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

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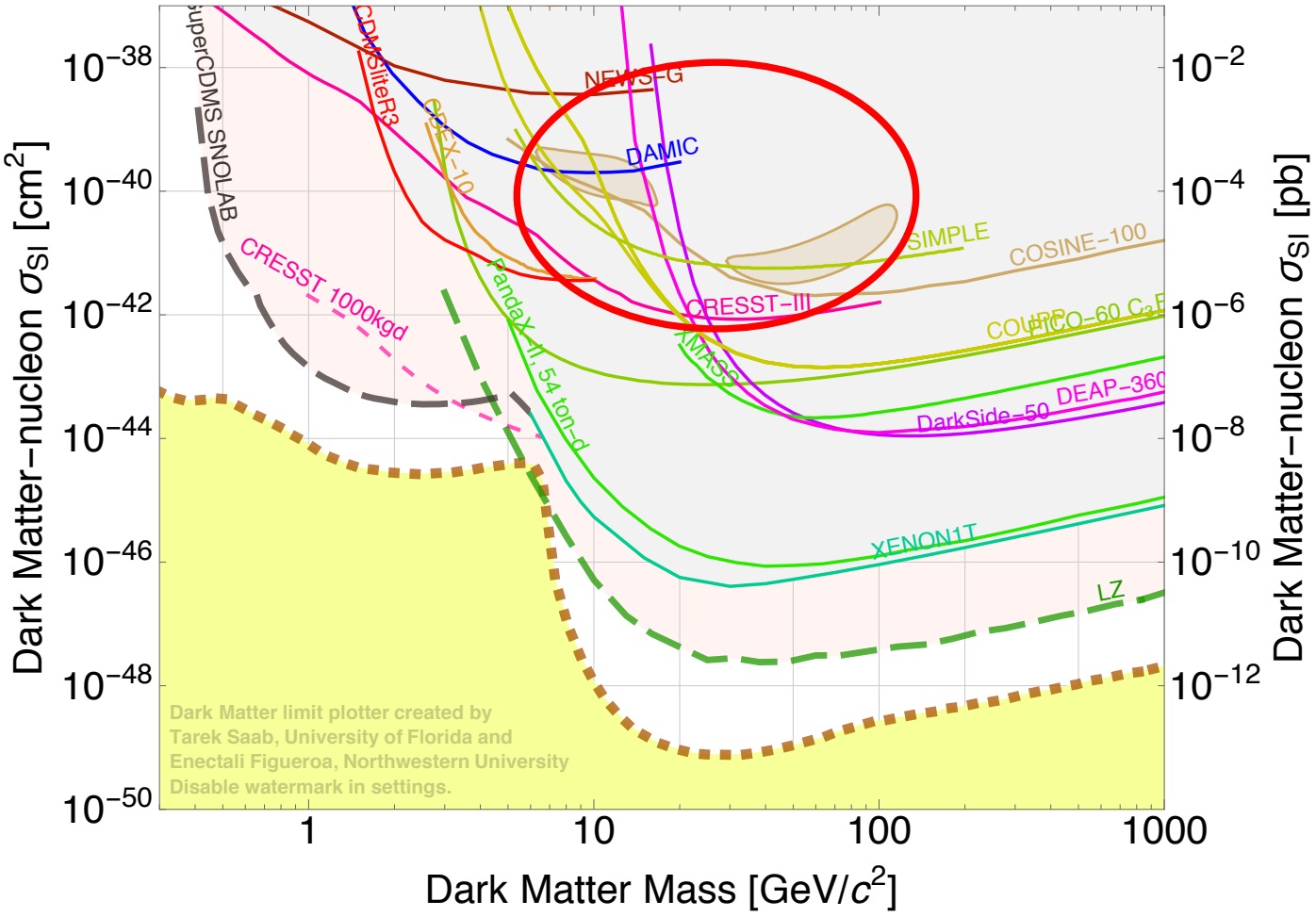
On behalf of COSINE collaboration
CUP, IBS, Korea

2020. 2. 25

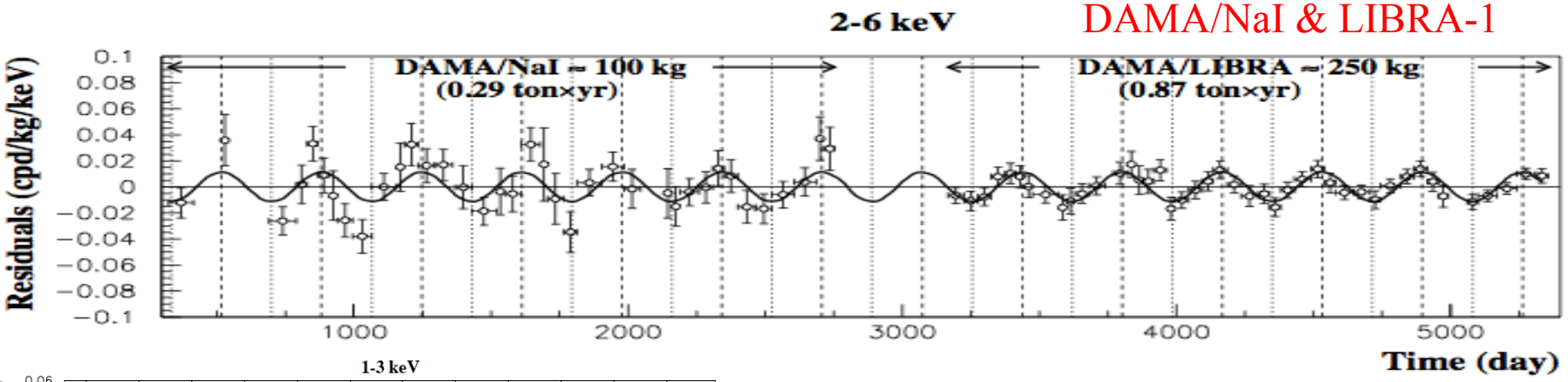
CNNP 2020, South Africa

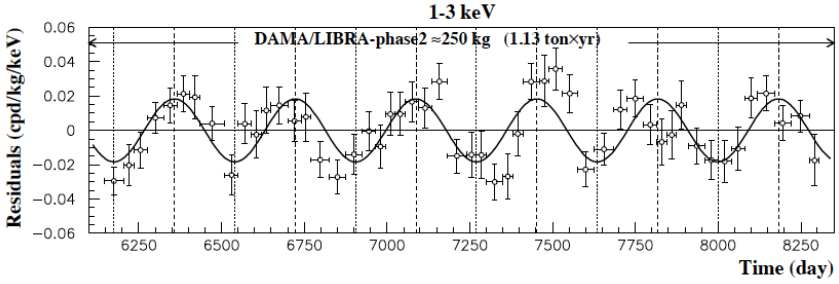
Dark Matter Direct Search

- **DAMA island is many orders off the limits set by other experiments under the SHM. → DAMA anomaly**

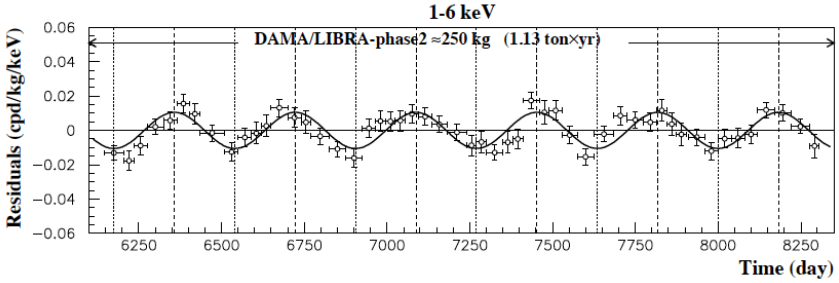


DAMA annual modulation





DAMA/LIBRA-2

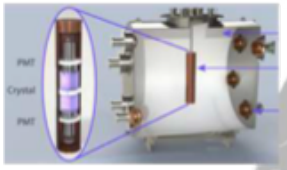


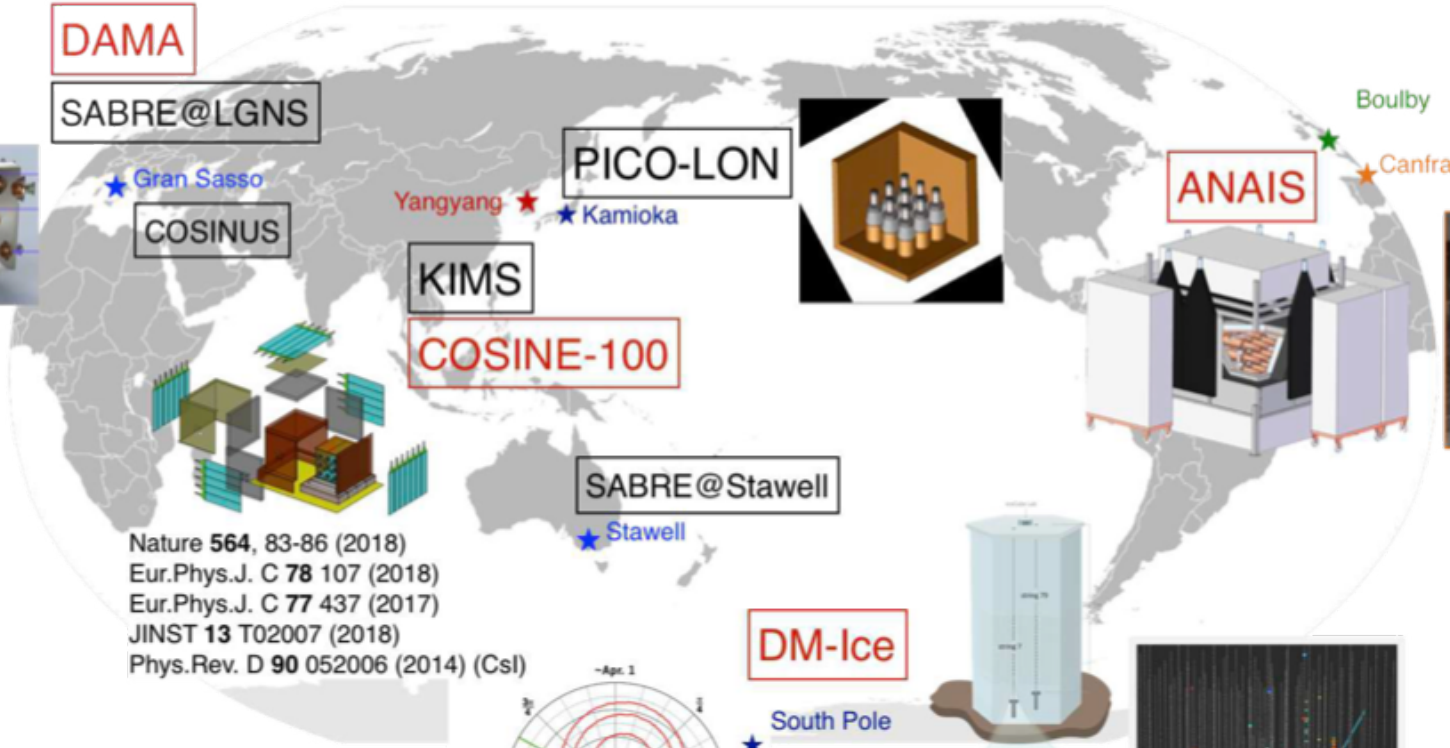
A simple question :
Can we reproduce this result ?

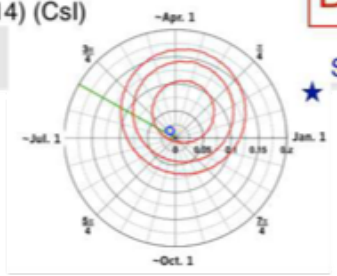
Until now, neither confirmation, nor rejection.

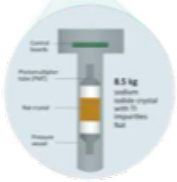
Same Target (NaI) Experiments

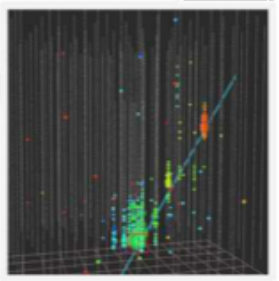
- **Since the properties of dark matter are not known, null results with different targets can't reject DAMA's claim completely.**
- **We must check DAMA's claim with the same target, NaI crystals.**











Nature **564**, 83-86 (2018)
Eur.Phys.J. C **78** 107 (2018)
Eur.Phys.J. C **77** 437 (2017)
JINST **13** T02007 (2018)
Phys.Rev. D **90** 052006 (2014) (CsI)

Astropart. Phys. **35** (2012) 749
Phys. Rev. D **90** 092005 (2014)
Phys. Rev. D **93** 042001 (2016)
Phys. Rev. D **95** 032006 (2017)

NaI crystals

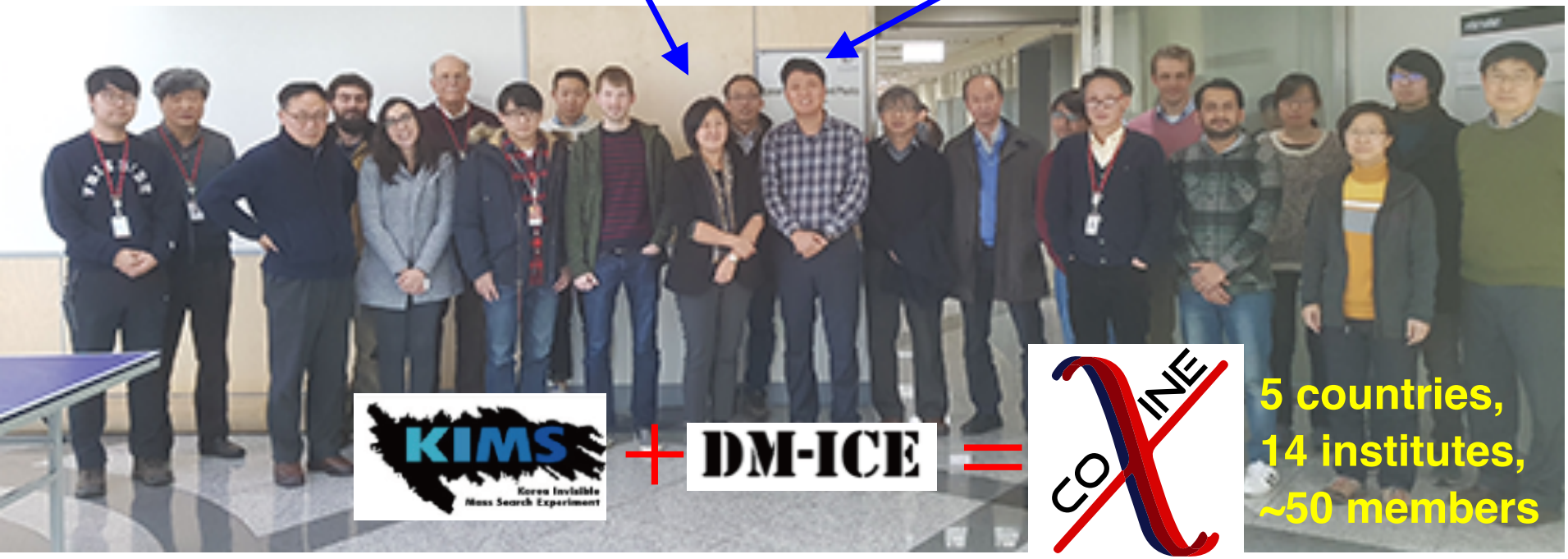
- To test DAMA/LIBRA experiment, we need low background NaI crystals.
- DAMA group :
  - DAMA/NaI – 9 crystals from Crismatec company in Paris
  - DAMA/LIBRA – 25 crystals from Saint-Gobain company.
- DM-ICE, KIMS, and ANAIS jointly developed low background NaI(Tl) crystals with Alpha Spectra company in USA between 2013 - 2016.
- High quality crystals with different backgrounds grown.
- Hilger (UK), RMD(USA), ISC (Japan) + … are trying.

Alpha Spectra
in Colorado. (2014. 8)

COSINE-100 : DM-ICE+KIMS

Joint effort to search for dark matter interactions in NaI(Tl) scintillating crystals.
(Goal to **check DAMA/LIBRA's observation**)

PI : Reina Maruyama Hyunsu Lee



YangYang(Y2L) Underground Laboratory

(Upper Dam) YangYang Pumped Storage Power Plant

Center for Underground Physics

IBS (Institute for Basic Science)

1000m

700m

(Power Plant)

양양양수발전소

(Lower Dam)

KIMS/COSINE (Dark Matter Search)

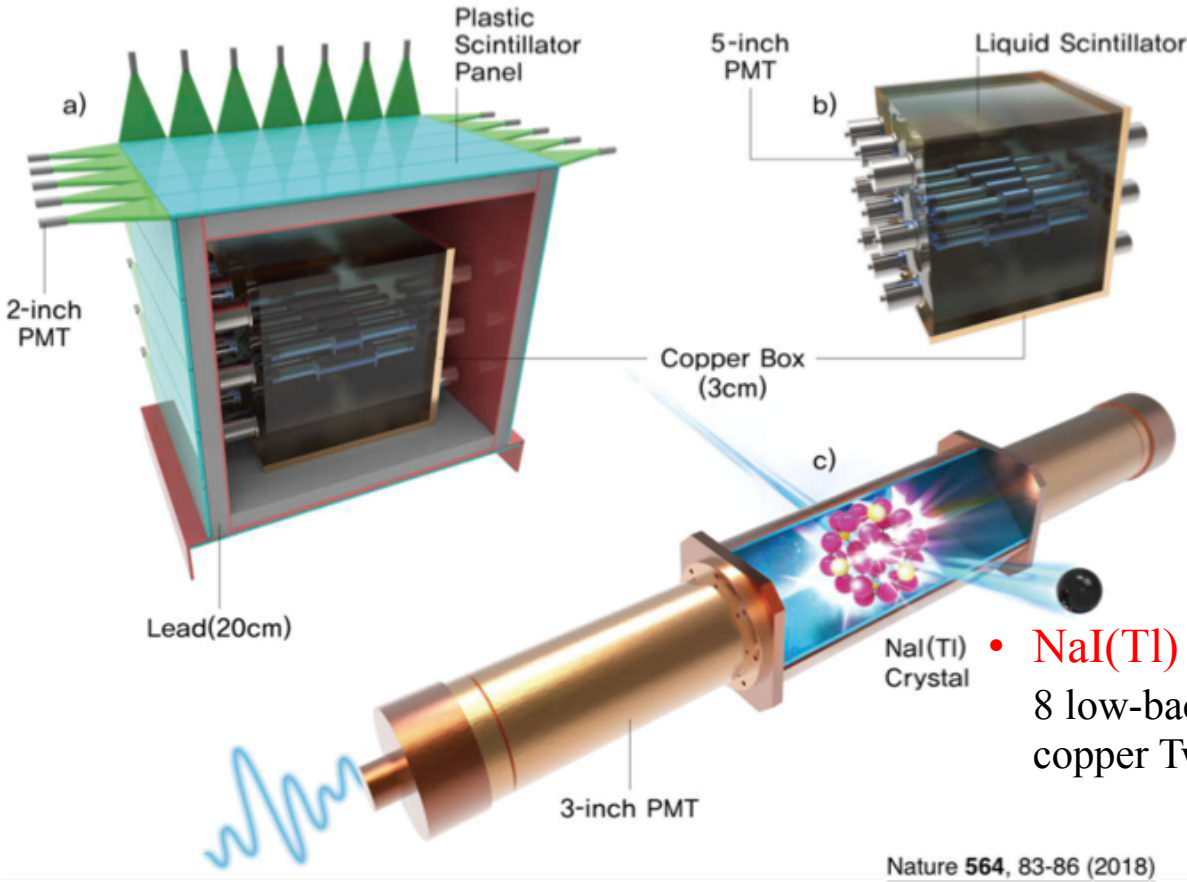
AMoRE (Double Beta Decay Experiment)

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

COSINE-100 detector configuration

- 4π of 37 plastic scintillator
  EJ-200 with 2-inch PMT (H7195)s.

- Liquid Scintillator
  2200-L LAB-based LS to tag internal/external background, 18 of 5-inch PMT(R877)s.



Nature **564**, 83-86 (2018)

- NaI(Tl) detector
  8 low-background crystals, encapsulated in copper Two 3-inch PMTs for each crystal.

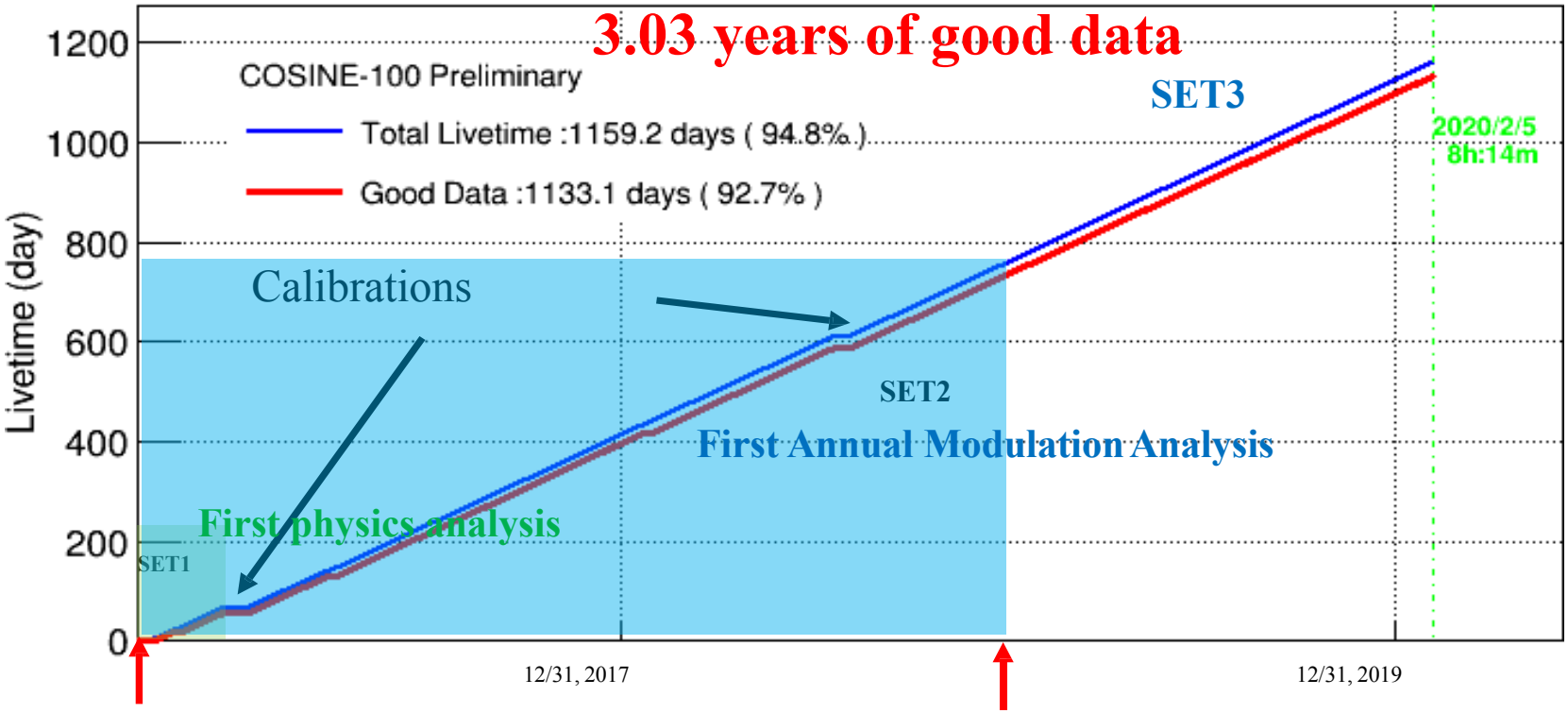
COSINE-100 NaI(Tl) crystals

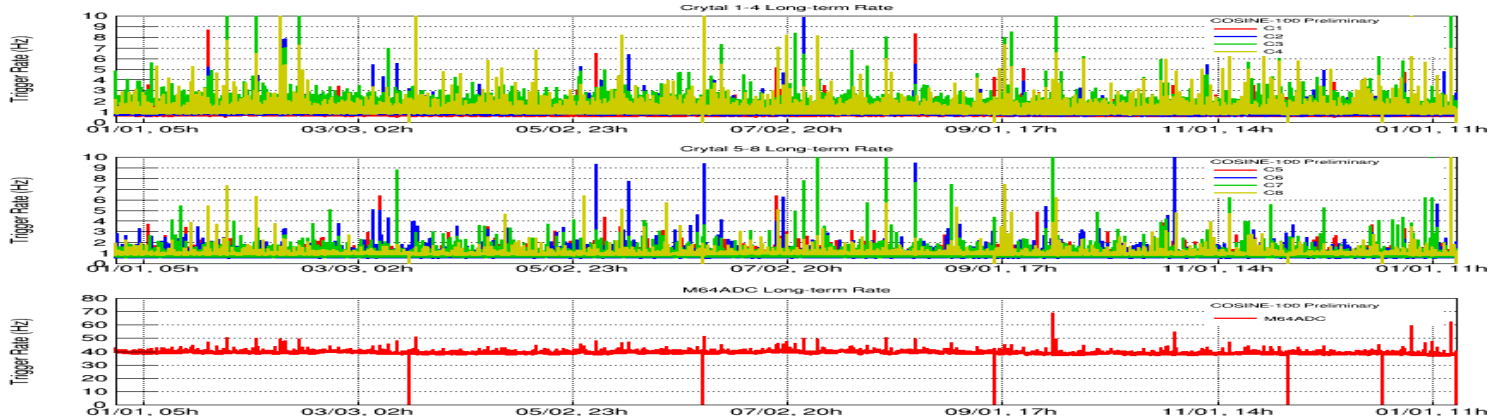
Eur. Phys. J. C 78 (2018) 107

- Different quality crystals from crystal R&D : 8 crystals, total 106 kg
- For best cases, U/Th/K contaminations are lower than DAMA.
- Total alphas (mainly due to ^{210}Pb) rates are higher than DAMA.

Crystal	Mass (kg)	Powder	Alpha rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light yield (p.e./keV)
Crystal 1	8.3	AS-B	3.20 ± 0.08	43.4 ± 13.7	< 0.02	1.31 ± 0.35	14.88 ± 1.49
Crystal 2	9.2	AS-C	2.06 ± 0.06	82.7 ± 12.7	< 0.12	< 0.63	14.61 ± 1.45
Crystal 3	9.2	AS-WS Ⅱ	0.76 ± 0.02	41.1 ± 6.8	< 0.04	0.44 ± 0.19	15.50 ± 1.64
Crystal 4	18.0	AS-WS Ⅱ	0.74 ± 0.02	39.5 ± 8.3		< 0.3	14.86 ± 1.50
Crystal 5	18.0	AS-C	2.06 ± 0.05	86.8 ± 10.8		2.35 ± 0.31	7.33 ± 0.70
Crystal 6	12.5	AS-WSⅢ	1.52 ± 0.04	12.2 ± 4.5	< 0.018	0.56 ± 0.19	14.56 ± 1.45
Crystal 7	12.5	AS-WSⅢ	1.54 ± 0.04	18.8 ± 5.3		< 0.6	13.97 ± 1.41
Crystal 8	18.3	AS-C	2.05 ± 0.05	56.15 ± 8.1		< 1.4	3.50 ± 0.33
DAMA			< 0.5	< 20	0.7 - 10	0.5 – 7.5	5.5 – 7.5

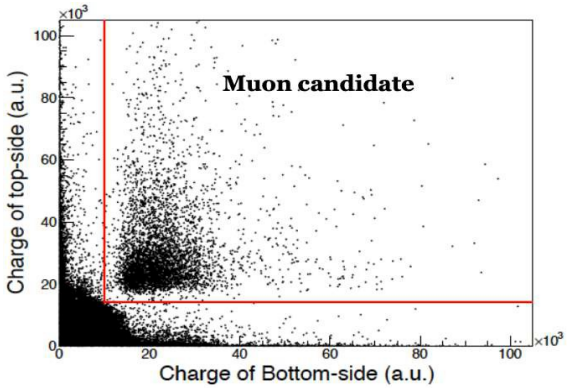
COSINE-100 operation

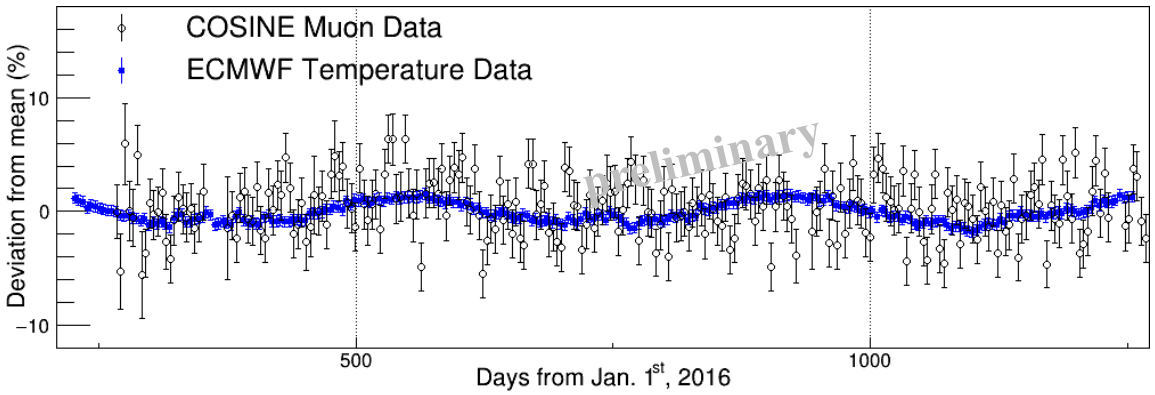




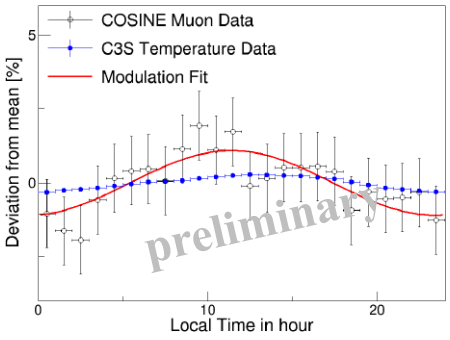
Muon data

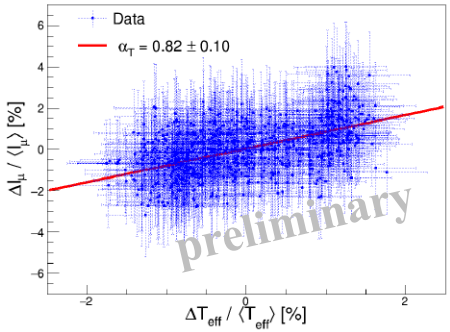
JINST 13, T02007 (2018)

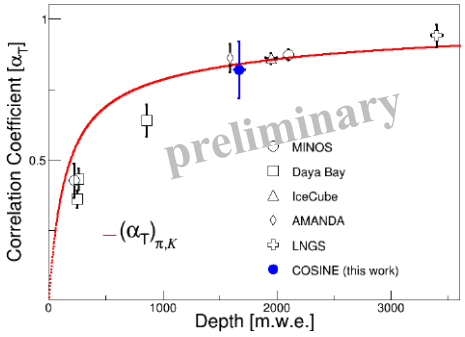




Diurnal Modulation







Muon flux (muon/m²/day)
328±1(stat.)±10(syst.)

Amplitude =
0.51 ± 0.19 %,
Phase = 178 day

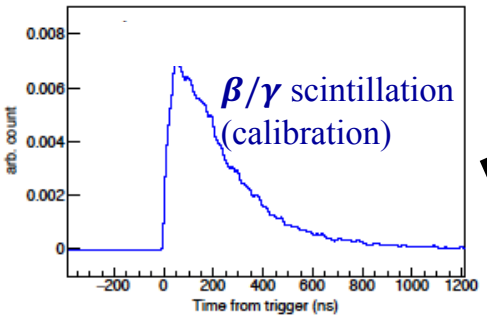
Experiment	Borexino (This Work)	Borexino I [6]	GERDA [7]	MACRO [31]	LVD I [4]	LVD II [5]
Location Time	Hall C 2007-2017	Hall C 2007-2011	Hall A 2010-2013	Hall B 1991-1997	Hall A 2001-2008	Hall A 1992-2016
Rate $[10^{-4}m^{-2}s^{-1}]$	3.432 ± 0.001	3.41 ± 0.01	3.47 ± 0.07	3.22 ± 0.08	3.31 ± 0.03	3.3332 ± 0.0005
Amplitude $[10^{-6}m^{-2}s^{-1}]$	4.7 ± 0.2	4.4 ± 0.2	4.72 ± 0.33	–	5.0 ± 0.2	5.2 ± 0.3
Amplitude (%)	1.36 ± 0.04	1.29 ± 0.07	1.36 ± 0.07	–	1.51 ± 0.03	1.56 ± 0.01
Period [d]	366.3 ± 0.6	366 ± 3	–	–	367 ± 15	365.1 ± 0.2
Phase [d]	181.7 ± 0.4	179 ± 3	191 ± 4	–	185 ± 15	187 ± 3

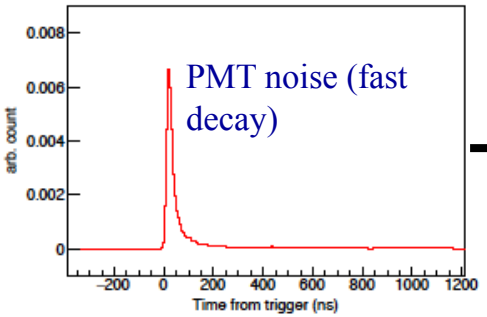
Cf. LNGS muon modulation

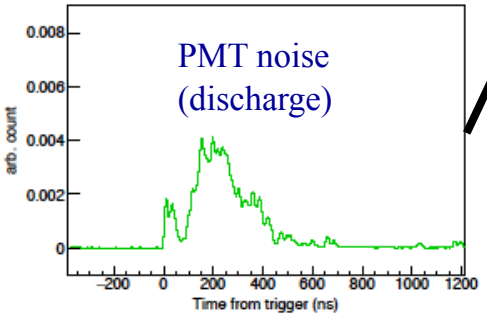
JCAP 1902 (2019) 046
Modulation amplitude ~1.5 %,
Phase ~ 184 day

Removing PMT induced noise

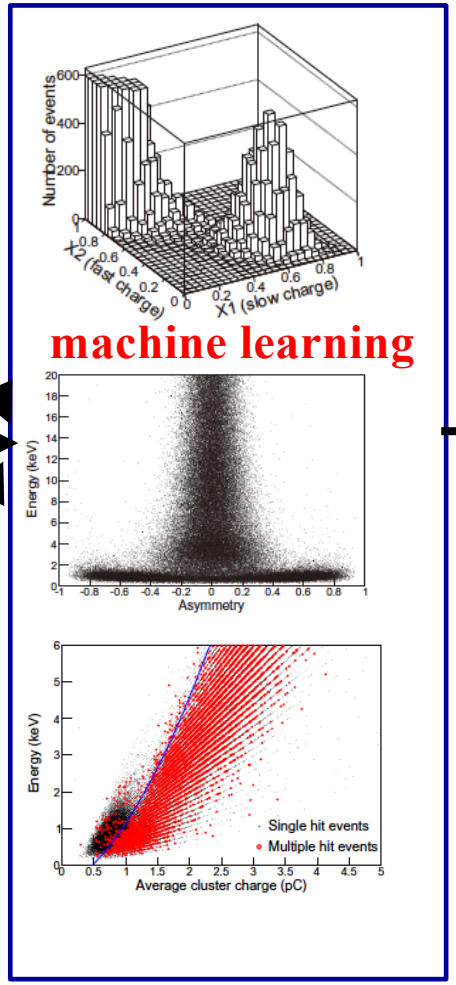
Accumulated waveforms



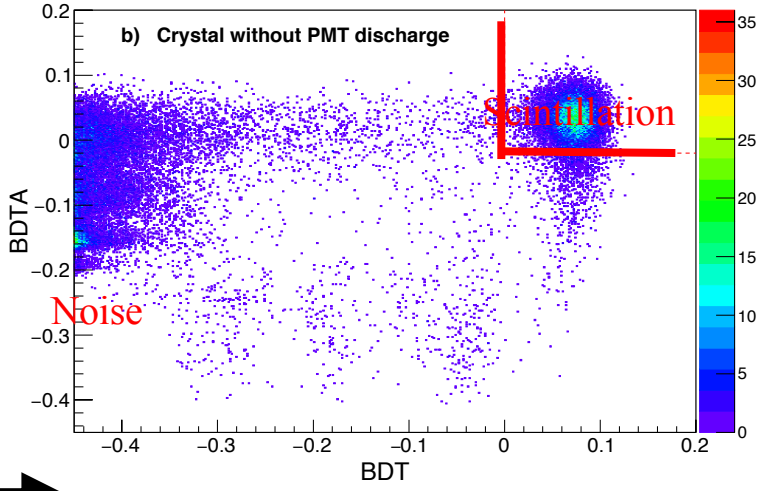




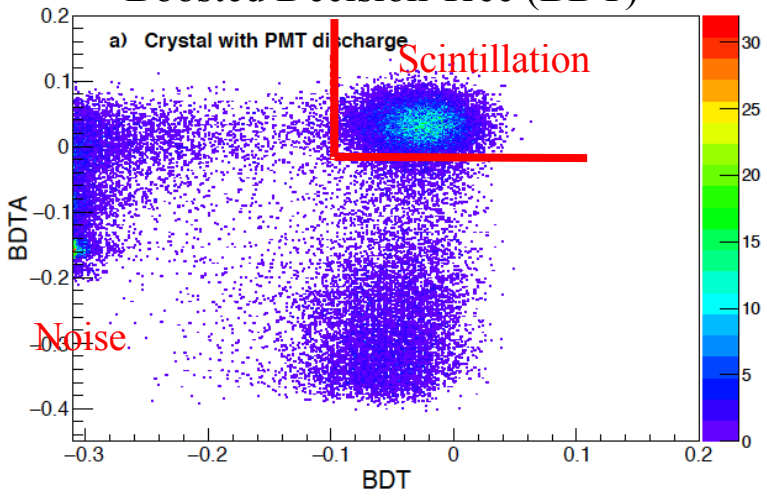
Discrimination parameters



Boosted Decision Tree (BDT)



Boosted Decision Tree (BDT)



WIMP interaction search from background study

- Thorough understanding of background spectra made it possible to constrain WIMP interaction in the detector. → Model dependent way.
- Used initial two month –SET1

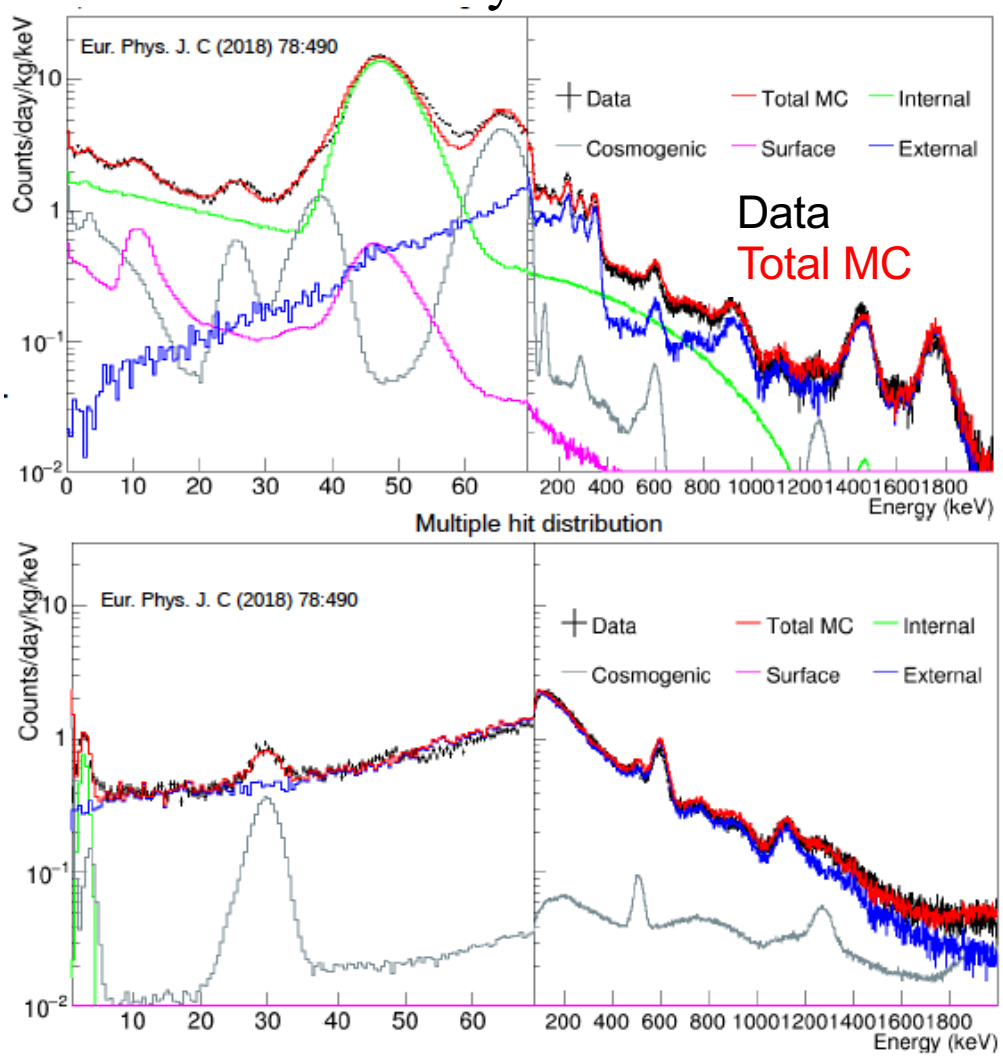
Single hit event
(6-2000 keV)

Background modeling was done using only 6- 2000keV events

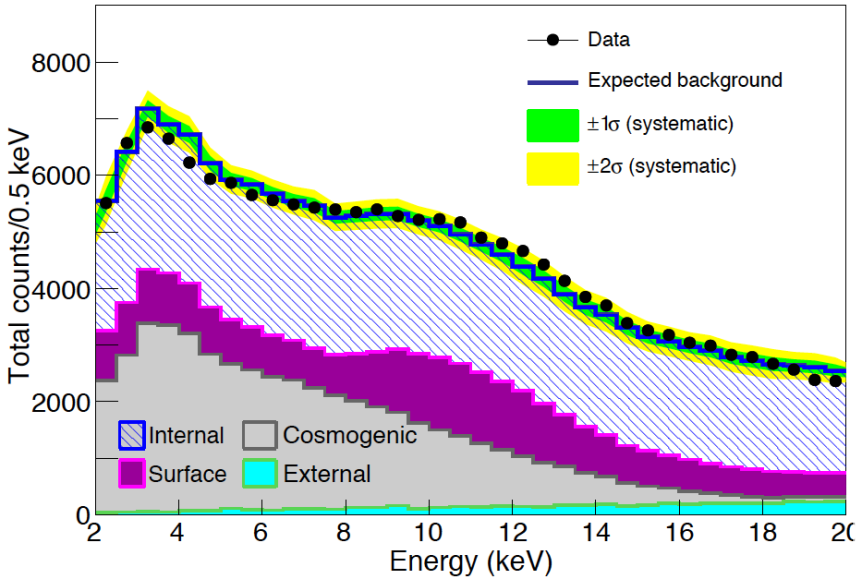
Multiple hit events
(2-2000 keV)

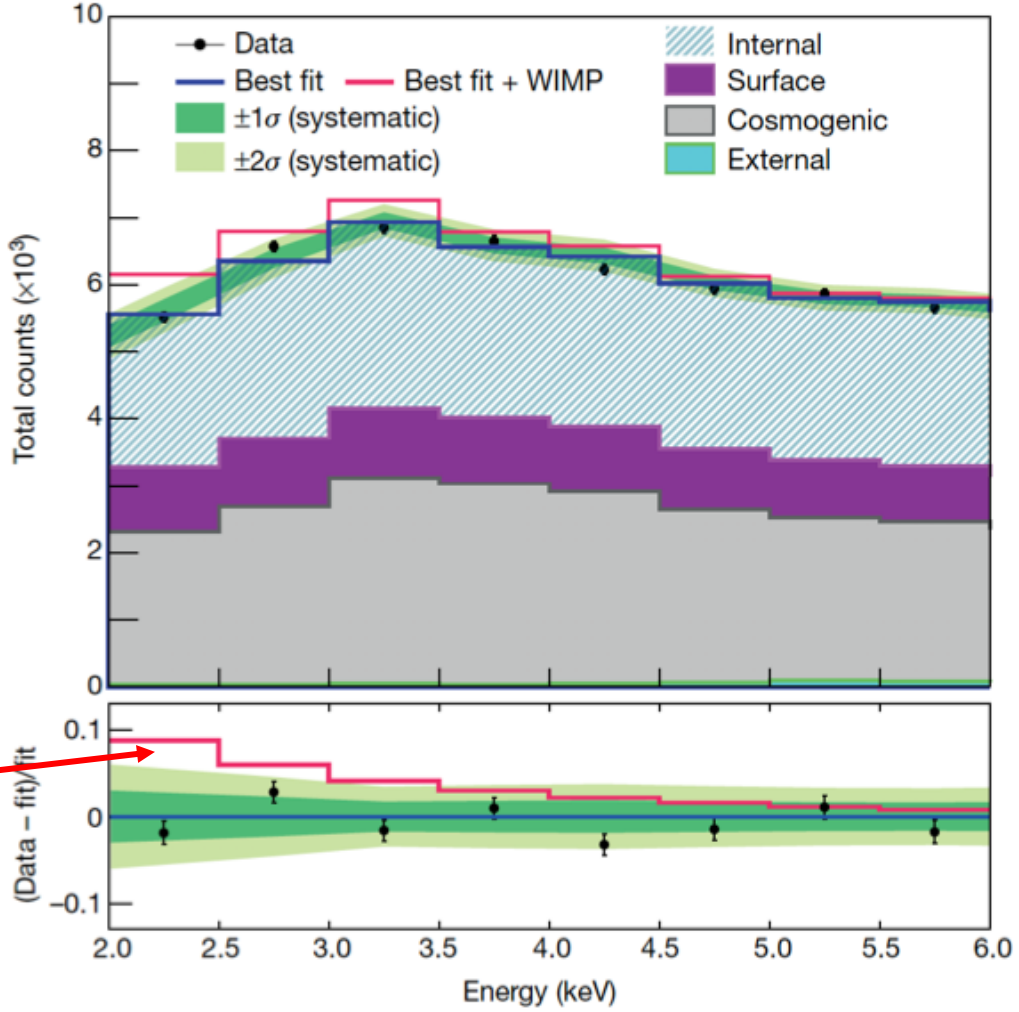
P. Adhikari *et al.*,
Eur. Phys. J. C 78 (2018) 490

Crystal 7



All crystals together



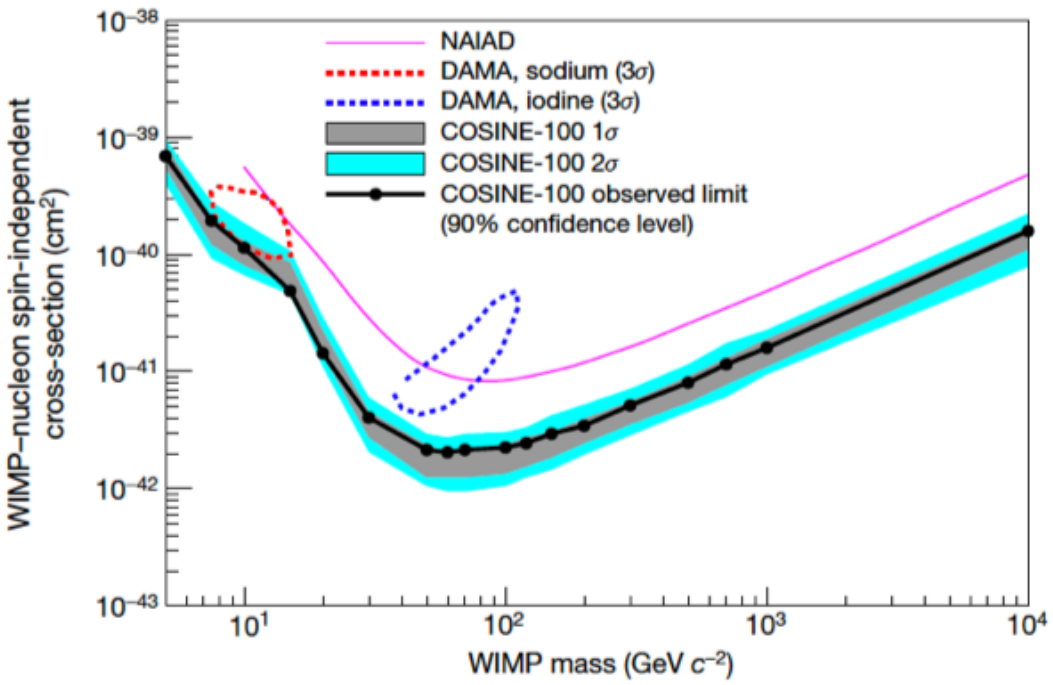


- 10 GeV, 2.35 x 10^{-40} cm^2 WIMP-nucleon cross section
- There is no room for WIMP signal.

Spin independent WIMP-nucleon cross section limit

Nature Vol 564, 83, 2018

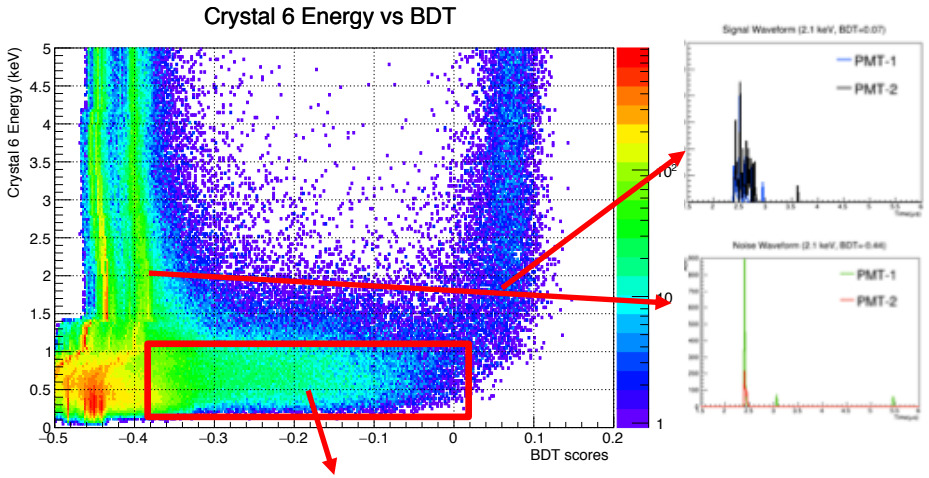
– First result constraining DAMA result with NaI crystals.

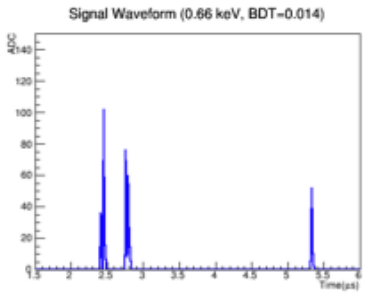


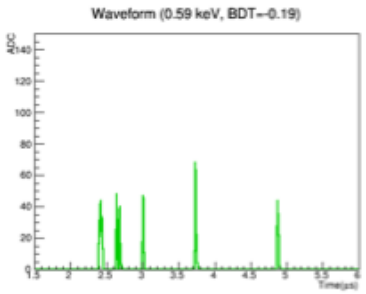
- COSINE-100 excludes DAMA/LIBRA-phase1's signal as spin- independent WIMP with Standard Halo Model.
- Consistent with null results from other direct detection experiments.

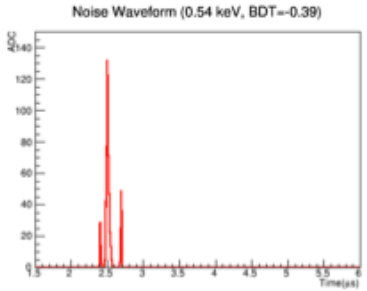
These results will generate tension for isospin violating models explaining DAMA along with null results from other experiments.

Analysis down to 1 keV energy threshold



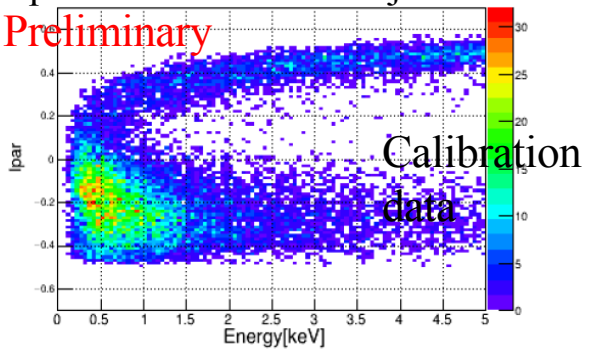




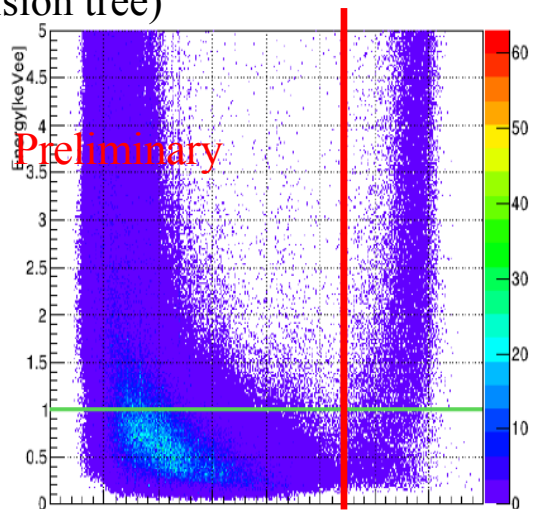


Understand signal-like events and noise-like events at low energies
Develop new parameter to reject noise-like events effectively

Likelihood parameters for noise rejection



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

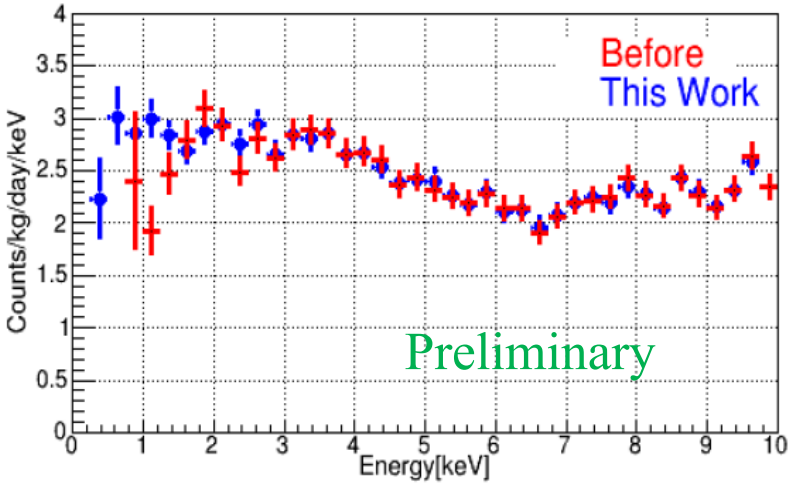


Boosted Decision Tree

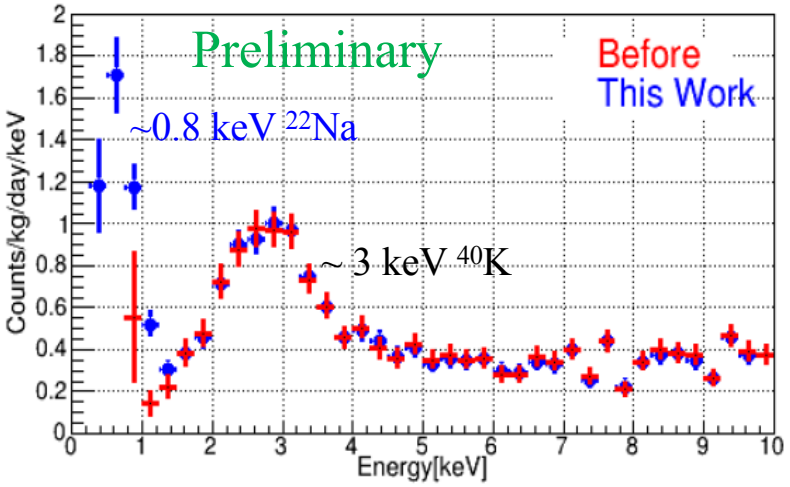
See Hyunsu Lee's talk 3:20pm Tue., "NEON"

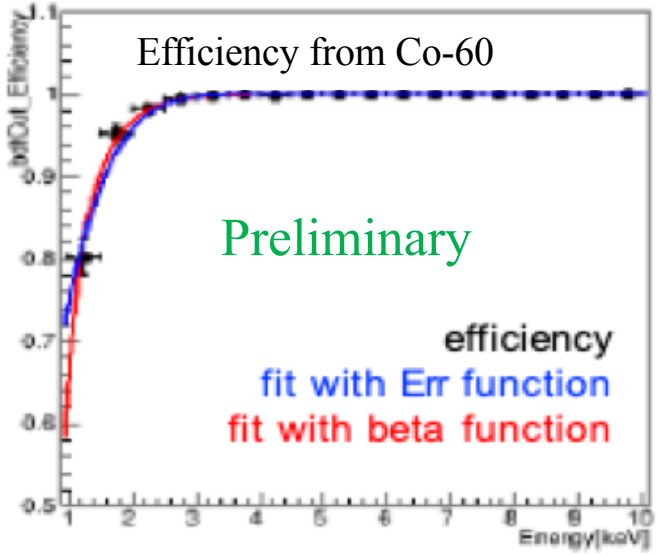
Analysis threshold less than 1keV!

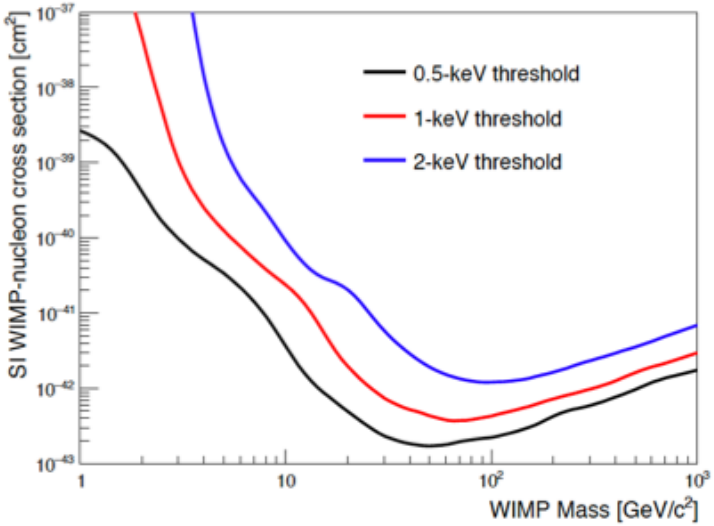
Single hit spectrum



Multiple hit spectrum



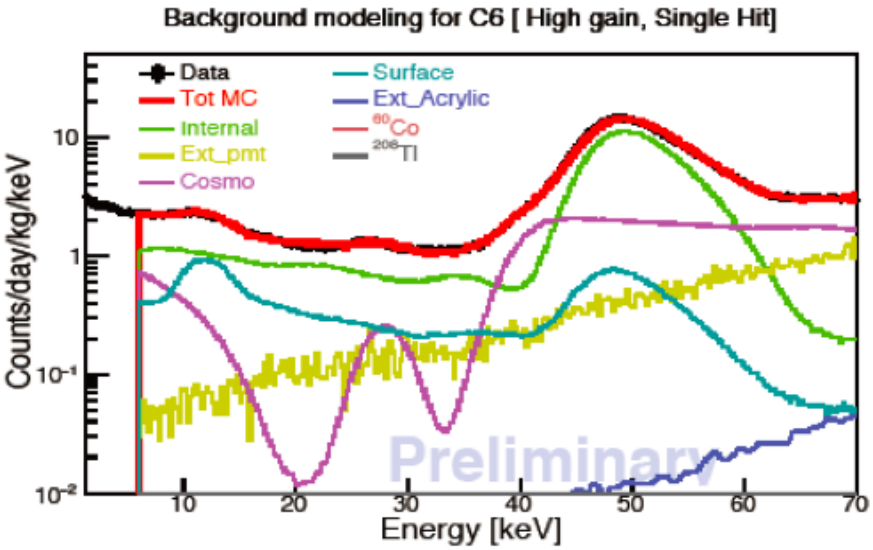


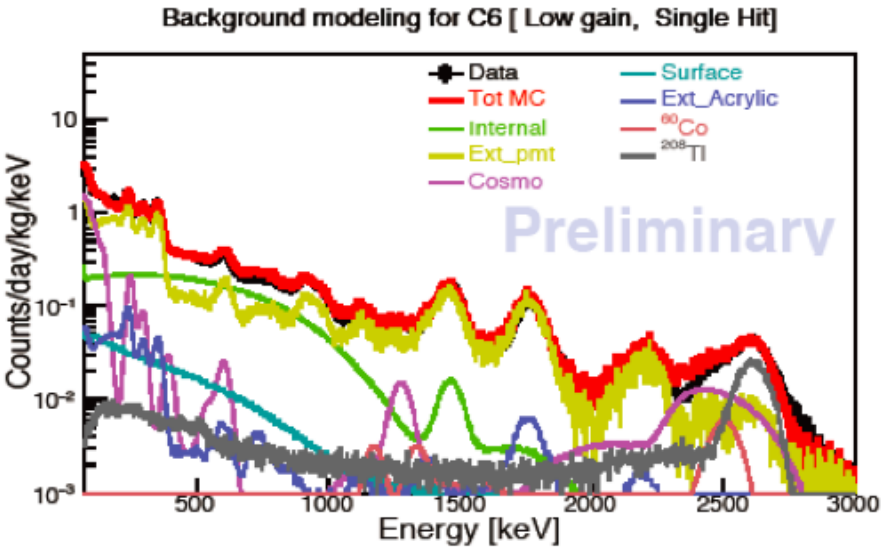


We can reduce our threshold below 1keV with high efficiency.

Improving Background Modeling

Single hit events





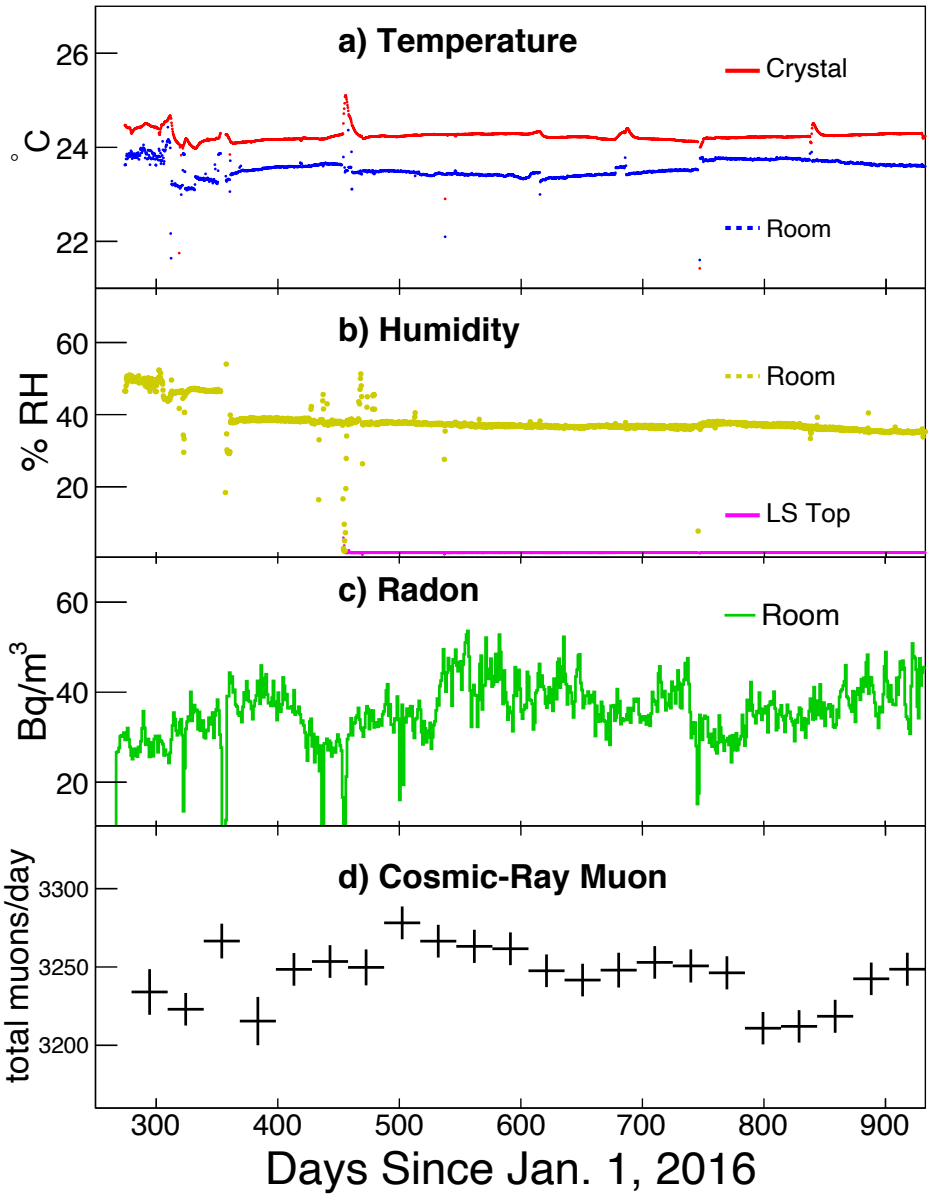
- ^{129}I, rock-gamma (^{208}Tl) are added.
- Better modeling of surface ^{210}Pb using contaminated crystal.

- With 1 keV threshold data, we will improve the sensitivity of SHM DM limits a few times lower than previous limits.

Does COSINE see the same modulation ?

- For annual modulation studies, we need absolutely stable condition for the environments and detector performance.

- < 0.1 ˚C temperature
- < 2% humidity fluctuation inside the shielding structure
- Current and voltage of detectors very stable.



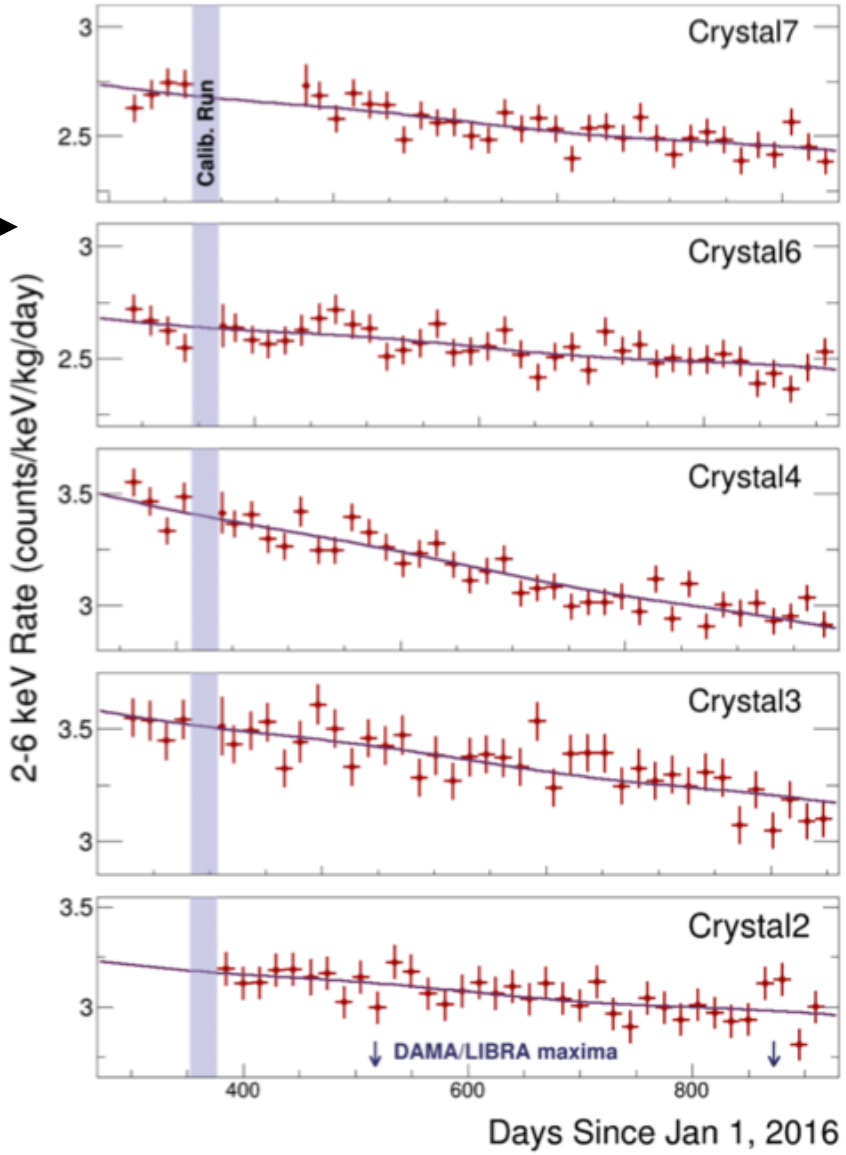
Modulation analysis - Set 2 data

- Data : October 21, 2016 - July 18, 2018.
- Exposure : 97.7 kg years, 1.7 years
- Time averaged energy spectra show 2.7 cpd/keV/kg on average in 2-6 keV.

$$R = C + P_0 e^{\left(-\frac{log2 \cdot t}{P_1}\right)} + A cos \frac{2\pi(t - t_0)}{T}$$

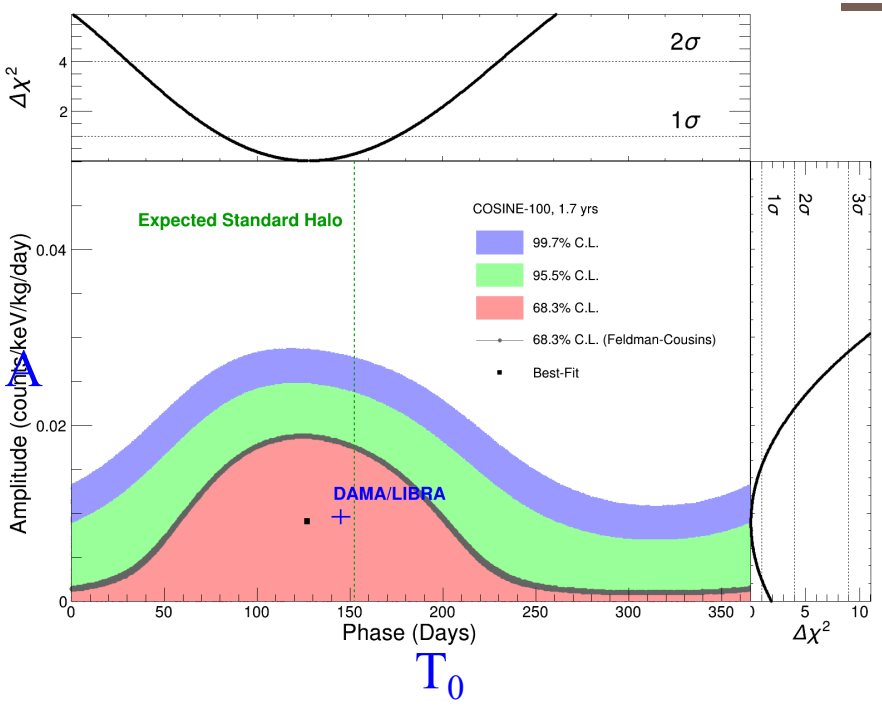
- Simultaneous fitting of 5 crystals.
- 15-day interval for binning.

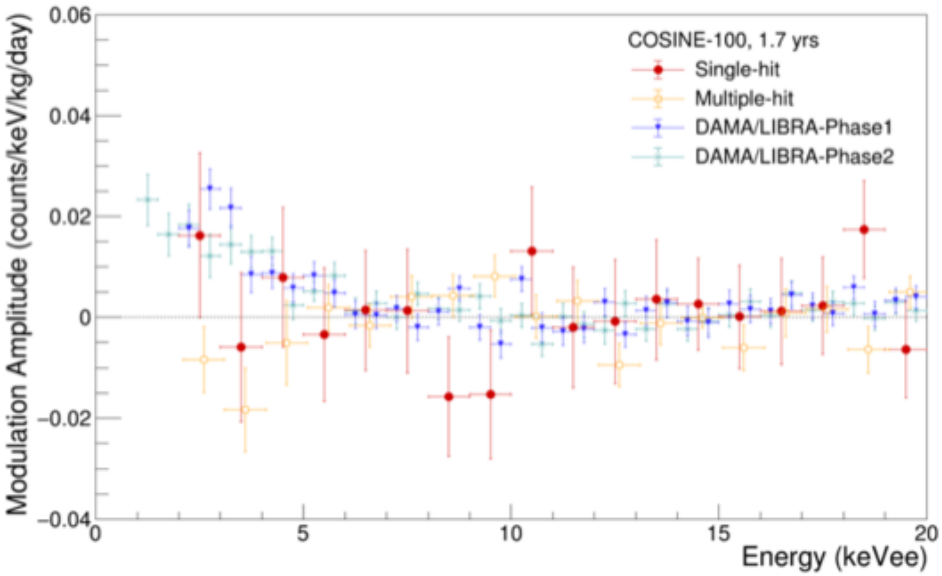
- Gradually decreasing backgrounds due to cosmogenic isotopes inside the crystal.



Results

PRL 122, 131802(2019)



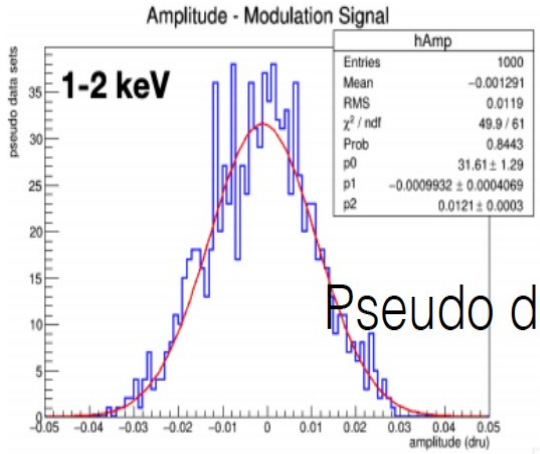


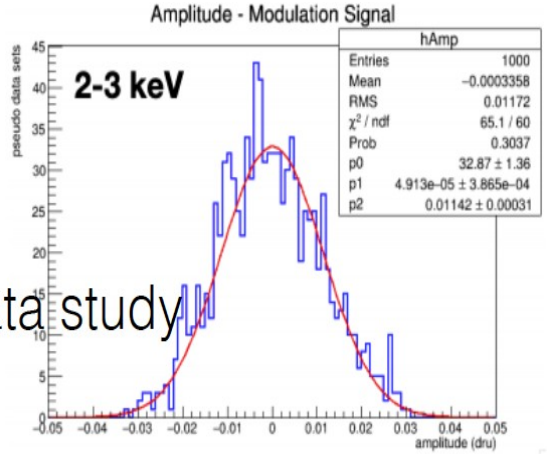
Configuration	χ^2	*d.o.f.*	p-value	Amplitude (counts/keV/kg/day)	Phase (Days)
COSINE-100	175.3	174	0.457	0.0092±0.0067	127.2±45.9
DAMA/LIBRA (Phase1+Phase2)	–	–	–	0.0096±0.0008	145±5
COSINE-100	175.6	175	0.473	0.0083±0.0068	152.5 (fixed)
COSINE-100 (Without LS)	194.7	175	0.143	0.0024±0.0071	152.5 (fixed)
ANAIS-112	48.0	53	0.67	-0.0044±0.0058	152.5 (fixed)
DAMA/LIBRA (Phase1+Phase2)	71.8	101	0.988	0.0095±0.0008	152.5 (fixed)

COSINE-100 data is consistent with both Null/DAMA modulation w/ 68% CL.

Improvements in analysis

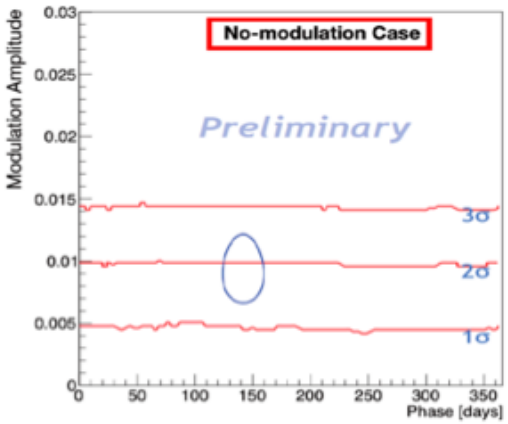
- ~3 years data at present with 1keV energy threshold.
- Improved event selection (Better selection efficiency)
- Realistic pseudo experiments for validity is in final stage.
- It is close to opening the box.

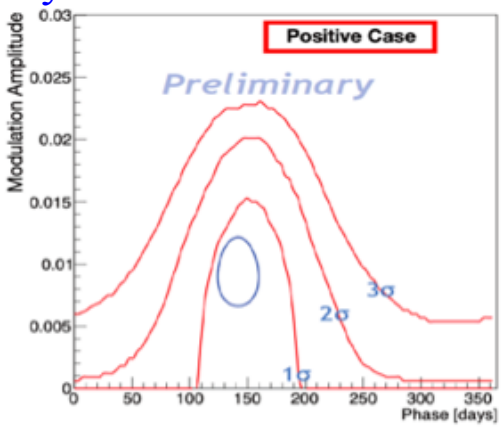




Pseudo data study

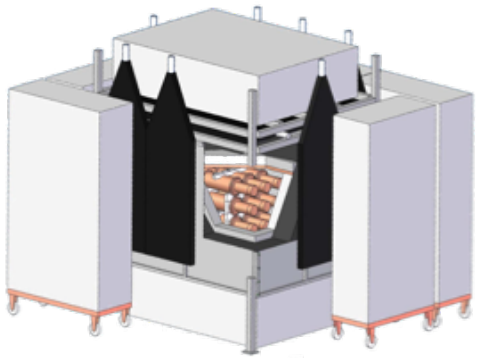
Sensitivity

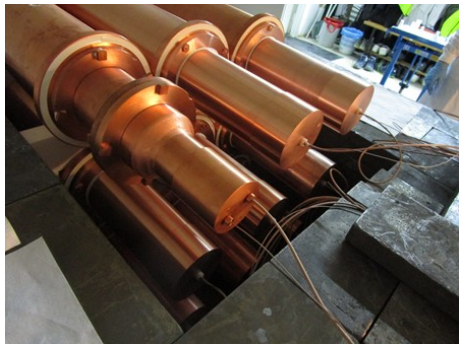




ANAIS

Updated in arXiv:1910.13365



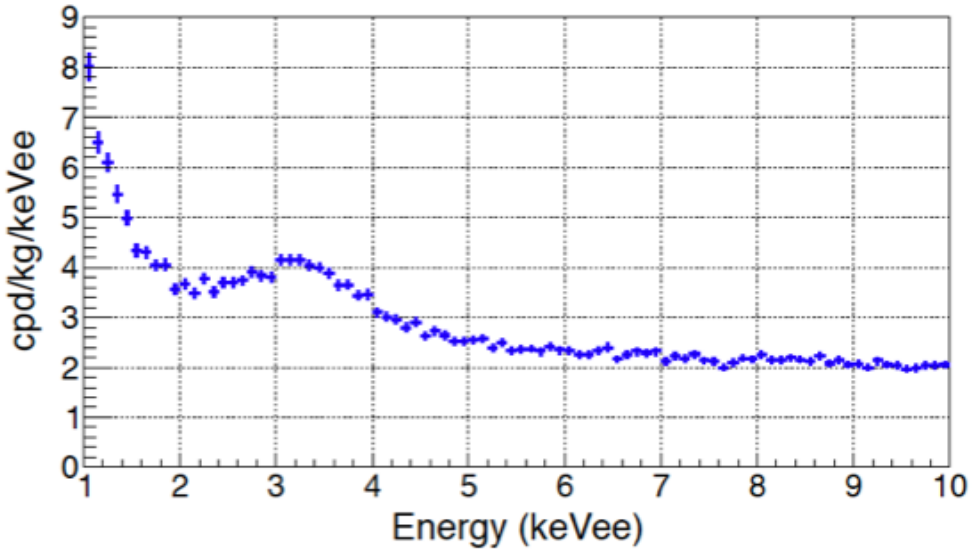


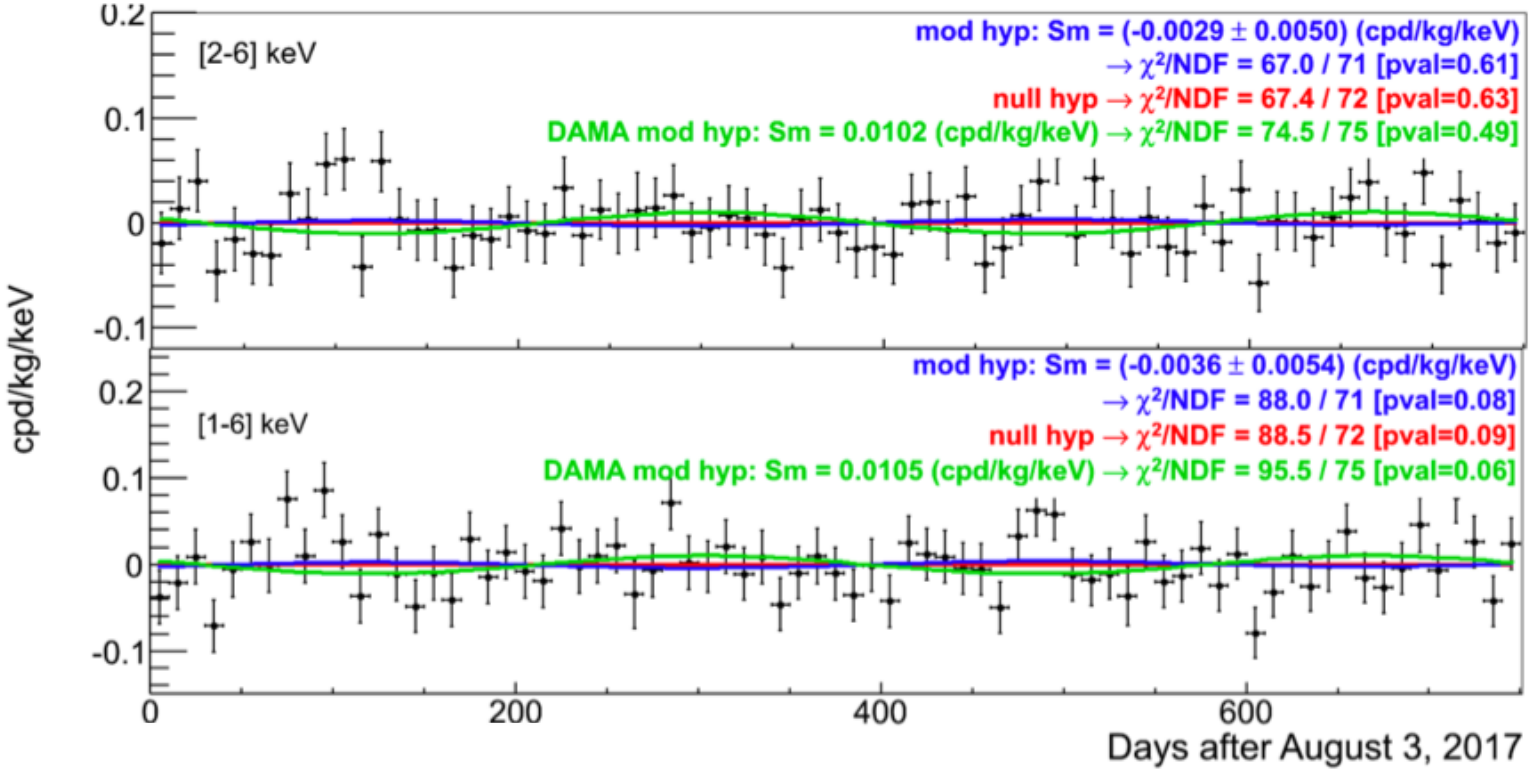
- Runs at Canfranc, Spain
- No LS veto.
- 9X12.5kg → 112.5 kg
- Data taken from Aug. 2017
- 220.69 kg·yrs data

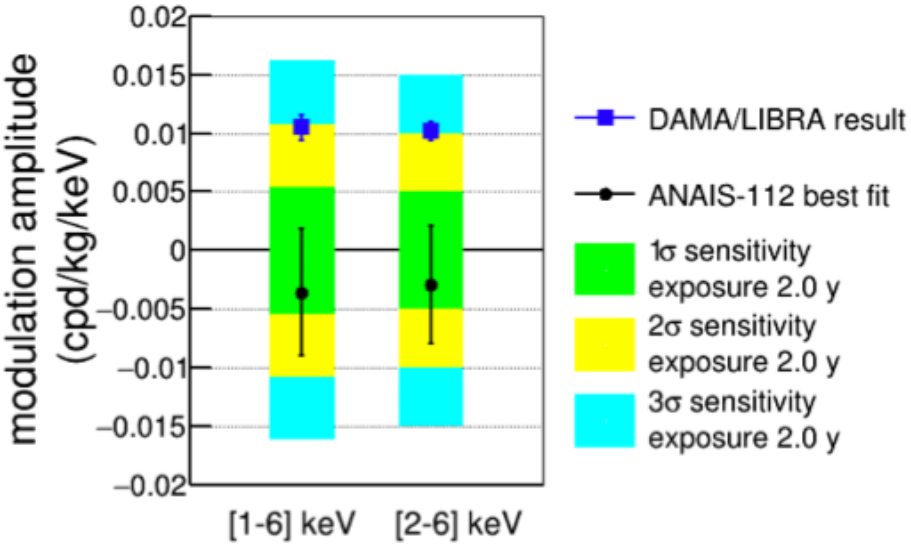
All crystals from Alpha Spectra

Detector	Quality powder	Date of arrival at Canfranc
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

Total averaged low energy spectum





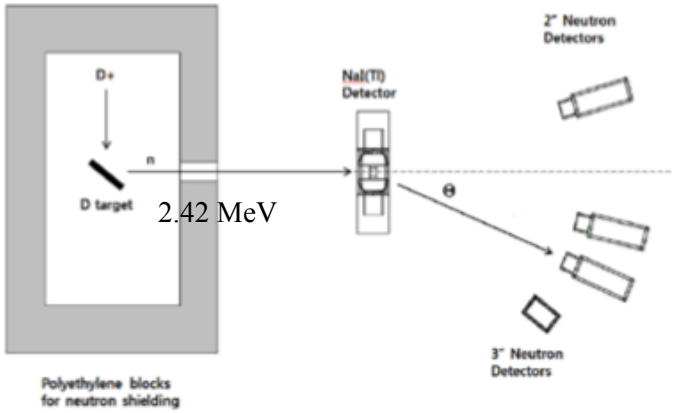


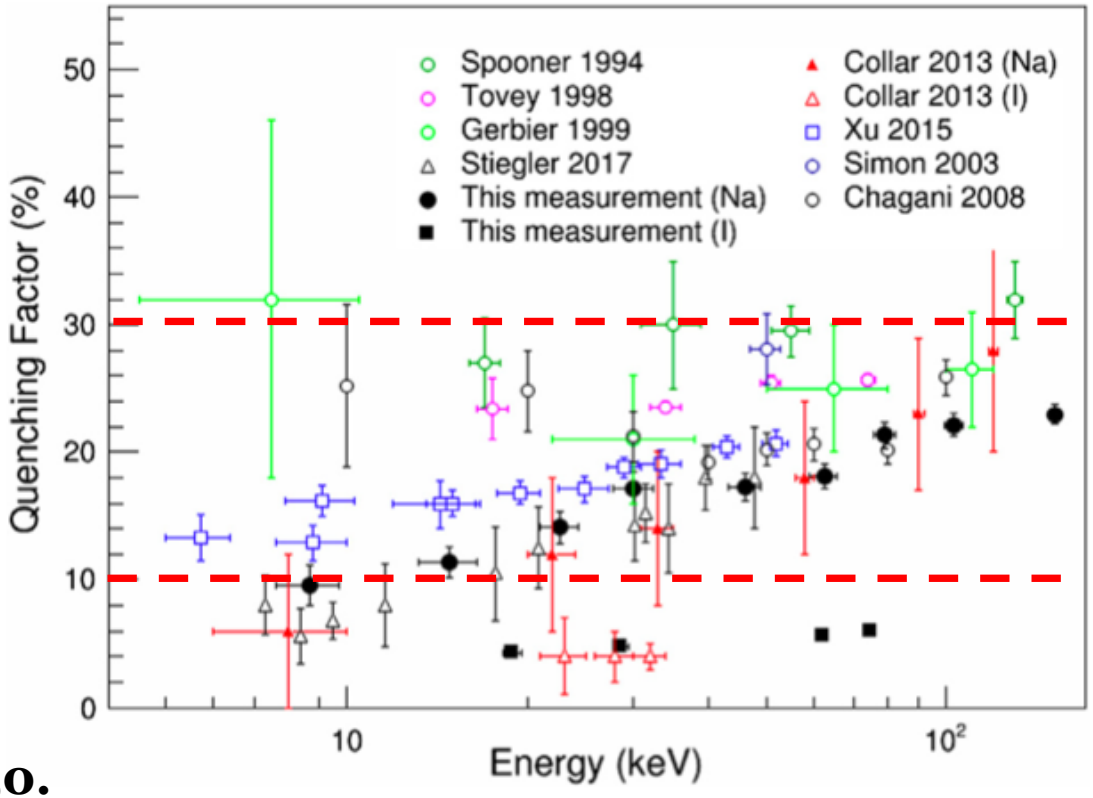
- **The sensitivity to test DAMA with 2 years data reaches 2 sigma.**
- **5 years data will be over 3 sigma.**

New Quenching Factors for Na, I

- Quenching factor is the ratio between electronic and nuclear recoil signals for the same energy deposition.
- New quenching factors are significantly smaller than the values used by DAMA group.

D-D neutron generator





Astropart. Phys. 108 (2019) 50.

Comments on quenching factor measurements

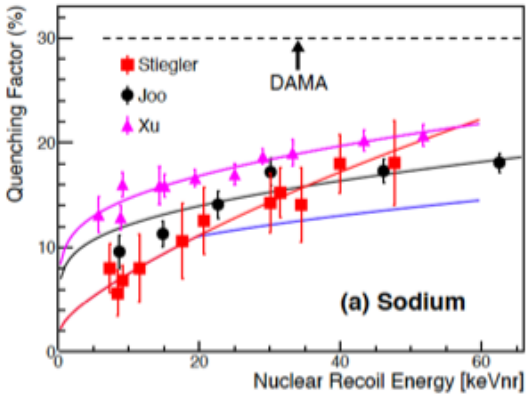
- Quenching factor measurements are delicate and spread widely.
- It is critical to compare different experimental data.
- Old data, data with lower photoelectron yields have higher QF.
- Need to confirm with more measurements.

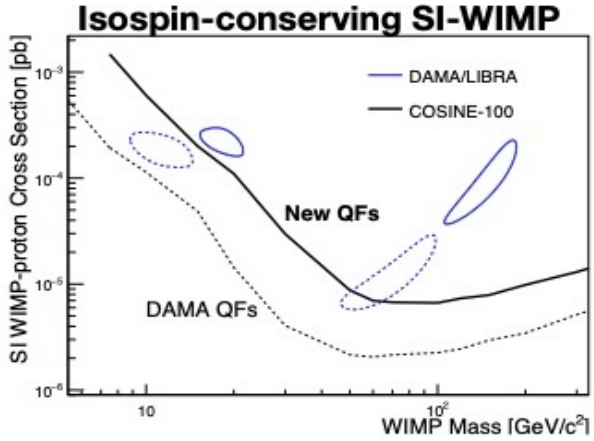
Paper	Year	Crystal				PMT	Effi.	Neutron	LY
		Supplier	Size	Method	Doping				
			cm		ppm			MeV	Pe/keV
Spooner	1994		2.5(D)x2.5		~1000	EM19924B	N	DD, 3.2-5.5	
Tovey	1998	Hilger	2.5x2.5		1000	ETL9266A	N	DD, 2.85	
Gervier	1999	Crismatec	2.5x2.5			2232 RTC	N	^{7}Li(p, 1.3,3.3	9
Simon	2002		2.5(D)x2.5				N	P(^{7}Li, 2.1	
Chagani	2008		5(D)x5.4			ETL9265KB	N	DD, 2.45	5.1
Collar	2013	Amcrys	1.7x1.7x2.7	Choch	700	R7600U-200	Y	DD, 2.2	20
Xu	2015	RMD	2.5x2.5x2.5	Brid		R6233	Y	^{7}Li(p, 0.69	18.2
Stiegler	2017							^{7}Li(p,	27-30
Ju	2019	AS	2x2x1.5	Stuck	?	R12669SEL	Y	DD, 2.45	14

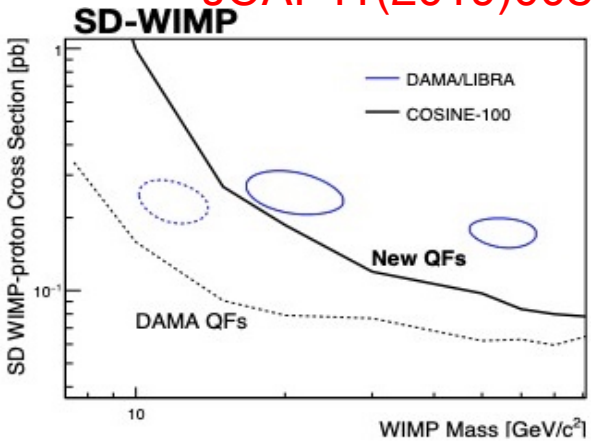
Parameter space with new quenching factor

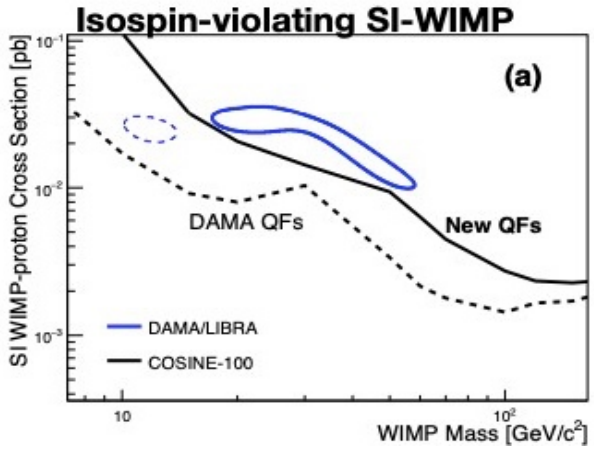
JCAP11(2019)008

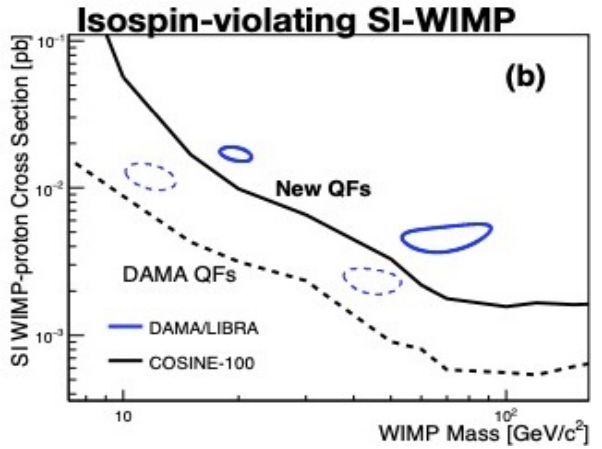
New quenching factors applied to DAMA data with systematics.











- Interpretation with SI and SD WIMP in SHM via new QF measurements.
- The parameter spaces are moved to higher regions with the new QFs.
- COSINE-100 data incompatible with DAMA signal region.

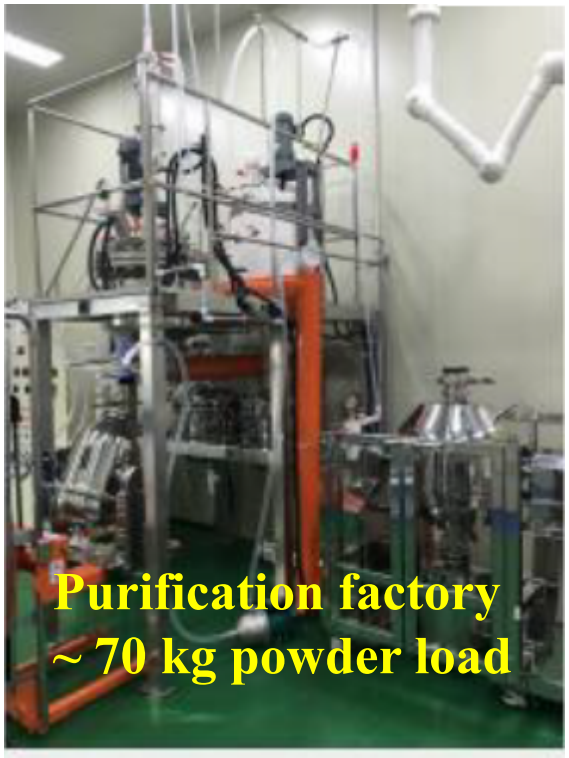
COSINE-200 (Phase-II)

- COSINE will go for lower background crystals for next phase.
- Powder purification/crystal growing/detector assembly are going on at IBS, Korea.

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

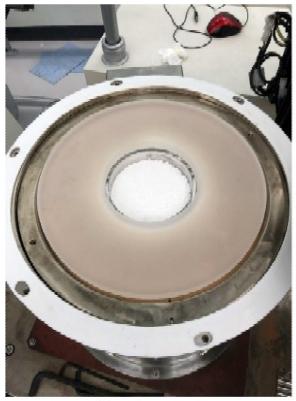
Powder purification performance

	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



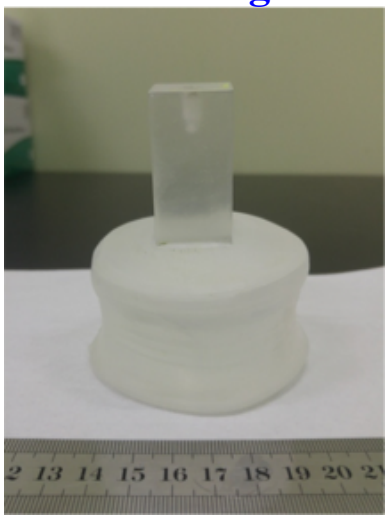
Crystals grown at CUP

Solution : Quartz cover & new refractory avoids Pb contamination !

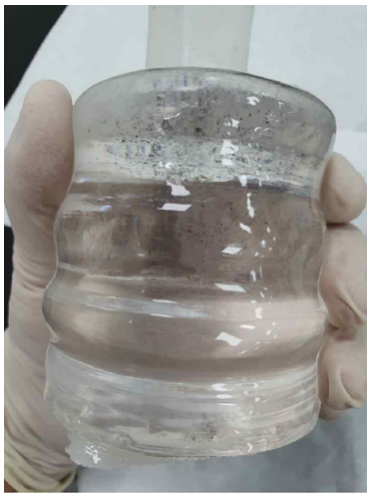


	K (ppb)	Pb (ppb)
Powder	<14	<300
Fume(old refractory)	1021000	10407
Fume(new refractory)	320	25
Mar/2019(NaI-024)	740	6
Sept/2019(NaI-034)	**8**	**0.4**
Nov/2019(NaI-035)	**13**	**2**

2018/Aug



2019/Sept

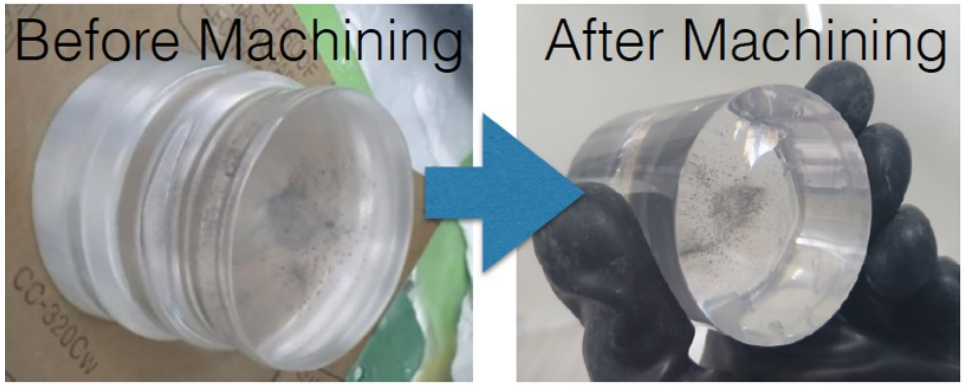


2019/Nov

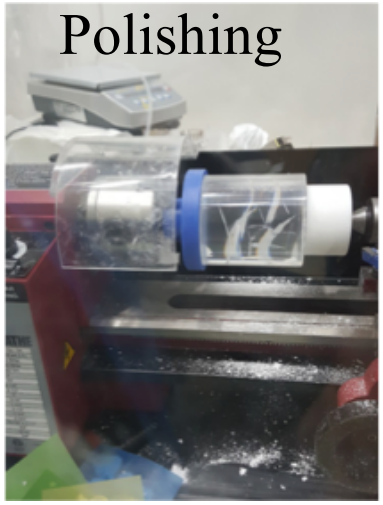
Crystal machining & detector assembly @ CUP

Machining

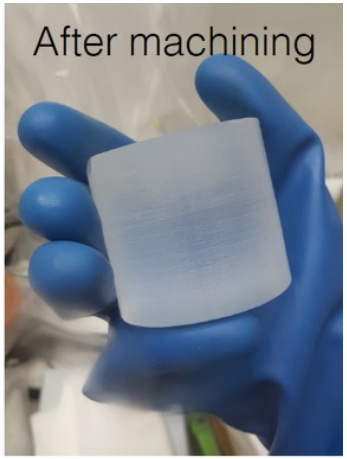
NaI-034 (Sept/2019)

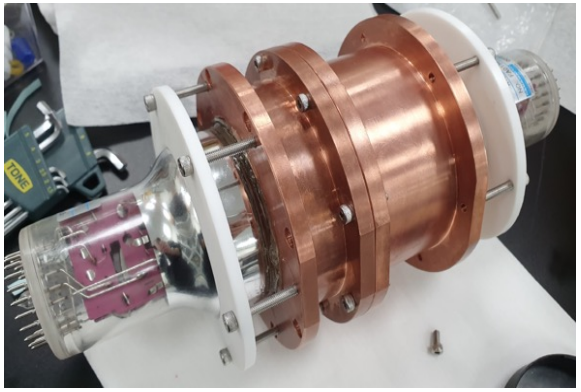


Polishing

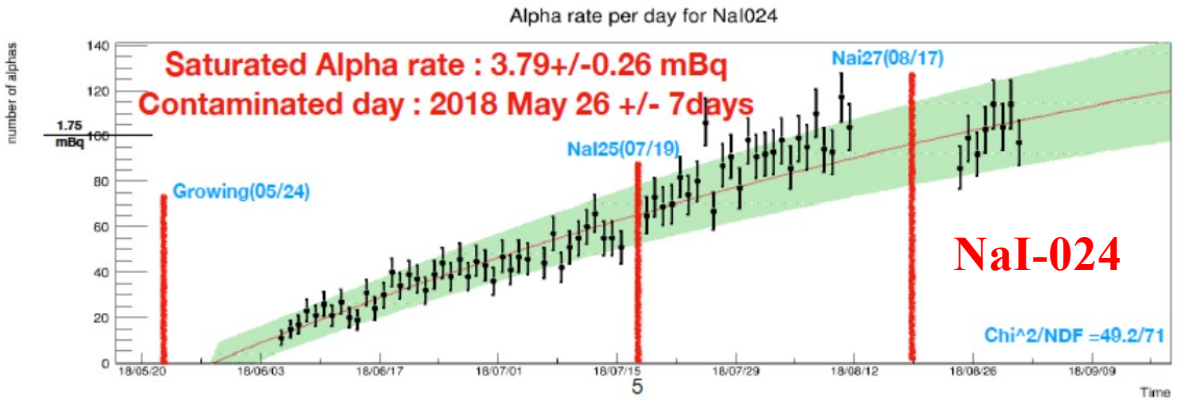


NaI-035 (Nov/2019)



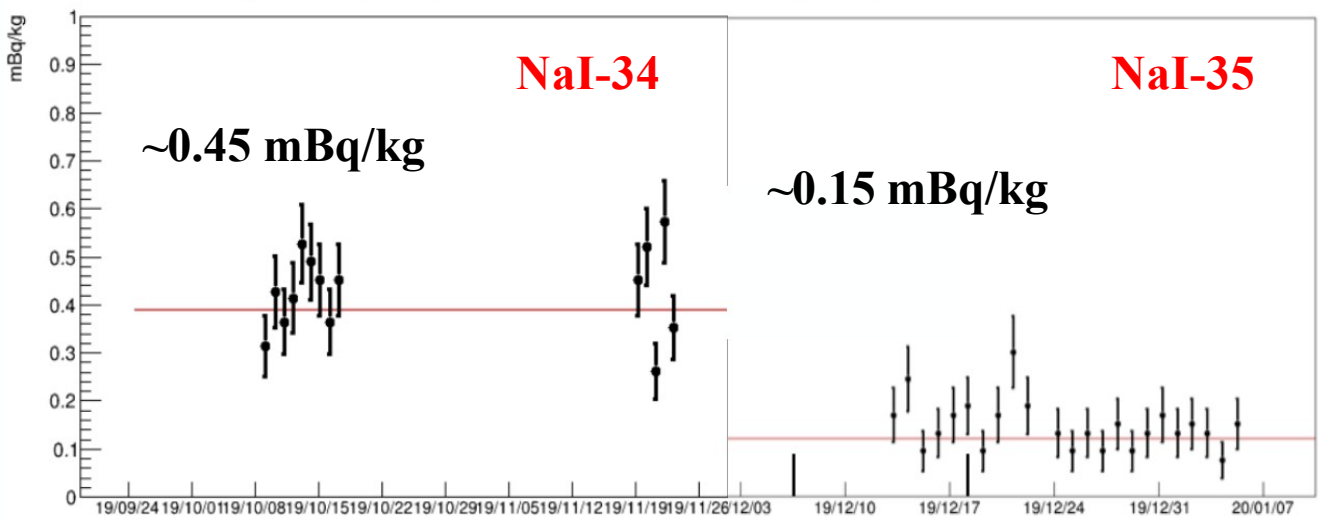


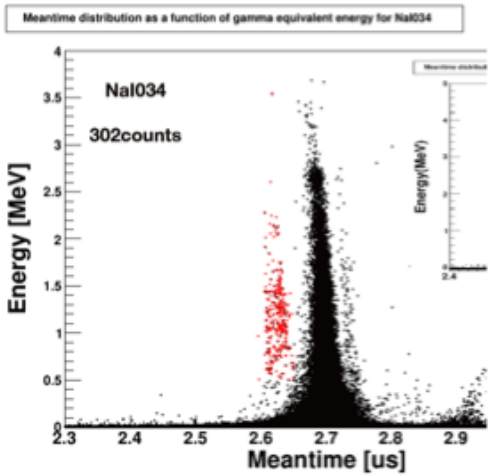
Underground measurements



Most of alpha from ^{210}Po

Preliminary

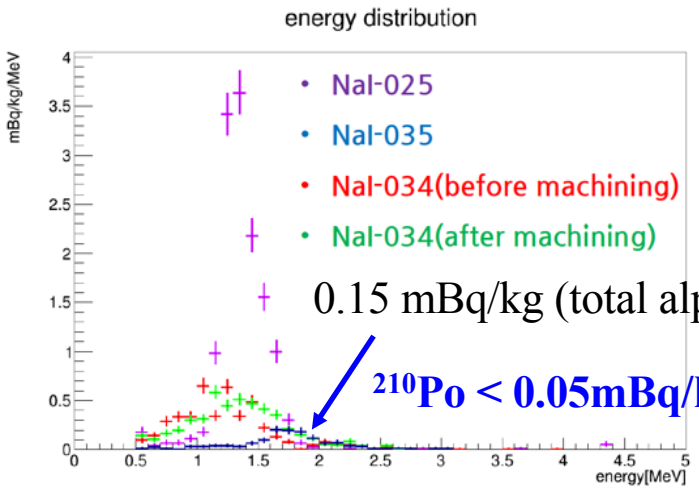




New crystals seem to have very low ^{210}Pb contamination.

Underground measurement (NaI-035)

^{210}Pb

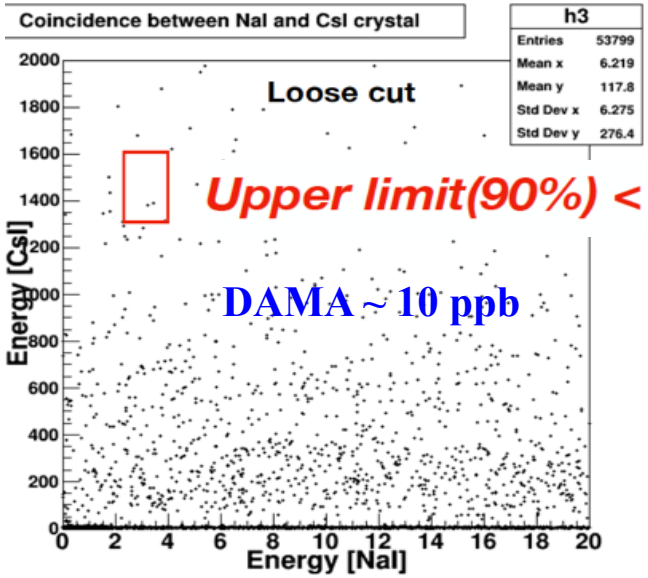


0.15 mBq/kg (total alpha)

^{210}Po < 0.05mBq/kg

DAMA ~ 0.05 mBq/kg

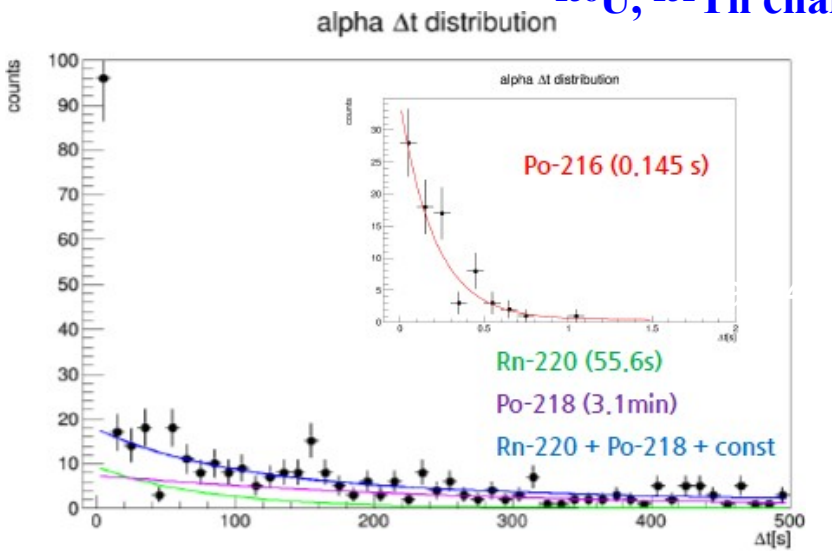
^{40}K

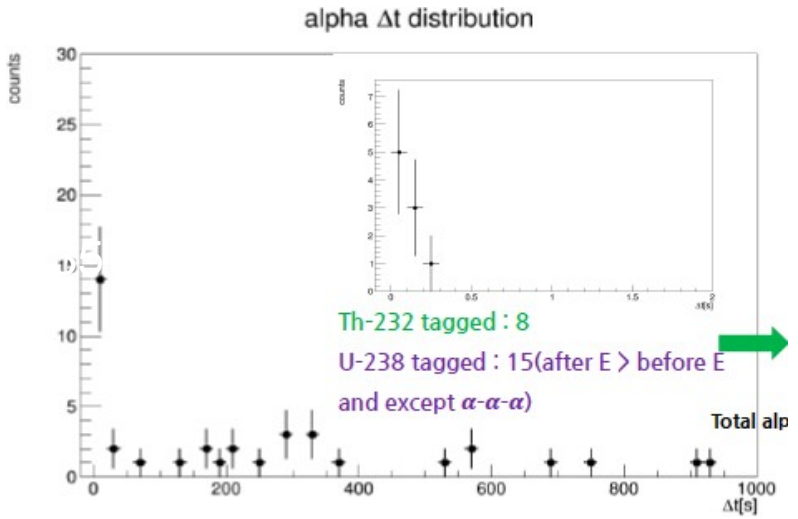


Upper limit(90%) < 11.66 ppb

DAMA ~ 10 ppb

^{238}U, ^{232}Th chain, alpha-alpha coincidence

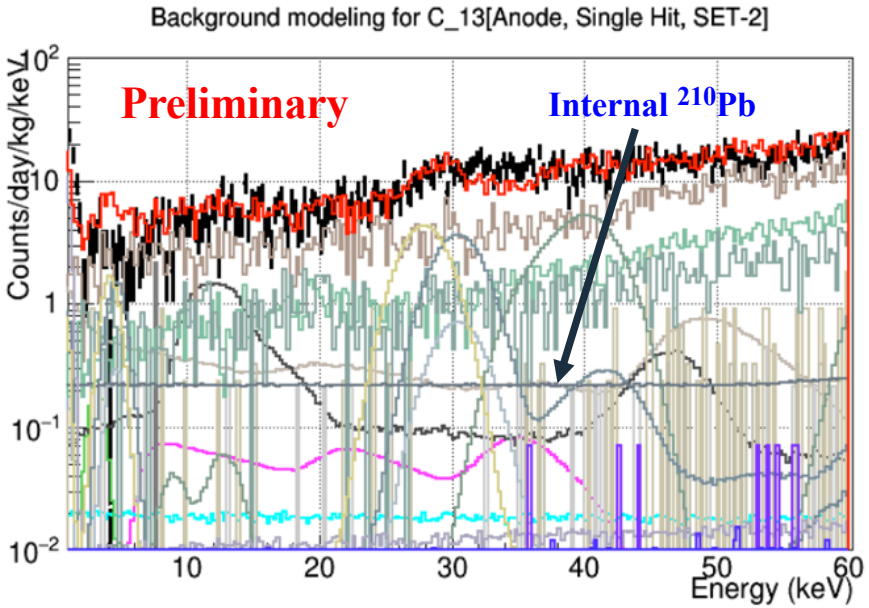




Underground measurement (NaI-035)

Preliminary

Crystal	Mass (kg)	Light (pe/keV)	^{232}Th (mBq/kg)	^{238}U (mBq/kg)	^{210}Po (mBq/kg)	40K (ppb)
NaI-034	0.666	~8.6	0.124	0.246	<0.07	<11.7
NaI-035	**0.613**	**~11.0**	**0.025**	**0.035**	**<0.08**	**<17.0**
				DAMA	**0.05**	**13**

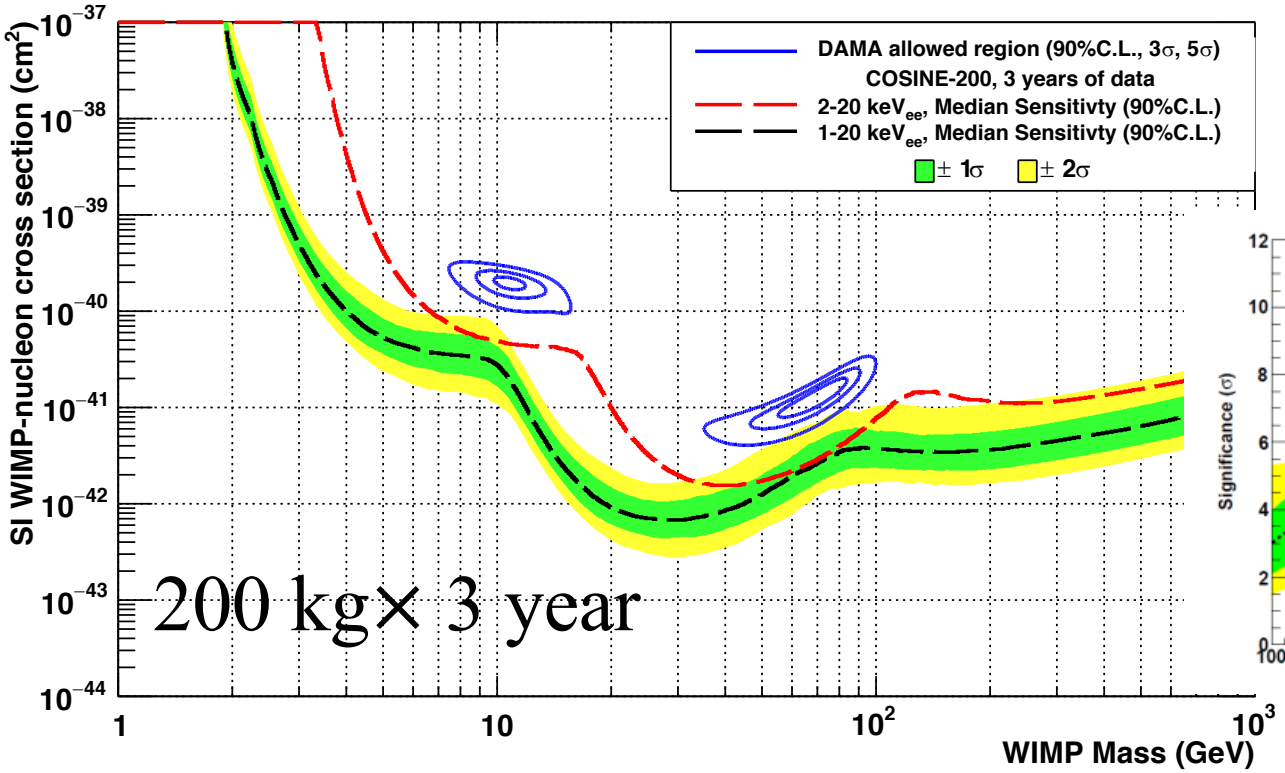


- We achieved level of DAMA/LIBRA
  - <0.5 dru seems to be achieved!!
- External & cosmogenic are dominant components
  - This will be reduced with full-sized detector & COSINE shield
- Need to optimize Tl concentration

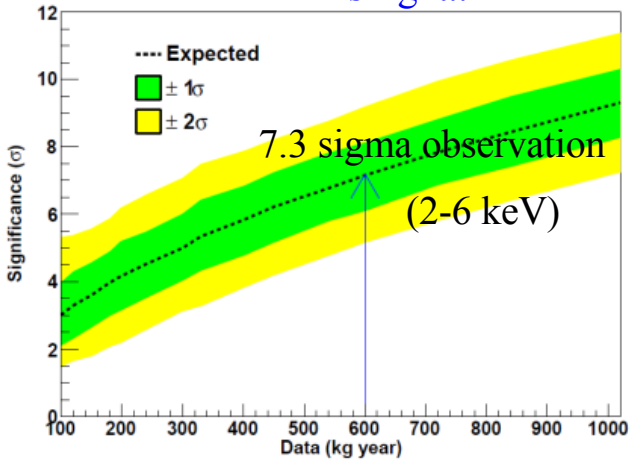
Both ^{40}K and ^{210}Po are low for the recently grown crystal, well controlled growing environment !! → Ready to grow Big crystals, ~ 100 kg.

COSINE-200 sensitivity (Modulation)

- Background $\leq$ 1 dru, threshold $\leq$ 1keV are achievable goal.
- Hope to close in DAMA/LIBRA conundrum in 3 years.
- This should be model independent check for DAMA/LIBRA signal regardless of kinds of interactions.

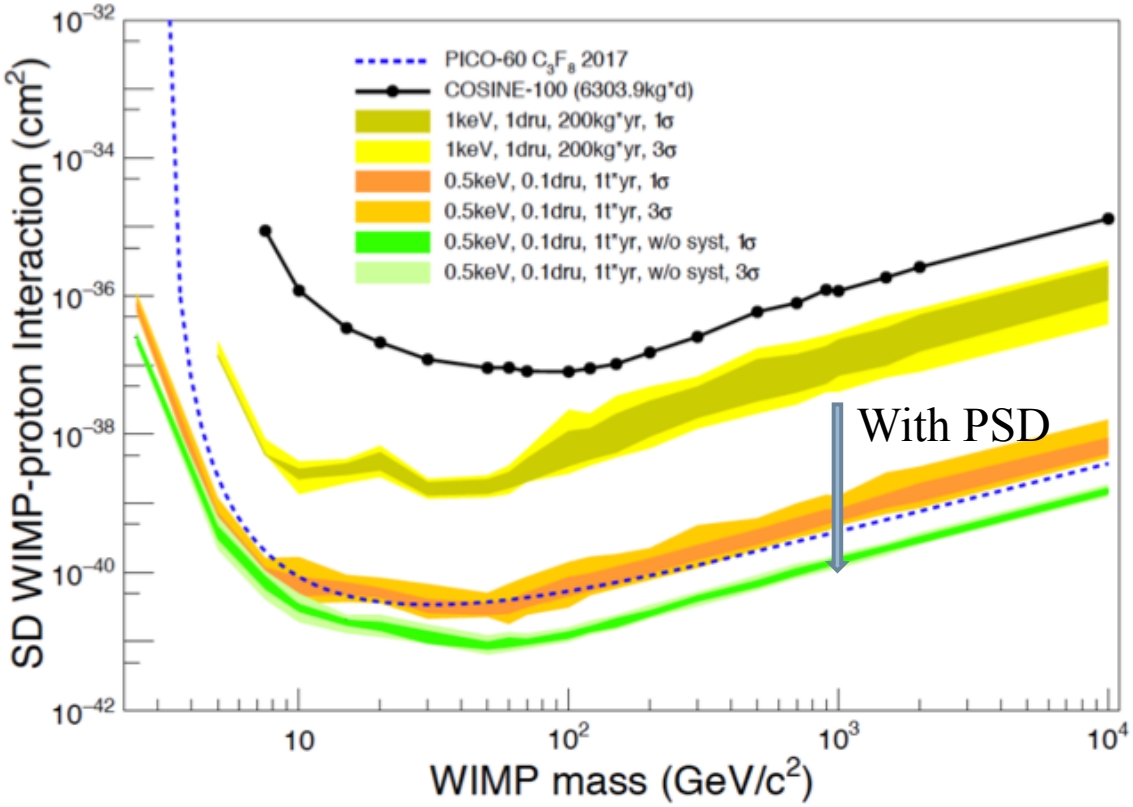


If DAMA is right..

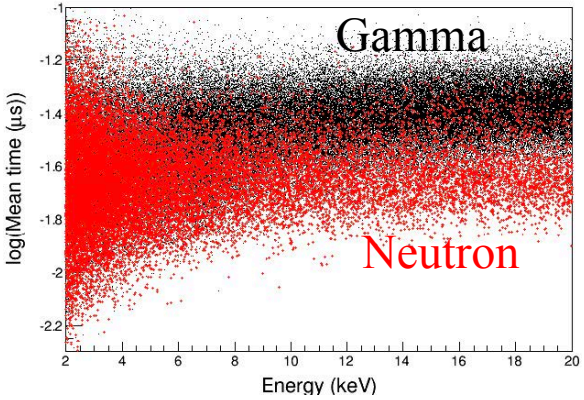


Further .. in addition to checking DAMA/LIBRA signal

- NaI(Tl) crystal is a unique target for WIMP-proton interaction except PICO.
- We can compete with next generation PICO experiment both at a few GeV WIMPs and high mass WIMPs with PSD.



Good PSD at high energy with NaI(Tl) crystals



Summary

- **COSINE-100 experiment ;**
  - **has been running smoothly for more than 3 years.**
  - **rejects DAMA/LIBRA results within the SHM.**
  - **will soon present new modulation and background results with 1 keV threshold.**
- **COSINE collaboration ;**
  - **has successfully produced NaI crystals with lower ^{210}Pb & ^{40}K backgrounds for COSINE-200.**
  - **is confident in finding out the cause of DAMA/LIBRA modulation signal with new detectors.**

Stay tuned, new results are coming soon !!