Dark matter searches with NaI(Tl) crystal detectors (COSINE experiment)

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Institute for Basic Science

Center for Underground Physics

The 1st Yemilab Workshop, October 17th 2022

NaI crystal for particle detection

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

Pro

- High light output
  - 40,000 photons/MeV
  - >60,000 photons/MeV?
- Easy to grow
  - Cheap
  - Large size
- The most widely used scintillator
- Mixture of low and high atomic numbers

Con

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

Properties	From Saint-Gobain
Density [g/cm^3]	3.67
Melting point [K]	924
Thermal expansion coefficient [C^{-1}]	47.4×10^{-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}

NaI(Tl) for rare event searches : Dark Matter

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

1993

RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 47, NUMBER 2 FEBRUARY 1993

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

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

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

NaI(Tl) for rare event searches : Dark Matter

ELSEVIER

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DAMA/LIBRA

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

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PICO-LON

ELSEVIER

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ANAIS

ELSEVIER

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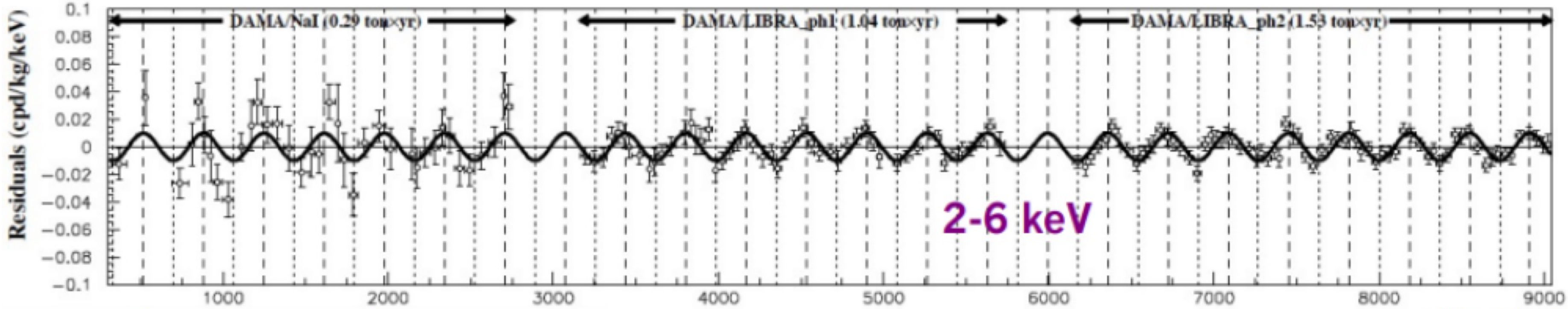
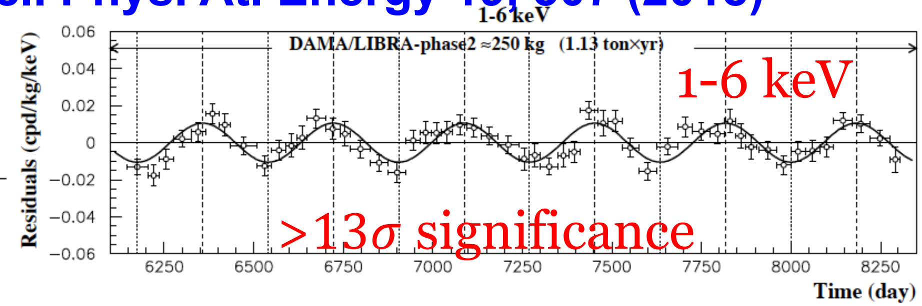
COSINE

Annual modulation signal from DAMA

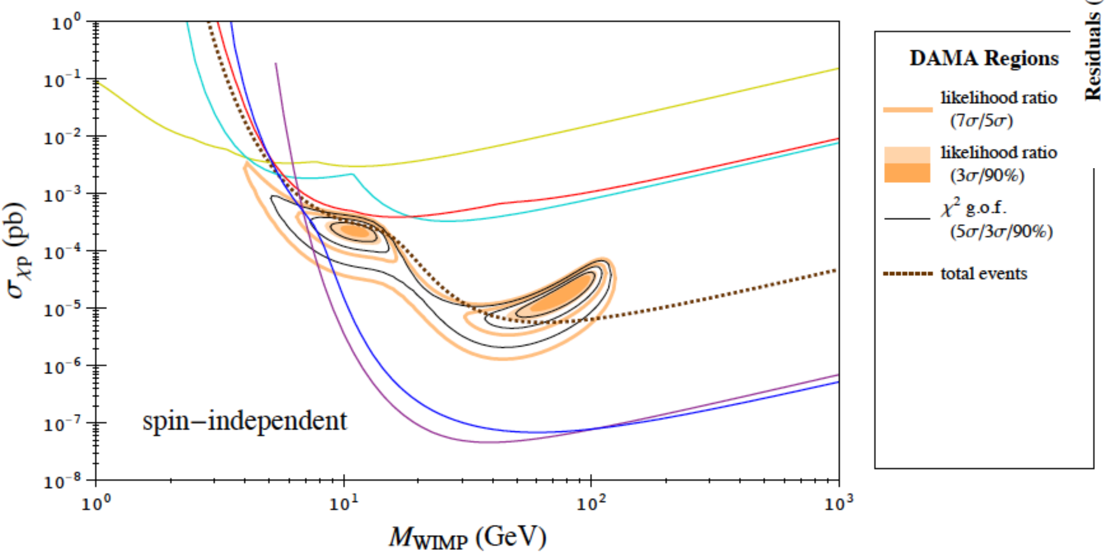


From talk at EPS-HEP Conference 2021

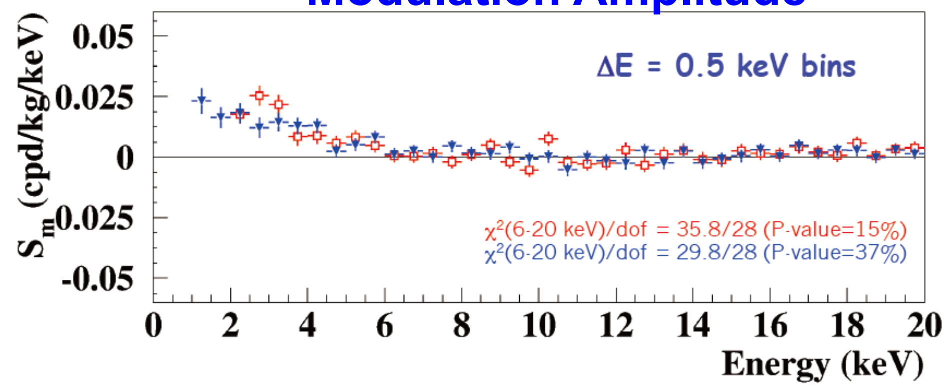
Nucl. Phys. At. Energy 19, 307 (2018)



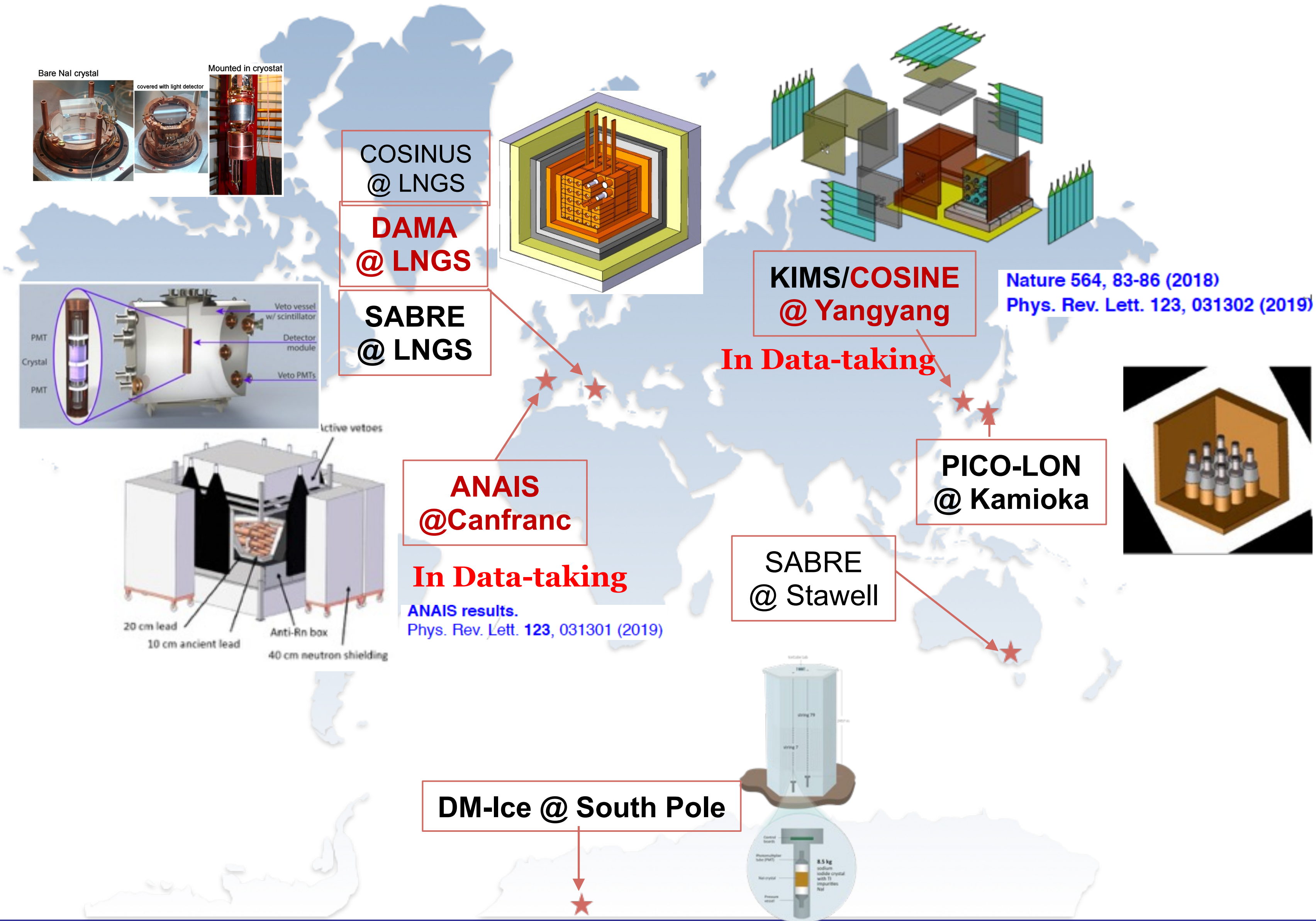
C. Savage *et al.,* JCAP 04 (2009) 010



Modulation Amplitude

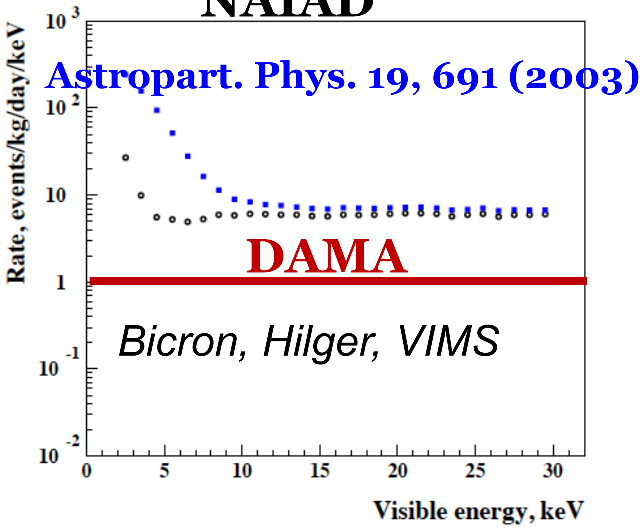


Global NaI(Tl) efforts

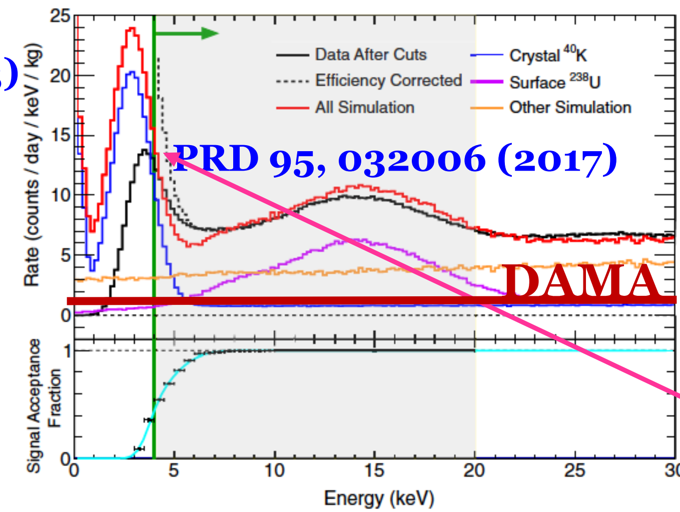


Why it is so hard to reproduce DAMA?

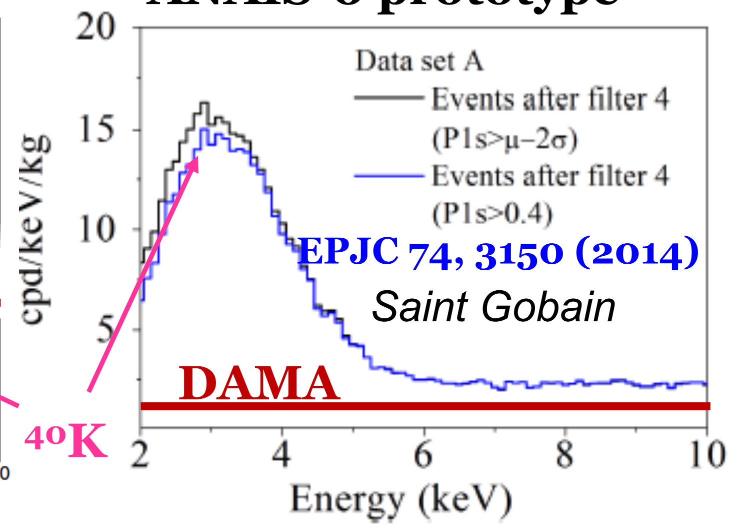
NAIAD



DM-Ice



ANAIS-0 prototype

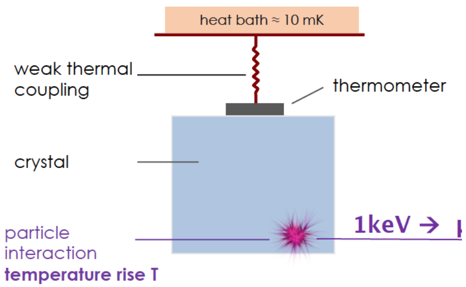


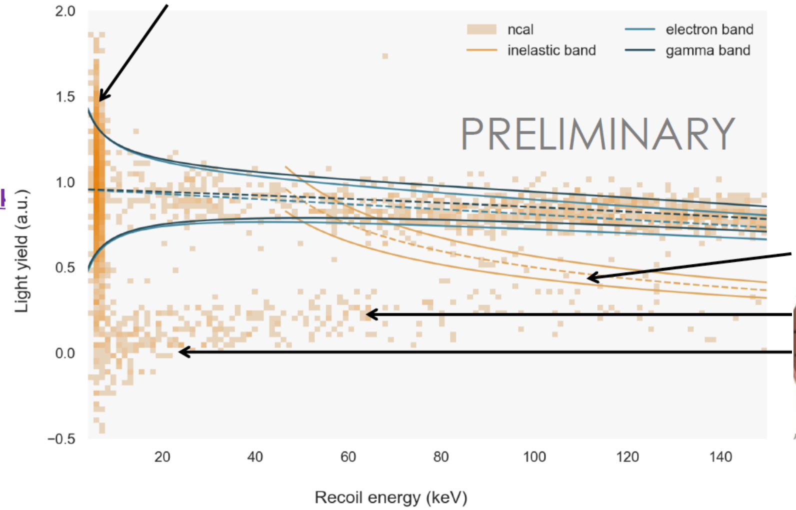
DAMA/LIBRA ~ 1 counts/kg/keV/day (=1 dru)

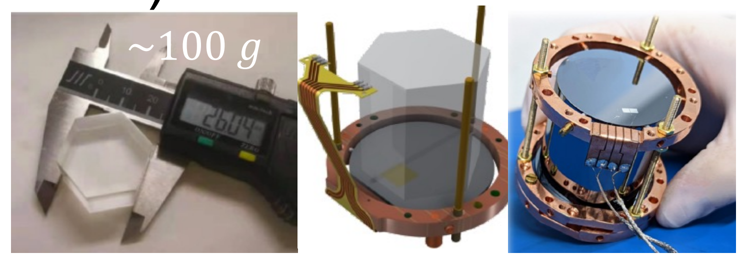
- No other experiments achieve the low-background rate of NaI(Tl)
- Saint-Gobain lost the technique for low-background NaI(Tl) crystals
  - Confidential contraction between DAMA and Saint-Gobain was finished already

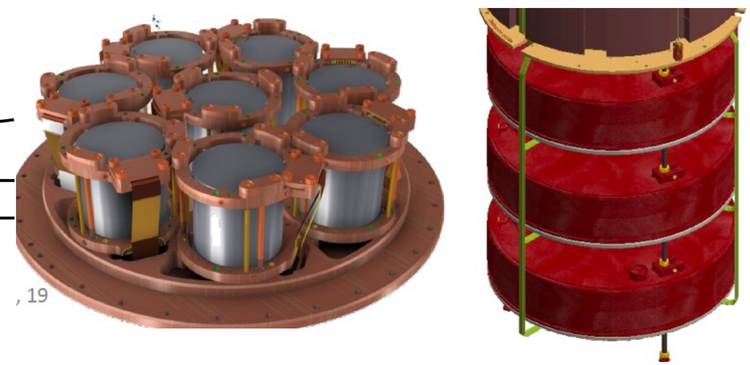
COSINUS

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







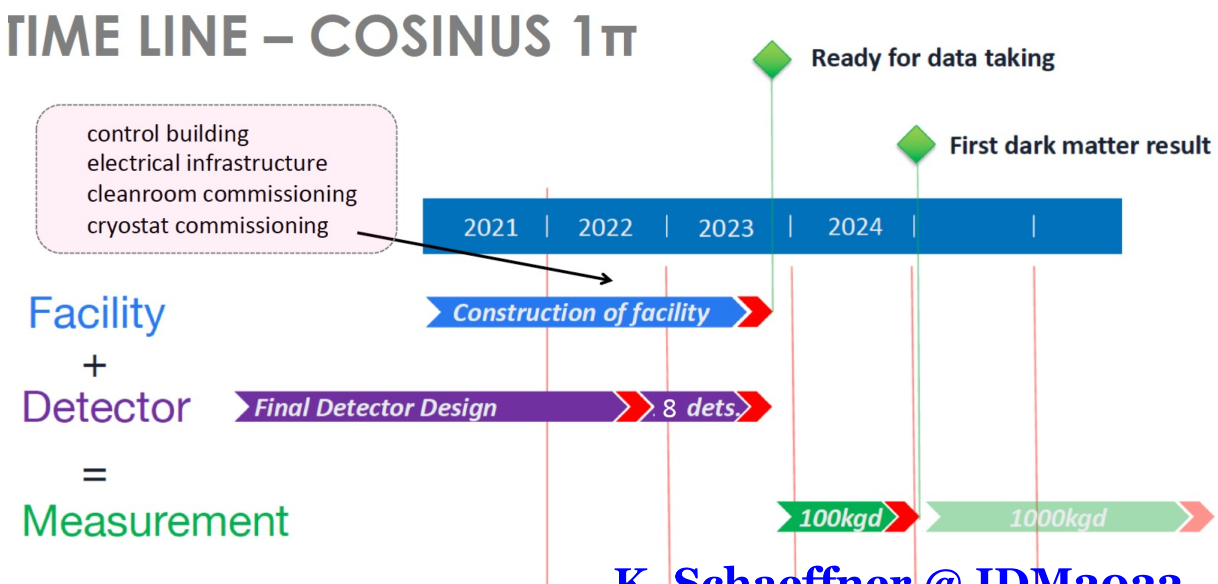


3x8 detector

- Crystal from SCICCAS, china
- COSINUS in LNGS was approved in 2021
- Detector installation at LNGS was started
- Plan to start physics operation by end of 2023

K. Schaeffner @ IDM2022

COSINUS @ LNGS



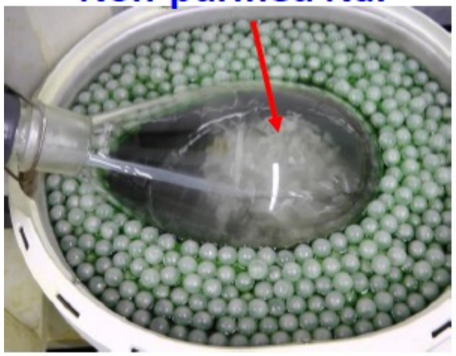
K. Schaeffner @ IDM2022

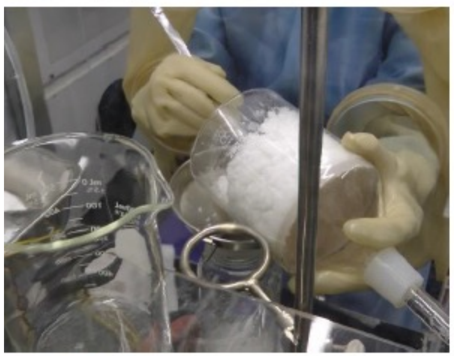
PICO-LON

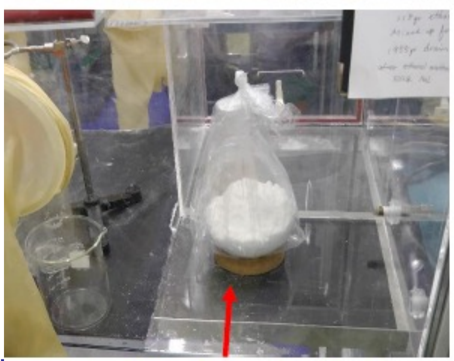
- Development of low-background NaI(Tl) crystals in Japan

A. Kozlov @ VCI 2019

Non-purified NaI





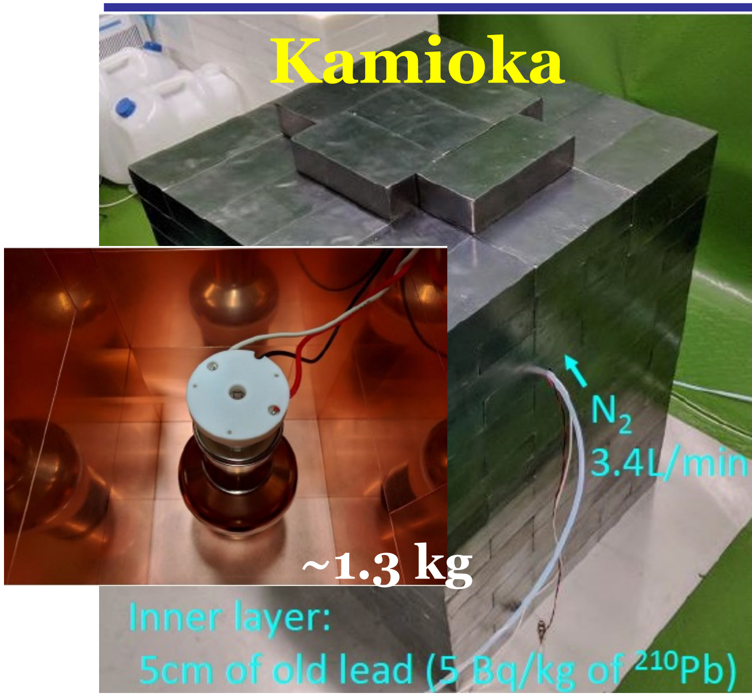


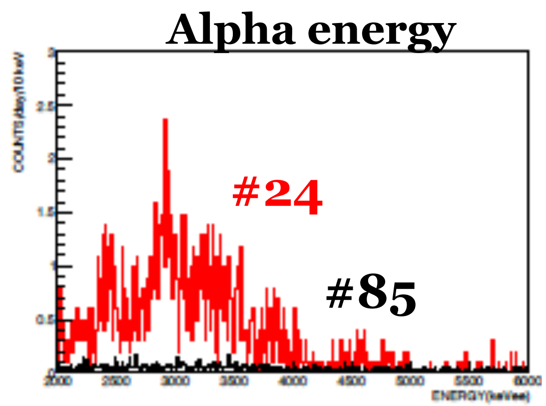
Purified NaI·$2H_2O$

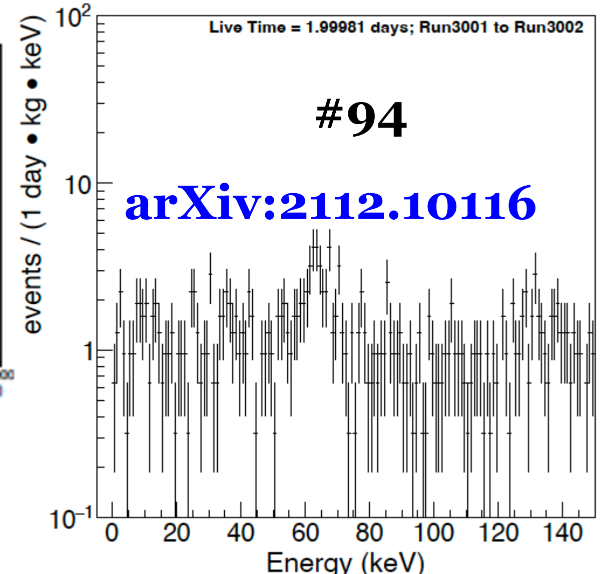
Machine cutting

PICO-LON : Background

K. Fushimi @ TAUP2021

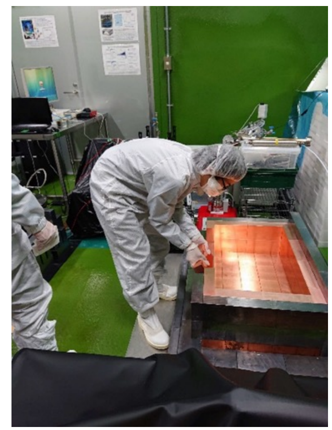


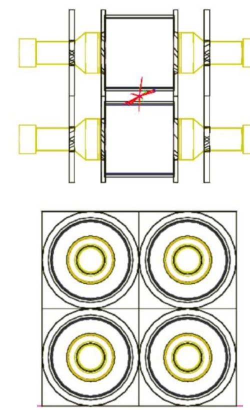




	Ingot26 (2015)	Ingot71 (2018)	Ingot73 (2018)	Ingot85 (2020)	Ingot94 (2021)	Goal
Crystal size	3” φ×3”	3” φ×3”	3” φ×3”	3” φ×3”	3” φ×3”	5” φ×5”
^{nat}K (ppb)	2630	<20	<30	<20	<20	<20
^{232}Th (ppt)	0.4±0.5	1.7±0.2	1.8±0.2	0.3±0.5	<6	<4
^{238}U (ppt)	4.7±0.3	9.7±0.8	9.4±0.8	1.0±0.4	2	<10
^{210}Pb (μBq/kg)	29.4±6.6	1500	1300	<5.7	<5	<10
Purification methods	Pb resin + Cation exchange resin	Re-crystallization×2	Re-crystallization× 3	Re-crystallization×2 + Resins	Re-crystallization×2 + Resins	-

Plan





2021~2022 Construction of large volume NaI(Tl).
Test experiment starts from 2022.

SABRE

Dual site experiment:

A. Mariani @ IDM2022

- **SABRE North** at **Laboratori Nazionali del Gran Sasso** (LNGS), in Italy;
- **SABRE South** at **Stawell Underground Physics Laboratory** (SUPL), in Australia

INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

STAWELL UNDERGROUND PHYSICS LAB

Several industrial partners involved:

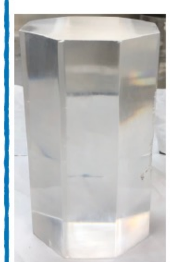
- **ultra-high purity NaI powder (Astro Grade)** with ^{nat}K levels consistently lower than 10 ppb and 1 ppt upper limit on U/Th content, in collaboration with **Sigma Aldrich**, now Merck;
- **clean growth procedure** using the vertical Bridgman-Stockbarger technique, where the powder is placed inside a sealed ampoule, in collaboration with **Radiation Monitoring Devices, Inc. (RMD)**.

NaI-31
before cut and polishing

Final mass: ~3 kg

^{nat}K content (ICP-MS): 17.7 ± 1.1 ppb

NaI-33
after cut and polishing



Final mass: ~3.4 kg

^{nat}K content (ICP-MS): 4.6 ± 0.2 ppb

lowest potassium level ever achieved

Already characterized @LNGS

NaI-35
encapsulated

Final mass: ~4.4 kg

SABRE South crystal

In measurement @LNGS

NaI-37
after cut and polishing

Final mass: ~4.5 kg

^{nat}K content (ICP-MS): 7.8 ± 0.5 ppb

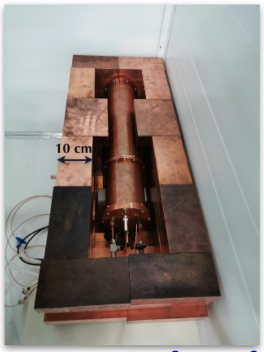
PRELIMINARY

To be characterized @LNGS in the next few months

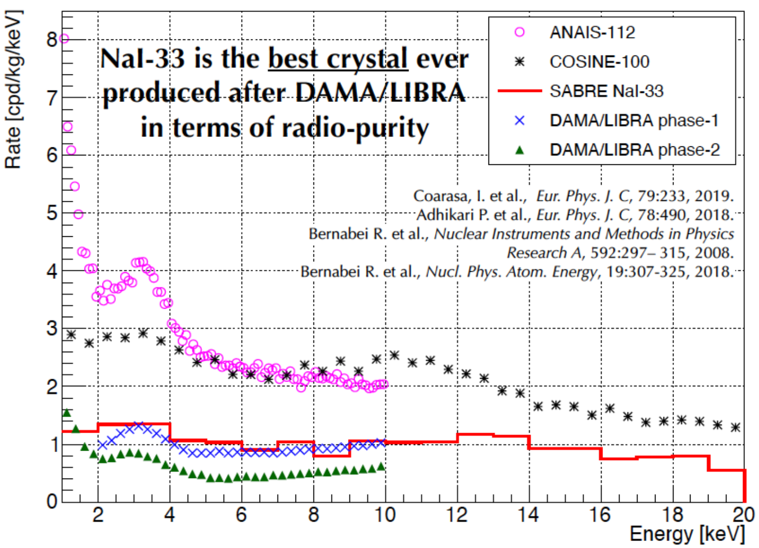
SABRE

SABRE PoP-dry

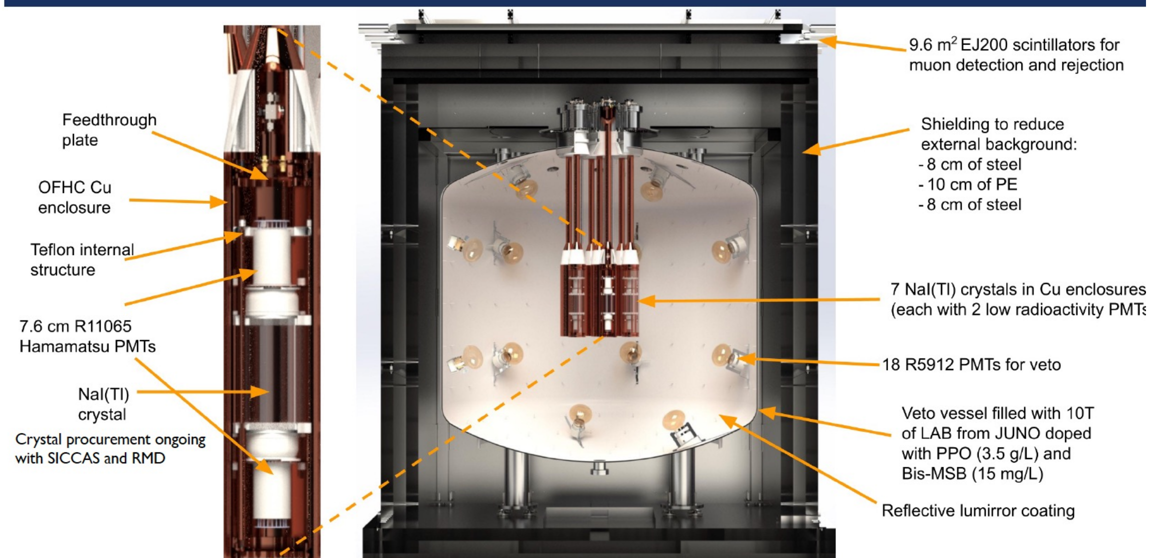
- Commissioned in March 2021, took data @LNGS until June 2022.
- The **goal** was to measure the background level in the ROI <u>without</u> an active veto.



A. Mariani @ IDM2022



SABRE SOUTH



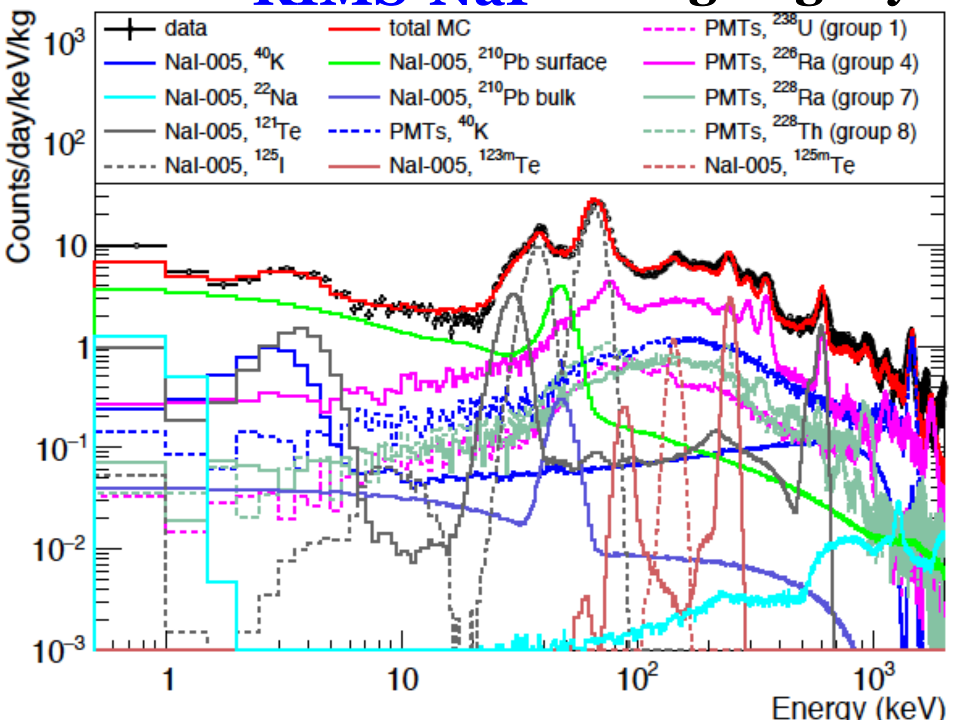
M.J. Zurowski@IDM2022

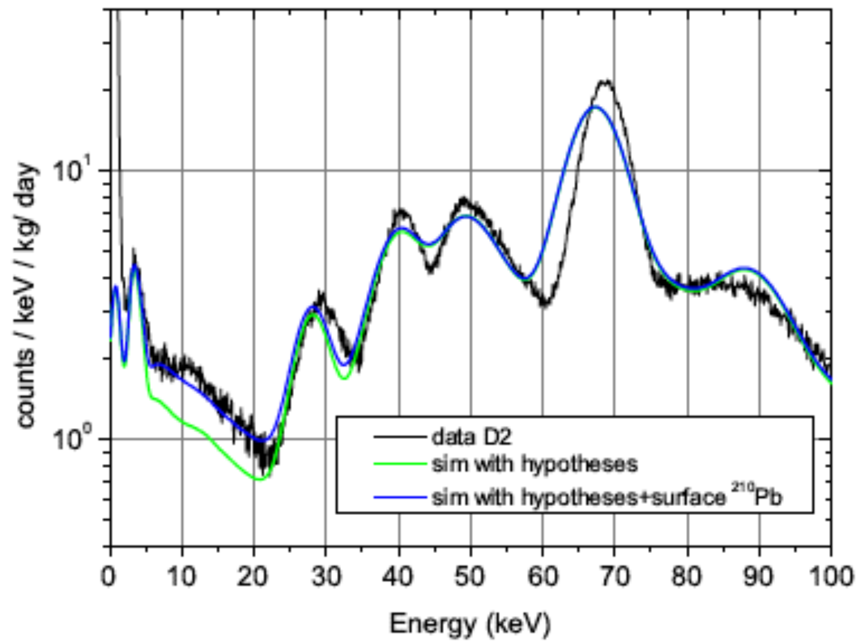
- Commissioning until 2023
- Plan to start data taking at late 2023

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 103, 851 (2017)

NIMA, 742, 197 (2014)

JCAP 1502, 046 (2015)

EPJC 76, 429 (2016)

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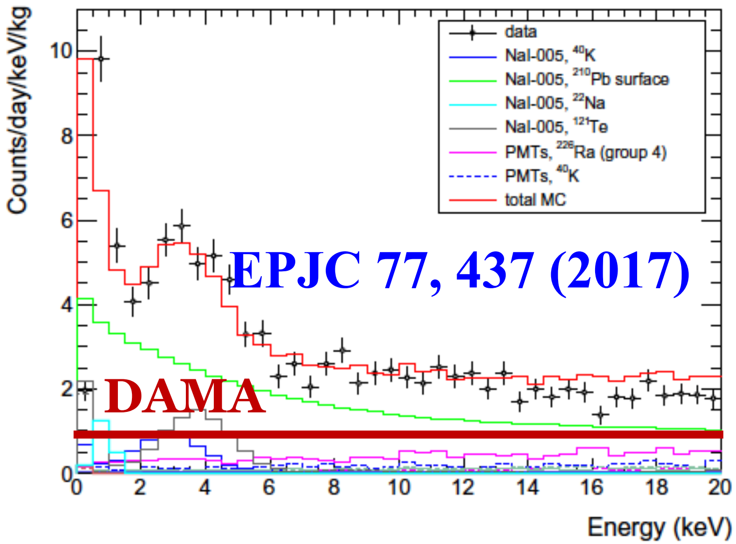
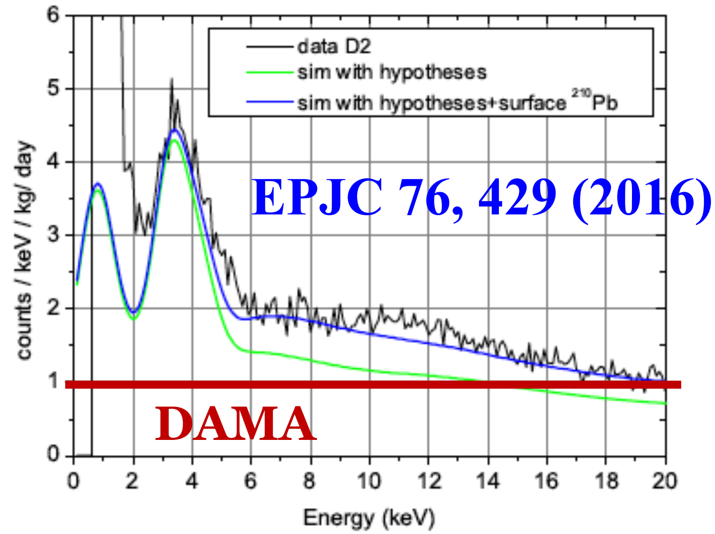


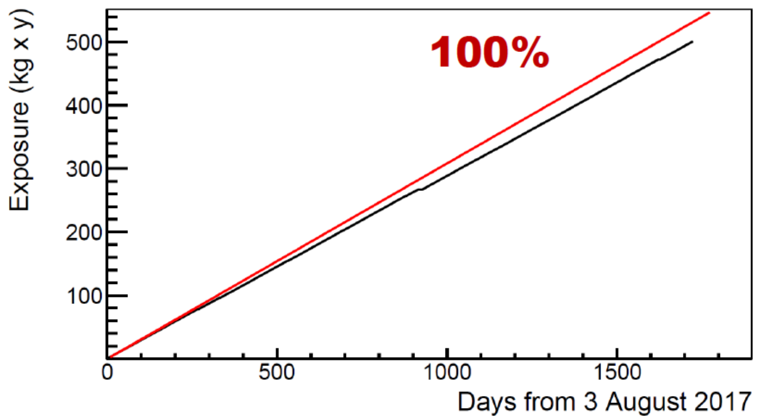


→ **COSINE-100** → **ANAIS-112**

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)

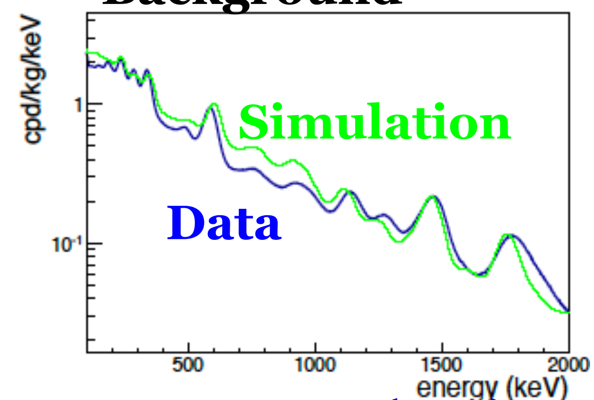
ANAIS-112 (Since Aug/2017)



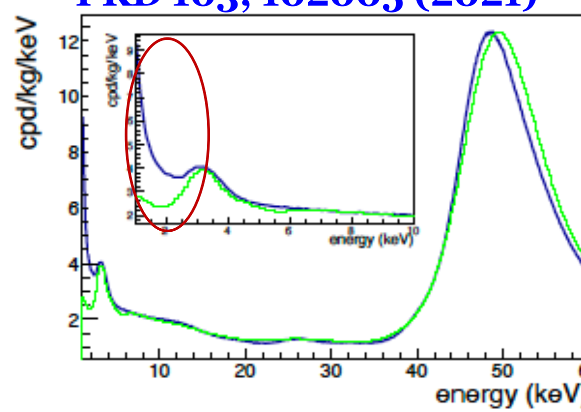
524.44 kg x y @ June 7, 2022

M.L. Sarsa @ IDM2022

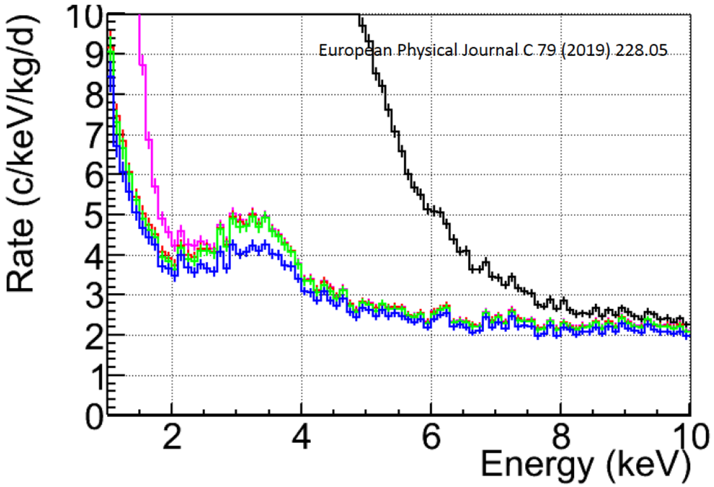
Background



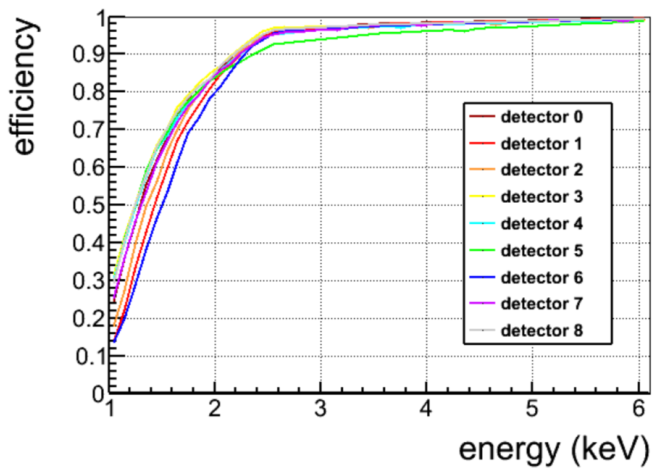
PRD 103, 102005 (2021)



Cut- based event selection



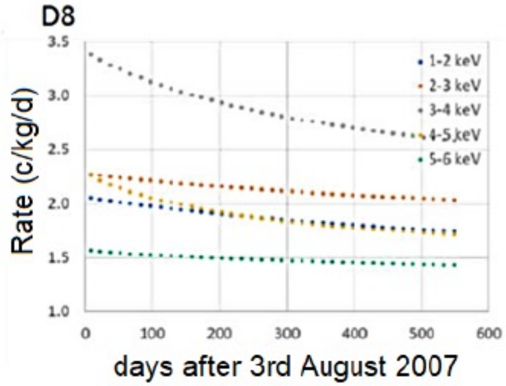
Efficiency



ANAIS-112 (3 years result)

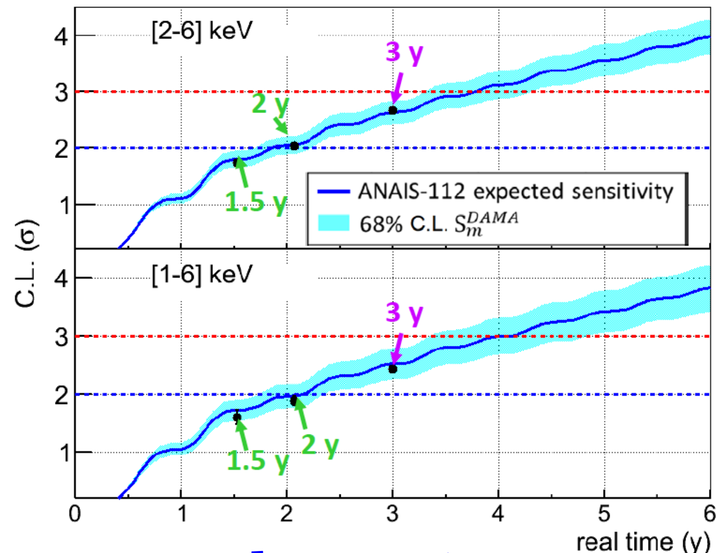
313 kg year data

Time dependent background modeling based on cosmogenic understanding



Unmatched background (PMT noise?) may be assumed constant (Eq5, 6)

Expected sensitivity



3 years data ~ 2.6 σ away from DAMA/LIBRA

Eq.4 $R(t) = R_0 + R_1 \exp(-t/\tau) + \boldsymbol{S_m} \cos(\omega(t+\phi))$ [3 nuisance par: R_0, R_1, τ]

Eq.5 $R(t) = R_0 + R_1 PDF_{bkg} + \boldsymbol{S_m} \cos(\omega(t+\phi))$ [2 nuisance par: R_0, R_1]

Eq.6 $R^i(t) = R_0^i + R_1^i PDF_{bkg}^i + \boldsymbol{S_m} \cos(\omega(t+\phi))$ [18 nuisance par: R_0^i, R_1^i]

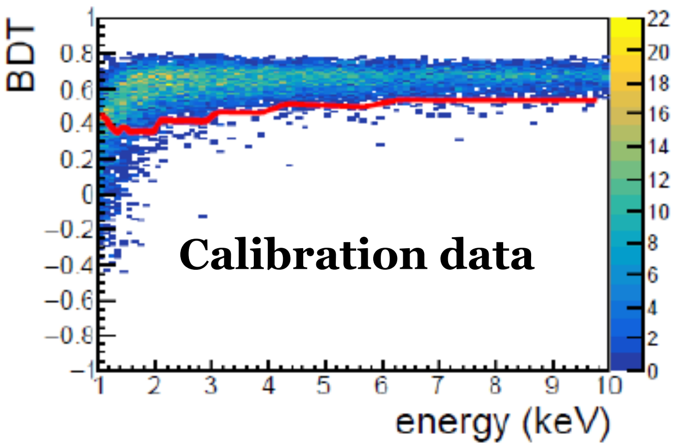
Energy region	Model	χ^2/NDF null hyp	nuisance params	S_m cpd/kg/keV	p-value mod	p-value null
[1-6] keV	eq. 4	132 / 107	3	-0.0045±0.0044	0.051	0.051
	eq. 5	143.1 / 108	2	-0.0036±0.0044	0.012	0.013
	eq. 6	1076 / 972	18	-0.0034±0.0042	0.011	0.011
[2-6] keV	eq. 4	115.7 / 107	3	-0.0008±0.0039	0.25	0.27
	eq. 5	120.8 / 108	2	0.0004±0.0039	0.17	0.19
	eq. 6	1018 / 972	18	0.0003±0.0037	0.14	0.15

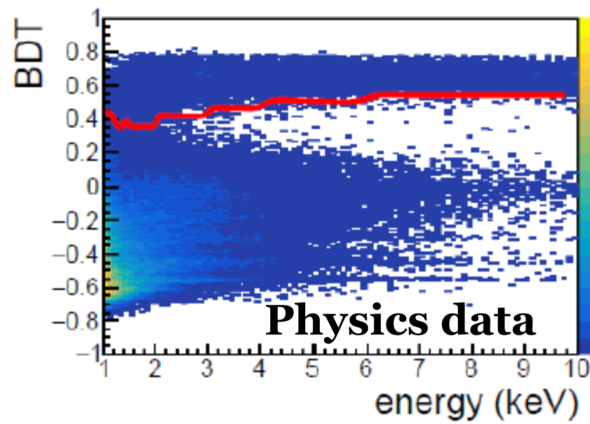
PRD 103, 102005 (2021)

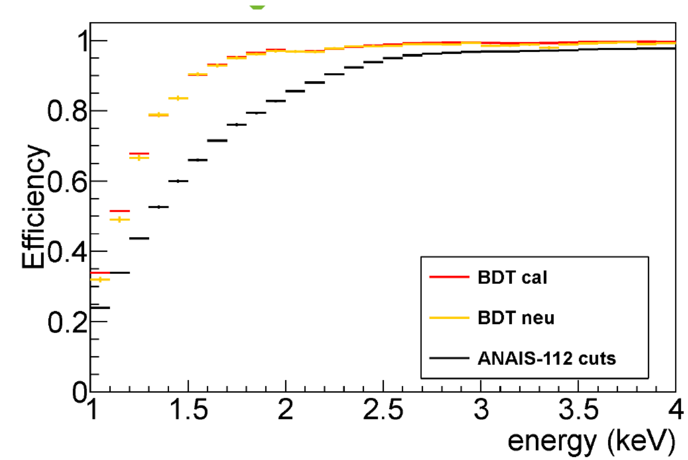
ANAIS-112 (3 years data revisiting)

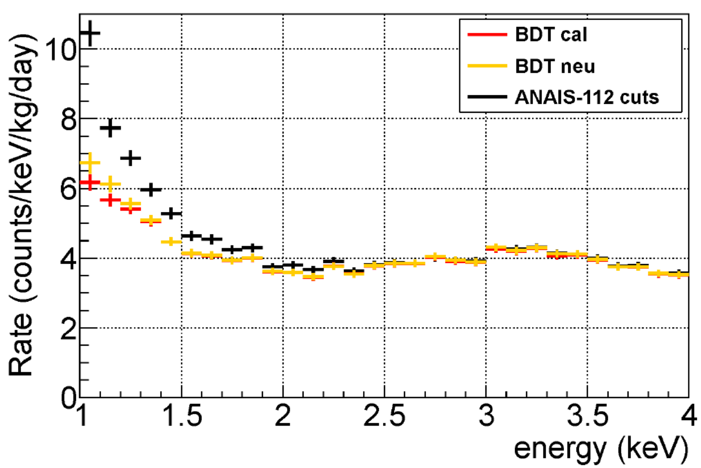
Boosted Decision Tree (BDT)-based machine learning

M.L. Sarsa @ IDM2022

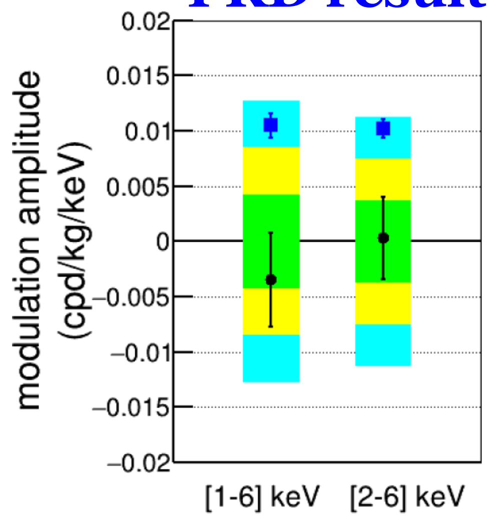




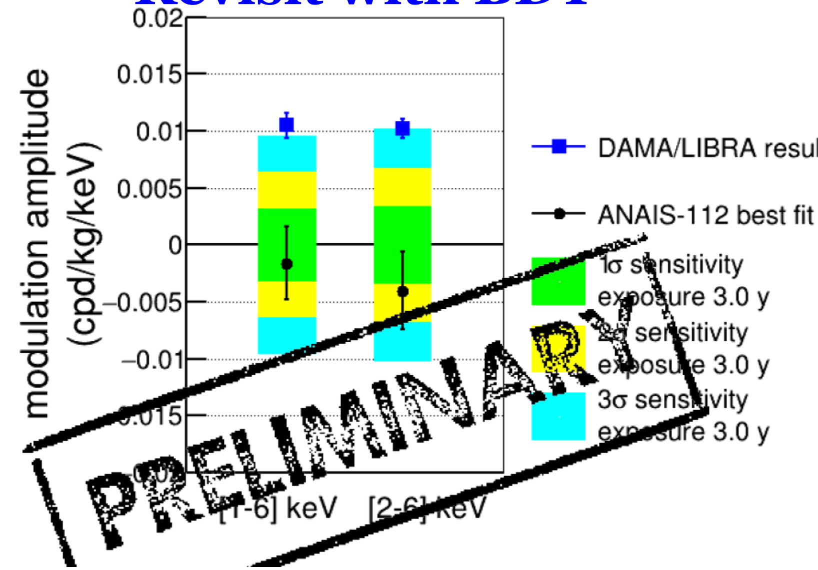




PRD result



Revisit with BDT



Incompatible with DAMA at 3.8σ (4.2σ) in 1-6 (2-6) keV region

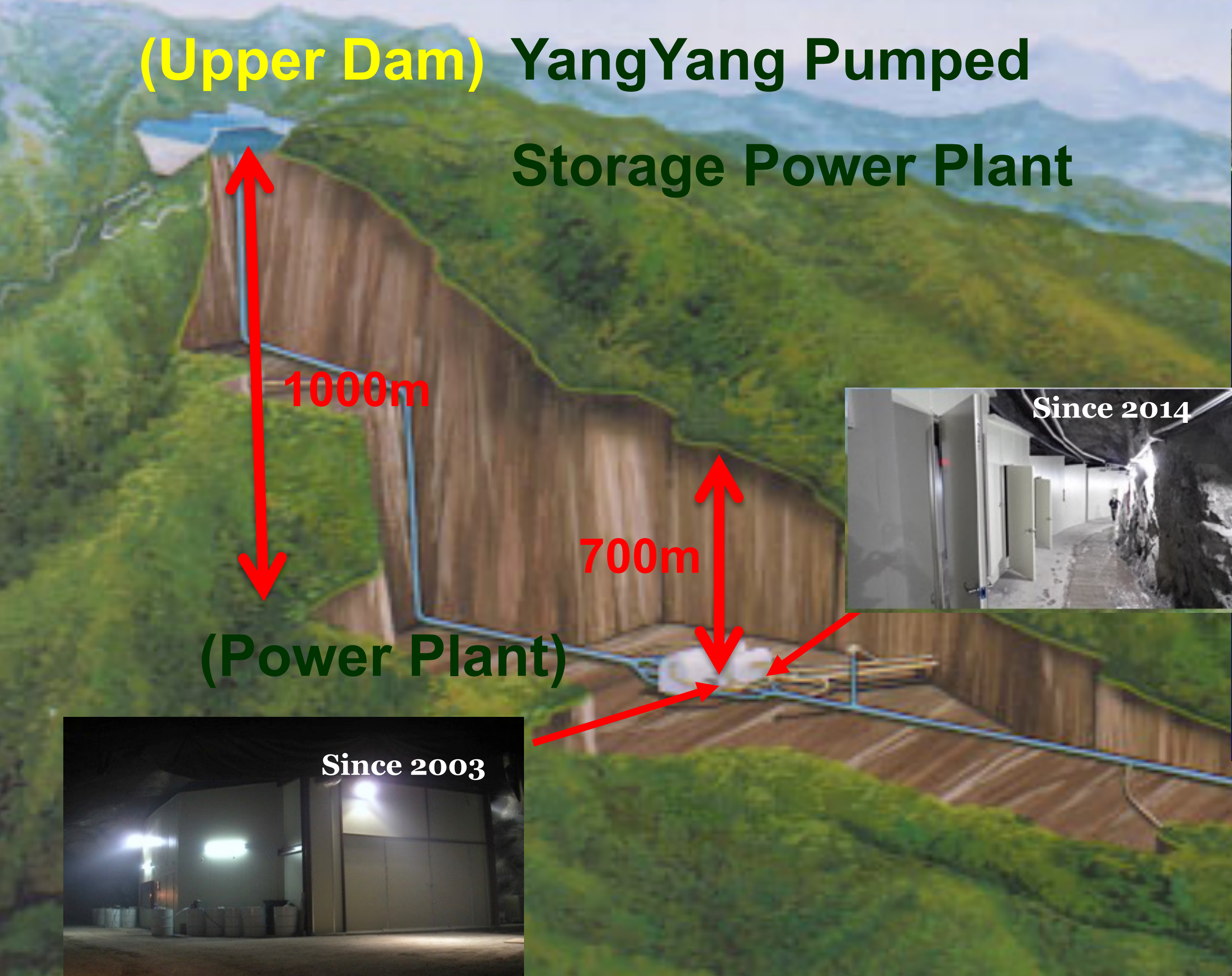
COSINE-100 collaboration

5 countries

14 institutes
~50 members

KIMS + DM-ICE = COSINE

YangYang(Y2L) Underground Laboratory



KIMS/COSINE (Dark Matter Search)

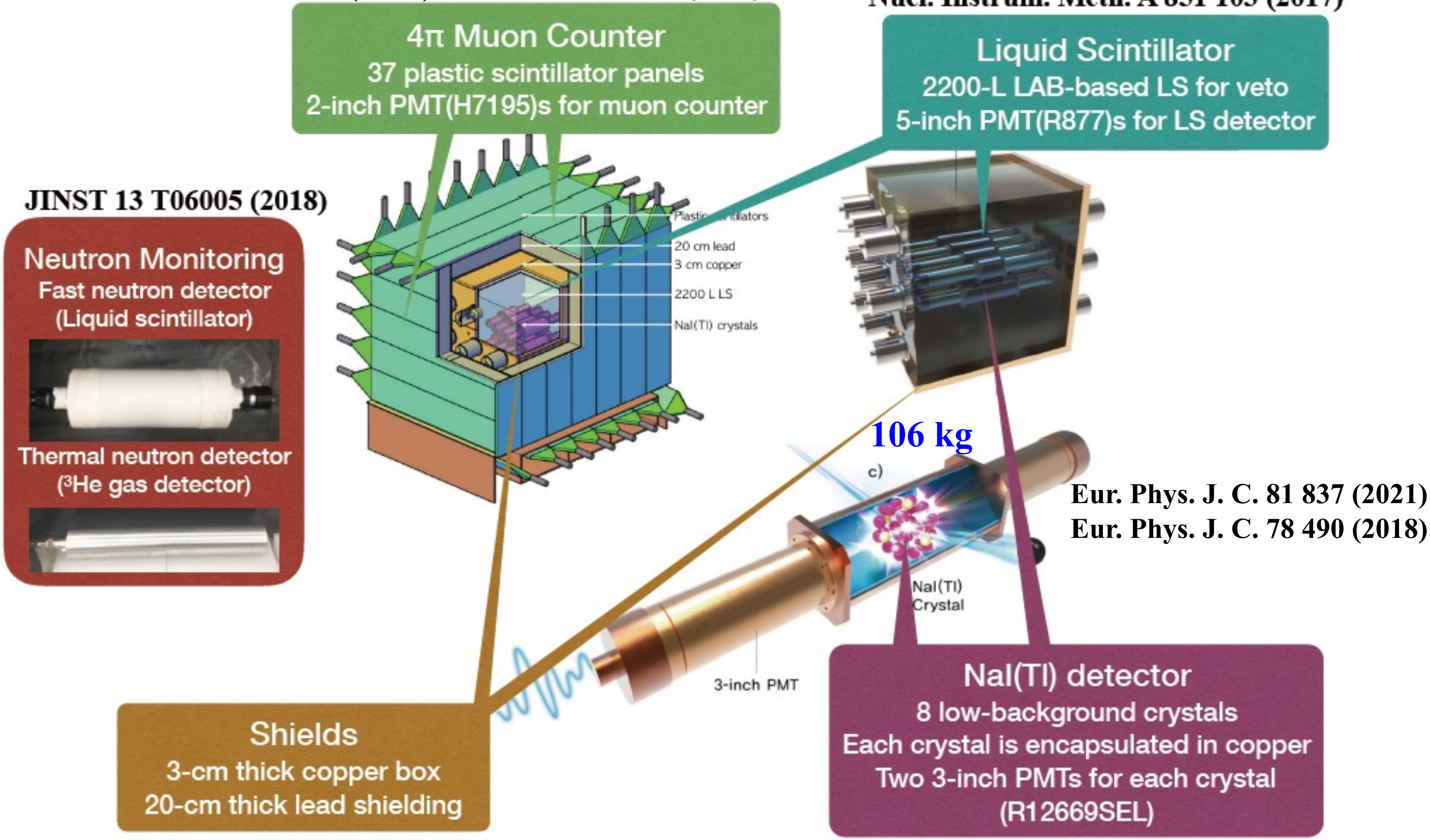
AMoRE (Double Beta Decay Experiment)

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

COSINE-100 detector configuration

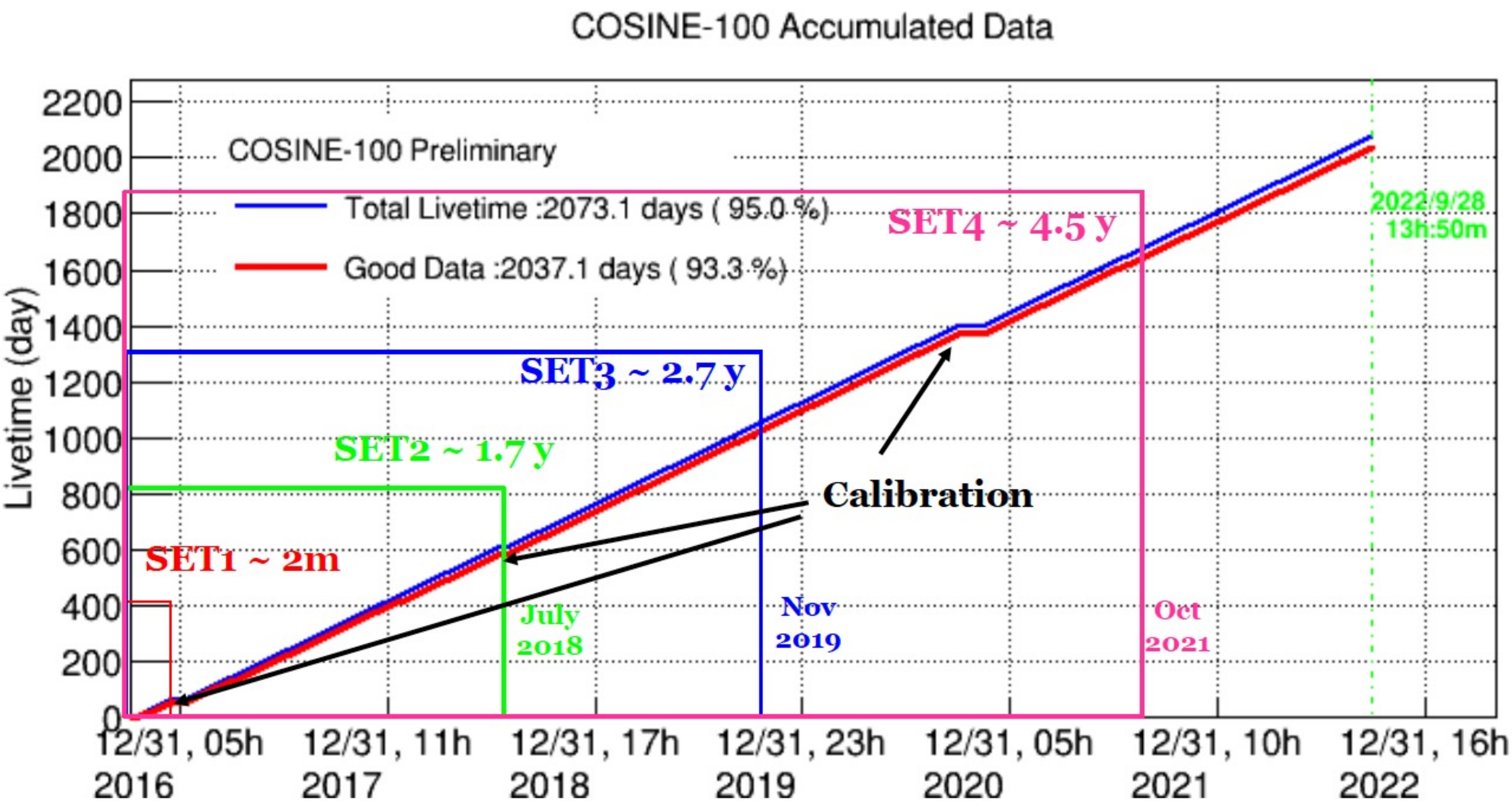
JCAP 02 013 (2021) JINST 13 T02007 (2018)

Nucl. Instrum. Meth. A 1006 165431 (2021)
Nucl. Instrum. Meth. A 851 103 (2017)



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

COSINE-100 data exposure

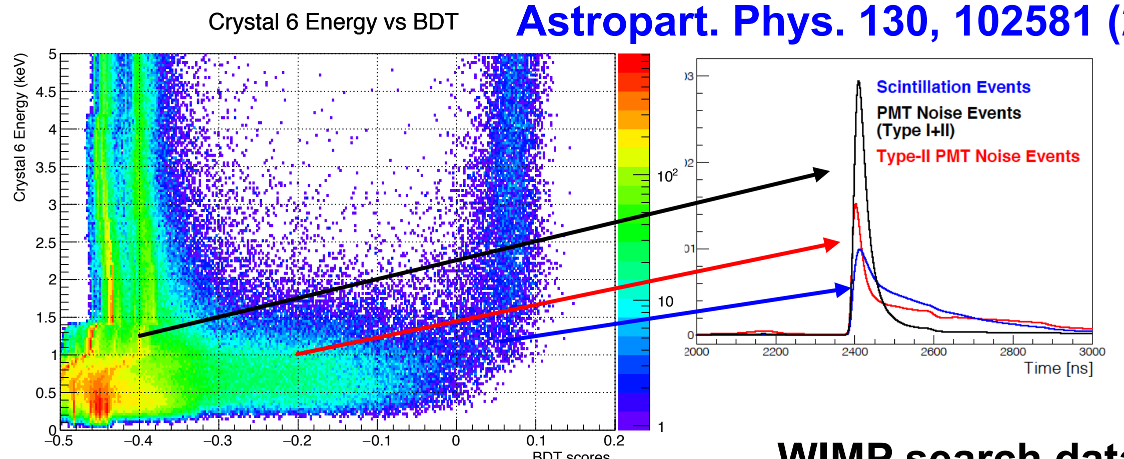


- **Stable operation Since Sep. 2016 for about 6 years**
  - **~95 % physics data**
  - **~93 % good quality data (~5.6 years data)**

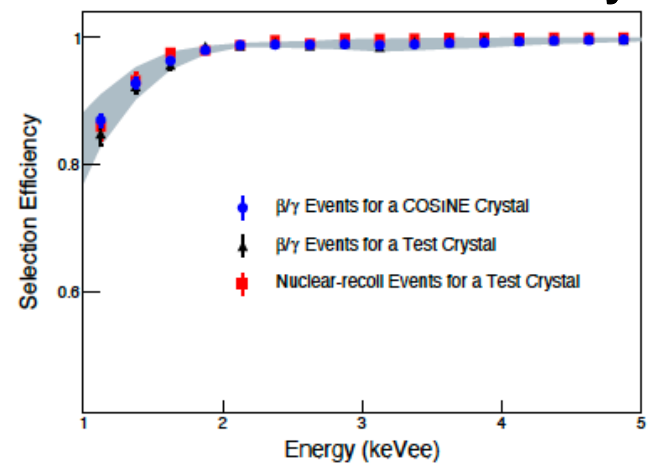
Event selection

- Two-fold trigger can reach to 0.15 keV trigger threshold
- PMT-induced noise significantly contribute for <2 keV
- Improved BDT applied to reduce analysis threshold to 1 keV
  - ❖ Event shape-based likelihood parameters

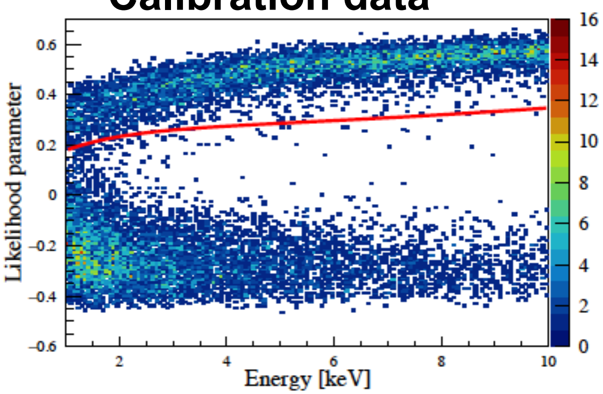
Astropart. Phys. 130, 102581 (2021)



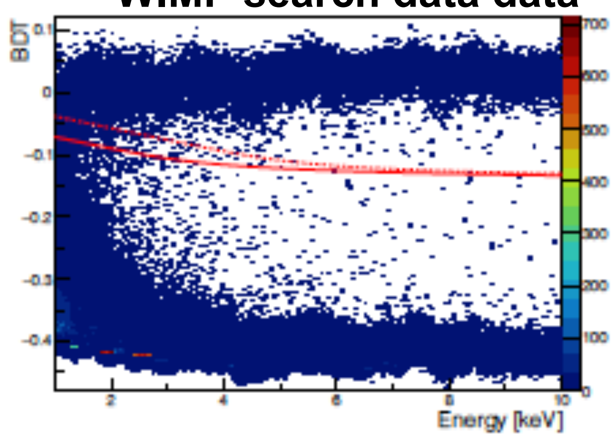
Event selection efficiency



Calibration data



WIMP search data data



85% efficiency @ 1-1.25 keV

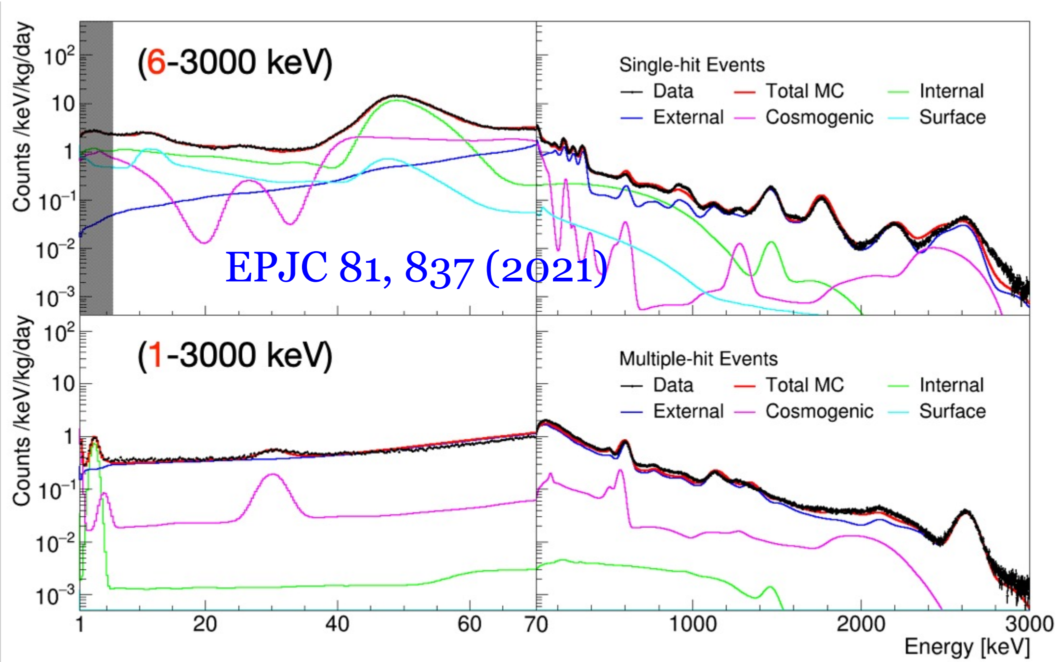
DAMA/LIBRA ~ 70%

ANAIS (BDT) ~ 35-55%

DM searches with energy spectra

Background modeling

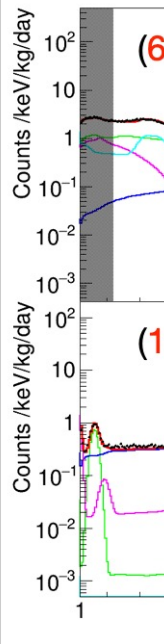
1.7 years data

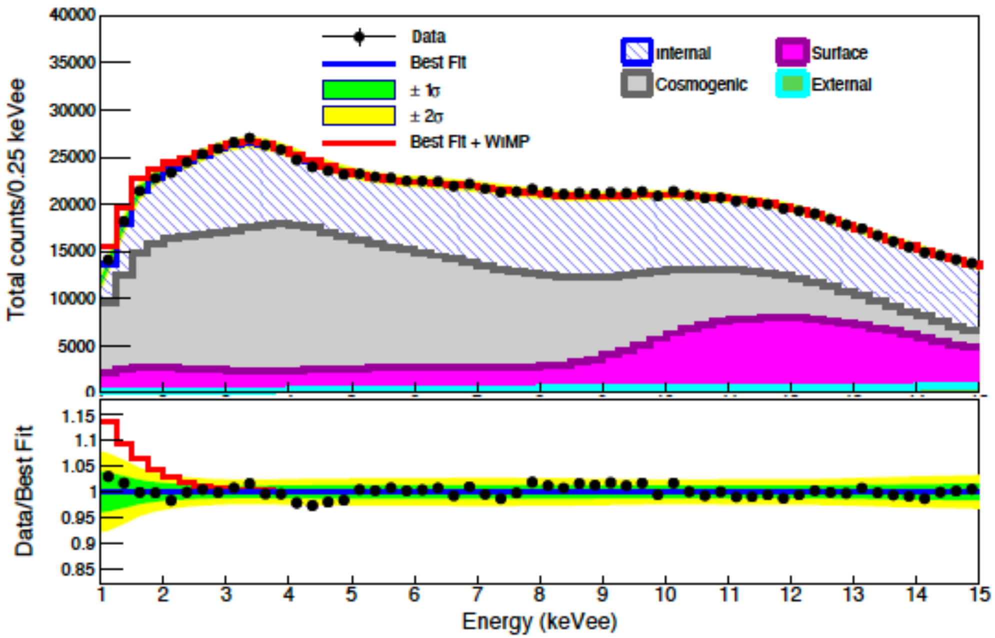


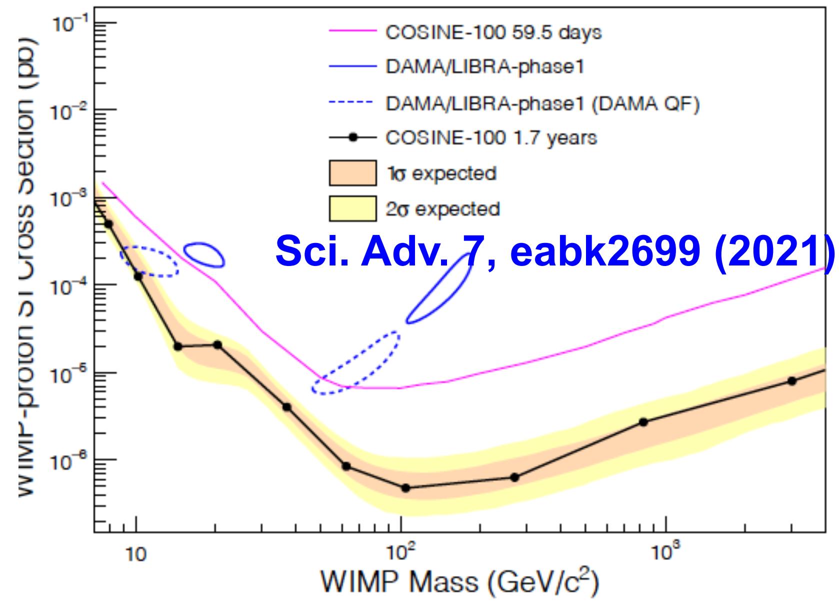
DM searches with energy spectra

Background modeling

1.7 years data





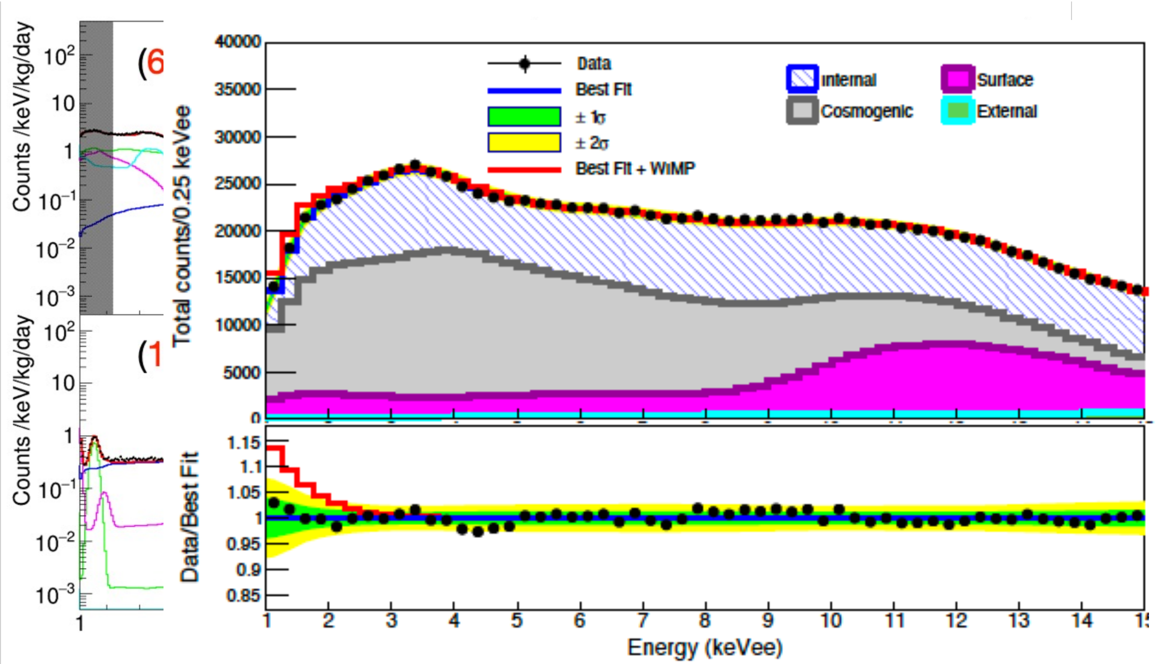


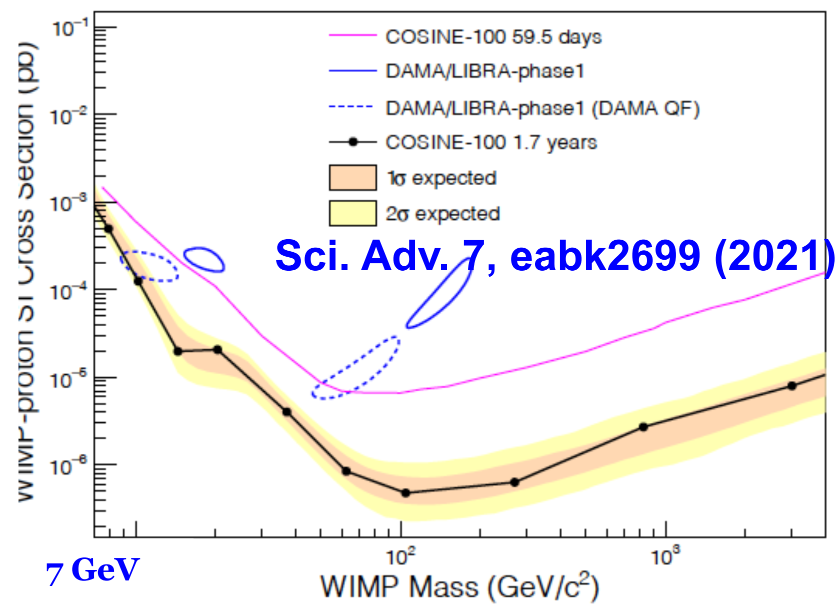
Sci. Adv. 7, eabk2699 (2021)

DM searches with energy spectra

Background modeling

1.7 years data





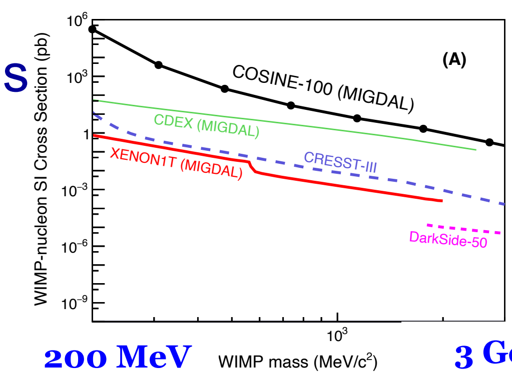
Sci. Adv. 7, eabk2699 (2021)

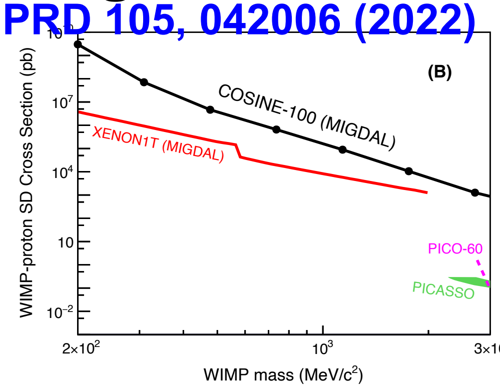
7 GeV

Low-mass search with Migdal effect

PRD 105, 042006 (2022)

- Migdal effect
  - ❖ Nuclear recoil → Boost of electrons → Secondary radiation
  - ❖ Because of nuclear recoil quenching, large visible energy
  - ❖ Sub-GeV DM search

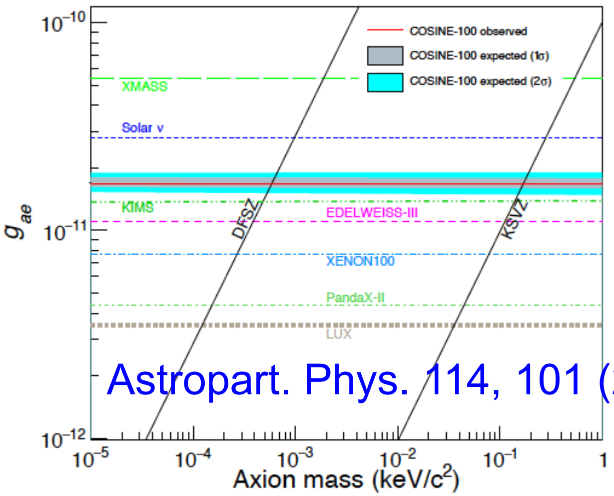




200 MeV 3 GeV

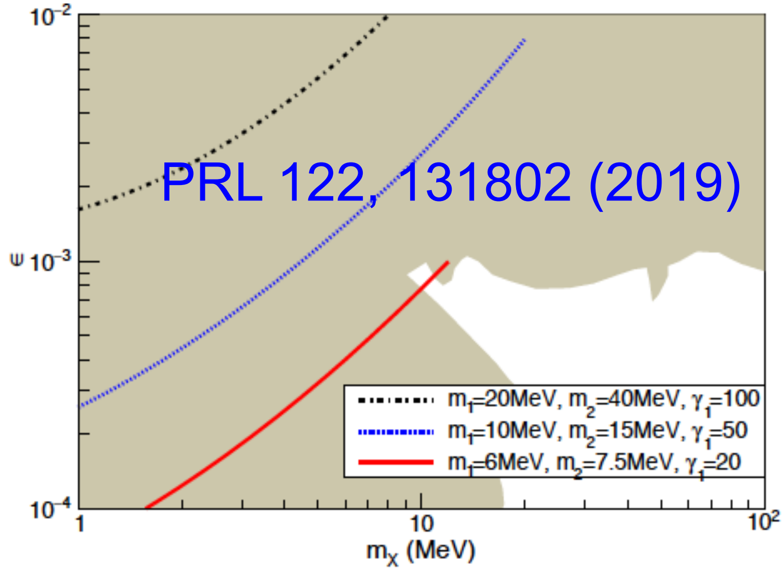
Other searches

Solar Axion



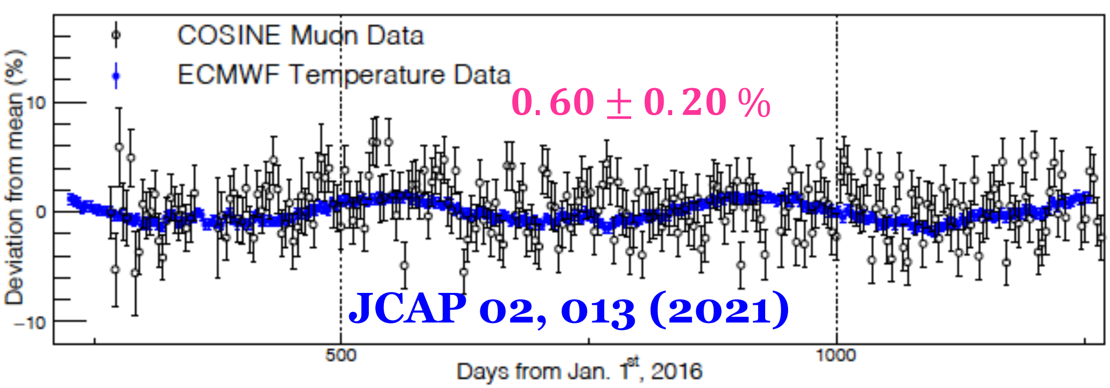
Astropart. Phys. 114, 101 (2020)

Inelastic boosted dark matter



PRL 122, 131802 (2019)

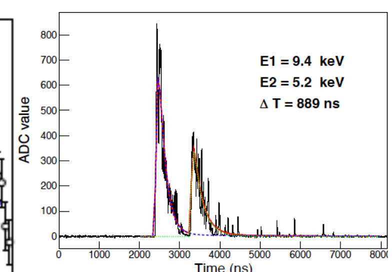
Annual modulation of muon rate

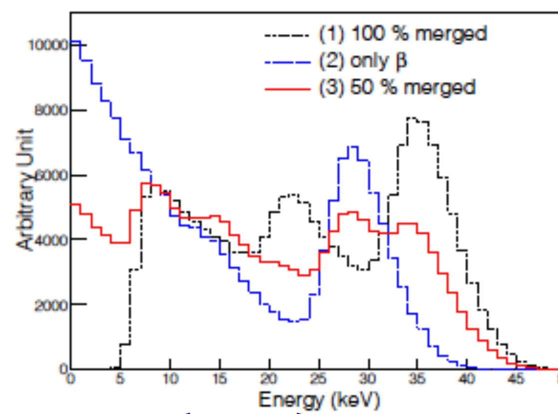


$0.60 \pm 0.20\ \%$

JCAP 02, 013 (2021)

New isomers in ^{228}Ac

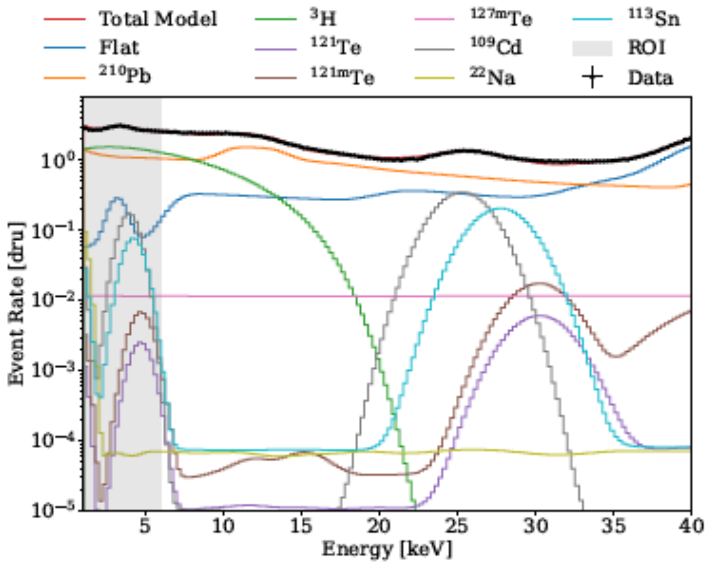




EPJC 81, 746 (2021)

Annual modulation (3 years data)

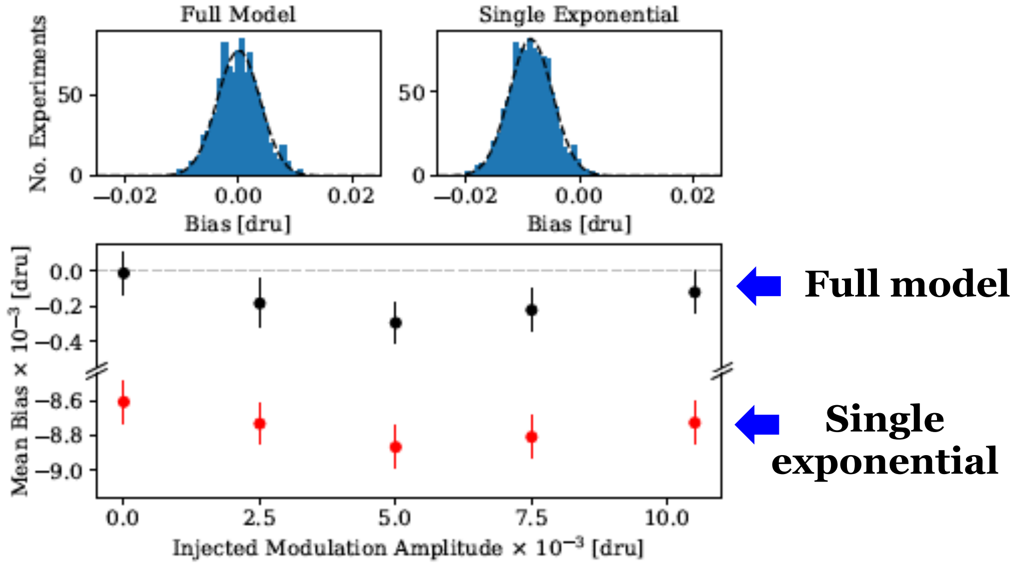
Time dependent background modeling

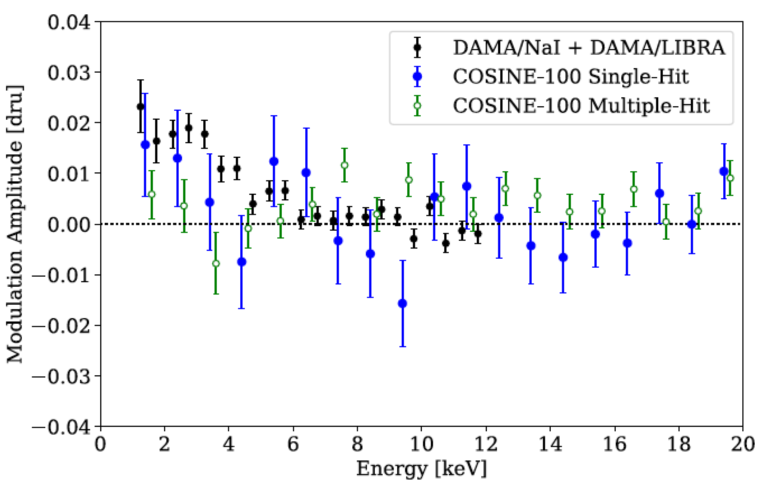


PRD 106, 052005 (2022)

$$R(t) = \sum_i \left[C^i + \sum_j^8 A_j^i e^{-\lambda_j t} \right] + S_m \cos\left(\frac{2\pi(t - t_0)}{T}\right)$$

Pseudo experiment





Precise understanding of the time-dependent backgrounds is crucial for the annual modulation searches

1-6 keV modulation amplitude

COSINE-100	$\mathbf{0.0067 \pm 0.0042}$
DAMA/LIBRA	0.0105 ± 0.0011
ANAIS-112	-0.0034 ± 0.0042

DAMA/LIBRA's method

- Event selection (single parameter)
- No liquid scintillator veto
- No Muon veto
- 600 ns integration window
- Time-dependent background model
  - ❖ Yearly average to obtain residual rate

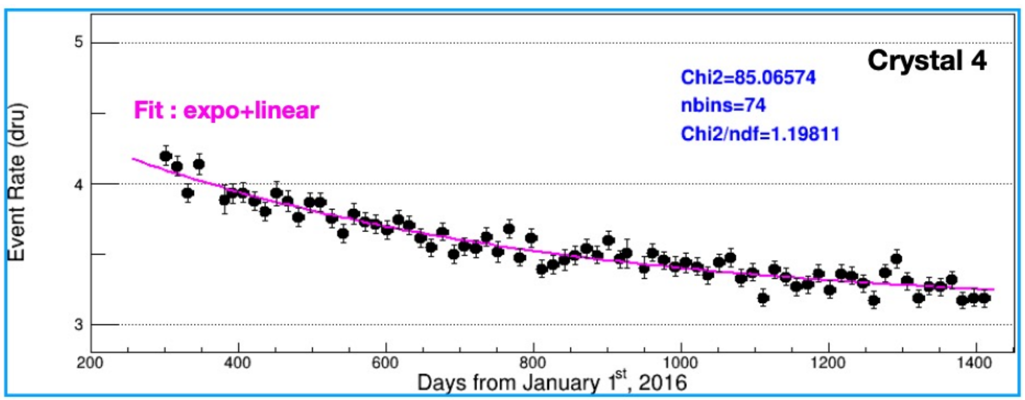
JHEP 20, 137 (2020)

Idea of time-dependent background as an explanation of DAMA signals

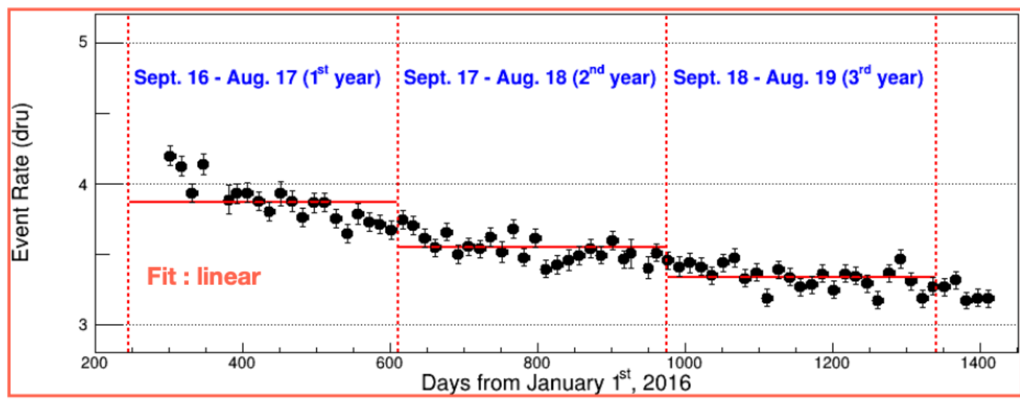
DAMA/LIBRA claimed that there is no time-dependent background in their data

Applying DAMA/LIBRA's method to the COSINE-100 data

Single exponential model (reference)

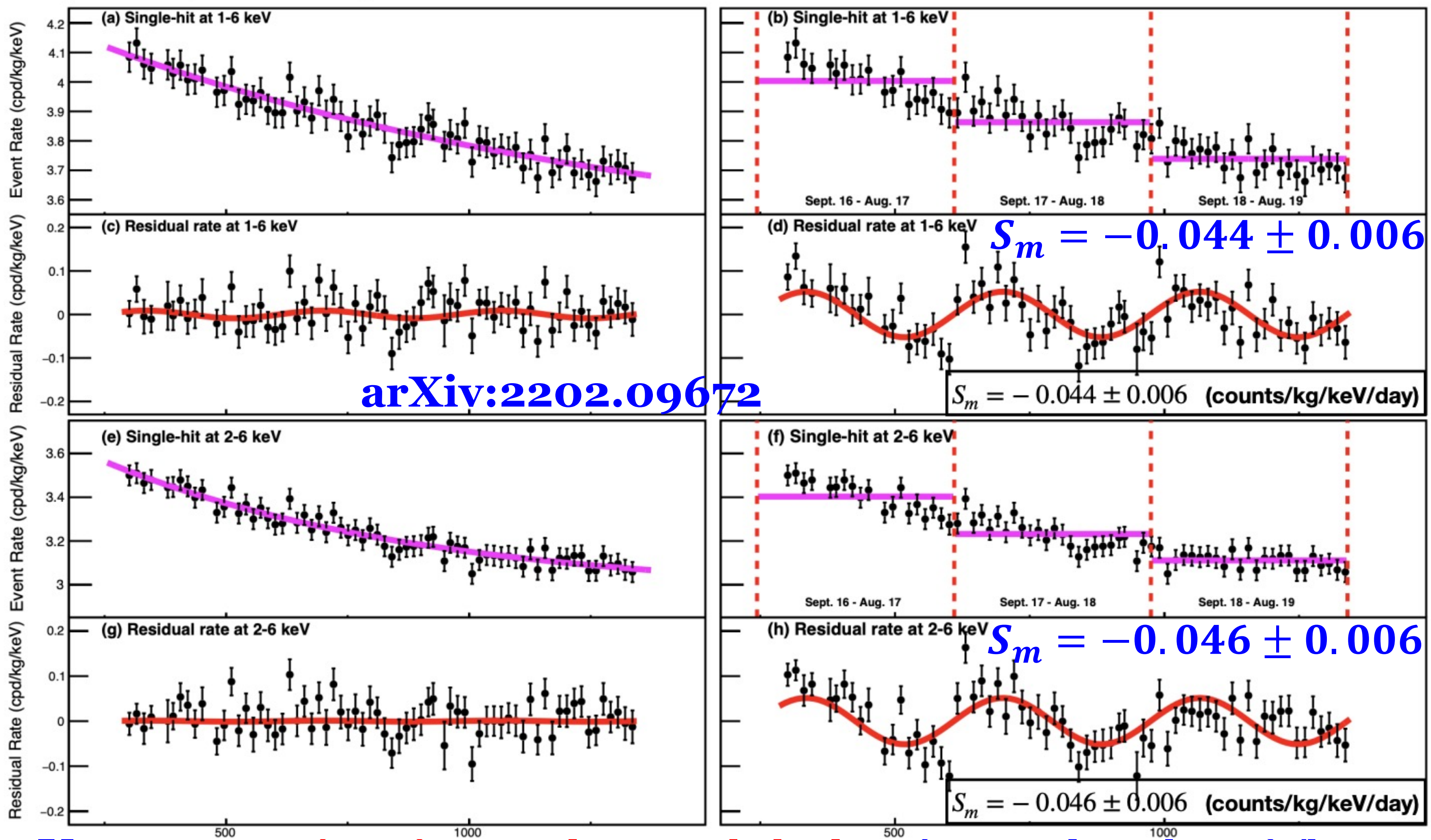


DAMA/LIBRA's method



Results from the COSINE-100 data

Single exponential model (reference) | **DAMA/LIBRA's method**



$S_m = -0.044 \pm 0.006$

arXiv:2202.09672

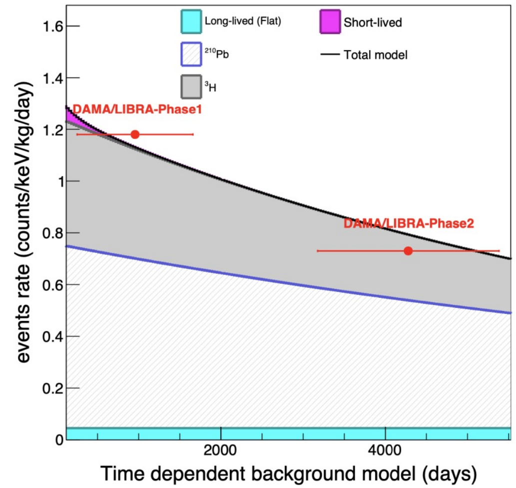
$S_m = -0.046 \pm 0.006$

Very strong (~7σ) negative modulation (opposite phase) from the COSINE-100 data using DAMA/LIBRA's method

Pseudo data for the DAMA/LIBRA

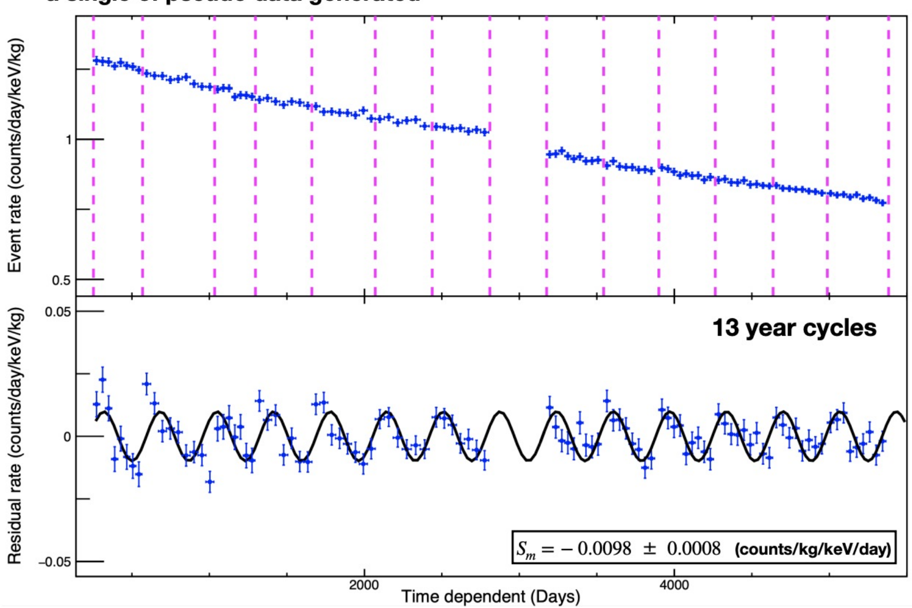
Assuming same background composition between COSINE-100 and DAMA

Component	Scaled at dru	Half life (d)
^{210}Pb	0.687	8140
^{238}U, ^{232}Th, ^{40}K (Long lived)	0.043	>10^{10}
^{3}H	0.474	4494
^{113}Sn	0.055	115.1
^{109}Cd	0.025	462
^{121m}Te	0.004	164.2
^{127m}Te	0.011	106.1
Total	1.3	

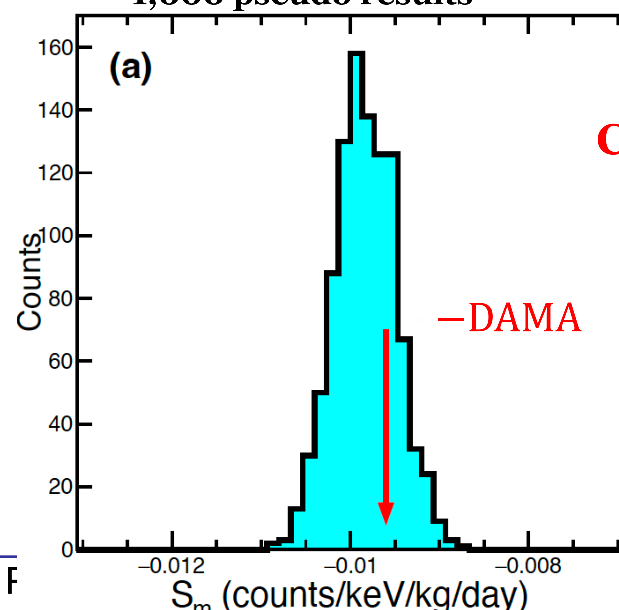


arXiv:2202.09672

a single of pseudo data generated



1,000 pseudo results



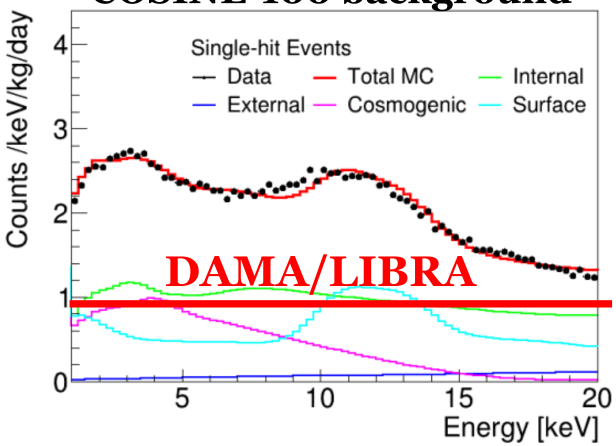
Consistent modulation amplitude

Opposite phase

Low-background NaI(Tl) developments

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

COSINE-100 background



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

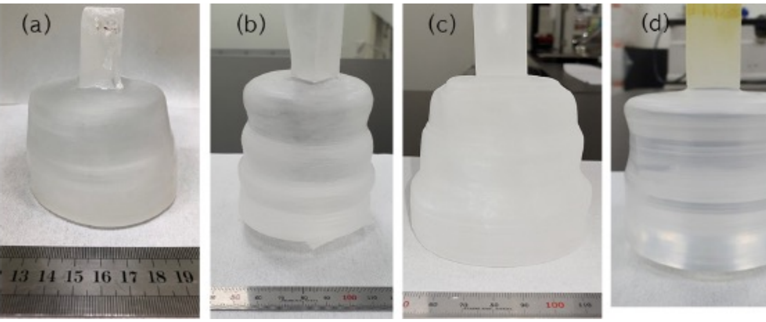

Purification factory ~ 70 kg powder load


Test grower ~ 1kg ingot


Full size grower ~ 100 kg ingot

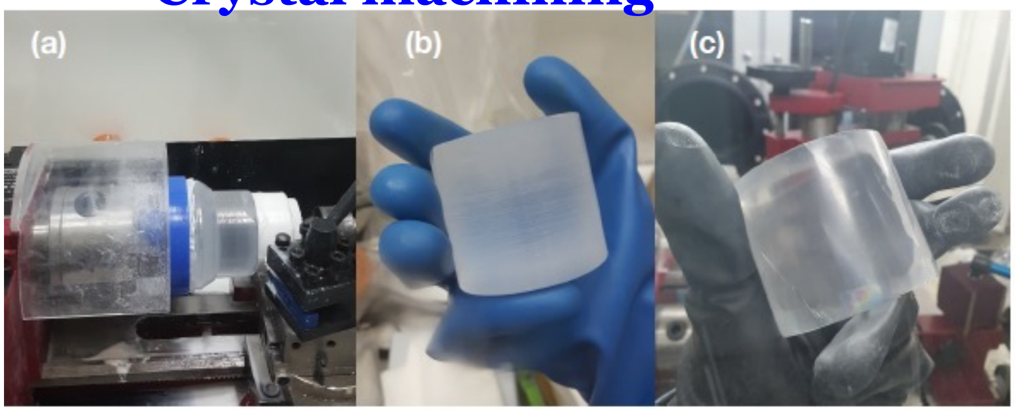
Our grown crystals

Crystal ingots



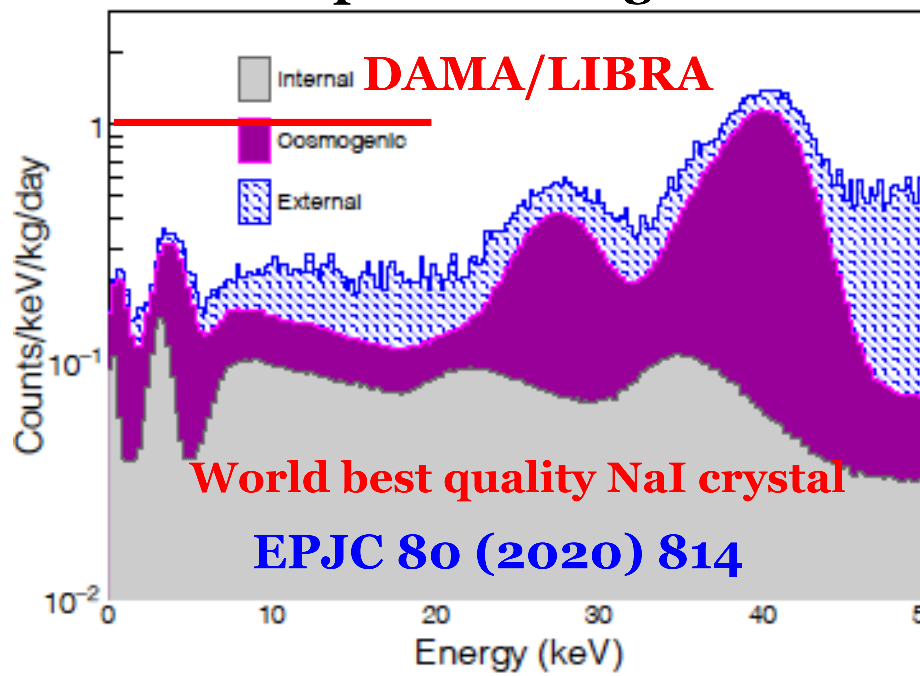
	K (ppb)	^{210}Pb (mBq/kg)	^{238}U (μBq/kg)	^{232}Th(μBq/k
Powder	5	-	<20	<20
Aug/2018	684	3.8+/-0.3	26+/-7	<6
Sept/2019	**8**	**0.01+/-0.02**	**11+/-4**	**7+/-2**
DAMA	<20	0.01~0.03	8.7~124	2~31

Crystal machining



Detector assembly

Expected background

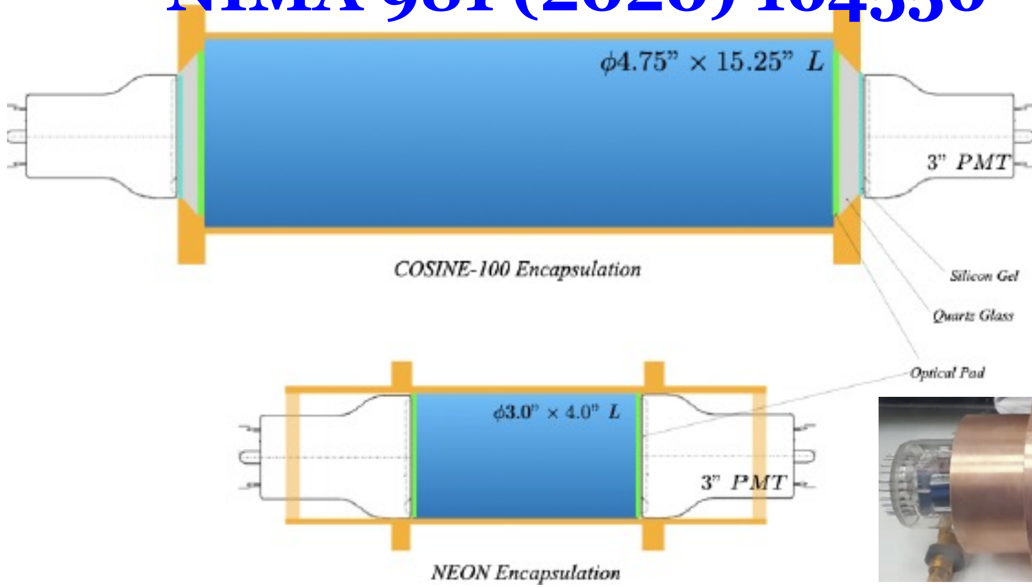


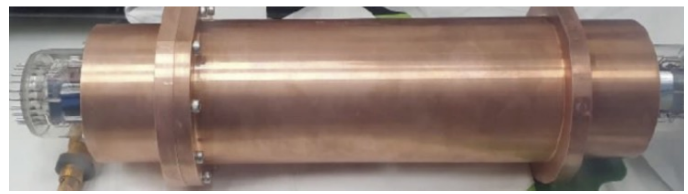
A proof of principle for low background NaI

Large crystal growing is going on

Novel technique of crystal encapsulation

NIMA 981 (2020) 164556





15 NPE/keV

(NPE=number of photoelectrons)

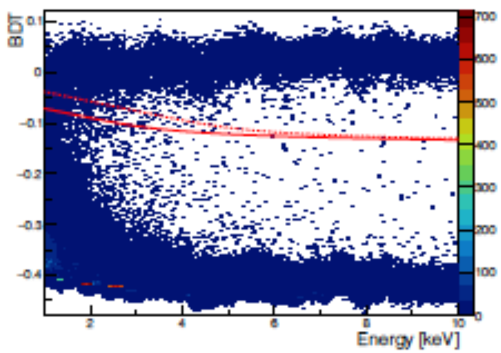
~23 NPE/keV

- Direct attachment of NaI(Tl) to PMTs
- ~50 % increased light yield was observed
  - Lower energy threshold!!
- This technique can be applied for COSINE-200 detector assembly

Low energy threshold of NaI(Tl)

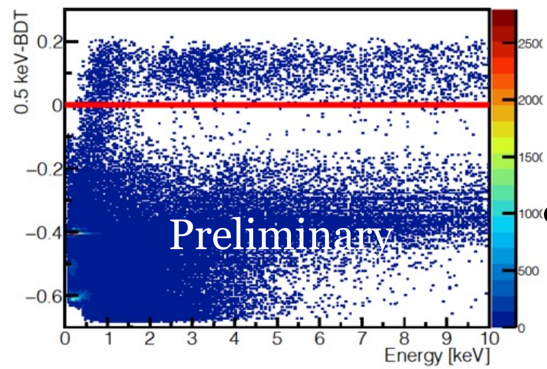
- Two-fold trigger is applied (trigger threshold : 2 NPE)
- PMT-induced noise makes difficulty to use low energy events
- 1 keV (15 NPE) threshold was achieved with multivariable technique
- 0.5 keV (7 NPE) threshold can be achieved with improved BDT

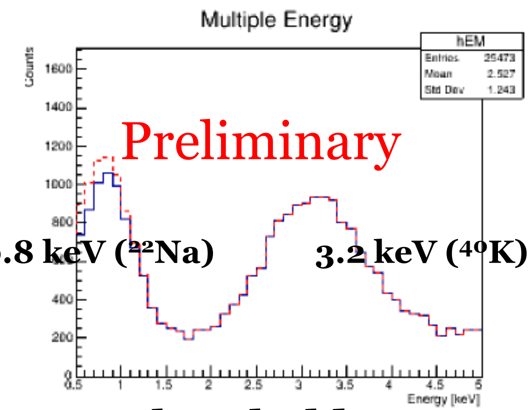
WIMP search data



Astropart. Phys 130, 102581 (2021)

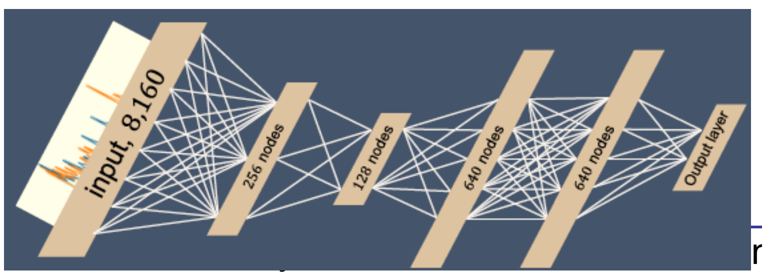
Categorizing noise type and develop new likelihood parameters

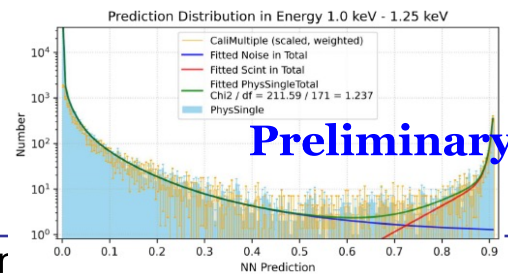




7 NPE threshold !!

Initiate Deep Machine learning

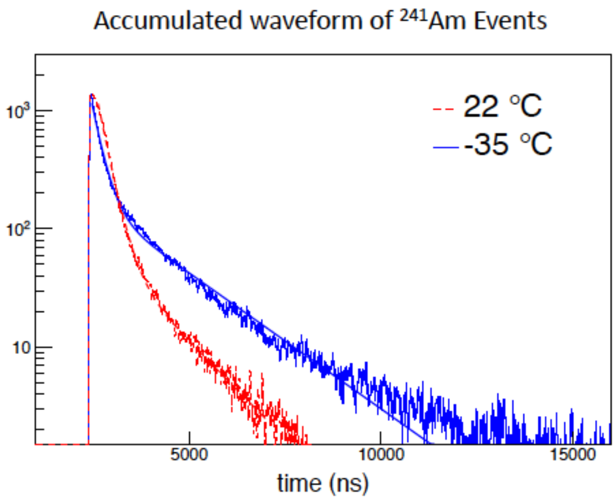


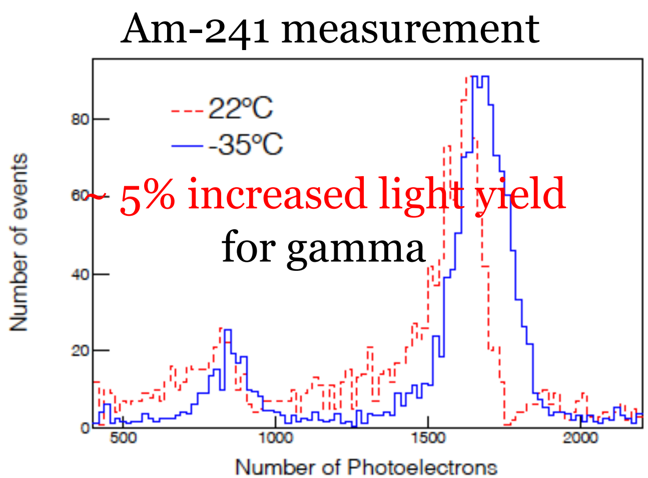


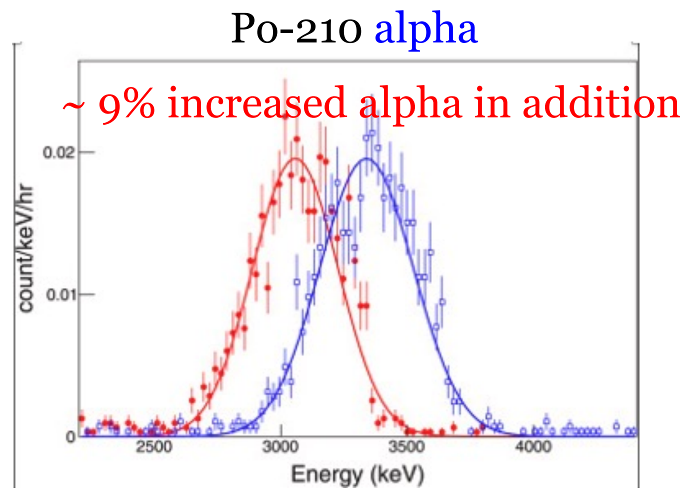
Final goal for ≤ 5NPE threshold!!

Low temperature (-30°C) response

PMT measurement

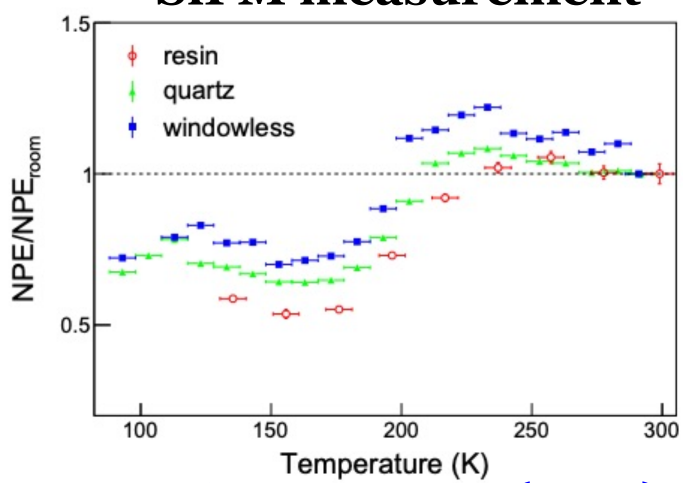






Astropart. Phys. 141, 102709 (2022)

SiPM measurement



JINST 17, P02027 (2022)

~ 5-15% increased light yield at -30°C

COSINE-200 can be operated at -30°C

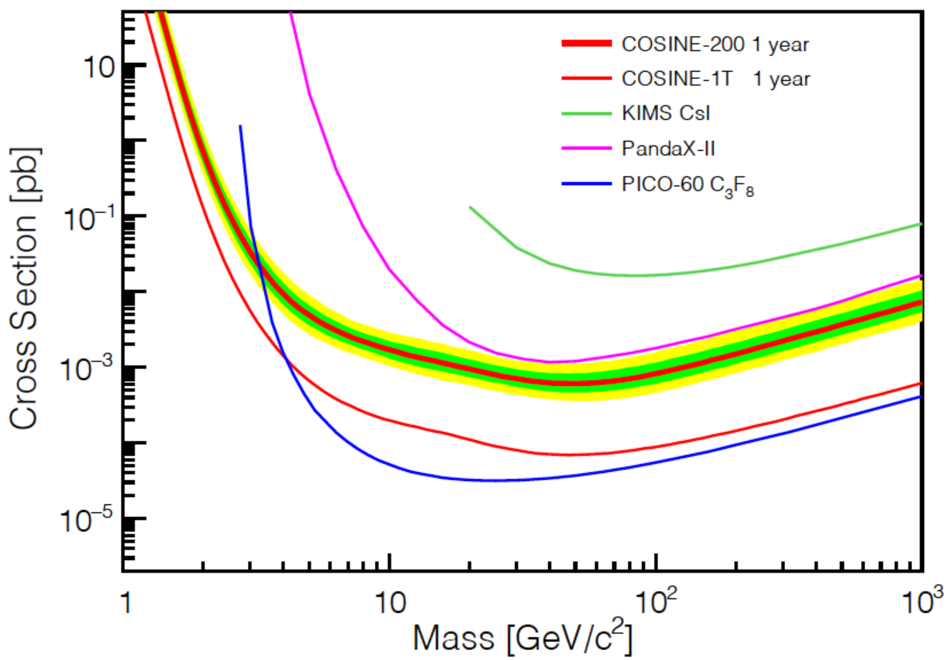
Yemilab facility is under construction

COSINE-200 for low-mass dark matter

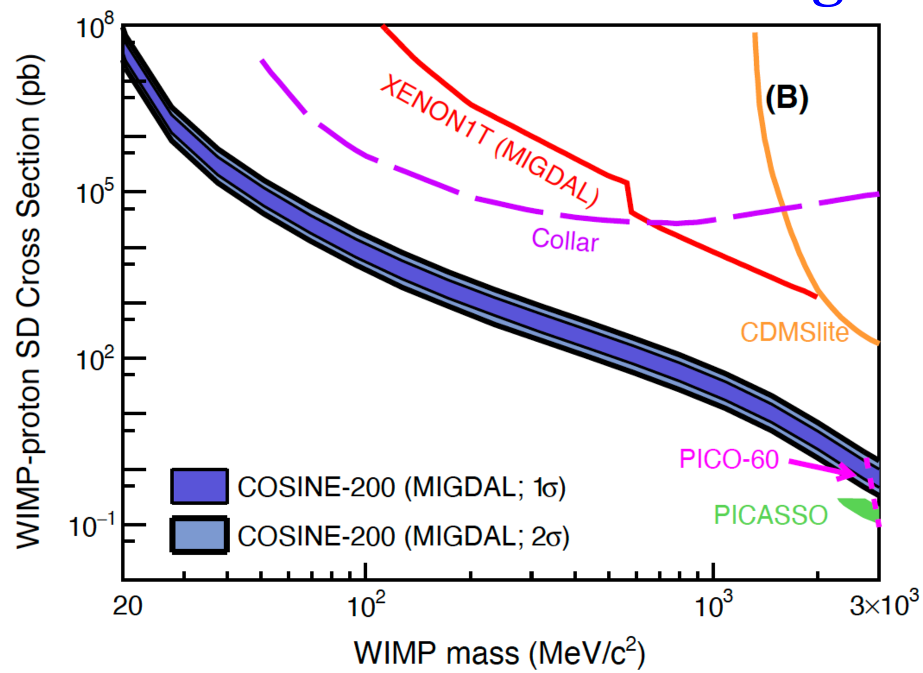
- Unambiguous conclusion on the DAMA/LIBRA

COSINE-200 sensitivities

WIMP-proton spin-dependent



Low mass search with Migdal

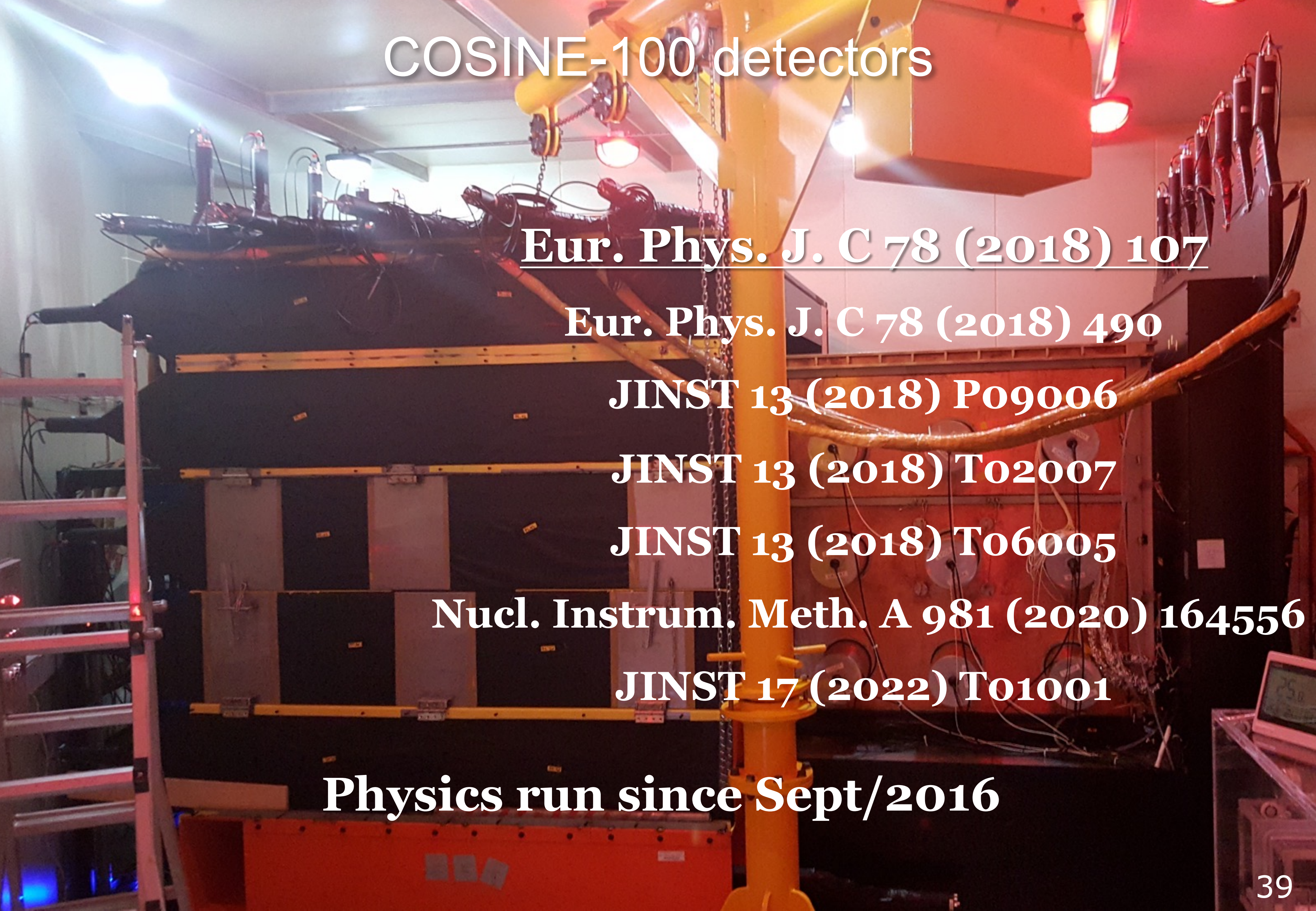


- A world best sensitive detector for low-mass WIMP-proton spin-dependent interaction
- Feasibility test of the COSINE-1T experiment

Summary & Conclusion

- World-wide efforts to understand DAMA/LIBRA's signature are actively ongoing
- Ongoing NaI(Tl) experiments brought more than 3 sigma tension with DAMA/LIBRA signals
- Precise time-dependent background understanding is crucial for annual modulation searches
- NaI(Tl) detectors have a great potential for low-mass dark matter searches
  - Sodium and Iodine are proton odd elements

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

Nucl. Instrum. Meth. A 981 (2020) 164556

JINST 17 (2022) T01001

Physics run since Sept/2016