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

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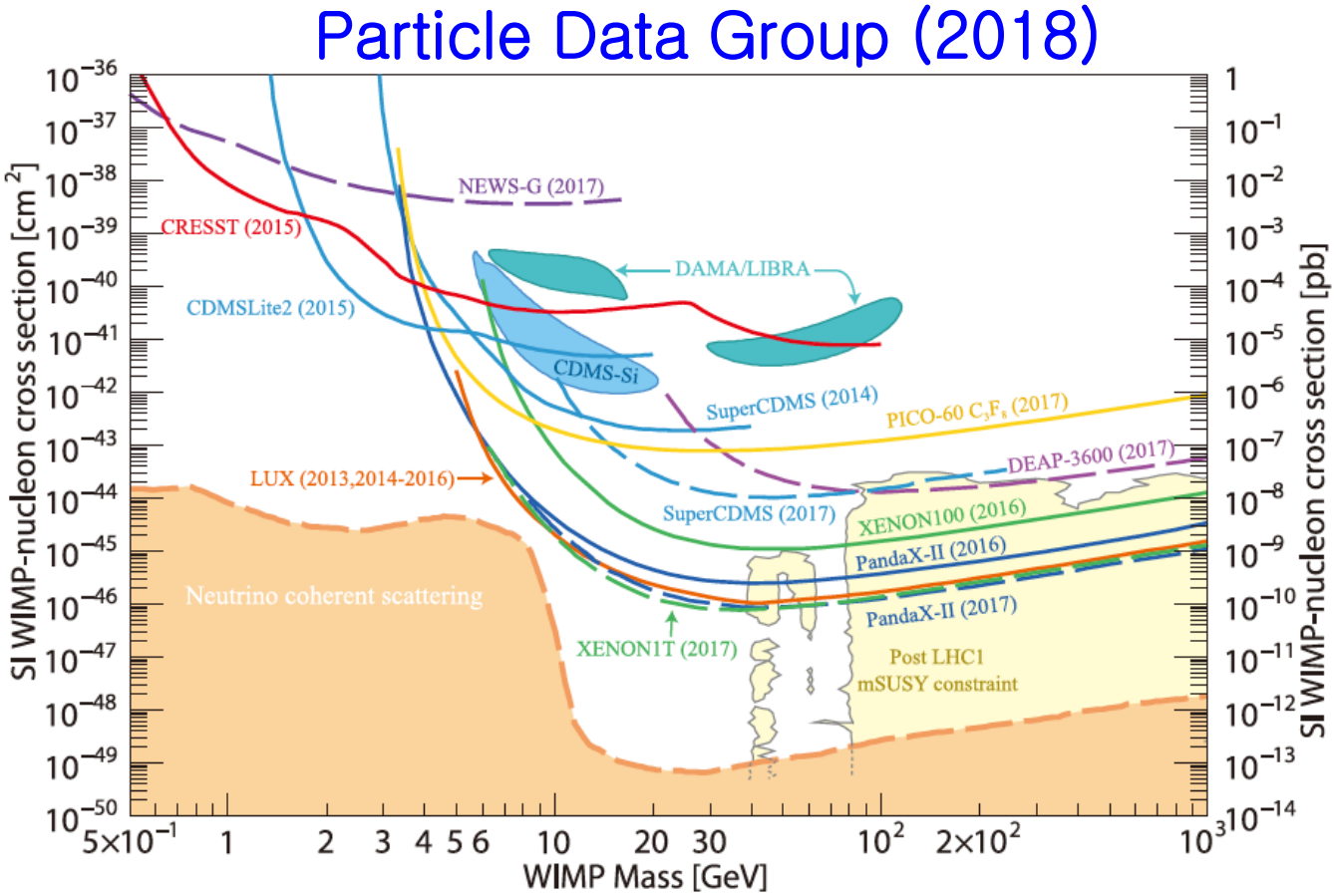
Center for Underground Physics (CUP)

Institute for Basic Science (IBS)

*IBS-KMI Joint Workshop Aug 24 - 26, 2020*

# 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

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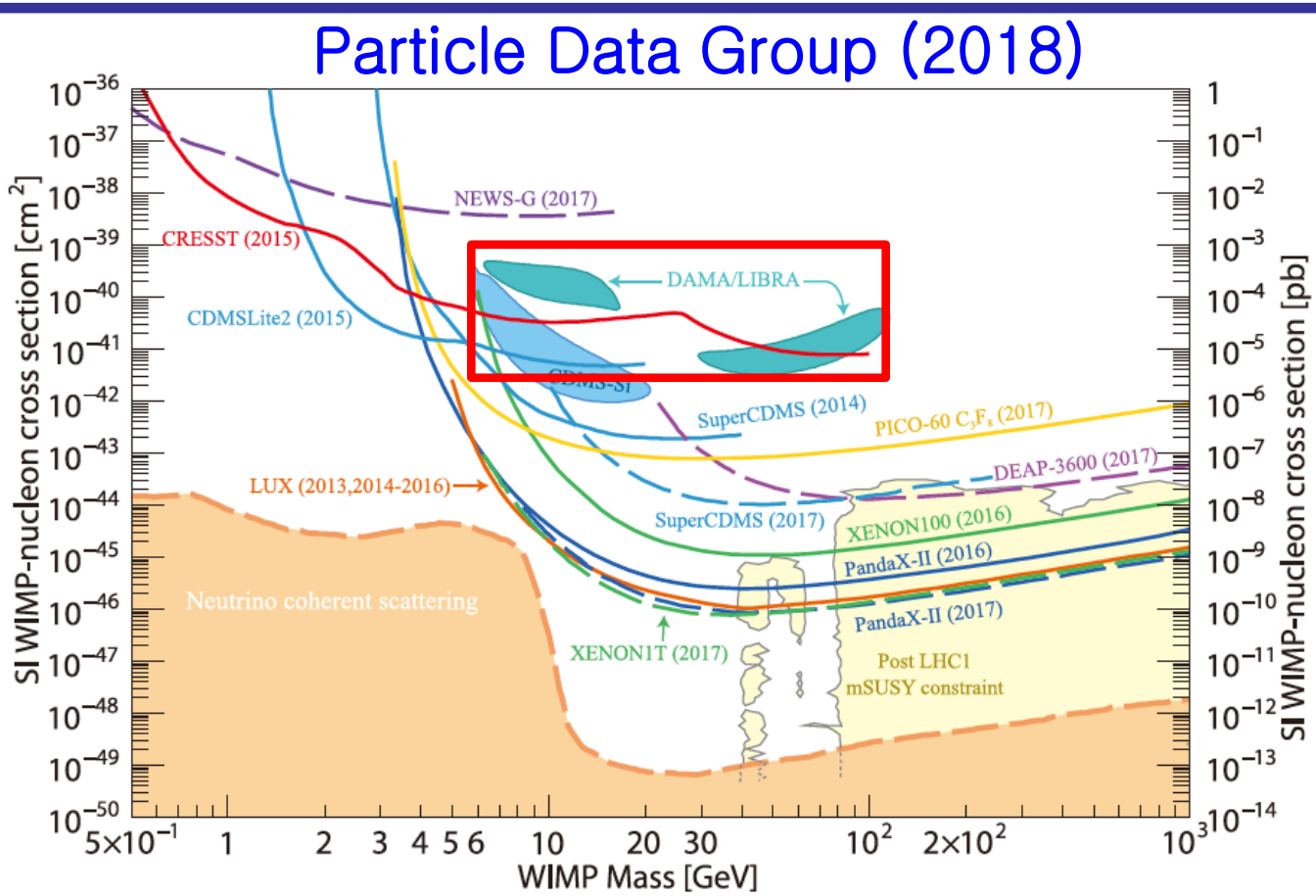


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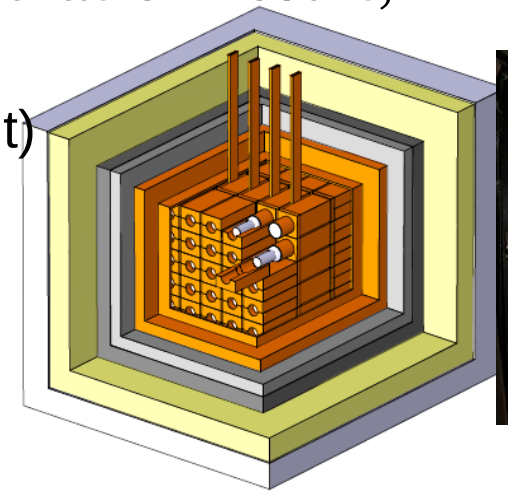
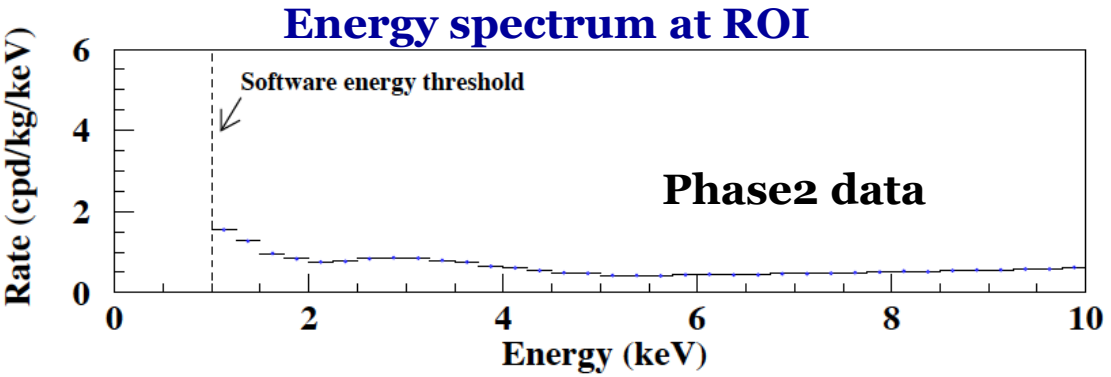
# DAMA/LIBRA experiment

- 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

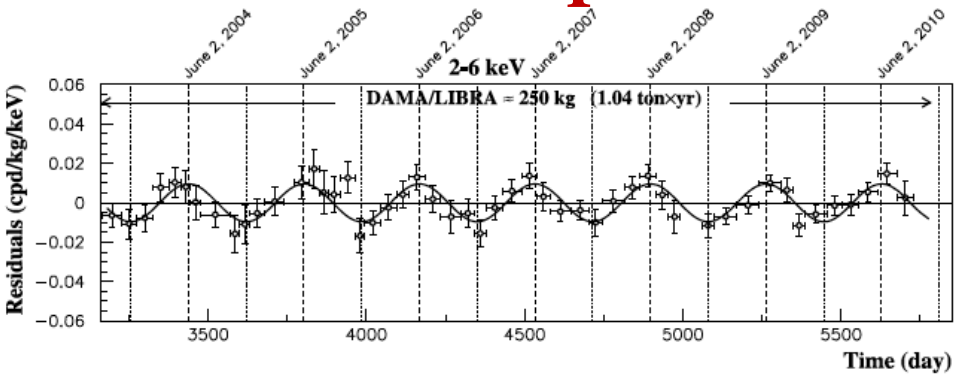

- DAMA/NaI (100 kg, 1996~2003) **First modulation result, PLB 424, 195 (1998)**
- DAMA/LIBRA-phase1 (250 kg, 2003-2010)
- DAMA/LIBRA-phase2 (250 kg, 2010~current)





# Annual modulation signal from DAMA/LIBRA

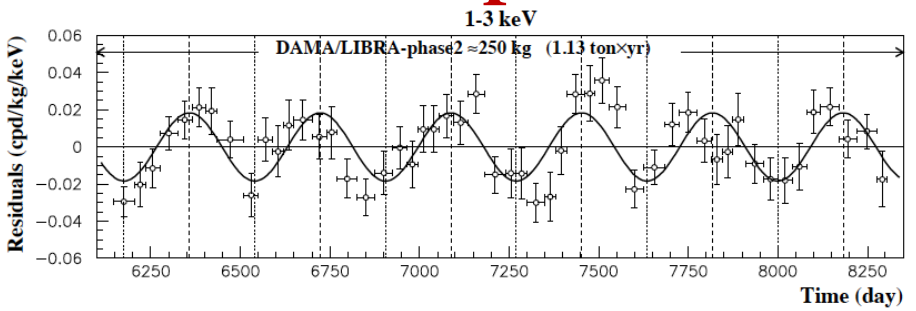
## Phase1 experiment



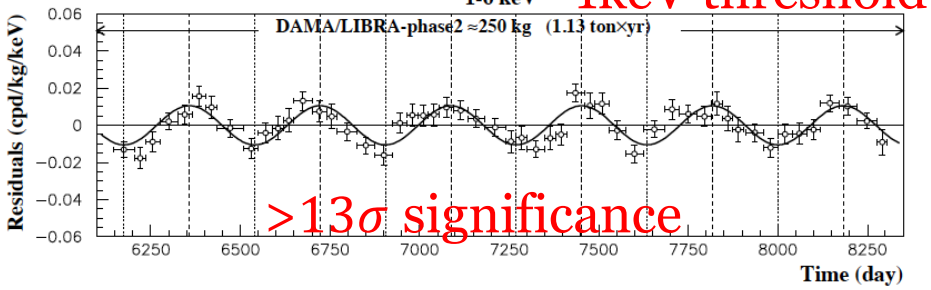

Eur. Phys. J. C 73:2648 (2013)

2keV threshold

## Phase2 experiment



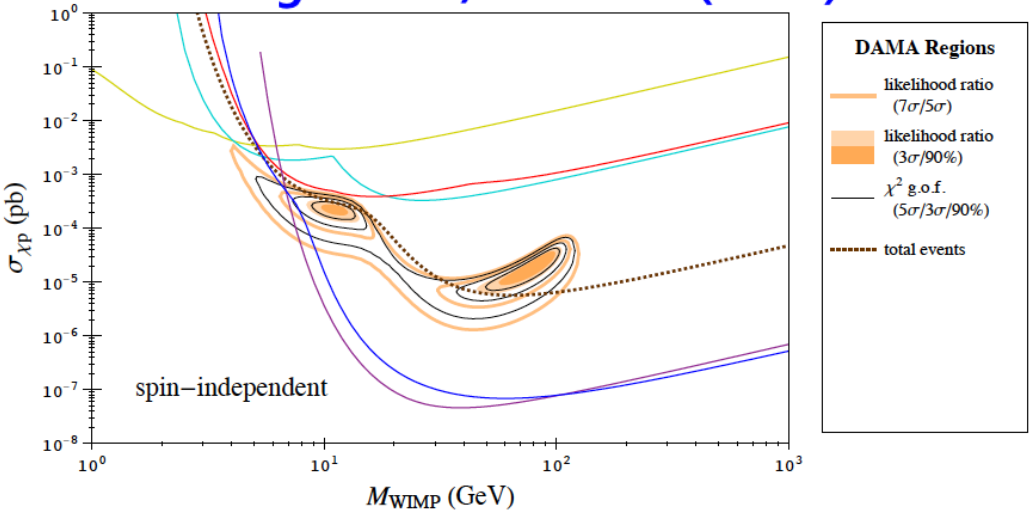

Nucl. Phys. At. Energy 19, 307 (2018)



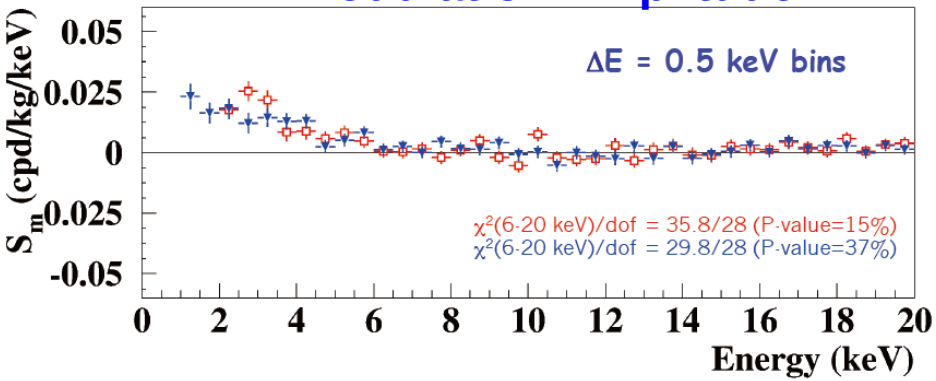

1keV threshold

>13σ significance

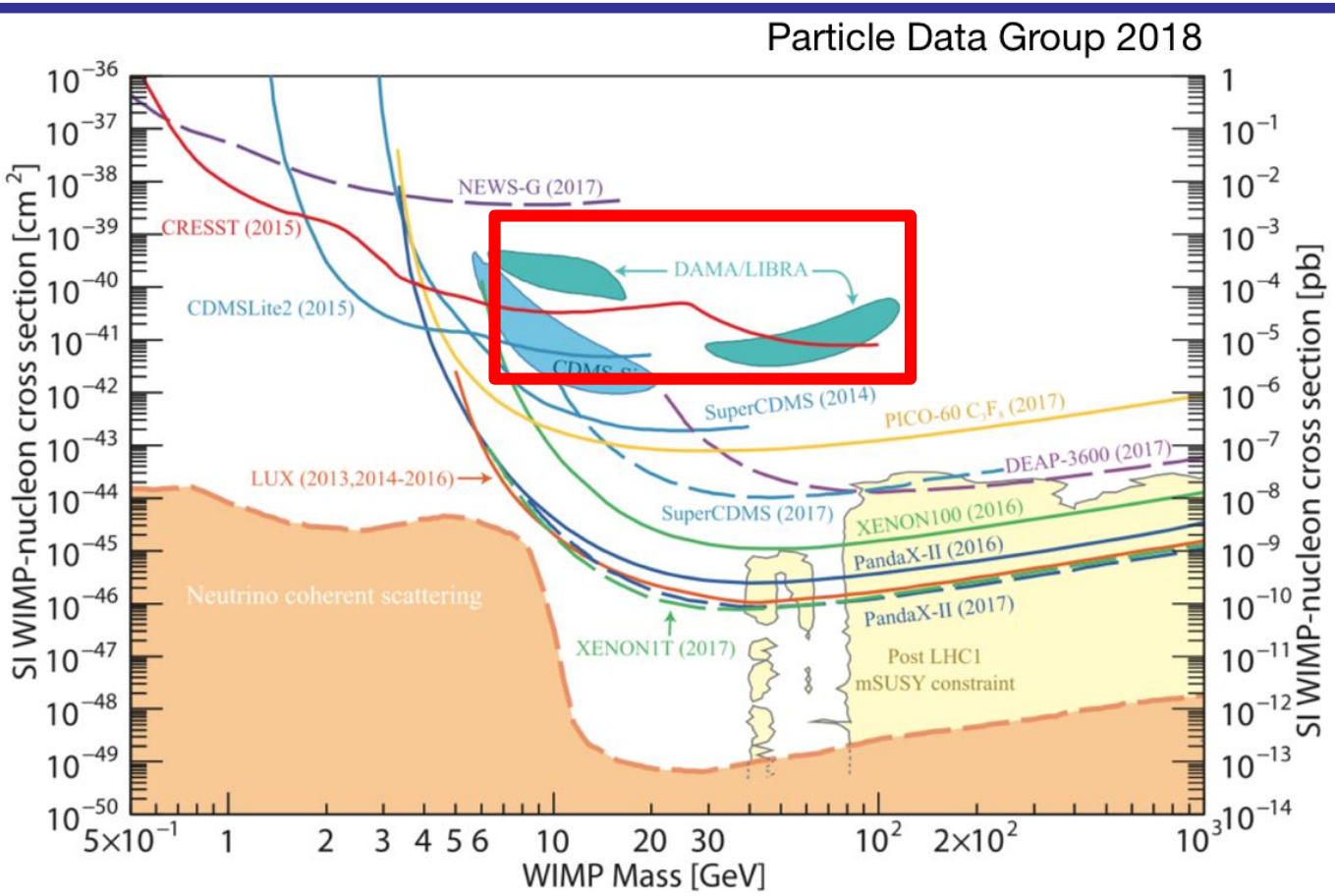
C. Savage *et al.*, JCAP 04 (2009) 010




## Modulation Amplitude



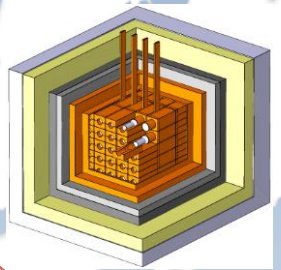
# However…




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

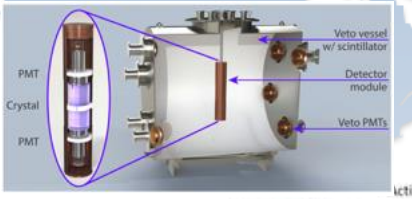
# Global NaI(Tl) efforts

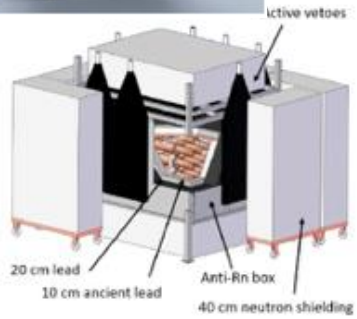

COSINUS
@ LNGS



**DAMA**
**@ LNGS**

**SABRE**
**@ LNGS**

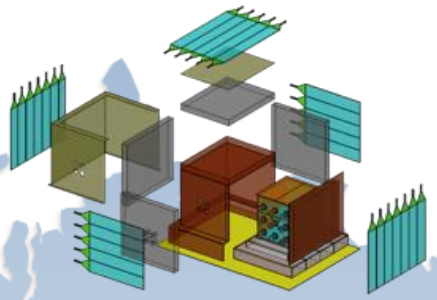



**ANAIS**
**@Canfranc**

**In Data-taking**

**ANAIS results.**
Phys. Rev. Lett. **123**, 031301 (2019)



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

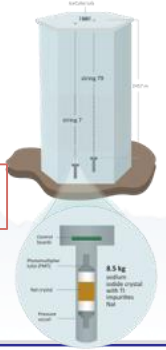
**In Data-taking**

Nature 564, 83-86 (2018)
Phys. Rev. Lett. 123, 031302 (2019)

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

SABRE
@ Stawell

**DM-Ice @ South Pole**



# COSINE collaboration (Since 2015)

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

# 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 detector configuration

JINST 13 T02007 (2018)

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

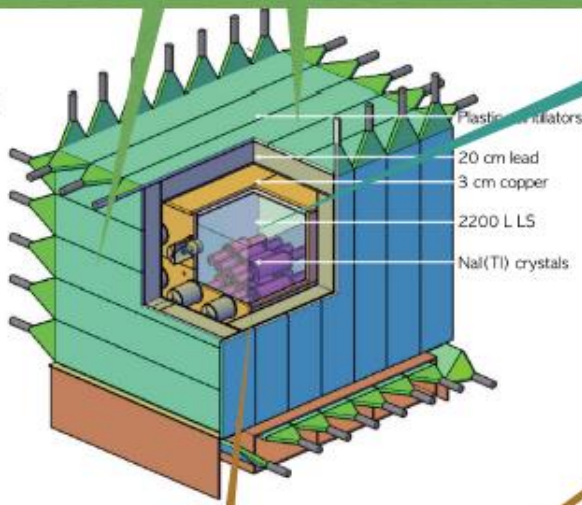
Nucl. Instrum. Meth. A 851 103 (2017)

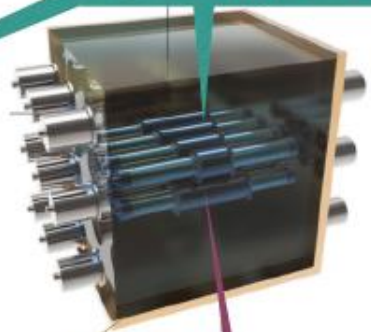
**Liquid Scintillator**
2200-L LAB-based LS for veto
5-inch PMT(R877)s for LS detector

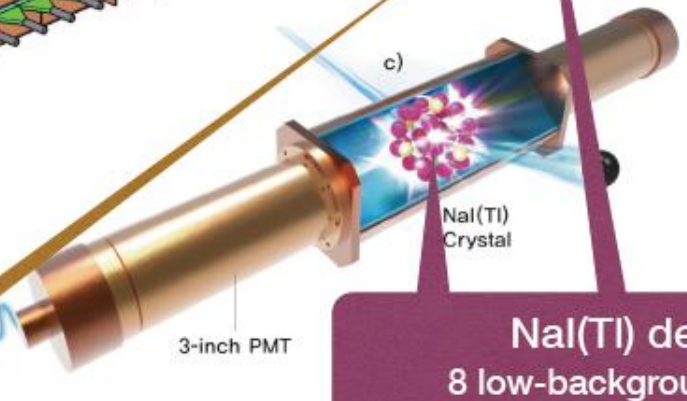
JINST 13 T06005 (2018)

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

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





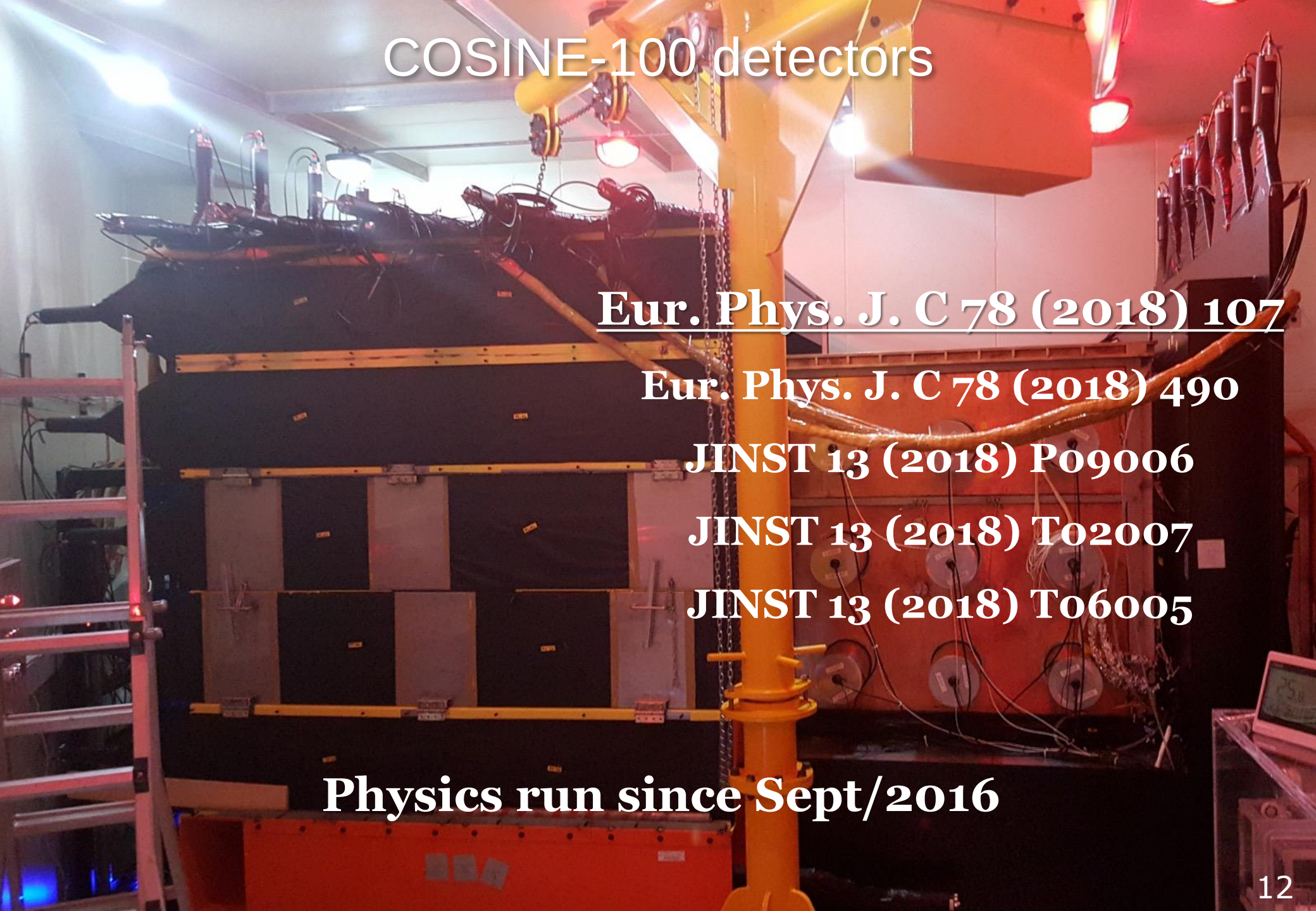

**Shields**
3-cm thick copper box
20-cm thick lead shielding

**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)

# COSINE-100 construction

# COSINE-100 detectors



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

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

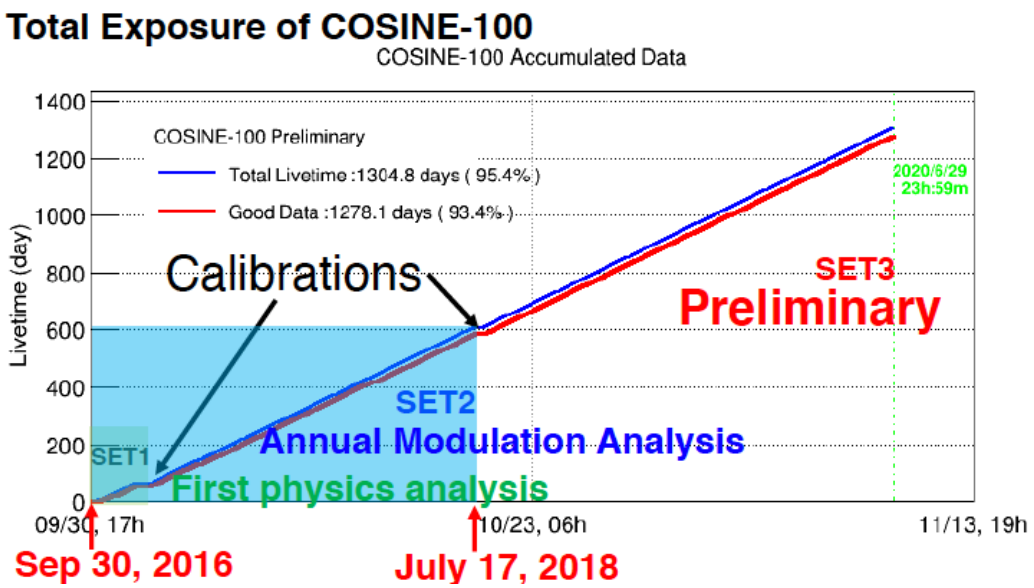
**JINST 13 (2018) P09006**

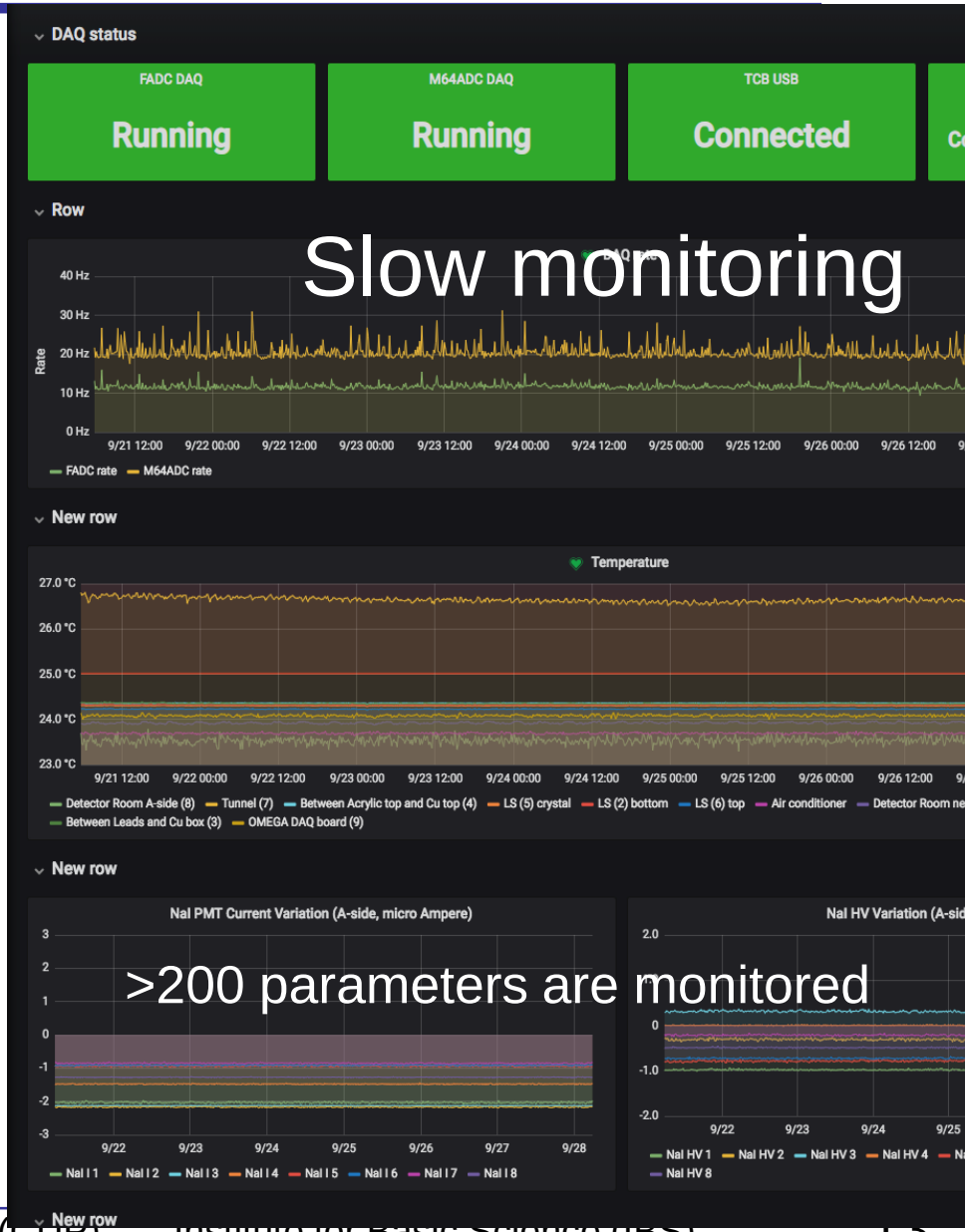
**JINST 13 (2018) T02007**

**JINST 13 (2018) T06005**

**Physics run since Sept/2016**

# COSINE-100 operation

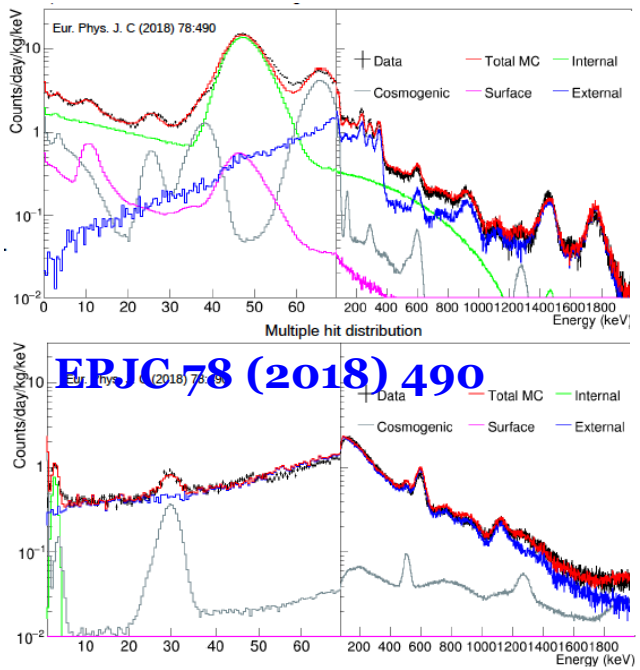



- Stable physics run
  - ❖ >90% physics data
  - ❖ >95% good runs
- In operation for > 3.5 years
  - ❖ > 3 years good data

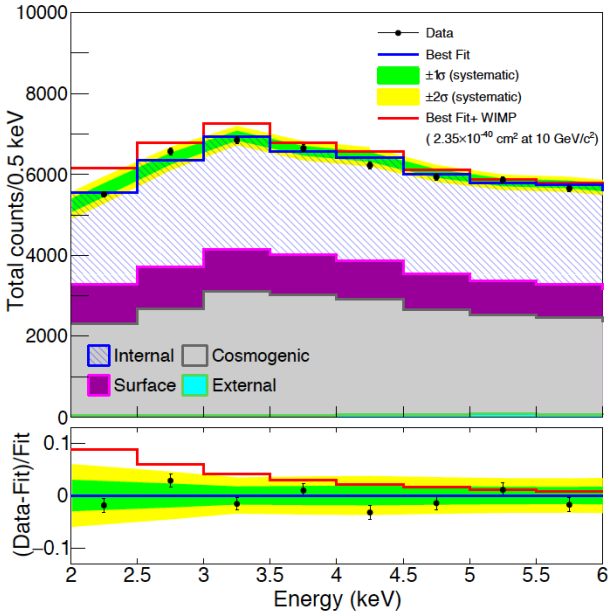
# COSINE-100 Physics results

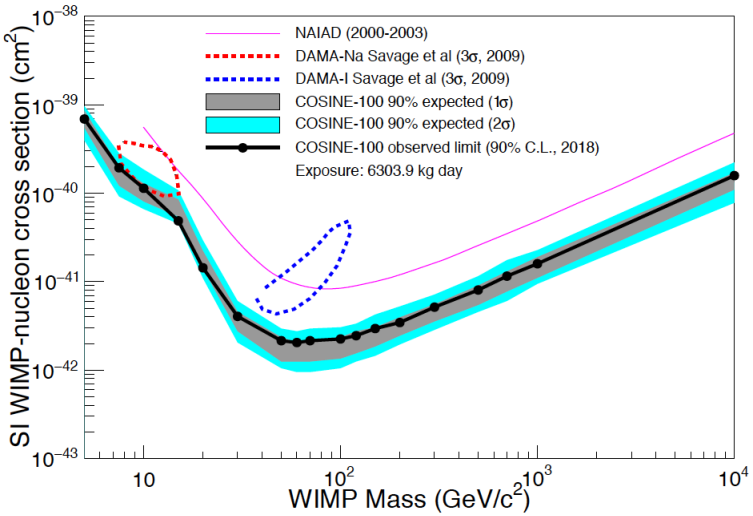
## Background modeling (59.5 days)




**EPJC 78 (2018) 490**

## WIMP Search (59.5 days)

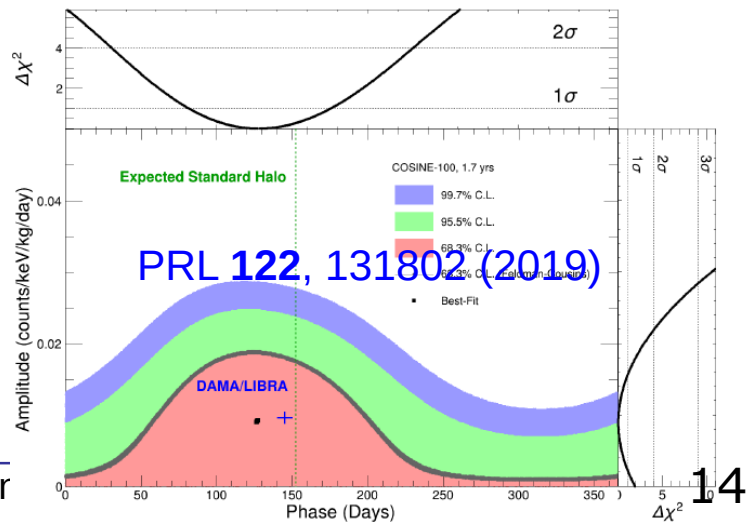



Nature **564**, 83 (2018)

## Annual Modulation analysis (1.7 years)

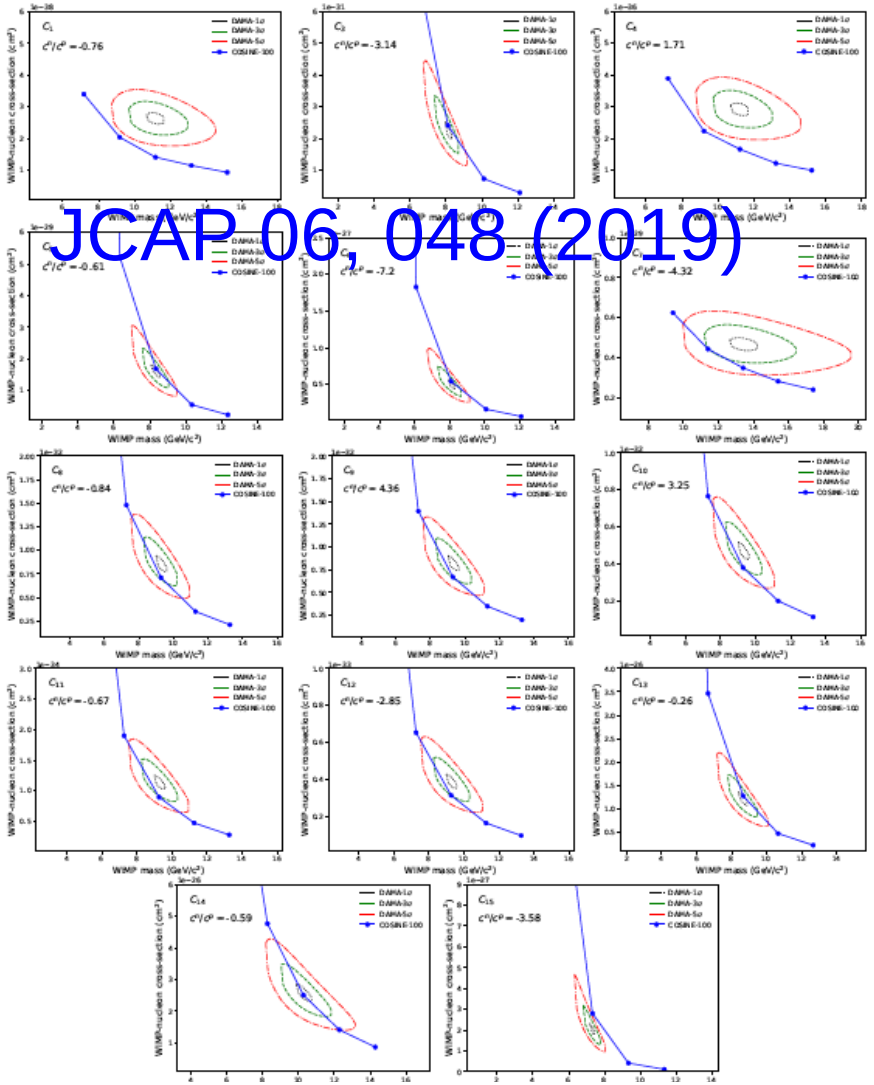
| Config | Amplitude (2-6 keV) | Phase (days) |
|---|---|---|
| **COSINE-100** | $\mathbf{0.0083 \pm 0.0068}$ | **152.5 (fixed)** |
| ANAIS | $-0.0044 \pm 0.0058$ | 152.5 (fixed) |
| DAMA | $0.0095 \pm 0.0008$ | 152.5 (fixed) |
| COSINE-100 | $0.0092 \pm 0.0067$ | $127 \pm 46$ |
| DAMA | $0.0096 \pm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




PRL **122**, 131802 (2019)

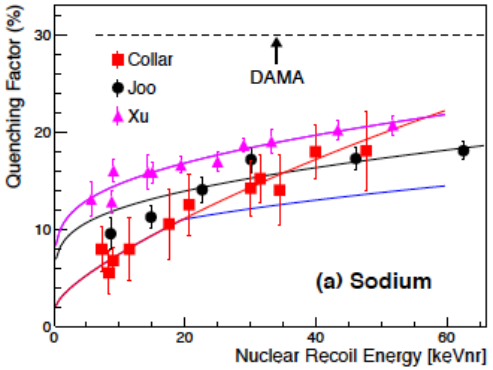
# Other interpretations

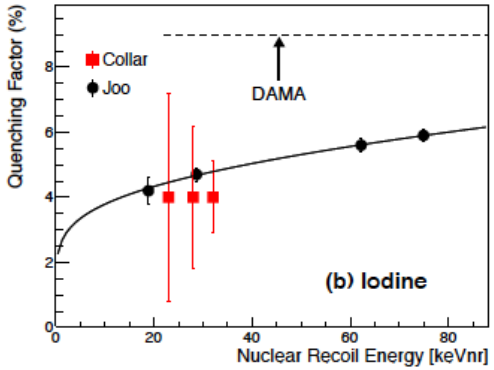
Test 15 Effective Field Theory operators



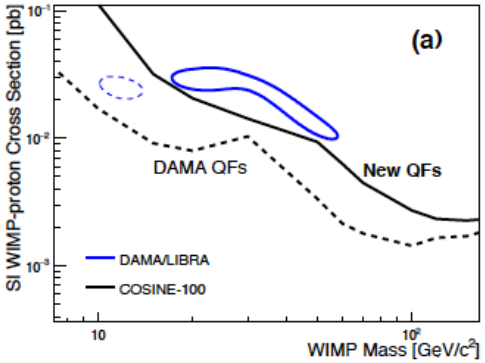
JCAP 06, 048 (2019)

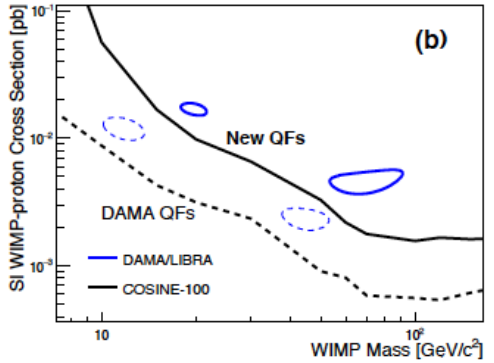
Quenching factors & DAMA/LIBRA phase1+phase2




JCAP 11, 008 (2019)



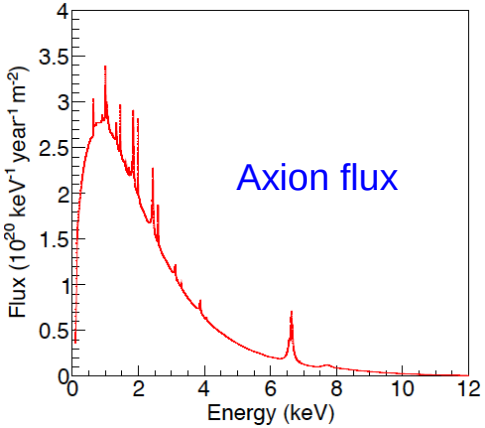



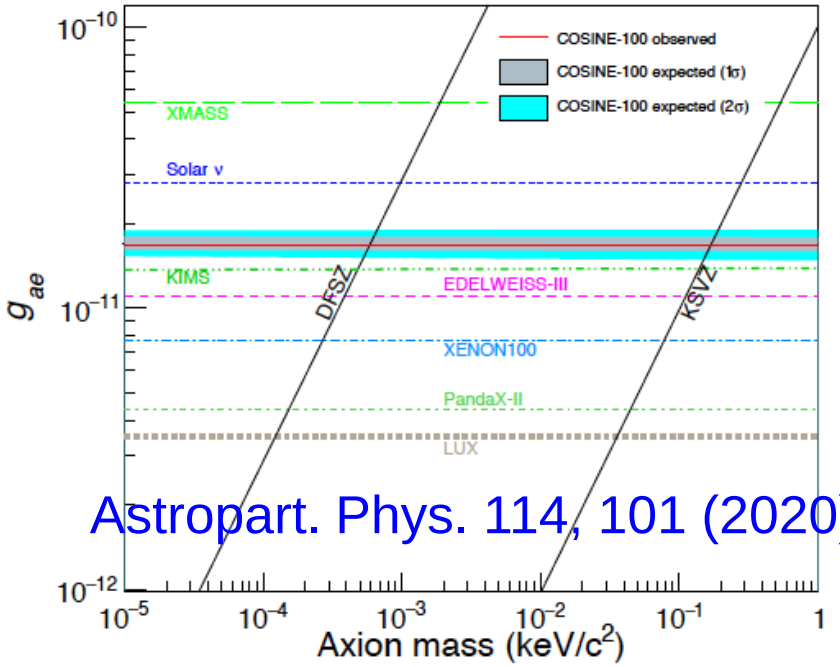

Isospin violating interaction

Best fit region of DAMA was not fully covered yet

# Other DM candidates

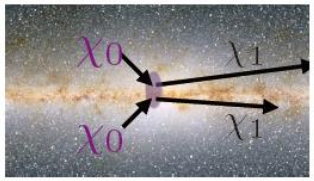
## Solar Axion

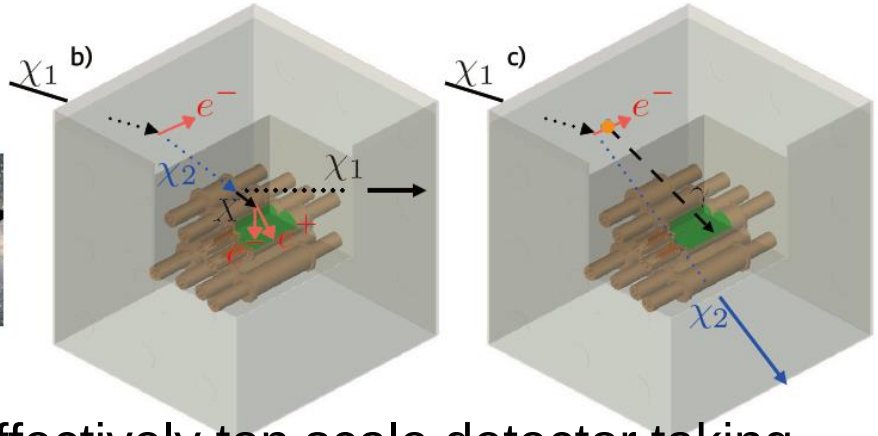


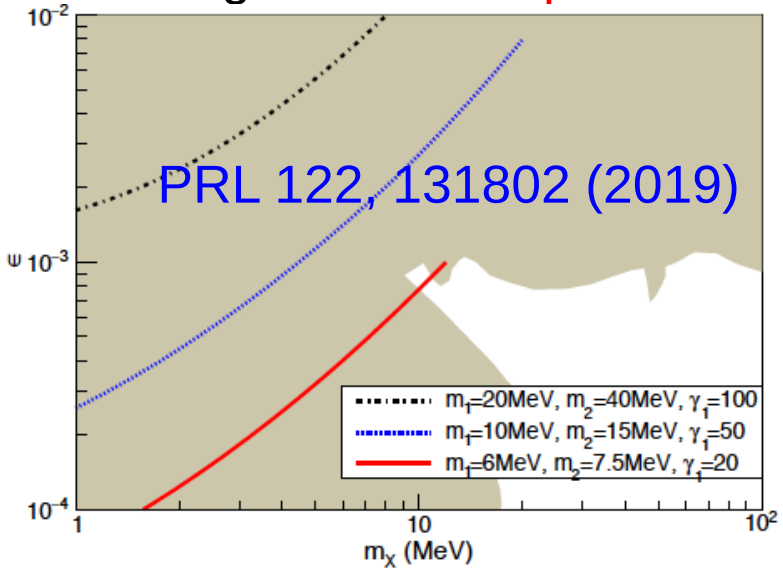

Astropart. Phys. 114, 101 (2020)

## Inelastic boosted dark matter




Effectively ton scale detector taking advantage of 2 ton liquid scintillator

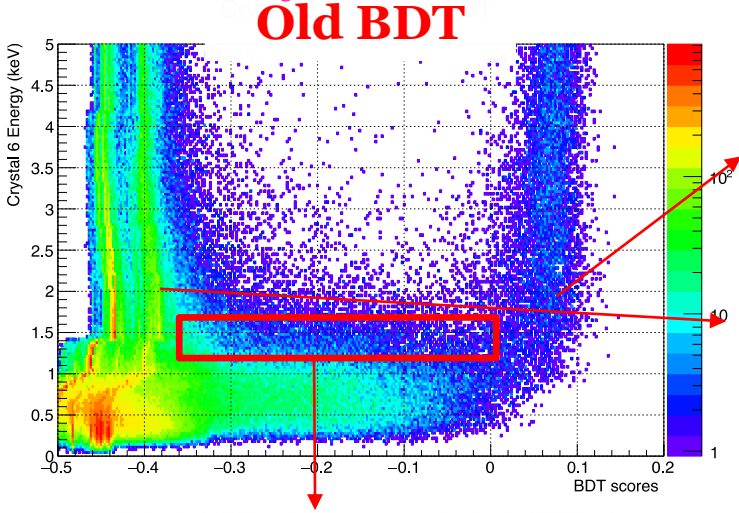


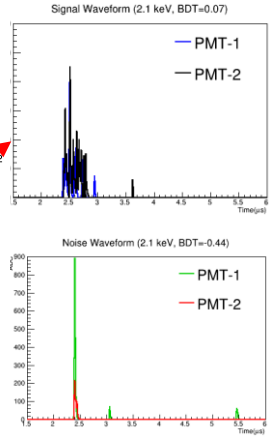
# Lowering energy threshold

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

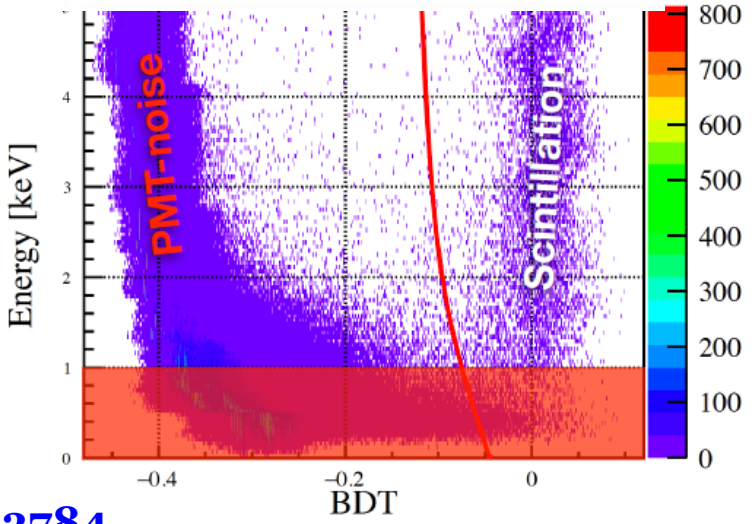
Use ~ two years data

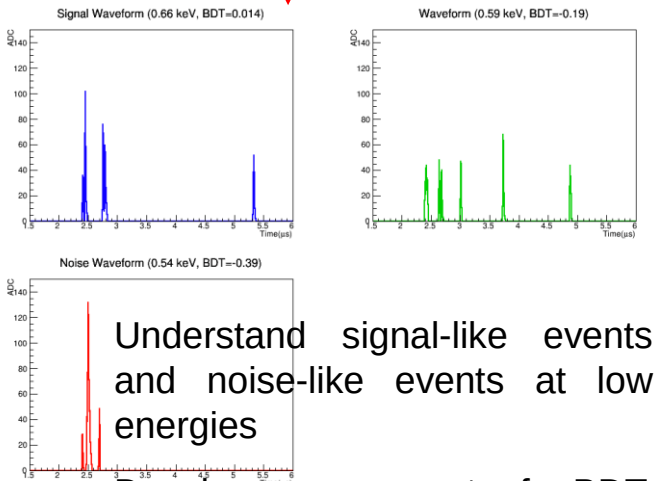
**Old BDT**




**New BDT**



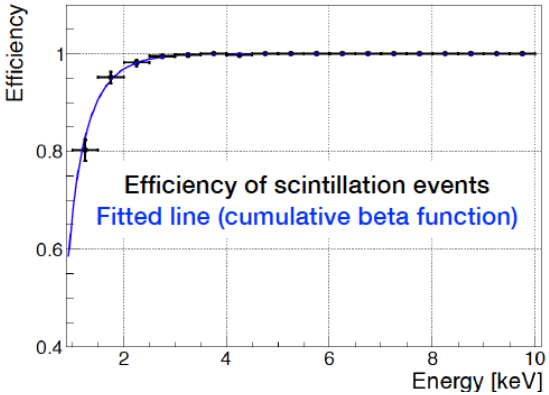




Understand signal-like events and noise-like events at low energies

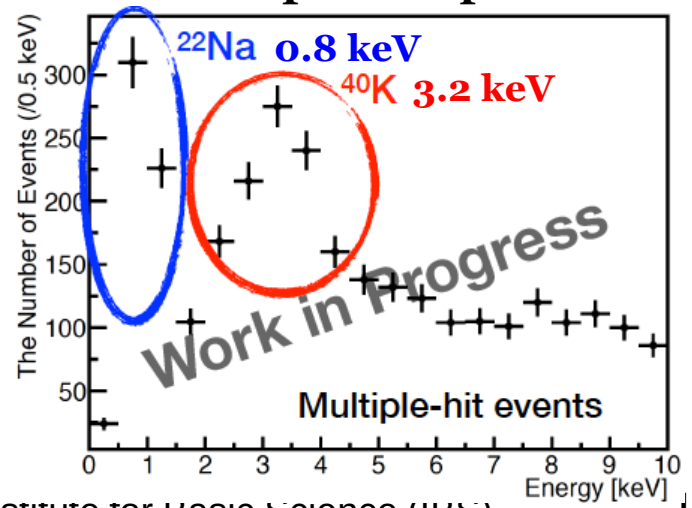
Develop new parameter for BDT

arXiv:2005.13784

**Selection Efficiency**

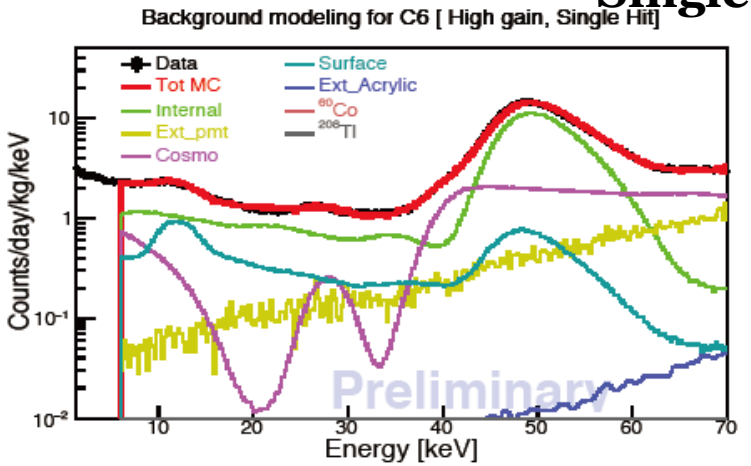


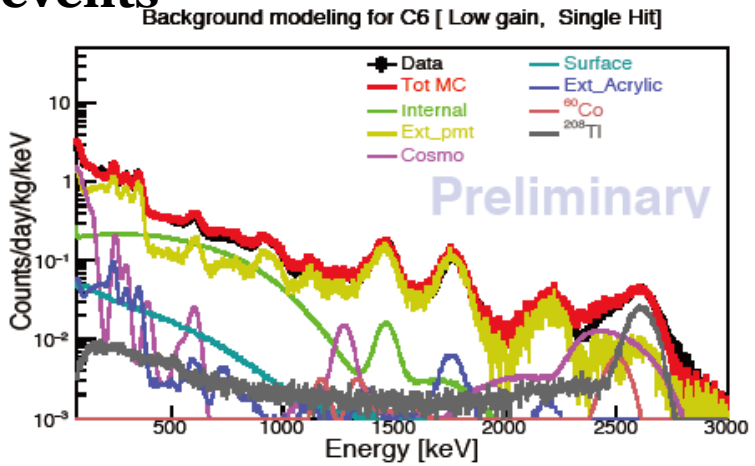

**Multiple-hit spectrum**



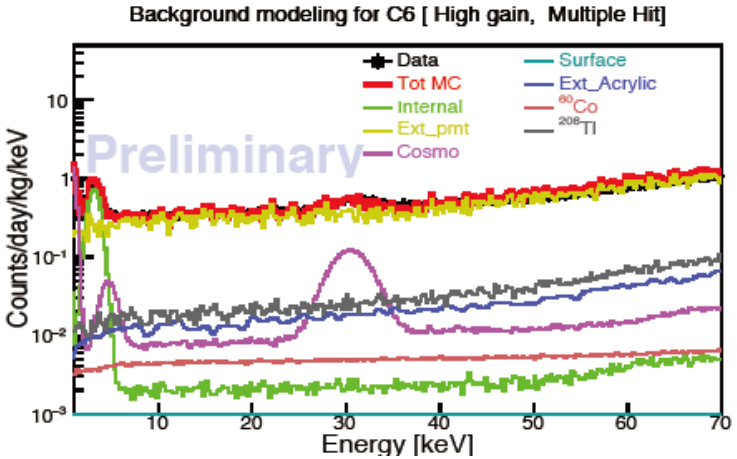
# Background modeling (1.7 years)

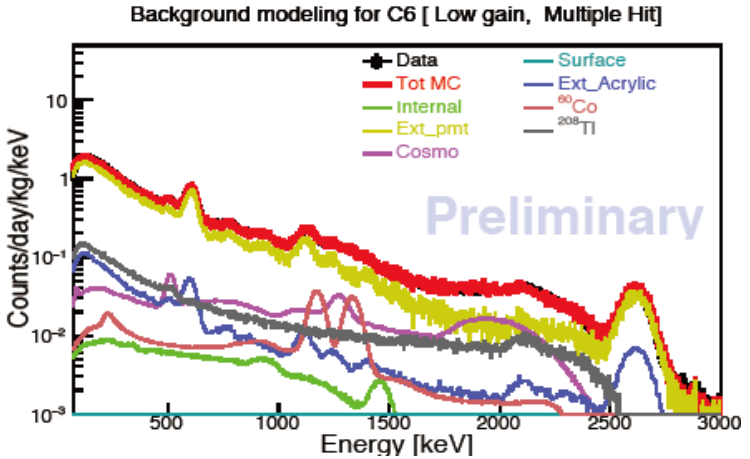
## Single-hit events




## Multiple-hit events

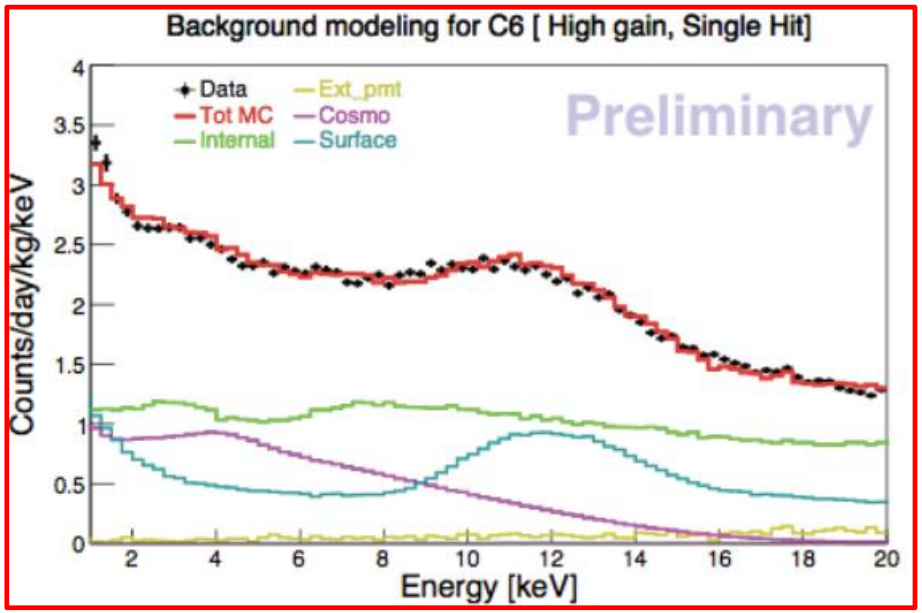


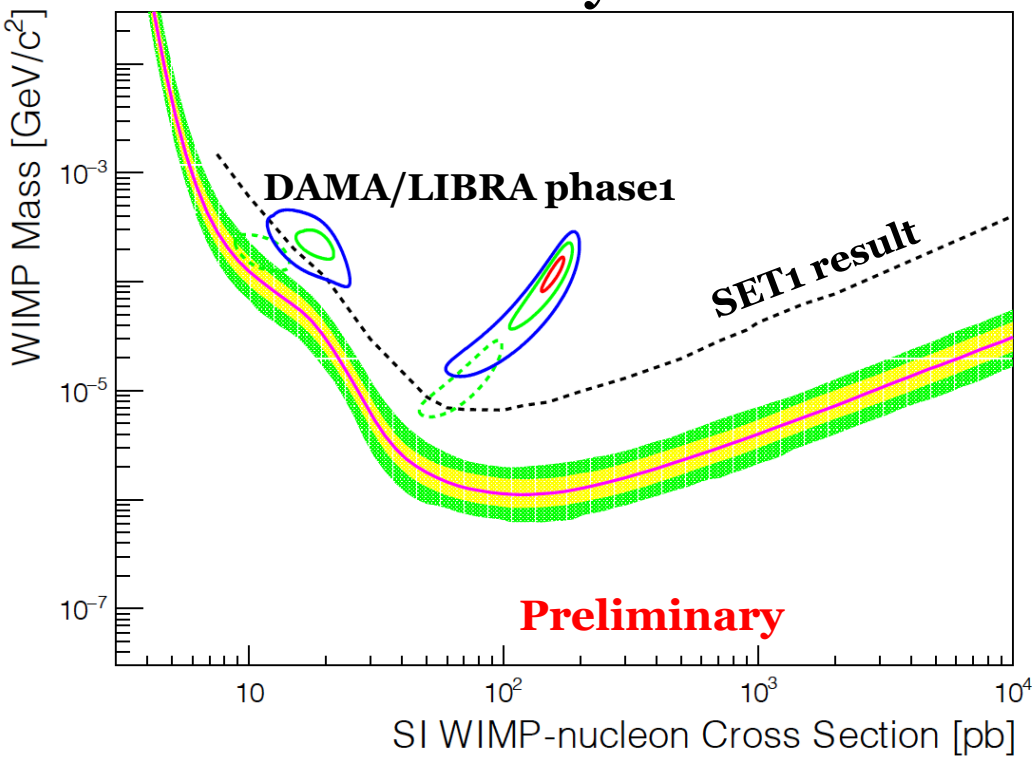

- Improved background modeling
  - $^{129}$I, rock-gamma ($^{208}$Tl) are added
  - Better modeling of surface $^{210}$Pb using contaminated crystal

# WIMP extraction (sensitivity)

**Low energy signal region**




**Sensitivity**



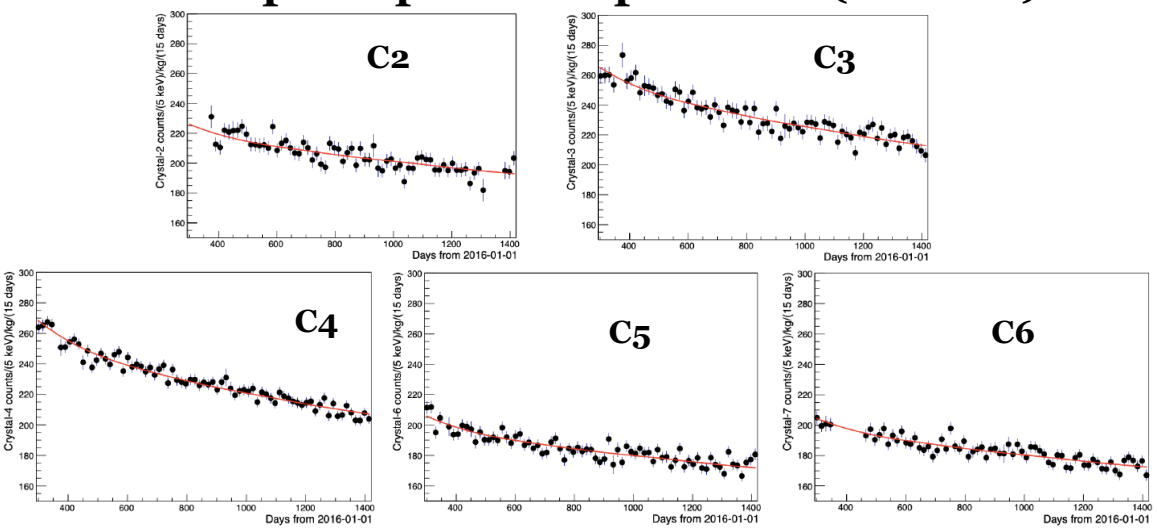

~ **an order of magnitude better sensitivity** than the previous result

Data fit is coming soon (Stay tune !!)

# Annual Modulation Analysis

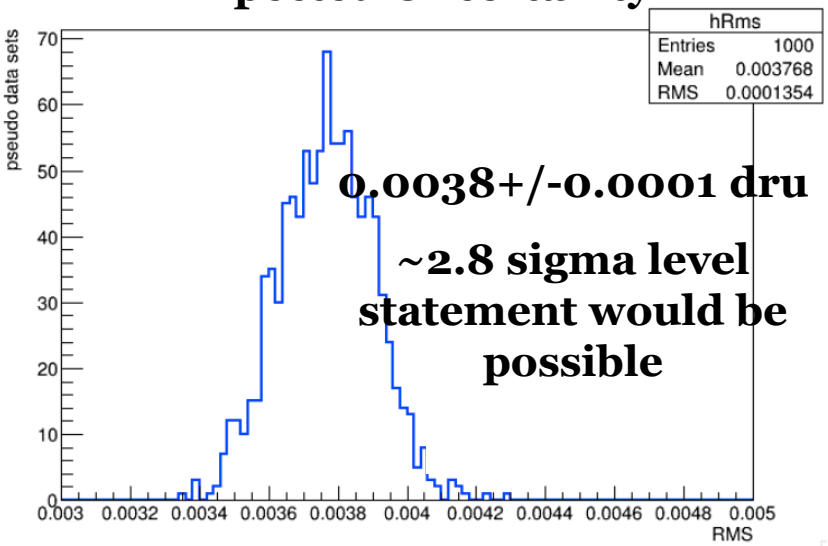
- More data ~ 3 years
- 1keV energy threshold
- Improved event selection (Better selection efficiency)
- Improved background modeling
- Develop Bayesian toolkits
- Realistic  pseudo experiments for testing machinery

**An example of pseudo experiment (1~6 keV)**




**DAMA/LIBRA : 0.0106+/-0.0011 dru**

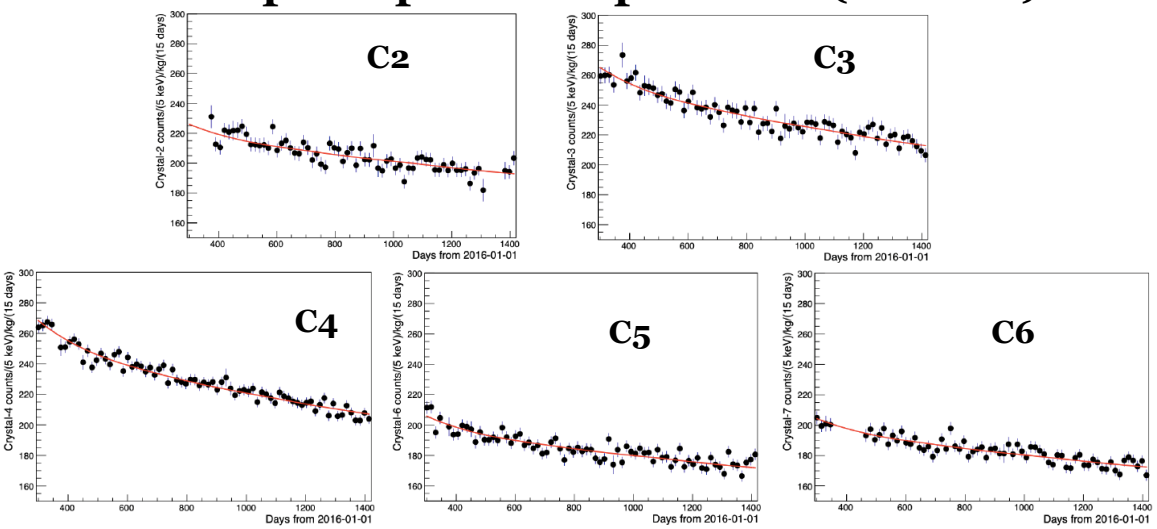
**Expected Uncertainty**



# Annual Modulation Analysis

- More data ~ 3 years
- 1keV energy threshold
- Improved event selection (Better selection efficiency)
- Improved background modeling
- Develop Bayesian toolkits **Data fit is coming soon (Stay tune!!)**
- Realistic pseudo experiments for testing machinery

**An example of pseudo experiment (1~6 keV)**

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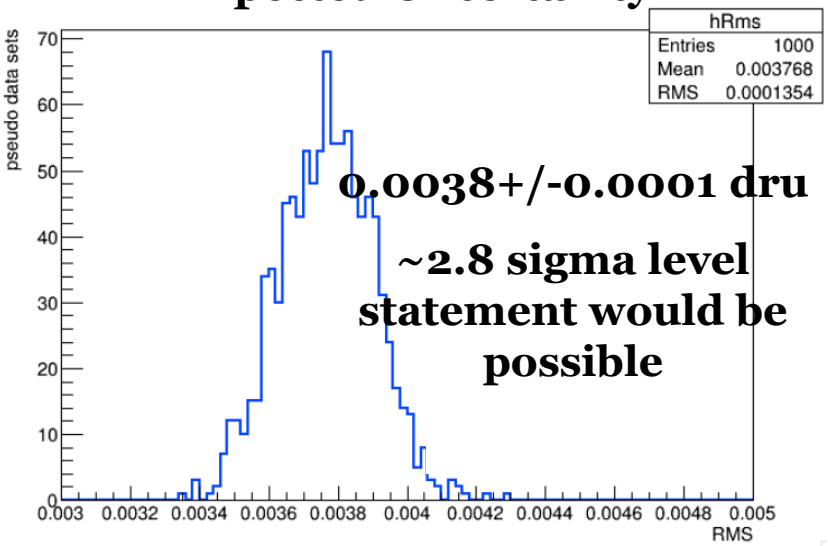


# COSINE-200 crystal development

- 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)

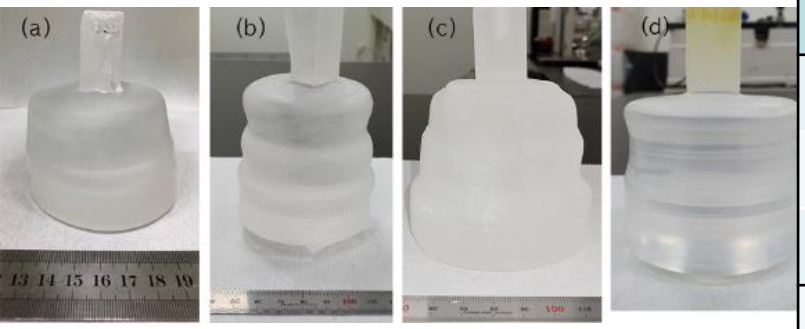
K.A. Shin et al., JINST 15, C07031 (2020)

| | 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 |



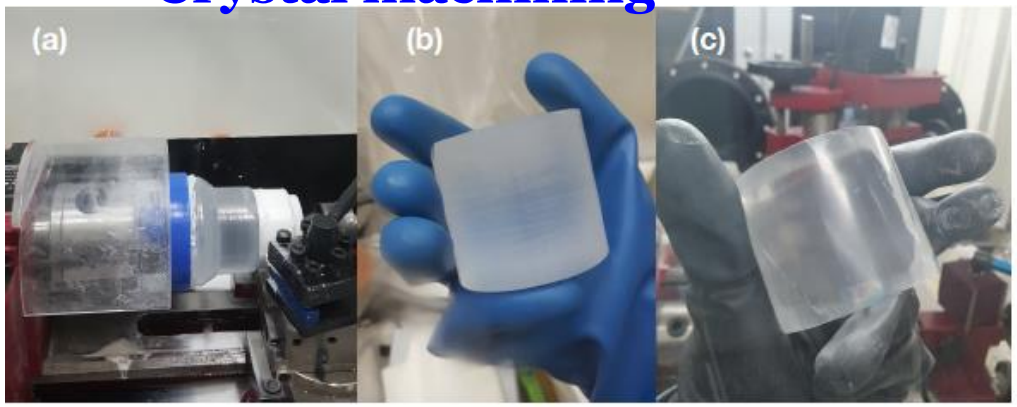
# Our grown crystals

## Crystal ingots



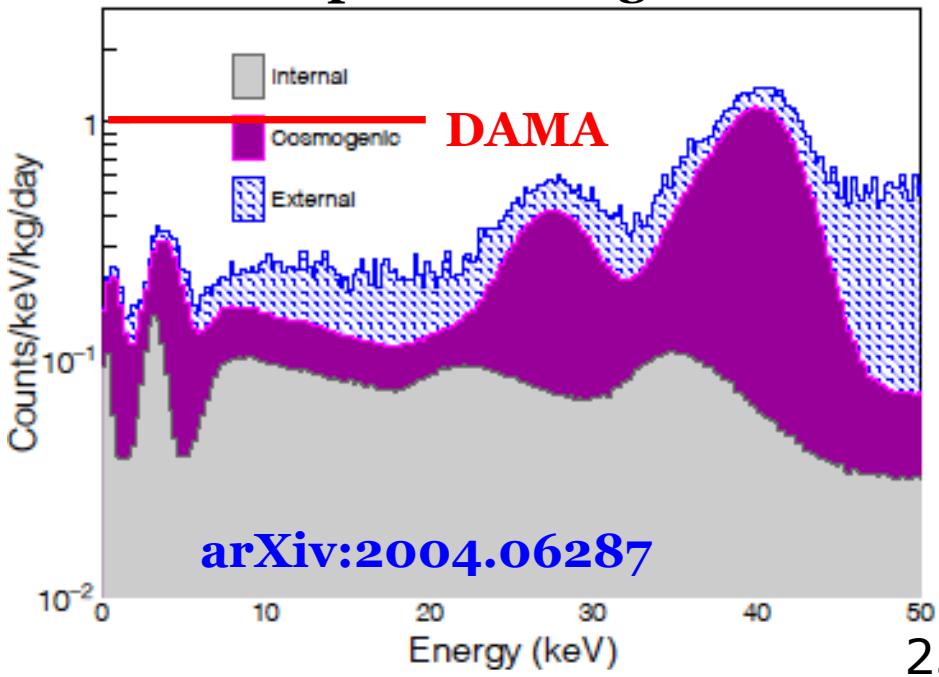

| | K | $^{210}$Pb | $^{238}$U | $^{232}$Th |
|---|---|---|---|---|
| Powder | 5 | - | <20 | <20 |
| Aug/2018 | 684 | 3.8+/-0.3 | 26+/-7 | <6 |
| **Sept/2019** | **8** | **0.05+/-0.09** | **11+/-4** | **7+/-2** |
| DAMA | <20 | 0.01~0.03 | 8.7~124 | 2~31 |

## Crystal machining




## Detector assembly


## Expected background




**A proof of principle for low background NaI**

# 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!**