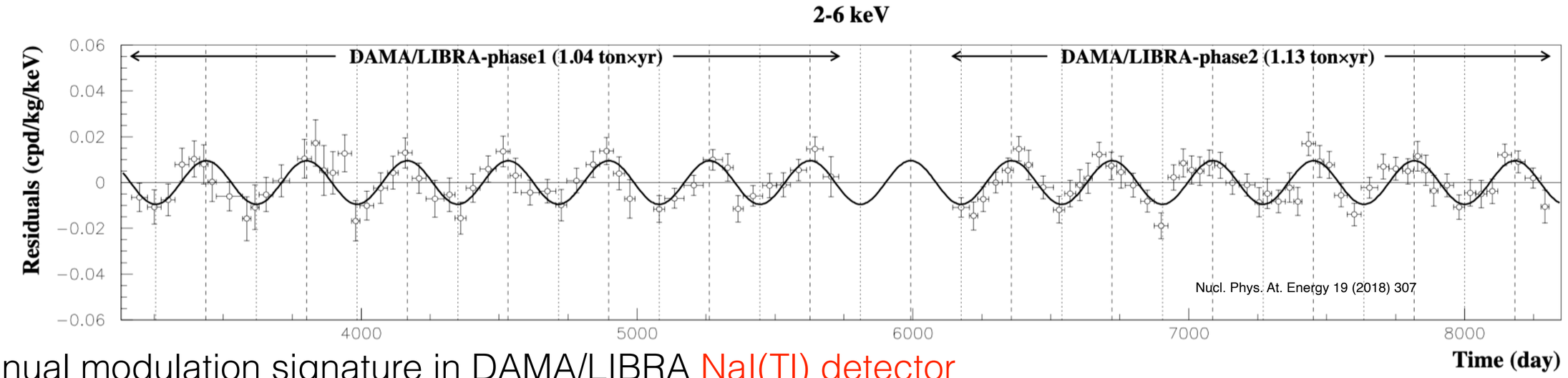
Dark Matter Direct Detection Searches with COSINE-100 Experiment

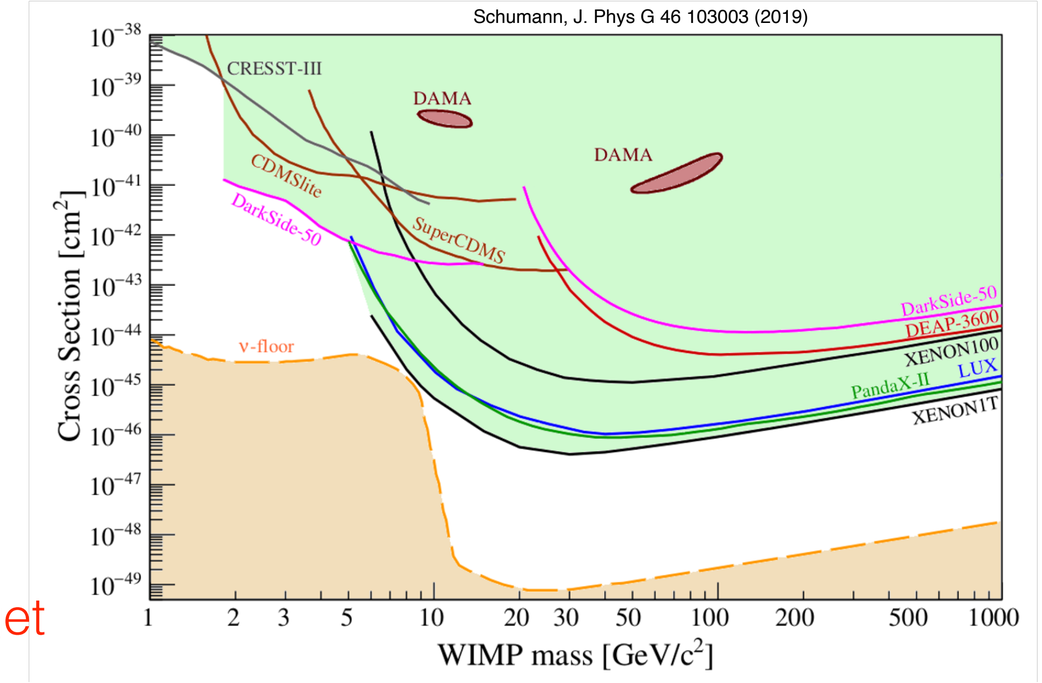
Govinda Adhikari
On behalf of the
COSINE-100 collaboration

UCLA Dark Matter
March 28 - April 01, 2023

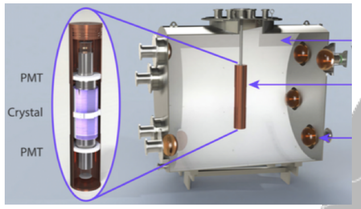
Motivation for the COSINE-100 experiment



- Annual modulation signature in DAMA/LIBRA NaI(Tl) detector
  - Modulation amp.: 0.0103± 0.0008 count/day/kg/keV
  - Phase (145 ± 5) day
  - Persists from last 2 decades
  - (1 - 6) keV: 9.5σ, (2 - 6) keV: 12.9σ
- Signal consistent with Dark Matter
- More exclusion limit from different target can't explain DAMA observation (?)
- Need to directly test DAMA's result with the same NaI(Tl) target



Global NaI(Tl) efforts



DAMA

SABRE@LGNS

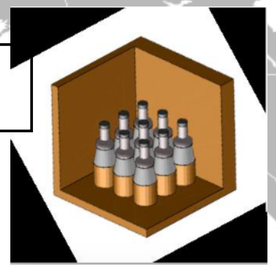
★ Gran Sasso

COSINUS

Yangyang★

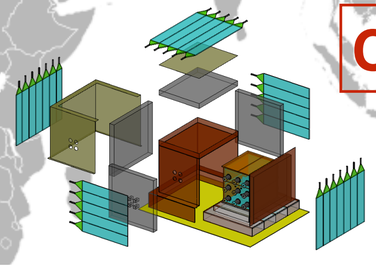
PICO-LON

★ Kamioka



KIMS

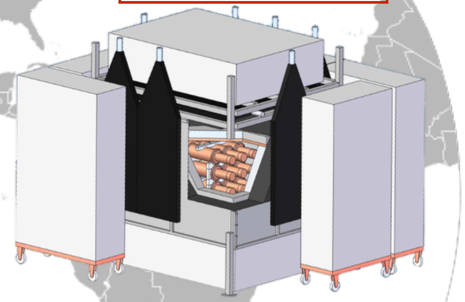
COSINE-100



Boulby ★

Canfranc ★

ANAIS



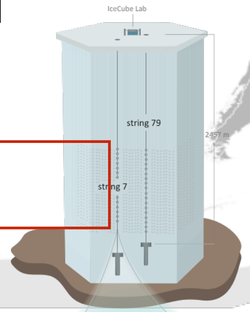
SABRE@Stawell

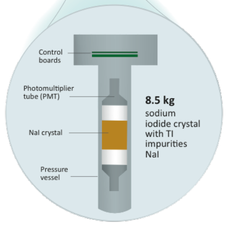
★ Stawell

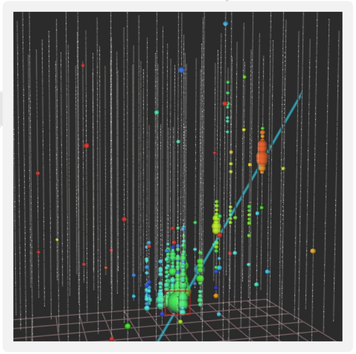
Nature **564**, 83-86 (2018)
Eur.Phys.J. C **78** 107 (2018)
Eur.Phys.J. C **77** 437 (2017)
JINST **13** T02007 (2018)
Phys.Rev. D **90** 052006 (2014) (CsI)

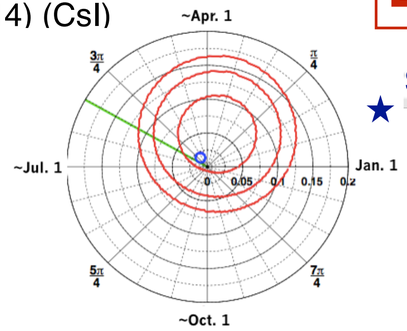
DM-Ice

South Pole ★









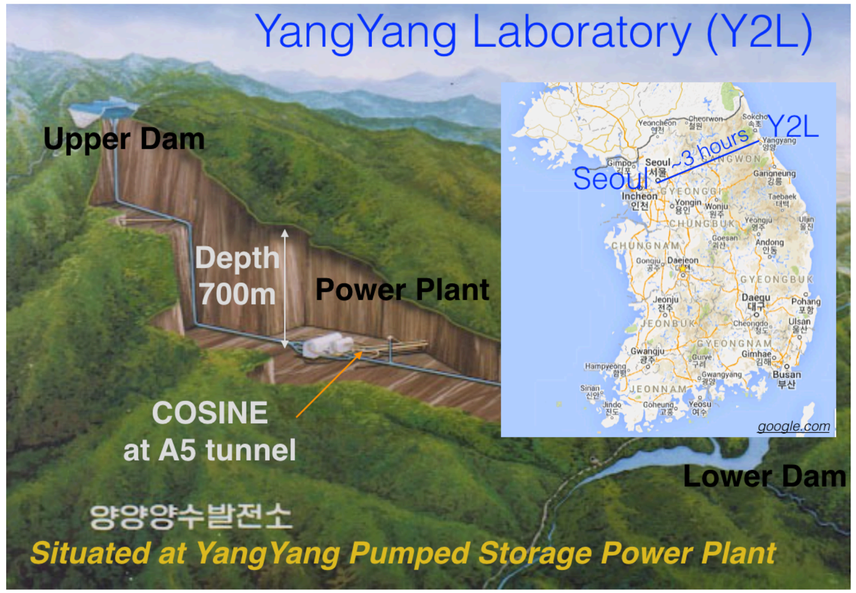
Astropart. Phys. **35** (2012) 749
Phys. Rev. D **90** 092005 (2014)
Phys. Rev. D **93** 042001 (2016)
Phys. Rev. D **95** 032006 (2017)

The COSINE-100 experiment

https://cosine.yale.edu/home

KIMS Korea Invisible Mass Search Experiment + DM-ICE

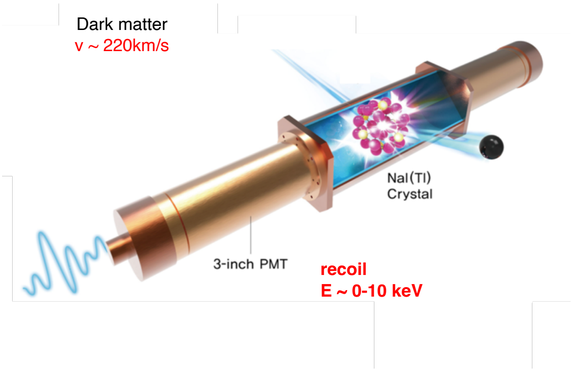
5 countries, 14 institutions, ~50 members



- Joint venture between KIMS and DM-Ice
- Located at Yangyang Underground Laboratory (Y2L), South Korea
  - ~700m rock overburden
- Physics run started September 2016

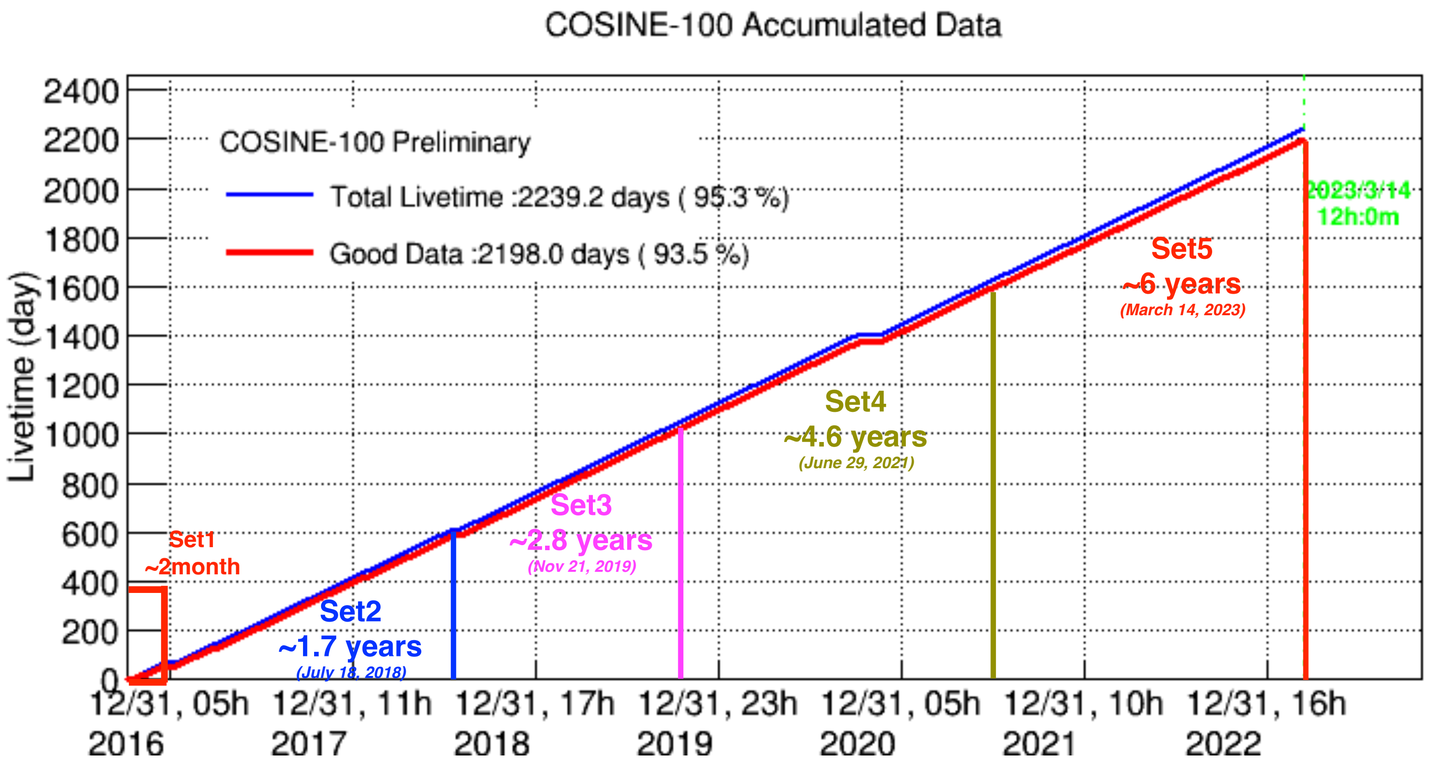
COSINE-100 detector configuration

- 8 NaI(Tl) crystals,106 kg total each coupled with two 3-inch PMTs
  - 2000L of liquid scintillator as a veto detector
  - 20 cm thick lead and 3 cm thick copper shielding
  - 37 plastic scintillator panels to tag muons



- COSINE-100 has been decommissioned for its upgrade after ~6.4 years of the stable operation

- ~6 years of good quality physics data



COSINE-100 active physics program

	2016	2017	2018	2019	2021	2022	2023
Research Highlights			Background modeling	Annual modulation (1.7 yrs, 2 keV threshold)	1 keV threshold	Modulation (1keV, 2.8 yrs data)	DAMAs analysis method
		2 keV threshold			Improved background modeling		Modulation (6 yrs, 0.5 keV threshold)
	Physics run		WIMP search		WIMP search (1.7 years data,1 keV threshold)		
		First 59.5 days data (2 keV threshold)					

Exotic dark matter candidate searches

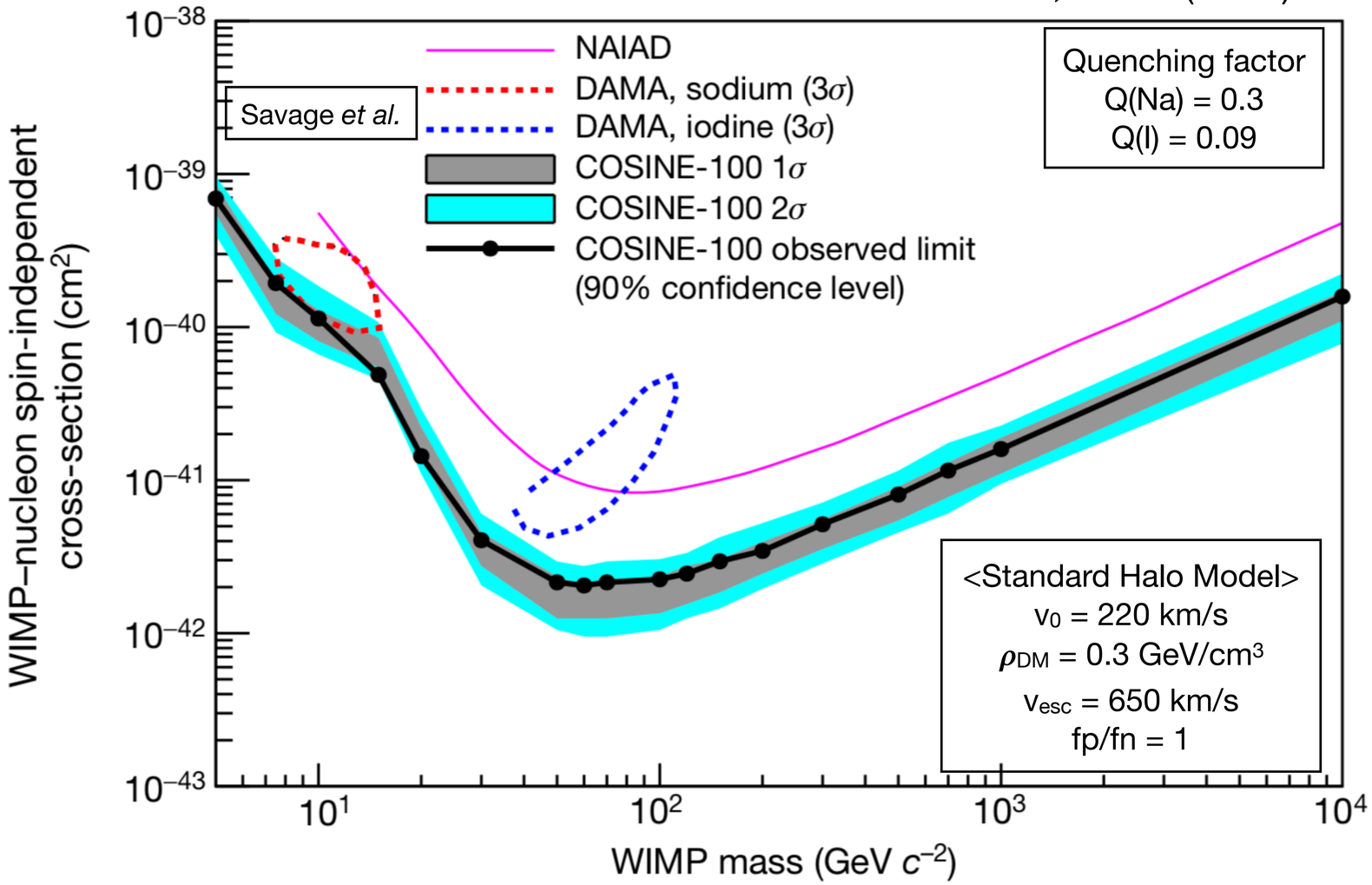
- Several EFT operators at different mass regions
- Migdal effect, Bosonic Super-WIMP, Boosted Dark Matter, Solar Axions, etc.

Spin independent WIMP search: 59.5 days of data

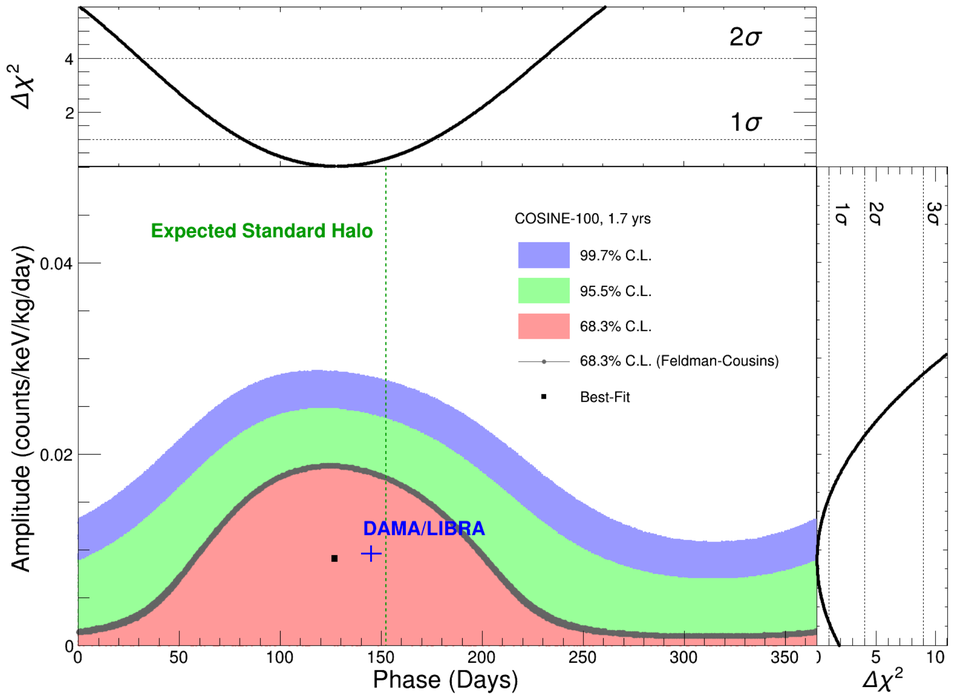
- COSINE 100 excludes DAMA/ LIBRA phase 1's interpretation with the spin-independent WIMP interaction with Standard Halo model in NaI(Tl) crystal

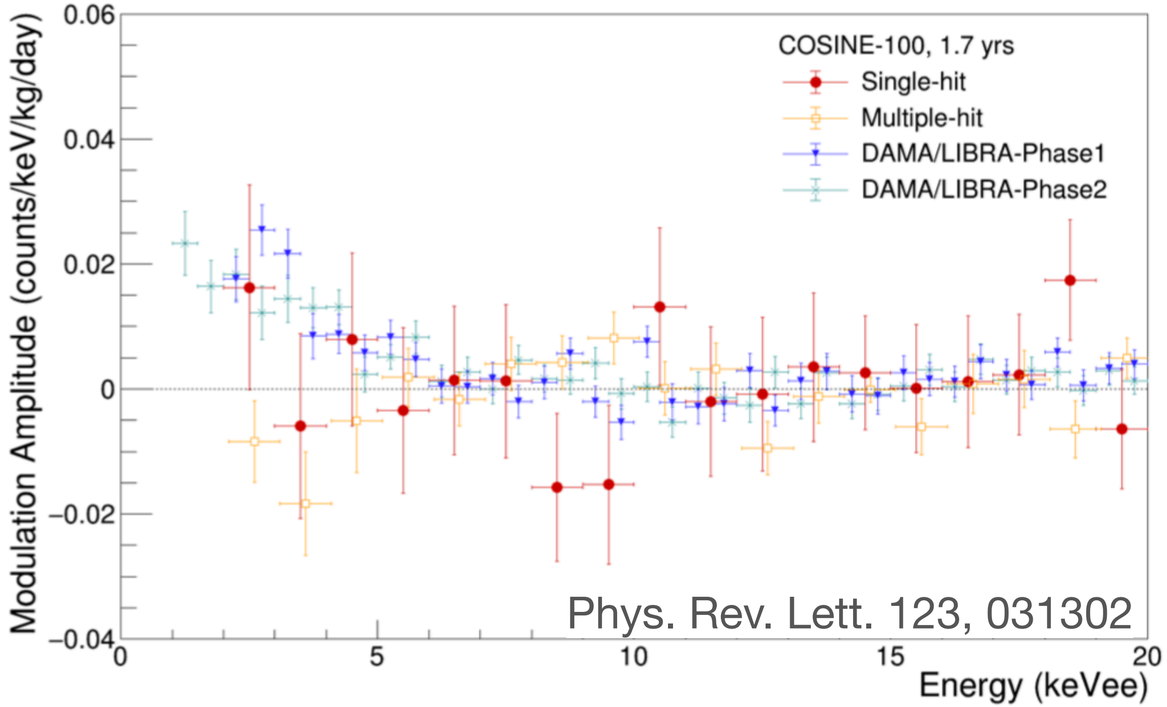
- Consistent with null results from other direct detect experiments with different targets

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



Annual modulation search: 1.7 years of data





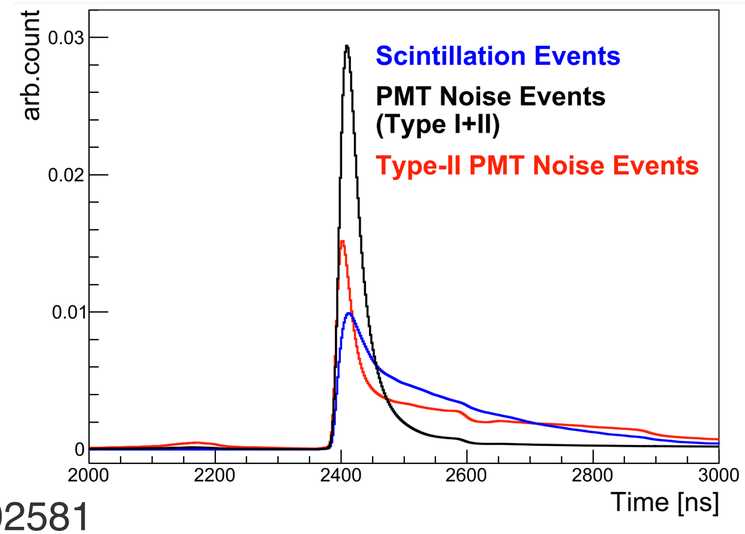
- COSINE 100 data is consistent with both a null hypothesis and DAMA/LIBRA's 2–6 keV best fit value w/ 68% CL

- Need more exposure and lower threshold

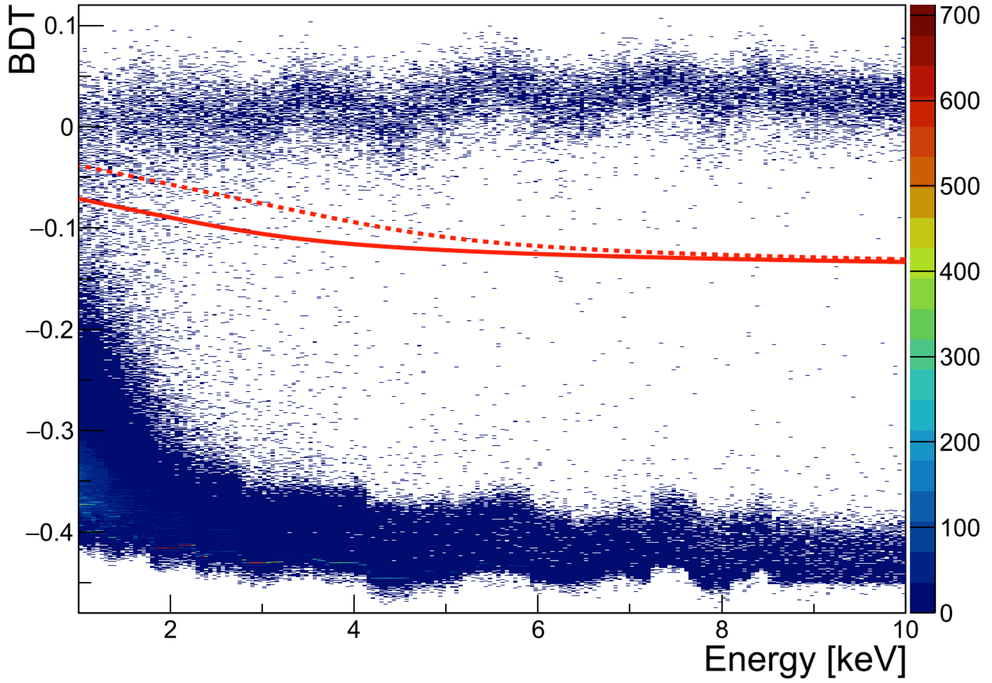
Configuration	χ^2	*d.o.f.*	p-value	Amplitude (counts/keV/kg/day)	Phase (Days)
COSINE-100	175.3	174	0.457	0.0092±0.0067	127.2±45.9
DAMA/LIBRA (Phase1+Phase2)	–	–	–	0.0096±0.0008	145±5
COSINE-100	175.6	175	0.473	0.0083±0.0068	152.5 (fixed)
COSINE-100 (Without LS)	194.7	175	0.143	0.0024±0.0071	152.5 (fixed)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

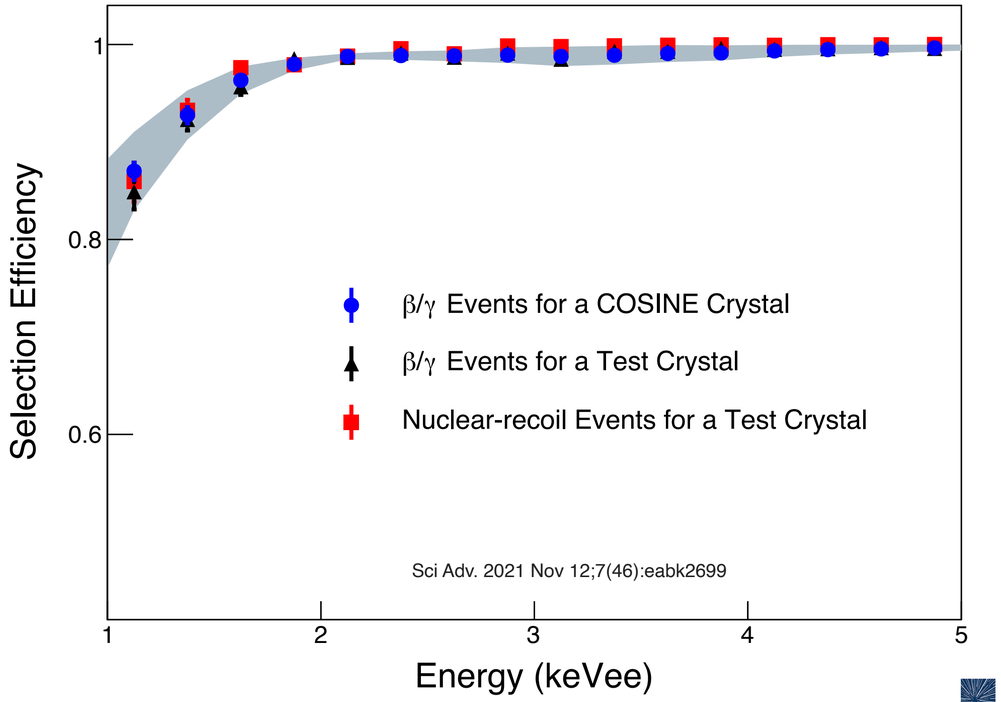
Lowering down threshold to 1 keV

- Developed event shape-based likelihood parameters
- Achieved a 1 keV threshold with an improved Boosted Decision Tree (BDT)
  - Attained over 80% efficiency at 1 keV
- Improved background budgeting with the 1 keV threshold



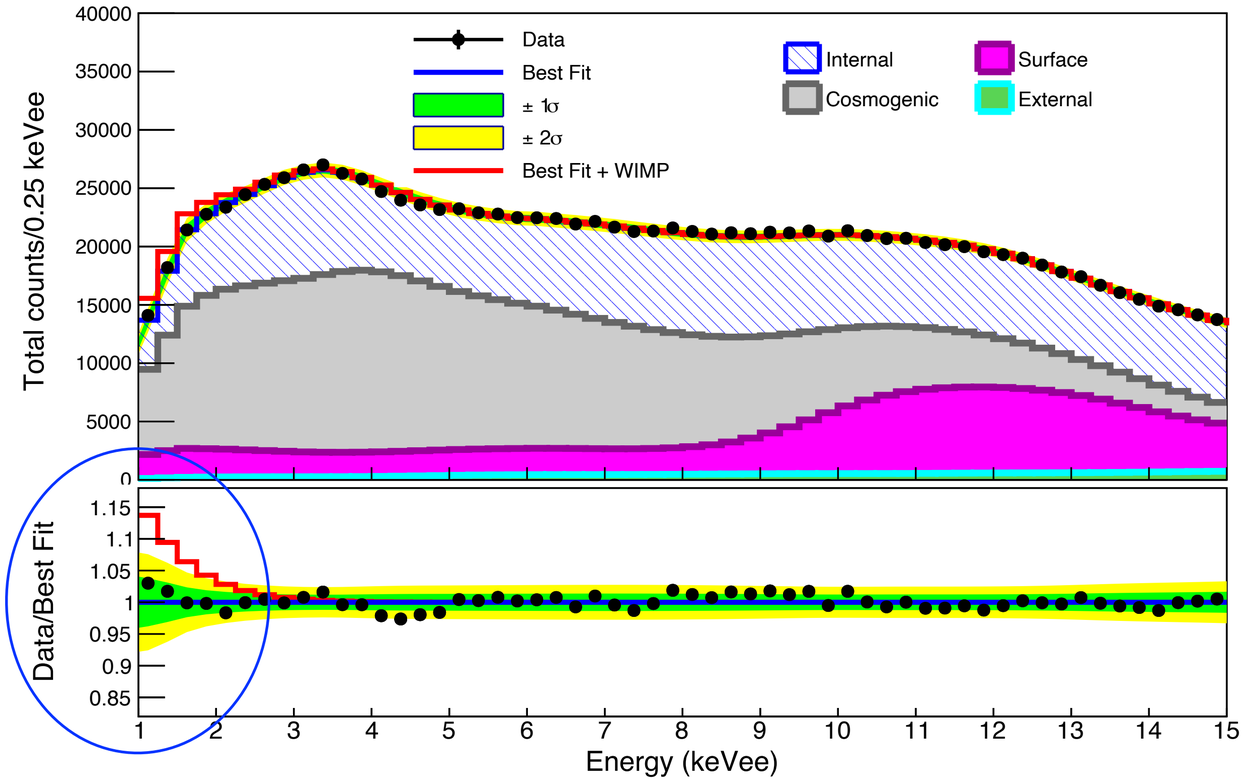
Astropart.Phys. 130 (2021) 102581

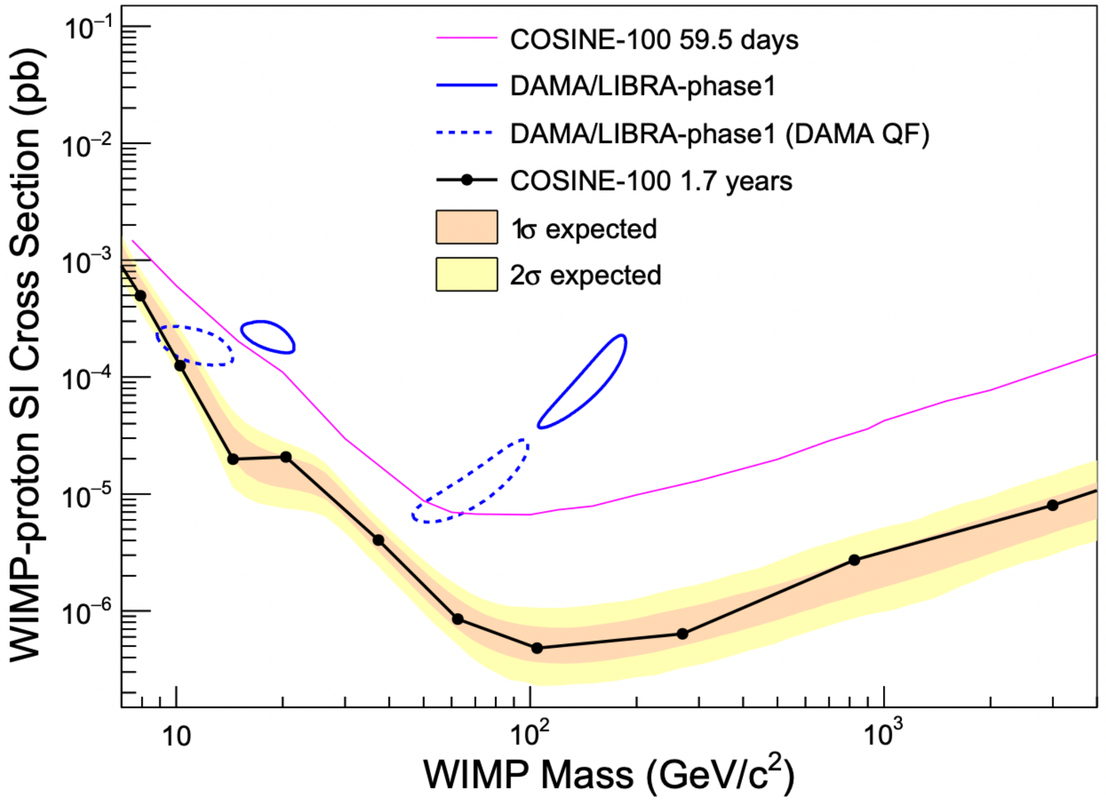




Spin independent WIMP search:1.7 years of data

Sci Adv. 2021 Nov 12;7(46):eabk2699



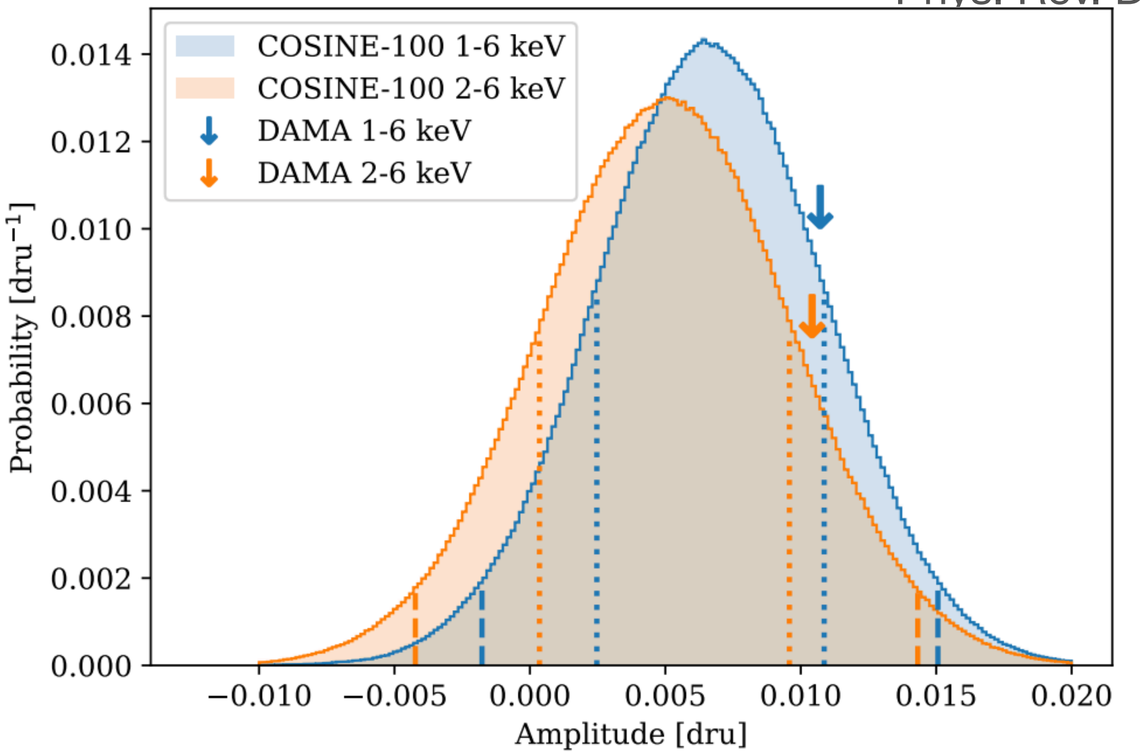


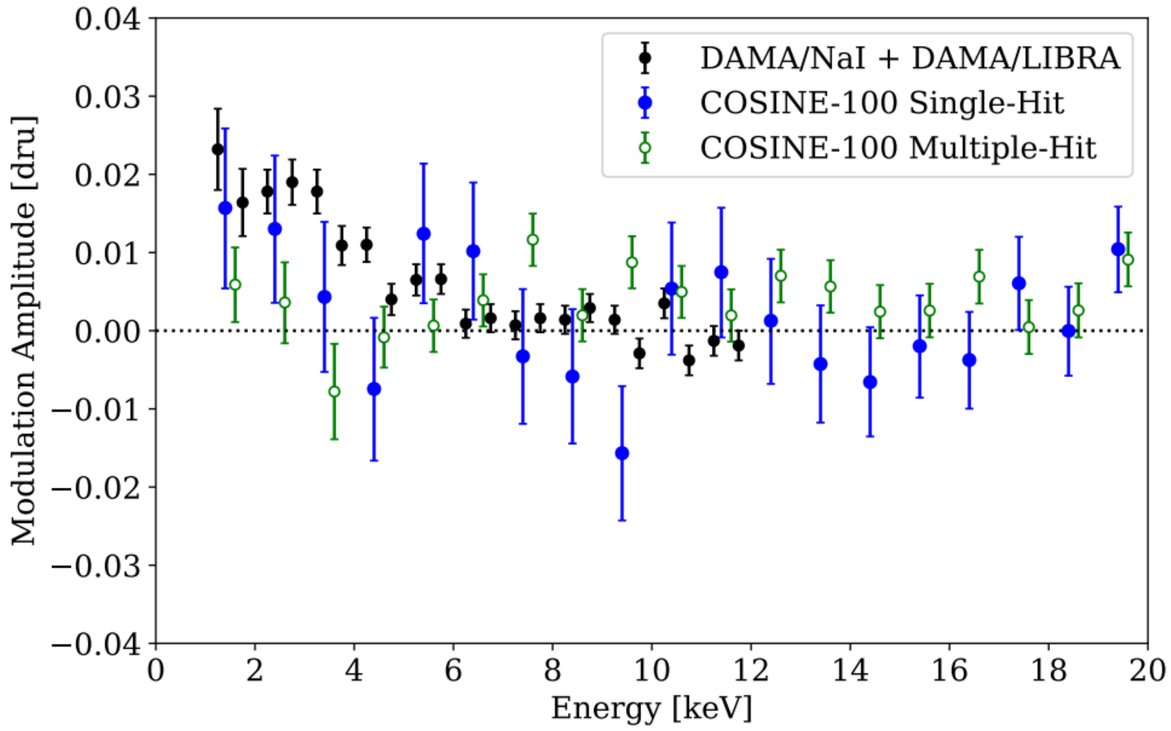
- 1.7 year exposure with 1 keV threshold
  - Spectrum fit was conducted for the energy range of 1 - 20 keV, which included background plus WIMP model

- The COSINE-100 excluded DAMA/LIBRA signal as a spin-independent WIMP with Standard Halo Model (SHM)

Annual modulation search: 2.8 years data

Phys. Rev. D. 106, 052005





- Best-fit modulation amplitude of 0.0067 ± 0.0042 cpd/kg/keV at 1- 6 keV
- Consistent with both DAMA and no modulation with 2.8 years of data
- Stay tune us for new result (2x exposure and lower threshold)

DAMA/LIBRA analysis method: 2.8 years data

- Analysis procedure used for COSINE-100 was adopted as closely as possible to the one used by DAMA
  - DAMA parameter for event selection
  - Excluded LS and muon Veto
  - 600 ns integration window
  - Yearly-averaged background model

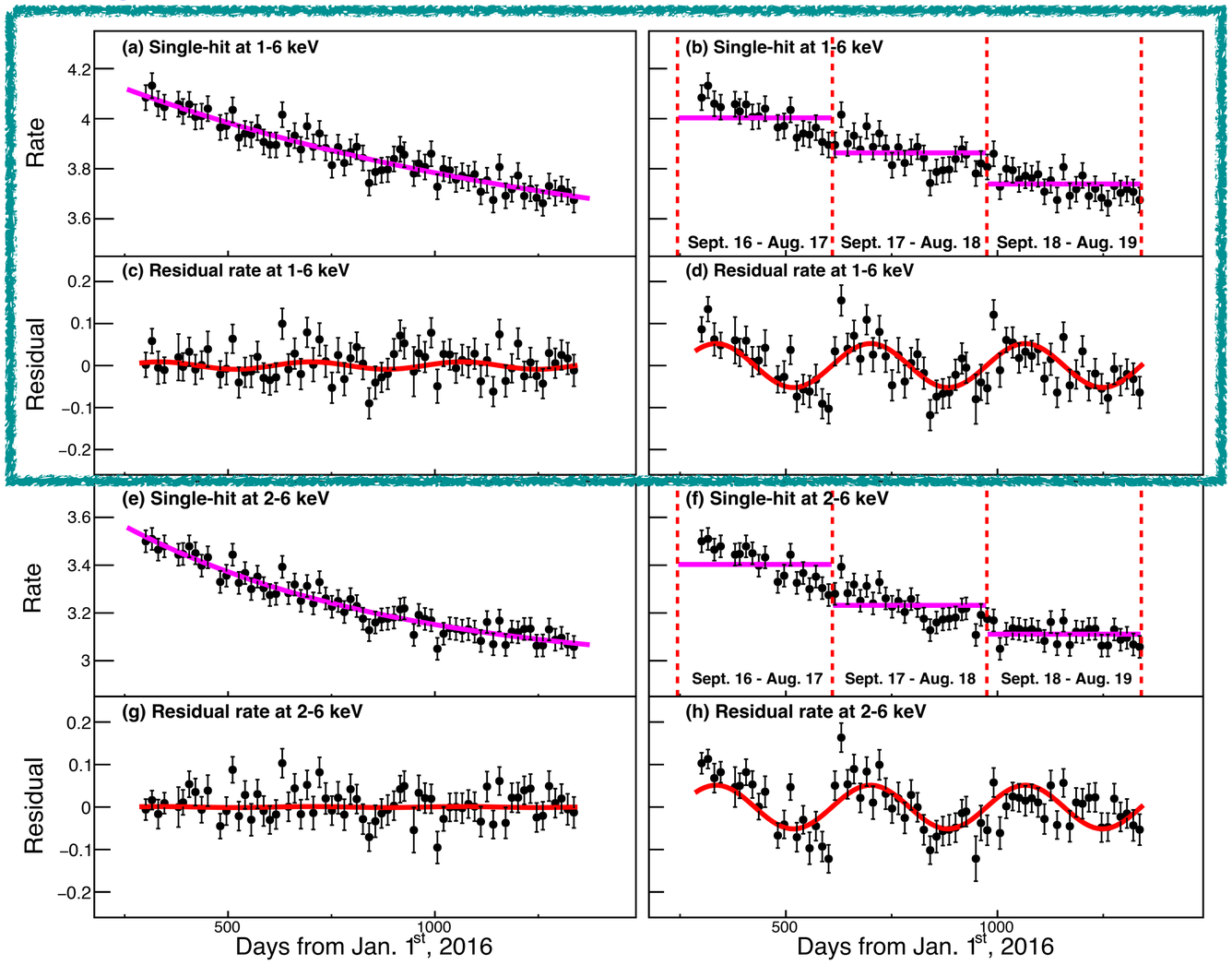
- Very strong negative modulation (~7σ) from COSINE data using DAMAs analysis method

- *Details will be covered in the upcoming talk by Reina Maruyama*

- *Posters @ UCLA*
  - *S. Hollick , Kim Jinyoung,Yujin Lee*

Scientific Reports 13, 4676 (2023)

Single exponential model | DAMA/LIBRA method

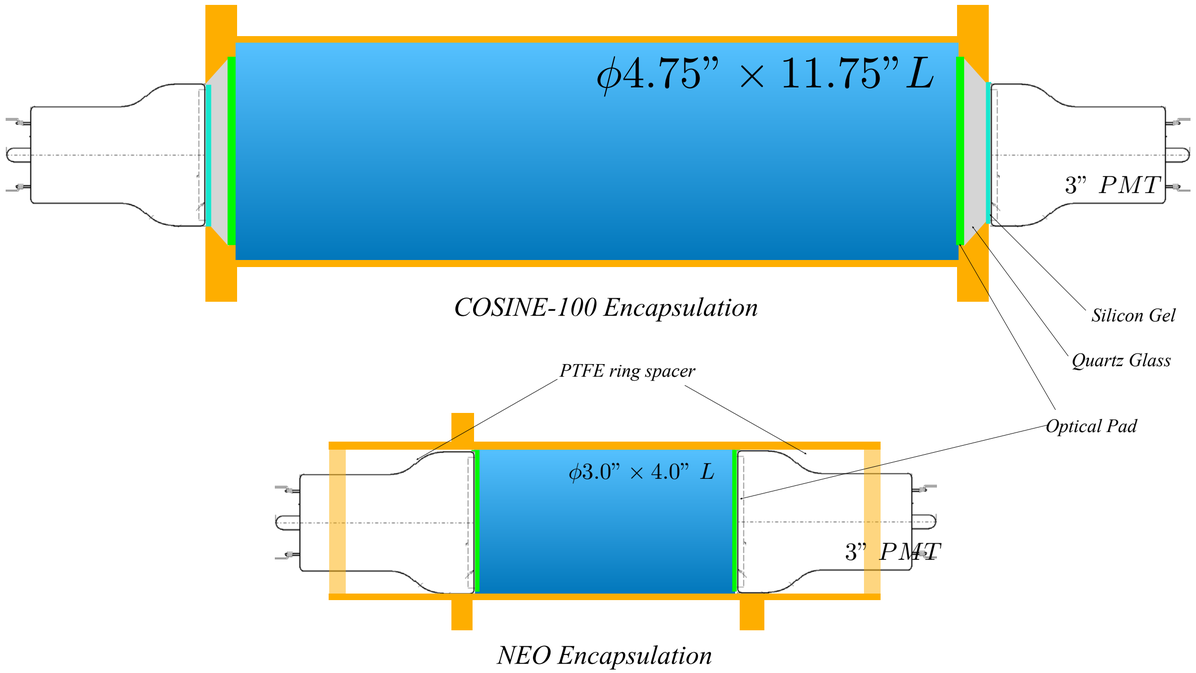


Wright Laboratory Yale

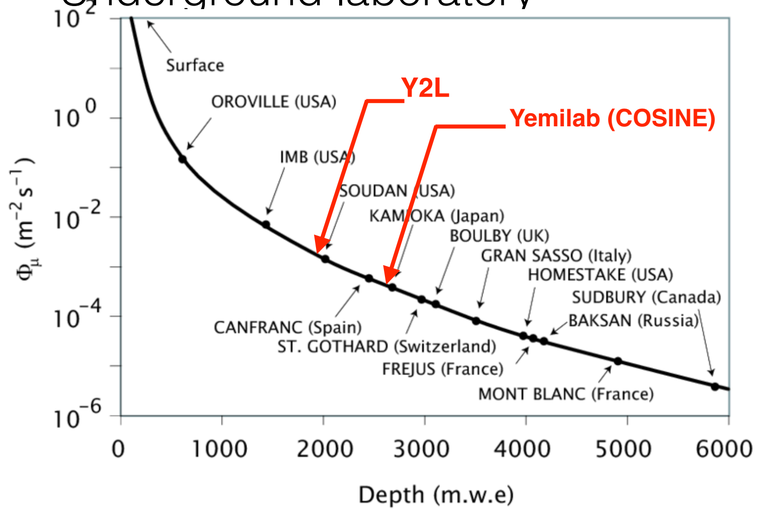
COSINE-100 Upgrade

An intermediate efforts prior to the commissioning of COSINE-200

- Move COSINE-100 to new underground lab (Yamilab South Korea)
- New encapsulation method was developed
  - Improved light yield > 20 PEs/keV
- Operate at -35°C



Underground laboratory



COSINE200 detector room @ Yamilab

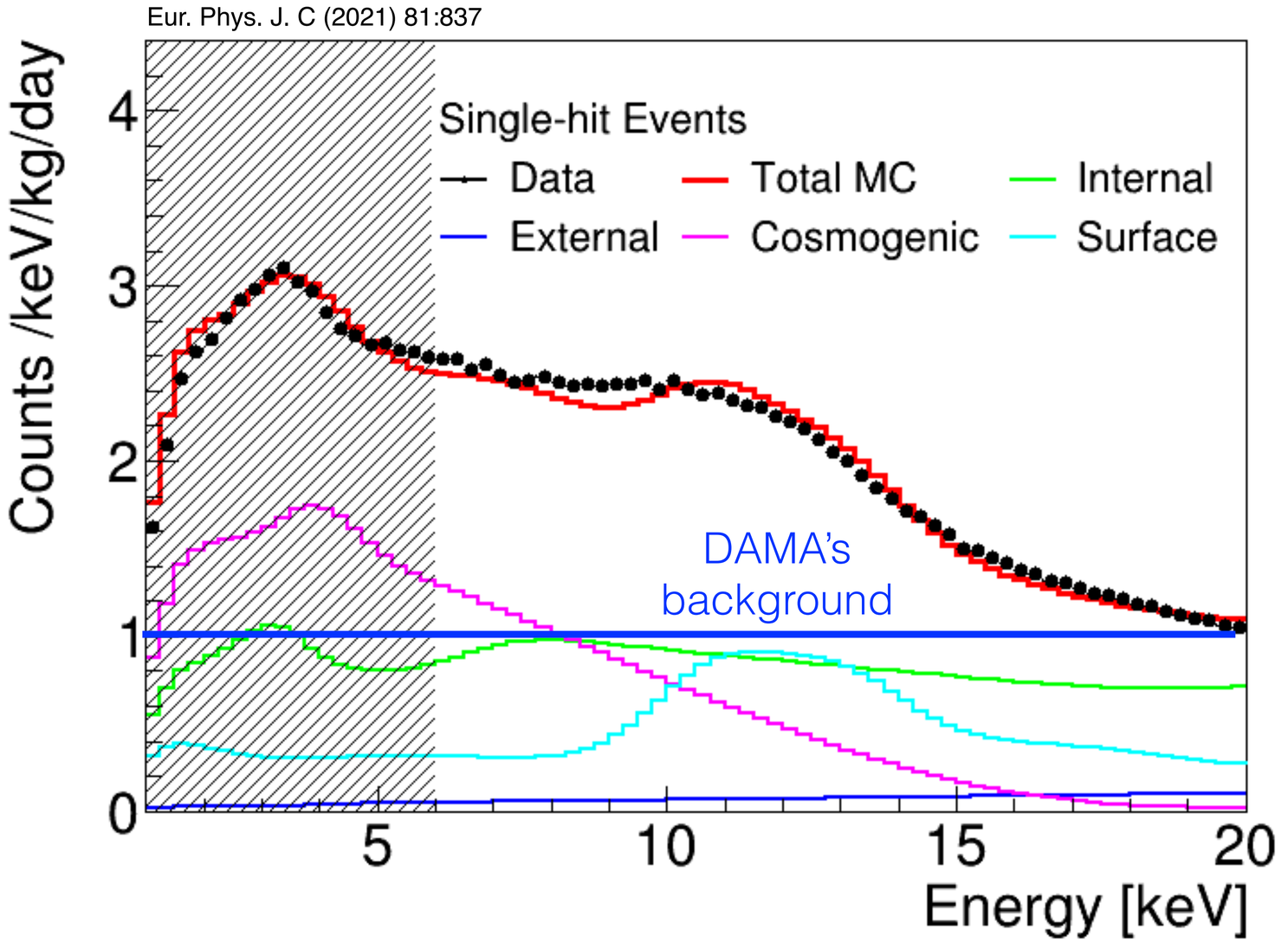
COSINE-200 [next phase of COSINE-100]

- Background level lower than DAMA
  - 1 counts/day/kg/keV
  - Powder purification, crystal growing, and its machining are developed

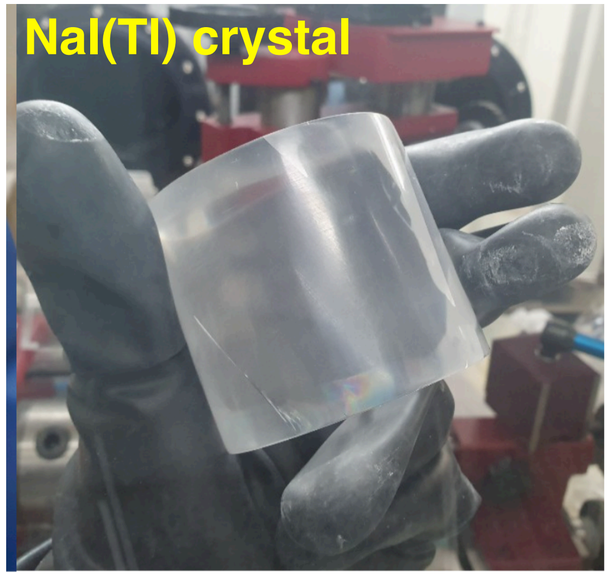
Physics Goal

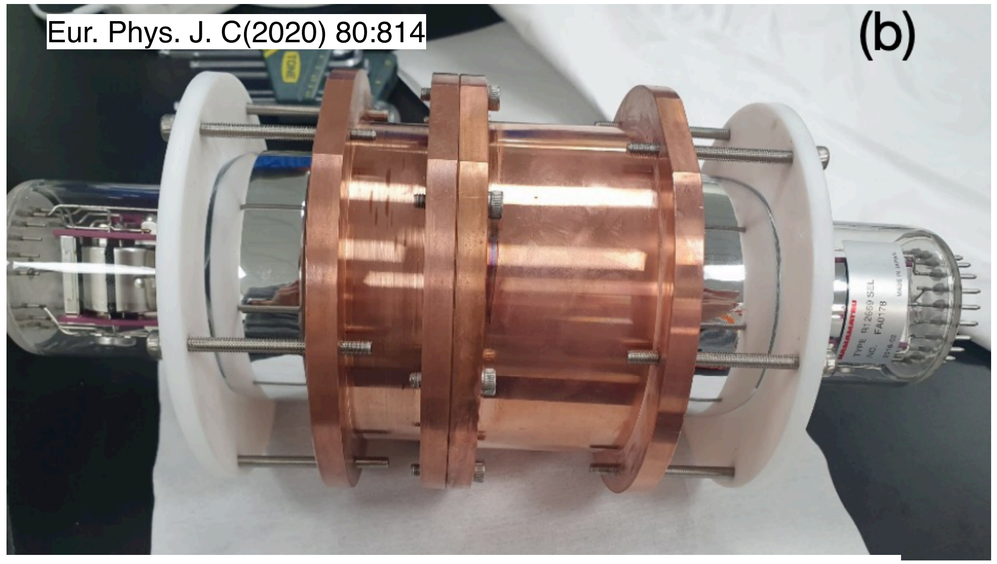
- Final conclusion on DAMA(5 sigma)

- Low mass spin dependent WIMP interaction
  - Milestone towards ton-scale NaI(Tl) experiment



Development for the COSINE-200

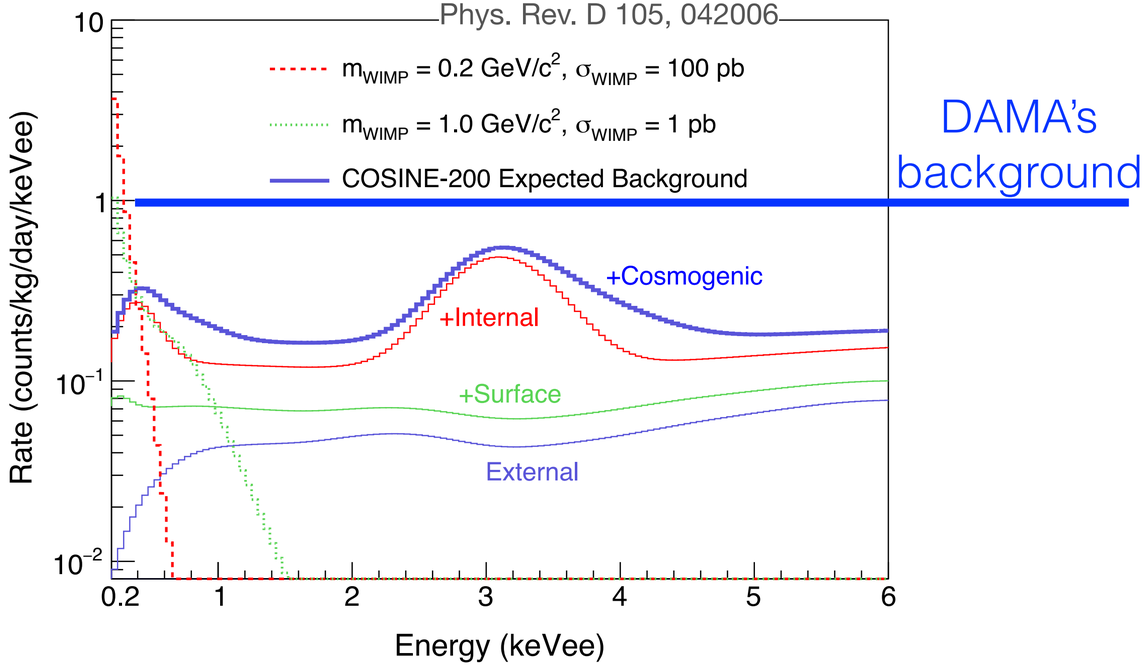




- Low background NaI(Tl) crystal growing
- Radio-purity with R&D crystal (0.6 kg) is promising

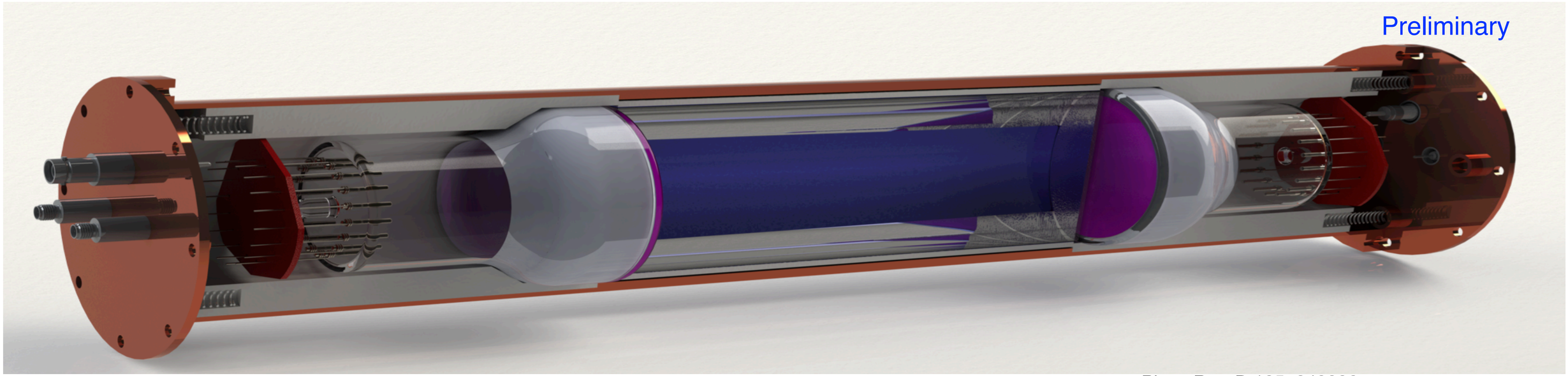
15

- Low background
  - Expect <1 counts/day/kg/keV



DAMA's background

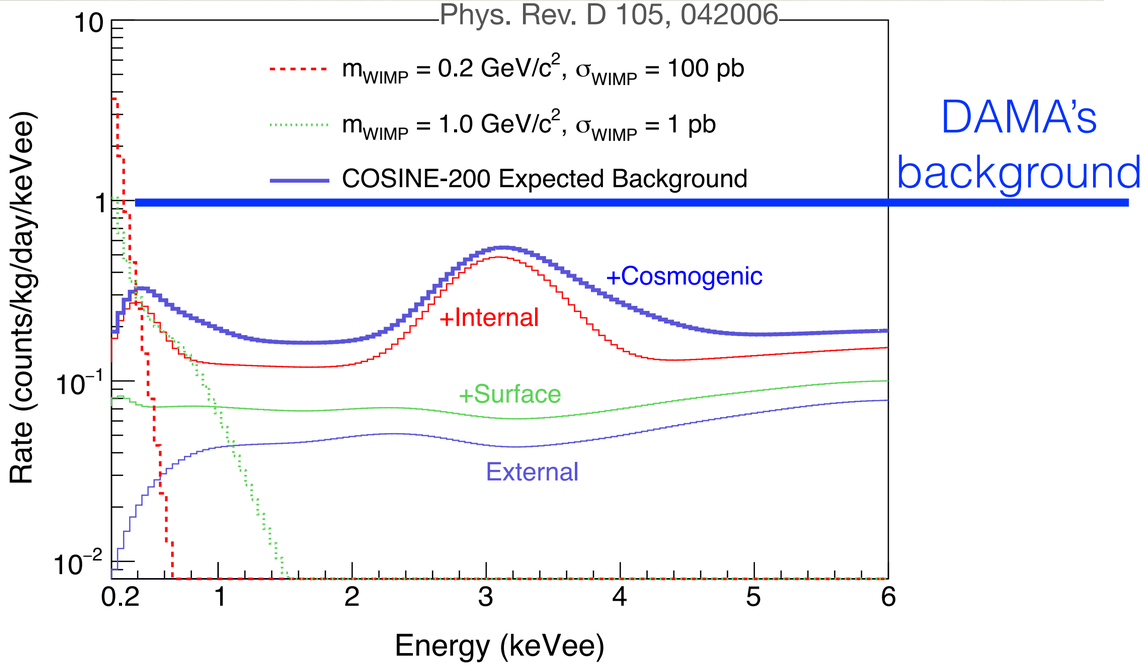
Development for the COSINE-200



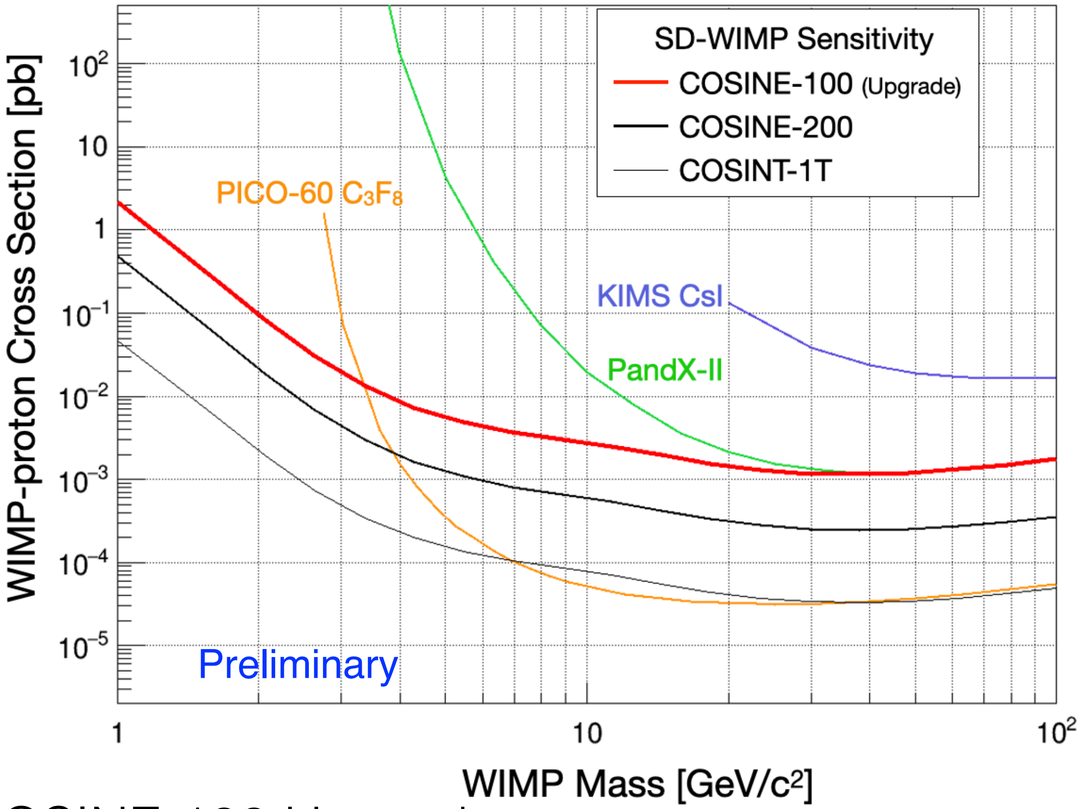
- Low background NaI(Tl) crystal growing
- Radio-purity with R&D crystal (0.6 kg) is promising

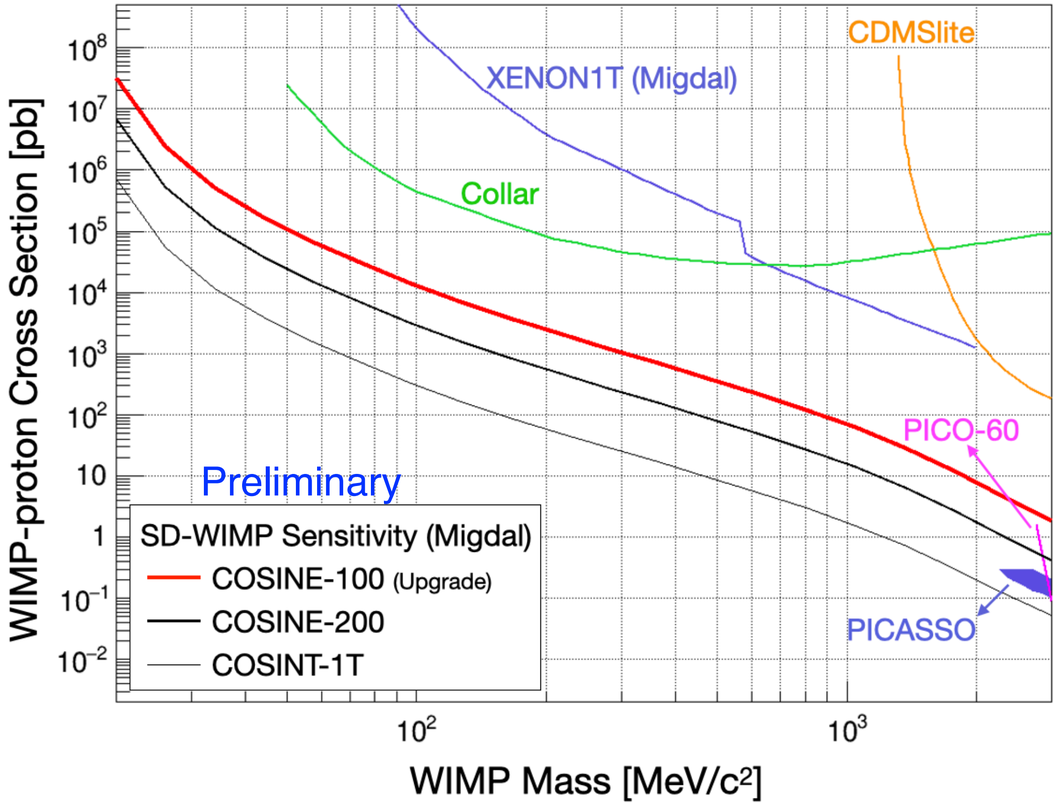
16

- Low background
  - Expect <1 counts/day/kg/keV
- Higher light yield (22 NPE/keV)
- Physics run will be started by end of 2023



Sensitivity of COSINE-200



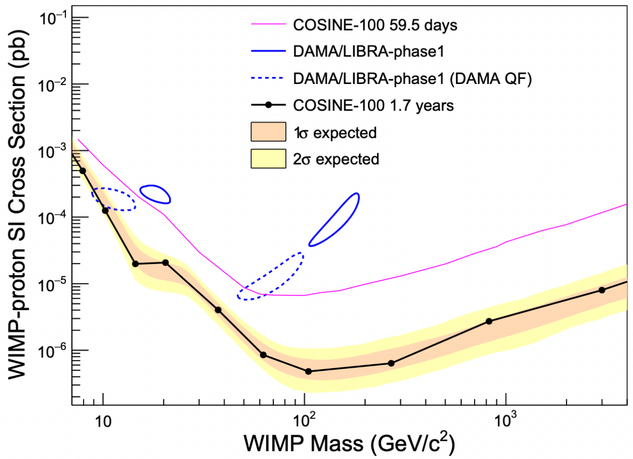


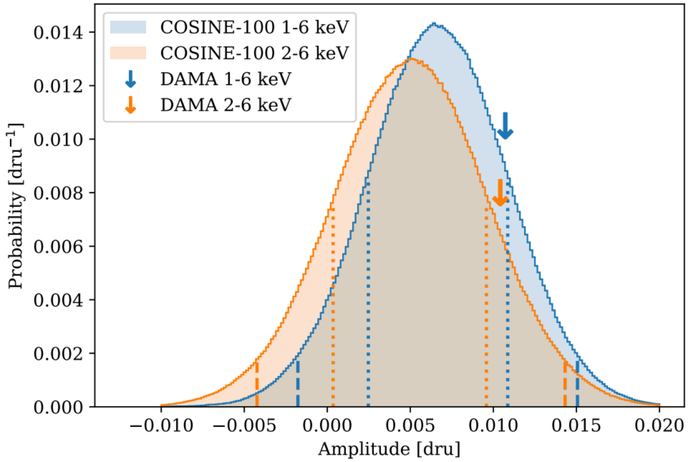
- COSINE-100 Upgrade
  - COSINE-100 backgrounds, 25 PEs/keV LY, 100 kg 1 year exposure including crystals 5 and 8

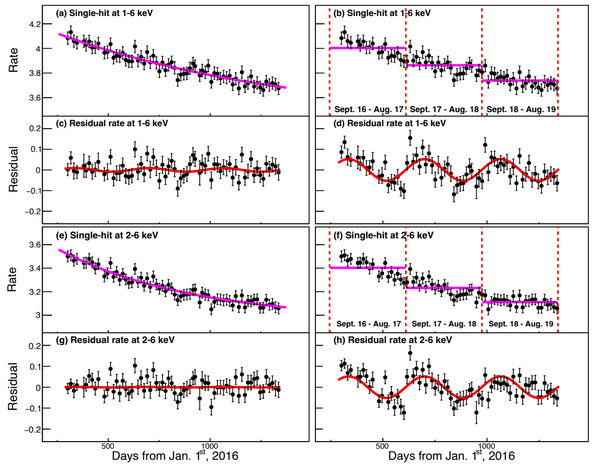
- COSINE-200
  - NaI-035 background (<1 dru), 25 PEs/keV LY, 200 kg 1 year exposure

- Sensitive for low-mass WIMP-proton SD cross-section

Summary







- COSINE-100 has been running smoothly for 6.4 years.
  - Confirm that DAMA's modulation signal can't be from standard WIMP & SHM with NaI(Tl).
  - Modulation analysis is statistically limited
- Adoption of the DAMA analysis techniques led to an interesting result.
- COSINE-200 is under preparation to run by end of 2023.
  - The new experimental site is ready.
  - A standard protocol to grow low background crystal is developed
  - Active R&D is ongoing for the detector's assembly

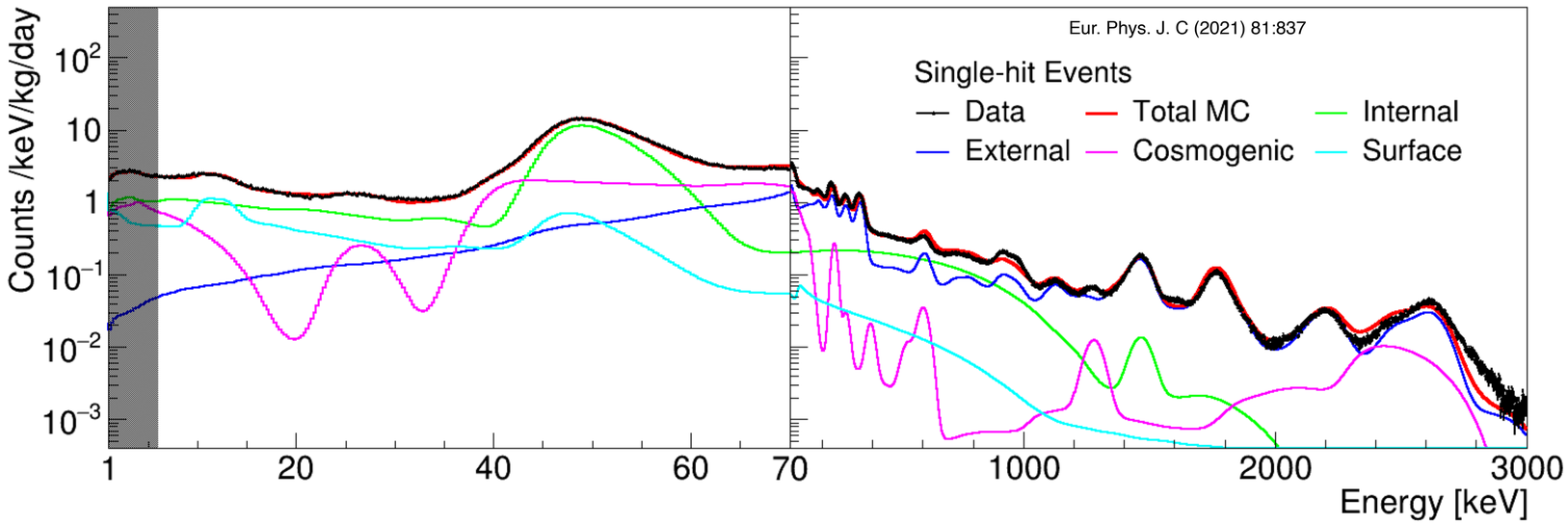

Thank you
Questions ??

Back-Up

COSINE-100 background budget

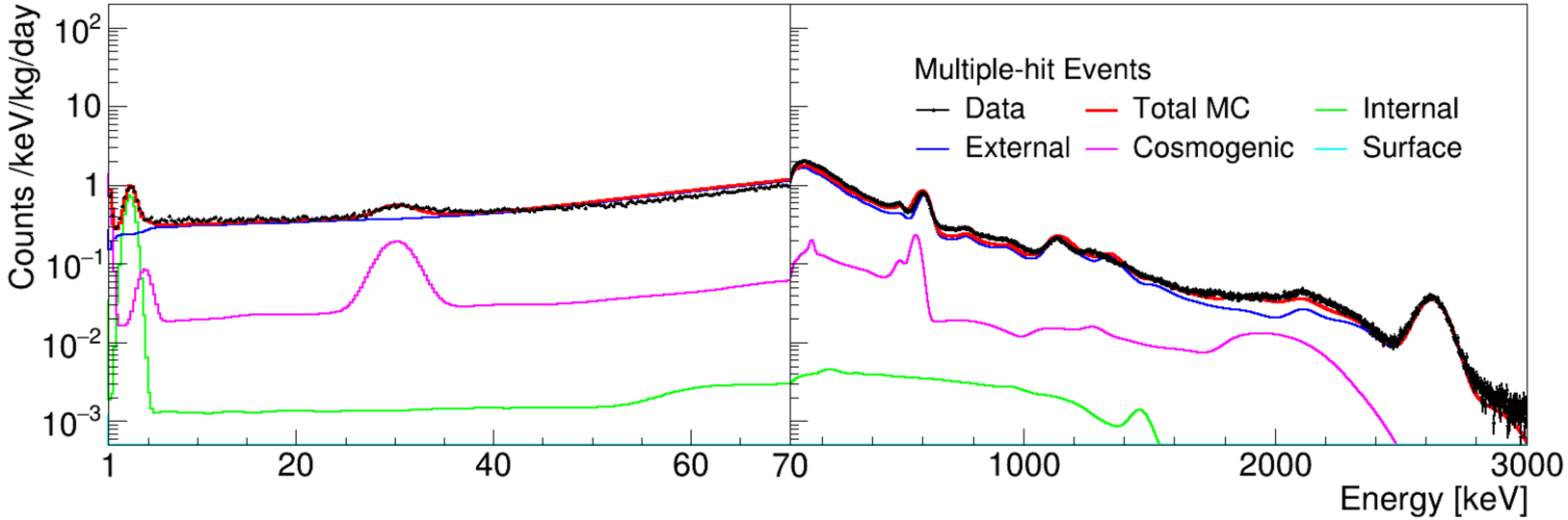
- Good agreement between data and Geant4 simulation
- ^{210}Pb, ^{40}K, and ^{3}H are the dominant backgrounds

Single Hit



ROI (1 - 6 keV) is not used in this fit

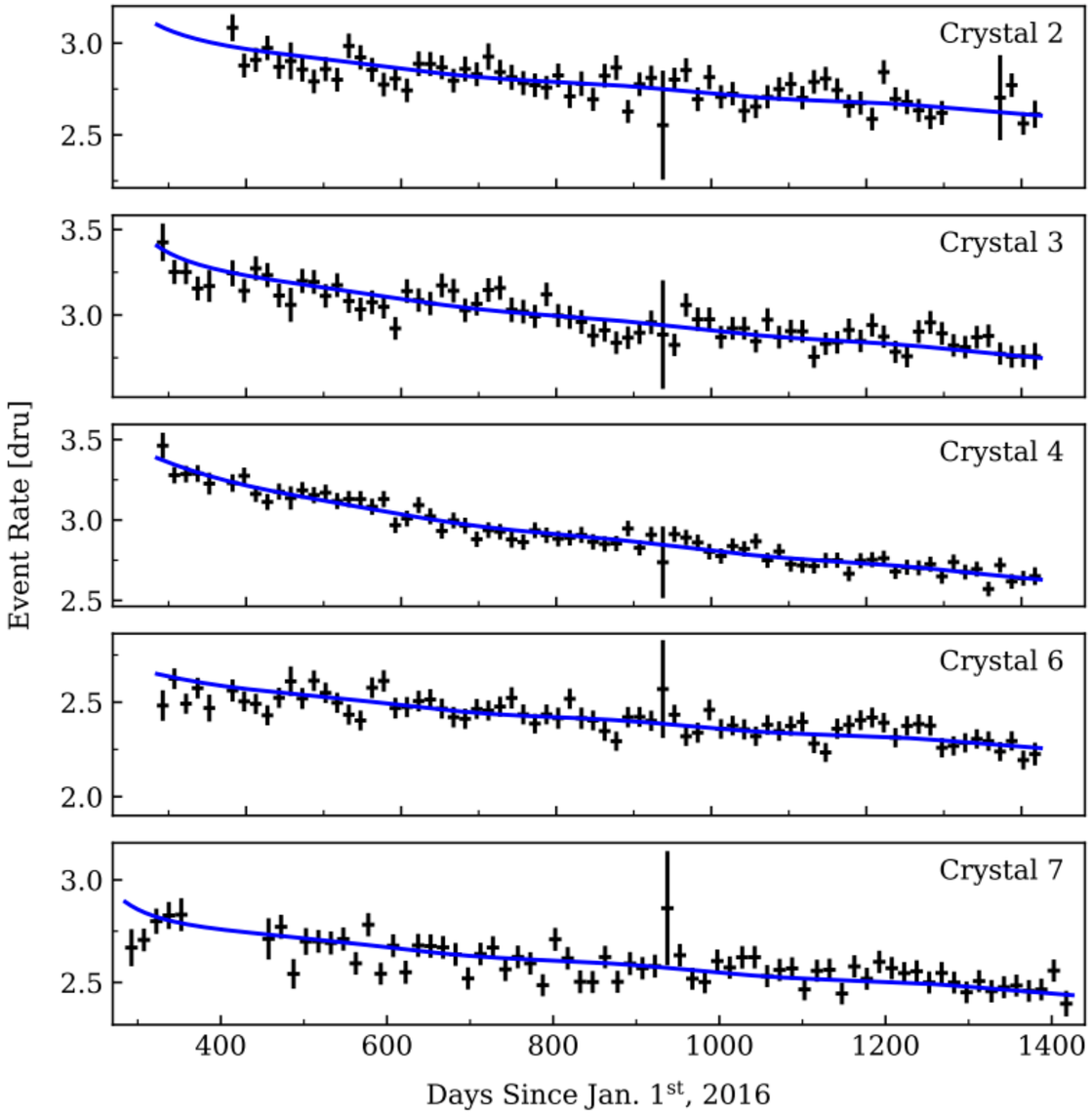
Multiple Hit



Annual modulation search: 2.8 years data

- Five detectors fit with
  - Exponential decays from short-lived cosmogenics
  - Constant from long-lived backgrounds
  - Modulation signal - fixed period and phase

Component	Average Activity (dru)
Total	$(2.74 \pm 0.23) \times 10^{0}$
^{3}H	$(1.41 \pm 0.18) \times 10^{0}$
^{210}Pb	$(1.12 \pm 0.15) \times 10^{0}$
^{109}Cd	$(4.13 \pm 0.39) \times 10^{-2}$
^{113}Sn	$(1.55 \pm 0.16) \times 10^{-2}$
^{127}Te	$(6.59 \pm 0.52) \times 10^{-3}$
^{22}Na	$(5.88 \pm 1.34) \times 10^{-3}$
^{121m}Te	$(1.50 \pm 0.16) \times 10^{-3}$
^{121}Te	$(5.07 \pm 1.23) \times 10^{-4}$
Flat	$(1.35 \pm 0.08) \times 10^{-1}$



Annual modulation search: 2.8 years data

Configuration	Amplitude [dru]	Phase [days]
COSINE-100 1–6 keV (This result)	0.0067±0.0042	152.5 (fixed)
COSINE-100 2–6 keV (This result)	0.0050±0.0047	152.5 (fixed)
COSINE-100 2–6 keV (2019 result [14])	0.0083±0.0068	152.5 (fixed)
ANAIS 1–6 keV (2021 result [16])	-0.0034±0.0042	152.5 (fixed)
ANAIS 2–6 keV (2021 result [16])	0.0003±0.0037	152.5 (fixed)
DAMA/LIBRA 1–6 keV (phase2 [7])	0.0105±0.0011	152.5 (fixed)
DAMA/NaI+LIBRA 2–6 keV [7]	0.0102±0.0008	152.5 (fixed)
COSINE-100 1–6 keV (This result)	$0.0094^{+0.0073}_{-0.0072}$	$194.5^{+49.0}_{-50.5}$
COSINE-100 2–6 keV (This result)	$0.0061^{+0.0064}_{-0.0061}$	Unconstrained
COSINE-100 2–6 keV (2019 result [14])	0.0092±0.0067	127.2±45.9
DAMA/LIBRA 1–6 keV (phase2 [7])	0.0106±0.0011	148±6
DAMA/NaI+LIBRA 2–6 keV [7]	0.0103±0.0008	145±5

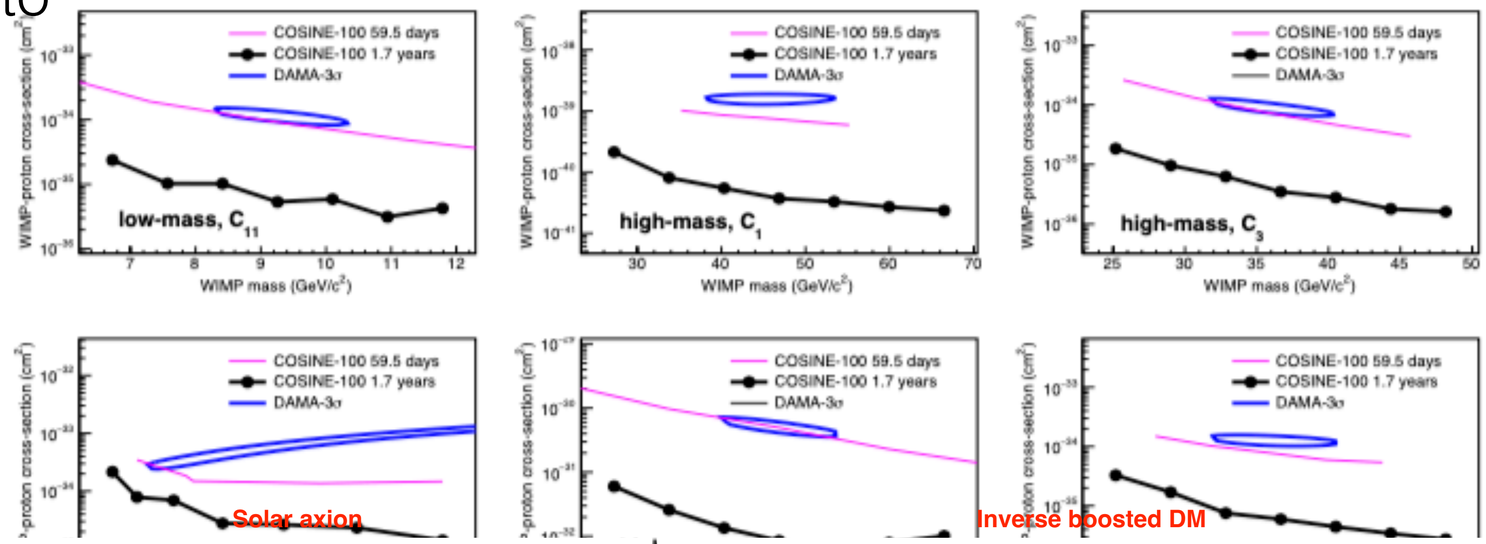
Other dark matter search

Background understanding and LS veto is used for other exotic dark matter candidate searches

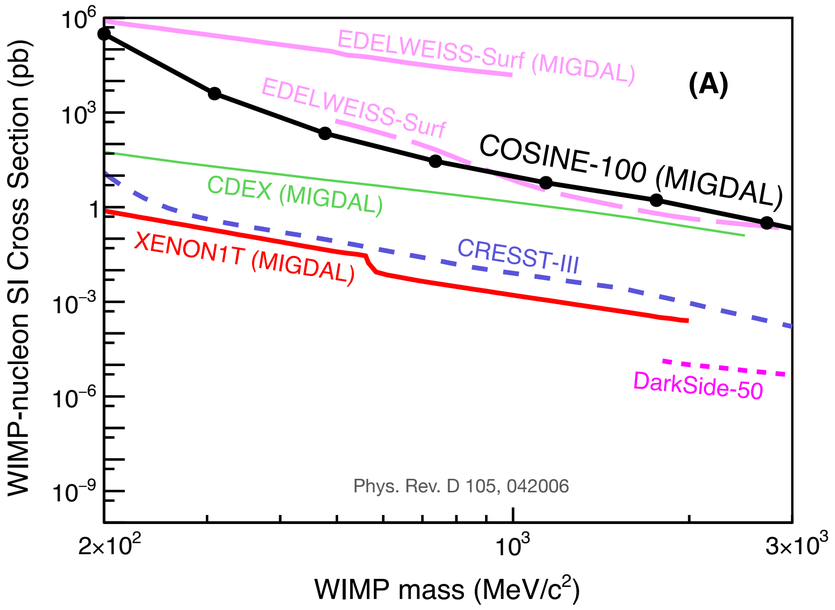
- Several EFT operators at different mass regions
- Migdal effect, Bosonic Super-WIMP, Boosted Dark Matter, Solar Axions, etc.

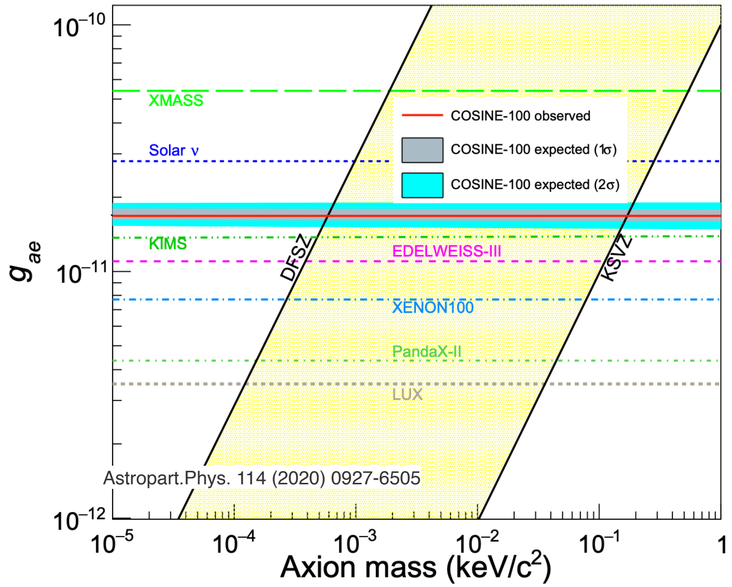
EFT Operators

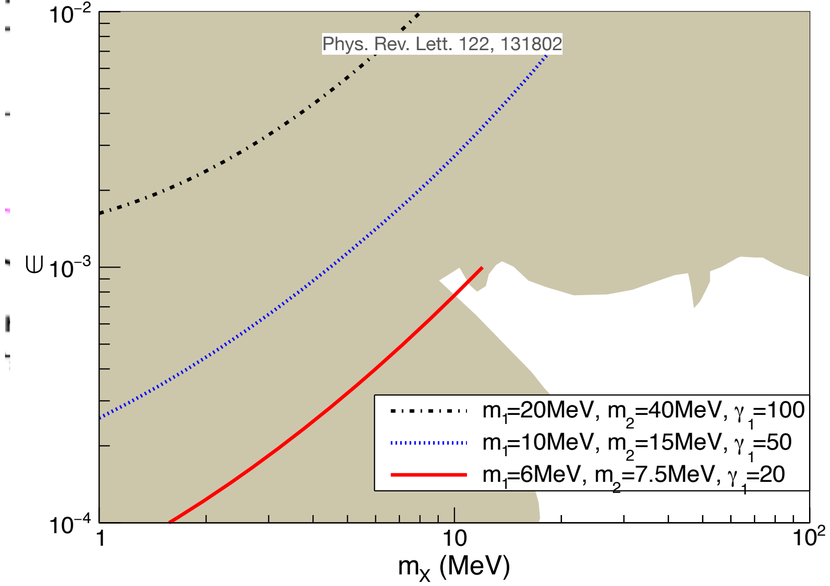
Sci Adv. 2021 Nov 12;7(46):eabk2699



Migdal effect







Quenching factor measurement

- Consistent quenching factor despite to the different geometries and powders