# COSINE experiment
## A WIMP dark matter search experiment with NaI(Tl) detectors

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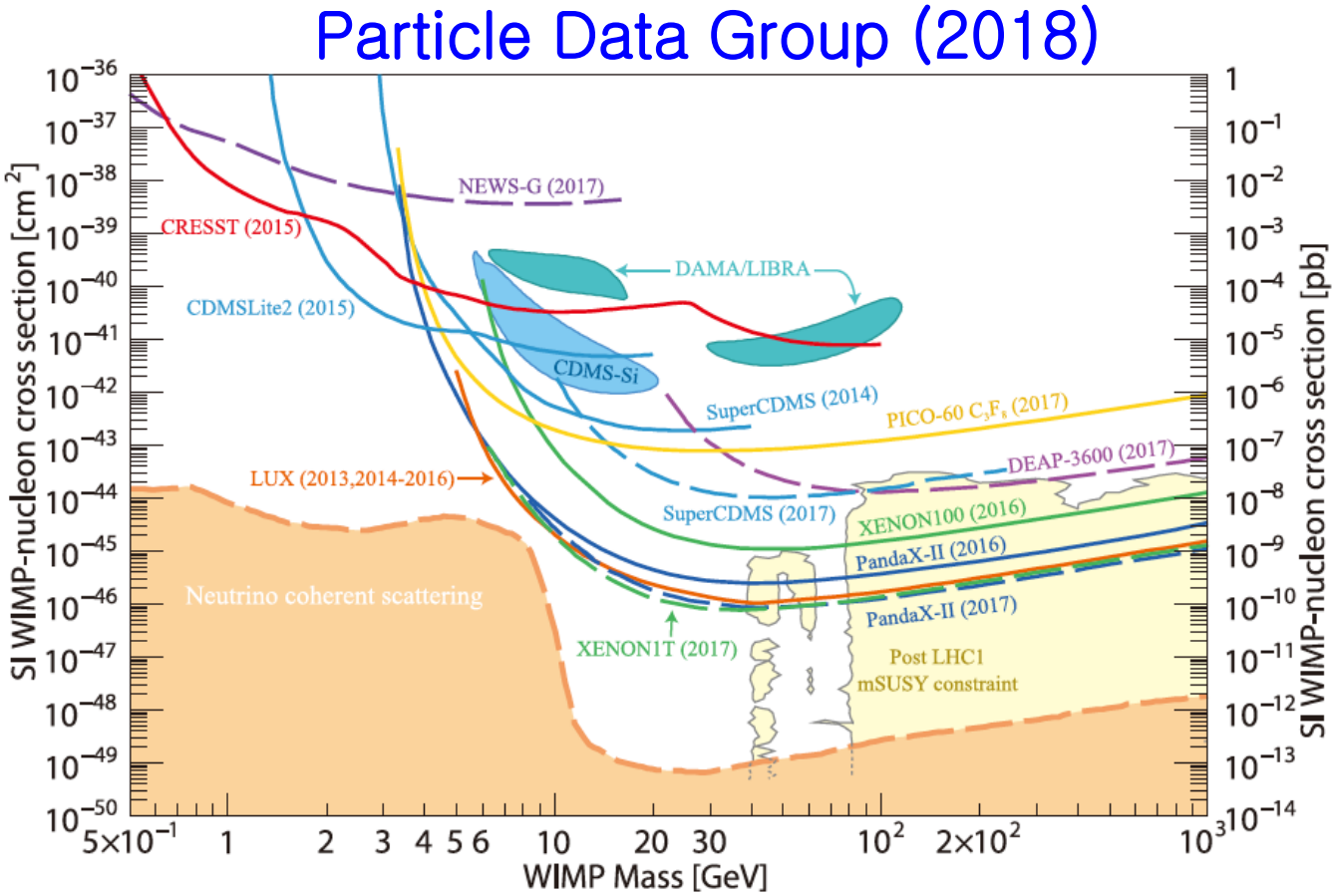
Center for Underground Physics (CUP)

Institute for Basic Science (IBS)

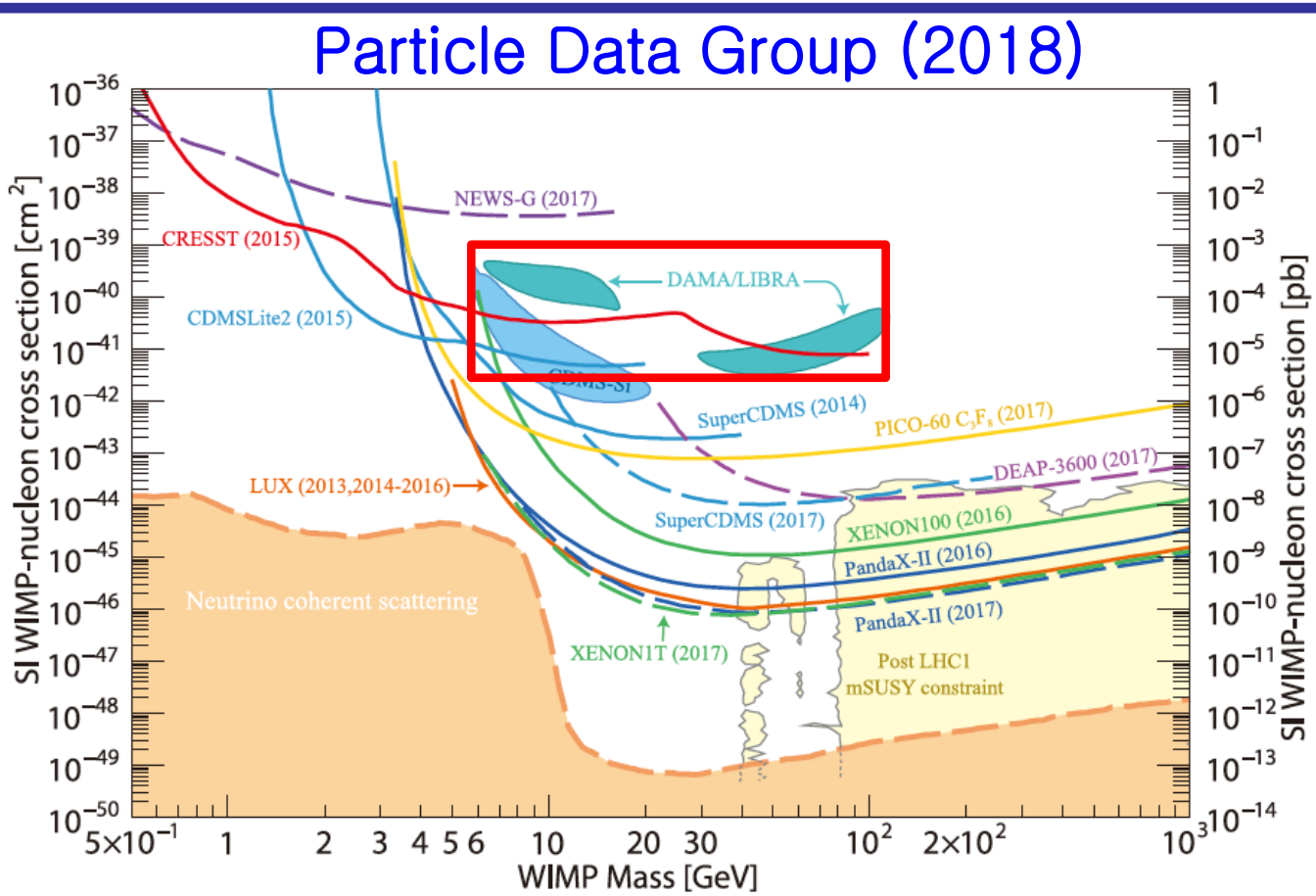
*IBS Conference on Dark World Nov 4 - 7, 2019*

# Current status of direct dark matter searches




- High mass limits are now at $10^{-46}$cm$^2$ for WIMP mass 50 GeV
- Extending searches for lower WIMP mass region
- Unresolved mystery from DAMA/LIBRA

# Current status of direct dark matter searches

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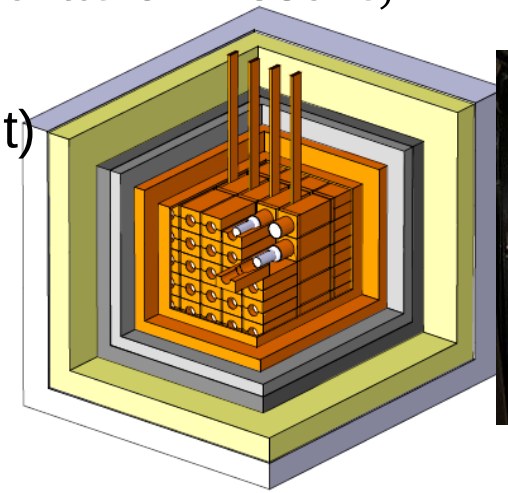
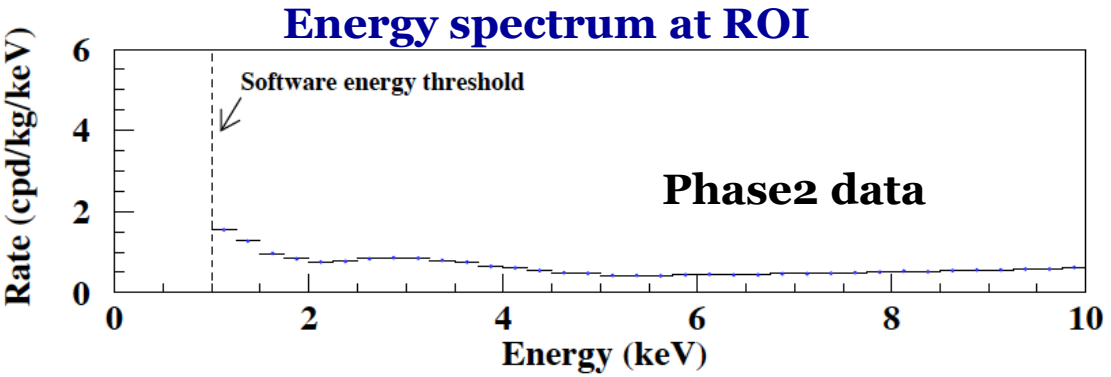
- Unresolved mystery from DAMA/LIBRA

# DAMA/LIBRA experiment

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


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

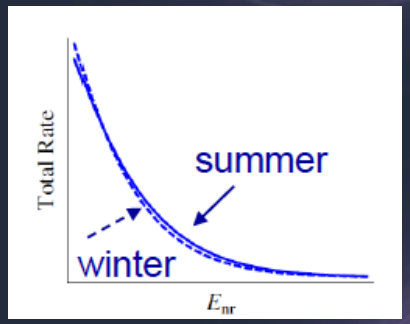




# Annual modulation of dark matter

**The Highs**

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




**The Lows**

In December, Earth moves at its slowest speed.



**June/2nd**

Sun and Earth move in the same relative direction

Earth passes through many dark matter particles

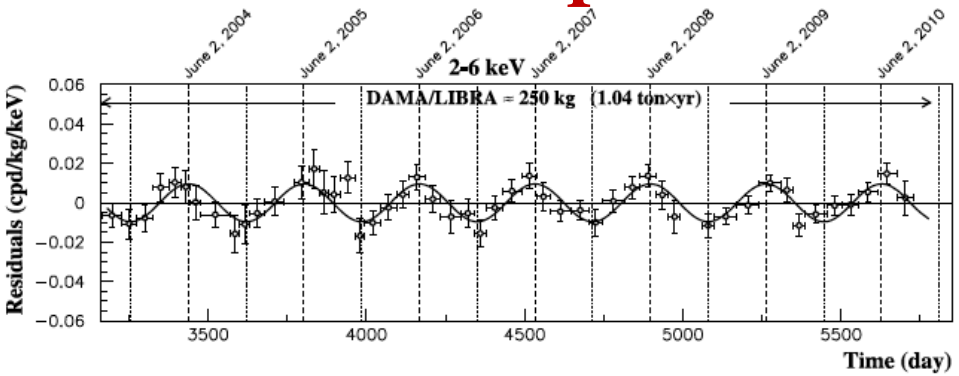
**December/2nd**

Earth and sun orbits are opposed

Earth encounters fewer particles

# Annual modulation signal from DAMA/LIBRA

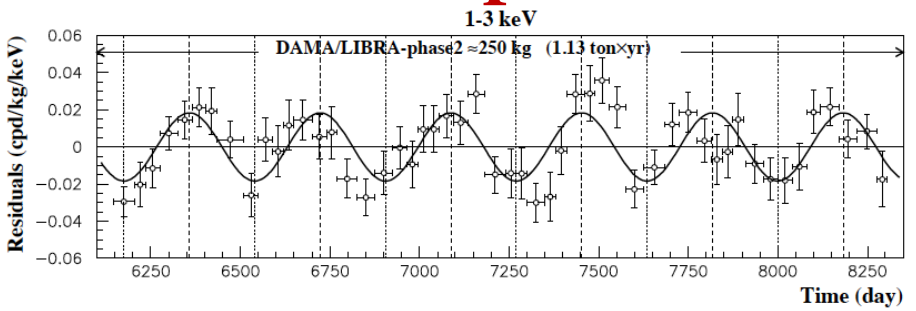
## Phase1 experiment



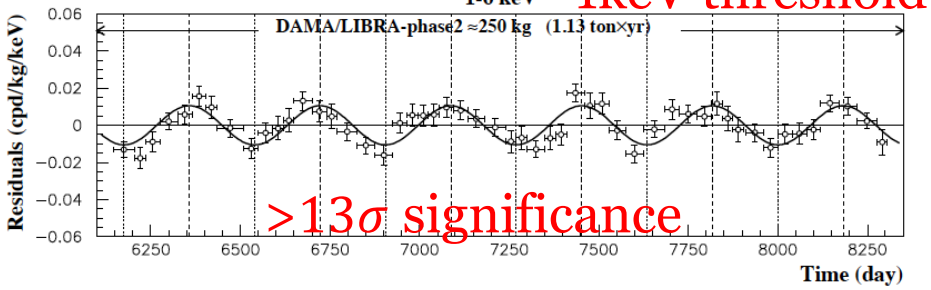

Eur. Phys. J. C 73:2648 (2013)

2keV threshold

## Phase2 experiment



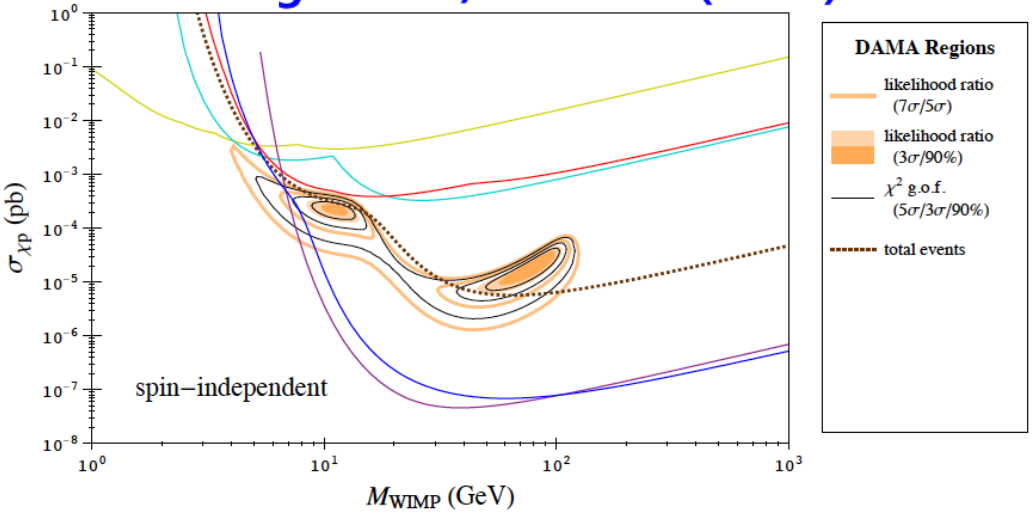

Nucl. Phys. At. Energy 19, 307 (2018)



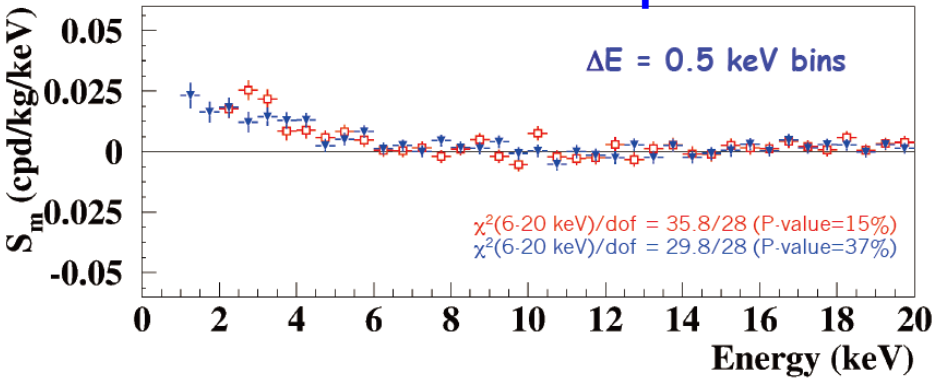

1keV threshold

>13σ significance

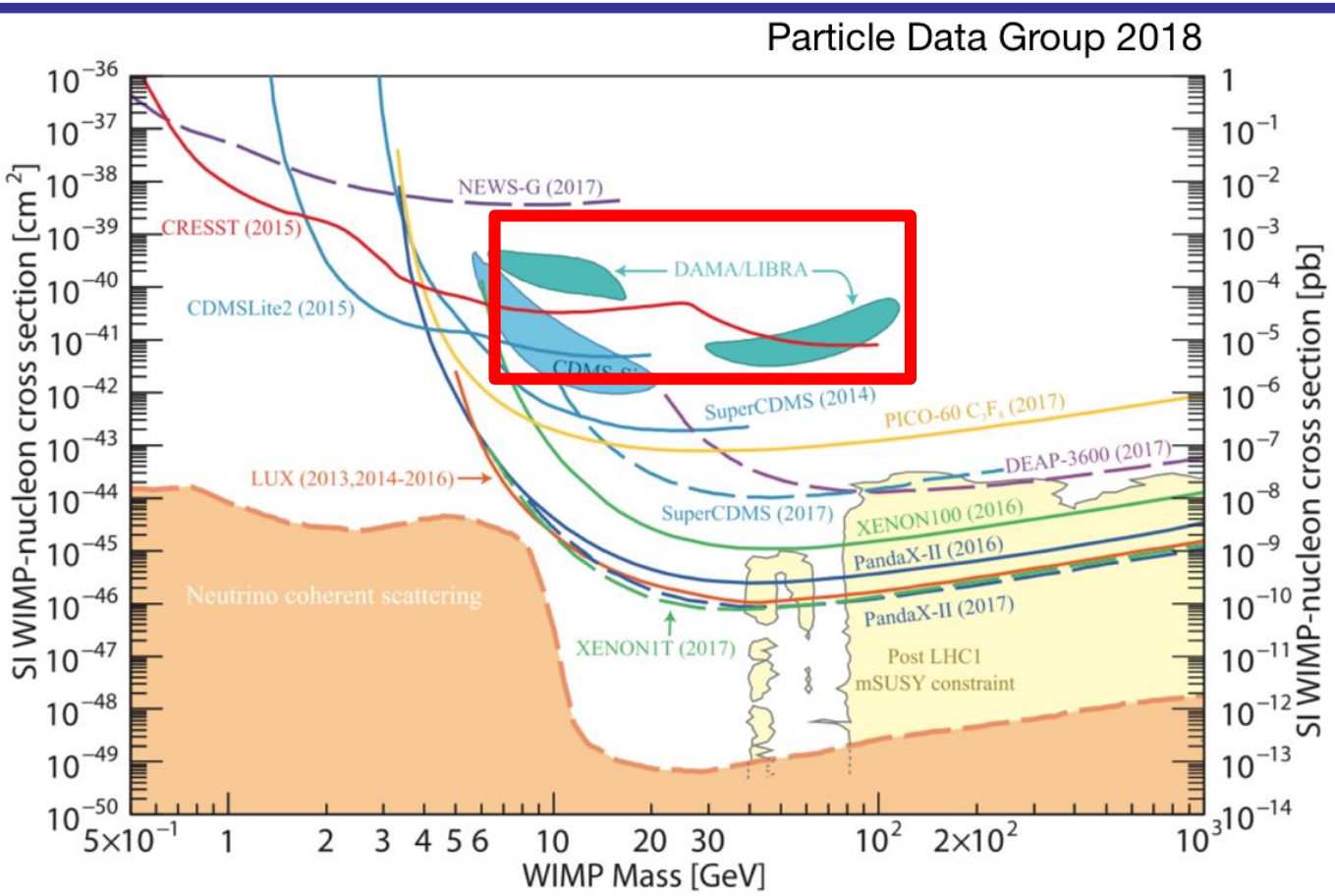
C. Savage *et al.*, JCAP 04 (2009) 010




## Modulation Amplitude



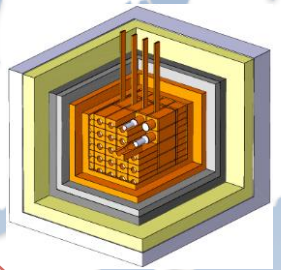
# However…




- Is NaI specific to certain types of dark matter?
- Modulation signals vs time-averaged limits?
- Environmental effects? **Need to have other NaI experiments**

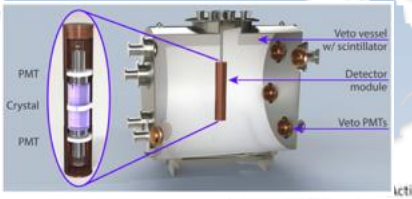
# Global NaI(Tl) efforts

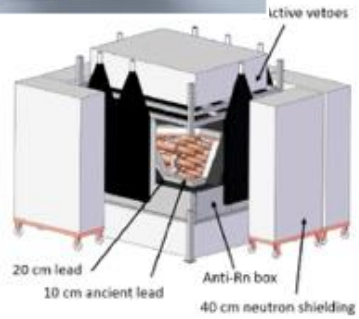

COSINUS
@ LNGS



**DAMA**
**@ LNGS**

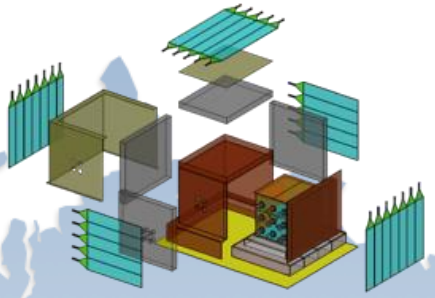
**SABRE**
**@ LNGS**




**ANAIS**
**@Canfranc**

**In Data-taking**

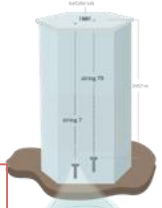


**KIMS/COSINE**
**@ Yangyang**

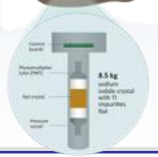
**In Data-taking**

**PICO-LON**
**@ Kamioka**

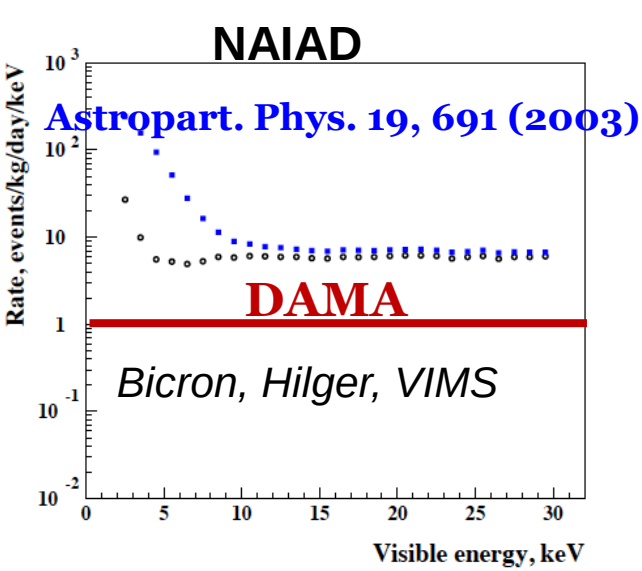
SABRE
@ Stawell

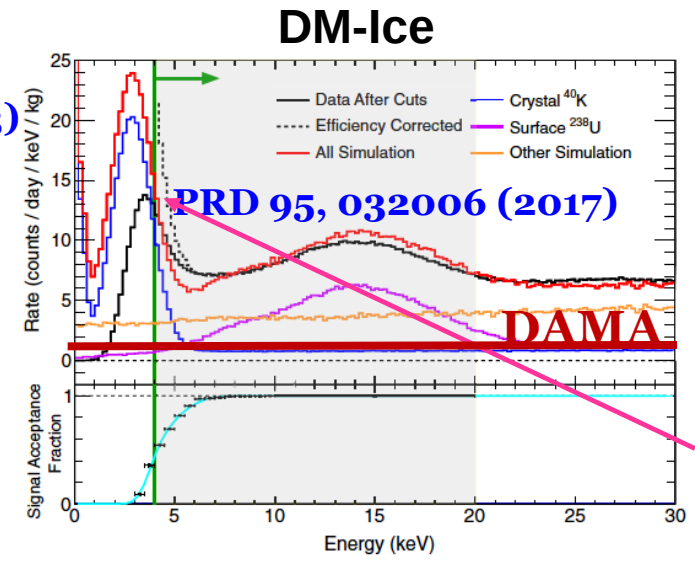


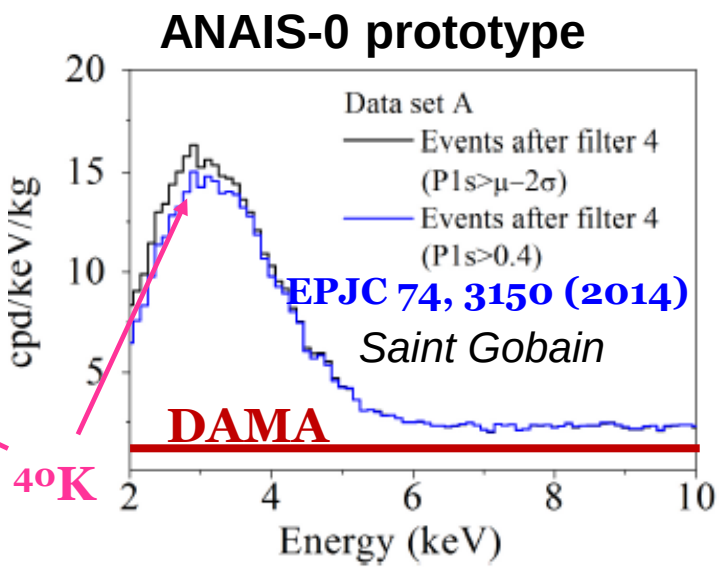
**DM-Ice @ South Pole**



# Why it is so hard to reproduce DAMA?



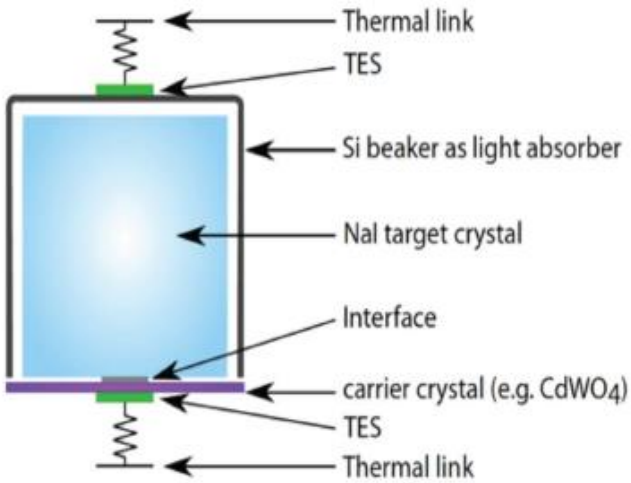



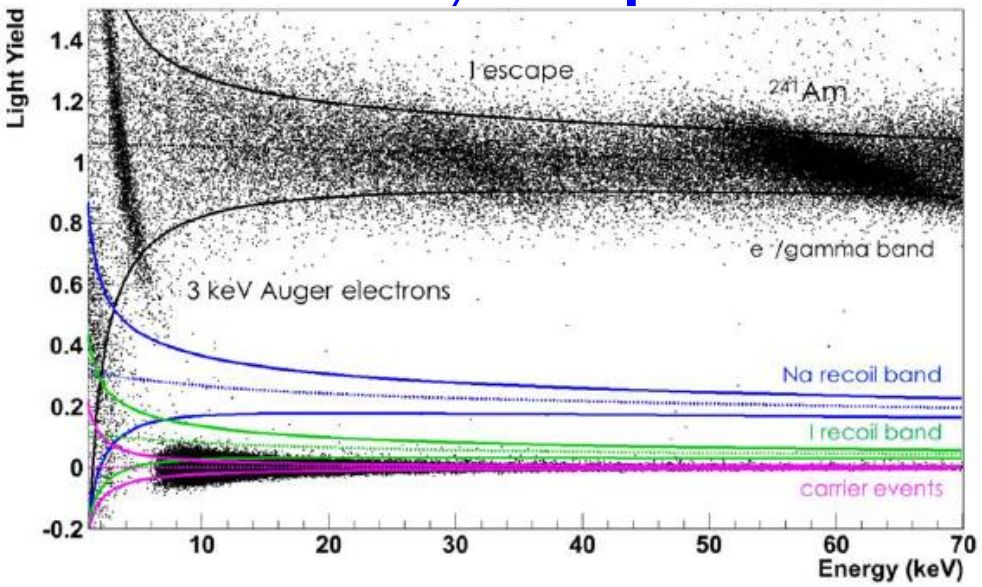

- No other experiments have the low-background rate of NaI(Tl)
- Saint-Gobain's technique for low-background NaI(Tl) crystals is lost

# COSINUS – Identification of nuclear recoil

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




**arXiv:1711.01482**

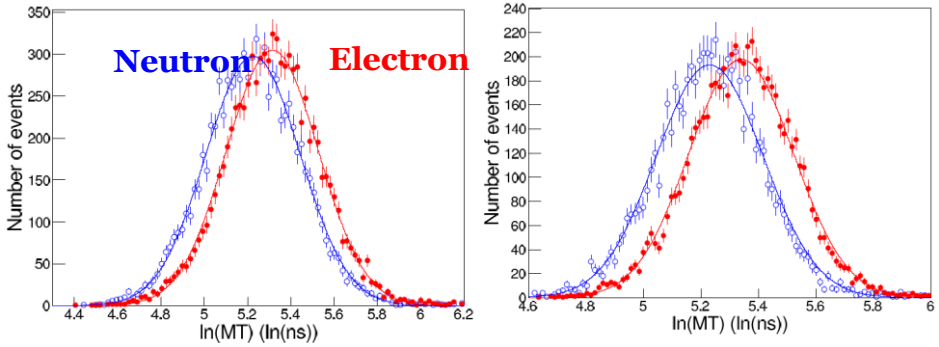



- Performing test measurements of pure NaI crystals using CRESST cryostat @ LNGS
- Can not test dark matter electron recoil scenarios

# KIMS experiment : Nuclear recoil extraction

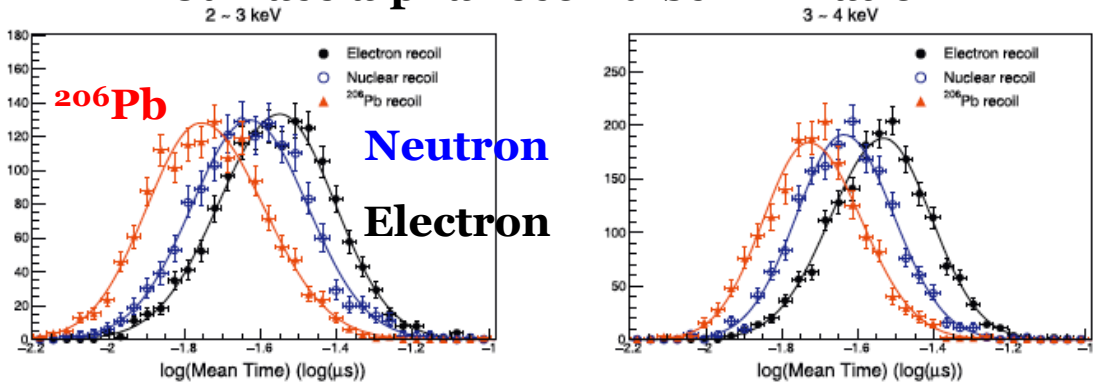
**JHEP 08, 093 (2015)**

**Nuclear recoil discrimination**

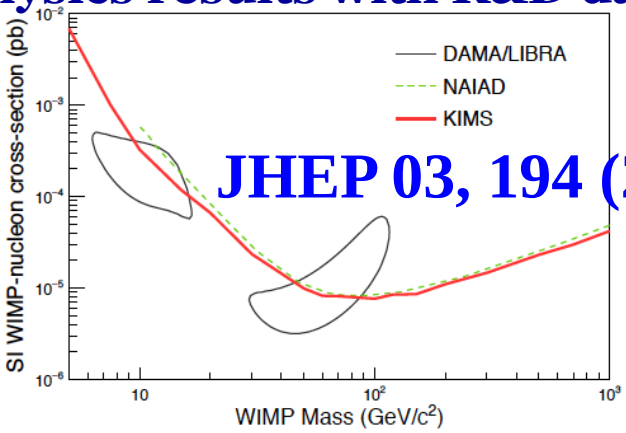



**Astropart. Phys. 102, 51 (2018)**

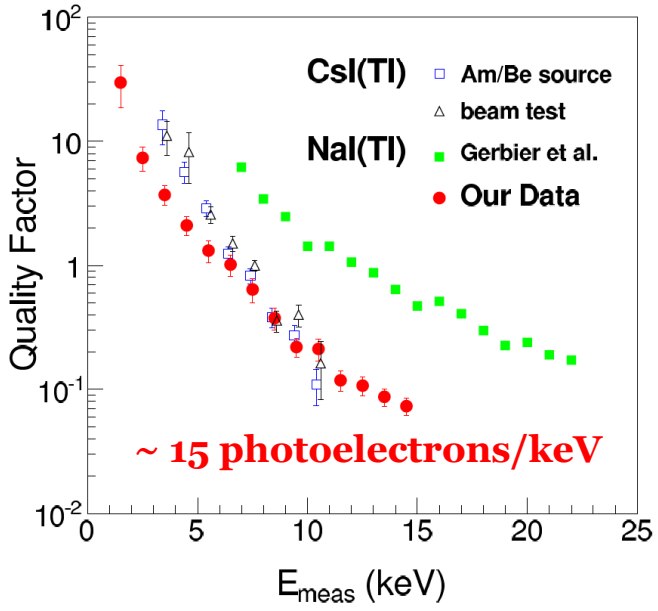
**Surface alpha recoil discrimination**




**Physics results with R&D data**




**JHEP 03, 194 (2019)**

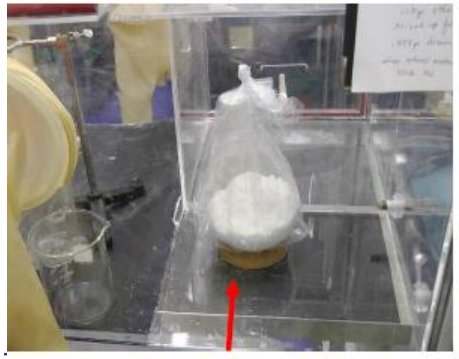



- Demonstrate discrimination of nuclear recoil events
- One can study the annual modulation of the nuclear recoil events

# PICO-LON

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

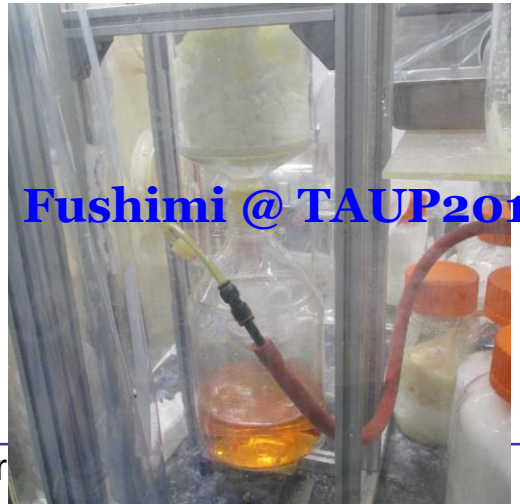
Non-purified NaI



Purified NaI·2$H_2$0

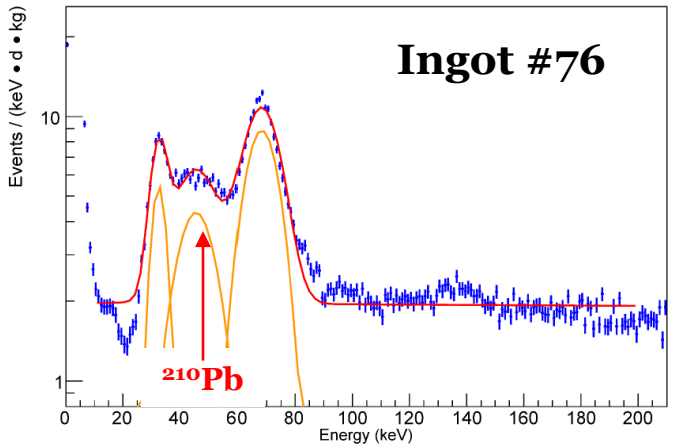

A. Kozlov @ VCI 2019

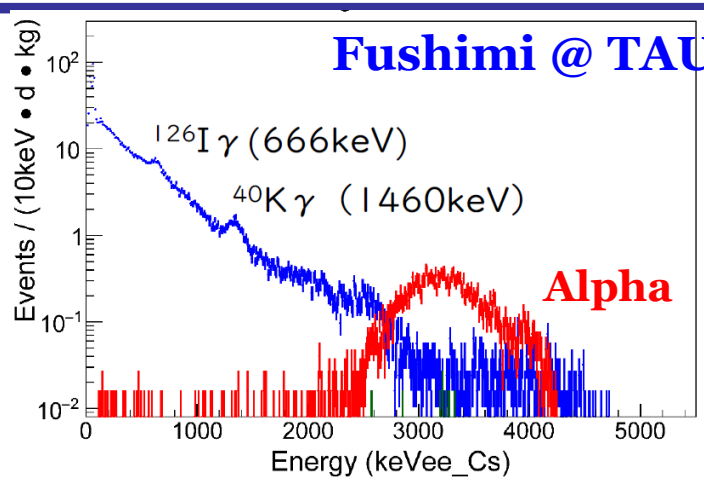

Recrystallization to remove $^{40}$K




Machine cutting

# PICO-LON : Background



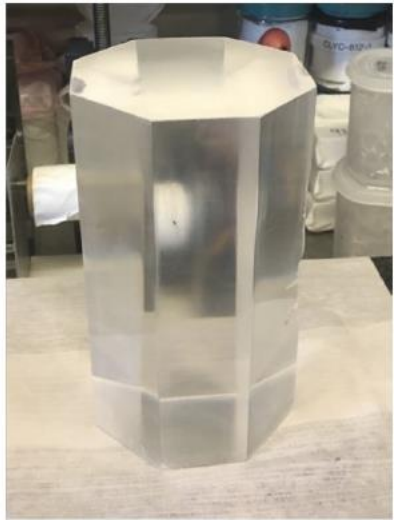




| RI | Ingot26 (2015) | Ingot37 (2016) | Ingot71 (2018) | Ingot76 (2019) | Goal |
|---|---|---|---|---|---|
| Size | 3”φX3” | 4”φX3# | 3”φX3” | 5”φX4”(*) | 5”φX5” |
| $^{40}$K (ppb) | 2630 | 120 | <20 | <20 | <20 |
| $^{232}$Th (ppt) | 0.4±0.5 | 3.7±0.5 | 1.7±0.2 | -- | <4 |
| $^{238}$U (ppt) | 4.7±0.3 | 5.9±0.3 | 9.7±0.8 | 4.4±0.2 | <10 |
| $^{210}$Pb (μBq/kg) | 30±7 | 2300 | 1076 | ~560 | <50 |
| Method | Resin for Pb | I26+cation resin | double re-crystallization | Pb resin + double re-crystallization | |

# SABRE

Underground at LNGS

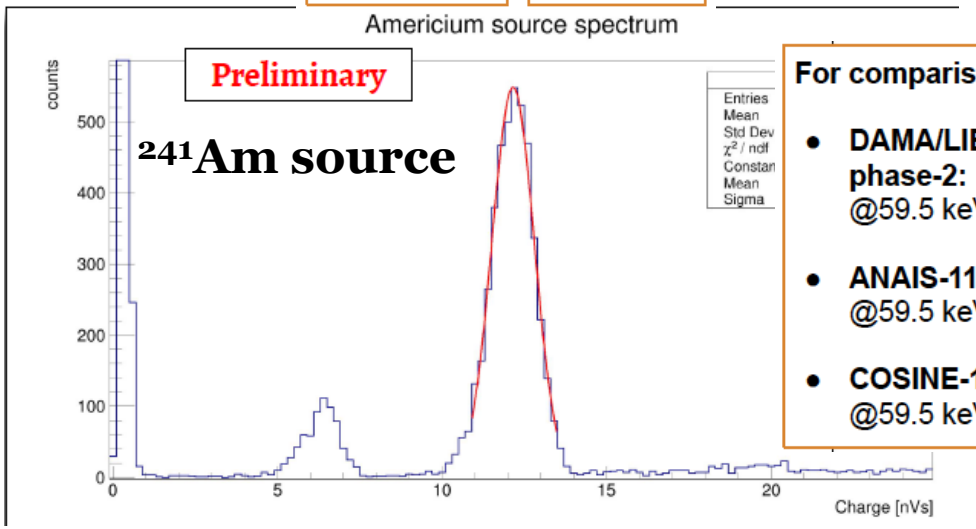
**S. Copello@ TAUP2019**



- **Astrograde powder** by Sigma Aldrich and crucible prepared at PU.
- **Ready October 2018 - Assembled in mid-May 2019**.
- **Potassium** measurement via ICP-MS: **~ 4 ppb**
- Mass **~ 3.5 kg** after cut and polishing
- Arrived at **LNGS on August 6, 2019** (by boat to reduce cosmogenic activation).

**Light Yield**
**11 phe/keV**

**FWHM/E**
**12.3%**



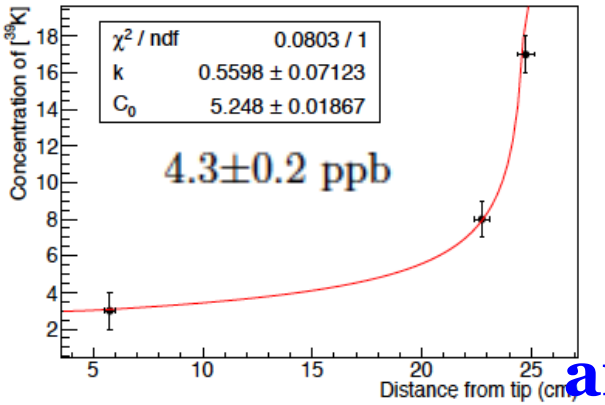

**For comparison…**

- **DAMA/LIBRA phase-2:** 15.8% @59.5 keV
- **ANAIS-112:** 11.2% @59.5 keV
- **COSINE-100:** 11.8% @59.5 keV

# SABRE

## Ground level measurement

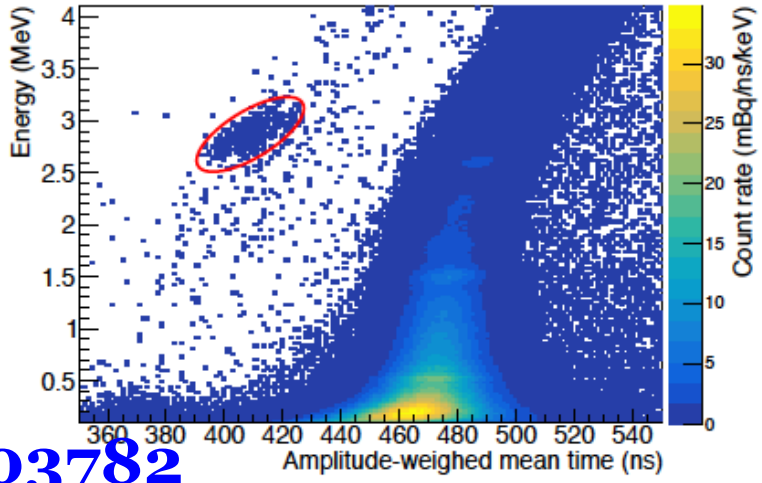
### ICP-MS for $^{40}$K

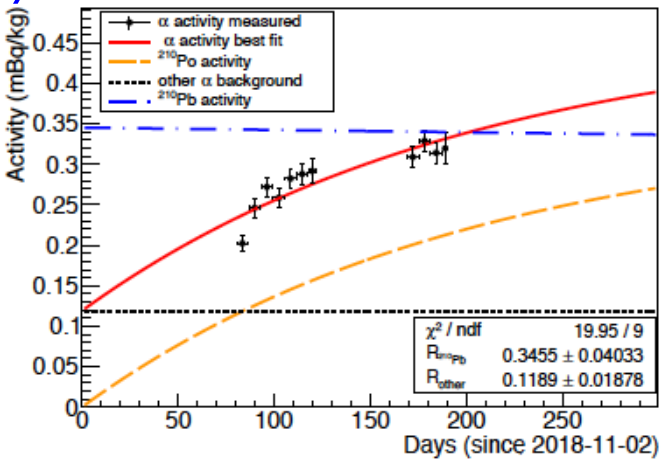



arXiv:1910.03782

| RI | NaI-34 |
|---|---|
| Mass | 3.4 kg |
| $^{40}$K (ppb) | 4.3+/-0.2 |
| Othr Alpha(μBq/kg) | 119+/-19 |
| $^{238}$U (ppt) | 4.4±0.2 |
| $^{210}$Pb (μBq/kg) | 340+/-4 |
| $^{3}$H (counts/kg/keV) | 0.04 (expected) |

## Alpha analysis




**Underground (Granssaso) measurement is ongoing**

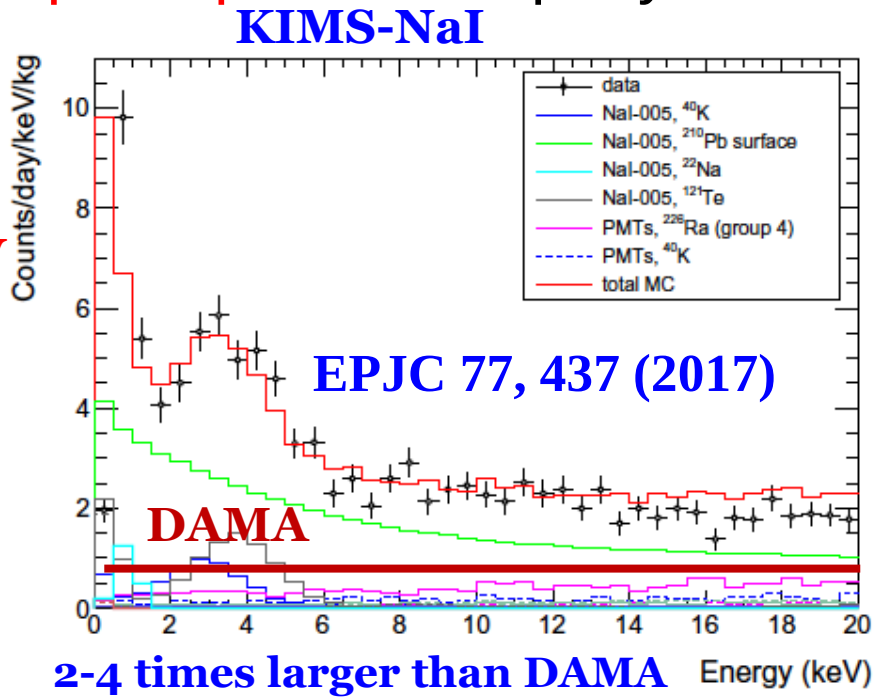
# NaI(Tl) development with Alpha Spectra (AS)

- Joint R&D between three collaborations (ANAIS, DM-Ice, and KIMS) and Alpha Spectra company since 2013

**12.5 kg crystal**

**High light yield ~ 15 PEs/keV**

**Underground measurement**




- Reduced $^{40}$K but, still significant
- $^{210}$Pb is the most troublesome
- Cosmogenic activation is unexpected problem from AS
  - ❖ AS is located in Grand Junction, Colorado (~1,000 m altitude)

# COSINE collaboration (Since 2015)

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

# YangYang(Y2L) Underground Laboratory

(Upper Dam) YangYang Pumped Storage Power Plant

1000m

700m

(Power Plant)



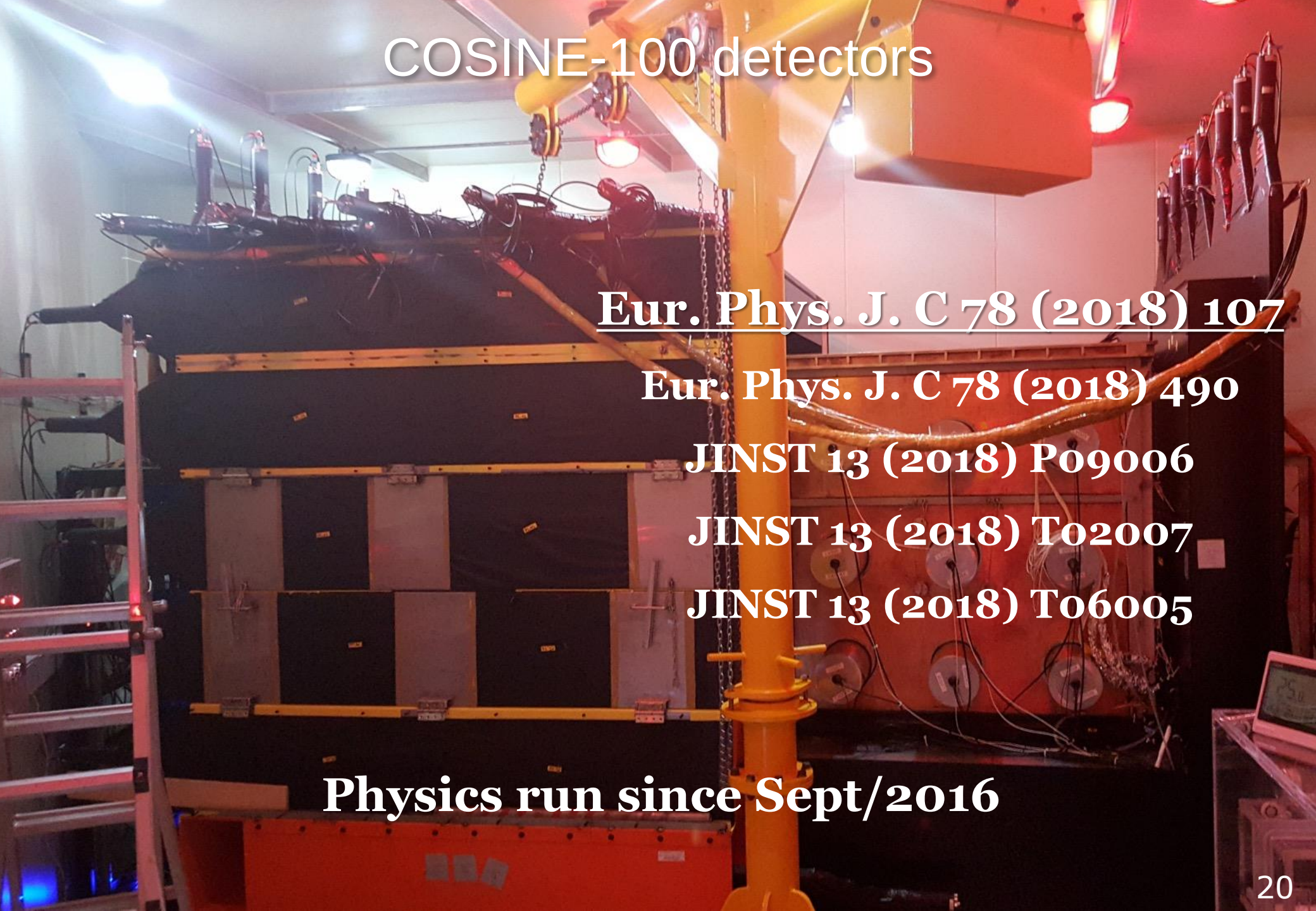

KIMS/COSINE (Dark Matter Search)

AMoRE (Double Beta Decay Experiment)

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

# COSINE-100 construction

# COSINE-100 detectors



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

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

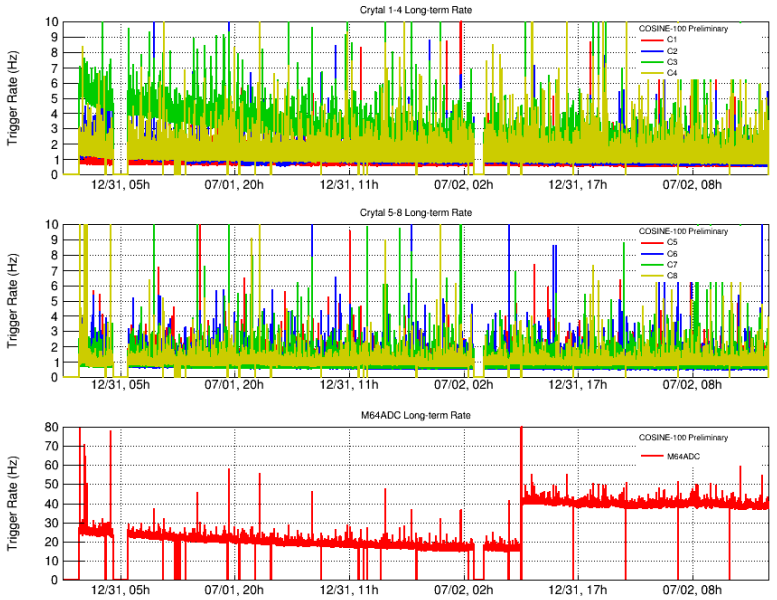
**JINST 13 (2018) P09006**

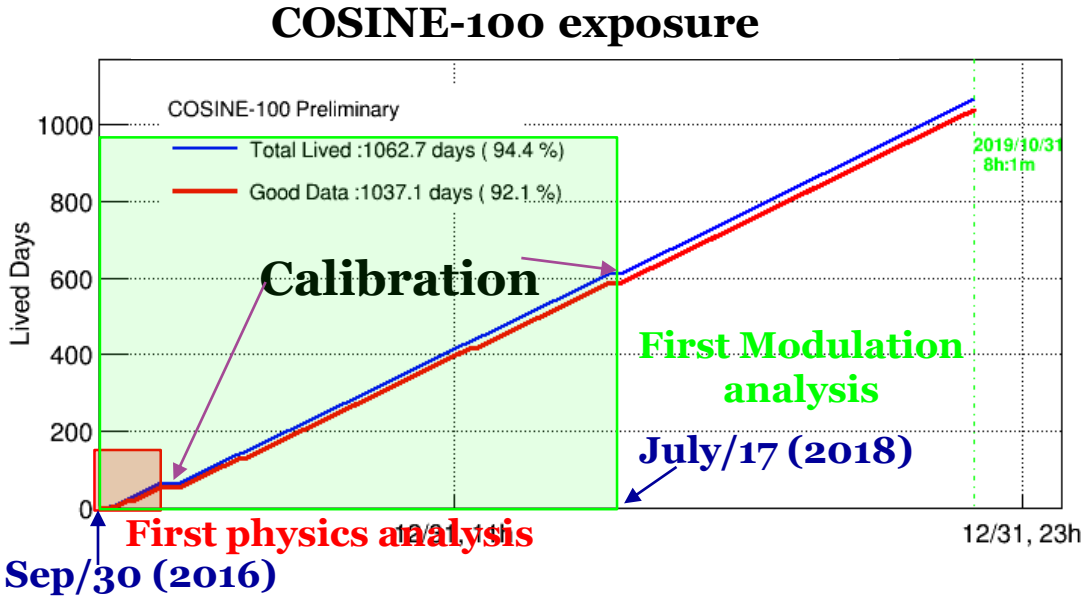
**JINST 13 (2018) T02007**

**JINST 13 (2018) T06005**

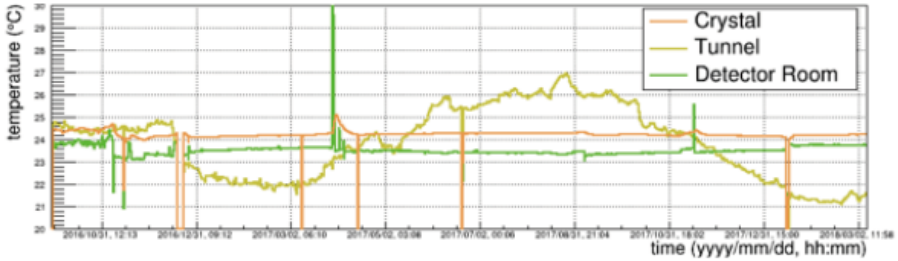
**Physics run since Sept/2016**

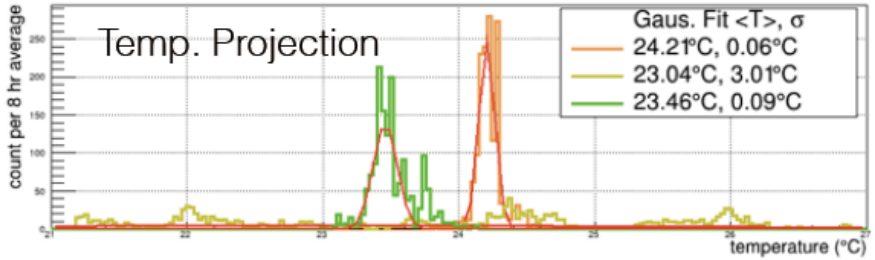
# COSINE-100 operation

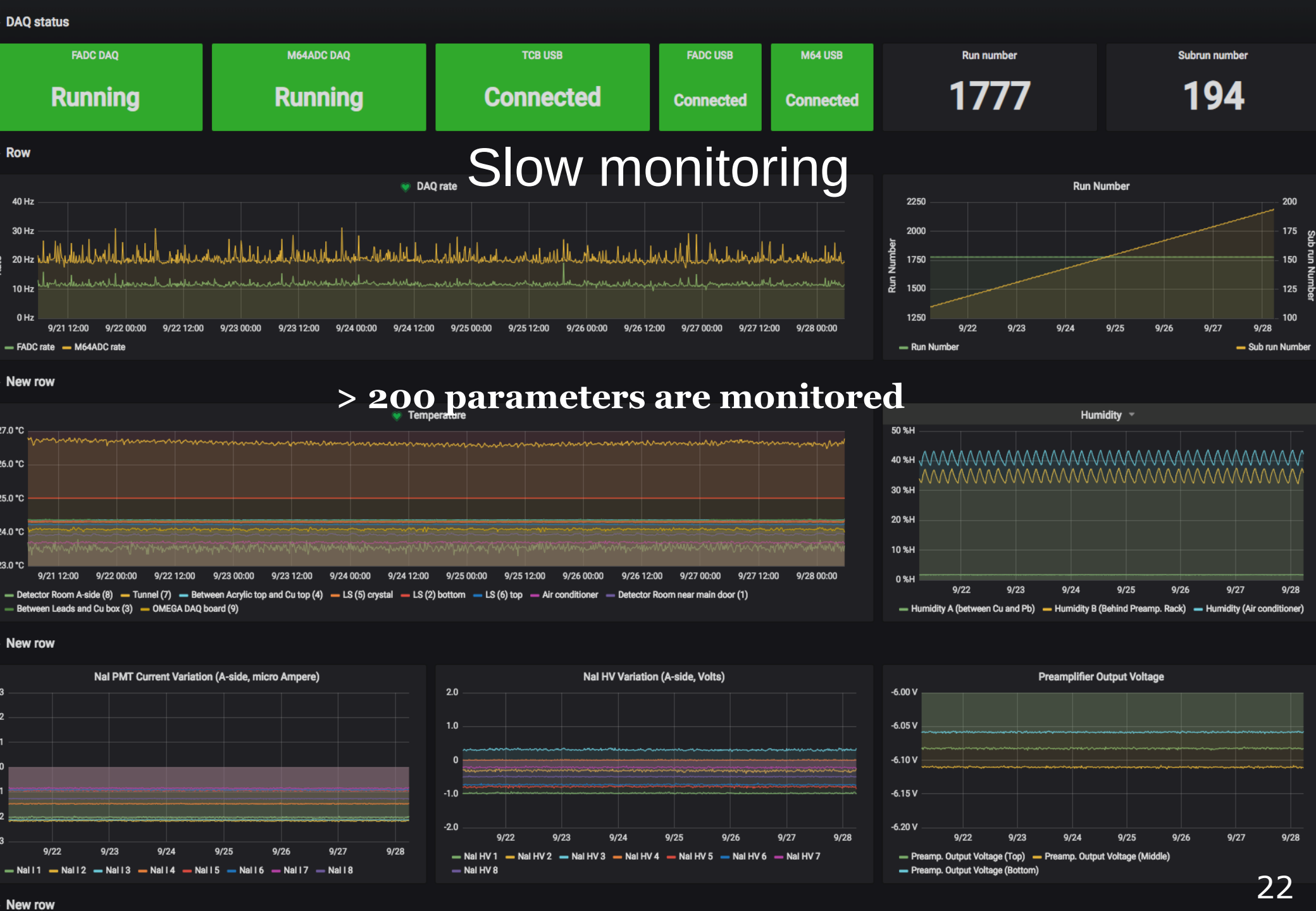



- Stable physics run
  - ❖ >90% physics data
  - ❖ >95% good runs
- In operation for more than 3 years
  - ❖ 2.85 years good data




DAQ status
FADC DAQ
Running
M64ADC DAQ
Running
TCB USB
Connected
FADC USB
Connected
M64 USB
Connected
Run number
1777
Subrun number
194
Row
Slow monitoring
DAQ rate
40 Hz
30 Hz
20 Hz
10 Hz
0 Hz
9/21 12:00
9/22 00:00
9/22 12:00
9/23 00:00
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9/25 12:00
9/26 00:00
9/26 12:00
9/27 00:00
9/27 12:00
9/28 00:00
FADC rate
M64ADC rate
Run Number
2250
2000
1750
1500
1250
200
175
150
125
100
9/22
9/23
9/24
9/25
9/26
9/27
9/28
Run Number
Sub run Number
New row
> 200 parameters are monitored
Temperature
27.0 °C
26.0 °C
25.0 °C
24.0 °C
23.0 °C
9/21 12:00
9/22 00:00
9/22 12:00
9/23 00:00
9/23 12:00
9/24 00:00
9/24 12:00
9/25 00:00
9/25 12:00
9/26 00:00
9/26 12:00
9/27 00:00
9/27 12:00
9/28 00:00
Detector Room A-side (8)
Tunnel (7)
Between Acrylic top and Cu top (4)
LS (5) crystal
LS (2) bottom
LS (6) top
Air conditioner
Detector Room near main door (1)
Between Leads and Cu box (3)
OMEGA DAQ board (9)
Humidity
50 %H
40 %H
30 %H
20 %H
10 %H
0 %H
9/22
9/23
9/24
9/25
9/26
9/27
9/28
Humidity A (between Cu and Pb)
Humidity B (Behind Preamp. Rack)
Humidity (Air conditioner)
New row
NaI PMT Current Variation (A-side, micro Ampere)
9/22
9/23
9/24
9/25
9/26
9/27
9/28
NaI l 1
NaI l 2
NaI l 3
NaI l 4
NaI l 5
NaI l 6
NaI l 7
NaI l 8
NaI HV Variation (A-side, Volts)
2.0
1.0
0
-1.0
-2.0
9/22
9/23
9/24
9/25
9/26
9/27
9/28
NaI HV 1
NaI HV 2
NaI HV 3
NaI HV 4
NaI HV 5
NaI HV 6
NaI HV 7
NaI HV 8
Preamplifier Output Voltage
-6.00 V
-6.05 V
-6.10 V
-6.15 V
-6.20 V
9/22
9/23
9/24
9/25
9/26
9/27
9/28
Preamp. Output Voltage (Top)
Preamp. Output Voltage (Middle)
Preamp. Output Voltage (Bottom)
New row

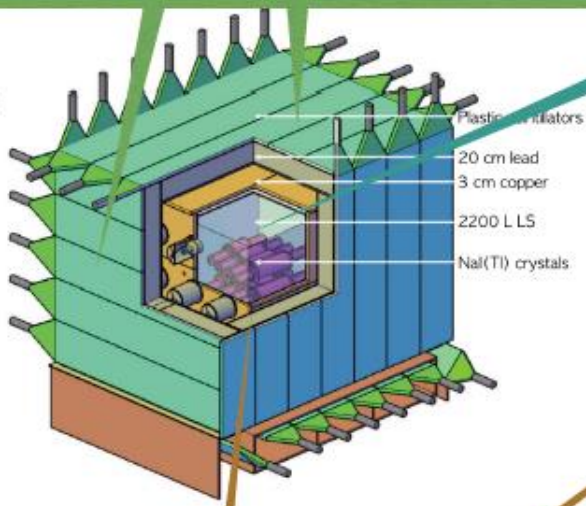
# COSINE-100 detector configuration

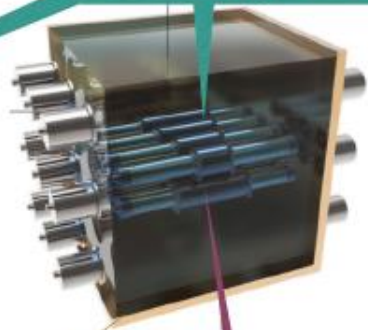
JINST 13 T02007 (2018)

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

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

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

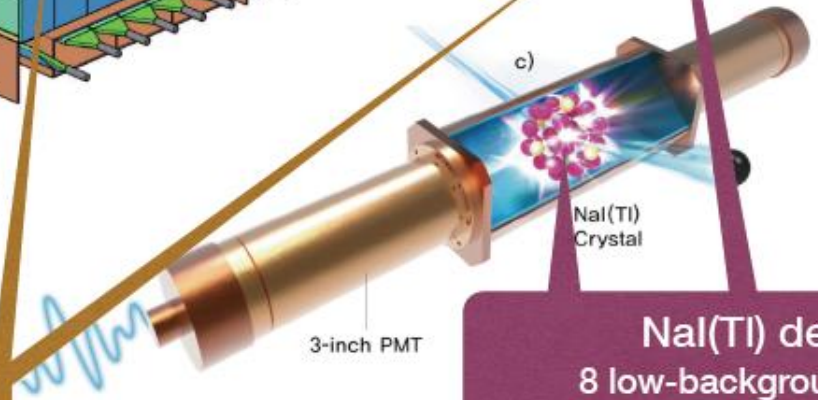


JINST 13 T06005 (2018)

**Neutron Monitoring**
Fast neutron detector
(Liquid scintillator)

Thermal neutron detector
($^3$He gas detector)




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

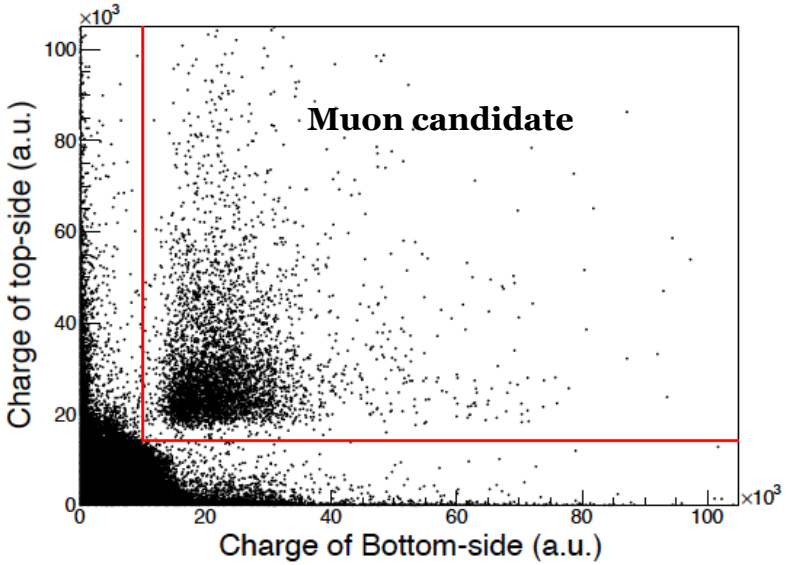
**NaI(Tl) detector**
8 low-background crystals
Each crystal is encapsulated in copper
Two 3-inch PMTs for each crystal
(R12669SEL)

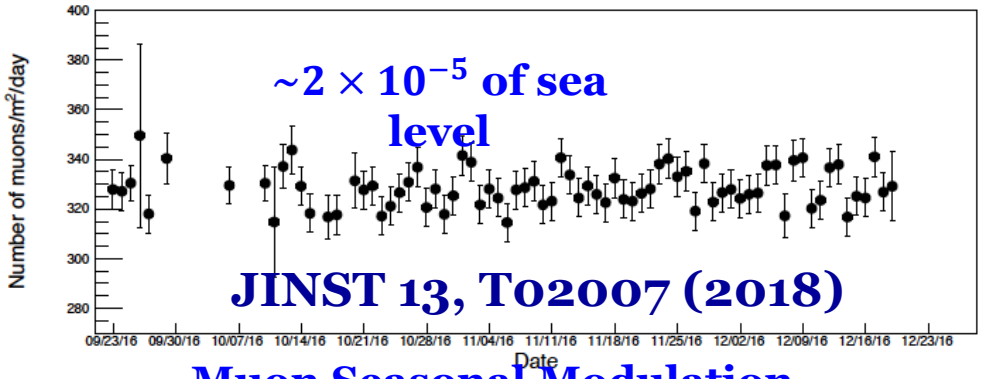
Eur. Phys. J. C. 78 107 (2018)

# Muon detector

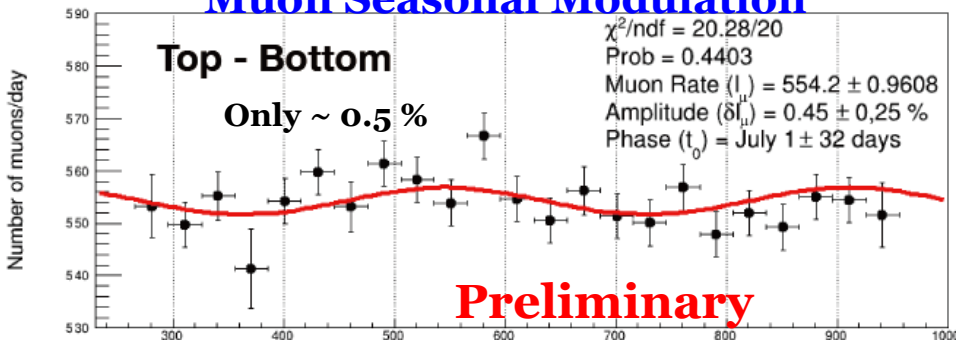
- Outer muon veto consists of 37 plastic scintillator panels

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




Muon Seasonal Modulation

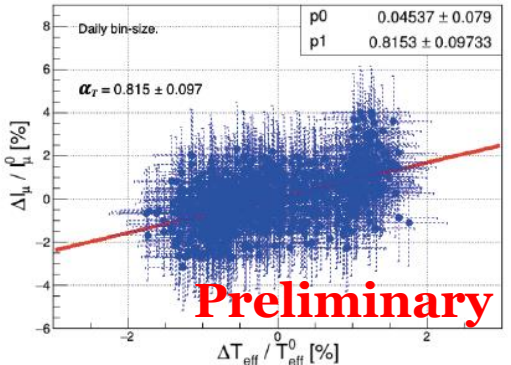


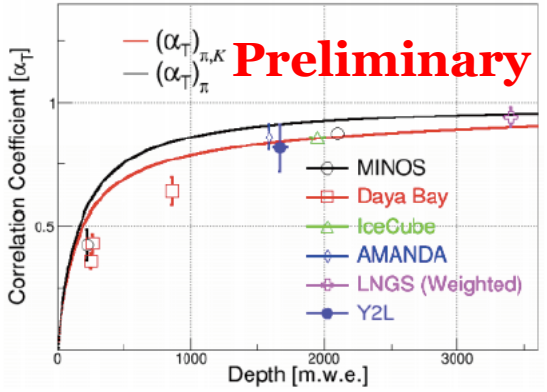

**Muon flux has been monitored stably**

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

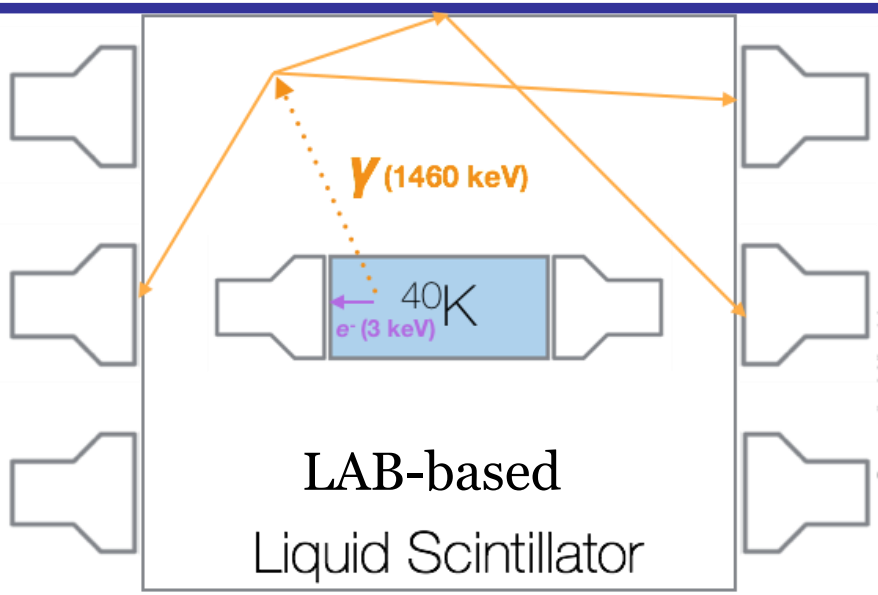
**Study on muon induced events with NaI(Tl) and liquid scintillator is ongoing**

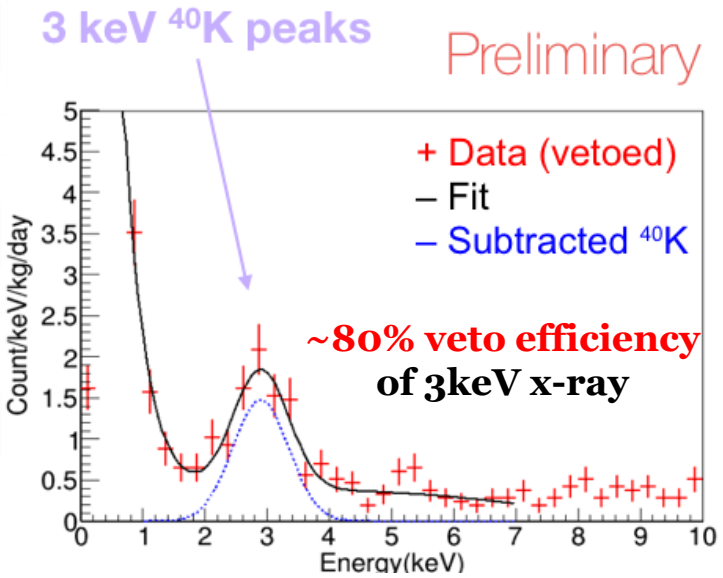
Correlation

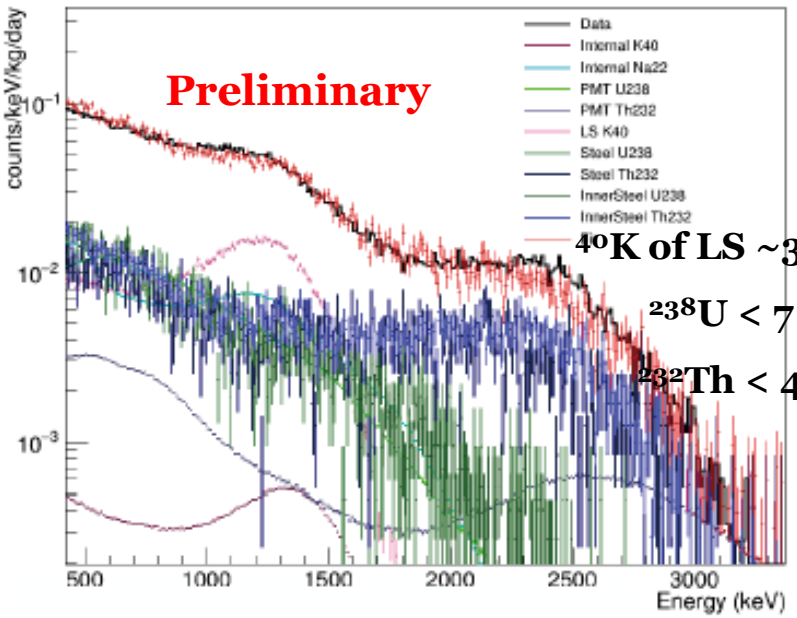


# Liquid scintillator veto system



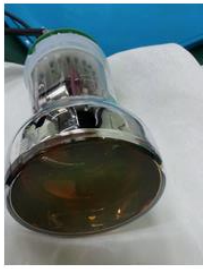

- Tagging rate of $^{40}$K is well understood with Geant4-based simulation
- Internal background of LS is well understood and low enough
- 20 keV tagging threshold is achieved


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

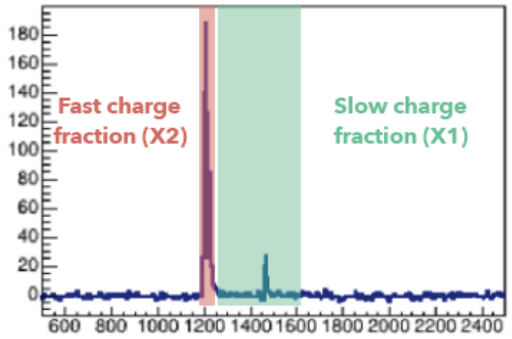
# COSINE-100 NaI(Tl) crystals

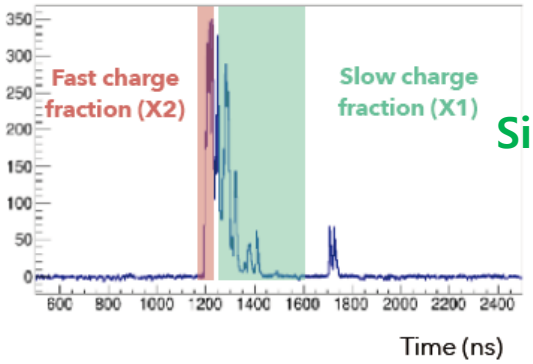
- 8 crystals, total 106 kg **Eur. Phys. J. C 78 (2018) 107**
- Different quality crystals from crystal R&D with Alpha Spectra (US)
- For best cases, U/Th/K are lower than DAMA
- Total alphas (~$^{210}$Pb) are higher than DAMA
- Light yield is 2-3 times higher than DAMA

| 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

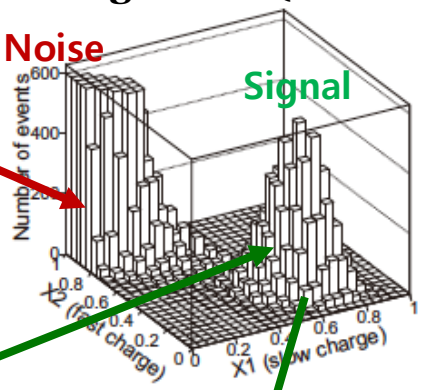


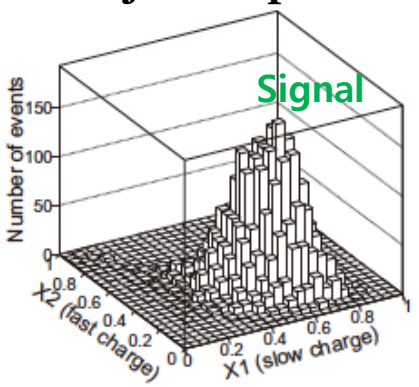

Noise

Signal

**Charge Ratio (DAMA noise rejection parameter)**

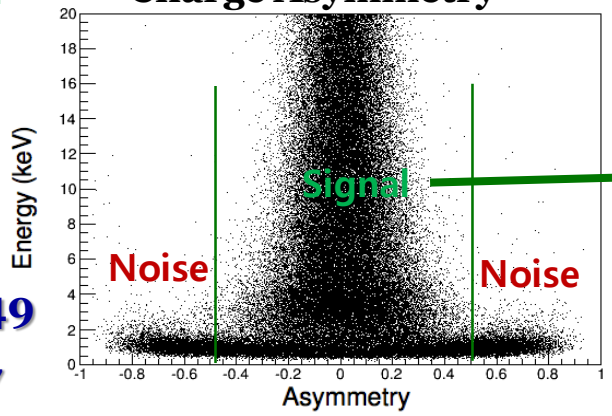



(a) Background data

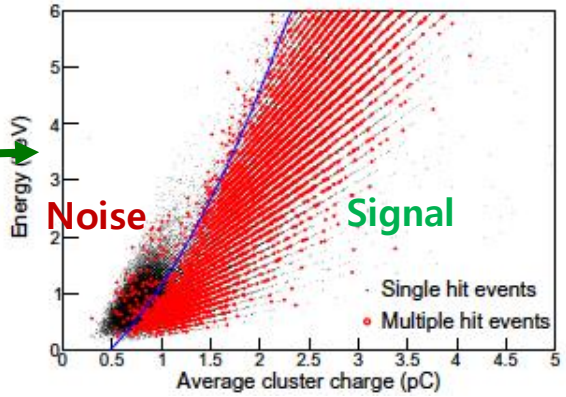



(b) $^{55}$Fe calibration data

**Charge Asymmetry**




**Average cluster charge**



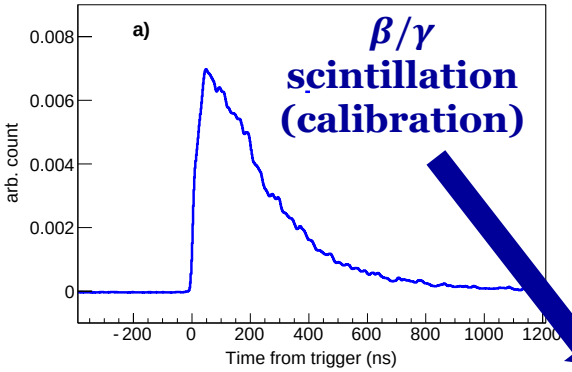

**Astropart. Phys. 62 (2015) 249**

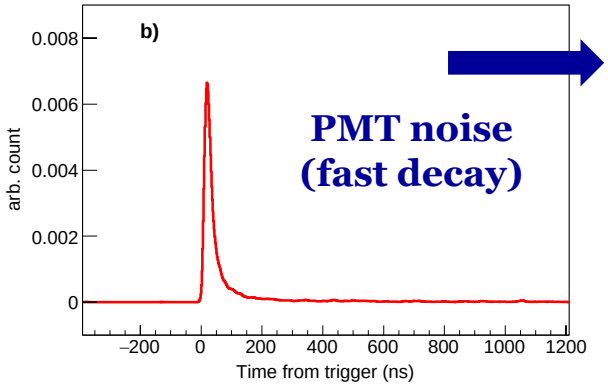
**Eur. Phys. J. C 78 (2018) 107**

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

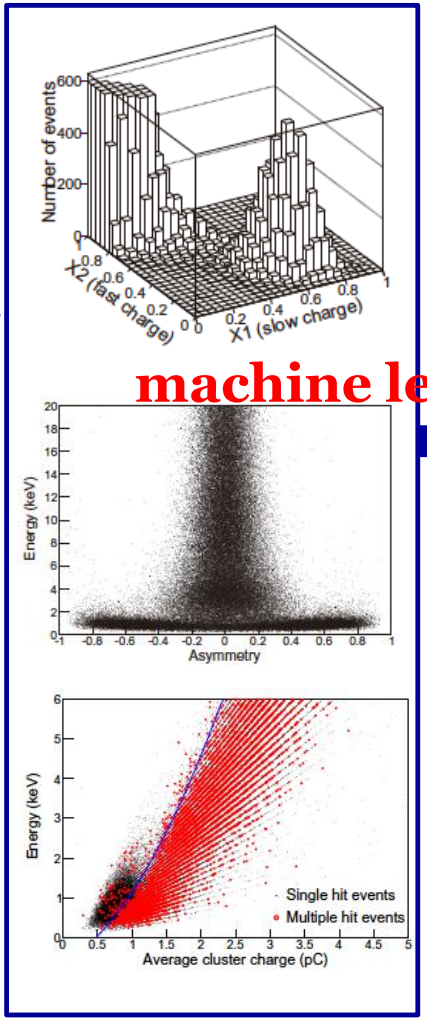
# Machine learning to remove PMT induced noise

**Accumulated waveforms**

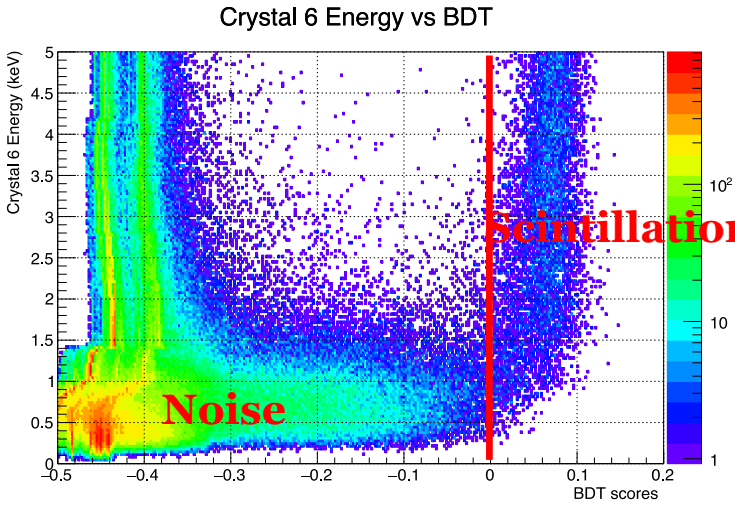


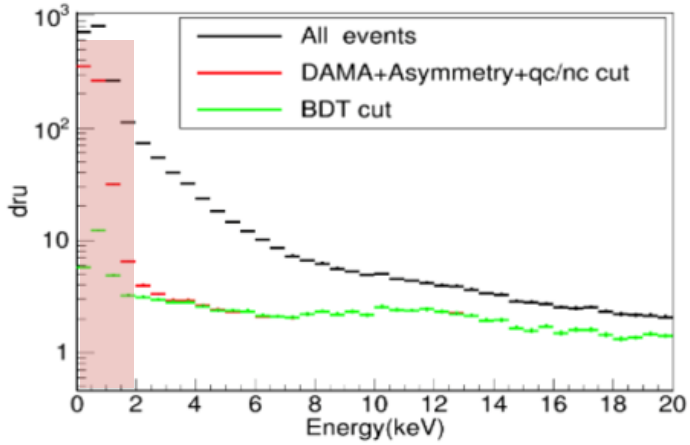




**Discrimination parameters**




**machine learning**

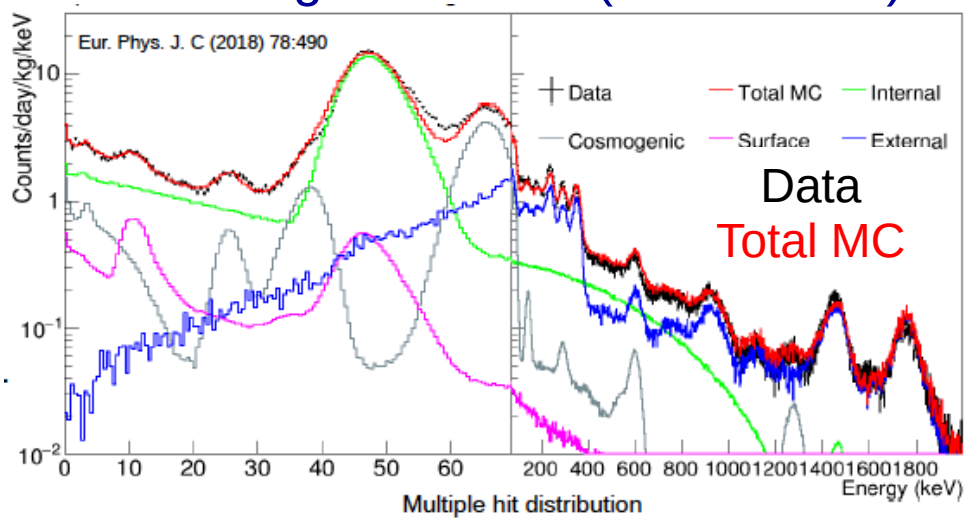


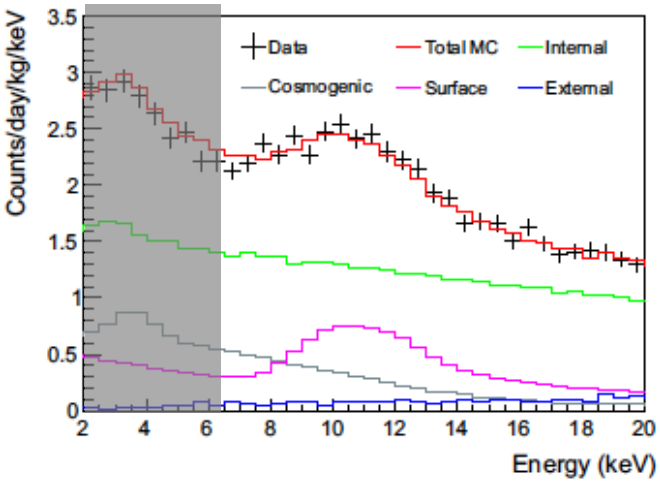




**Machine learning (BDT) is more effective at low energy**

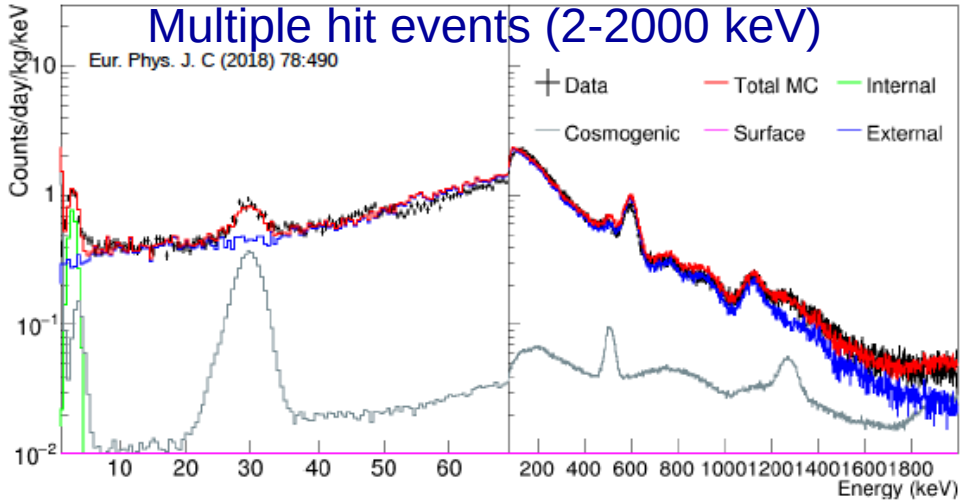
# Background understanding (COSINE-100)

## Single hit event (6-2000 keV)



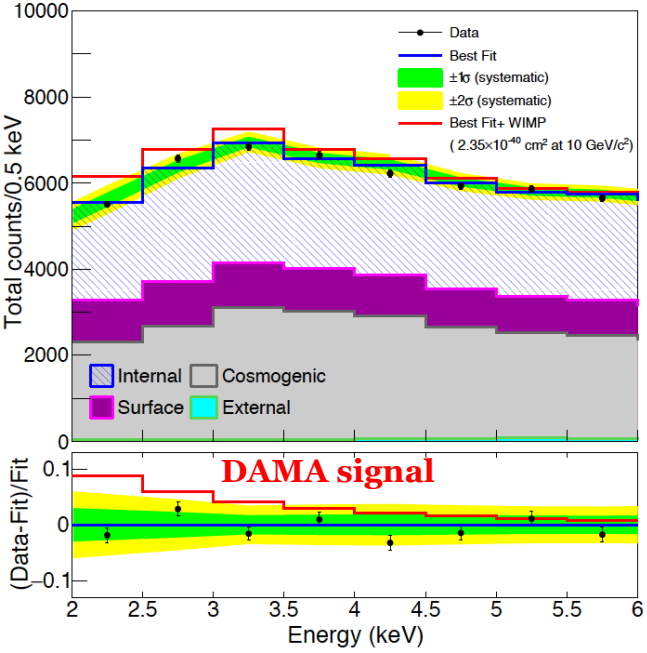




## Multiple hit events (2-2000 keV)

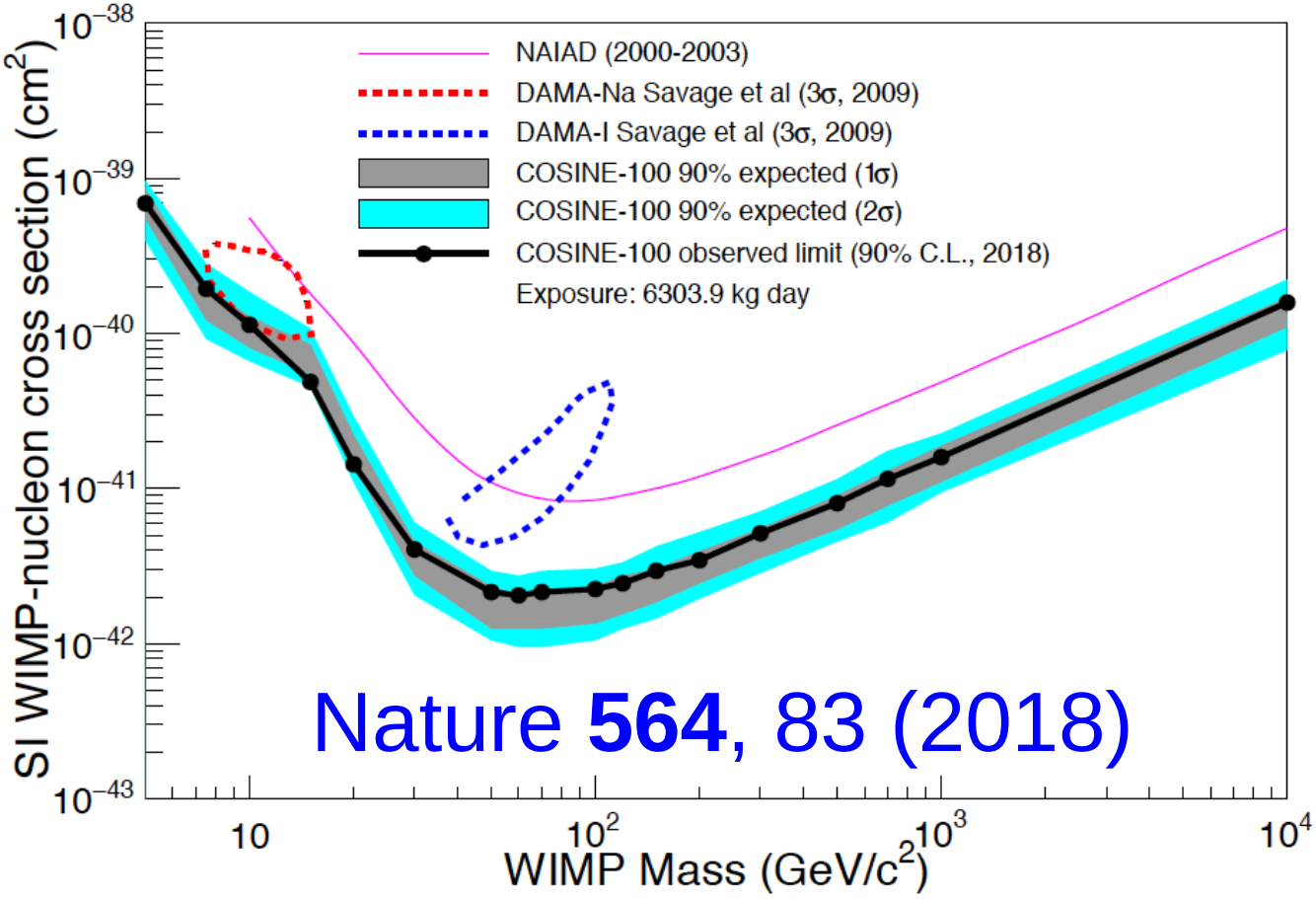



**EPJC 78 (2018) 490**

## Signal region fit with 10GeV WIMP



# Limit on WIMP-nucleon cross section from COSINE-100



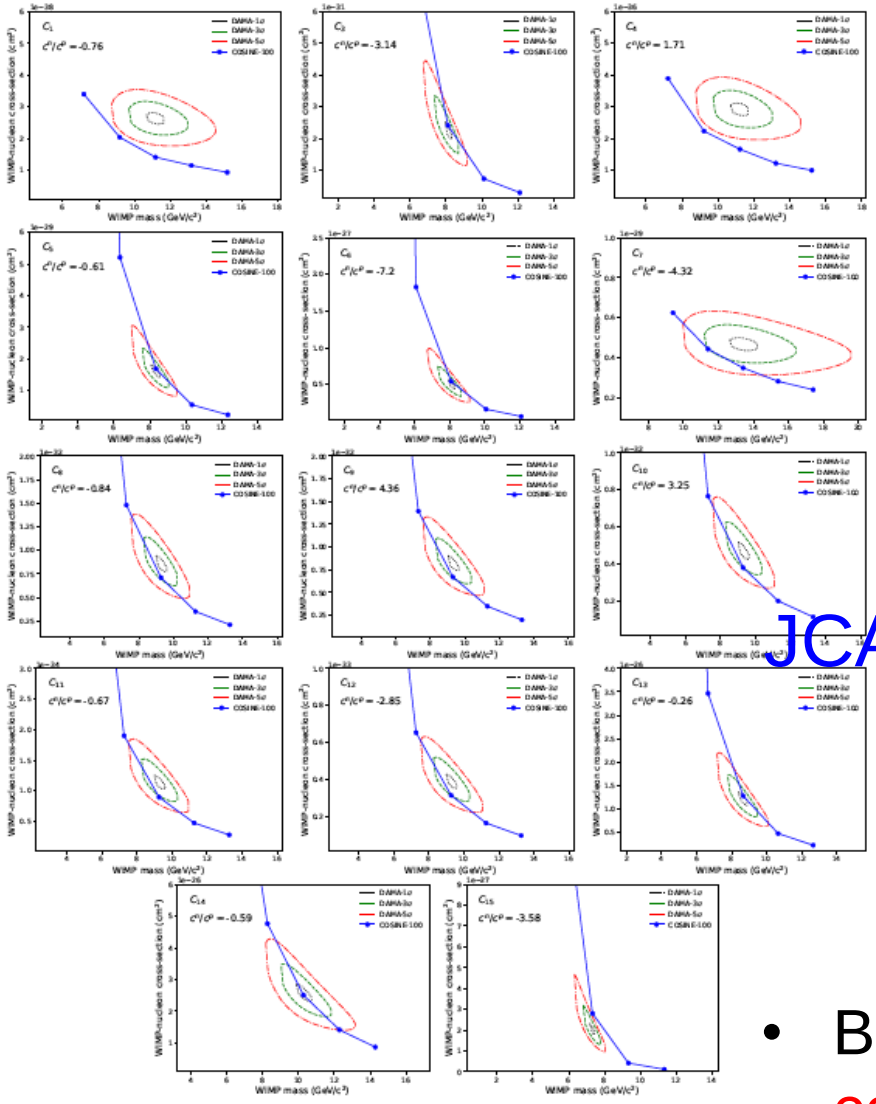

COSINE-100 excludes DAMA/LIBRA-phase1's interpretation with the spin-independent WIMP interaction in Standard Halo Model

**First time with same NaI(Tl) target**

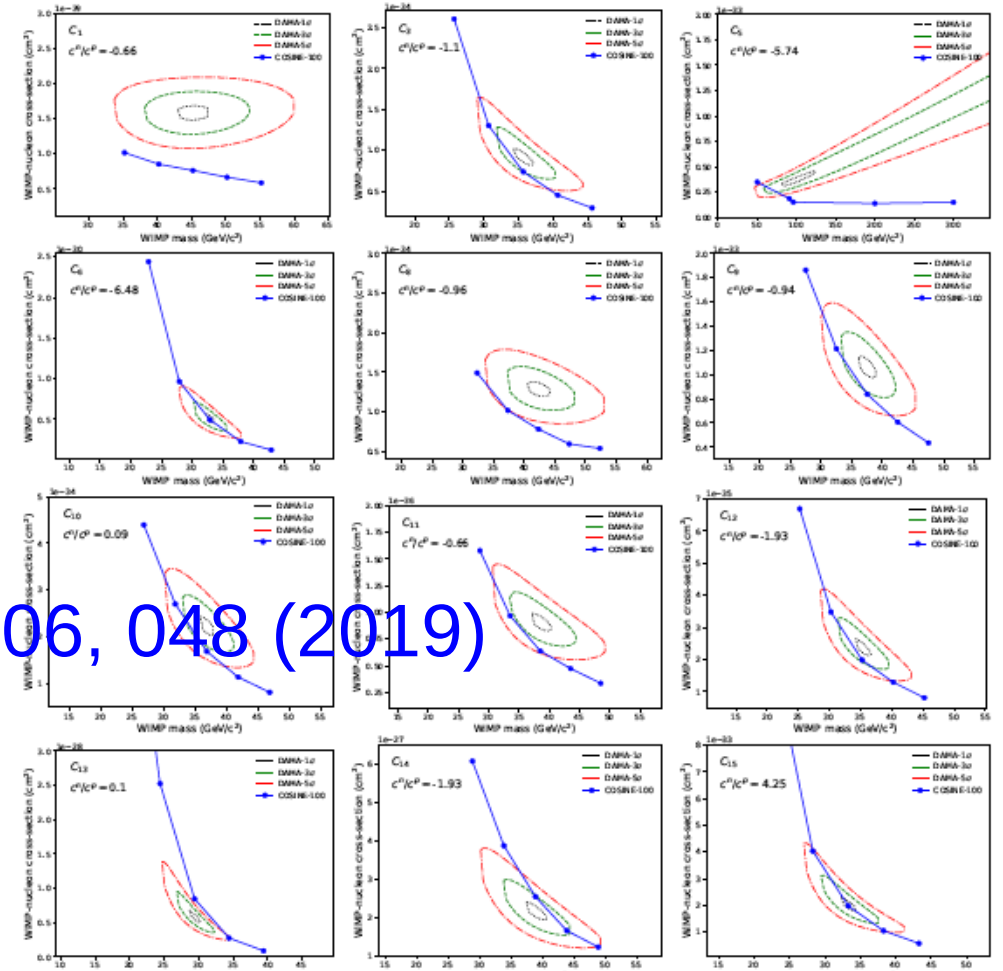
Consistent with other null experiments

# Other dark matter models?

- Test 15 Effective Field Theory operators

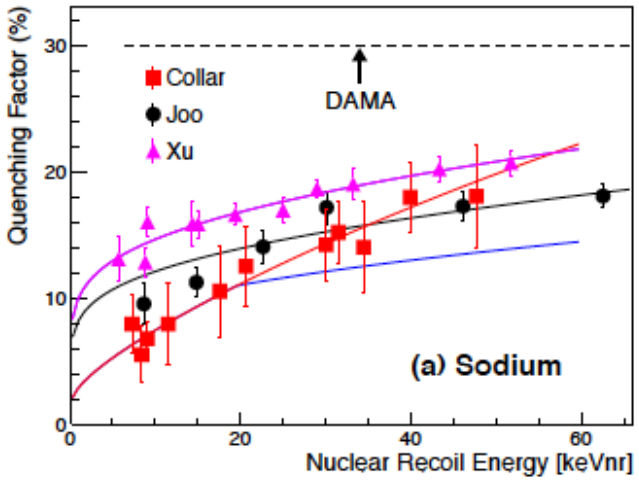


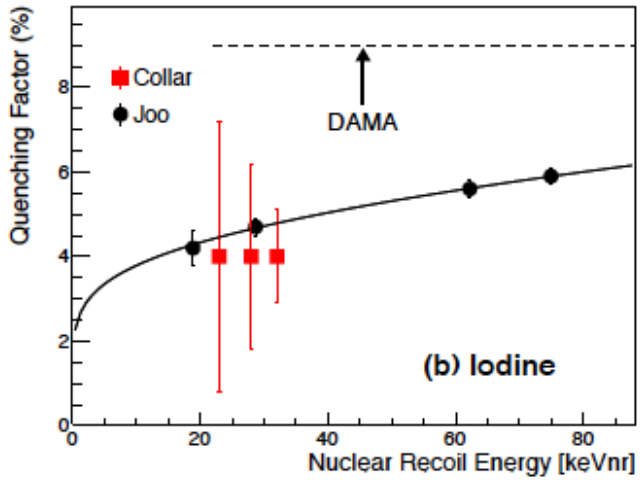
JCAP 06, 048 (2019)



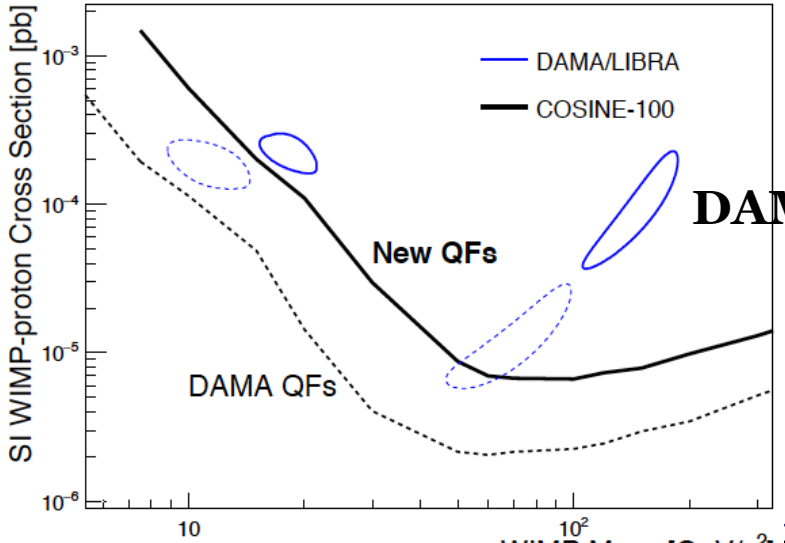
- Best fit region of DAMA was not fully covered yet

# Quenching factors?




## Canonical SI interaction

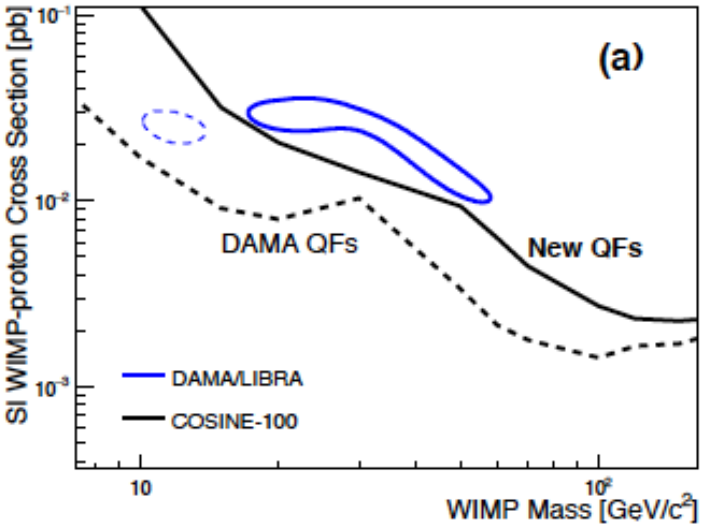


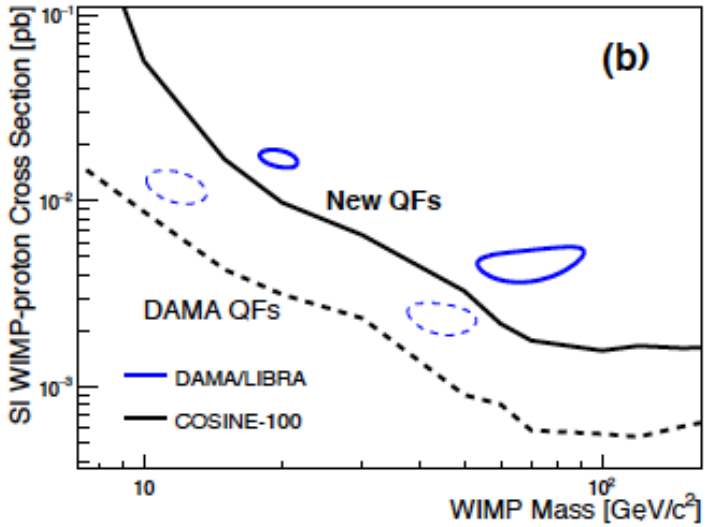

**DAMA/LIBRA-phase1 only**

**arXiv:1907.04963**

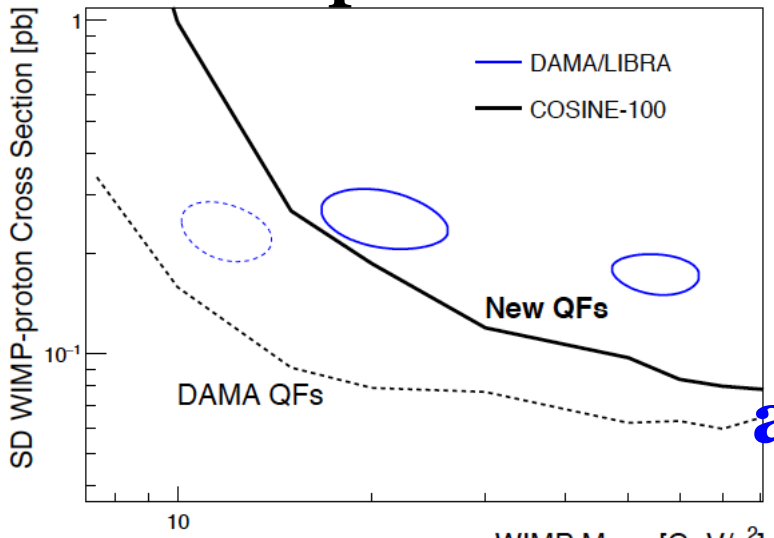
# Quenching factors? (DAMA/LIBRA-phase1+2)

## Isospin-violating SI WIMP interaction



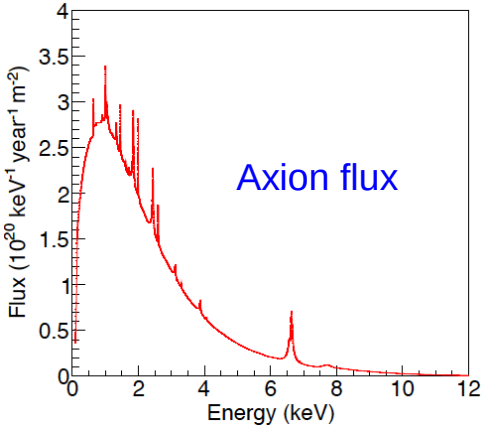

## SD WIMP-proton interaction

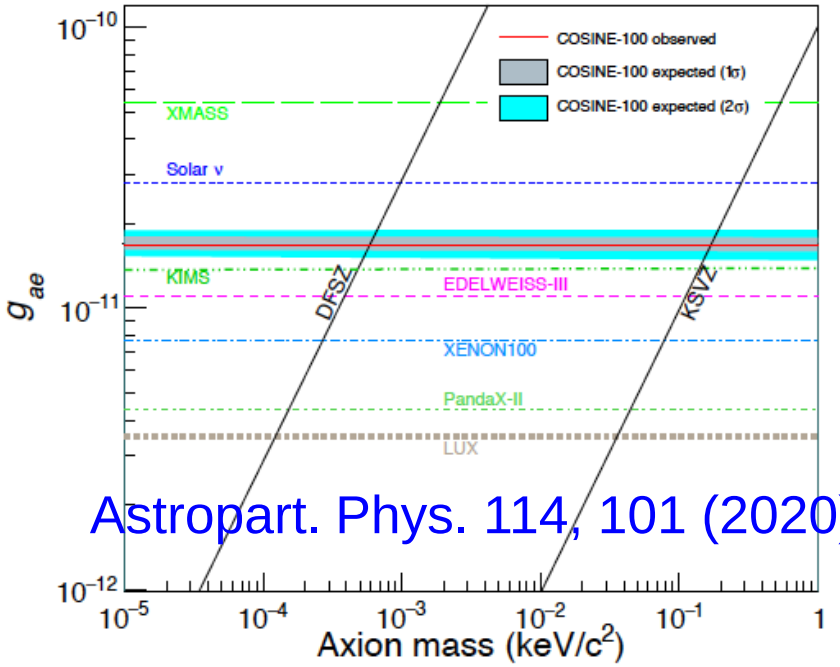



**arXiv:1907.04963**

# Other DM candidates

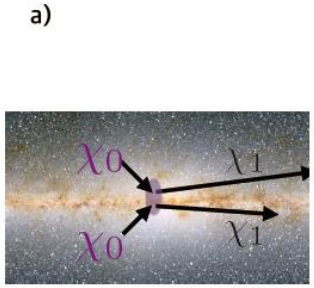
## Solar Axion

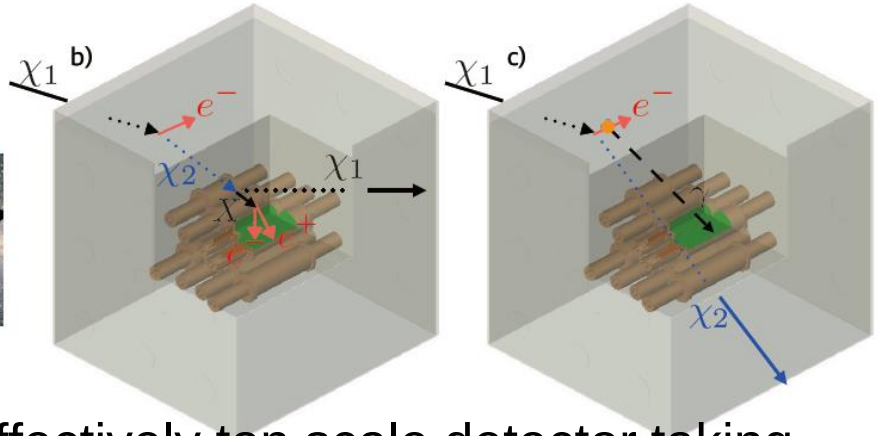


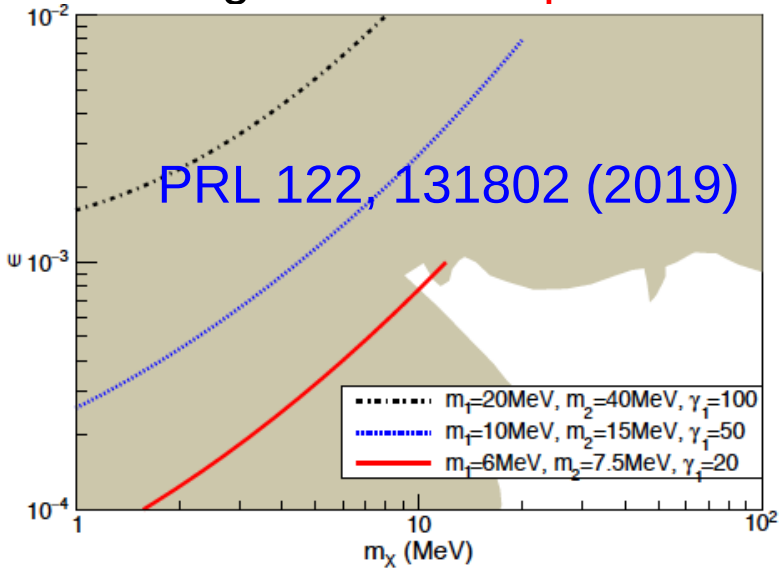

Astropart. Phys. 114, 101 (2020)

## Inelastic boosted dark matter




Effectively ton scale detector taking advantage of 2 ton liquid scintillator

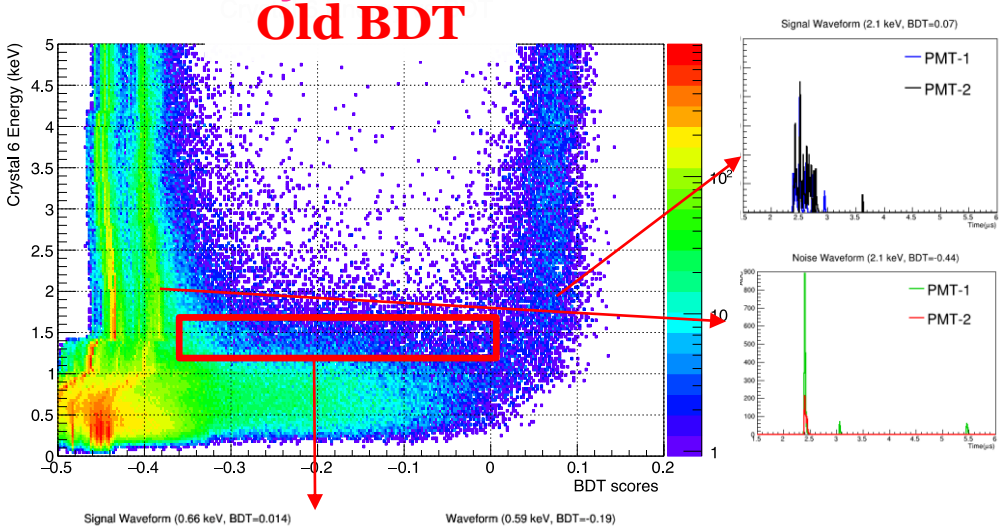


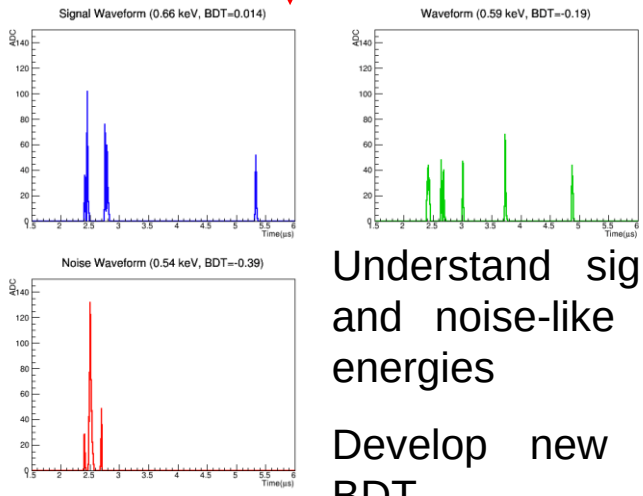
# Lowering energy threshold

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

Use ~ two years data

**Old BDT**

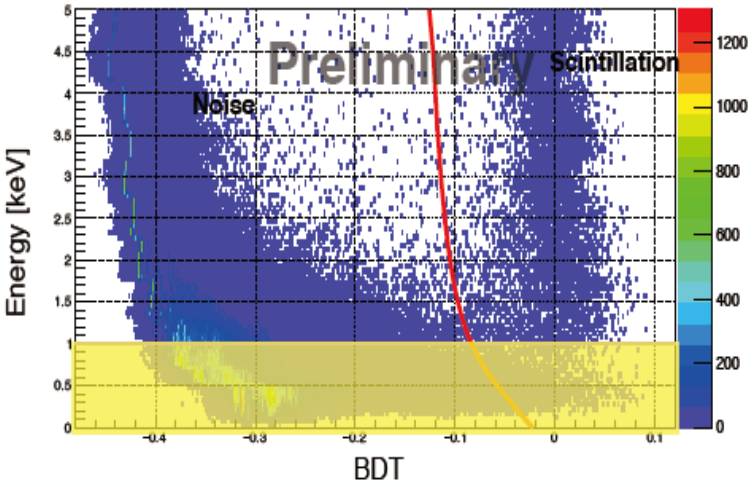


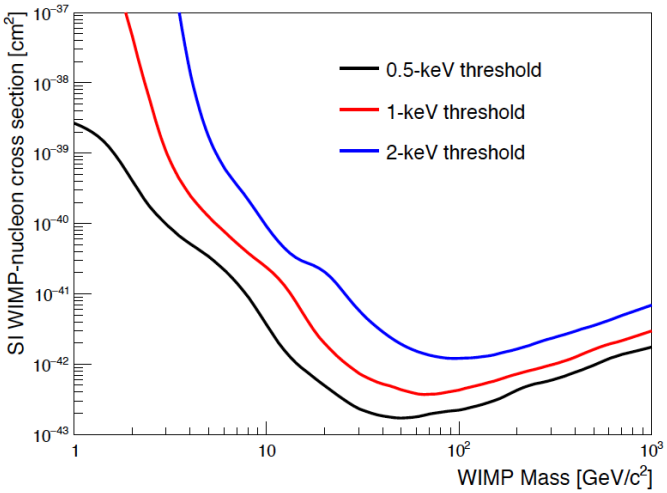




Understand signal-like events and noise-like events at low energies

Develop new parameter for BDT

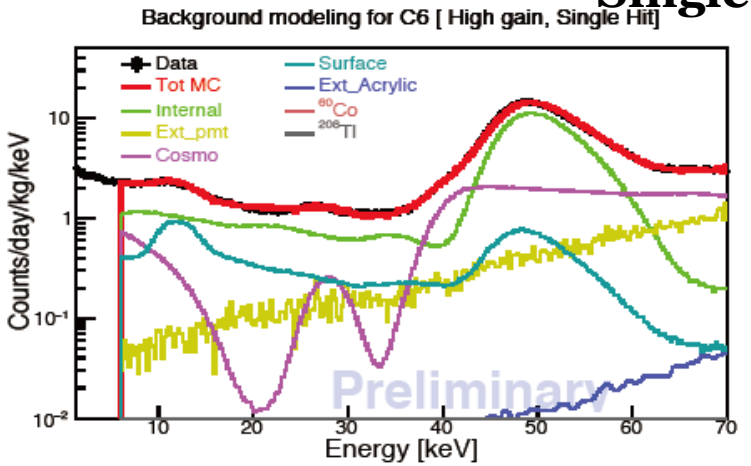
**New BDT**

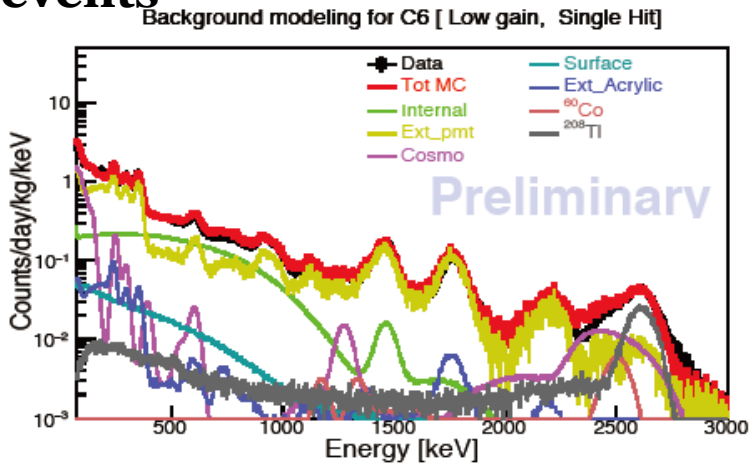


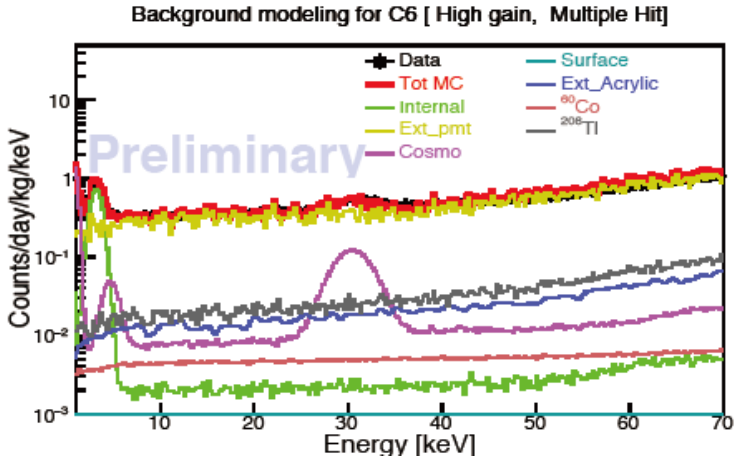
# Background modeling

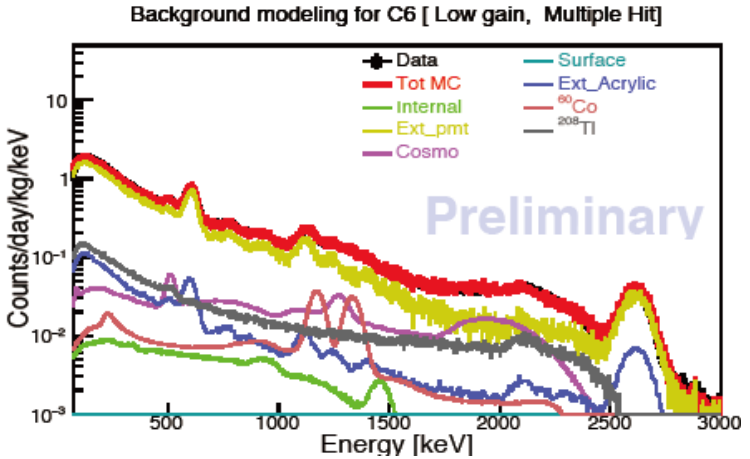
## Single-hit events



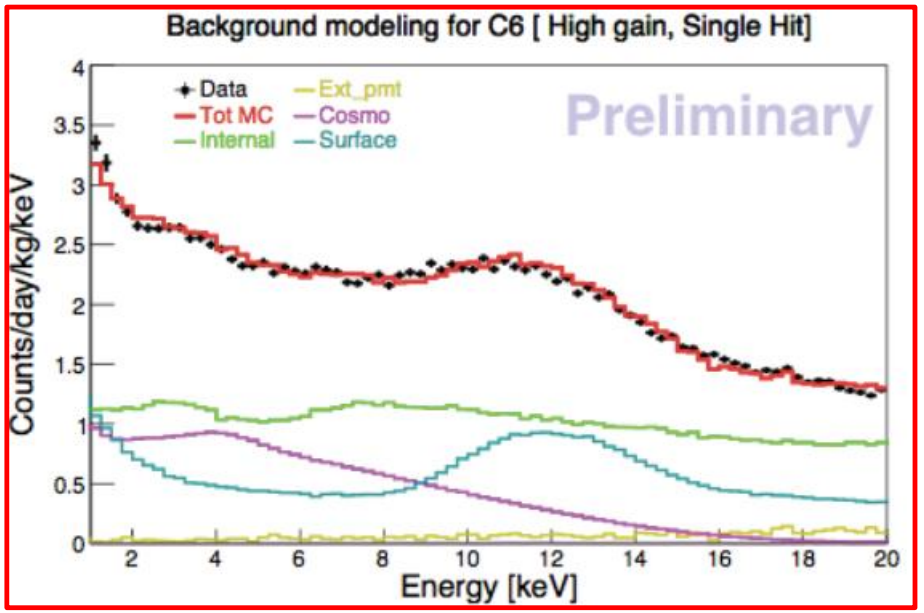

## Multiple-hit events




- Improved background modeling
  - $^{129}$I, rock-gamma ($^{208}$Tl) are added
  - Better modeling of surface $^{210}$Pb using contaminated crystal

# Signal region extrapolation




| Components | Bkgd (dru in 1-6 keV) |
|---|---|
| Internal | 2.65 ± 0.019 |
| External | 0.03 ± 0.002 |
| Surface | 0.53 ± 0.008 |
| Cosmogenic | 0.91 ± 0.01 |
| Other | 0.002 ± 0.0005 |
| Total Expected | 2.65 ± 0.019 |
| Data | 2.62 ± 0.018 |

Preliminary

**Dark matter extraction with same dataset is ongoing**

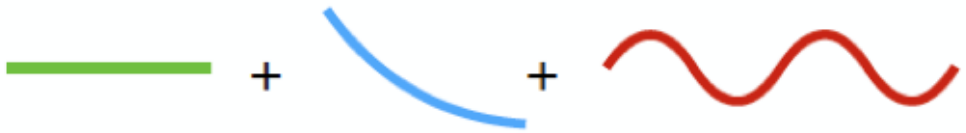
**Stay tuned!!**

Final model independent comparison would come from same annual modulation analysis

# Annual modulation analysis (1.7 years data)

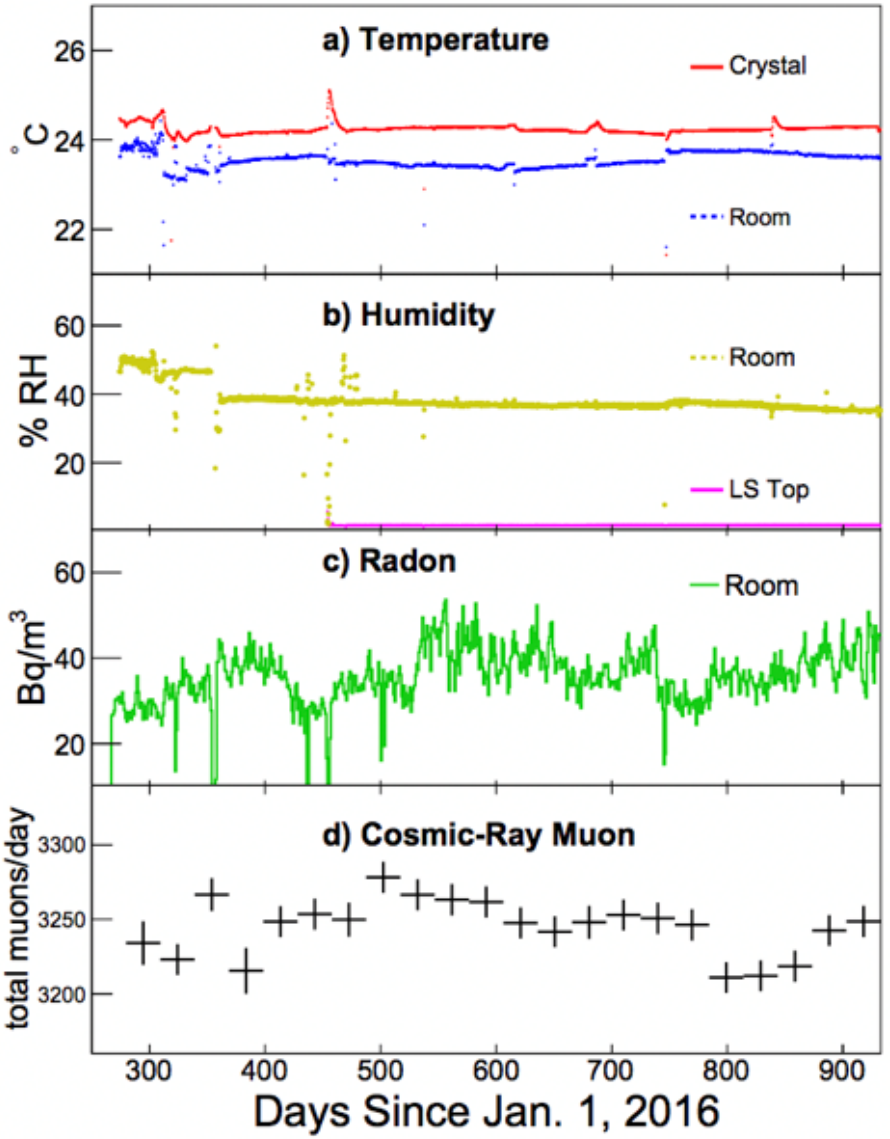
Backgrounds, constrained
*Different* for each crystal

Signal, floated
*Same* for all the crystals



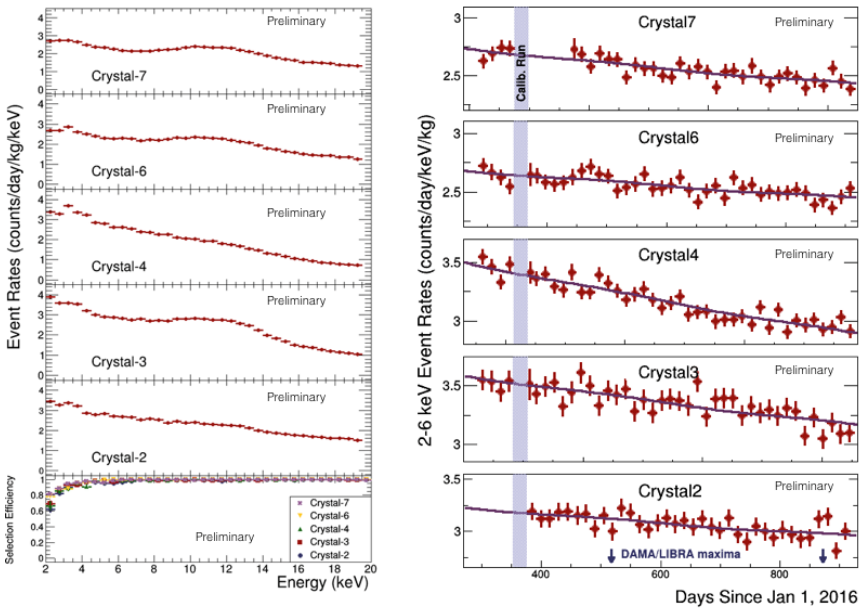
$$\text{Rate} = C + p_0 \cdot \exp\left(-\frac{ln2 \cdot t}{p_1}\right) + A \cdot \cos\frac{2\pi(t - t_0)}{T}$$

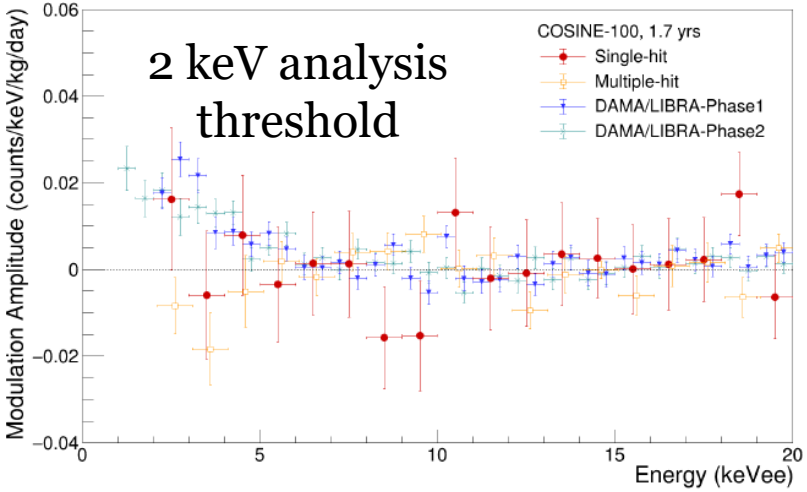
- Require long-term measurements (>3year)
- 97.7 kg•yrs exposure (1.7 years)
- Background + modulation signal fit to data (2-6 keV)
- Simultaneous fitting of 5 crystals
- Analysis based on likelihood ratio method
- Analysis specially concerns the sidebands.



# Annual modulation result with COSINE-100

2-6 keV data

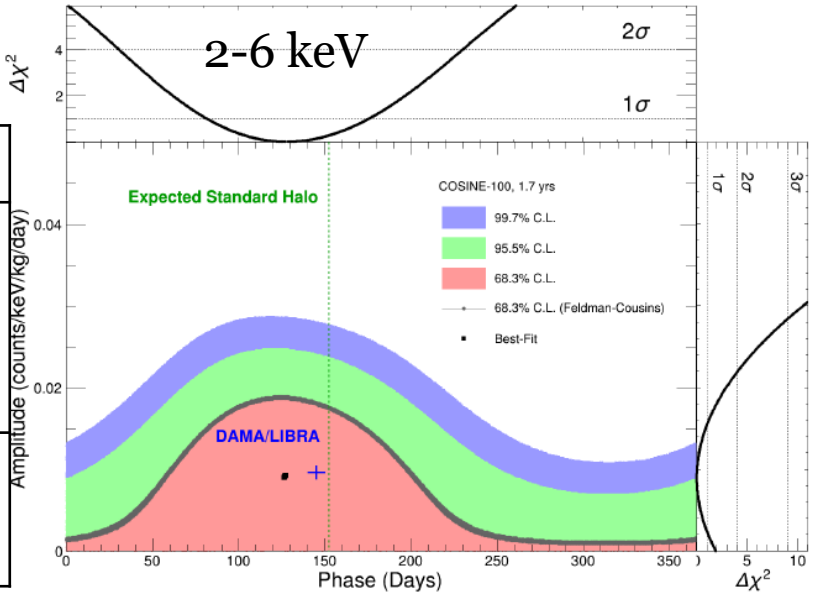



PRL **122**, 131802 (2019)

Global fit of cosmogenic and sinusoidal components for crystals

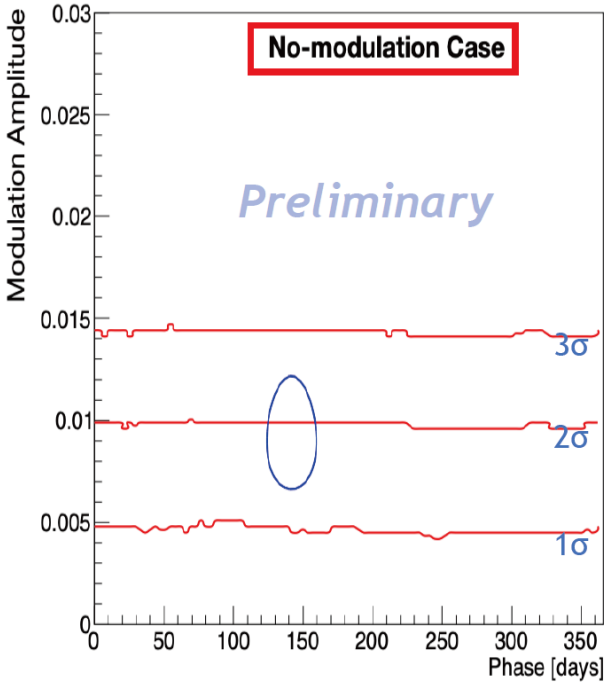
| Config | Amplitude (2-6 keV) | Phase (days) |
|---|---|---|
| **COSINE-100** | $\mathbf{0.0083 \pm 0.0068}$ | **152.5 (fixed)** |
| ANAIS | $-0.0044 \pm 0.0058$ | 152.5 (fixed) |
| DAMA | $0.0095 \pm 0.0008$ | 152.5 (fixed) |
| COSINE-100 | $0.0092 \pm 0.0067$ | $127 \pm 46$ |
| DAMA | $0.0096 \pm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

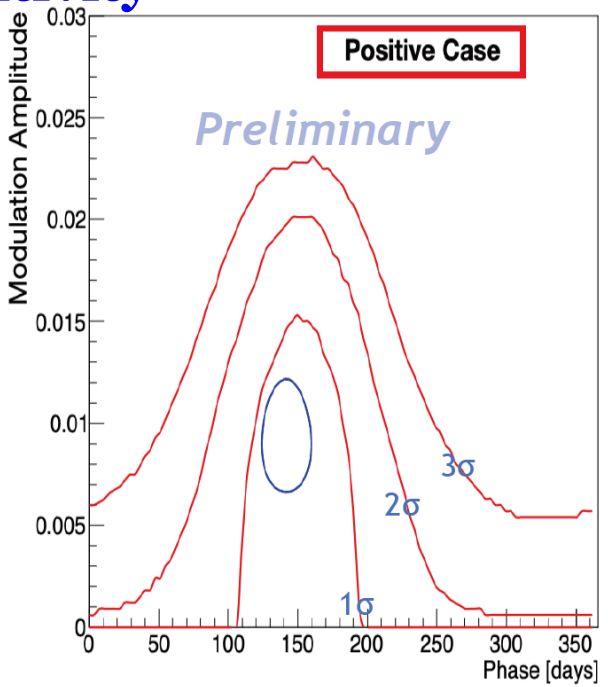


# Upcoming data analysis

- More data ~ 2.5 years
- 1keV energy threshold
- Improved event selection (Better selection efficiency)
- Develop Bayesian toolkits
- Realistic  pseudo experiments for testing machinery

**Sensitivity**




**~ 2 sigma level statement**

# COSINE-200 crystal development

- Goal : Background less than DAMA/LIBRA (1 dru)
  - ❖ Needs a factor two or more improvement
  - ❖ Powder purification/crystal growing/detector assembly will be done at IBS, Korea

**Powder purification performance**

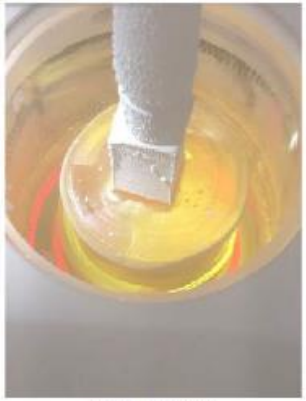
**K.A. Shin et al., J. Rad. Nucl. Chem. 317, 1329 (2018)**

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



# Recent crystal

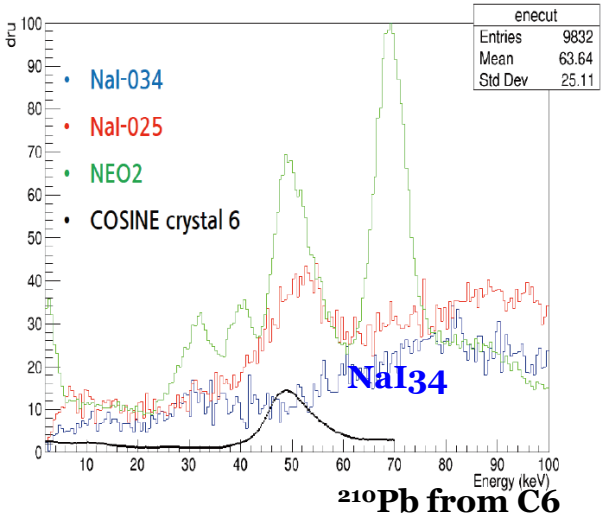
**Recent improvement (Quartz cover)**

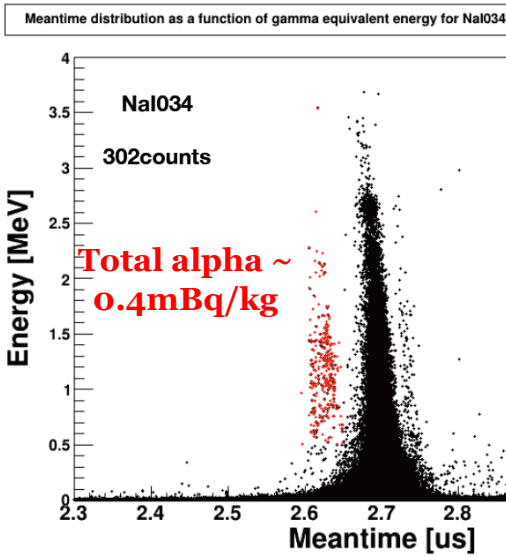




| | K (ppb) | Pb (ppt) | U (ppt) | Th (ppt) |
|---|---|---|---|---|
| Powder | <14 | <300 | <5.2 | <4.6 |
| Aug/2018 | 300 | 9000 | <5.2 | <4.6 |
| Mar/2019 | 100 | 17000 | <4.3 | <2.6 |
| **Sept/2019** | **<50** | **<240** | **<4.3** | **<2.6** |

**922g detector**


**Light yield 8.2 +/- 1.1 PEs/keV**

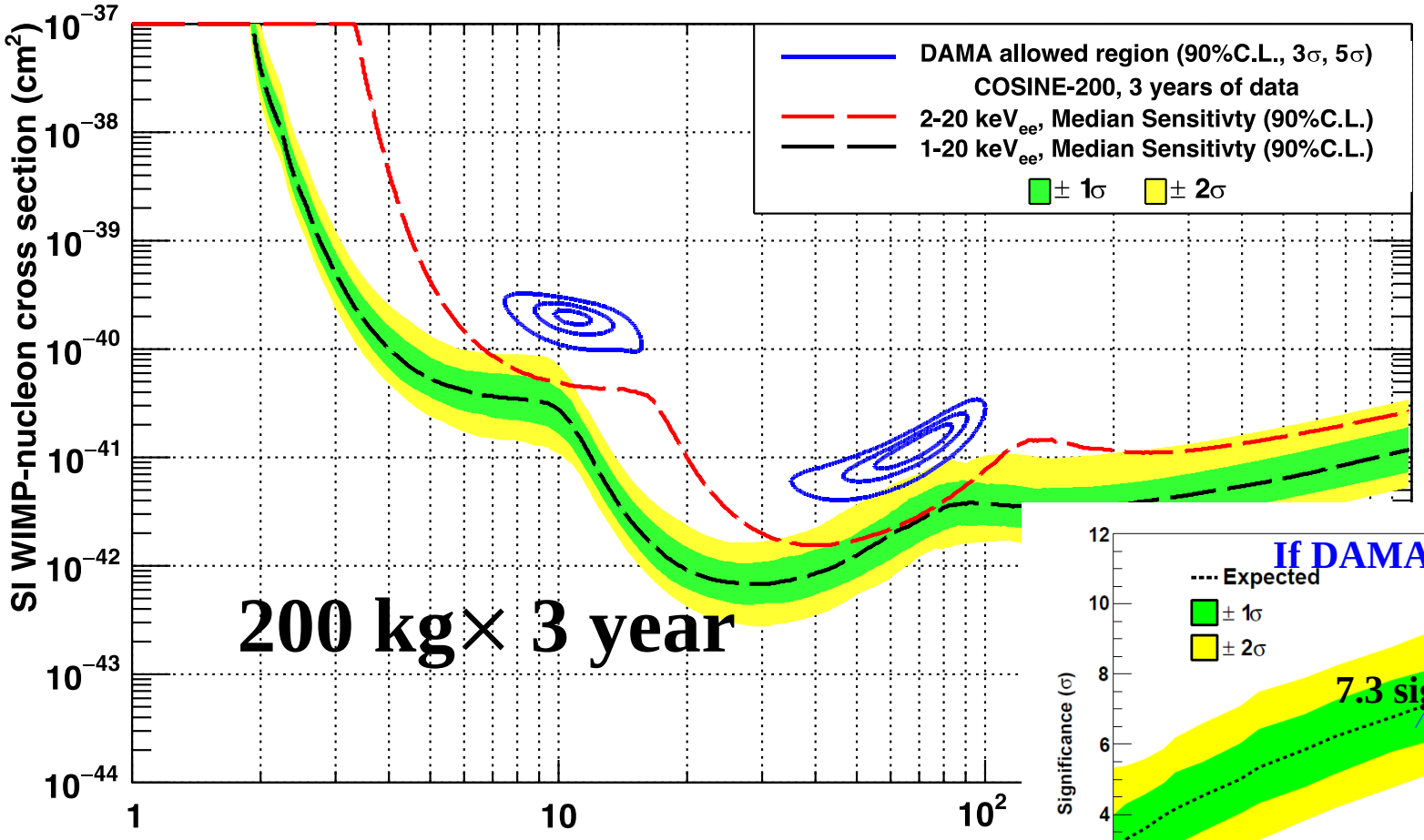


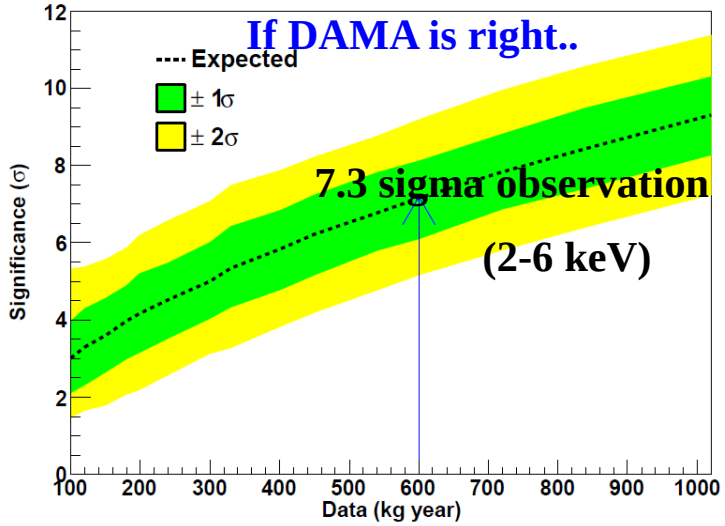




- Is this surface contamination?
  - ❖ Machining for perfect cylinder is in preparation

# COSINE-200 sensitivity (similar for all future project)

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

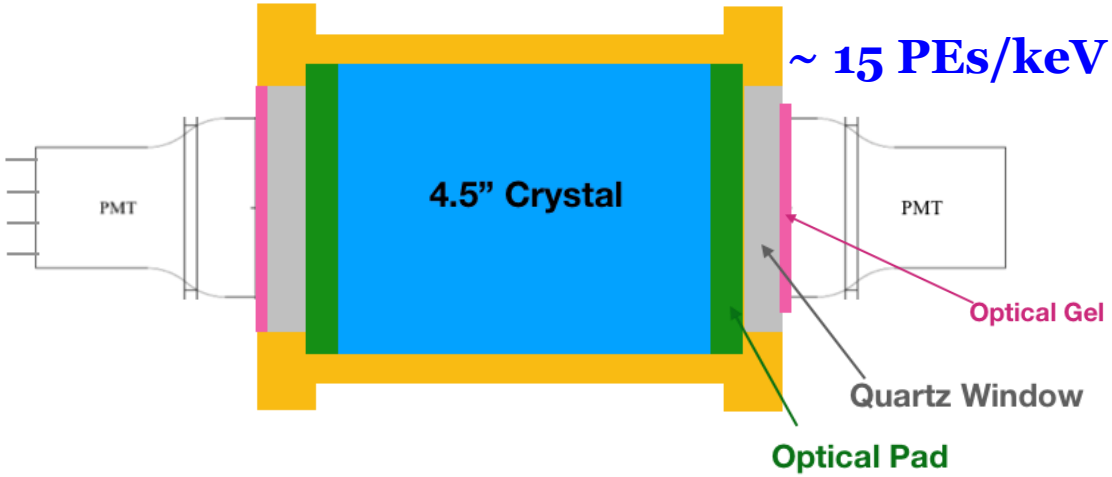


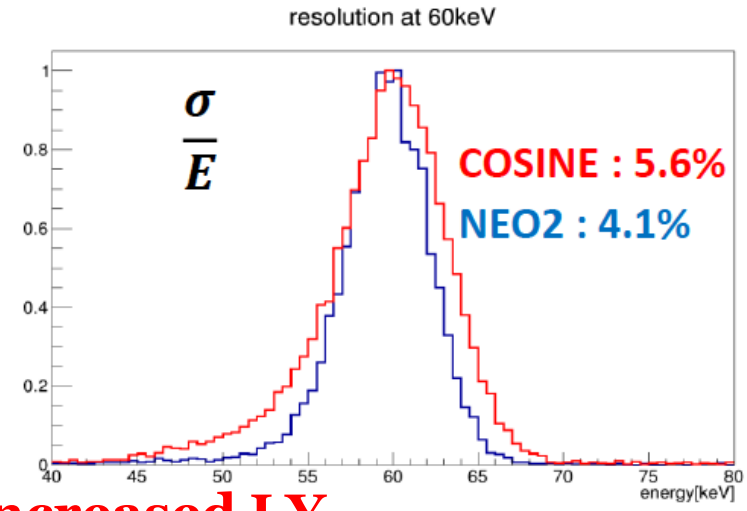

**Model independent comparison of the modulation amplitude at 2-6 keV will be performed**

# Higher light yield NaI(Tl) detectors?

**COSINE-100 design (12.5 kg)**

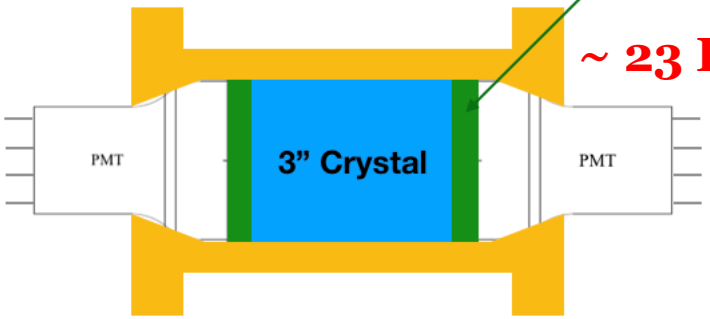



**~ 15 PEs/keV**

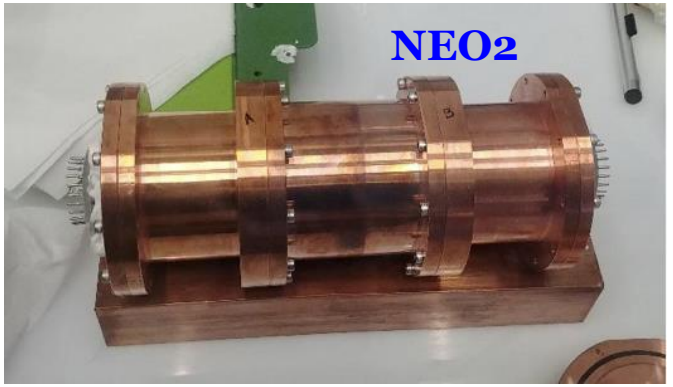



**~50% increased LY**

**New design (1.7 kg)**




**~ 23 PEs/keV**

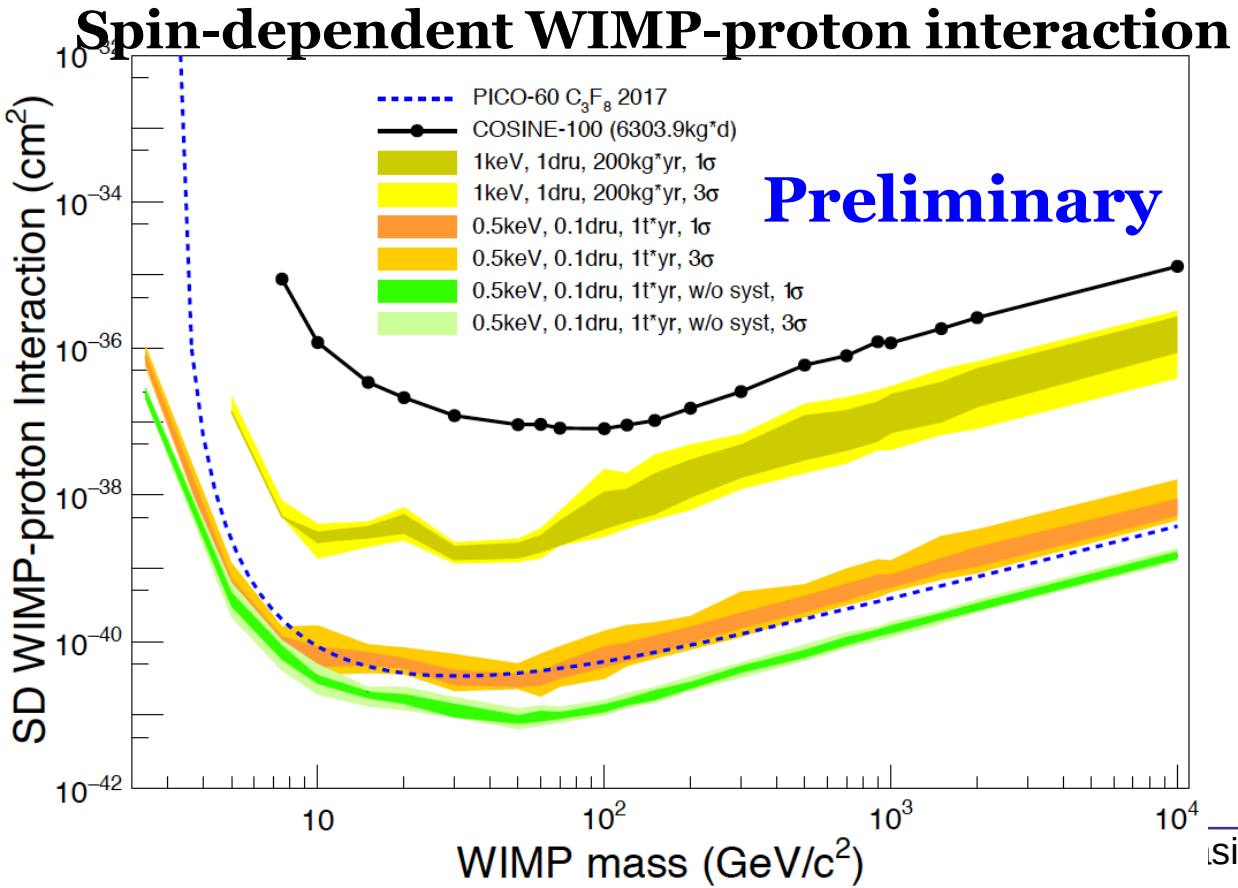



- Match crystal size to PMT size
- Reduce optical interface

Future : Better control of humidity & fewer cracks in the crystals

# Further .. in addition to check DAMA/LIBRA

- NaI(Tl) crystals may be a unique target for spin-dependent (SD) WIMP-proton interaction below a few GeV WIMP, where PICO has a difficulty due to threshold
- With pulse shape discrimination, it can compete with next generation PICO experiment at high WIMP mass region



# Summary

- DAMA modulation signals have persisted for 20 years
- Many efforts to reproduce DAMA are ongoing
- COSINE-100 data rejects DAMA result as SI WIMP interaction for standard halo model
- First annual modulation results from ANAIS-112 and COSINE-100 were published but, still need more data
- COSINE-200 R&D are actively ongoing

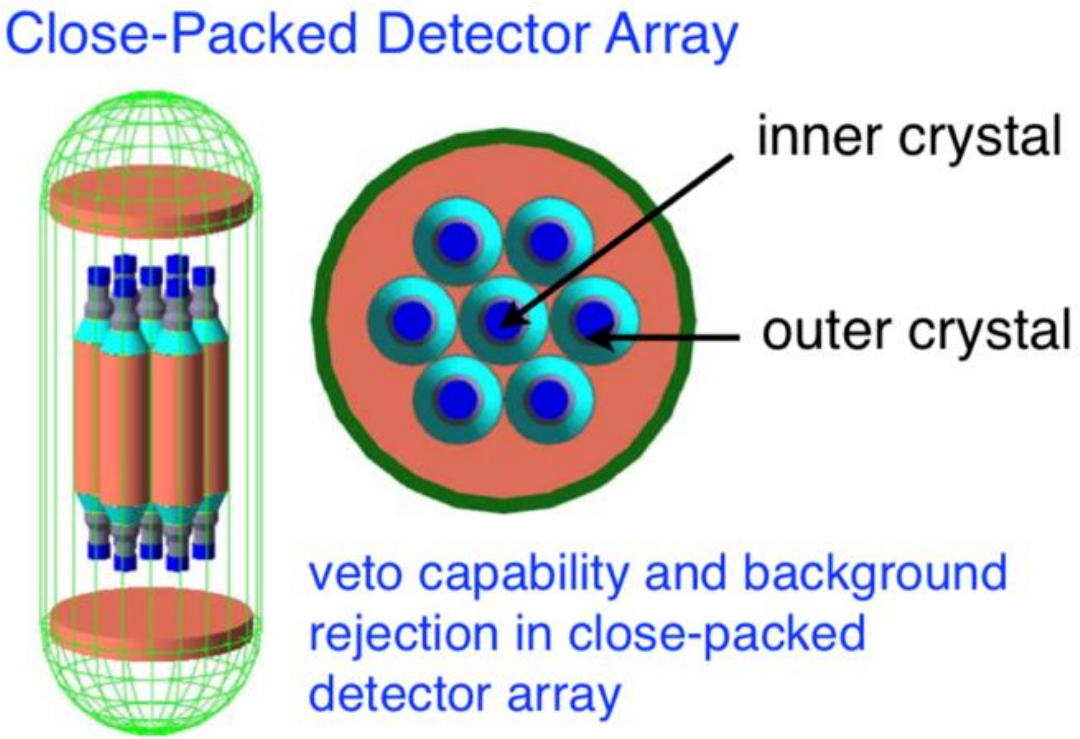
- We hope to find out the cause of DAMA modulation with lower background detectors

**Stay tuned for more exciting results to come from COSINE-experiment!**

# Backup

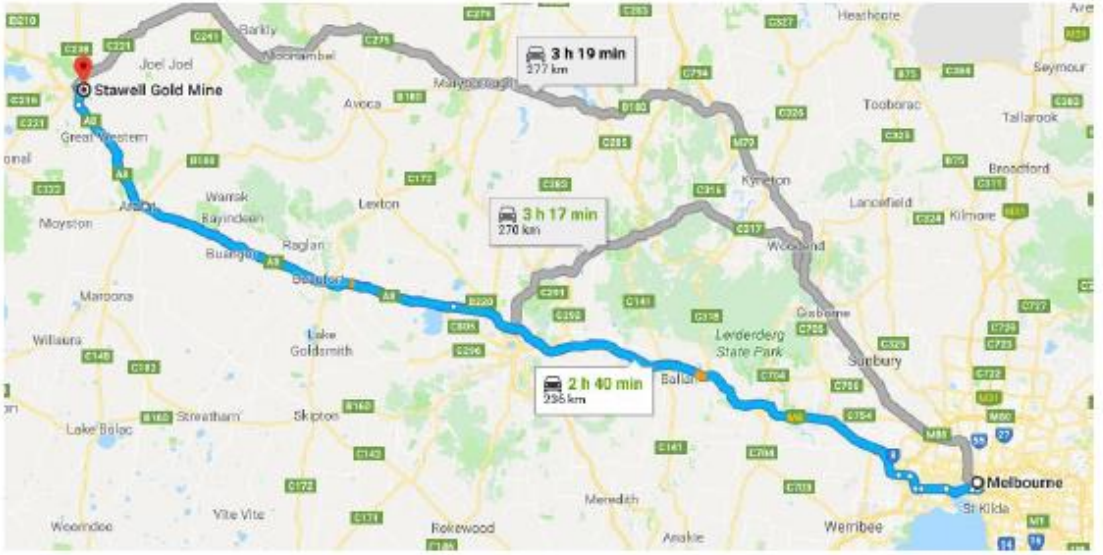
# COSINE in South Pole

- If we observe similar modulation signals as DAMA
  - ❖ Southern hemisphere experiment is required
  - ❖ South pole is natural choice for COSINE and DM-Ice
- Great chance with IceCube upgrade at 2022-2023

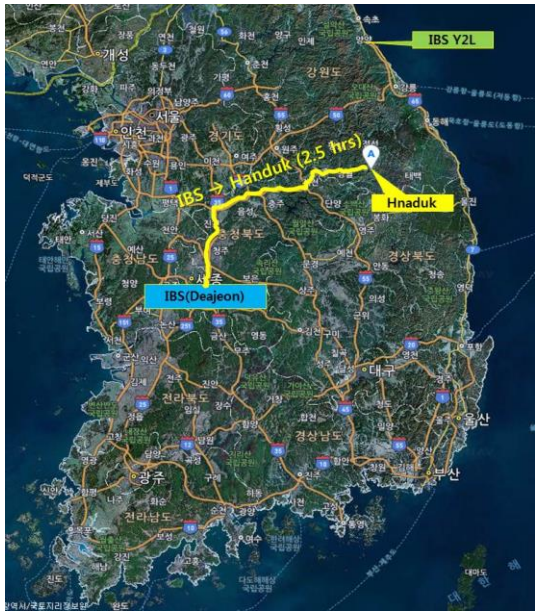


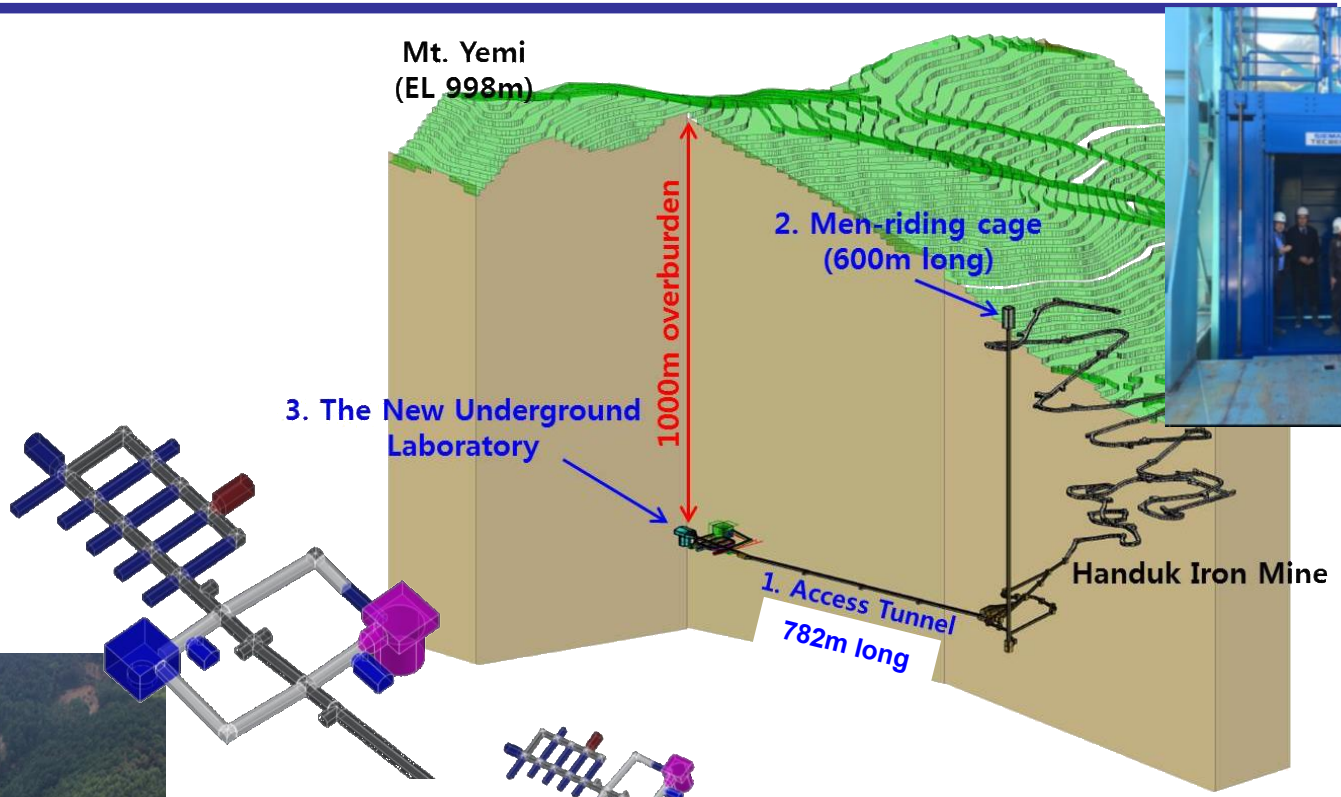
# SABRE in the South

- Hosted in Stawell Underground Physics Laboratory
- 250 km from Melbourne
- 3000 m w.e.
- excavation expected to be finished in 2019
- lab ready in 2020




# Yemilab : New underground lab in Korea



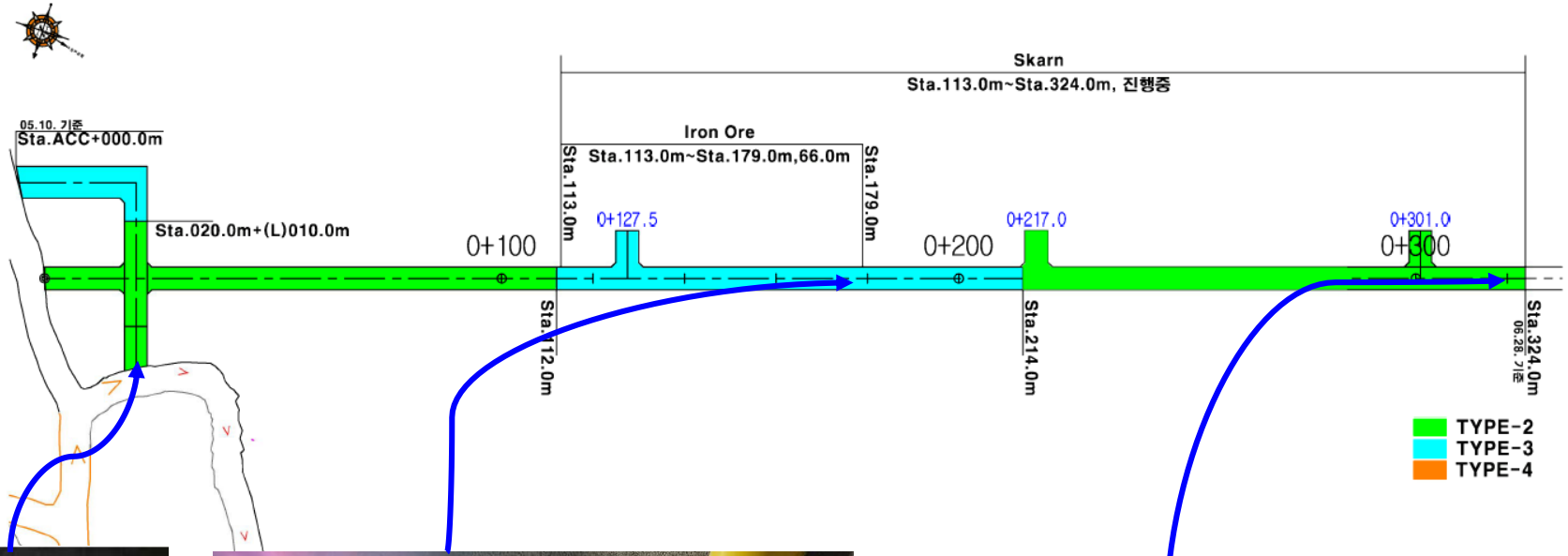




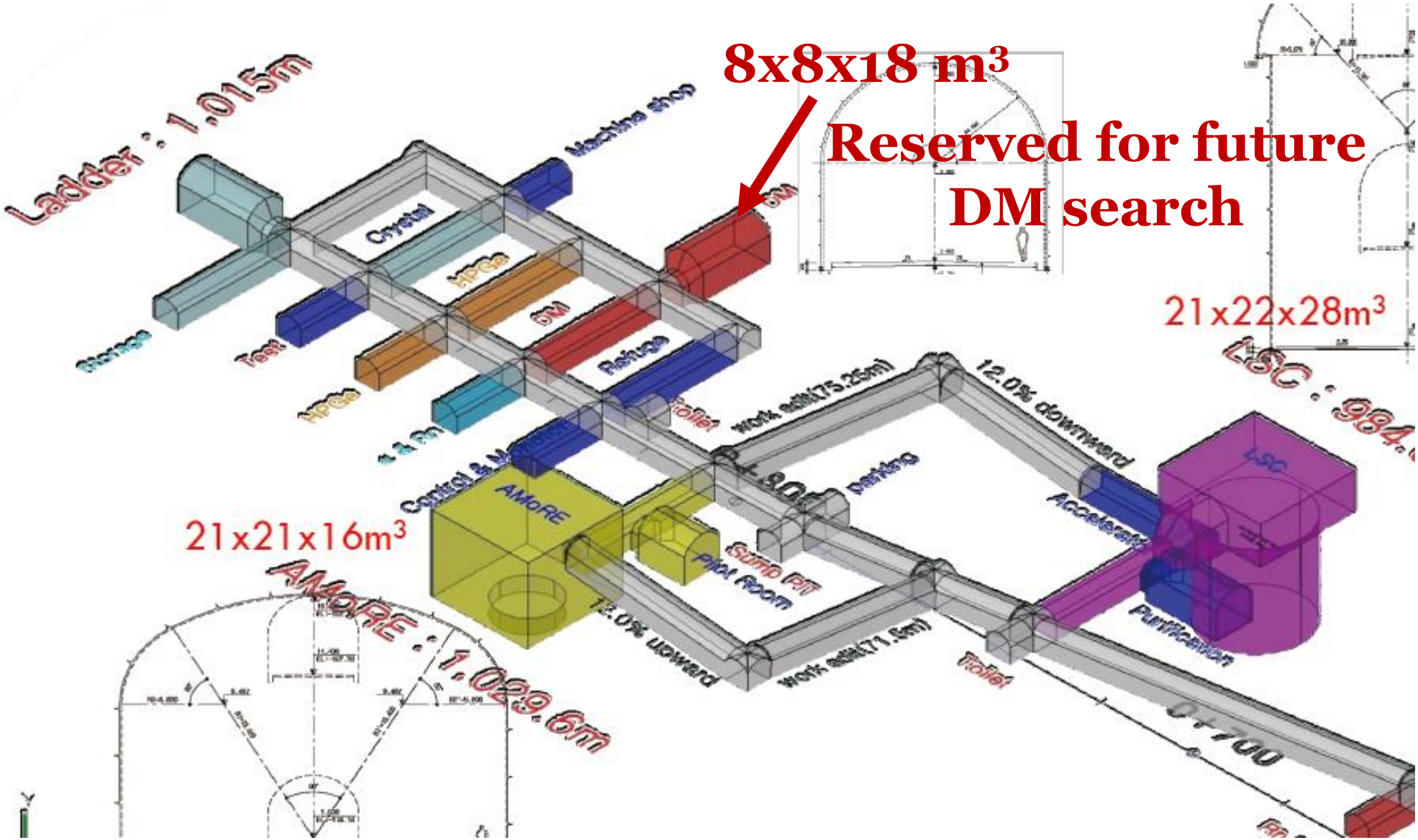
- 7 experiments with 12 spaces
- 10 utility spaces

# Yemilab status

- Tunnel excavation started March/2019




# COSINE-1ton in Yemilab



# NaI(Tl) crystals

## Pro

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

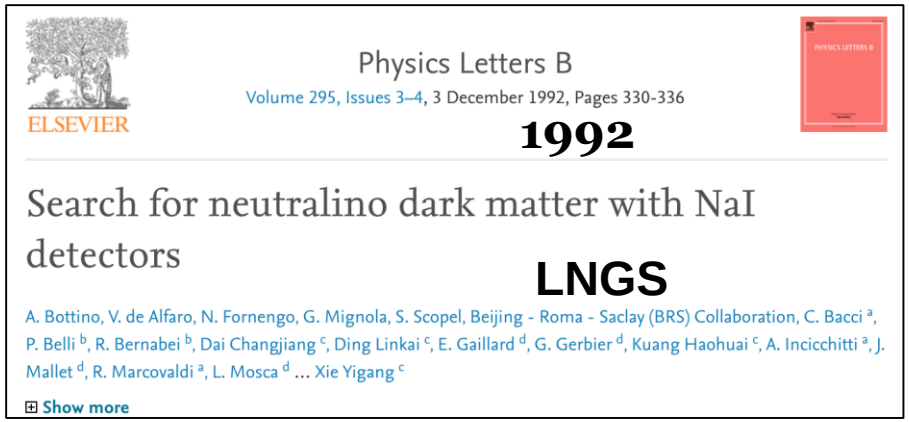
The first 32 inch diameter NaI(Tl) crystal. Pictured from left to right are Dr. Swinehart, Ed Jablon, Joe Knaus and Marko Sfilgoi.

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

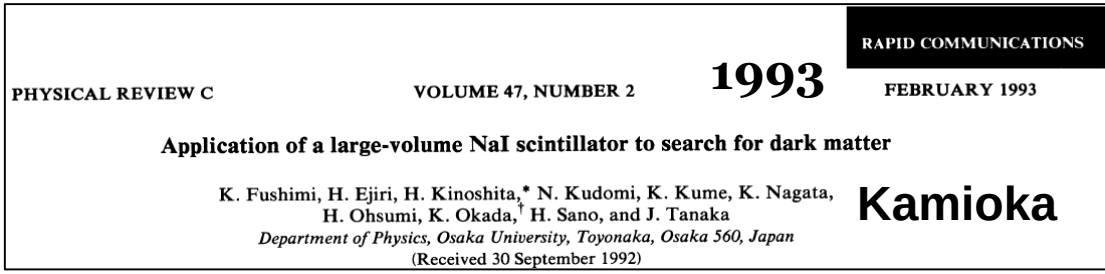
## Con

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

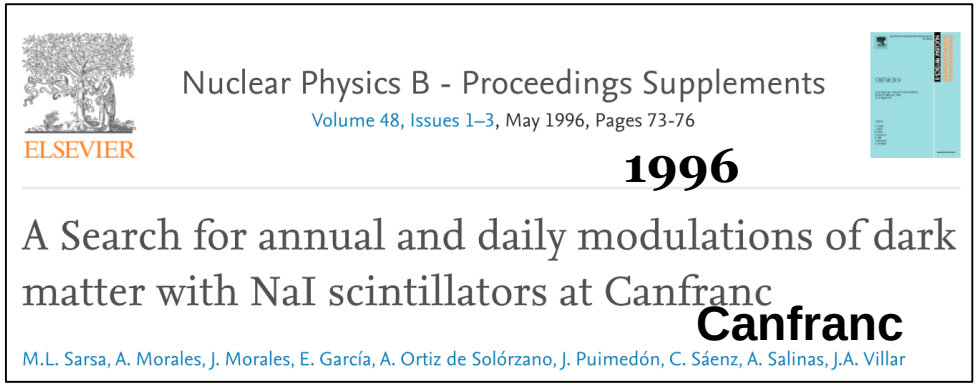
# Dark matter search with NaI(Tl)



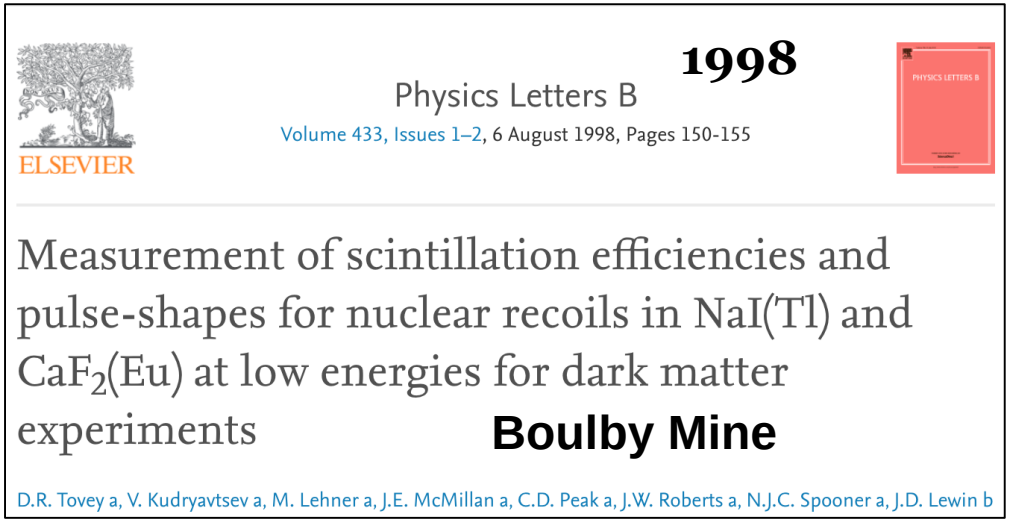

**DAMA/LIBRA**




**PICO-LON**



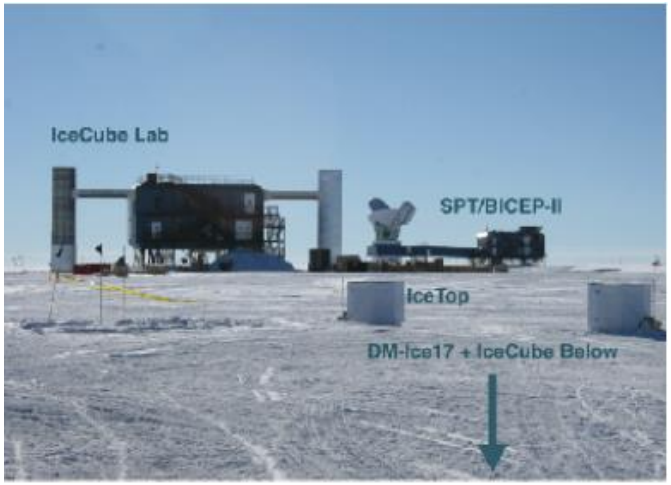

**ANAIS**




**COSINE**

# DM-Ice17

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

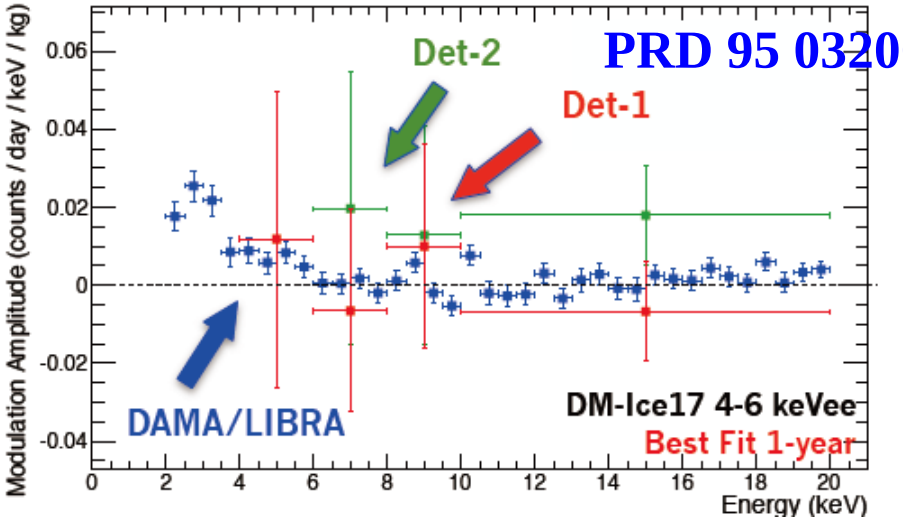



Two 8.47 kg crystals

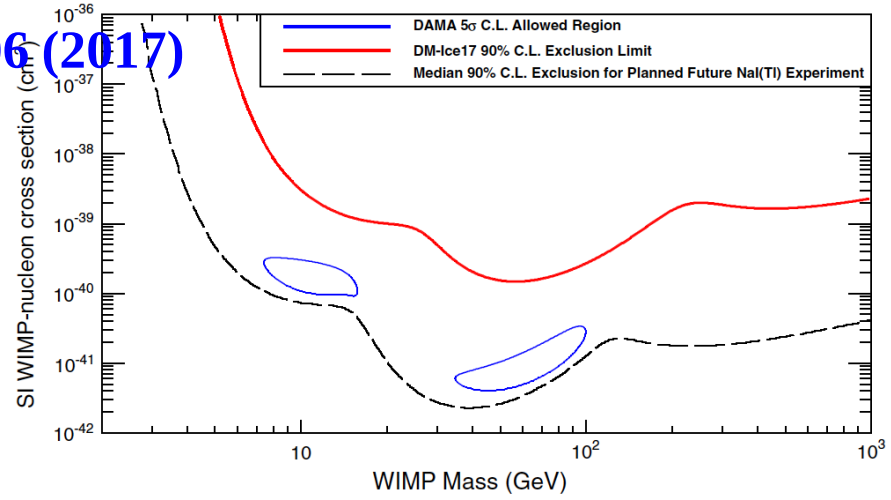
2200 m.w.e overburden

**Proof of principle of south pole experiment**

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

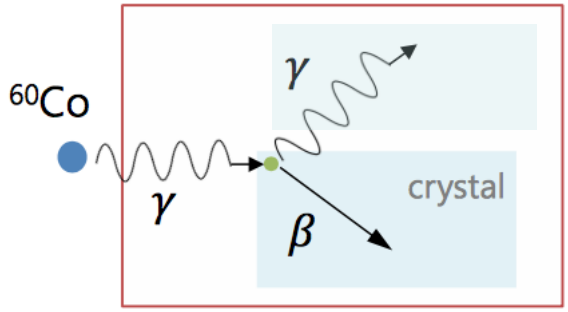



**PRD 95 032006 (2017)**

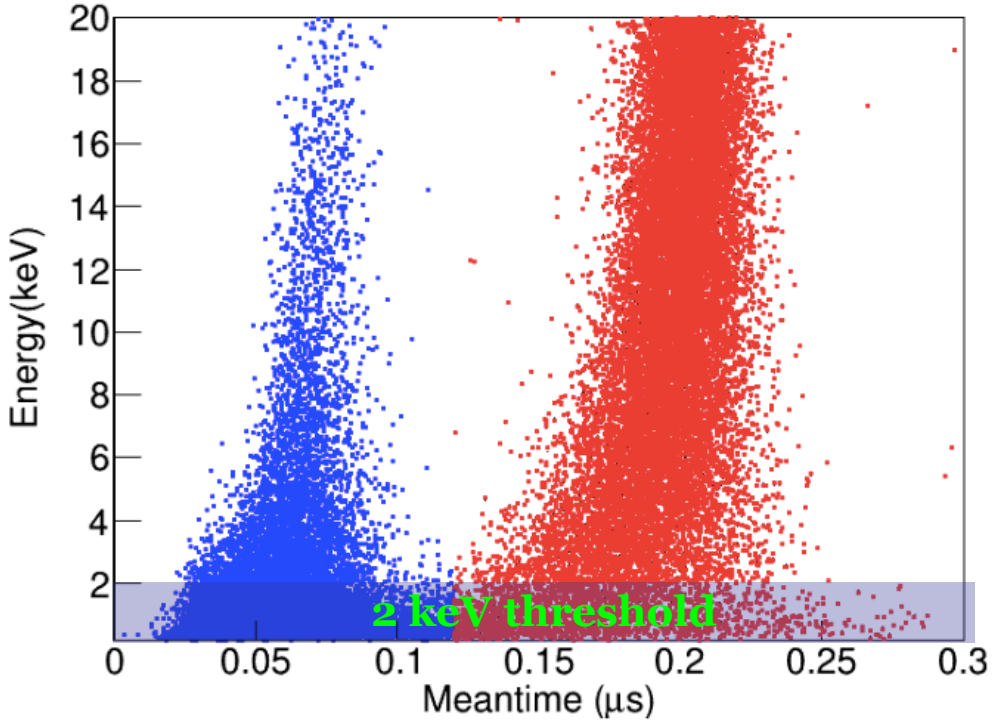


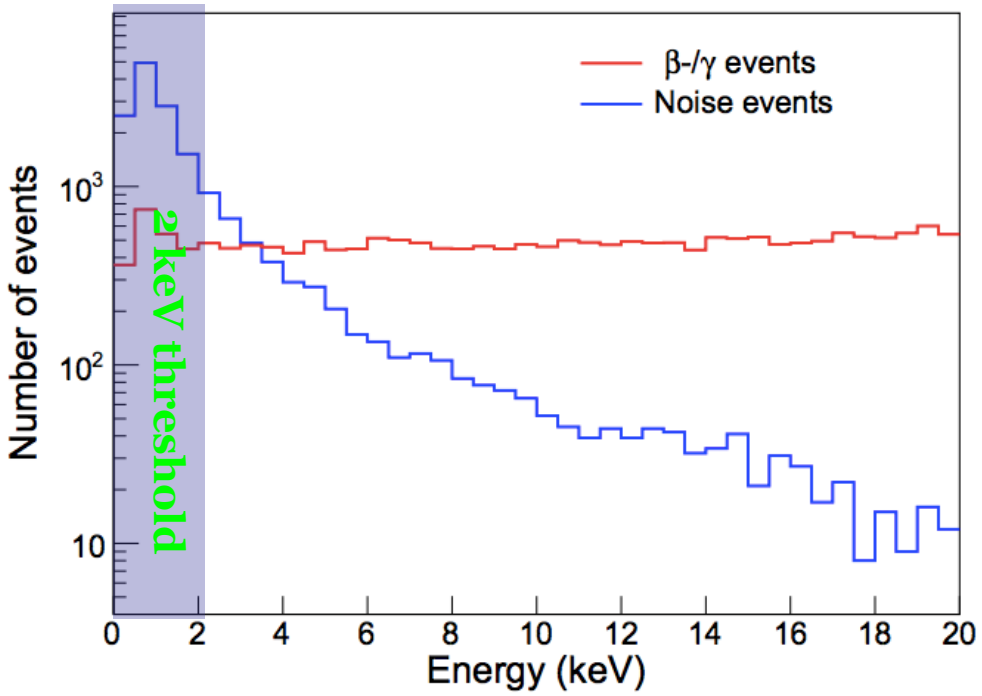
# Pure electron recoil samples

- Two weeks long $^{60}$Co calibration data



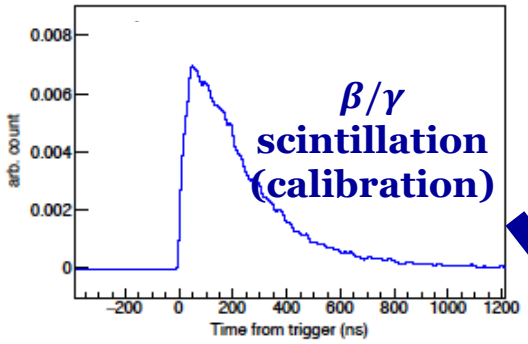

- Used to model scintillating events
- Used to estimate signal efficiency

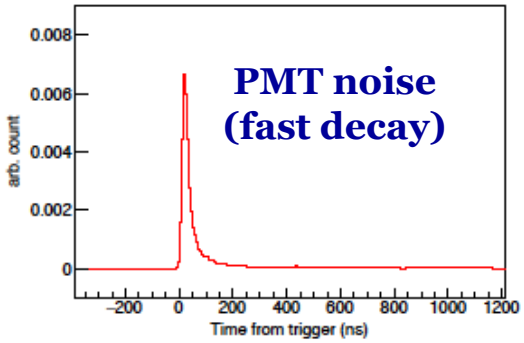


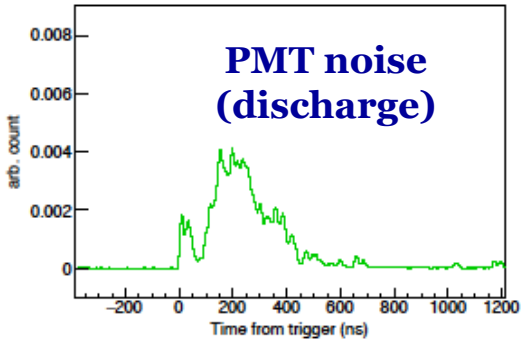



# Machine learning to remove PMT induced noise

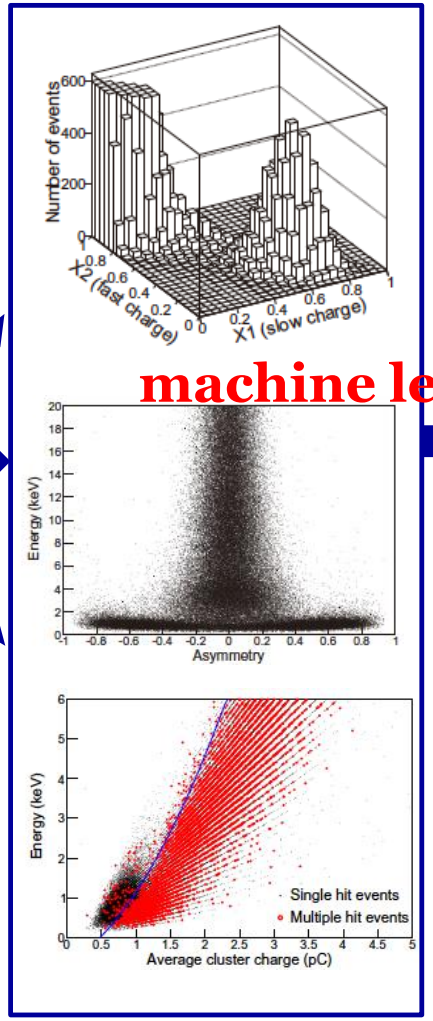
**Accumulated waveforms**



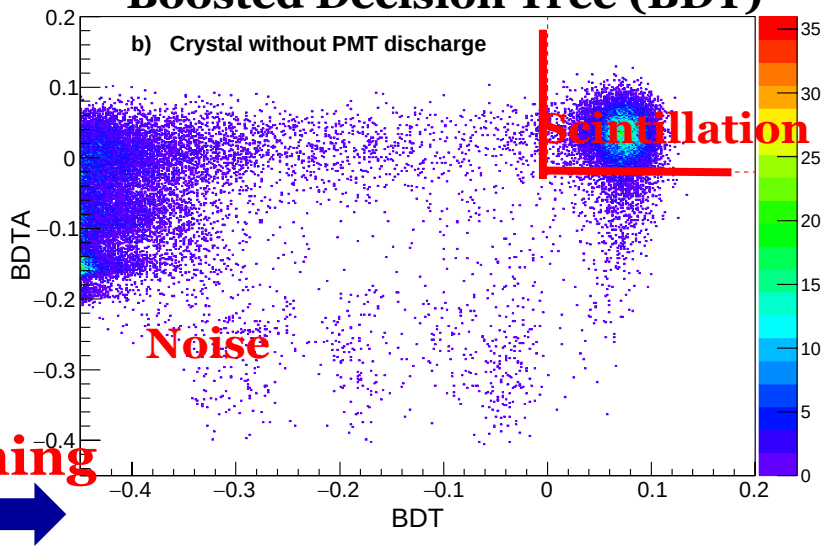



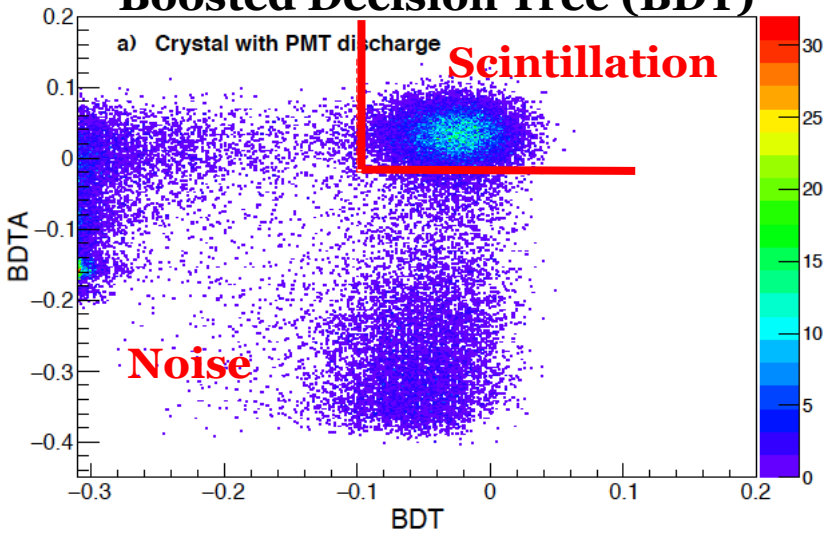

**Discrimination parameters**



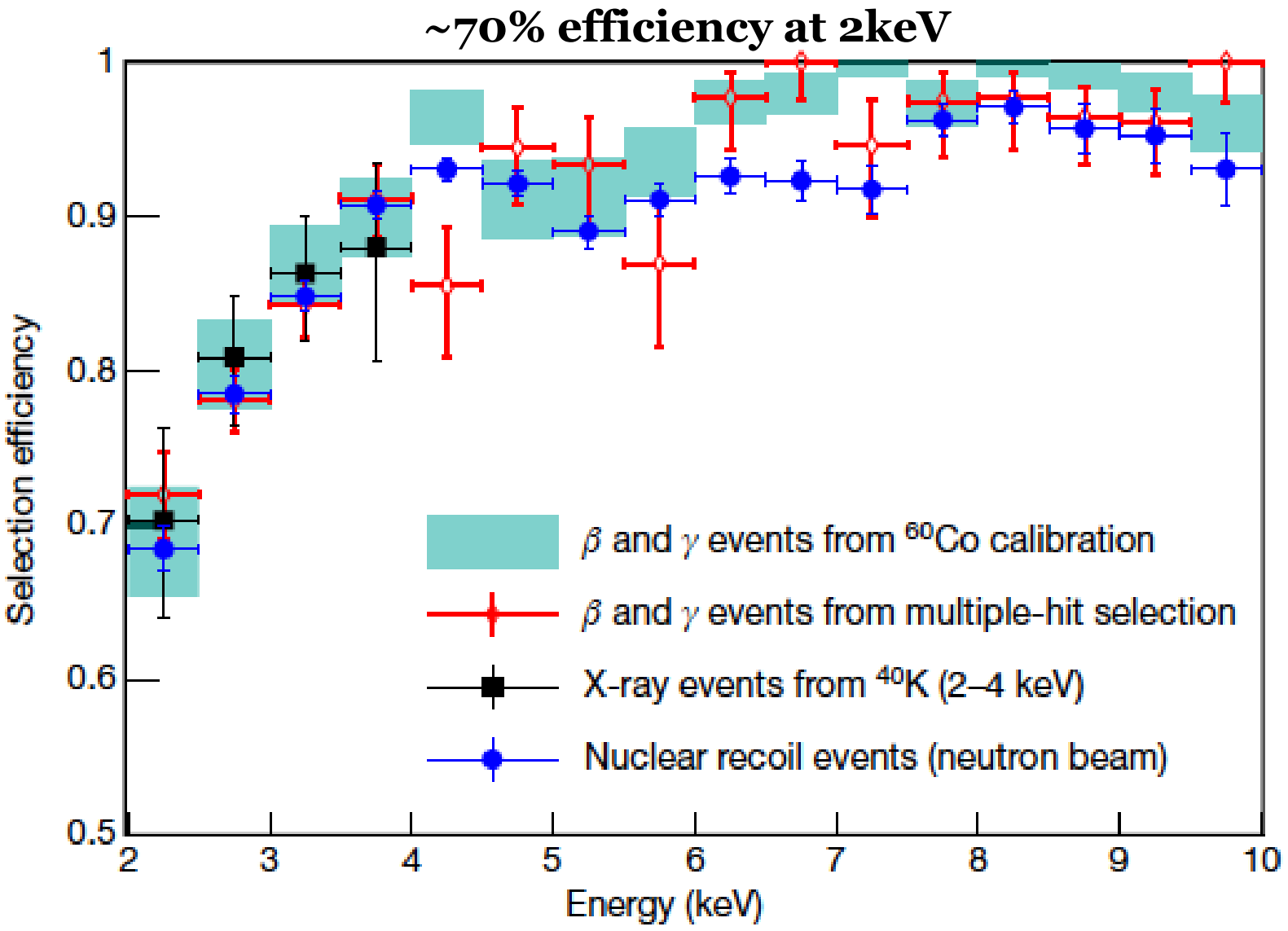

**Boosted Decision Tree (BDT)**



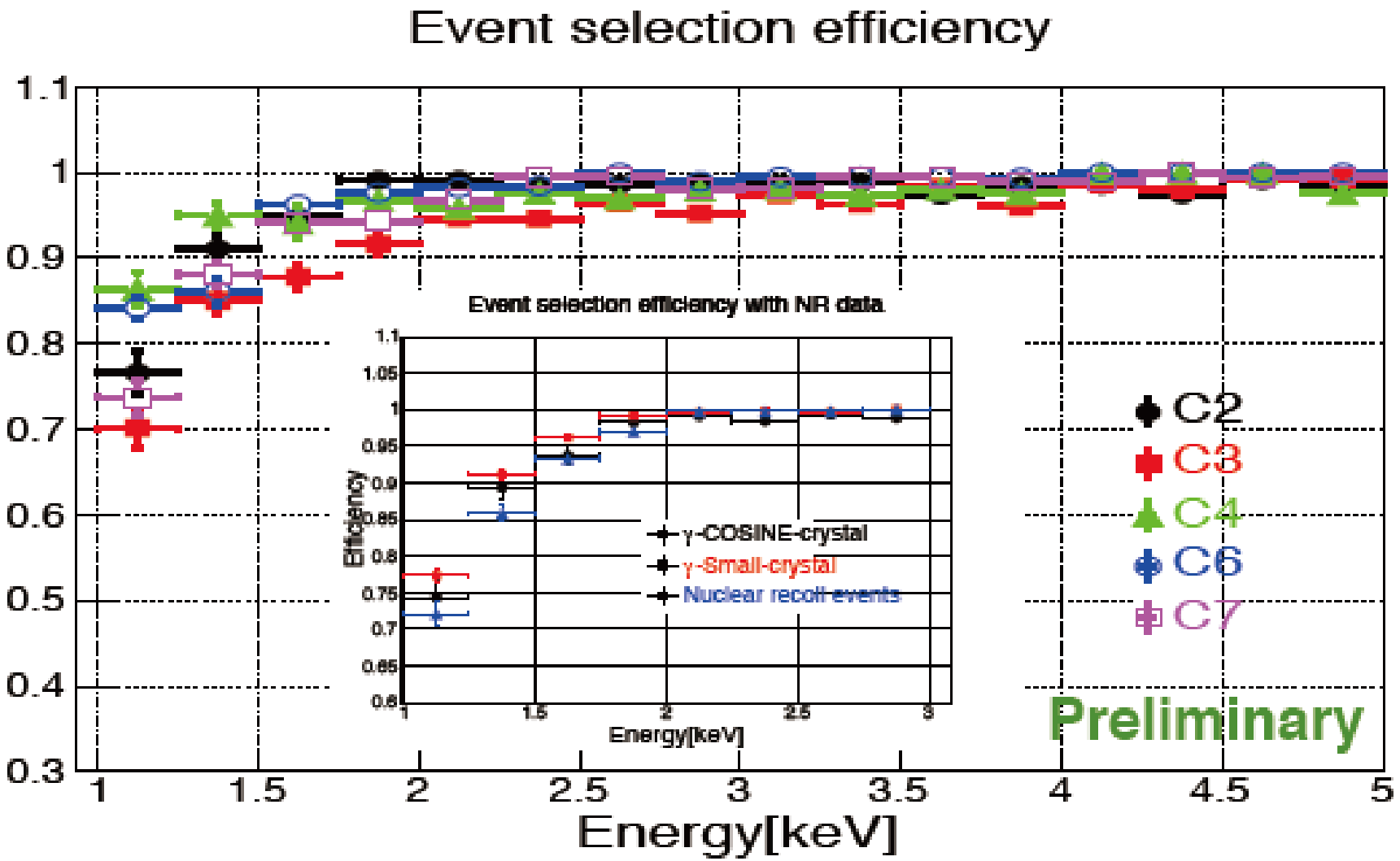

**Boosted Decision Tree (BDT)**



# Selection efficiency (SET1 analysis)

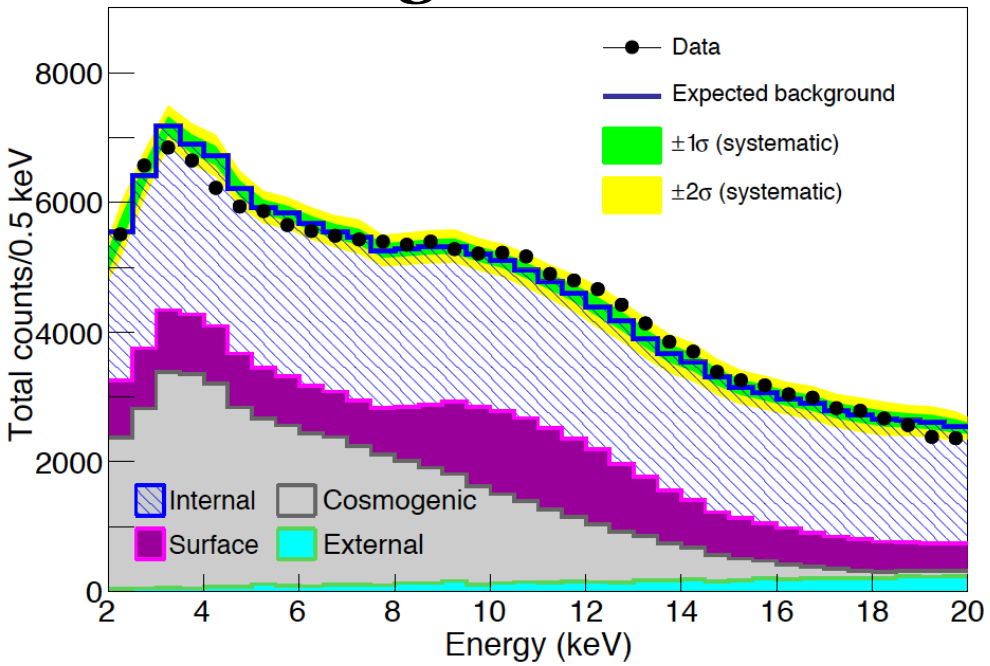


# Selection efficiency (SET2 analysis)

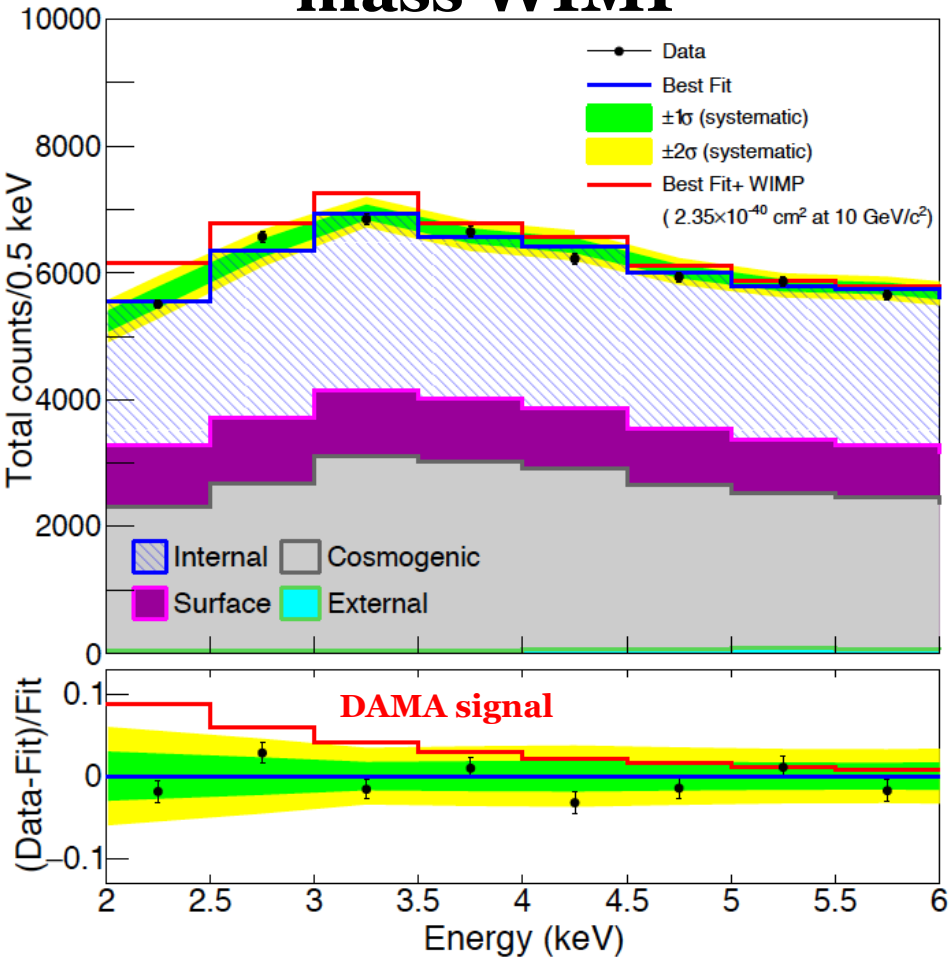


# COSINE-100 59.5 days data (2-20 keV)

**All crystals background**




**Signal fit with 10 GeV mass WIMP**




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