Dark matter search with NaI(Tl) crystals
COSINE-100 experiment

Hyun Su Lee

Center for Underground Physics (CUP)

Institute for Basic Science (IBS)

On behalf of the COSINE-100 Collaboration

Revealing the history of the universe with underground particle and nuclear research

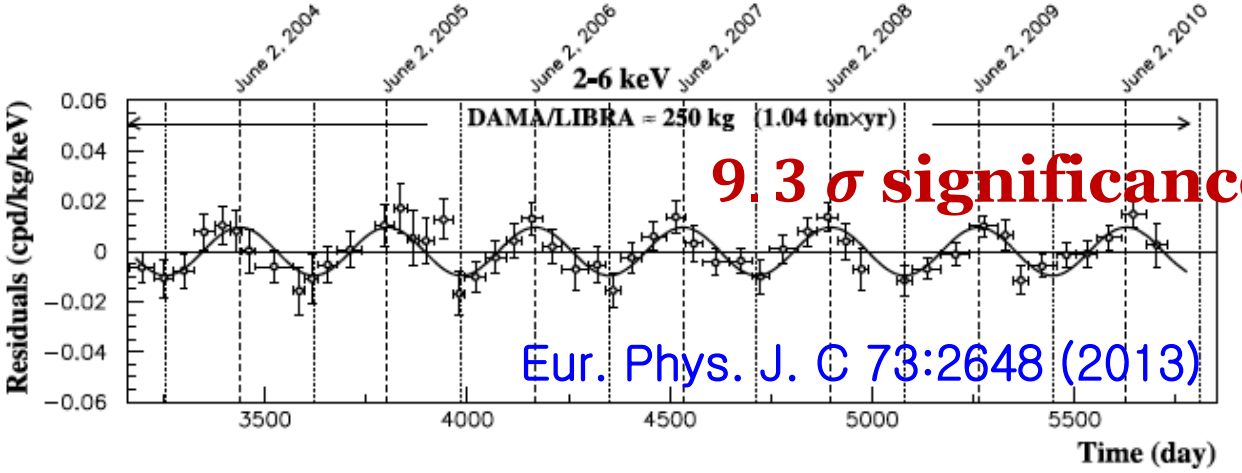
March 8, 2019

Motivation

DAMA/LIBRA experiment

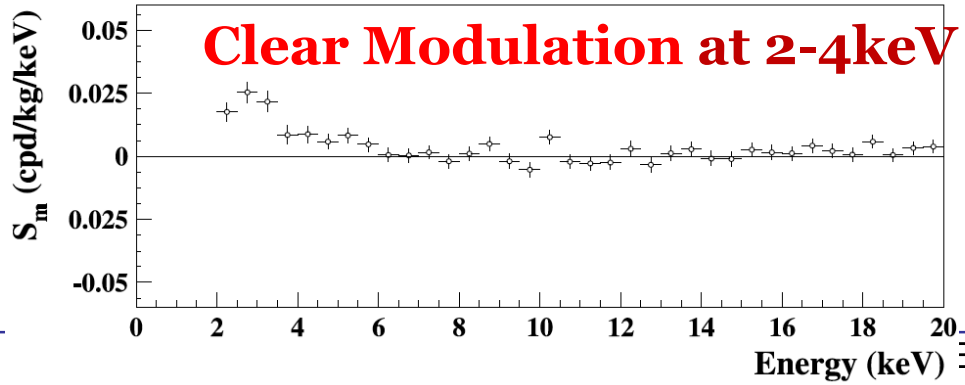
- Annual Modulation Searches with an array of NaI(Tl) crystals

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

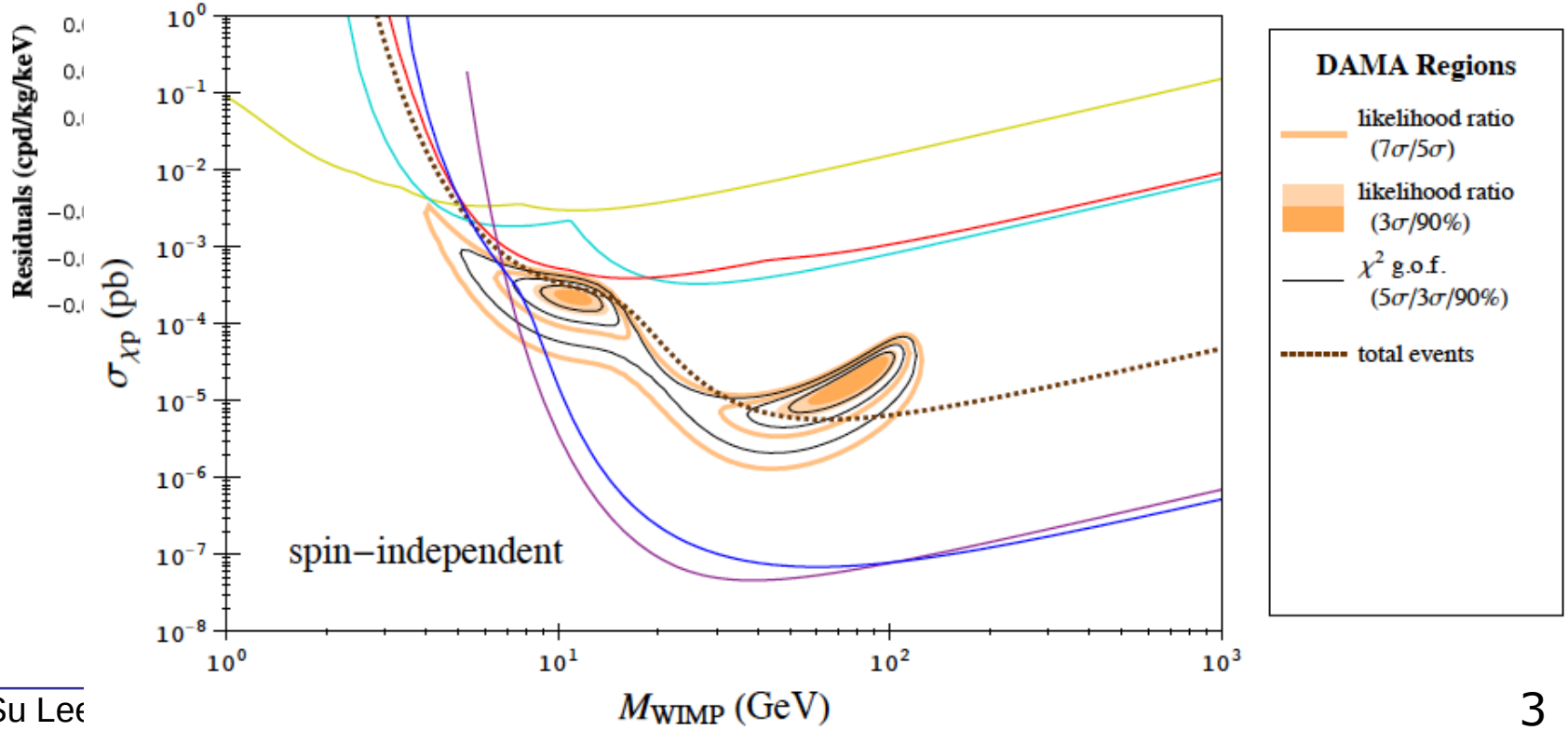
Motivation

DAMA/LIBRA experiment

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

Claimed an observation of the dark matter

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



Motivation

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

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

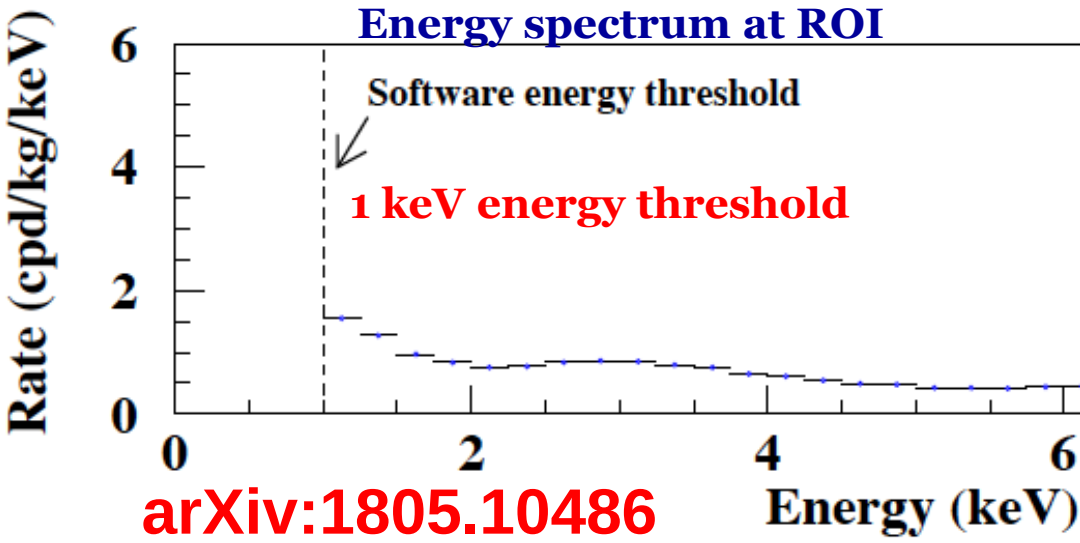
arXiv:1805.10486

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]

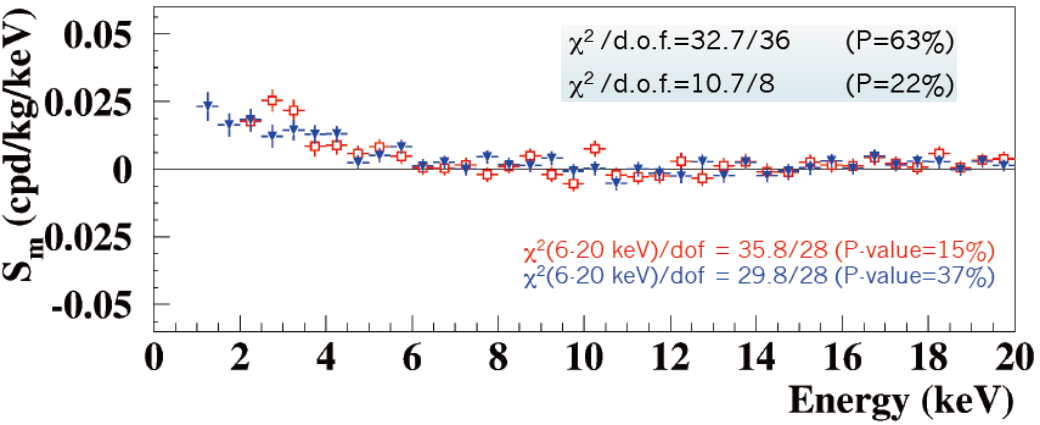
e 1

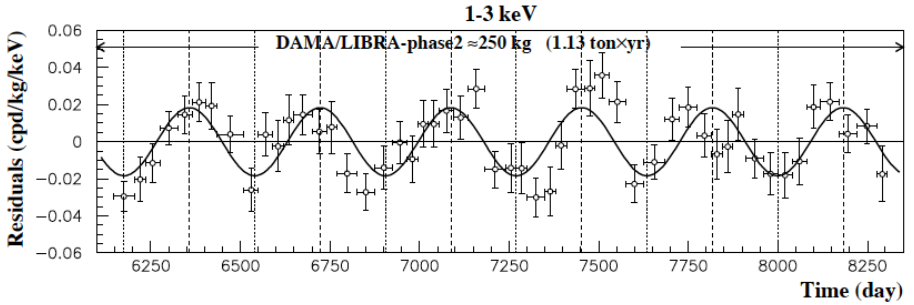
DAMA/LIBRA-phase2

- Energy threshold reached 1keV 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

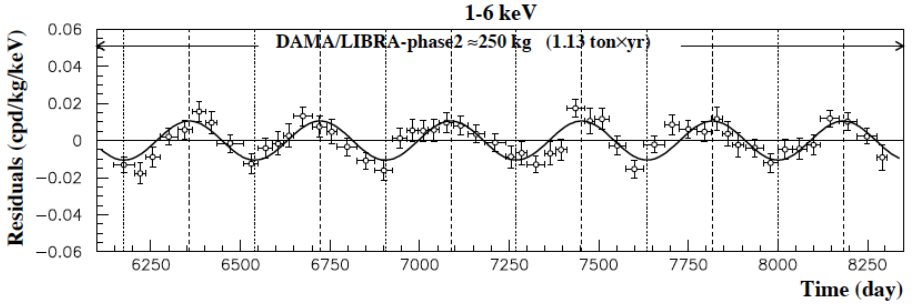


arXiv:1805.10486



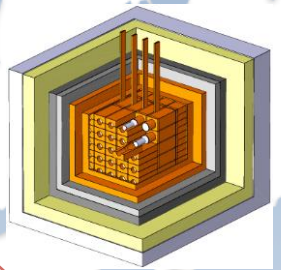


Modulation amplitude



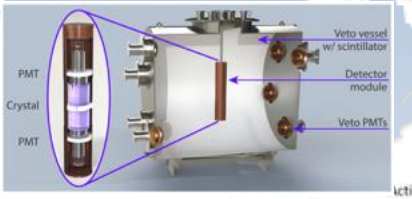
Global NaI(Tl) efforts

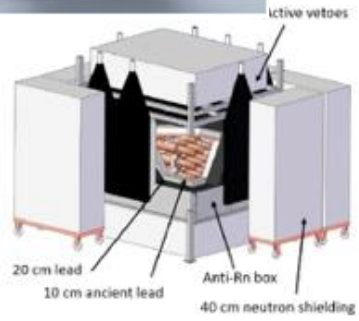
COSINUS
@ LNGS



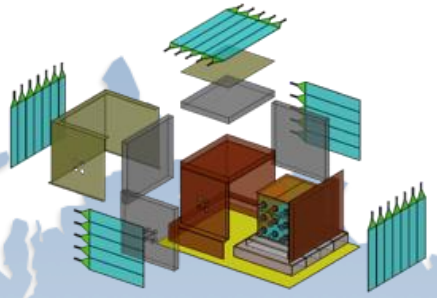
DAMA
@ LNGS

SABRE
@ LNGS





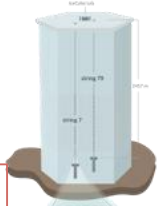
ANAIS
@Canfranc



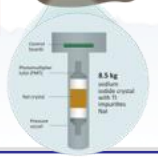
KIMS/COSINE
@ Yangyang

PICO-LON
@ Kamioka

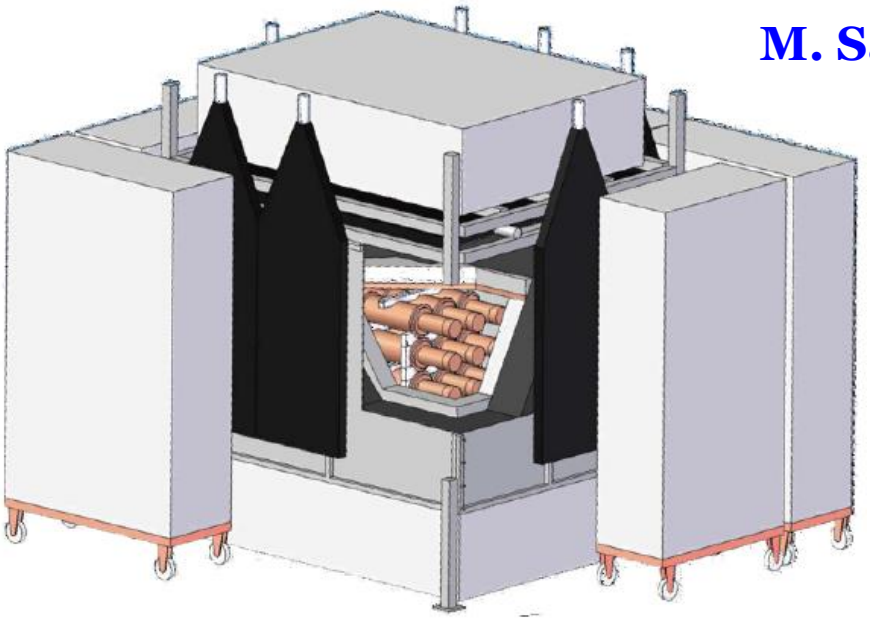
SABRE
@ Stawell



DM-Ice @ South Pole



ANAIS-112

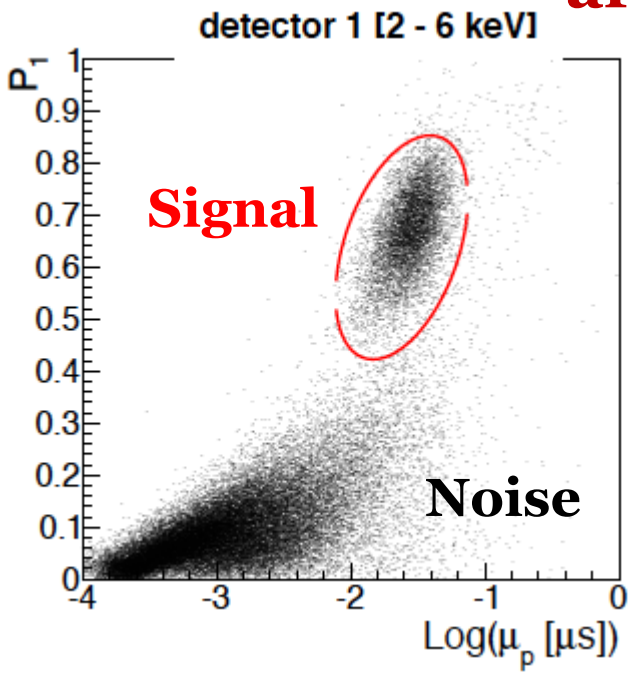


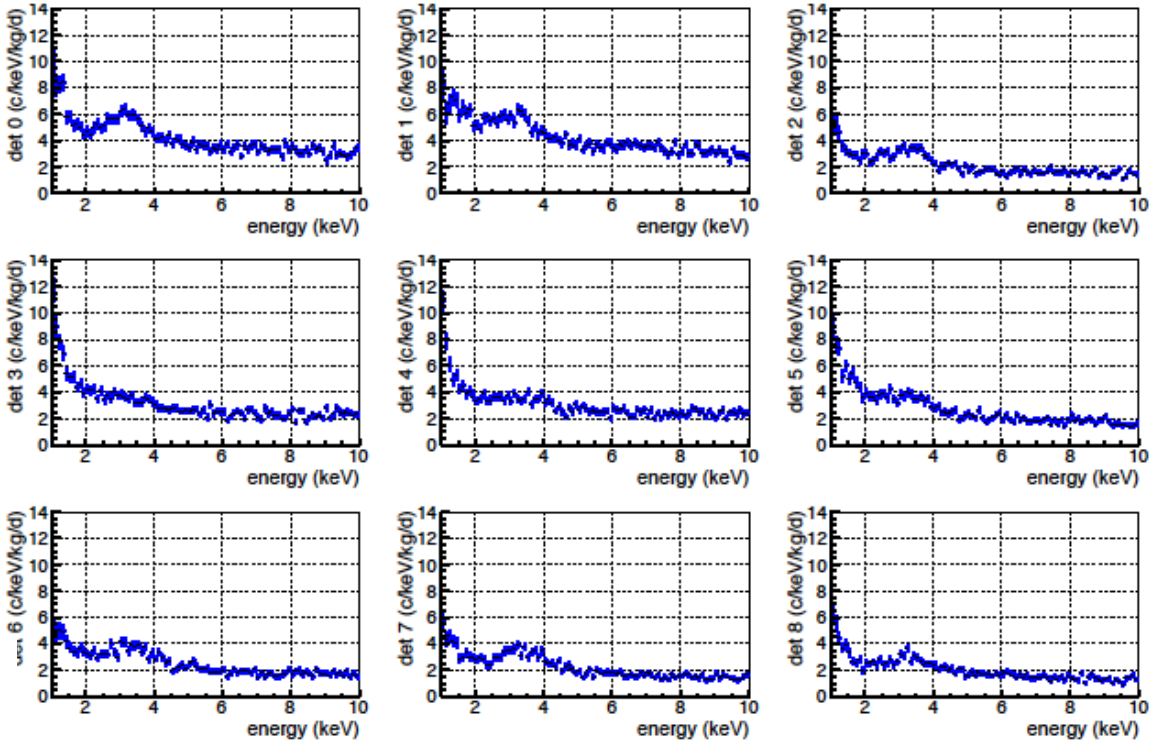
M. Sarsa

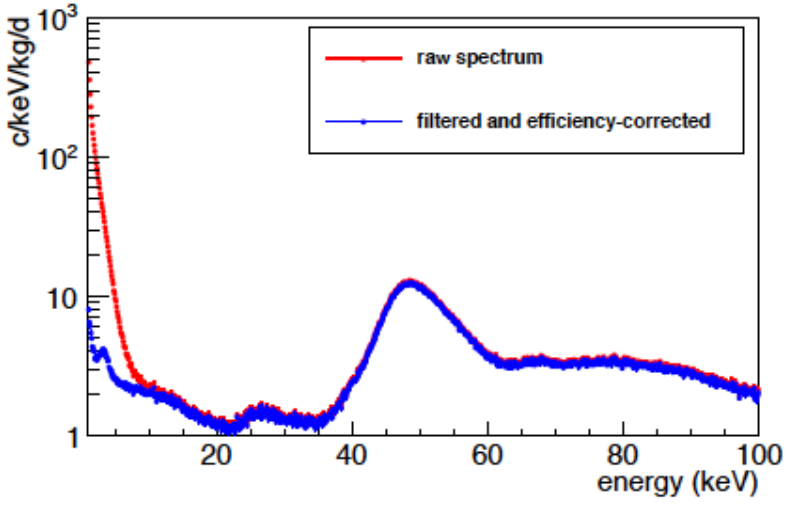
- 3x3 matrix of 12.5 kg cylindrical modules = 112.5 kg
- All crystals built from Alpha Spectra Co (US) with selected powder and specific radiopurity protocols
- Two Hamamatsu R12669SEL PMTs
- High light yields :13~16 photoelectrons/keV (DAMA 5-10)
- Taking physics data since Aug. 2017 at Canfranc (Spain)

ANAIS-112

arXiv:1812.01472





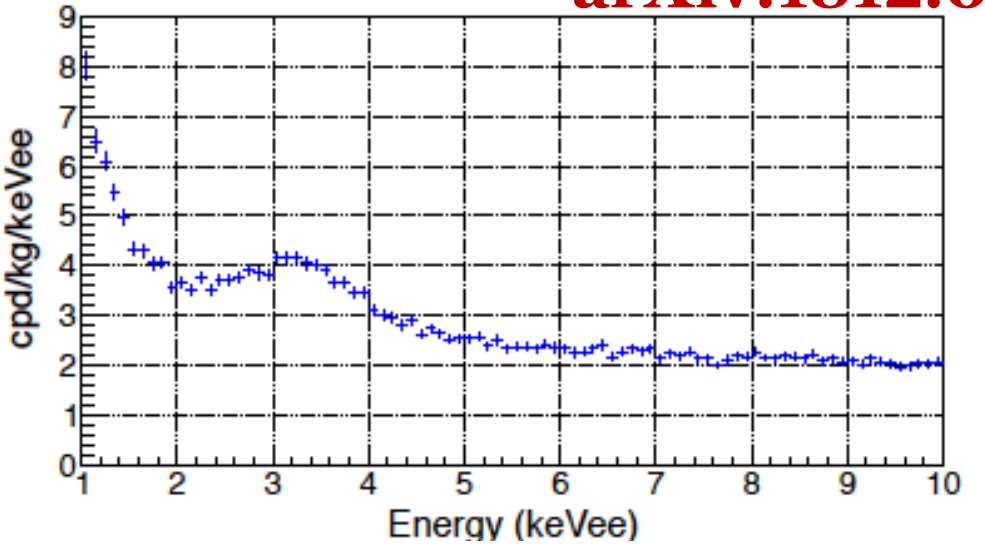


1 keV energy threshold!!

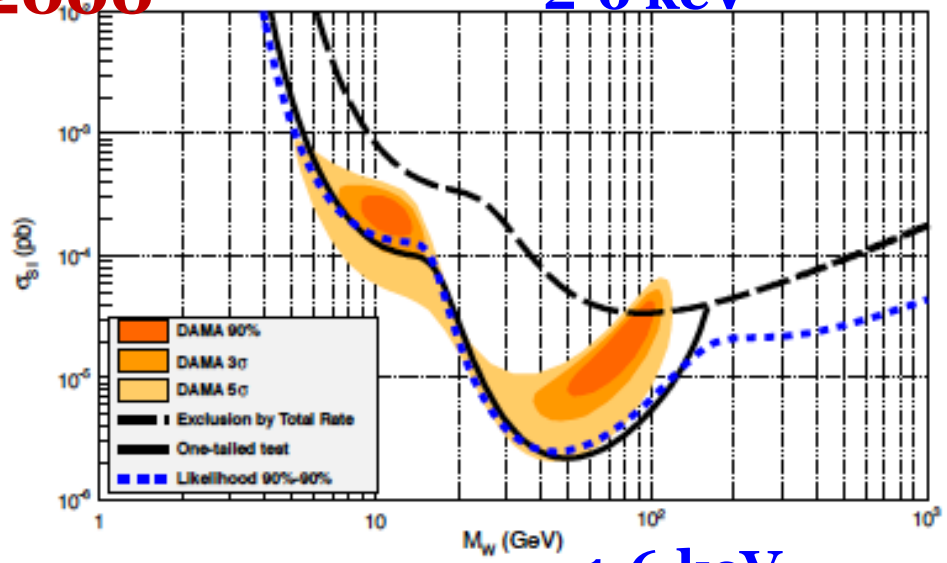
- 2~5 counts/keV/kg/day (dru) background @ 2keV
  - ❖ DAMA ~ 1 dru

ANAIS-112 : Sensitivity of 5 years operation

arXiv:1812.02000



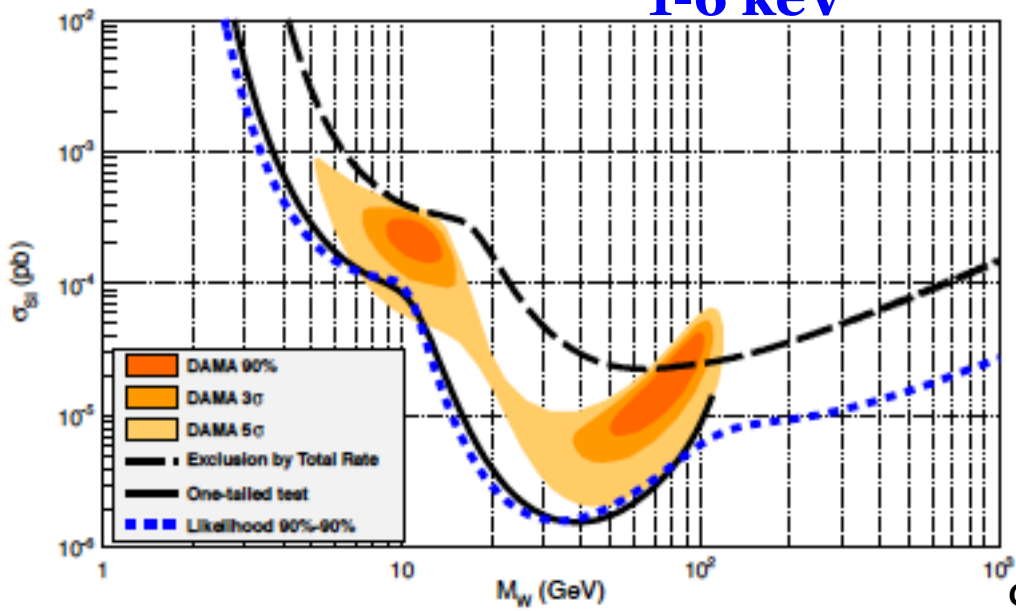
2-6 keV



1-6 keV

Module	$\langle B/\varepsilon \rangle$ (cpd/kg/keV$_{ee}$)
D0	4.99±0.06
D1	5.04±0.06
D2	2.68±0.04
D3	3.81±0.05
D4	3.60±0.05
D5	3.54±0.05
D6	3.15±0.05
D7	2.85±0.04
D8	2.58±0.04
ANAIS–112	3.58±0.02

1-6 keV

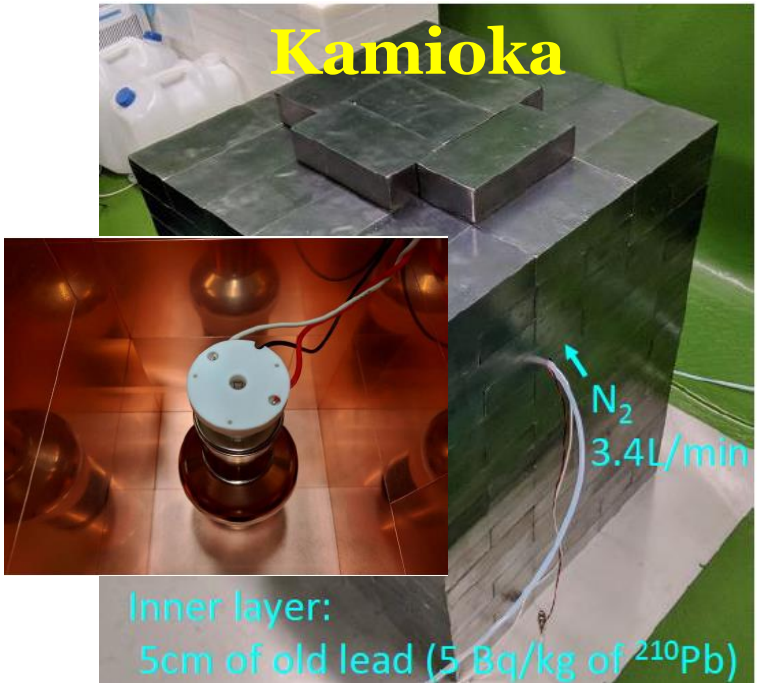


PICO-LON

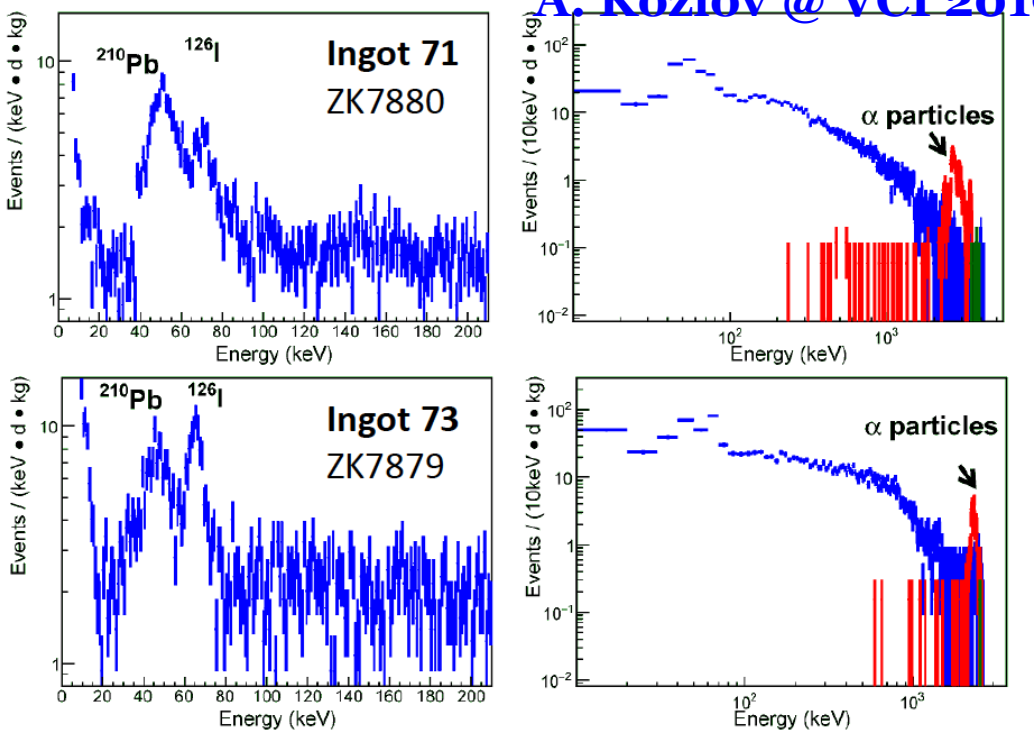
- Development of low-background NaI(Tl) crystals in Japan

A. Kozlov @ VCI 2019

PICO-LON : Background



A. Kozlov @ VCI 2019



NaI(Tl)/ Isotope	^{238}U, ppt	^{232}Th, ppt	^{40}K, ppb	^{210}Pb, mBq
Ingot 71†	9.7 ± 0.8	0.96 ± 0.23	40*	1.29 ± 0.06
Ingot 73‡	2.2 ± 0.1	1.0 ± 0.6	12.5*	0.98 ± 0.05
DAMA det.	0.7 - 10	0.7 - 10	20	0.024

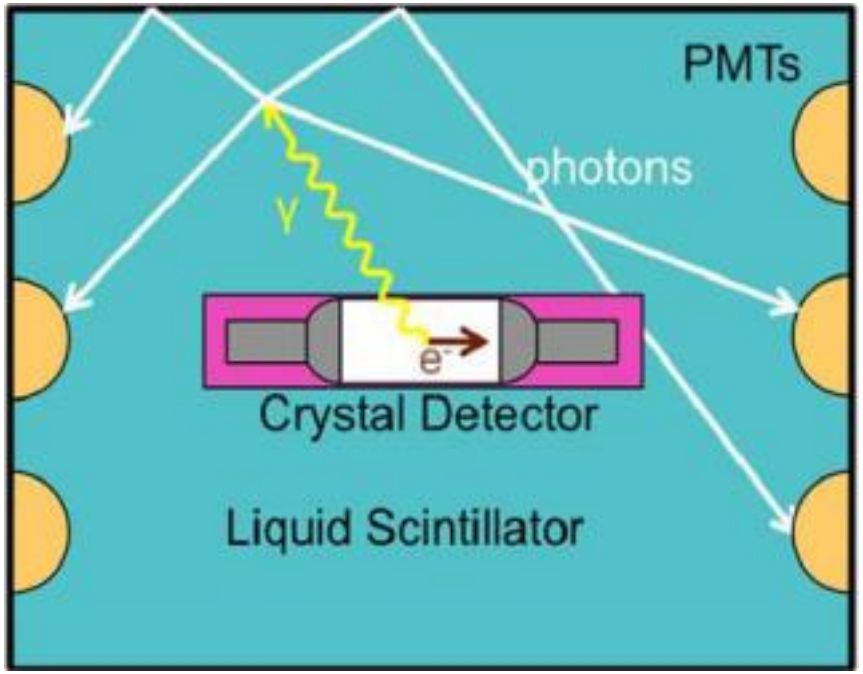
SABRE

4 key features:

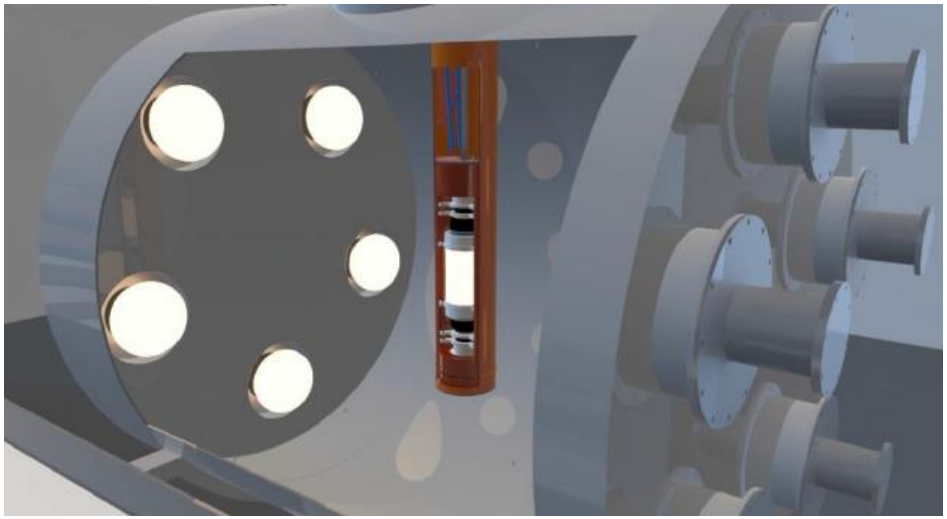
S. Copello@ NDM2018

1. High purity crystals: High purity powder and clean crystal growth method
2. Active background rejection: active veto of liquid scintillator
3. Low energy threshold: High QE Hamamatsu PMTs, directly coupled to the crystals
4. Double location: both in Northern and Southern hemispheres

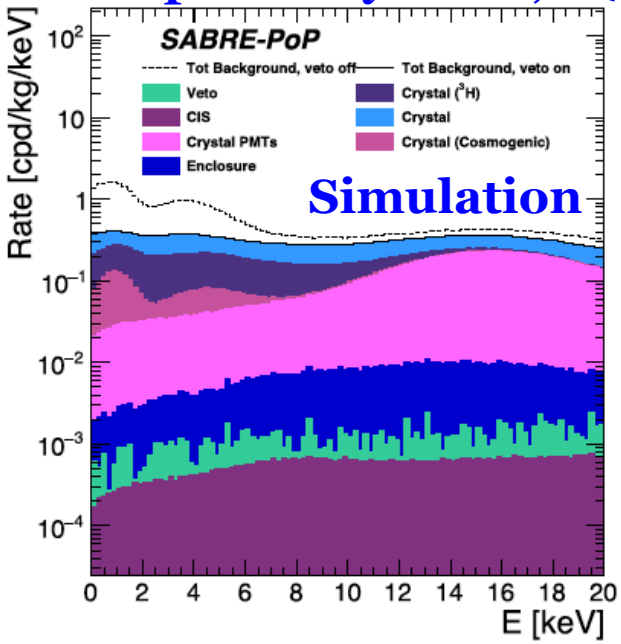
4”(D) X 8”(H) ingot



SABRE-PoP (Proof of Principle)



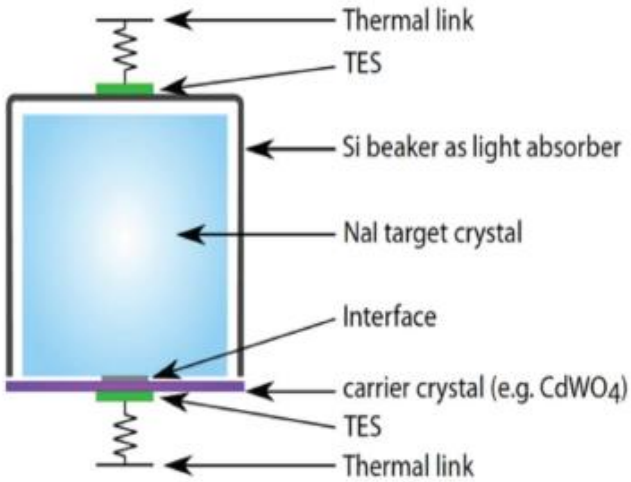
Astropart. Phys. 106, 1 (2019)

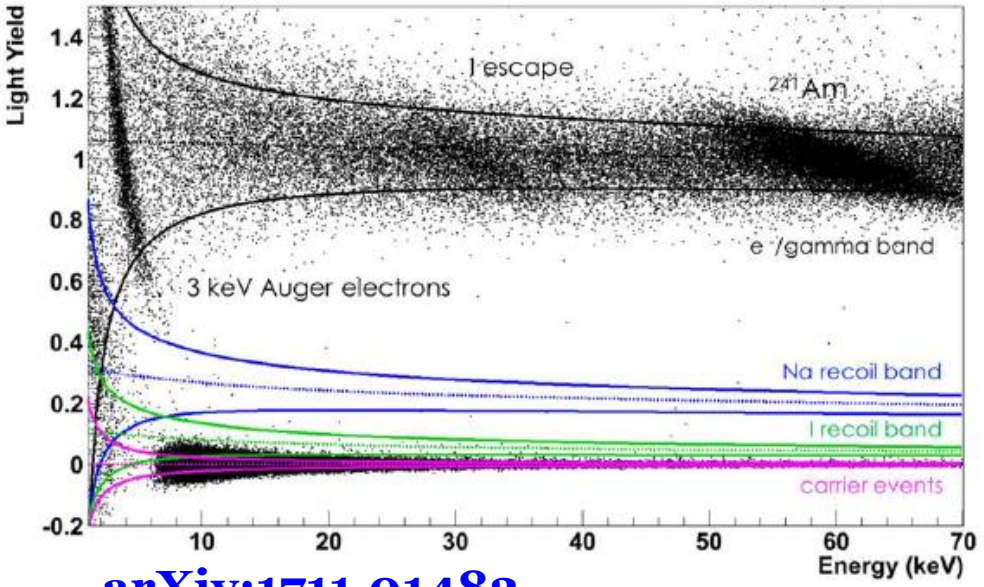


- Test setup (PoP) is ready in LNGS
- Expected background level ~0.36 dru (2-6 keV) based on Geant4 MC simulation

COSINUS

- Simultaneous measurement of photon and phonon using pure NaI crystals (low temperature detector)
  - ❖ Nuclear recoil can be identified almost perfectly



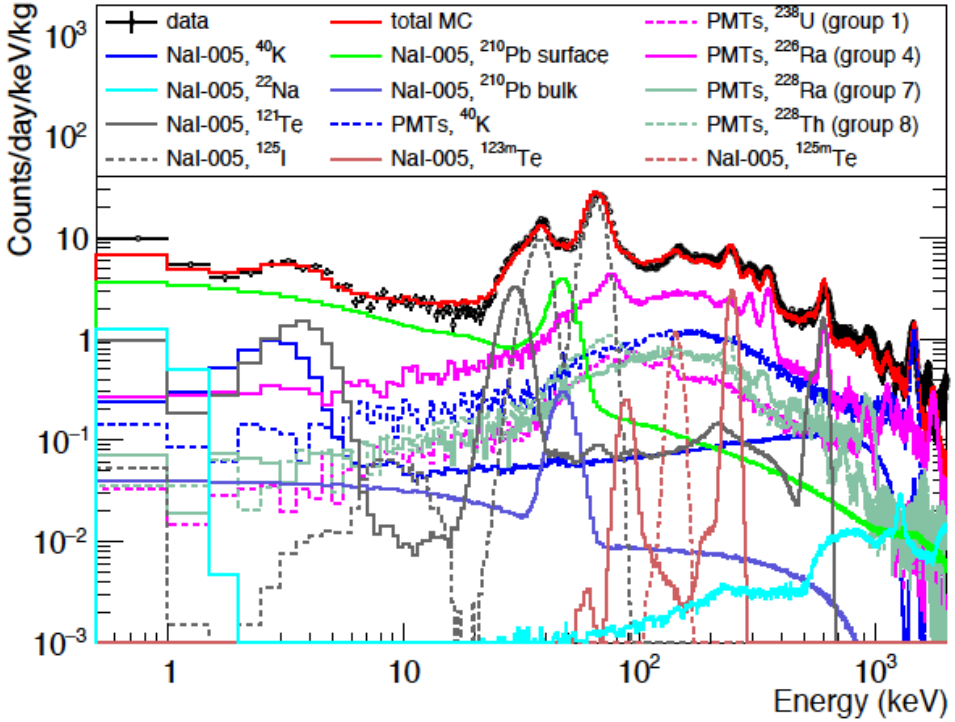


arXiv:1711.01482

- Performing test measurements of pure NaI crystals using CRESST cryostat @ LNGS

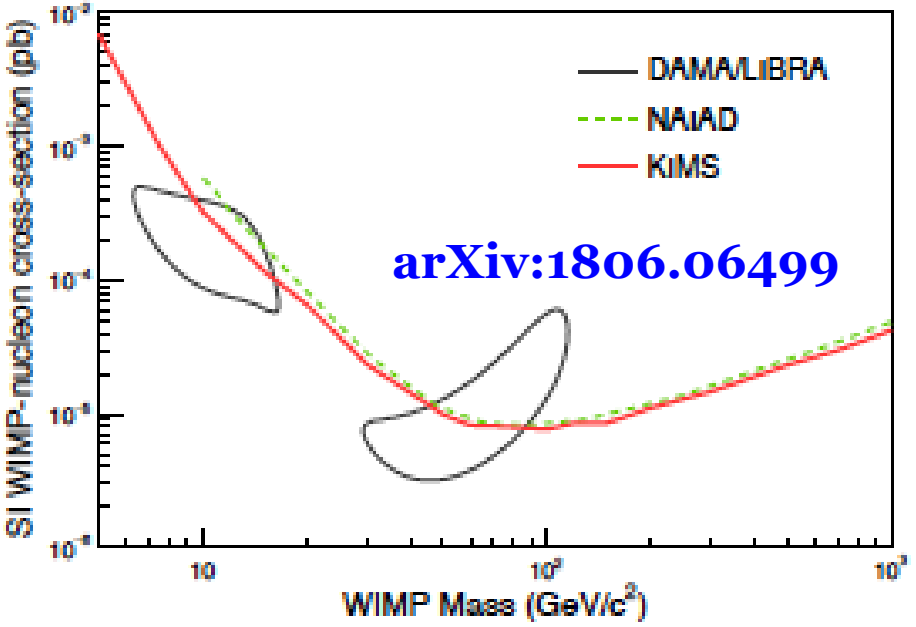
KIMS

NaI(Tl) crystals : Background understanding and rejection



Astropart. Phys. 62, 249 (2015)
EPJC 76, 185 (2016)
EPJC 77, 437 (2017)
NIMA, 851 (2017) 103

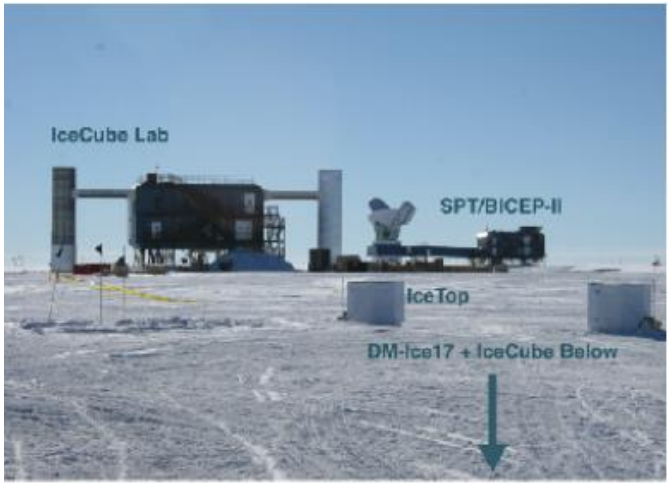
Pulse shape discrimination for nuclear recoil separation



JHEP 08, 93 (2015)
Astropart. Phys. 102, 51 (2018)
Astropart. Phys. 108, 50 (2019)

DM-Ice17

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

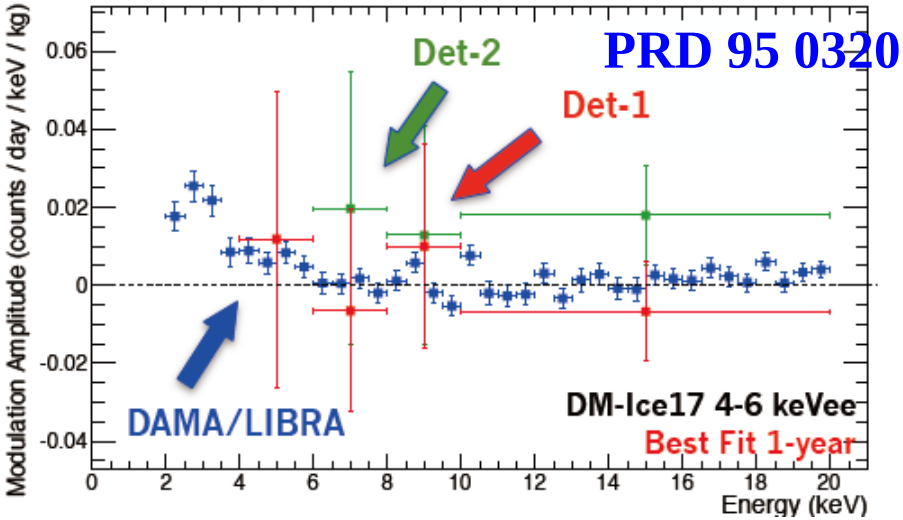


Two 8.47 kg crystals

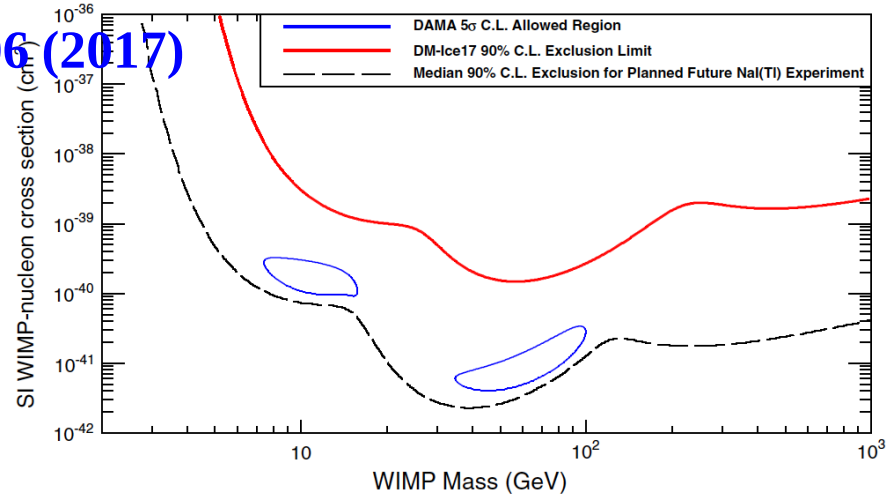
2200 m.w.e overburden

Proof of principle of south pole experiment

PRD 90 092005 (2014) **PRD 93 042001 (2016)**



PRD 95 032006 (2017)



COSINE project (Since 2015)

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

YangYang(Y2L) Underground Laboratory

(Upper Dam) YangYang Pumped

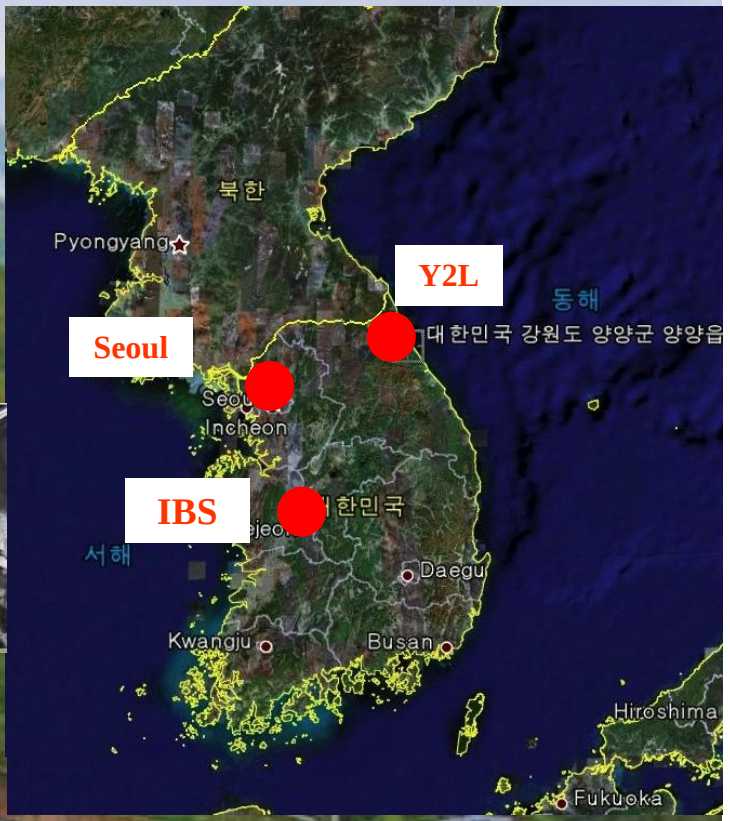
Storage Power Plant

Center for Underground Physics

IBS (Institute for Basic Science)

1000m

700m



(Power Plant)

양양양수발전소

(Lower Dam)

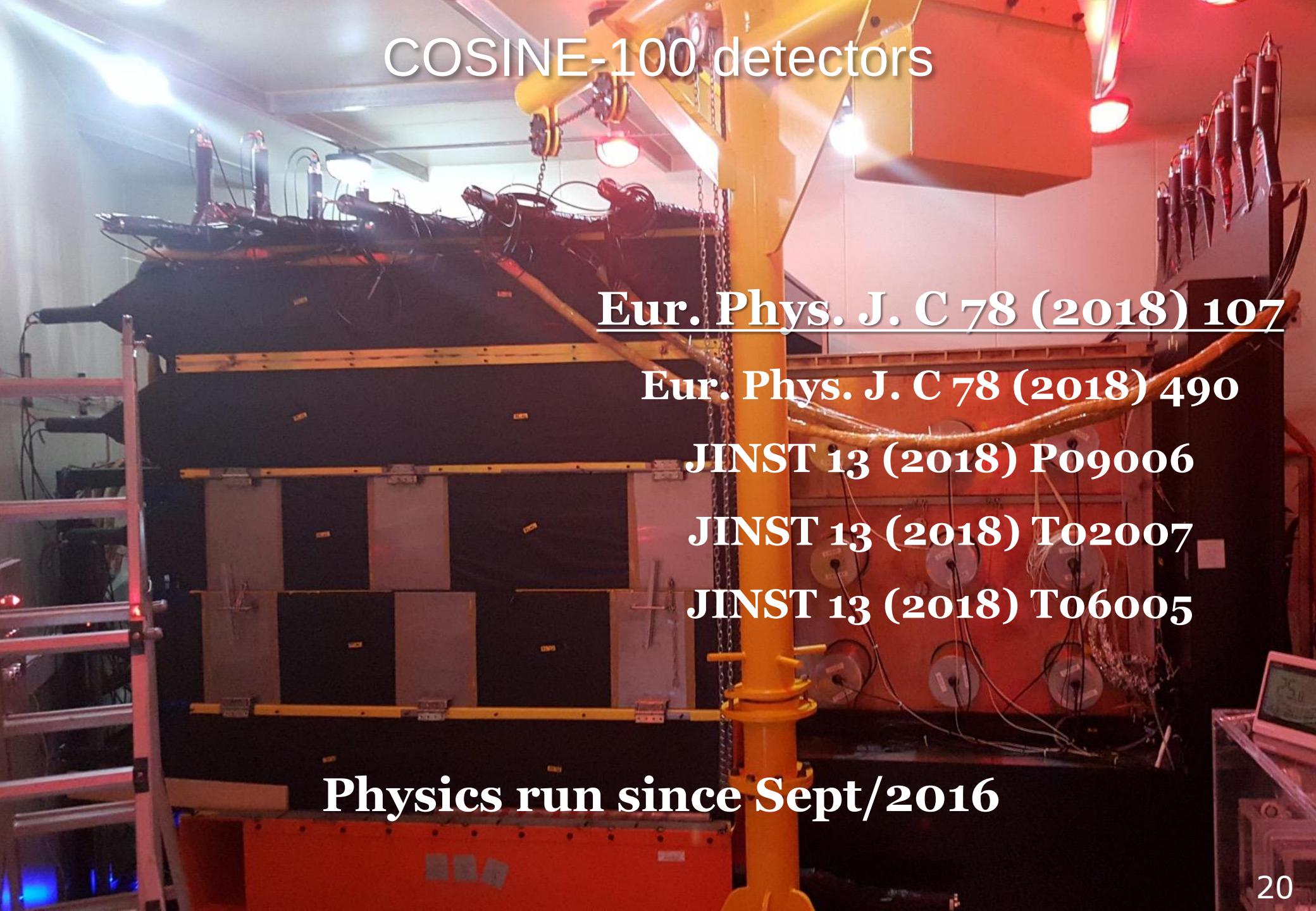
KIMS/COSINE (Dark Matter Search)

AMoRE (Double Beta Decay Experiment)

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

COSINE-100 construction

COSINE-100 detectors



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

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

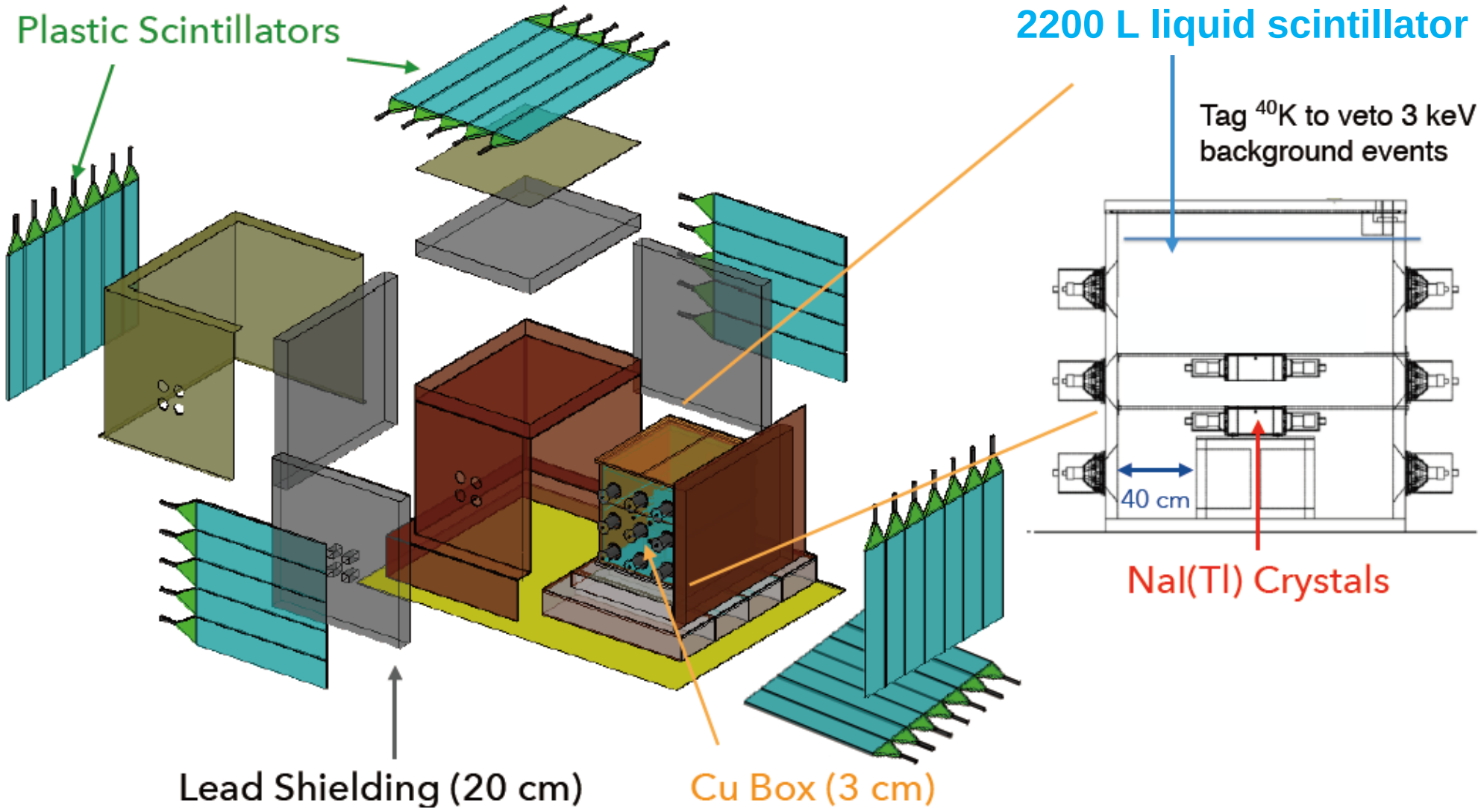
JINST 13 (2018) P09006

JINST 13 (2018) T02007

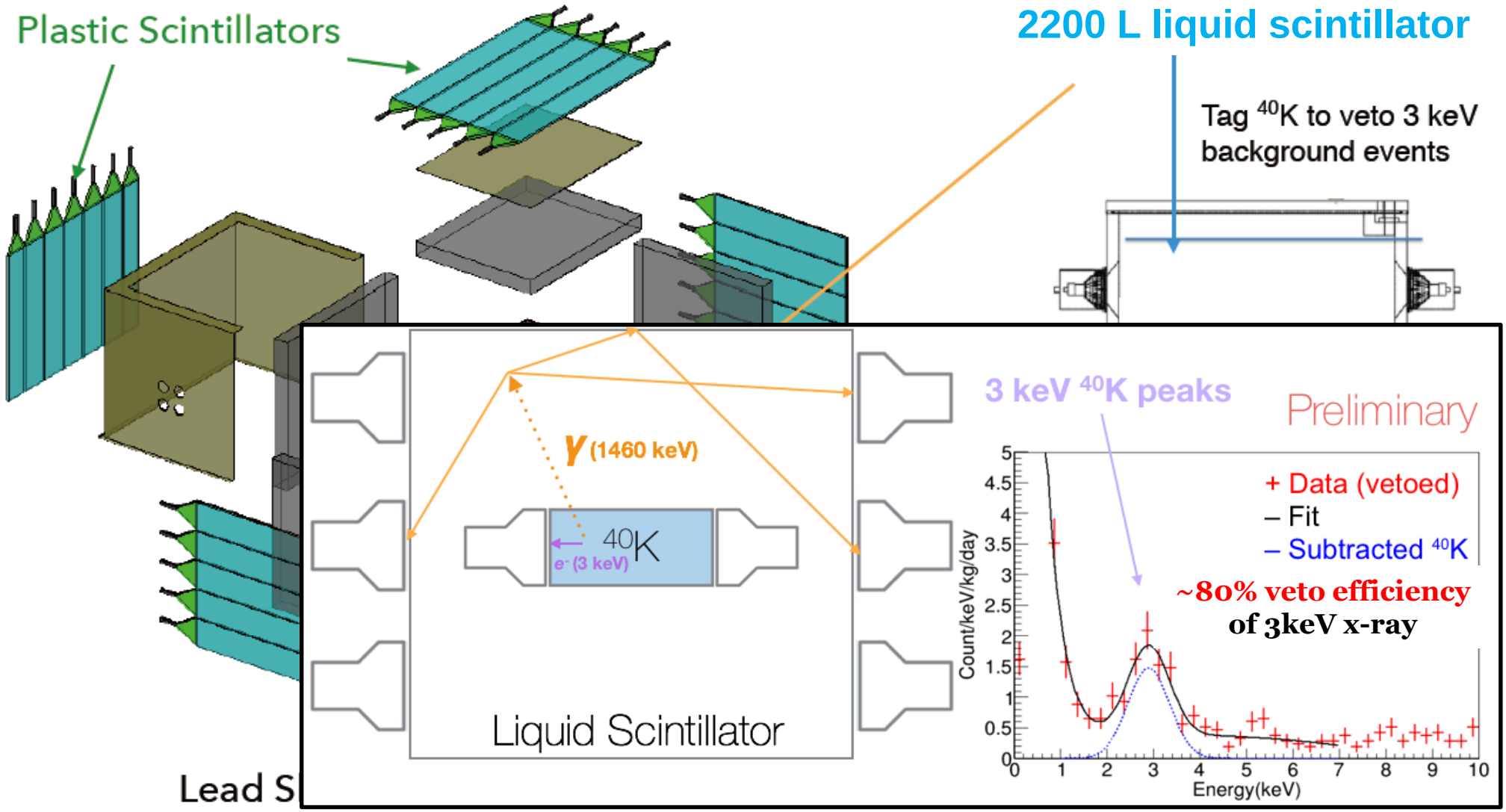
JINST 13 (2018) T06005

Physics run since Sept/2016

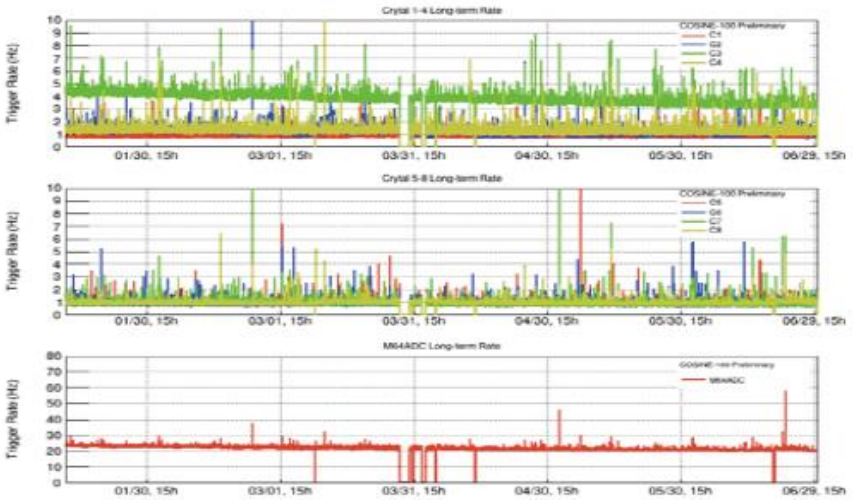
COSINE-100 shield

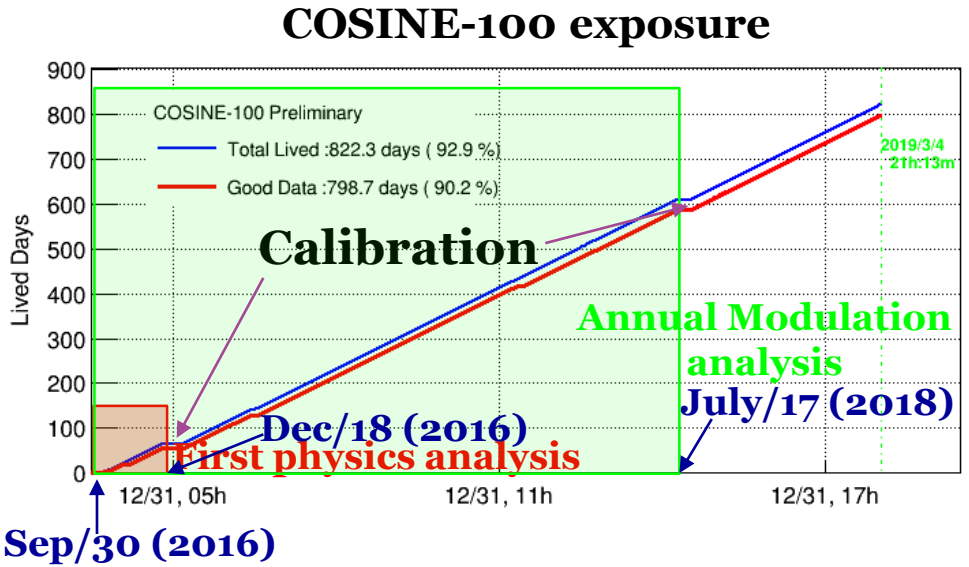


COSINE-100 shield

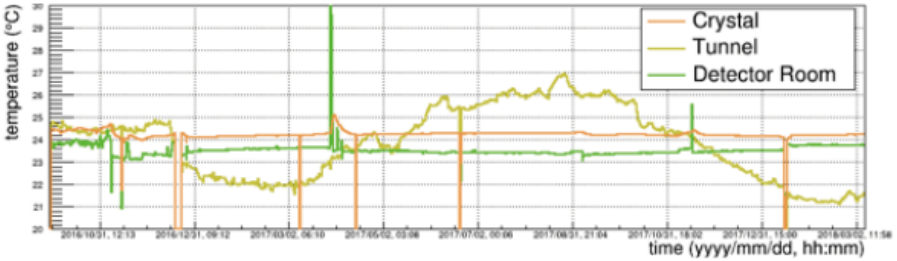


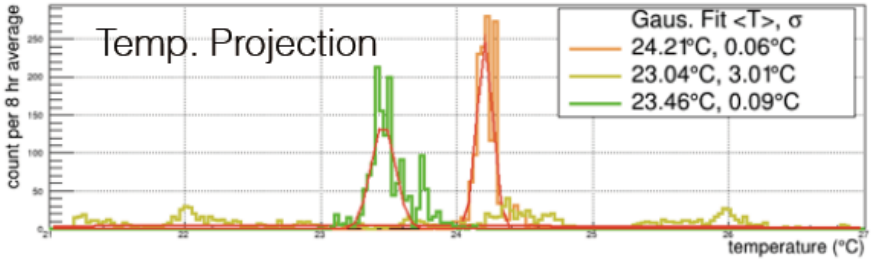
COSINE-100 operation





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



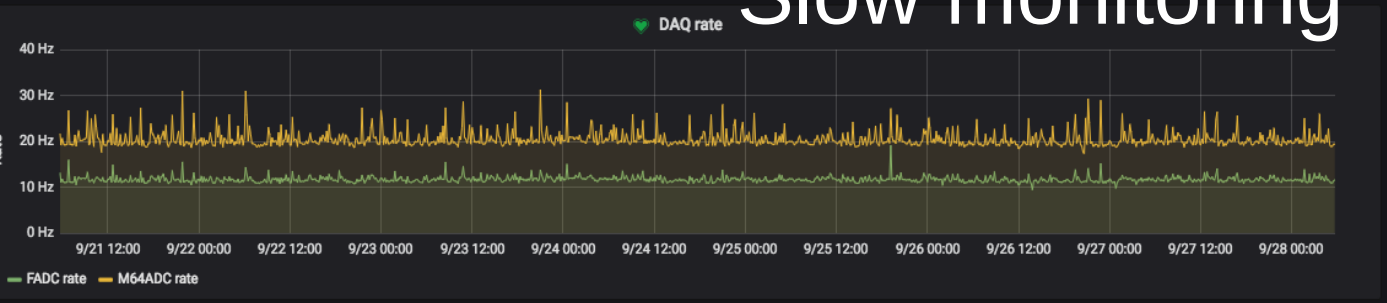


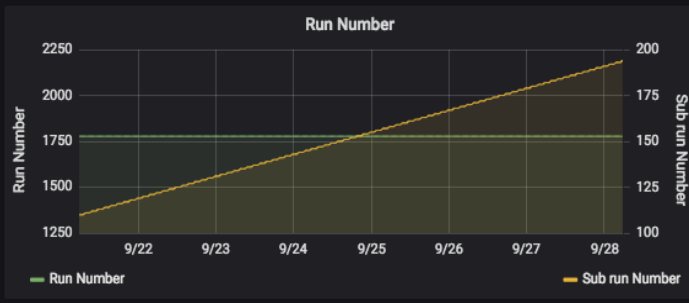
DAQ status

FADC DAQ	M64ADC DAQ	TCB USB	FADC USB	M64 USB	Run number	Subrun number
Running	Running	Connected	Connected	Connected	1777	194

Slow monitoring

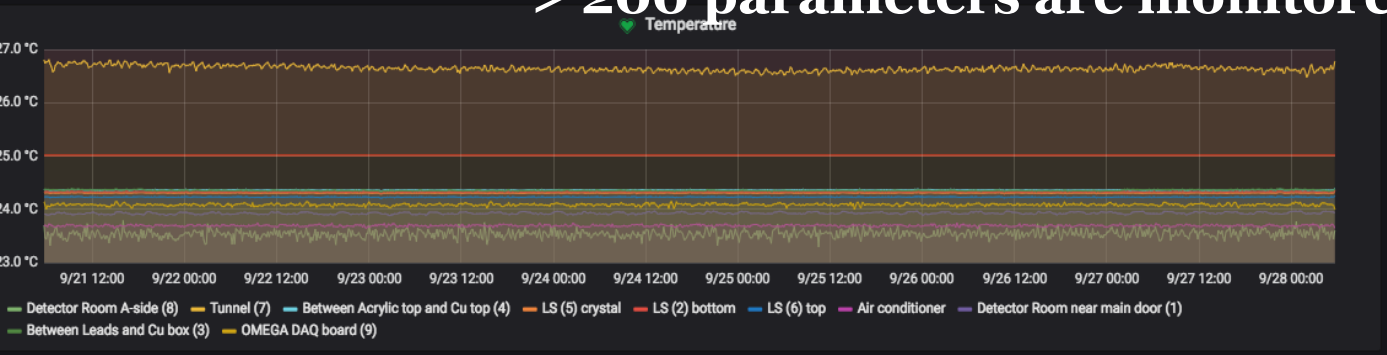
Row

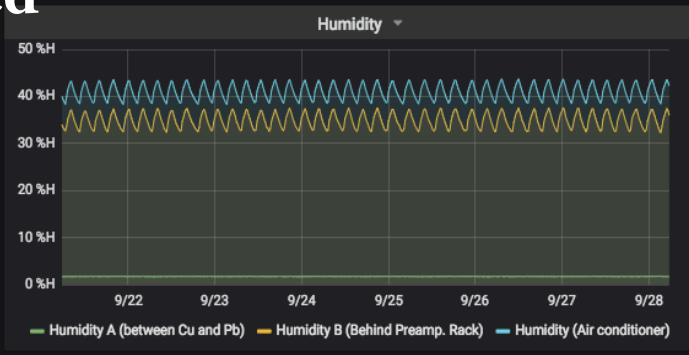




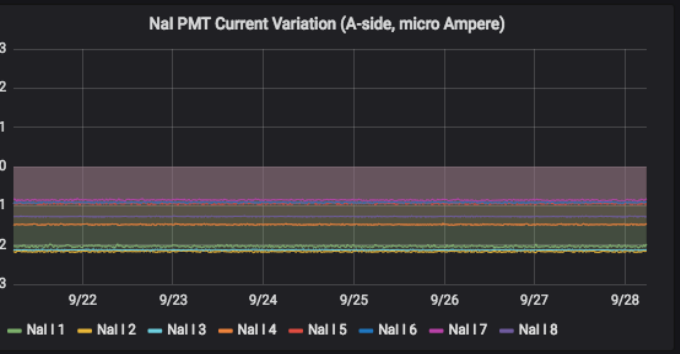
New row

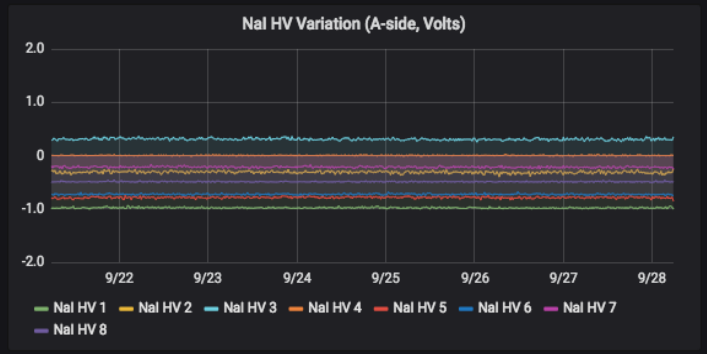
> 200 parameters are monitored

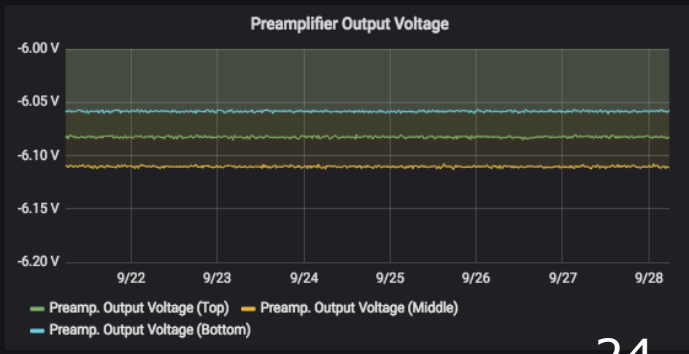




New row







New row


COSINE-100 NaI(Tl) crystals
8 crystals, 106 kg in total

COSINE-100 NaI(Tl) crystals

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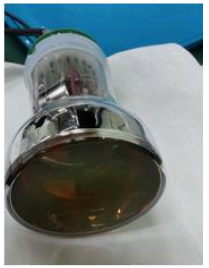
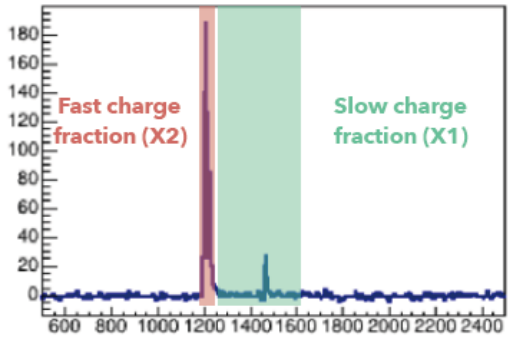
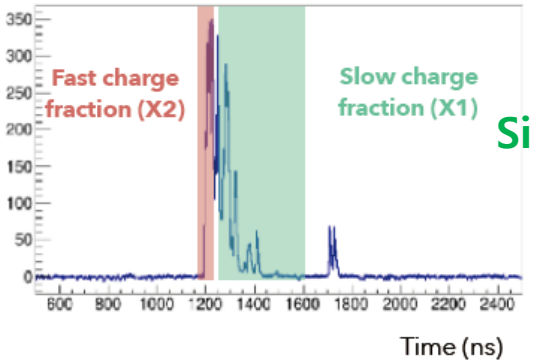
- 8 crystals, total 106 kg
- Different quality crystals from crystal R&D with Alpha Spectra (US)
- For best cases, U/Th/K are lower than DAMA
- Total alphas (~^{210}Pb) are higher than DAMA

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-WS Ⅱ	0.76 ± 0.02	41.1 ± 6.8	< 0.04	0.44 ± 0.19	15.50 ± 1.64
Crystal 4	18.0	AS-WS Ⅱ	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-WS Ⅲ	1.52 ± 0.04	12.2 ± 4.5	< 0.018	0.56 ± 0.19	14.56 ± 1.45
Crystal 7	12.5	AS-WS Ⅲ	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



Fast (mostly PMT induced) event rejection

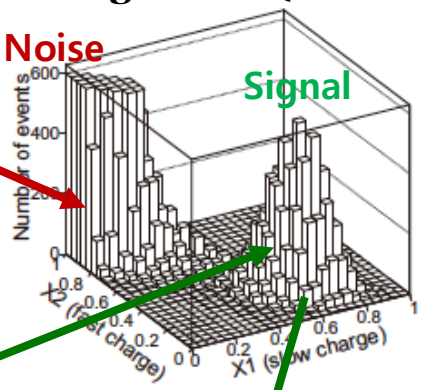




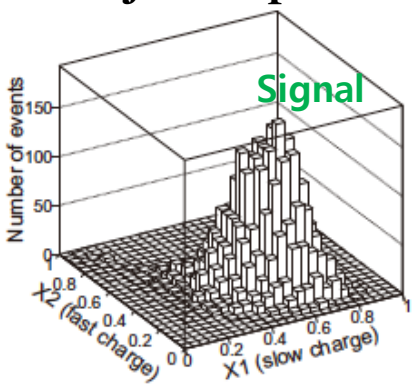
Noise

Signal

Charge Ratio (DAMA noise rejection parameter)

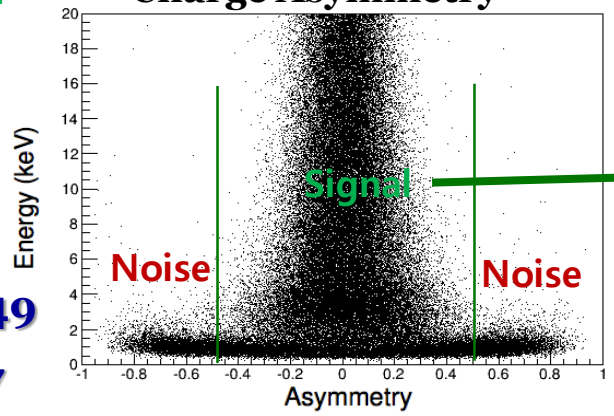


(a) Background data

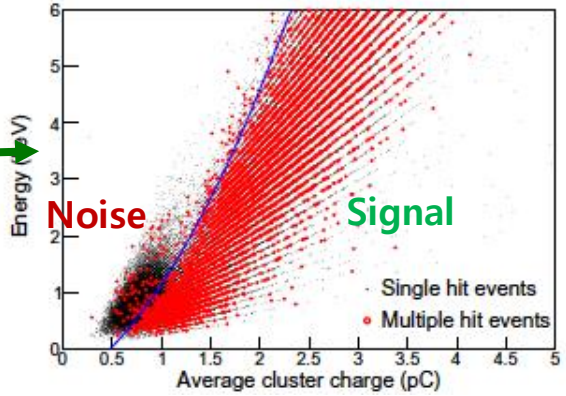


(b) ^{55}Fe calibration data

Charge Asymmetry



Average cluster charge



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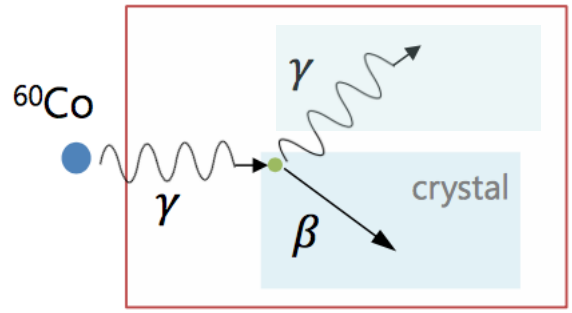
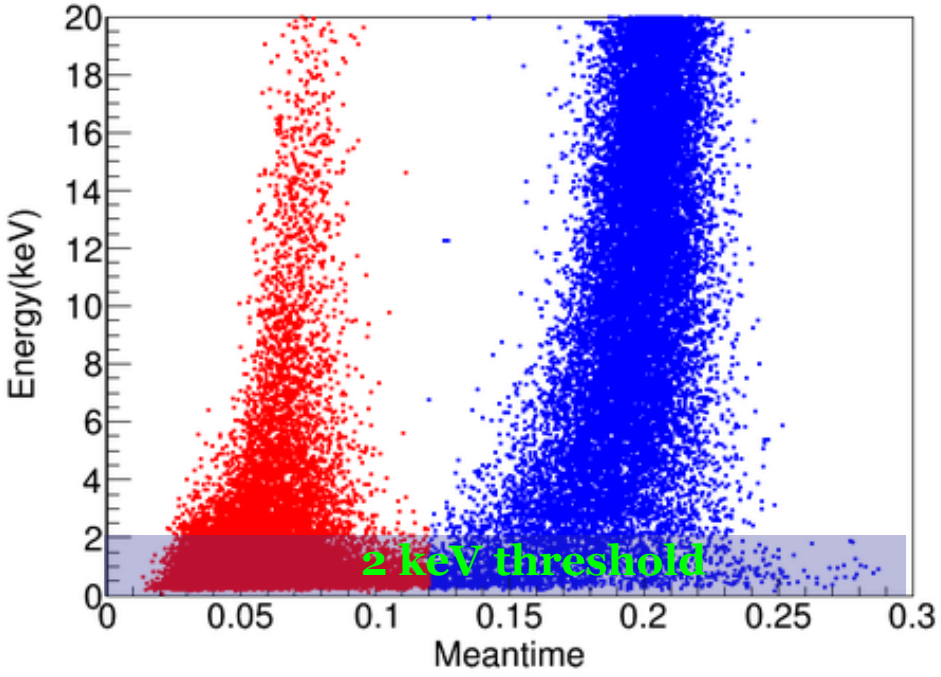
- Charge ratio (DAMA cut) is effective to reject fast noise but, it is not enough to remove all the noise!!

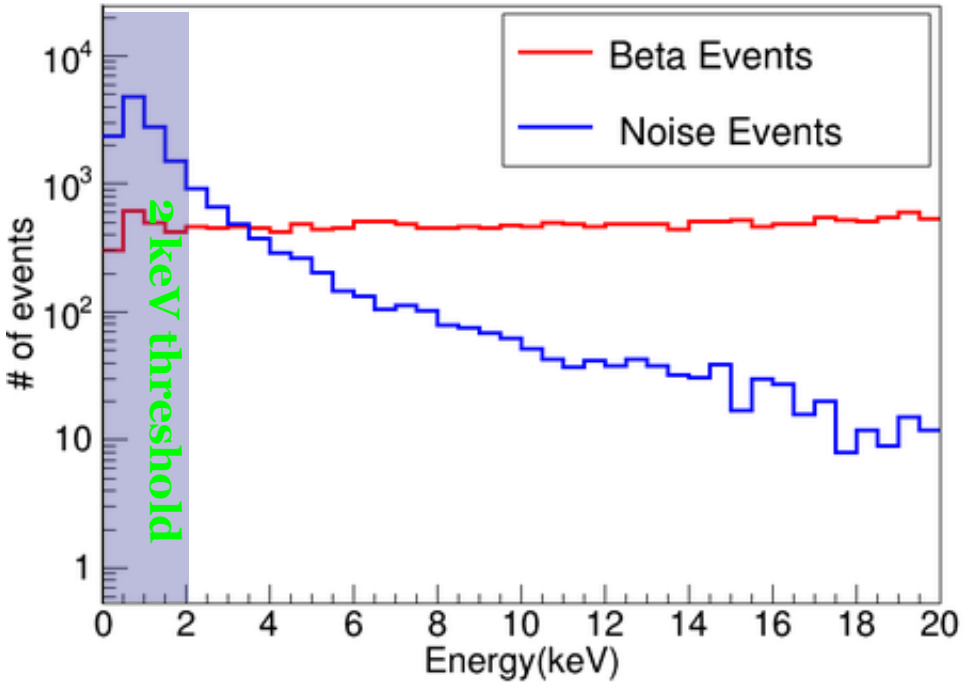
Pure electron recoil samples

- Two weeks long ^{60}Co calibration data



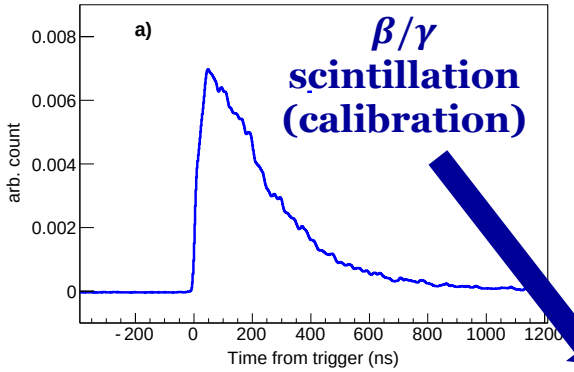
- Used to model scintillating events
- Used to estimate signal efficiency

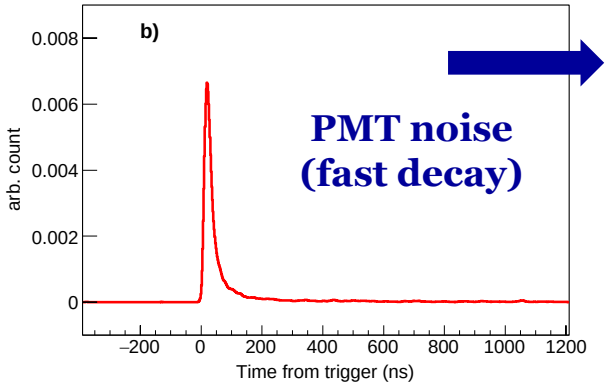




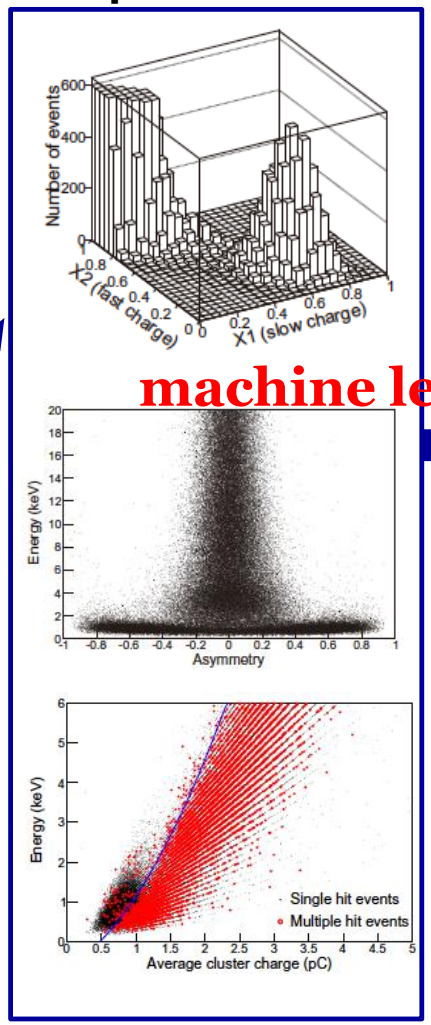
Machine learning to remove PMT induced noise

Accumulated waveforms

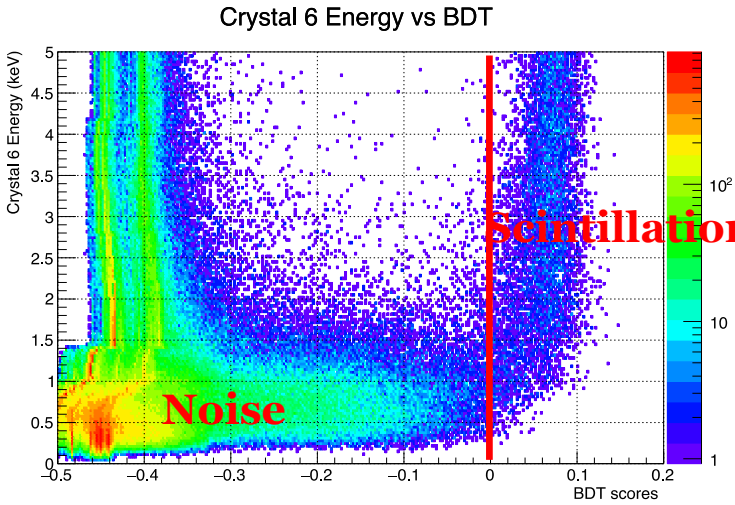


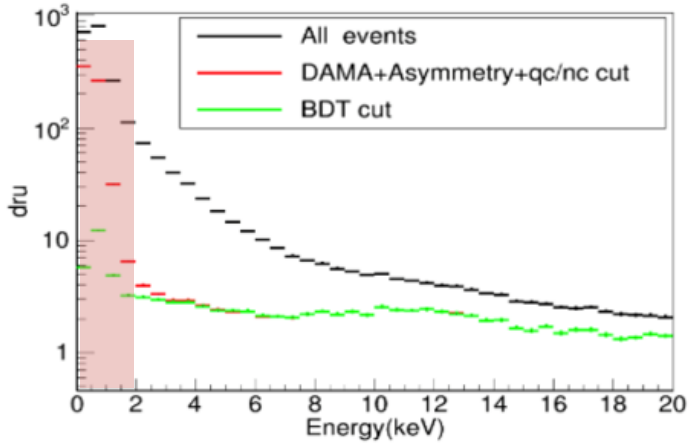


Discrimination parameters



machine learning

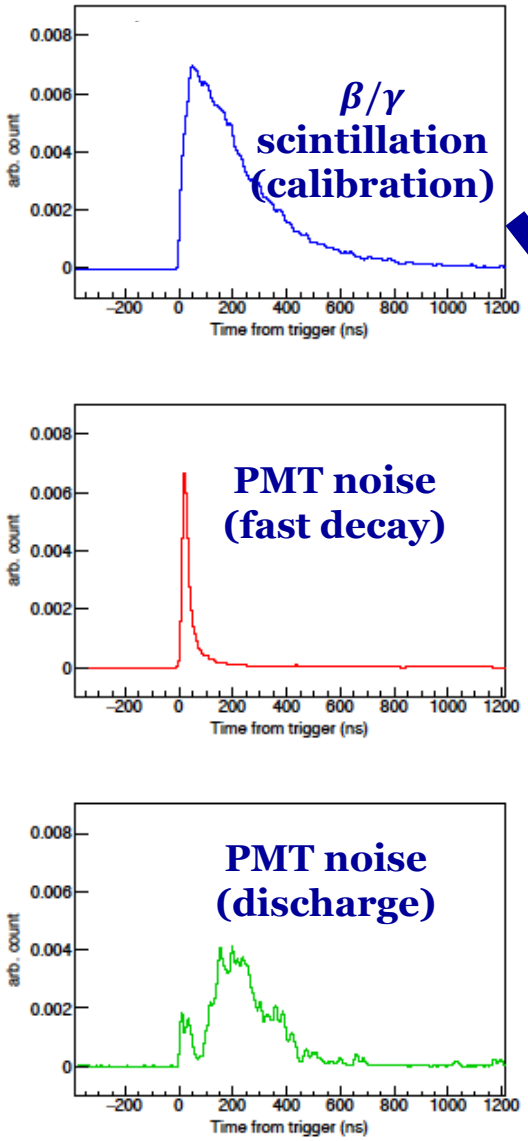




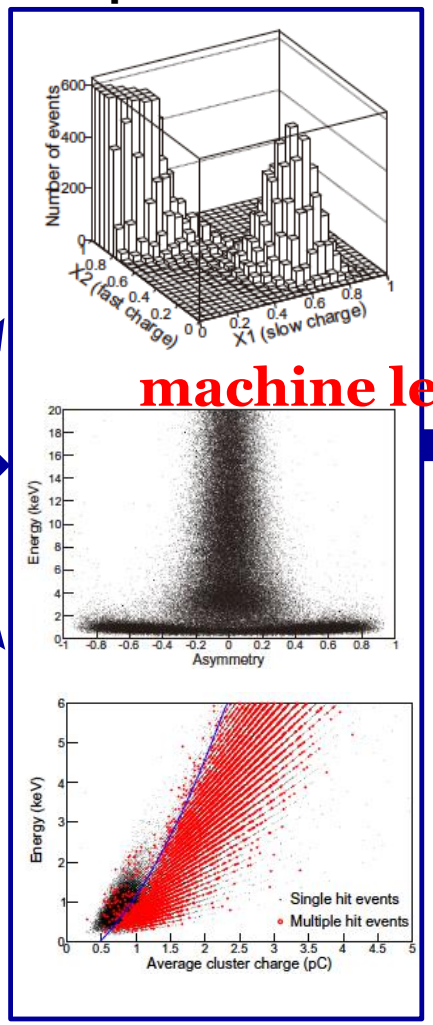
Machine learning (BDT) is more effective at low energy

Machine learning to remove PMT induced noise

Accumulated waveforms

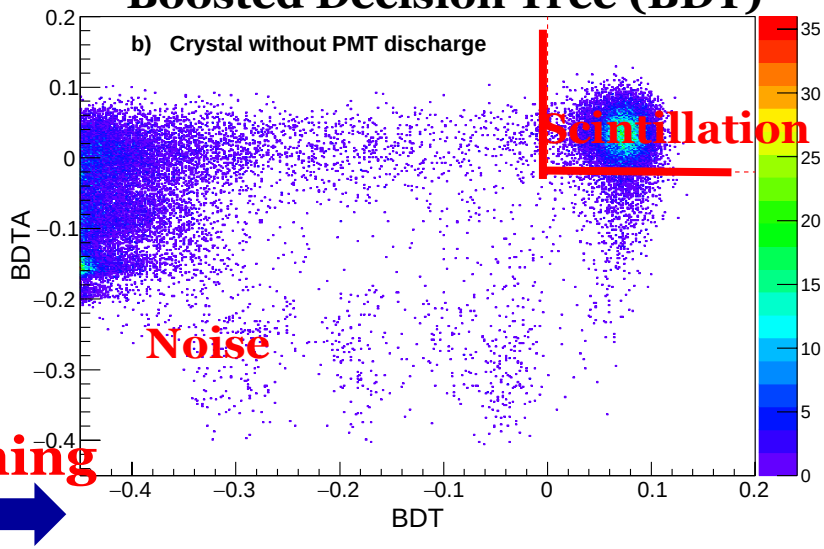


Discrimination parameters

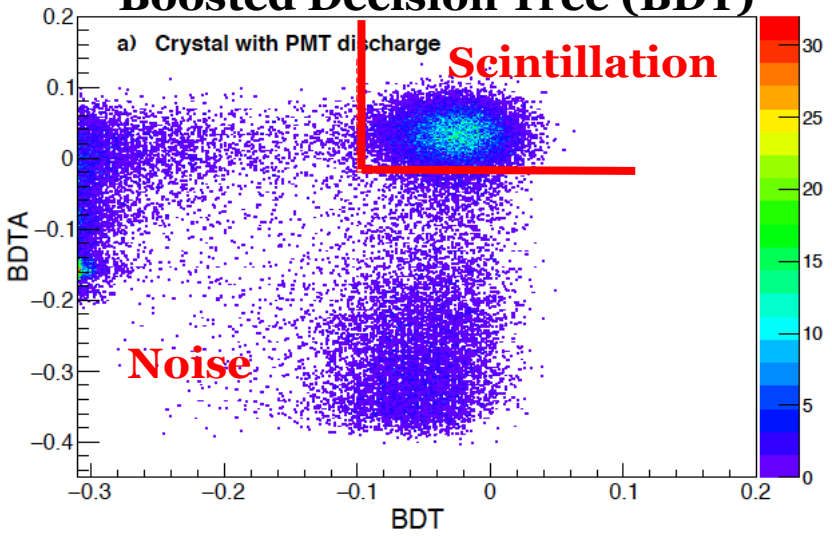


machine learning

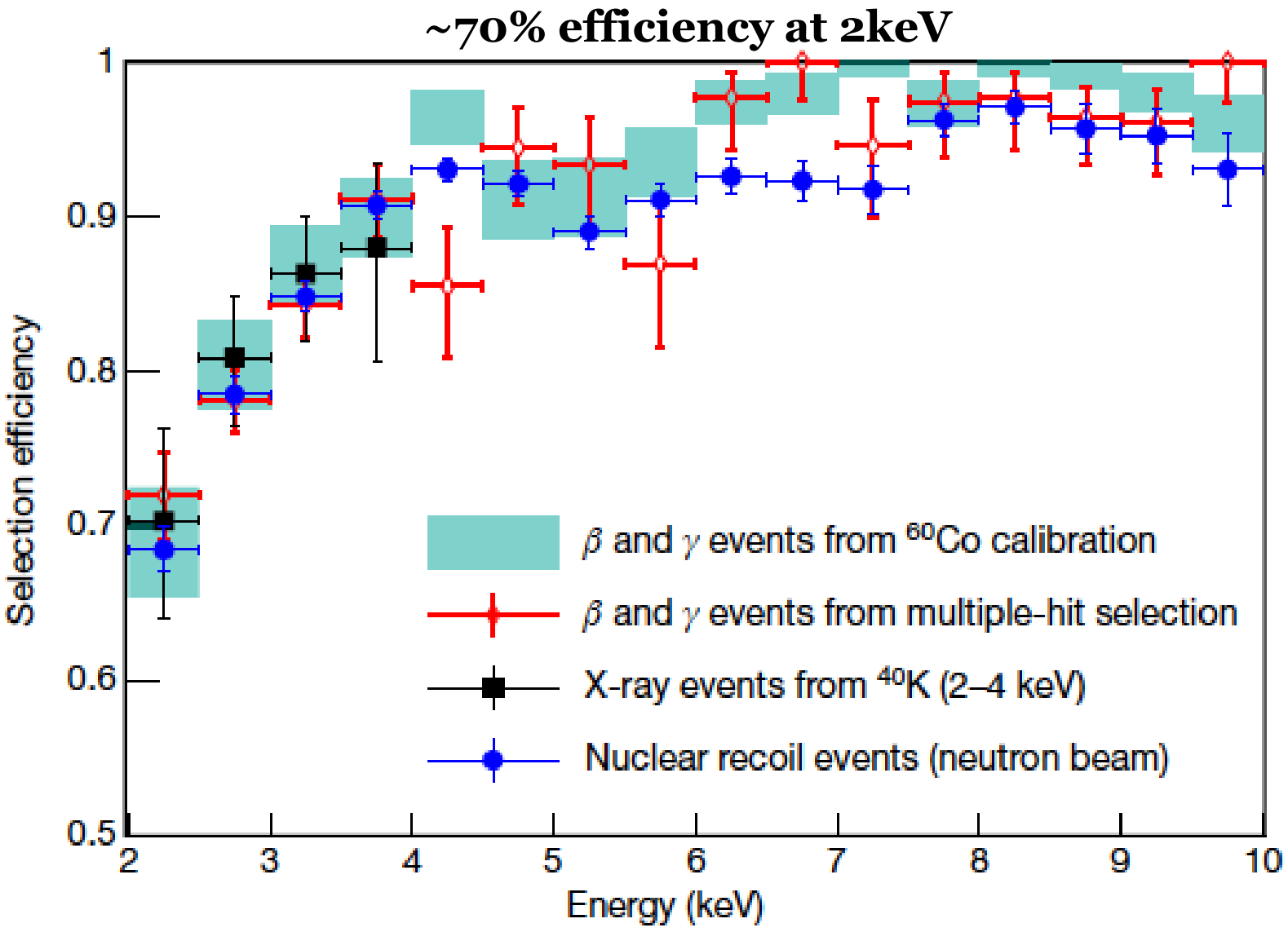
Boosted Decision Tree (BDT)



Boosted Decision Tree (BDT)



Event selection efficiency

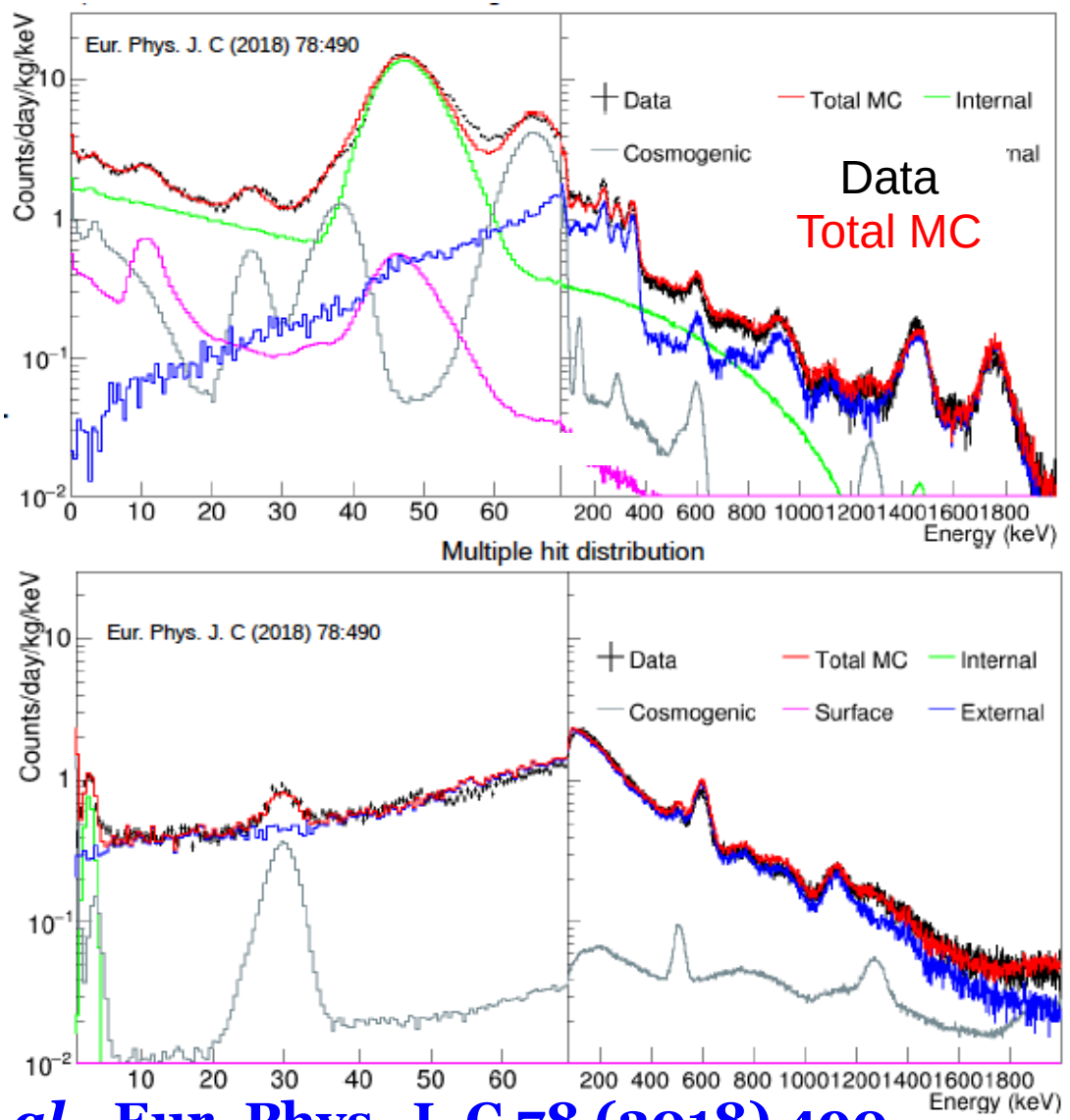


Background understanding (initial two month –SET1)

Single hit event
(6-2000 keV)

Crystal 7

Multiple hit events
(2-2000 keV)



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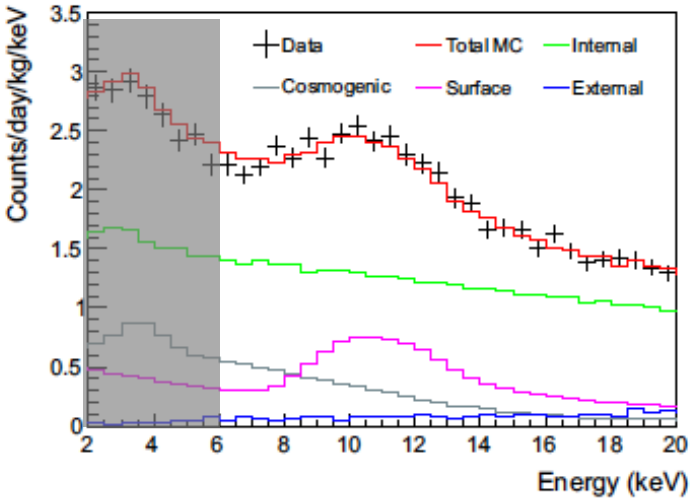
Expected background @ 2-6 keV (SET1 data)



Crystal 7

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**

DAMA : 1 dru

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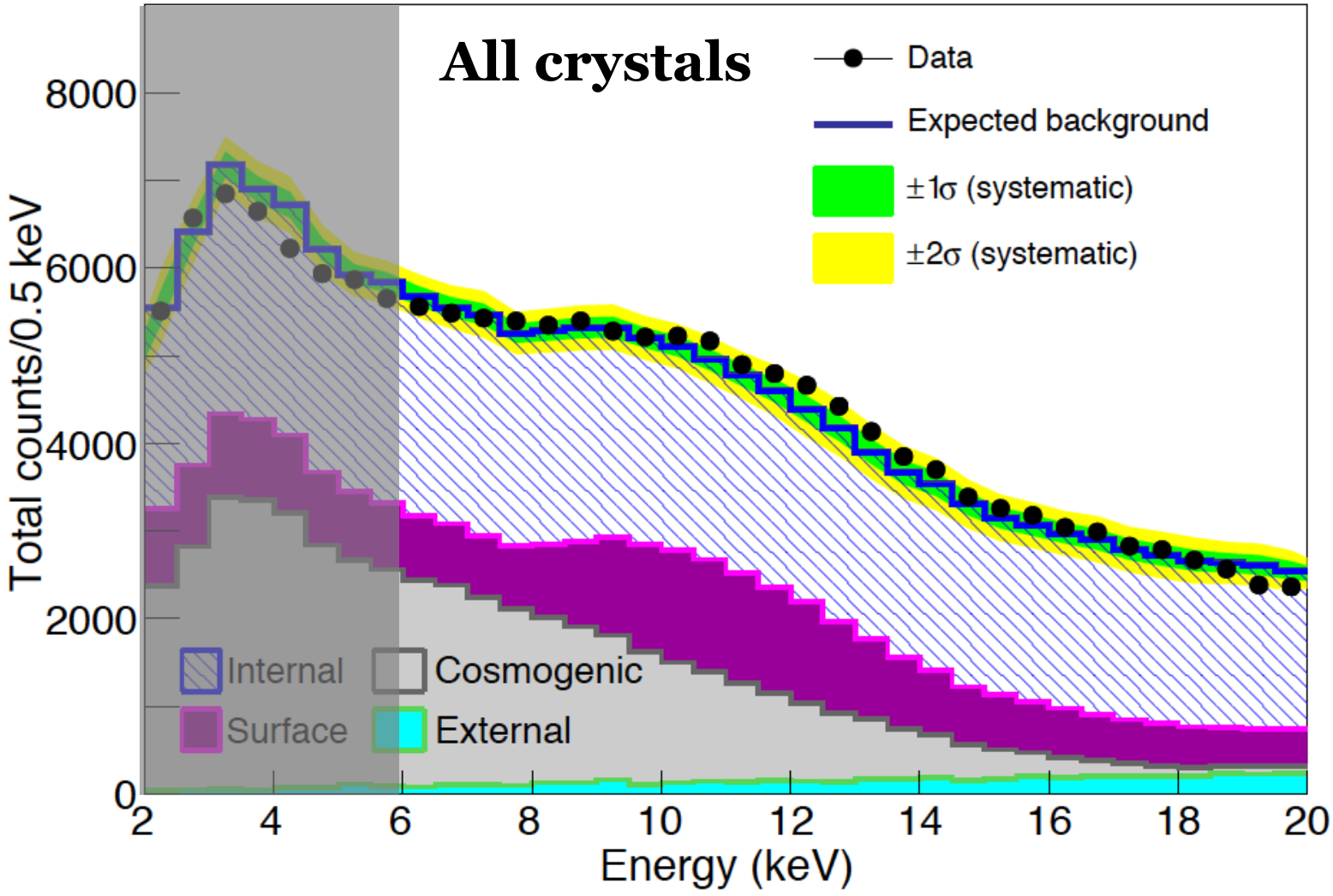
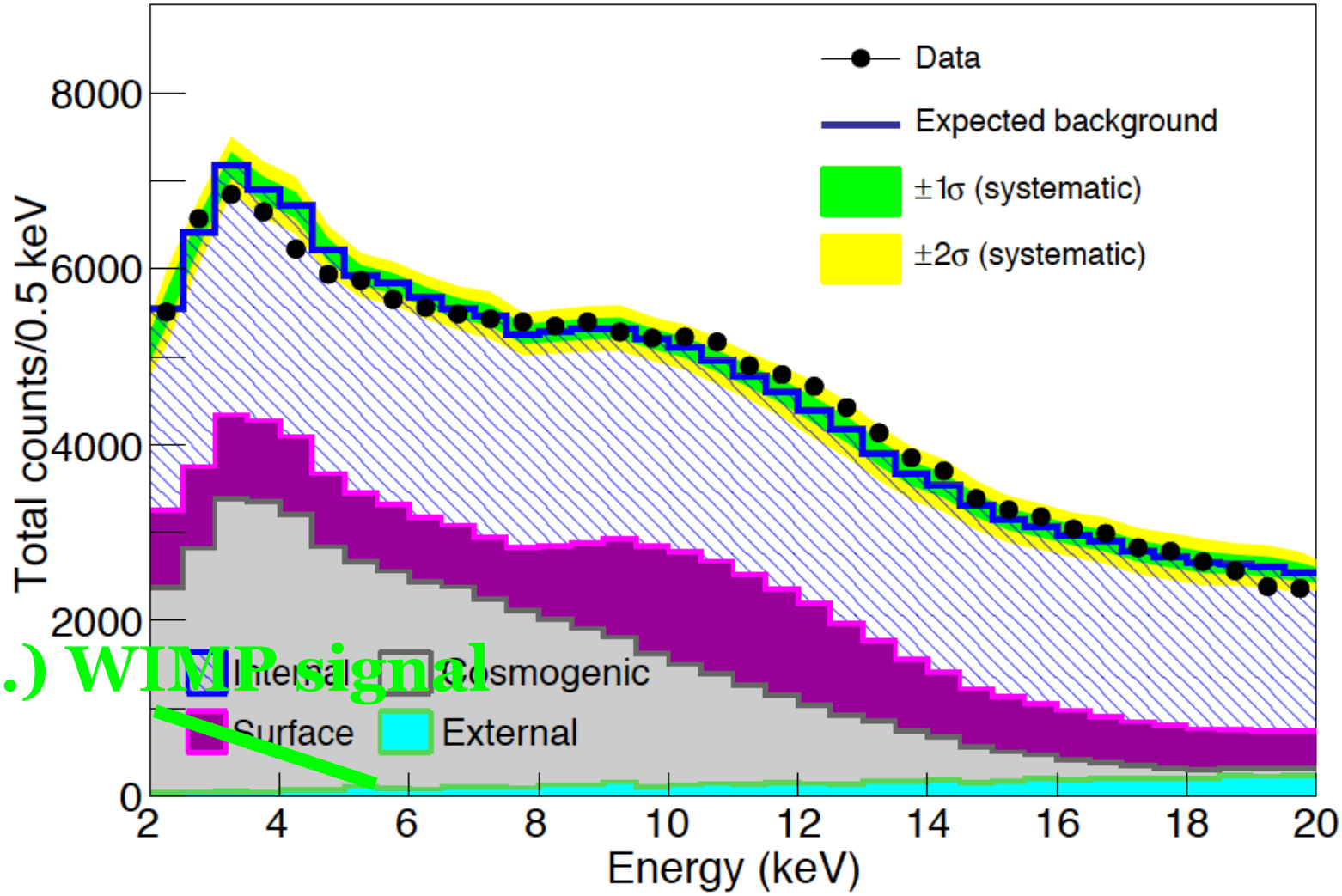
59.5 days data (2-20 keV)



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

59.5 days data (2-20 keV)

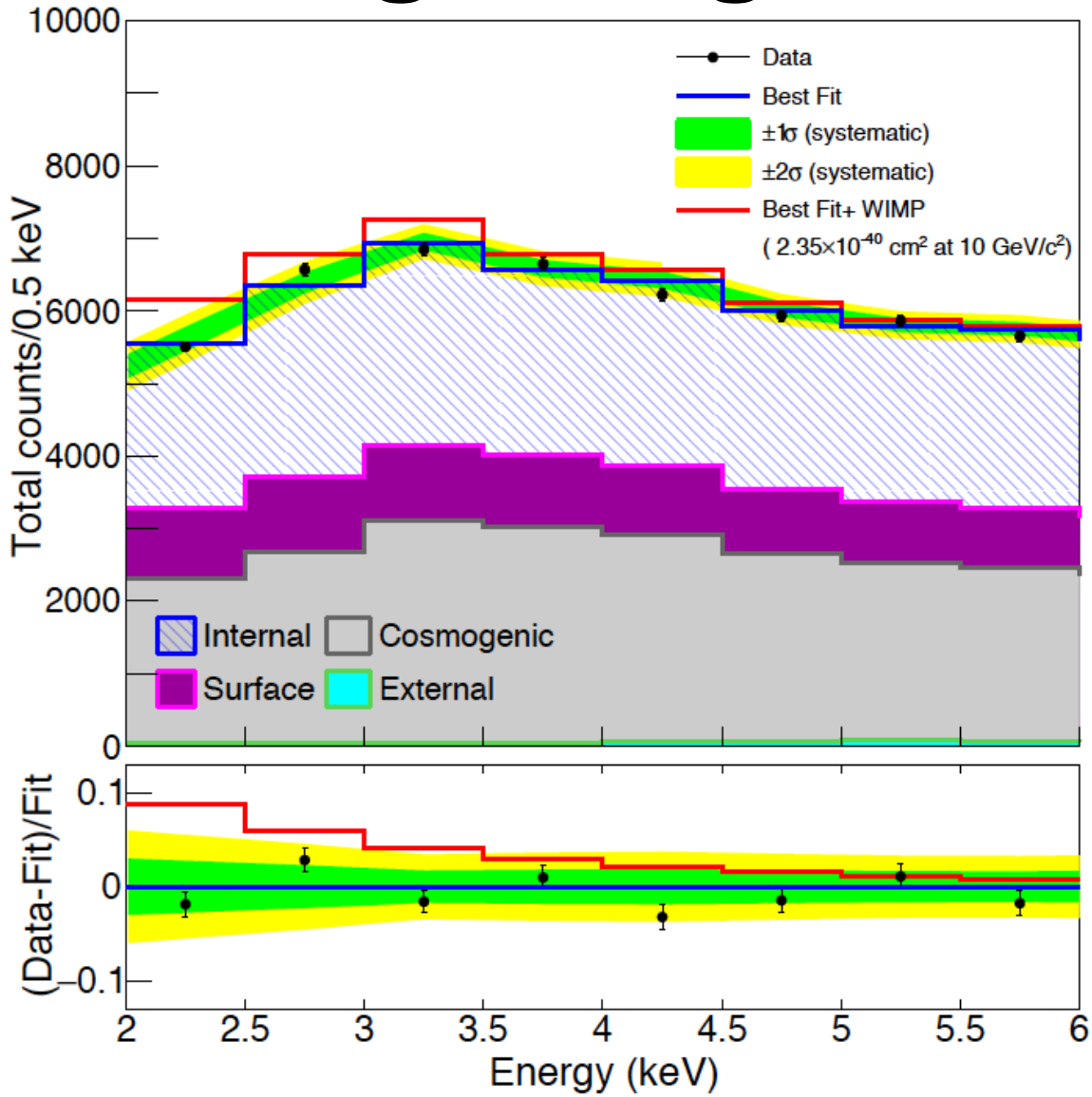


(i.e.) WIMP signal

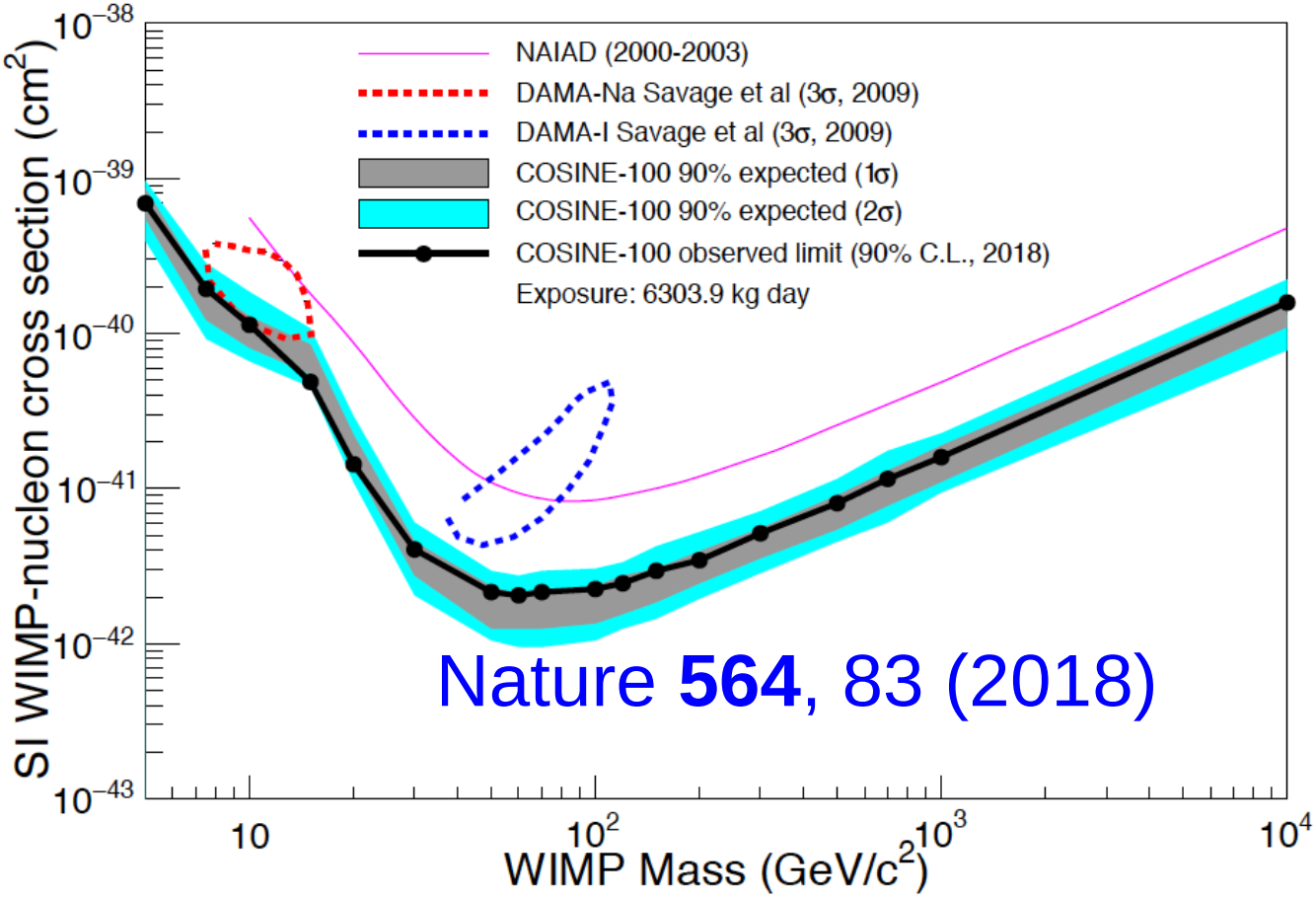
Background modeling was done only using only 6- 2000keV events

Data Fit with 10 GeV WIMP signal

No Sign of signal excess



Limit on WIMP-nucleon cross section



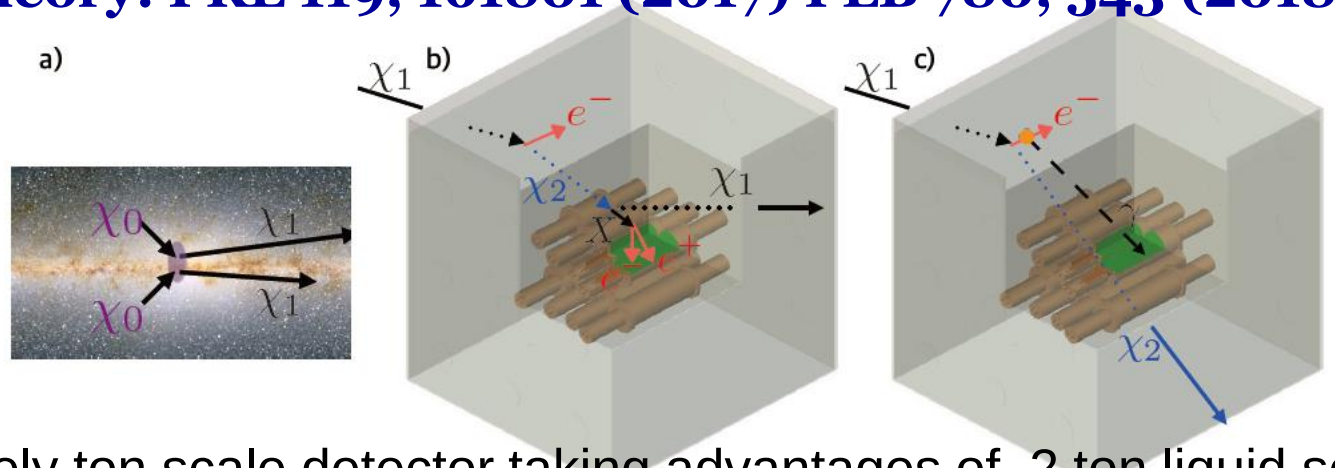
COSINE-100 excludes DAMA/LIBRA-phase1's interpretation with the spin-independent WIMP interaction in Standard Halo Model

First time with same NaI(Tl) target

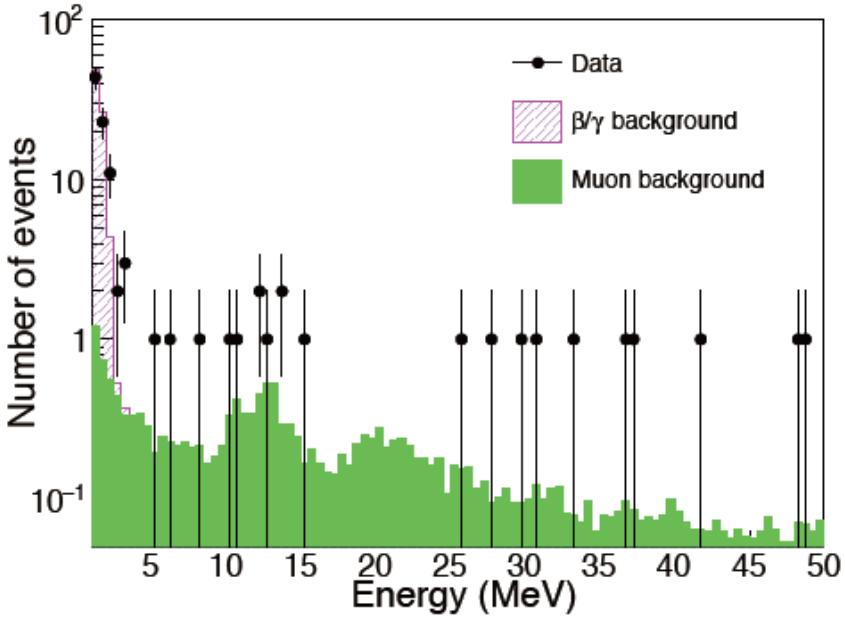
Consistent with other null experiments

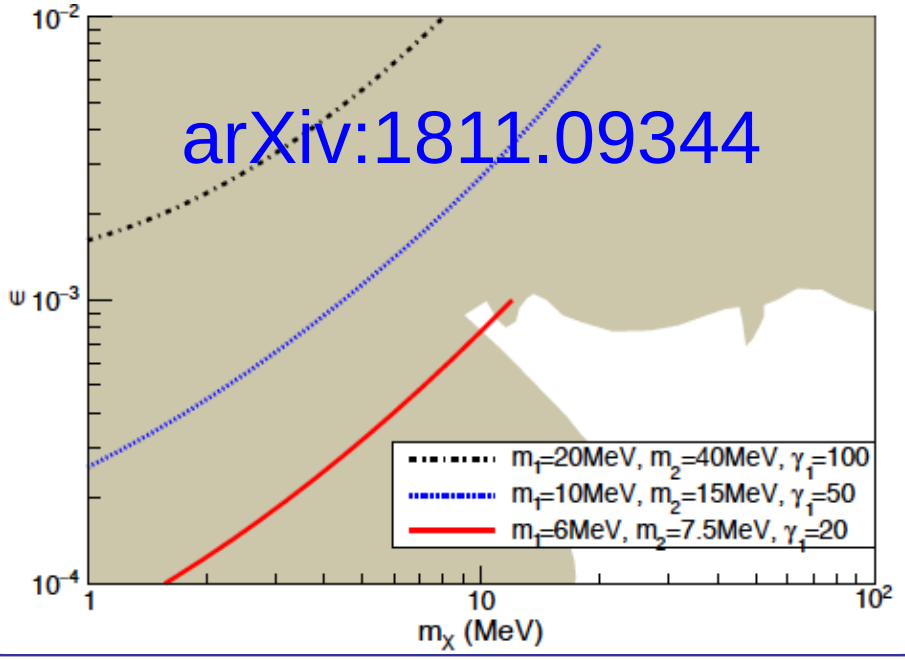
Boosted inelastic dark matter search

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



Effectively ton scale detector taking advantages of 2 ton liquid scintillator

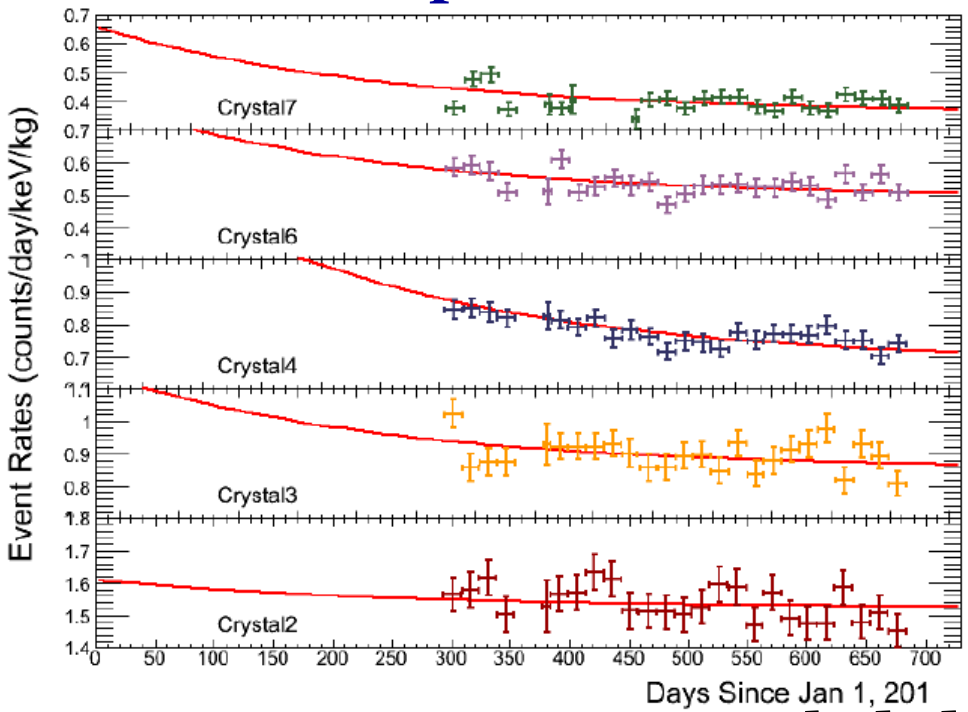




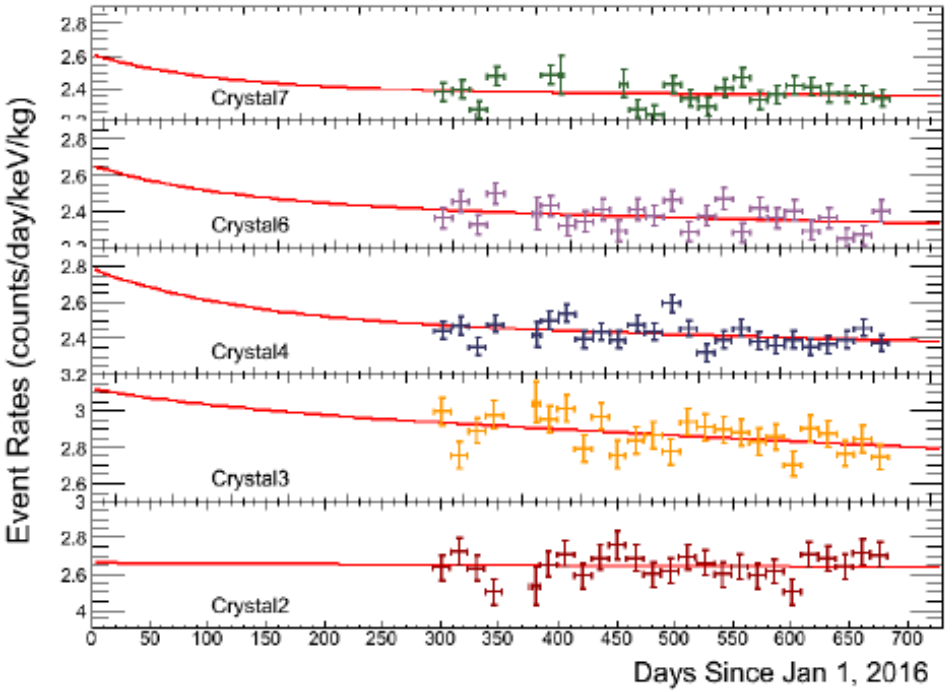
Annual Modulation (Side band study)

- Amount of internal backgrounds were constrained
- Floating ^{3}**H** and other cosmogenic components

Multiple 2-6 keV



Single 6-10 keV



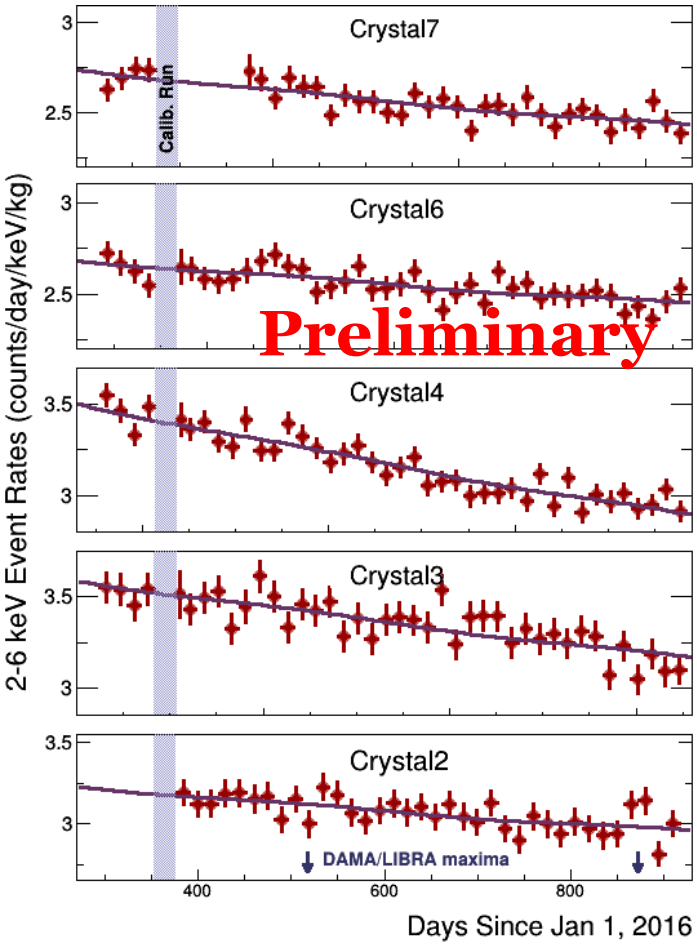
C5 & C8 were excluded due to low light output

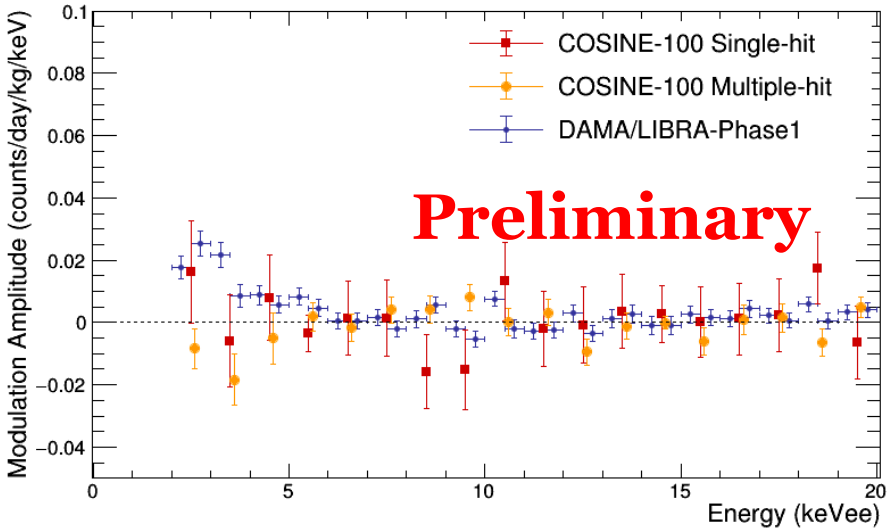
C1 was excluded due to uncontrolled PMT induced noise (discharge)

- Side bands are well explained by known background

Modulation fit result with SET2 (2016.9~2018.7)

2~6 keV result





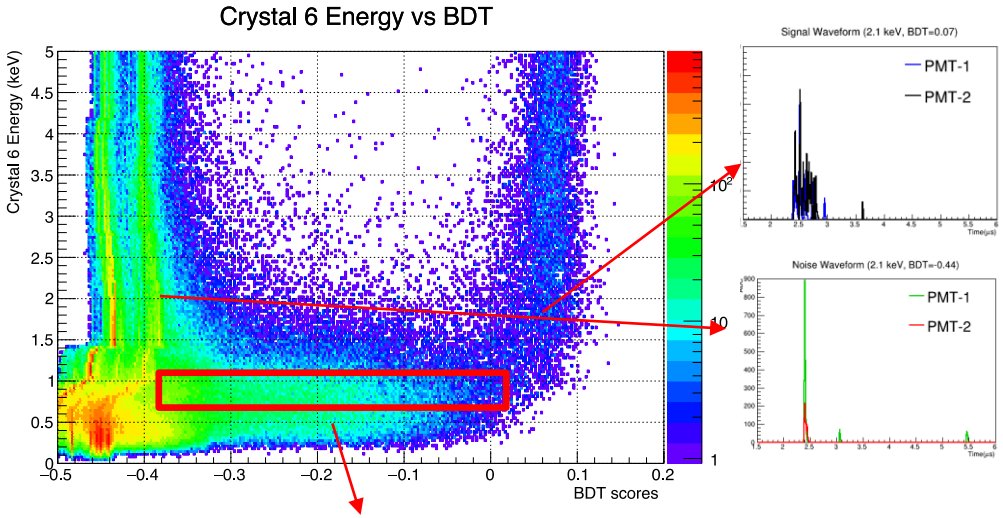
2~6 keV result

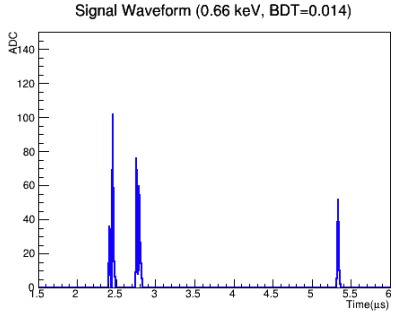
Config	Amplitude	Phase (days)
COSINE-100	$\mathbf{0.0083 \pm 0.0068}$	**152.5 (fixed)**
Without LS	0.0024 ± 0.0073	152.5 (fixed)
DAMA	0.0095 ± 0.0008	152.5 (fixed)
COSINE-100	0.0092 ± 0.0067	127 ± 46
DAMA	0.0096 ± 0.0008	145 ± 5

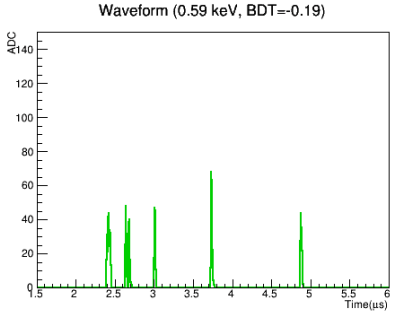
Preliminary

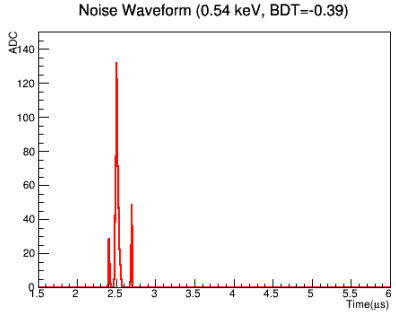
Our data are consistent with both DAMA/LIBRA and no dark matter

Analysis with 1 keV energy threshold





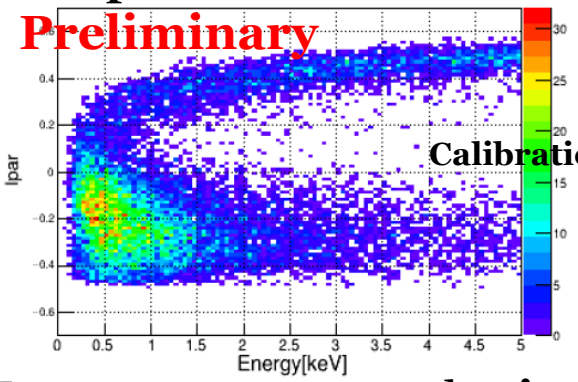




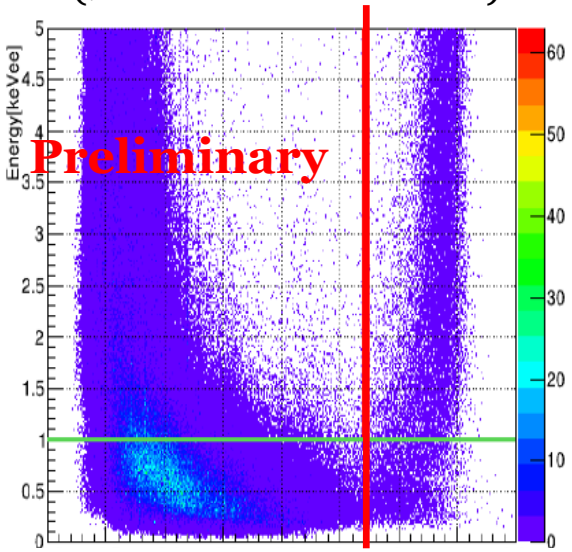
Understand signal-like events and noise-like events at low energies

Develop new parameter to reject noise-like events effectively

Likelihood parameters for noise rejection



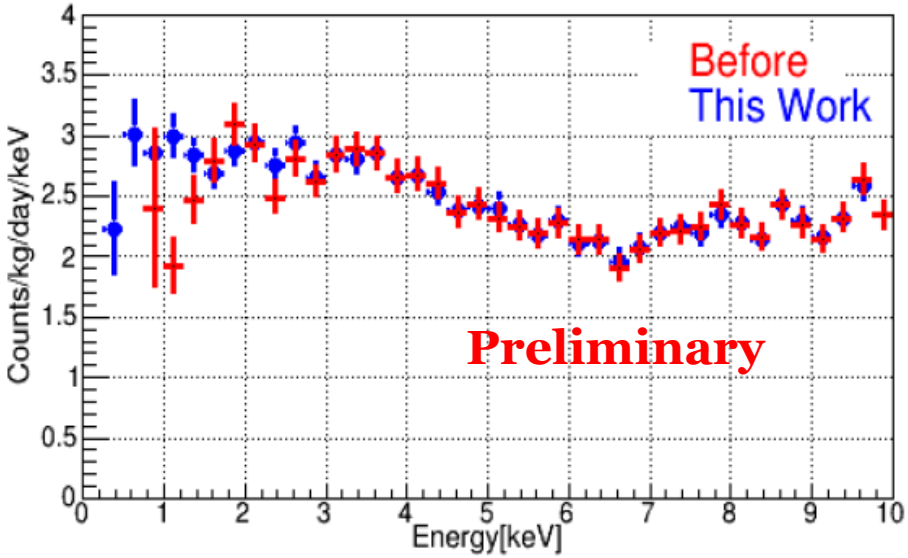
New parameters are used as **inputs for multi-variable technique** (boosted decision tree)



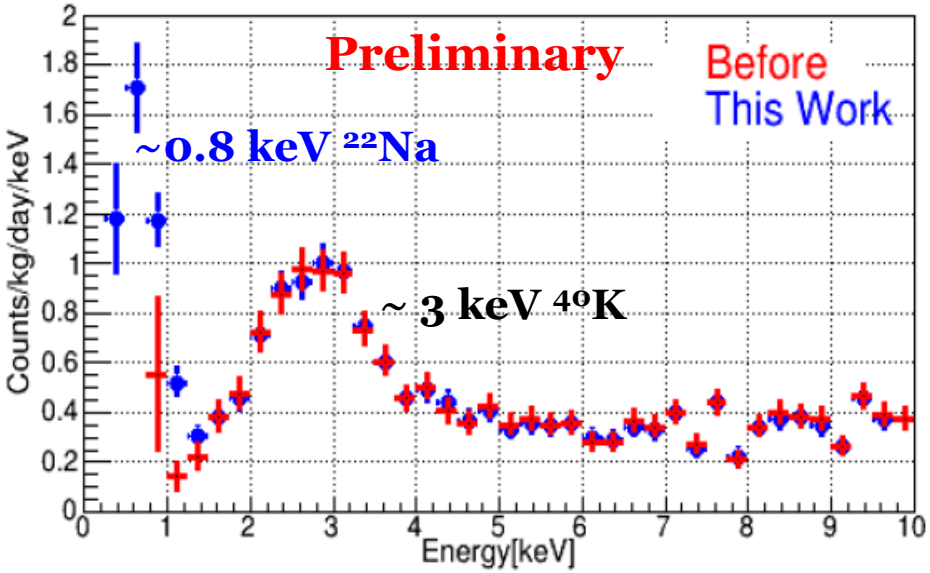
Boosted Decision Tree

Analysis threshold less than 1keV!

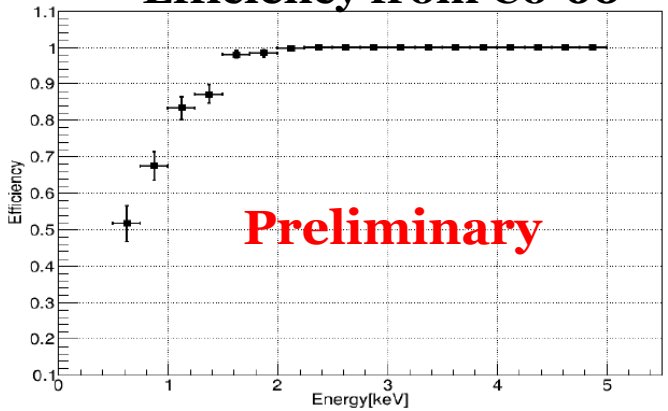
Single hit spectrum



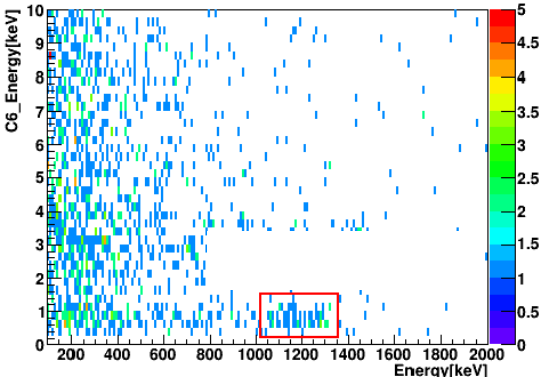
Multiple hit spectrum

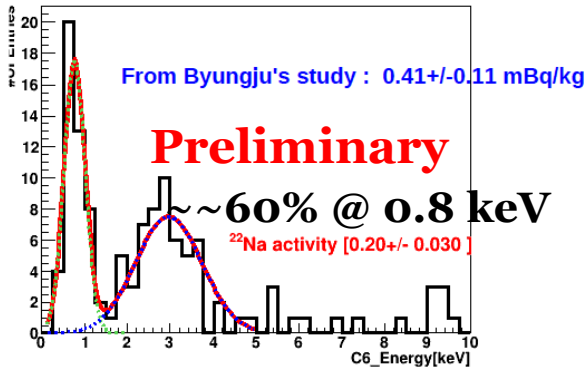


Efficiency from Co-60



Efficiency of Na-22 (0.8 keV)





- We can reduce our threshold below 1keV
- Better comparison with DAMA/LIBRA-phase2

COSINE-200 (Phase-II)

- 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

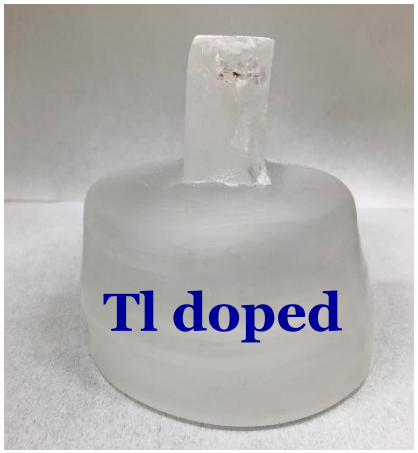
Powder purification performance

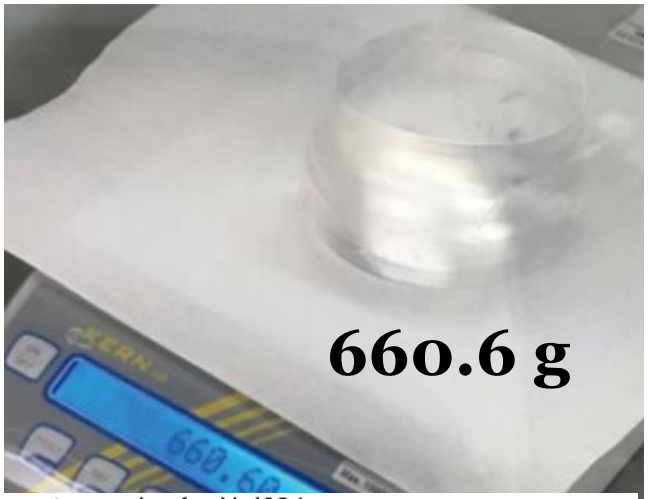
K.A. Shin et al., J. Rad. Nucl. Chem. 317, 1329 (2018)

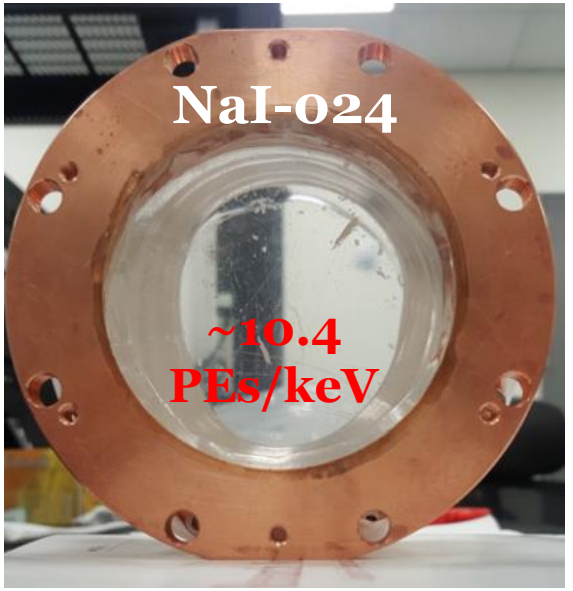
	K (ppb)	Pb (ppb)	U (ppb)	Th (ppb)
Initial NaI	248	19.0	<0.01	<0.01
Purified NaI	<16	0.4	<0.01	<0.01

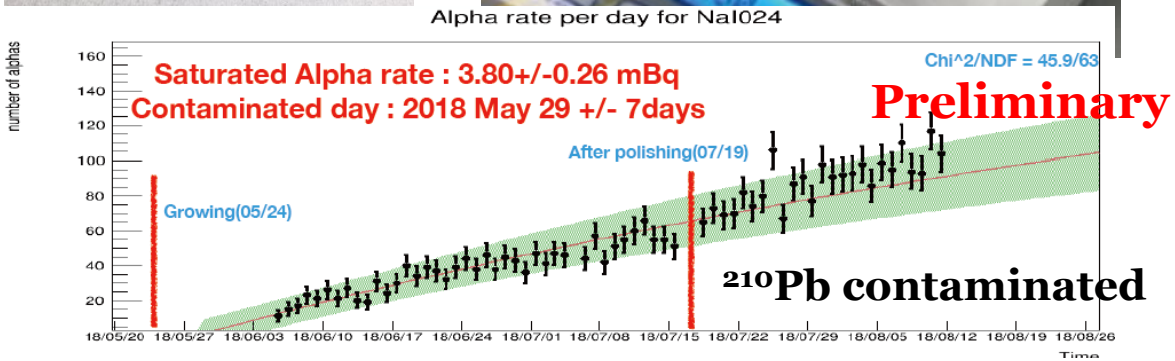
Detector assembly of our own small crystal

May/2018





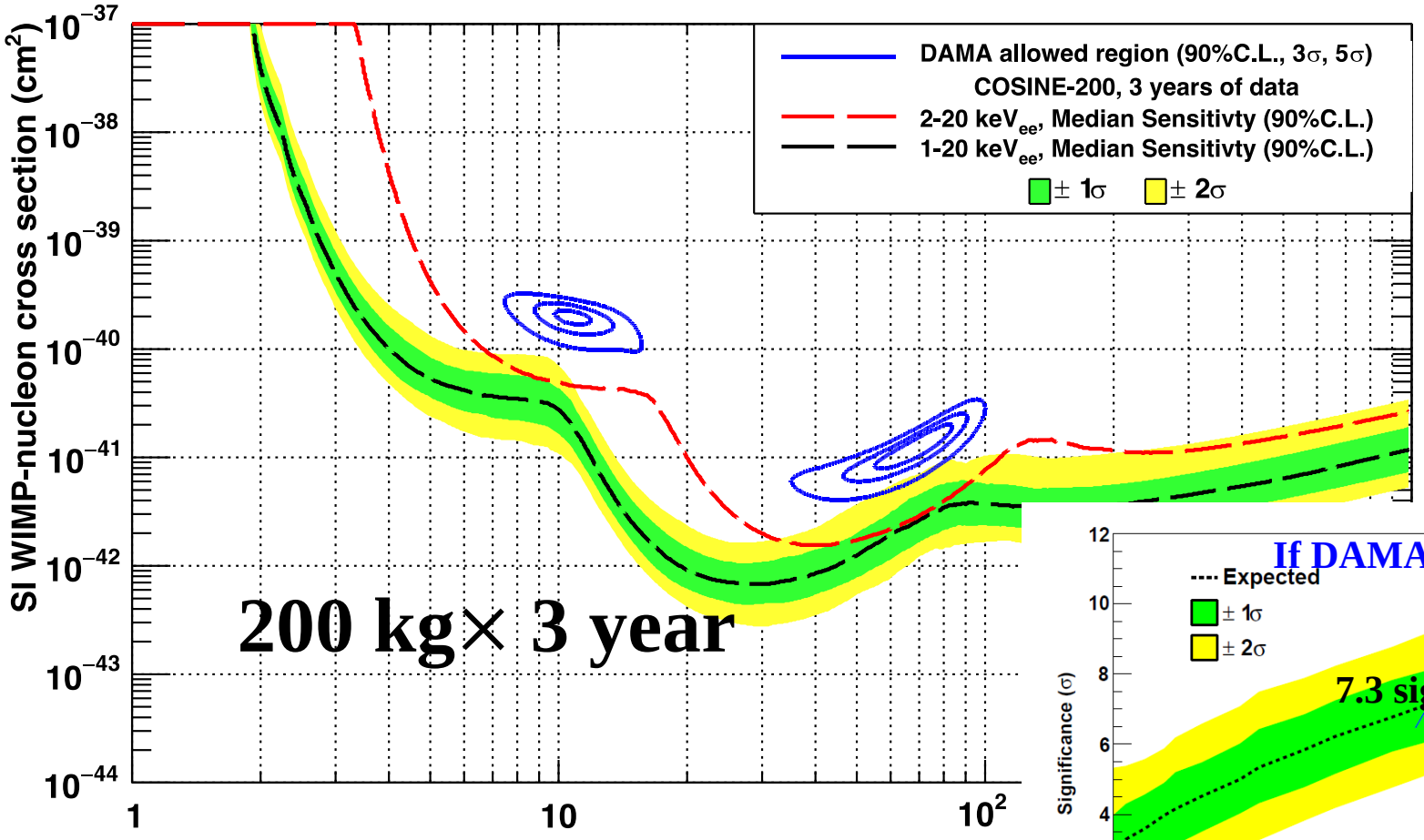


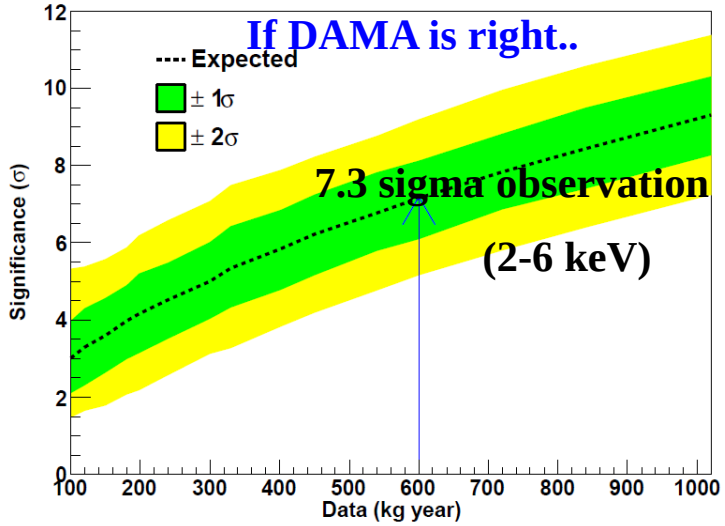


- Demonstrated quick detector assembly and underground measurements!!
- Good optical quality
- Need to improve radiopurity of the crystal
  - Plan to prove the low-background crystal by this summer

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 has been running smoothly for more than 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 the SHM using same NaI(Tl)
- Modulation analysis of COSINE-100 shows consistent result with both DAMA and no dark matter
- Preparing 1keV threshold (or below) analysis

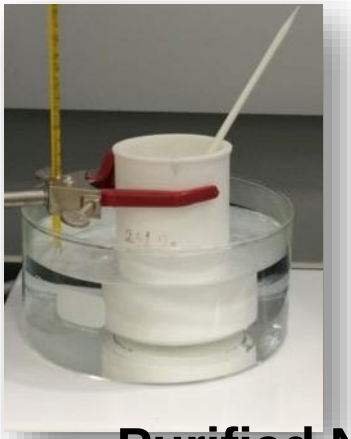
- COSINE-200 is under preparation
  - Unambiguous conclusion for the DAMA/LIBRA modulation signals
  - Goal to start ~200 kg experiment at 2020 with less than 1dru background

Backup

NaI powder purification (Lab experiment)

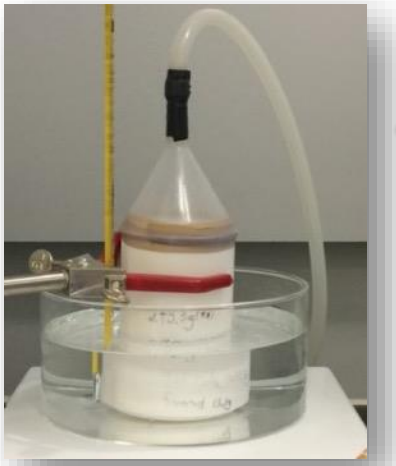
- Recrystallization

Saturated NaI solution @ 25 ° C



T↑ 110 ° C

Evaporation of 40 % of H_2O under vacuum



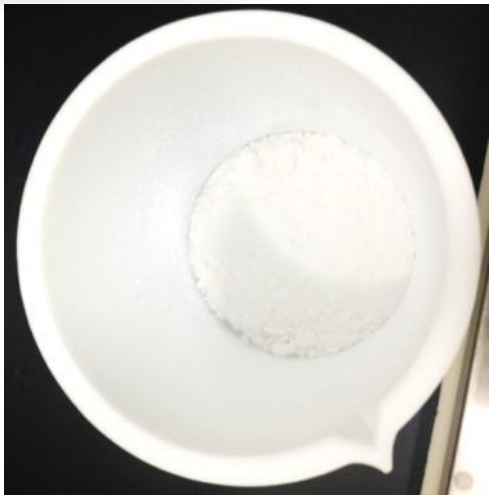
T↓ 25 ° C

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

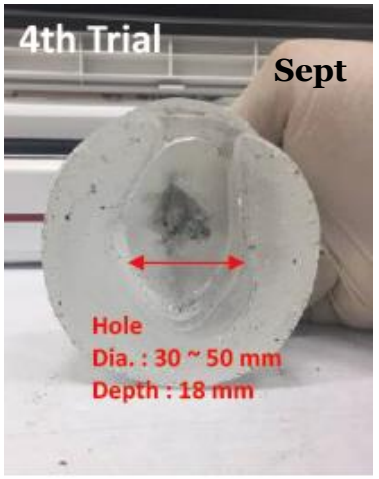
Our system is more effective than small experiment

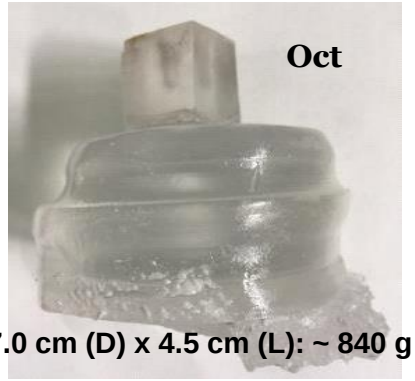
Crystal growing

- Small crystal grower was installed at 2017

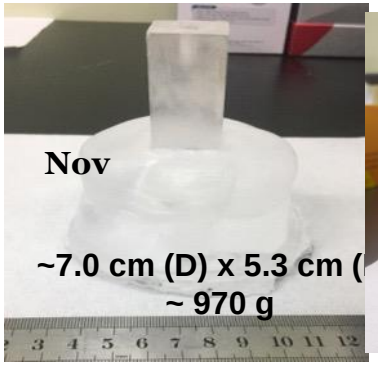
Crucible diameter is $\phi = 15$ cm;
1~2 kg test crystal can be grown

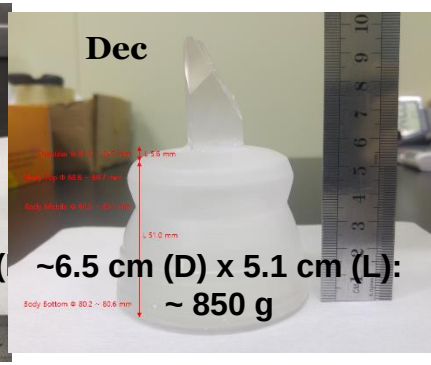
2017 summer





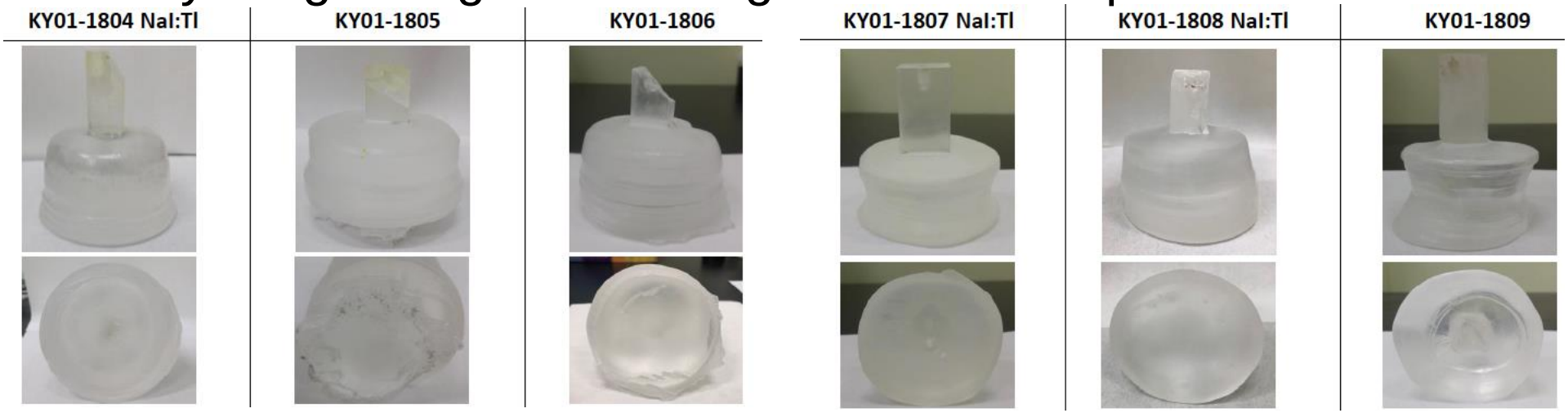
~ 7.0 cm (D) x 4.5 cm (L): ~ 840 g





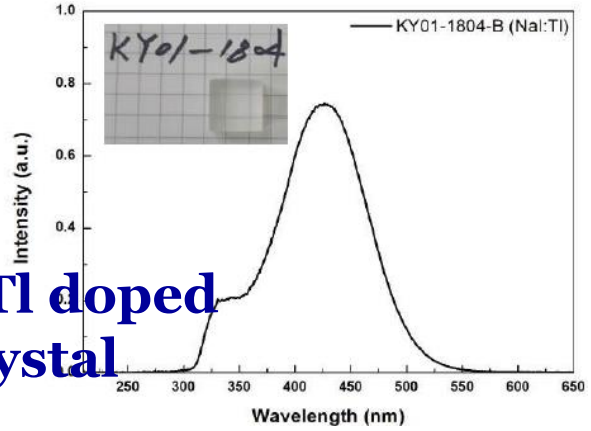
NaI growing @ 2018

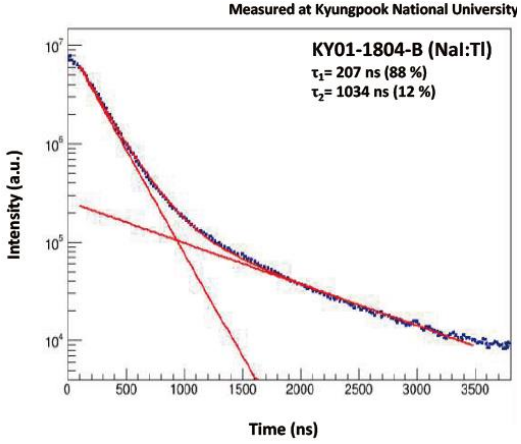
- Crystal growing with small grower is well optimized

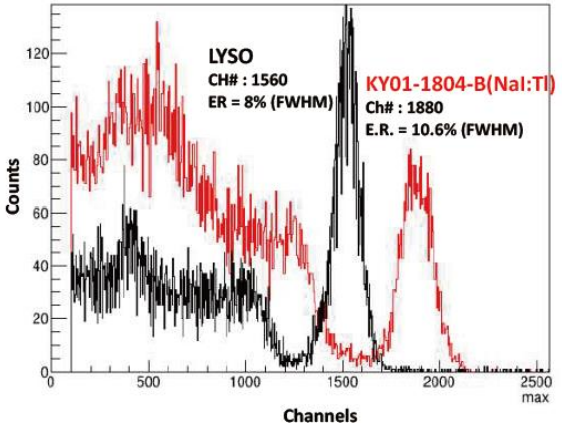


Feb/2018

First Tl doped crystal



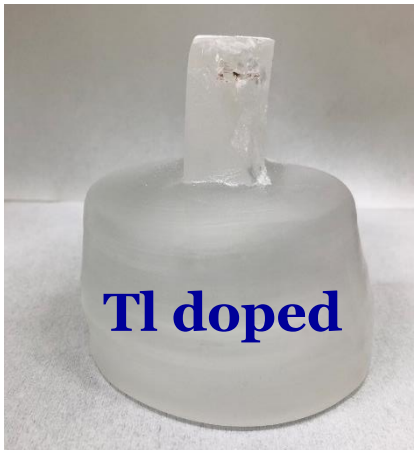


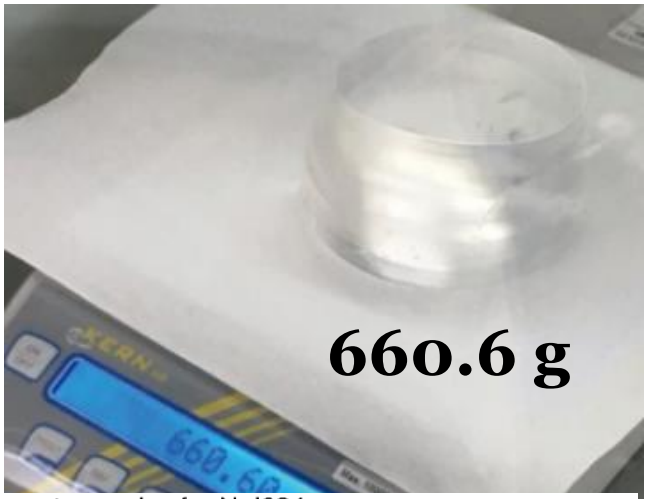


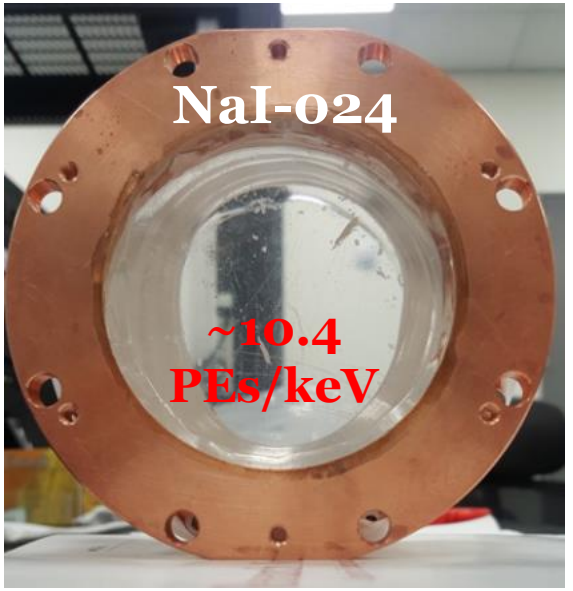
~40,000 Photons/MeV

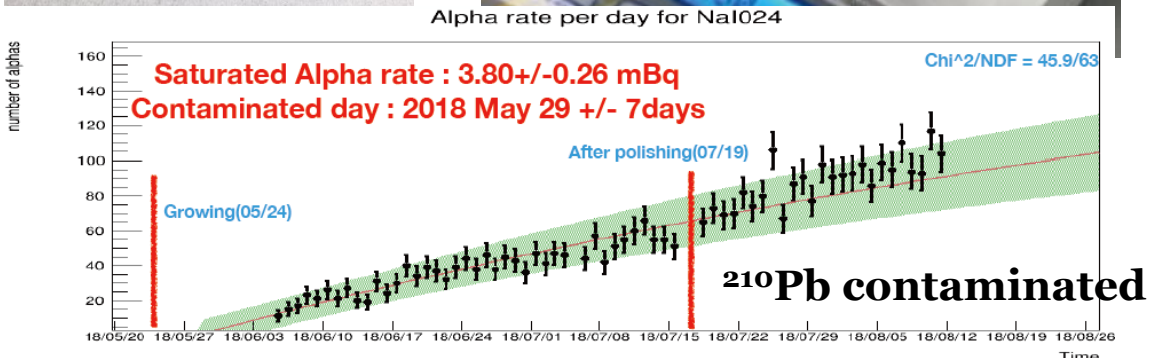
Detector assembly with small crystal

May/2018









Preliminary

- Demonstrated quick detector assembly and underground measurements!!
- Need to prove low background crystal.
- Due to IBS HQ laboratory movement, NaI growing was stopped last six months. It will be resumed from mid-December.

A full size grower

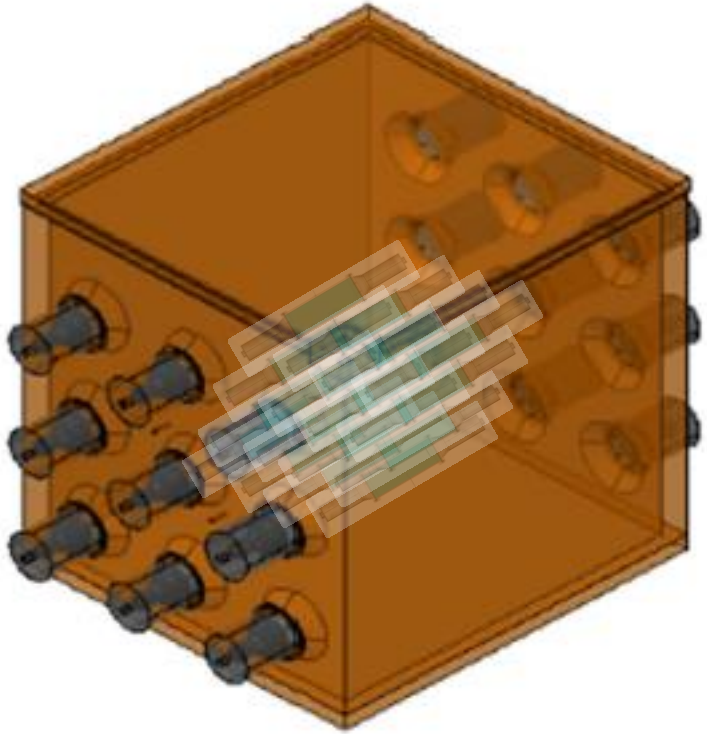
- Full size grower & annealing furnace were installed ($\phi = 60$ cm)
  - ❖ Similar growing machine as the DAMA/LIBRA crystals
  - ❖ Maximum powder loading :120 kg
    - ❑ About three full size detectors (12.5 kg) per ingot

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

COSINE-200

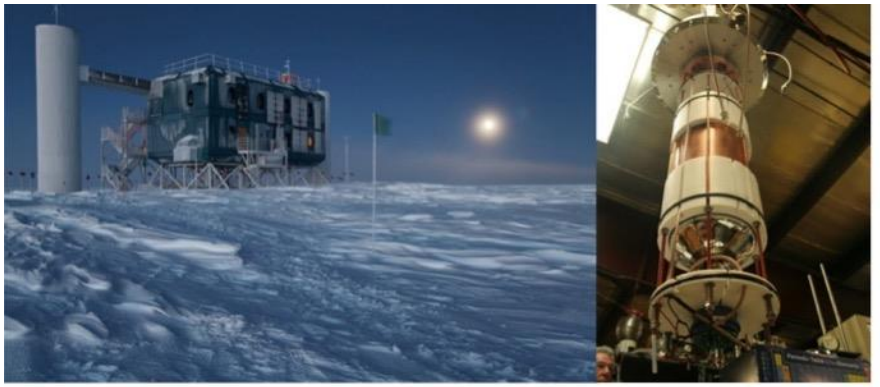
- Current COSINE-100 shield designed to accommodate 16 of 12.5 kg crystals = 200 kg

Total 200 kg



Y2L

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



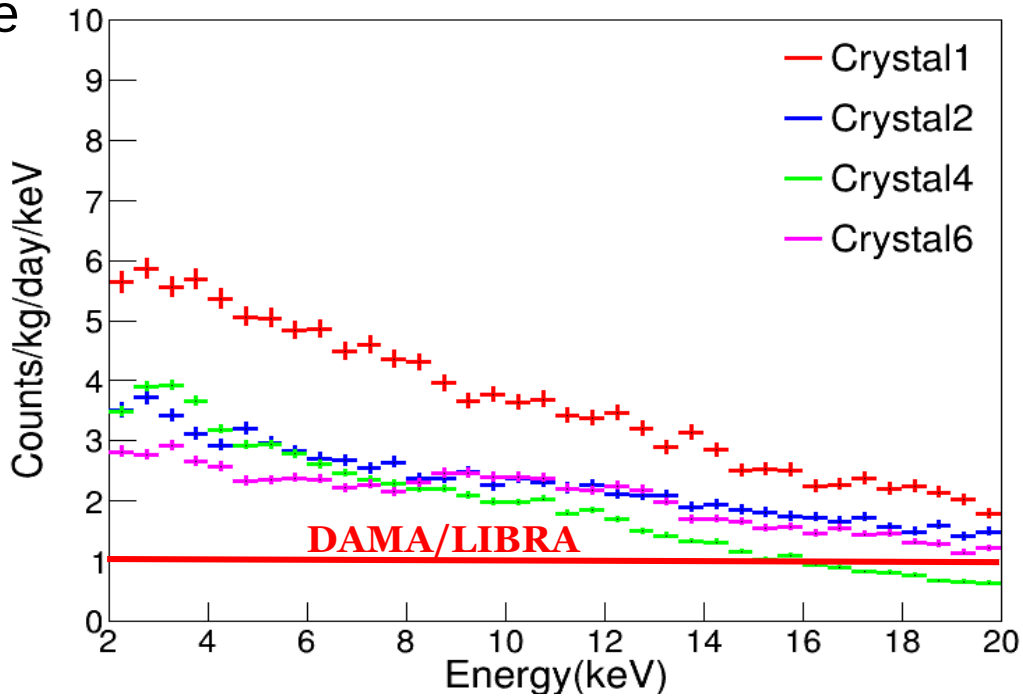
Under consideration

2022-2023 (IceCube upgrade)

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

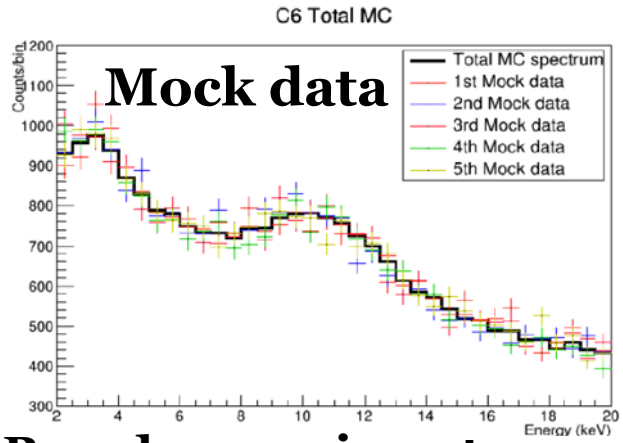


- **Extremely pure crystal** development
  - From initial materials to detector assembly, we need **very careful handling**
  - These are very **difficult jobs** for a private **company**
  - We decided to do our own development for the entire process

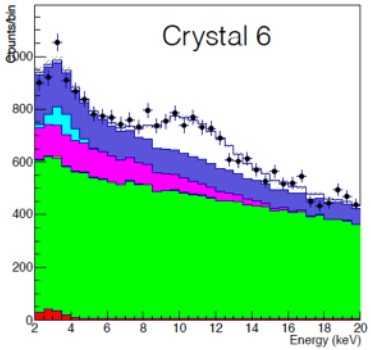
Cosmogenic activation will be naturally reduced if we grow the crystals in Korea

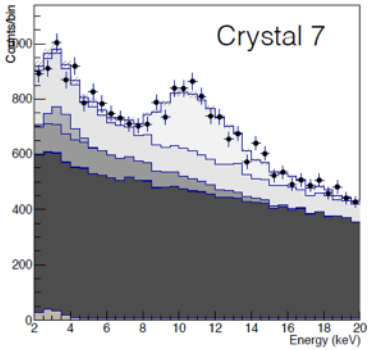
Sensitivity of 59.5 days data for WIMP search

- Generate mock data from MC modeling

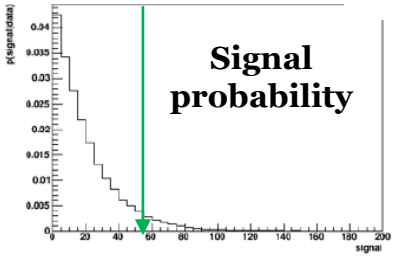


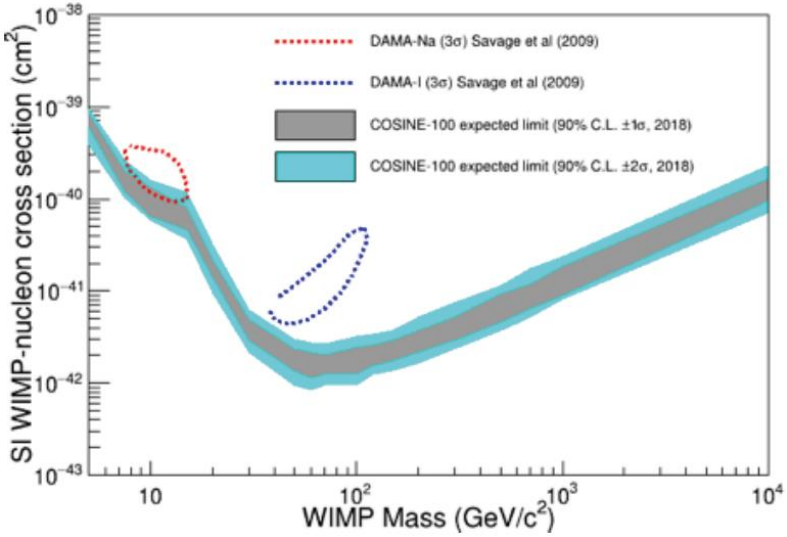
Pseudo experiment





Set 90% CL upper limit





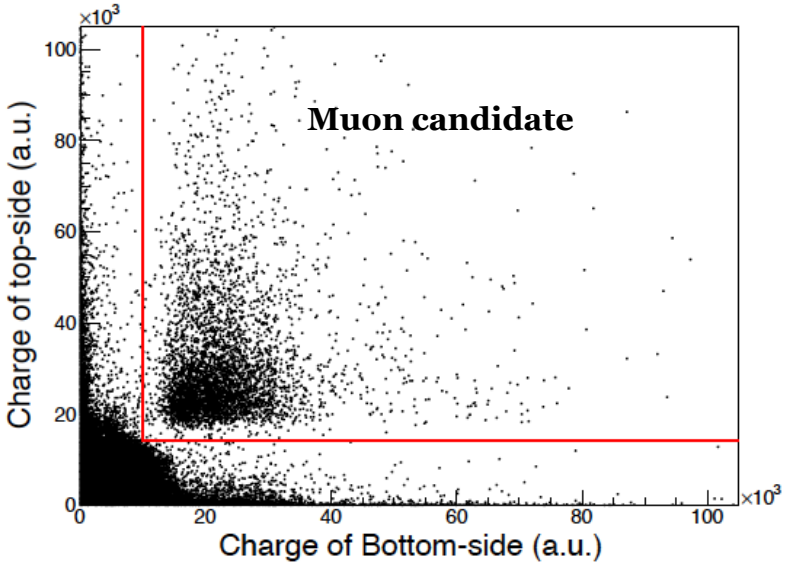
Single hit-spectra from eight crystals are fit simultaneously with an assumed WIMP signal

Same parameters as Savage et al. (2009)

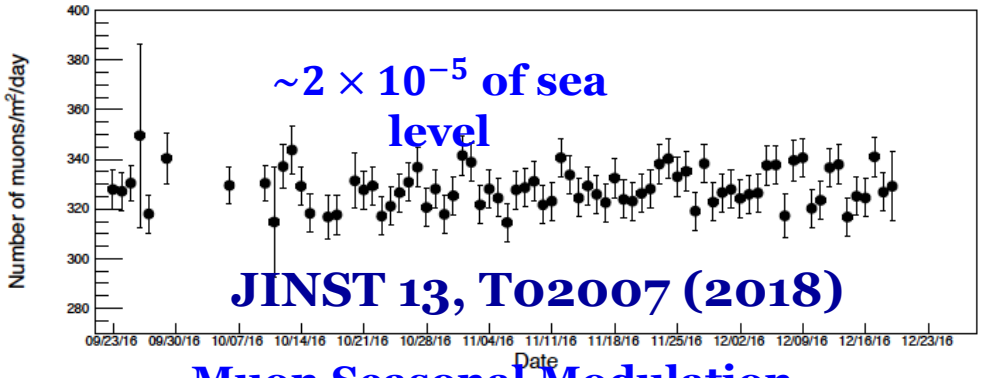
- Sensitivity estimation is done

Muon detector

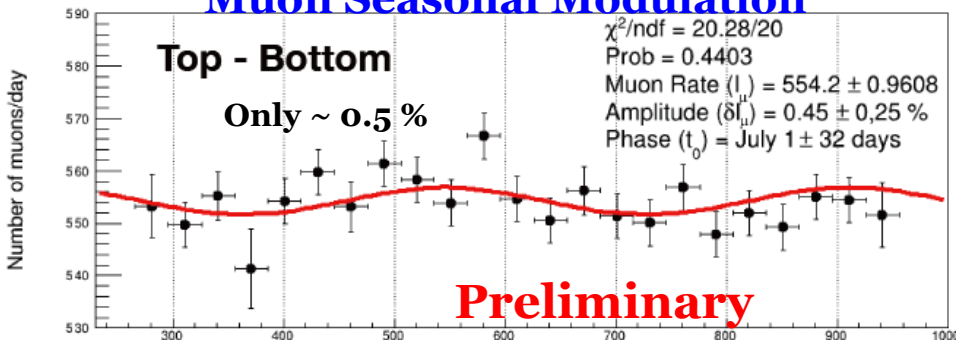
- Outer muon veto consists of 37 plastic scintillator panels



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



Muon Seasonal Modulation

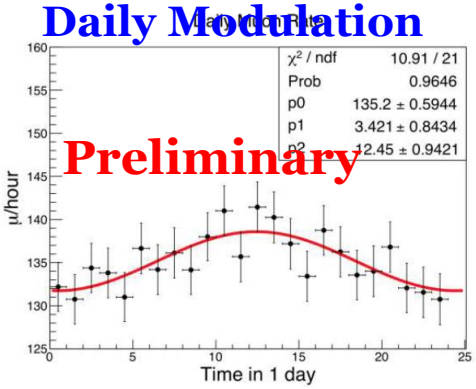


Muon flux has been monitored stably

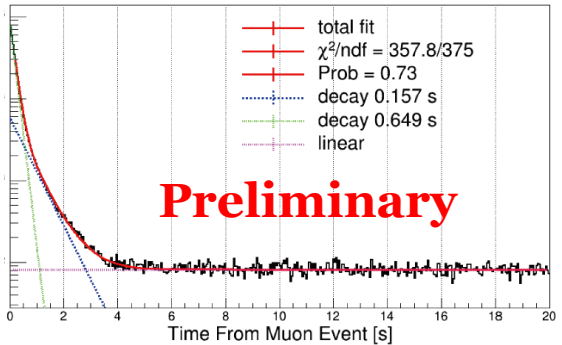
Vetoing of muon correlated events in NaI(Tl) crystals was implemented

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

Daily Modulation



Muon induced events at NaI

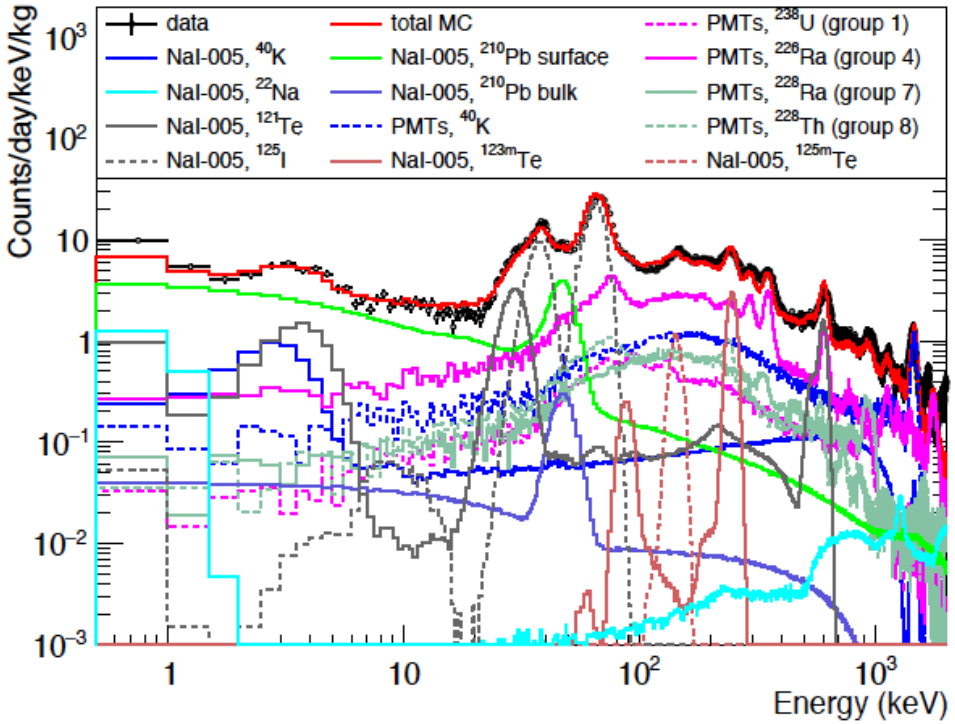


Crystal backgrounds and reduction (KIMS)

K.W. Kim *et al.*, Astropart. Phys. 62, 249 (2015)

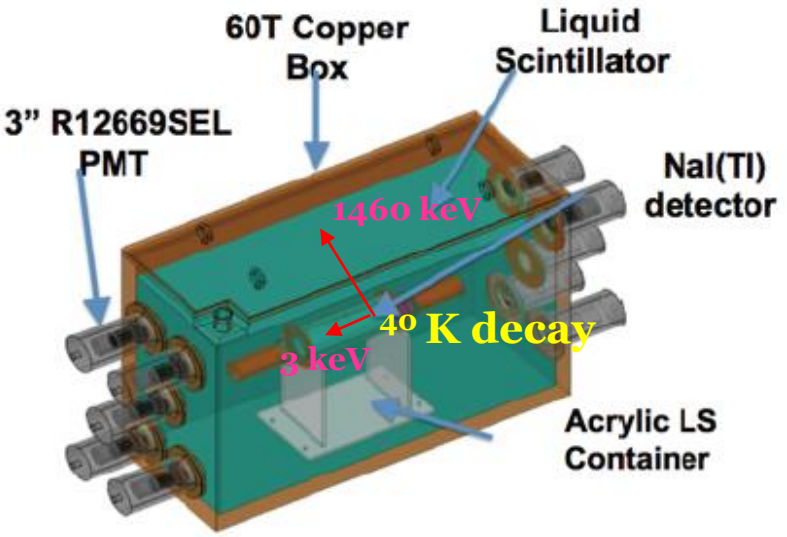
P. Adhikari *et al.*, EPJC 76, 185 (2016)

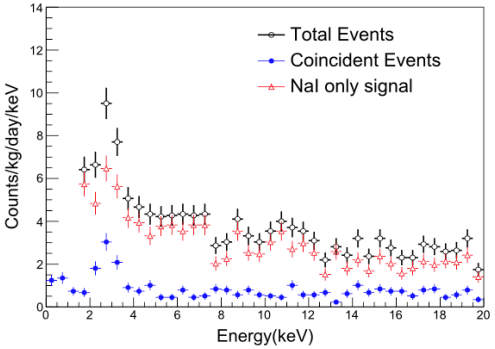
G. Adhikari *et al.*, EPJC 77, 437 (2017)



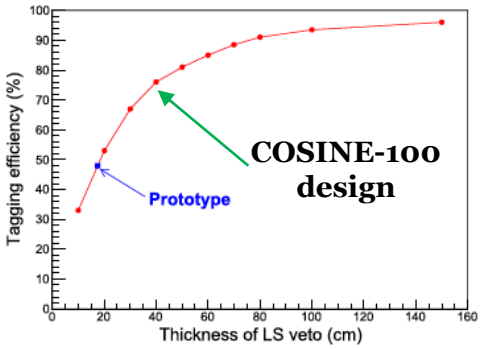
- Internal ^{210}Pb, ^{40}K, and cosmogenics are dominant backgrounds

J.S. Park *et al.*, NIMA, 851 (2017) 103





~50 % ^{40}K tagging

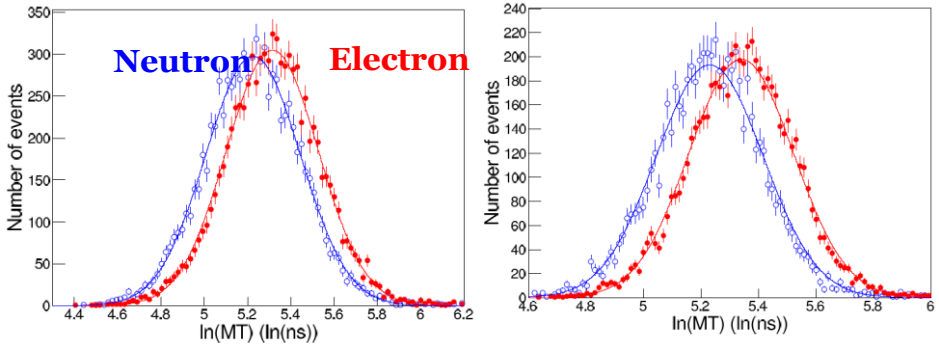


~80% tagging efficiency with 40cm of LS

Pulse shape discrimination of nuclear recoils

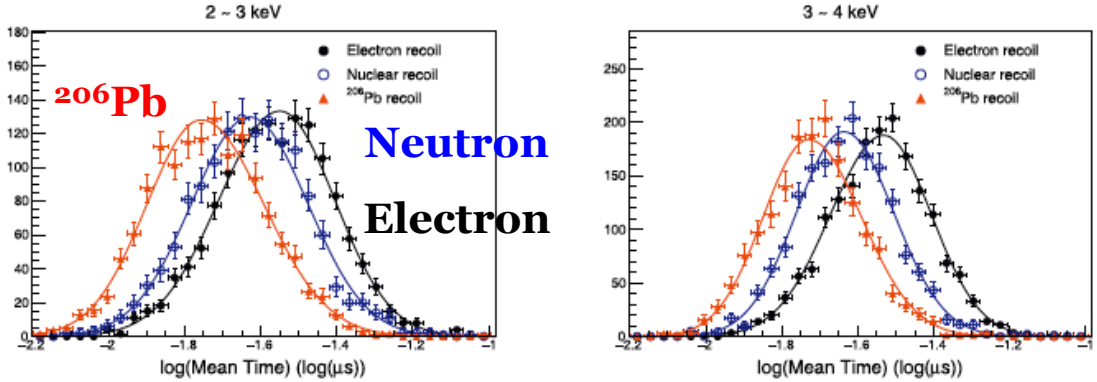
JHEP 08, 093 (2015)

Nuclear recoil discrimination

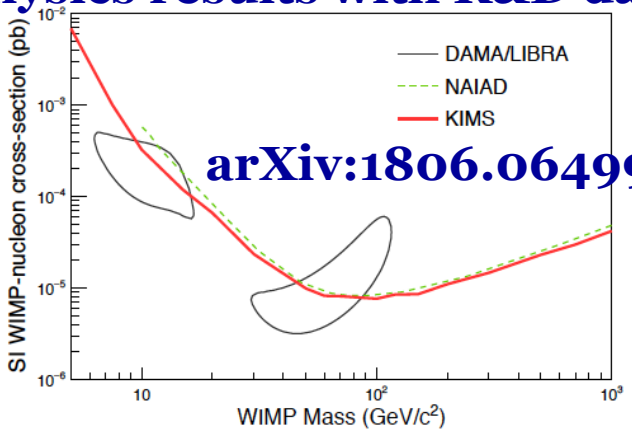


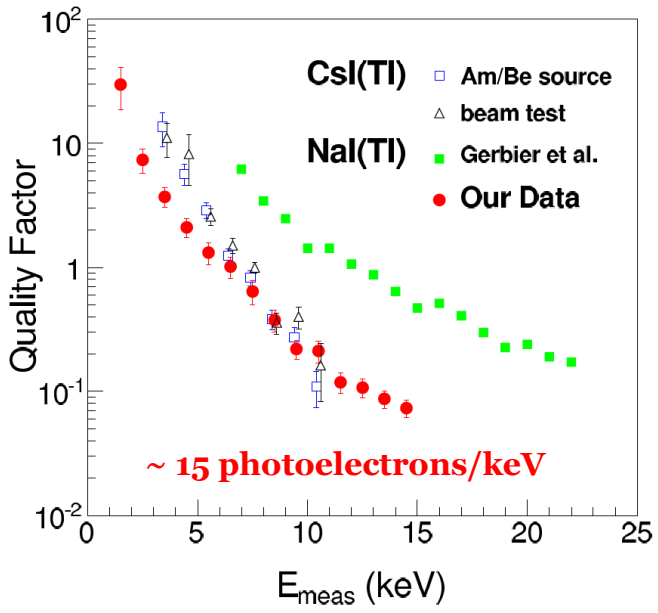
Astropart. Phys. 102, 51 (2018)

Surface alpha recoil discrimination



Physics results with R&D data



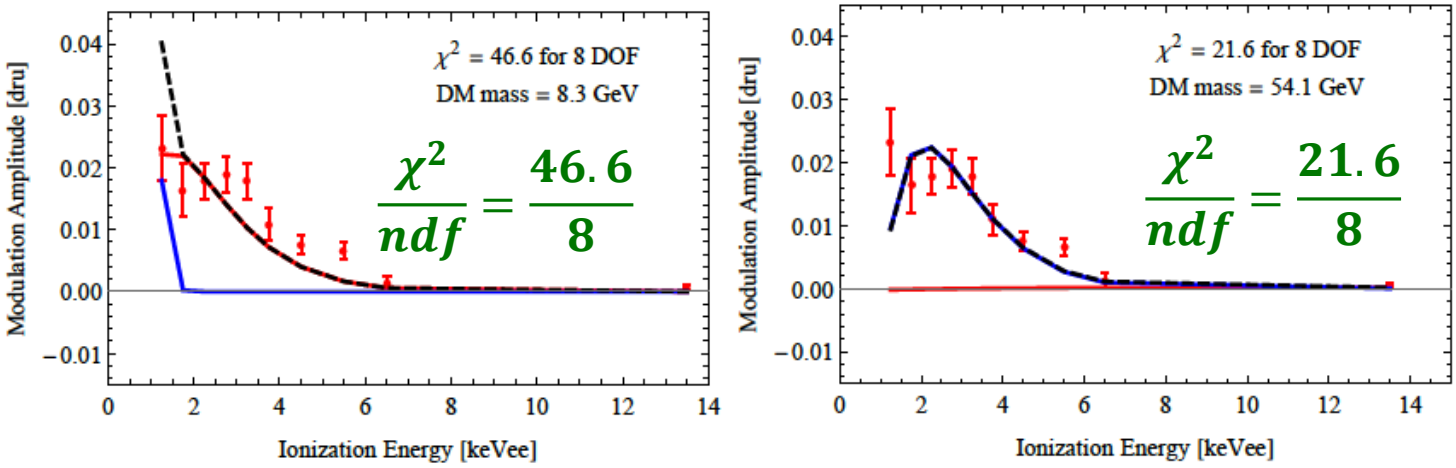


- Demonstrate discrimination of nuclear recoil events
- We can study the annual modulation of the nuclear recoil events

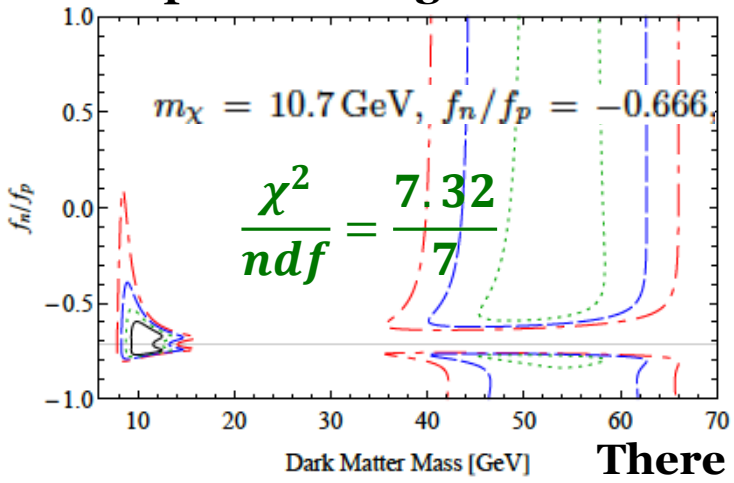
DAMA/LIBRA-phase2 interpretation?

- Typical isospin conserving SI interpretation is not work

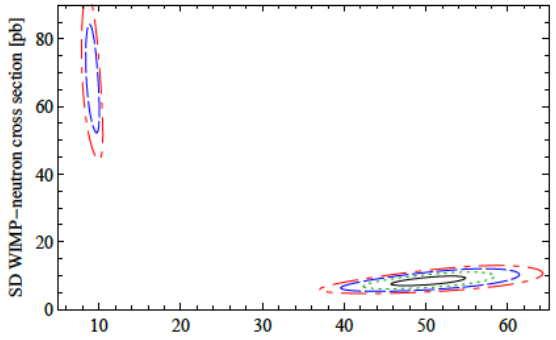
S. Baum, K. Freese, and C. Kelso, arXiv:1804.01231



Isospin violating interaction



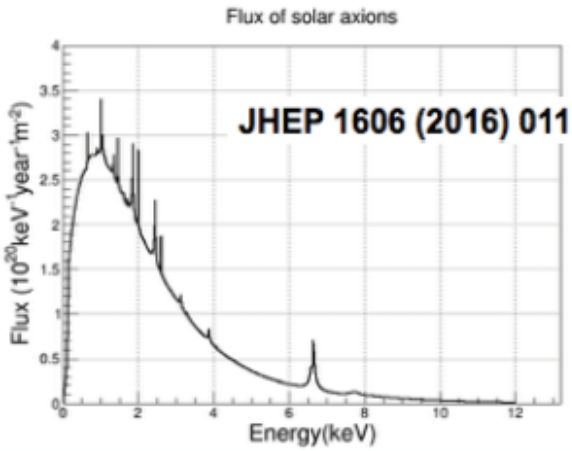
Spin dependent interaction

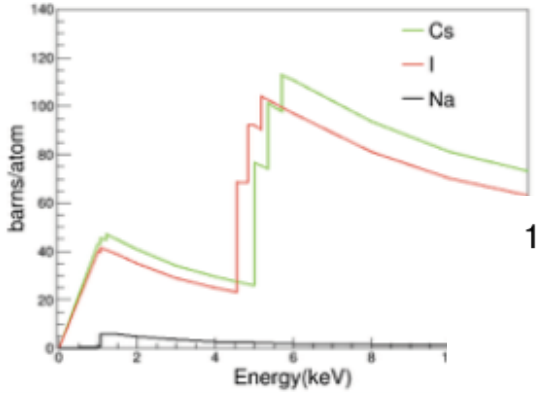


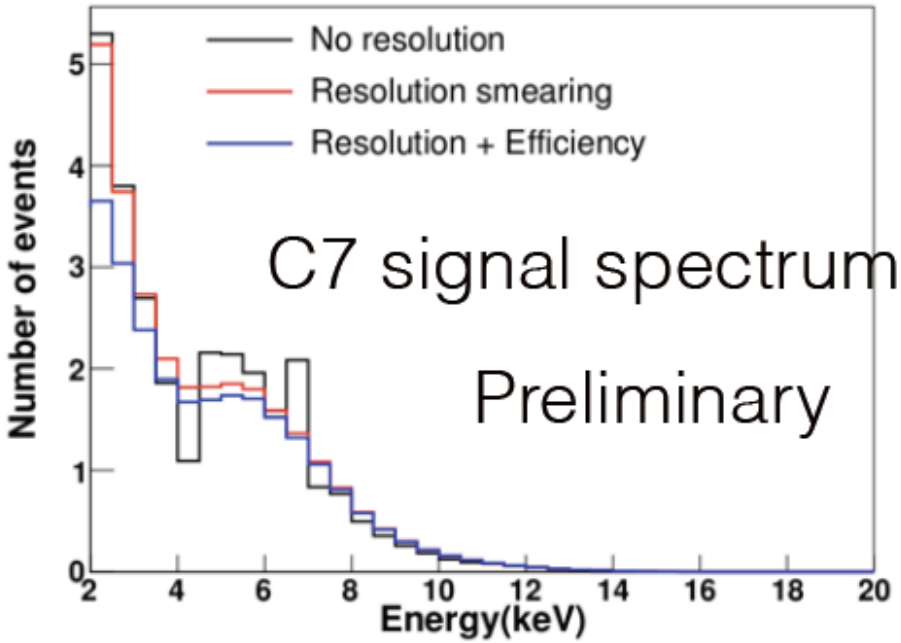
	m_χ [GeV]	σ_i^{SD} [pb]	a_n/a_p	χ^2/dof
n-only	9.3	68.0	∞	24.5/8 (3.1 σ)
	50.2	8.4	∞	12.0/8 (1.4 σ)
p-only	10.8	0.53	0	7.4/8 (0.7 σ)
	41.5	0.38	0	39.8/8 (4.6 σ)
mixed	10.7	1.9	-6.32	7.3/8 (0.7 σ)
	10.8	0.47	0.665	7.3/8 (0.7 σ)
	44.2	0.43	-7.46	9.6/8 (1.0 σ)

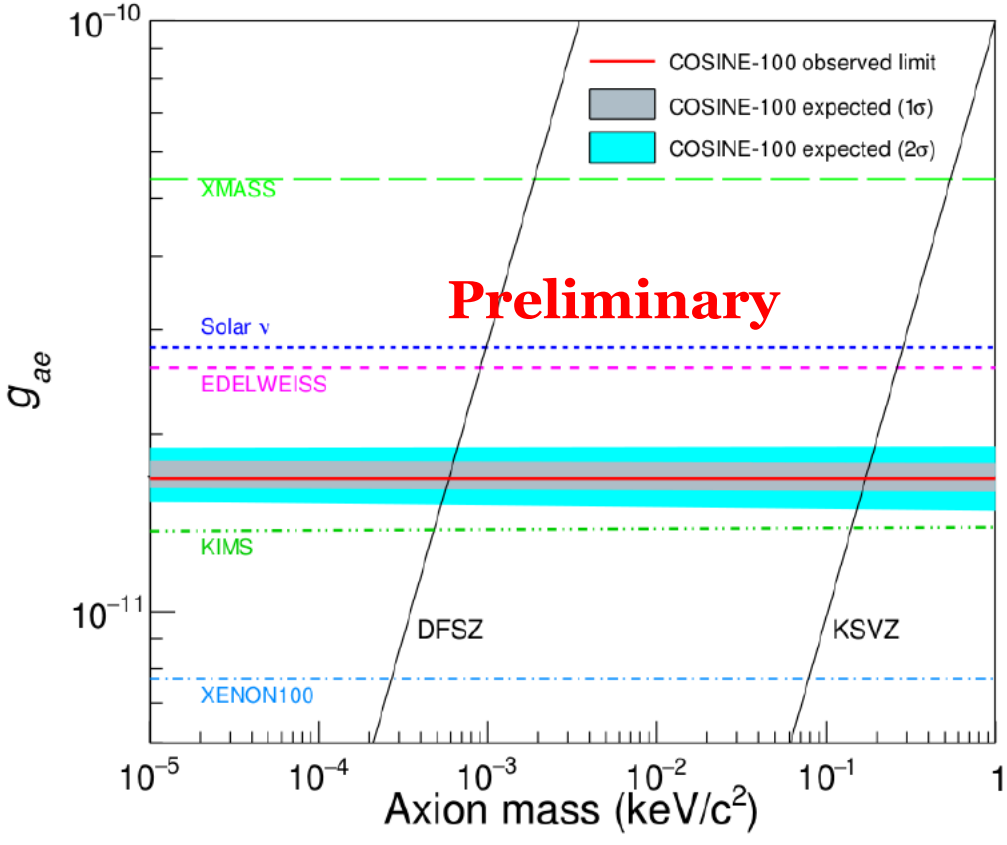
There is possible parameter spaces to interpret DAMA/LIBA phase2

Solar axion search



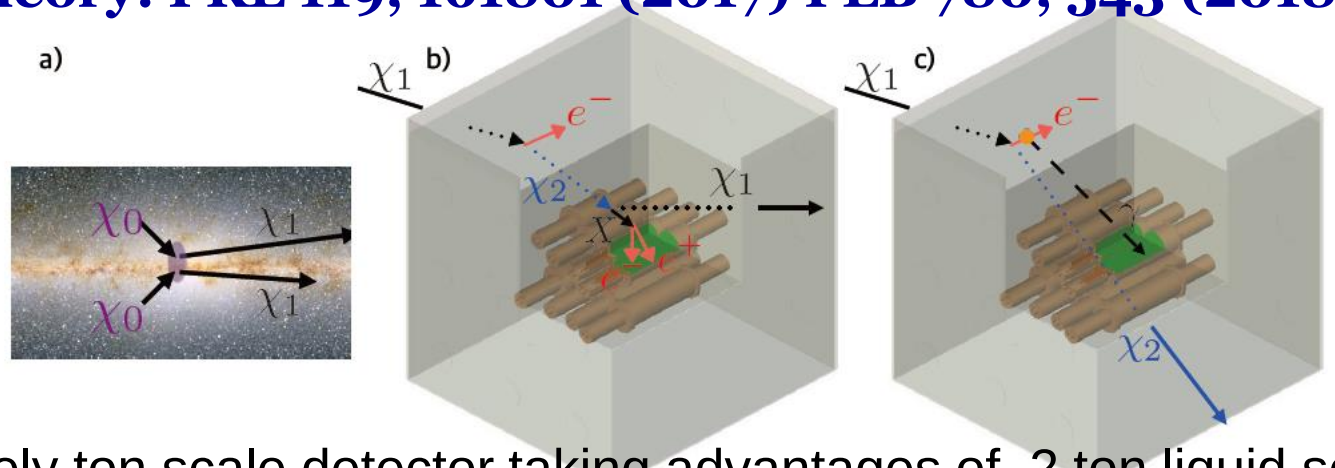






Boosted inelastic dark matter search

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



Effectively ton scale detector taking advantages of 2 ton liquid scintillator