

XXXIIIrd Rencontres de Blois  
Château de Blois, May 22-27, 2022  
Exploring the Dark Universe



Blois 2022: Exploring the Dark Universe

# Dark Matter Search with COSINE-100

YoungJu Ko

Center for Underground Physics @ Institute for Basic Science  
on behalf of the COSINE Collaboration

May 25, 2022



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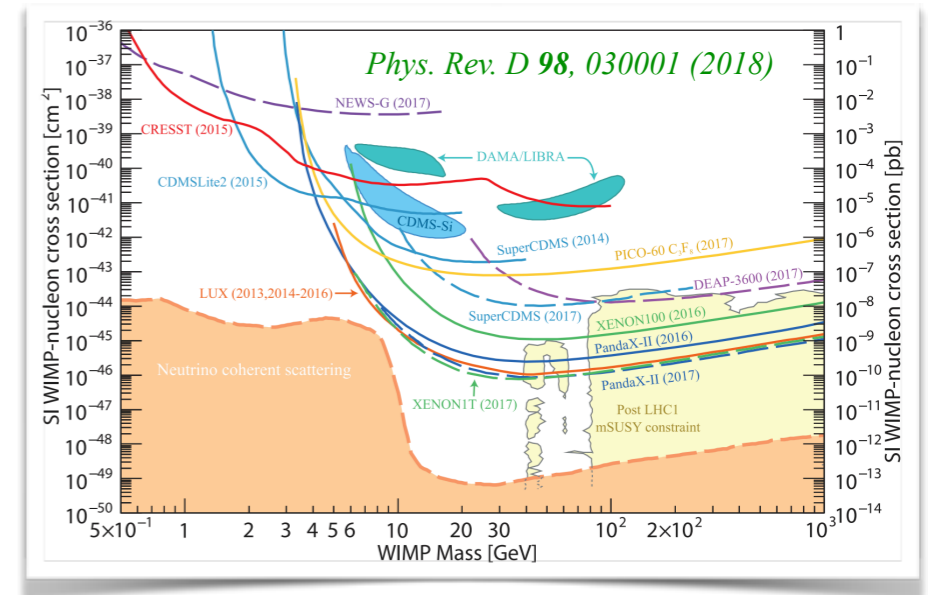
- Introduction to COSINE-100
  - Motivations
  - Experimental site
  - Detector configuration
  - Detector operation & monitoring system
- Data analysis
  - Extraction analysis
  - Annual modulation analysis
- Plan for next phase
  - Crystal development
  - Lowering threshold
  - Detector sensitivity



# Motivation

## DAMA/LIBRA Experiment

- **No experiments** have succeeded in **direct detection** of dark matter (DM), except **DAMA/LIBRA**.

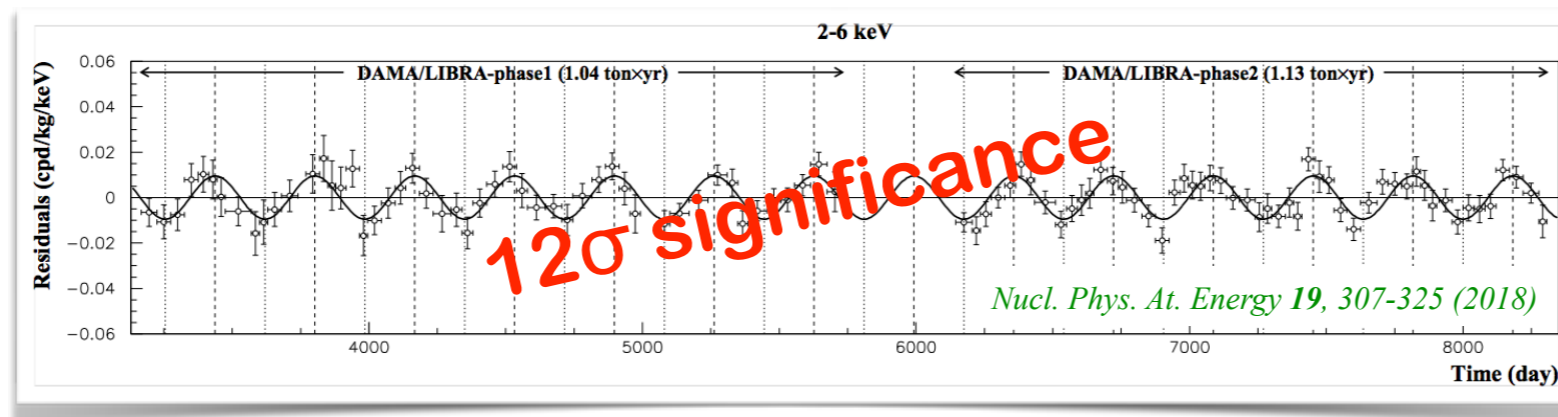
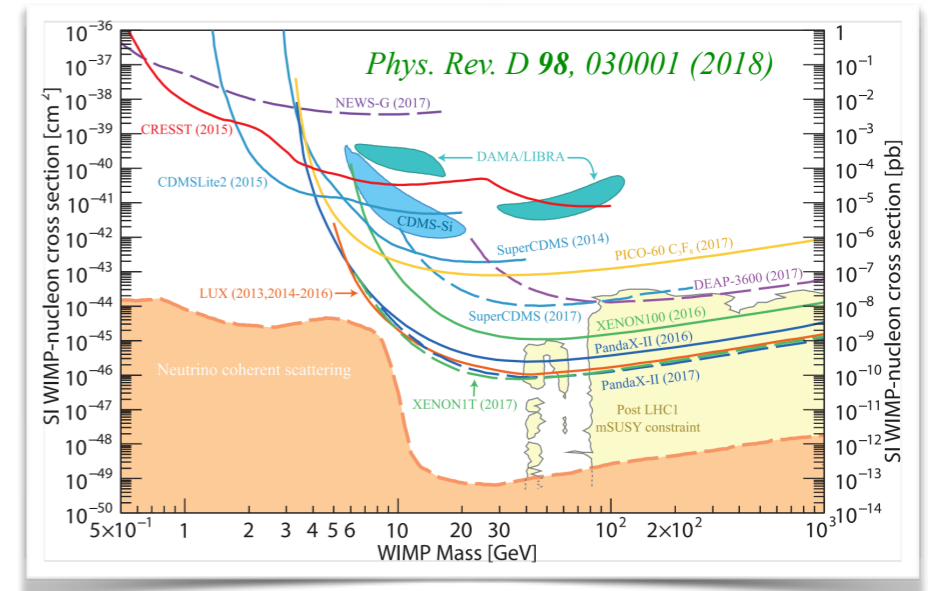




# Motivation

## DAMA/LIBRA Experiment

- No experiments have succeeded in direct detection of dark matter (DM), except DAMA/LIBRA.
- DAMA/LIBRA experiment
  - Search for **annual modulation signature by DM**
  - Claim an **observation of the DM at  $12\sigma$  C.L**  
(2-6 keV, 2.17-ton·yr)
  - The results are **compatible with the nature of DM candidates.**  
( $A = 0.0096 \pm 0.0008$  counts/day/kg/keV,  $\varphi = 145 \pm 5$  days,  $T = 0.9987 \pm 0.0008$  yr)

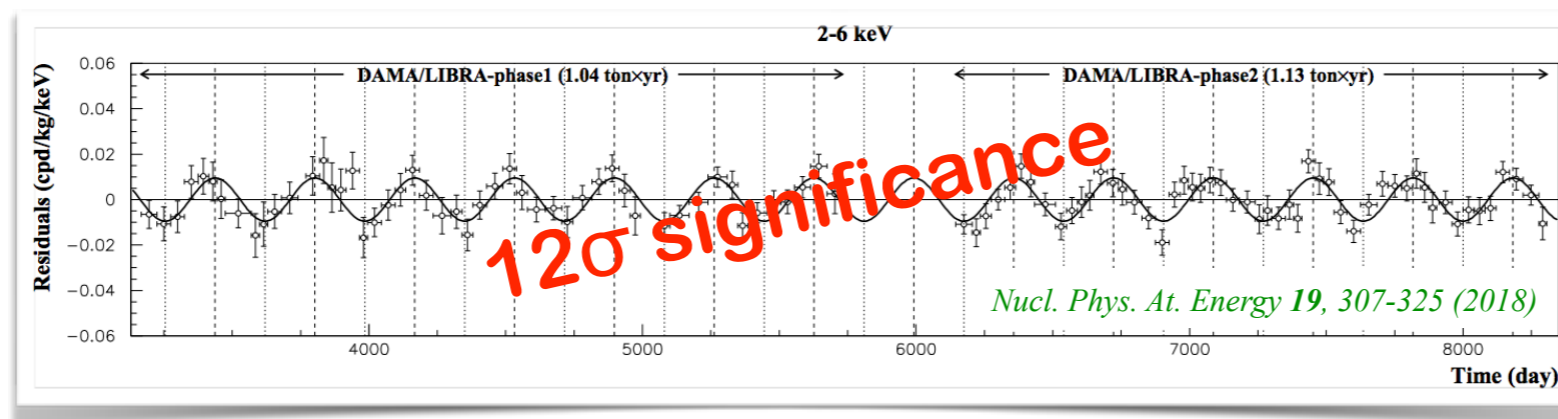
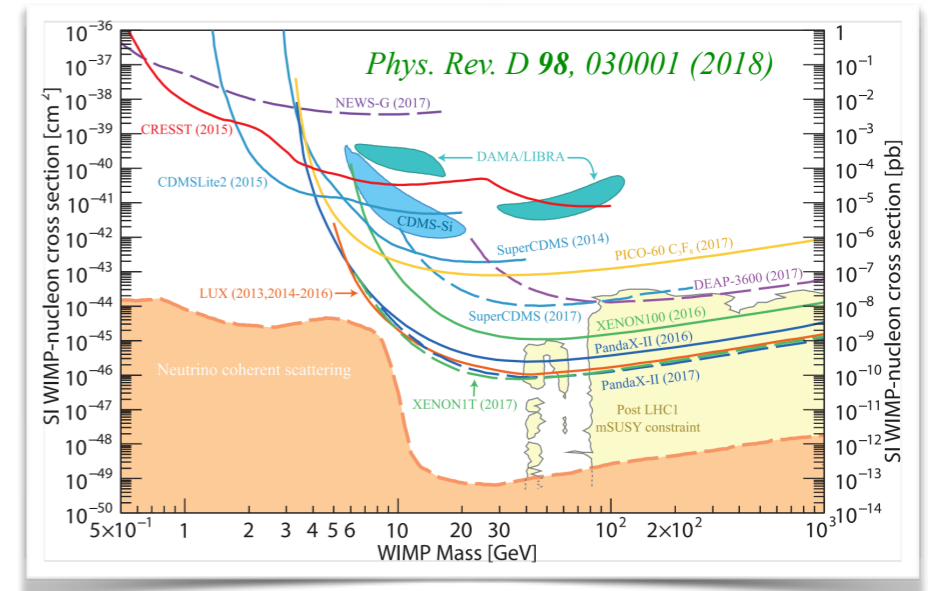




# Motivation

## DAMA/LIBRA Experiment

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  - DAMA/LIBRA experiment
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    - The results are compatible with the nature of DM candidates.
- ( $A = 0.0096 \pm 0.0008$  counts/day/kg/keV,  $\varphi = 145 \pm 5$  days,  $T = 0.9987 \pm 0.0008$  yr)



- Only observe in DAMA/LIBRA
  - NaI(Tl) crystal is special for DM interaction?
  - There are many efforts to test DAMA/LIBRA's signal, using NaI(Tl) crystal.



# COSINE-100

## Collaboration

- DM-Ice and KIMS joint effort to search for dark matter interactions
  - ~50 collaborators in 17 institutes
  - To verify the DAMA/LIBRA's claim via the same target material

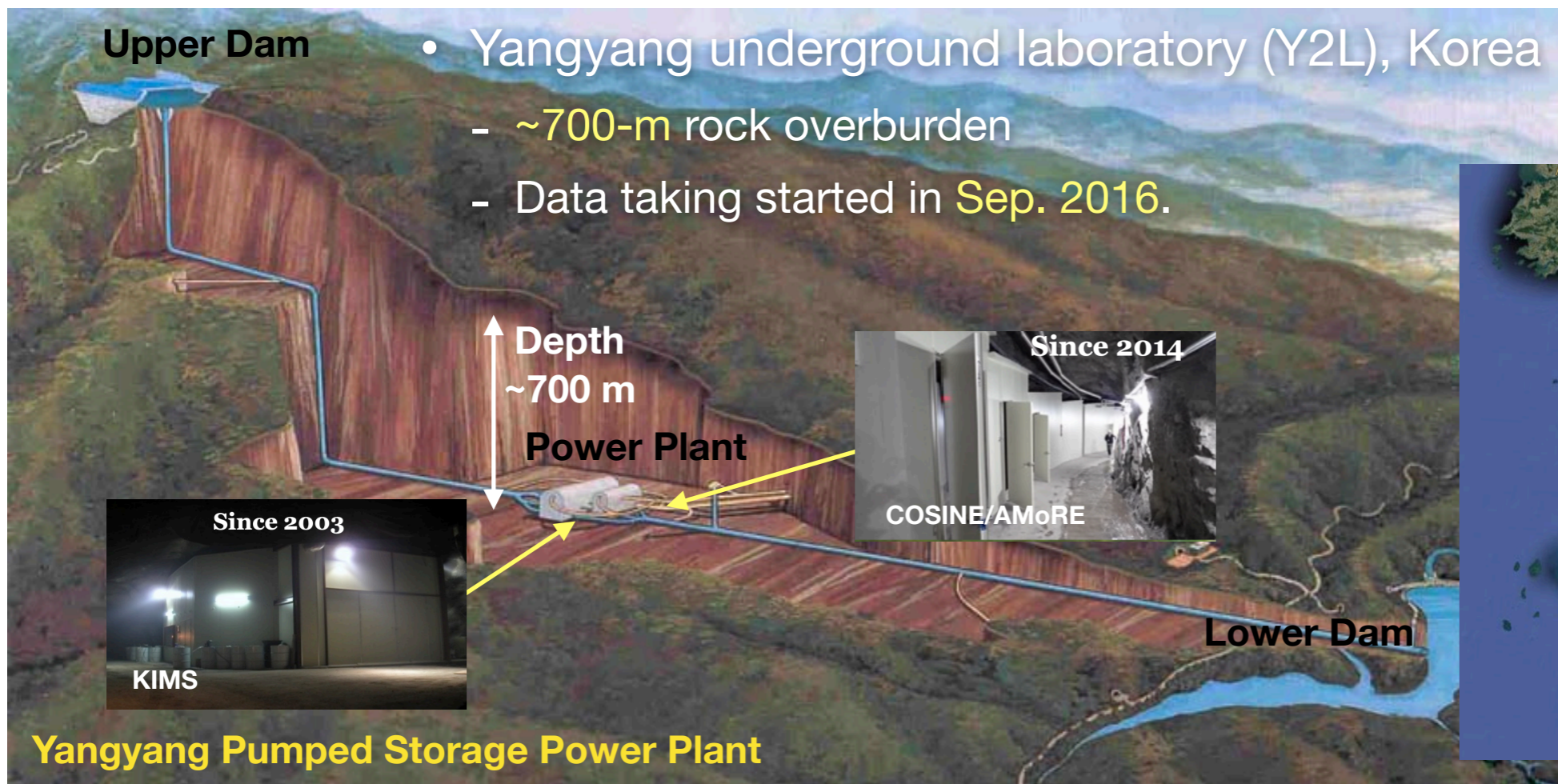




# COSINE-100

## Experimental Site

- DM-Ice and KIMS joint effort to search for dark matter interactions
  - ~50 collaborators in 17 institutes
  - To verify the DAMA/LIBRA's claim via the same target material

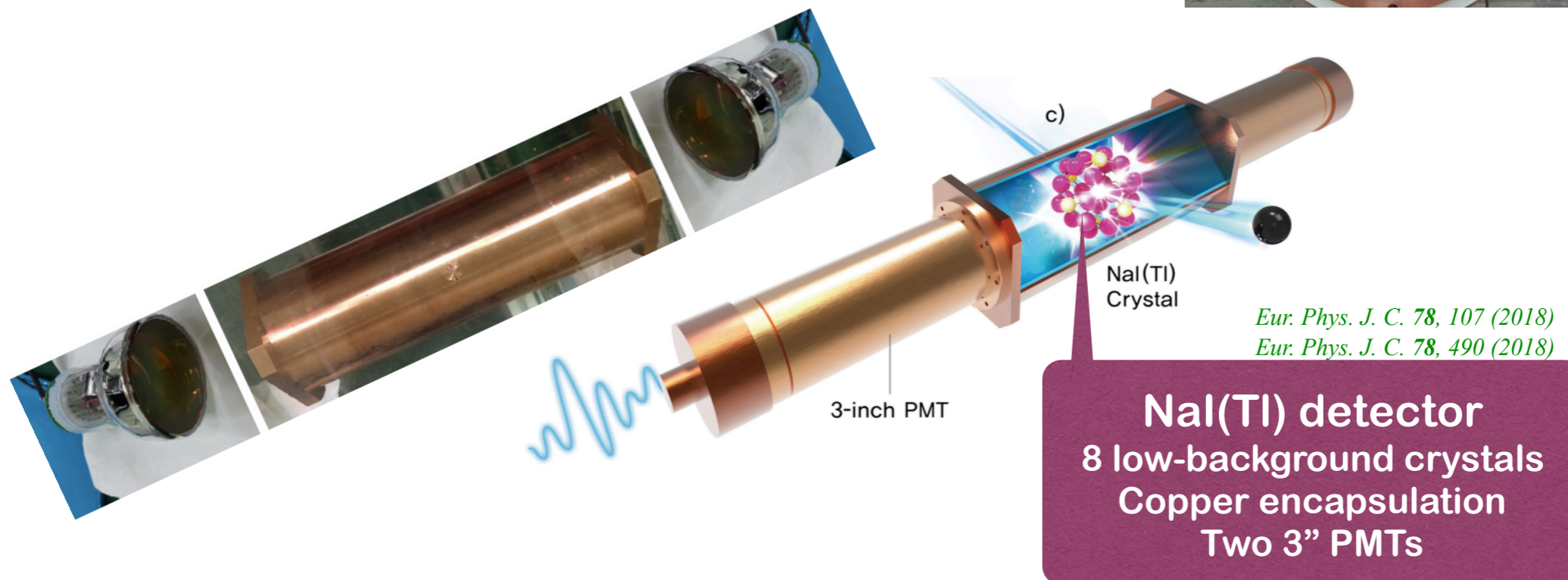
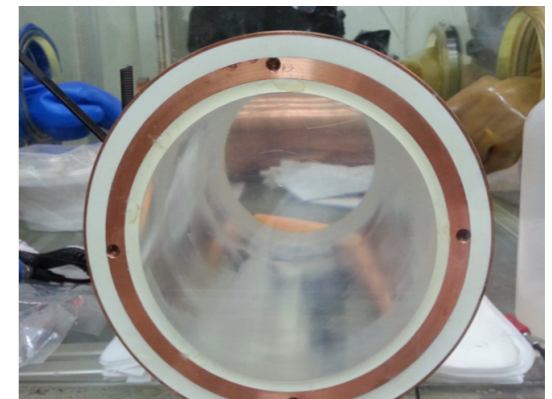




# COSINE-100

## Detector Configuration

- 8 low-background NaI(Tl) crystals w/ 106 kg in total
  - U/Th/K levels are less than DAMA, but total  $\alpha$  ( $\sim^{210}\text{Pb}$ ) are higher than DAMA.
  - Total background is 2-3 times that of DAMA.
  - Higher light yield (15 p.e/keV) than DAMA (5-10 p.e/keV)
- Each crystal is encapsulated in copper
- Two 3" PMTs (R12669SEL) are attached to each crystal.

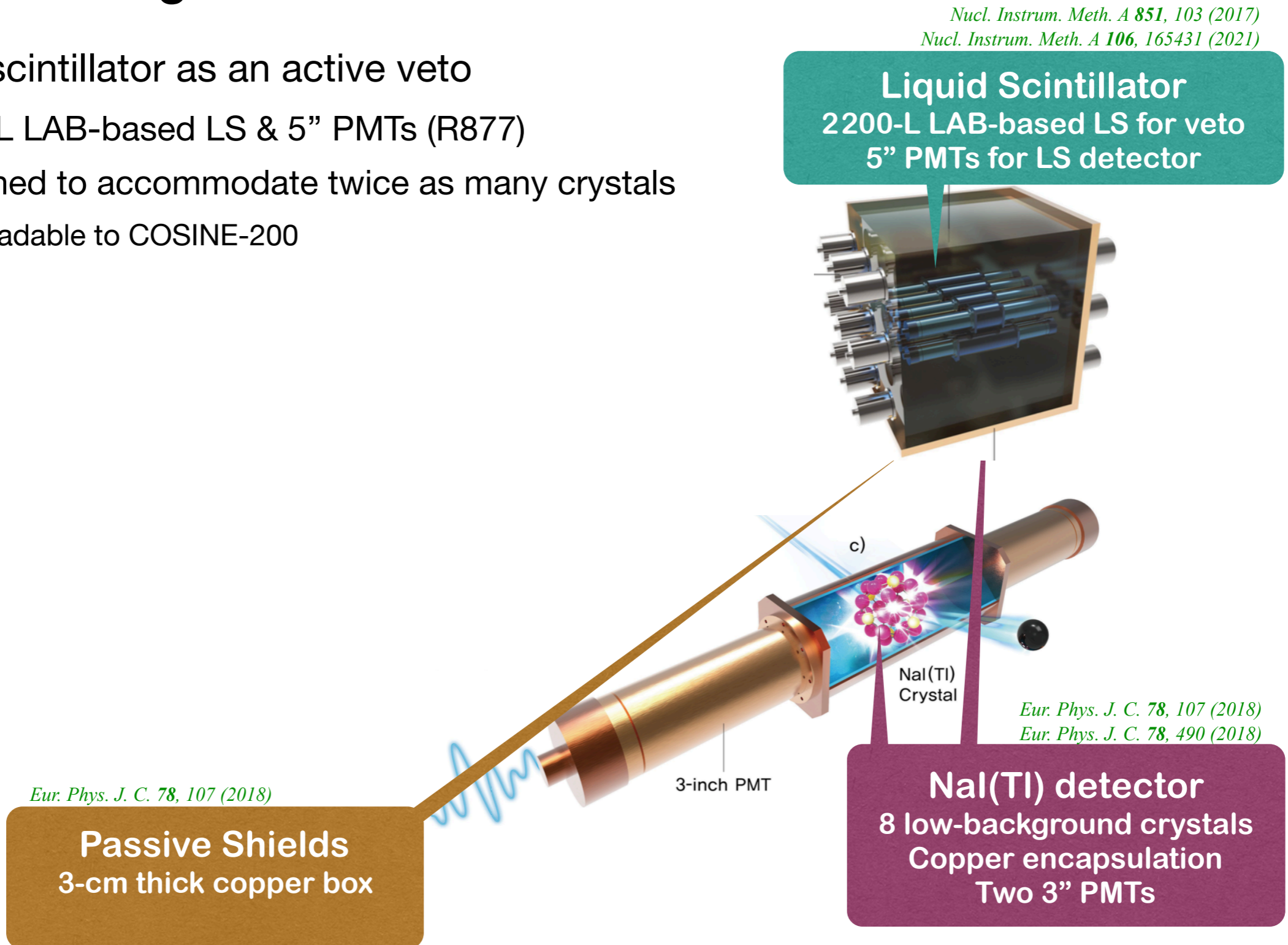




# COSINE-100

## Detector Configuration

- Liquid scintillator as an active veto
  - 2200-L LAB-based LS & 5" PMTs (R877)
  - Designed to accommodate twice as many crystals
    - Upgradable to COSINE-200





# COSINE-100

## Detector Configuration

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

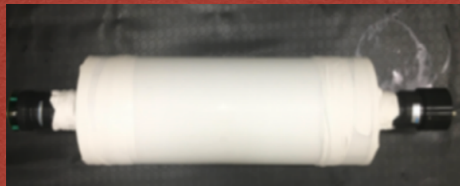
*Nucl. Instrum. Meth. A 851, 103 (2017)*  
*Nucl. Instrum. Meth. A 106, 165431 (2021)*

**4 $\pi$  Muon Counter**  
37 plastic scintillator panels  
2" PMTs (H7195) for muon counter

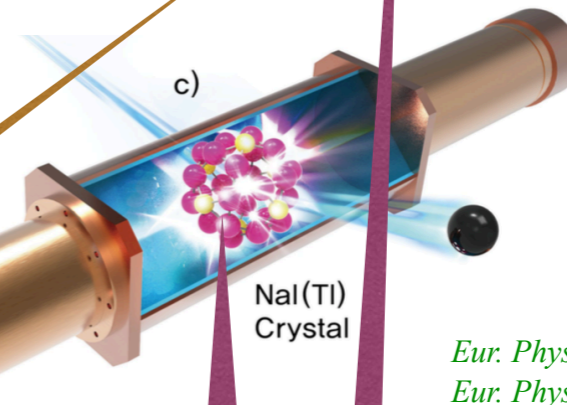
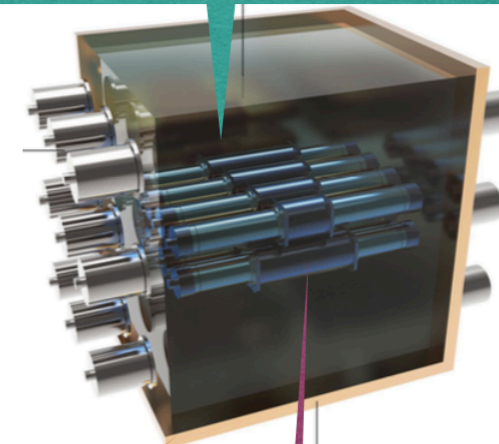
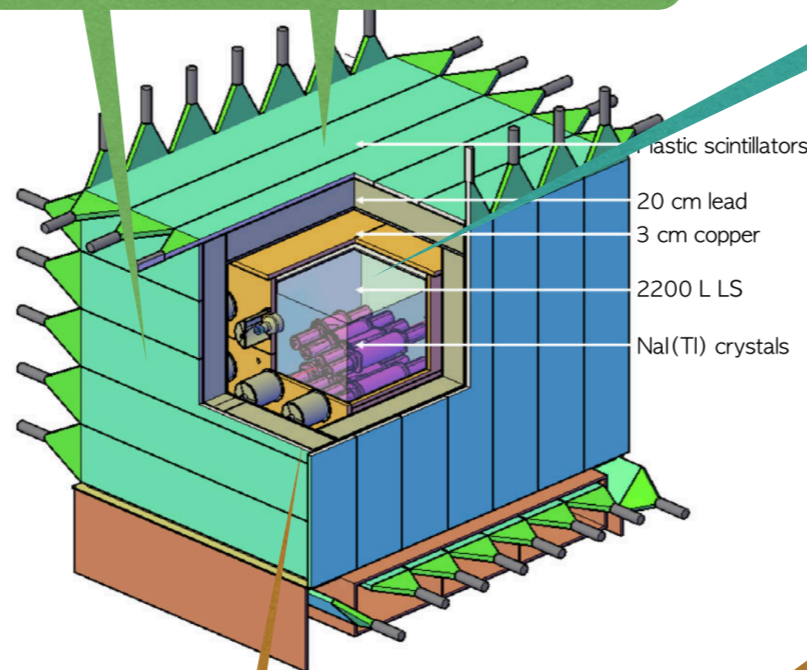
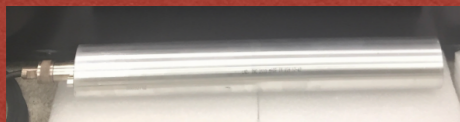
**Liquid Scintillator**  
2200-L LAB-based LS for veto  
5" PMTs for LS detector

*JINST 13, T06005 (2018)*

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



Thermal neutron detector  
(<sup>3</sup>He gas detector)



*Eur. Phys. J. C. 78, 107 (2018)*  
*Eur. Phys. J. C. 78, 490 (2018)*

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

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

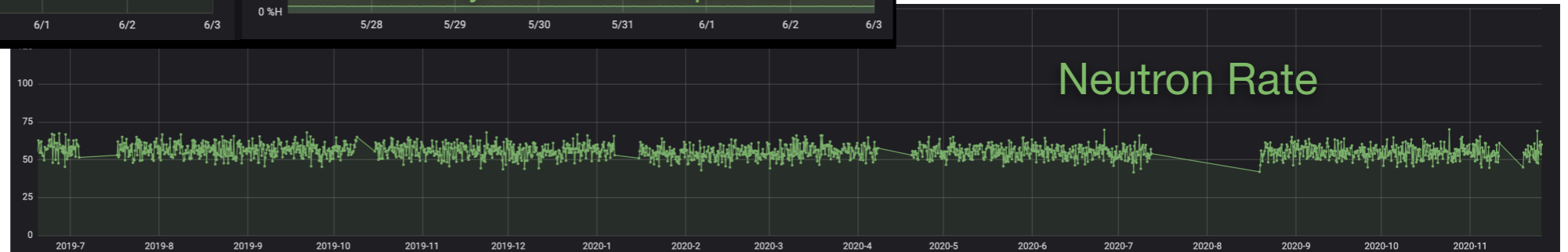
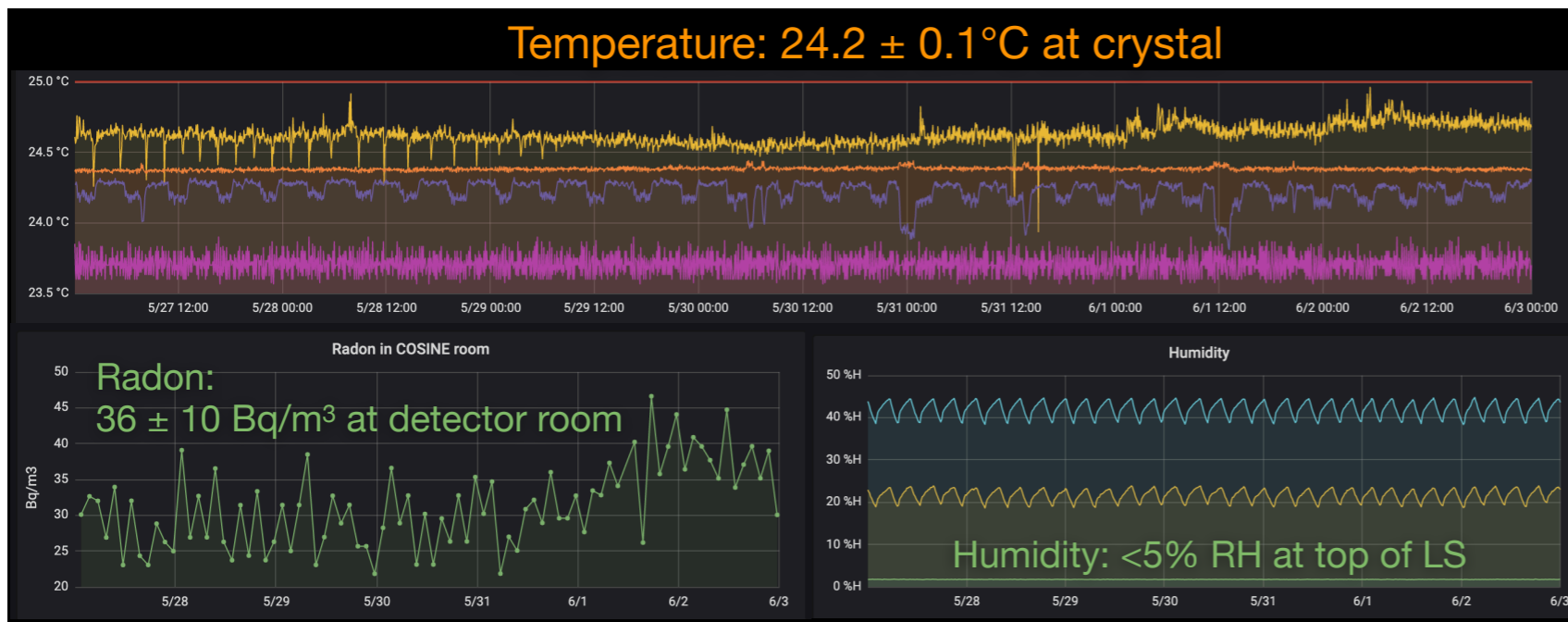
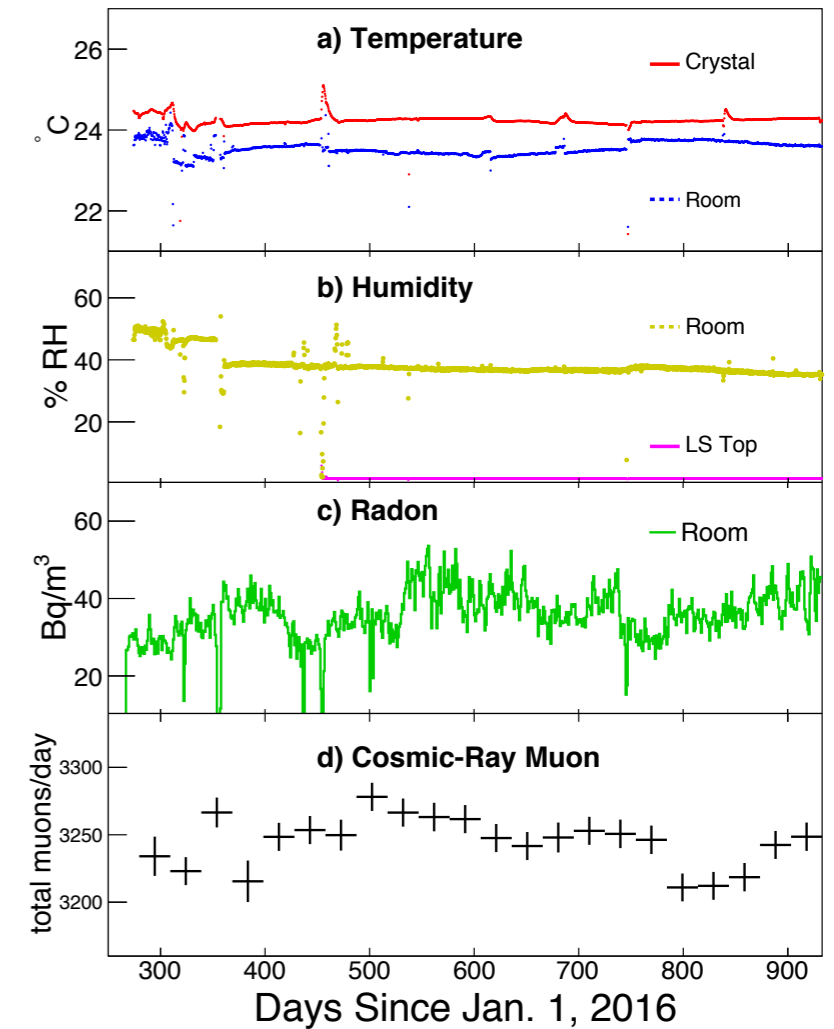
**NaI(Tl) detector**  
8 low-background crystals  
Copper encapsulation  
Two 3" PMTs

# COSINE-100

## Operation & Monitoring

- Monitoring system has **>200 parameters**.
  - DAQ system: trigger rate, electronics status
  - Environmental parameters are stable.
  - Neutron rates are also monitored.

*Phys. Rev. Lett. 123, 031302 (2019)*



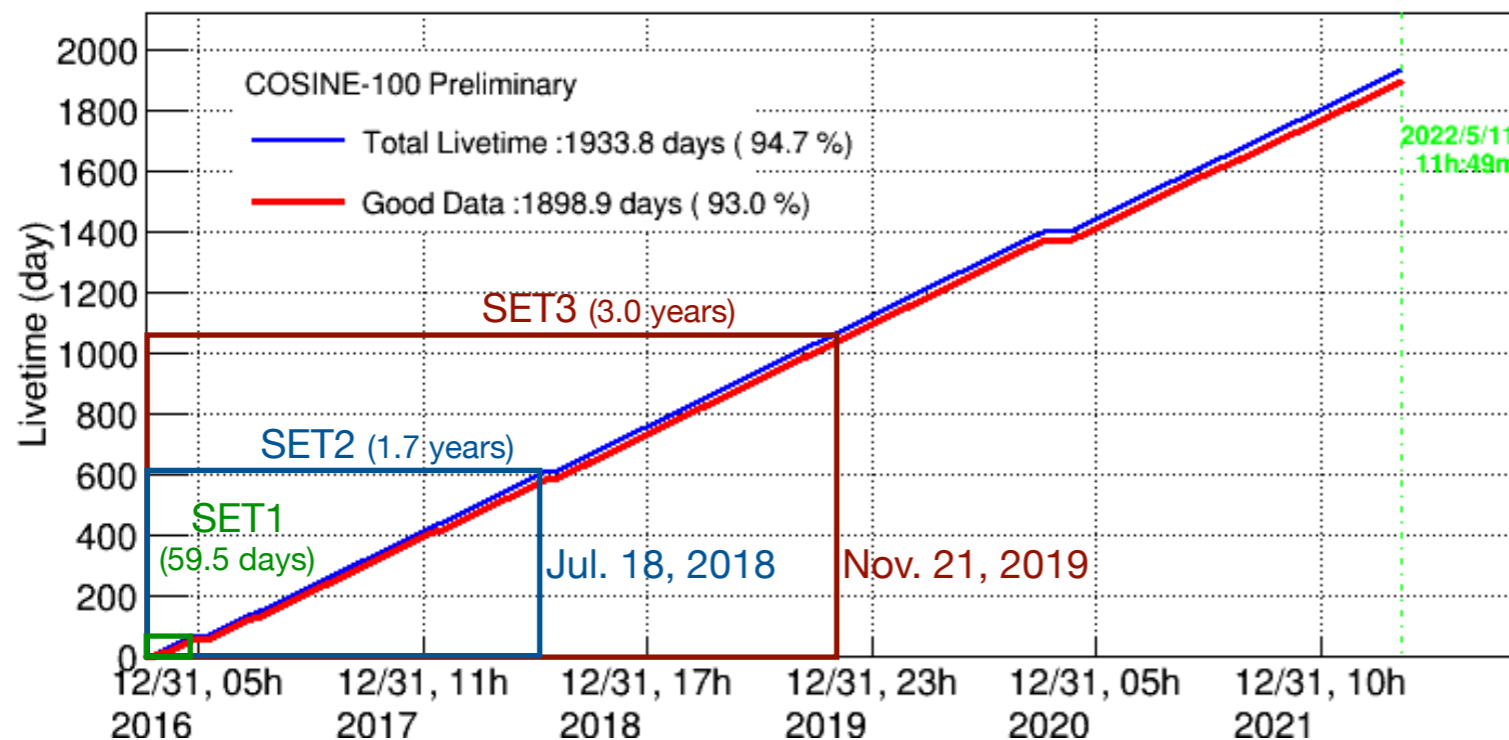
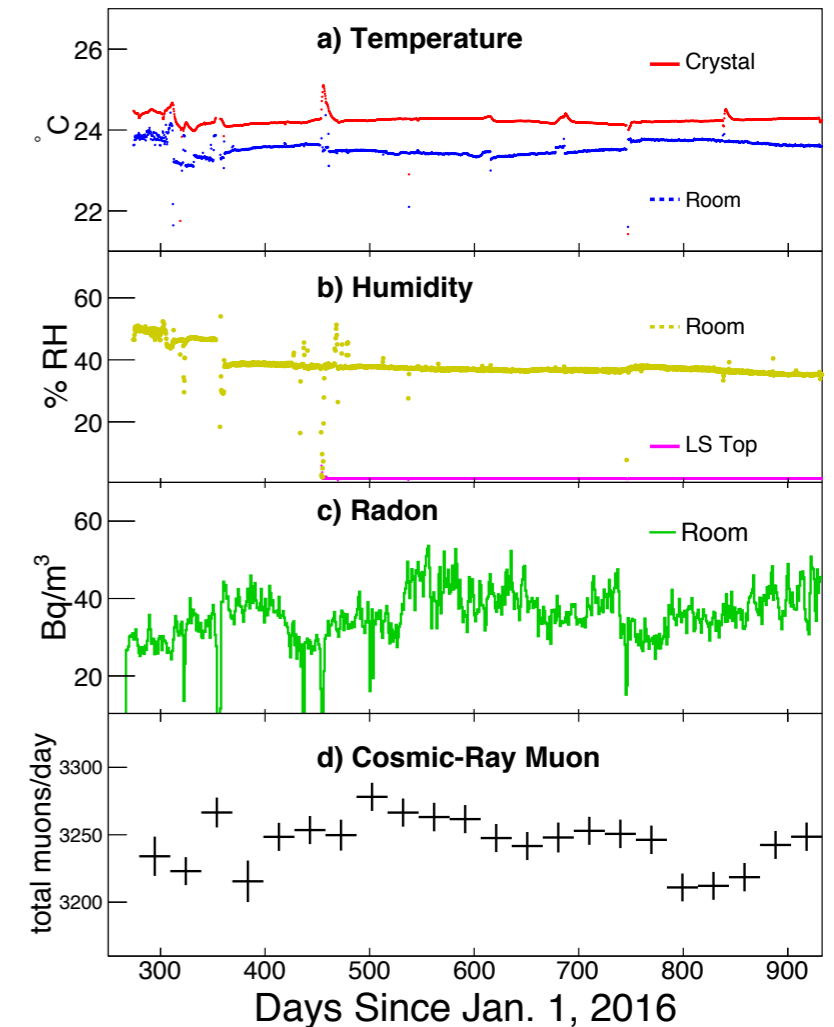


# COSINE-100

## Operation & Monitoring

- Monitoring system has >200 parameters.
  - DAQ system: trigger rate, electronics status
  - Environmental parameters are stable.
  - Neutron rates are also monitored.
- Stable running from Sep. 30, 2016 (5.6 years)
  - DAQ efficiency ~95% (calibration runs, power outage)
  - Exposure time: ~1900 days

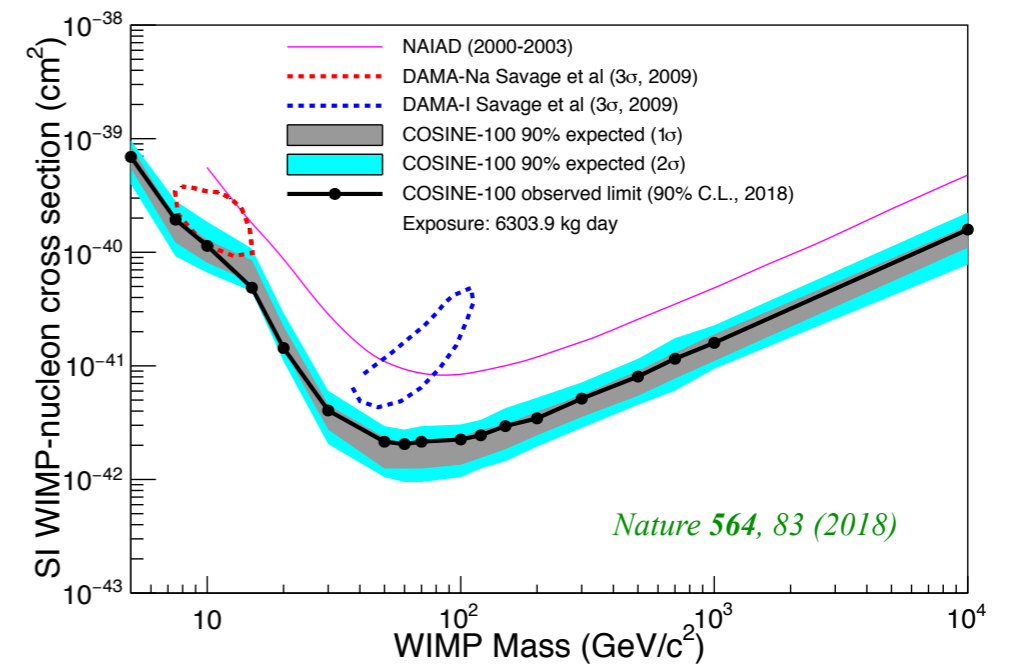
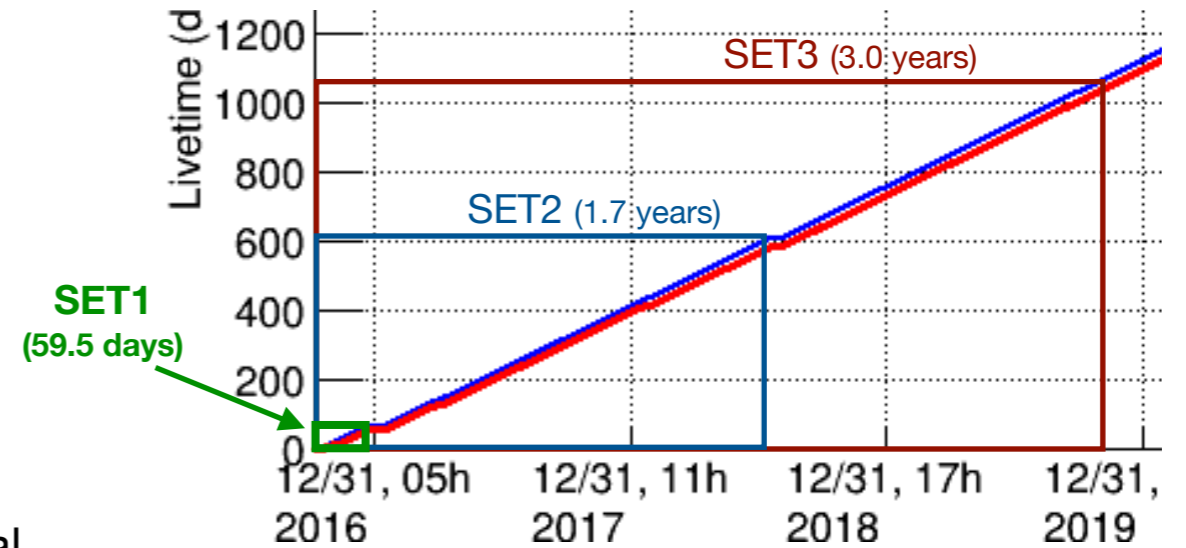
*Phys. Rev. Lett.* **123**, 031302 (2019)



# SET1 Data Analysis

## WIMP Search

- First physics analysis
  - WIMP extraction analysis: SI WIMP & SHM
  - Excluding DAMA/LIBRA w/ the same target material

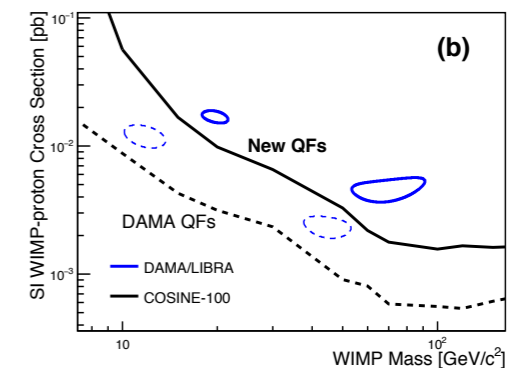
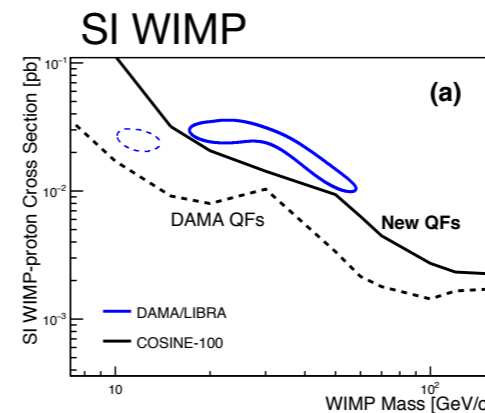
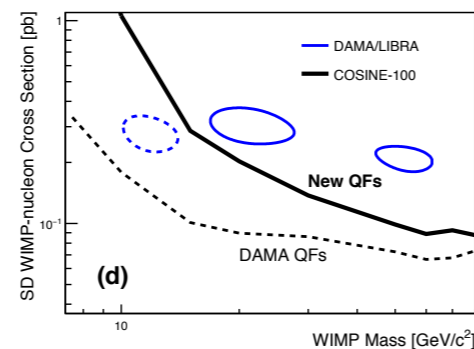
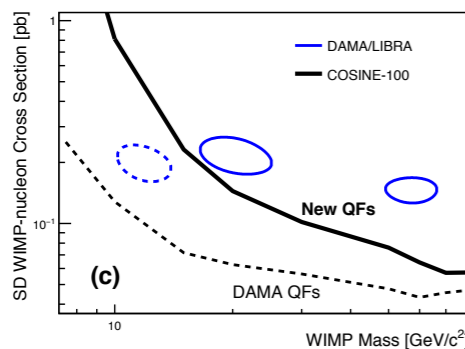
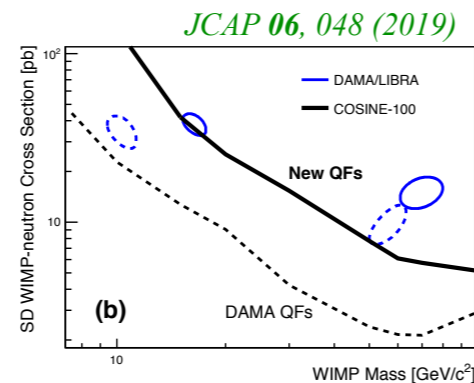
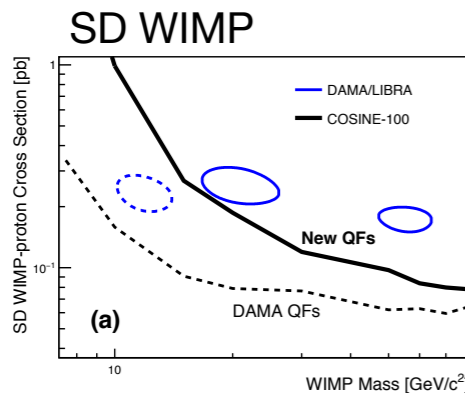
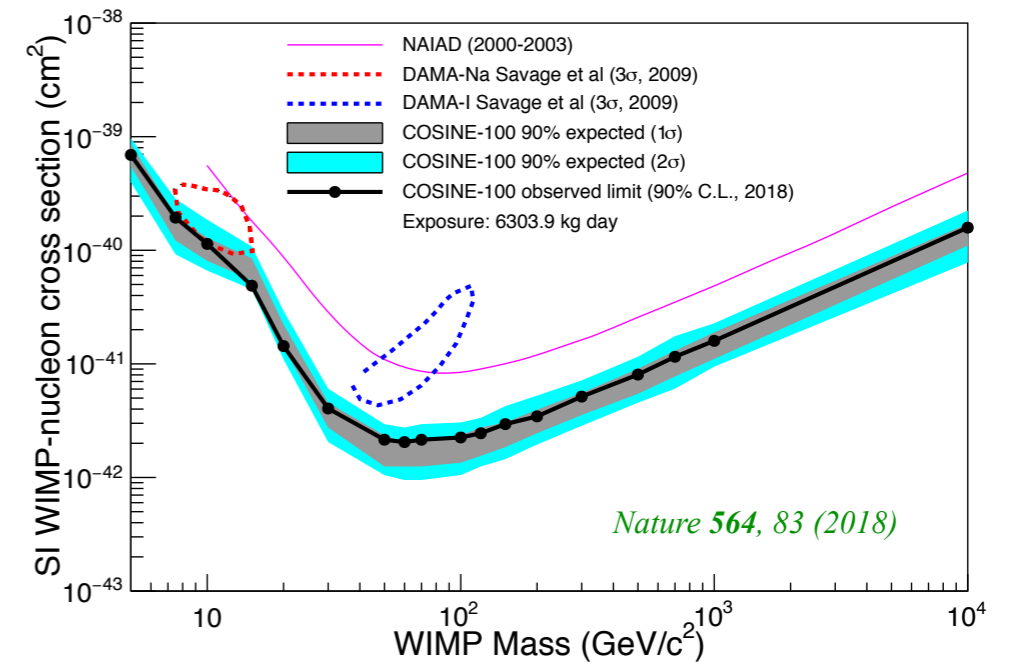
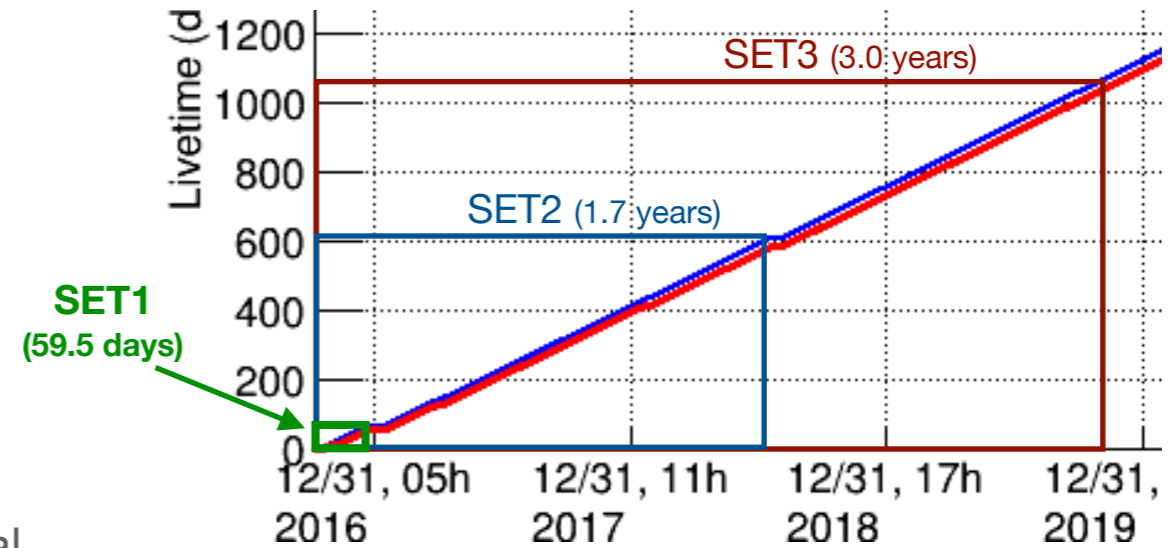




# SET1 Data Analysis

## WIMP Search

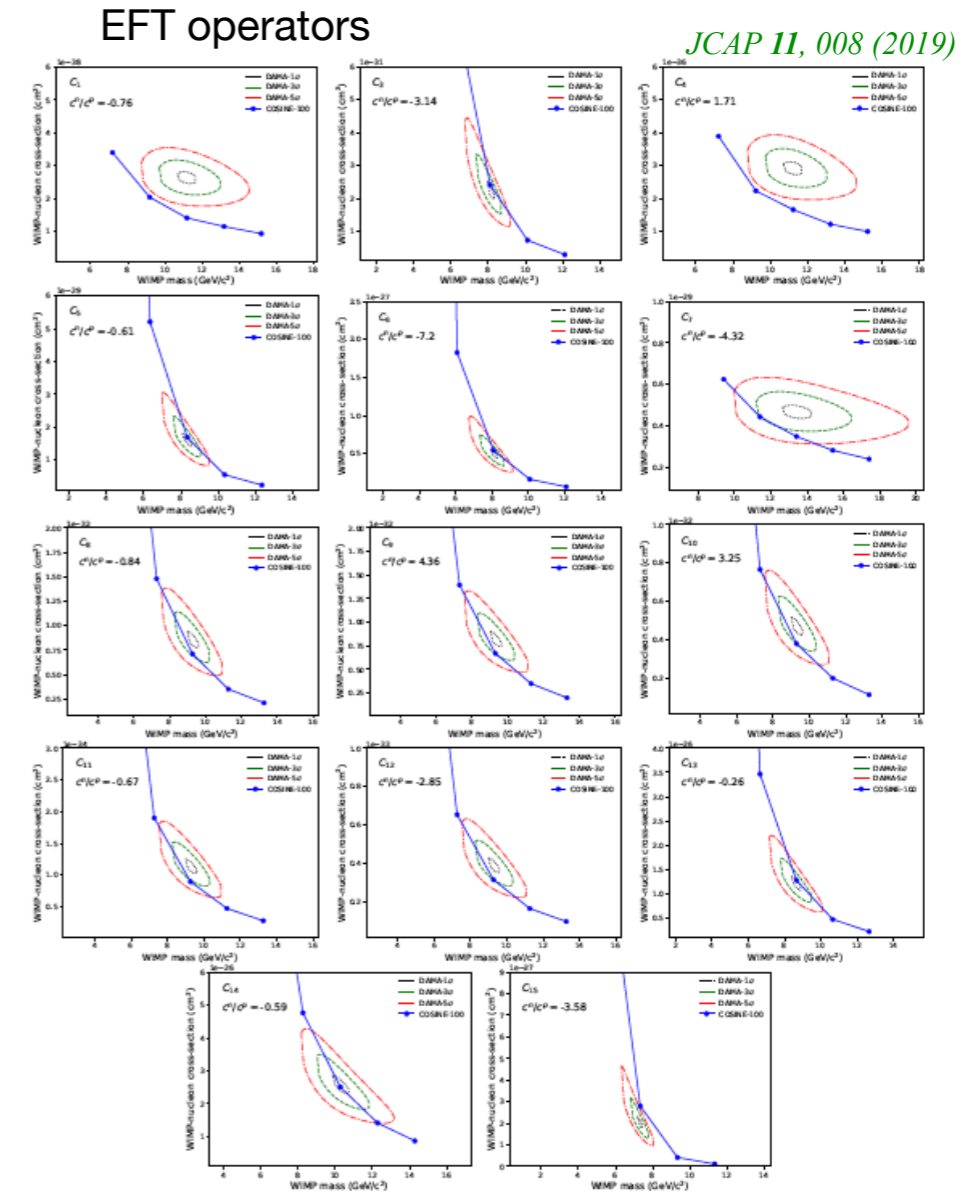
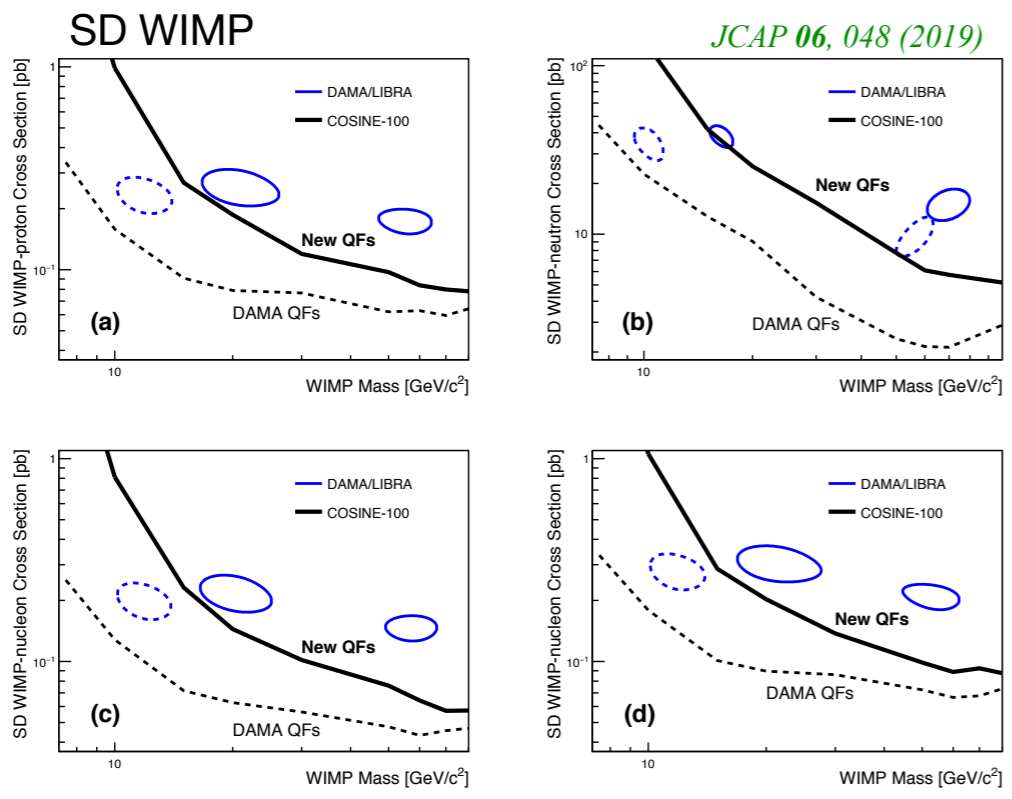
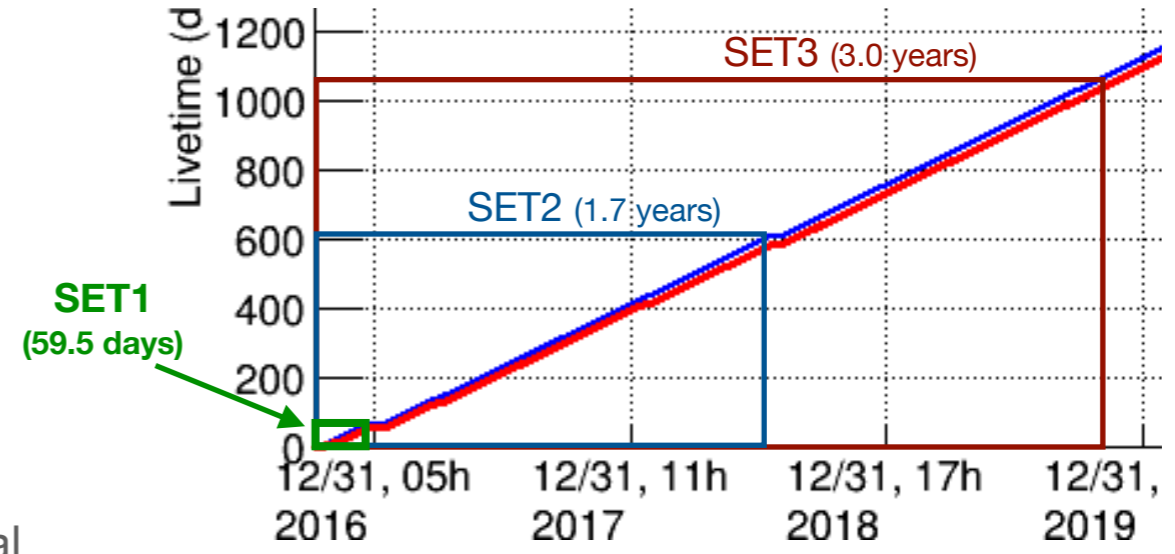
- First physics analysis
  - WIMP extraction analysis: SI WIMP & SHM
  - Excluding DAMA/LIBRA w/ the same target material
- Various model & quenching factor (QF)
  - SI & SD WIMP
  - Assuming different QF → cannot exclude DAMA/LIBRA



# SET1 Data Analysis

## WIMP Search

- First physics analysis
  - WIMP extraction analysis: SI WIMP & SHM
  - Excluding DAMA/LIBRA w/ the same target material
- Various model & quenching factor (QF)
  - SI & SD WIMP
  - Assuming different QF  $\rightarrow$  cannot exclude DAMA/LIBRA
- Effective field theory (EFT) operators
  - Cannot cover DAMA/LIBRA for several operators

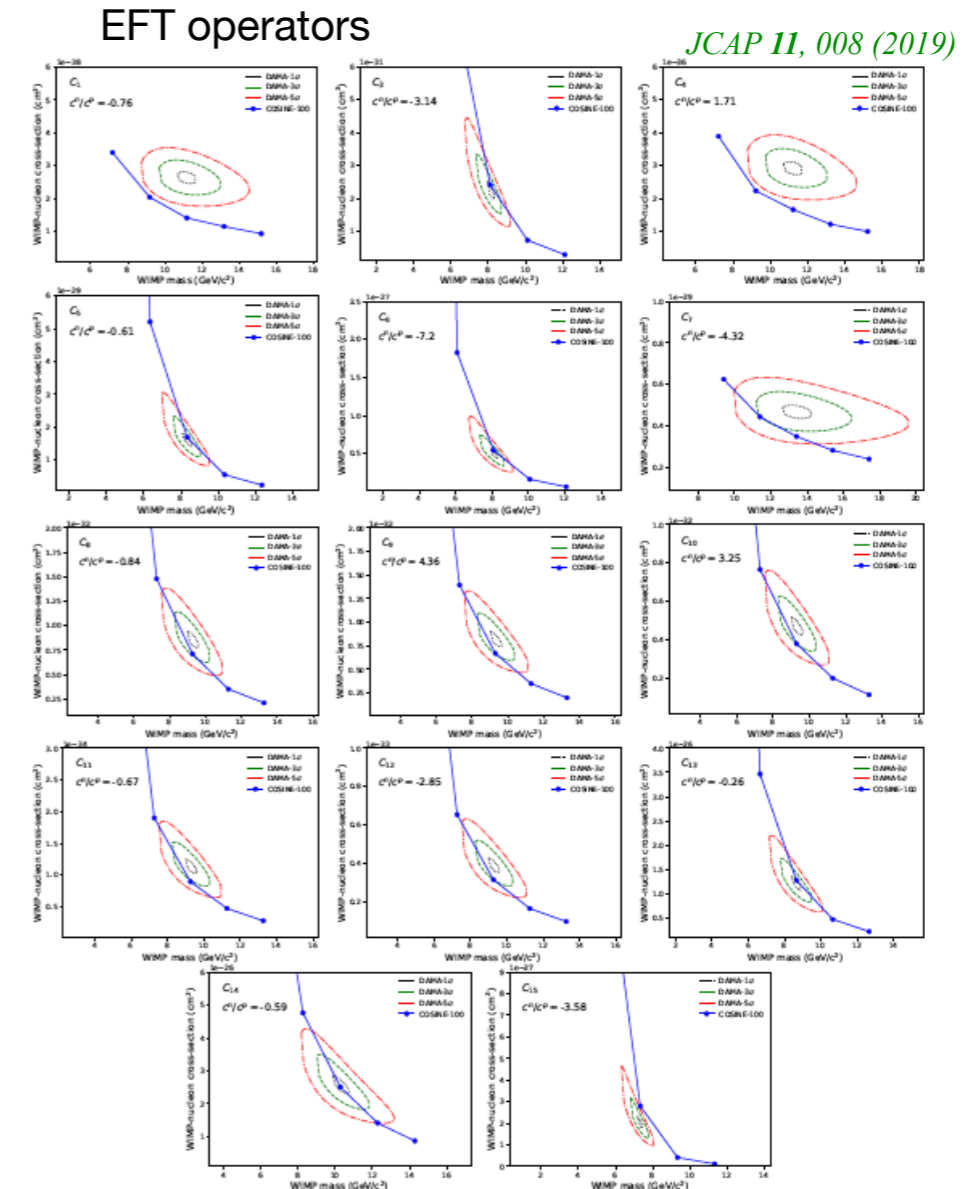
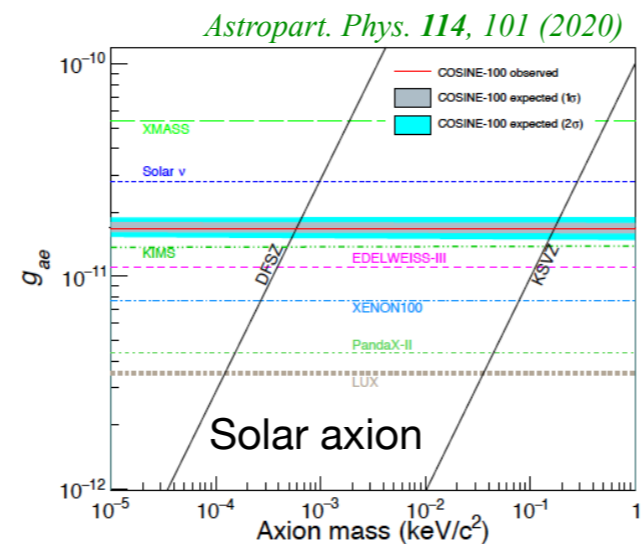
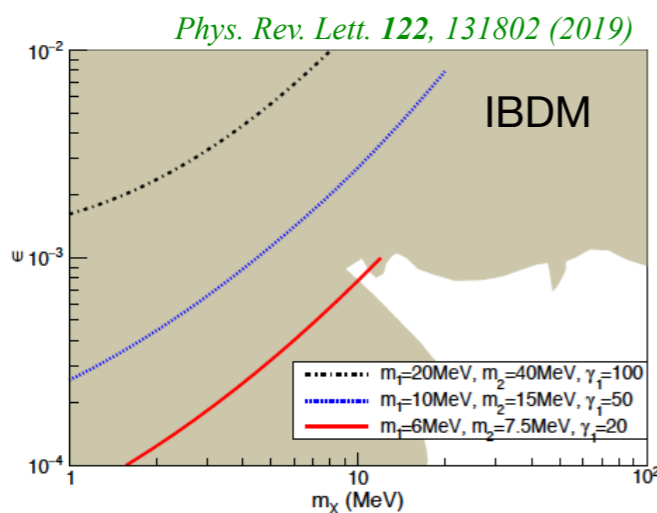
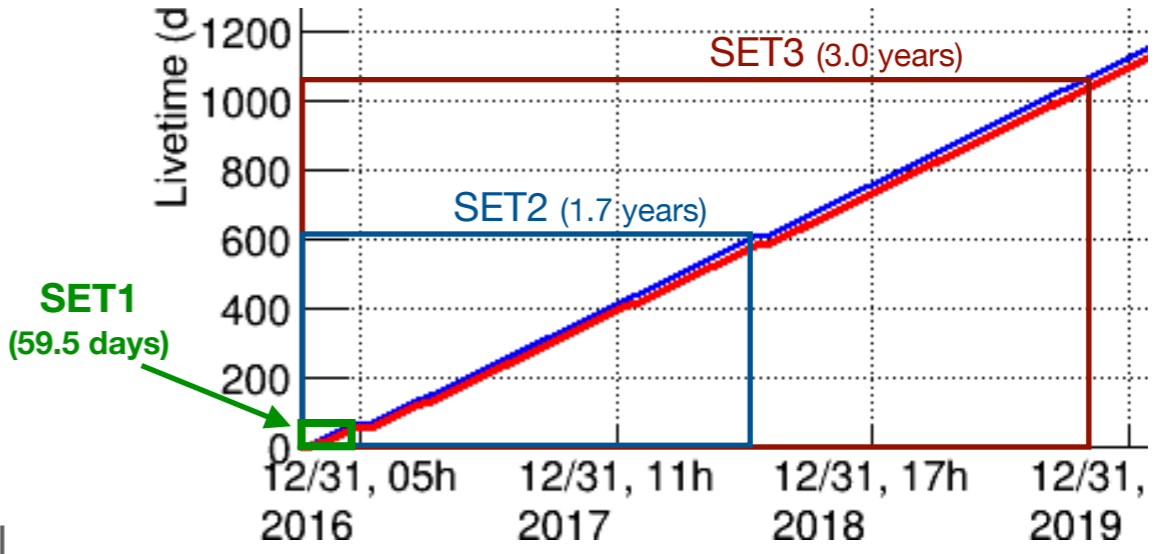




# SET1 Data Analysis

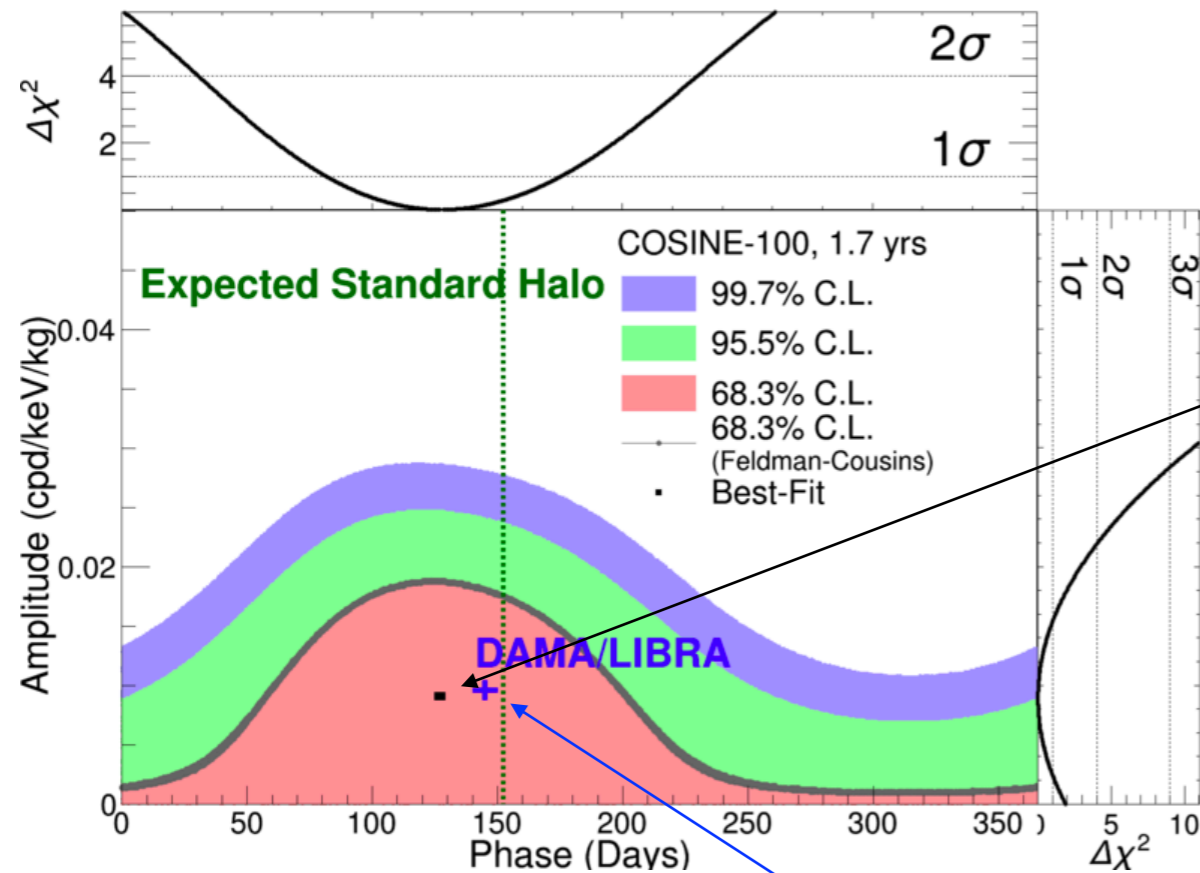
## Other Scenarios

- First physics analysis
  - WIMP extraction analysis: SI WIMP & SHM
  - Excluding DAMA/LIBRA w/ the same target material
- Various model & quenching factor (QF)
  - SI & SD WIMP
  - Assuming different QF → cannot exclude DAMA/LIBRA
- Effective field theory (EFT) operators
  - Cannot cover DAMA/LIBRA for several operators
- Other scenarios of DM
  - Inelastic boosted dark matter
  - Solar axion

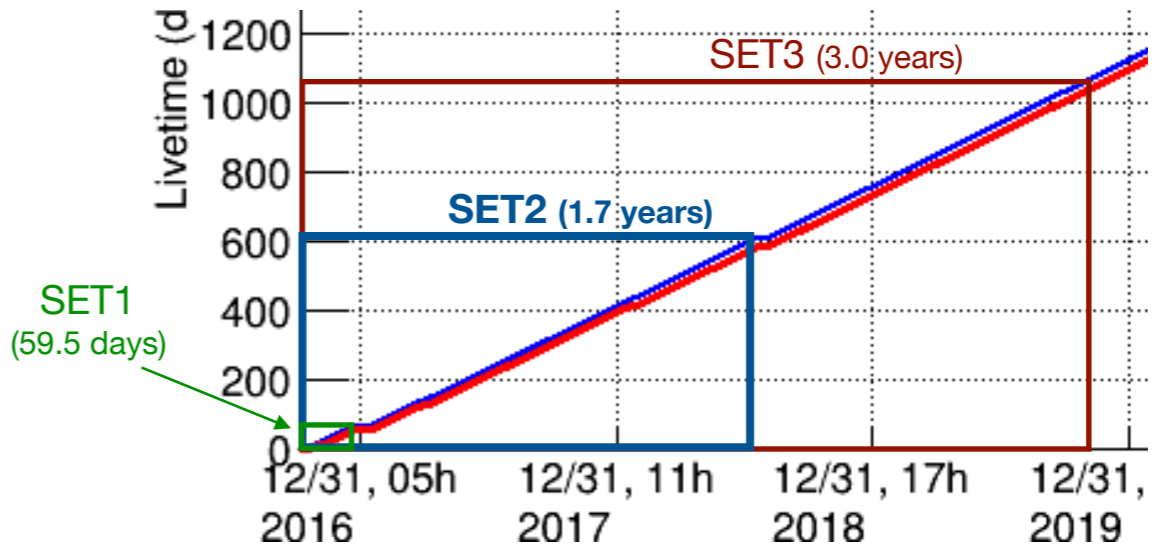


# SET2 Data Analysis

## Annual Modulation Analysis



DAMA/LIBRA-phase1+2  
 Amp. =  $0.0096 \pm 0.0008$  cpd/keV/kg  
 Phase =  $145 \pm 5$  days



COSINE-100 data-set2  
 Amp. =  $0.0092 \pm 0.0067$  cpd/keV/kg  
 Phase =  $127.2 \pm 45.9$  days

Configuration	Amplitude [cpd/kg/keV]	Phase (Days)
COSINE-100	$0.0092 \pm 0.0067$	$127.2 \pm 45.9$
DAMA/LIBRA (Phase1 + Phase2)	$0.0096 \pm 0.0008$	$145 \pm 5$
COSINE-100	$0.0083 \pm 0.0068$	152.5 (fixed)
COSINE-100 (Without LS)	$0.0024 \pm 0.0071$	152.5 (fixed)
ANAIS-112	$-0.0044 \pm 0.0058$	152.5 (fixed)
DAMA/LIBRA (Phase1 + Phase2)	$0.0095 \pm 0.0008$	152.5 (fixed)

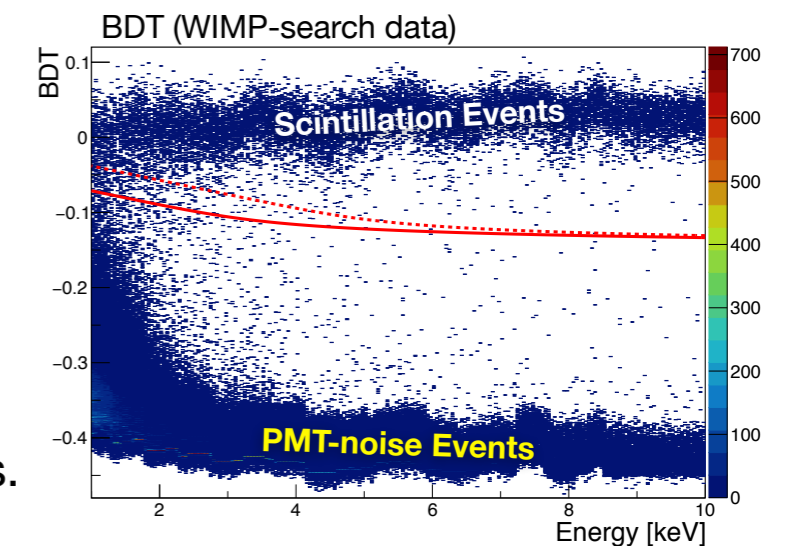
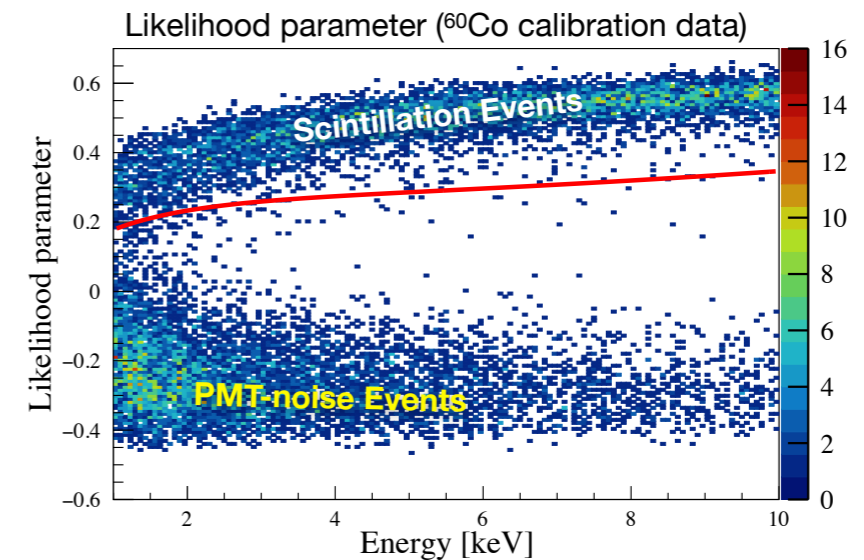
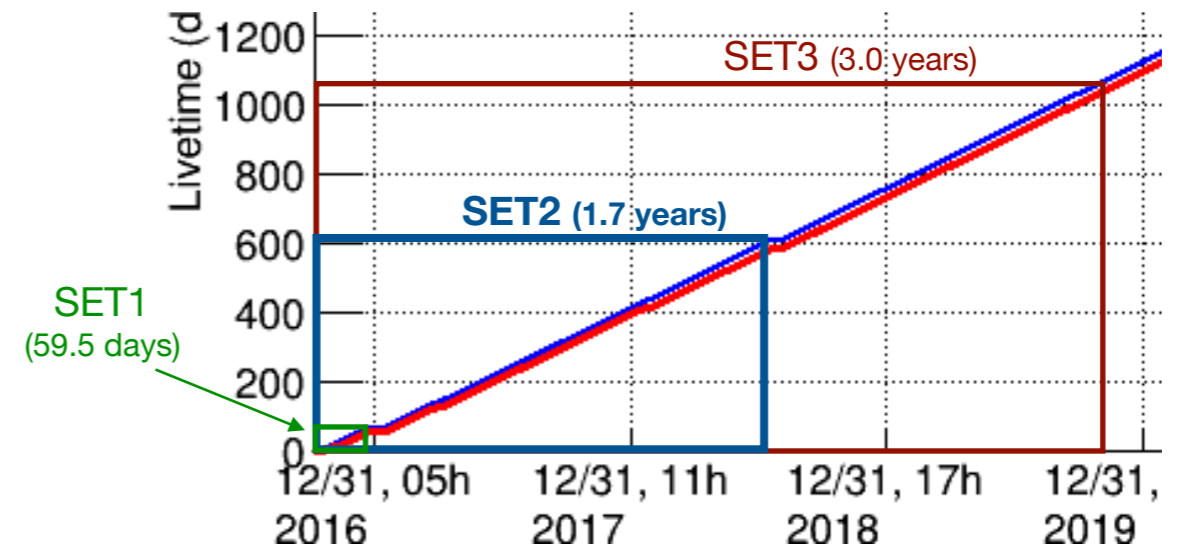
*Phys. Rev. Lett.* **123**, 031302 (2019)

- Model-independent DM search
- The results agree both of DAMA/LIBRA and null hypothesis



# SET2 Data Analysis

## Improvements in SET2



- Event selection
  - Development of a new **likelihood parameter** based on **pulse shape**
  - **Boosted decision tree (BDT)** is used to separate the signals from the noises.
  - Lowering threshold from 2 to 1 keV

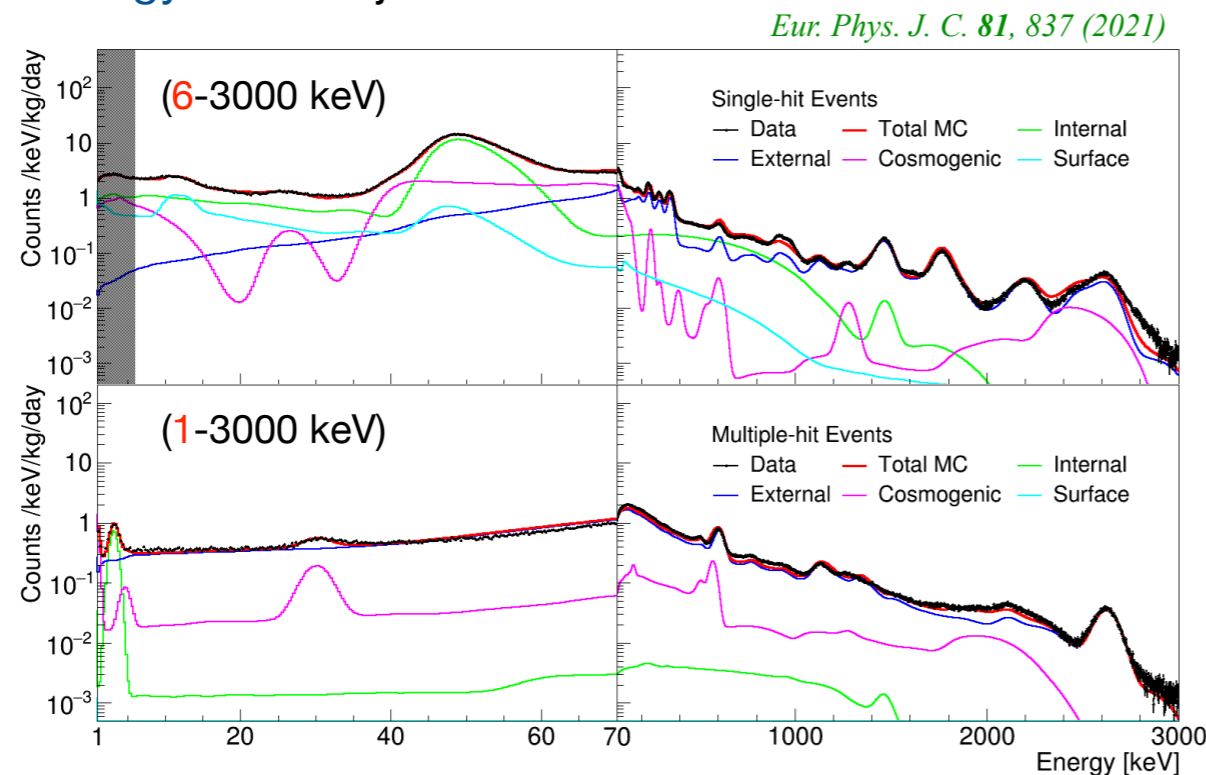
*Astropart. Phys.* **130**, 102581 (2021)

# SET2 Data Analysis

## Improvements in SET2

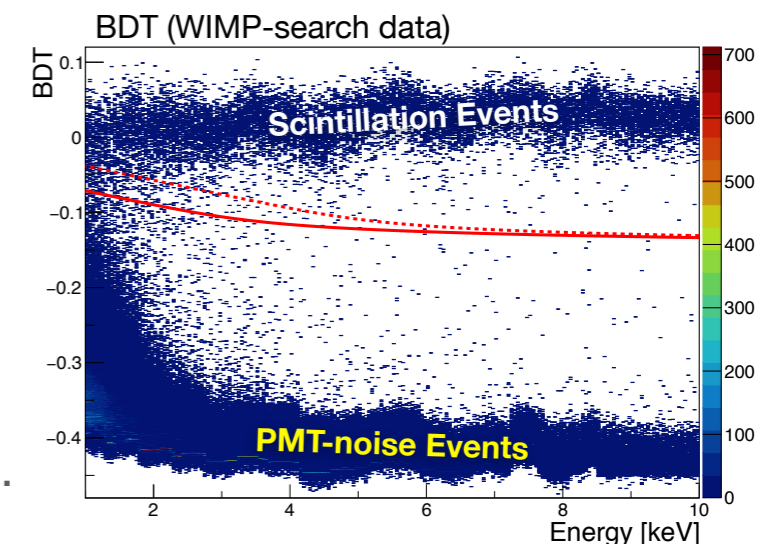
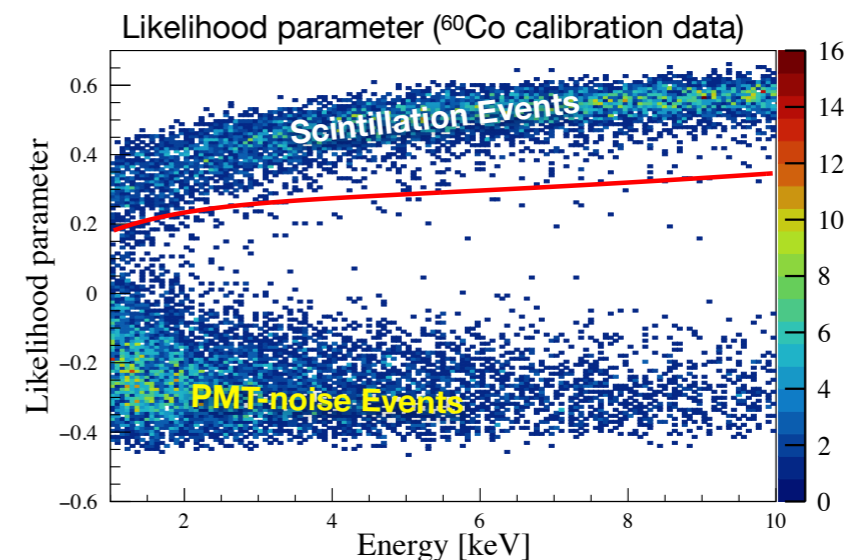
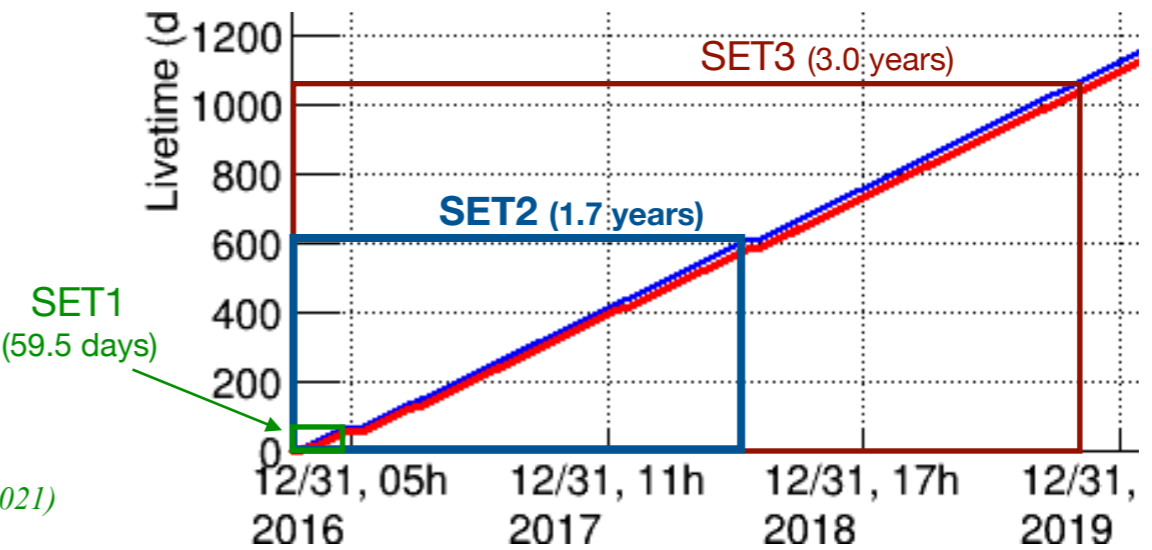
- Improvements in background modeling

- Better understanding of surface  $^{210}\text{Pb}$  *Astropart. Phys. 126, 102528 (2021)*
- Adding  $^{129}\text{I}$  and rock  $\gamma$  ( $^{208}\text{Tl}$ )
- Energy scale adjustment



- Event selection

- Development of a new likelihood parameter based on pulse shape
- Boosted decision tree (BDT) is used to separate the signals from the noises.
- Lowering threshold from 2 to 1 keV



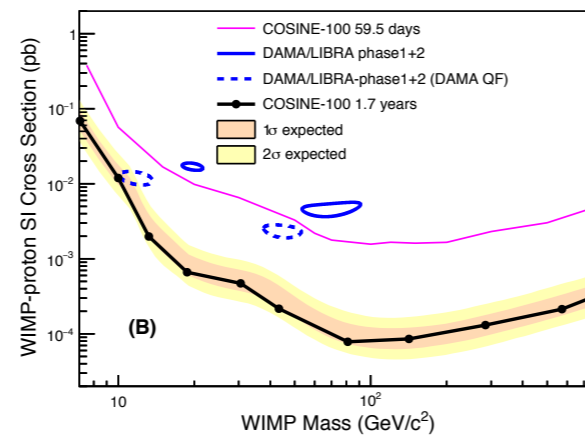
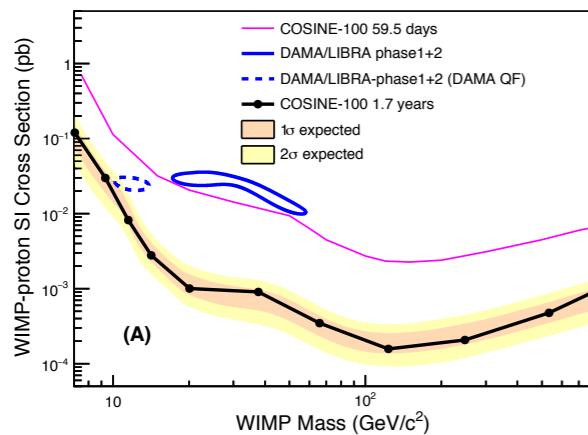
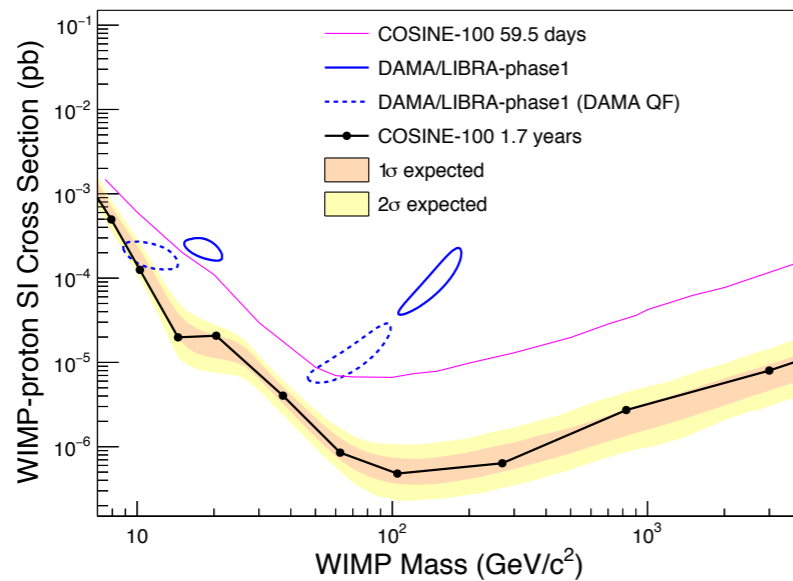
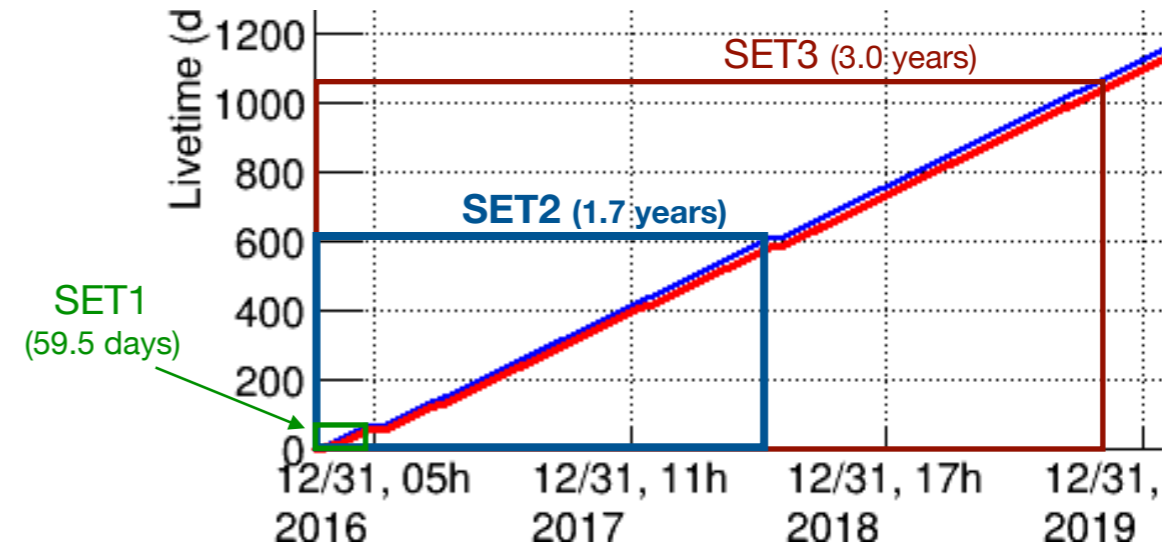
*Astropart. Phys. 130, 102581 (2021)*



# SET2 Data Analysis

## WIMP Search

- WIMP extraction analysis
  - SI WIMP & different QF

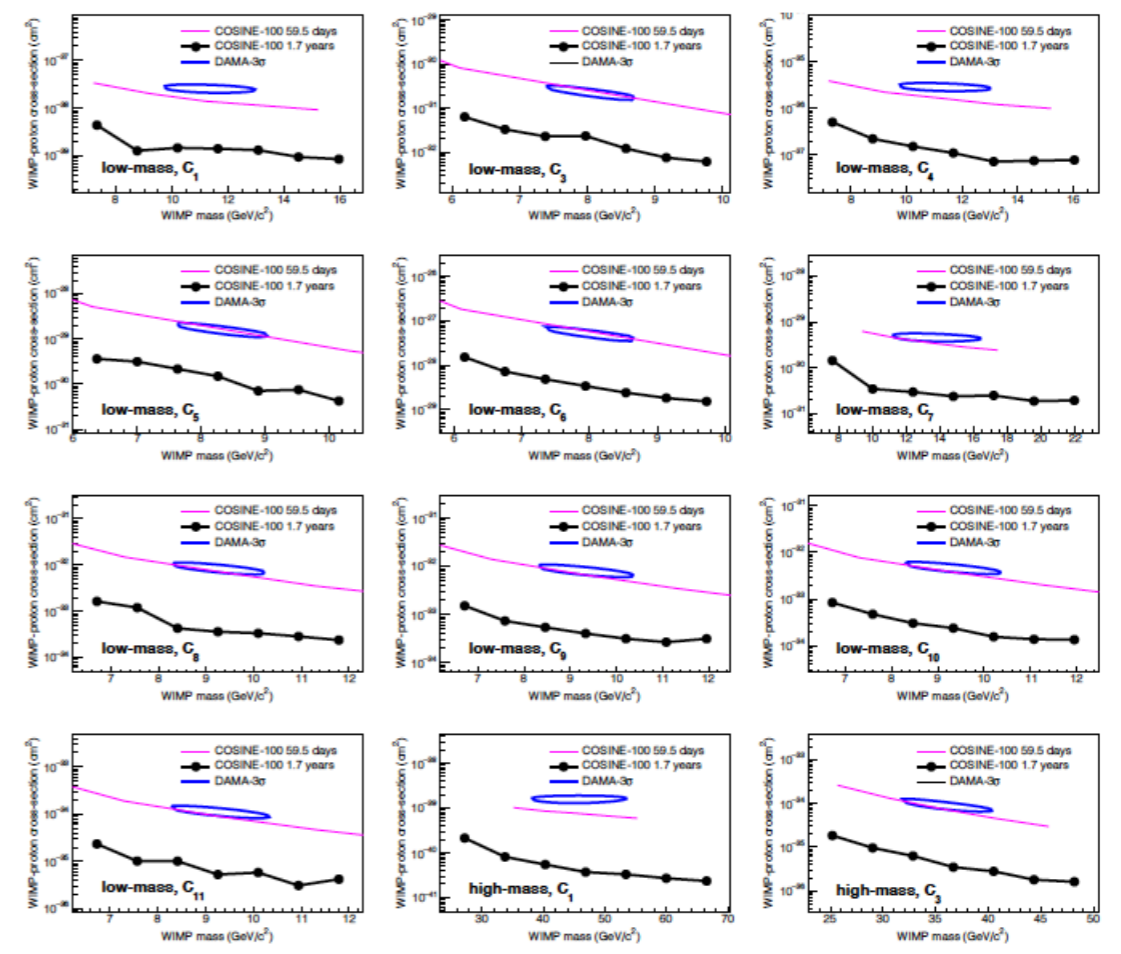
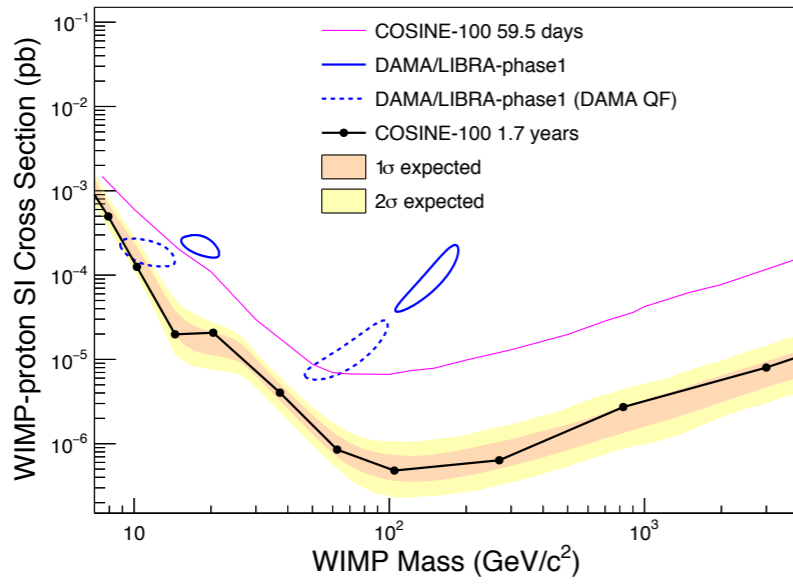
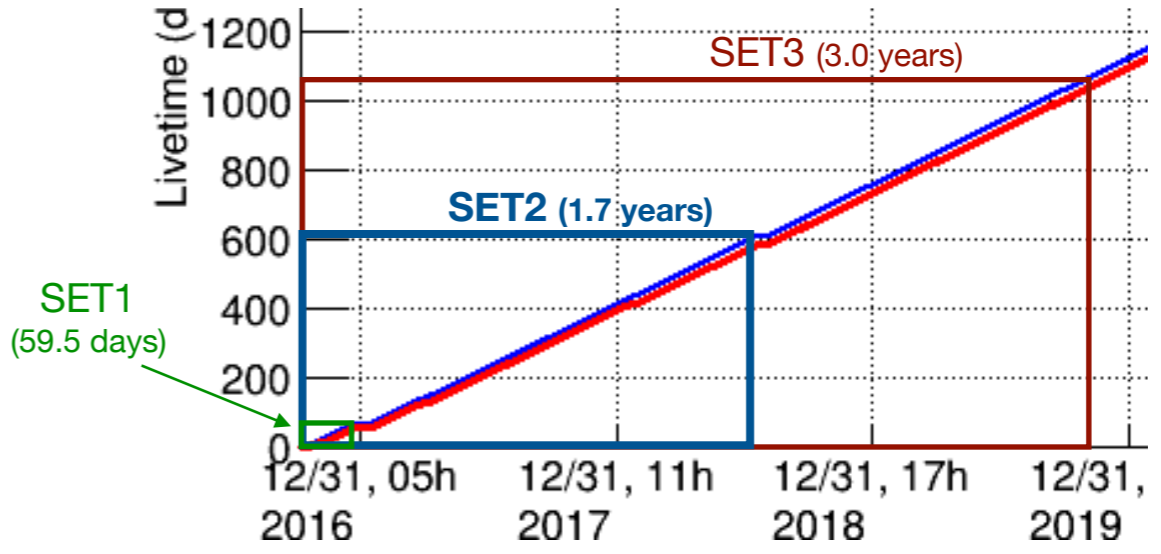


*Sci. Adv. 7, eabk2699 (2021)*

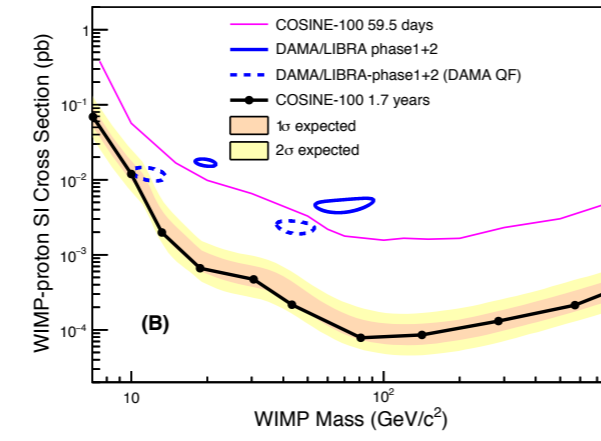
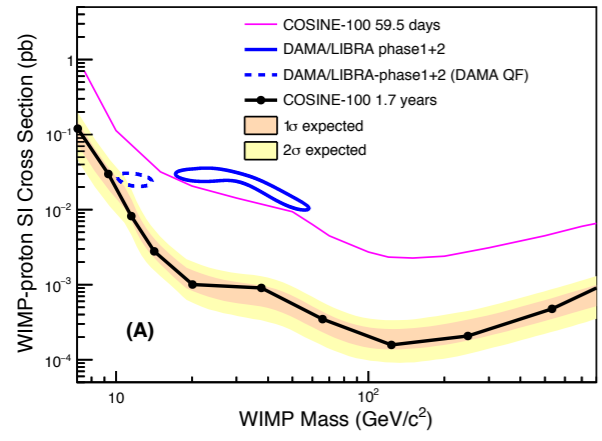
# SET2 Data Analysis

## WIMP Search

- WIMP extraction analysis
  - SI WIMP & different QF
  - EFT operators
  - Fully cover the alternative scenarios for QF & EFT



*Sci. Adv. 7, eabk2699 (2021)*

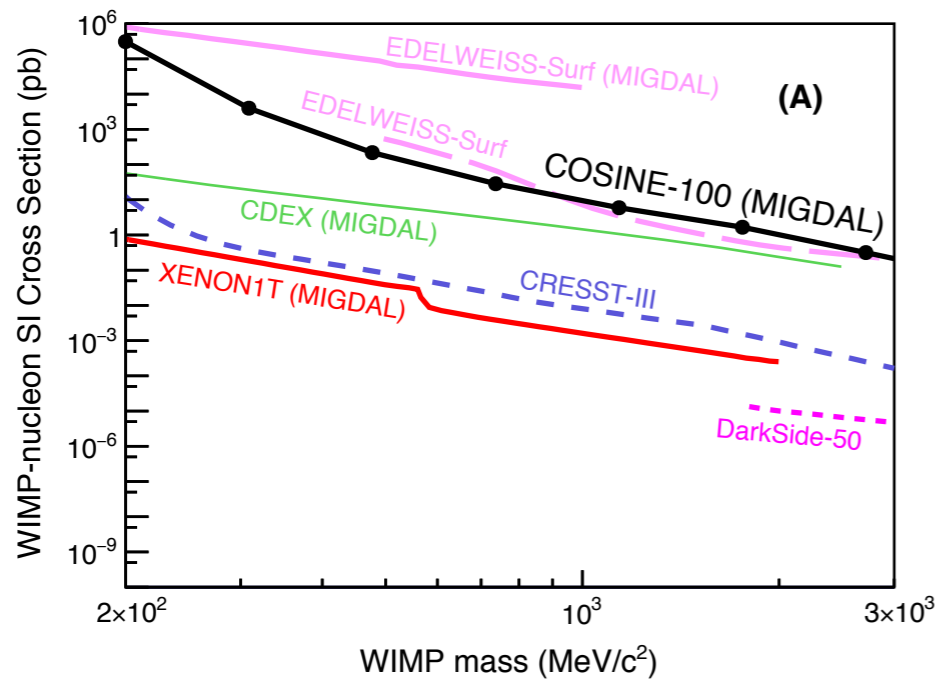
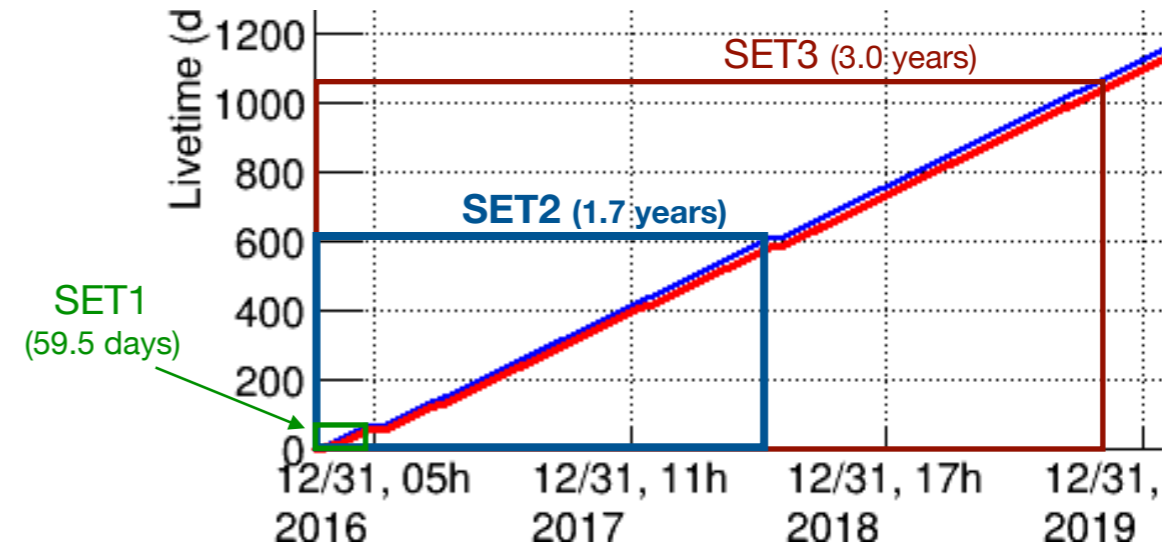




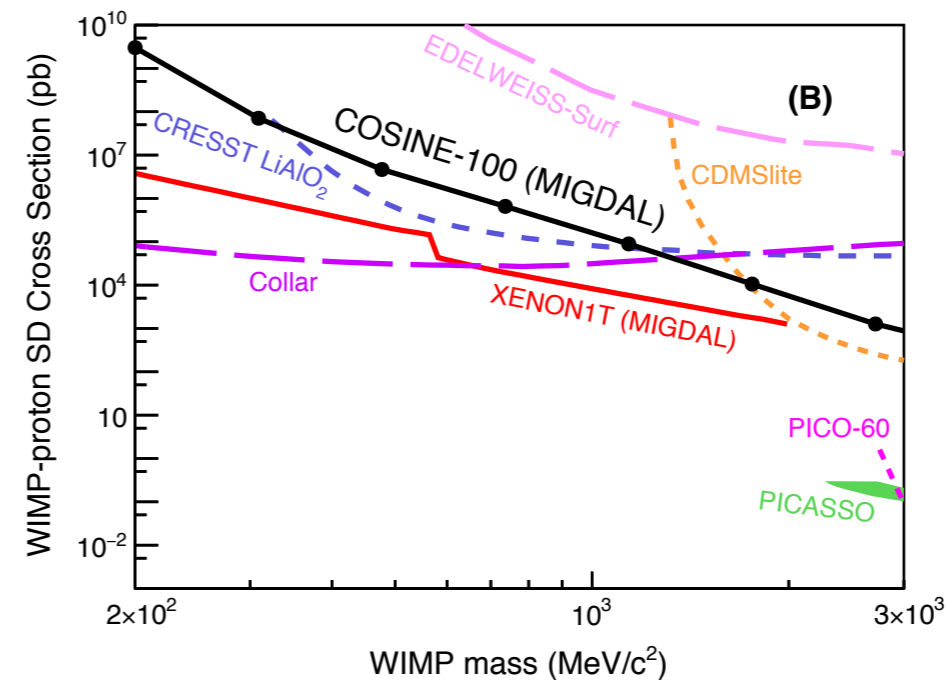
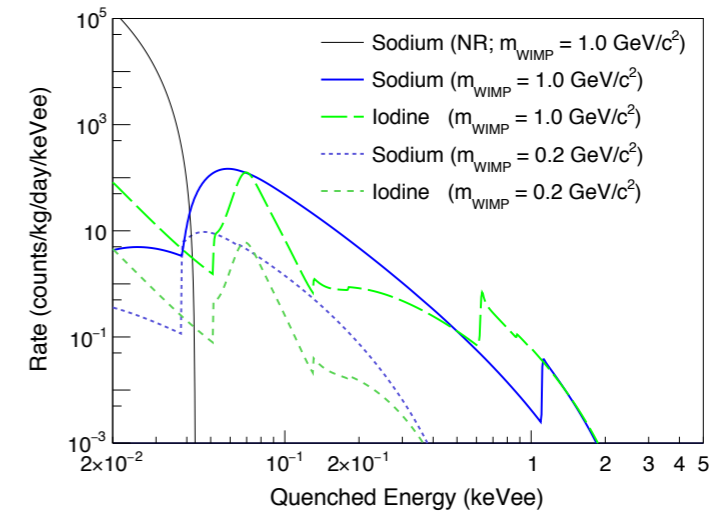
# SET2 Data Analysis

## WIMP Search

- WIMP extraction analysis
  - SI WIMP & different QF
  - EFT operators
  - Fully cover the alternative scenarios for QF & EFT
- WIMP search via Migdal effect
  - Sub-GeV DM search (from 7 to 0.2  $\text{GeV}/c^2$ )



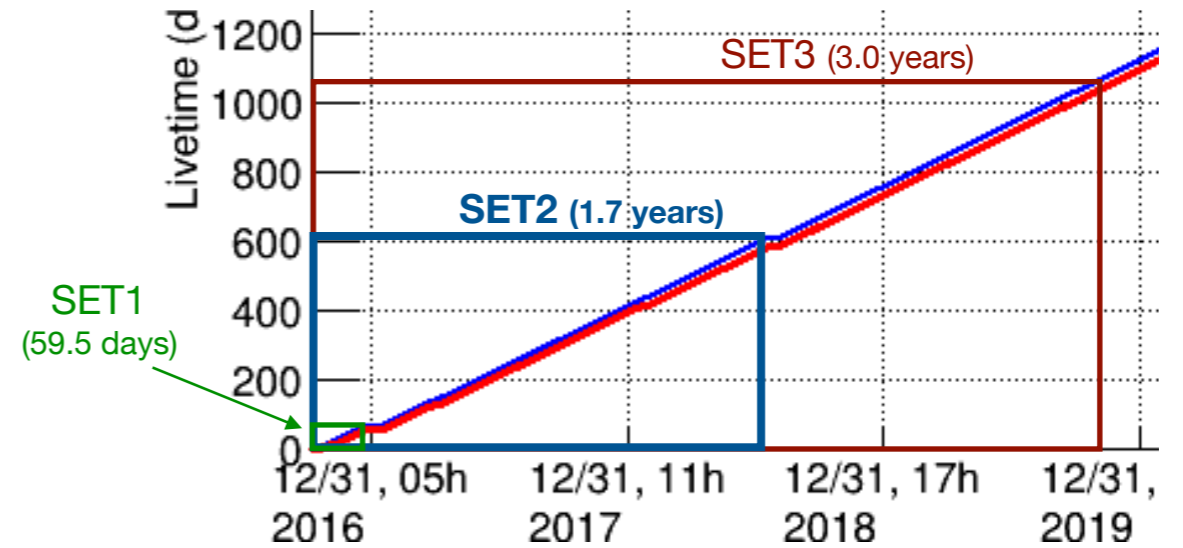
*Phys. Rev. D* **105**, 042006 (2022)



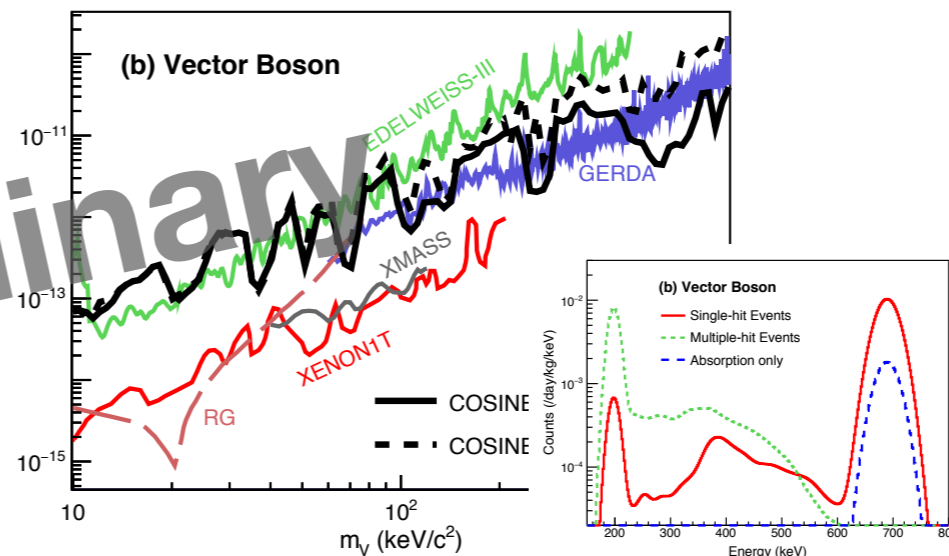
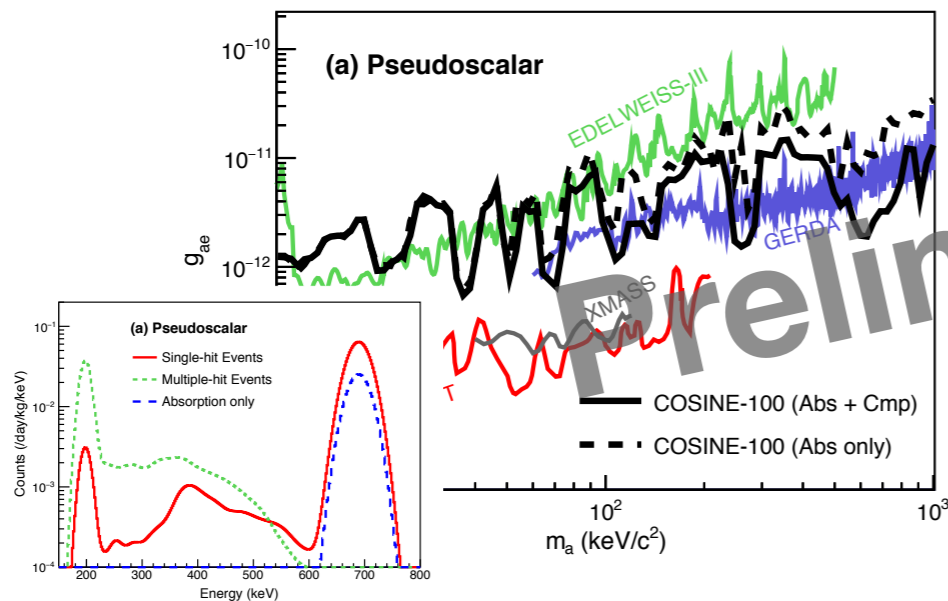
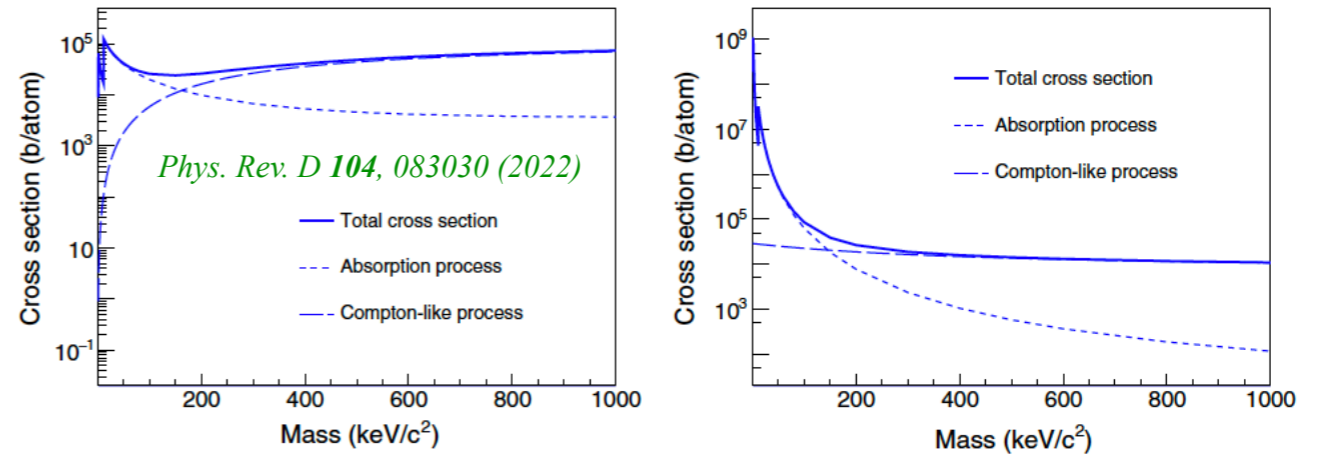
# SET2 Data Analysis

## Bosonic super-WIMP

- WIMP extraction analysis
  - SI WIMP & different QF
  - EFT operators
  - Fully cover the alternative scenarios for QF & EFT
- WIMP search via Migdal effect
  - Sub-GeV DM search (from 7 to 0.2 GeV/c<sup>2</sup>)
- Bosonic super-WIMP search
  - Adding Compton-like process
  - Work in progress



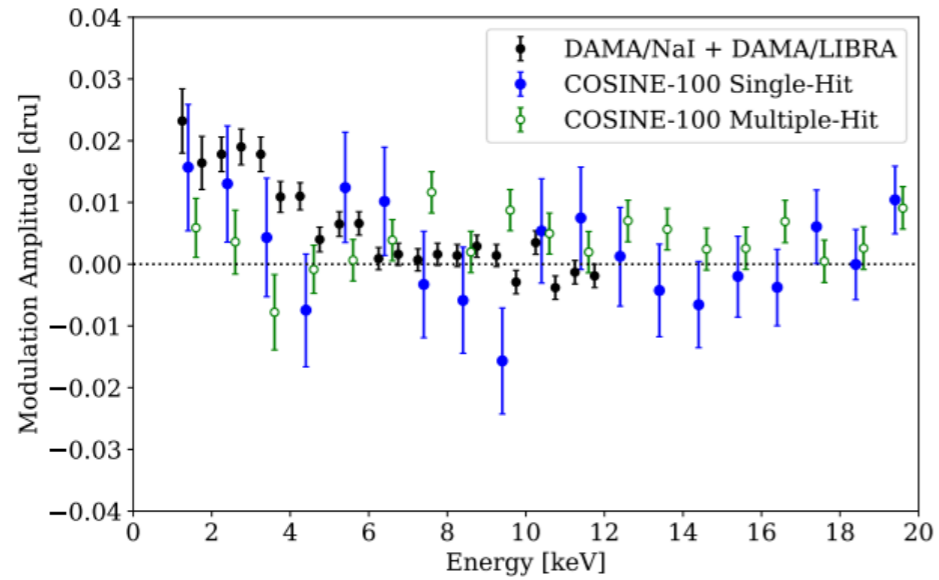
Comparison b/w absorption & Compton-like process



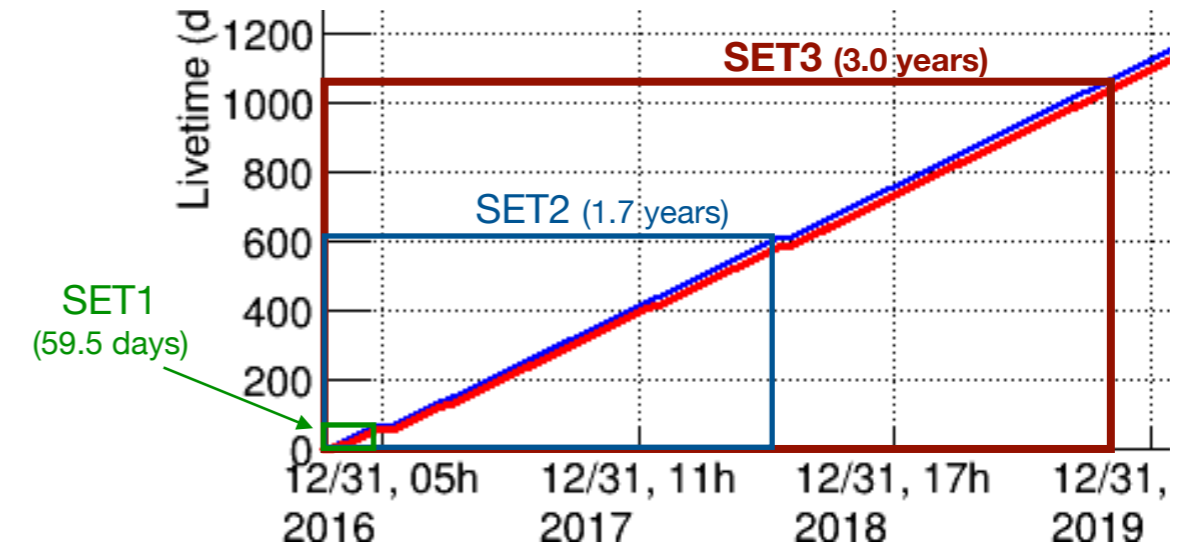
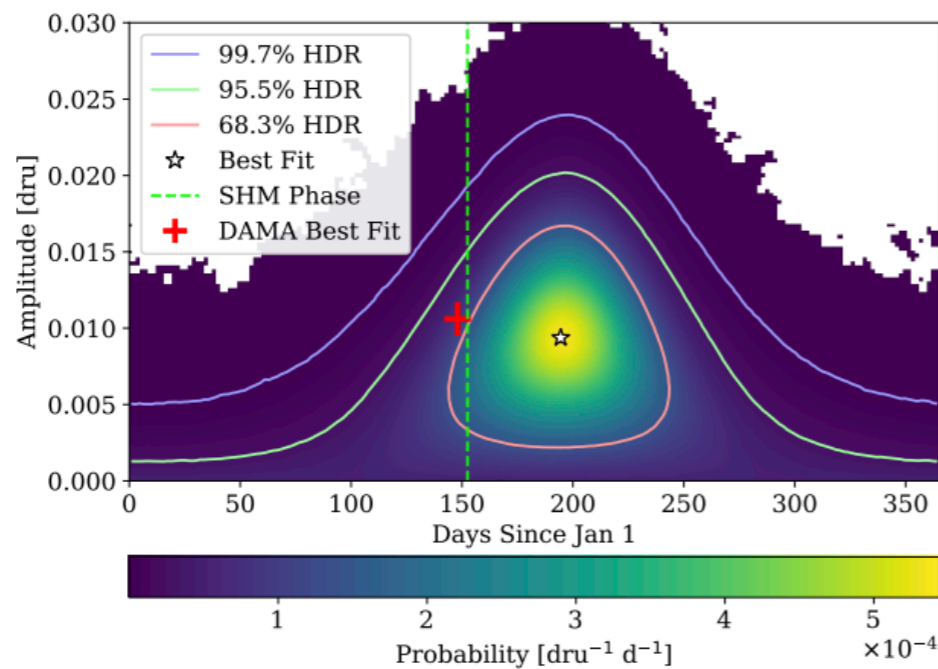


# SET3 Data Analysis

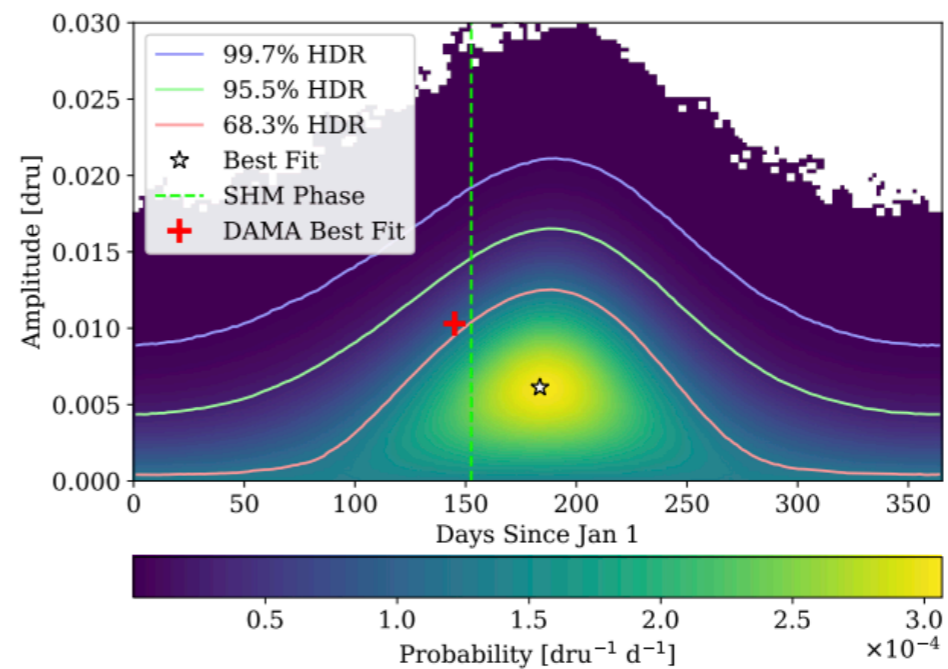
## Annual Modulation Analysis



*arXiv:2111.08863 [hep-ex]*



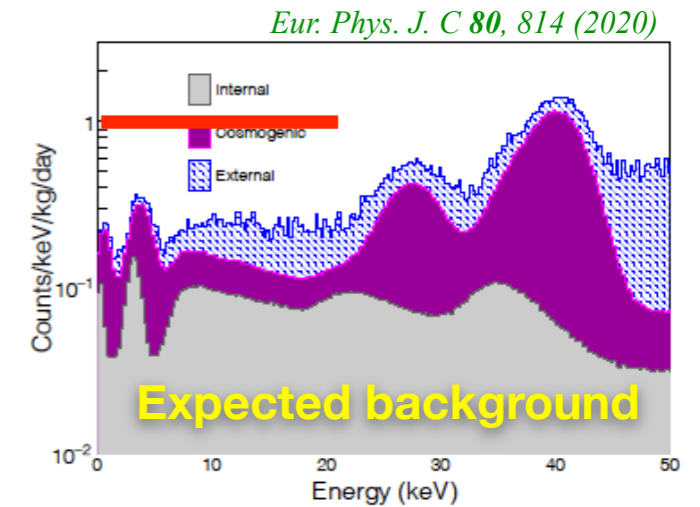
- Still cannot rule out any of DAMA/LIBRA & null hypotheses.
- 5-years data analysis is ongoing.



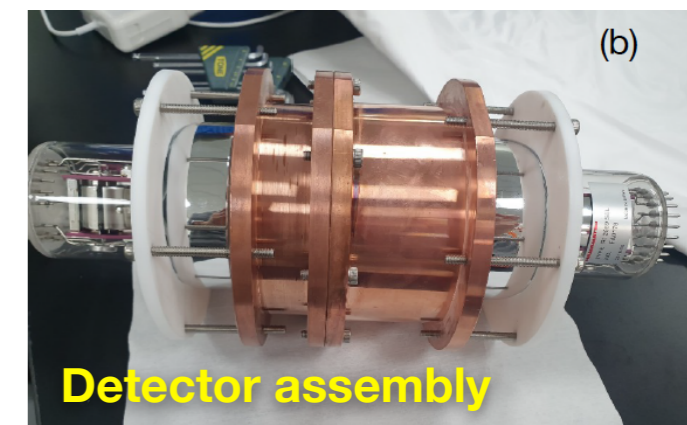
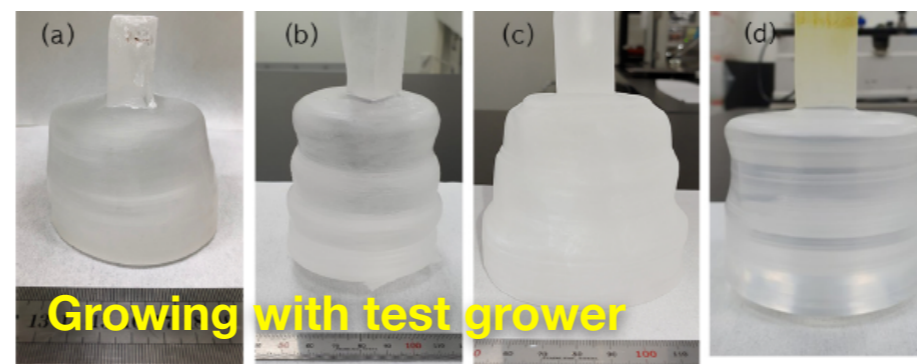
# Plan for Next Phase

## Crystal Development

- Goal: lower background level than DAMA/LIBRA
  - COSINE-100 has **2-3 times higher background** than DAMA/LIBRA
  - In-house development for the **entire process**
    - NaI powder purification
    - Crystal growing
    - Detector assembly



	K [ppb]	<sup>210</sup> Pb [mBq/kg]	<sup>238</sup> U [Bq/kg]	<sup>232</sup> Th [Bq/kg]
Powder	5	-	< 20	< 20
Aug., 2018	684	3.8 ± 0.3	26 ± 7	< 6
Sep., 2019	<b>8</b>	<b>0.01 ± 0.02</b>	11 ± 4	7 ± 2
DAMA	< 20	0.01 ~ 0.03	8.7 ± 124	2 ~ 31

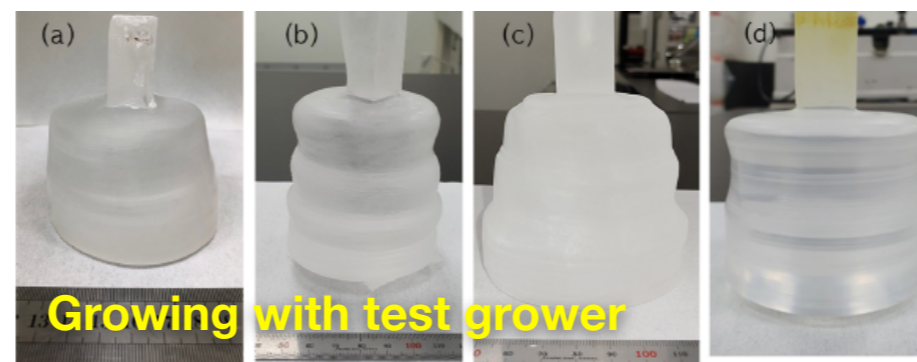
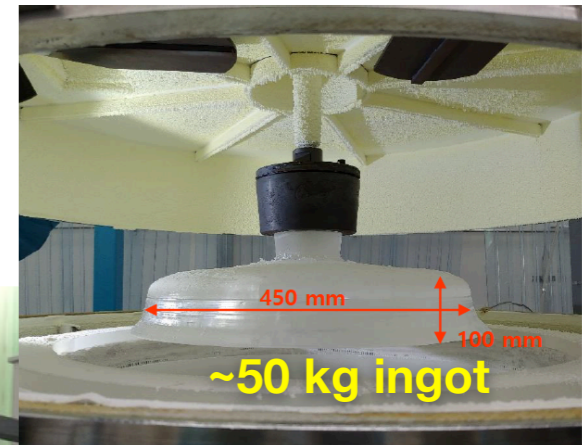




# Plan for Next Phase

## Crystal Development

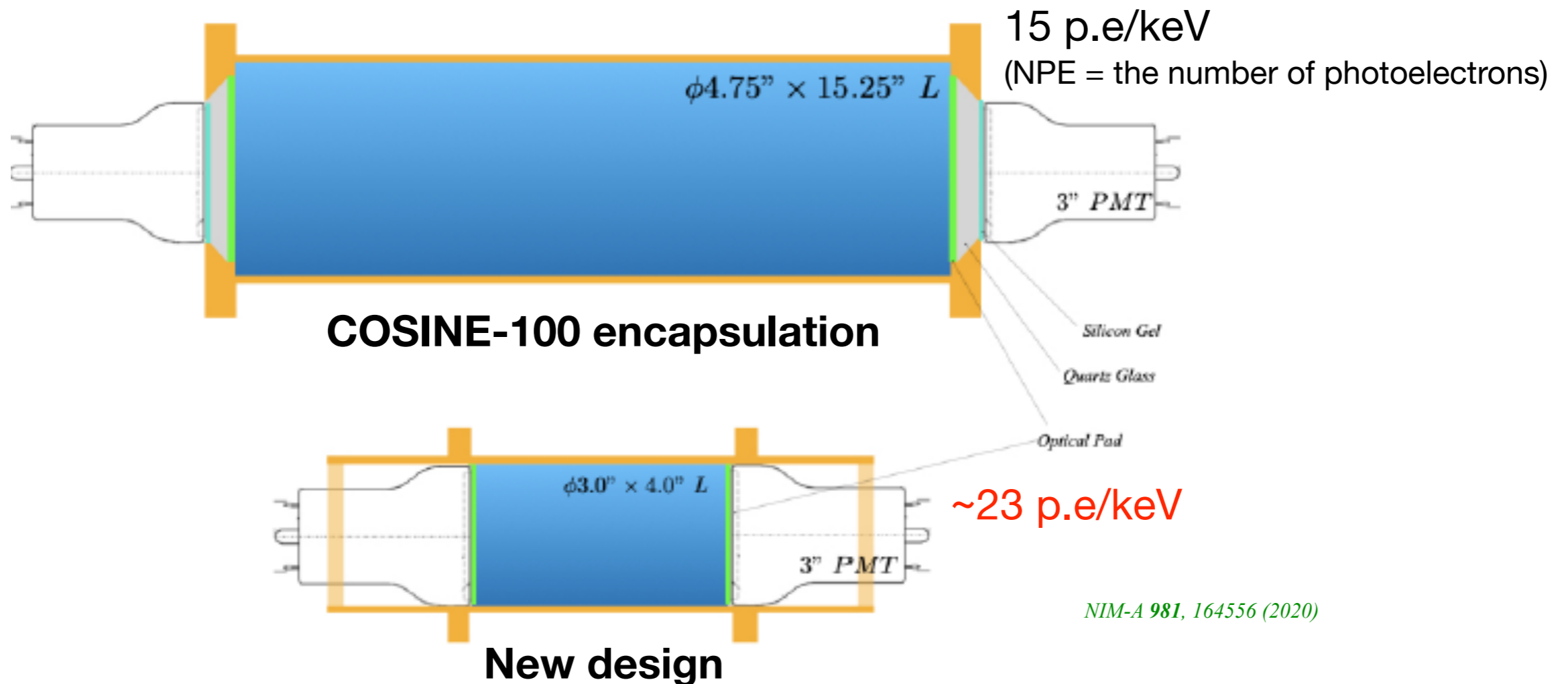
- Goal: lower background level than DAMA/LIBRA
  - COSINE-100 has 2-3 times higher background than DAMA/LIBRA
  - In-house development for the entire process
    - NaI powder purification
    - Crystal growing
    - Detector assembly
  - Full size grower
    - Designed and built based on small test grower
    - **Successful seeding and growing** ~10-cm ingot



# Plan for Next Phase

## Efforts for Lower Threshold

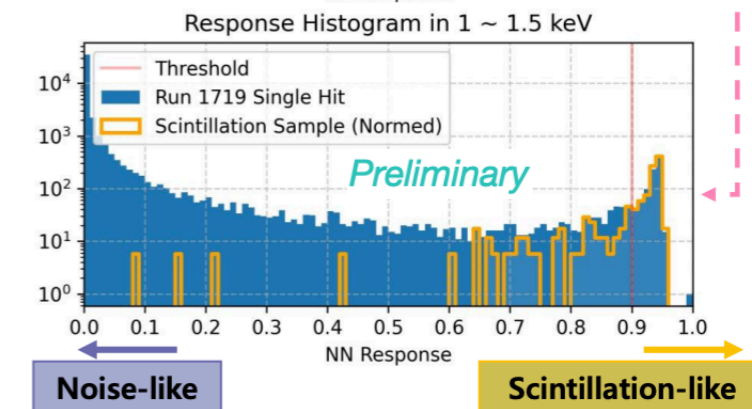
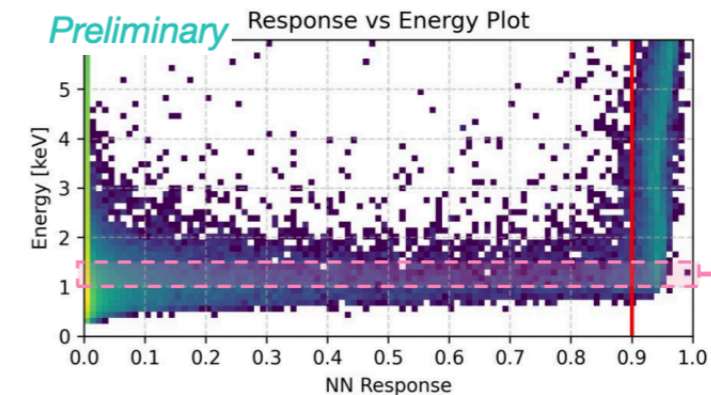
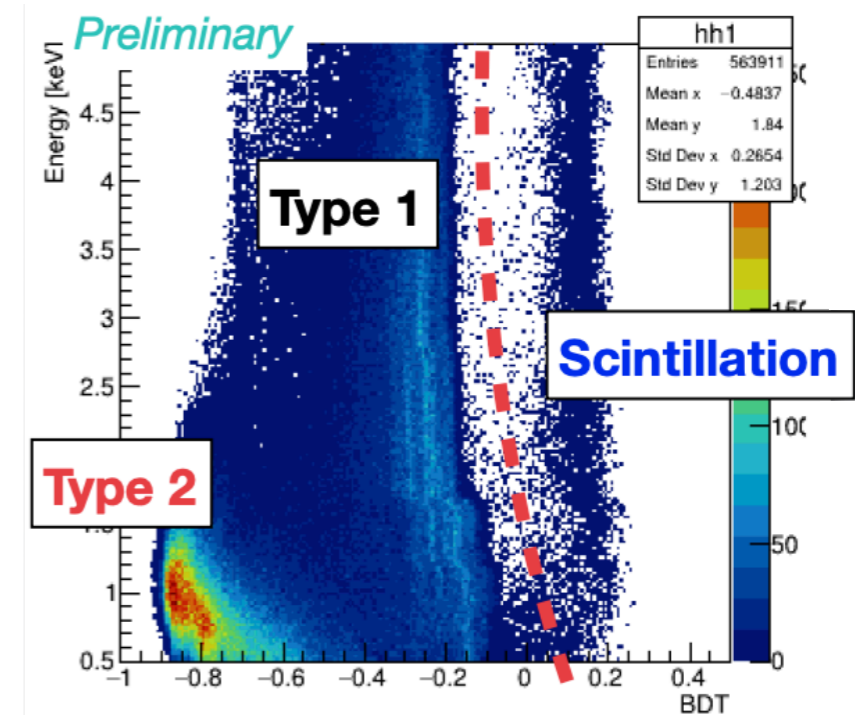
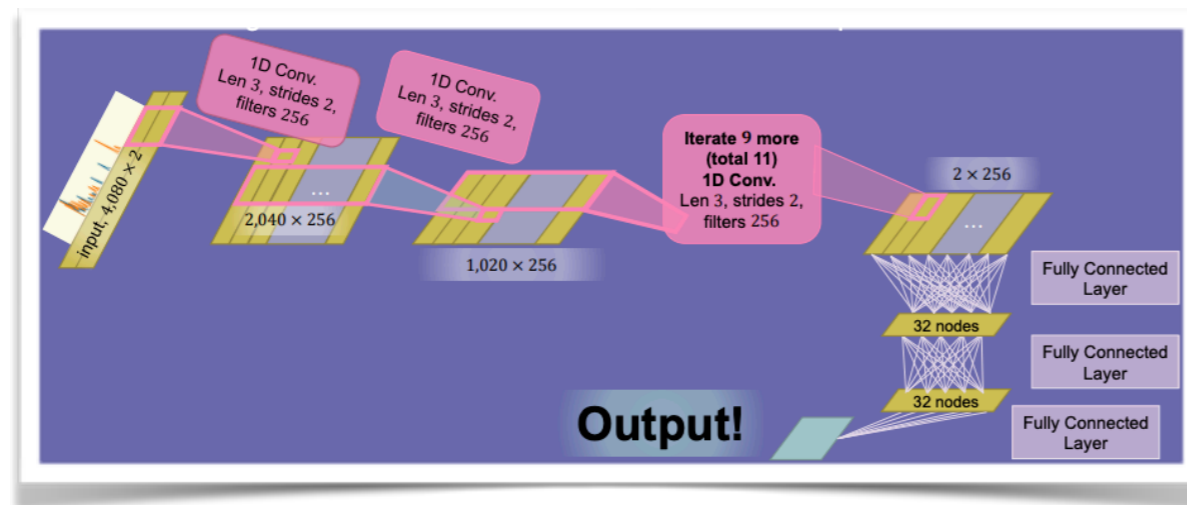
- Novel technique of crystal encapsulation
  - Direct attachment of crystal to PMTs
  - ~50% increased light yield
  - It will be applied to COSINE-200 detector assembly



# 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
- Event selection
  - Improved multi-variable technique
    - ~0.5 keV (7 p.e) of energy threshold achievable
  - Deep learning

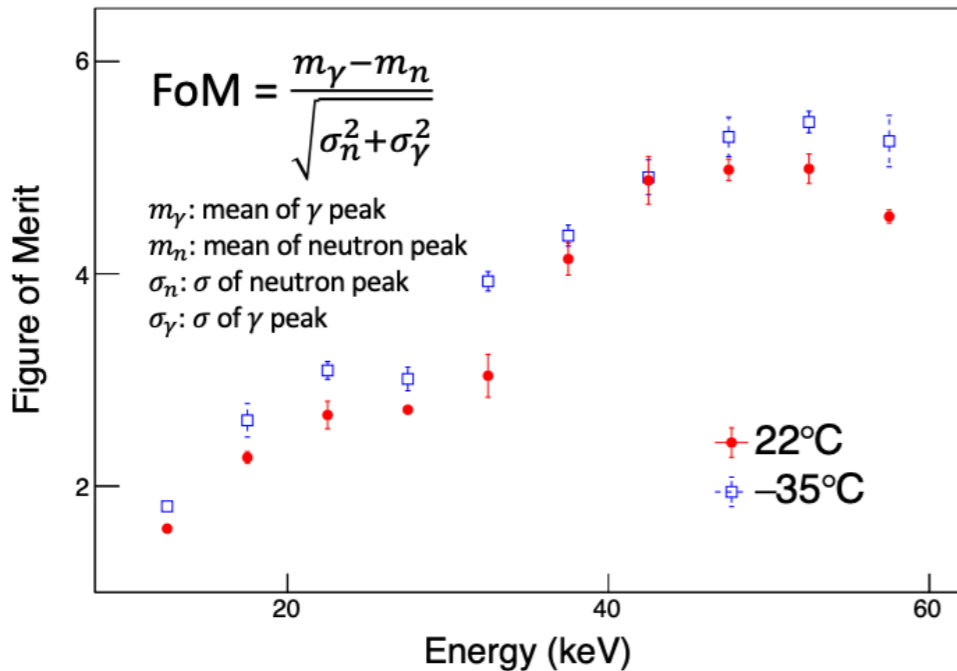




# Plan for Next Phase

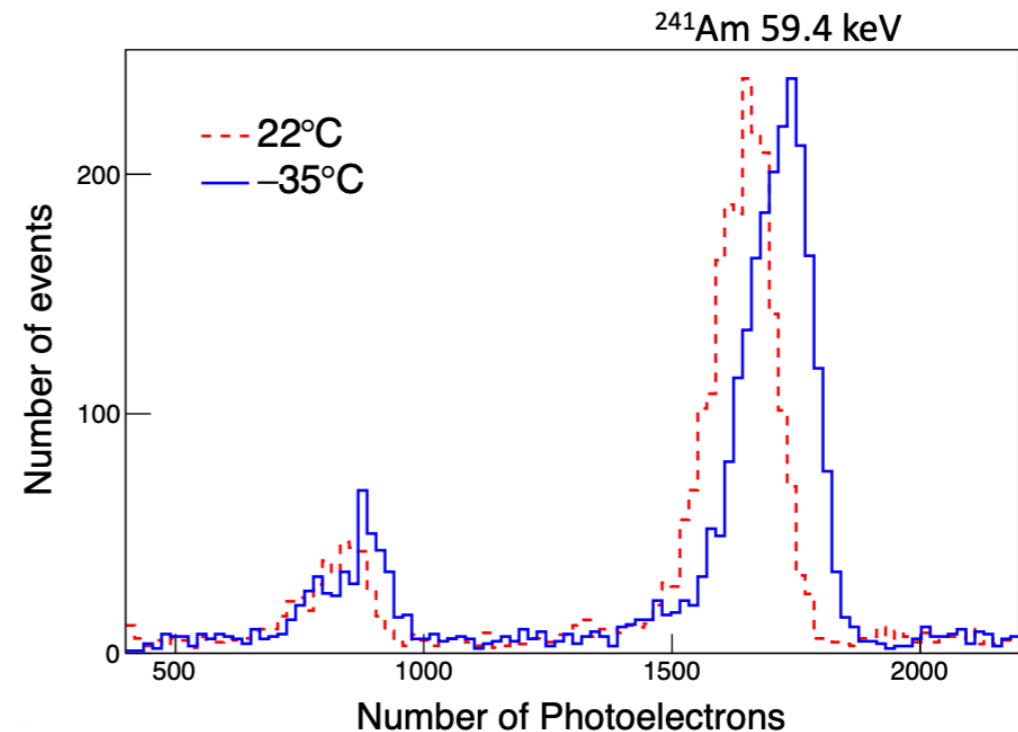
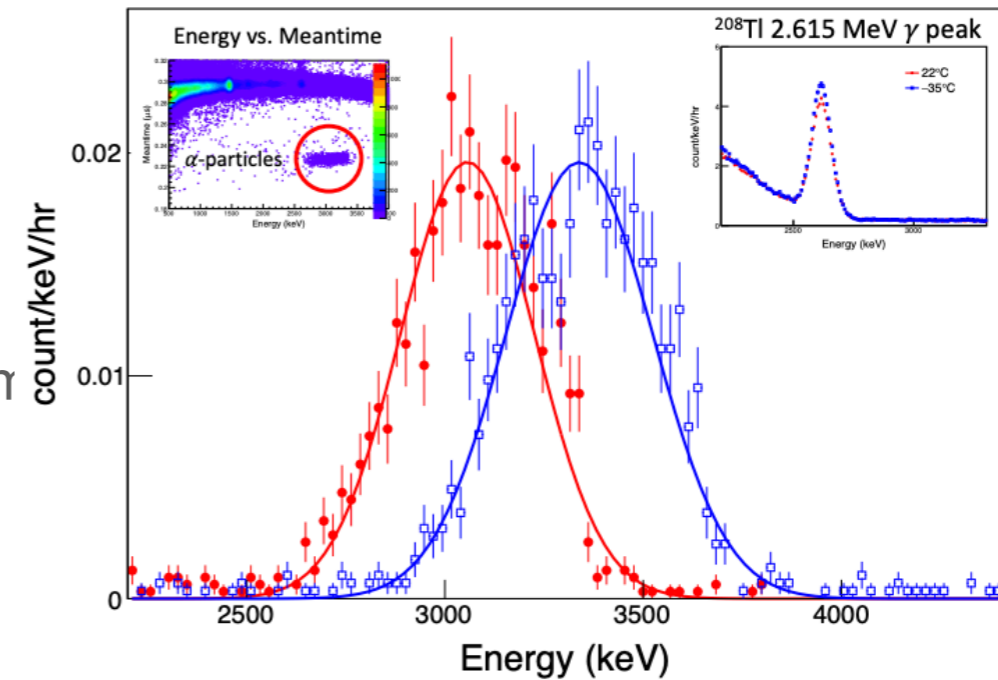
## Efforts for Lower Threshold

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- Low temperature measurement
  - Improved PSD for  $\gamma$  and n
  - ~10% increased  $\alpha$  quenching
  - Increased light yield
    - $27.6 \pm 0.3$  p.e/keV  $\rightarrow$   $28.9 \pm 0.2$  p.e/keV
  - Consider operating COSINE-200 at  $-30^\circ\text{C}$



on

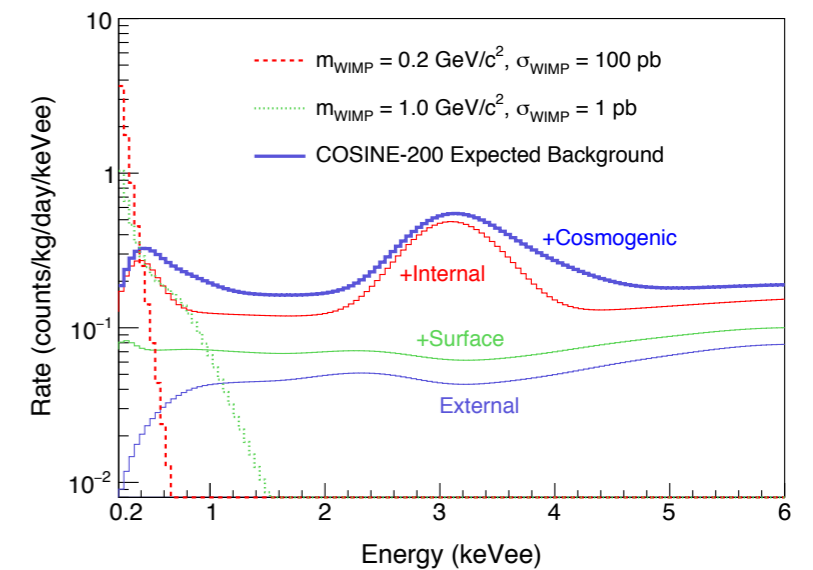
assen



# Plan for Next Phase

## Sensitivity Study

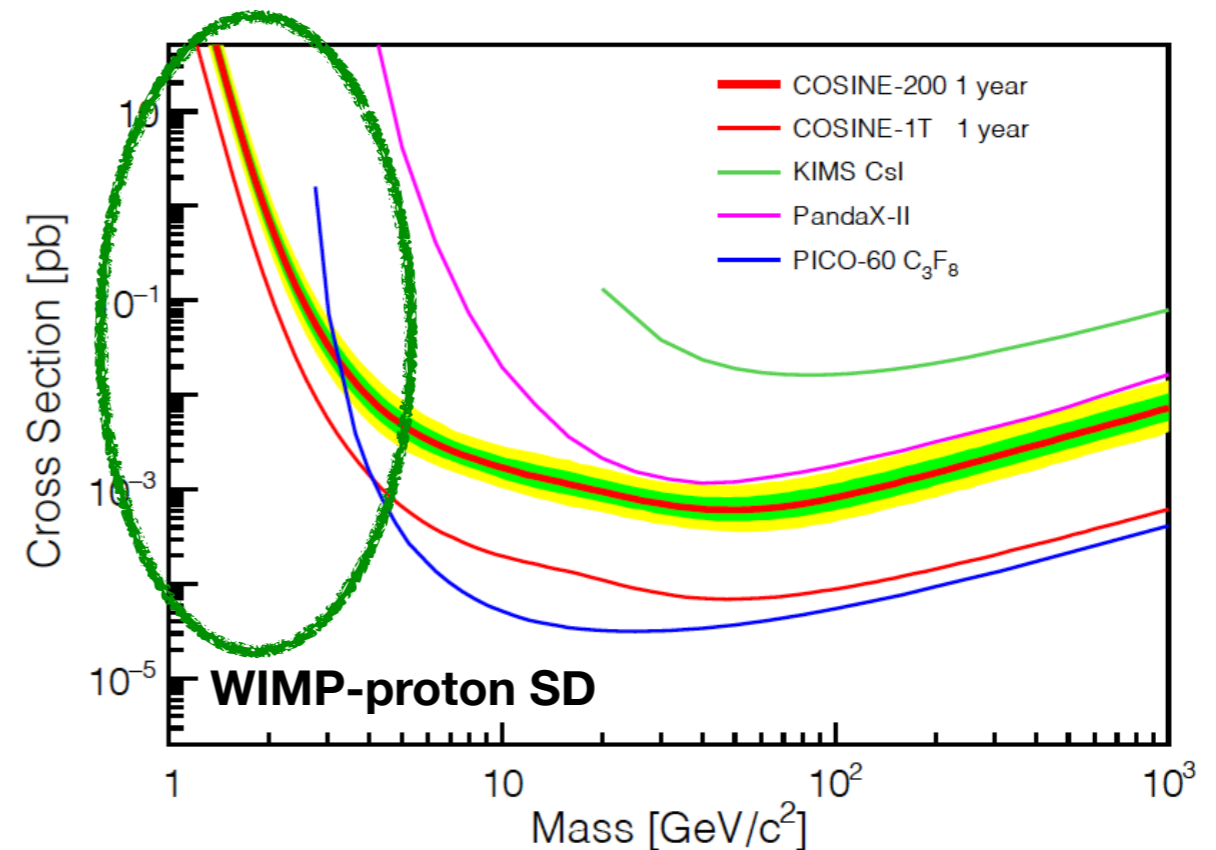
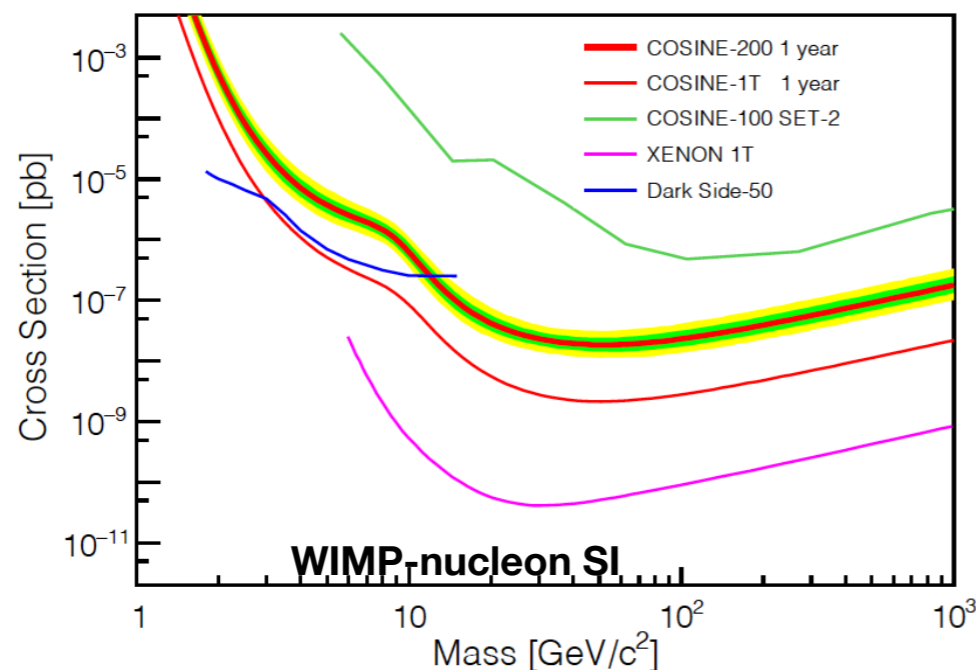
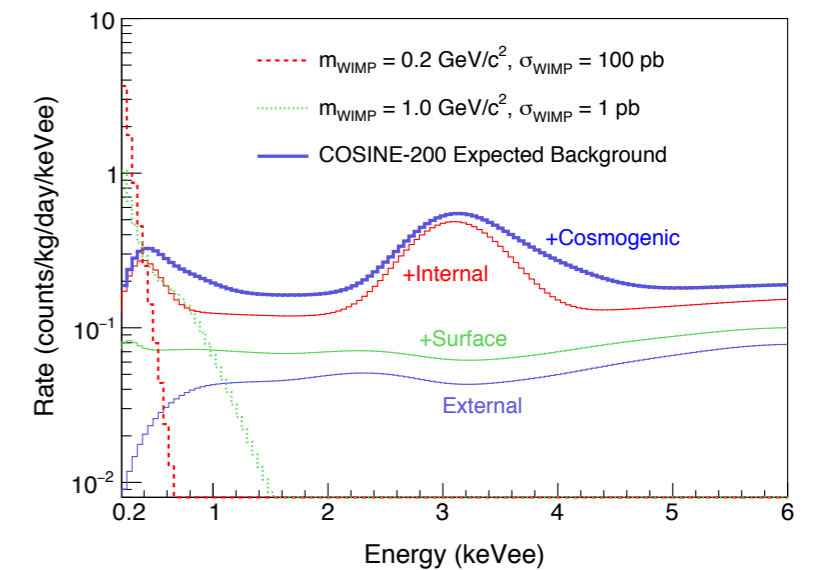
- Assuming expected improvements
  - 200 kg of mass and 0.2~0.3-counts/day/kg/keV background
  - ~22 p.e/keV of light yield w/ 5 p.e threshold



# Plan for Next Phase

## Sensitivity Study

- Assuming expected improvements
  - 200 kg of mass and 0.2~0.3-counts/day/kg/keV background
  - ~22 p.e/keV of light yield w/ 5 p.e threshold
- Sensitivity of COSINE-200
  - Both of Na & I are **proton-odd** elements
  - Competition w/ PICO-60 in low mass region for **WIMP-proton SD** interaction

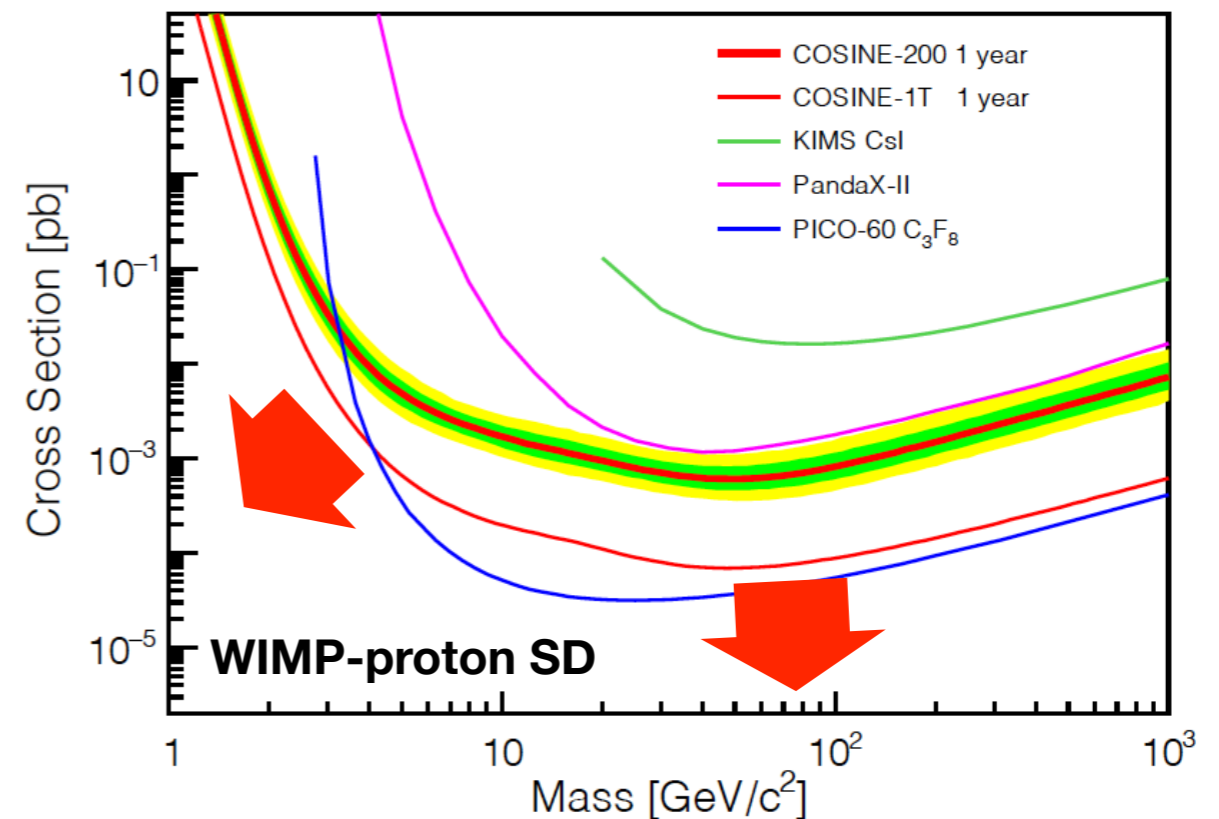
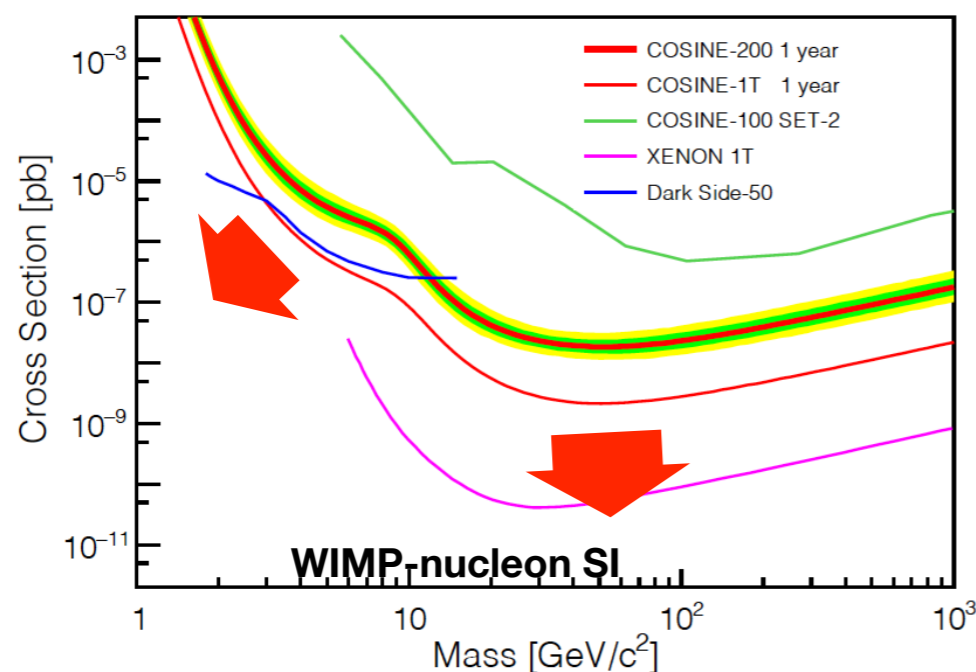
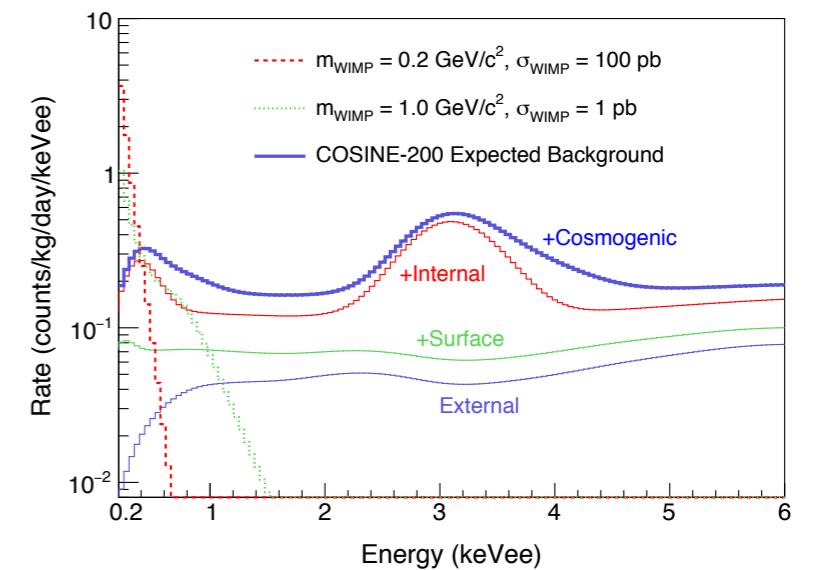




# Plan for Next Phase

## Sensitivity Study

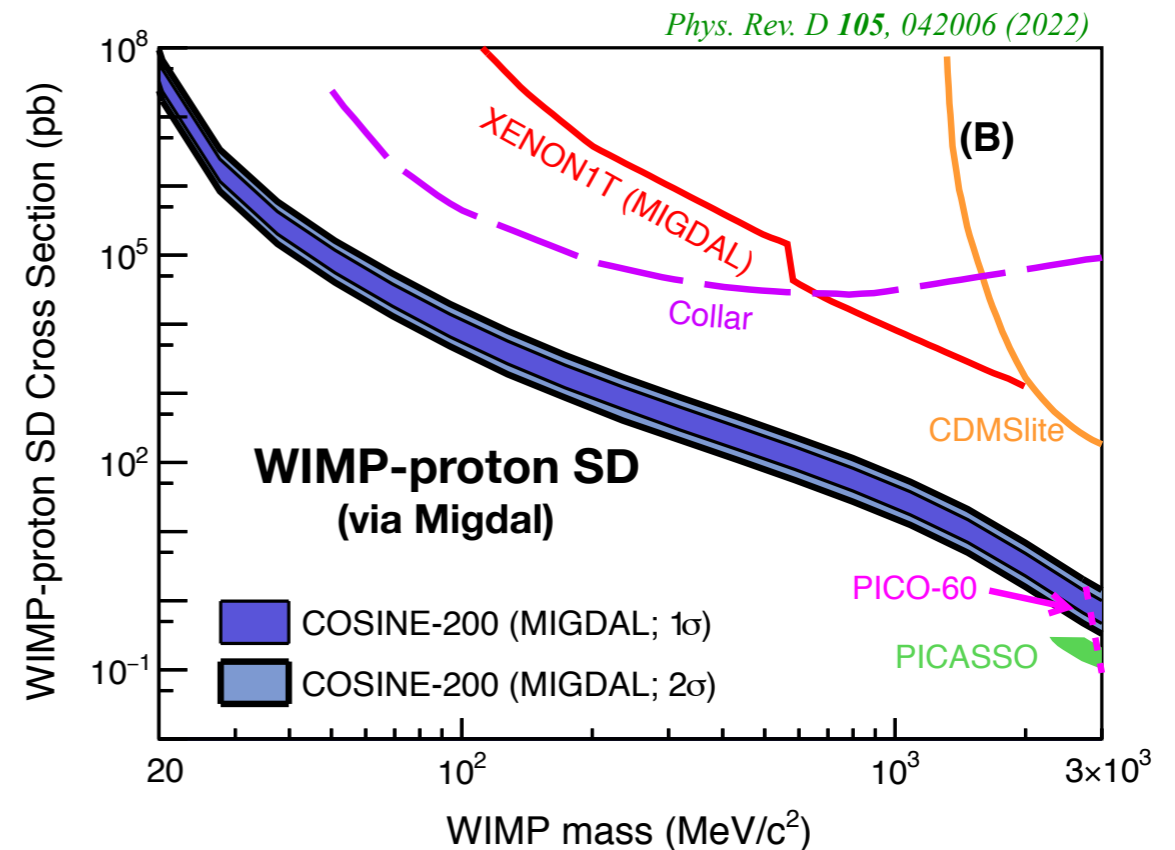
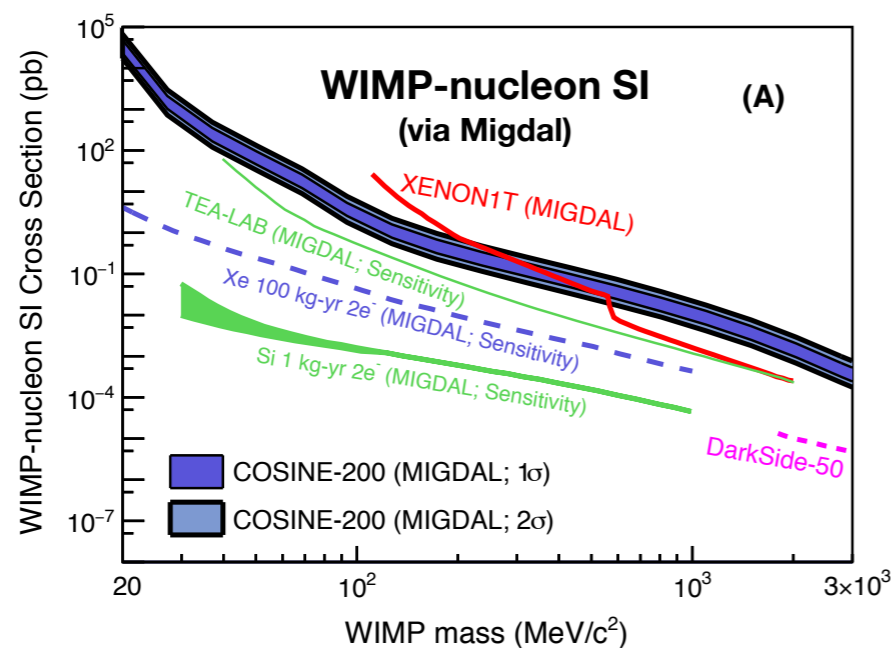
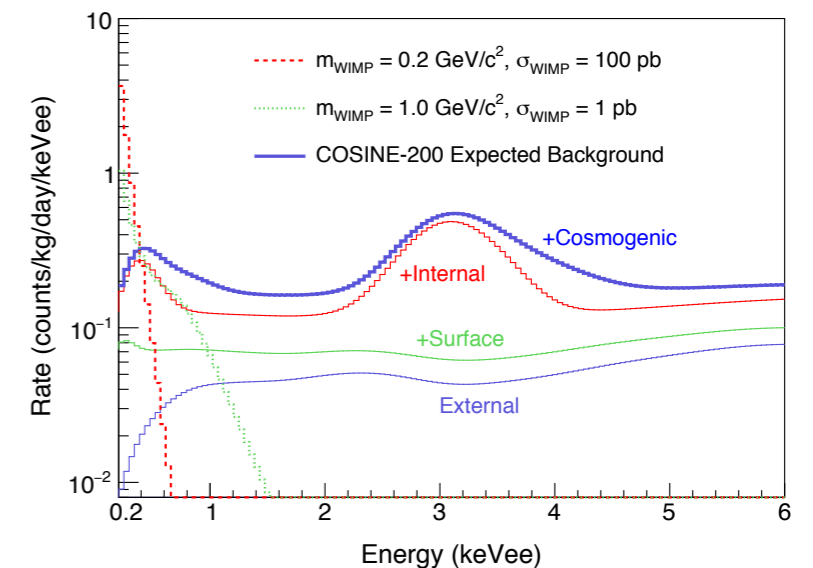
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    - Competition w/ PICO-60 in low mass region for **WIMP-proton SD** interaction
  - Low temperature
    - Improved **PSD**,  $\alpha$  quenching & light yield



# Plan for Next Phase

## Sensitivity Study

- Assuming expected improvements
  - 200 kg of mass and 0.2~0.3-counts/day/kg/keV background
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- Sensitivity of COSINE-200
  - Both of Na & I are proton-odd elements
    - Competition w/ PICO-60 in low mass region for WIMP-proton SD interaction
  - Low temperature
    - Improved PSD,  $\alpha$  quenching & light yield
  - Migdal process for very low mass region



# Summary

- COSINE-100 is an experiment to reproduce the DAMA/LIBRA signal via the same target material, NaI(Tl).
- Dark matter search
  - DAMA/LIBRA is excluded by COSINE-100 data under the several scenarios.
    - SI/SD WIMP interactions and EFT operators in the SHM
    - Considering different quenching factors
  - DAMA/LIBRA & the null hypothesis have not yet been excluded via the annual modulation analysis:
    - 5-years data are being analyzed.
  - Other DM scenarios are also covered.
- R&D for COSINE-200 is in progress.
  - In-house development for ultra pure crystal: Purification, growing & encapsulation
  - Lowering threshold: Encapsulation design, event selection & low-temperature measurement
  - The feasibility test with expected improvements, demonstrates global competitiveness of COSINE-200, after DAMA/LIBRA verification.





**Thank You  
for Your Attention !!!**