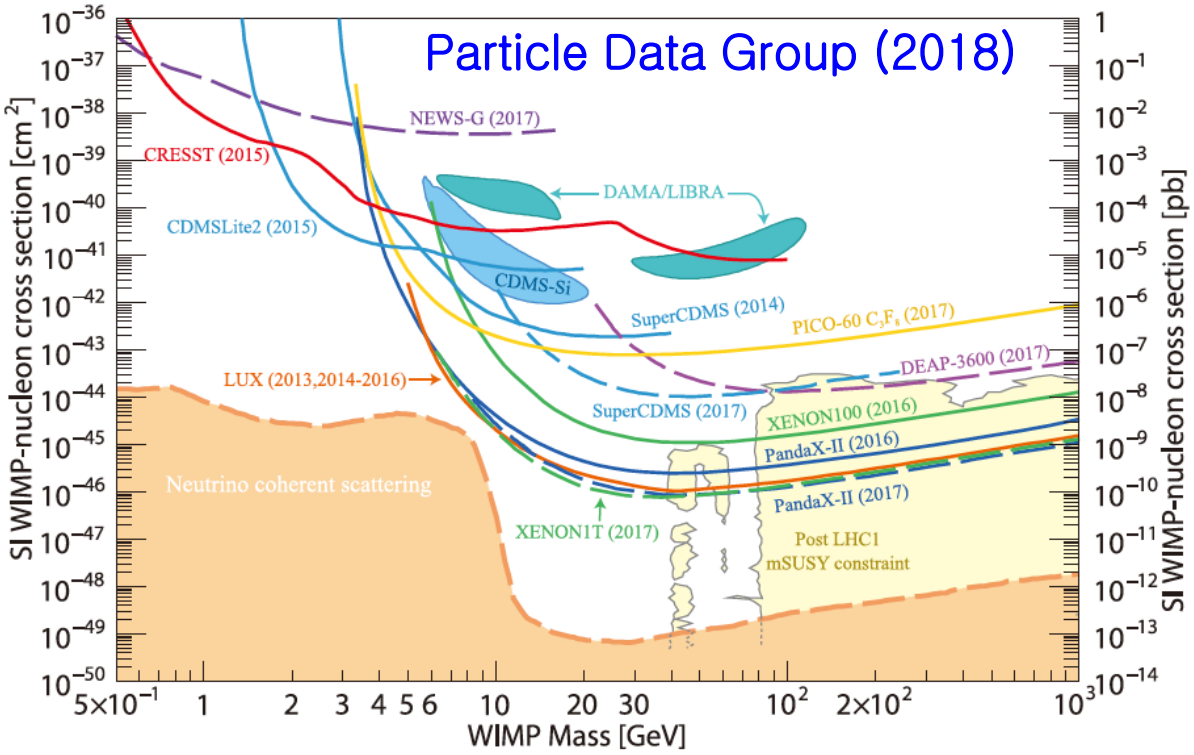
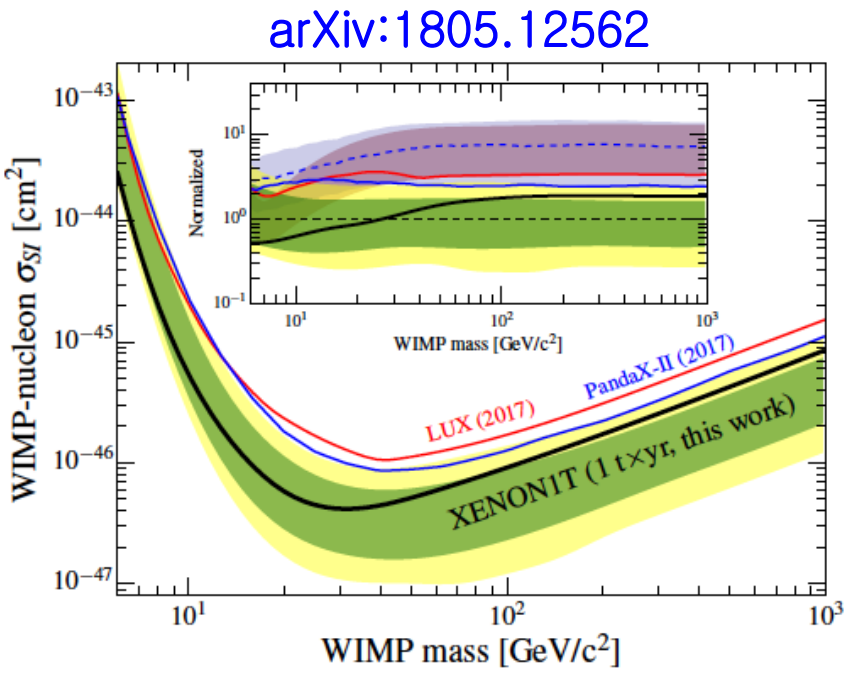
Status of COSINE experiment

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





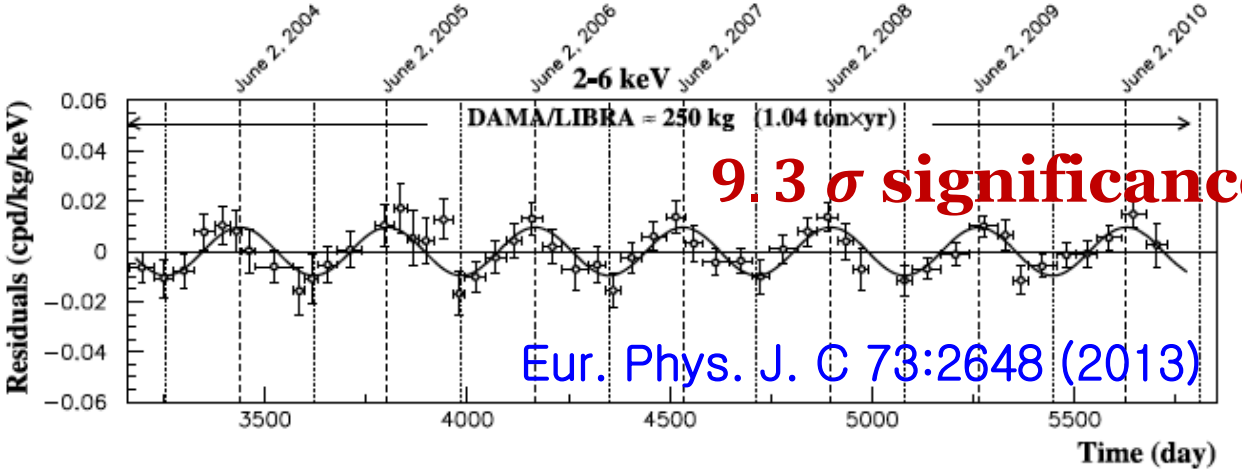
- No sign of WIMP dark matter down to 4×10^{-47}cm^2 @ 30 GeV
- Exploring low-mass dark matter
- Unresolved signal from DAMA

Observation (?) of dark matter annual modulation signal

DAMA/LIBRA experiment

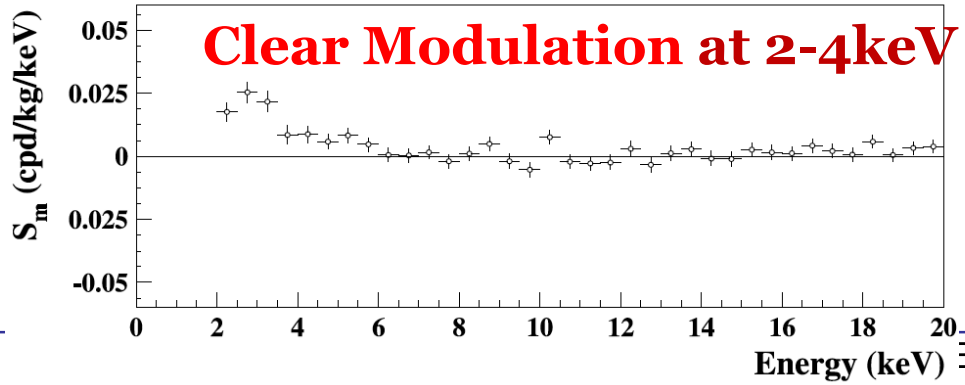
- Annual Modulation Searches with an array of NaI(Tl) crystals

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

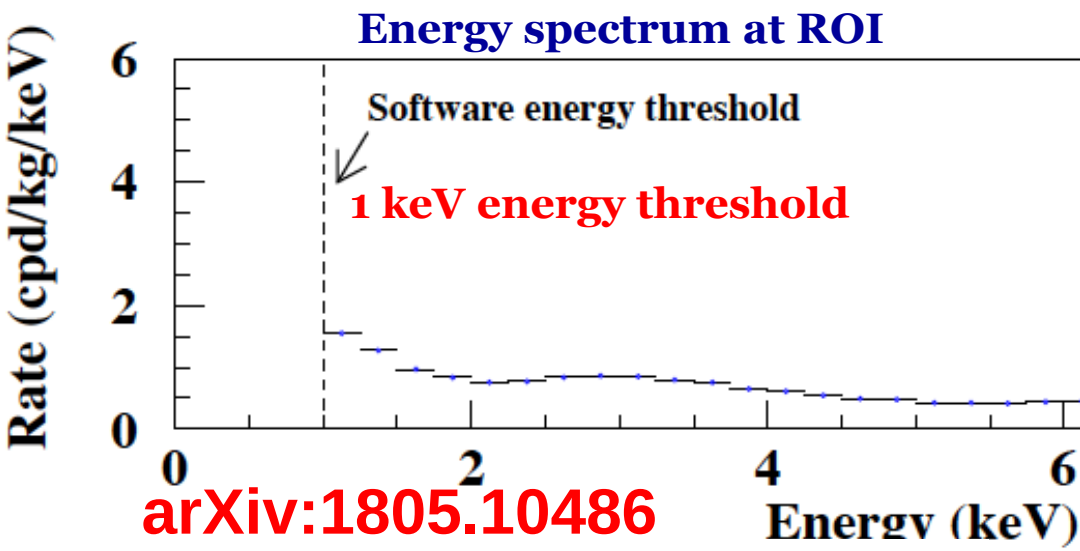
R. Bernabei[a,b], P. Belli[a,b], A. Bussolotti[b], F. Cappella[c,d], V. Caracciolo[e], R. Cerulli[a,b], C.J. Dai[f], A. d'Angelo[c,d], A. Di Marco[b], H.L. He[f], A. Incicchitti[c,d], X.H. Ma[f], A. Mattei[d], V. Merlo[a,b], F. Montecchia[b,g], X.D. Sheng[f], Z.P. Ye[f,h]

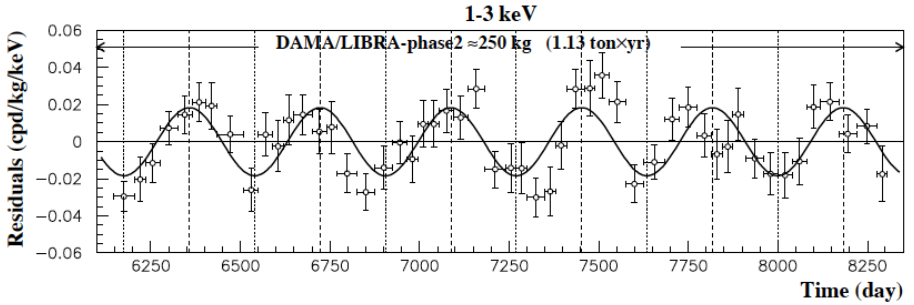
arXiv:1805.10486

e 1

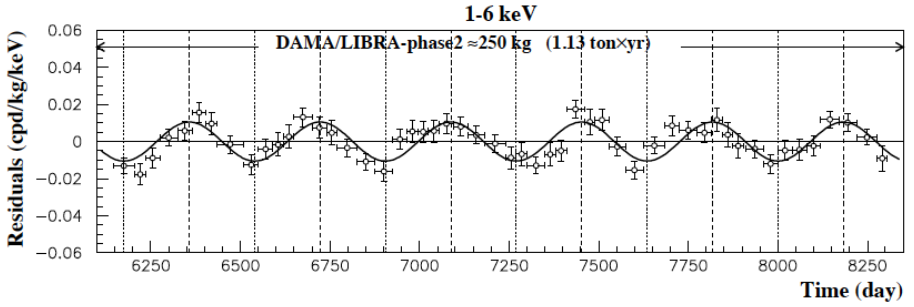
DAMA/LIBRA phase 2

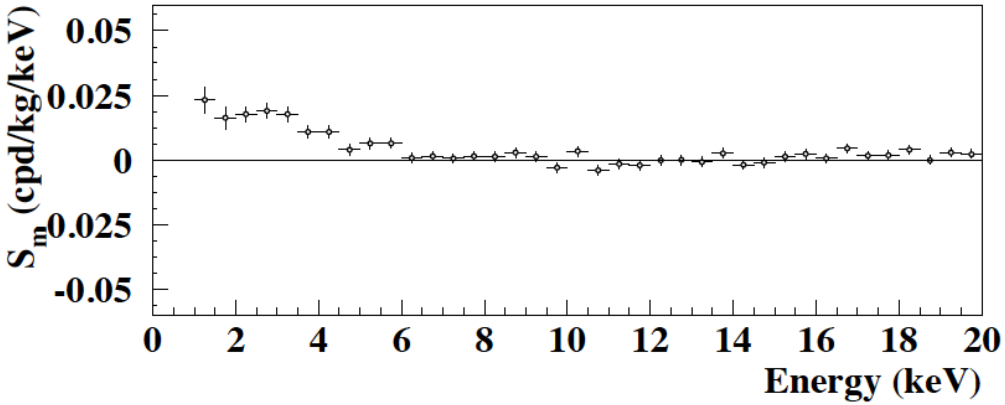
- Energy threshold reached to 1 keV with better PMTs
- Still there is modulation
- Significance
  - ❖ 1-6 keV : **9.5 σ** (phase 2)
  - ❖ 2-6 keV : **12.9 σ** (phase 1+2)
- Increased modulation amplitude below 2keV



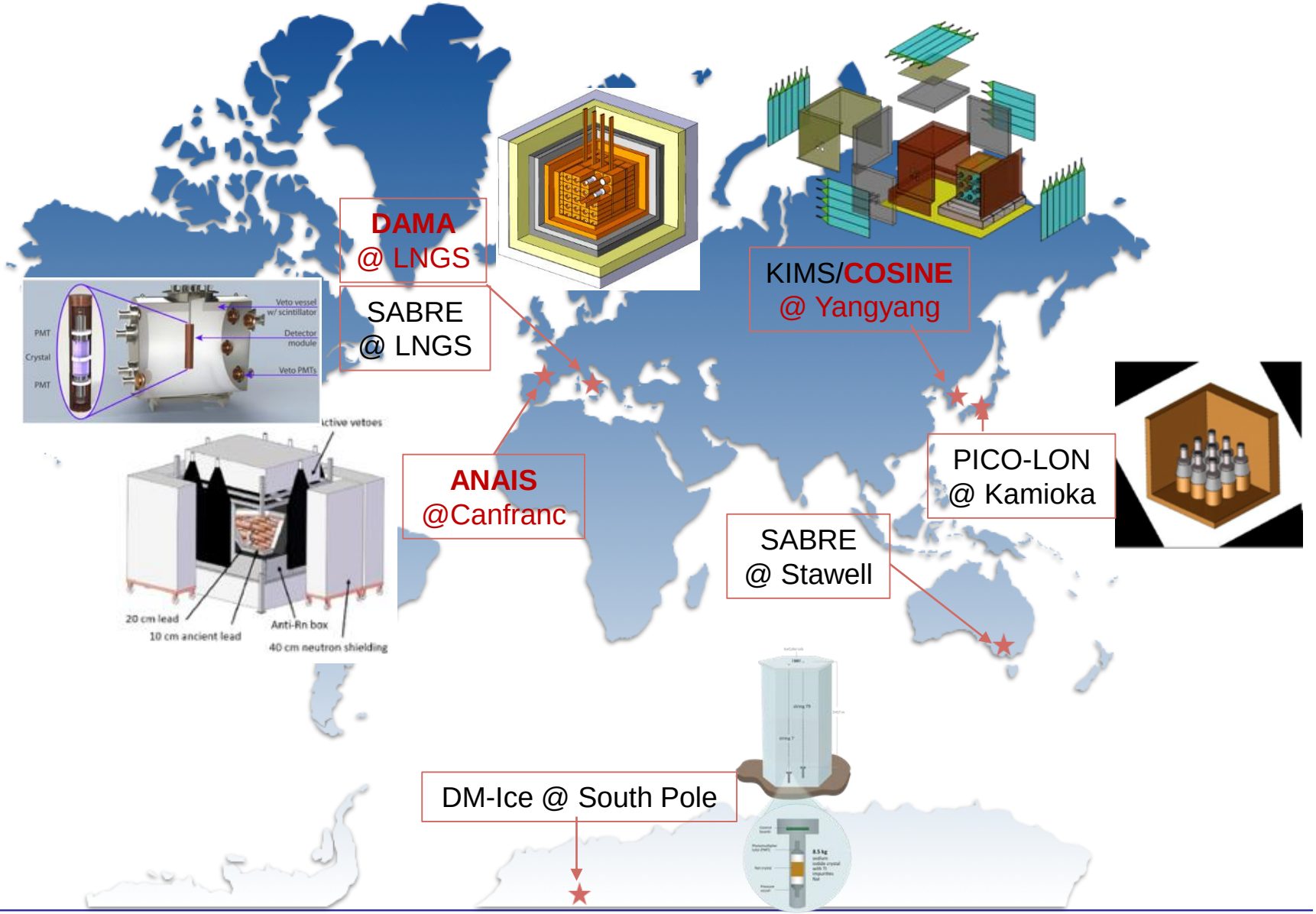


Modulation amplitude



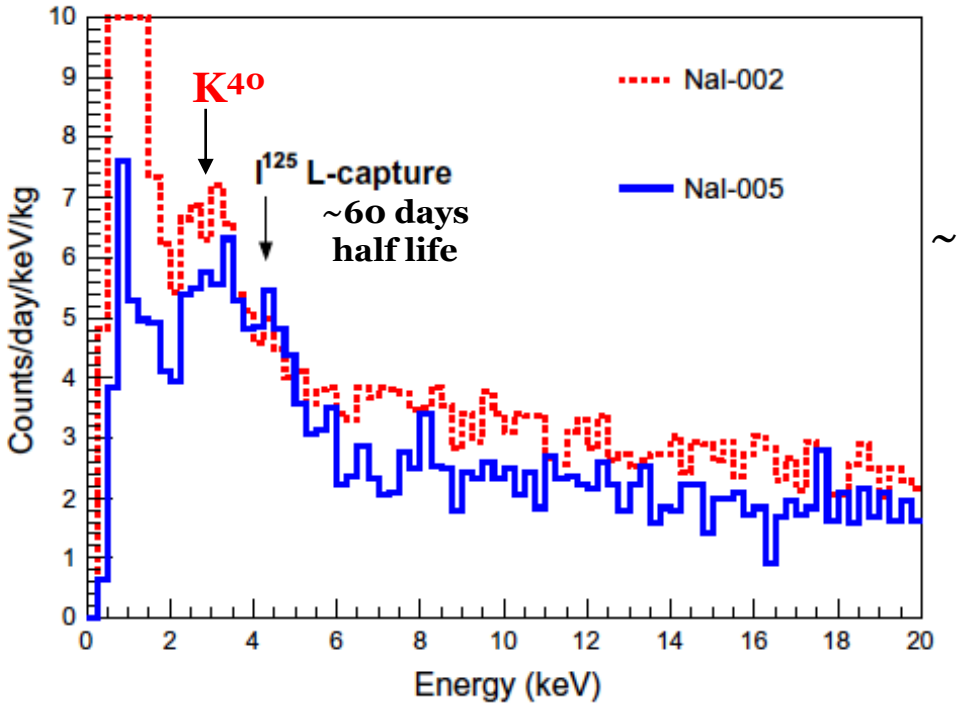


Global NaI(Tl) efforts



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)



~ 2keV energy threshold

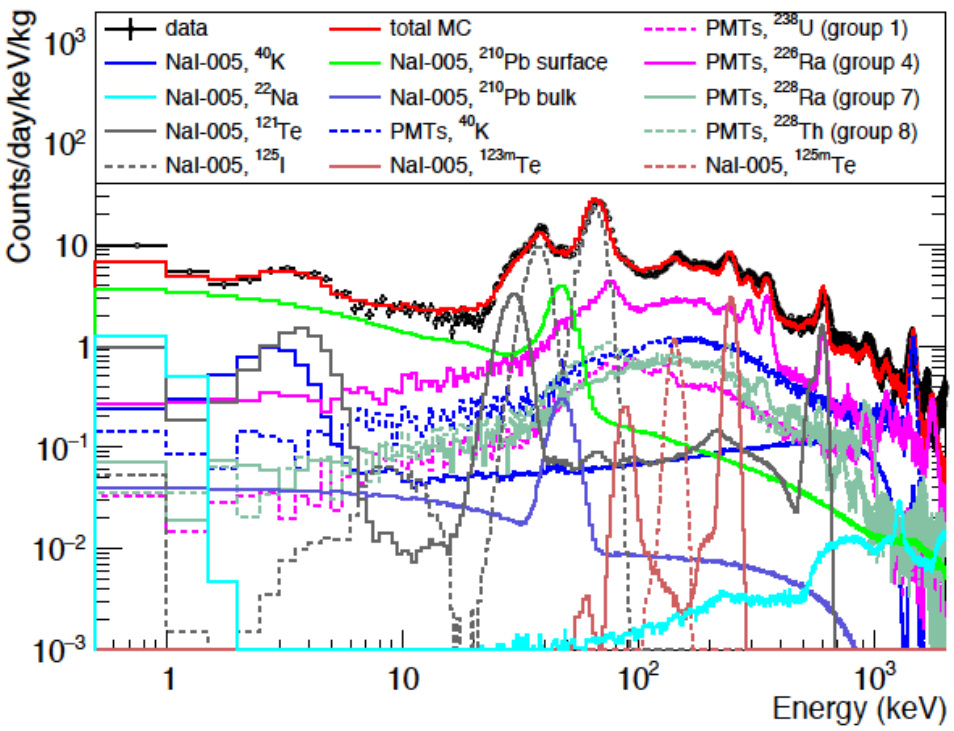
~ 2 dru background @ 6keV

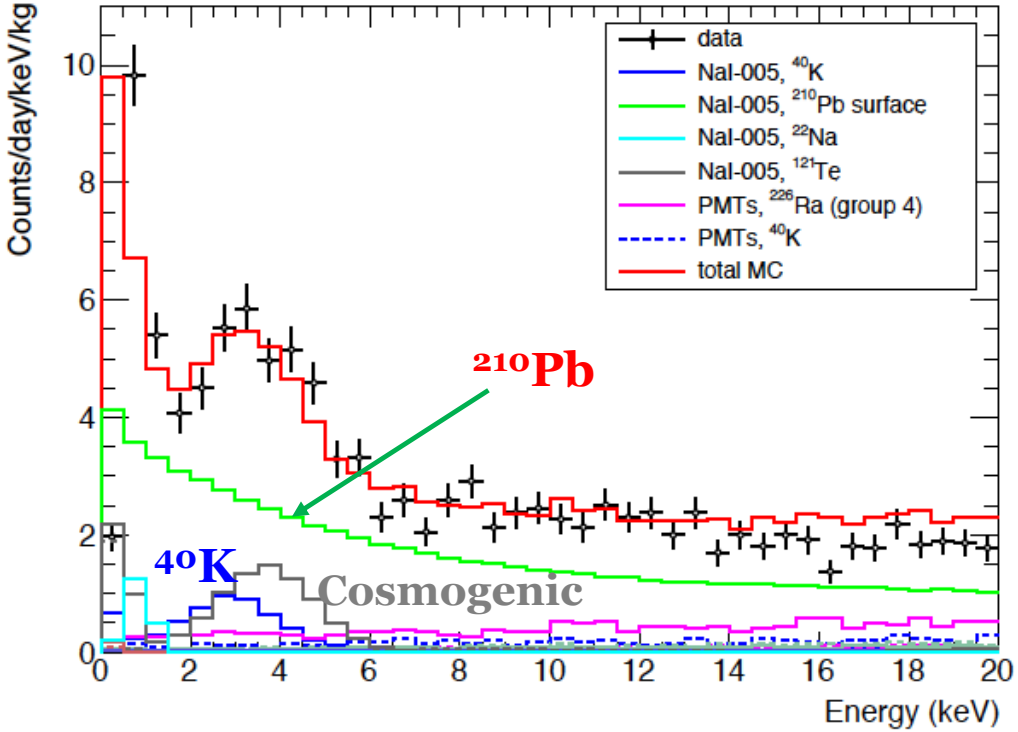
^{40}K and ^{210}Pb are main background at low energy

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

Background understanding of a NaI(Tl) crystal

G. Adhikari *et al.*, EPJC 77, 437 (2017)

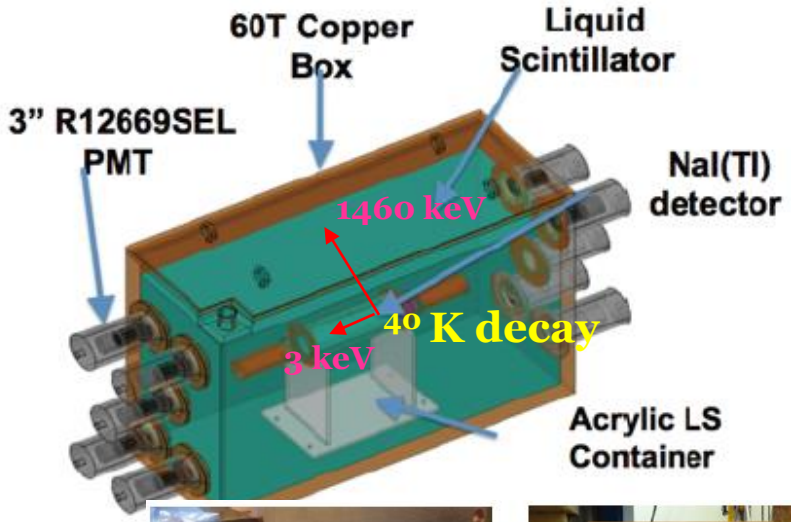




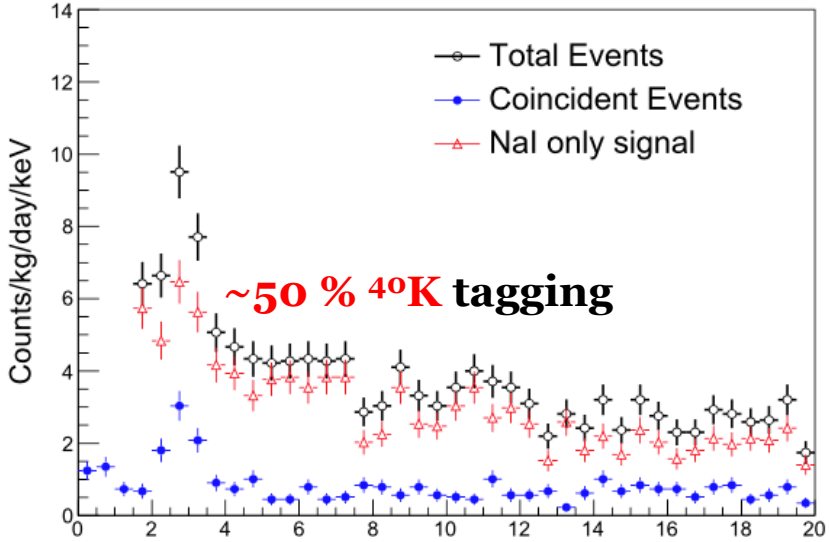
- Geant4 based MC simulation describes background of a NaI(Tl) crystal reasonably well
- Main background at low energies due to internal ^{210}Pb, ^{40}K, and ^{121}Te ($\tau = 19.2$ days) cosmogenic

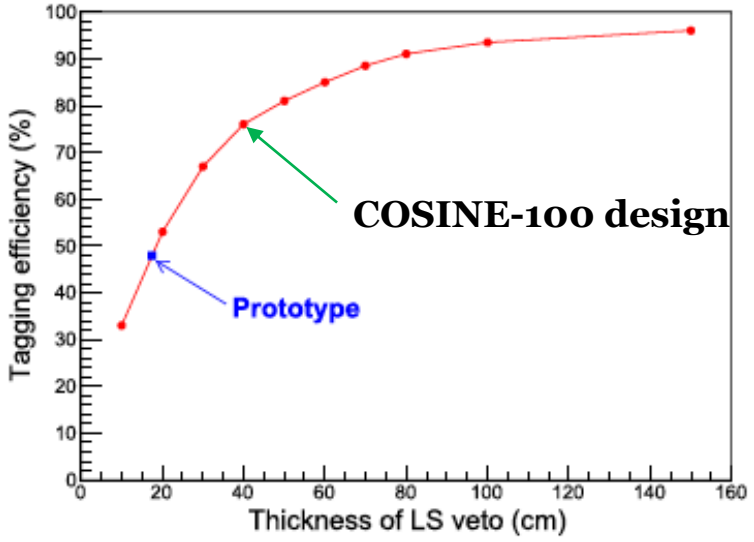
Internal ^{40}K and external background reduction

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



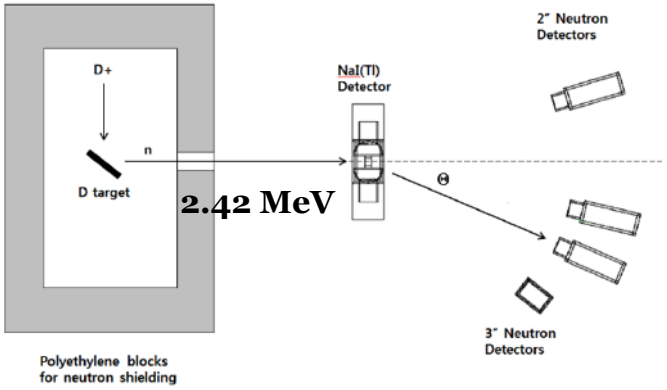
Prototype design for single crystal



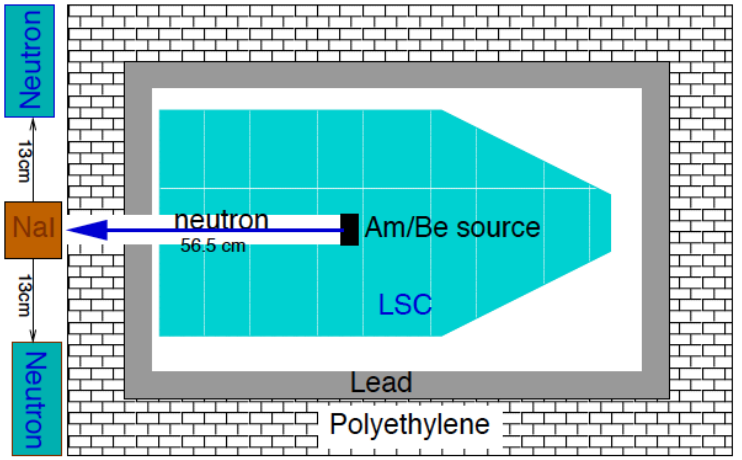


Nuclear recoil data

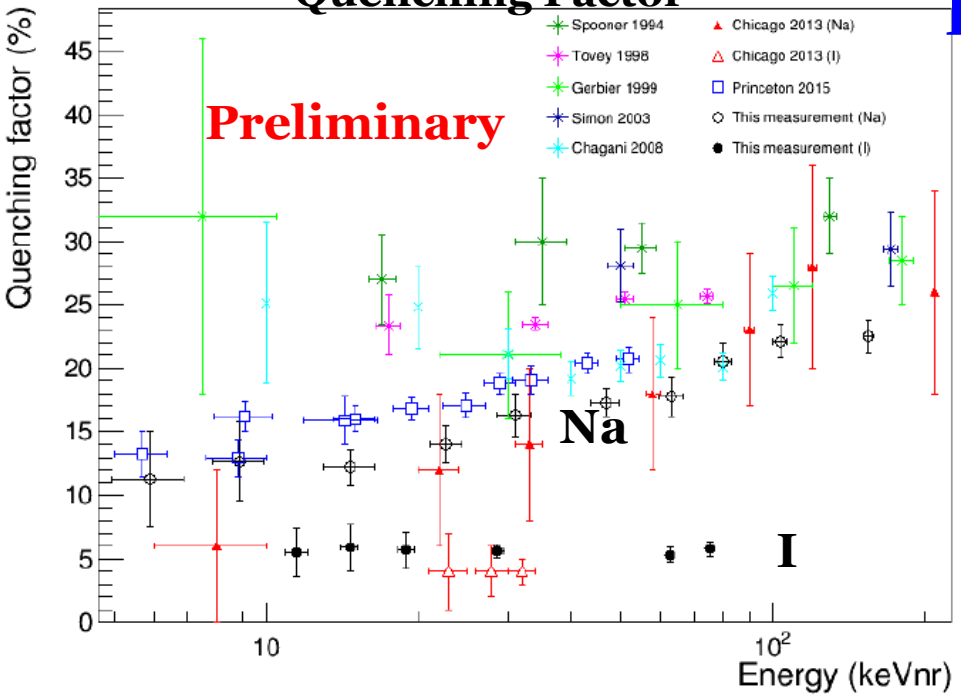
D-D neutron generator



Am/Be source

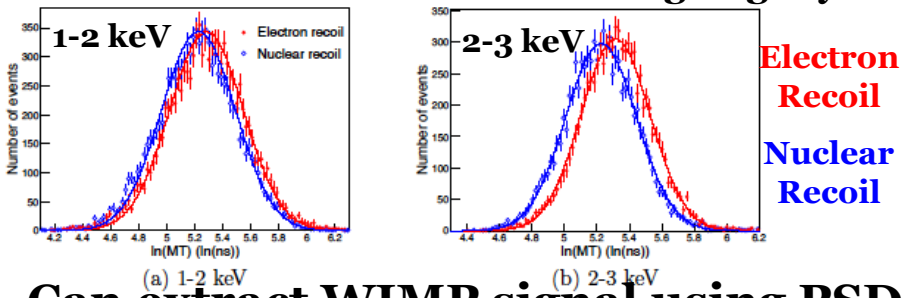


Quenching Factor



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

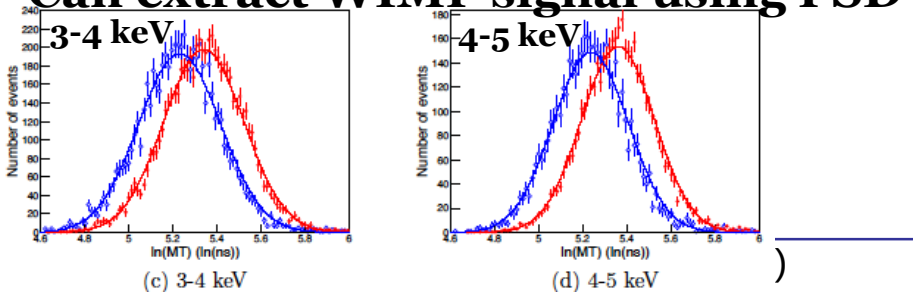
Good discrimination due to high light yield !!



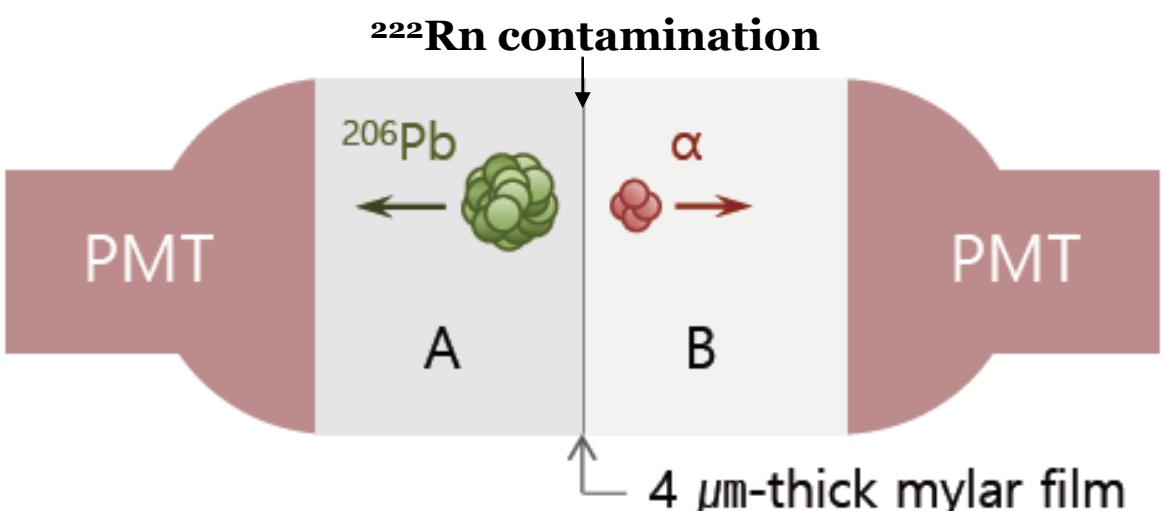
Electron Recoil

Nuclear Recoil

Can extract WIMP signal using PSD

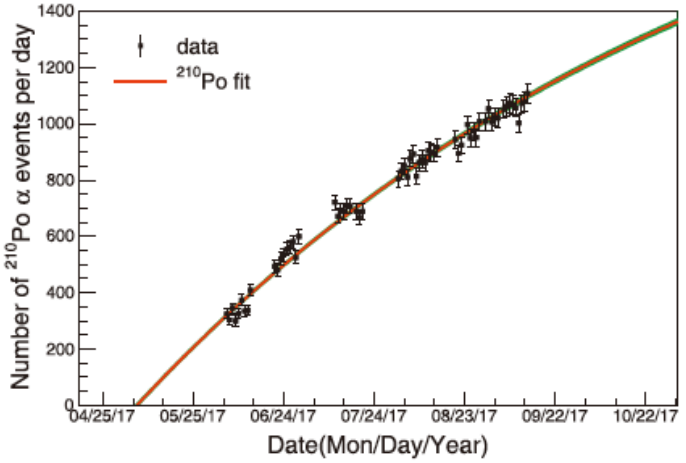


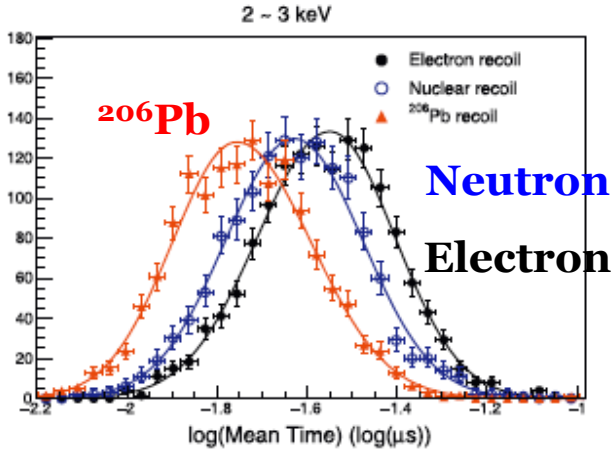
Surface ^{206}Pb recoil measurement

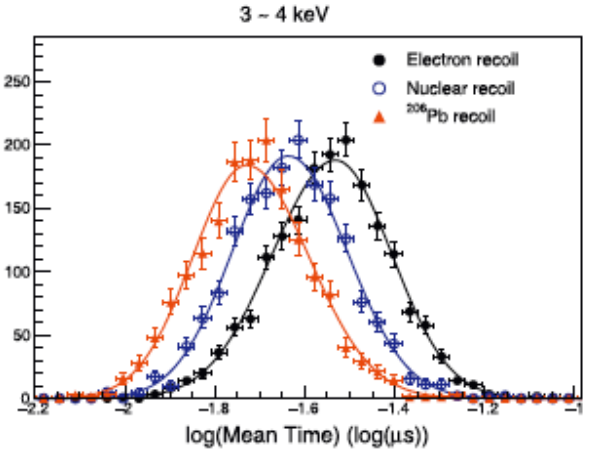


K.W. Kim *et al.*, Astropart. Phys. 102 (2018) 51

^{210}Po has been increased



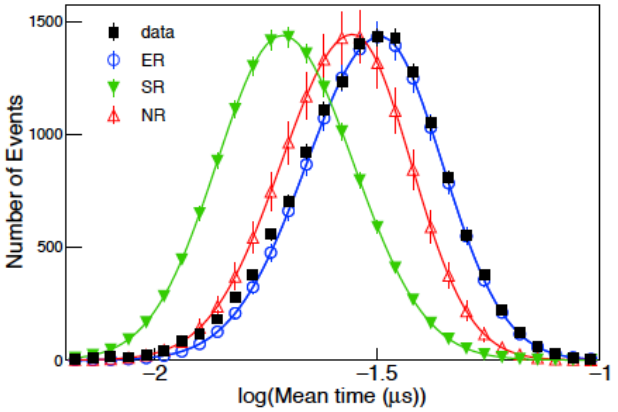




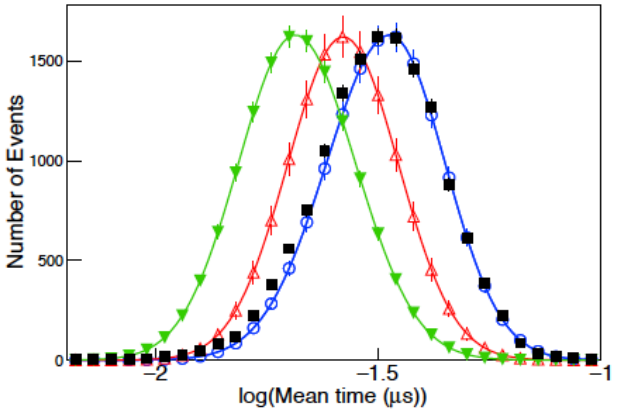
- Surface ^{206}Pb recoils are much faster than typical NaI nuclear recoils
- We will use those shapes to extract WIMP signals

Nuclear recoil event extraction using pulse shape discrimination

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



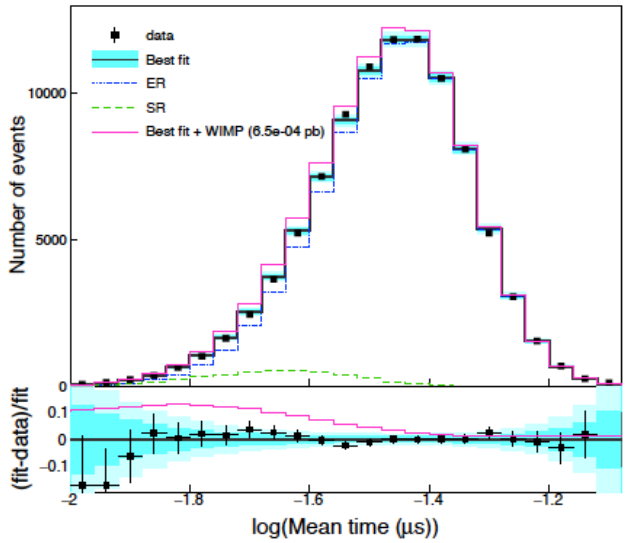
(a) 2–3 keV



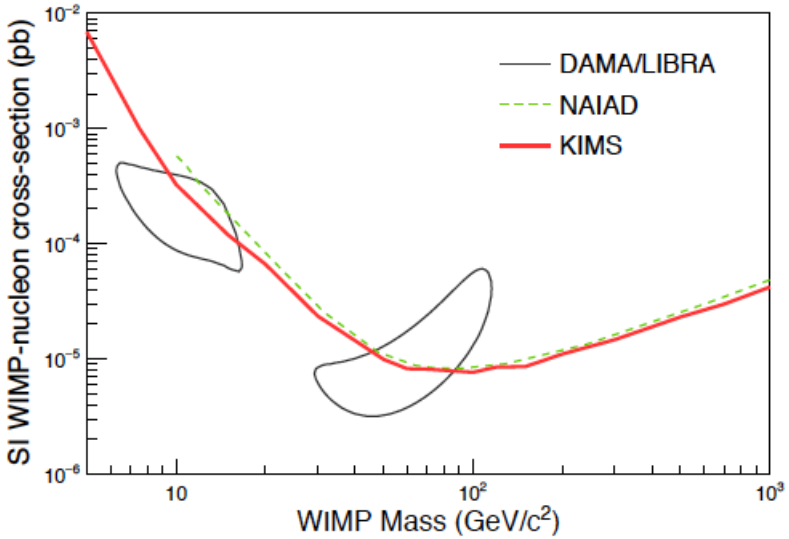
(b) 3–4 keV

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

Fit results (2-8 keV)

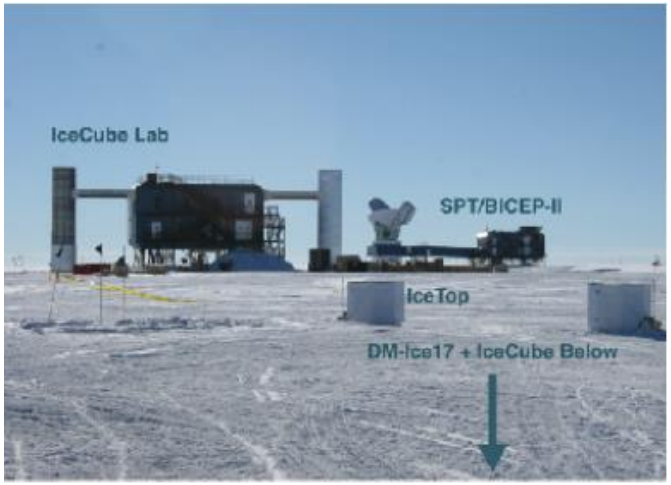


Spin Independent WIMP-nucleon interaction



DM-Ice17

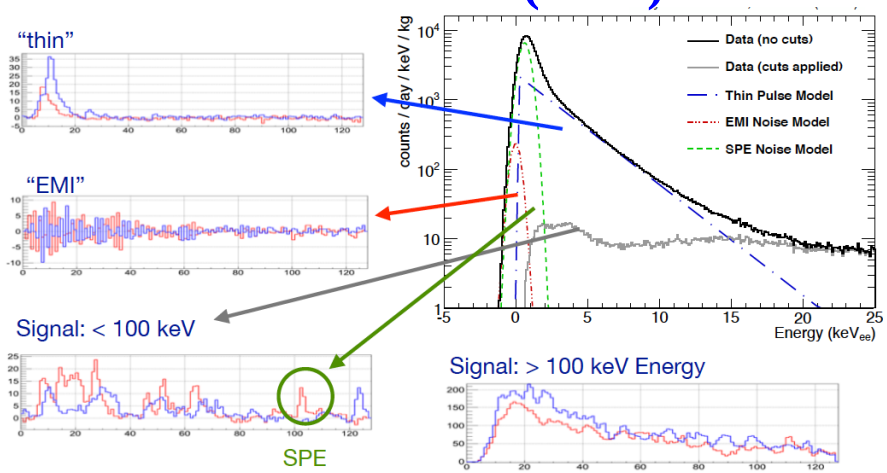
- DM-Ice17 in South pole (Jun.2011 – Jan.2015)



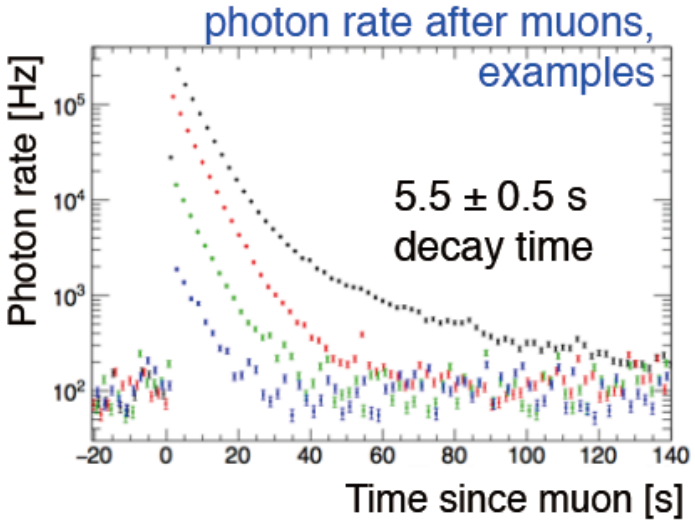
Two 8.47 kg crystal

2200 m.w.e overburden

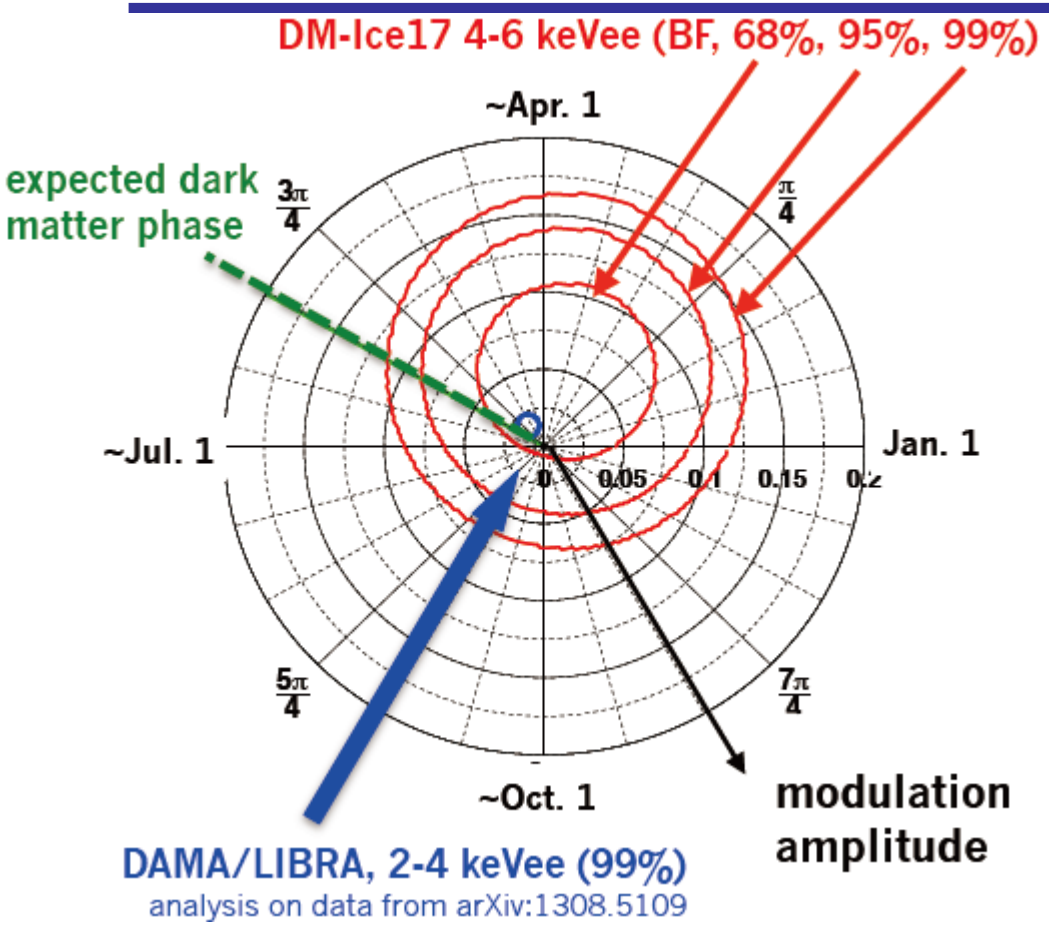
PRD 90 092005 (2014)

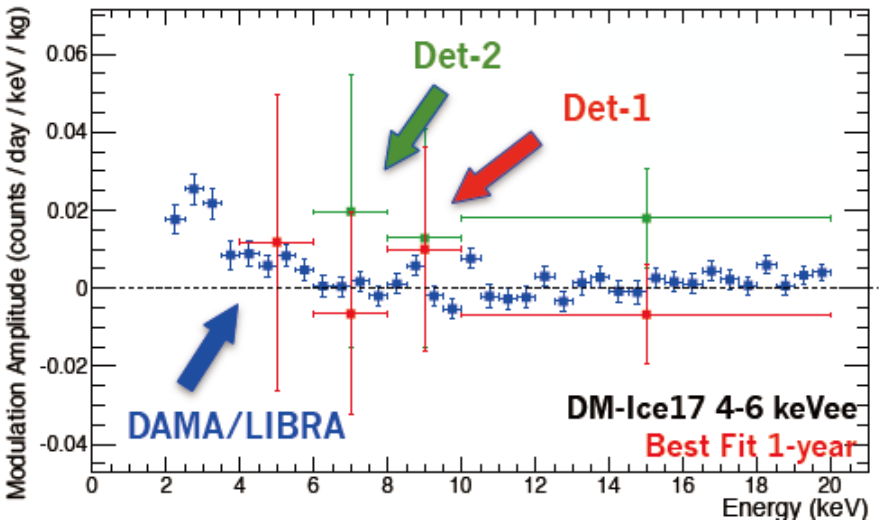


PRD 93 042001 (2016)



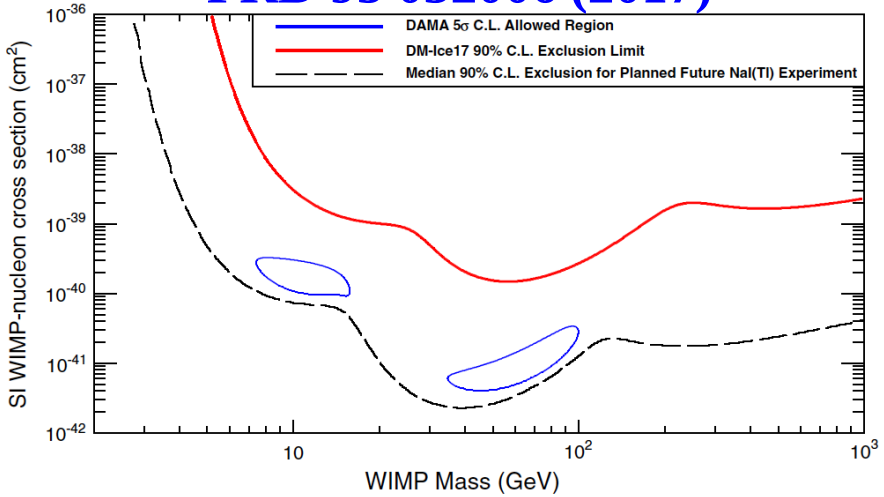
Annual modulation study with DM-Ice17





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

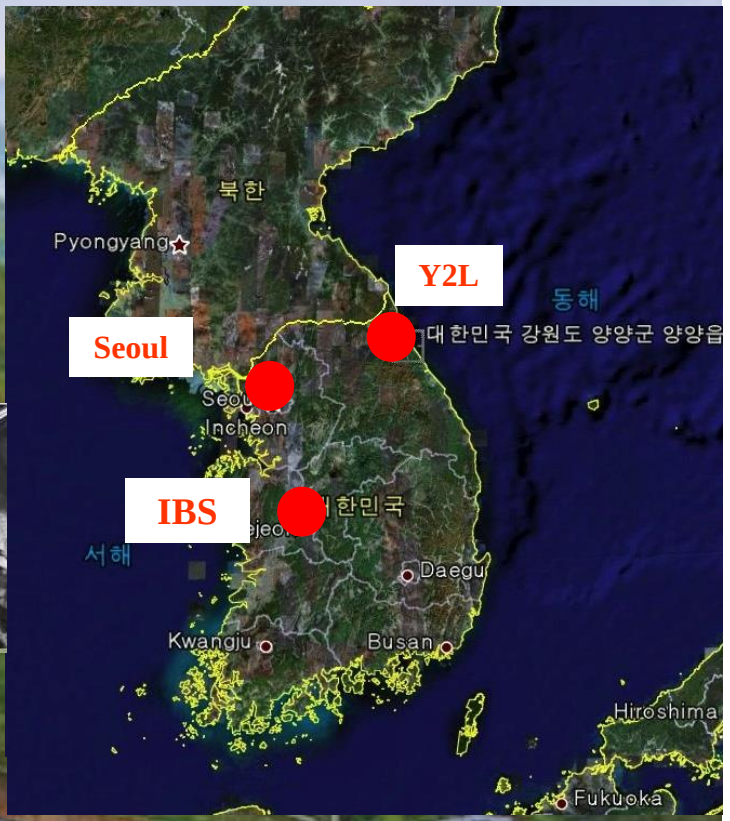
(Upper Dam) YangYang Pumped Storage Power Plant

Center for Underground Physics

IBS (Institute for Basic Science)

1000m

700m



(Power Plant)

양양양수발전소

(Lower Dam)

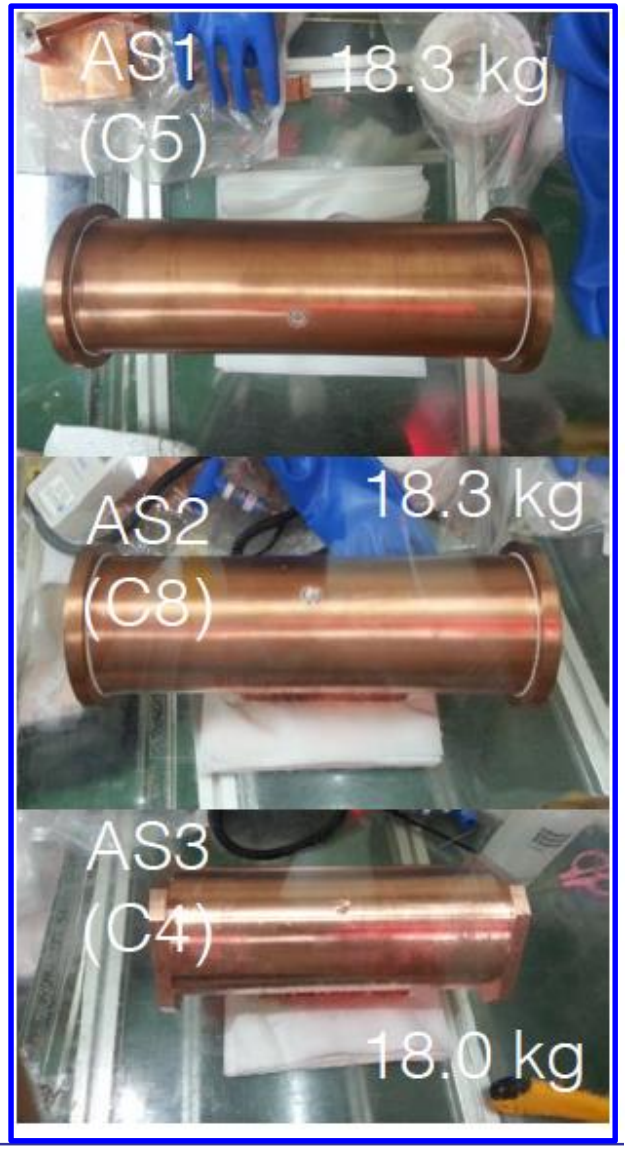
KIMS (Dark Matter Search)

AMoRE (Double Beta Decay Experiment)

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

COSINE-100 detectors

- ~106 kg crystals running since Sept/2016



COSINE-100 crystals

Crystal	Mass (kg)	Powder	Alpha rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light yield (p.e./keV)
Crystal 1	8.3	AS-B	3.20 ± 0.08	43.4 ± 13.7	< 0.02	1.31 ± 0.35	14.88 ± 1.49
Crystal 2	9.2	AS-C	2.06 ± 0.06	82.7 ± 12.7	< 0.12	< 0.63	14.61 ± 1.45
Crystal 3	9.2	AS-WSII	0.76 ± 0.02	41.1 ± 6.8	< 0.04	0.44 ± 0.19	15.50 ± 1.64
Crystal 4	18.0	AS-WSII	0.74 ± 0.02	39.5 ± 8.3		< 0.3	14.86 ± 1.50
Crystal 5	18.0	AS-C	2.06 ± 0.05	86.8 ± 10.8		2.35 ± 0.31	7.33 ± 0.70
Crystal 6	12.5	AS-WSIII	1.52 ± 0.04	12.2 ± 4.5	< 0.018	0.56 ± 0.19	14.56 ± 1.45
Crystal 7	12.5	AS-WSIII	1.54 ± 0.04	18.8 ± 5.3		< 0.6	13.97 ± 1.41
Crystal 8	18.3	AS-C	2.05 ± 0.05	56.15 ± 8.1		< 1.4	3.50 ± 0.33
DAMA			< 0.5	< 20	0.7 - 10	0.5 – 7.5	5.5 – 7.5

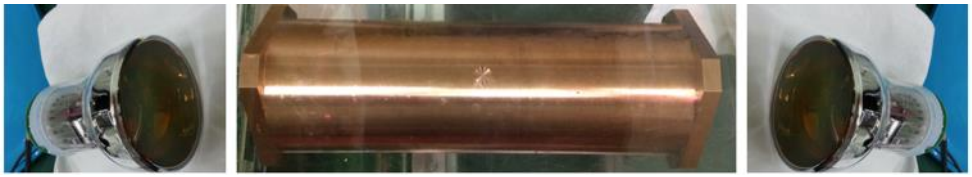
AS: Alpha Spectra (company)

WS: WIMPScint (powder grade)

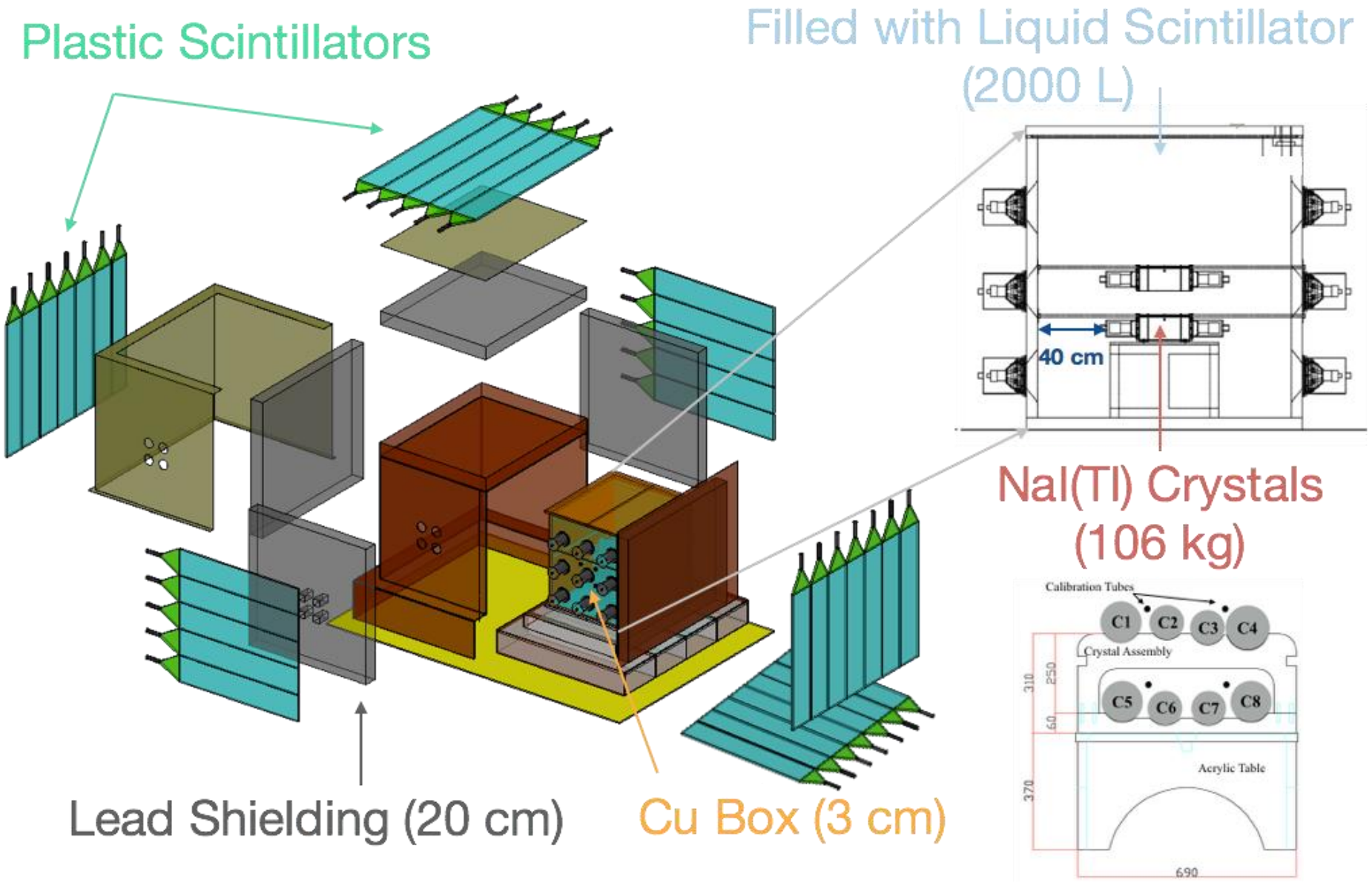
- Alpha rate corresponds to ^{210}Po (^{210}Pb)
- ^{210}Pb and ^{40}K levels are higher than DAMA/LIBRA

- **Hamamatsu R12669 PMTs**

quantum efficiency: 35% @ 420 nm

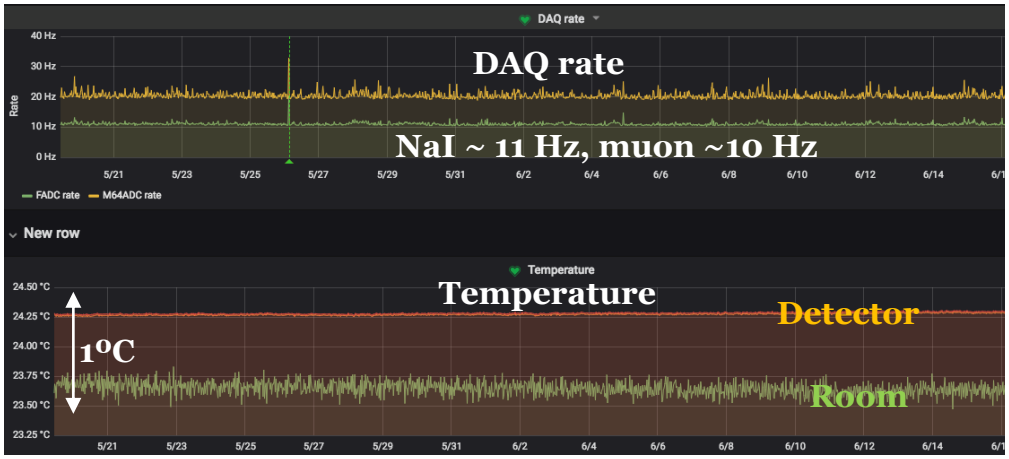


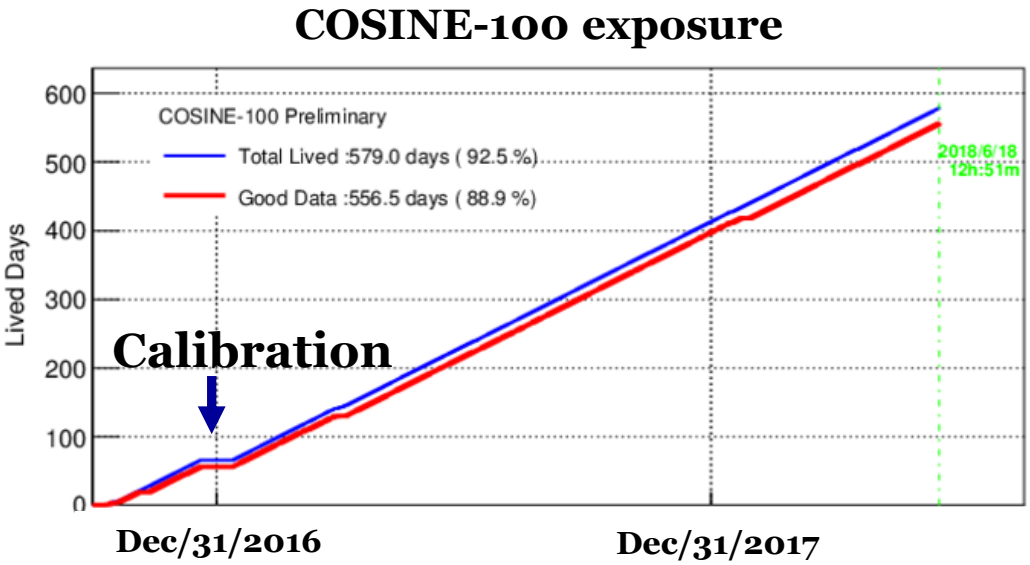
Shield for COSINE-100 Experiment




COSINE-100 detectors
Physics run started since Sept/2016
Eur. Phys. J. C 78 (2018) 107

COSINE-100 operation

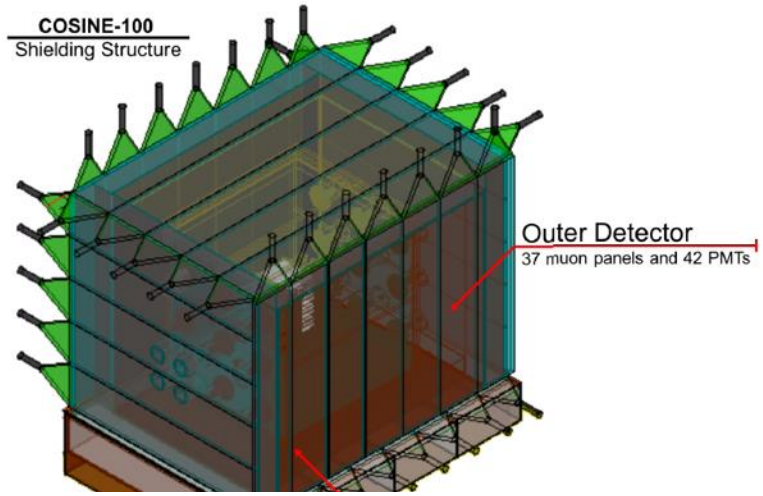


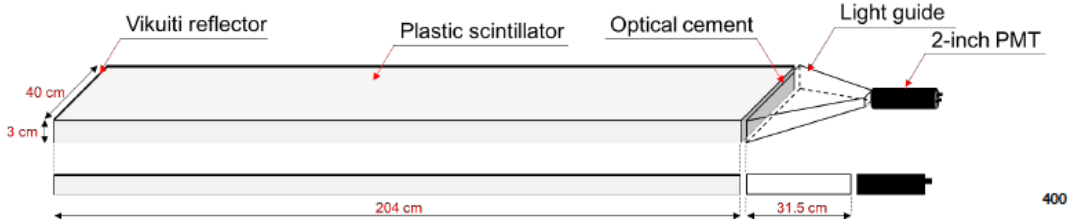


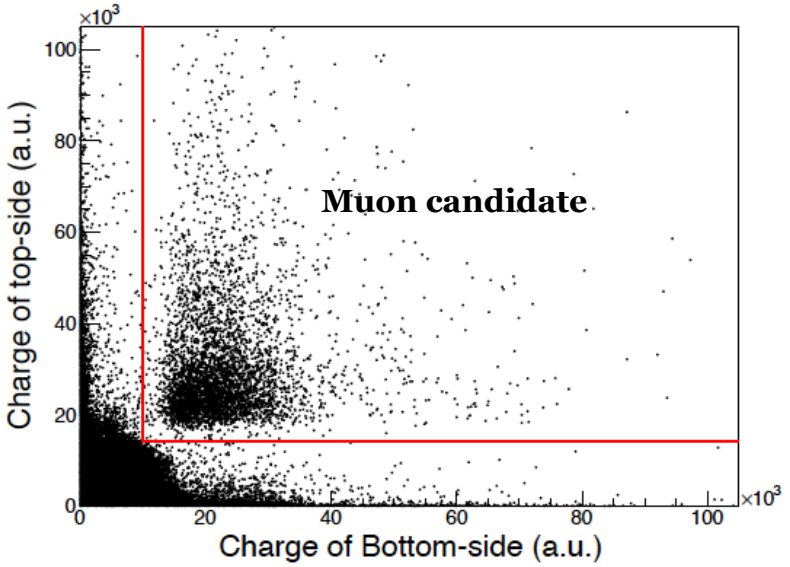
- Stable physics run
  - More than 90% live time!! Most of data are marked as good quality data
- About 21 month data taking
  - SET1 data (59.5 days) – Background modeling, detector understanding
  - SET2 data (406 days) – Annual modulation analysis

Muon detector

- Outer muon veto consists of 37 plastic scintillator panels





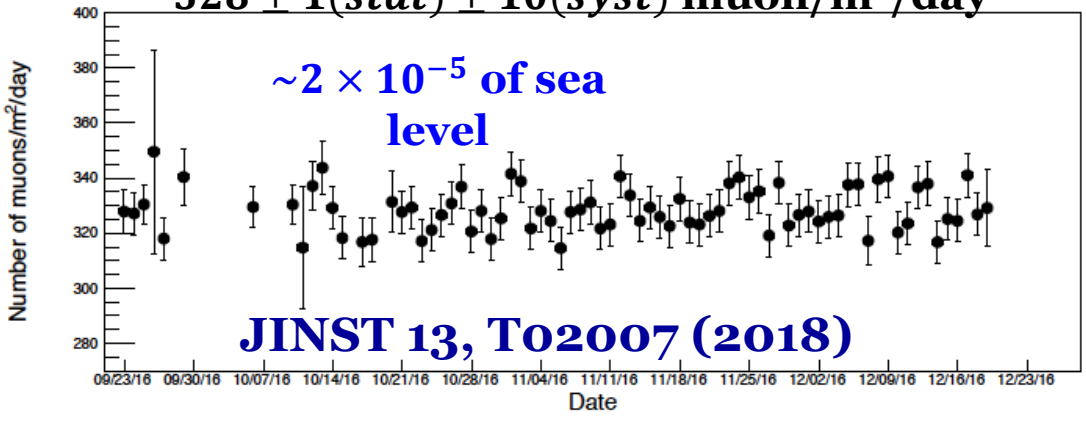


Muon flux has been monitored stably

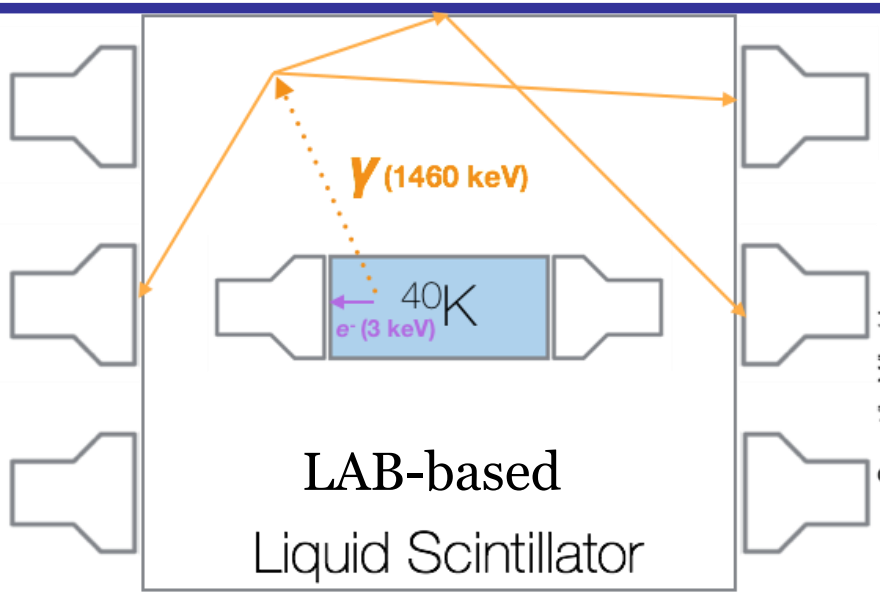
Vetoing of muon correlated events in NaI(Tl) crystals was implemented

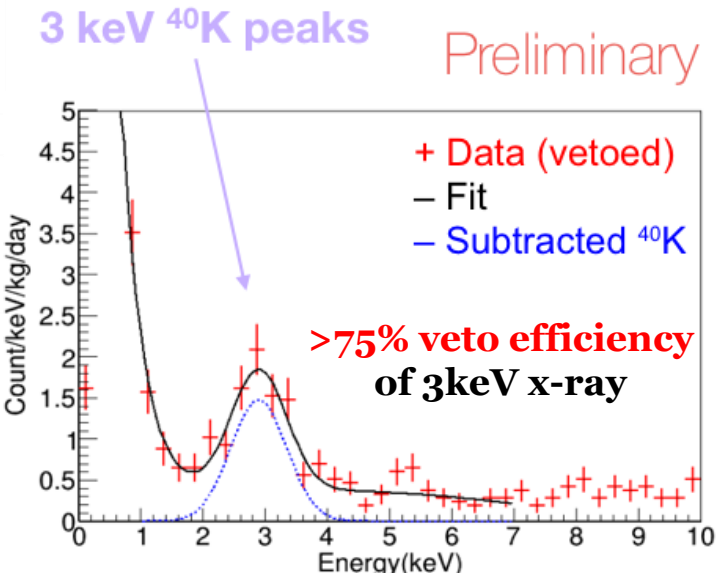
Study on muon induced events with NaI(Tl) and liquid scintillator is ongoing

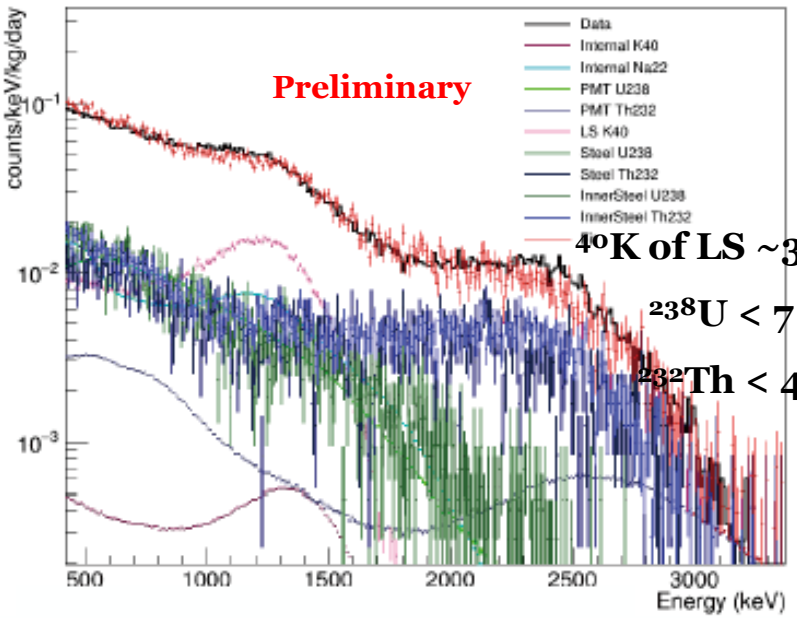
$328 + 1(stat) + 10(syst)$ muon/m²/day



Liquid scintillator veto system

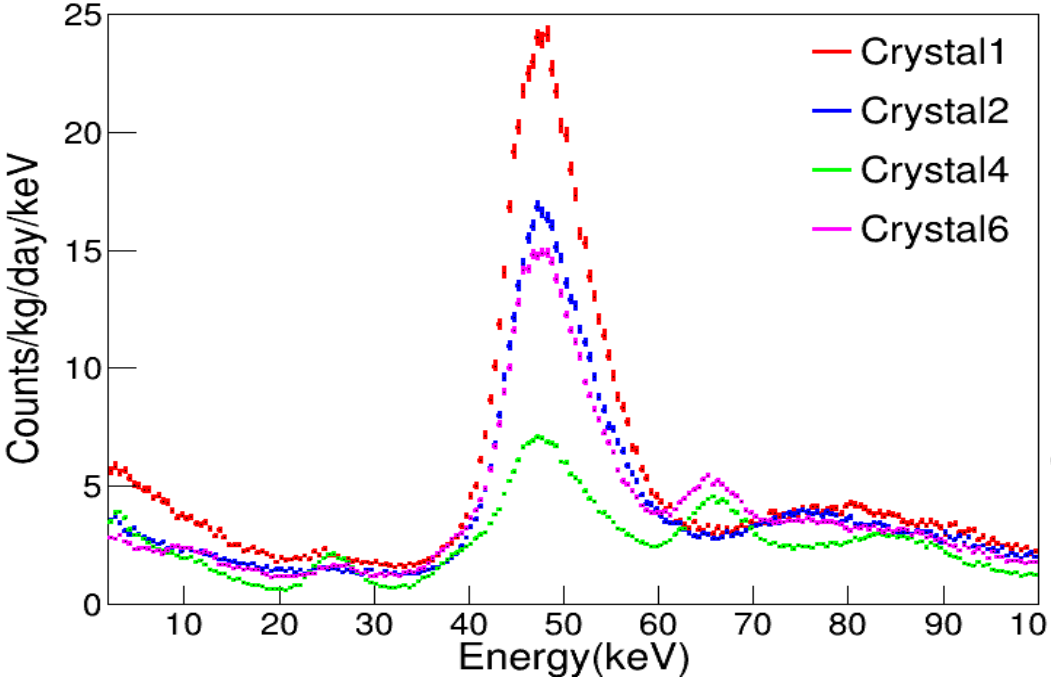


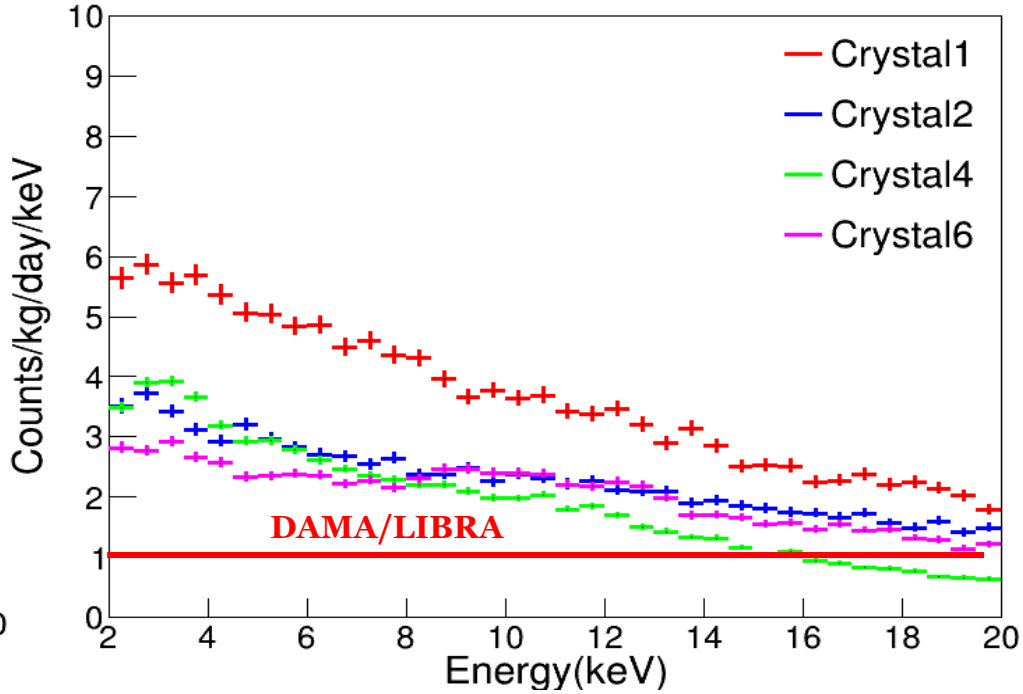




- Tagging rate of ^{40}K is well understood with Geant4-based simulation
- Internal background of LS is well understood and low enough
- 20 keV tagging threshold is achieved

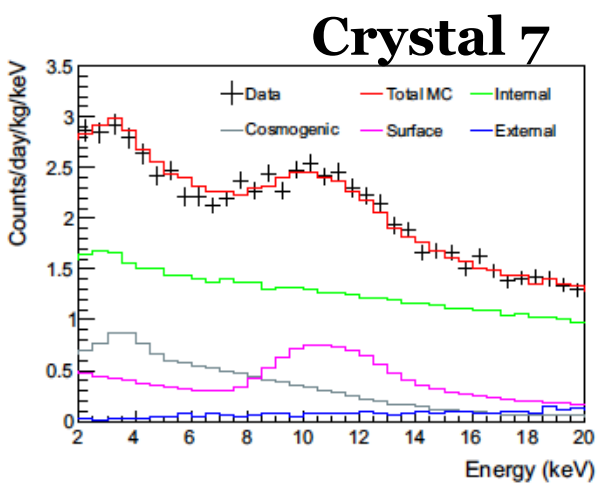
Crystal data (initial two month – SET1)

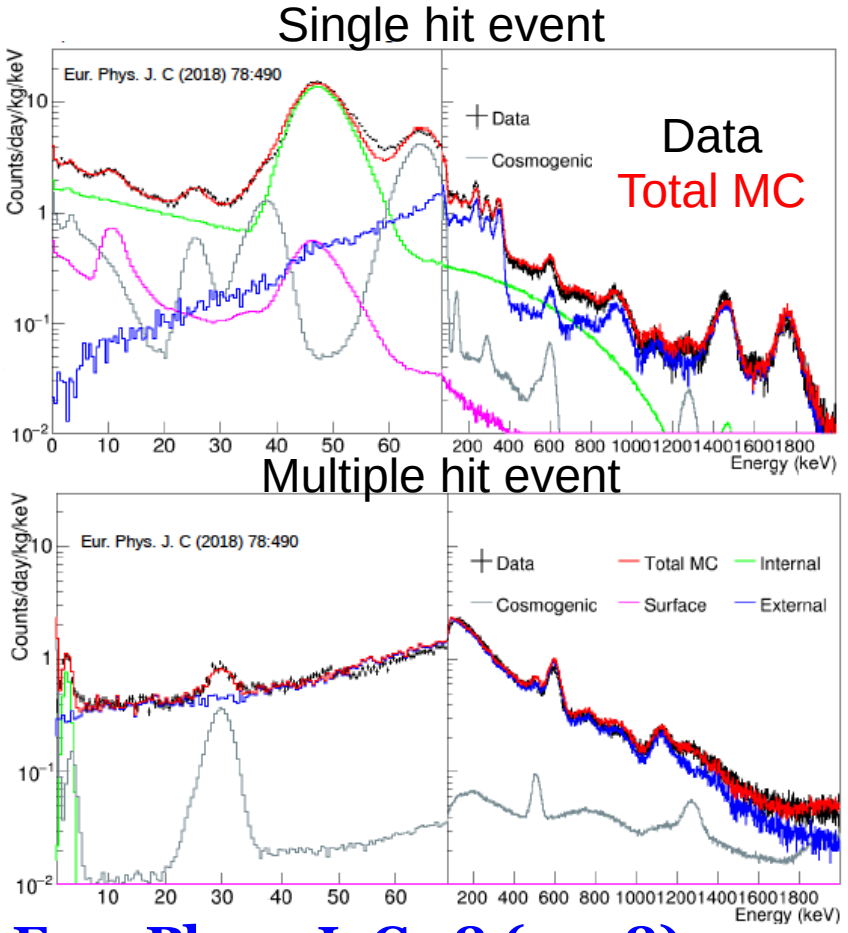




- **Background levels** from 2 to 4 dru (counts/kg/day/keV)
  - Higher than DAMA/LIBRA crystals
  - Efficiency corrected spectra

Background understanding



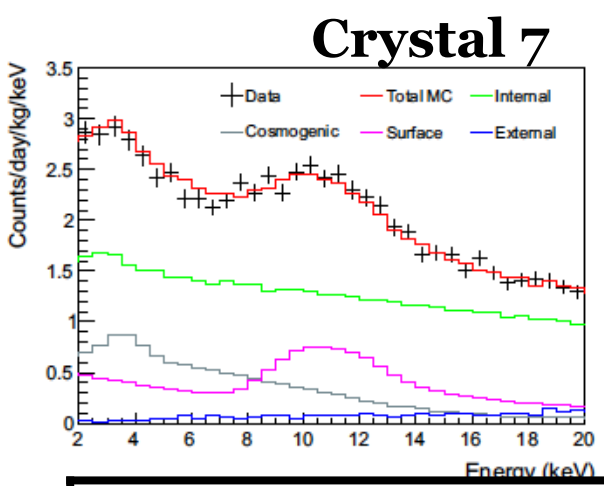


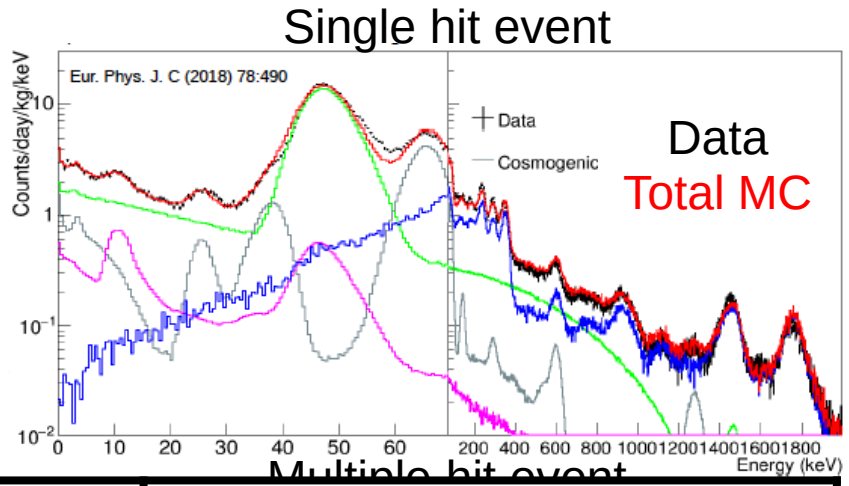
P. Adhikari *et al.*, Eur. Phys. J. C 78 (2018) 490

Good understanding of the backgrounds in NaI(Tl) crystals

Only use 6-2000 keV region for modeling

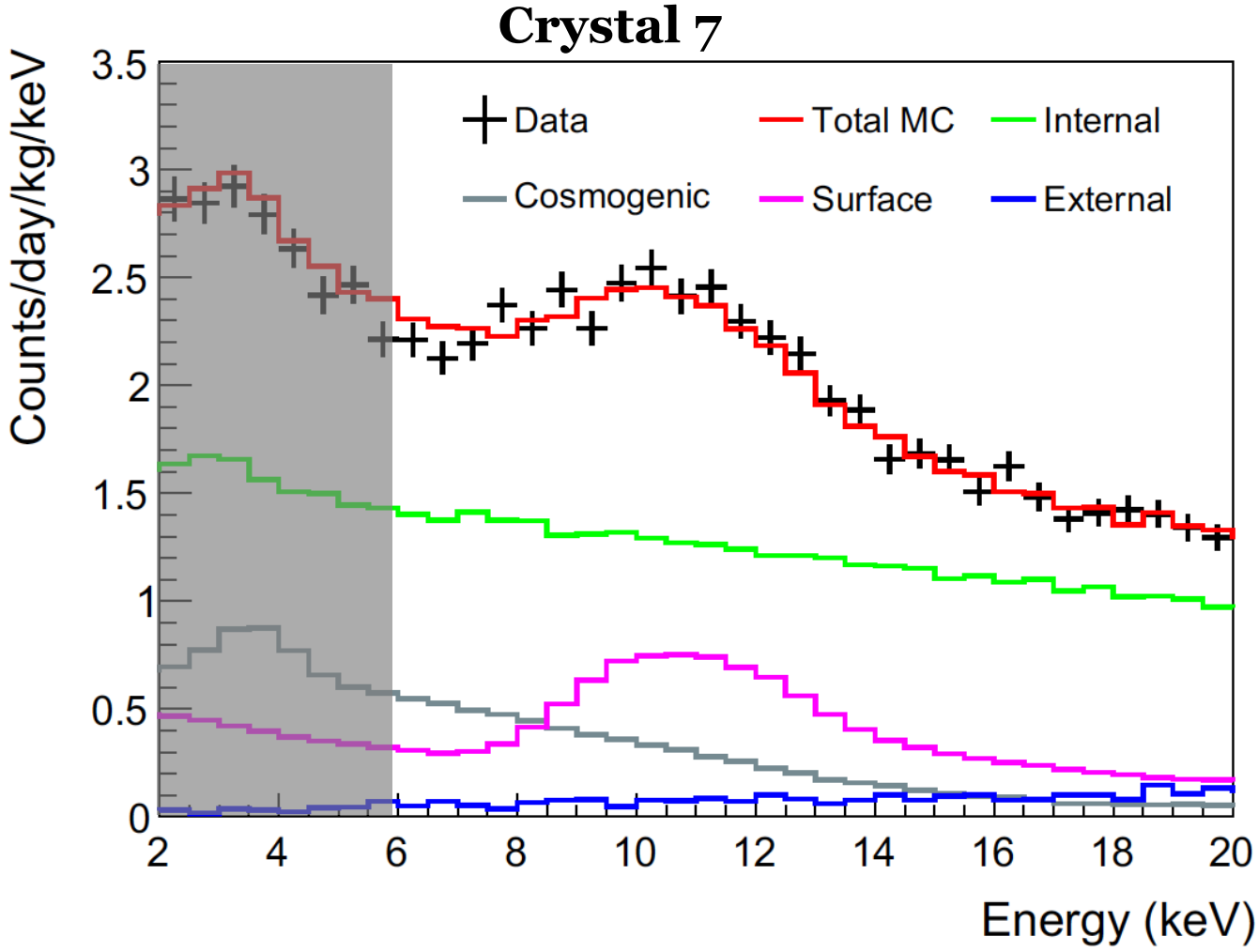
Background understanding





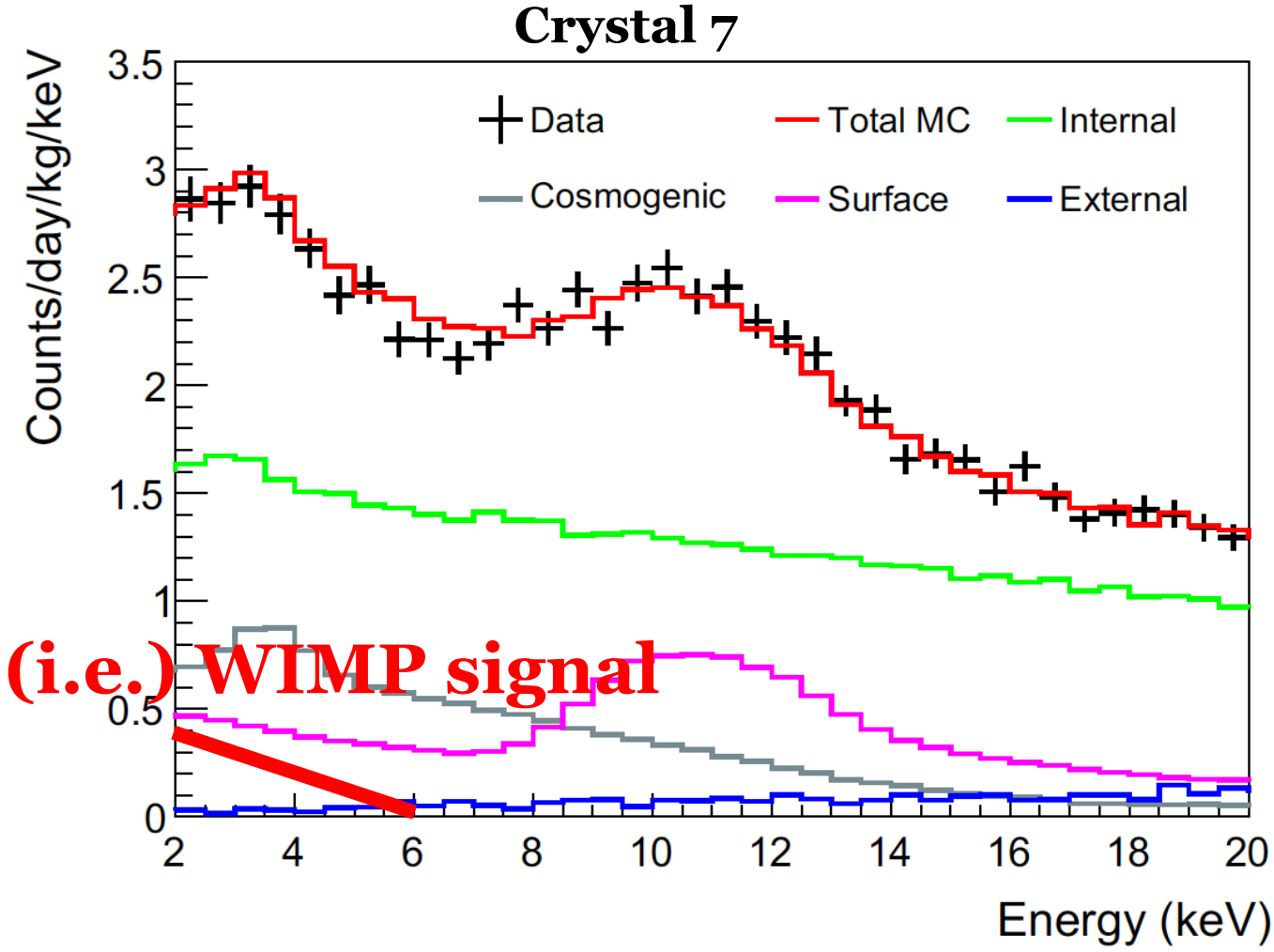
Componentç	Background 2-6 keV (dru)
Internal ^{210}Pb	1.50 +/- 0.07
Internal ^{40}K	0.05 +/- 0.01
Surface ^{210}Pb	0.38 +/- 0.21
^{3}H (Cosmogenic)	0.58 +/- 0.54
^{109}Cd (Cosmogenic)	0.09 +/- 0.09
Other cosmogenic	0.05 +/-0.03
External	0.03 +/- 0.02
Total expected	**2.70 +/- 0.59**
Data	**2.64 +/- 0.05**

Fit with WIMP signals



Background modeling was done only using events at 6- 2000keV

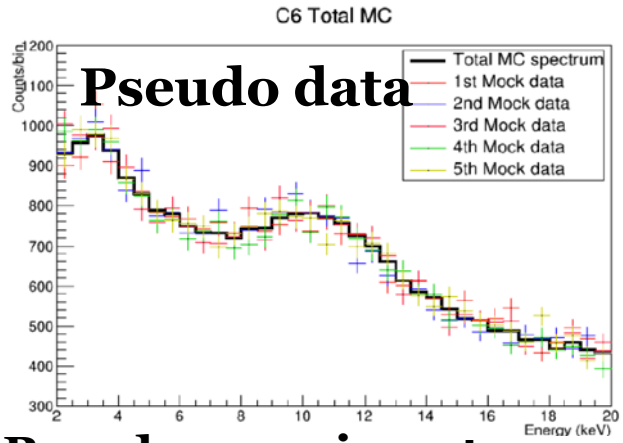
Fit with WIMP signals

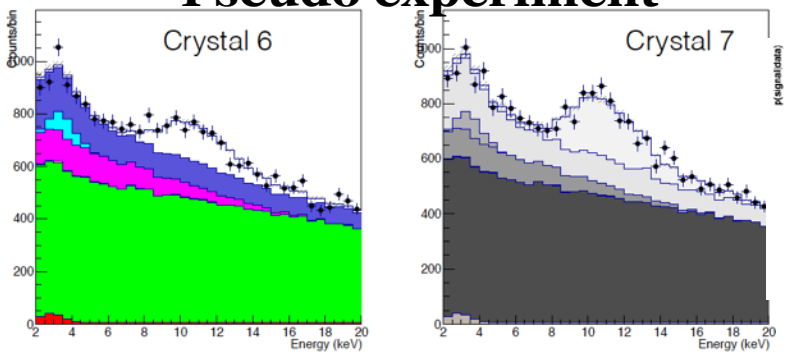


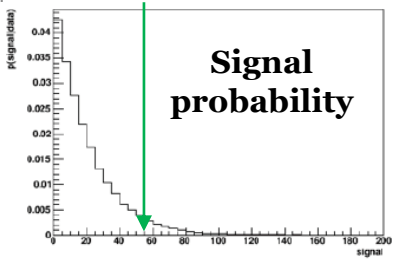
Background modeling was done only using events at 6- 2000keV

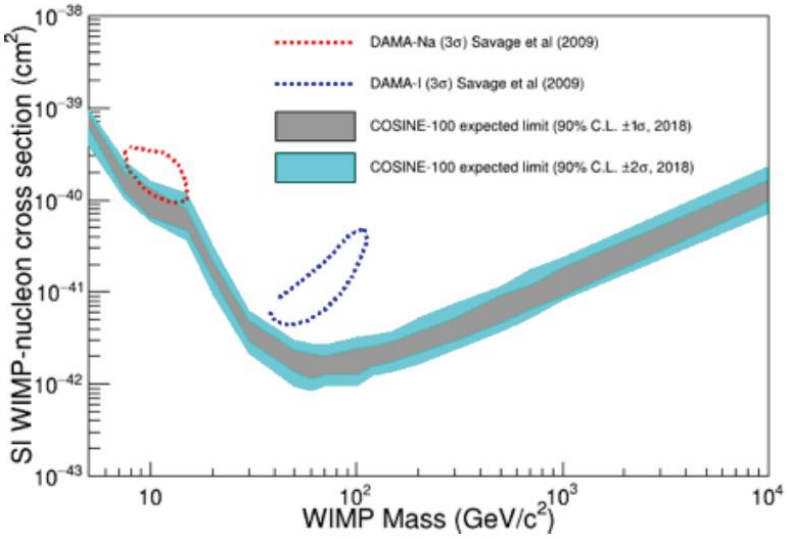
Mock data and pseudo experiments

- Generate mock data from MC modeling







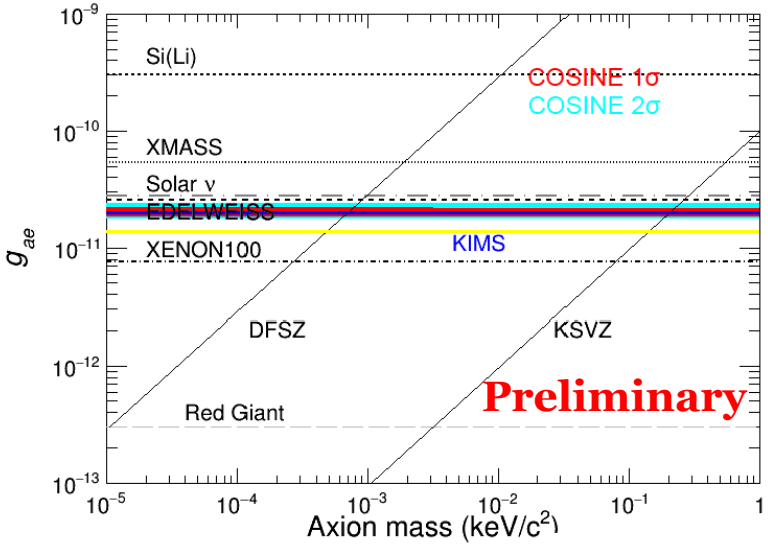


C5 & C8 are excluded due to low light output

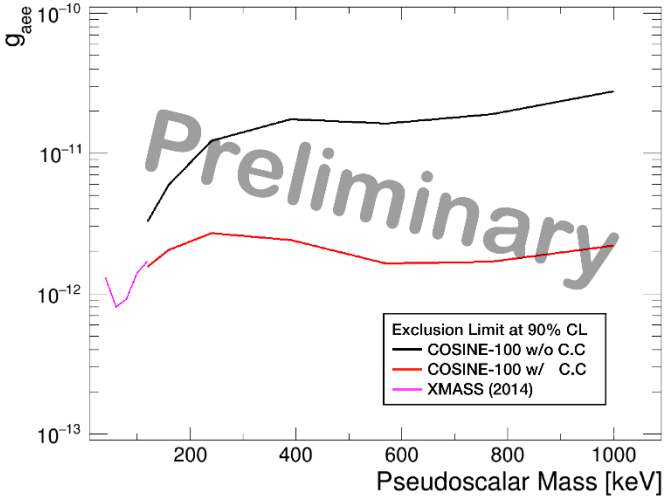
- Sensitivity estimation is done
- Data fit is almost ready

Another physics analysis (SET1 data)

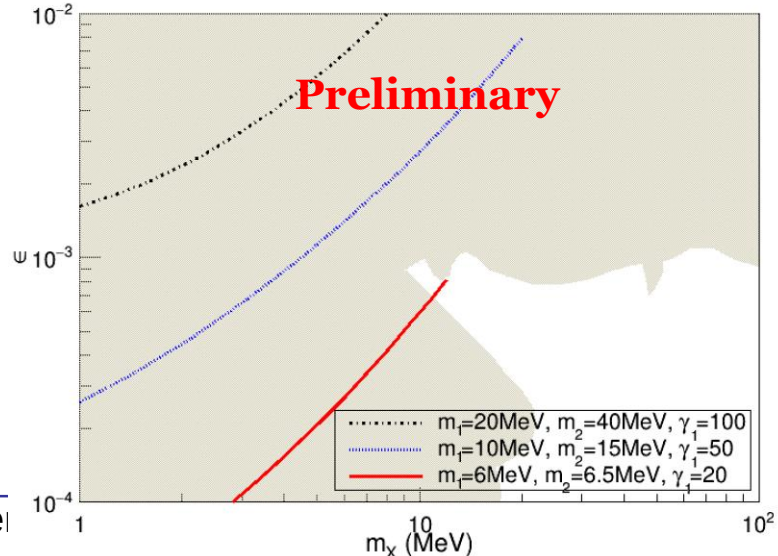
Solar axion



Bosonic Super WIMP

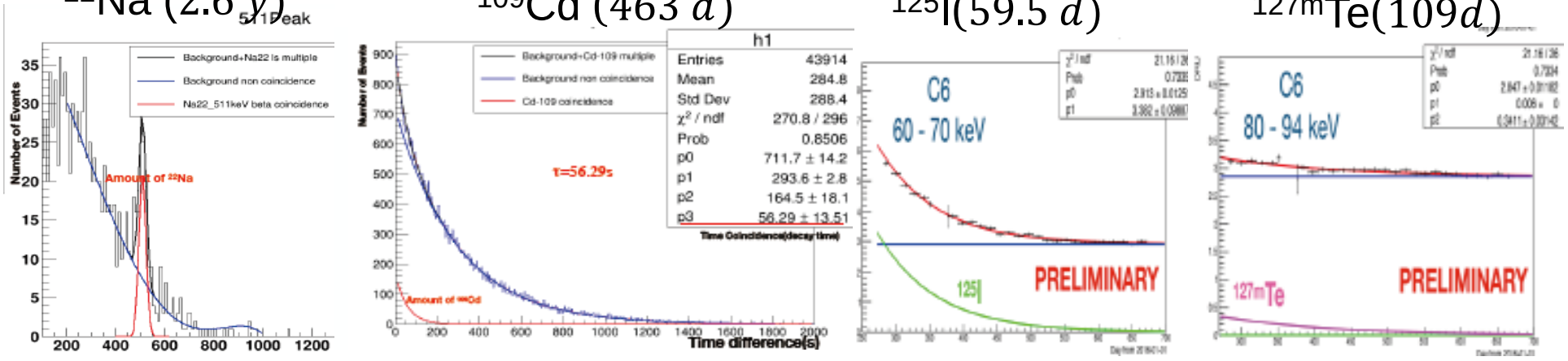


Boosted inelastic dark matter



Cosmogenic background

^{22}Na (2.6 y) ^{109}Cd (463 d) ^{125}I(59.5 d) ^{127m}Te(109d)



Cosmogenic isotope activities

mBq/kg

	C1	C2	C3	C4	C6	C7
^{22}Na	0.78±0.18	0.67±0.16	0.56±0.11	0.90±0.15	0.55±0.14	0.69±0.19
^{109}Cd	0.013±0.008	0.003±0.006	0.06±0.006	0.10±0.007	0.002±0.007	0.015±0.005
^{121m}Te	-	-	0.17±0.03	0.46±0.03	0.20±0.03	0.19±0.03
^{125m}Te	-	-	-	0.01±??	0.037±0.12	0.039±0.11
^{127m}Te	-	-	0.066±0.012	0.176±0.009	0.037±0.12	0.039±0.11
^{125}I	-	-	0.09±0.01	0.56±0.02	0.59±0.02	0.62±0.02

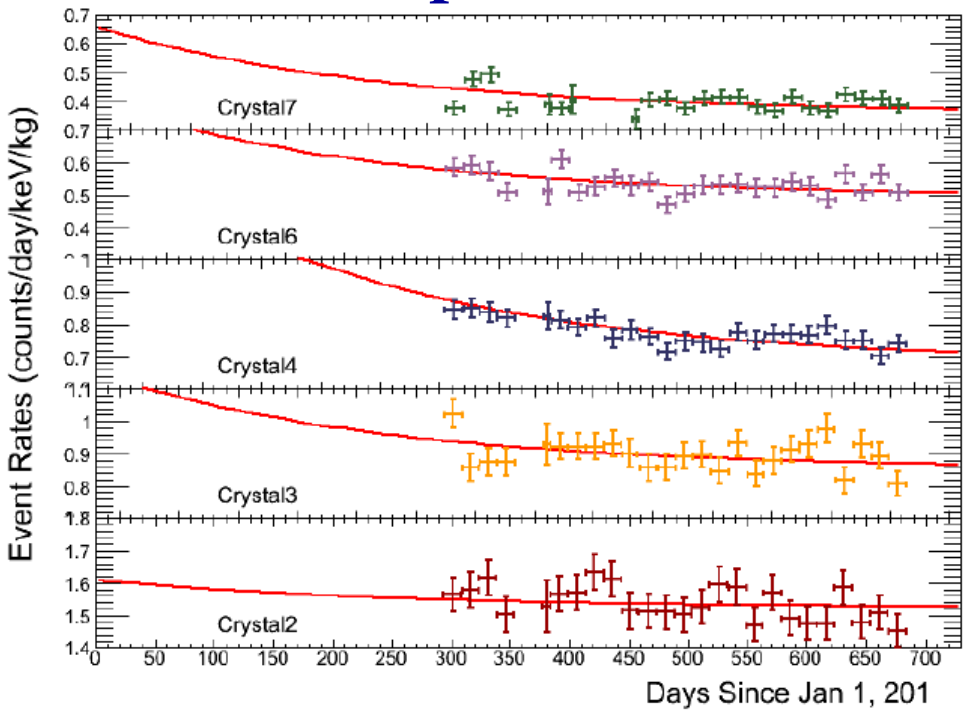
and

^{3}H (12.3 y)

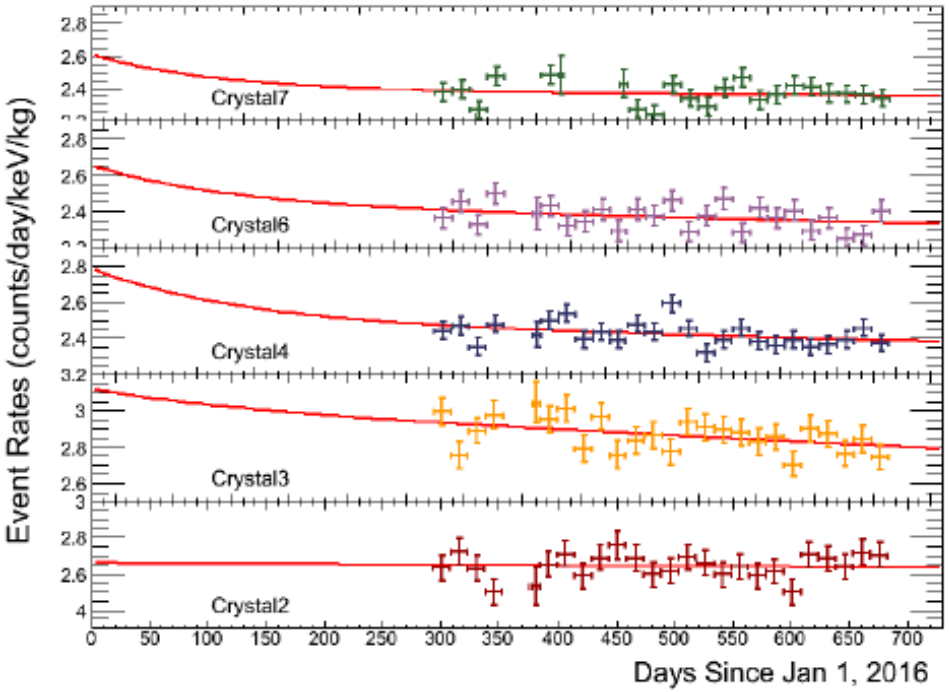
Side band study for modulation (SET2 data)

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

Multiple 2-6 keV



Single 6-10 keV



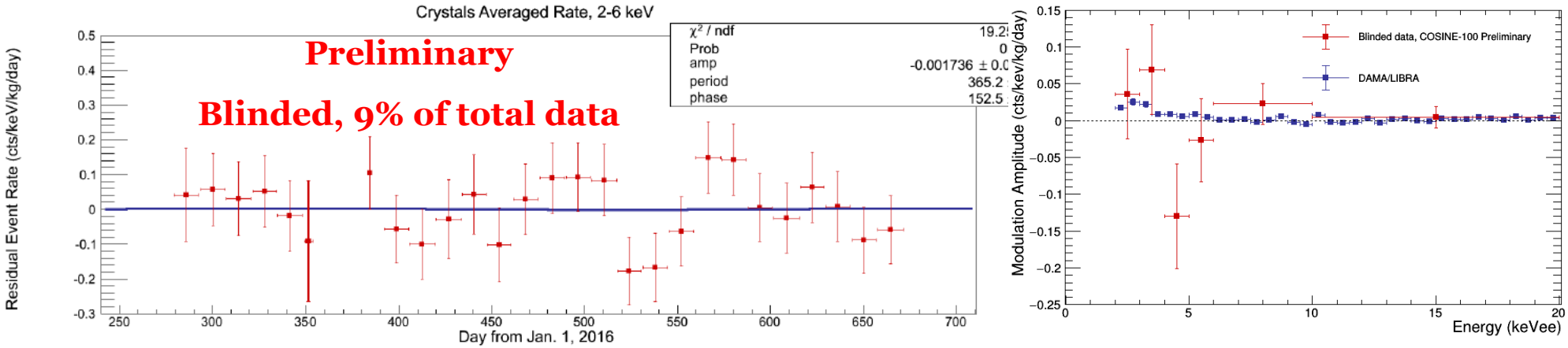
C5 & C8 were excluded due to low light output

C1 was excluded due to uncontrolled noise

- Side bands are well explained by known background

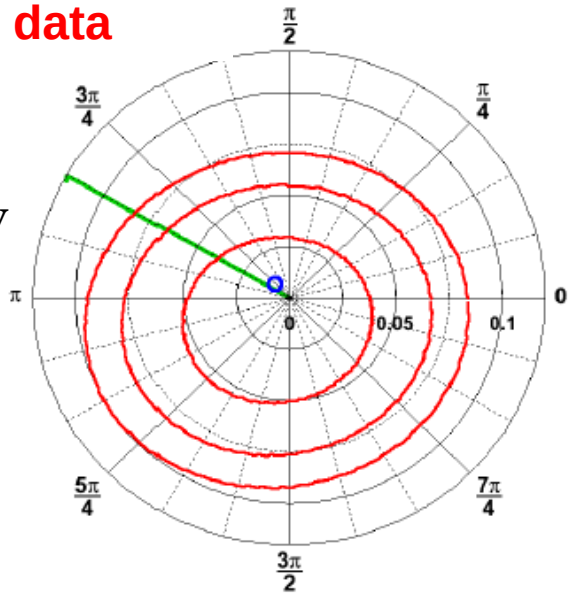
~ 9% data opened (blinded analysis)

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

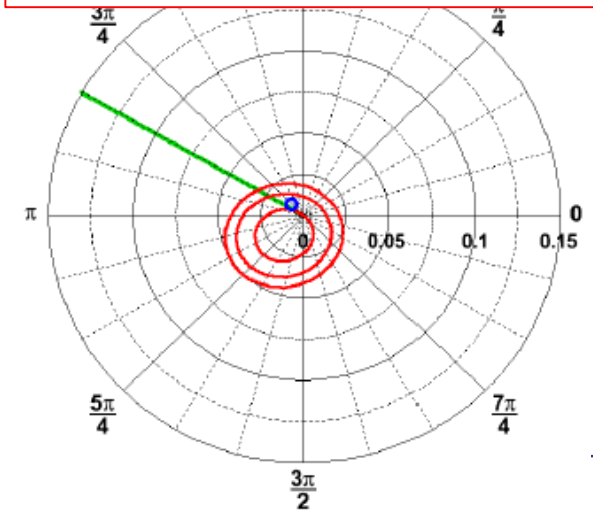


Data quality, cosmogenic component subtraction, and background modeling almost done

9% data

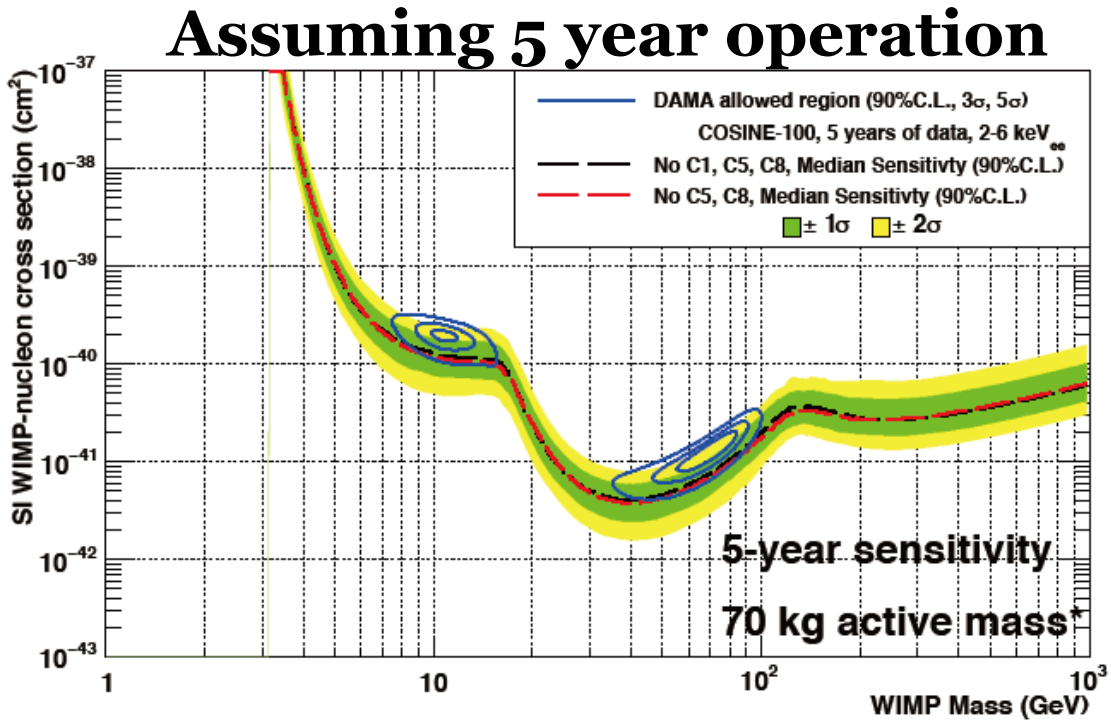


Assuming total SET2 data (error reduction only)



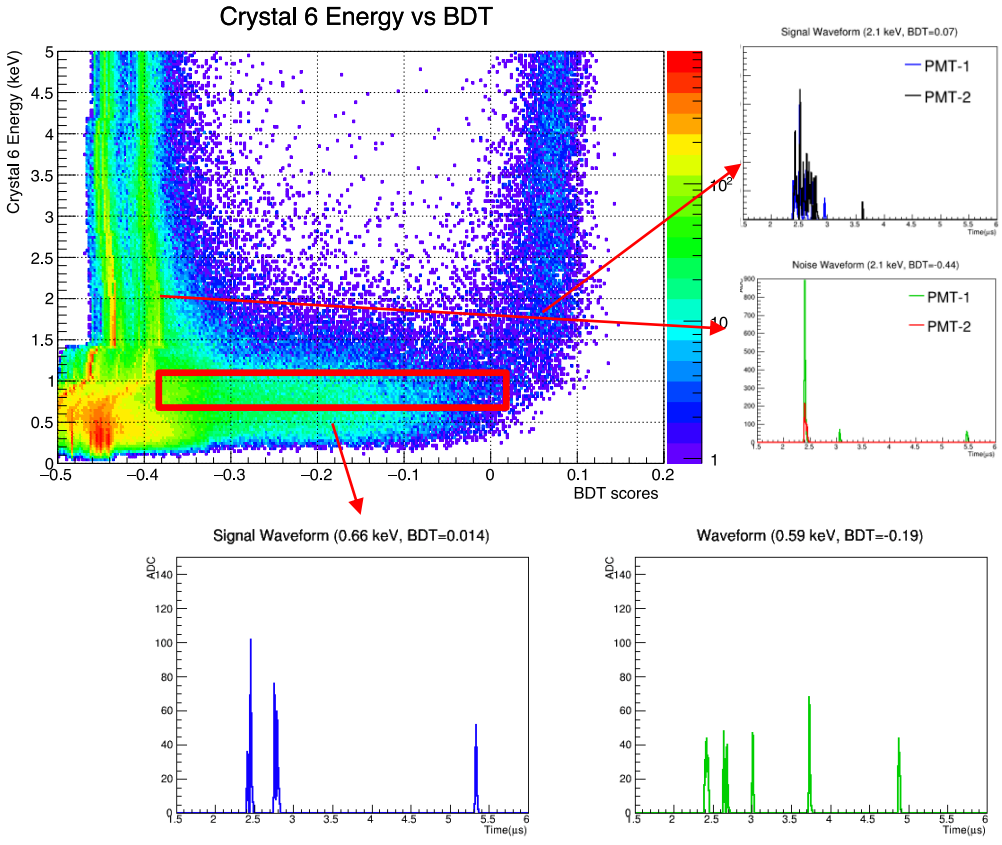
Under evaluating systematic uncertainty

COSINE-100 Expected Sensitivity



- C5 & C8 are excluded due to low light output
- Combining data between COSINE-100 & ANAIS-112 are agreed between two groups

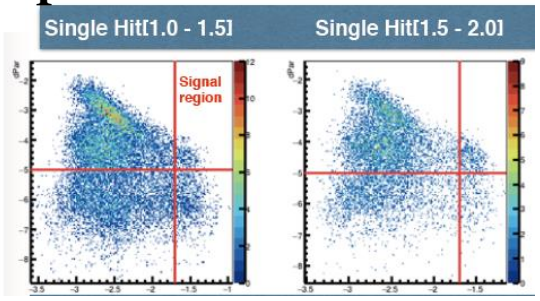
Analysis with 1 keV energy threshold



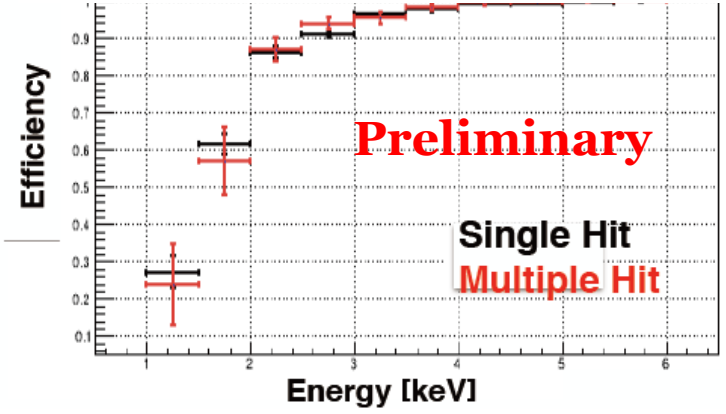
Understand signal-like events and noise-like events at low energy

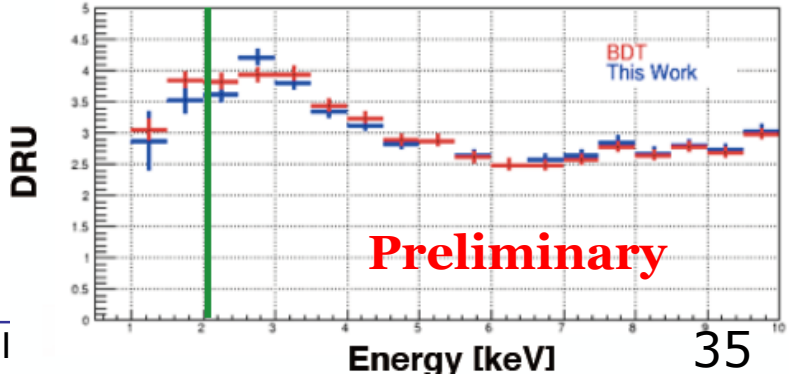
Develop new parameter to reject noise-like events effectively

New parameters for noise rejection



Efficiency

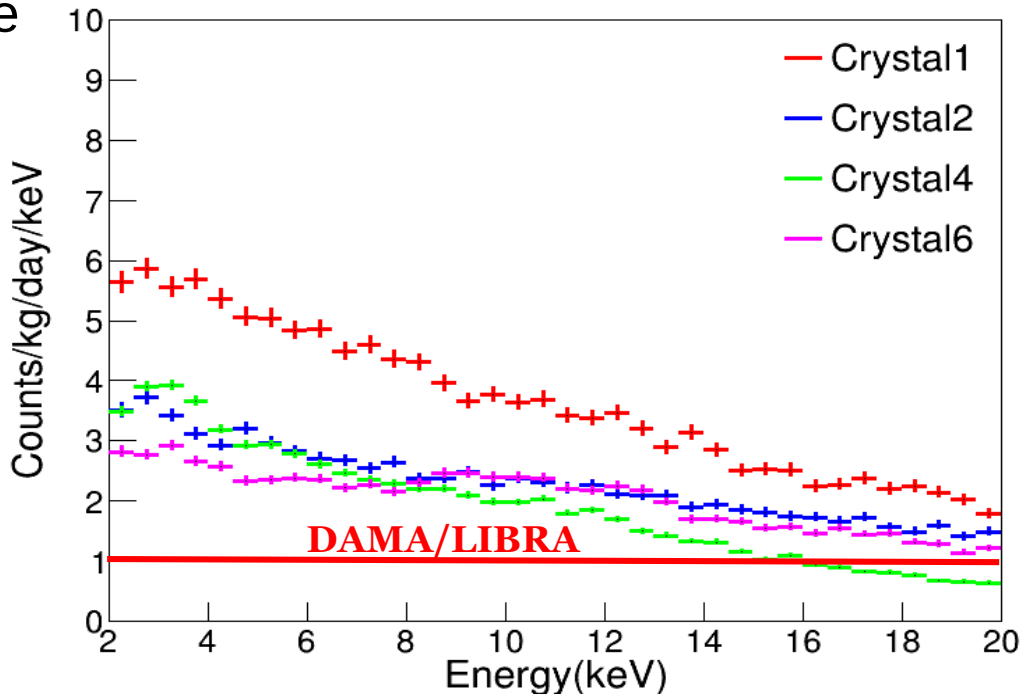




Next phase of COSINE (COSINE-200)

- **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



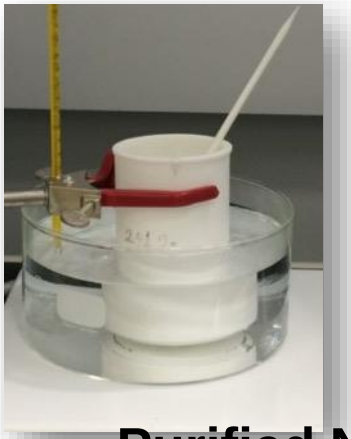
- **Extremely pure crystal** development
  - From initial materials to detector assembly, we need **very careful handling**
  - These are very **difficult jobs** for a private **company**
  - We decided to do our own development for the entire process

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

NaI powder purification (Lab experiment)

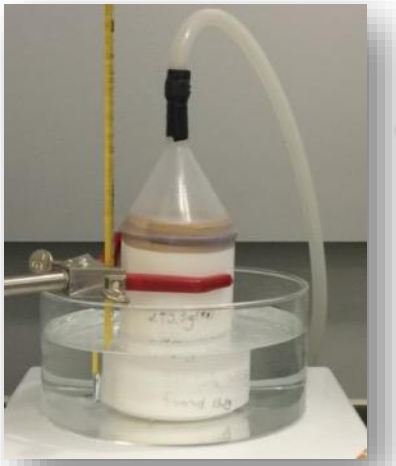
- Recrystallization

Saturated NaI solution @ 25 ° C



T↑ 110 ° C

Evaporation of 40 % of H_2O under vacuum



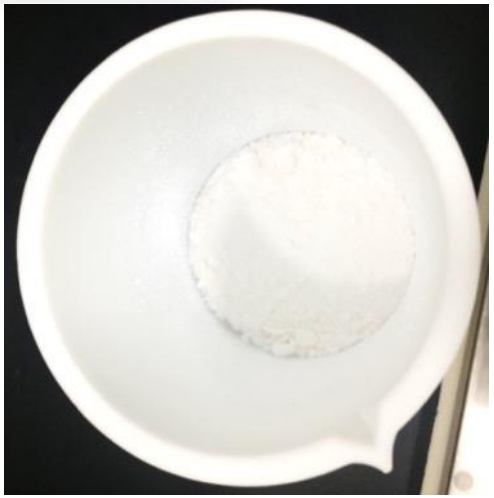
T↓ 25 ° C

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

Goal : K less than 20 ppb

1 ton of Crystal grade powder is ready to use

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

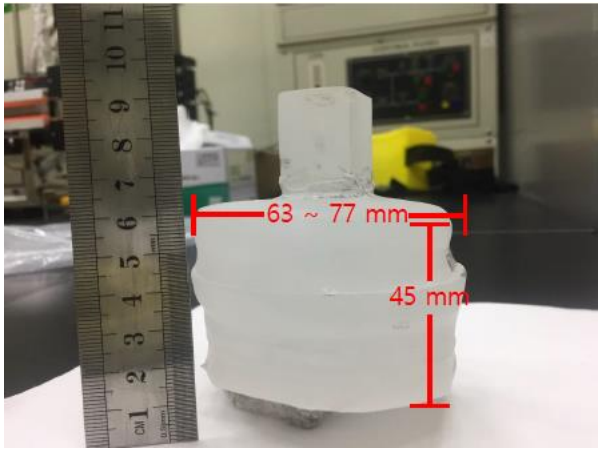
Our system is more effective than lab experiment

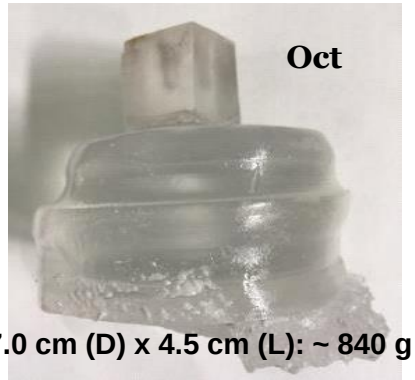
Crystal growing

- Small crystal grower was installed at 2017

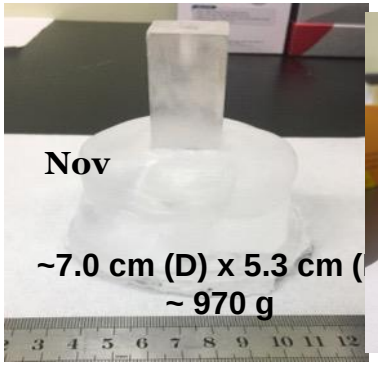
Crucible diameter is $\phi = 15$ cm; **1~2 kg** test crystal can be grown

Sept/2017 **Pure NaI**

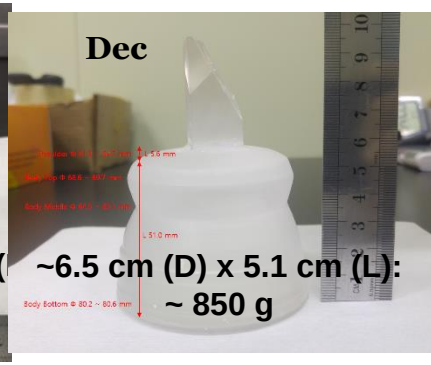




~ 7.0 cm (D) x 4.5 cm (L): ~ 840 g



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

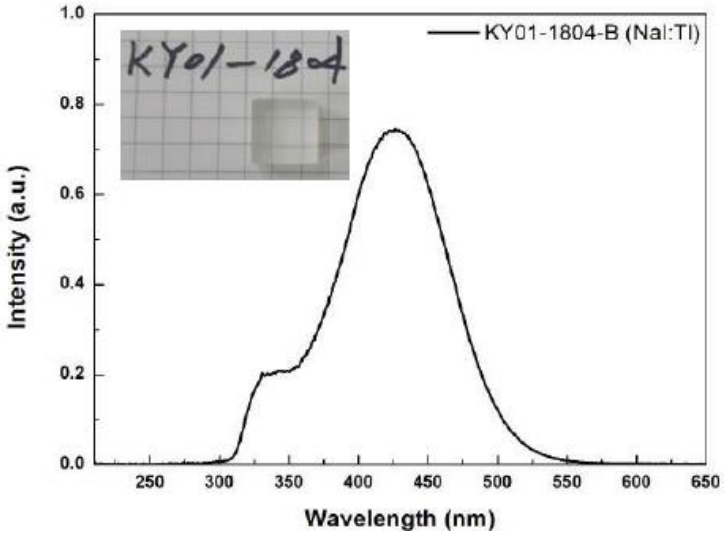


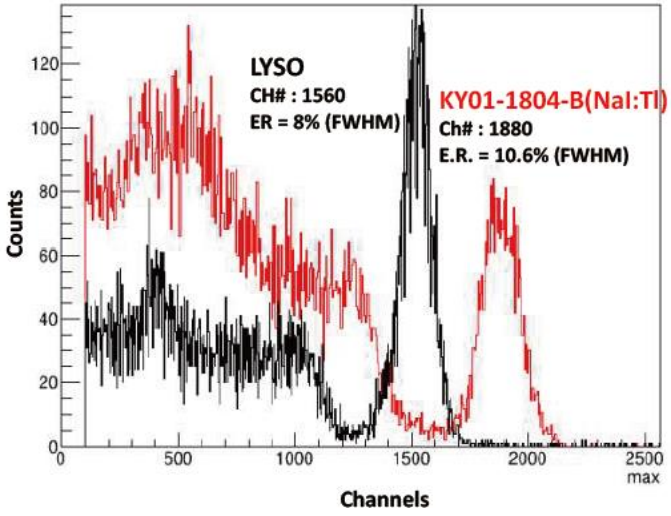
~6.5 cm (D) x 5.1 cm (L):
~ 850 g

Tl doped crystals

Feb/2018

Crystal grade

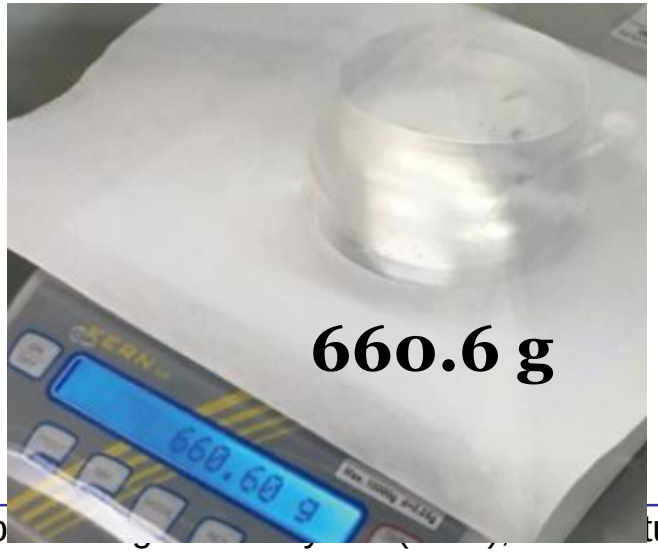


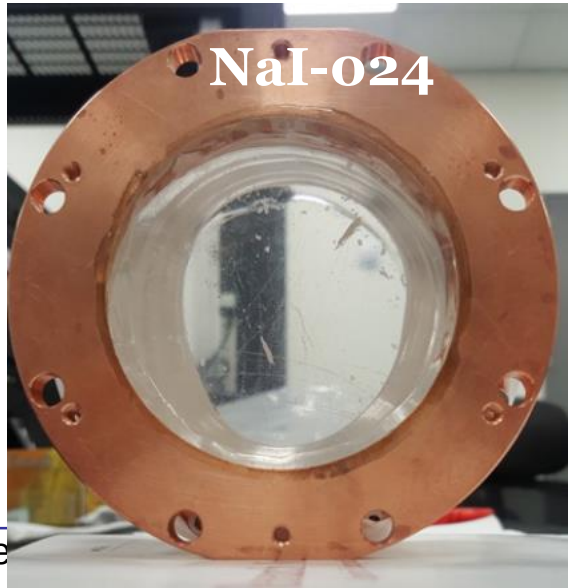


~40,000 Photons/MeV

May/2018

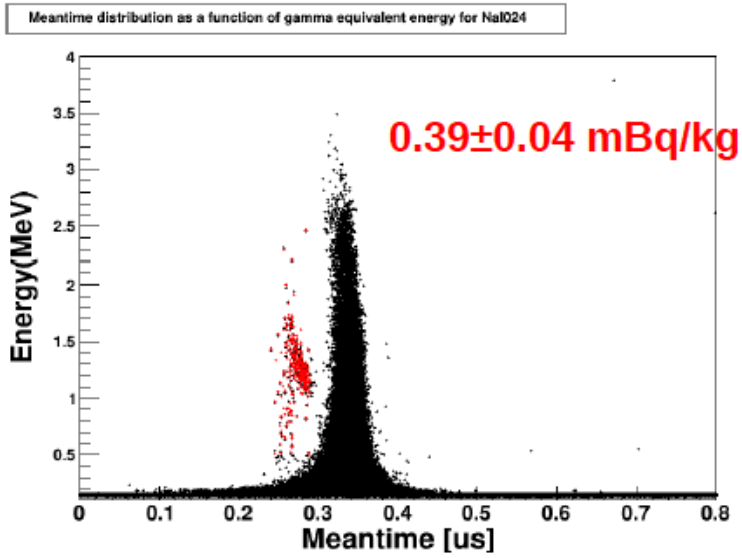
Astro grade

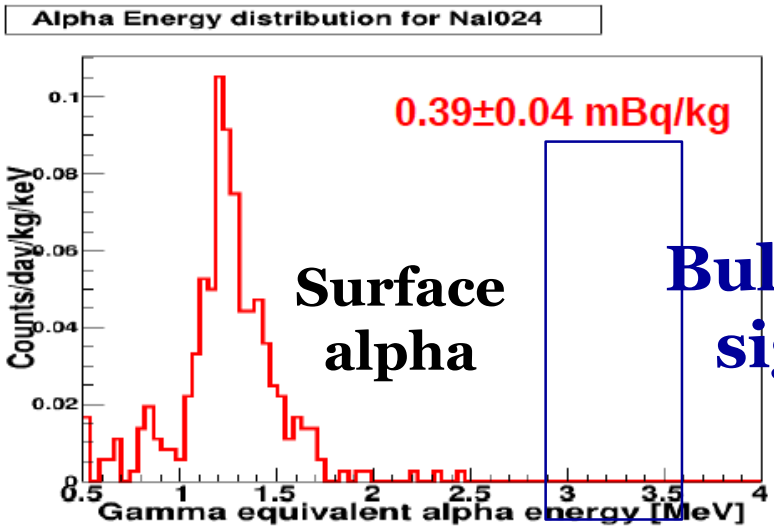




NaI-024 underground measurement

Measurement started from June 4th (2018)





- Light Yield ~ 6.5 photoelectrons/keV
- The lowest total alpha level from NaI crystals which we measured
- No bulk ^{210}Pb contamination (<0.005 mBq/kg)
- Surface contamination : failure of ^{222}Rn control for encapsulation
  - ❖ We will do the encapsulation process again
- 1 dru background is achievable!!

A full size grower

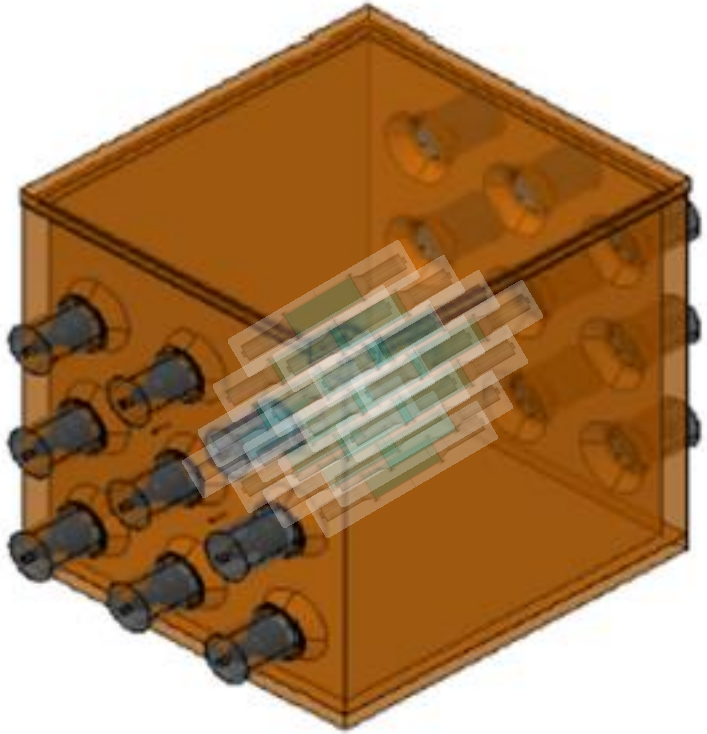
- Full size grower & annealing furnace were installed ($\phi = 60$ cm)
  - ❖ Similar growing machine as the DAMA/LIBRA crystals
  - ❖ Maximum powder loading :120 kg
    - ❑ About three full size detectors (12.5 kg) per ingot

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

COSINE-200

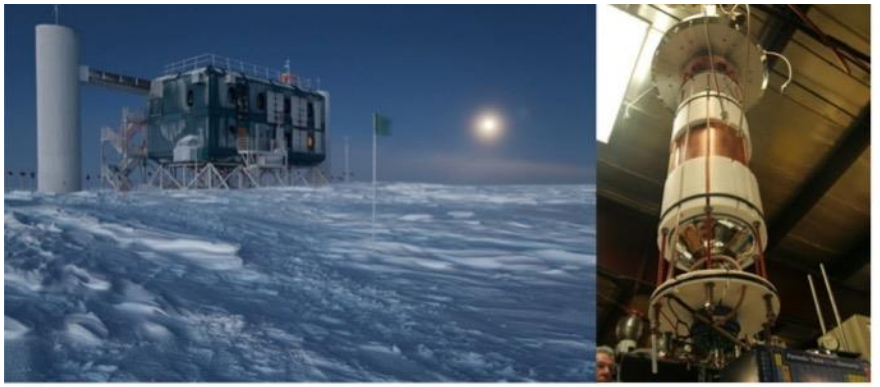
- Current COSINE-100 shield designed to accommodate 16 of 12.5 kg crystals = 200 kg

Total 200 kg



Y2L

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

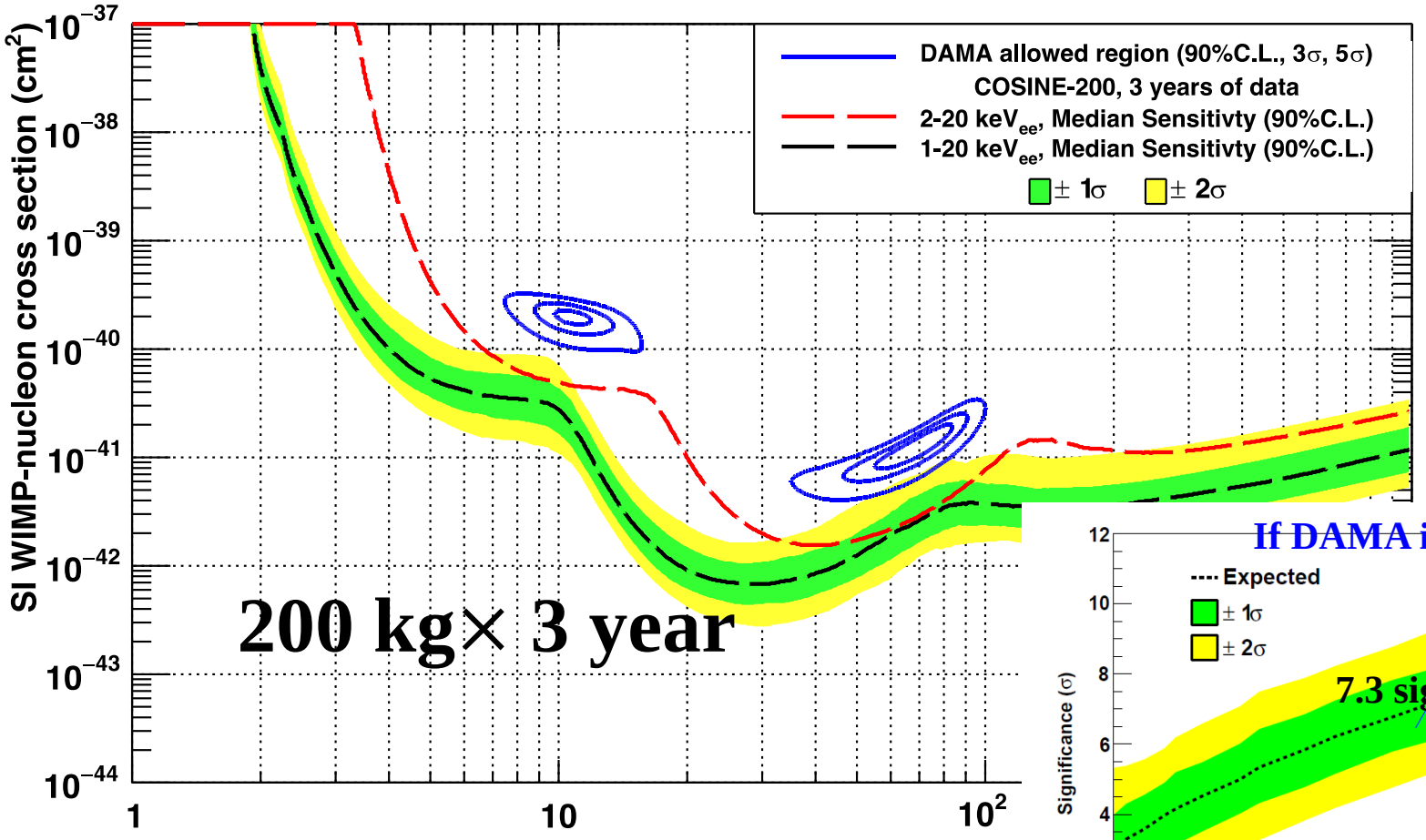


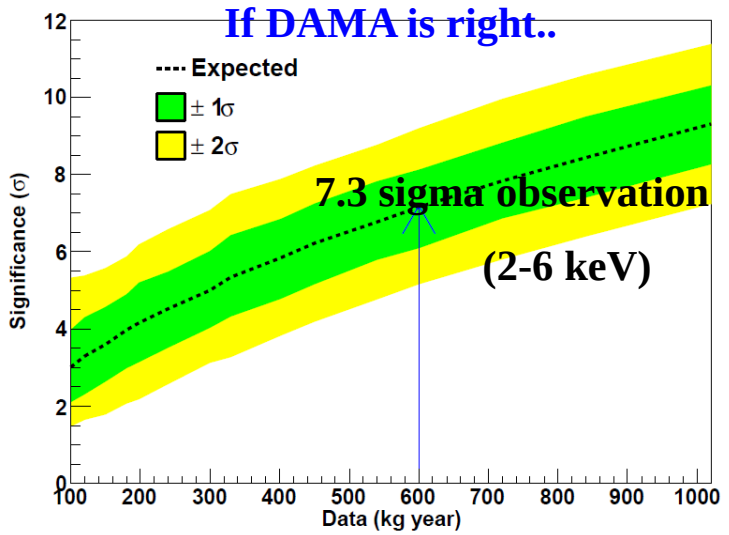
Under consideration

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 is running well
  - ❖ We understood our detector well
  - ❖ Physics analyses are ongoing
- 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