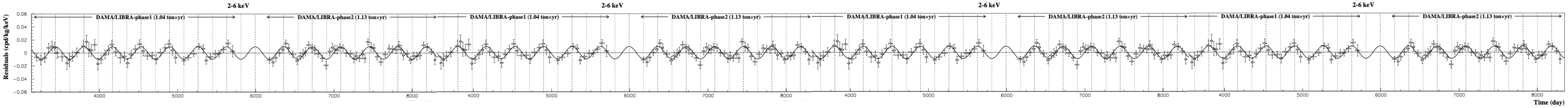
Searching for Dark Matter with COSINE-100

Sophia Hollick | Saturnalia

18 December 2023



Yale

CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

Wright Laboratory

Dark Matter: History

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

1884

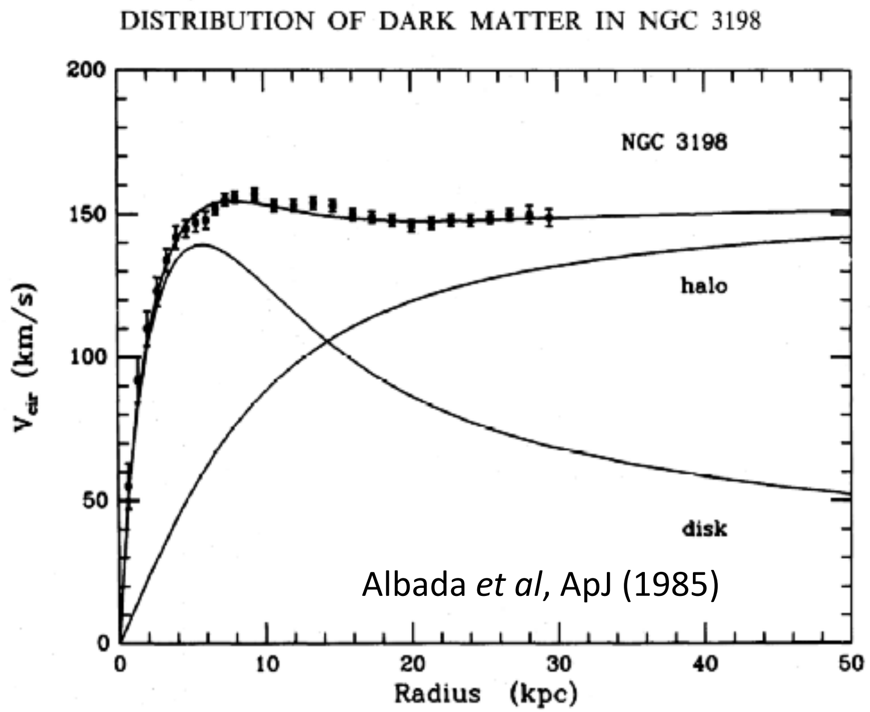
1933

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

1960s & 1970s

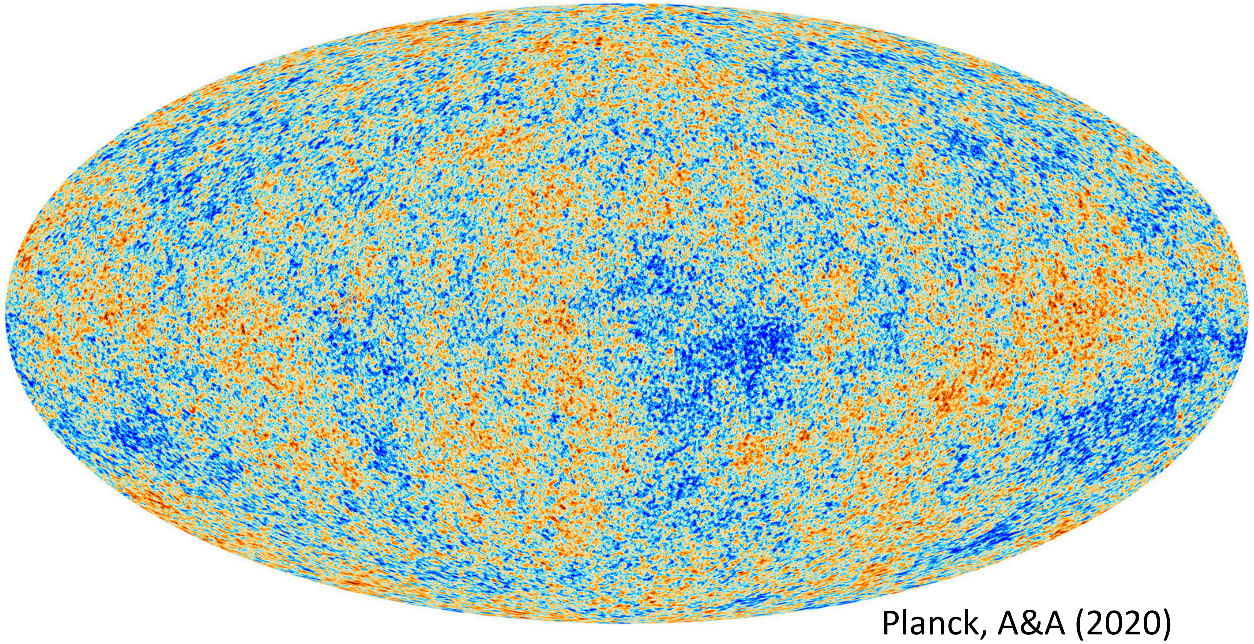
Rubin and Ford observe galactic rotation curves indicating existence of dark matter

Coma Cluster
(image credits: earthsky.org)



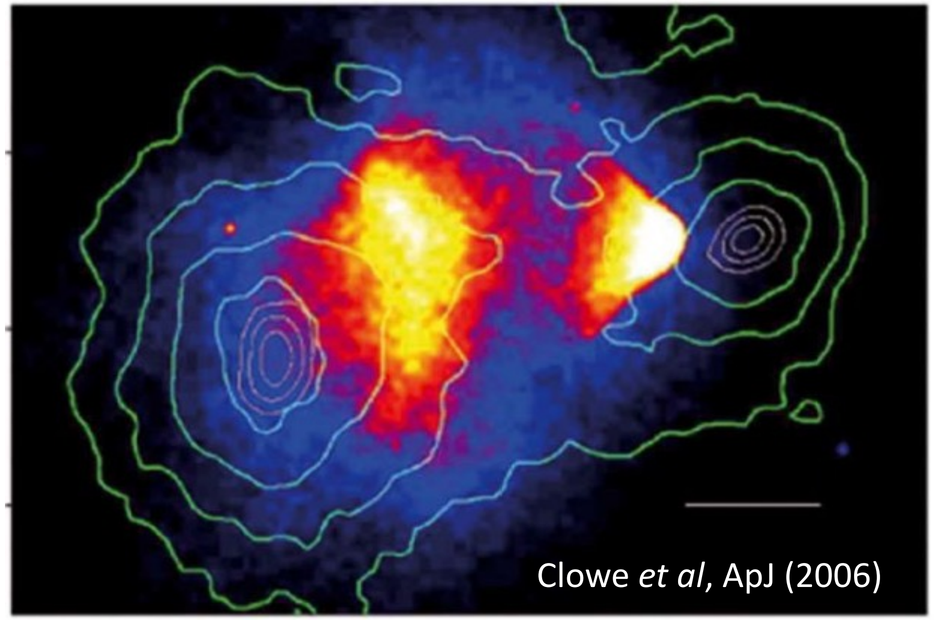
Albada *et al*, ApJ (1985)

Dark Matter: Cosmological Evidence



Planck, A&A (2020)

CMB Observations



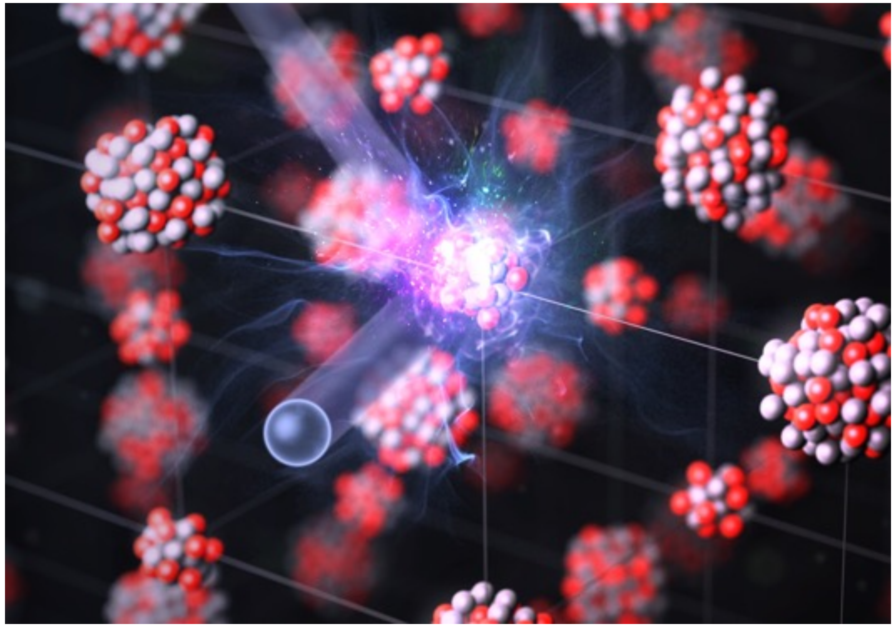
Clowe *et al*, ApJ (2006)

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
- The WIMP-nucleon cross section is tiny, so the event rate is low
- Low event rate requires us to maintain low background levels
  - Use ultra-pure crystal scintillating detectors
  - Locate experiment underground



DM-nucleus scattering

Annual Modulation Signature

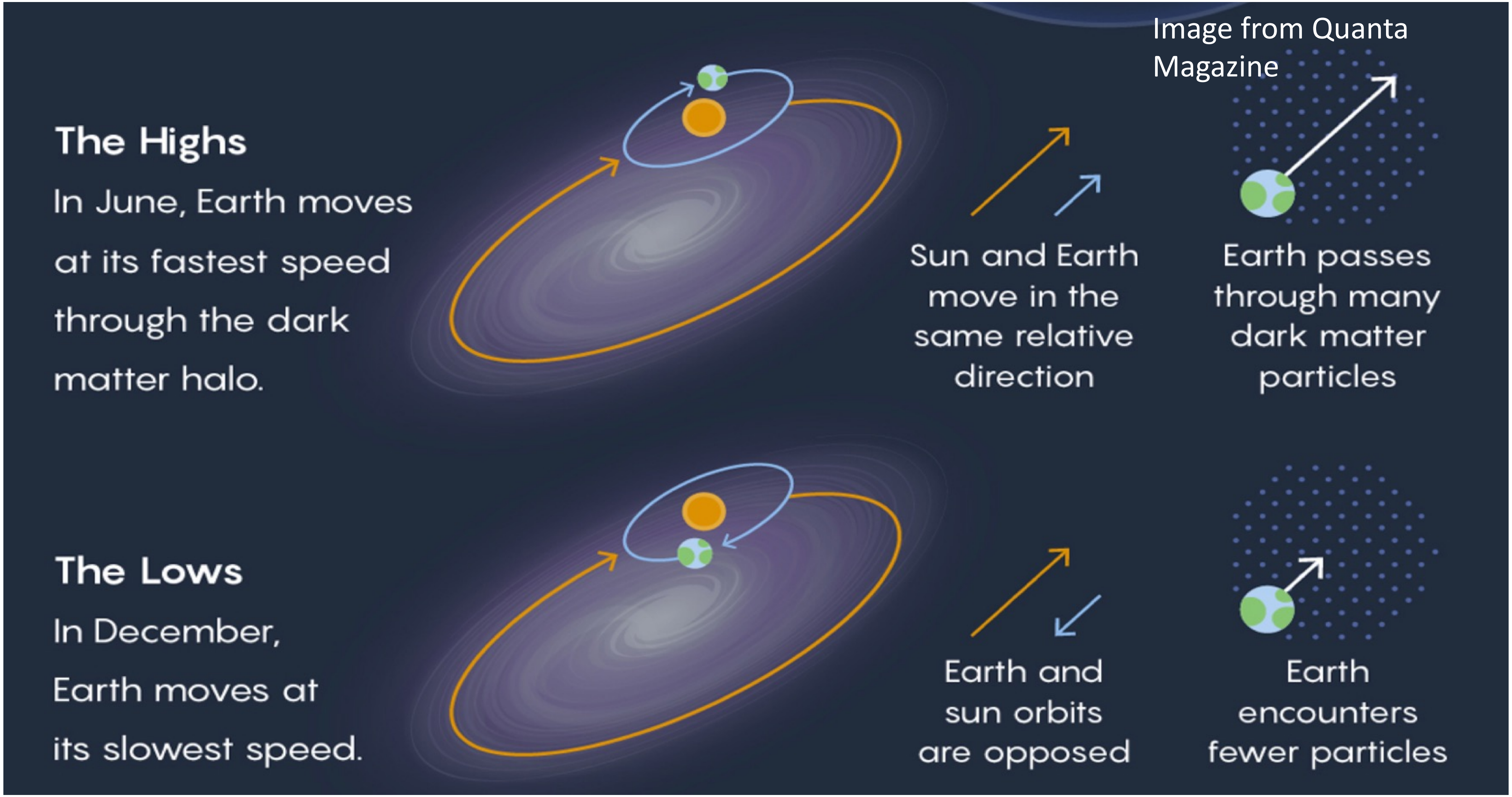
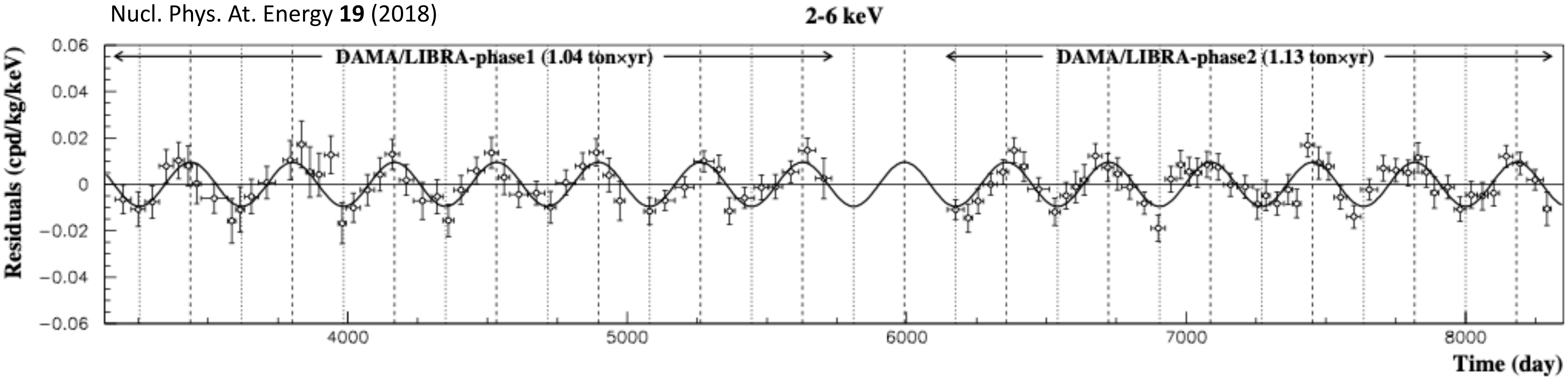


Image from Quanta Magazine

DAMA/LIBRA and NaI(Tl)

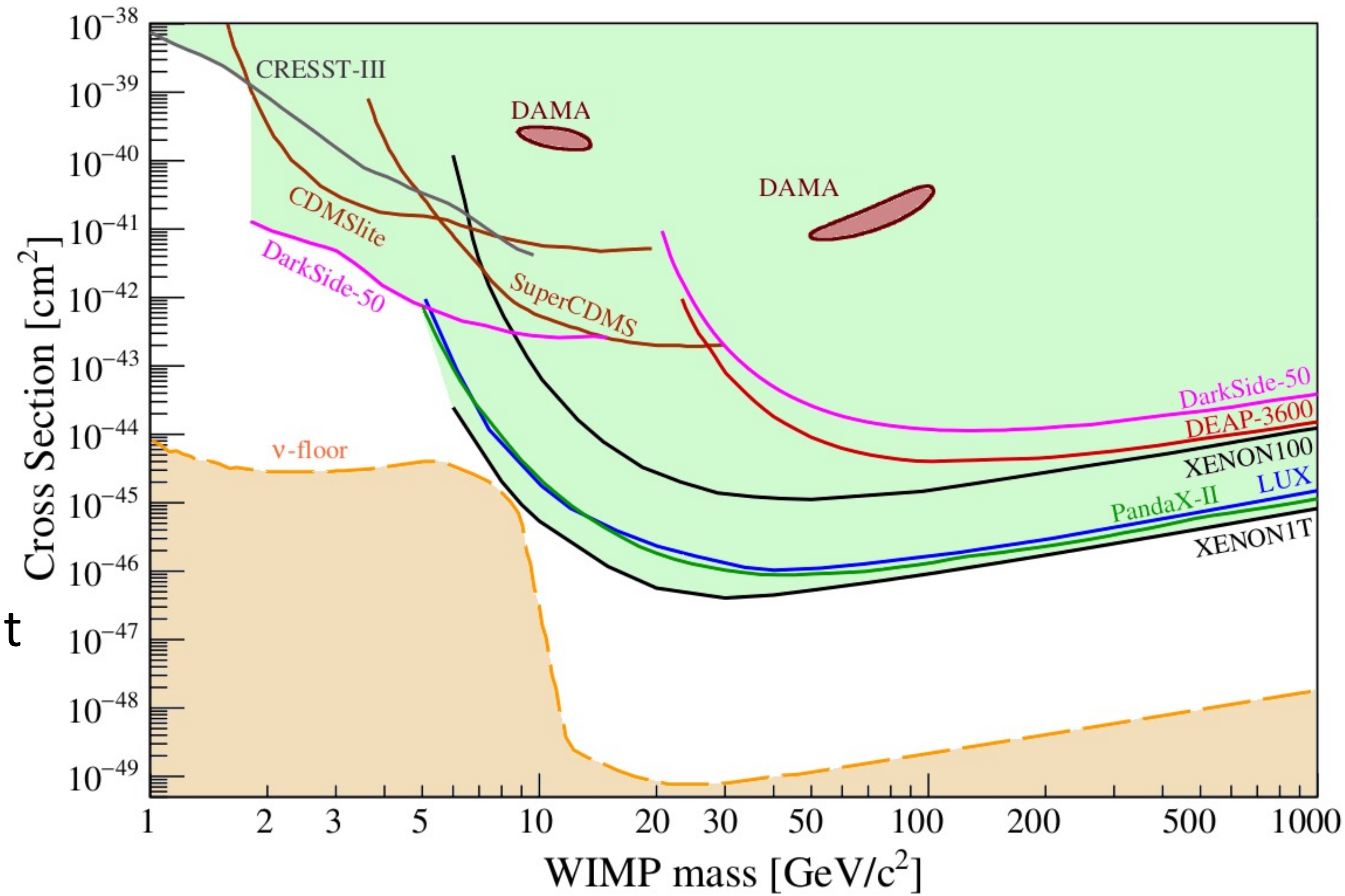
DAMA/LIBRA Collaboration
Nucl. Phys. At. Energy **19** (2018)



- DAMA/LIBRA: 250 kg of NaI(Tl) operating 2003-now 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

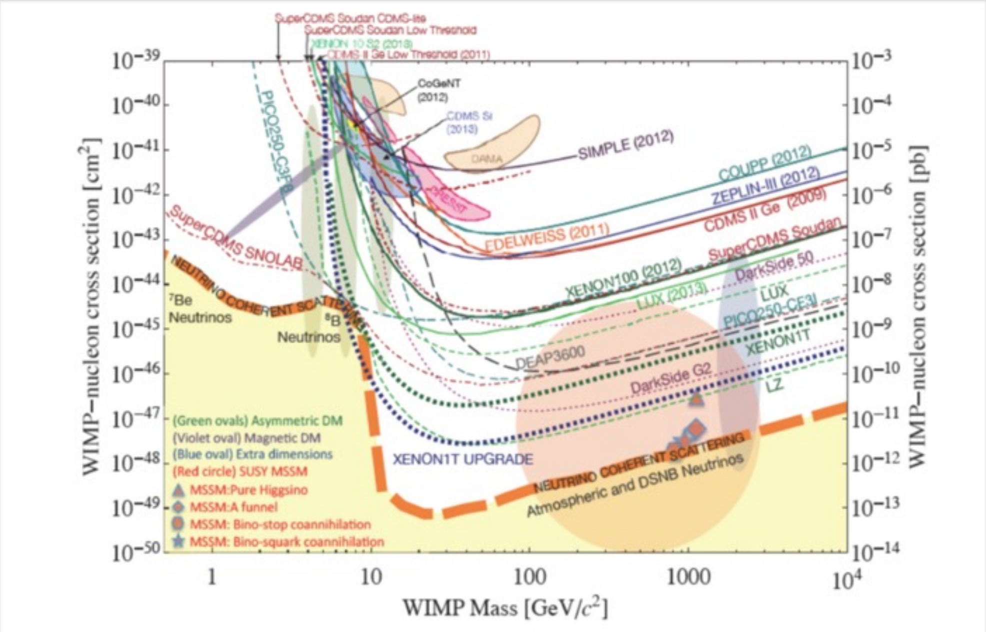
- Much of the WIMP phase space has been explored and excluded
- DAMA appears in the excluded region for many experiments
- Note: No other experiment in this plot uses NaI(Tl) target material



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

Response from DAMA

Is it an "universal" and "correct" way to approach the problem of DM and comparisons?



No, it isn't. This is just a largely arbitrary/partial/incorrect exercise

About interpretation and comparisons

See e.g.: Riv.N.Cim.26 ono.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, JMPA28(2013)1330022

...models...

- Which particle?
- Which interaction coupling?
- Which EFT operators contribute?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- ...

...and experimental aspects...

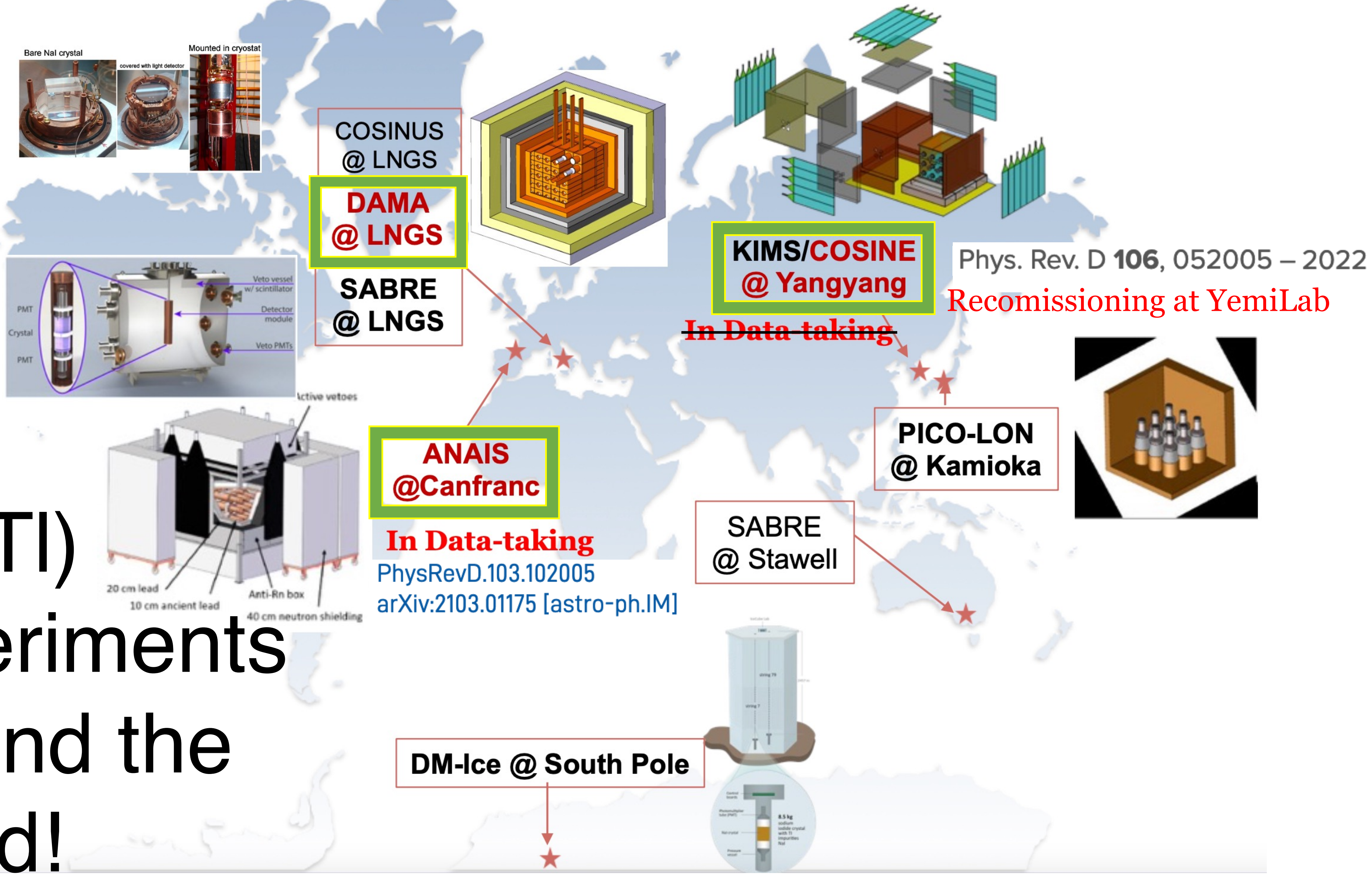
- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- Efficiencies
- Definition of fiducial volume and non-uniformity
- Quenching factors, channeling
- ...

Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions and parameters' values are intrinsically strongly uncertain.

No experiment can – at least in principle – be directly compared in a model independent way with DAMA so far

Need to directly test DAMA's result using the same target material

NaI(Tl) Experiments Around the World!

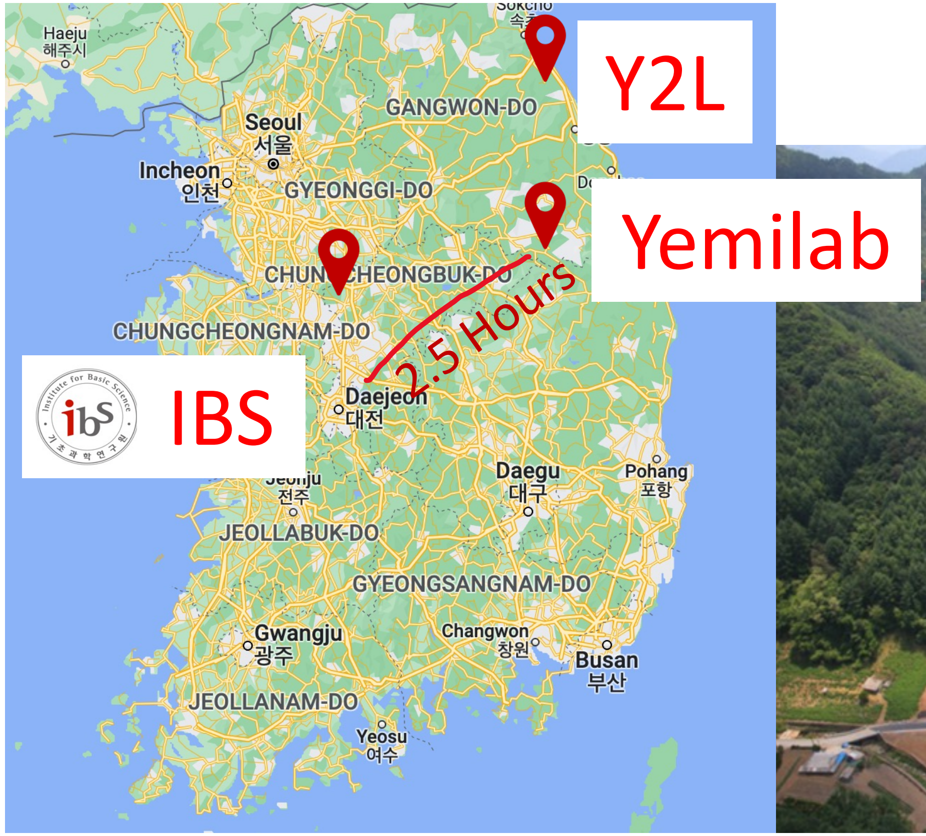


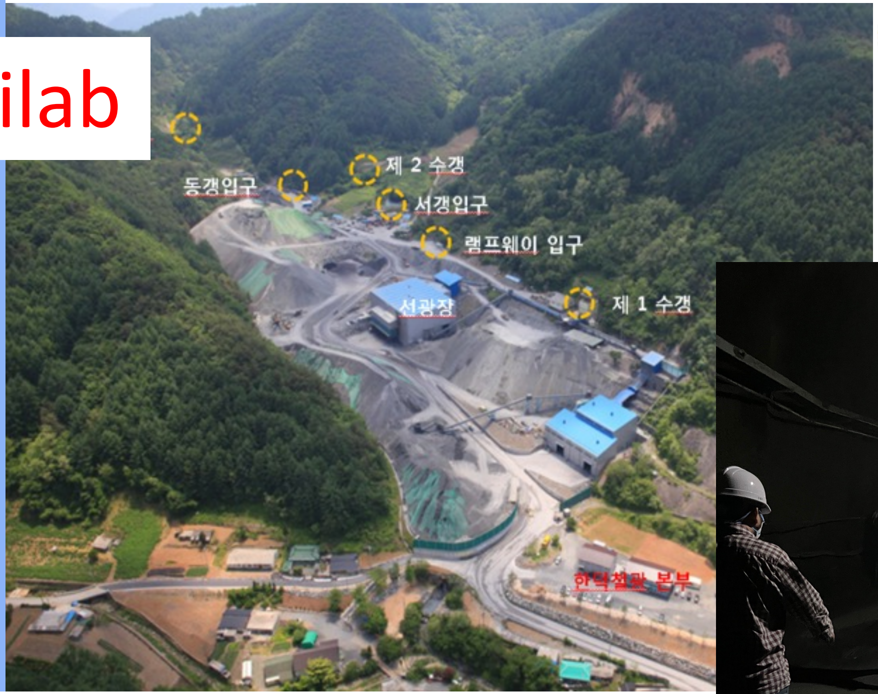
- COSINE-100 is located in Y2L Underground Lab 700m under Yangyang, South Korea
- 106 kg of NaI(Tl) across 8 detectors
- Data taking began Sept. 2016

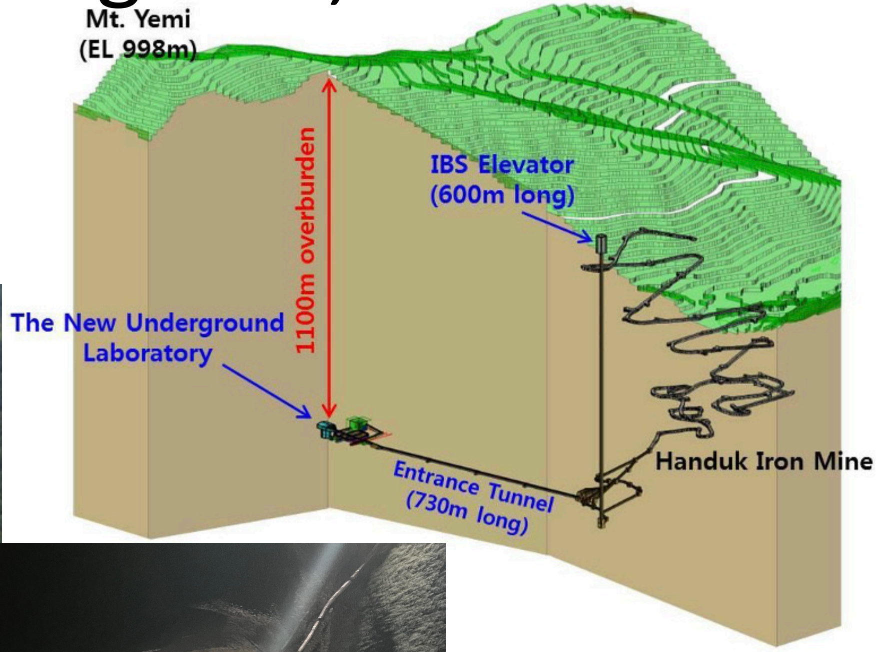
14 institutes
~50 members

KIMS + DM-ICE =

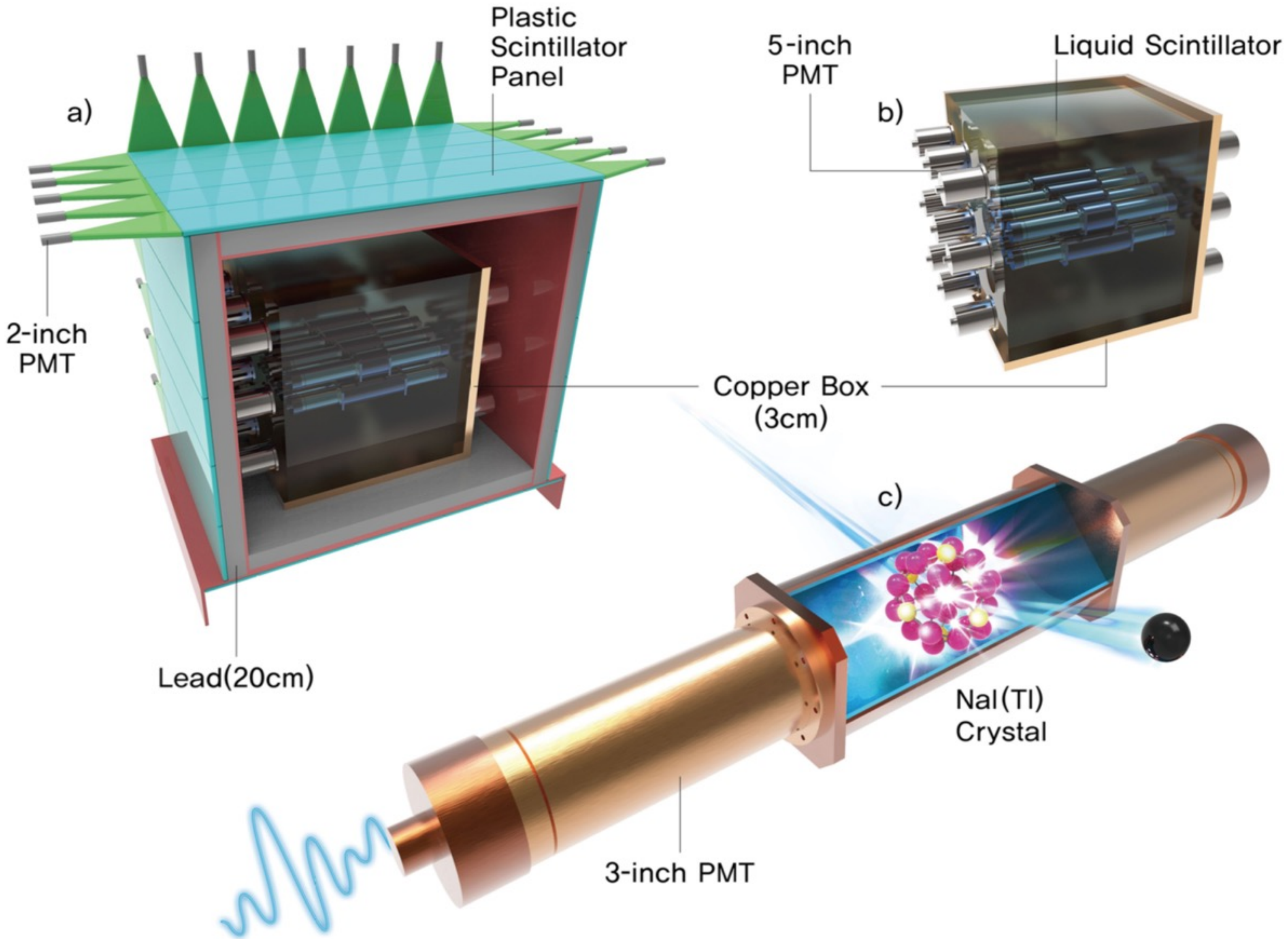
Y2L, Yangyang, South Korea → Yemilab, Jeongseon, South Korea







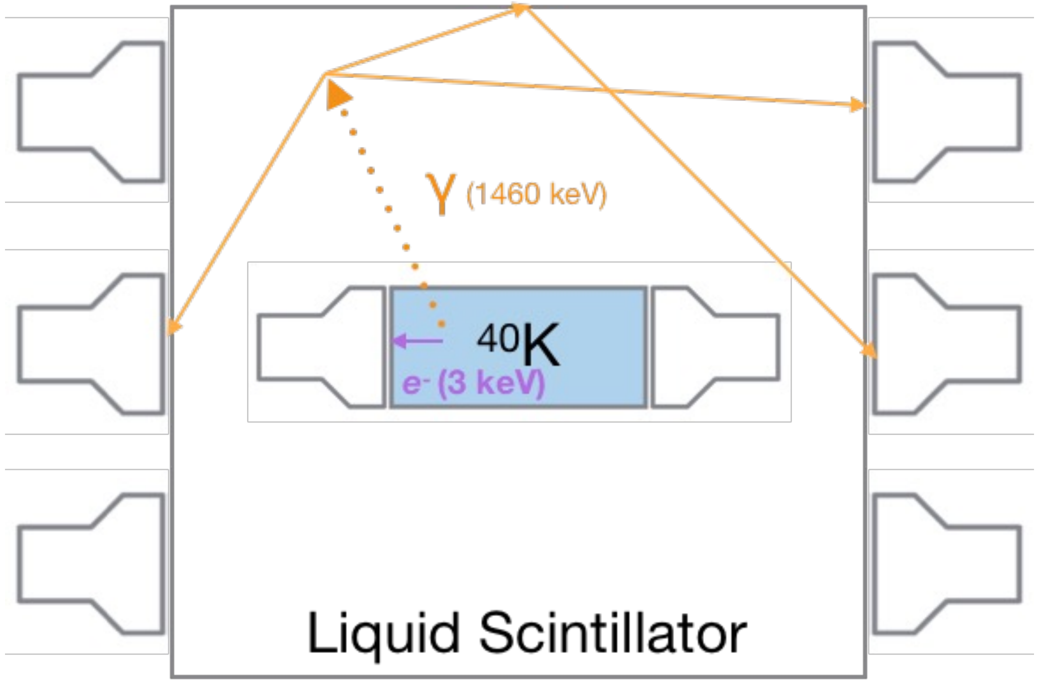
COSINE-100 Detector

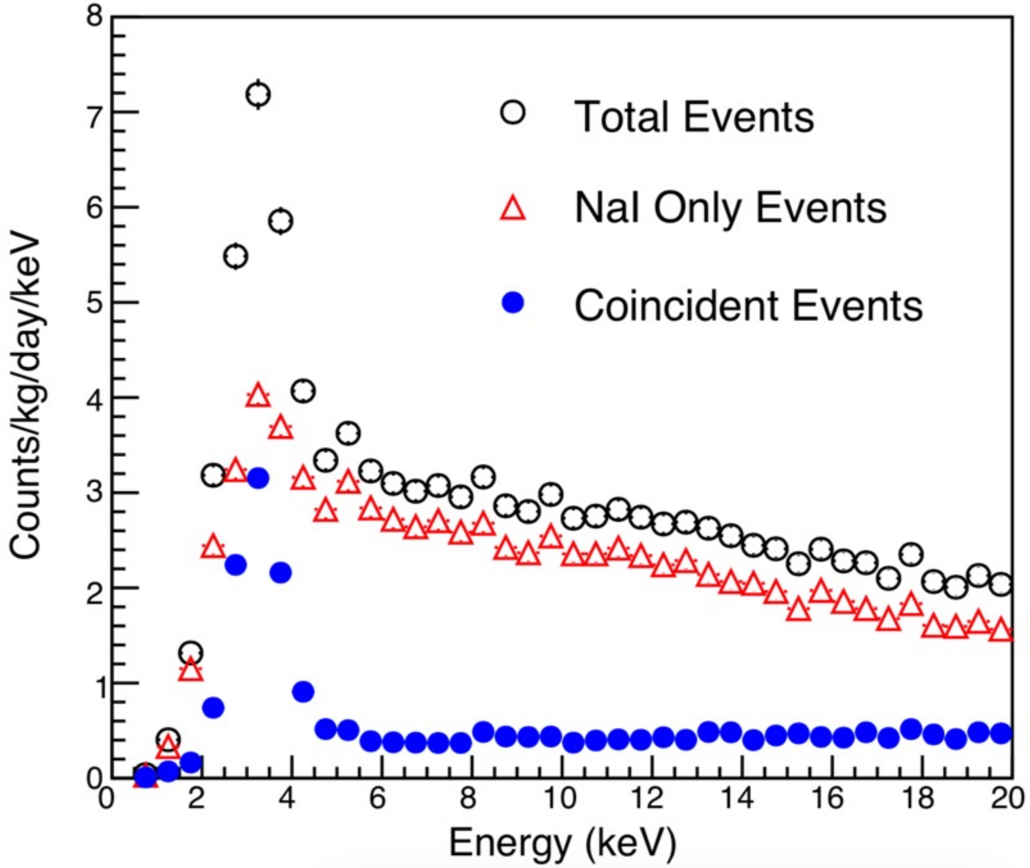


- 8 low-background NaI(Tl) detectors
- 2200 L liquid scintillator veto
- 3 cm-thick copper box and 20 cm-thick lead shielding
- 37 plastic scintillator panels for 4π muon detection

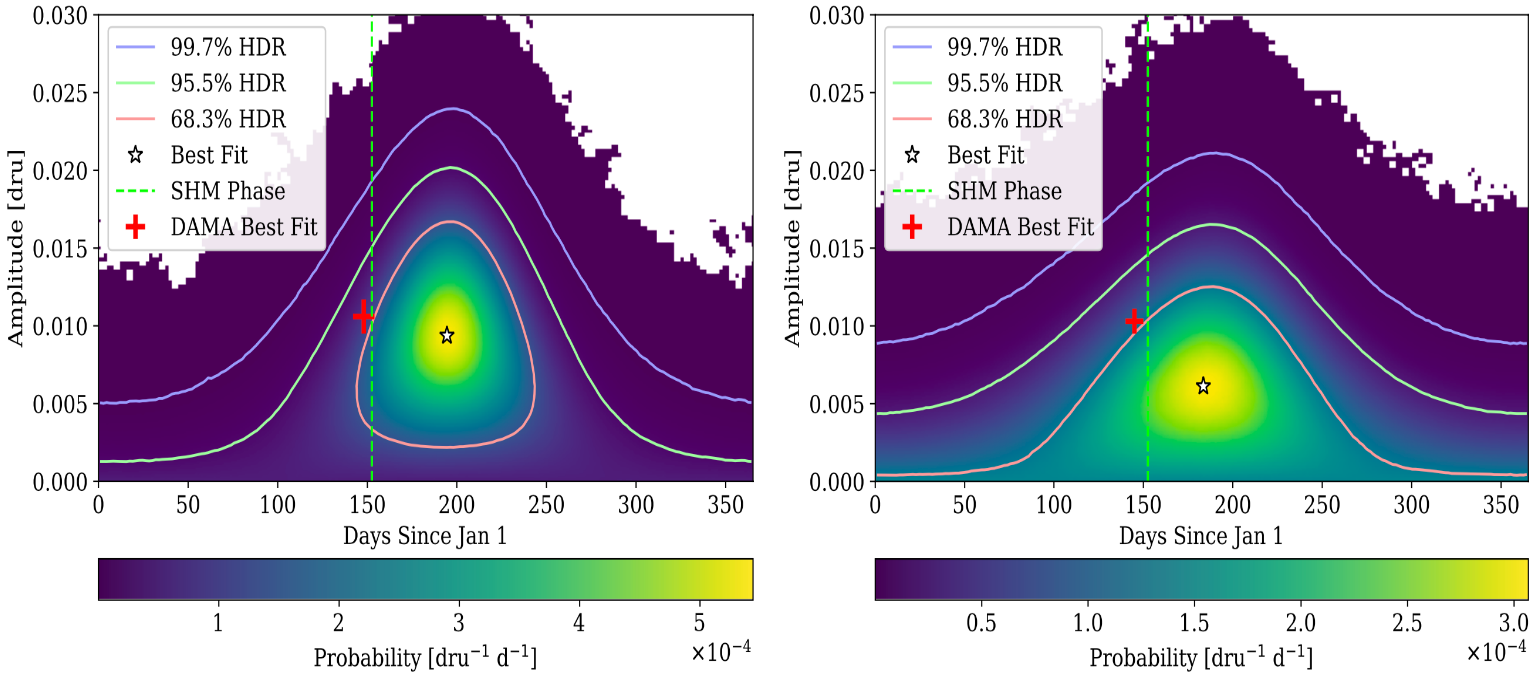
Liquid Scintillator Veto

- 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

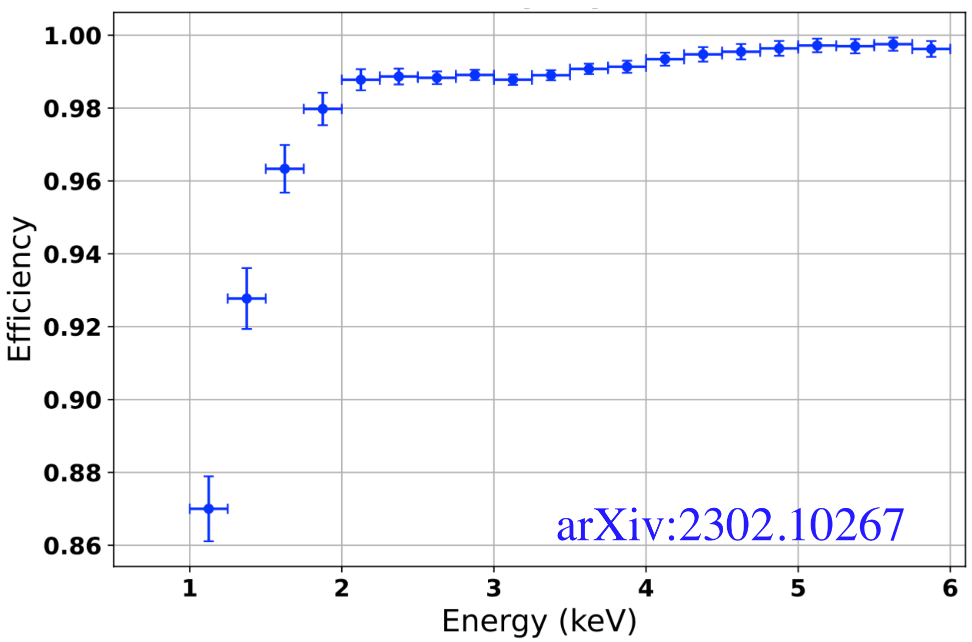




3-year Annual Modulation Results



COSINE-100 Collaboration
arXiv:2111.08863

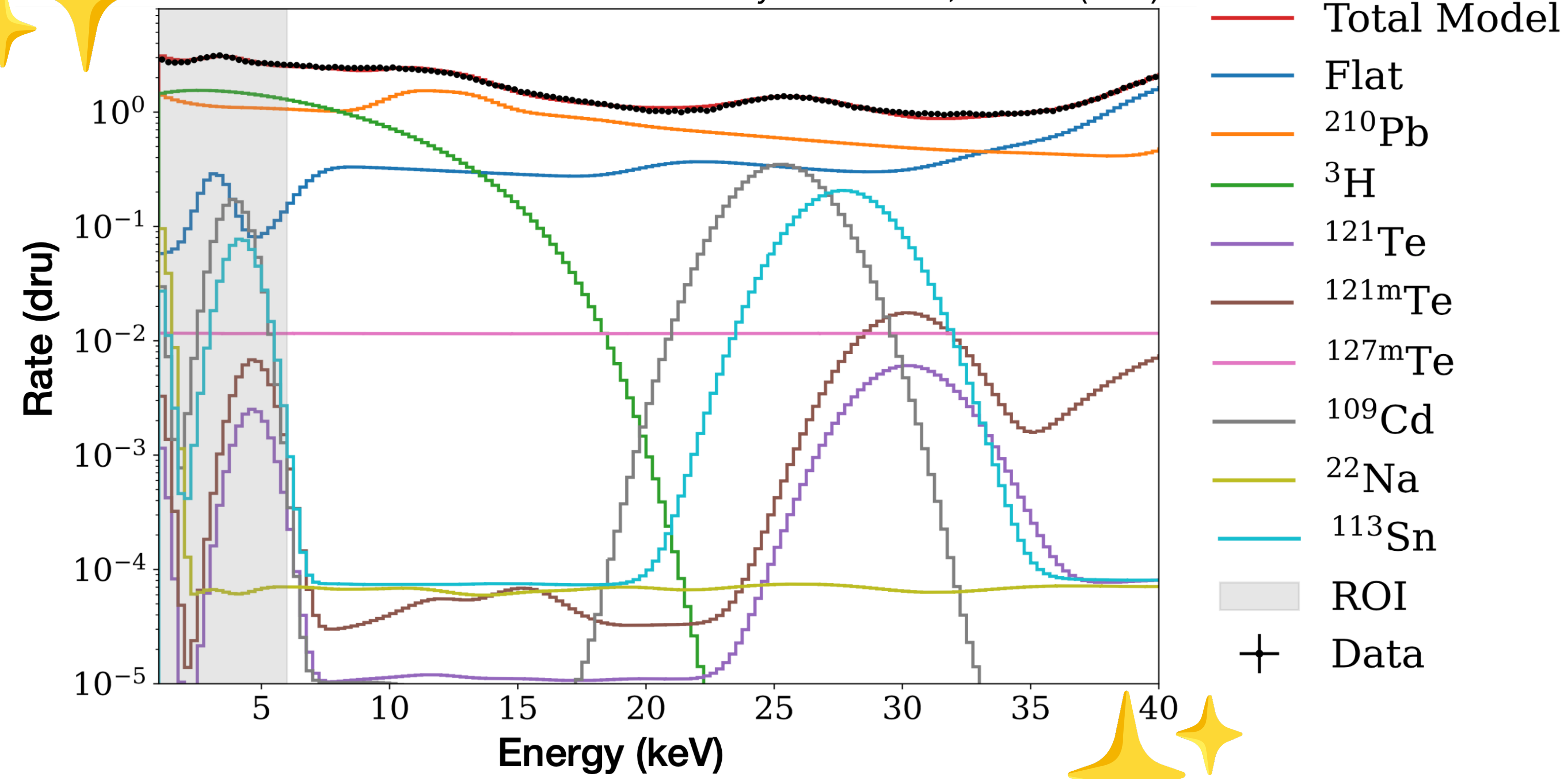


- COSINE-100 both agrees with DAMA's results and no modulation
  - Lower background levels are needed to improve sensitivity/statistics

What is limiting the COSINE Experiment?

Backgrounds

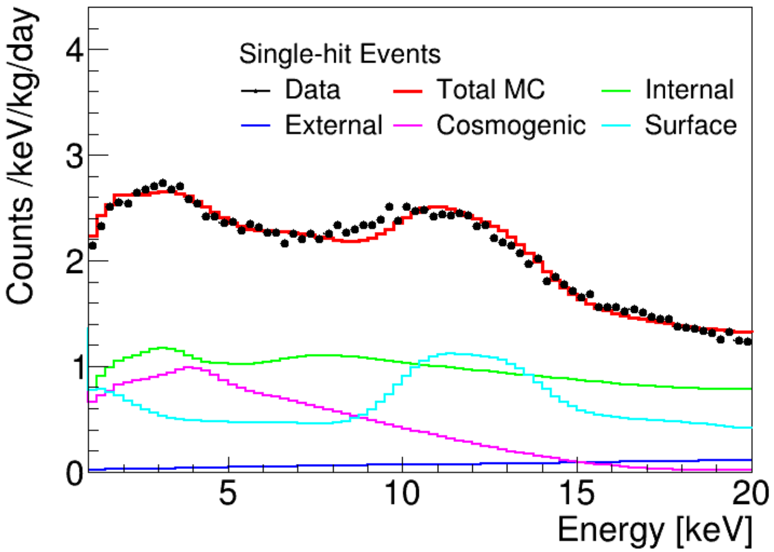
Phys. Rev. D **106**, 052005. (2022).



NaI(Tl) Background Components

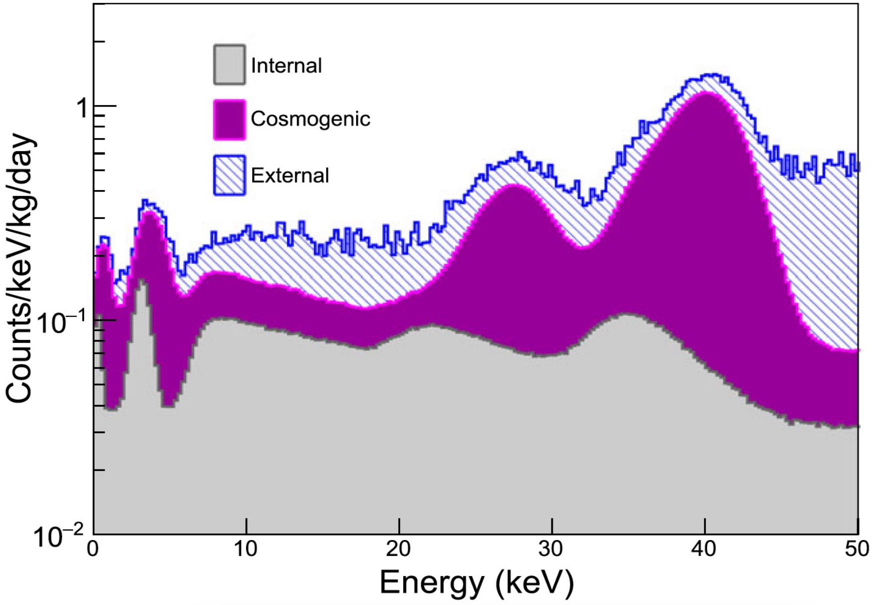
Cosmic rays activate isotopes in NaI

COSINE-100



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

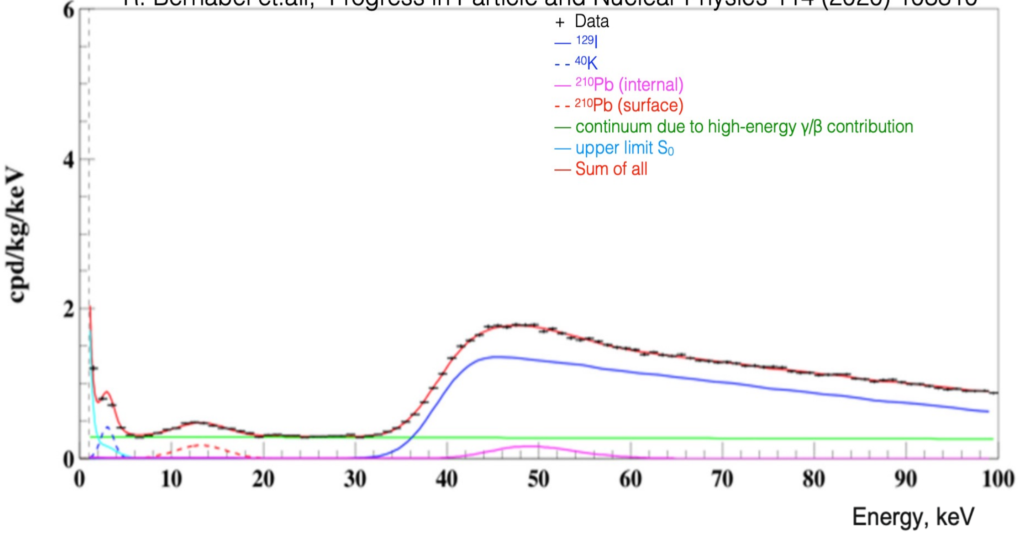
Prototype COSINE-200 Detector

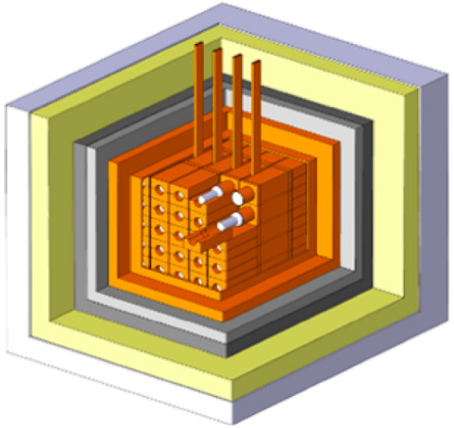


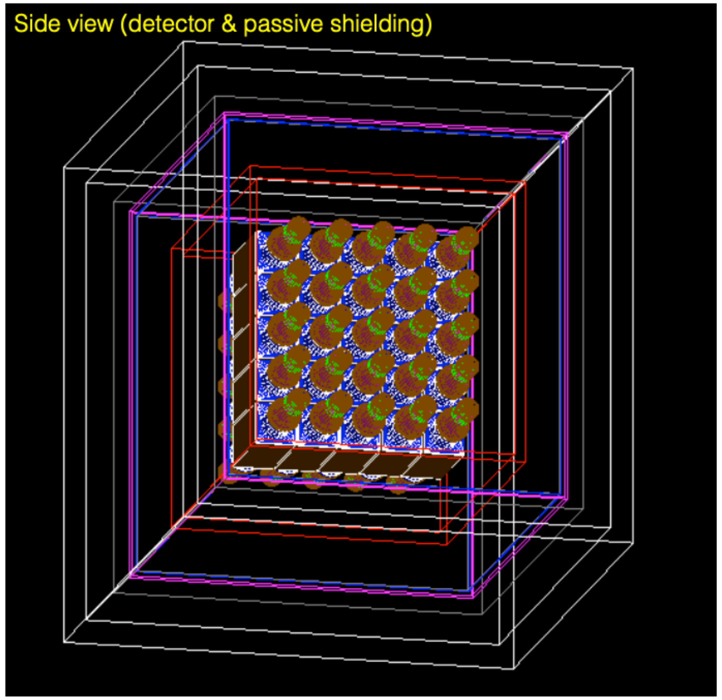
- ^{40}K and ^{210}Pb internal isotopes dominate the background, new detectors minimize these
- Cosmic rays activate ^{3}H, ^{22}Na, and others in detectors over time
- NaI(Tl) experiments share these backgrounds, but at different purity levels

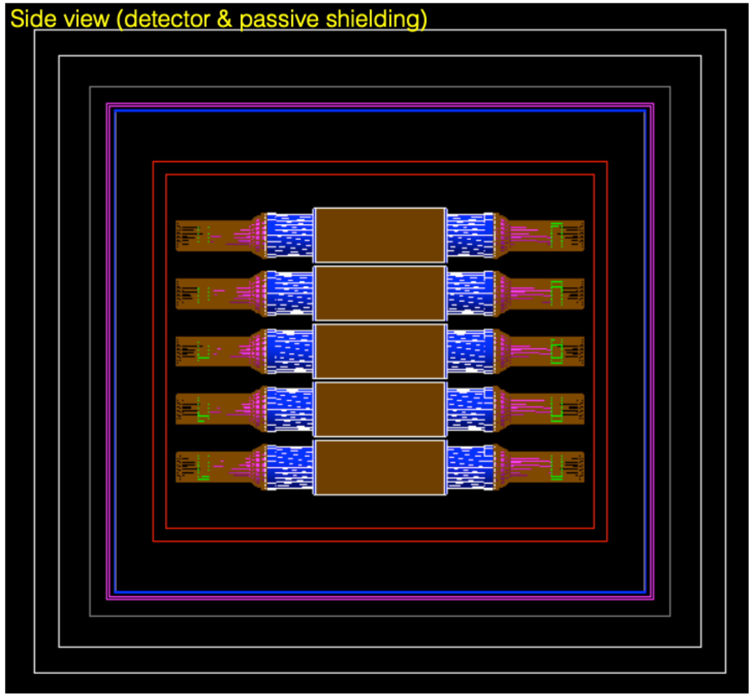
DAMA/LIBRA Geometry in GEANT4

R. Bernabei et.all, Progress în Particle and Nuclear Physics 114 (2020) 103810



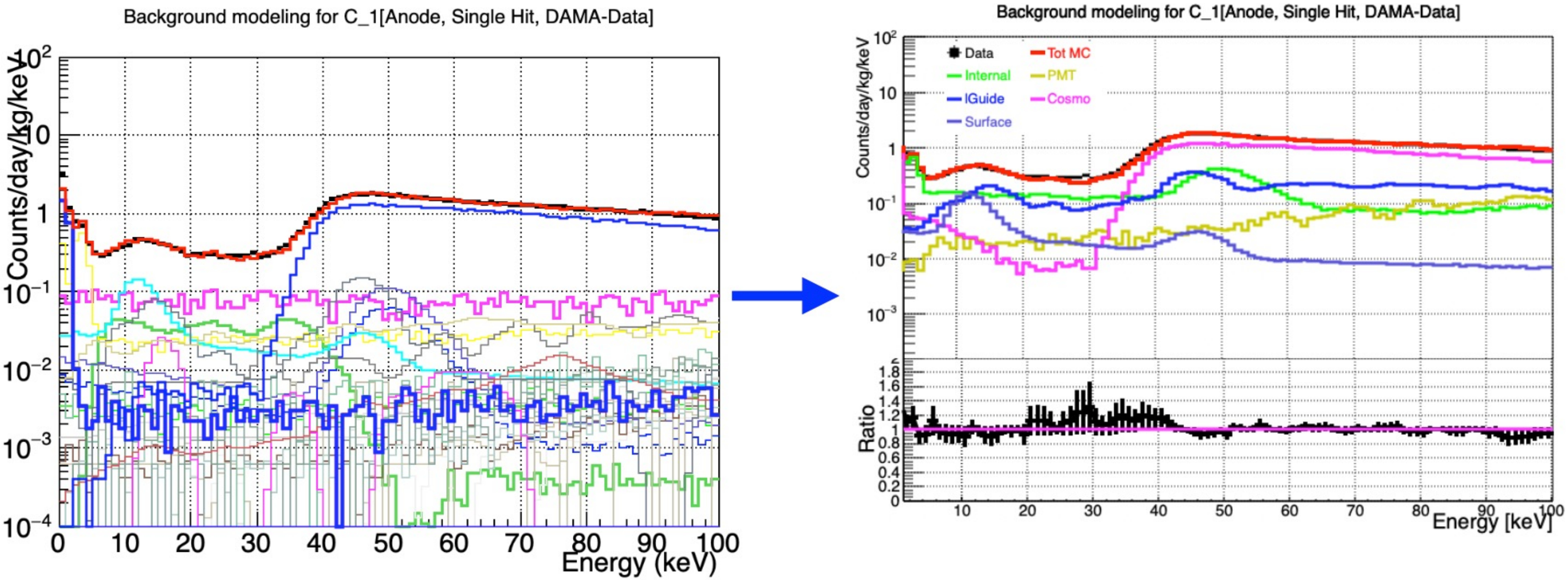






DAMA publishes details about their detector geometries which we can use to construct a GEANT4 simluation.

Simulate Isotopes and Fit to DAMA/LIBRA Data



- Detailed background budget points to possible Th232 excesses
- Good agreement between fit and data suggests no room in DAMA/LIBRA for a WIMP signal
  - <2 keV not provided by DAMA

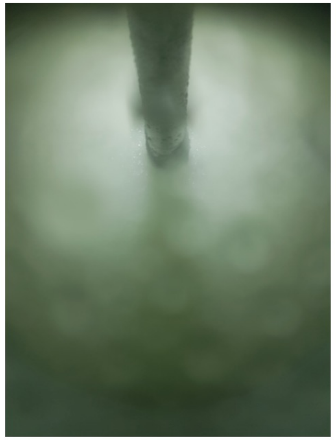
Background dominated by:
U238
Th232
Pb210
K40
Na22

How can we improve our statistics from background budgeting?

Use Purer Crystals – Grow New Crystals

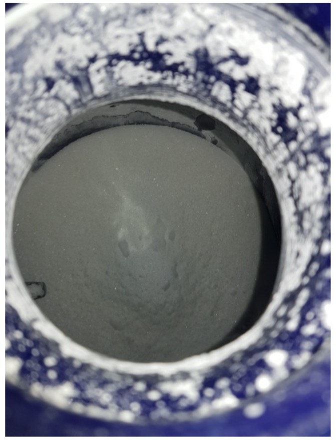
Purify Powder

Boiling of solution



Recrystallized crystals and mother solution

Filtration and washing the crystals



Dry the crystals in the conical dryer

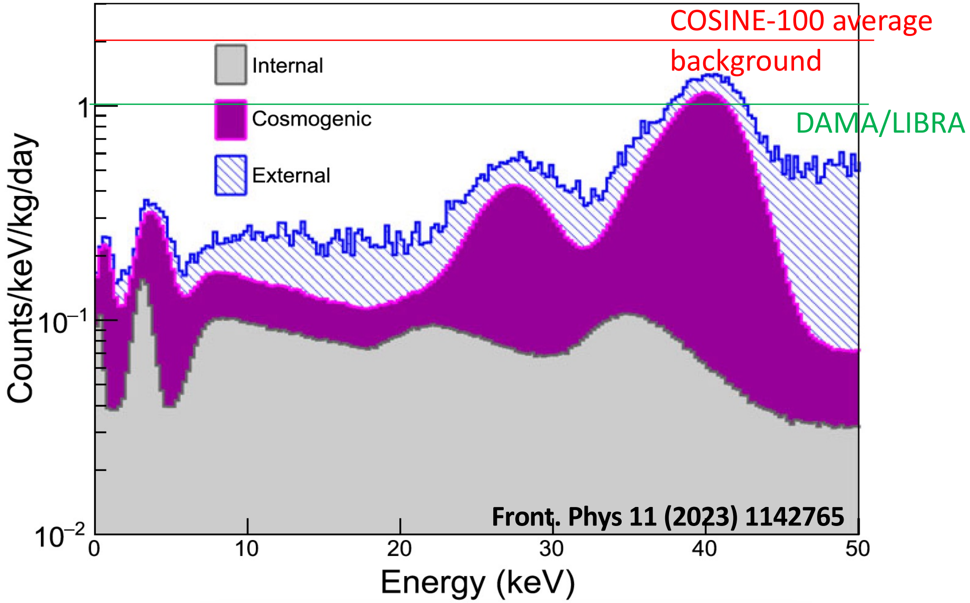
	K (ppb)	Pb (ppb)
Initial NaI	248	19.0
Purified NaI	<16	0.4

K.A. Shin et al., Front. Phys. 11, 1142849 (2023)

Grow Crystal

Construct Detector

Prototype COSINE-200 Detector



- Prototypes for COSINE-200 show promising backgrounds below 1 dru (daily rate unit)

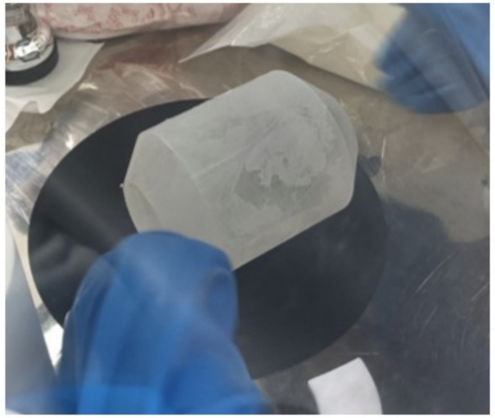
Use Purer Crystals – Refurbish Old Crystals

Remove the copper case

Crystal machine

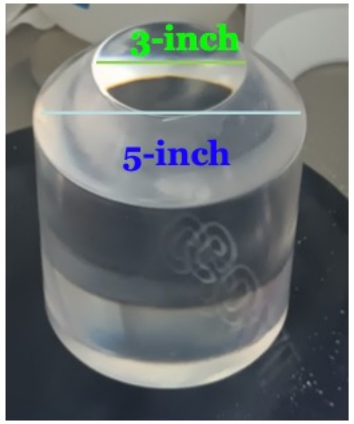
Mass : 8.26 kg → 7.34 kg

Deliver to glove box



COSINE crystal-1

Polishing



Updated Detector Encapsulation

COSINE-100

14.9 +/- 0.5 NPE/keV →

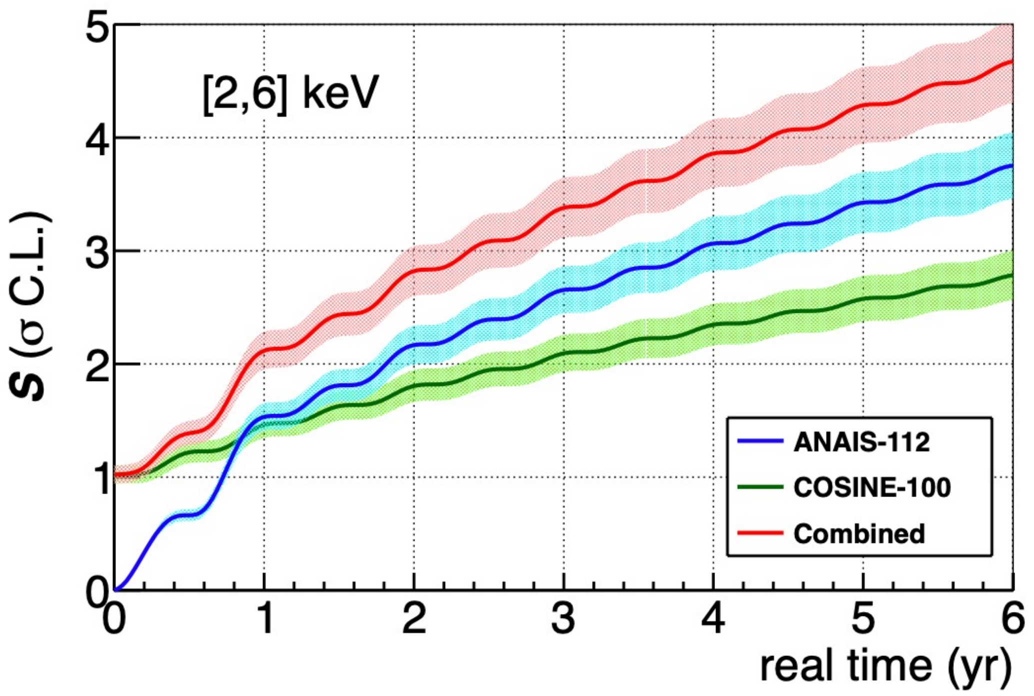
COSINE-100U

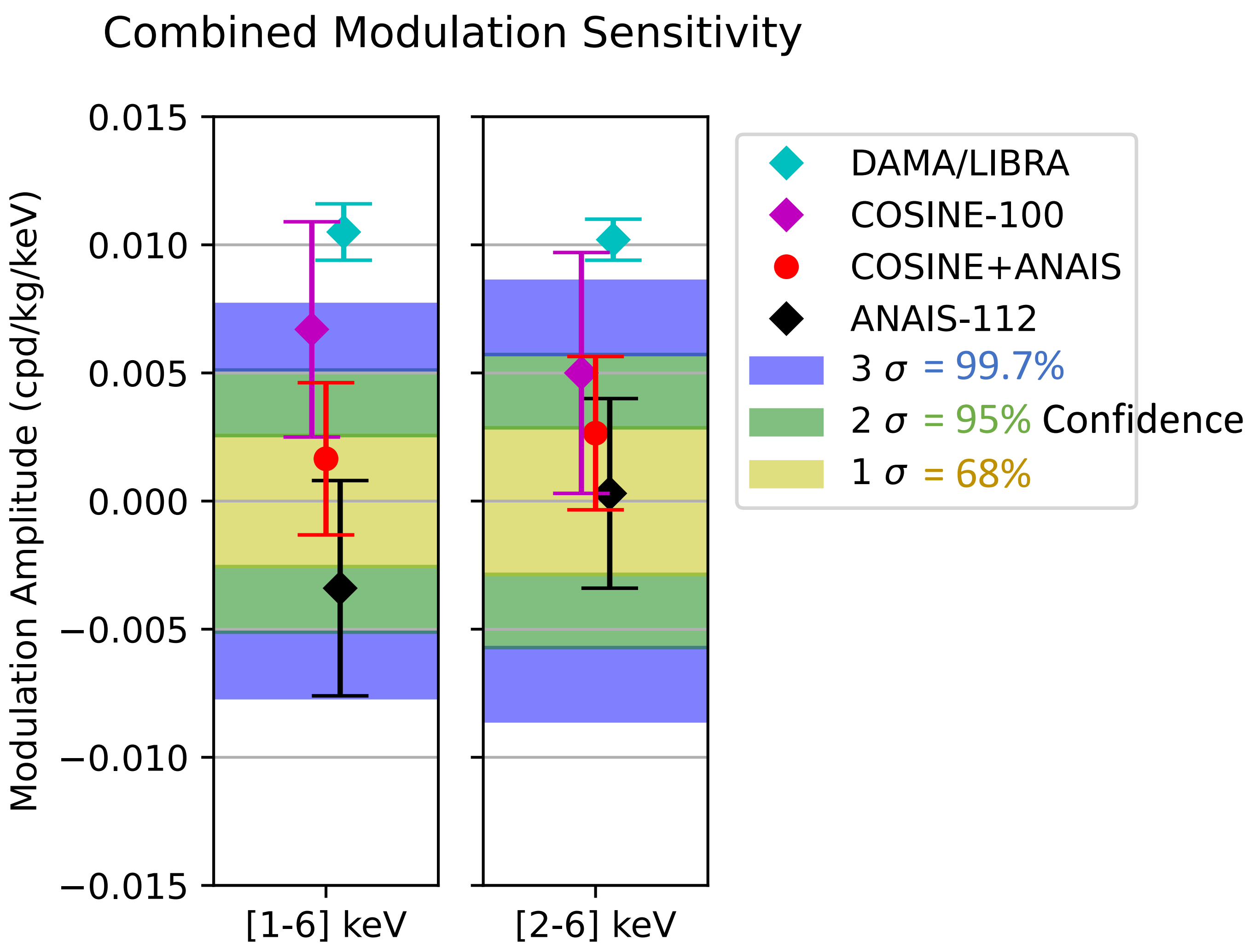
21.6 +/- 0.6 NPE/keV

- Current refurbishment has seen ~45% increase in light yield

Combine 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





Can a Poor Analysis Result in False Positives?

Time (In)dependent Background Subtraction Methods

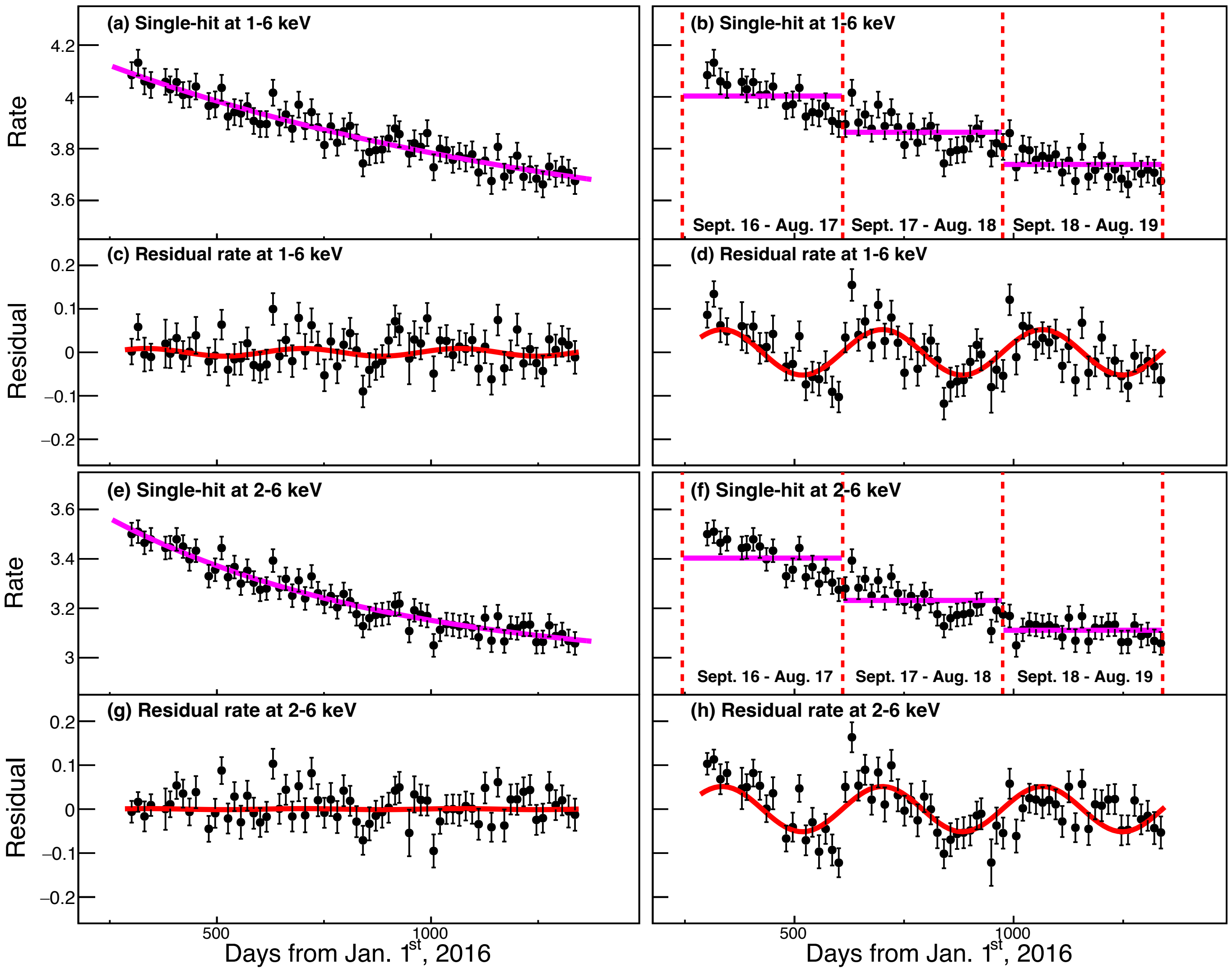
DAMA Claims only this background! (Time independent)

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

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

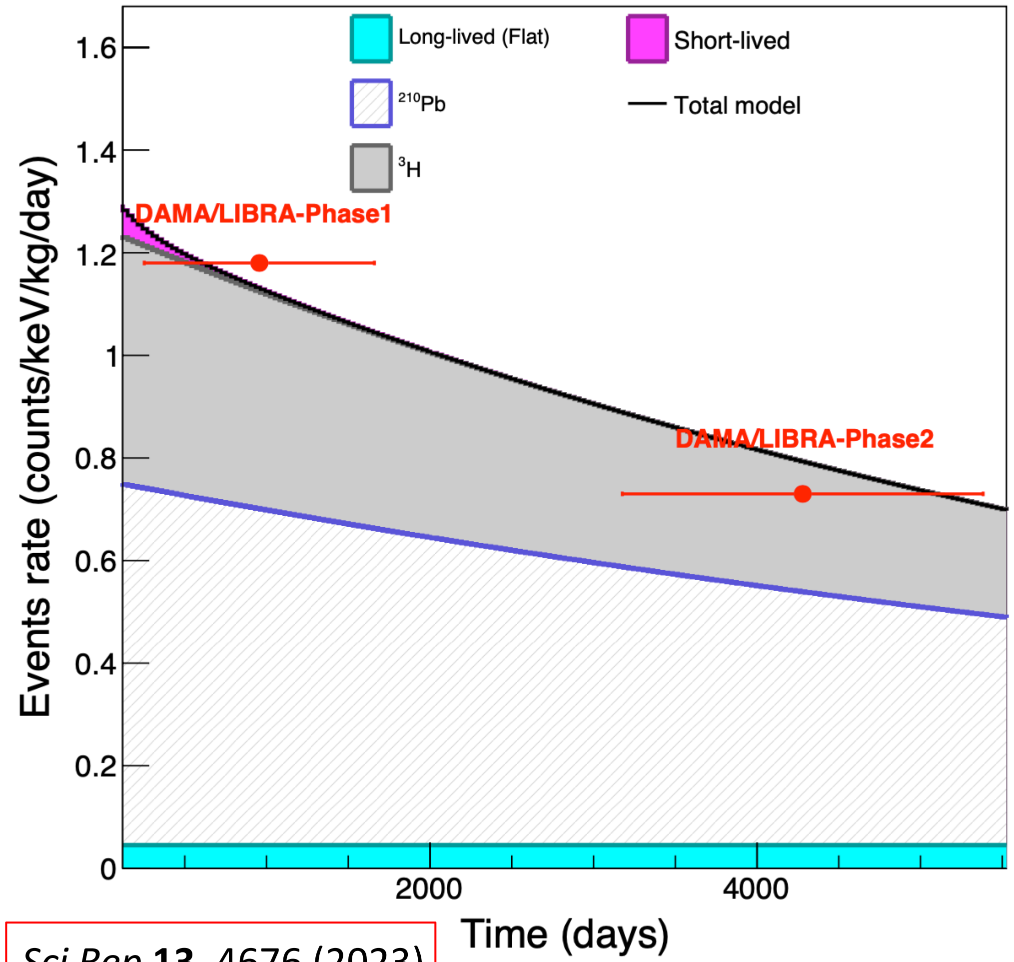
+ model and subtract

only, average and subtract

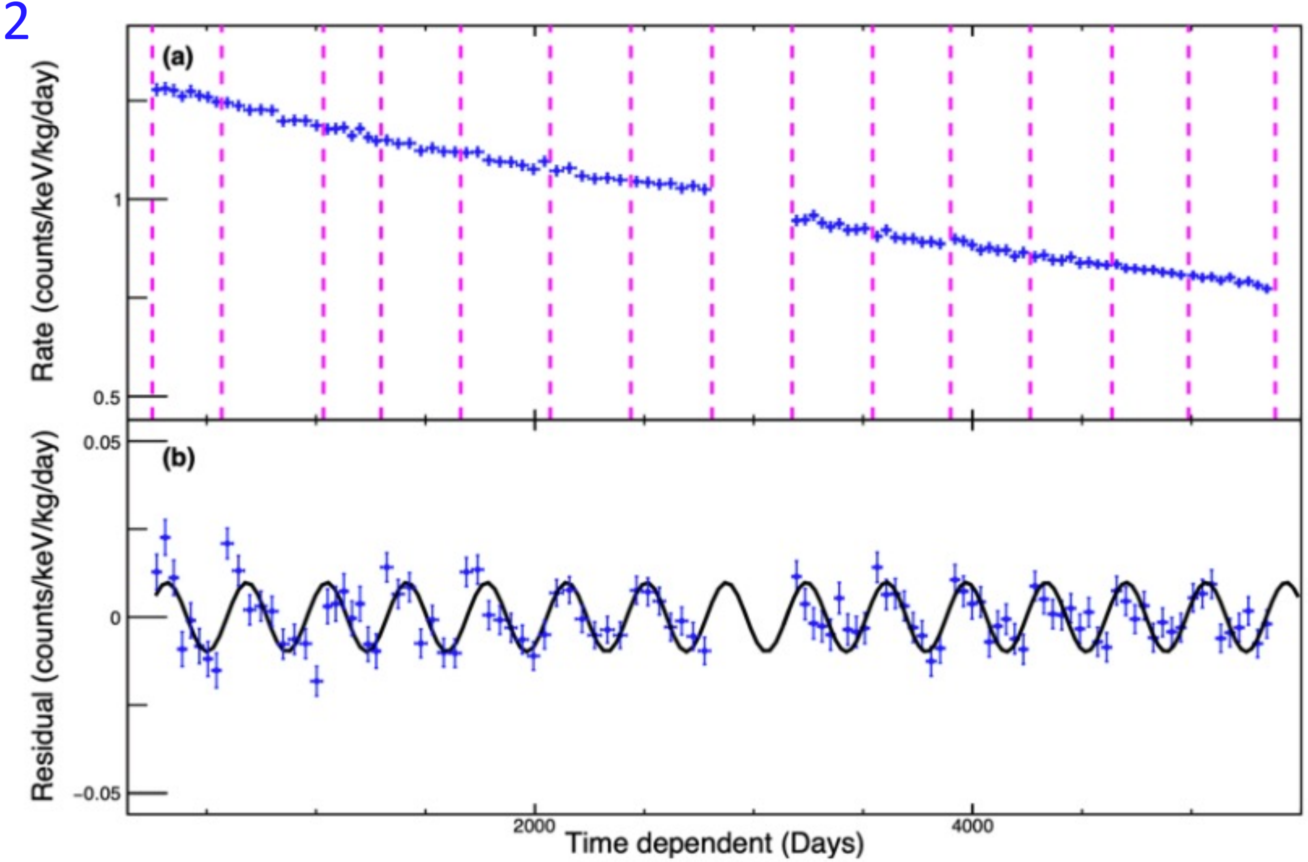


Simulated DAMA Data from COSINE-like Backgrounds

Background Rate difference for DAMA phase1&2 agree with simulated background decay rate



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



The declared annual cycles are in the table and shown by pink

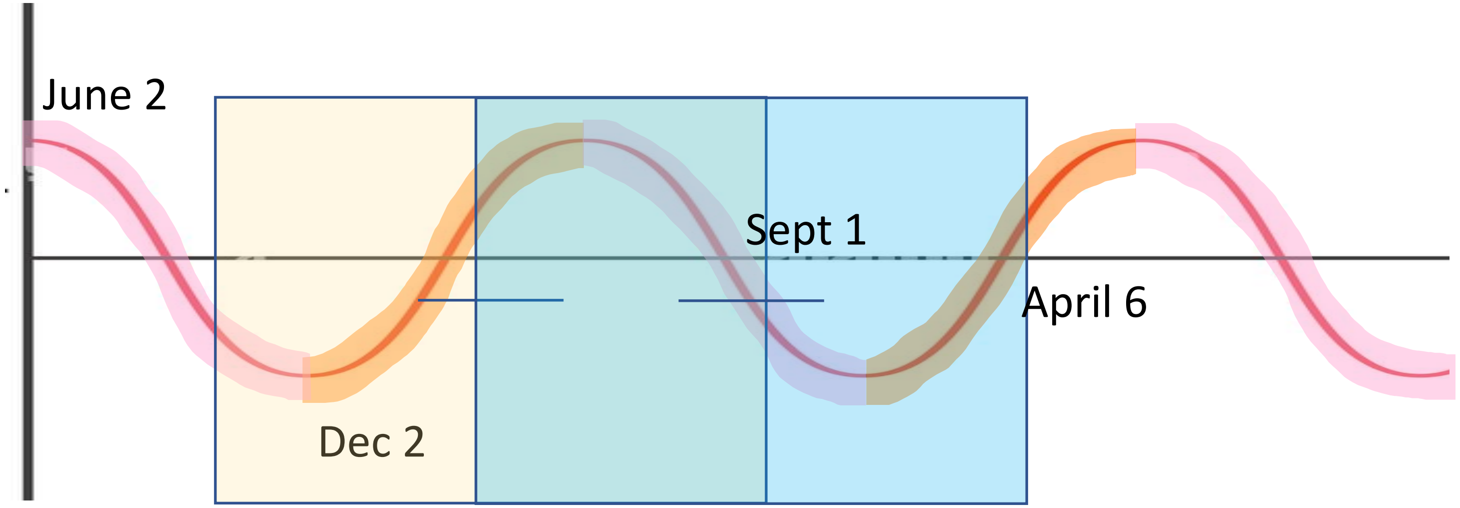
Annual modulation is fitted after average background subtraction. This modulation has opposite phase!

Shifting Declared Annual Cycles

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

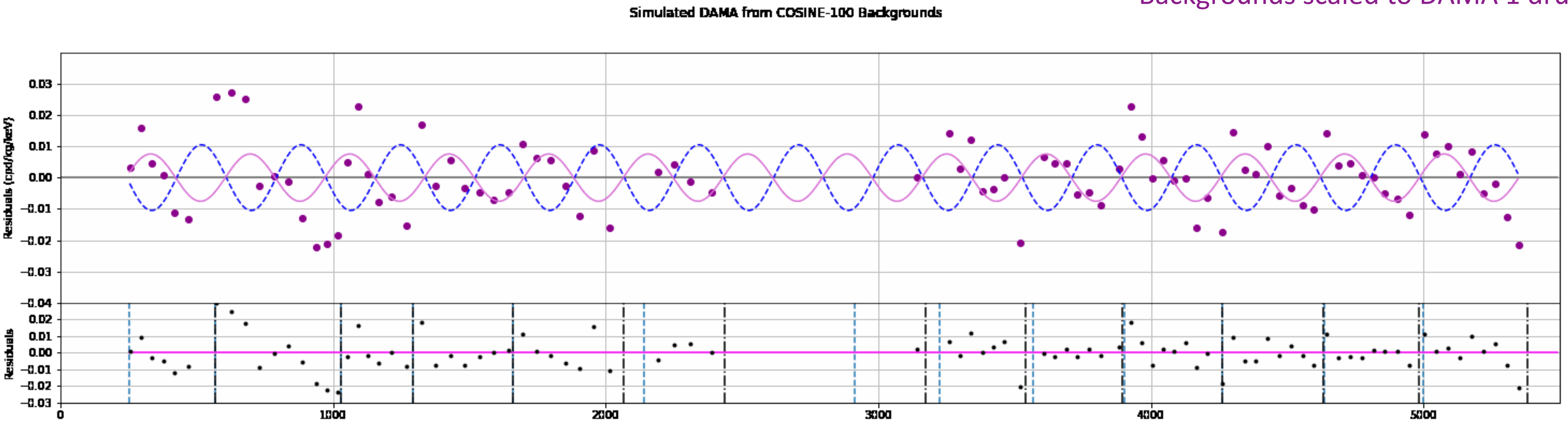
+ 183 days (π) =

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
11	March 3, 2015 - March 10, 2016	71,180
12	March 11, 2016 - Feb. 23, 2017	67,527
13	March 9, 2017 - March 27, 2018	75,135



Shifting Phase with Shifting Annual Cycles

Backgrounds scaled to DAMA 1 dru

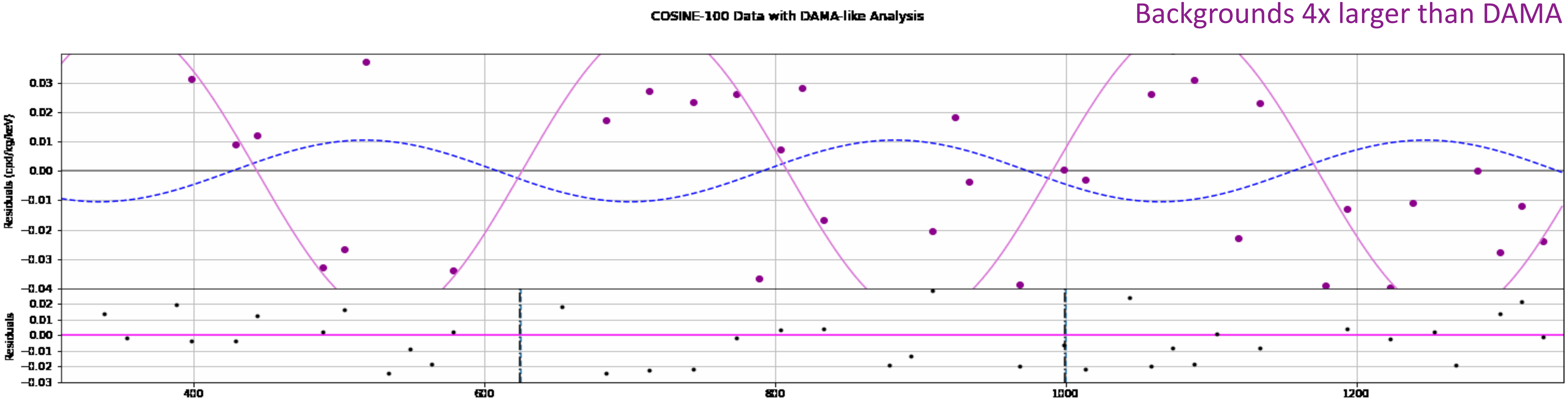


- Modulation phase clearly dependent on declared annual cycles
  - Vertical lines show the outline for declared cycles
  - The modulation peaks shift when the cycle declarations shift
  - Amplitude roughly consistent

Shifting cycles by 183 (pi) days >> phase shifts by pi

Similar Shifty Behavior Observed on COSINE-100 Data

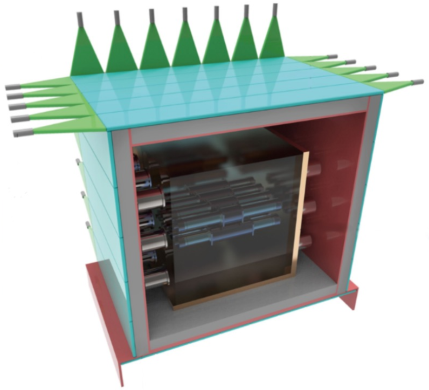
Backgrounds 4x larger than DAMA



- Modulation clearly dependent on declared annual cycles
  - Vertical lines show the outline for declared cycles
  - The modulation peaks shift when the cycle declarations shift
  - Amplitude can fluctuate by factor of 2

Shifting cycles by 150 days >> phase shifts by pi

Concluding Remarks


- COSINE-100 and ANAIS-112 will soon publish 5 yr annual modulation searches
  - Combining the two experiments can lead to competitive sensitivity for challenging DAMA
- COSINE-100U crystal refurbishment currently taking place at Yemilab
- Modulation can be induced by DAMA background subtraction method on backgrounds with time dependency
  - DAMA's phase and amplitude can be matched by adjusting declared annual cycles
- A complete understanding of detector backgrounds is crucial!

****DAMA plz give us your backgrounds****

Thank you for your attention!

Acknowledgements

Center for Underground Physics ibs

Wright Laboratory

CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

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