Searching for Dark Matter with COSINE-100

20th MultiDark | October 25, 2023

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Yale

Wright Laboratory

Dark Matter: History

"Many of our stars, perhaps a great majority of them, may be dark bodies." – William Thomson (Lord Kelvin)

1884

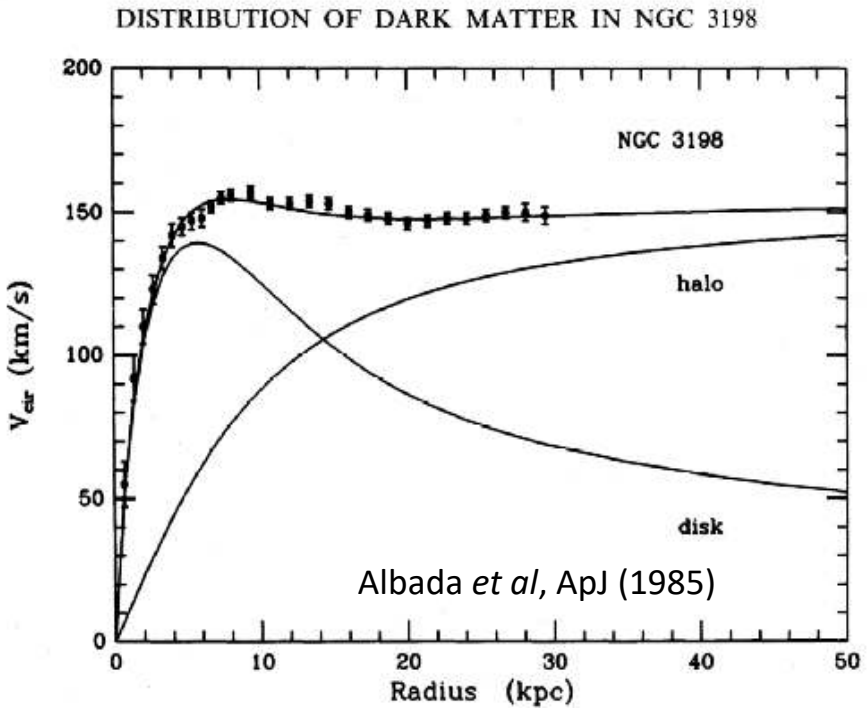
Zwicky claims virial theorem indicates presence of dark matter in galaxy clusters (Coma Cluster)

1933

Rubin and Ford observe galactic rotation curves indicating existence of dark matter

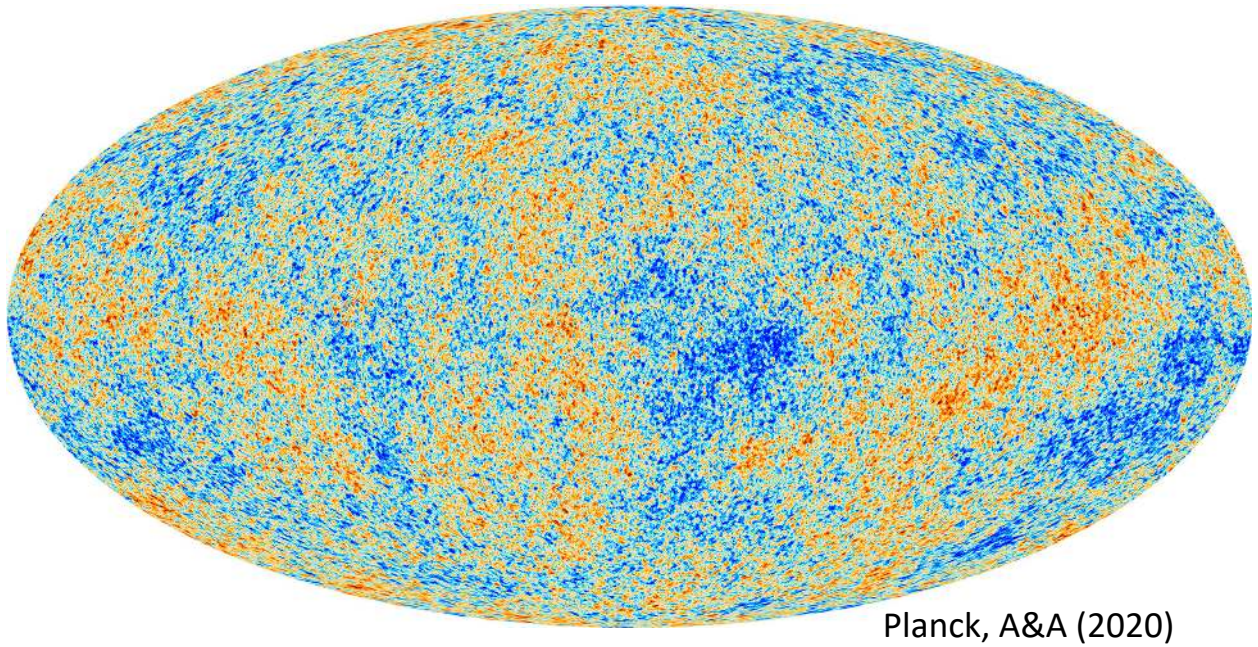
1960s & 1970s

Coma Cluster
(image credits: earthsky.org)



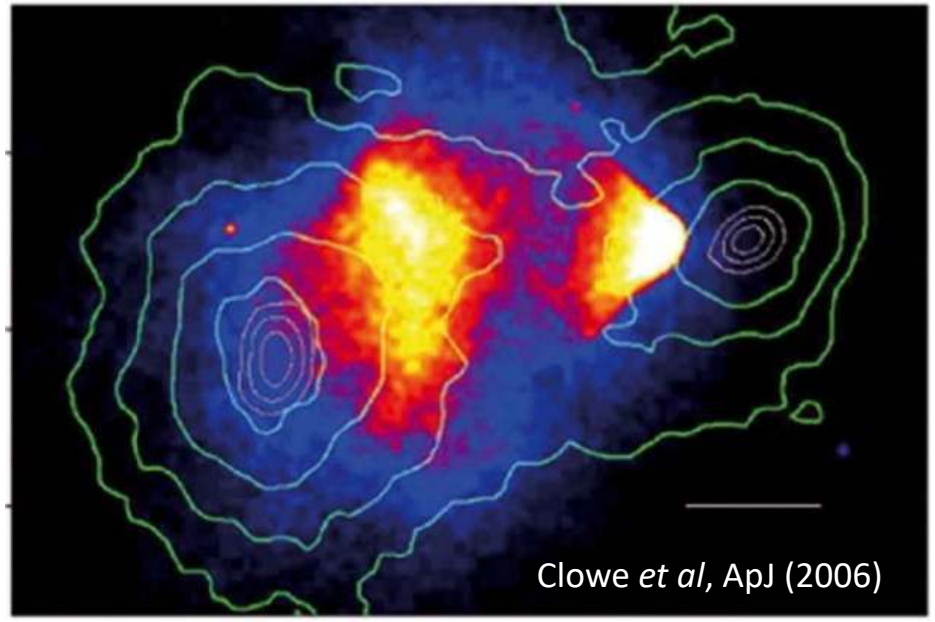
Albada *et al*, ApJ (1985)

Dark Matter: Cosmological Evidence



Planck, A&A (2020)

CMB Observations



Mass Distribution in Bullet Cluster

- Lots of cosmological evidence, but what about direct lab observations?

WIMPs and Detection Method

- When a WIMP interacts with an atom in scintillator, a flash of light is given
- Collect these events over time to find an annual signal

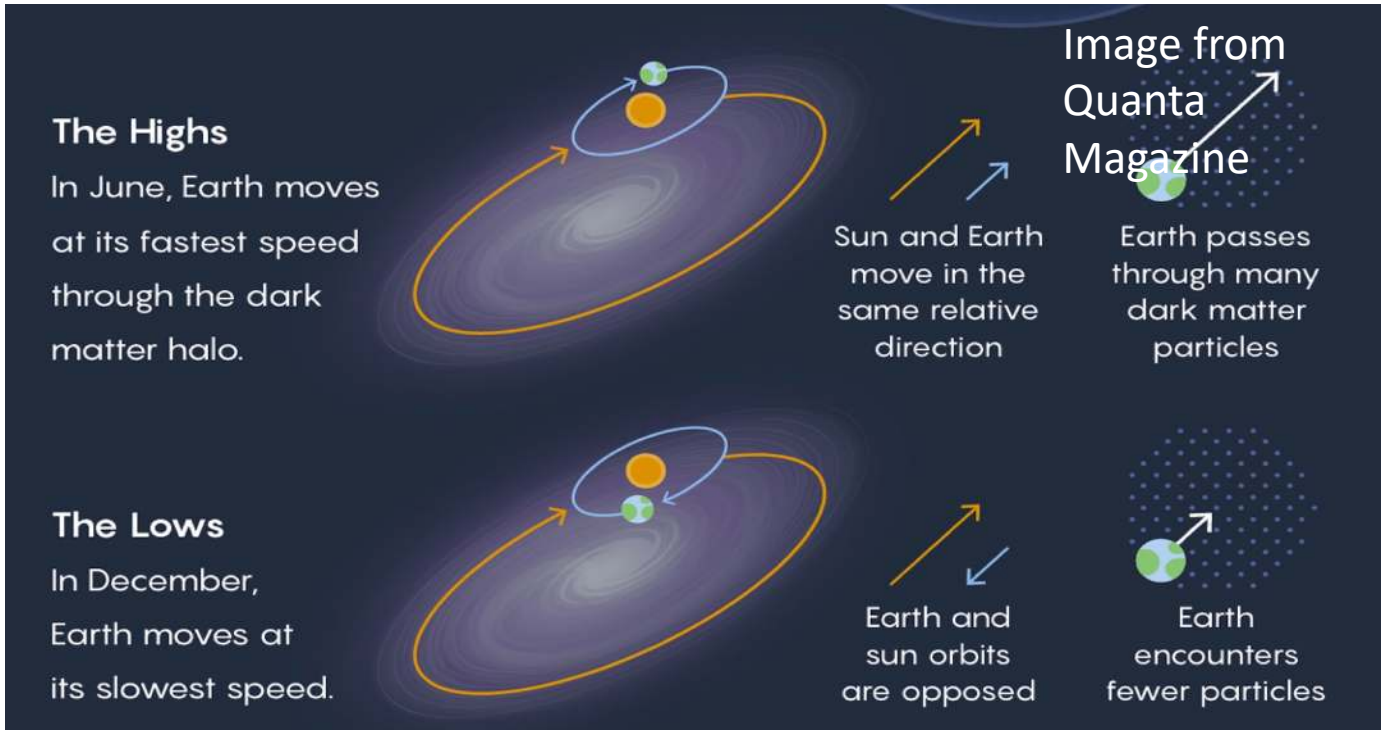
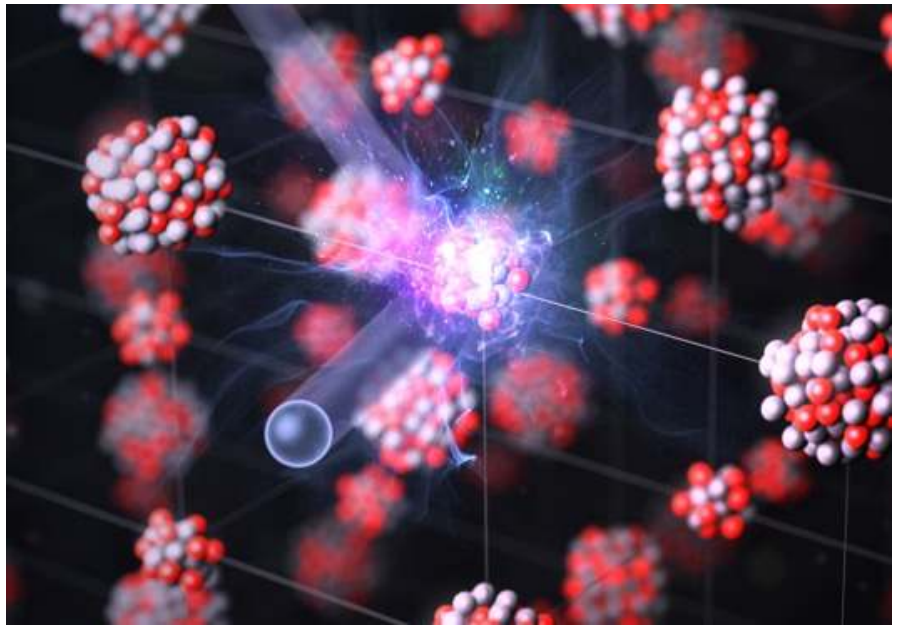


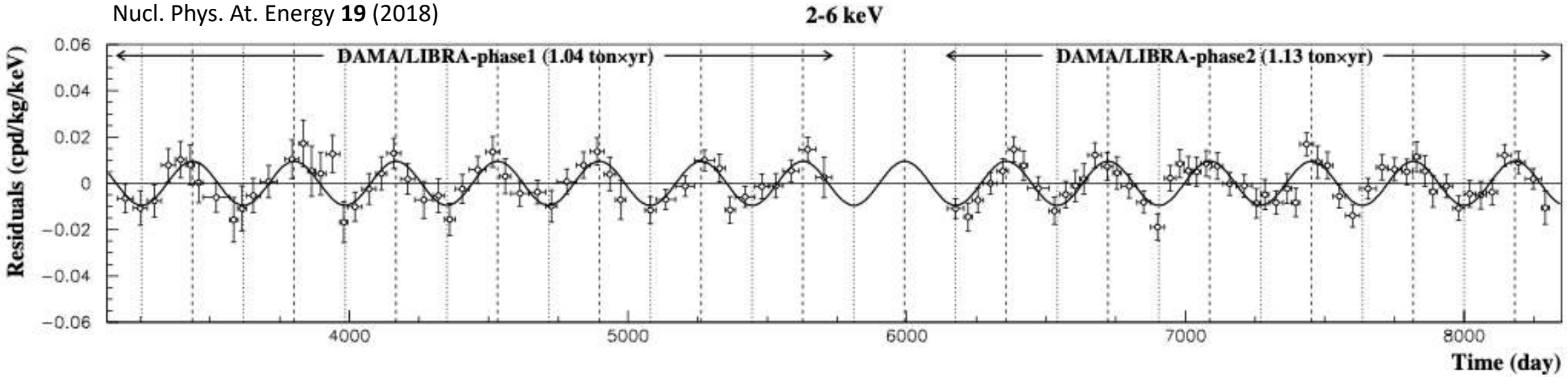
Image from Quanta Magazine



DM-nucleus scattering

DAMA/LIBRA and NaI(Tl)

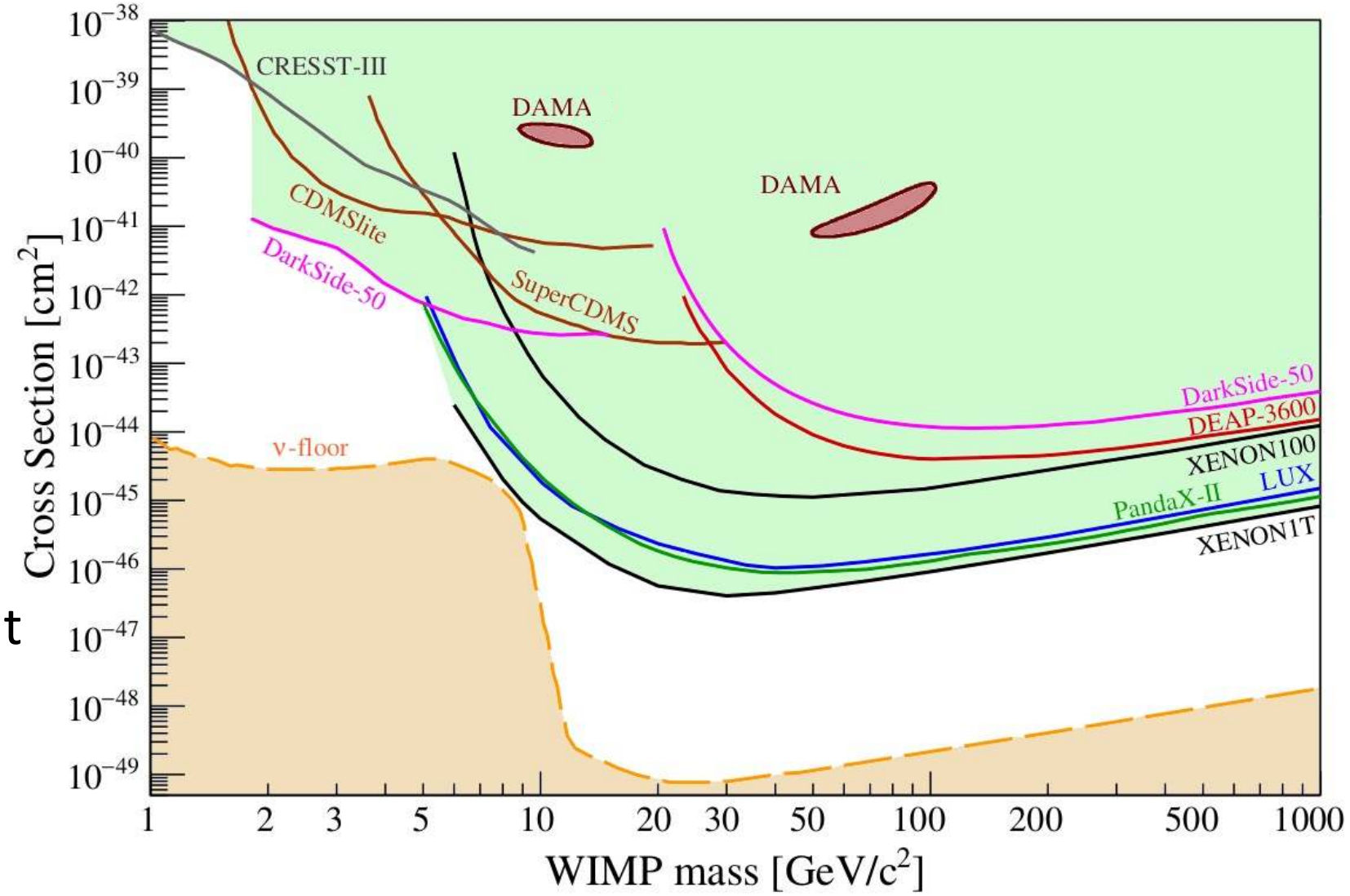
DAMA/LIBRA Collaboration
Nucl. Phys. At. Energy **19** (2018)



- DAMA/LIBRA: 250 kg of NaI(Tl) operating from 2003 at Gran Sasso
  - Purest NaI(Tl) detectors in DM experiment (1 cpd/kg/keV)
- Observe modulation signal over 20 annual cycles
  - 13σ significance, 2.5 ton · yr exposure

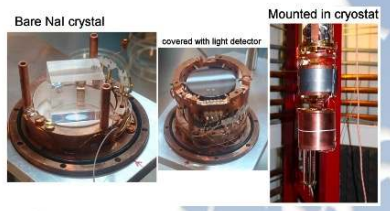
Direct Detection Community

- Much of the WIMP phase space has been explored and excluded
- DAMA appears in the excluded region for many experiments
- Note: No other experiment in this plot uses NaI(Tl) target material

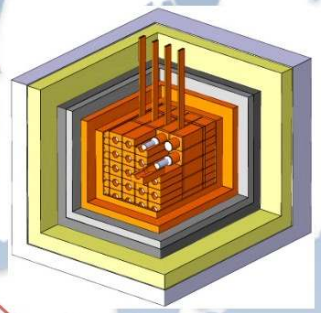


Adapted from Schumann, J. Phys G **46** 103003 (2019)

NaI(Tl) Experiments Around the World!

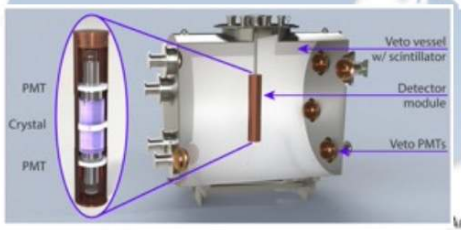


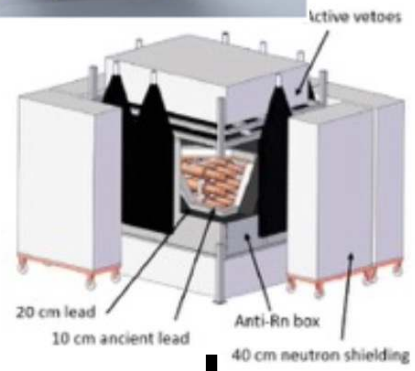
COSINUS @ LNGS



DAMA @ LNGS

SABRE @ LNGS

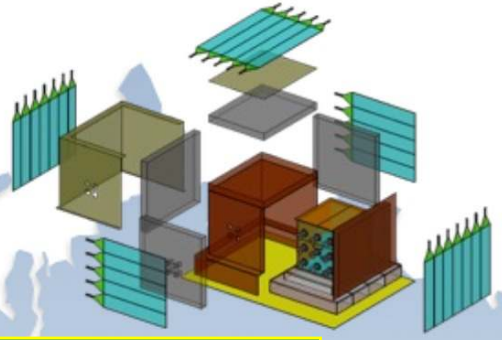




ANAIS @Canfranc

In Data-taking

ANAIS results.
Phys. Rev. Lett. **123**, 031301 (2019)



KIMS/COSINE @ Yangyang

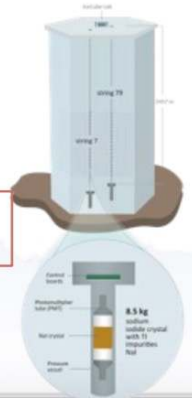
In Data-taking

Nature 564, 83-86 (2018)
Phys. Rev. Lett. 123, 031302 (2019)

PICO-LON @ Kamioka

SABRE @ Stawell

DM-Ice @ South Pole



The COSINE Collaboration

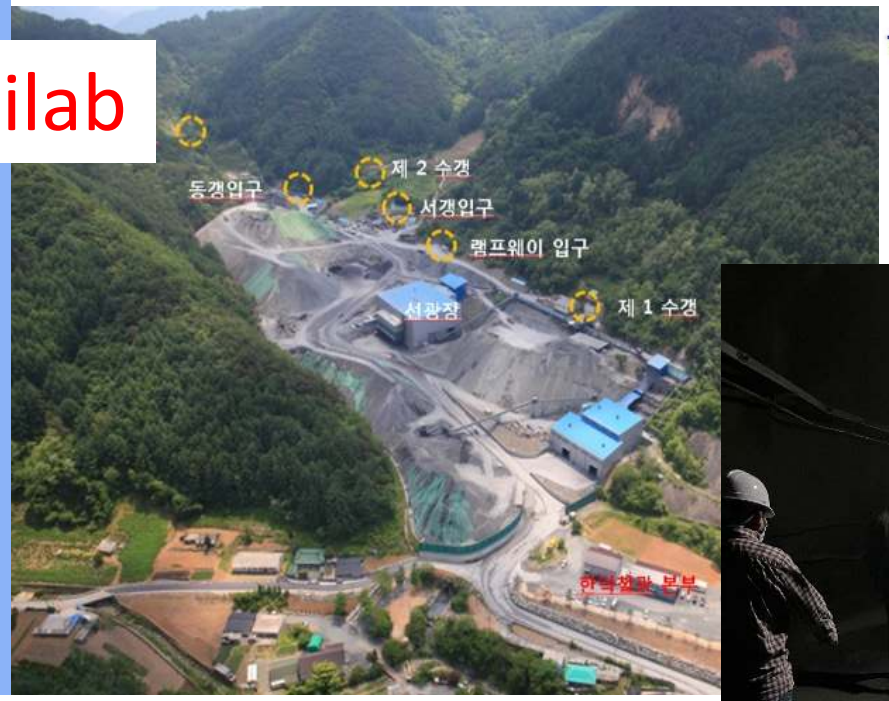
- COSINE-100 is located in Y2L Underground Lab 700m under Yangyang, South Korea
- 106 kg of NaI(Tl) across 8 detectors
- Data taking began Sept. 2016

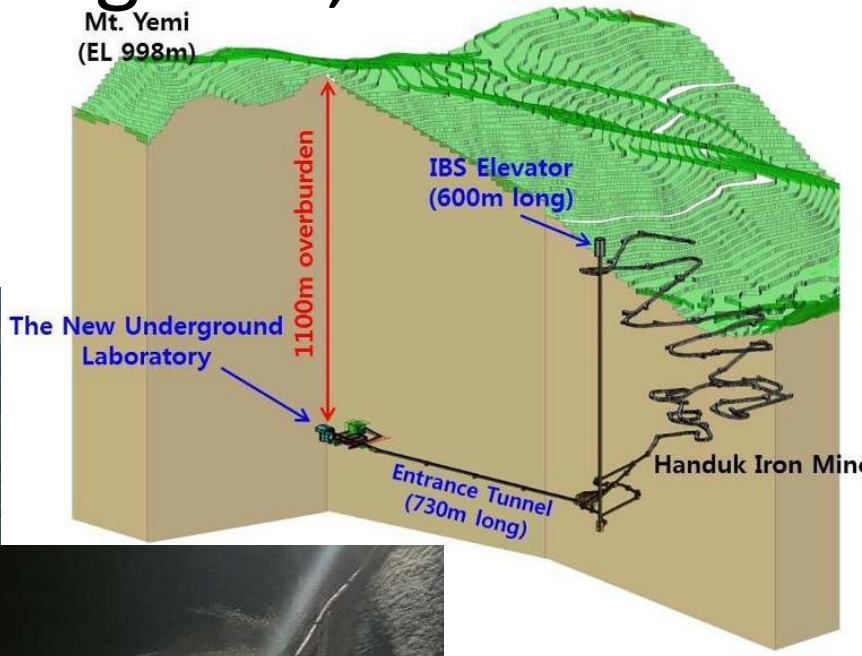
14 institutes
~50 members

KIMS + DM-ICE =

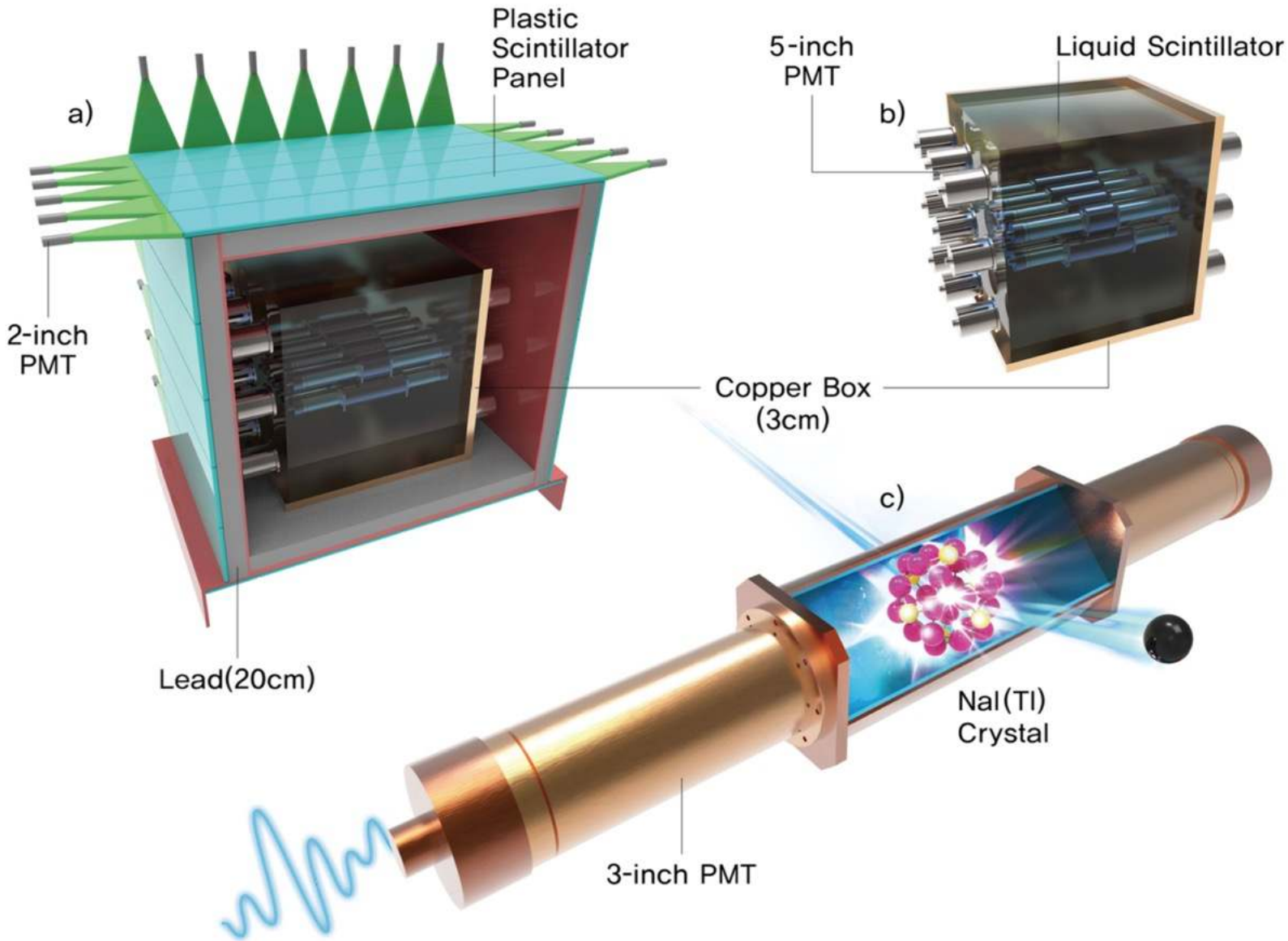
The COSINE Collaboration

Y2L, Yangyang, South Korea → Yemilab, Jeongseon, South Korea



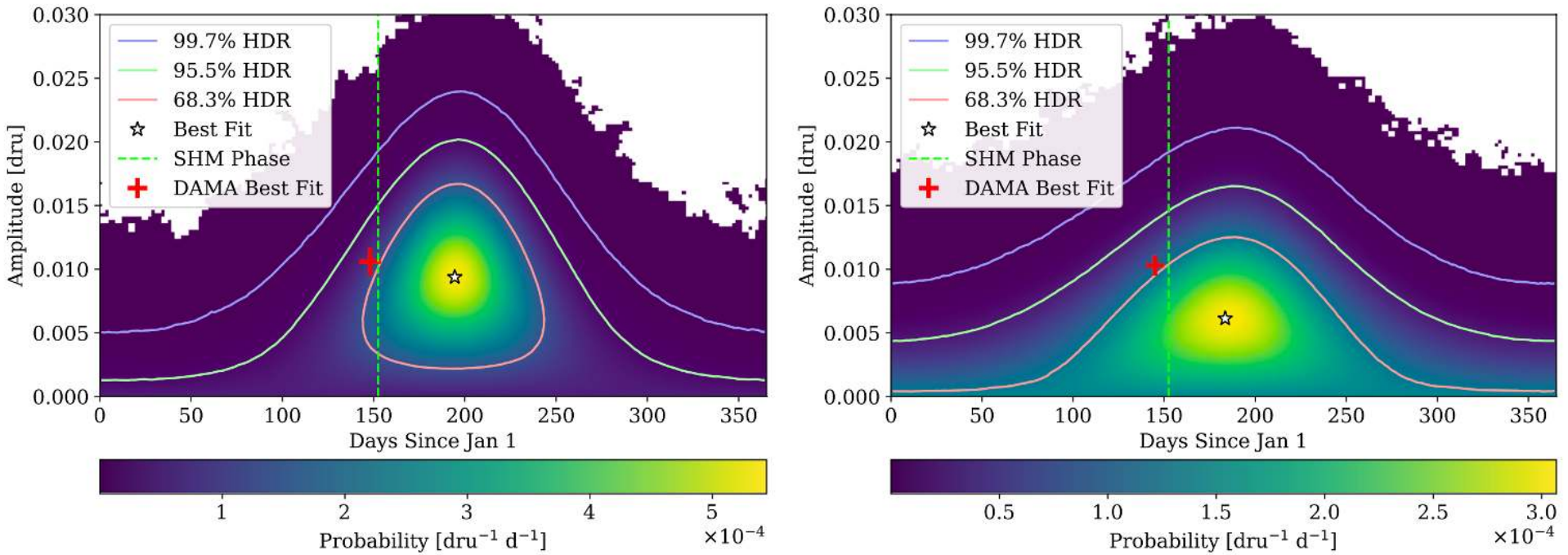


COSINE-100 Detector



- 8 low-background NaI(Tl) detectors
- 2200 L liquid scintillator veto
- 3 cm-thick copper box and 20 cm-thick lead shielding
- 37 plastic scintillator panels for 4π muon detection

COSINE-100 3-year Results

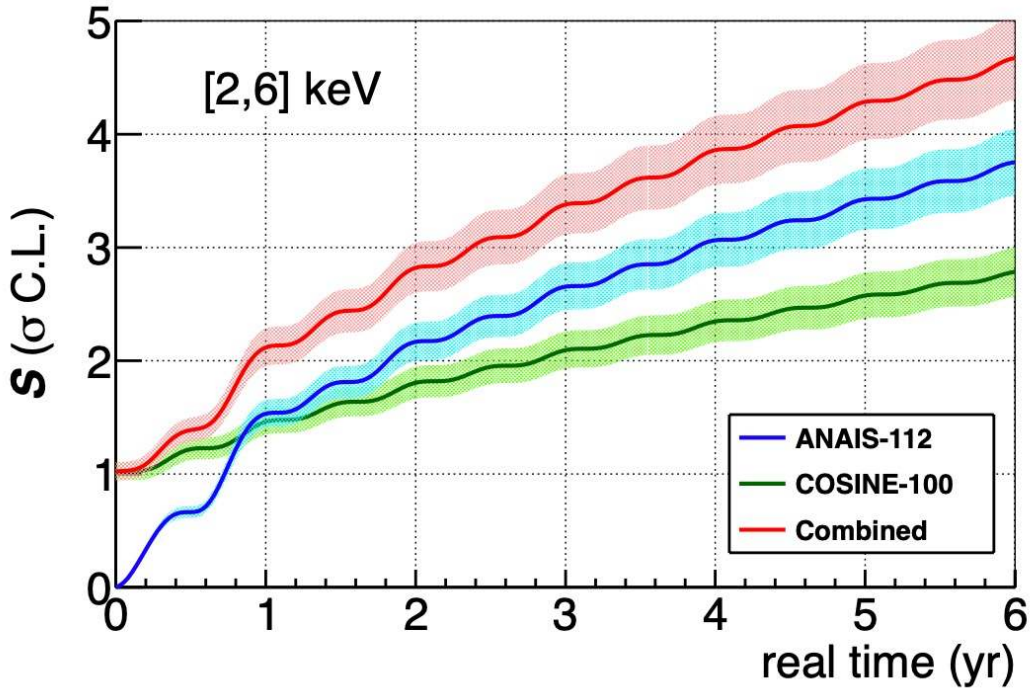


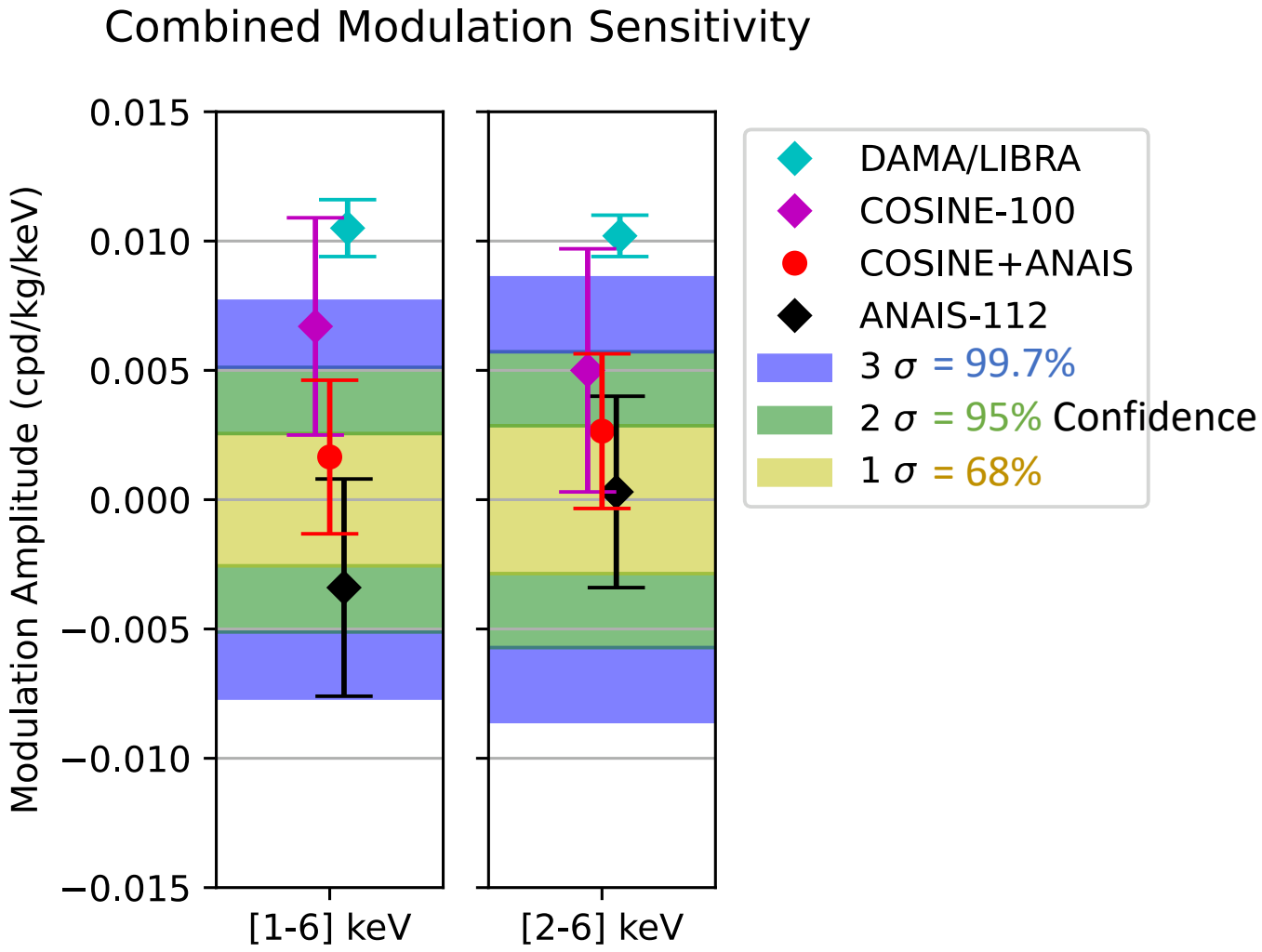
COSINE-100 Collaboration arXiv:2111.08863

- COSINE-100 both agrees with DAMA's results and no modulation
  - Lower background levels are needed to improve sensitivity/statistics
- COSINE-100 4.5yr results to publish soon with improved statistics to 1 keV
  - COSINE-100U underway and see a 45% light yield increase with refurbished crystals

Combining COSINE and ANAIS Data

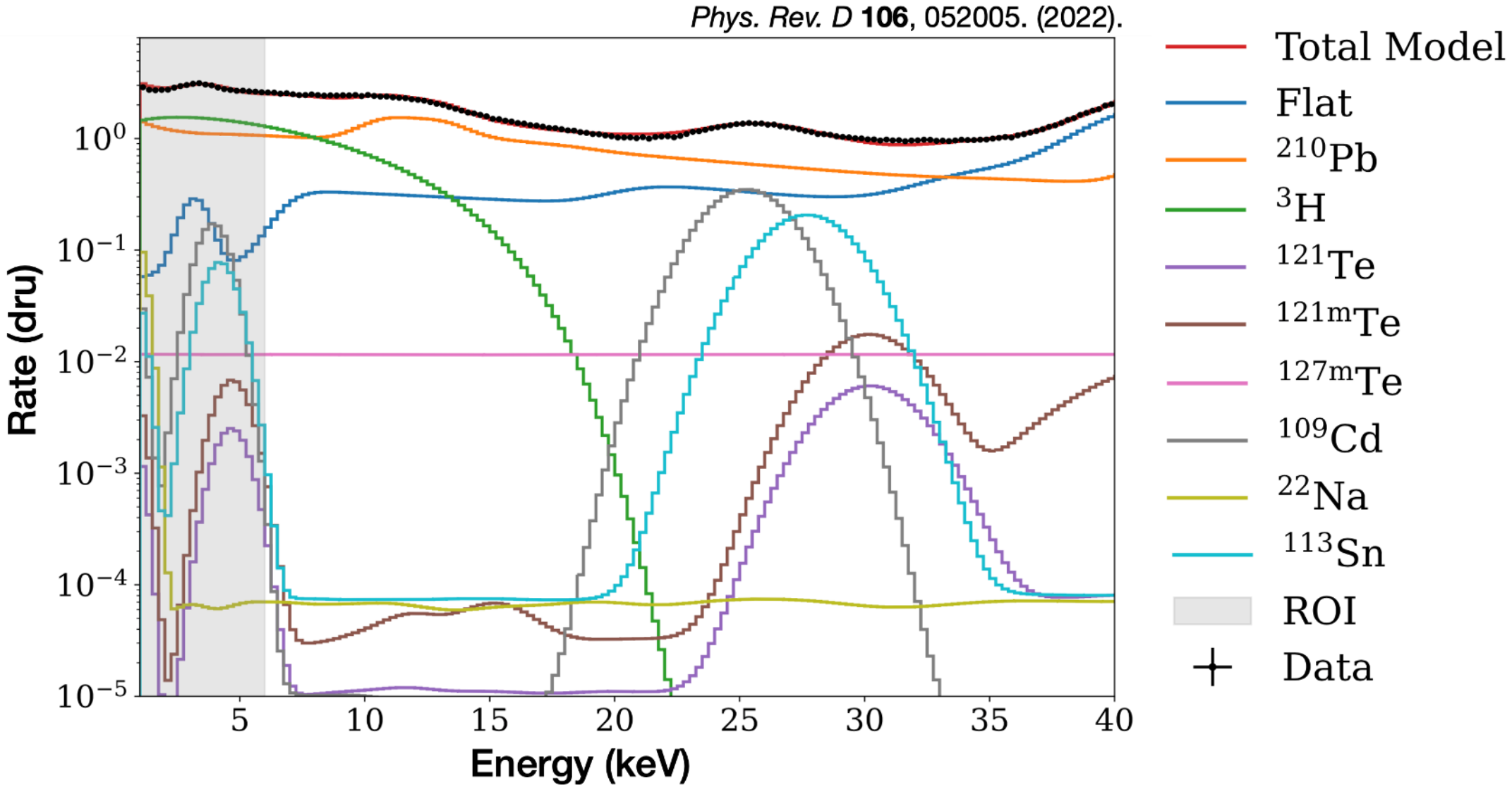
- Using existing 3-year data for both experiments, a 3σ significance can be achieved
- Such a combination would pressure the DAMA/LIBRA collaboration to release their data as well





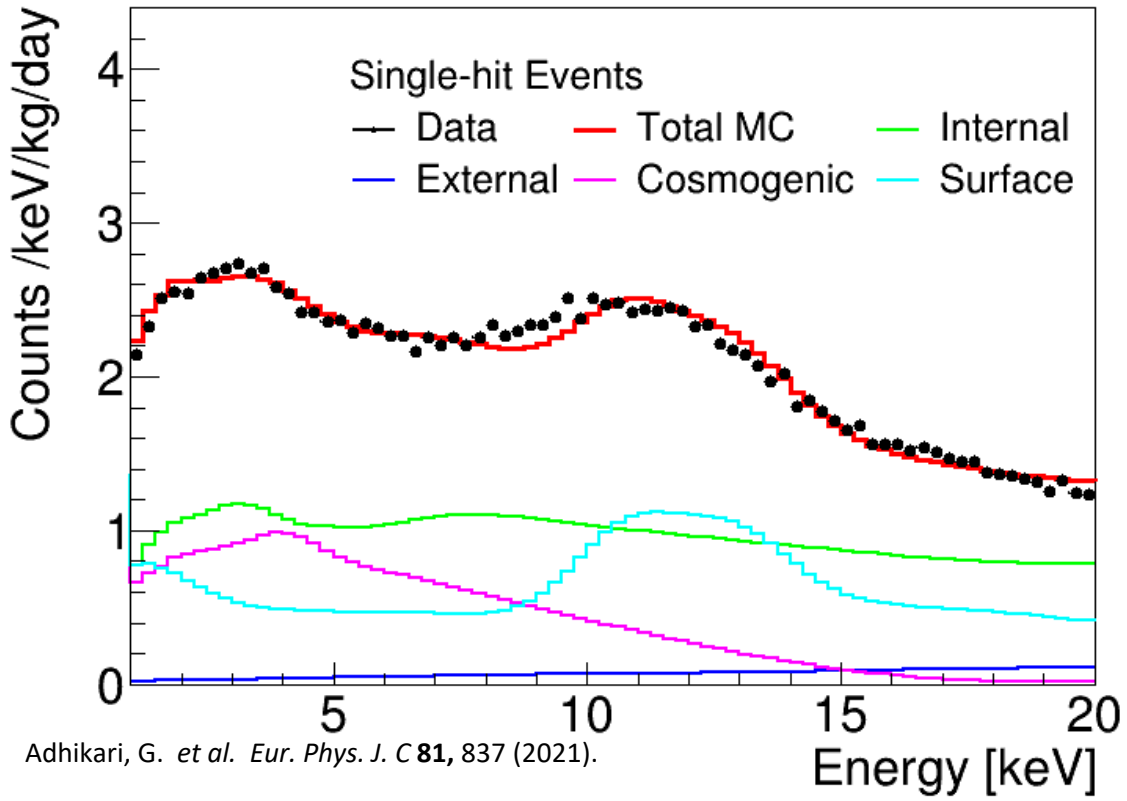
COSINE-100 Background Modeling and Subtraction

Backgrounds



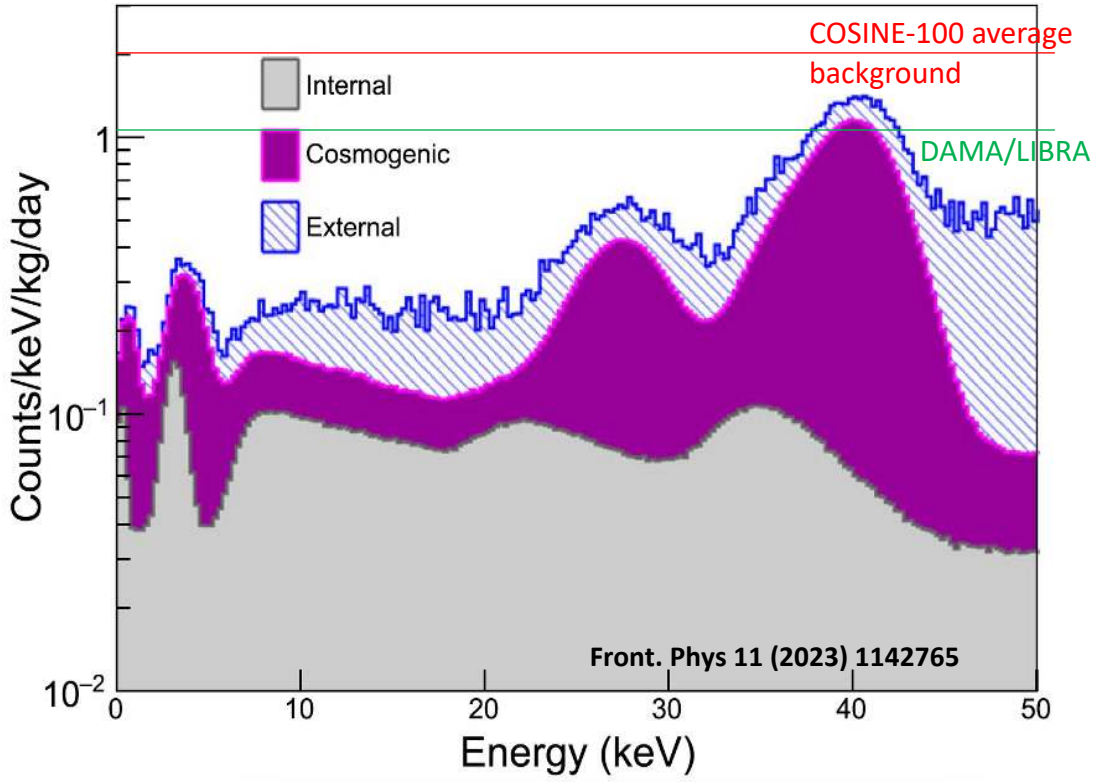
NaI(Tl) Background Components

COSINE-100



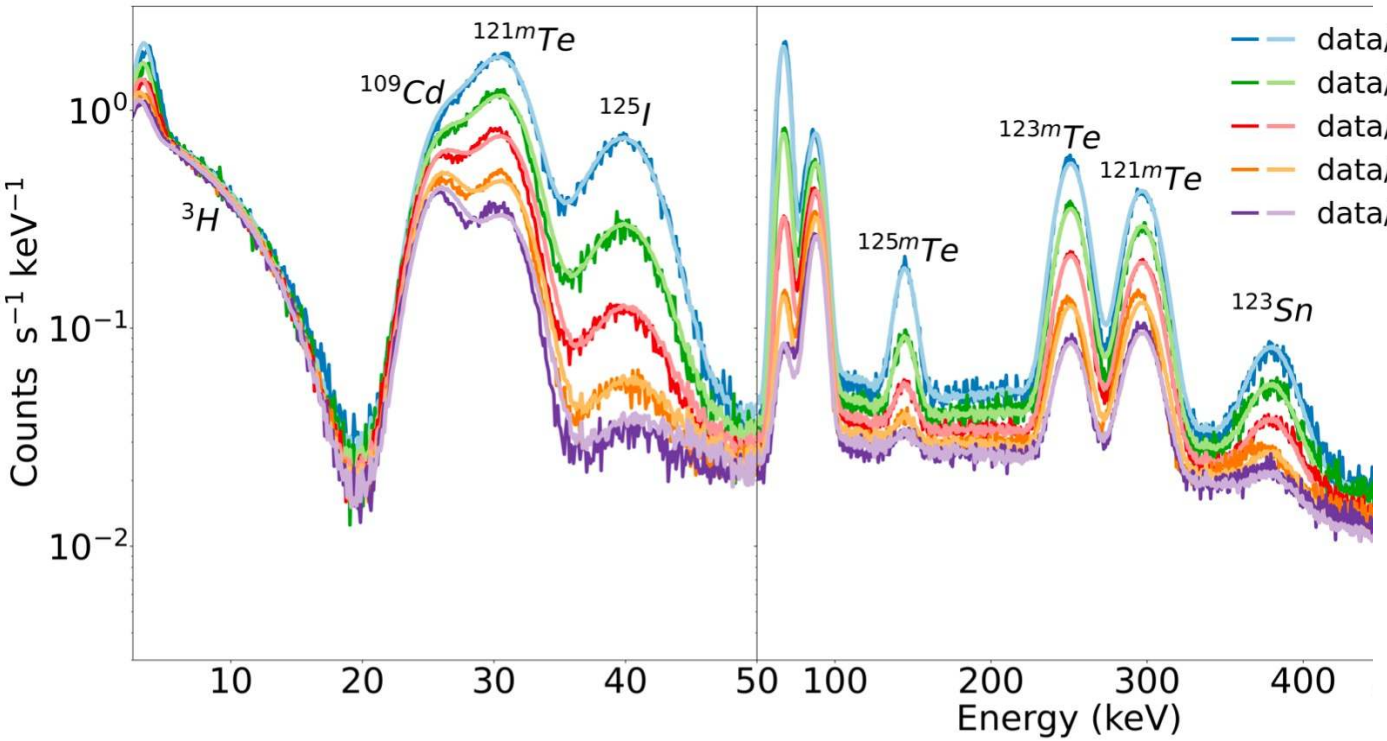
Adhikari, G. *et al. Eur. Phys. J. C* **81,** 837 (2021).

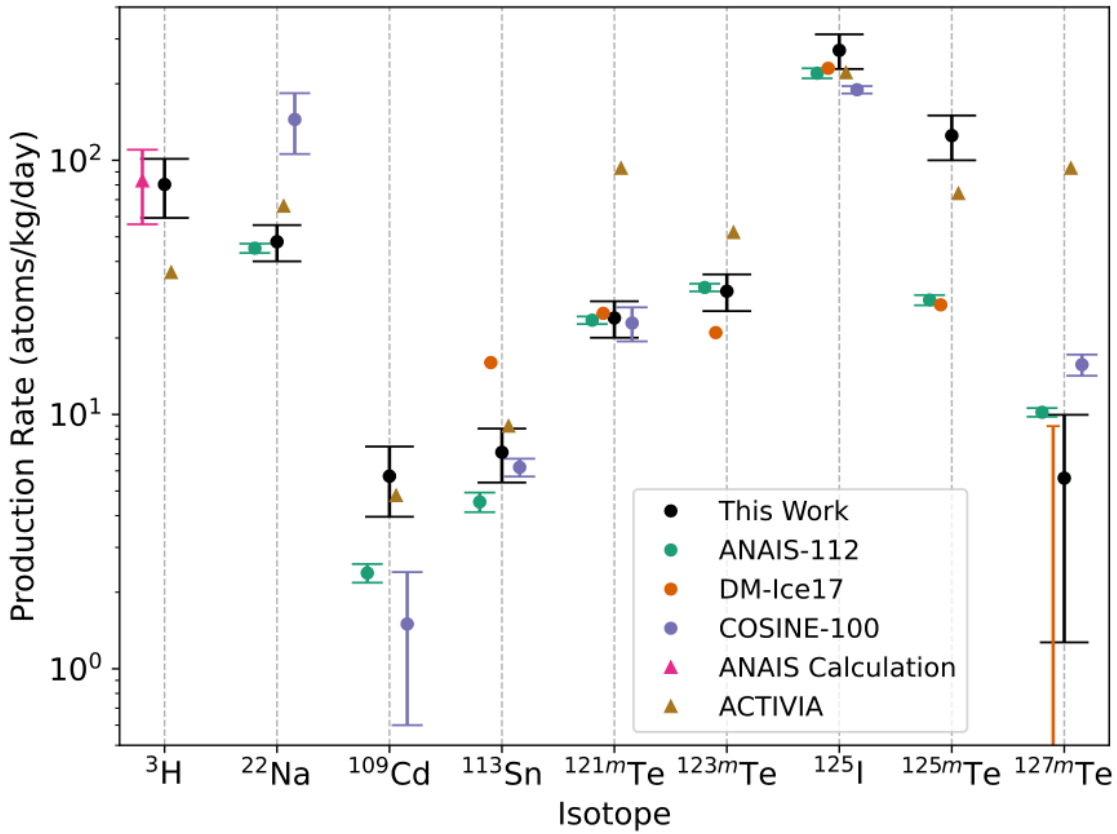
Prototype COSINE-200 Detector



- ^{40}K and ^{210}Pb internal isotopes used to dominate backgrounds
- Cosmogenic isotopes (^{3}H, ^{22}Na etc.) activated over time

Cosmogenic Isotope Activation Rates





- Fitting over isotopes allows knowledge of activity levels
- This gives controlled study of their activation rates

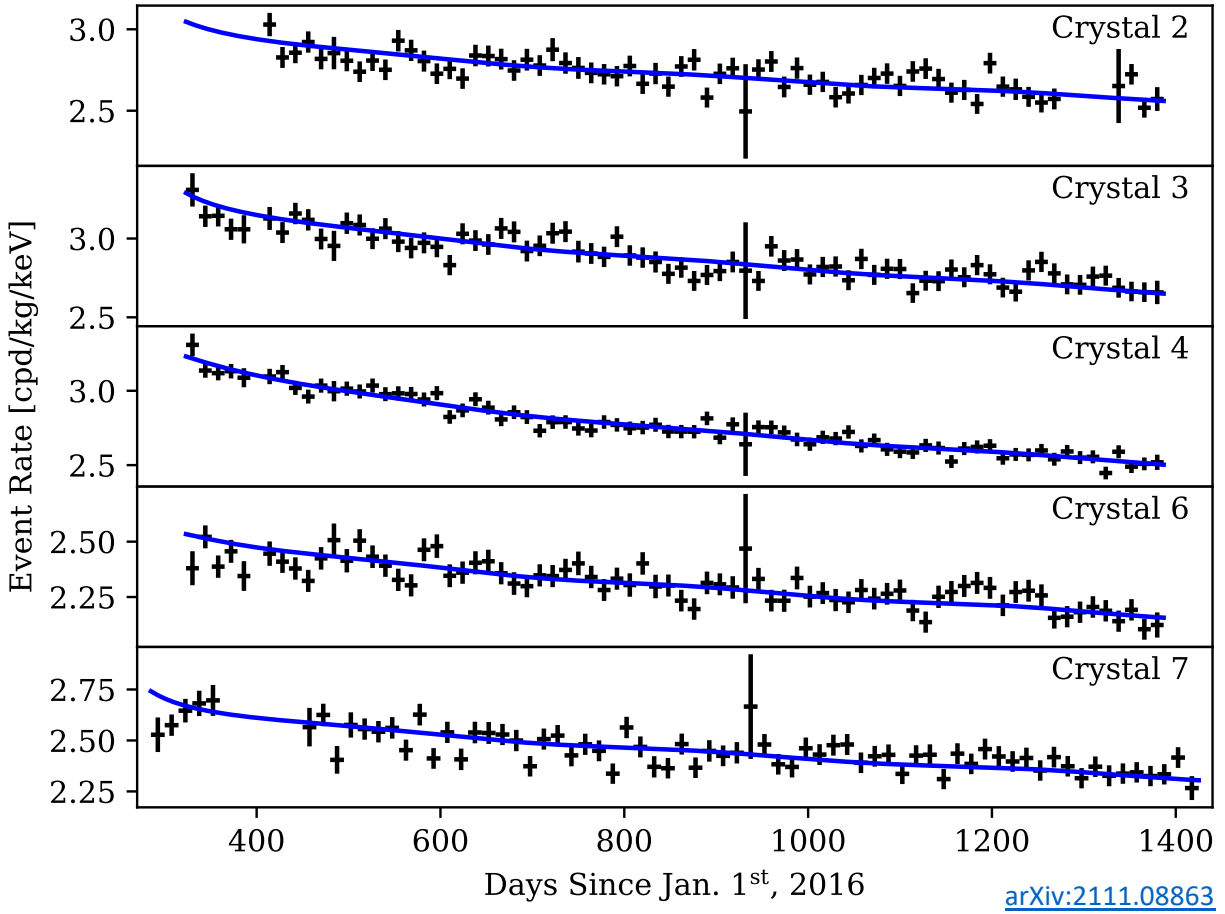
Phys. Rev. D **107,** 022006. (2023).

Modulation Search – Background Subtraction

DAMA Claims only this background component! (Time independent)

$$R(t) = \sum_i \left[C^i + \sum_{j=1}^{8} A_j^i e^{-\lambda_j t} \right] + S_m \cos\left(\frac{2\pi(t-t_0)}{T}\right)$$

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

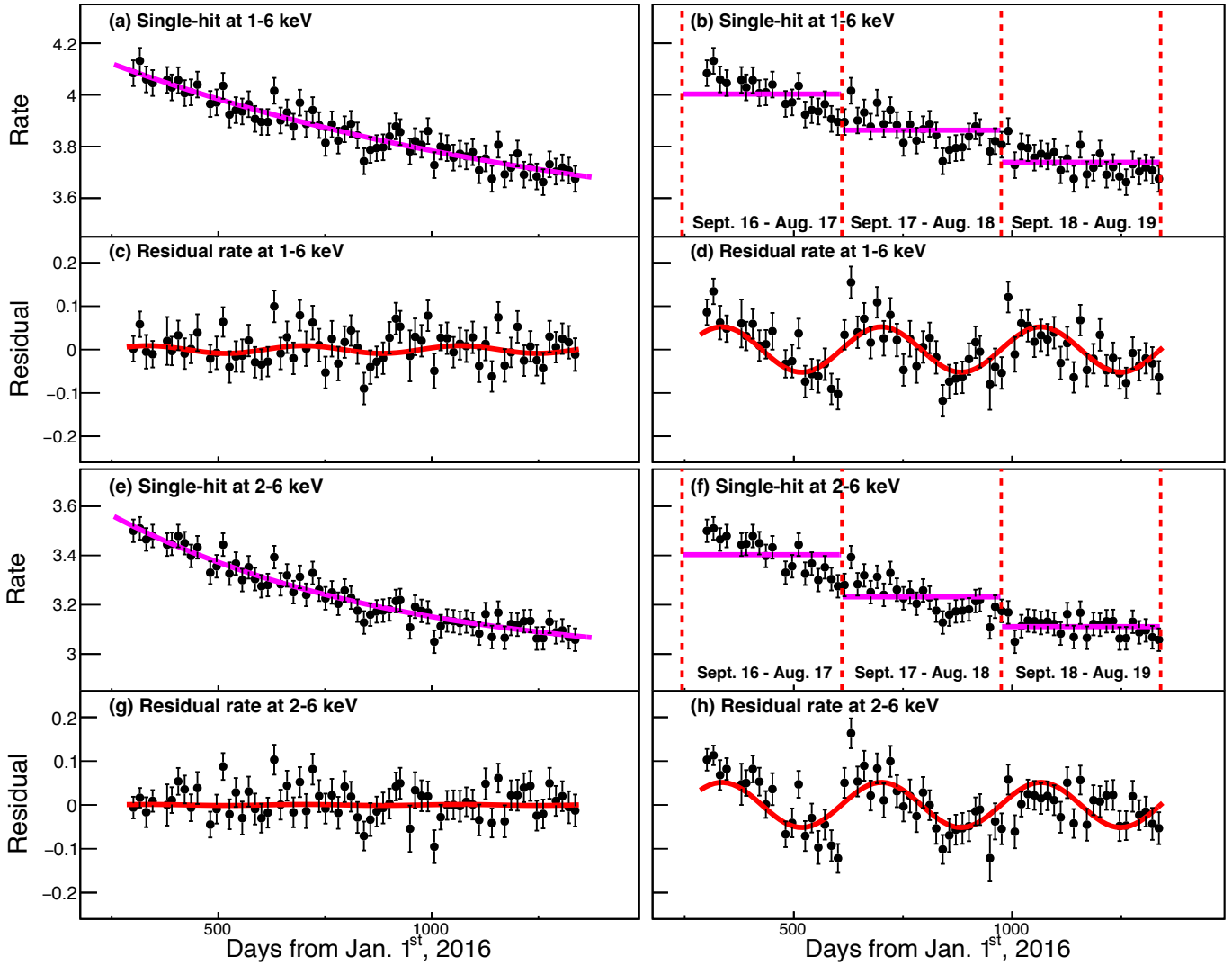


arXiv:2111.08863

Time (In)dependent Background Subtraction Methods

- If a background decays exponentially over time, the subtracted background must account for this decay
- If a background does not decay over time (is flat), the subtracted background can be assumed to be the average annual rate

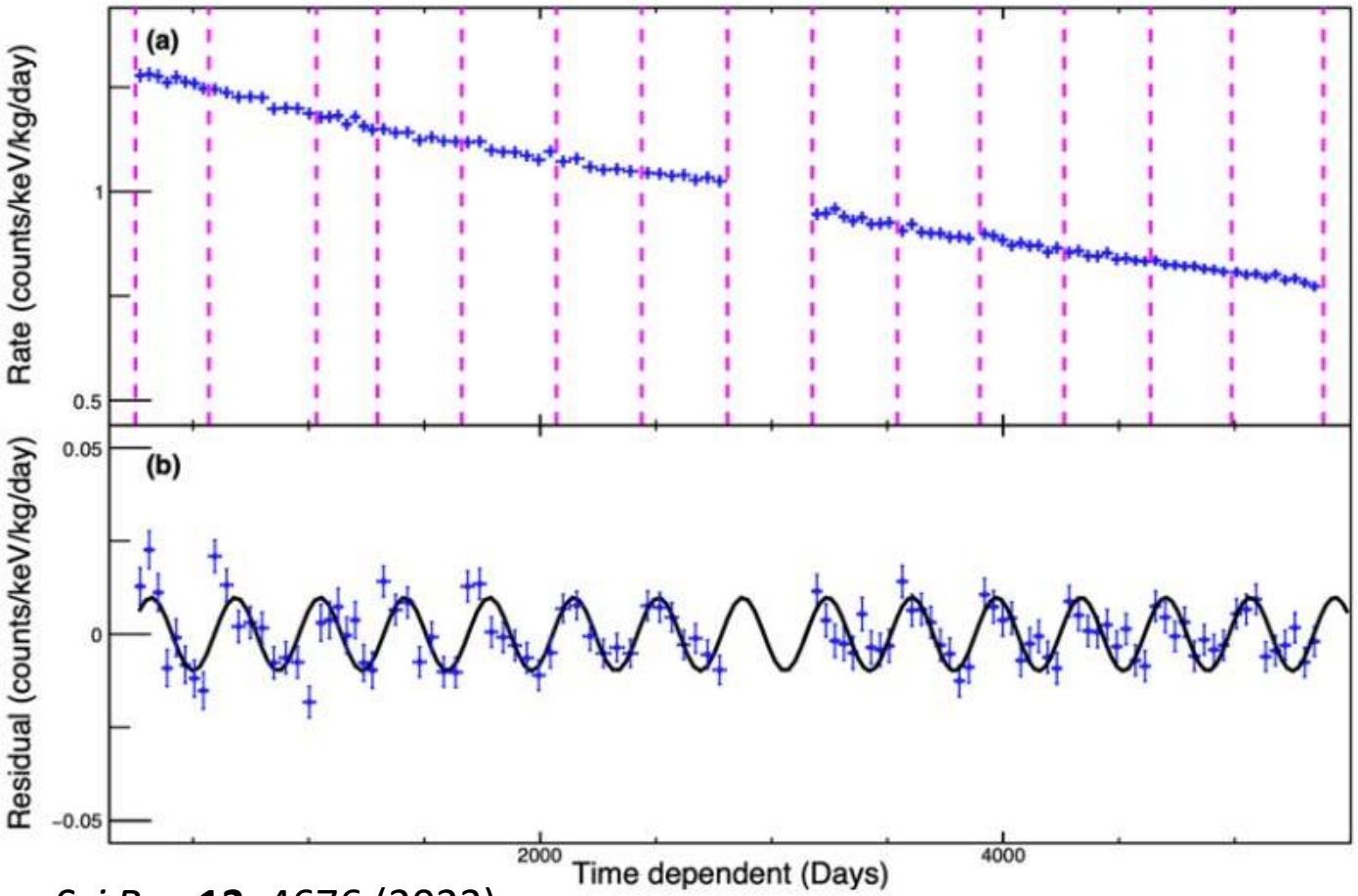
Paper!



Cannot assume backgrounds are unchanging!

Simulated DAMA Data

- Assumes COSINE-like backgrounds on a DAMA-like experiment



Sci Rep **13**, 4676 (2023).

Cycle	Date period	Exposure (kg × day)
1	Sept. 9, 2003 – July 21, 2004	51,405
2	July 21, 2004 – Oct. 28, 2005	52,597
3	Oct. 28, 2005 – July 18, 2006	39,445
4	July 19, 2006 – July 17, 2007	49,377
5	July 17, 2007 – Aug. 29, 2008	66,105
6	Nov. 12, 2008 – Sept. 1, 2009	58,768
7	Dec. 23, 2010 – Sept. 9, 2011	Commissioning
8	Nov. 2, 2011 – Sept. 11, 2012	62,917
9	Oct. 8, 2012 – Sept. 2, 2013	60,586
10	Sept. 8, 2013 – Sept. 1, 2014	73,792
11	Sept. 1, 2014 – Sept. 9, 2015	71,180
12	Sept. 10, 2015 – Aug. 24, 2016	67,527
13	Sept. 7, 2016 – Sept. 25, 2017	75,135

This modulation has opposite phase!

Shifting Declared Annual Cycles

Cycle	Date period	Exposure (kg × day)
1	Sept. 9, 2003 – July 21, 2004	51,405
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+ 183 days (π) =

Cycle	Date Period	Exposure (kg x day)
1	March 10, 2004 - Jan. 20, 2005	51,405
2	Jan. 20, 2005 - April 29, 2006	52,597
3	April 29, 2006 - Jan. 17, 2007	39,445
4	Jan. 18, 2007 - Jan. 16, 2008	49,377
5	Jan. 16, 2008 - Feb. 28, 2009	66,105
6	May 14, 2009 - March 3, 2010	58,768
7	June 24, 2011 - March 10, 2012	Commissioning
8	May 3, 2012 - March 13, 2013	62,917
9	April 9, 2013 - March 4, 2014	60,586
10	March 10, 2014 - March 3, 2015	73,792
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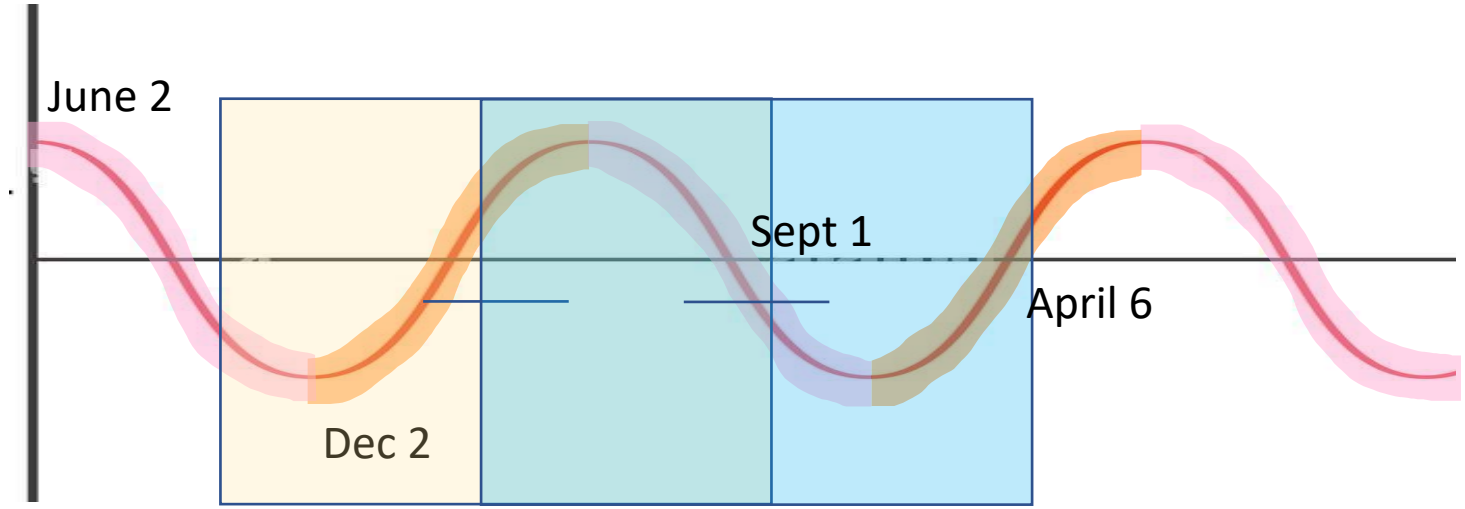
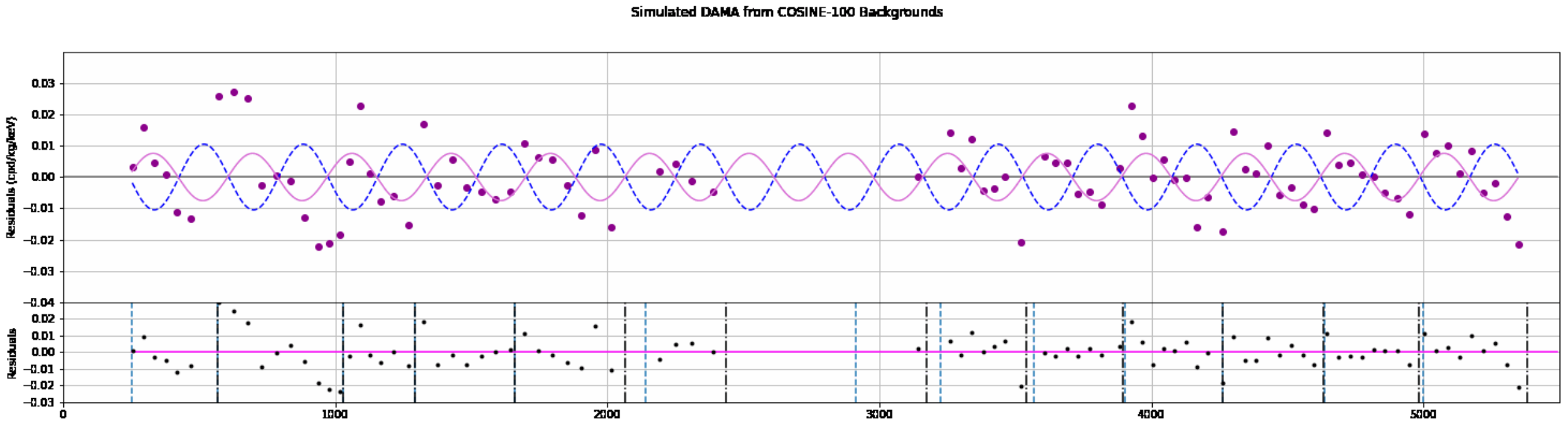


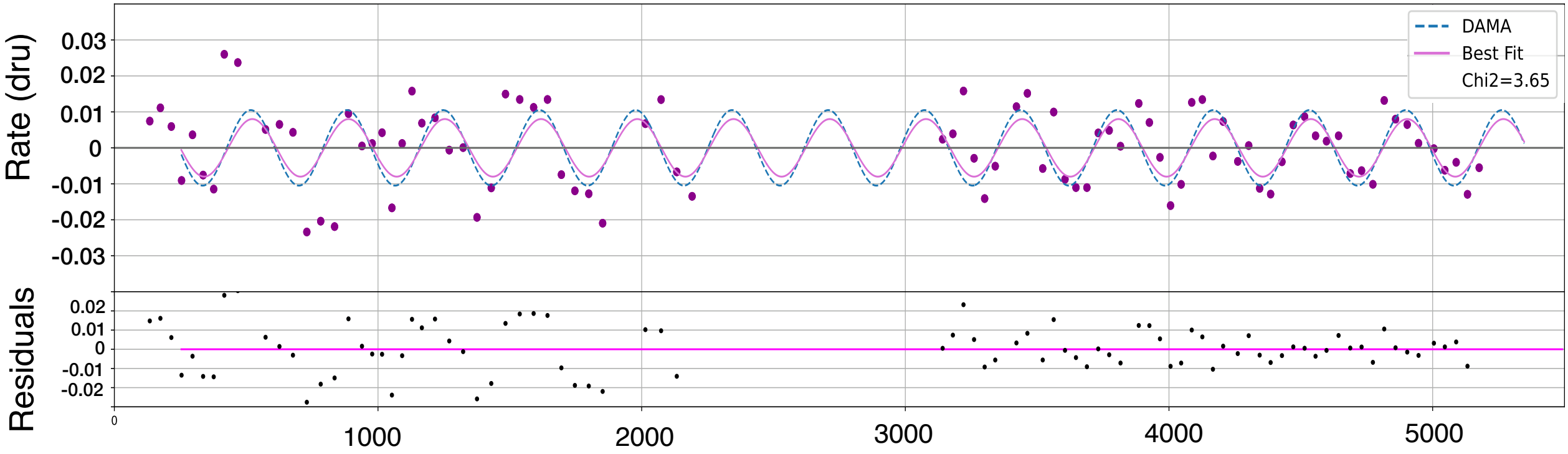
Shifting Phase with Shifting Annual Cycles



- Modulation phase clearly dependent on declared annual cycles
  - Vertical lines show the outline for the cycles
  - The modulation peaks move inline with the shifting cycle times
  - Amplitude roughly consistent

Optimal Fit from Shifted Cycles at 183 days

- A compelling way to achieve DAMA's phase is to shift annual cycles by 183 days (π)



Amplitude 0.0082

Concluding Remarks

- COSINE-100 will soon publish 5 yr modulation search
  - Combining with ANAIS-112 can lead to competitive sensitivity for testing DAMA/LIBRA
- DAMA/LIBRA's background subtraction procedure does not work with time-dependent backgrounds
  - Would like to see DAMA/LIBRA background data and detector efficiencies to confirm valid background modelling

Thank you for your attention!

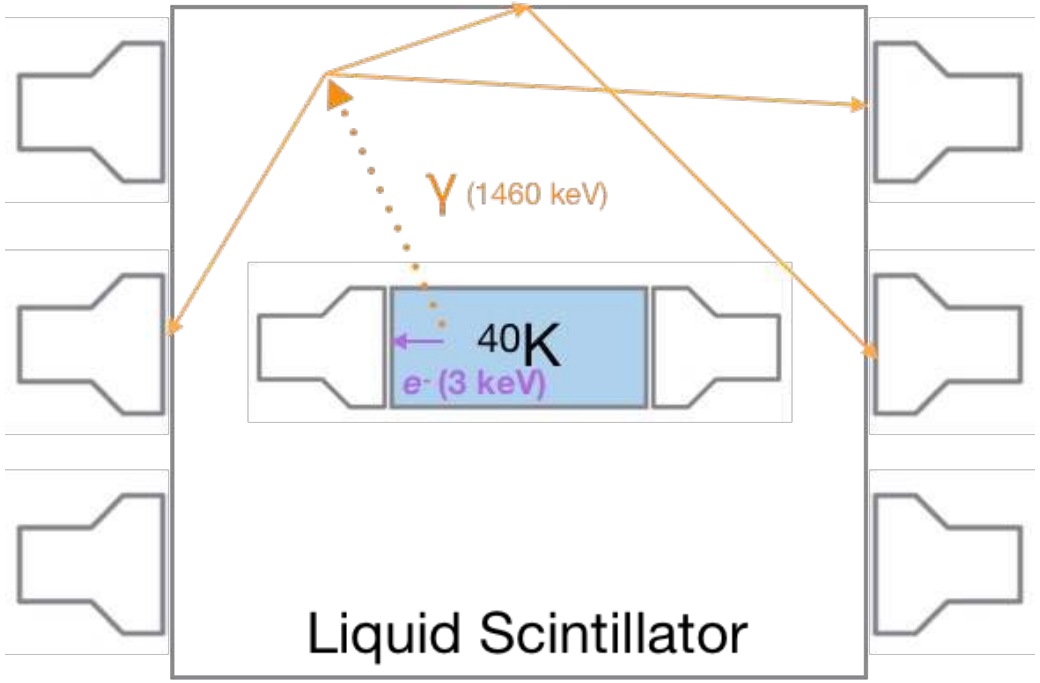
Acknowledgements

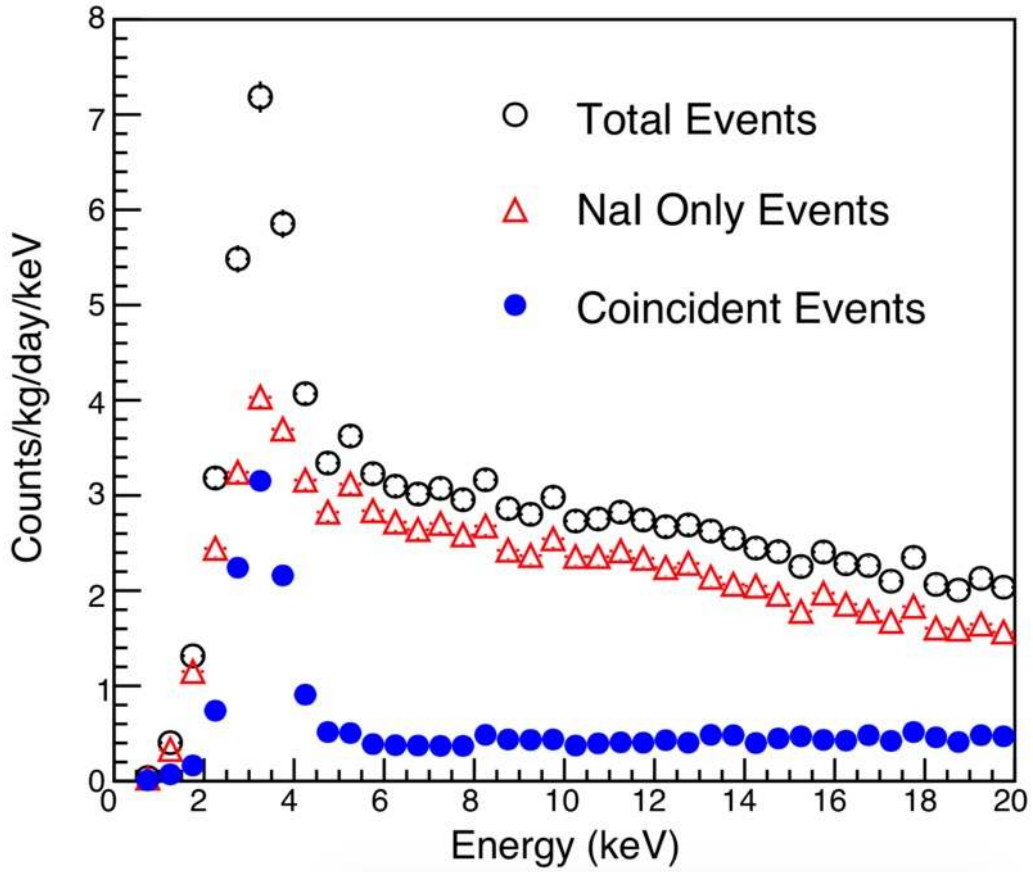
The Institute for Basic Science (IBS) under project code IBS-R016-A1 and NRF-2021R1A2C3010989, Republic of Korea; NSF Grants No. PHY-1913742, DGE- 1122492, WIPAC, the Wisconsin Alumni Research Foundation, United States; STFC Grant ST/N000277/1 and ST/K001337/1, United Kingdom; Grant No. 2017/02952-0 FAPESP, CAPES Finance Code 001, CNPq 131152/2020-3, Brazil.

Backup

Liquid Scintillator Veto

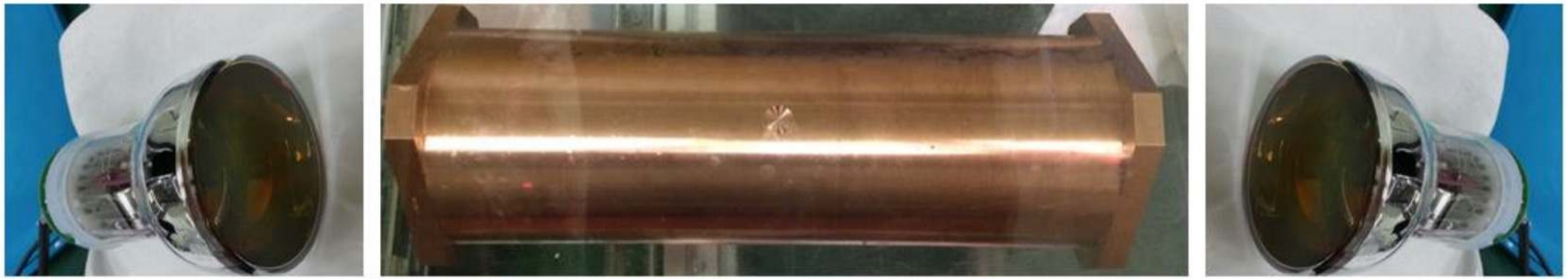
- NaI(Tl) detectors immersed in 2200 L active LAB liquid scintillator veto
  - Scintillator contained in acrylic vessel lined with reflector
- LS veto ~80% efficient at rejecting ^{40}K events



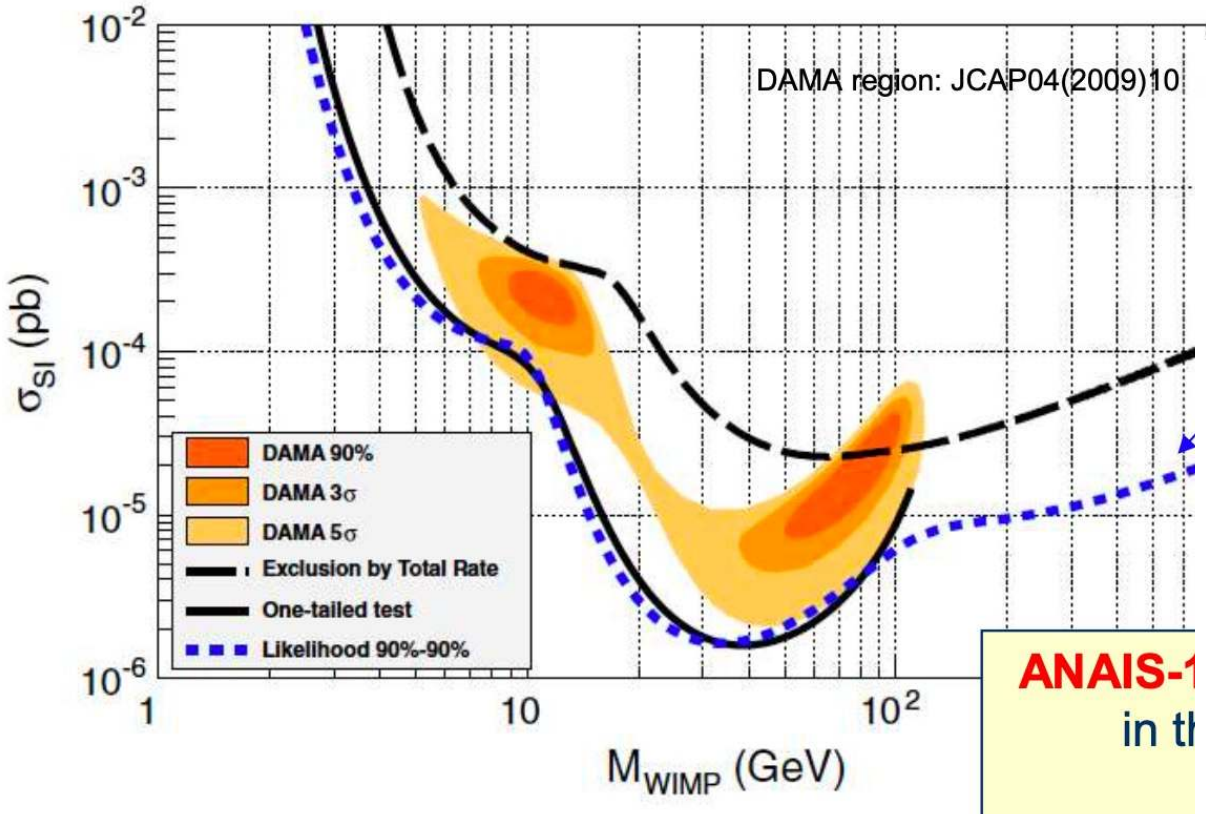


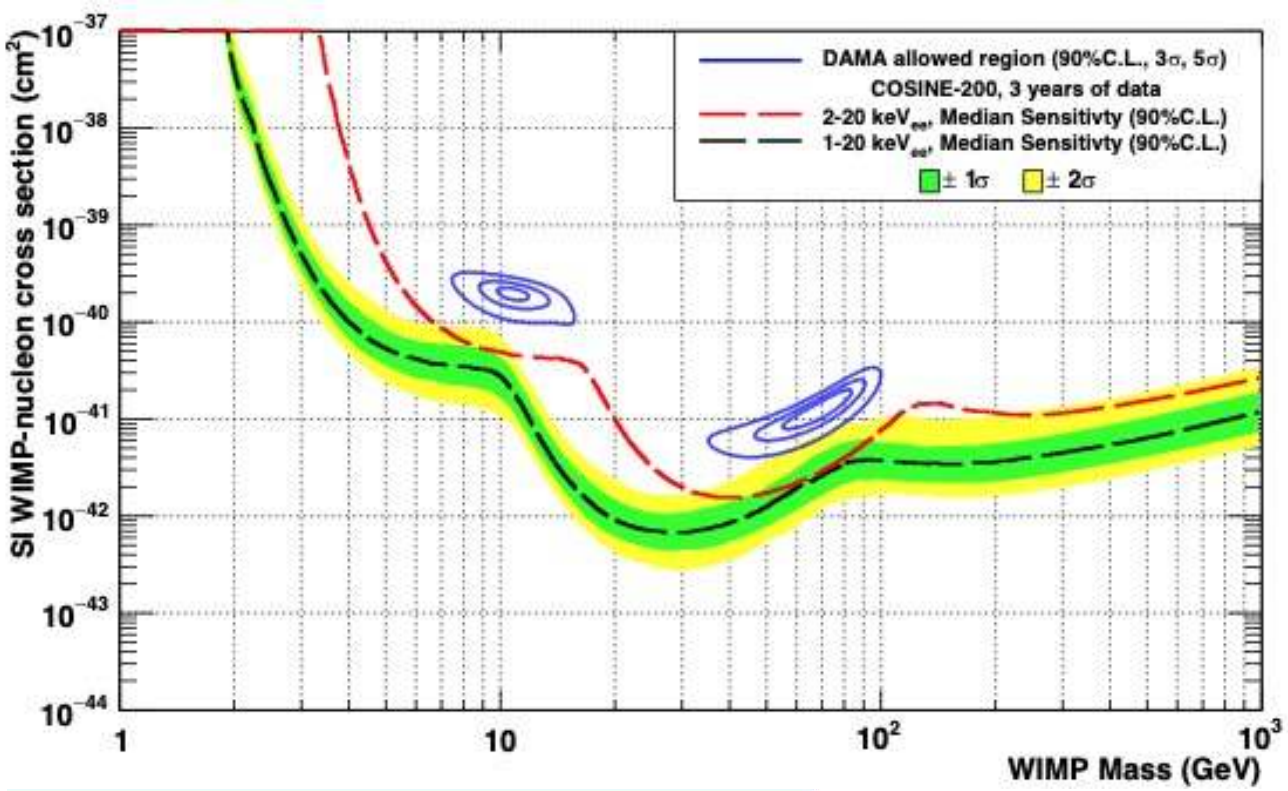
NaI(Tl) Detector Preparation

- Crystals wrapped in Teflon and encapsulated in copper housings
- Both ends of crystals coupled to low background PMTs through quartz windows
  - PMTs feature anode and dynode readout for high dynamic range (sub-keV to ~5 MeV)
- Full setup contained in light-tight copper case wrapped in reflector



COSINE-200 Sensitivity for Model-Dependent Analysis





S. Cebrián, 28 April 2021

- Sensitivity pairs well with ANAIS-112 for COSINE-200