



The
University
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Update on dark matter searches after five years of data taking in NaI crystals at COSINE-100

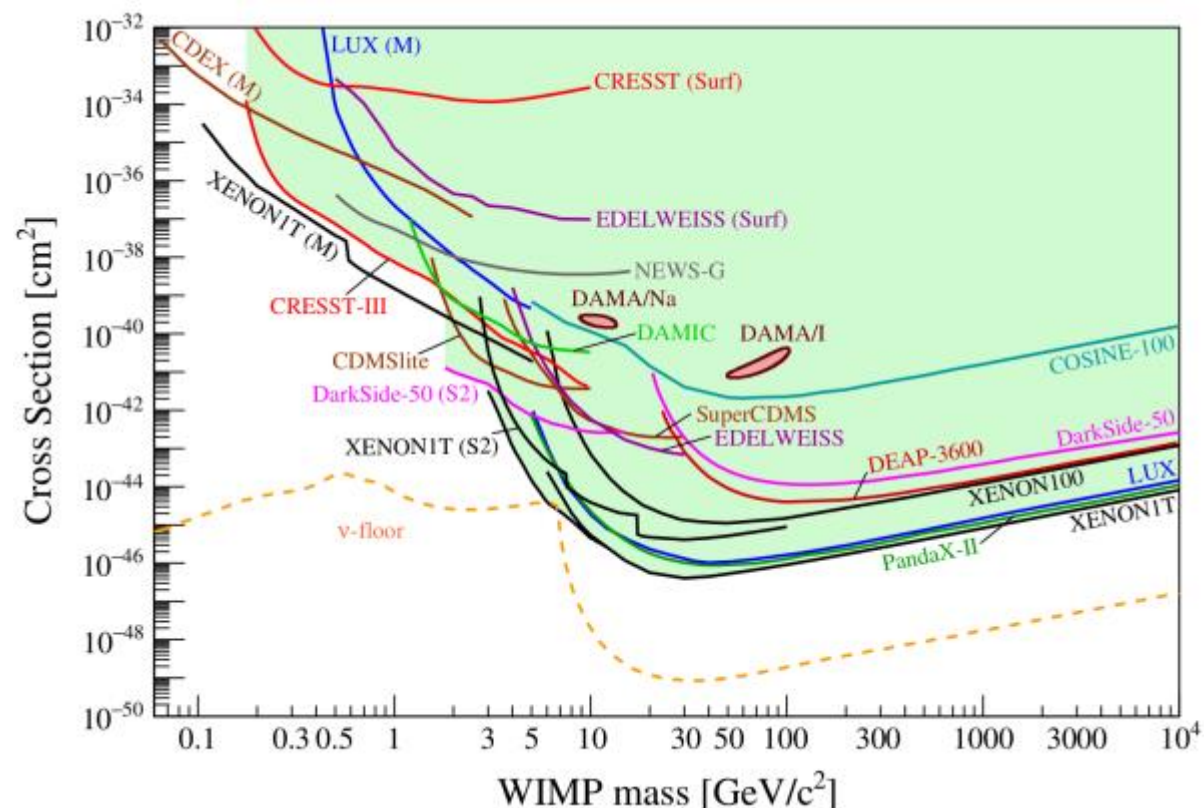
Robert. J. Neal.

University of Sheffield

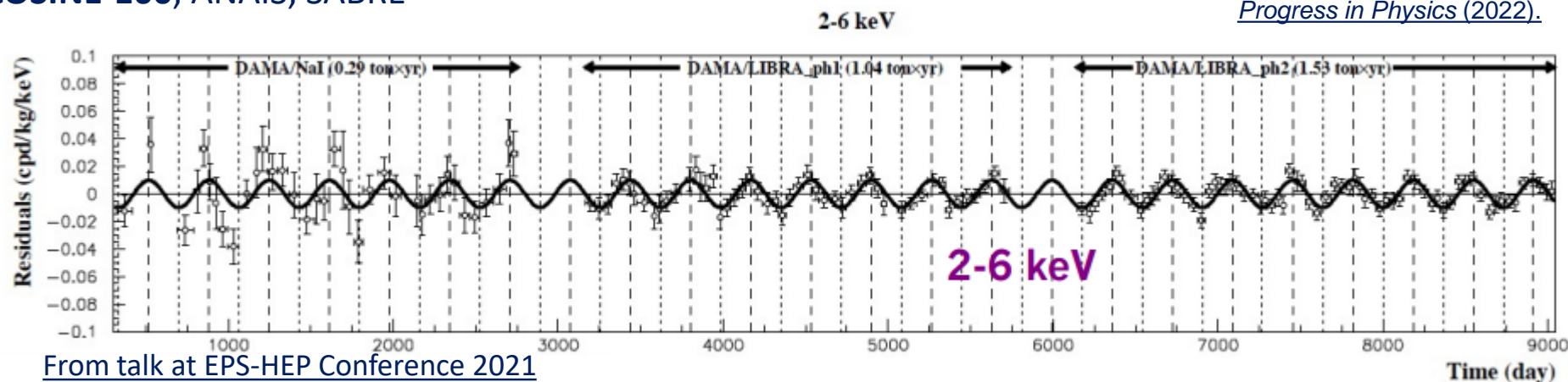
On behalf of the COSINE Collaboration

Motivation

- Many experiments have searched for experimental evidence of dark matter but **none have succeeded yet**
- An exception is the DAMA experiments** which report an **annual modulation signal in NaI crystals** consistent with dark matter
 - Extremely high confidence level (arXiv:1805.10486v2)
 - Two decades of data taking
- Model independent test** of the DAMA signal is required to resolve tension
 - COSINE-100, ANAIS, SABRE**



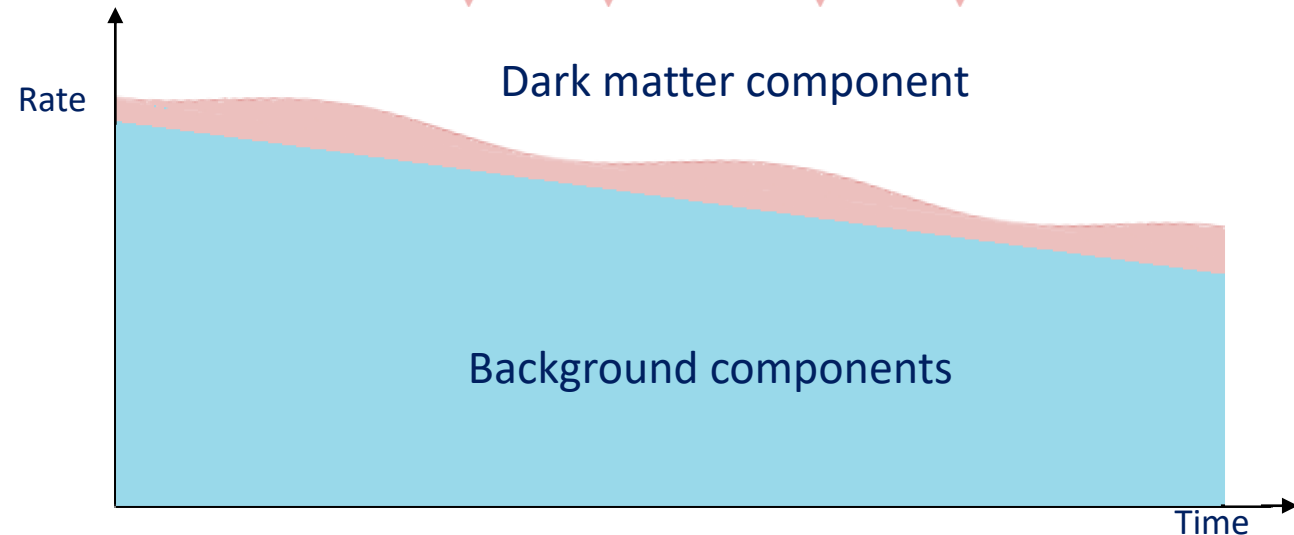
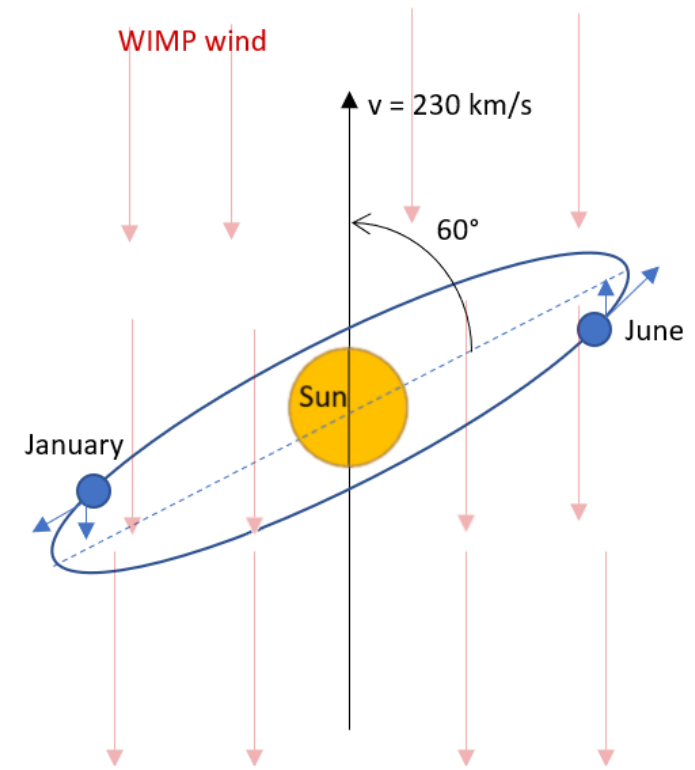
Billard, Julien, et al. "Direct detection of dark matter–APPEC committee report." *Reports on Progress in Physics* (2022).



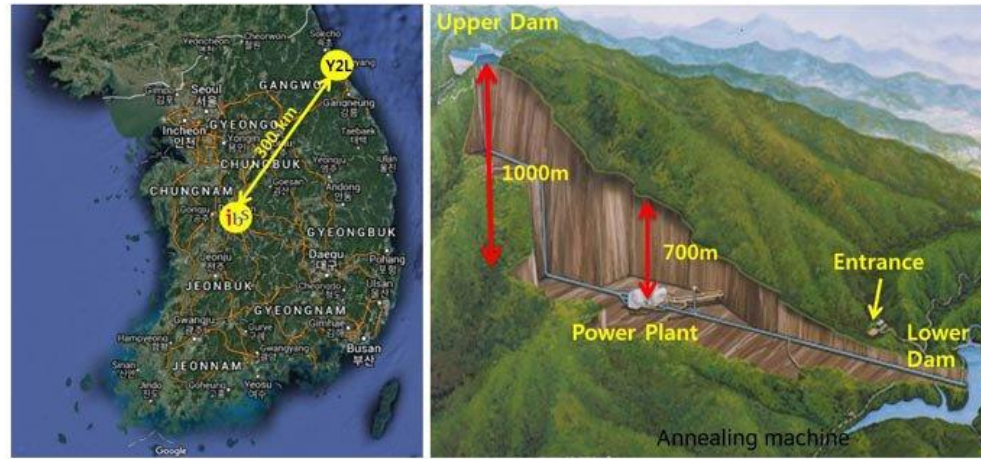
From talk at EPS-HEP Conference 2021

Annual modulation

- Given a spherical halo of dark matter in the Milky Way that is not co-rotating with the galaxy, a **flux of dark matter is expected in the Solar System** (aka “WIMP wind”)
- Earth orbits the Sun at an angle relative to this flux. Therefore **an annual modulation of the dark matter flux on Earth is expected**
 - Claimed origin of DAMA signal



COSINE-100

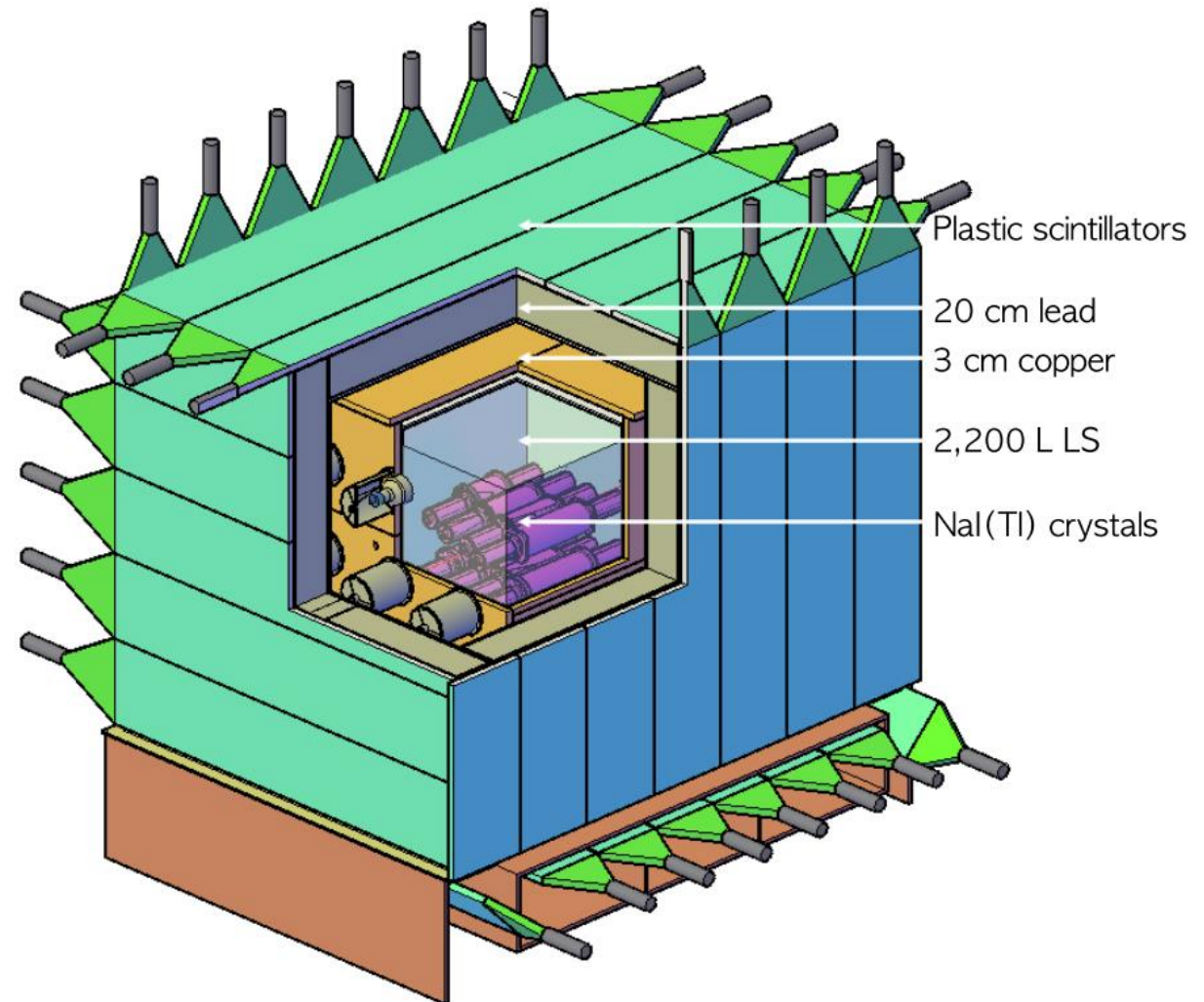


- Formed out of the KIMS and DM-Ice experiments and based at the **Yangyang Underground Laboratory** in South Korea
 - 700 m rock overburden
- Approx 150 km from Seoul and 300 km from Daejeon (location of the Institute for Basic Science)
- Operational since 2016



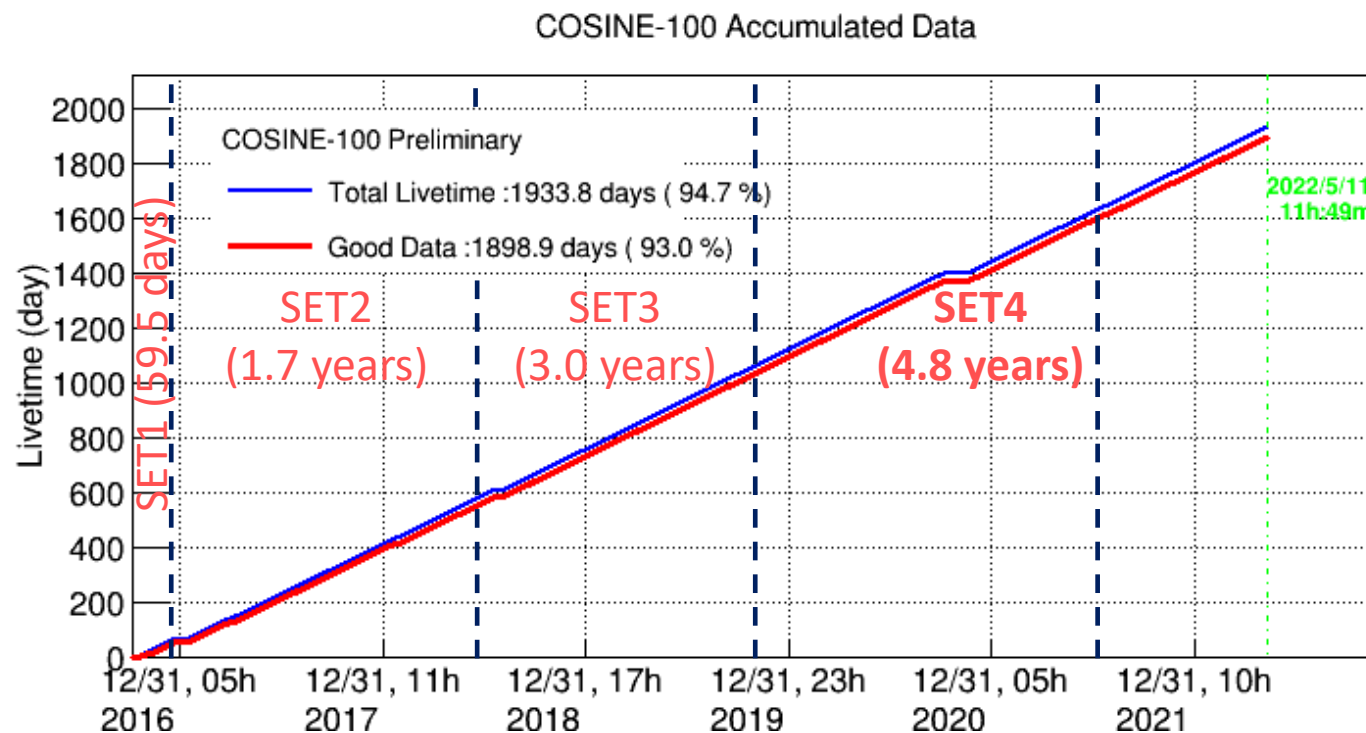
COSINE-100 detector

- 8 high-purity NaI(Tl) crystals
 - Total mass 106 kg
 - ~ 15 p.e/keV
 - Two PMTs per crystal
- Liquid scintillator active veto
 - 2200 L volume
 - Outfitted with 18 PMTs
 - Signals with LS coincidence are vetoed for DM searches
- Copper (3 cm) and lead (20 cm) passive shielding
- Plastic scintillators for 4π active muon veto
 - 37 panels
 - Also veto signals with muon coincidence in DM searches
- Constant monitoring of environmental variables
- Fully upgradable to COSINE-200



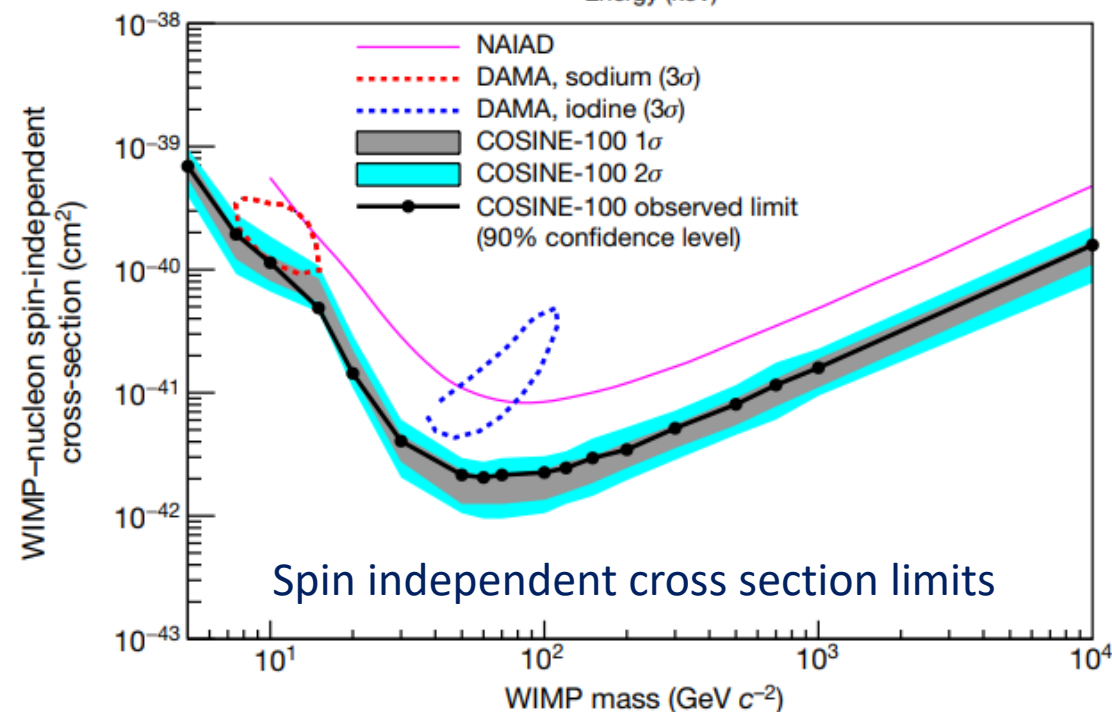
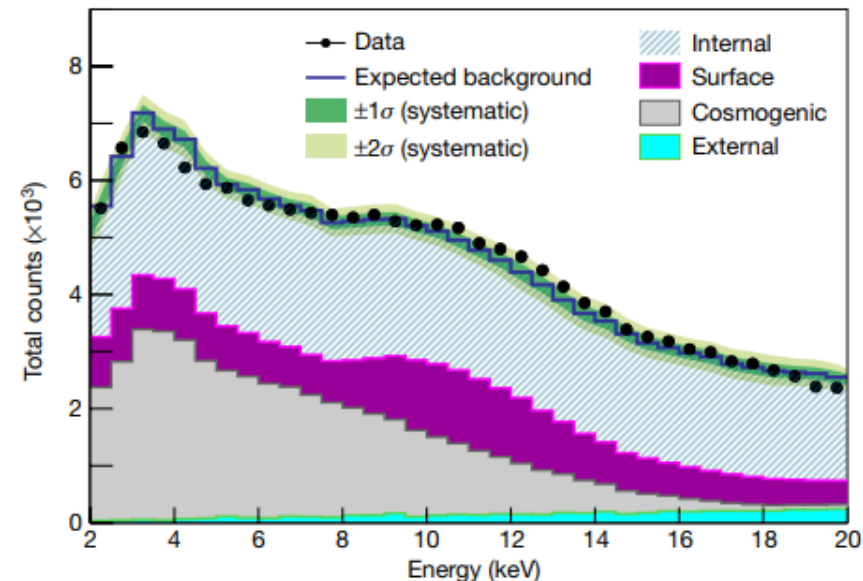
Detector operation

- Mostly continuous operation since October 2016
 - Three short breaks for calibration runs (two ^{60}Co and one ^{22}Na)
- Continuous monitoring of detector and environmental variables
- **~93% good data**
 - Losses due do muon events, calibration runs, power outages etc



First dark matter search

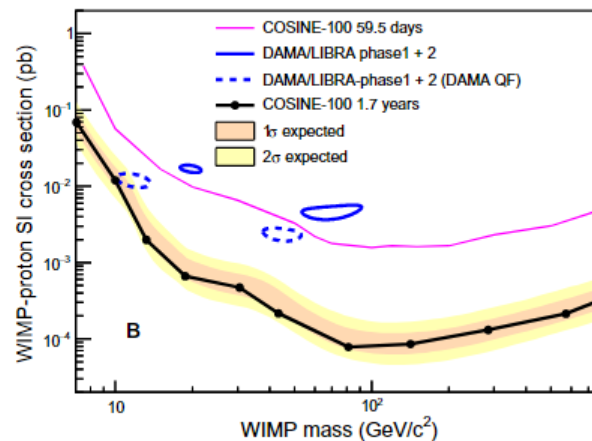
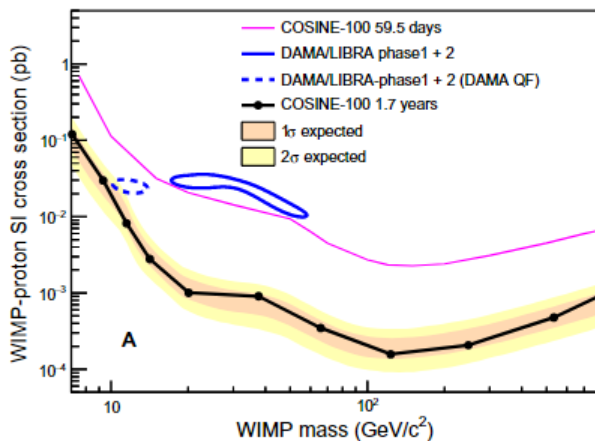
- Model dependent search with **59.5 days of data** (single-hit data)
 - [The COSINE-100 Collaboration. An experiment to search for dark-matter interactions using sodium iodide detectors. *Nature* **564**, 83–86 \(2018\)](#)
- **Excludes DAMA in terms of spin-independent interactions between WIMPs and sodium or iodine in the context of the standard halo model**
 - **Not an annual modulation (model independent) search**



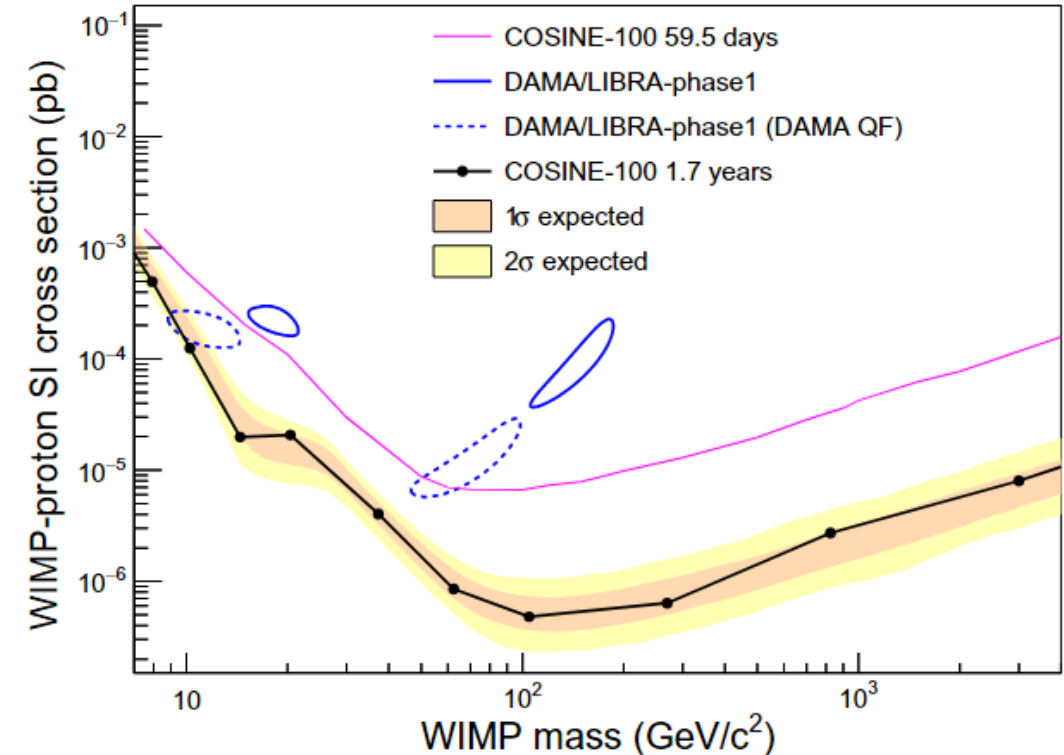
Further model dependent search (1.7 years data)

- Uses lowered 1 keV low energy threshold and improved background model as in 3 years annual modulation search
- **Fully excludes DAMA with alternative WIMP EFT operators and QFs**

Proton spin-independent cross section for isospin violating interaction



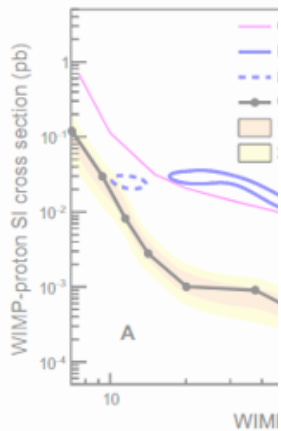
WIMP nucleon spin-independent cross section for isospin conserving interaction



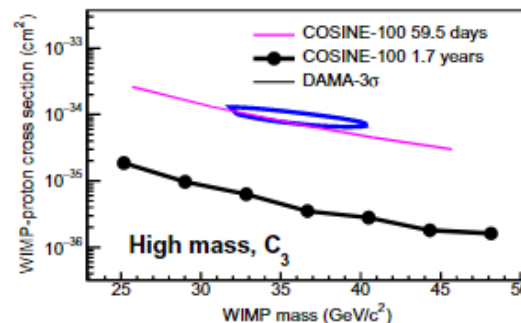
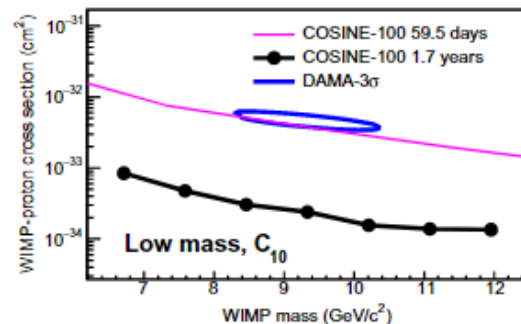
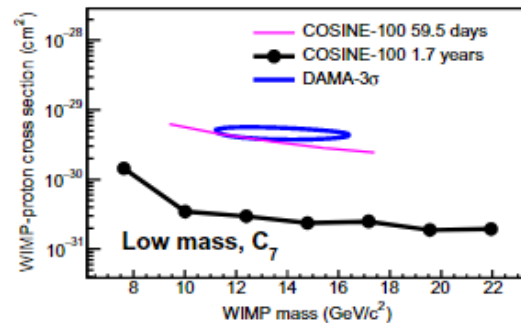
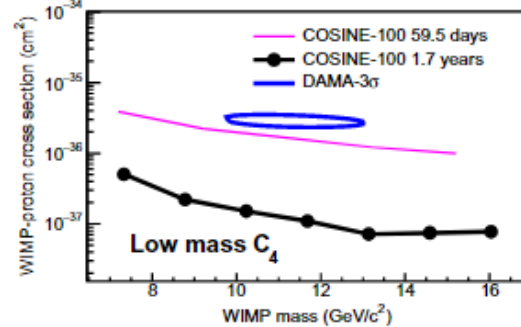
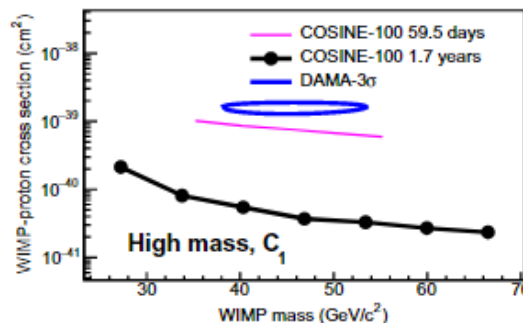
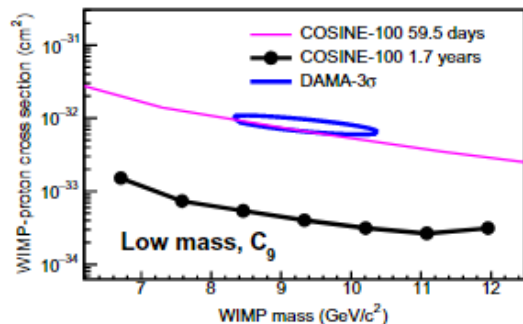
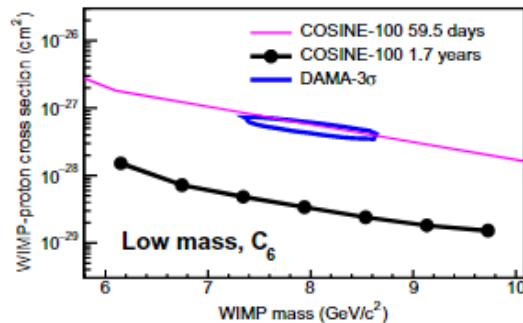
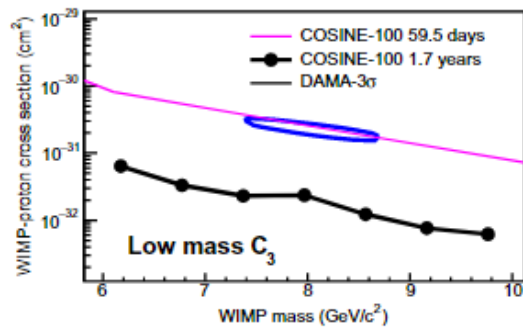
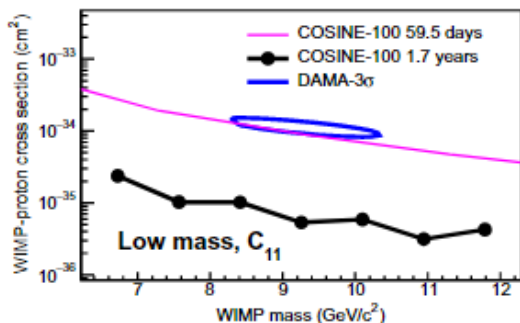
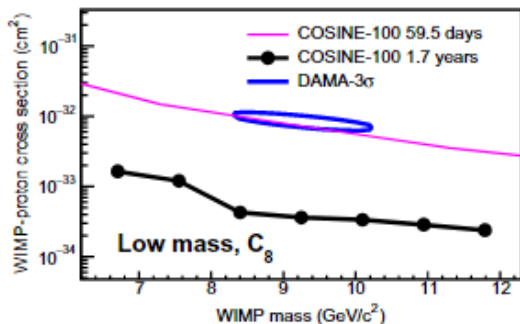
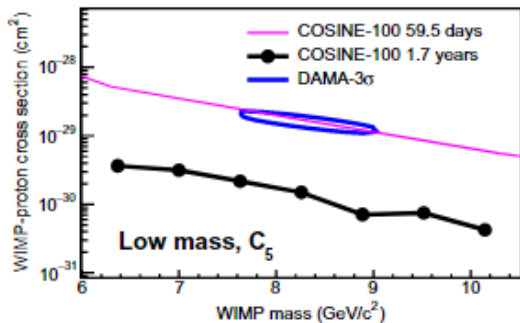
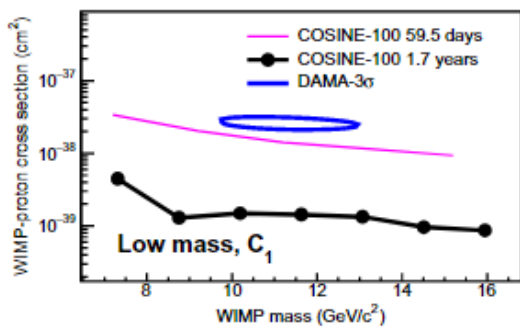
COSINE-100, Strong constraints from COSINE-100 on the DAMA dark matter results using the same sodium iodide target, Science Advances 7, 46, (2021)

Further

- Uses 100 GeV threshold model search
- Fully efficient WIMP



ICHEP 2022



data)

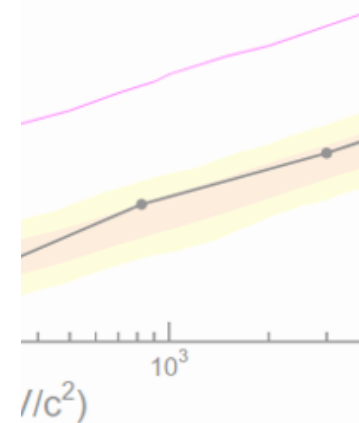
ident cross
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5 days

ase1

ase1 (DAMA QF)

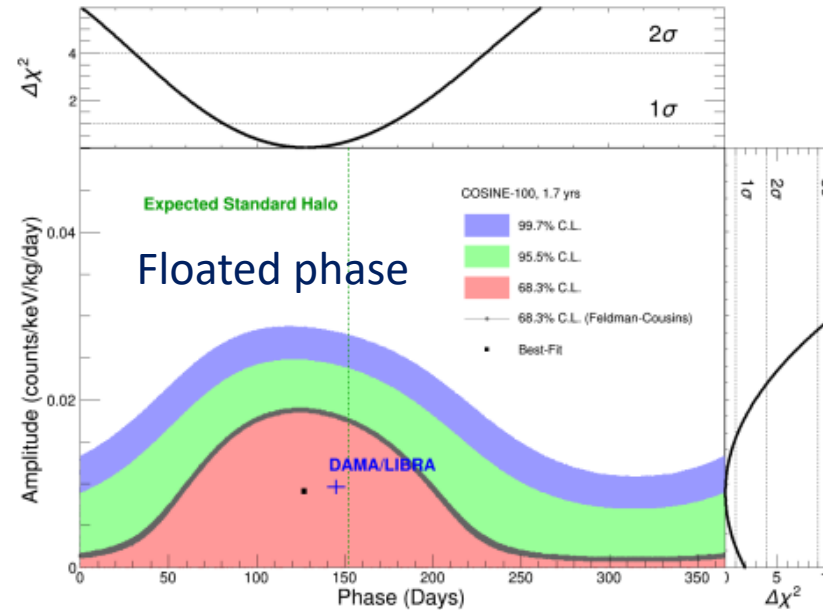
years



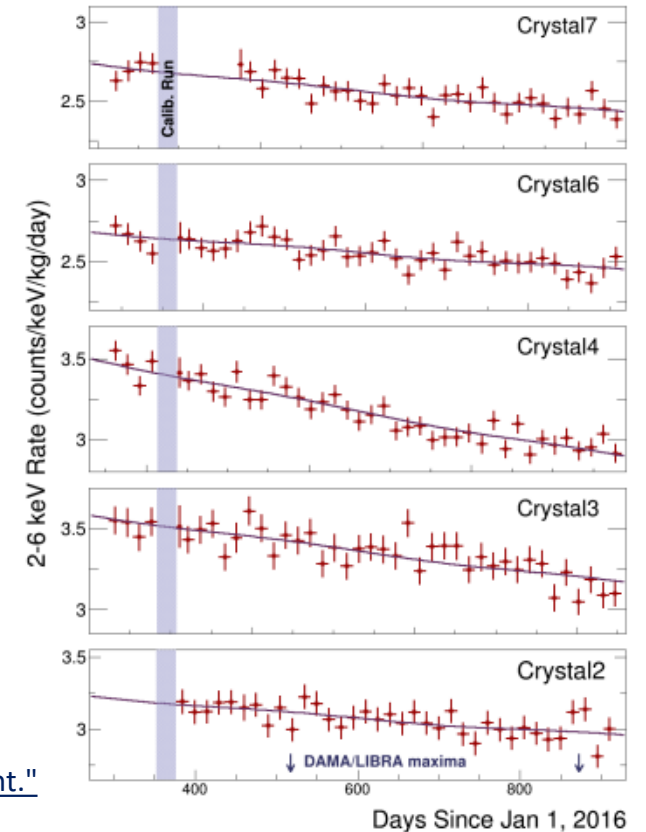
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First annual modulation search (1.7 years data)

- 2-6 keV energy range searched
- Consistent with both DAMA and null hypotheses
- Modulation amplitude of 0.0092 ± 0.0067 counts/day/kg/keV and phase of 127.2 ± 45.9 day for floated phase fit



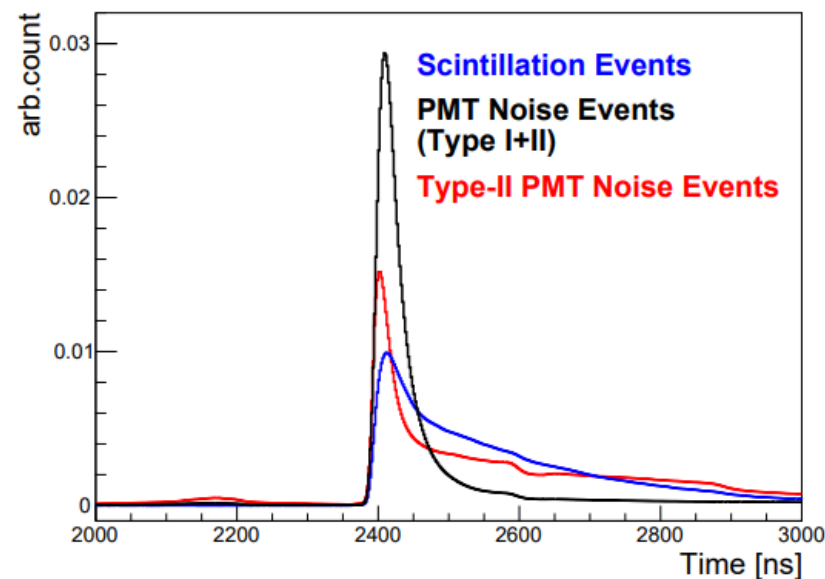
Adhikari, G., et al. "Search for a dark matter-induced annual modulation signal in NaI (TI) with the COSINE-100 experiment." *Physical review letters* 123.3 (2019): 031302.



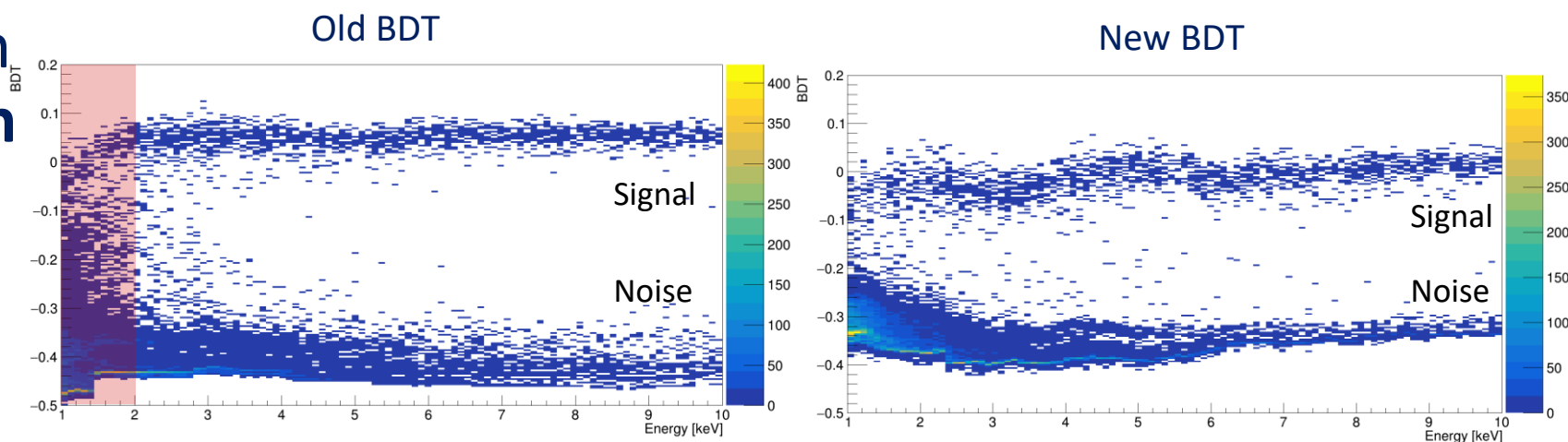
Configuration	χ^2	DOF	p-value	Amplitude (cpd/kg/keV)	Phase (d)
COSINE-100	175.3	174	0.457	0.0092 ± 0.0067	127.2 ± 45.9
DAMA/LIBRA (Phase1+Phase2)	0.0096 ± 0.0008	145 ± 5
COSINE-100	175.6	175	0.473	0.0083 ± 0.0068	152.5 (fixed)
COSINE-100 (Without LS)	194.7	175	0.147	0.0024 ± 0.0071	152.5 (fixed)
ANAIS-112	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)

Improvements for second annual modulation search

- Low energy threshold lowered from **2 keV to 1 keV**
 - New parameter based on likelihood of event waveform compared with **signal and noise templates**
 - This likelihood parameter is used in the training of an **updated BDT** variable, effective to 1 keV
- BDT training samples taken from **^{60}Co calibration run** (signal) and physics run (noise)



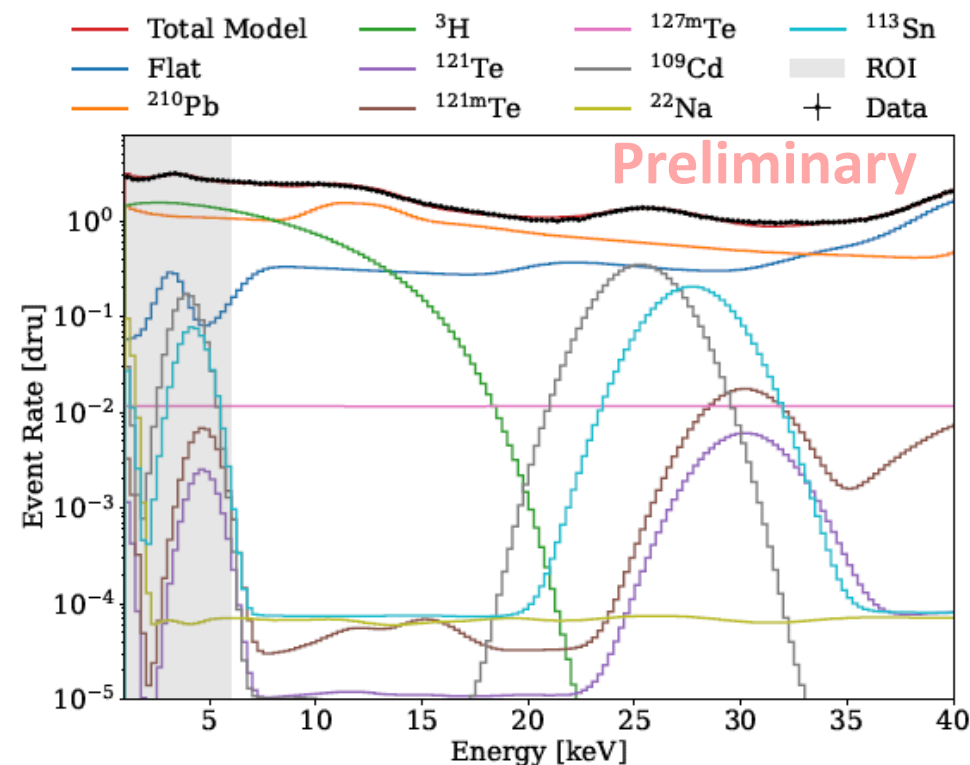
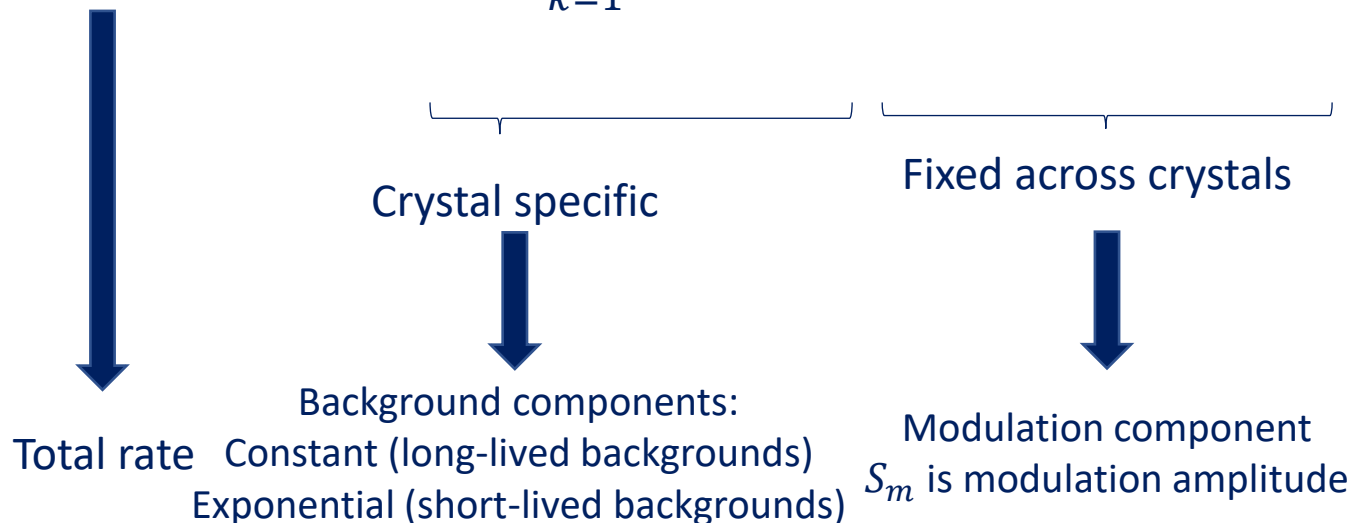
COSINE-100, Lowering the energy threshold in COSINE-100 dark matter searches [Astroparticle Physics 130 \(2021\): 102581](#)



Improvements for second annual modulation search

- **Background model updated** from one used in 1.7 years search
 - Gives improved and more accurate fit
- Fitting method changed from considering a **single exponential background model to each short-lived component being considered separately**

$$R_i(t|S_m, \alpha_i, \beta_i) = \alpha^i + \sum_{k=1}^{N_{bkgd}} \beta_k^i e^{-\lambda_k t} + S_m \cos(\omega(t - t_0))$$



- Updated background model created using first 1.7 years of data
- Geant4 used for MC simulations
- ["Background modeling for dark matter search with 1.7 years of COSINE-100 data." *The European Physical Journal C* 81.9 \(2021\): 1-9.](#)

Three years modulation search fitting

- Bayesian fitting approach
- Fitting procedure **verified with pseudo-data**
- Data normalised by live-time and efficiency in **15 day bins** before fitting

$$R_i(t|S_m, \alpha_i, \beta_i) = \alpha^i + \sum_{k=1}^{N_{bkgd}} \beta_k^i e^{-\lambda_k t} + S_m \cos(\omega(t - t_0))$$

Crystal specific

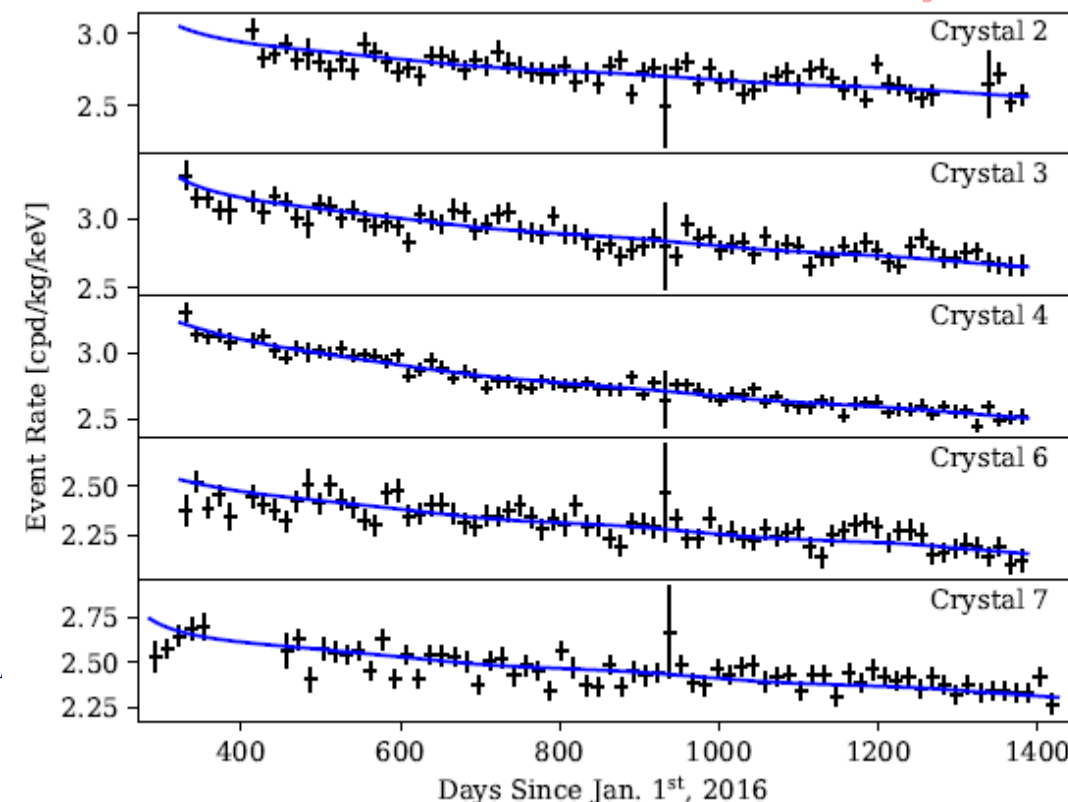
Fixed across crystals

Background components:

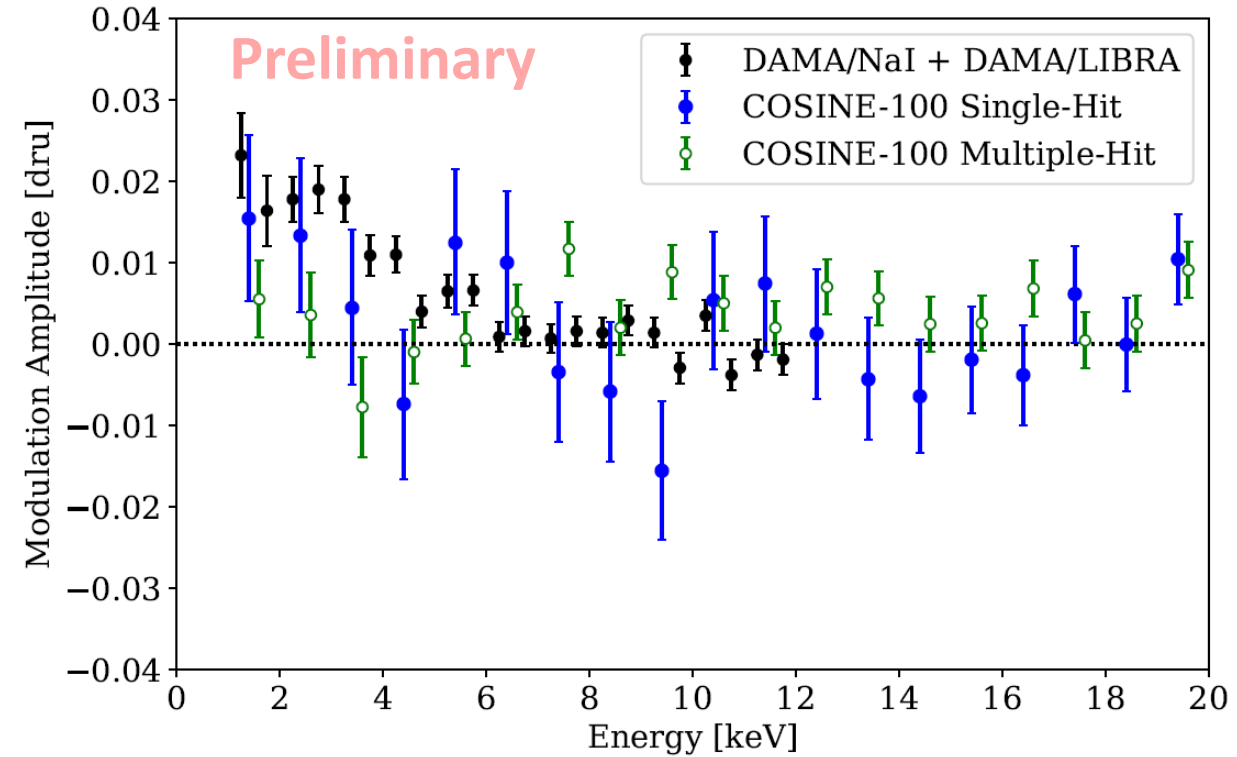
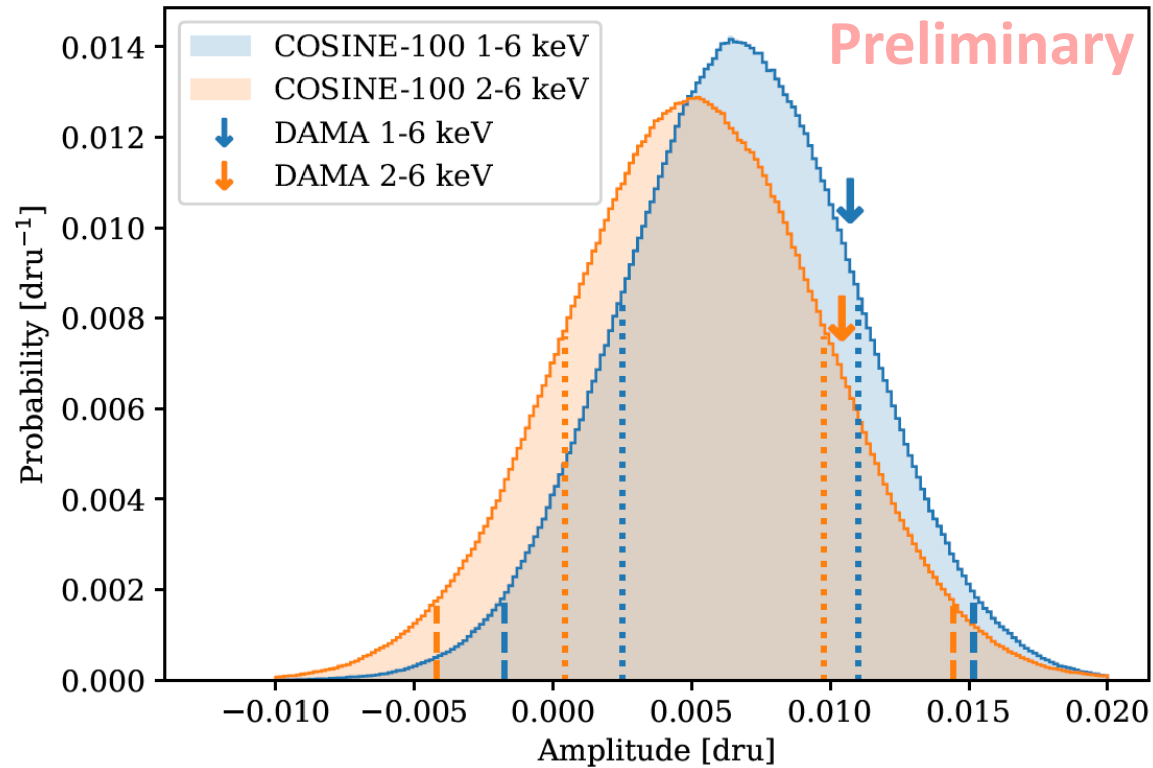
Total rate Constant (long-lived backgrounds)
Exponential (short-lived backgrounds)

Modulation component
 S_m is modulation amplitude

Preliminary

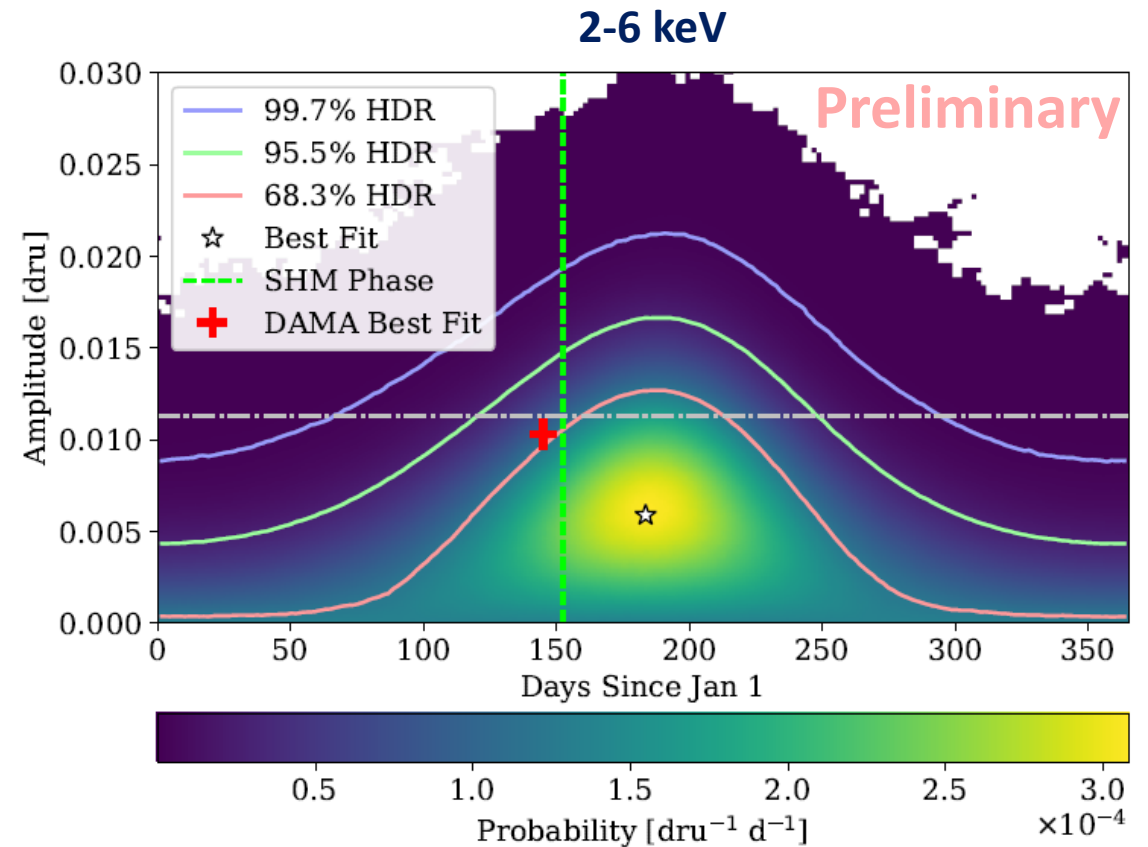
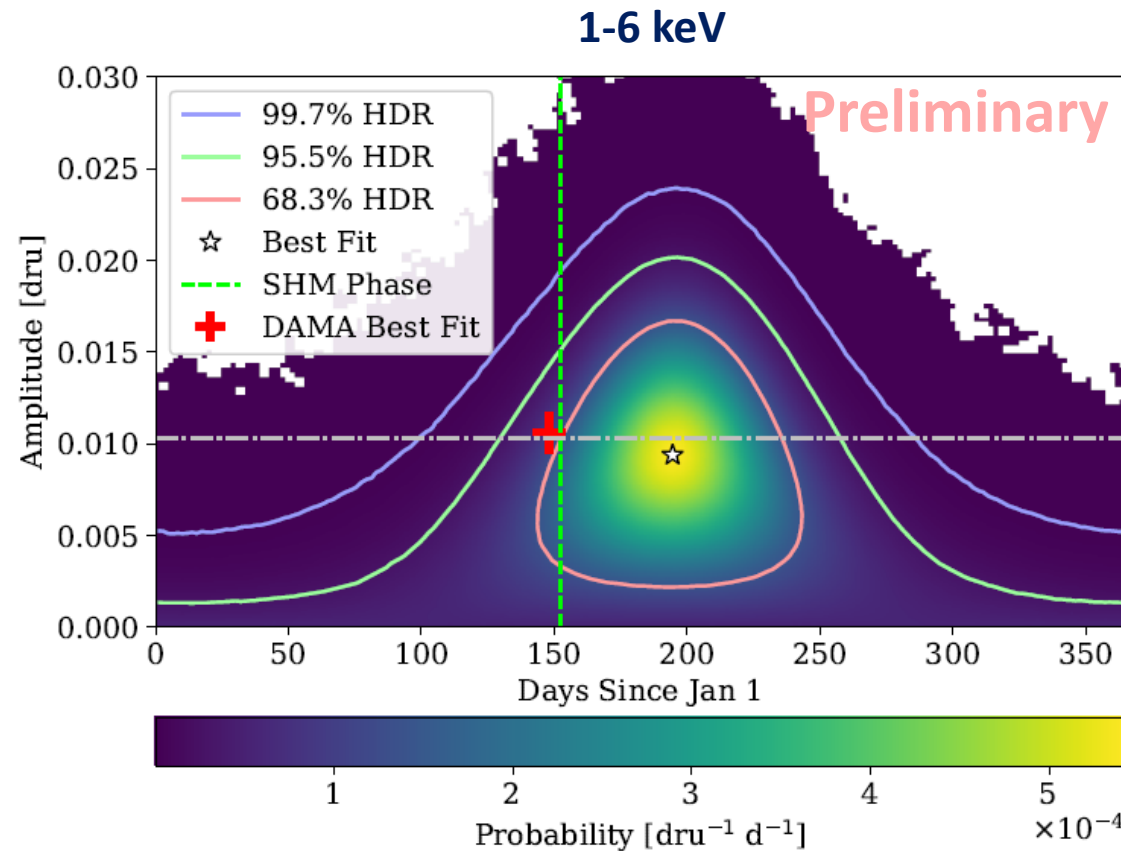


Three years modulation search results (fixed phase)



- **Best-fit modulation amplitude of 0.0067 ± 0.0042 counts/day/kg/keV at 1-6 keV with phase fixed at 152.5 days**
- **Also consistent with both DAMA and null hypothesis**
- **No modulation seen in sidebands**
- [Three-year annual modulation search with COSINE-100 arXiv:2111.08863](#)

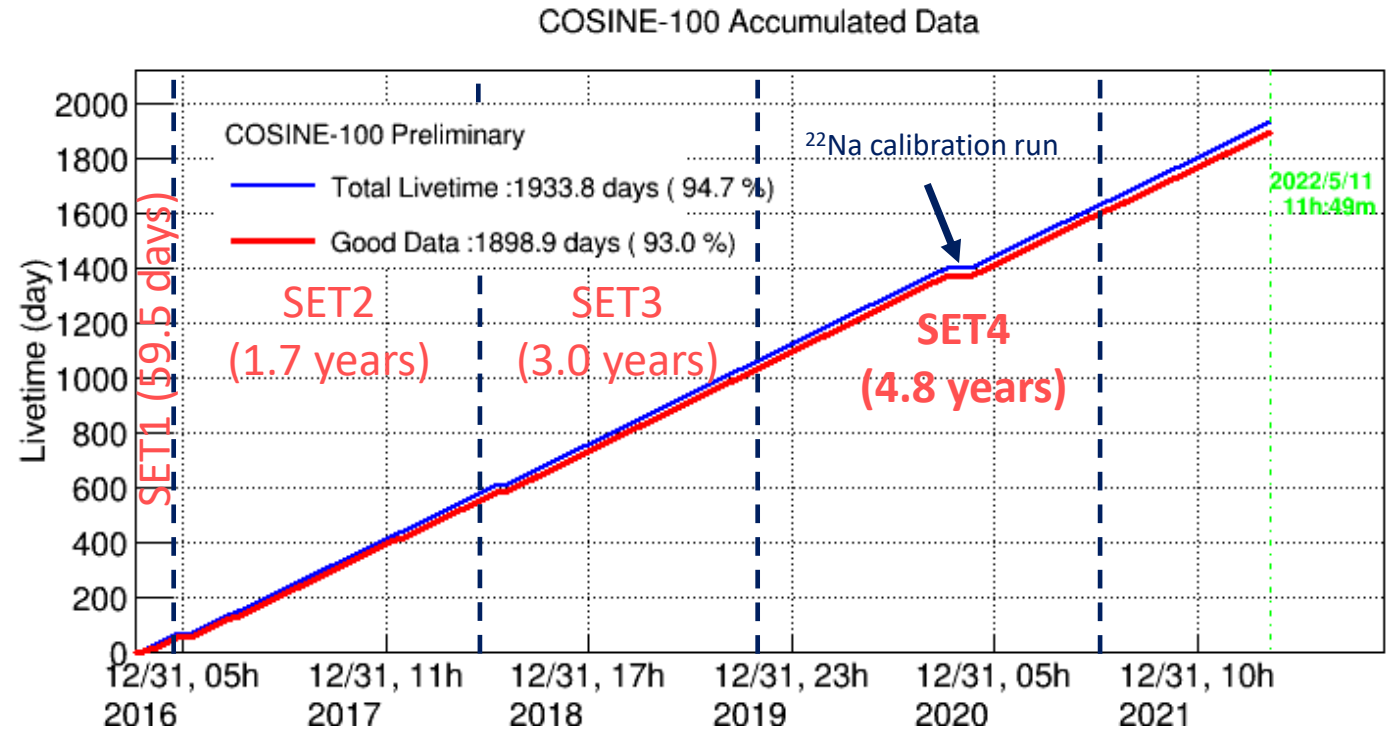
Three years modulation search results (floated phase)



- Also search for a modulation with phase floated
- **Best fit modulation amplitude of $0.0094^{+0.0073}_{-0.0072}$ counts/day/kg/keV and phase of $194.5^{+49.0}_{-50.5}$ days for 1-6 keV**
- **Again consistent with both modulation and null hypotheses**

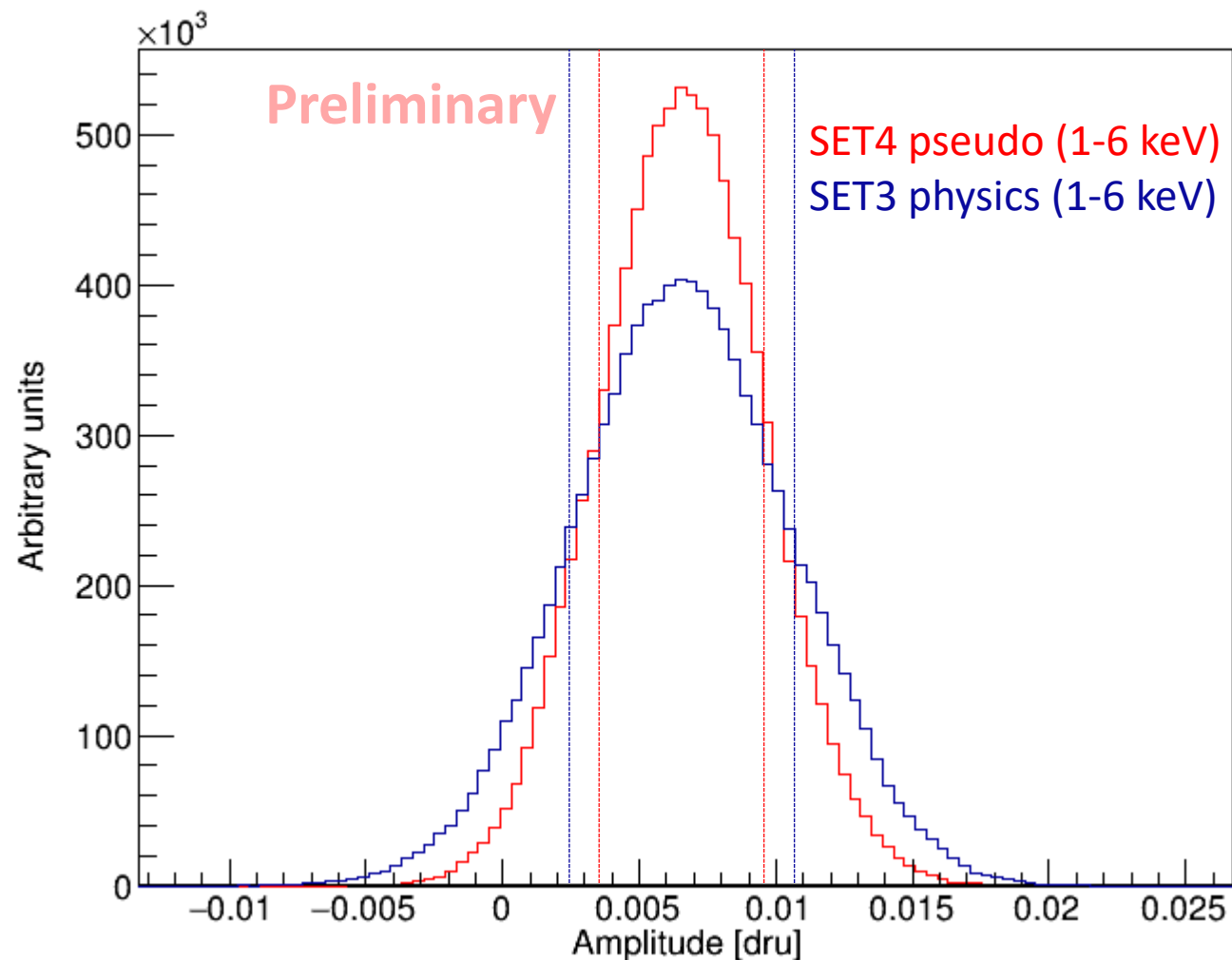
Improvements for third annual modulation search

- Work currently underway on further **lowering of low energy threshold to 0.5 keV**
 - **Significantly updated BDT** focussed on rejection of low energy noise events
 - Signal training sample comes from 6 week **^{22}Na calibration run**
- Fitting method and background model also tweaked



Projected improved sensitivity 3 years -> 4.8 years

- Using pseudo-data, improved **sensitivity for 1-6 keV ROI in 4.8 years data has been estimated**
- Posteriors for SET3 physics data and SET4 pseudo data (both 1-6 keV) shown
- Expected decrease in uncertainty in best fit modulation amplitude **from ± 0.0042 to ± 0.0031 cpd/kg/keV**

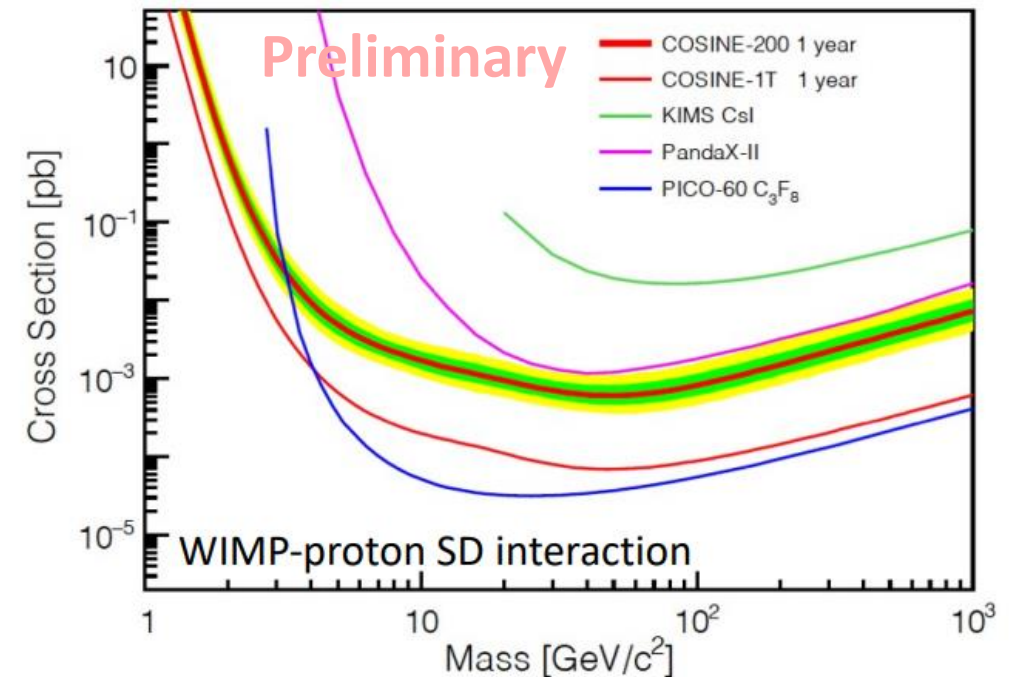
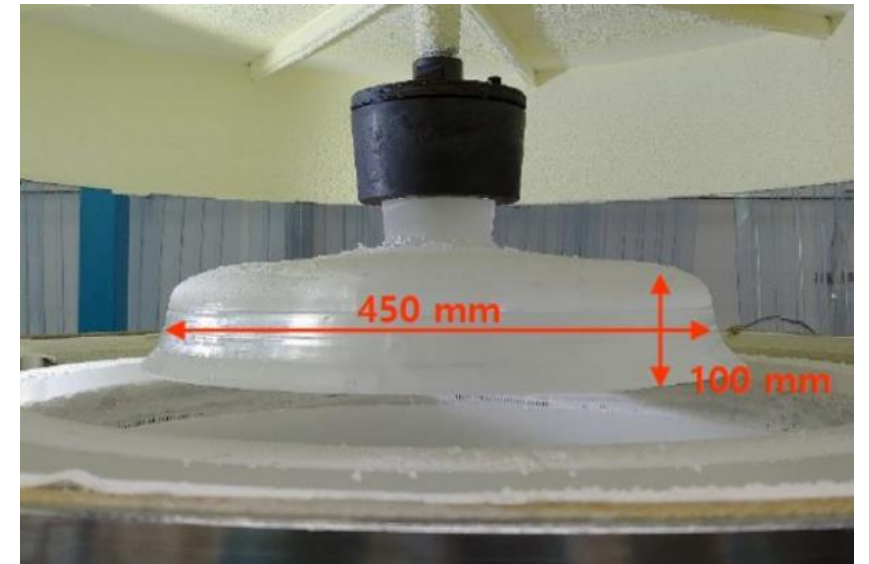


Other physics efforts with COSINE-100

- Using COSINE-100 data to test DAMA background subtraction method (see poster by Hafizh Prihtiadi)
- Searches for WIMPs via the Migdal effect
- Muon rate studies
- Studies of novel radio-isomers
- Searches for exotic DM
 - Inelastic boosted DM
 - Solar axions
 - Bosonic super-WIMPs

Beyond COSINE-100

- COSINE-100 apparatus is designed with **upgrade to 200 kg of NaI possible with minimal alteration**
- **In house crystal growth** with goal of similar or lower background than DAMA
 - Currently ~2-3 times higher background than DAMA
- Novel crystal encapsulation to give **~50% increase in light yield**



Summary

- COSINE-100 has searched for dark matter with NaI to test the positive signal from DAMA/LIBRA
- Excludes DAMA/LIBRA signal in several model dependent cases in the context of the SHM
- Neither DAMA/LIBRA signal or null modulation hypothesis is yet ruled out in annual modulation search from three years of data taking
 - Five years search to be finalised soon
- Work on upgrade to COSINE-200 ongoing

Thank You!

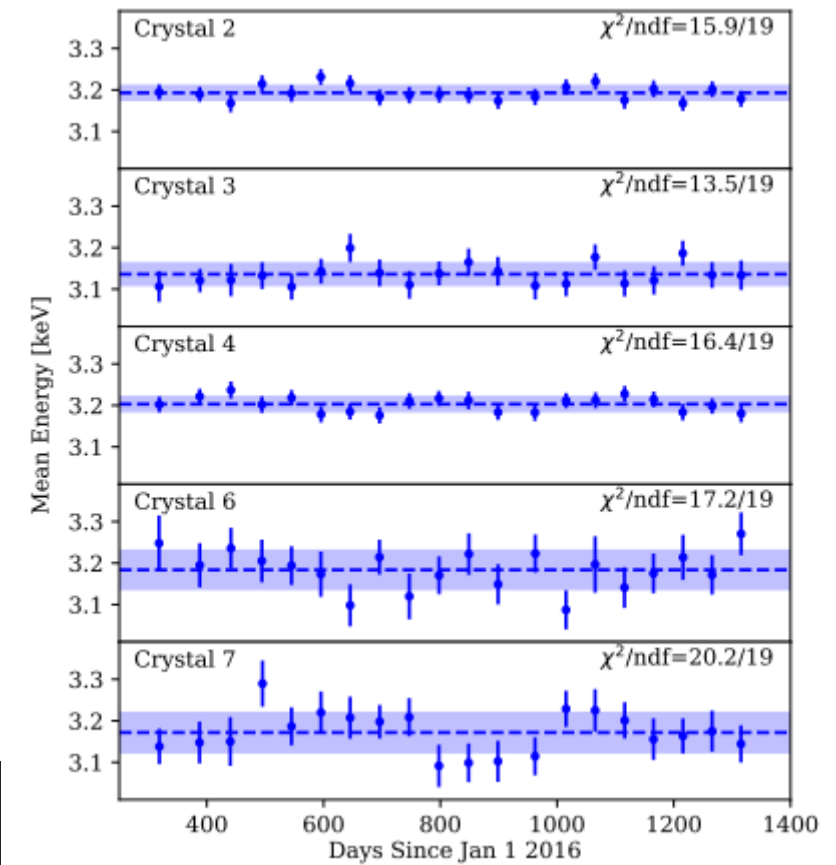
Backup slides

Detector stability

- Many-pronged effort to ensure detector stability
 - Constant monitoring of environmental and detector variables
 - Regular checks of gain shifts from looking at internal peaks
 - Additional verification in ROI during physics searches, e.g. by tracking peaks in ROI of interest



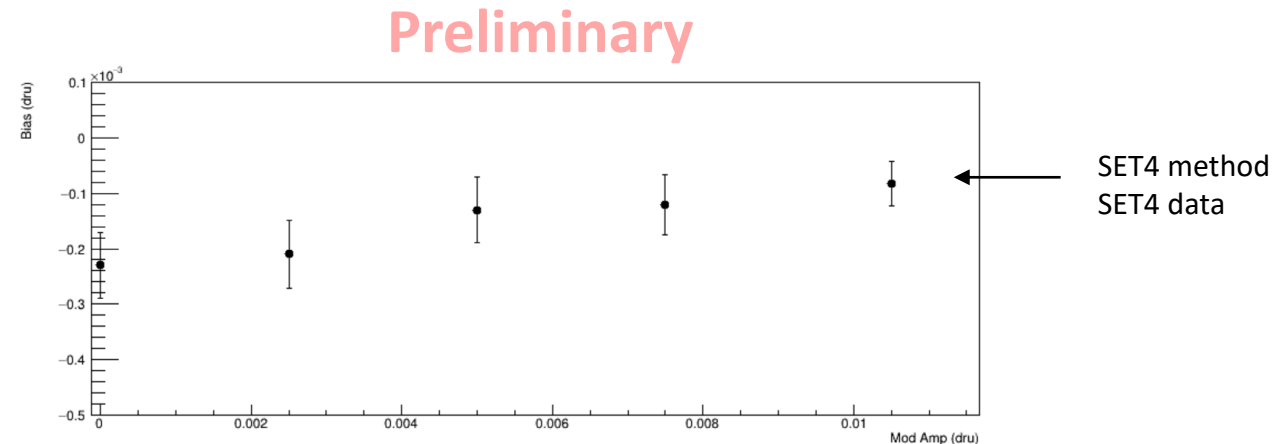
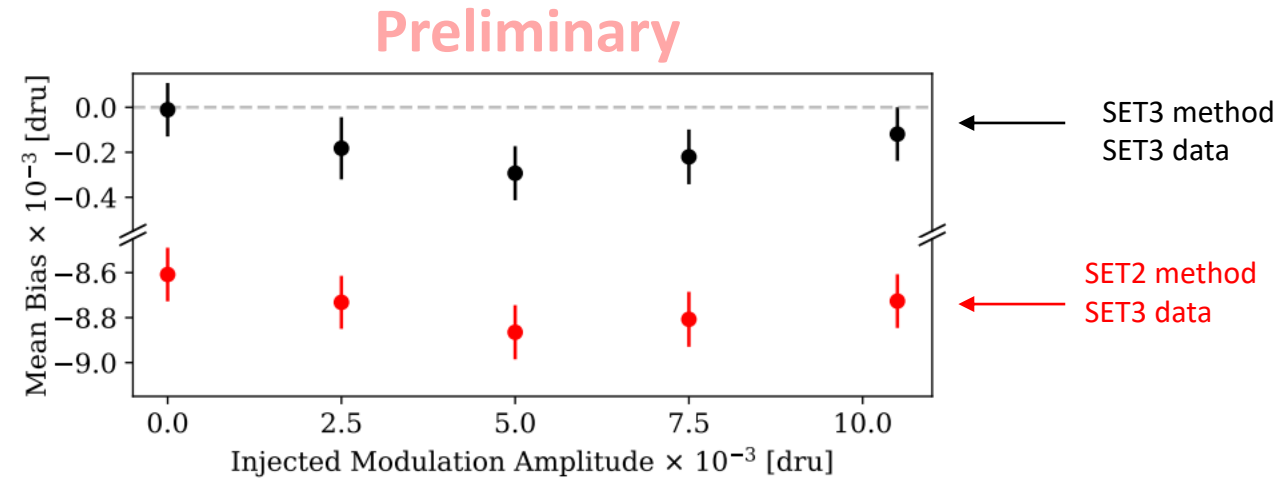
Temperature of various detector and laboratory thermometers since beginning of data taking



3.2 keV ^{40}K peak in each crystal during SET3

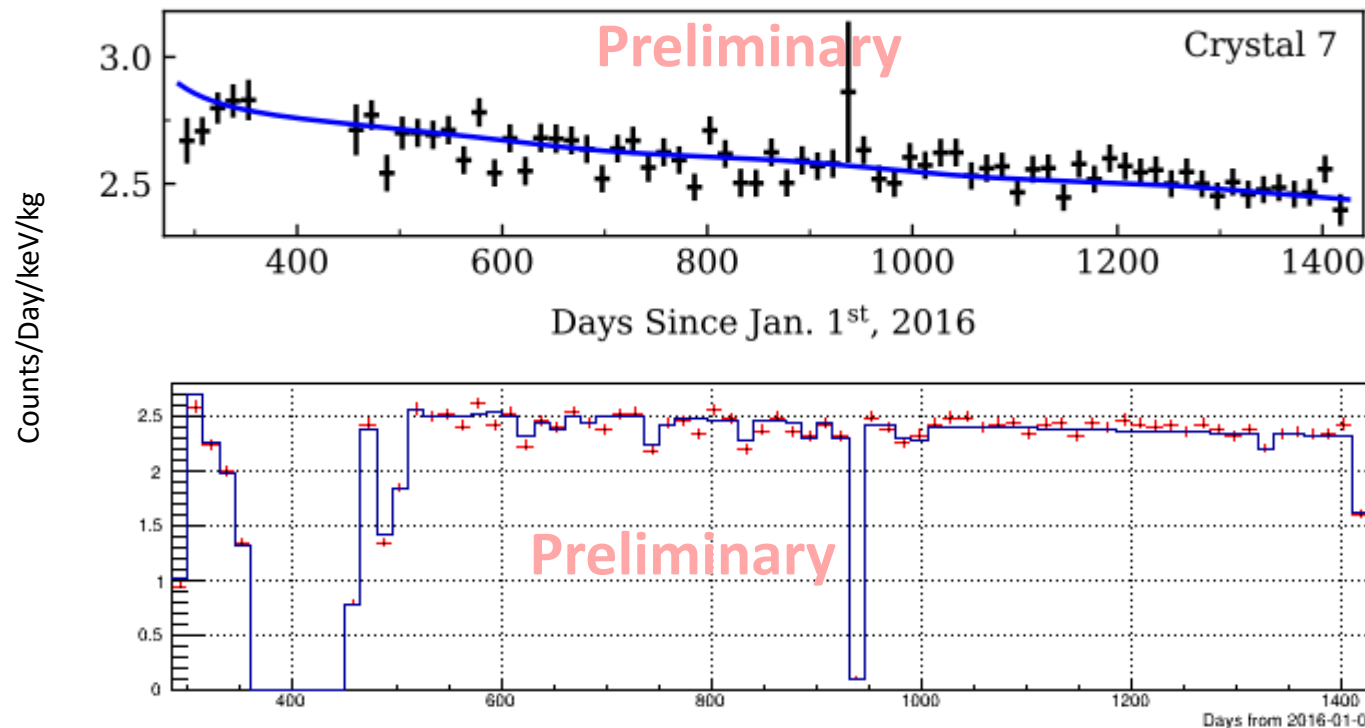
Pseudo-data validation

- Ensemble of 1000 pseudo-experiments created for five different modulation amplitudes in each modulation analysis
- Each pseudo-experiment is fitted using the same fitting process a physics data to search for bias and find expected uncertainties
- Measured bias is of an order of magnitude smaller than expected uncertainty so no adjustment is required



New fitting method SET4

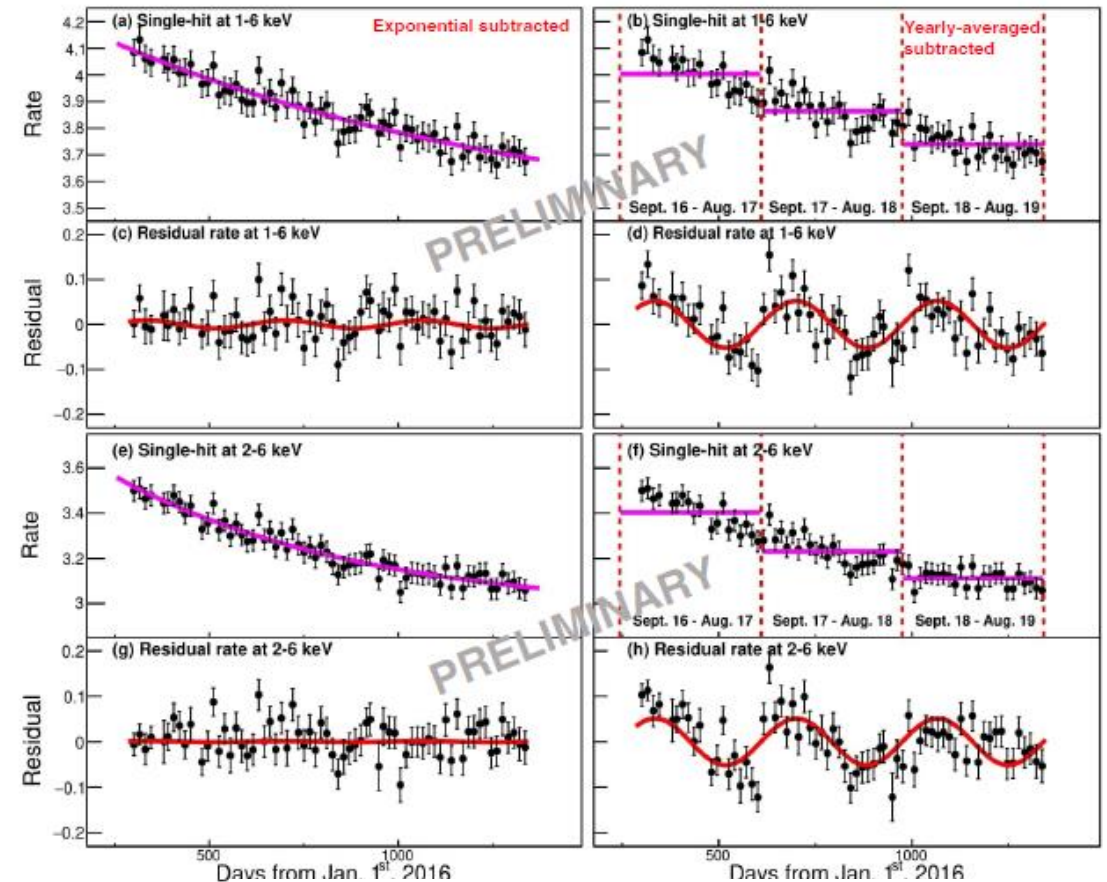
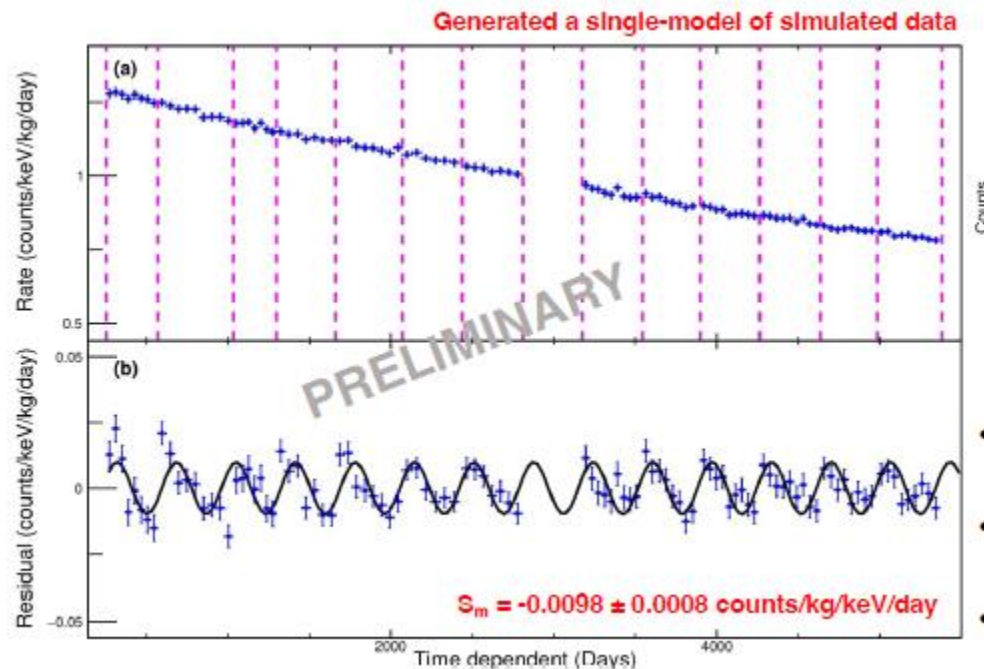
- Detector down-time now modelled in MCMC of fitter and log likelihood minimised
- Previously data was scaled to 100% live-time then χ^2 minimised
- **Good agreement between both method in SET3 data**



SET3 data shown

COSINE data with DAMA technique

- Suggested that DAMA's analysis can generate modulation signal
- Tested with COSINE-100 data with DAMA technique and in pseudo-data to replicate DAMA data
- Negative modulation amplitude induced at DAMA phase in both cases

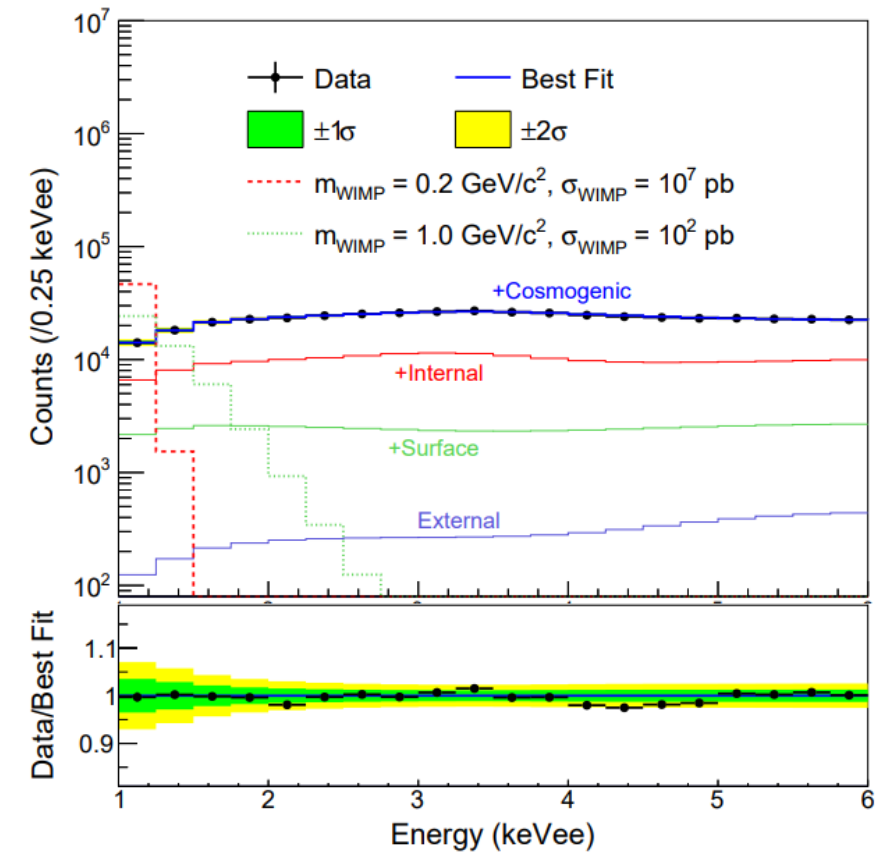
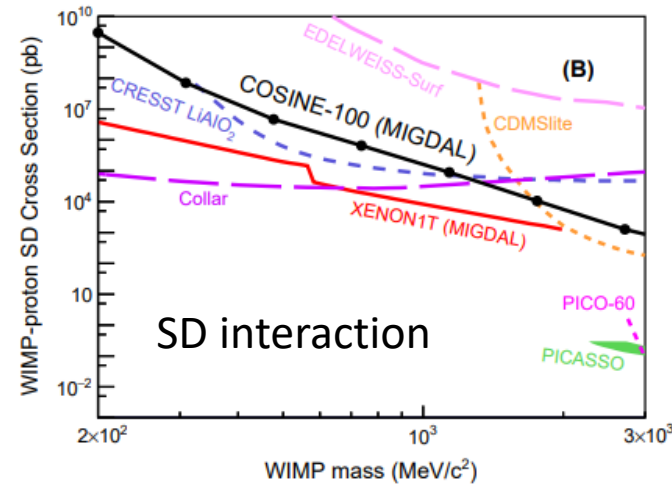
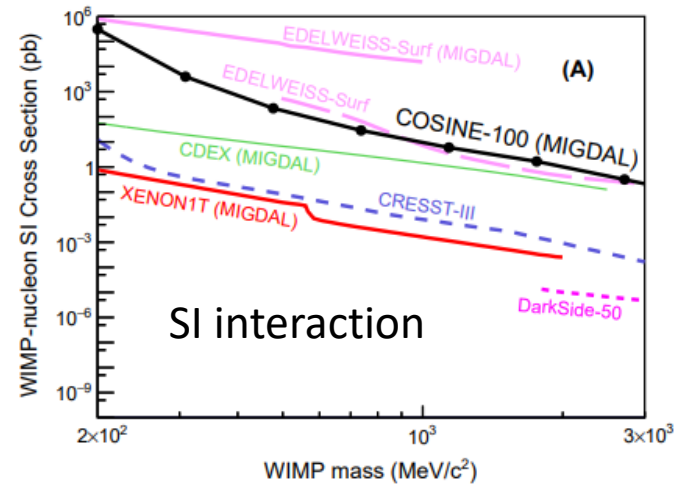


Results

counts/kg/keV/day	1-6 keV	2-6 keV
This work ✓	-0.0441 ± 0.0057	-0.0456 ± 0.0056
DAMA/LIBRA	0.0105 ± 0.0011	0.0095 ± 0.0008
COSINE-100	0.0067 ± 0.0042	0.0050 ± 0.0047
ANAIS-112	-0.0034 ± 0.0042	0.0003 ± 0.0037

WIMP search via Migdal effect

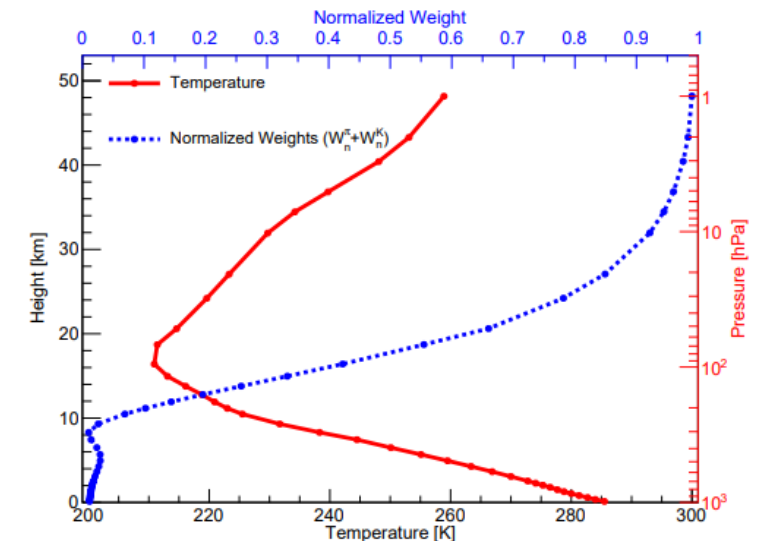
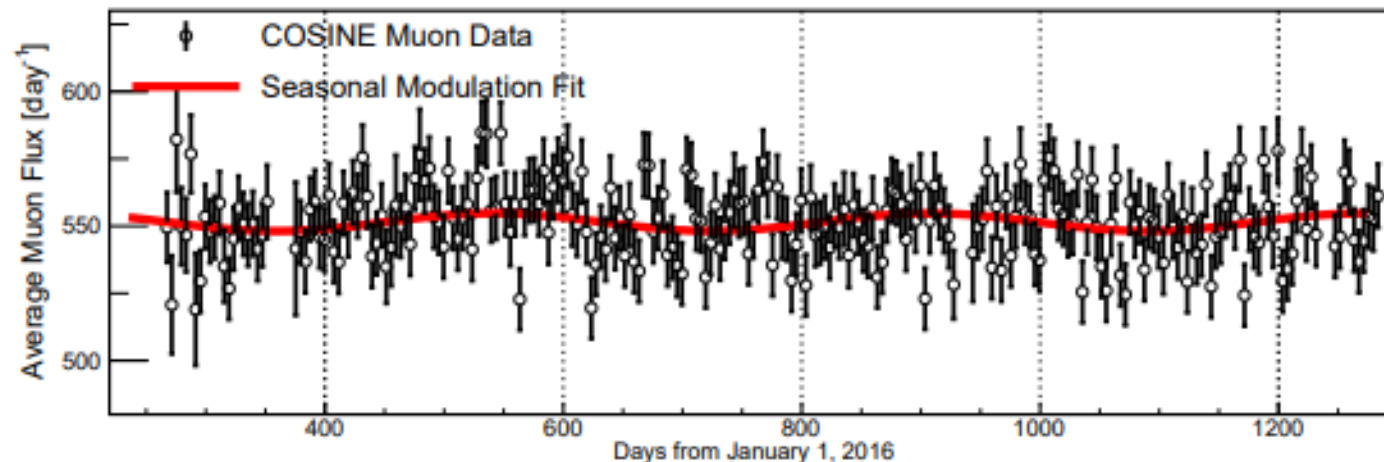
- WIMPs can interact with NaI crystals and produce energetic electrons alongside nuclear recoil via Migdal effect
 - Good candidate for searching for low mass DM
 - Search window of COSINE-100 lowered to 200 MeV/c²
- Search using 1.7 years data with 1 keV low energy threshold
- No WIMP signal observed
- [Adhikari, G., et al. "Searching for low-mass dark matter via the Migdal effect in COSINE-100." Physical Review D 105.4 \(2022\): 042006.](#)



Example of fit to 1.1 GeV/c² WIMP

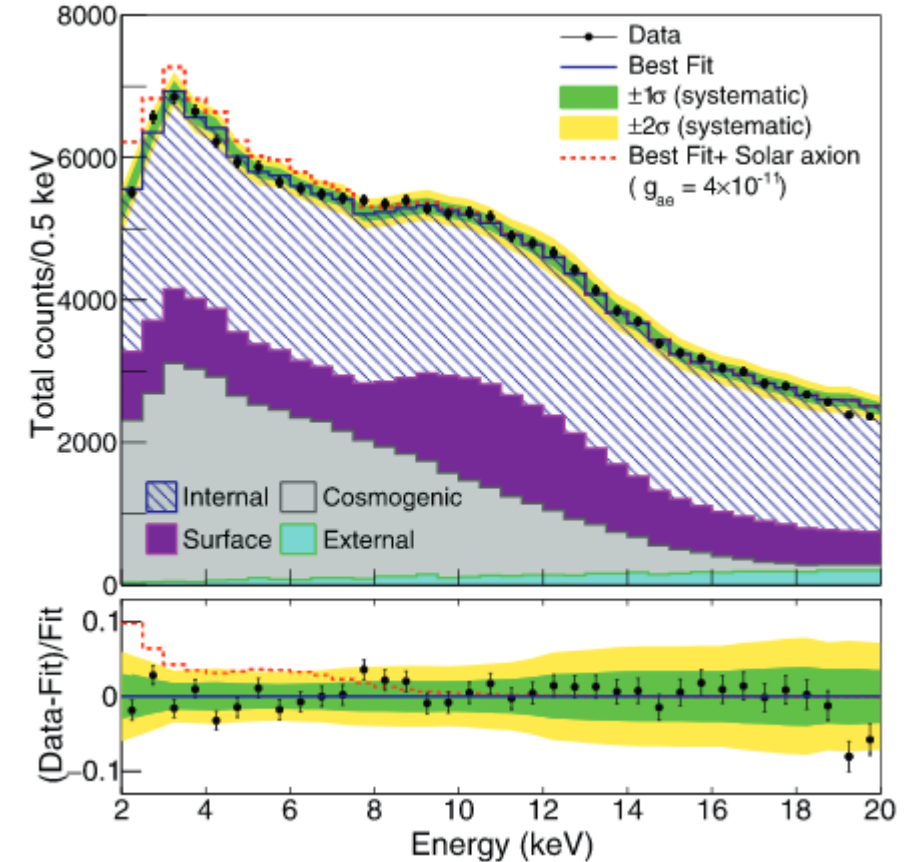
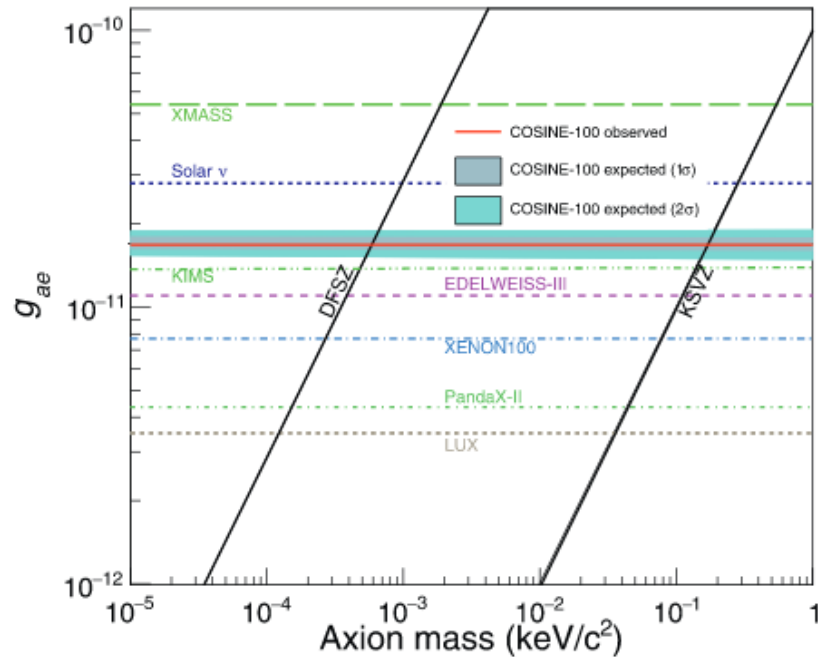
Muon rate studies

- Plastic scintillator shielding for muon veto allows muon rate at COSINE-100 to be studied
 - 952 days of data studied
- Expected annual modulation in muon rate observed
 - Limits also placed on diurnal muon modulation
- Atmospheric temperature above Y2L also measured
- [Prihtiadi, Hafizh, et al. "Measurement of the cosmic muon annual and diurnal flux variation with the COSINE-100 detector." Journal of Cosmology and Astroparticle Physics 2021.02 \(2021\): 013.](#)



Solar axion search

- Solar axions searched for using SET1 data
- Attempt to observe via the axio-electric effect the effects of axions coupling with NaI crystals
- No axion signal observed
- [Adhikari, P., et al. "A search for solar axion induced signals with COSINE-100." Astroparticle Physics 114 \(2020\): 101-106](#)

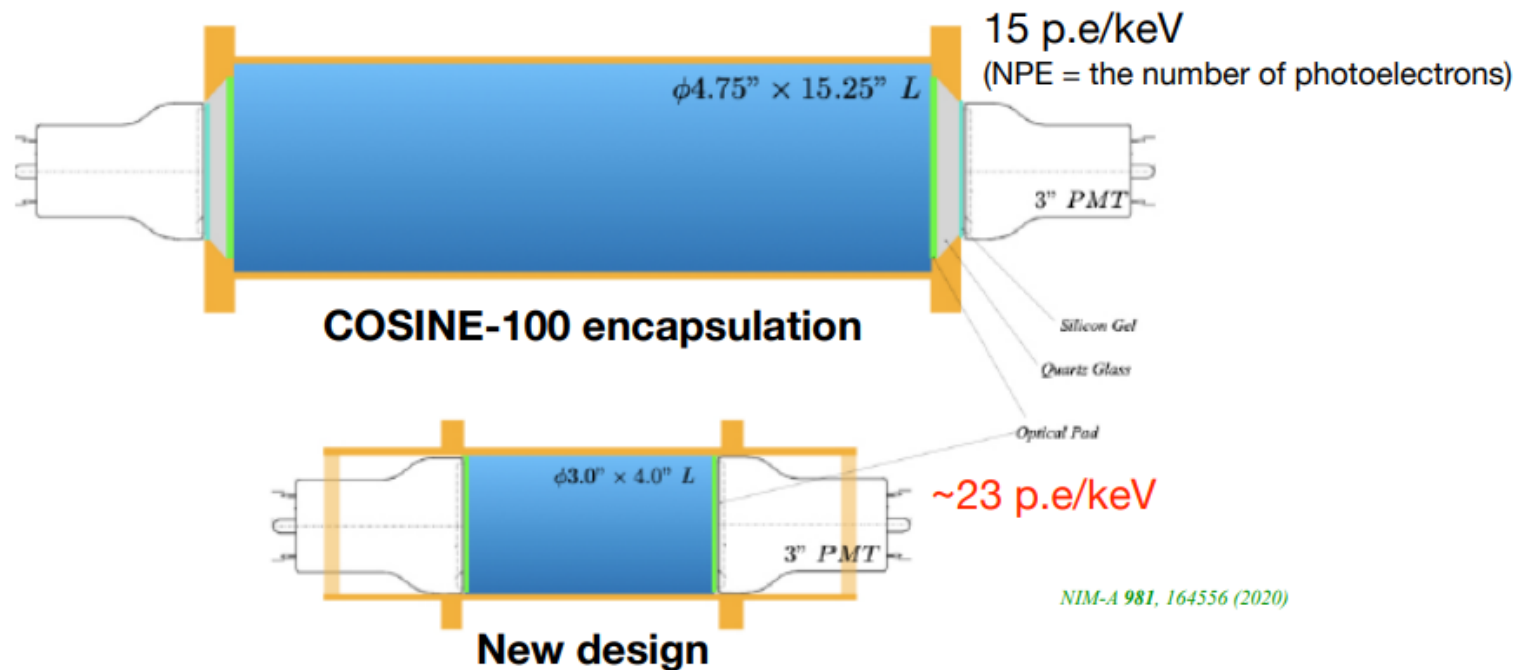


Example of fit to 0 keV/c² axion

Plan for Next Phase

Efforts for Lower Threshold

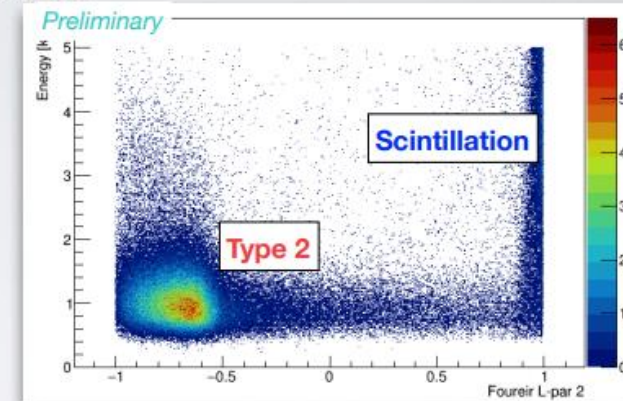
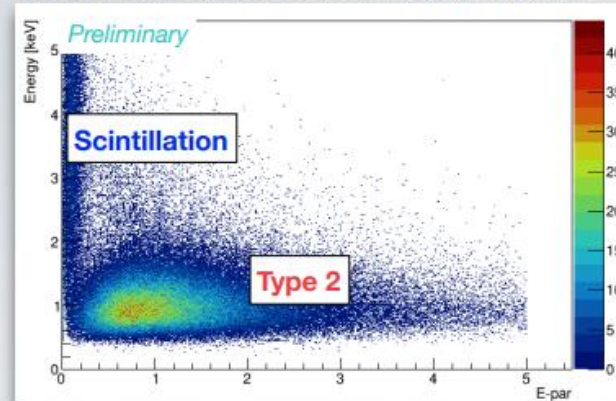
- Novel technique of crystal encapsulation
 - Direct attachment of crystal to PMTs
 - ~50% increased light yield
 - It will be applied to COSINE-200 detector assembly



Next update : Lowering threshold to 0.5keV

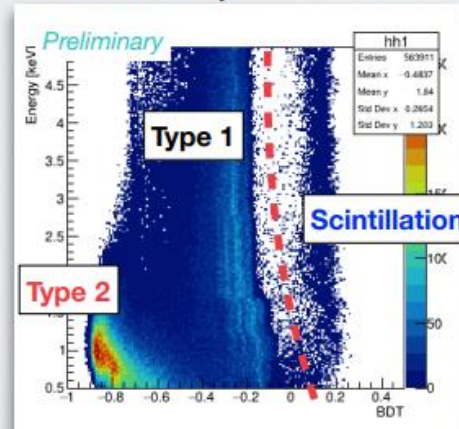
New parameter development example :

End time parameter & Fourier Transformed Likelihood parameter



New BDT example

BDT Training



Lowering Threshold 1keV \rightarrow 0.5keV

- World-best limit on low WIMP mass is expected.
- Type 2 Noise hard to separated from scintillation in 0.5 ~ 1 keV region.
- New Parameters & BDT for Type2 Noise is being developed.

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Gyunho Yu