Dark matter search with NaI(Tl) crystals

Hyun Su Lee

Center for Underground Physics (CUP)

Institute for Basic Science (IBS)

New Tools for the Next Generation of Particle Physics and Cosmology

Gordon Research Conference June30-July 5, 2019

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

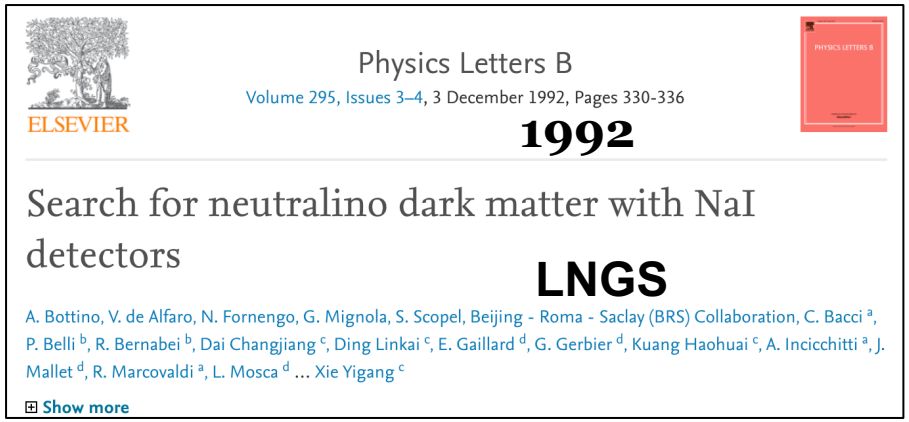
The first 32 inch diameter NaI(Tl) crystal. Pictured from left to right are Dr. Swinehart, Ed Jablon, Joe Knaus and Marko Sfilgoi.

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/keVγ]	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)



ELSEVIER

Physics Letters B

Volume 295, Issues 3–4, 3 December 1992, Pages 330-336

1992

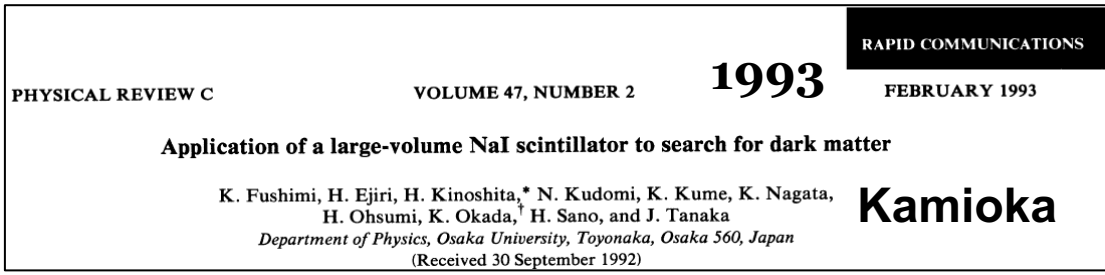
Search for neutralino dark matter with NaI detectors

LNGS

A. Bottino, V. de Alfaro, N. Fornengo, G. Mignola, S. Scopel, Beijing - Roma - Saclay (BRS) Collaboration, C. Bacci [a], P. Belli [b], R. Bernabei [b], Dai Changjiang [c], Ding Linkai [c], E. Gaillard [d], G. Gerbier [d], Kuang Haohuai [c], A. Incicchitti [a], J. Mallet [d], R. Marcovaldi [a], L. Mosca [d] ... Xie Yigang [c]

Show more

DAMA/LIBRA



PHYSICAL REVIEW C VOLUME 47, NUMBER 2 **1993** FEBRUARY 1993

RAPID COMMUNICATIONS

Application of a large-volume NaI scintillator to search for dark matter

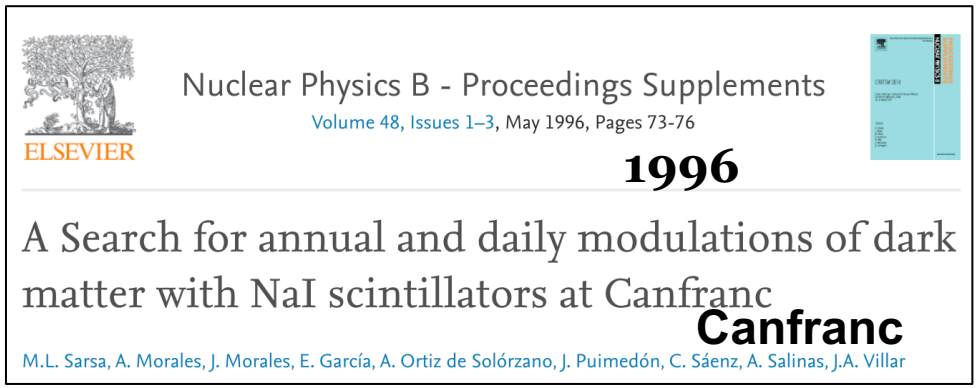
K. Fushimi, H. Ejiri, H. Kinoshita,* N. Kudomi, K. Kume, K. Nagata, H. Ohsumi, K. Okada,† H. Sano, and J. Tanaka

Department of Physics, Osaka University, Toyonaka, Osaka 560, Japan

(Received 30 September 1992)

Kamioka

PICO-LON



ELSEVIER

Nuclear Physics B - Proceedings Supplements

Volume 48, Issues 1–3, May 1996, Pages 73-76

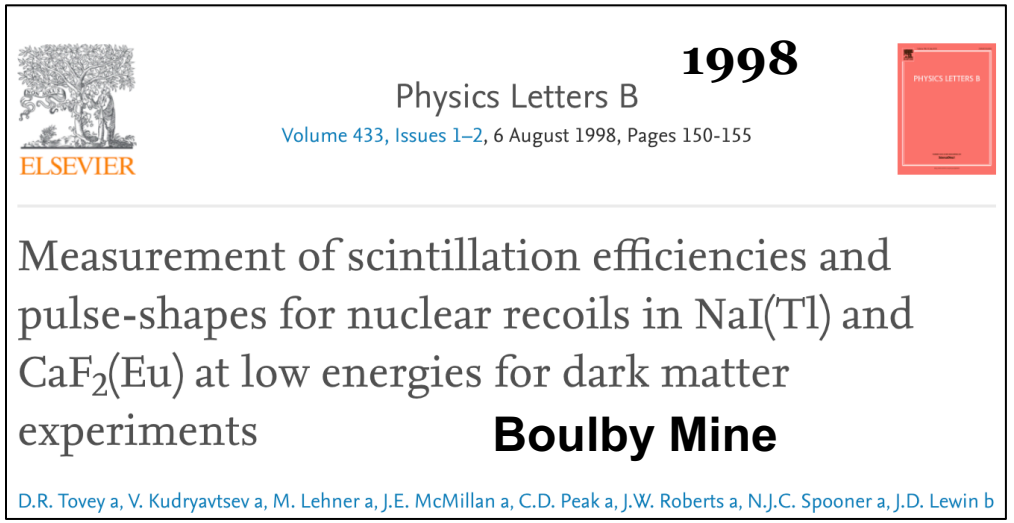
1996

A Search for annual and daily modulations of dark matter with NaI scintillators at Canfranc

Canfranc

M.L. Sarsa, A. Morales, J. Morales, E. García, A. Ortiz de Solórzano, J. Puimedón, C. Sáenz, A. Salinas, J.A. Villar

ANAIS



ELSEVIER

1998

Physics Letters B

Volume 433, Issues 1–2, 6 August 1998, Pages 150-155

Measurement of scintillation efficiencies and pulse-shapes for nuclear recoils in NaI(Tl) and $CaF_2(Eu)$ at low energies for dark matter experiments

Boulby Mine

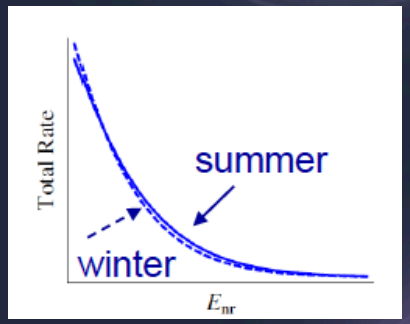
D.R. Tovey a, V. Kudryavtsev a, M. Lehner a, J.E. McMillan a, C.D. Peak a, J.W. Roberts a, N.J.C. Spooner a, J.D. Lewin b

COSINE

Annual modulation of dark matter

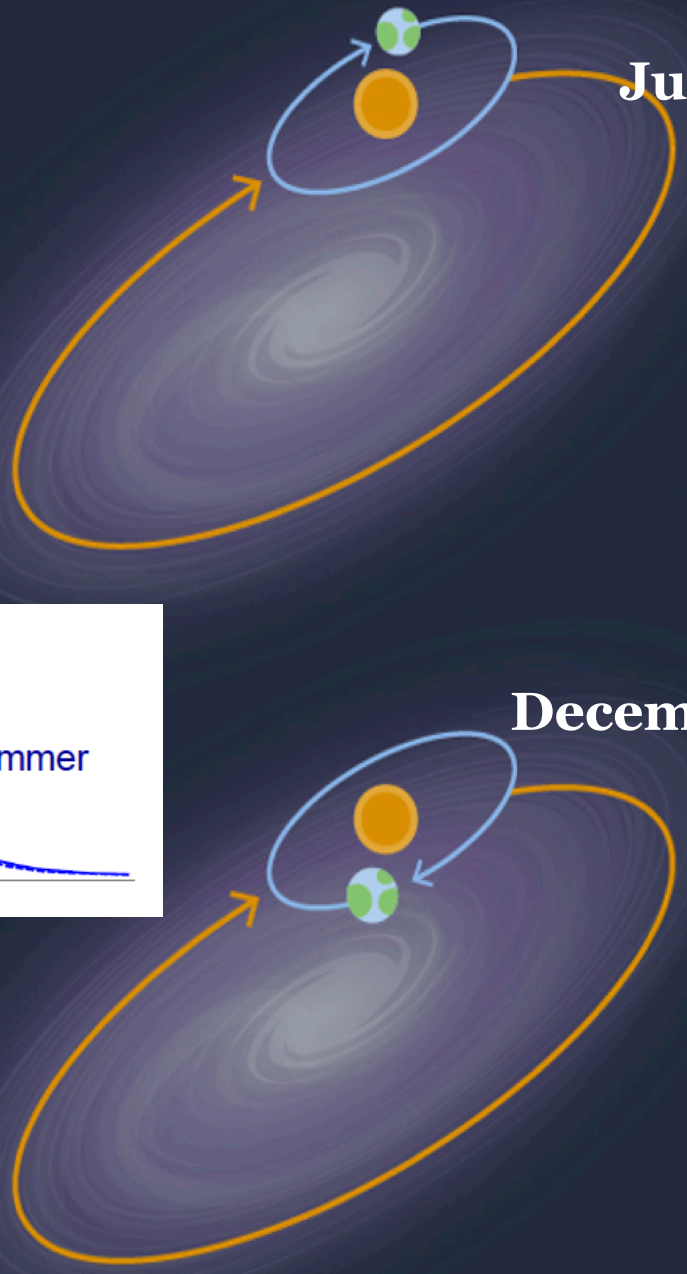
The Highs

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



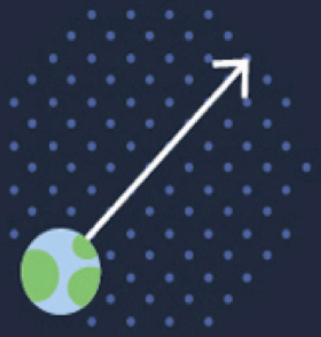
The Lows

In December, Earth moves at its slowest speed.

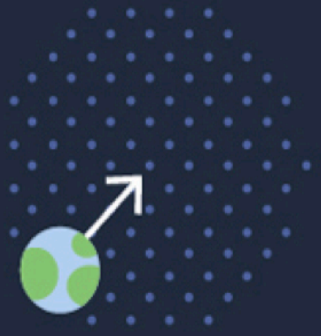


Sun and Earth move in the same relative direction

Earth and sun orbits are opposed



Earth passes through many dark matter particles

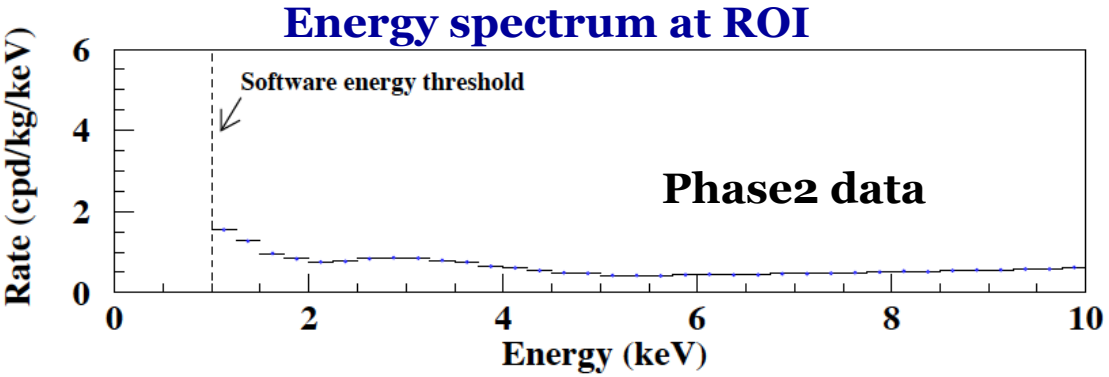


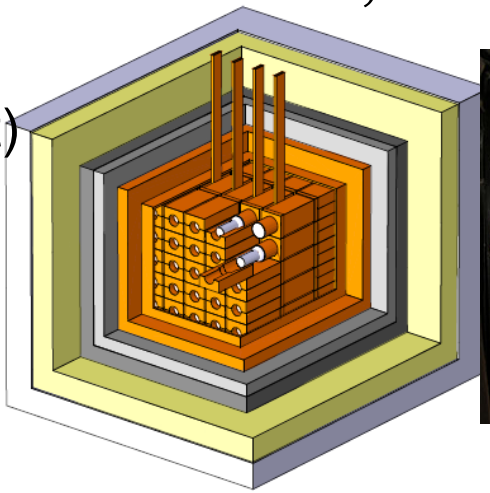
Earth encounters fewer particles

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

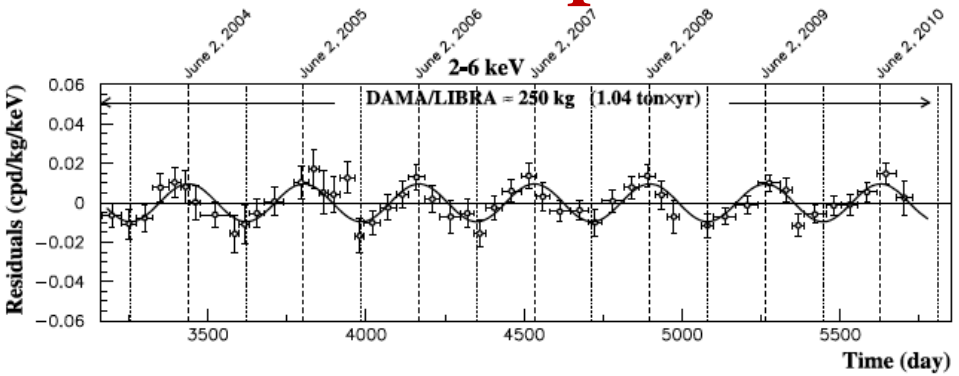
- DAMA/NaI (100 kg, 1996~2003) **First modulation result, PLB 424, 195 (1998)**
- DAMA/LIBRA-phase1 (250 kg, 2003-2010)
- DAMA/LIBRA-phase2 (250 kg, 2010~current)





DAMA/LIBRA experiment

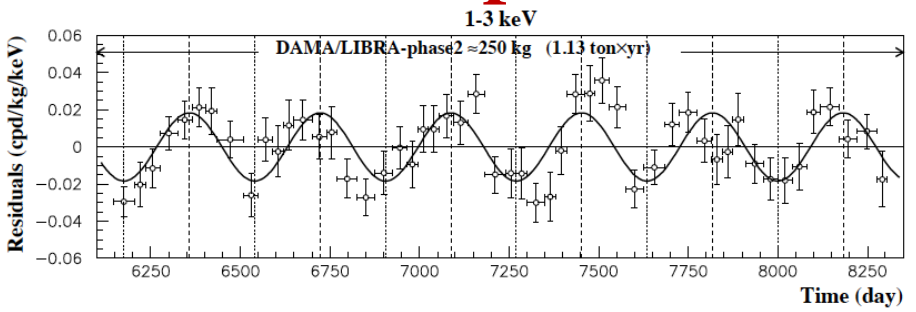
Phase1 experiment



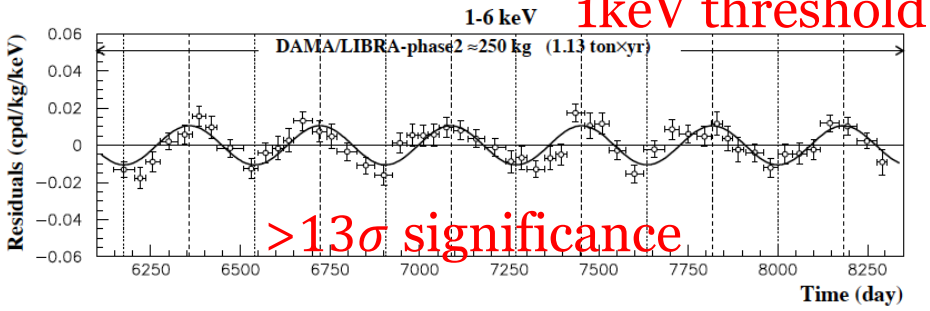
Eur. Phys. J. C 73:2648 (2013)

2keV threshold

Phase2 experiment



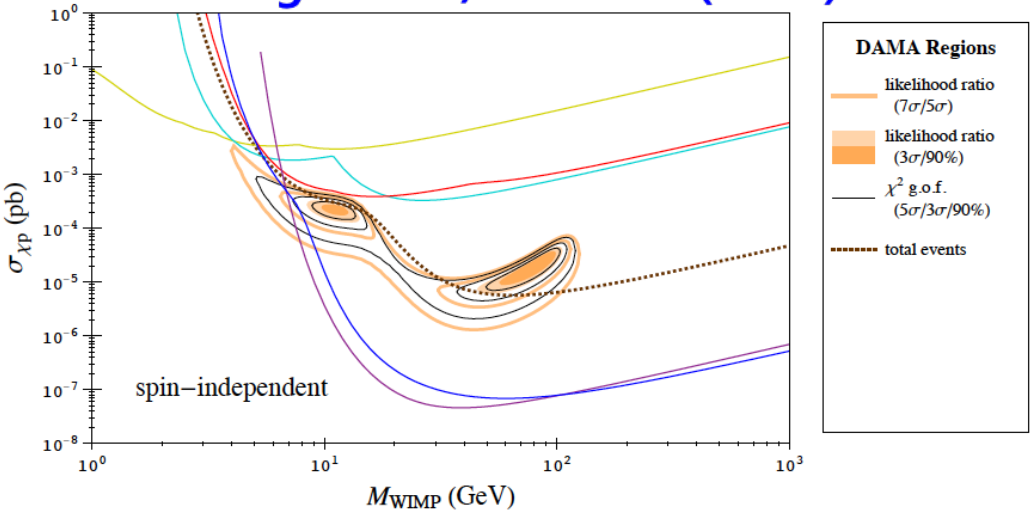
Nucl. Phys. At. Energy 19, 307 (2018)



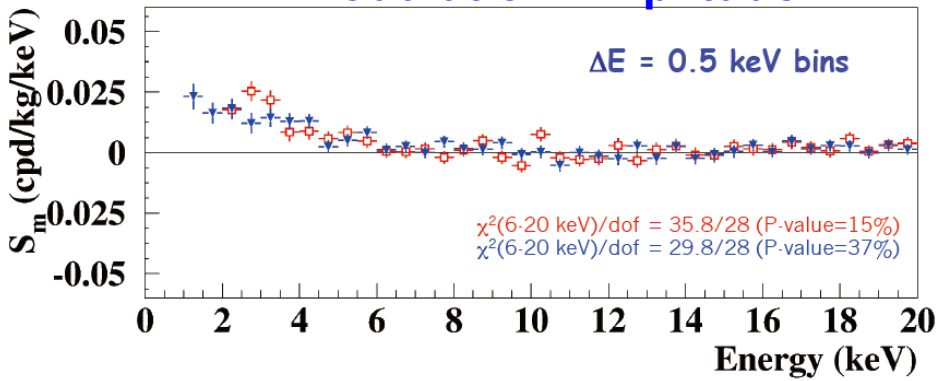
1keV threshold

>13σ significance

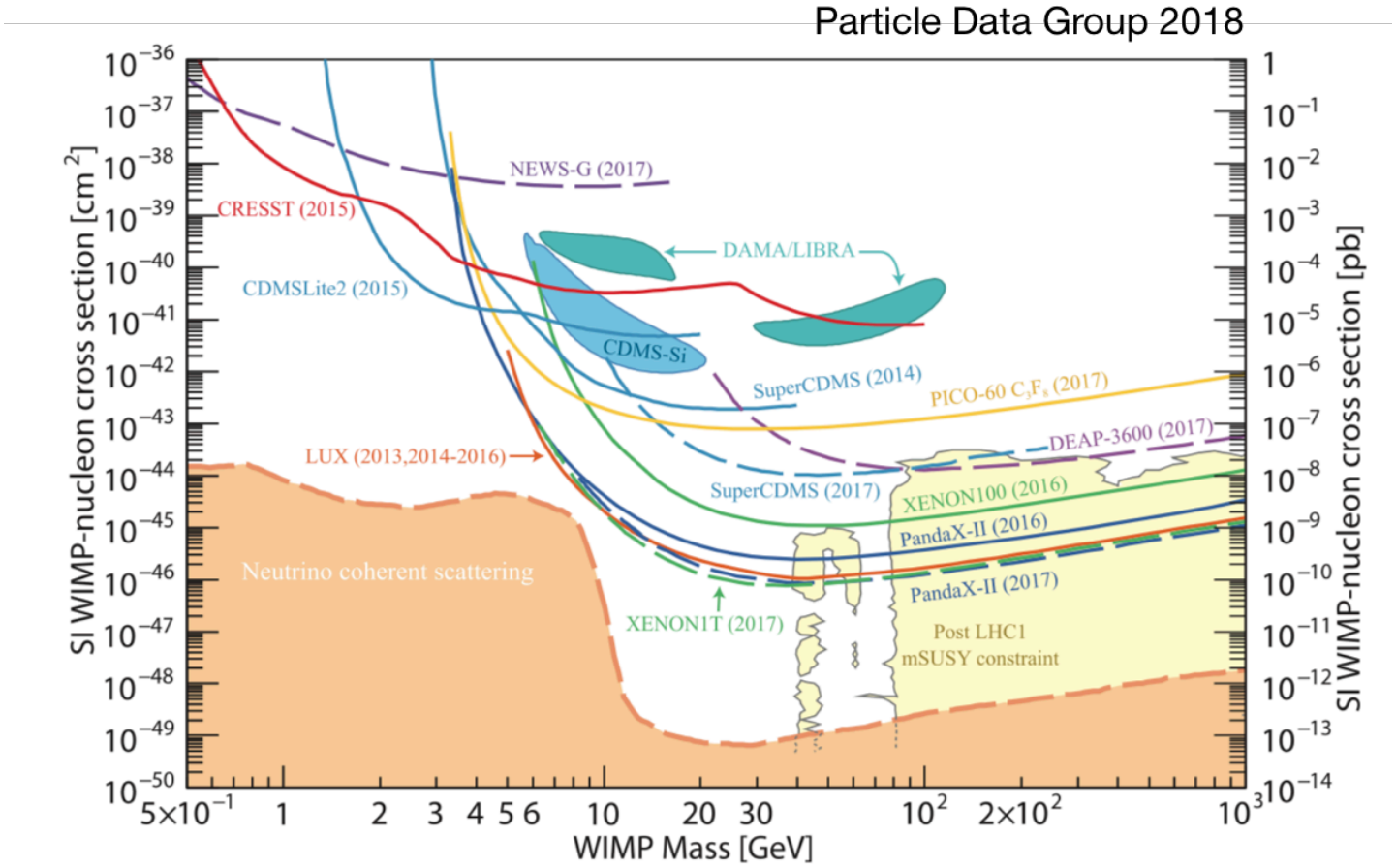
C. Savage *et al.*, JCAP 04 (2009) 010



Modulation Amplitude

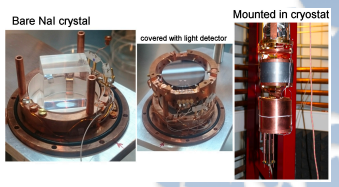


However…

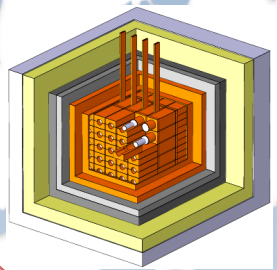


- Is NaI special for certain types of dark matter?
- Modulation signals vs time-averaged limits?
- Environmental effects? **Better to have another NaI experiments**

Global NaI(Tl) efforts

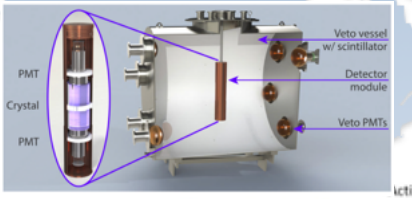


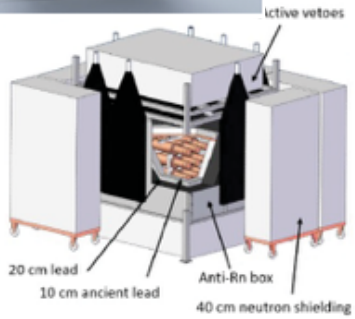
COSINUS @ LNGS

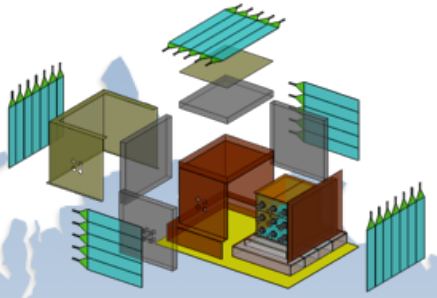


DAMA @ LNGS

SABRE @ LNGS







KIMS/COSINE @ Yangyang

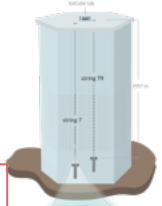
In Data-taking

PICO-LON @ Kamioka

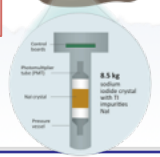
ANAIS @Canfranc

In Data-taking

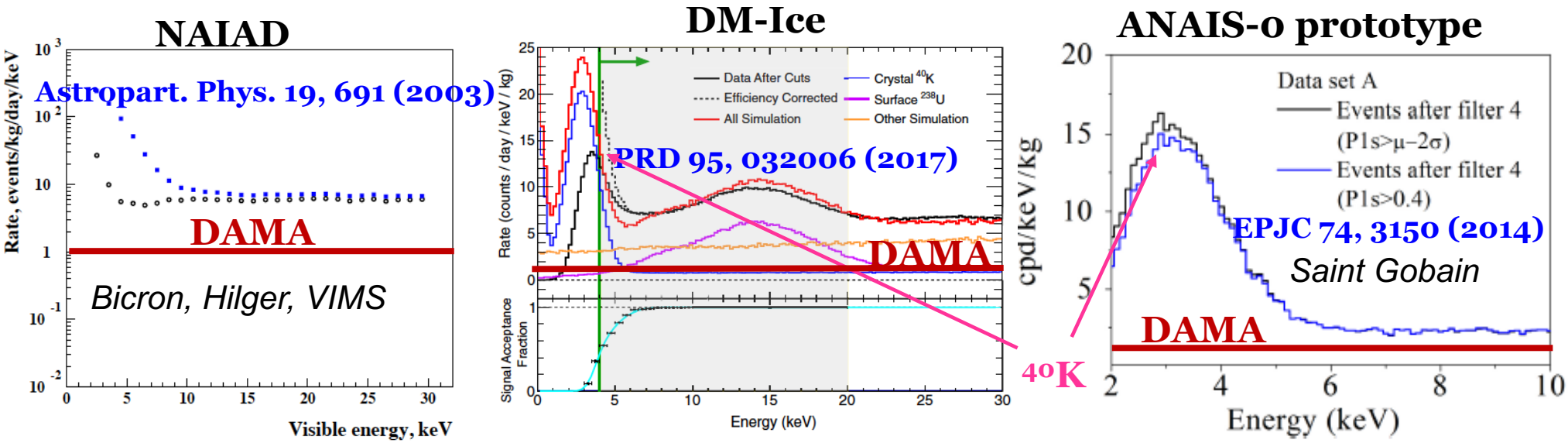
SABRE @ Stawell



DM-Ice @ South Pole



Why it is so hard to reproduce DAMA?

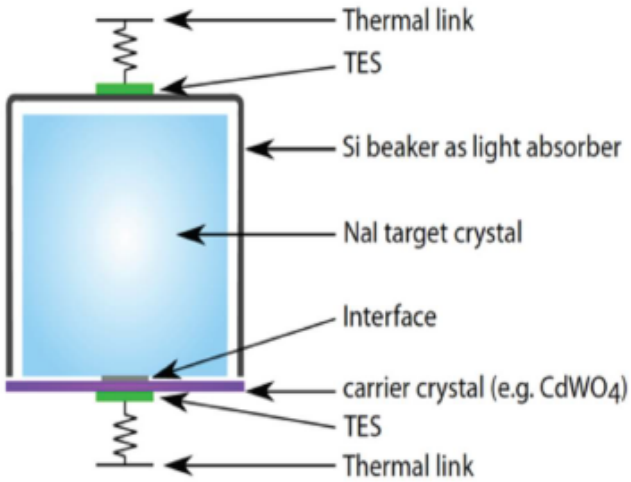


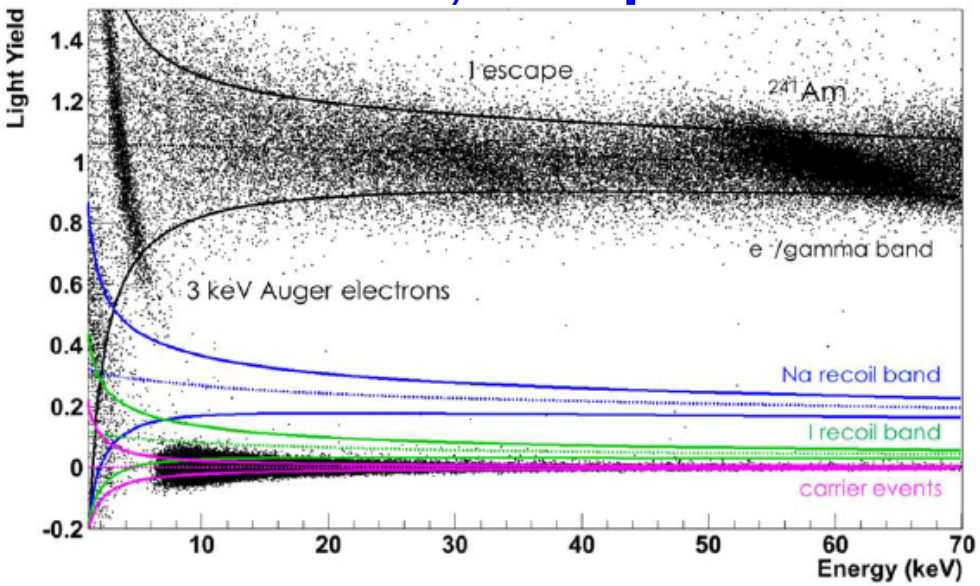
- No other experiments achieve the low-background rate of NaI(Tl)
- Saint-Gobain lost the technique for low-background NaI(Tl) crystals
  - Confidential contraction between DAMA and Saint-Gobain was finished already

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



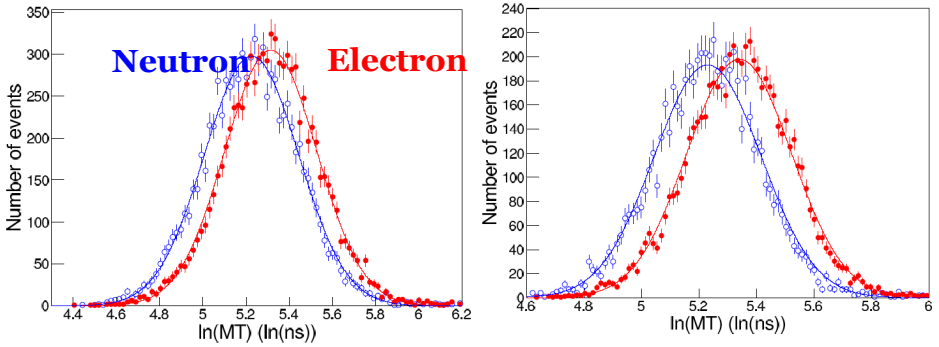


- Performing test measurements of pure NaI crystals using CRESST cryostat @ LNGS
- Can not test dark matter electron recoil scenarios

Nuclear recoil extraction with KIMS-NaI R&D data

JHEP 08, 093 (2015)

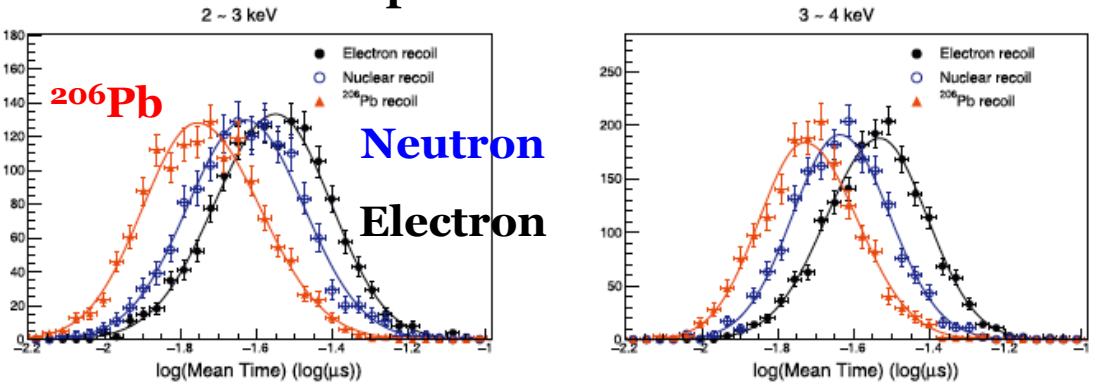
Nuclear recoil discrimination



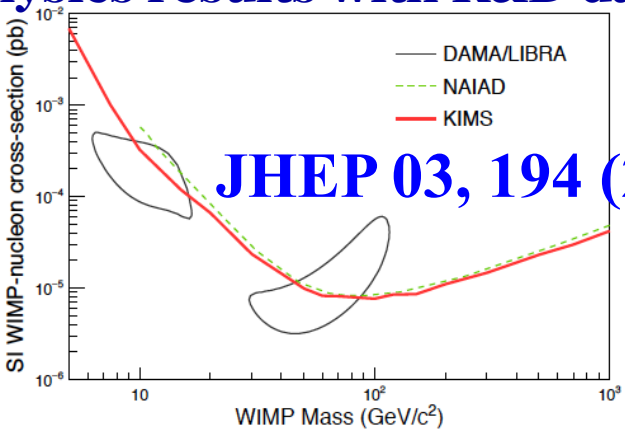
(b) 2-3 keV (c) 3-4 keV

Astropart. Phys. 102, 51 (2018)

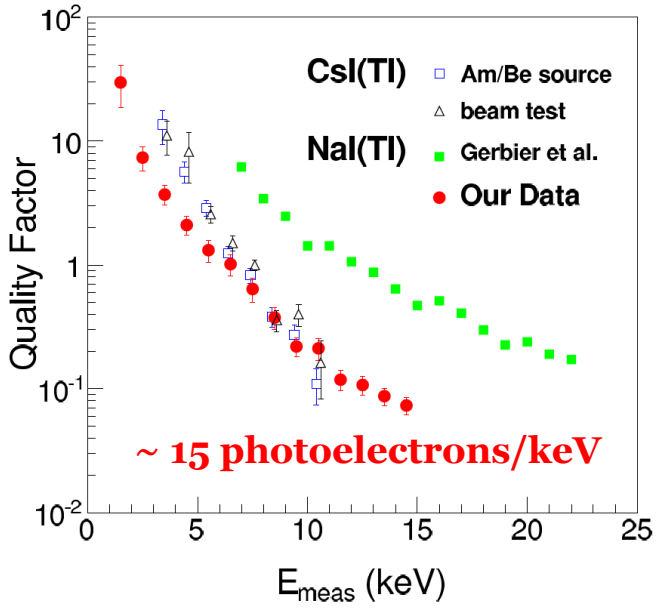
Surface alpha recoil discrimination



Physics results with R&D data



JHEP 03, 194 (2019)

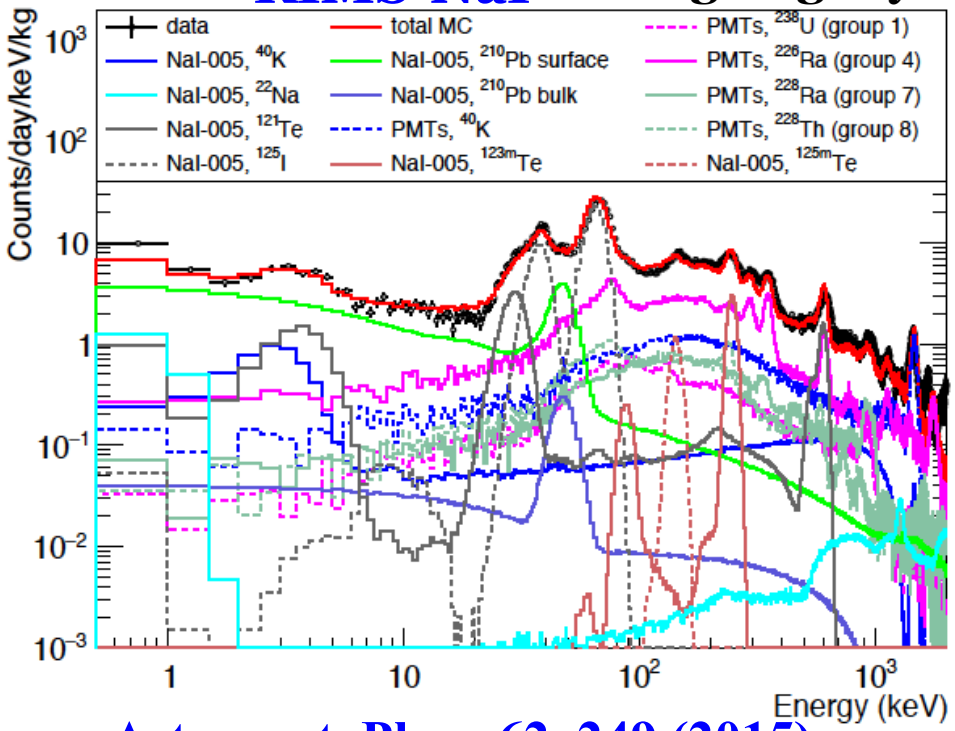


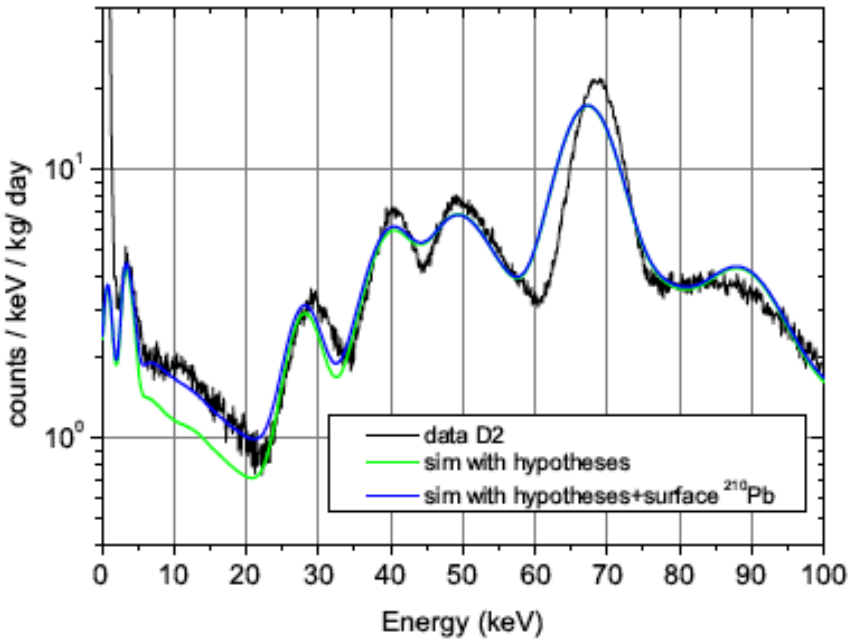
- Demonstrate discrimination of nuclear recoil events
- One can study the annual modulation of the nuclear recoil events

NaI(Tl) development with Alpha Spectra (AS)

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

KIMS-NaI **High light yield ~ 15 PE/keV** **ANAIS**





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

NIMA, 742, 197 (2014)
JCAP 1502, 046 (2015)
EPJC 76, 429 (2016)

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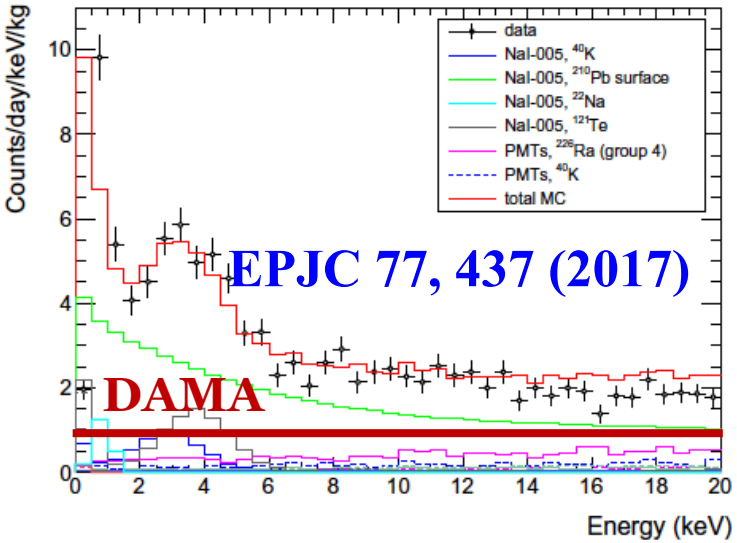
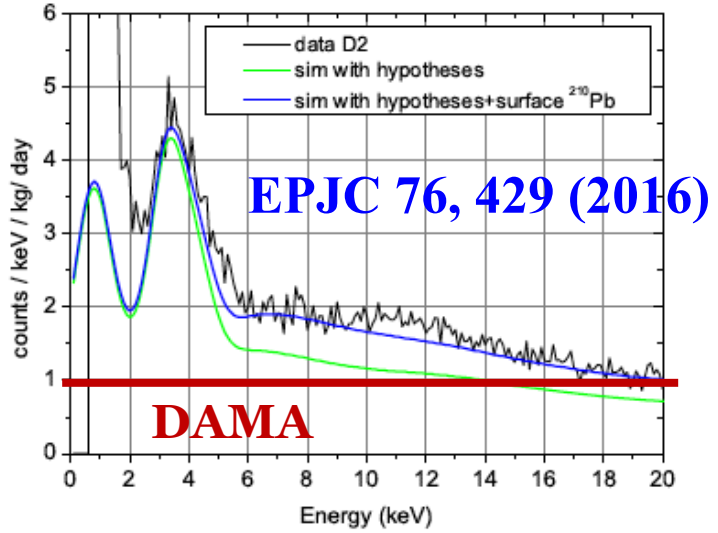




COSINE-100 **ANAIS-112**

2-4 times larger than DAMA

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

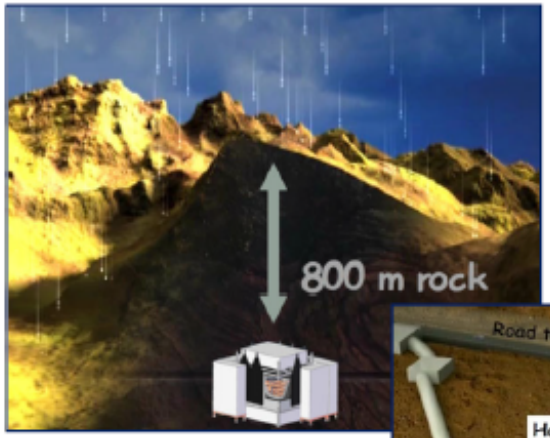
Goals and history

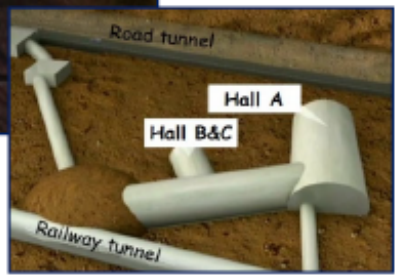
ANAIS (*Annual modulation with NAI Scintillators*) intends

to confirm the **DAMA/LIBRA** modulation signal

using the **same target and technique**

in a different environment at the **Canfranc Underground Laboratory** (Spain)





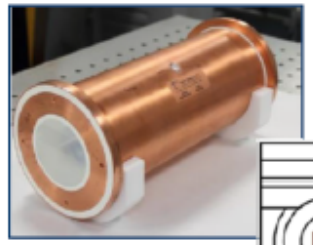
Experimental requirements:

- Energy **threshold** at or below 1-2 keV_{ee}
- **Background** as low as possible below 10 keV_{ee} (at or below a few cpd/keV/kg)
- Very stable operation conditions

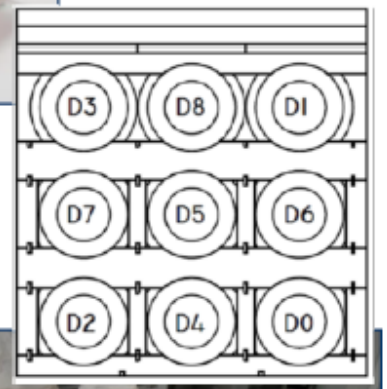
Detector set-up: detectors

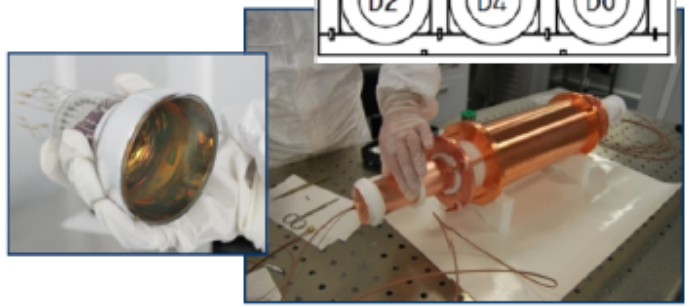
Nine modules produced by Alpha Spectra Inc (US) following low radioactivity protocols

Detector	*Quality powder*	*Received at Canfranc in*
D0, D1	<90 ppb K	December 2012
D2	WIMPScint-II	March 2015
D3	WIMPScint-III	March 2016
D4, D5	WIMPScint-III	November 2016
D6, D7, D8	WIMPScint-III	March 2017



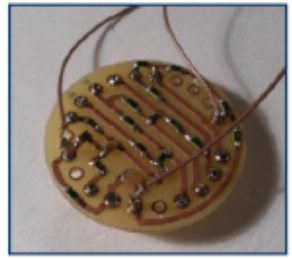
12.5 kg each
4.75" diameter
11.75" length





- **NaI(Tl) crystals** grown from selected ultrapure NaI powder and housed in OFE copper
- Mylar **window** allowing low energy calibration

- Two Hamamatsu R12669SEL2 **photomultipliers** coupled to each crystal at Canfranc clean room
  - Low background and high Quantum Efficiency
  - Radioactivity screening at Canfranc



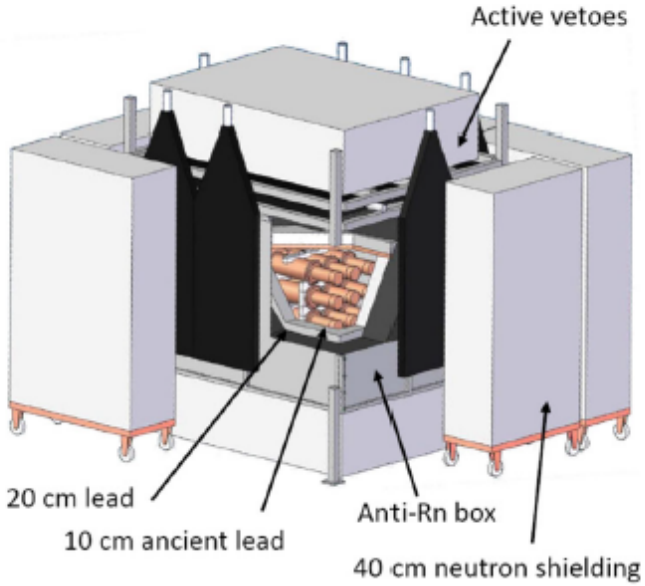
Voltage dividers in cuflon PCB

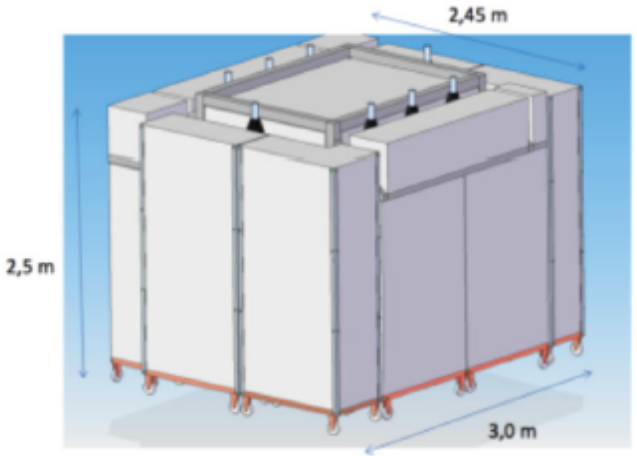
Housing made at LSC of electroformed copper

Light yields ~ 15 PEs/keV

Detector set-up: shielding

ANAIS-112 is located inside a hut in hall B at Canfranc laboratory under 2450 m.w.e.



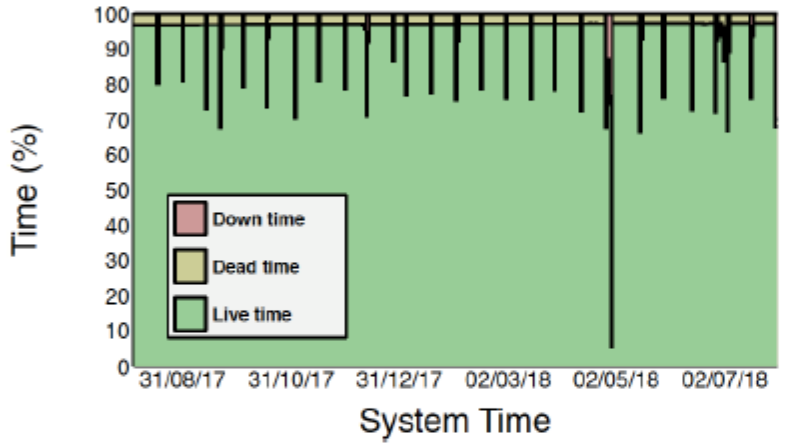


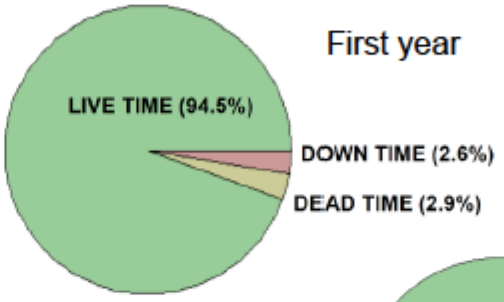
Radon-free **system** to allow periodic calibration at low energy with ^{109}**Cd sources** on flexible wires

Detector performance

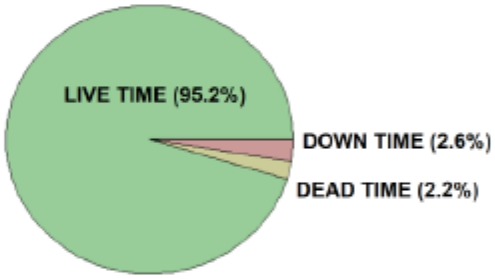
Performance of ANAIS-112 experiment after the first year of data taking ➡ 341.72 days, 105.32 kg y
J. Amaré et al, Eur. Phys. J. C (2019) 79:228

- Excellent **duty cycle**



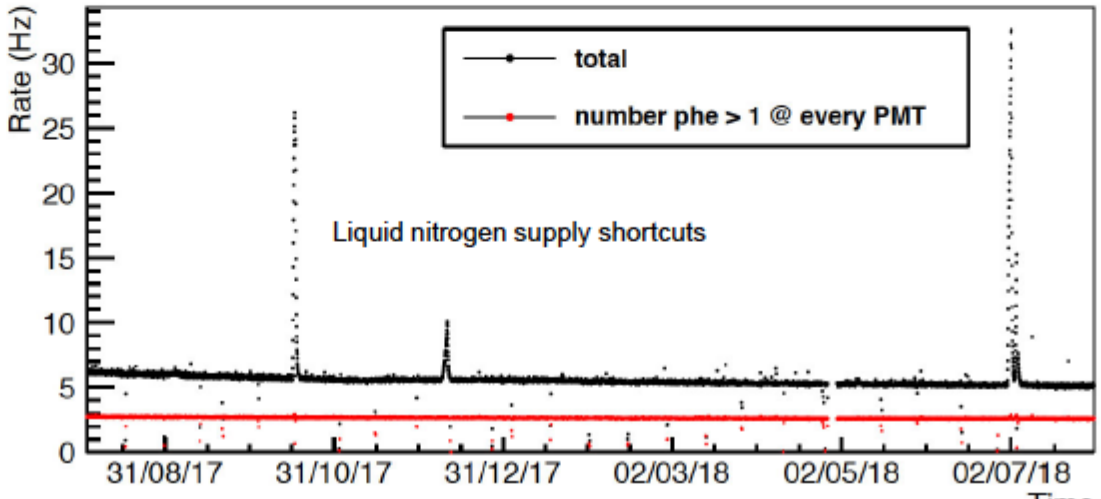


Half second year
(185.36 days)



- Good **stability**

Total trigger rate



Physics run started from Aug/2017

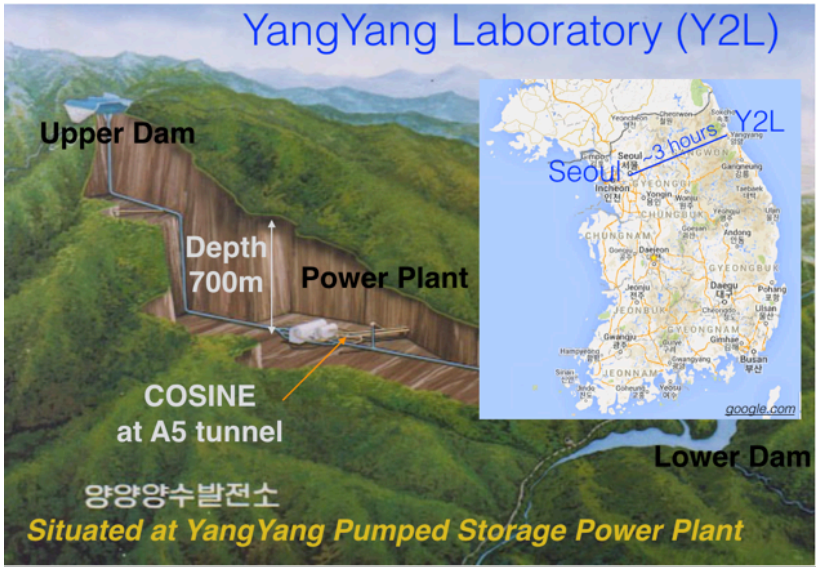
COSINE-100

- A joint effort between DM-Ice and KIMS

KIMS (Korea Invisible Mass Search Experiment) + DM-ICE = COSINE

- 8 NaI(Tl) crystals with 106 kg in total
- Yangyang underground laboratory in South Korea with about 700m overburden
- **Physics run started Sep/2016**

5 countries,
14 institutes,
~50 members



COSINE-100 detector configuration

JINST 13 T02007 (2018)

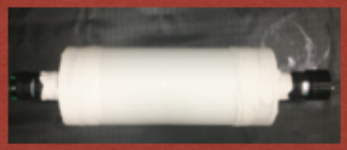
4π Muon Counter
37 plastic scintillator panels
2-inch PMT(H7195)s for muon counter

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

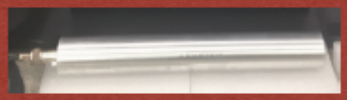
Liquid Scintillator
2200-L LAB-based LS for veto
5-inch PMT(R877)s for LS detector

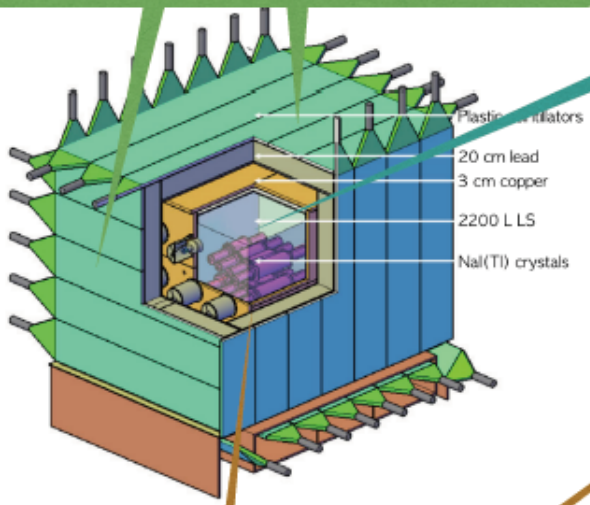
JINST 13 T06005 (2018)

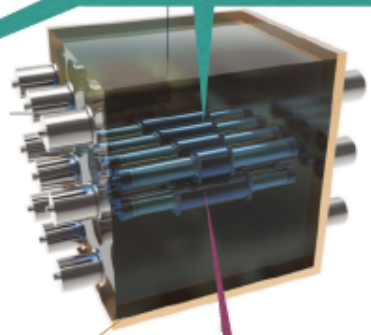
Neutron Monitoring
Fast neutron detector
(Liquid scintillator)

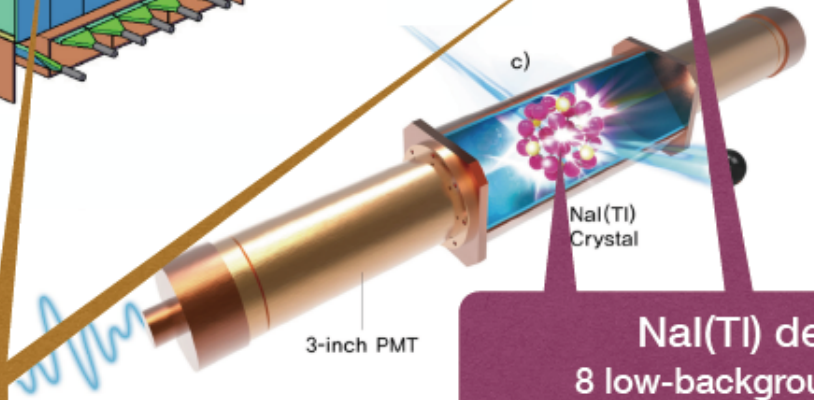


Thermal neutron detector
(^{3}He gas detector)









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 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)

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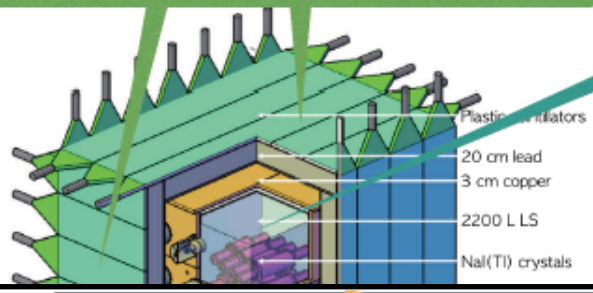
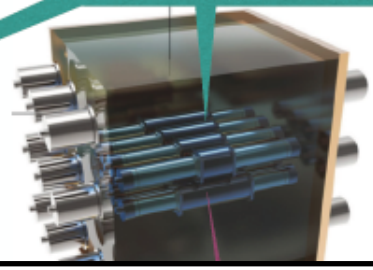
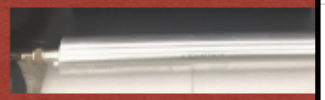




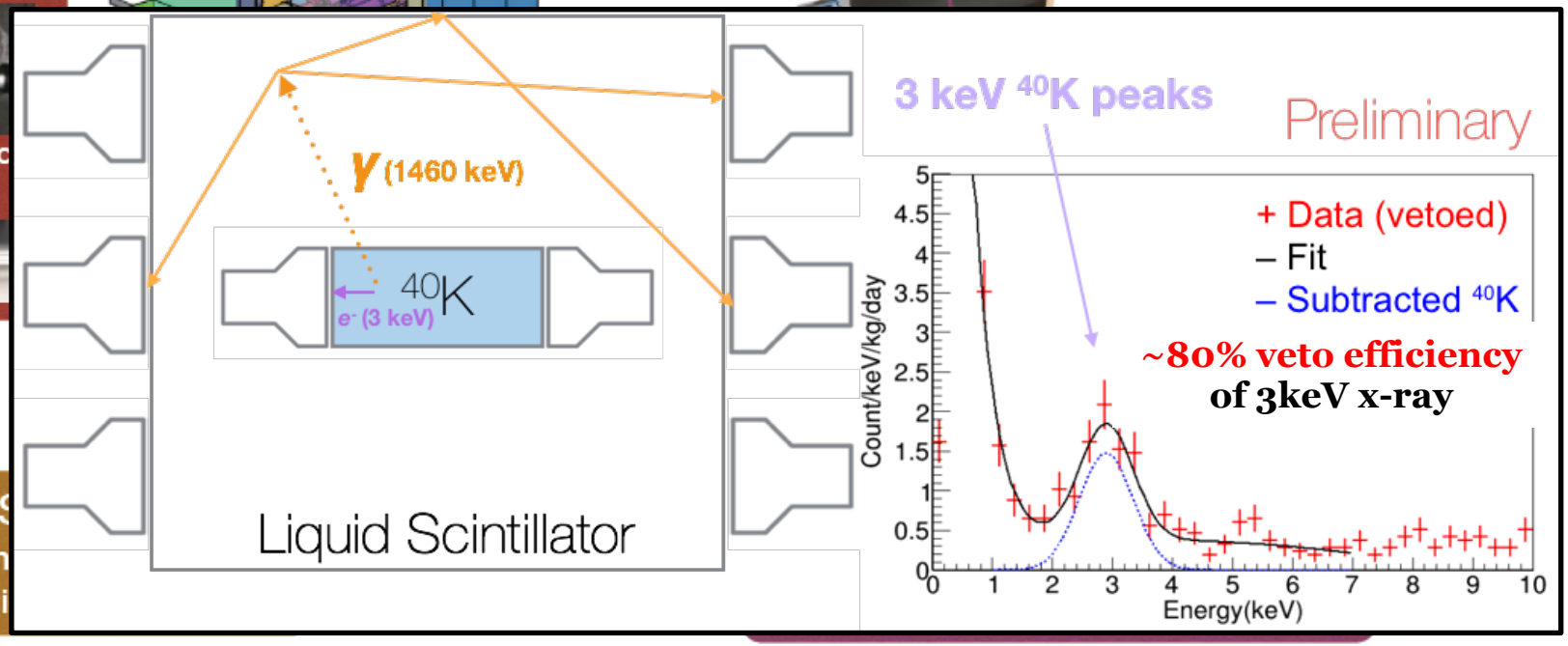
JINST 13 T06005 (2018)

Neutron Monitoring
Fast neutron detector
(Liquid scintillator)

Thermal neutron detec
(³He gas detector)

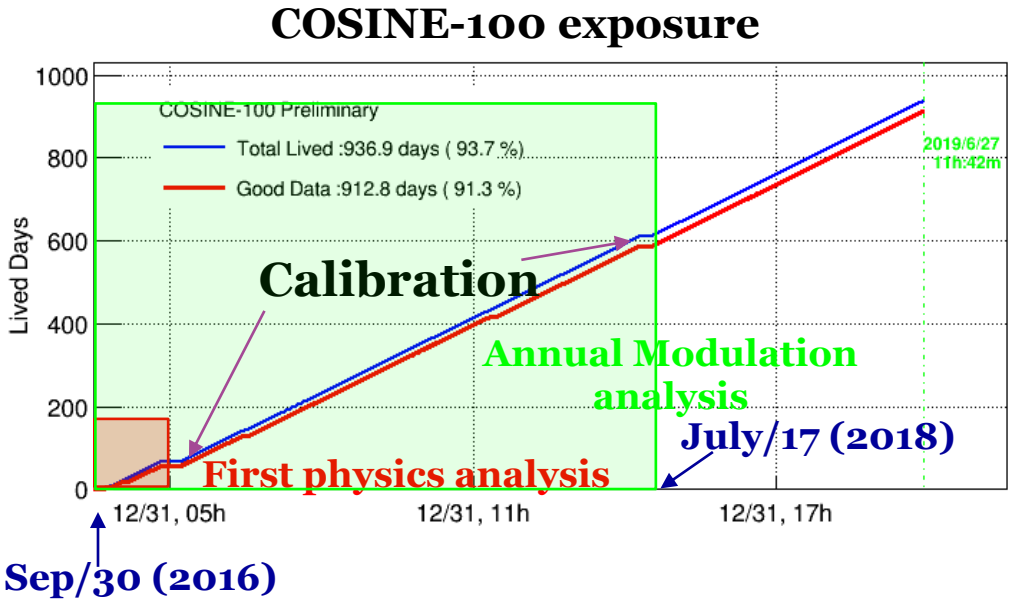


3-cm th
20-cm thi

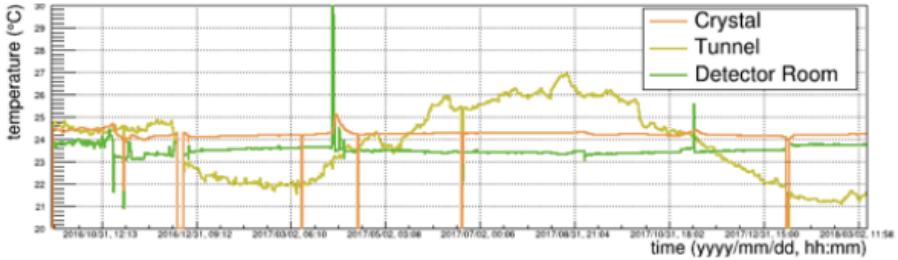


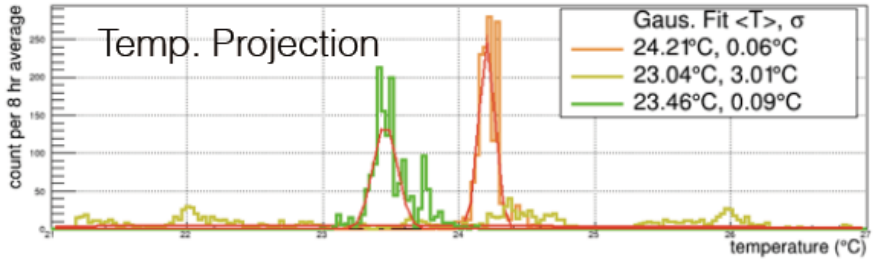
Eur. Phys. J. C. 78 107 (2018)

COSINE-100 operation

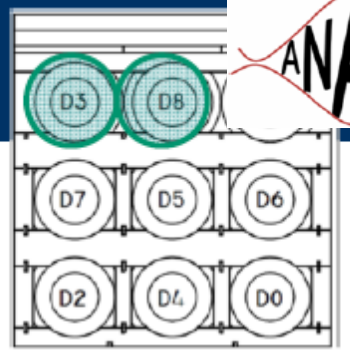


- Stable physics run
  - ❖ >90% physics data
  - ❖ >95% good runs
- Operating more than 2.8 years
  - ❖ 2.5 years good data





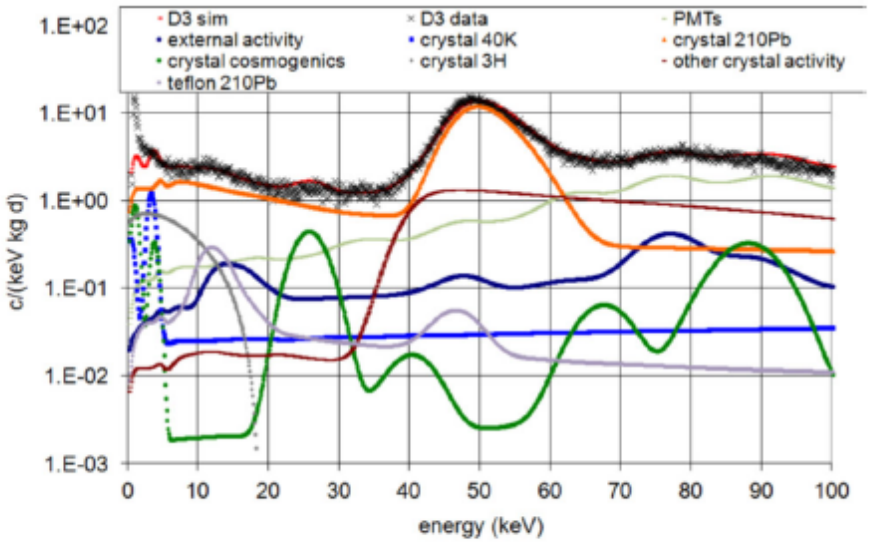
Background model: contributions

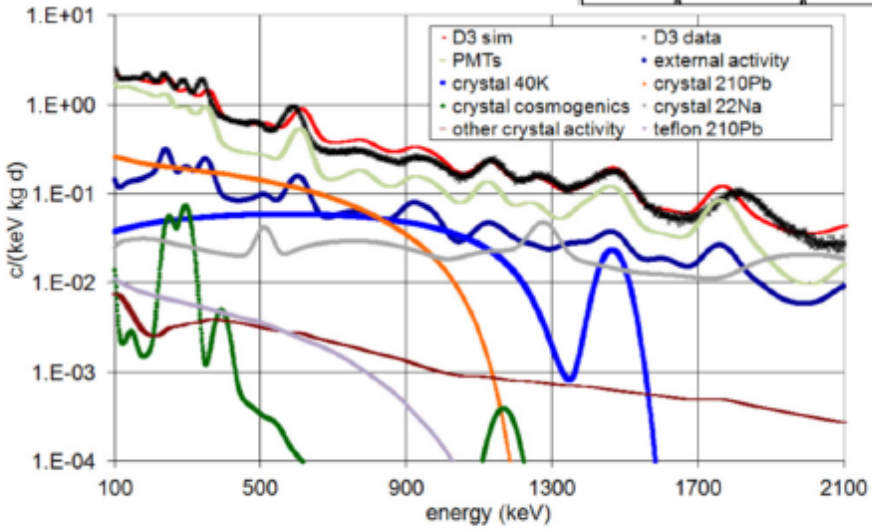


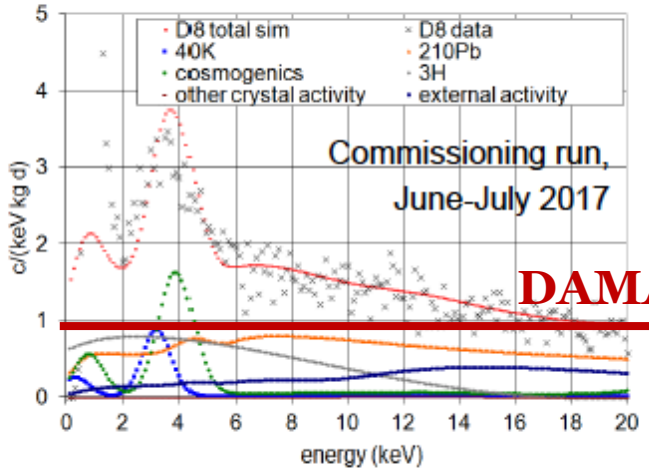
➢ **Individual contributions** for first year of ANAIS-112 data

(3 August 2017 to 31 July 2018, 341.72 d)

EPJC 79, 412 (2019)







^{40}K and **^{22}Na** peaks and **^{210}Pb** (bulk+surface) and **^{3}H** continua are the most significant contributions in 1-6 keV region:

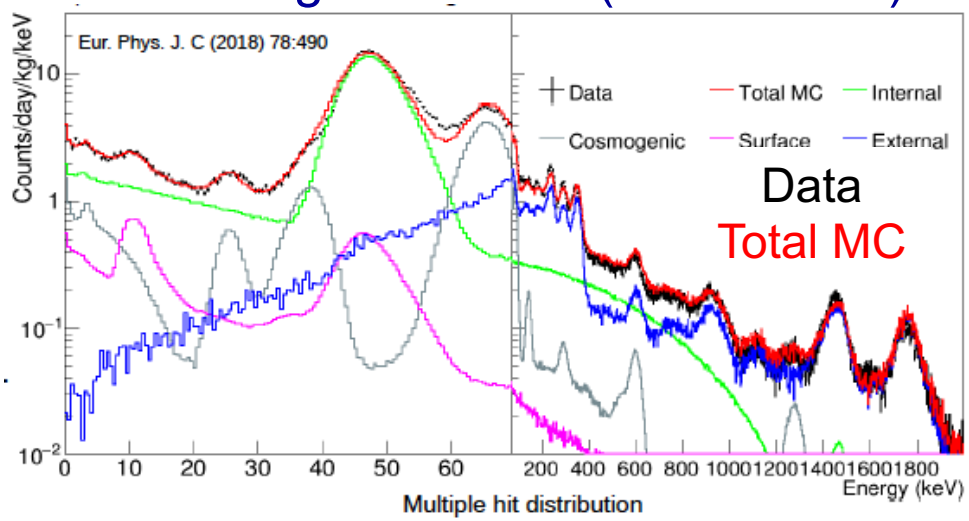
^{210}Pb:	32.5%
^{3}H:	26.5%
^{40}K:	12%
^{22}Na:	2.0%

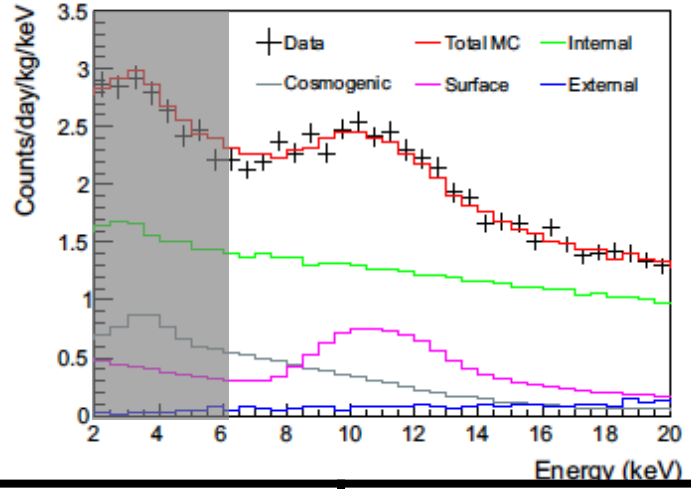
Internal → ^{210}Pb, ^{40}K

Cosmogenic → ^{3}H, ^{22}Na

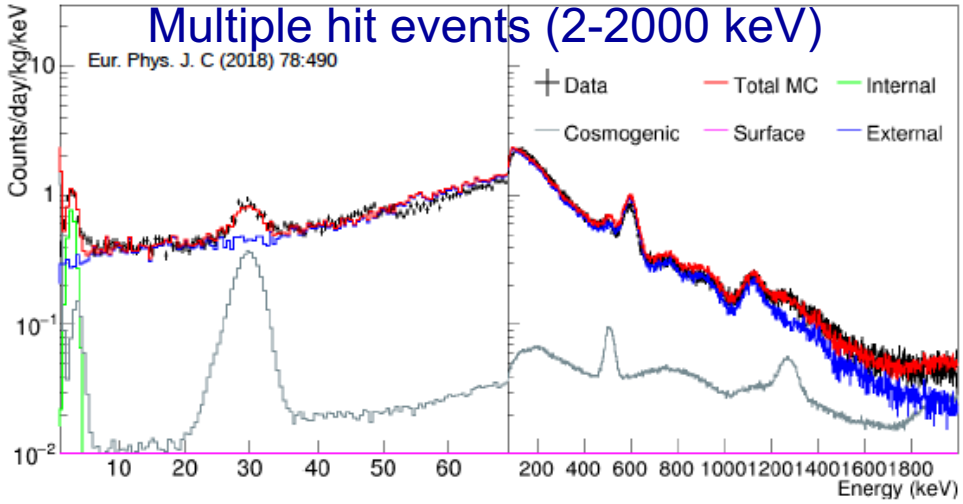
Background understanding (COSINE-100)

Single hit event (6-2000 keV)





Multiple hit events (2-2000 keV)

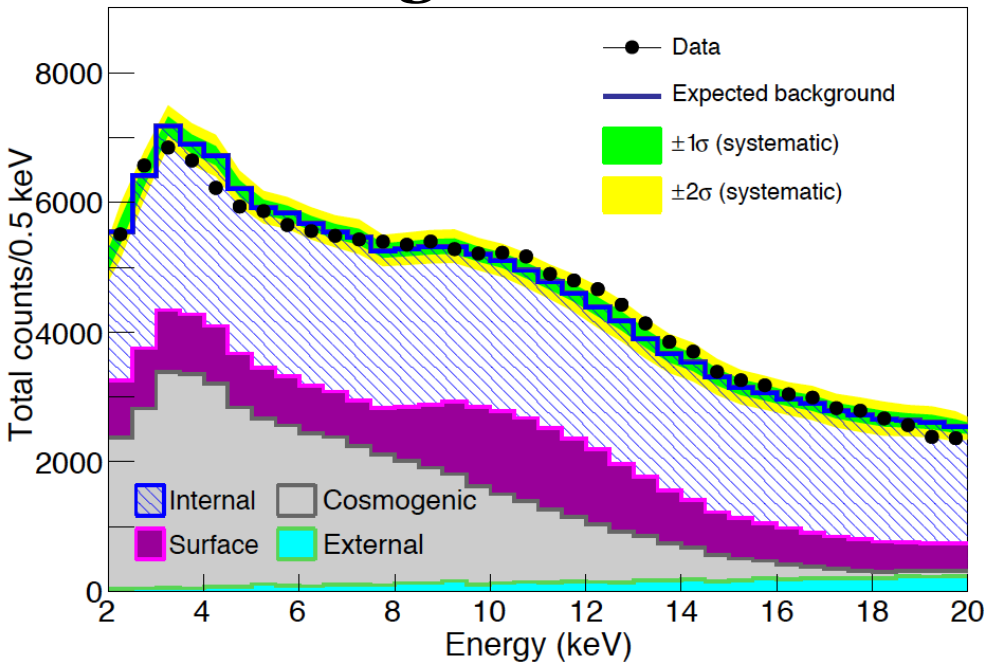


EPJC 78 (2018) 490

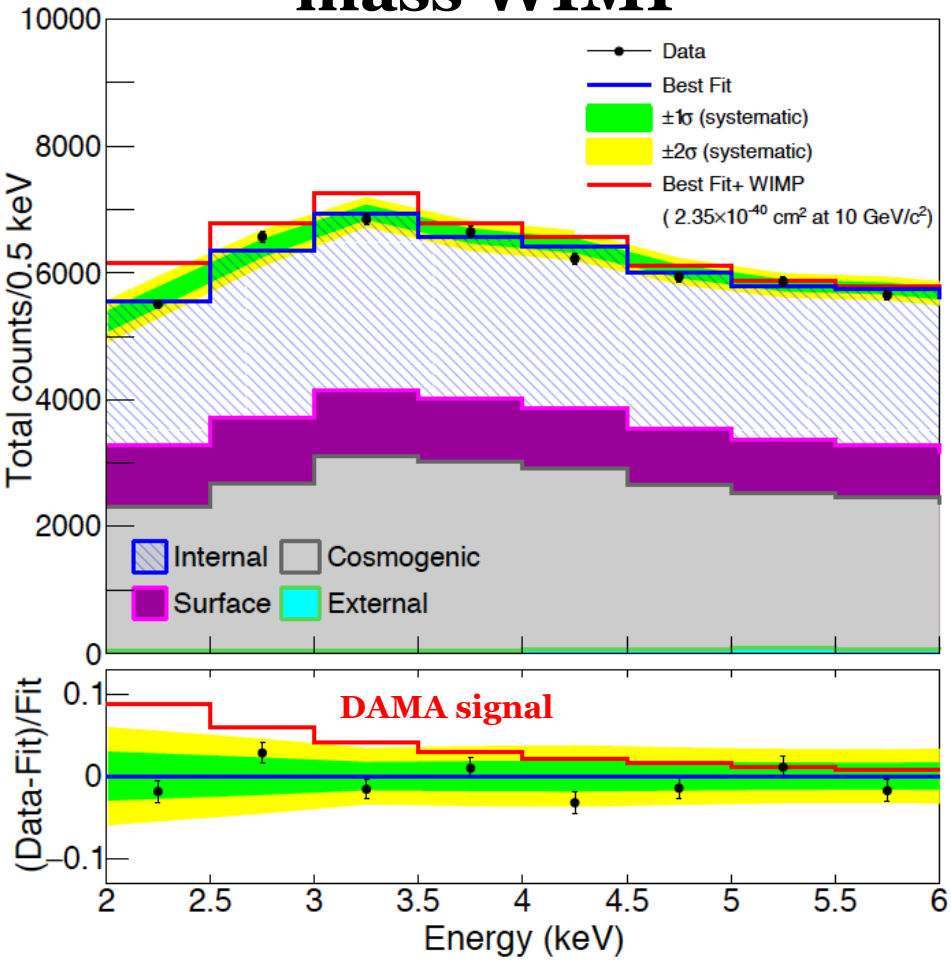
Components	Background 2-6 keV (dru)
Internal ^{210}Pb	1.50 +/- 0.07
Internal ^{40}K	0.05 +/- 0.01
Surface ^{210}Pb	0.38 +/- 0.21
^{3}H (Cosmogenic)	0.58 +/- 0.54
^{109}Cd (Cosmogenic)	0.09 +/- 0.09
Other cosmogenic	0.05 +/-0.03
External	0.03 +/- 0.02
Total expected	**2.70 +/- 0.59**
Data	**2.64 +/- 0.05**

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

All crystals background

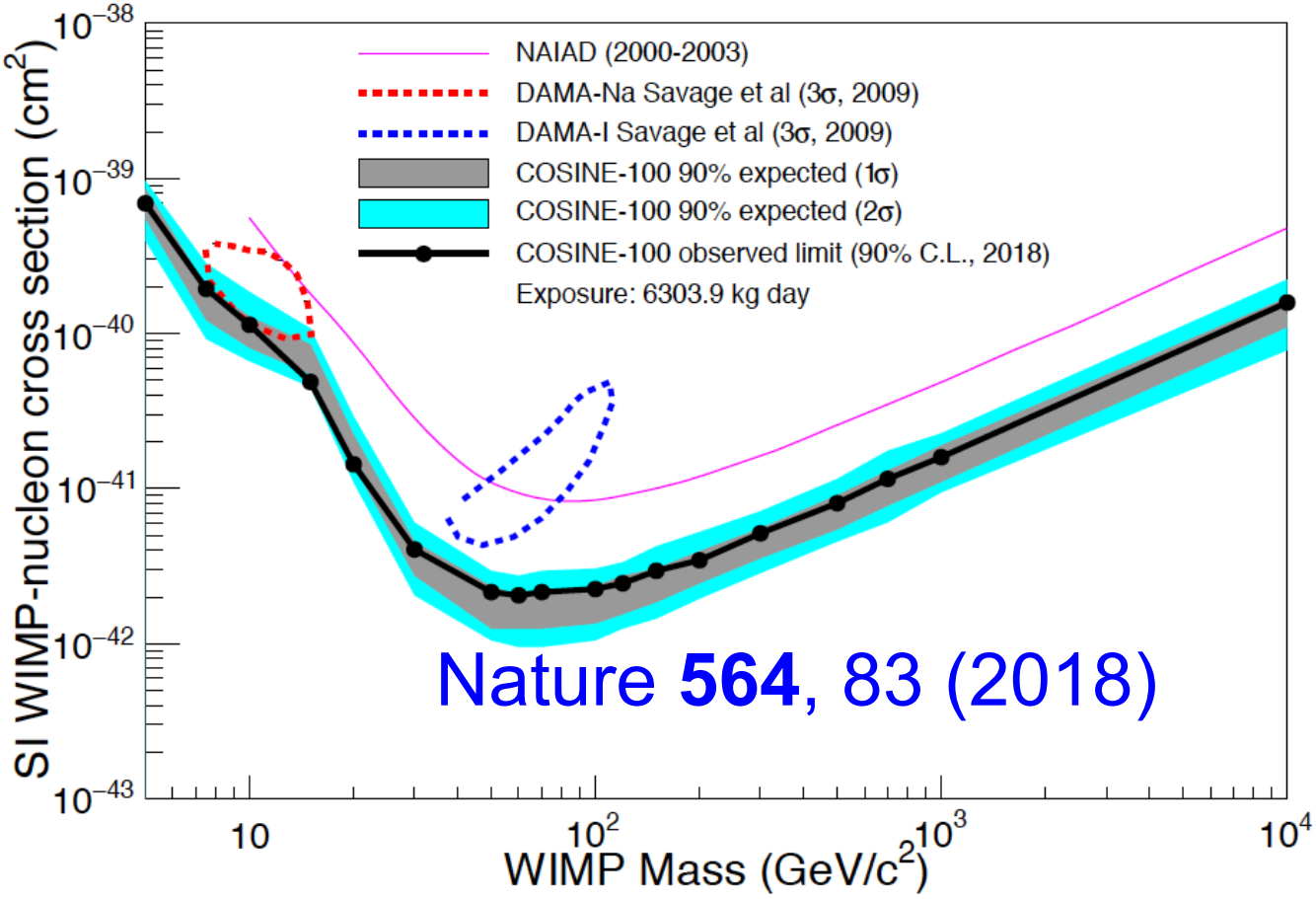


Signal fit with 10 GeV mass WIMP



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

Limit on WIMP-nucleon cross section from COSINE-100



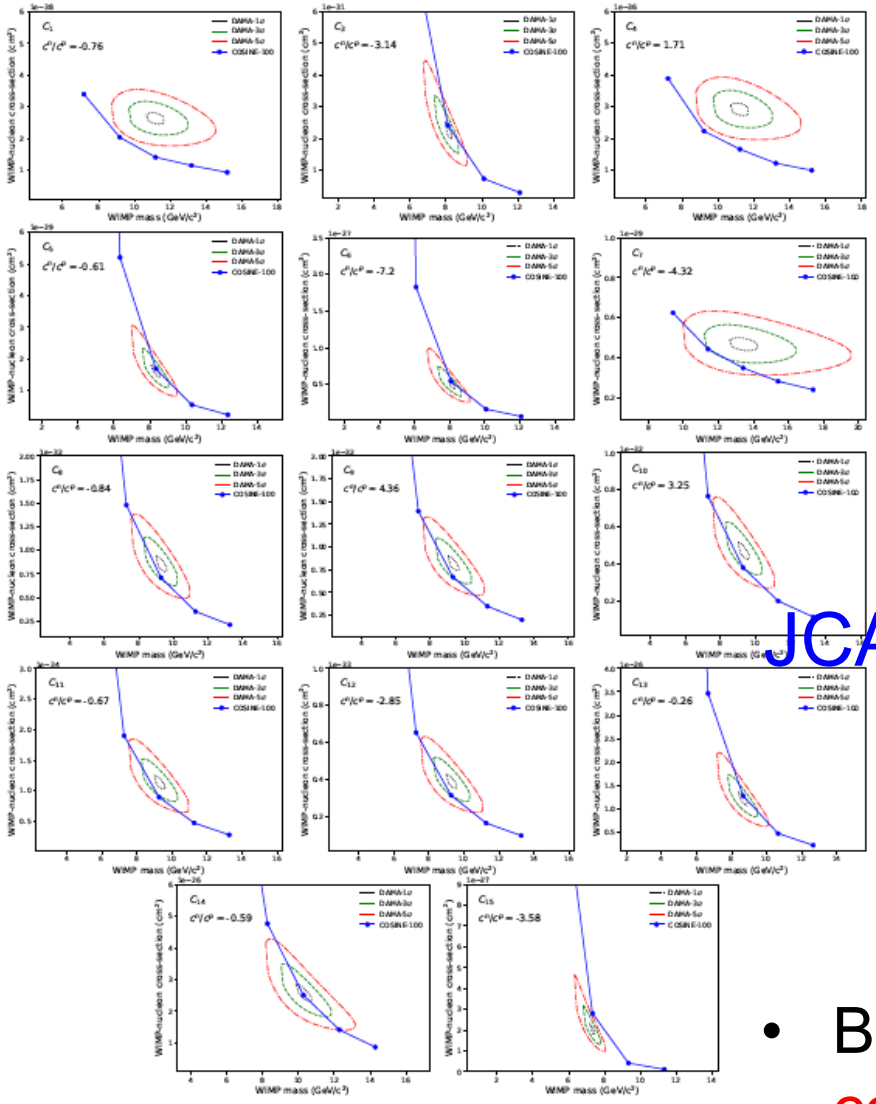
COSINE-100 excludes DAMA/LIBRA-phase1's interpretation with the spin-independent WIMP interaction in Standard Halo Model

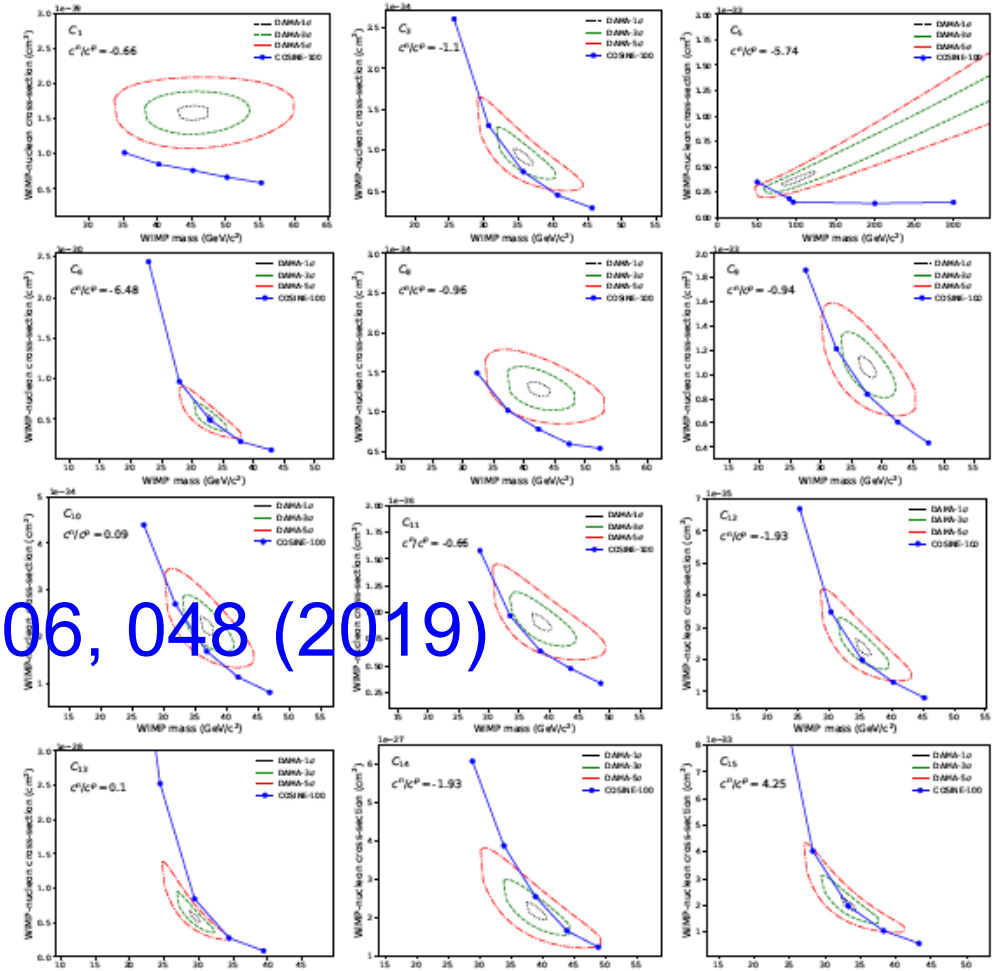
First time with same NaI(Tl) target

Consistent with other null experiments

The other models?

- Test 15 Effective Field Theory operators



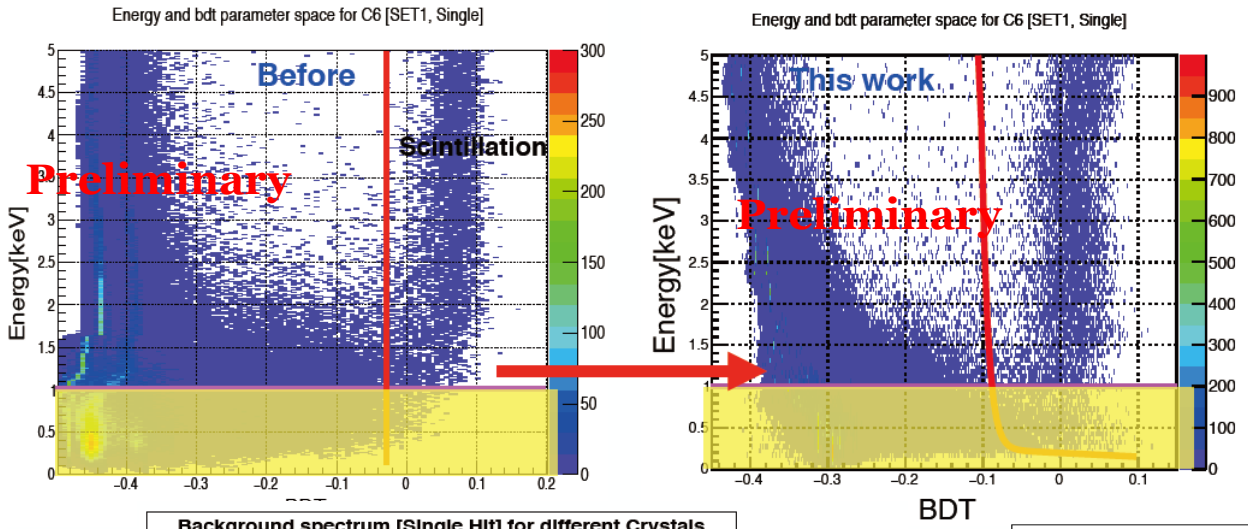


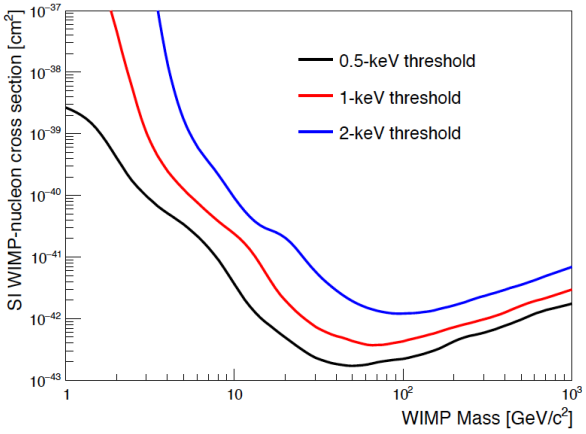
JCAP 06, 048 (2019)

- Best fit region of DAMA was not fully covered yet

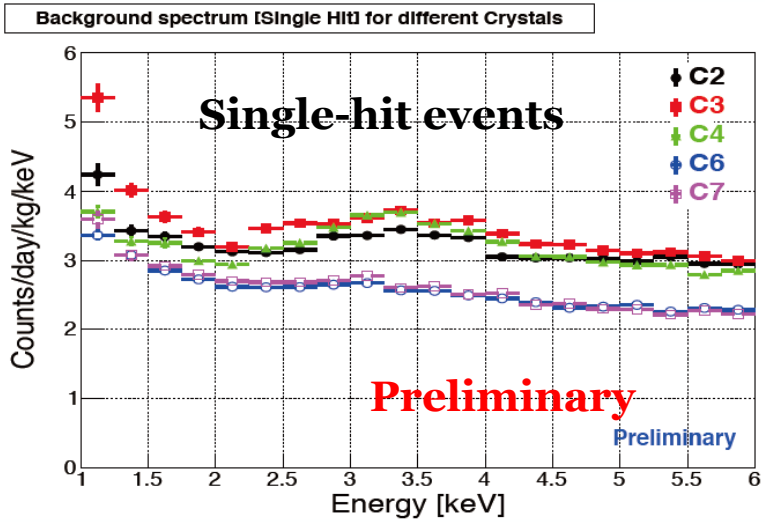
Updated analysis is ongoing

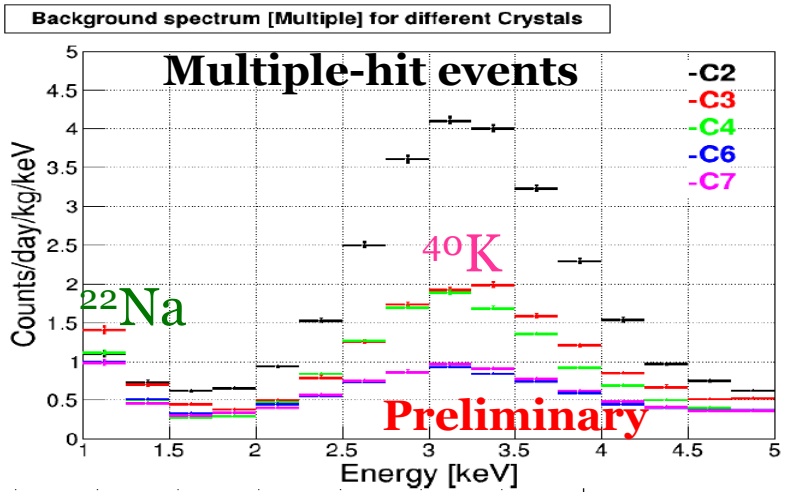
- Lower analysis threshold from 2 keV to 1 keV with better noise controls





Stay tuned!!



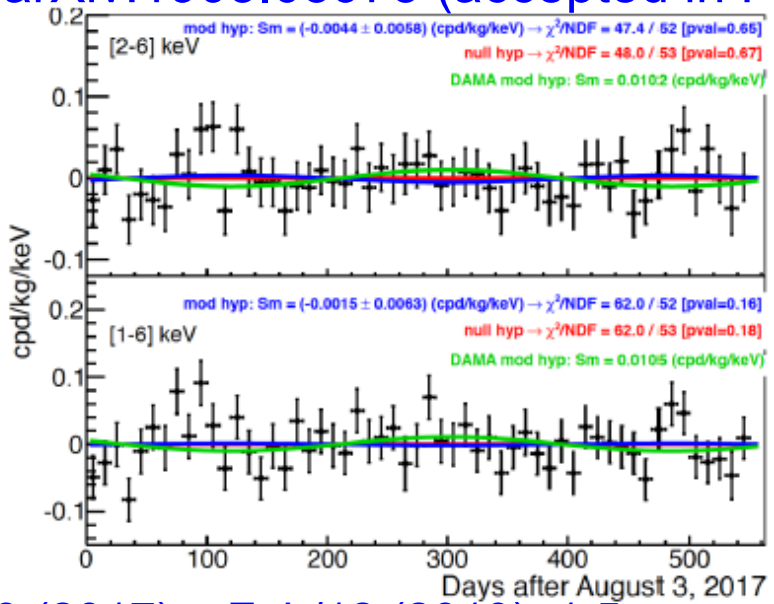


Annual modulation result from ANAIS-112

Least-squares fit of ANAIS-112 10-day time-binned data in 1-6 / 2-6 keV to

$$R(t) = R_0 + R_1 \cdot exp(-t/\tau) + S_m \cdot cos(\omega \cdot (t + \phi))$$

arXiv:1903.03973 (accepted in PRL)



Aug/3 (2017) ~ Feb/12 (2019), 1.5 year

Null hypothesis well supported by the χ^2 test

Modulation hypothesis best fits for 2-6 and 1-6 keV

DAMA/LIBRA result also shown

$$S_m = -0.0044 \pm 0.0058\ cpd/kg/keV$$
$$S_m = -0.0015 \pm 0.0063\ cpd/kg/keV$$

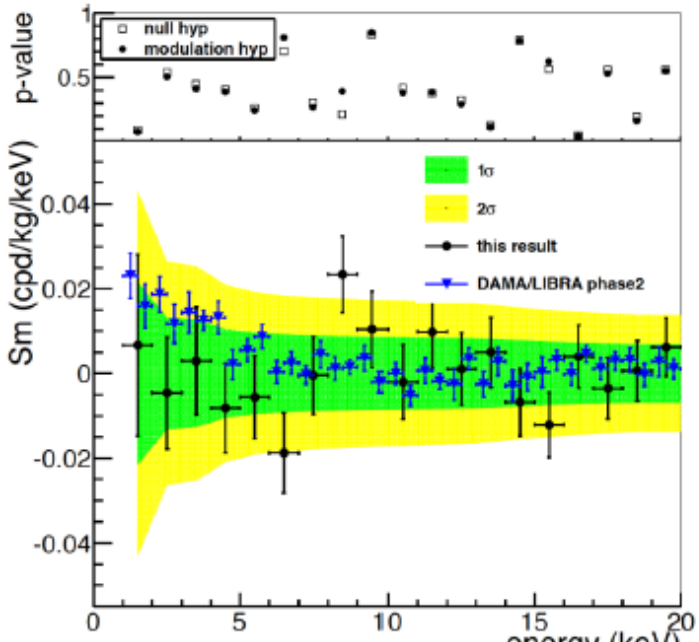
τ fixed from our background model

ω fixed corresponding to 1 year period

φ fixed to have the cosine maximum in June, 2nd

S_m fixed to 0 in the null hypothesis and left unconstrained for the modulation hypothesis

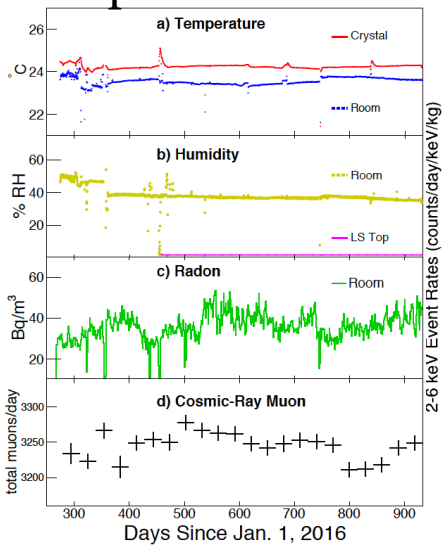
Modulation amplitudes estimates in 1 keV bins from 1 to 20 keV



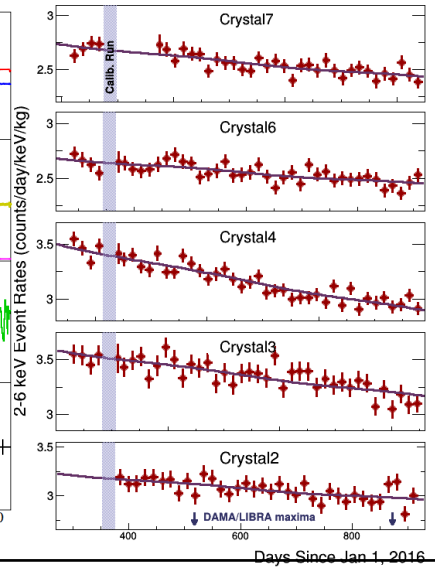
Annual modulation result with COSINE-100

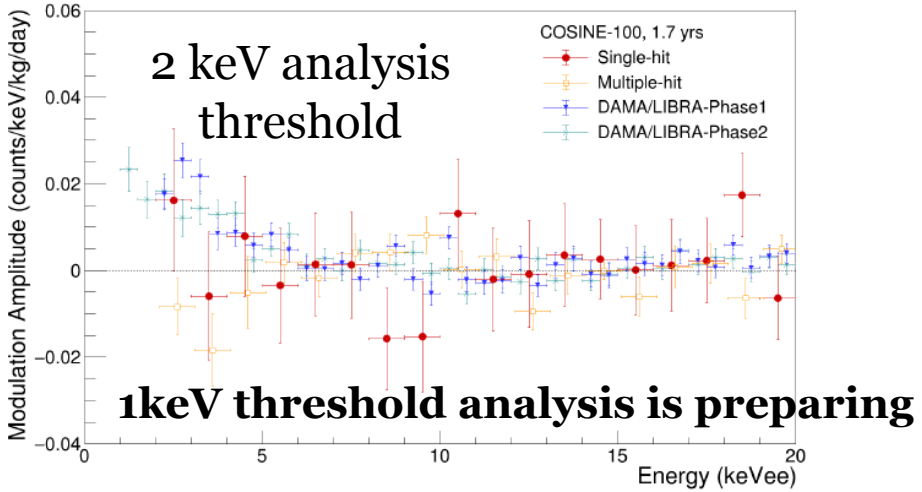
Oct/21 (2016) ~ Jul/18 (2018), 1.7 year

Environmental parameters

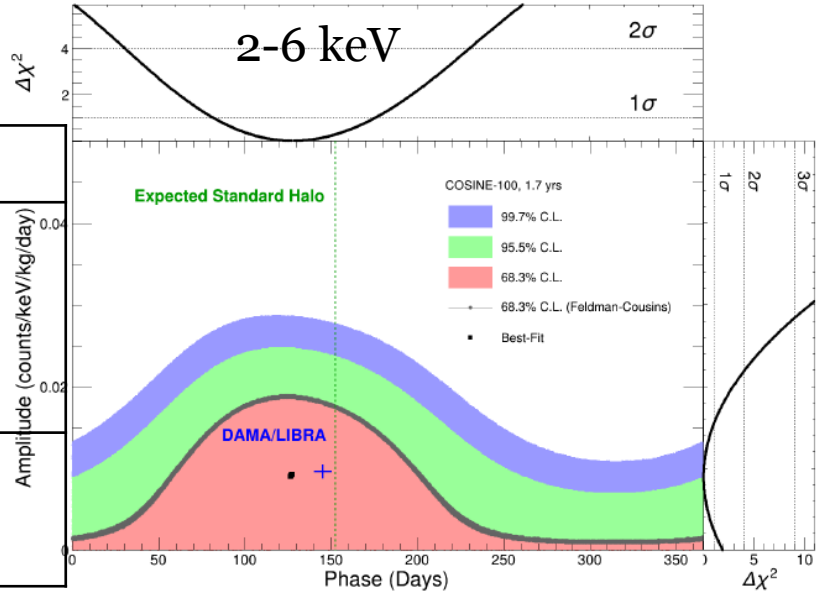


2-6 keV data





arXiv:1903.100098 (accepted in PRL)

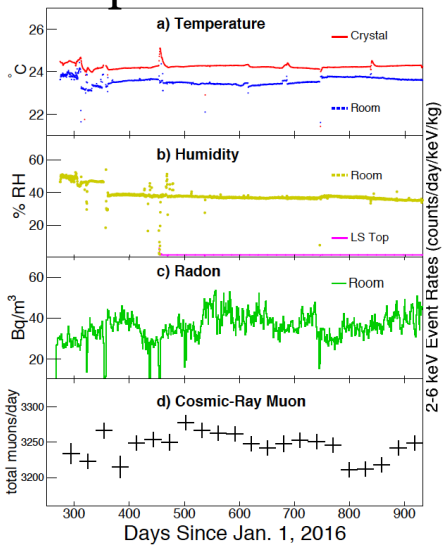


Config	Amplitude (2-6 keV)	Phase (days)
COSINE-100	$\mathbf{0.0083 \pm 0.0068}$	**152.5 (fixed)**
ANAIS	-0.0044 ± 0.0058	152.5 (fixed)
DAMA	0.0095 ± 0.0008	152.5 (fixed)
COSINE-100	0.0092 ± 0.0067	127 ± 46
DAMA	0.0096 ± 0.0008	145 ± 5

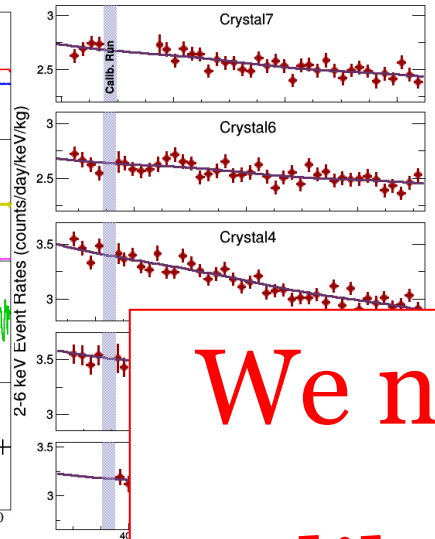
Annual modulation result with COSINE-100

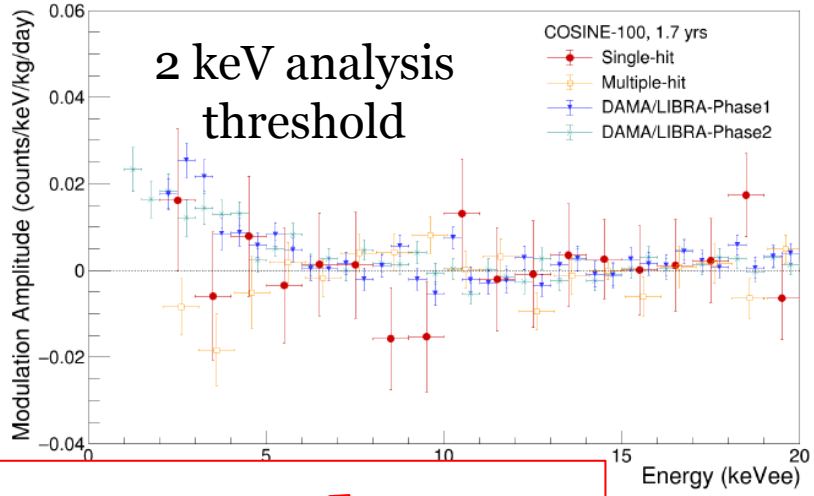
Oct/21 (2016) ~ Jul/18 (2018), 1.7 year

Environmental parameters



2-6 keV data





in PRL)

We need more data!

...like everyone else

Config	Amplitud	
COSINE-100	$\mathbf{0.0083 \pm 0.0068}$	**152.5 (fixed)**
ANAIS	-0.0044 ± 0.0058	152.5 (fixed)
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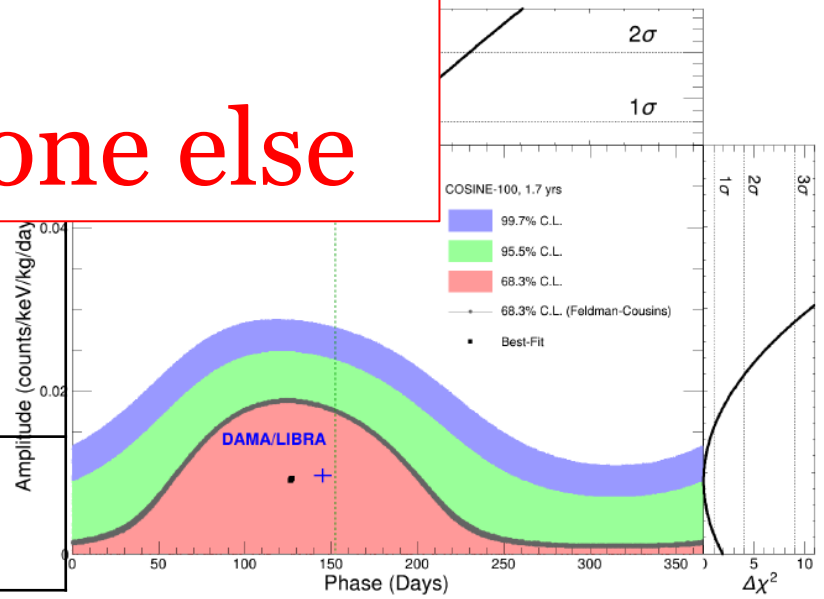
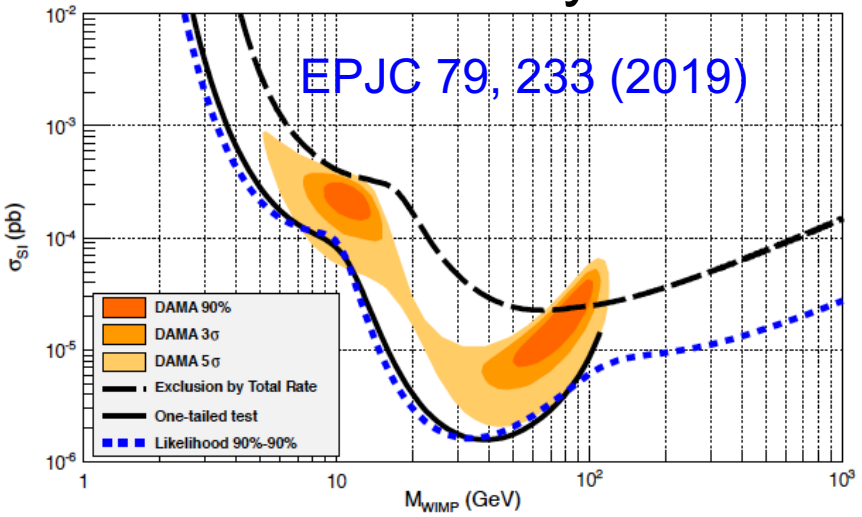
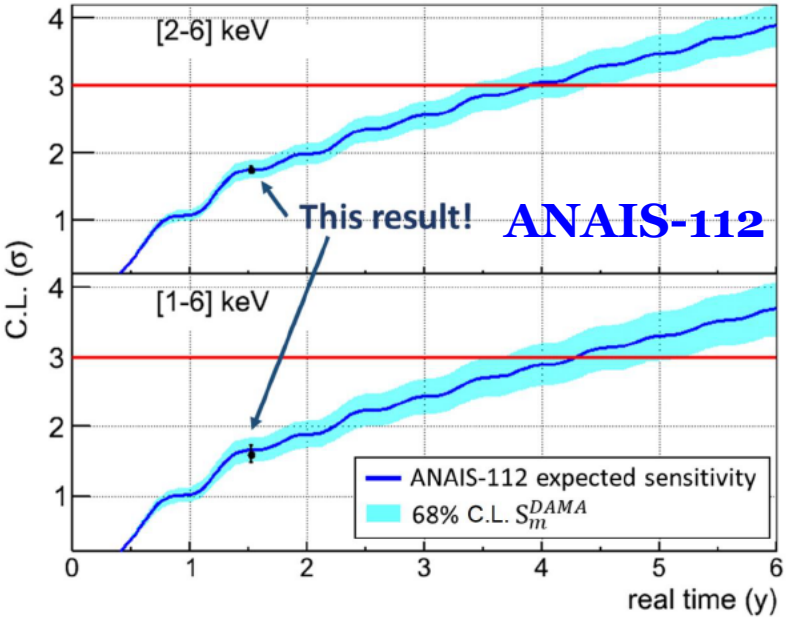


How much data?

ANAIS-112 five years sensitivity





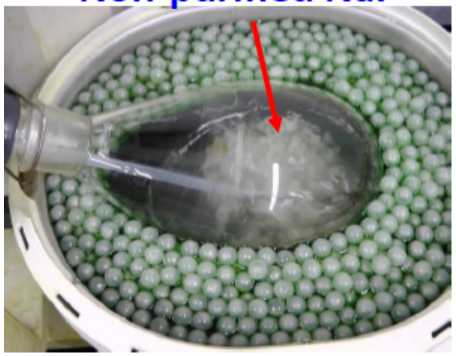
- About 3σ level statement with five years data
- ANAIS-112 and COSINE-100 agree to combine their data
  - ❖ Within a year, we can have 3σ level conclusion if nothing is there
- Perhaps, we still need better quality crystals for clear understanding

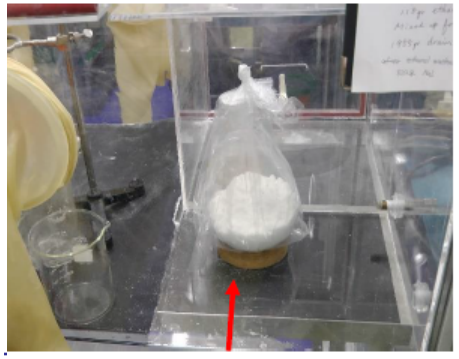
PICO-LON

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

A. Kozlov @ LRT2019

Non-purified NaI

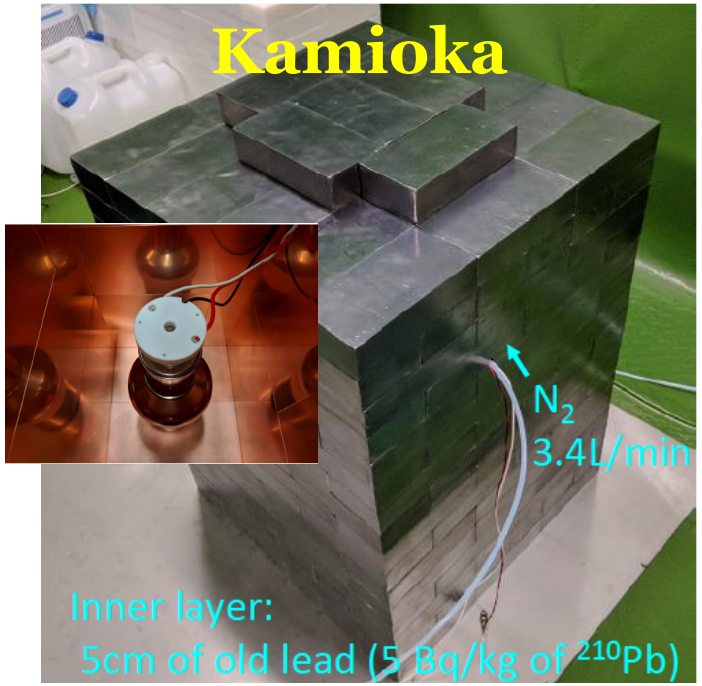




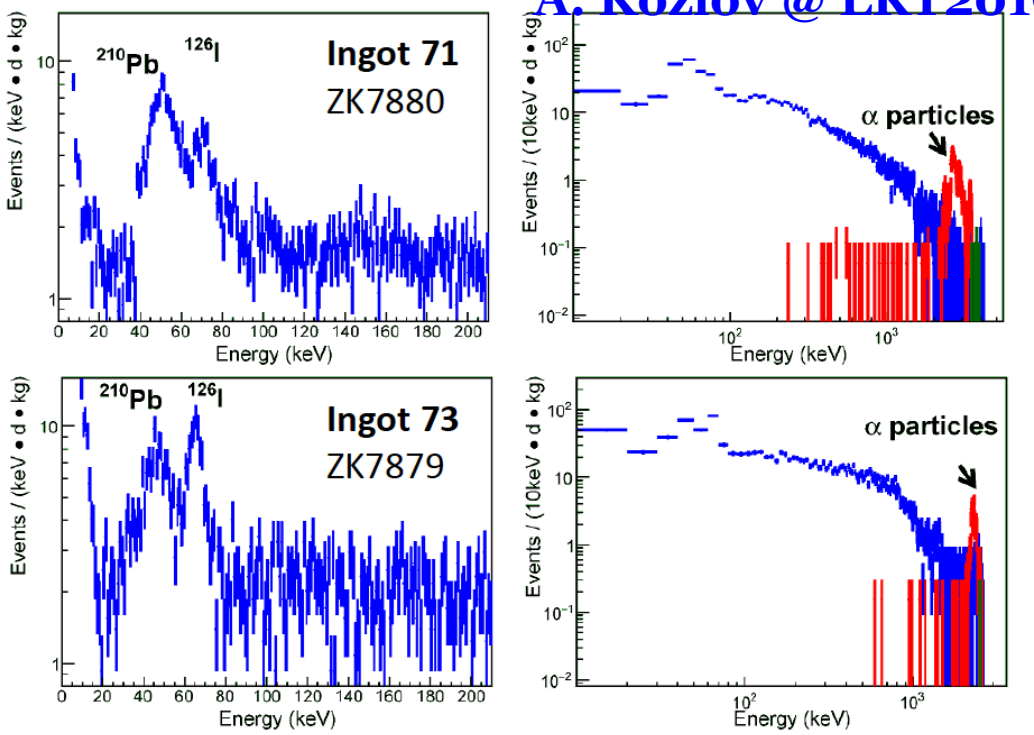
Purified NaI·2$H_2$0

Machine cutting

PICO-LON : Background



A. Kozlov @ LRT2019



NaI(Tl)/ Isotope	^{238}U, ppt	^{232}Th, ppt	^{40}K, ppb	^{210}Pb, mBq
Ingot 71†	9.7 ± 0.8	1.7 ± 0.2	<20	1.5
Ingot 73‡	3.6 ± 0.6	1.8 ± 0.7	<30	1.3
DAMA det.	0.7 - 10	0.7 - 10	20	0.024

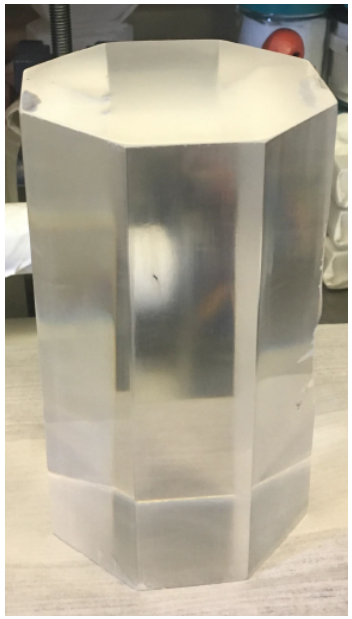
SABRE

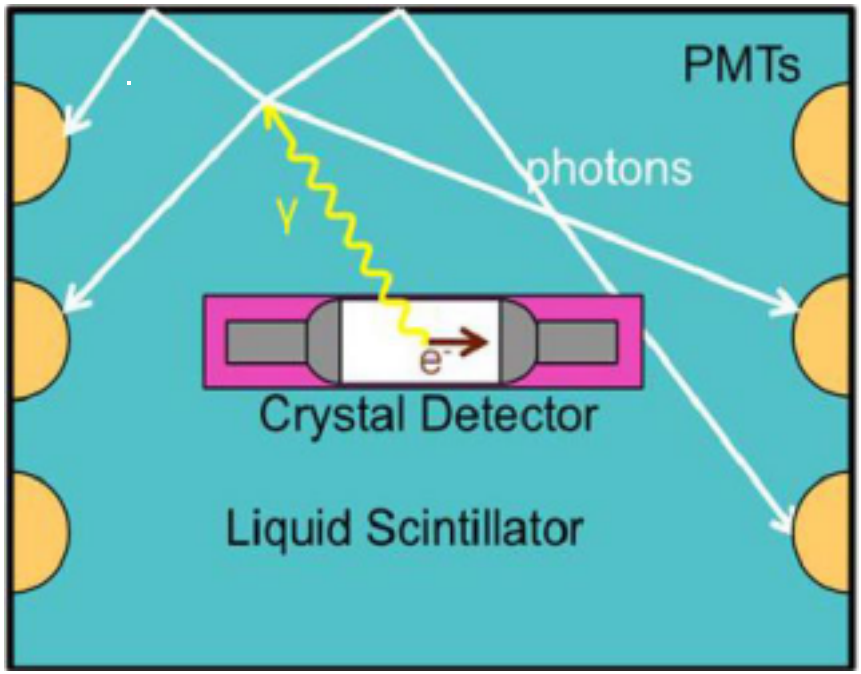
4 key features:

B. Suerfu@ NDM2018

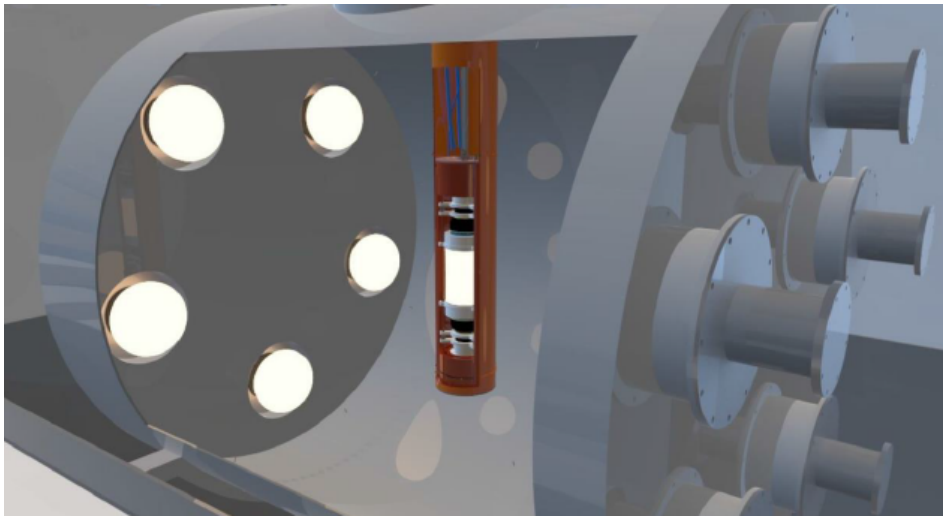
1. High purity crystals: High purity powder and clean crystal growth method
2. Active background rejection: active veto of liquid scintillator
3. Low energy threshold: High QE Hamamatsu PMTs, directly coupled to the crystals
4. Double location: both in Northern and Southern hemispheres

96 mm dia, 3.4 kg

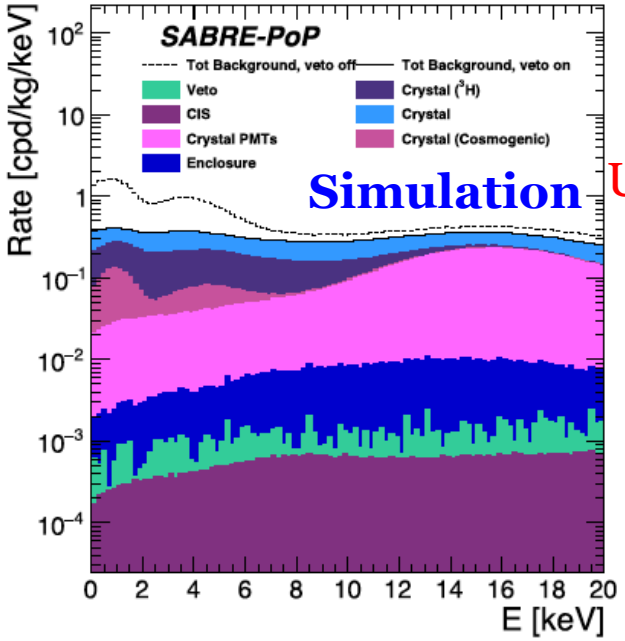




SABRE-PoP (Proof of Principle)



Astropart. Phys. 106, 1 (2019)



Crystal is ready to deliver from USA to LNGS at May/2019

Underground measurement :

This summer

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

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

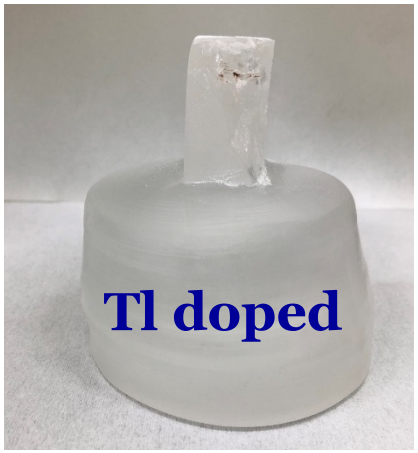
Powder purification performance

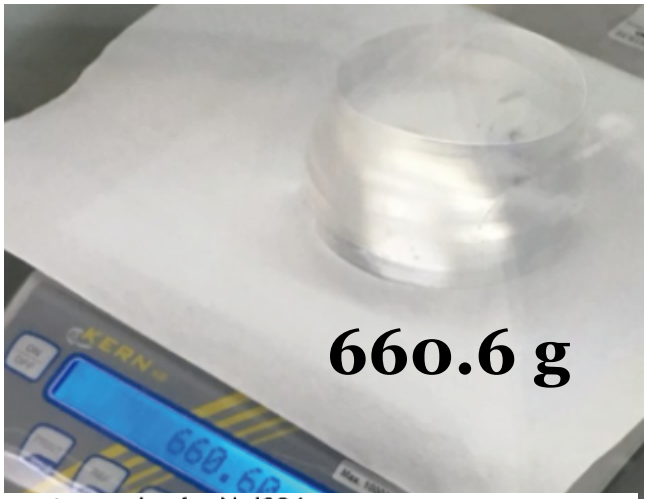
K.A. Shin et al., J. Rad. Nucl. Chem. 317, 1329 (2018)

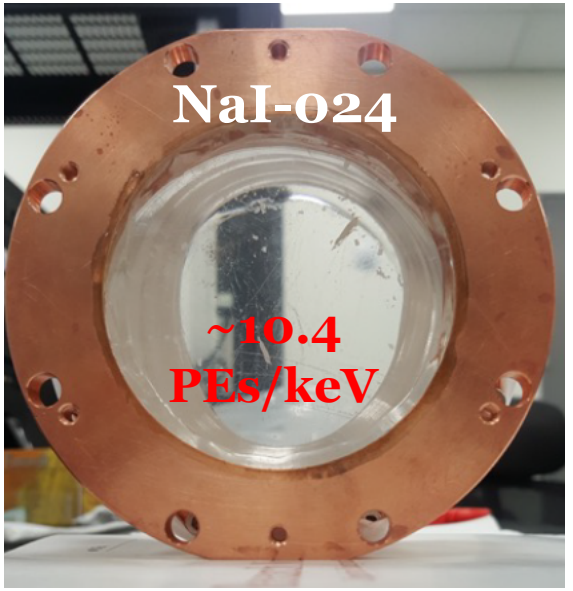
	K (ppb)	Pb (ppb)	U (ppb)	Th (ppb)
Initial NaI	248	19.0	<0.01	<0.01
Purified NaI	<16	0.4	<0.01	<0.01

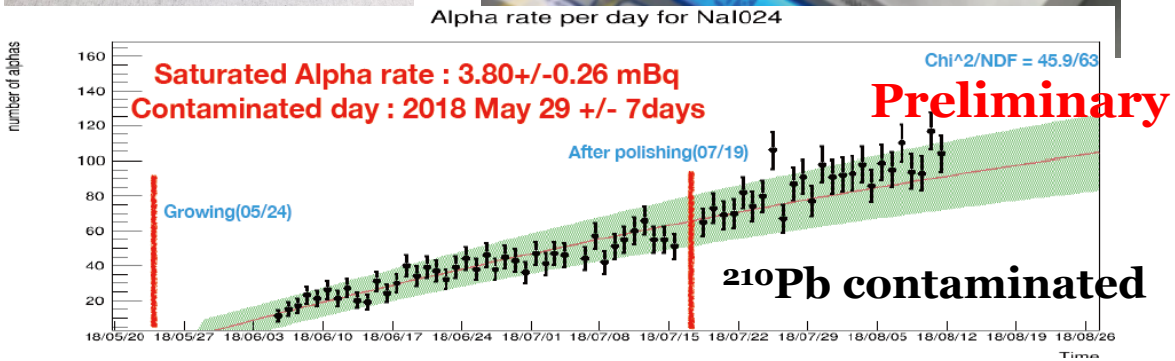
COSINE-200 crystal development

May/2018





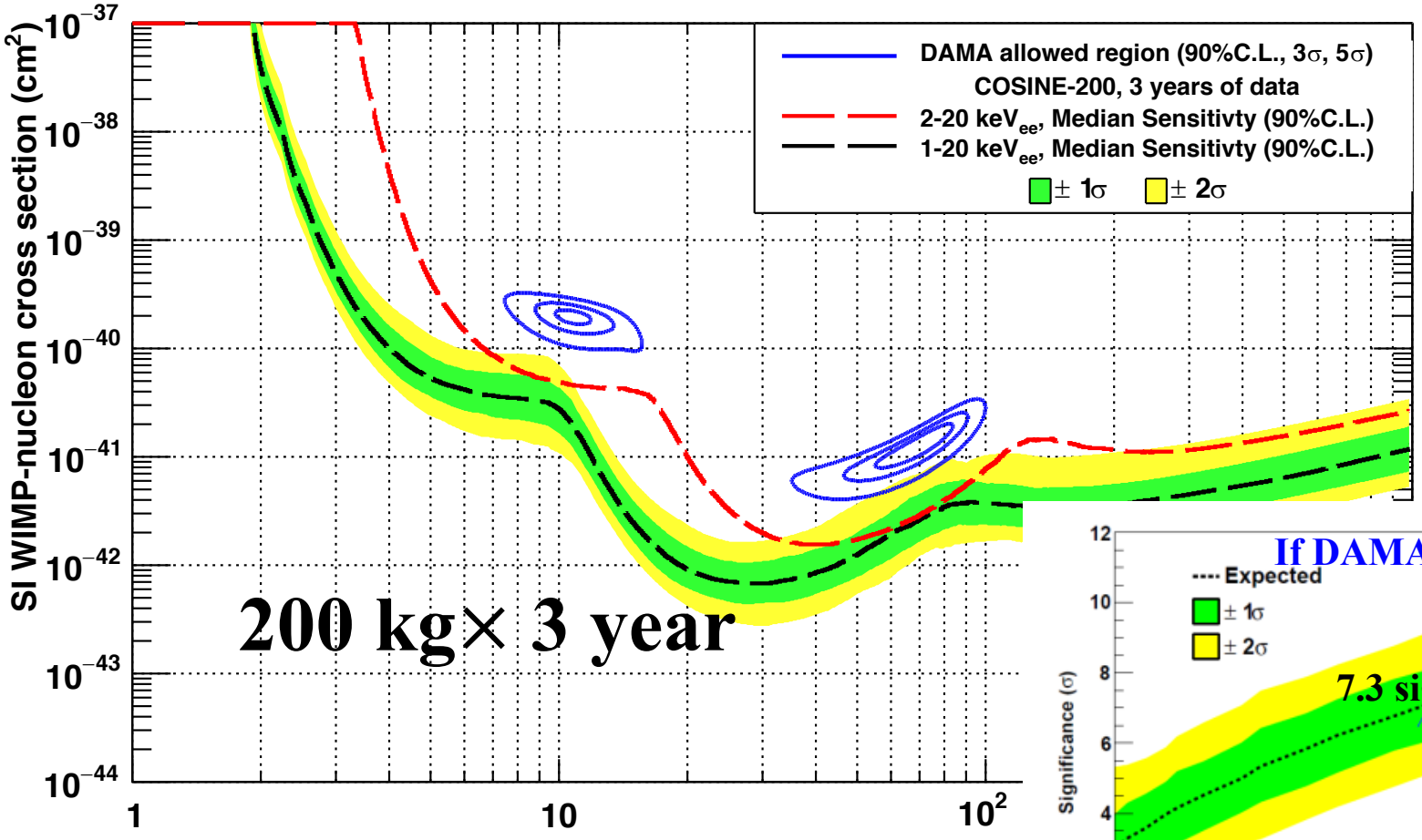


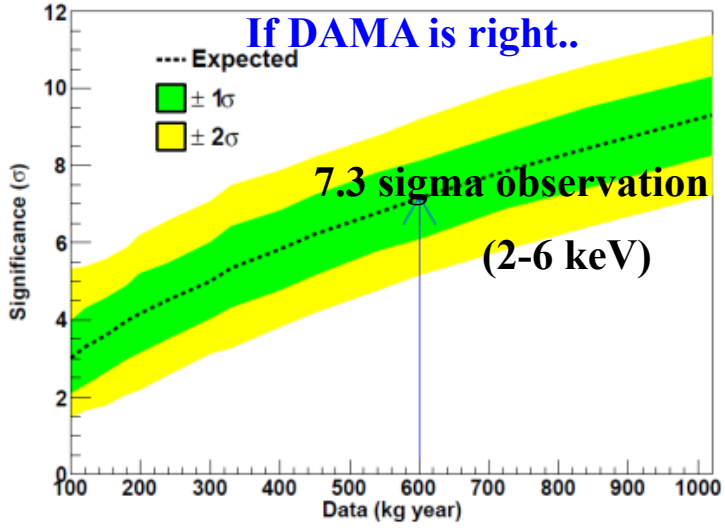


- Demonstrated quick detector assembly and underground measurements!!
- Good optical quality
- Need to improve radiopurity of the crystal
  - Plan to prove the low-background crystal by this summer

COSINE-200 sensitivity (similar for all future project)

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

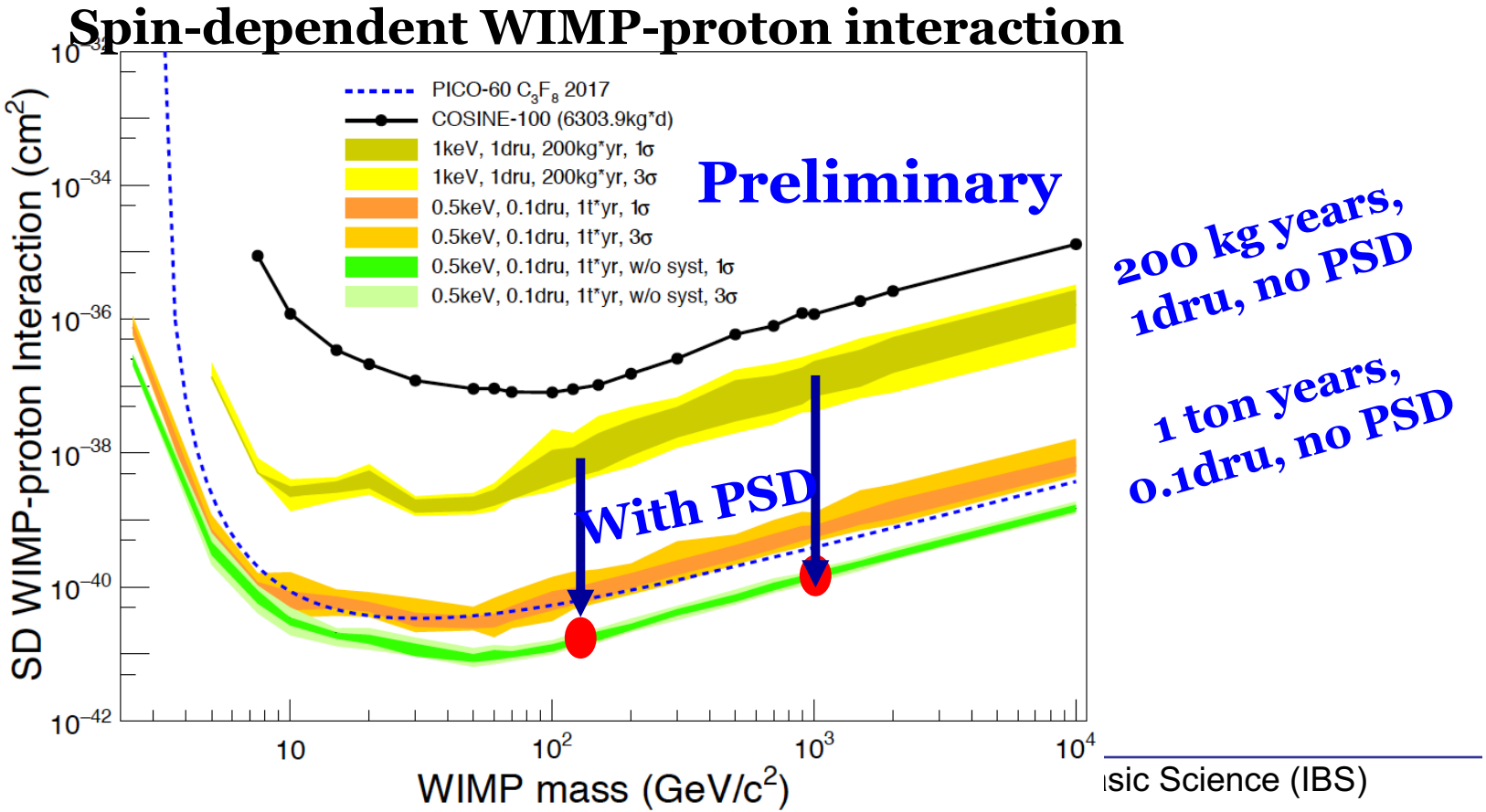




Model independent comparison of the modulation amplitude at 2-6 keV will be performed

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 continue for last 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, need more data
- PICO-LON/SABRE/COSINE try to produce NaI crystals with lower backgrounds than those of DAMA/LIBRA

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

Stay tuned for more exciting results to come from Sodium Iodine detectors!