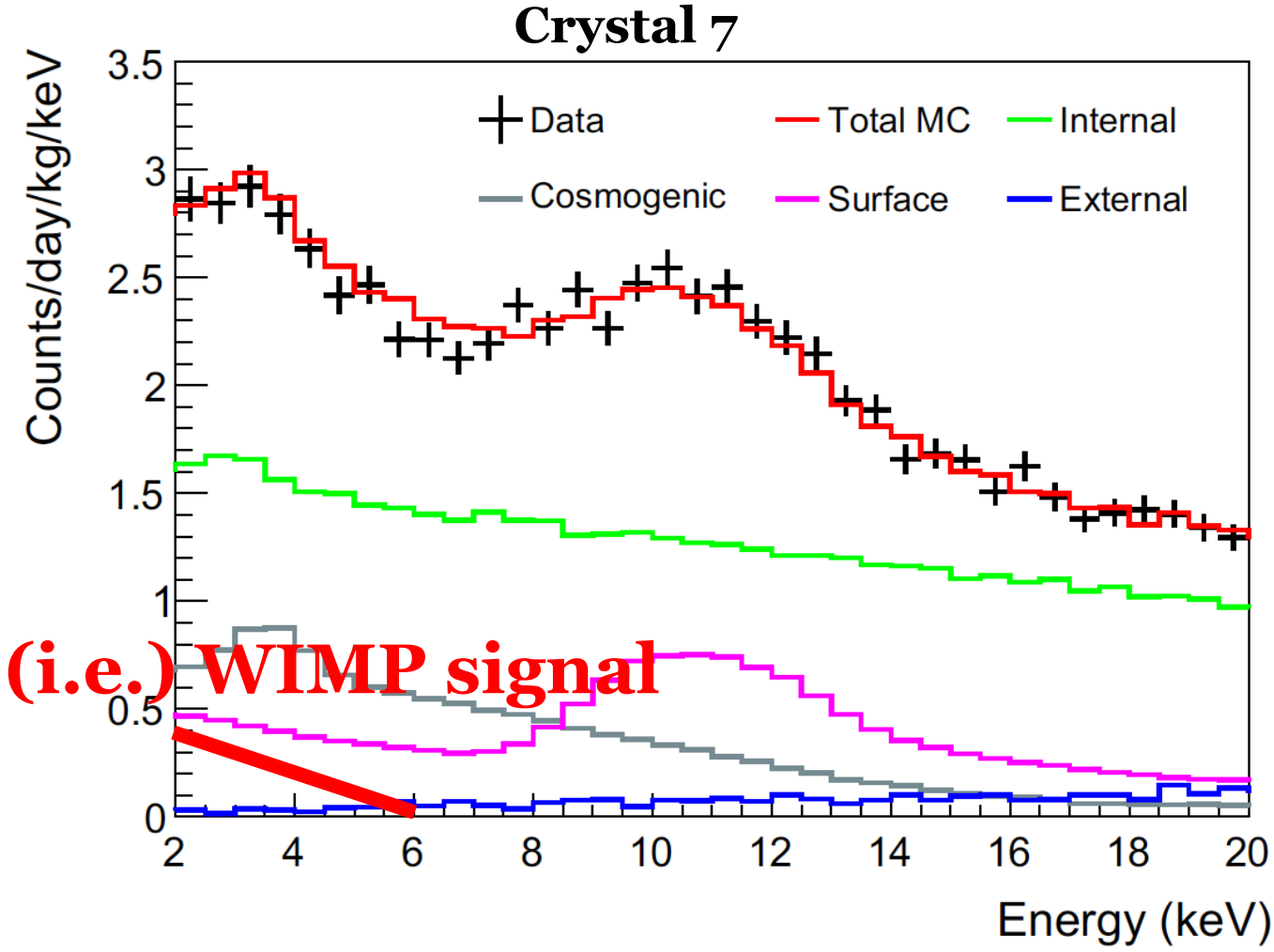
Fit with WIMP signals



Background modeling was done only using 6- 2000keV events

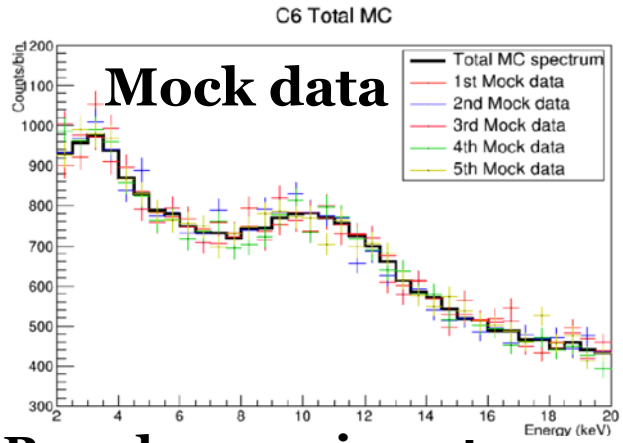
Fit with WIMP signals



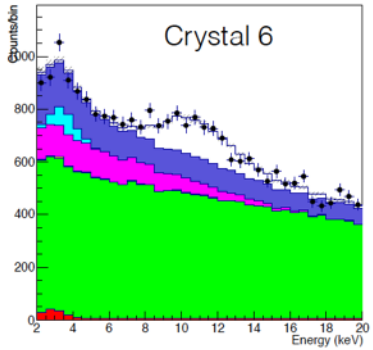
Background modeling was done only using 6- 2000keV events

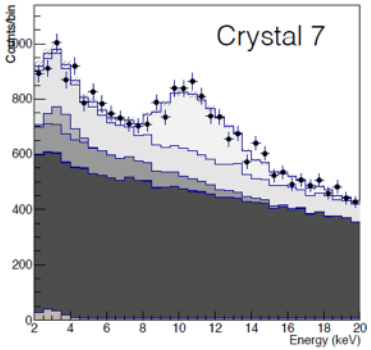
Sensitivity of COSINE-100 59.5 days data

- Generate mock data from MC modeling

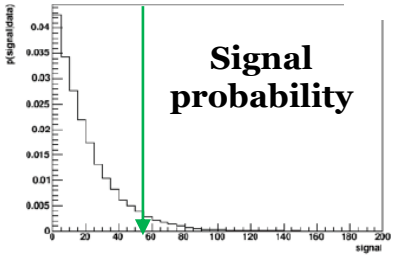


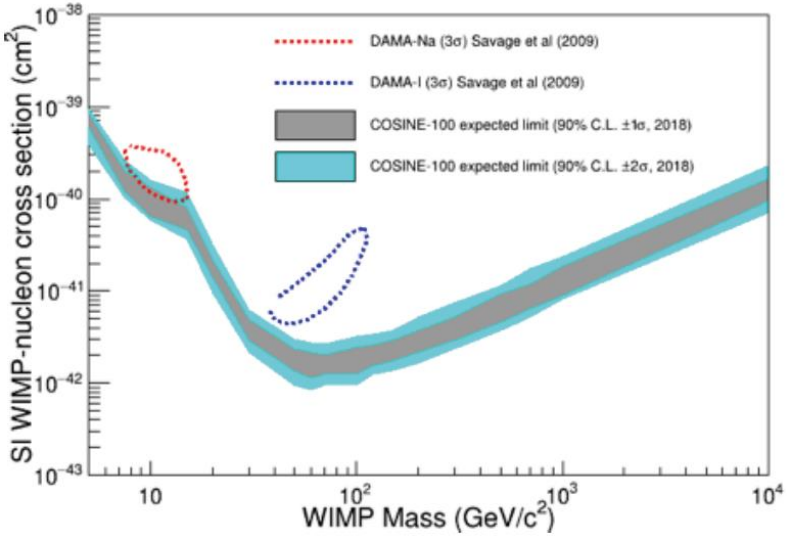
Pseudo experiment





Set 90% CL upper limit





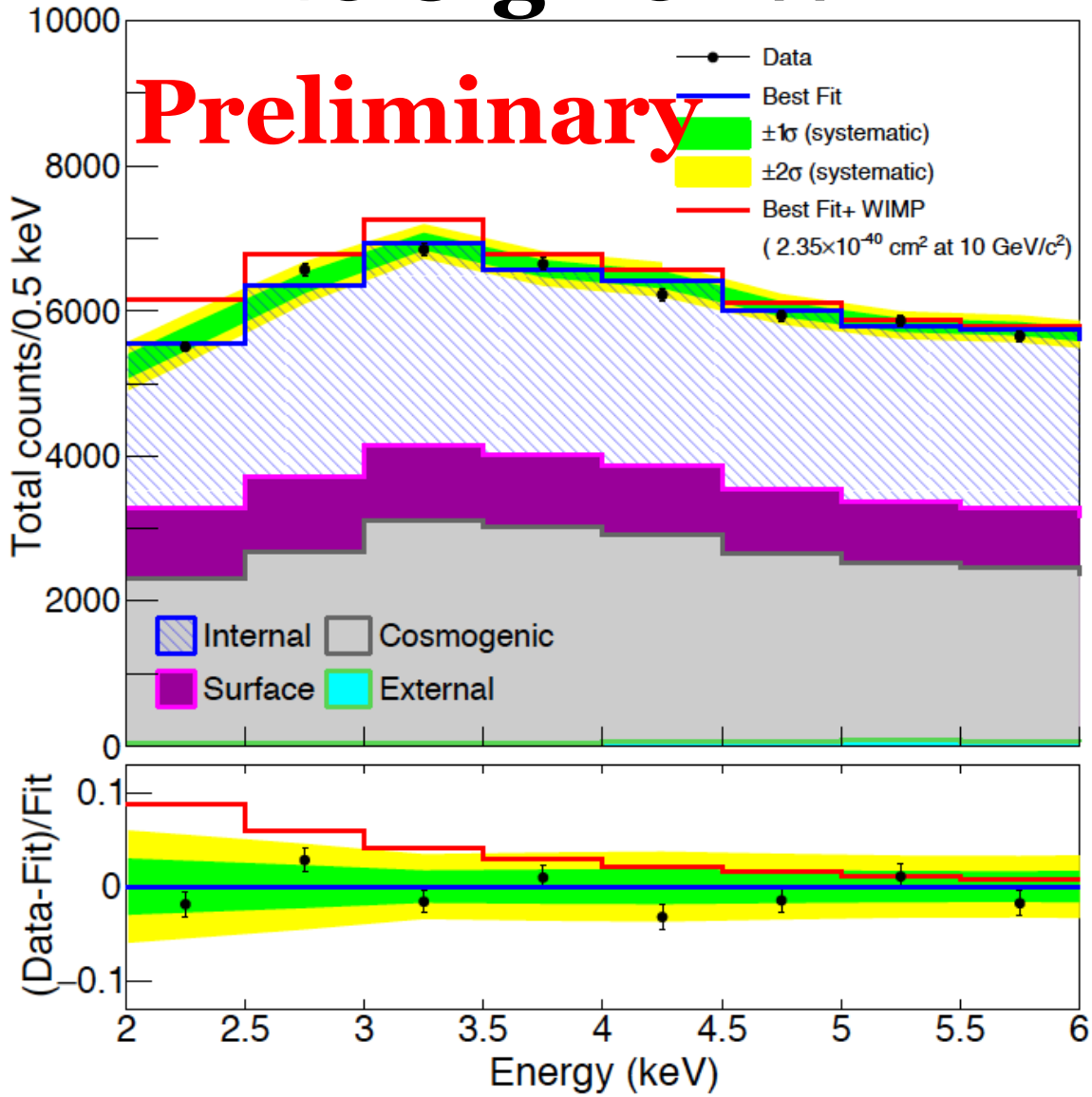
Single hit-spectra from eight crystals are fit simultaneously with an assumed WIMP signal

Same parameters as Savage et al. (2009)

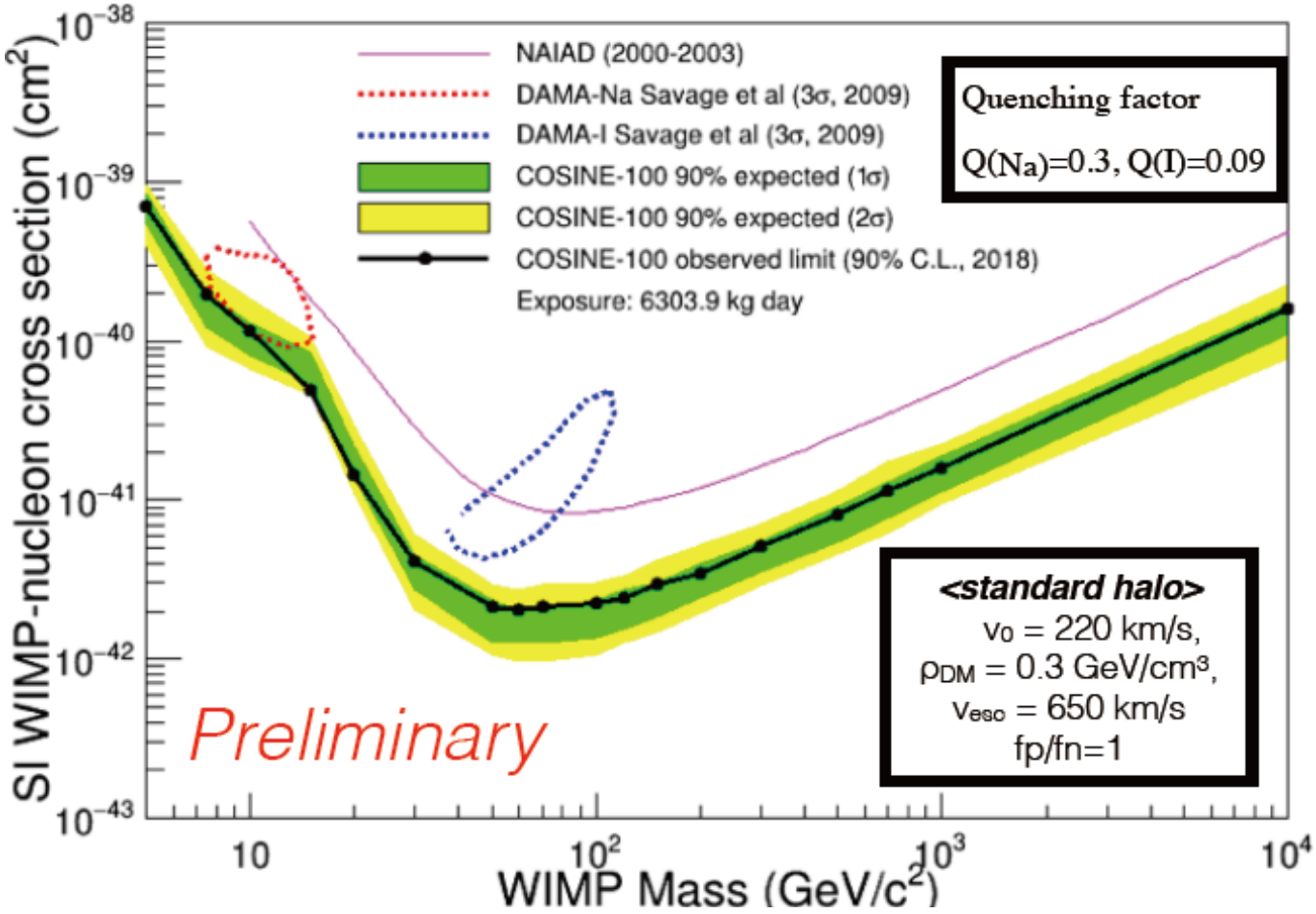
- Sensitivity estimation is done

Data fit (COSINE 59.5 days)

No Sign of WIMP



Limit on WIMP-nucleon cross section



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

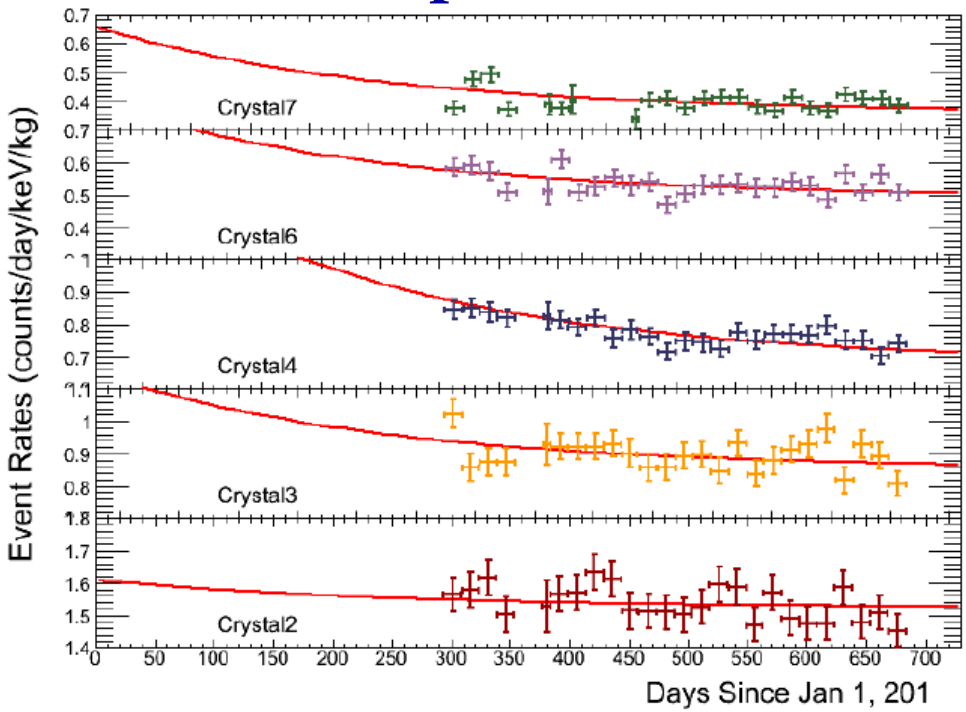
First time with same NaI(Tl) target

Consistent with other null experiments

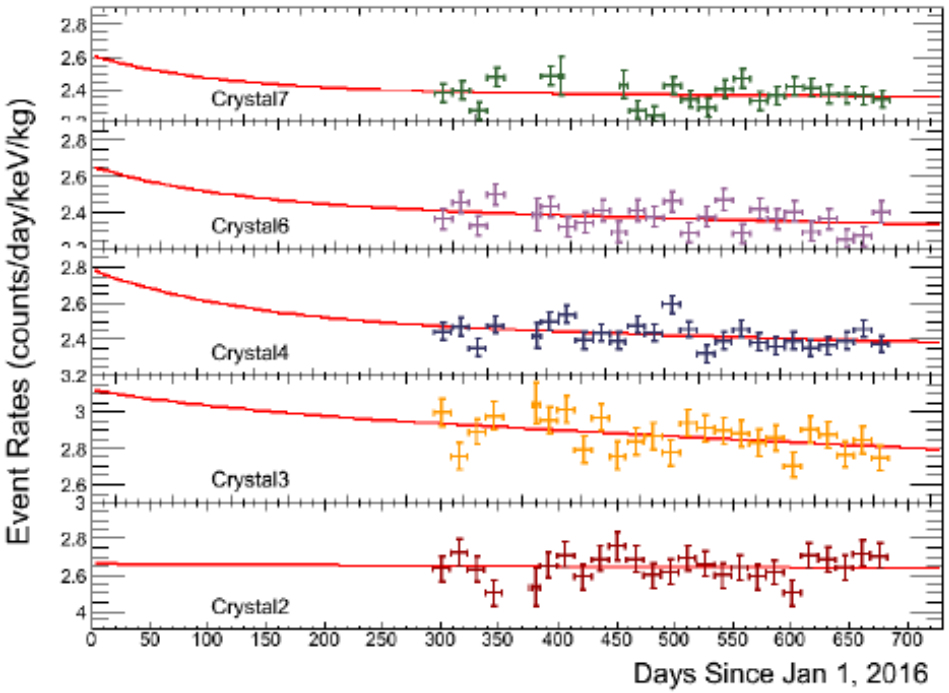
Annual Modulation

- Cosmogenic components were constraint by the measurements
- Floating **^{3}H** and constant (**internal background**)

Multiple 2-6 keV



Single 6-10 keV



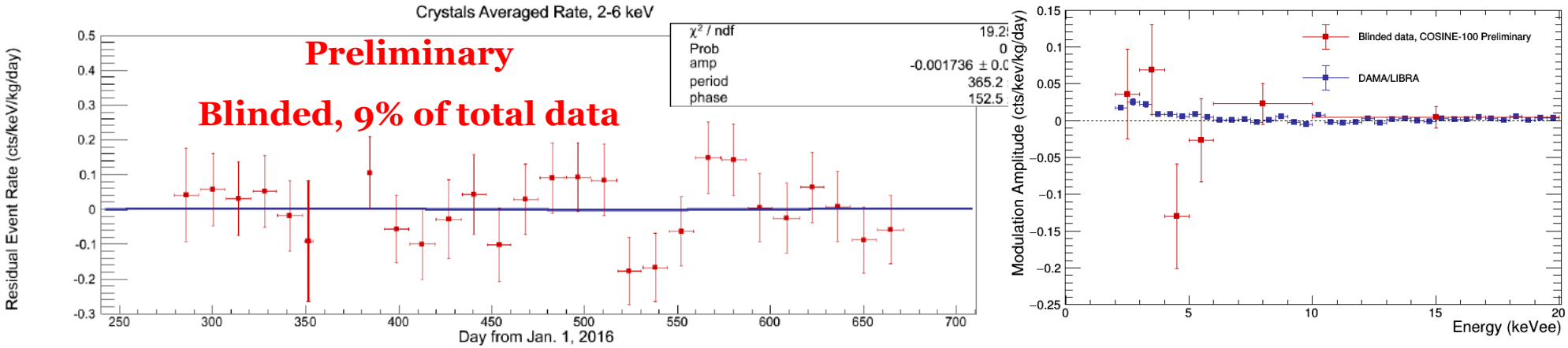
C5 & C8 were excluded due to low light output

C1 was excluded due to uncontrolled PMT induced noise

- Side bands are well explained by known background

~ 9% data opened (blinded analysis)

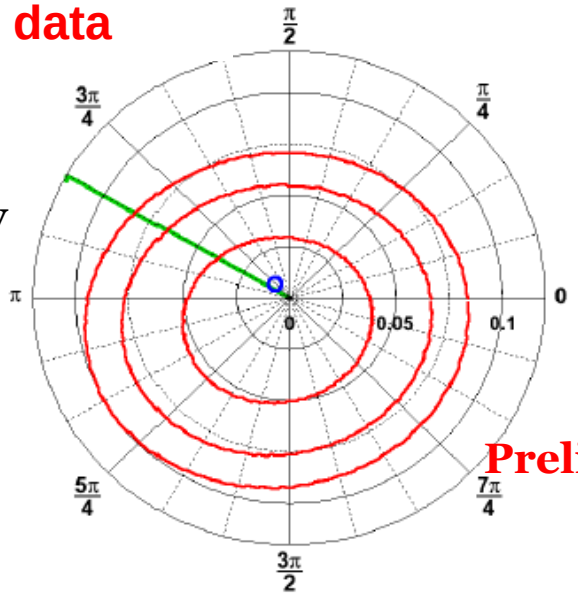
- Current data is blinded, only 9% of total data



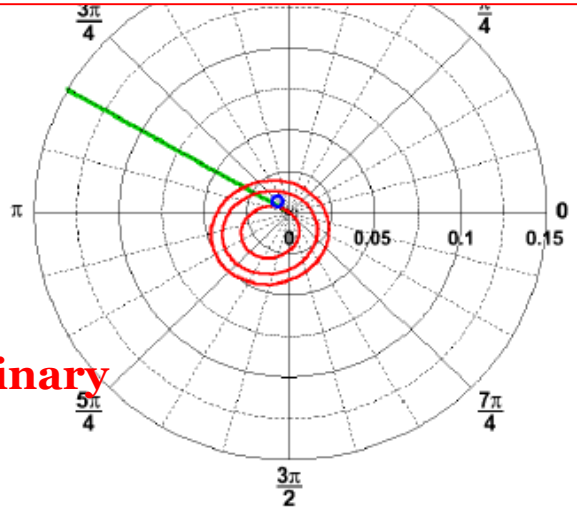
Data quality, cosmogenic component subtraction, and background modeling almost done

Under evaluating systematic uncertainty

9% data

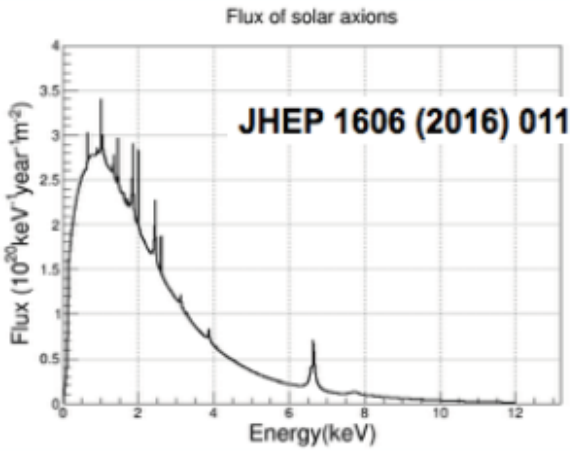


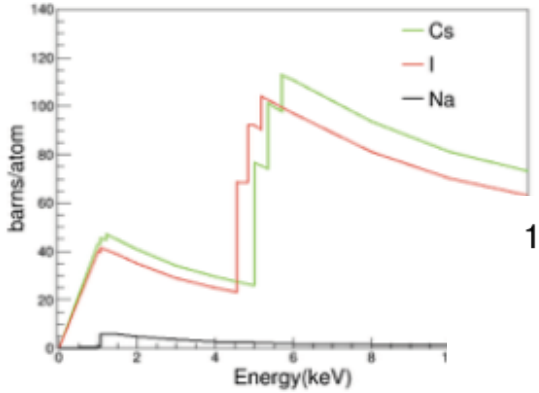
Assuming total SET2 data (error reduction only)

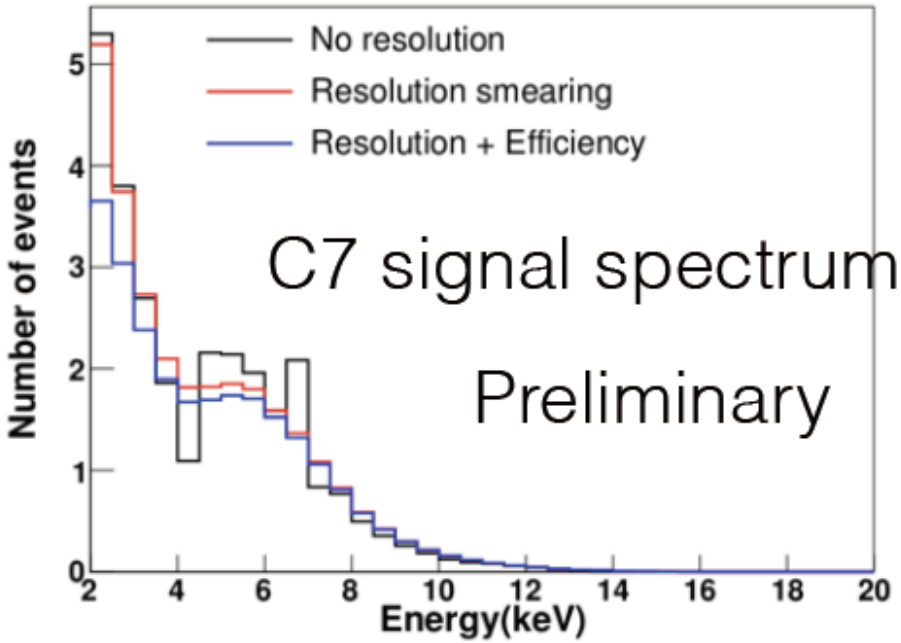


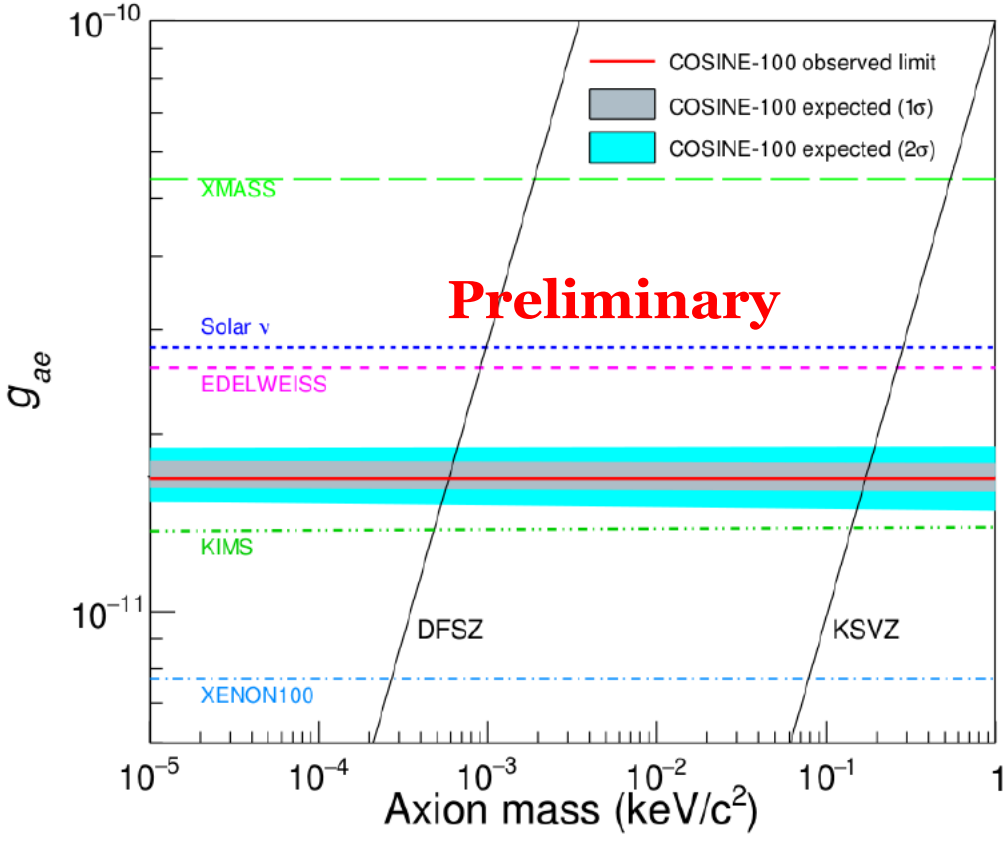
Preliminary

Solar axion search



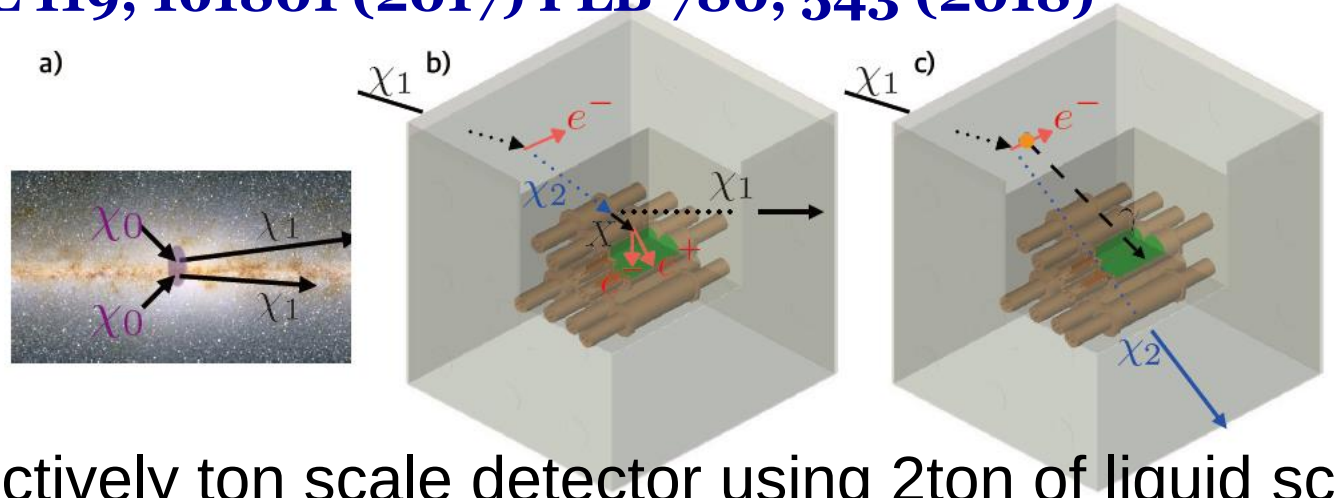




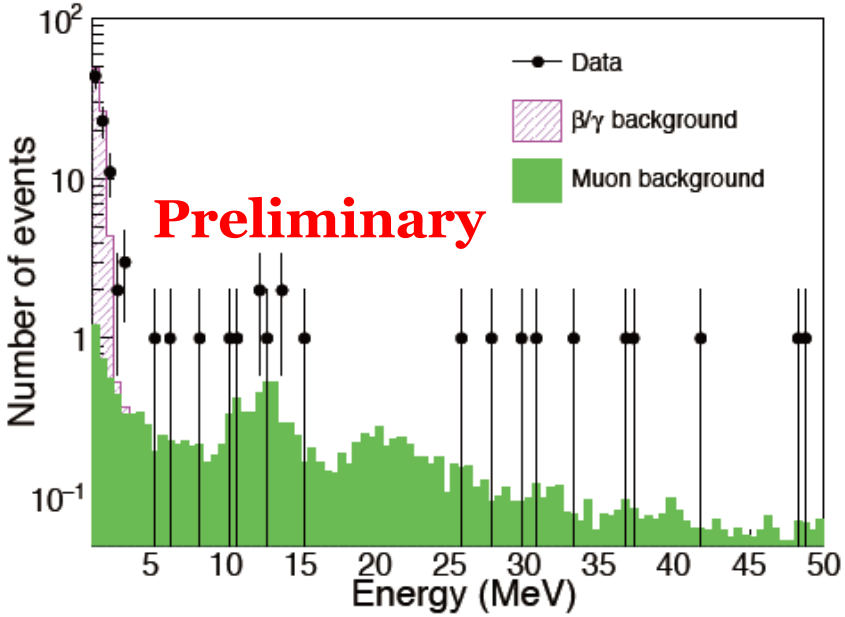


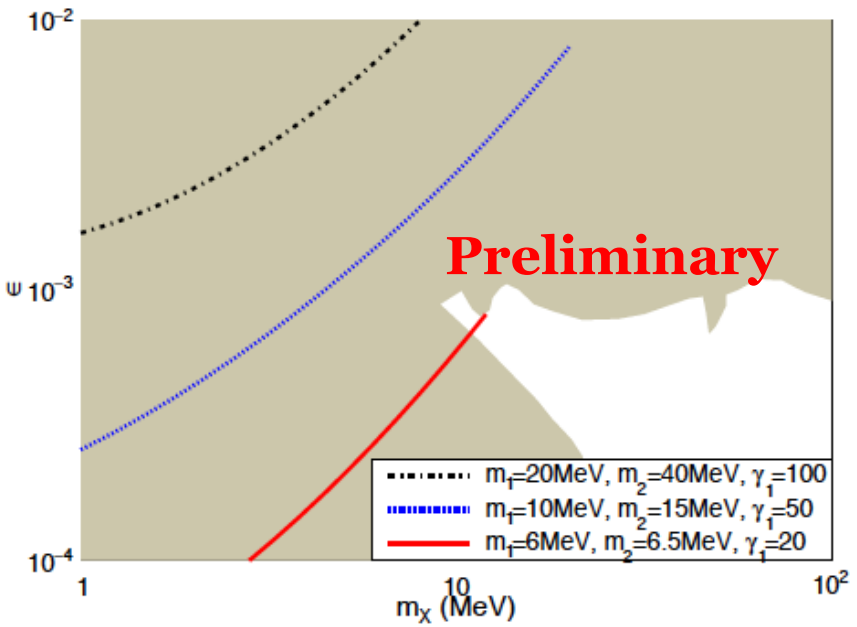
Boosted inelastic dark matter search

PRL 119, 161801 (2017) PLB 780, 543 (2018)

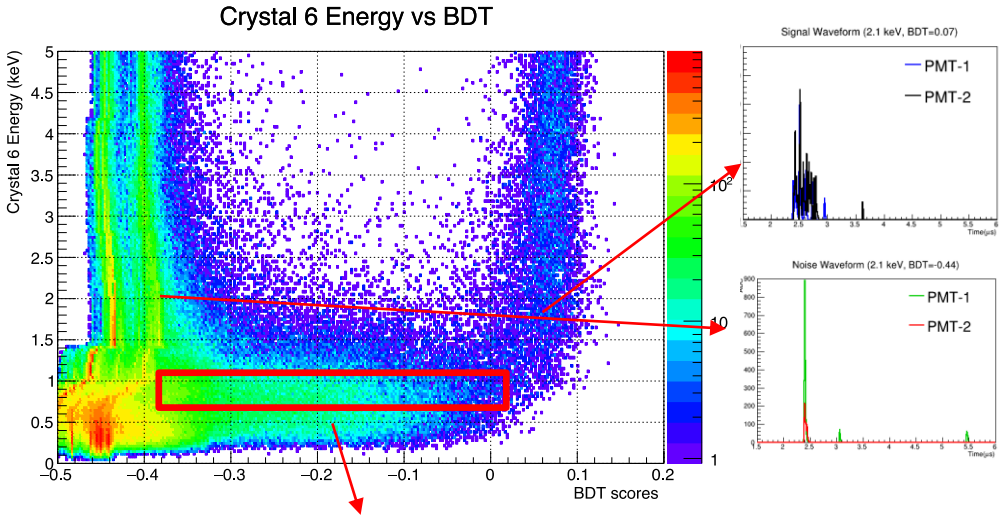


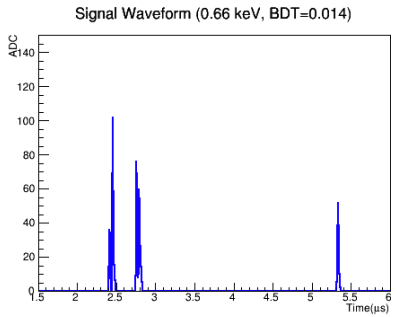
- Effectively ton scale detector using 2ton of liquid scintillator

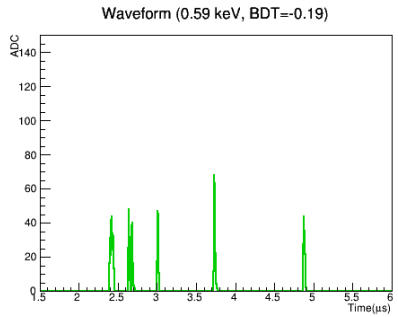


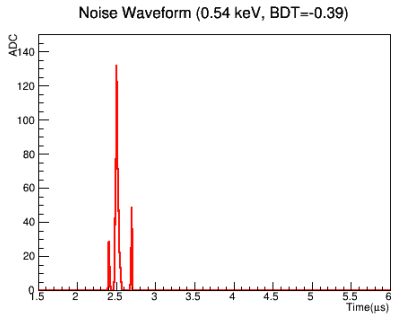


Analysis with 1 keV energy threshold





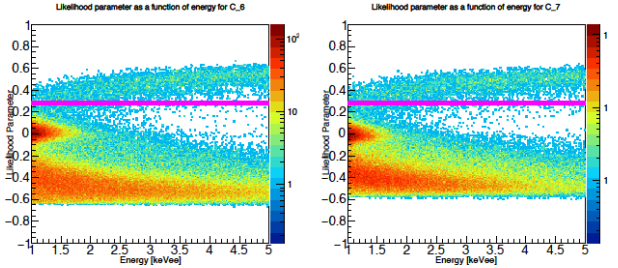




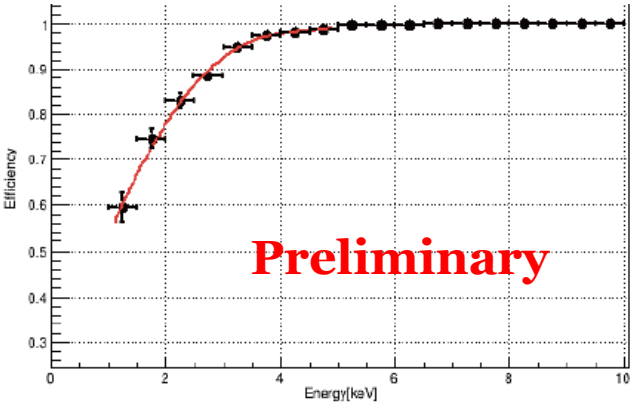
Understand signal-like events and noise-like events at low energy

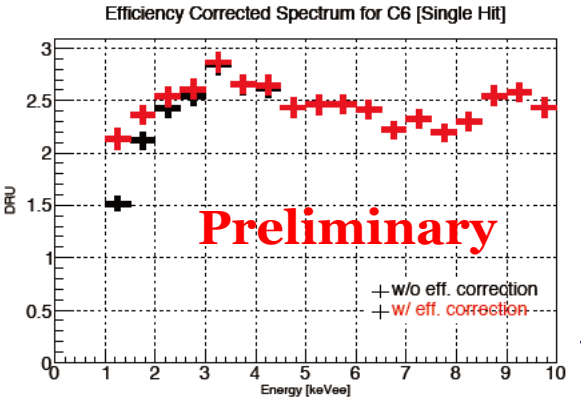
Develop new parameter to reject noise-like events effectively

Likelihood parameters for noise rejection



Efficiency

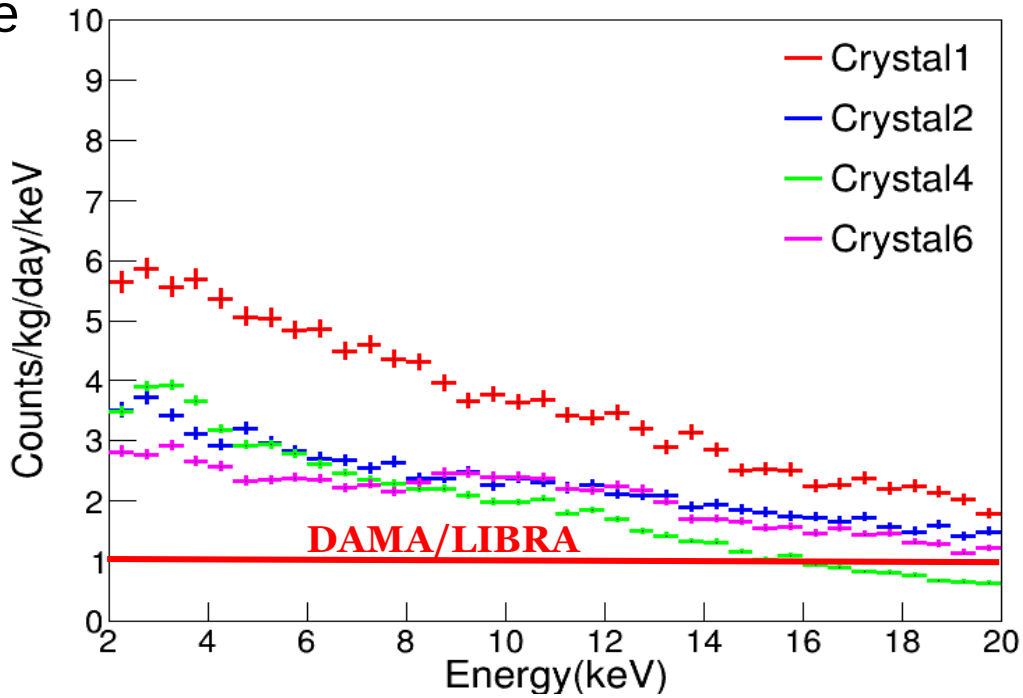




Next phase of COSINE (COSINE-200)

- **Background** levels of COSINE-100 are **2-3 times higher** than DAMA/LIBRA
  - We may not resolve all possible scenarios in interpreting DAMA/LIBRA signals
  - Still need to develop better crystals

- Issues are internal ^{40}K, ^{210}Pb, and ^{3}H
  - ^{40}K : Powder purification
  - ^{210}Pb : Any part of powder, crystal growing, and crystal handling can make it
  - ^{3}H : Cosmogenic activation



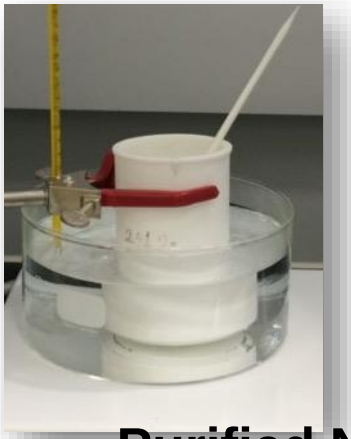
- **Extremely pure crystal** development
  - From initial materials to detector assembly, we need **very careful handling**
  - These are very **difficult jobs** for a private **company**
  - We decided to do our own development for the entire process

Cosmogenic activation will be naturally reduced if we grow the crystals in Korea

NaI powder purification (Lab experiment)

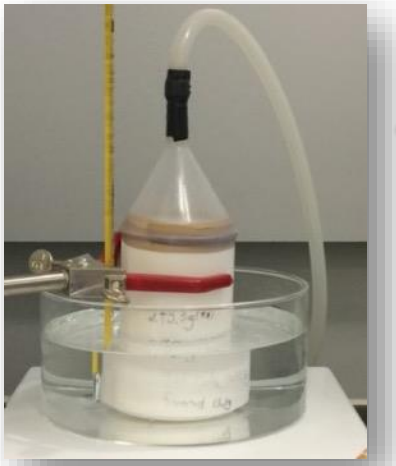
- Recrystallization

Saturated NaI solution @ 25 ° C



T↑ 110 ° C

Evaporation of 40 % of H_2O under vacuum



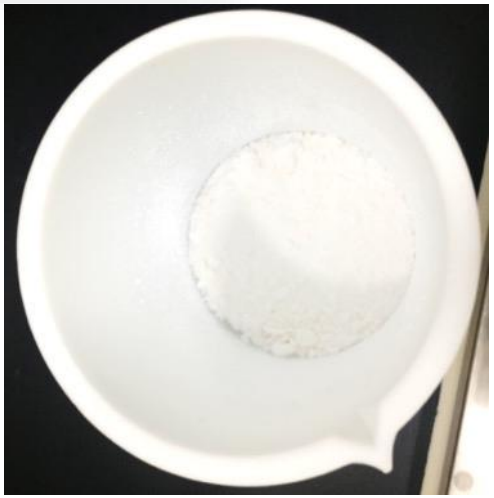
T↓ 25 ° C

Crystallization: Cooling down with stirring

NaI crystal

Drying crystal under vacuum @ 130 ° C

Purified NaI powder



Purification of NaI powder

- Recrystallization three times for normal grade while one times for the other pure grade powders

ICP-MS results

Powder	^{39}K (ppb)		^{208}Pb (ppb)		^{232}Th (ppb)		^{238}U (ppb)	
	initial	After	Initial	After	Initial	After	Initial	After
Astro grade	5	< 1	0.9	<0.4	<0.1	<0.1	<0.1	<0.1
Crystal grade	45	6	3.3	0.8	<0.1	<0.1	<0.1	<0.1
Normal grade	240,000	210	6.9	0.2	<0.1	<0.1	<0.1	<0.1

- **Efficiency: 40% – 50%**
- **Mother solution can be reused for next recrystallization.**

Reduction for K and Pb after one recrystallization

- K : ~ 10 reduction
- Pb: ~ 3 reduction

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

Goal : K less than 20 ppb

Purification factory

70 kg NaI powder can be loaded

Feed tank

Mixing tank

Filter unit

Receiver tank 1, 2

Conical dryer

Goal : K less than 20 ppb

~ 30 kg of purified NaI powder

	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

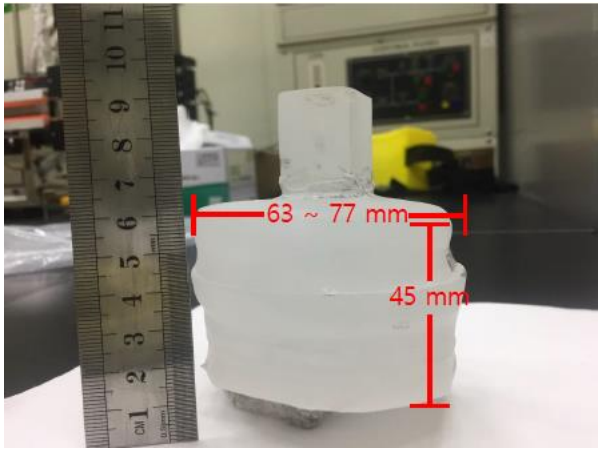
Our system is more effective than lab experiment

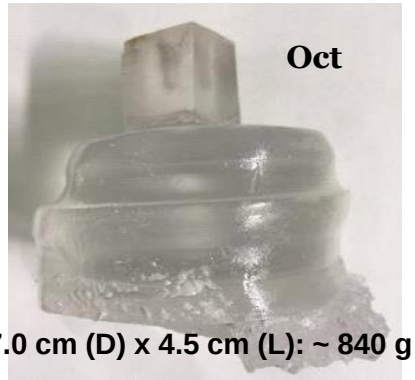
Crystal growing

- Small crystal grower was installed at 2017

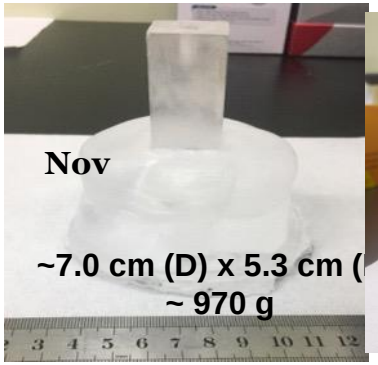
Crucible diameter is $\phi = 15$ cm; **1~2 kg** test crystal can be grown

Sept/2017 **Pure NaI**

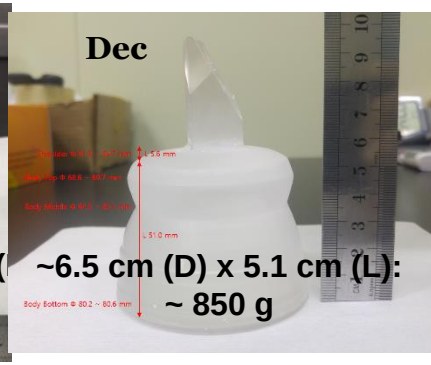




~ 7.0 cm (D) x 4.5 cm (L): ~ 840 g



~7.0 cm (D) x 5.3 cm (
~ 970 g

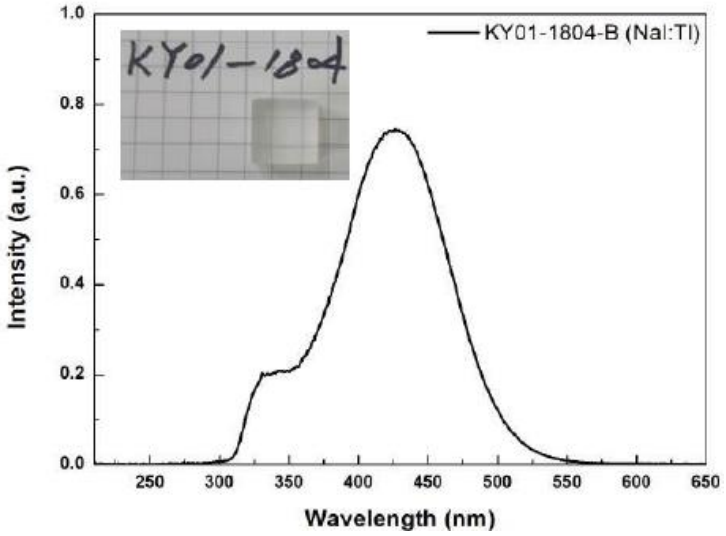


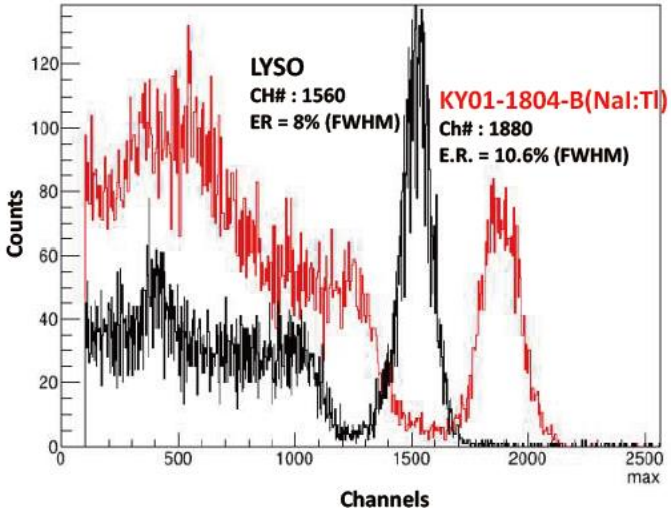
~6.5 cm (D) x 5.1 cm (L):
~ 850 g

Tl doped crystals

Feb/2018

Crystal grade

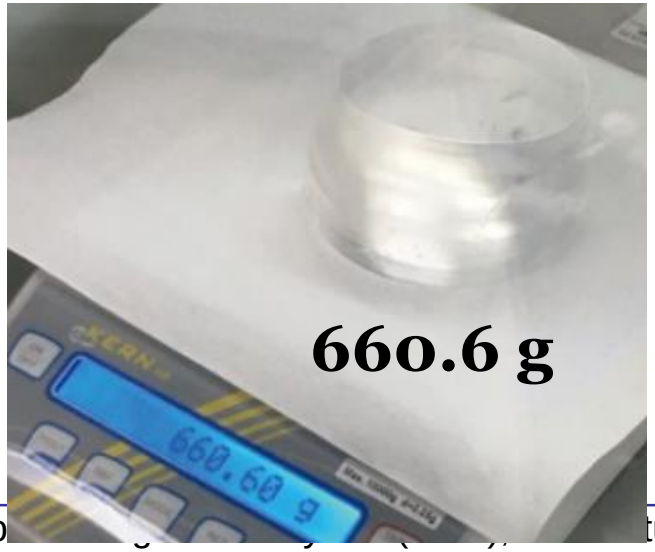


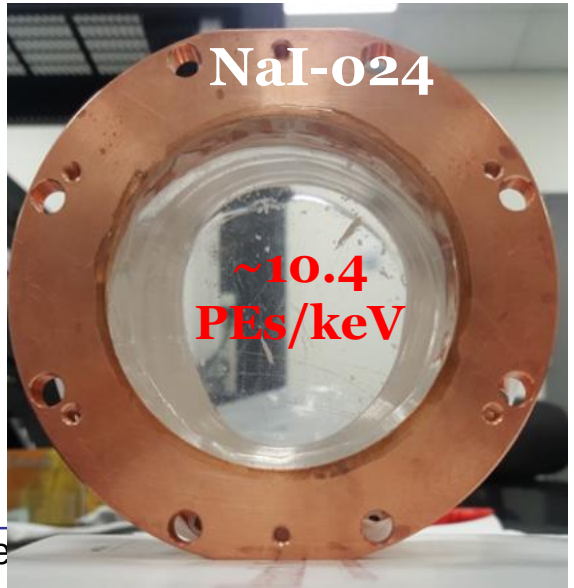


~40,000 Photons/MeV

May/2018

Astro grade





A full size grower

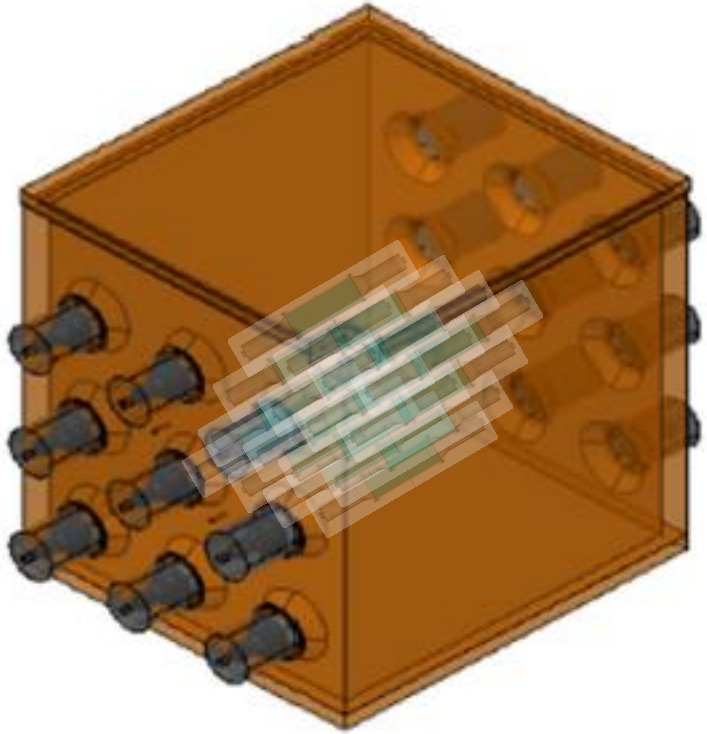
- Full size grower & annealing furnace were installed ($\phi = 60$ cm)
  - ❖ Similar growing machine as the DAMA/LIBRA crystals
  - ❖ Maximum powder loading :120 kg
    - ❑ About three full size detectors (12.5 kg) per ingot

- Tests on temperature control & mechanical operation were done
- Real experiments will be started soon

COSINE-200

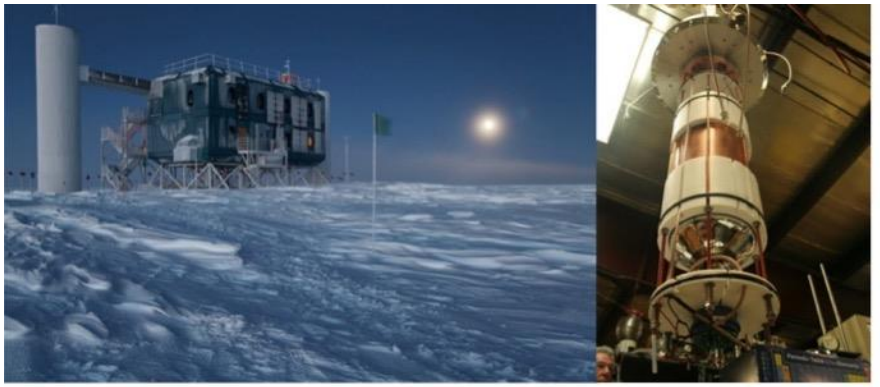
- Current COSINE-100 shield designed to accommodate 16 of 12.5 kg crystals = 200 kg

Total 200 kg



Y2L

Another 200 kg in south pole ? If we have same modulation..

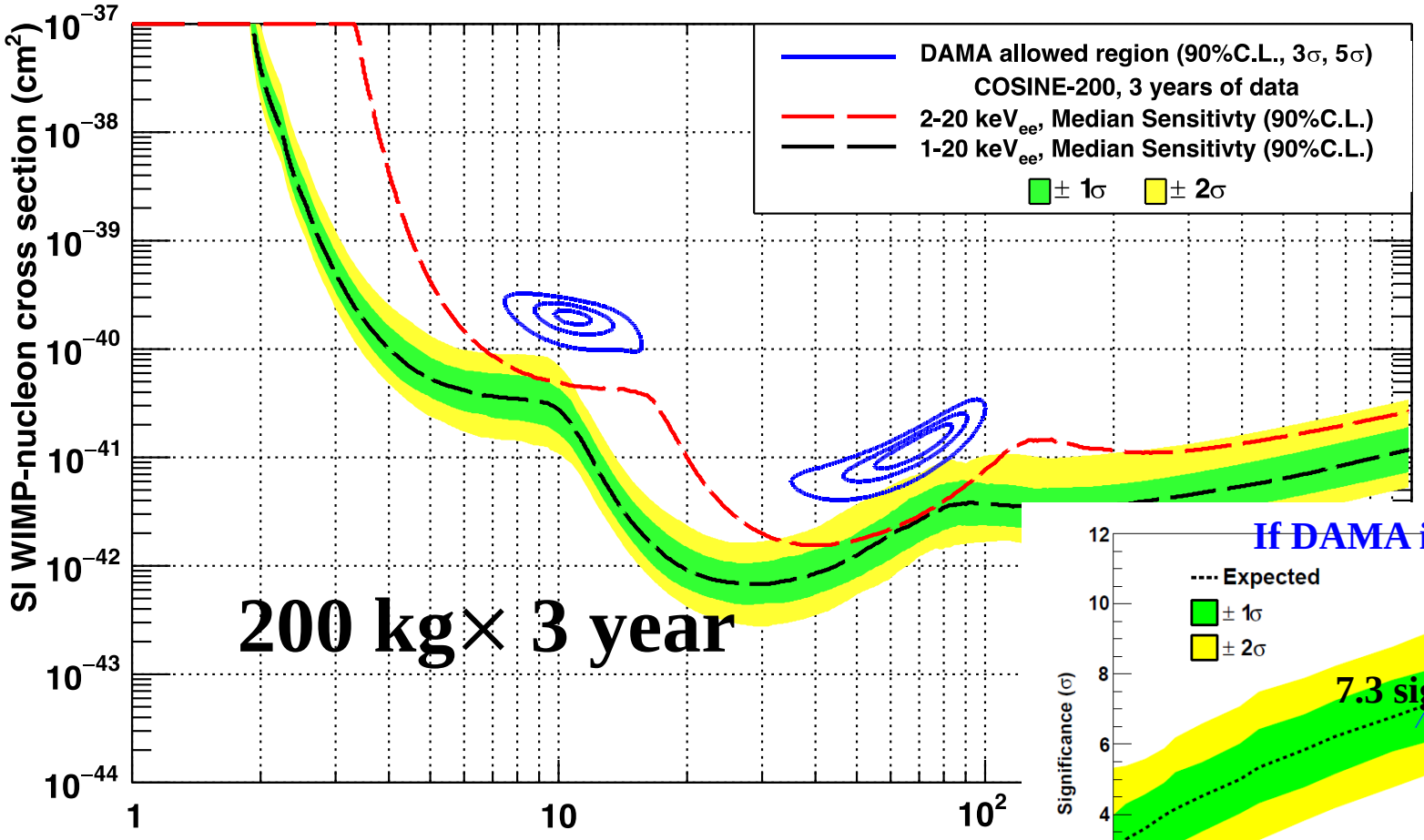


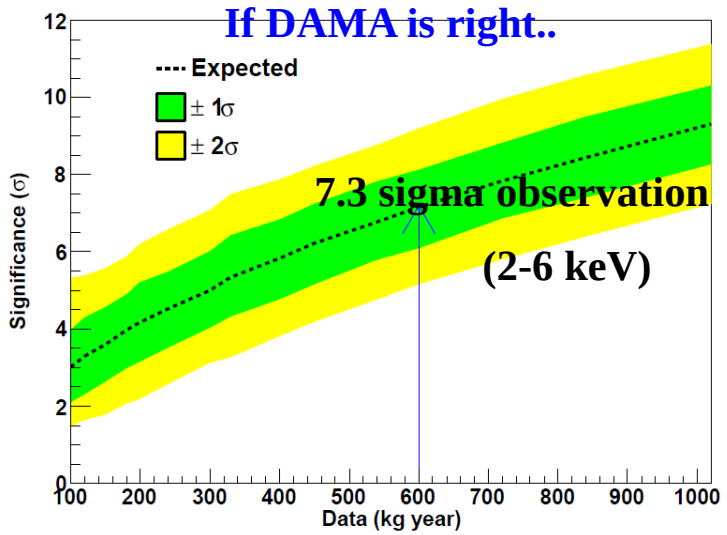
Under consideration

2022-2023 (IceCube upgrade)

COSINE-200 sensitivity (Modulation)

- 1 dru background (same as DAMA/LIBRA)





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

Summary

- COSINE-100 detector was installed at Y2L and runs smoothly for about two years
- COSINE-100 detector is well understood
  - ~ 2.7 counts/day/kg/keV with 2 keV threshold for best crystal
- COSINE-100 confirms that DAMA's modulation signal cannot be from standard WIMP in SHM with same NaI(Tl)
- Modulation analysis of COSINE-100 is ongoing
- Preparing 1keV threshold analysis

- COSINE-200 is under preparation
  - Unambiguous conclusion for the DAMA/LIBRA signals
  - Goal to start ~200 kg experiment at 2019 with less than 1dru background