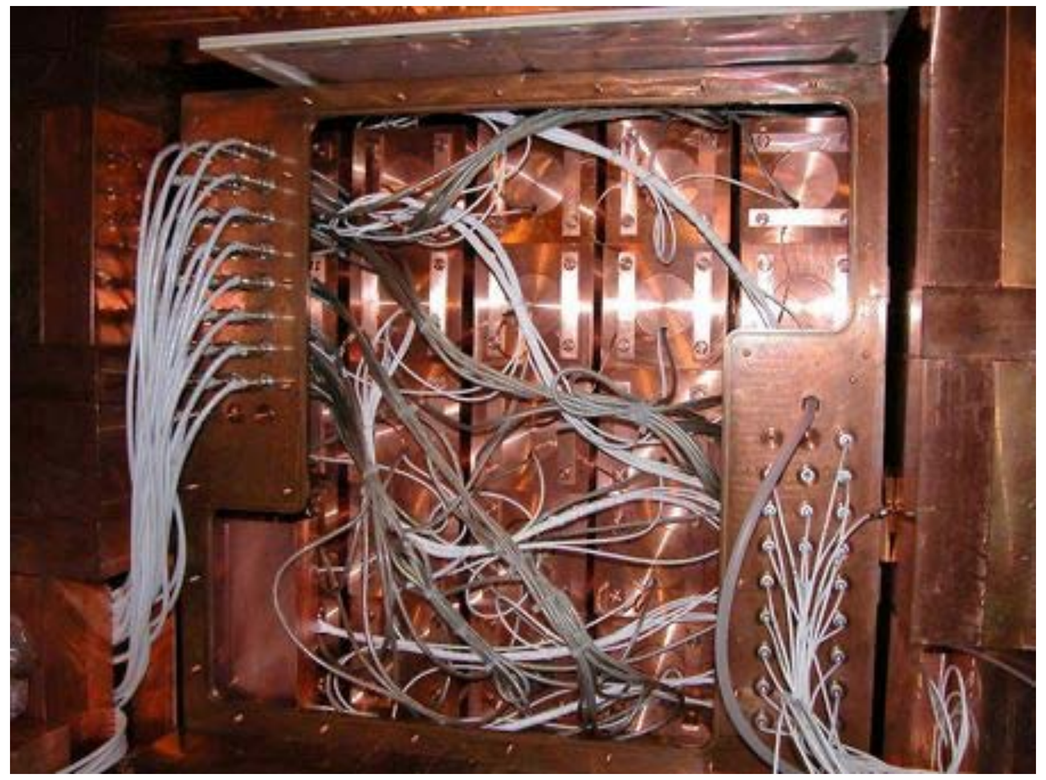
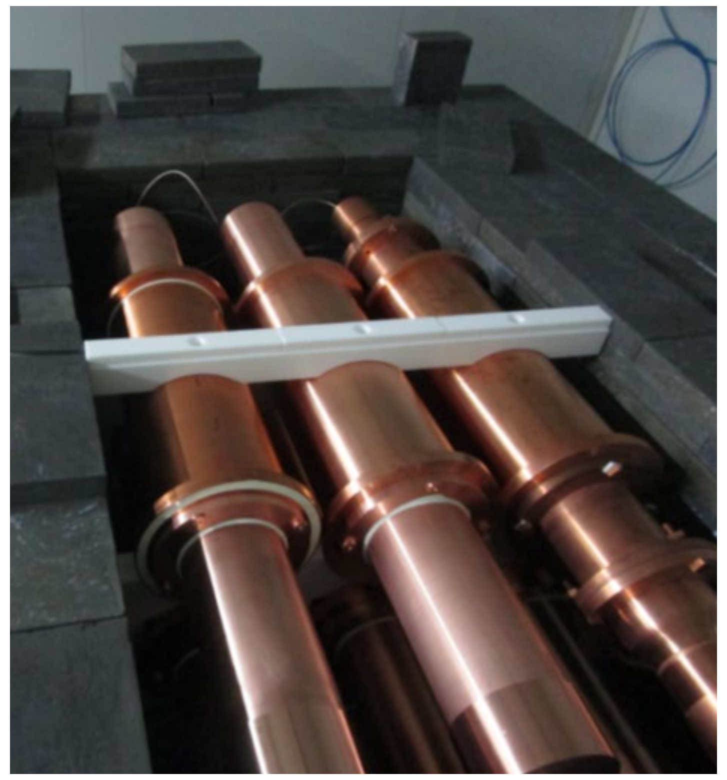
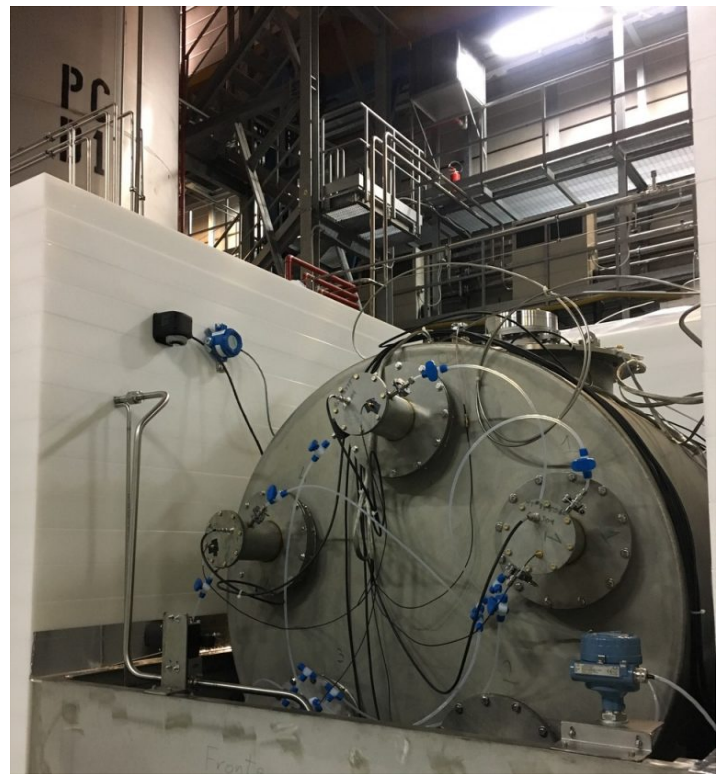
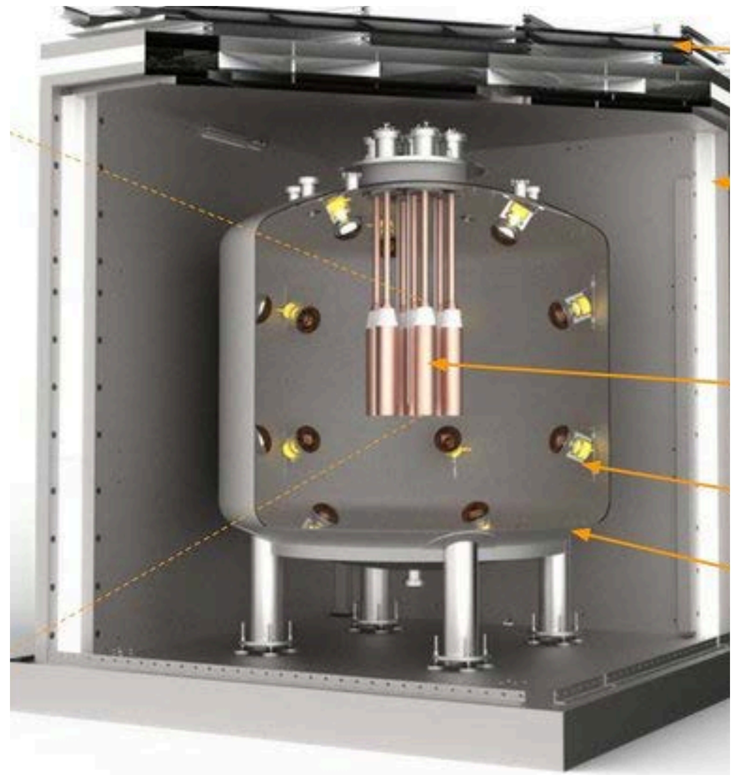
Resolving DAMA




Reina Maruyama
Yale University

UCLA Dark Matter 2023
March 29 – April 1, 2023

NSF
COSINE
Wright Laboratory
Yale

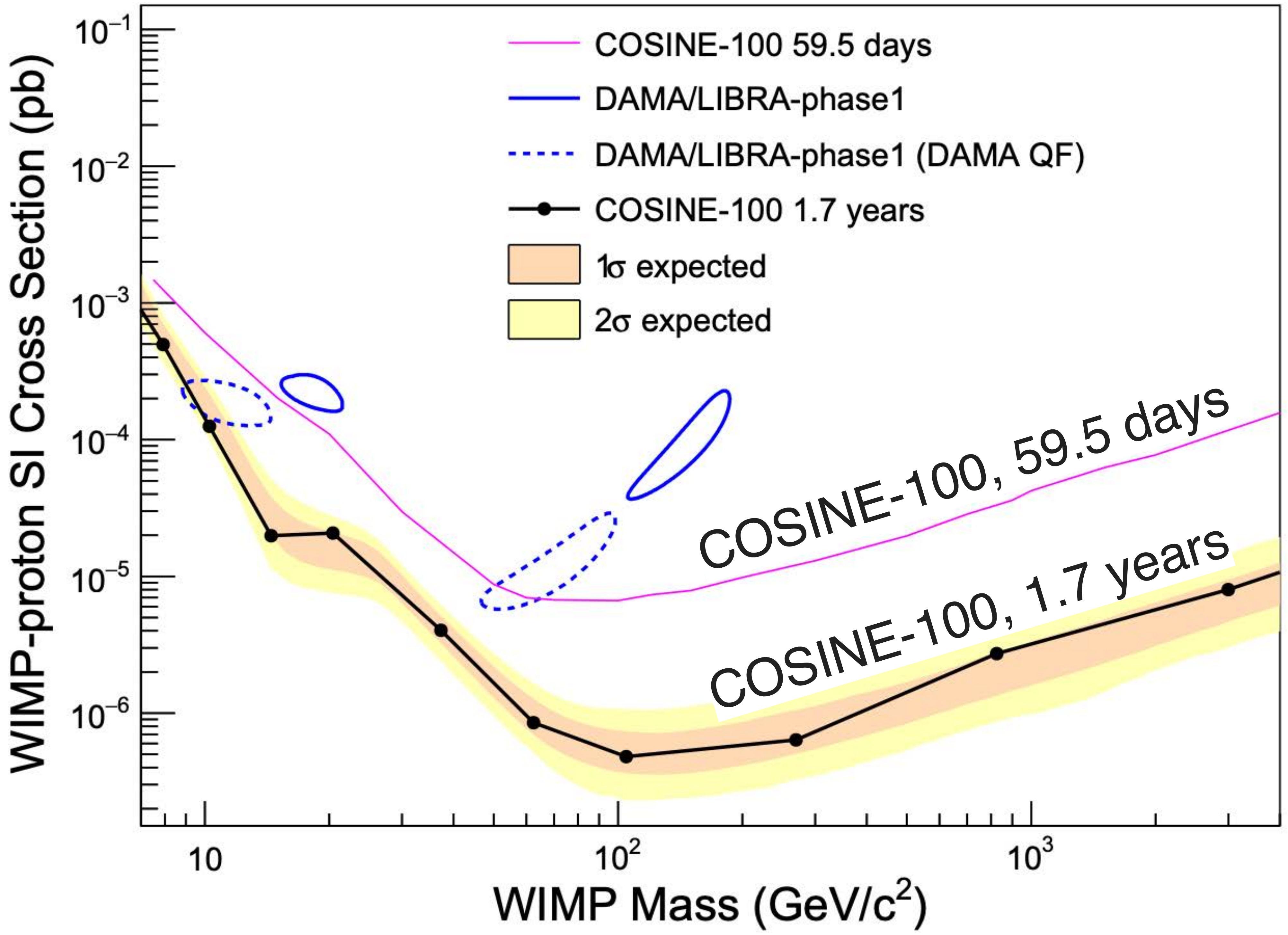
NaI Experiments: a Global Effort

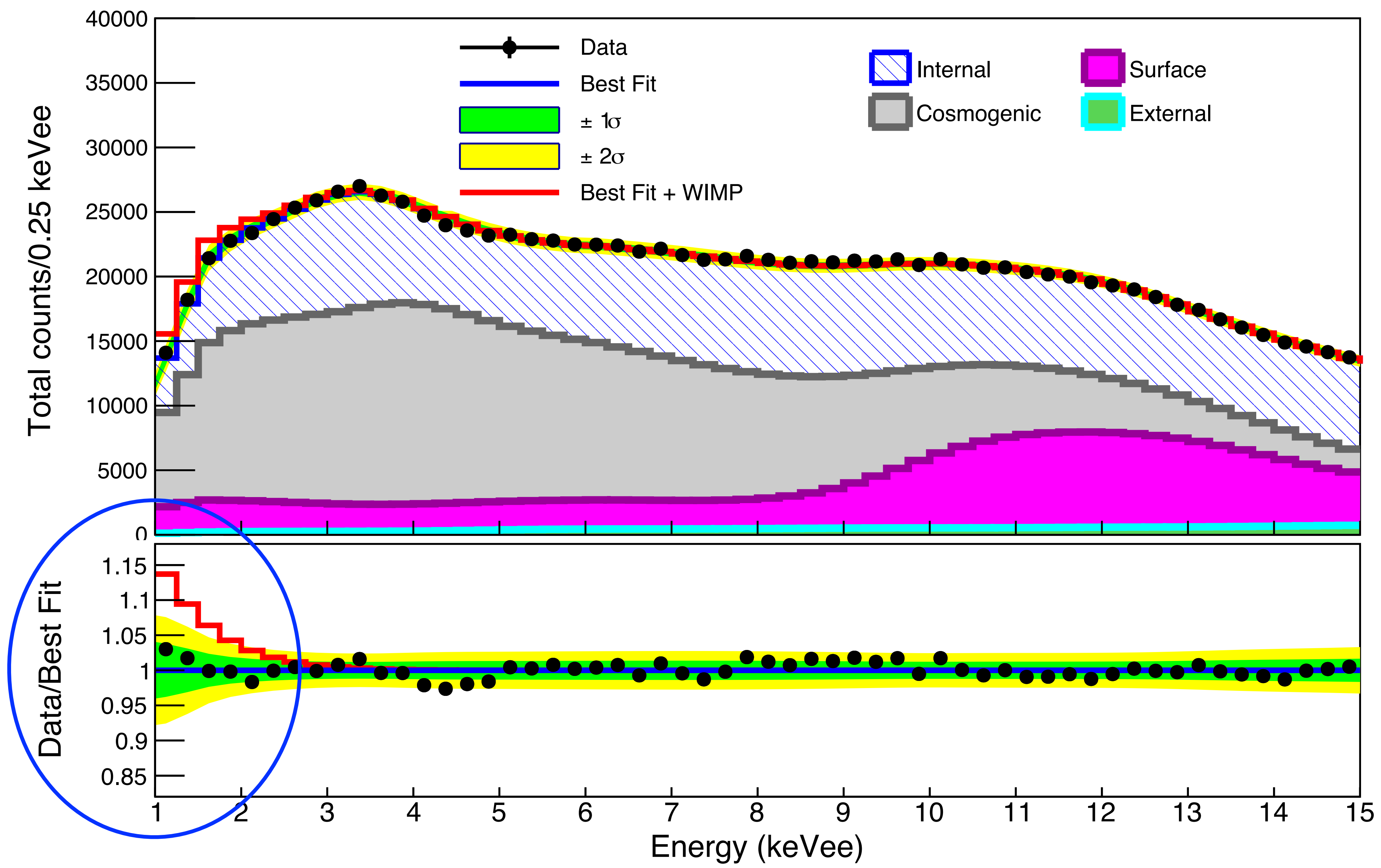
Goal for this talk:
Summarize where we are,
Start discussion on
reconciling DAMA

COSINE-100: no excess over known backgrounds

Same target medium, potential for variation among crystals

Nature 564, 83 (2018)
Sci Adv. 2021 Nov 12;7(46):eabk2699

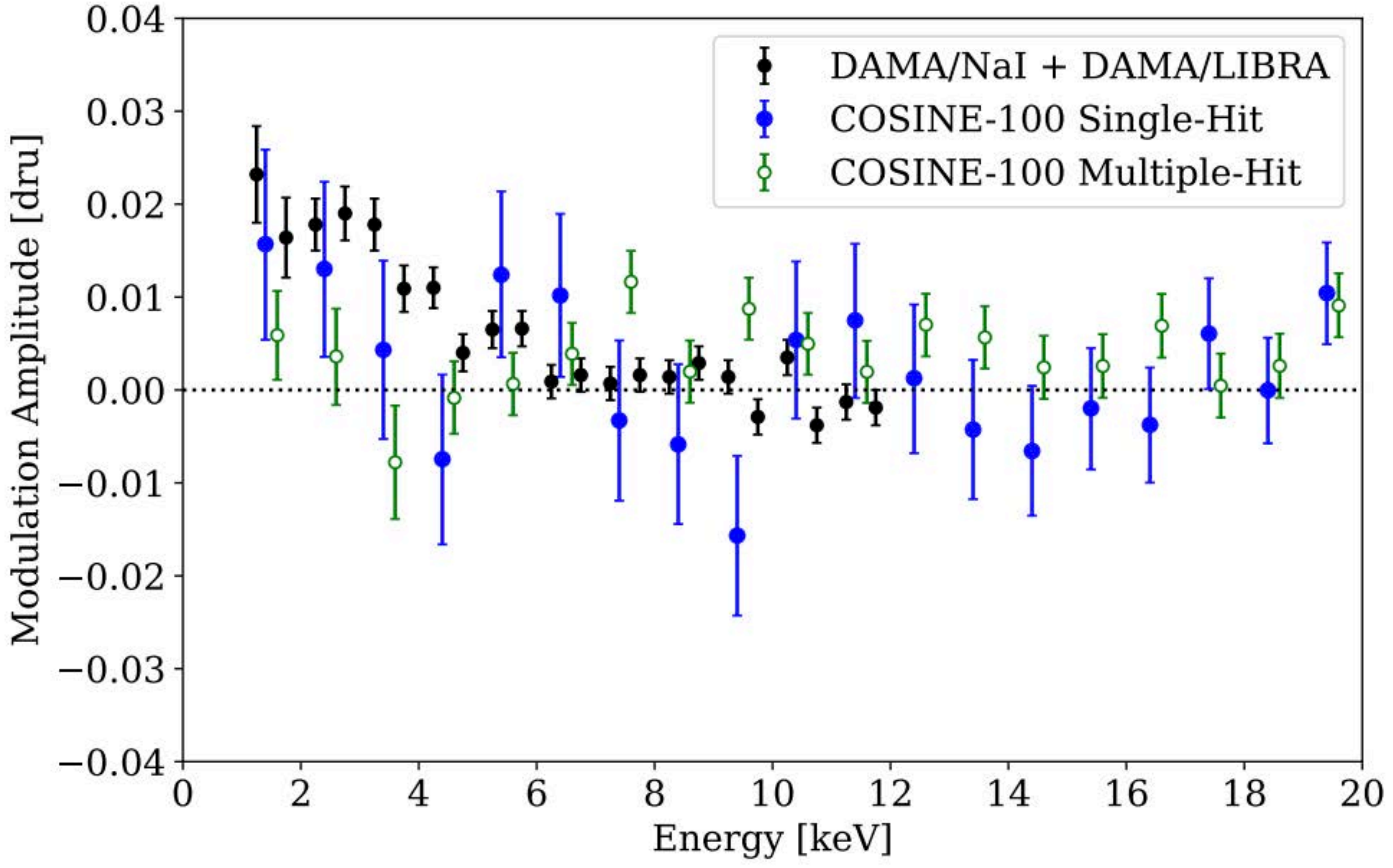


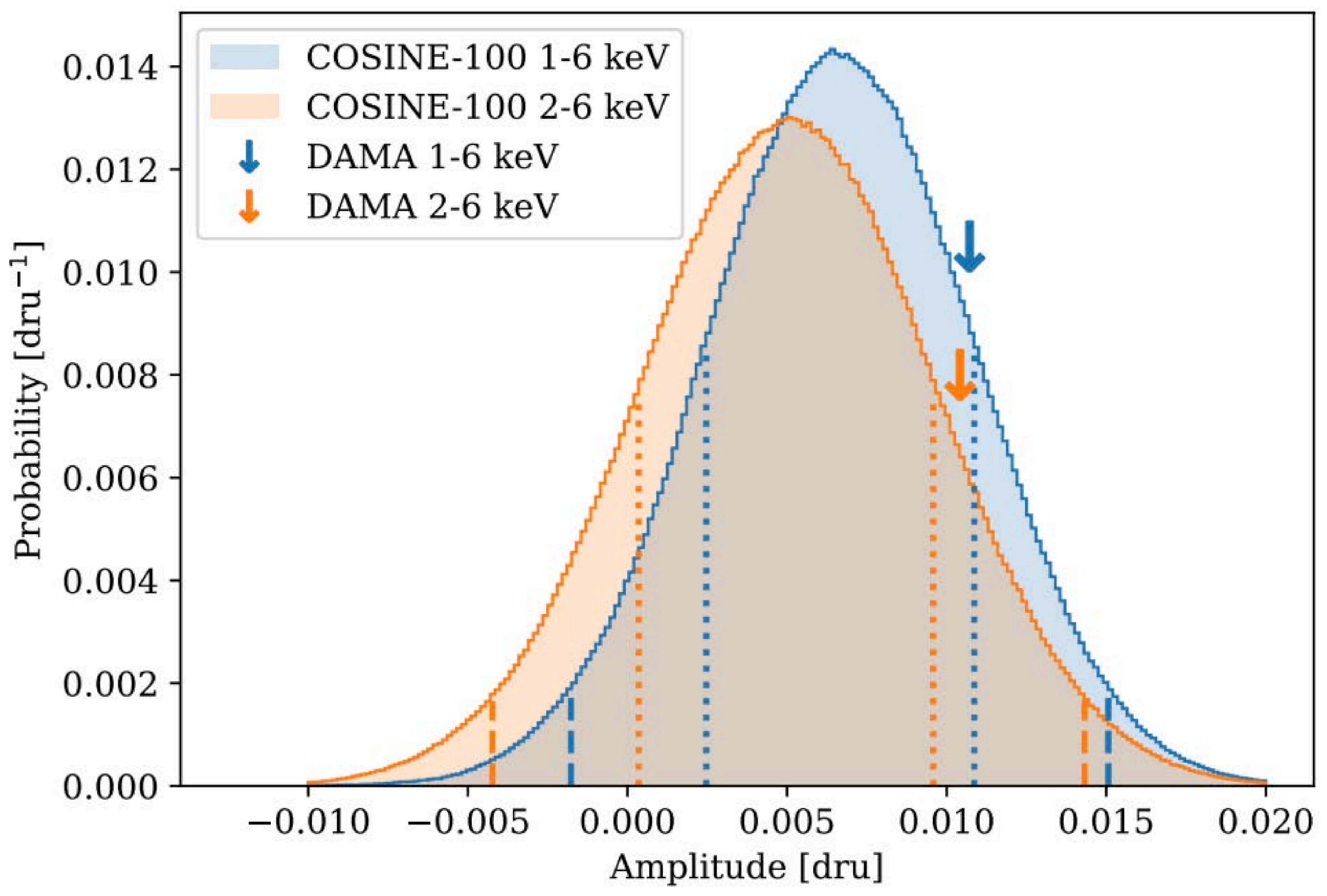


- Rules out WIMPs for DAMA with 60 days of data
- 1.7 yrs of data excludes WIMPs for pessimistic quenching factor

Phys. Rev. D. 106, 052005

2.8 yrs of COSINE-100 not yet conclusive

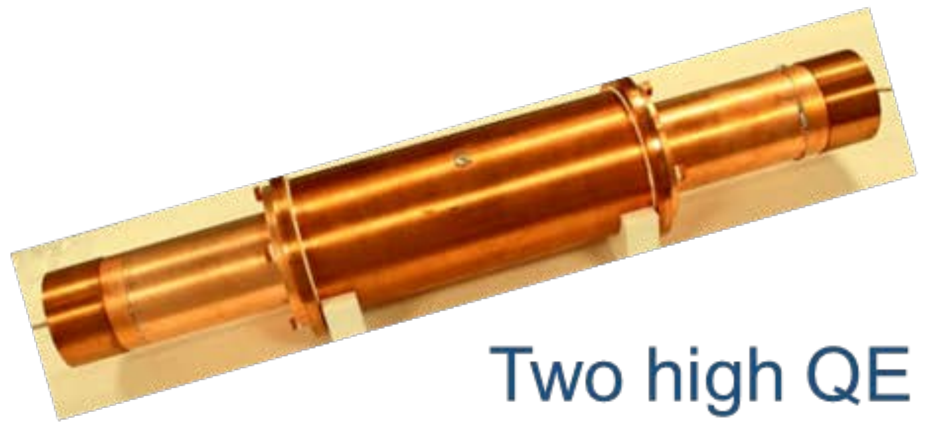




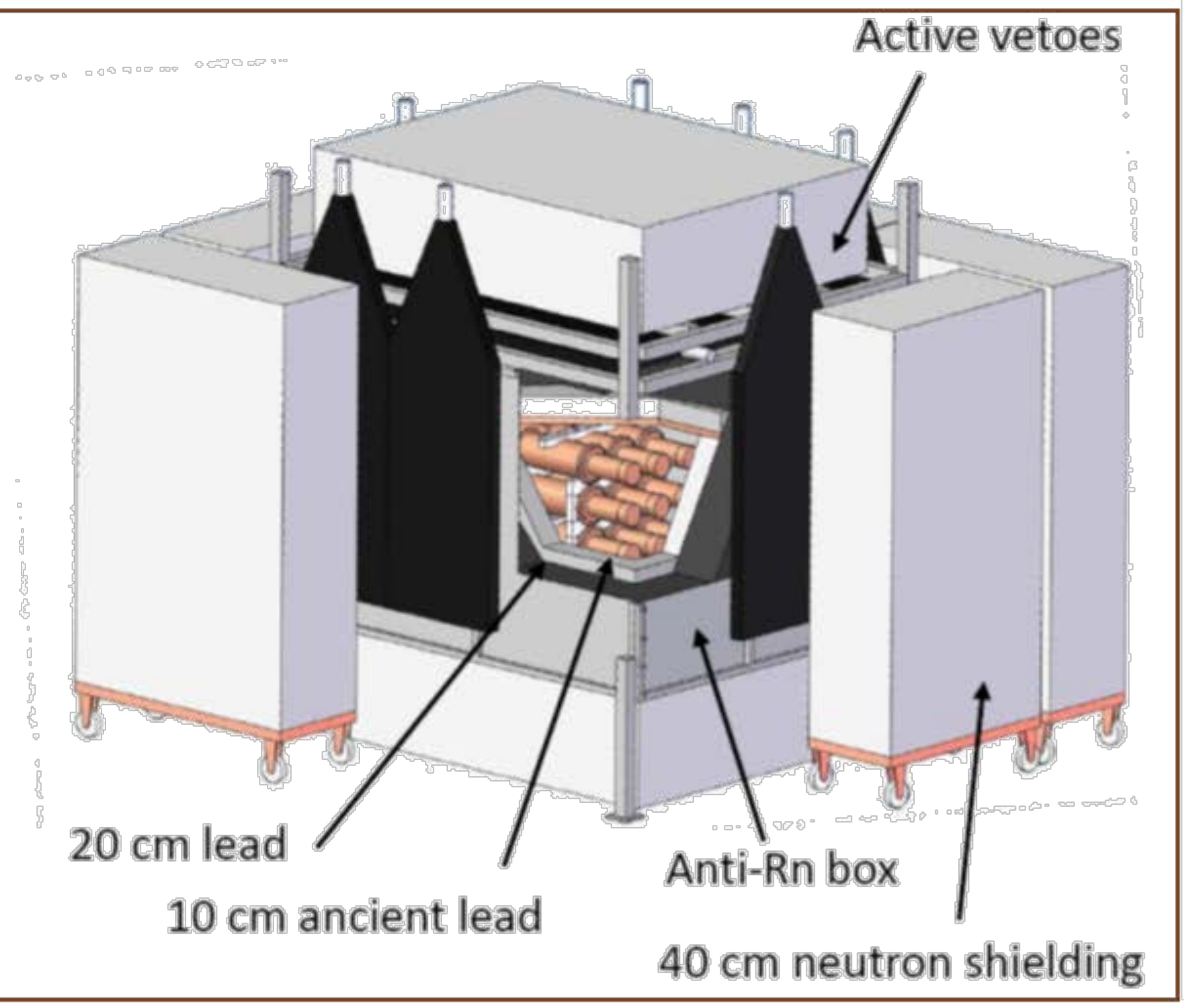
- 0.0067 ± 0.0042 cpd/kg/keV @ 1 – 6 keV
- Consistent with both DAMA and zero modulation
- Data ready for 3 more years exposure

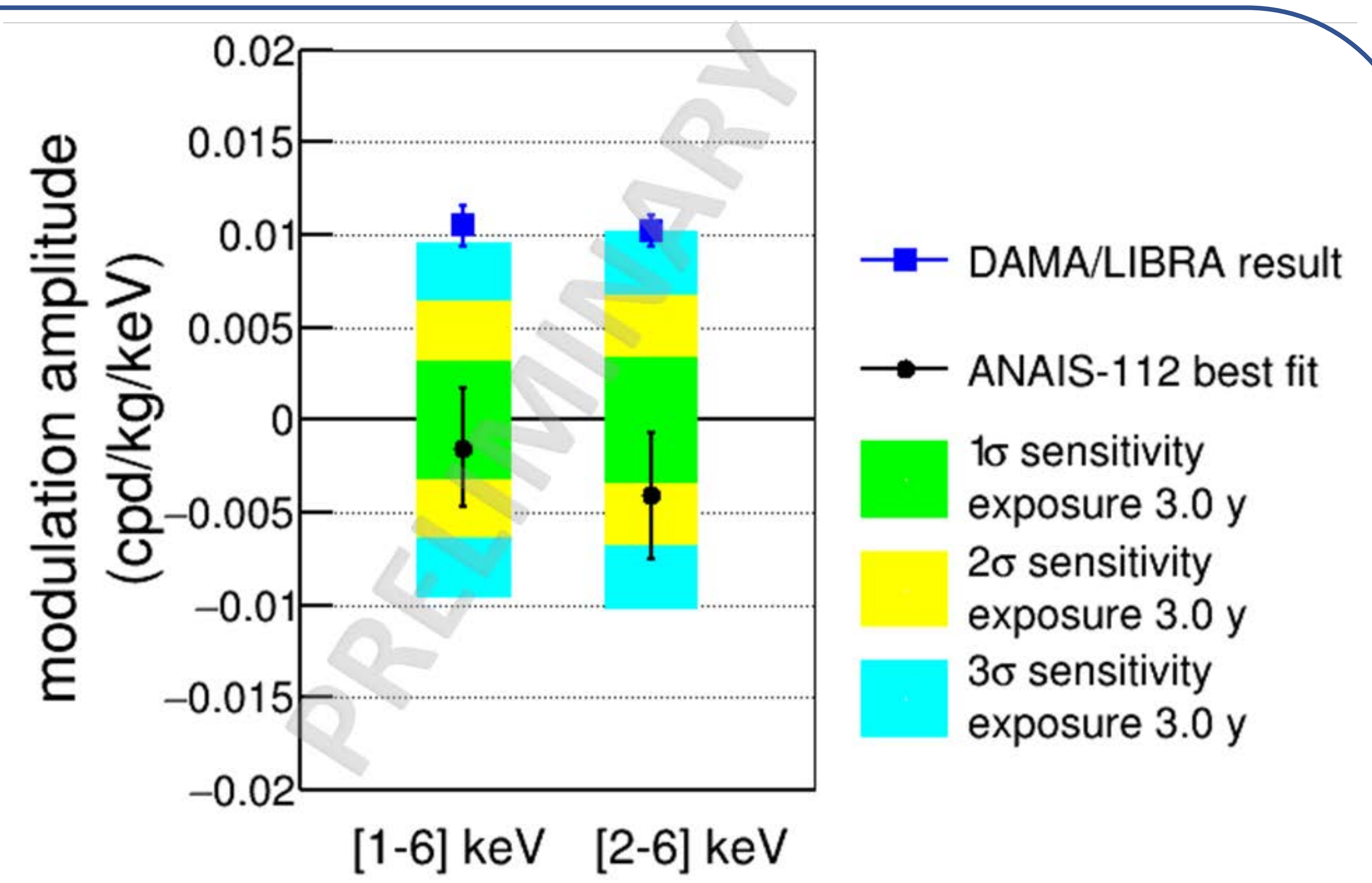
ANAIS-112, Canfranc Underground Laboratory (LSC, Spain)

THE DETECTOR:
3x3 matrix of 12.5 kg
NaI(Tl) cylindrical modules
= **112.5 kg** of active mass



Two high QE PMTs per detector



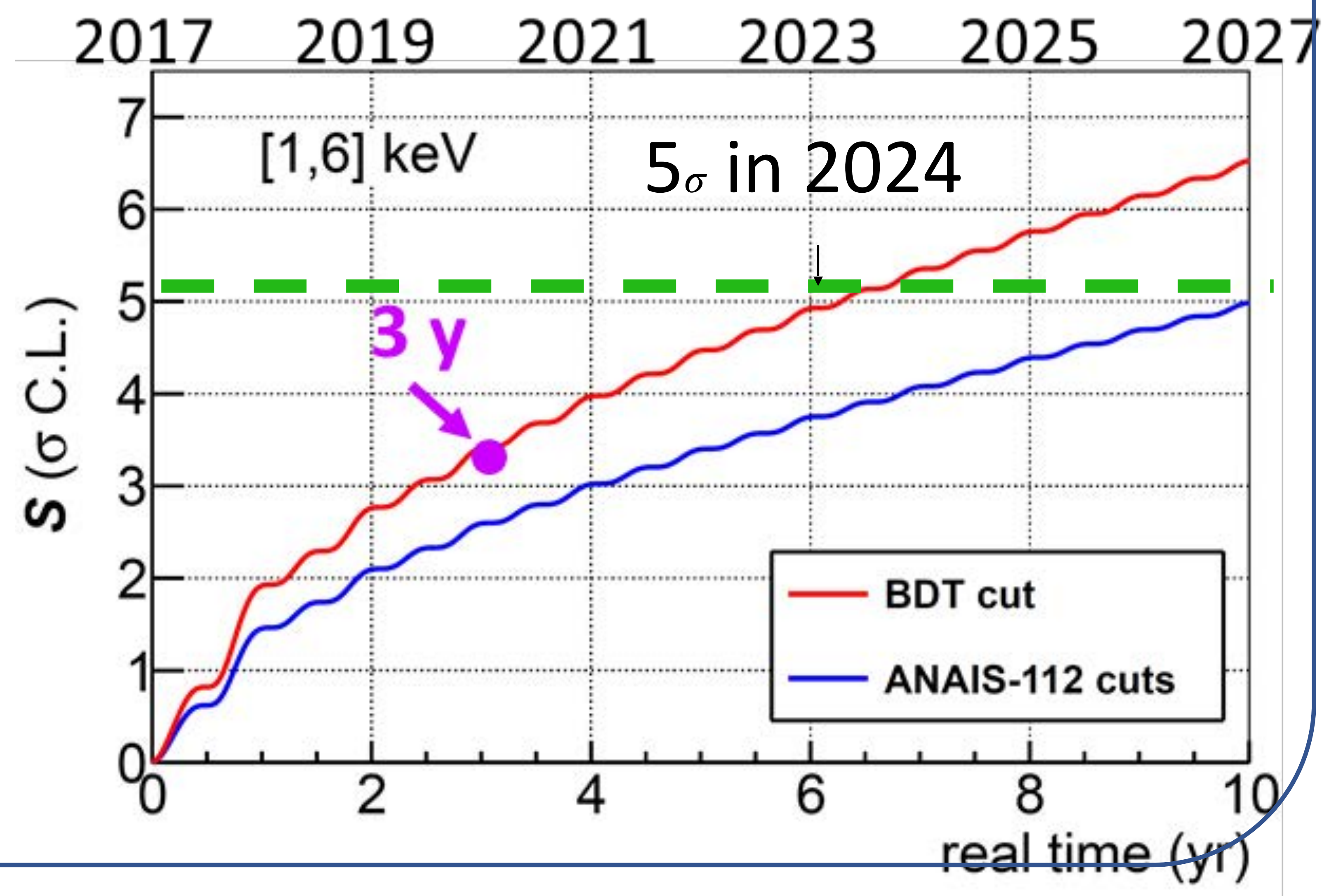


best fit modulation compatible with zero (1σ)

Best fit incompatible with DAMA/LIBRA at 3.75 (4.2) σ for [1-6] ([2-6]) keV

Sensitivity with 3 years data: 3.3 (3.0) σ @ [1-6] ([2-6]) keV

5_σ sensitivity at reach in 2024

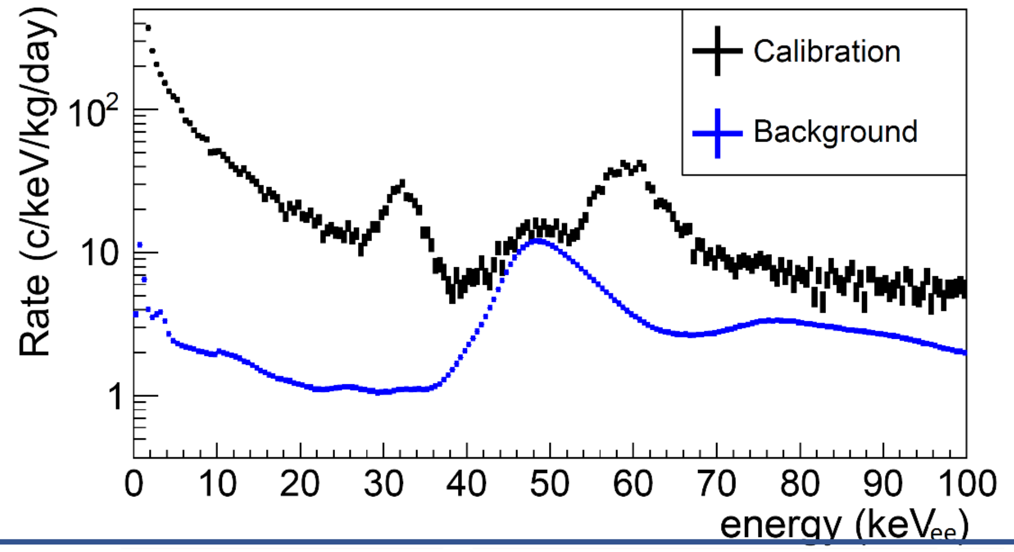


ANAIS-112 modulation results:

- 1.5y: Phys. Rev. Lett. 123, 031301 (2019)
- 2y: J. Phys. Conf. Ser. **1468,** 012014 (2020)
- 3y: arXiv: Phys. Rev. D 103, 102005 (2021)

"Improving ANAIS-112 sensitivity to DAMA/LIBRA signal with machine learning techniques", I. Coarasa et al, JCAP11(2022)048

SIGNAL EVENTS: Neutron calibrations



NOISE EVENTS: "Blank" module (No NaI(Tl))

Summary of the results obtained in the additional investigations of possible systematics or side reactions – DAMA/LIBRA-phase1

(NIMA592(2008)297, EPJC56(2008)333, J. Phys. Conf. ser. 203(2010)012040, arXiv:0912.0660, S.I.F.Atti Conf.103(211), Can. J. Phys. 89 (2011) 11, Phys.Proc.37(2012)1095, EPJC72(2012)2064, arxiv:1210.6199 & 1211.6346, IJMPA28(2013)1330022, EPJC74(2014)3196)

Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	$<2.5\times10^{-6}$ cpd/kg/keV
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	$<10^{-4}$ cpd/kg/keV
NOISE	Effective full noise rejection near threshold	$<10^{-4}$ cpd/kg/keV
ENERGY SCALE	Routine + intrinsic calibrations	$<1\text{-}2\times10^{-4}$ cpd/kg/keV
EFFICIENCIES	Regularly measured by dedicated calibrations	$<10^{-4}$ cpd/kg/keV
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	$<10^{-4}$ cpd/kg/keV
SIDE REACTIONS	Muon flux variation measured at LNGS	$<3\times10^{-5}$ cpd/kg/keV

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

Summary ... of possibl... ...ons ...se1

...2.0660, ...)2064, ...)3196)

arXiv:1006.5255

One Model Explains DAMA/LIBRA, CoGENT, CDMS, and XENON

John P. Ralston
Department of Physics & Astronomy, The University of Kansas, Lawrence, KS 66045

Source	Main comment	Cautious upper limit (90%C.L.)
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TAUP 2015, P. Belli

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arXiv:1102.0815

A testable conventional hypothesis for the DAMA-LIBRA annual modulation

David Nygren
Physics Division, Lawrence Berkeley National Laboratory
1 Cyclotron Road, Berkeley, CA 94720

Source		
RADON		
TEMPERATURE	with multi-ton shield→ huge heat capacity + T continuously recorded	
NOISE	Effective full noise rejection near threshold	$<10^{-4}$ cpd/kg/keV
ENERGY SCALE	Routine + intrinsic calibrations	$<1\text{-}2 \times 10^{-4}$ cpd/kg/keV
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Progress in Particle and Nuclear Physics 114 (2020) 103810

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PRL 113, 081302 (2014) PHYSICAL REVIEW LETTERS week ending 22 AUGUST 2014

Fitting the Annual Modulation in DAMA with Neutrons from Muons and Neutrinos

Jonathan H. Davis*
Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, United Kingdom
(Received 10 July 2014; revised manuscript received 5 August 2014; published 21 August 2014)

Source		
RADON		
TEMPERATURE		
NOISE		
ENERGY SCALE		
EFFICIENCIES		
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arXiv: 1803.10110

Is DAMA Bathing in a Sea of Radioactive Argon?

D. N. McKinsey[1,2,*]

[1] *University of California Berkeley, Department of Physics, Berkeley, CA 94720, USA*
[2] *Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., Berkeley, CA 94720, USA*
(Dated: March 28, 2018)

Source

RADON

TEMPERATURE

NOISE

ENERGY SCALE

EFFICIENCIES

BACKGROUND

SIDE REACTIONS

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arXiv: 1803.10110

Is DAMA Bathing in a Sea of Radioactive Argon?

arXiv: 1901.02139

Helium Migration through Photomultiplier Tubes – The Probable Cause of the DAMA Seasonal Variation Effect

Daniel Ferenc[1,3,*] Dan Ferenc Šegedin[2,3], Ivan Ferenc Šegedin[3], Marija Šegedin Ferenc[3]

Progress in Particle and Nuclear Physics 114 (2020) 103810

arXiv:1102.0815

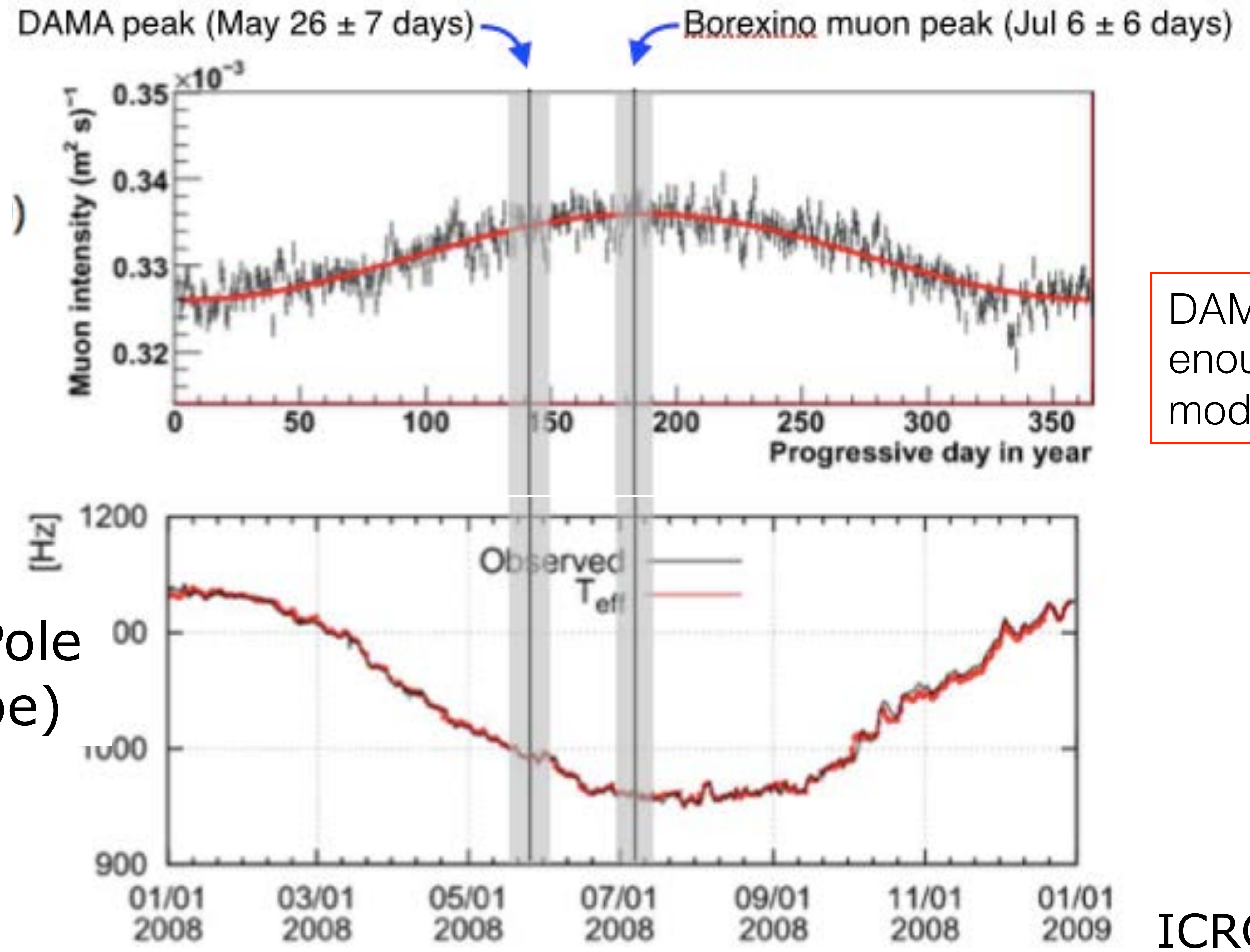
A testable conventional hypothesis for the DAMA-LIBRA annual modulation

David Nygren
Physics Division, Lawrence Berkeley National Laboratory
1 Cyclotron Road, Berkeley, CA 94720

DAMA's signal may be caused by phosphorescence or relaxation of crystal defects caused by muons

LNGS
(LVD)

South Pole
(IceCube)



ICRC 2009

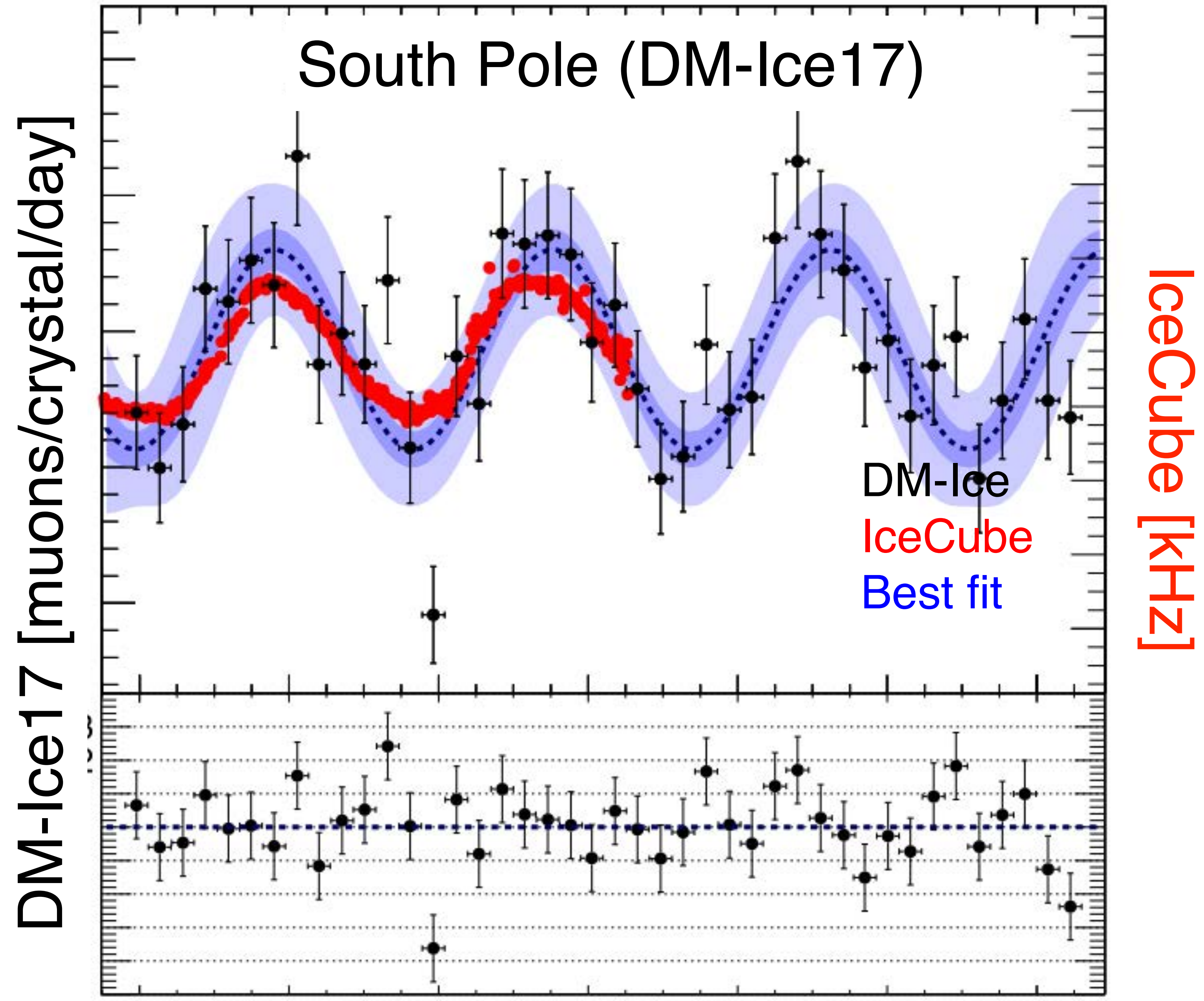
DAMA: No. The muon rate is not high enough, and it is out of phase with the modulation. *Bernabei 1202.4179*

UCLA DM 2012

DM-Ice17 Muon Events

Muon Flux

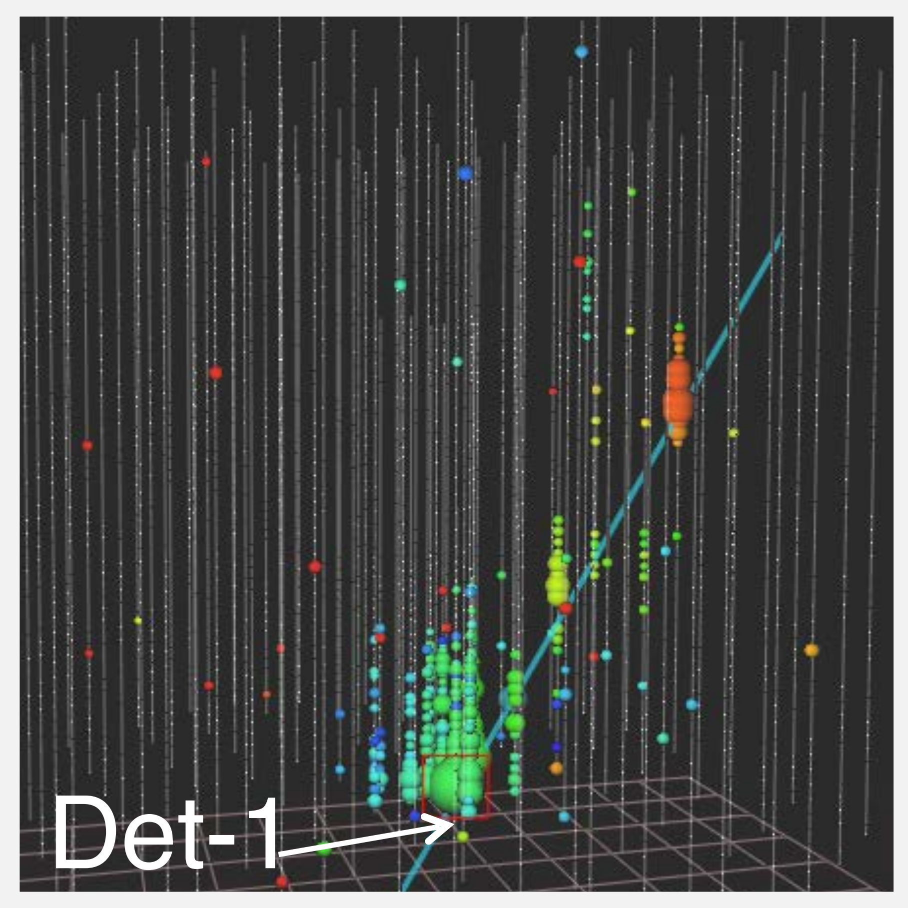
2.93 ± 0.04 muons/crystal/day,
12.3 ± 1.7% modulation amplitude

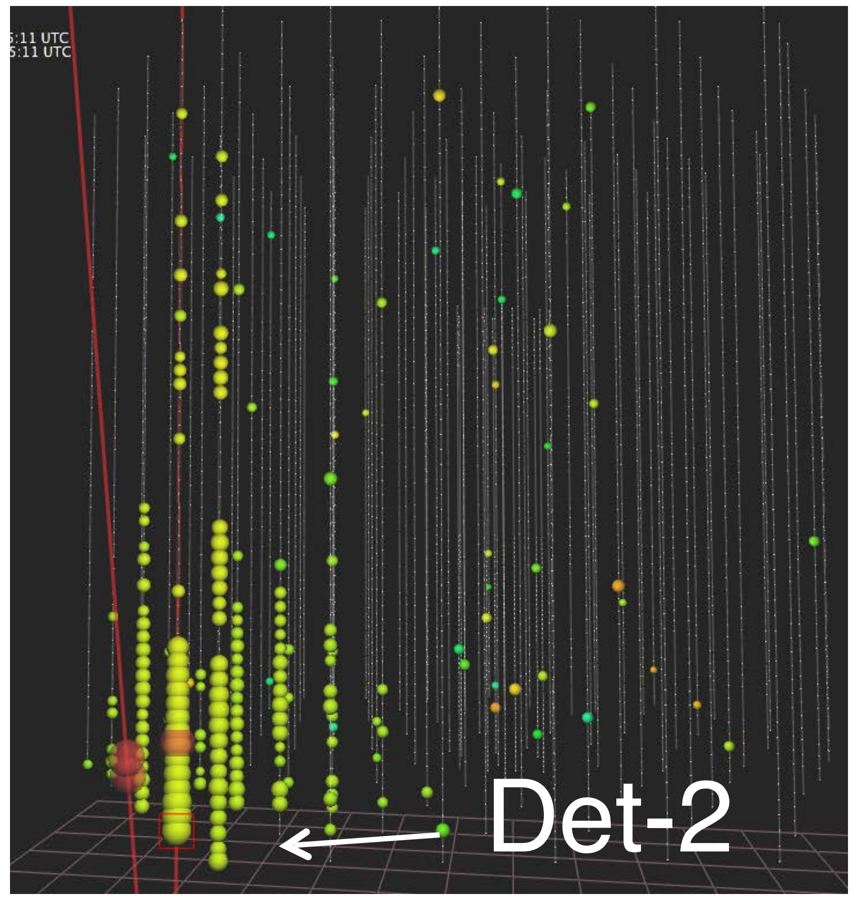


PRD 93, 042001 (2016)

IceCube Coincidence

- 93% of DM-Ice Det-1 muons are coincident with IceCube events
- DM-Ice location information lowers misreconstruction rates and improves location reconstruction through IceCube
  - Little impact on astrophysical parameters



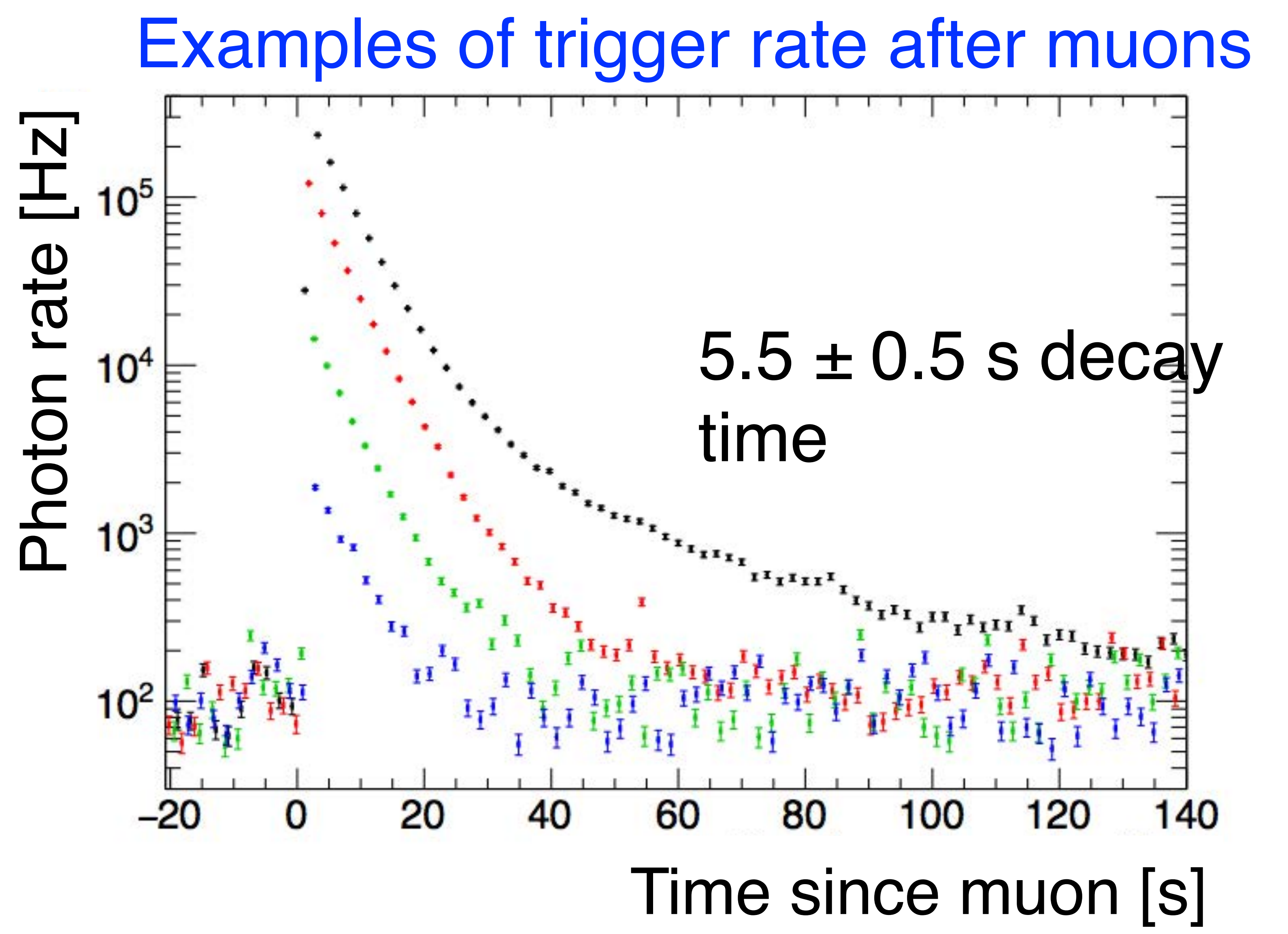


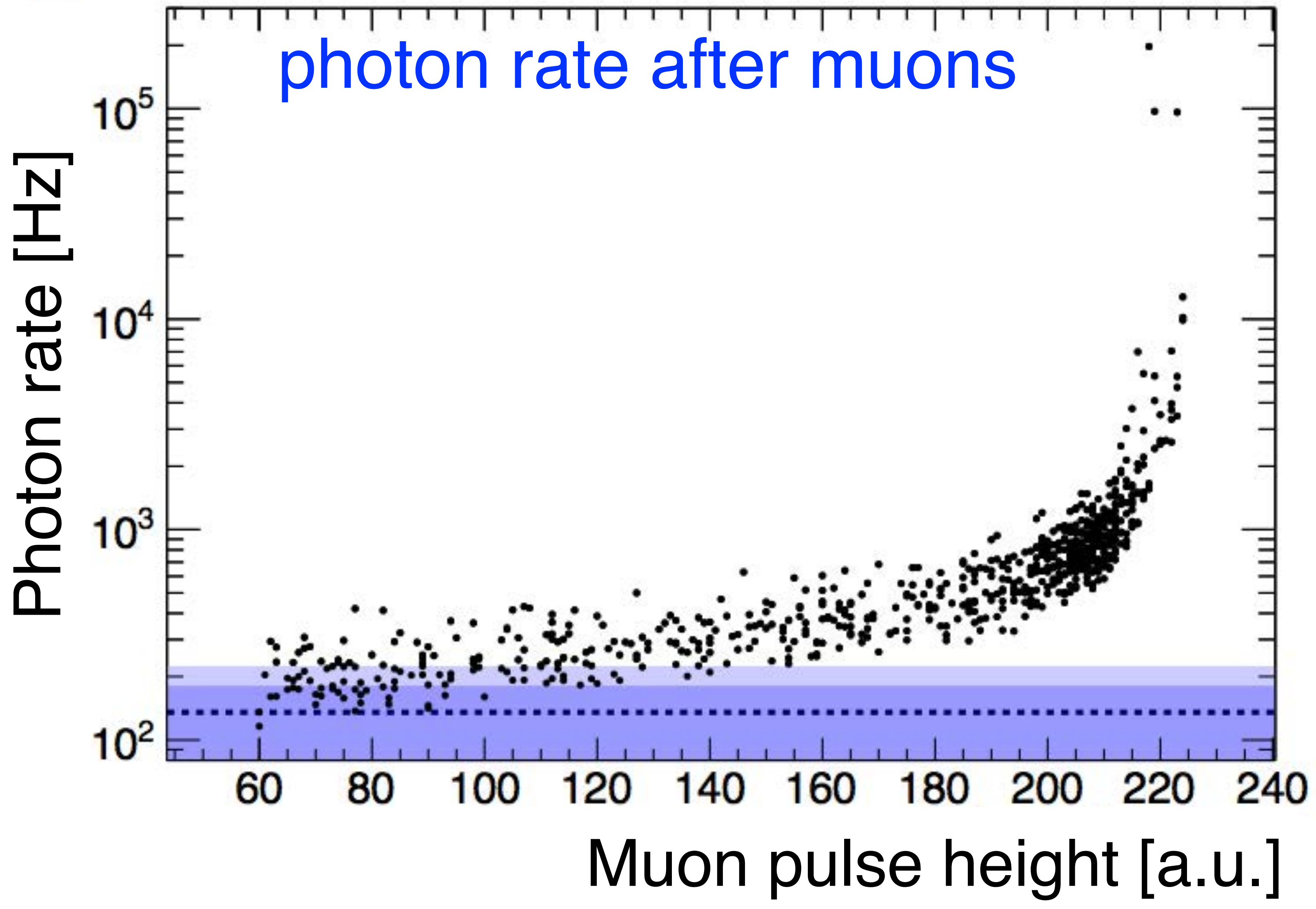
Muon-Induced Phosphorescece in DM-Ice17

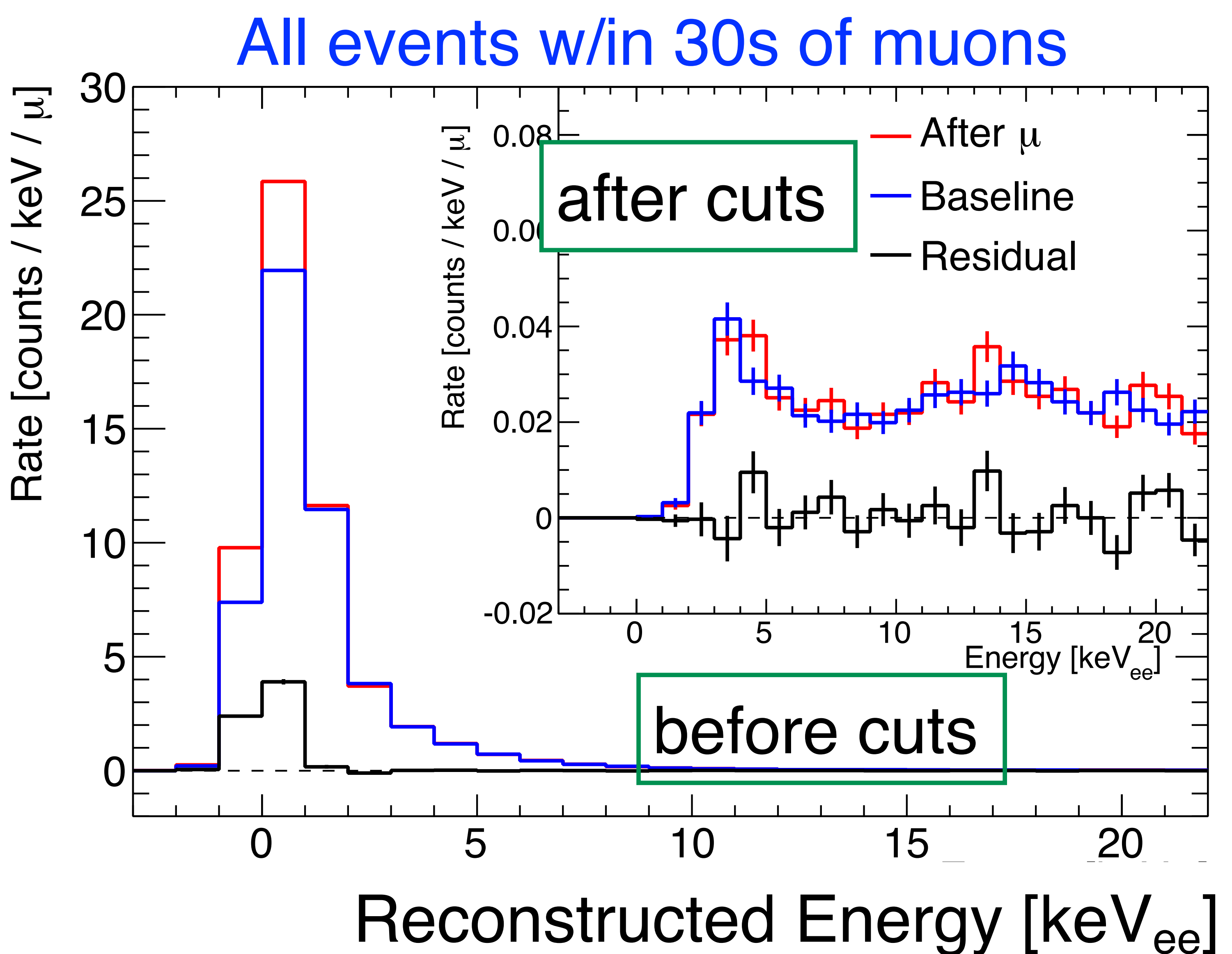
PRD 93, 042001 (2016)

- Long-lived phosphorescence observed in DM-Ice17
- Muon hits followed by sharp increase in photon rate
  - ➡ low energy pulses with 5.5 s decay time

Take away: too few muons & not enough photons for > 1 keV



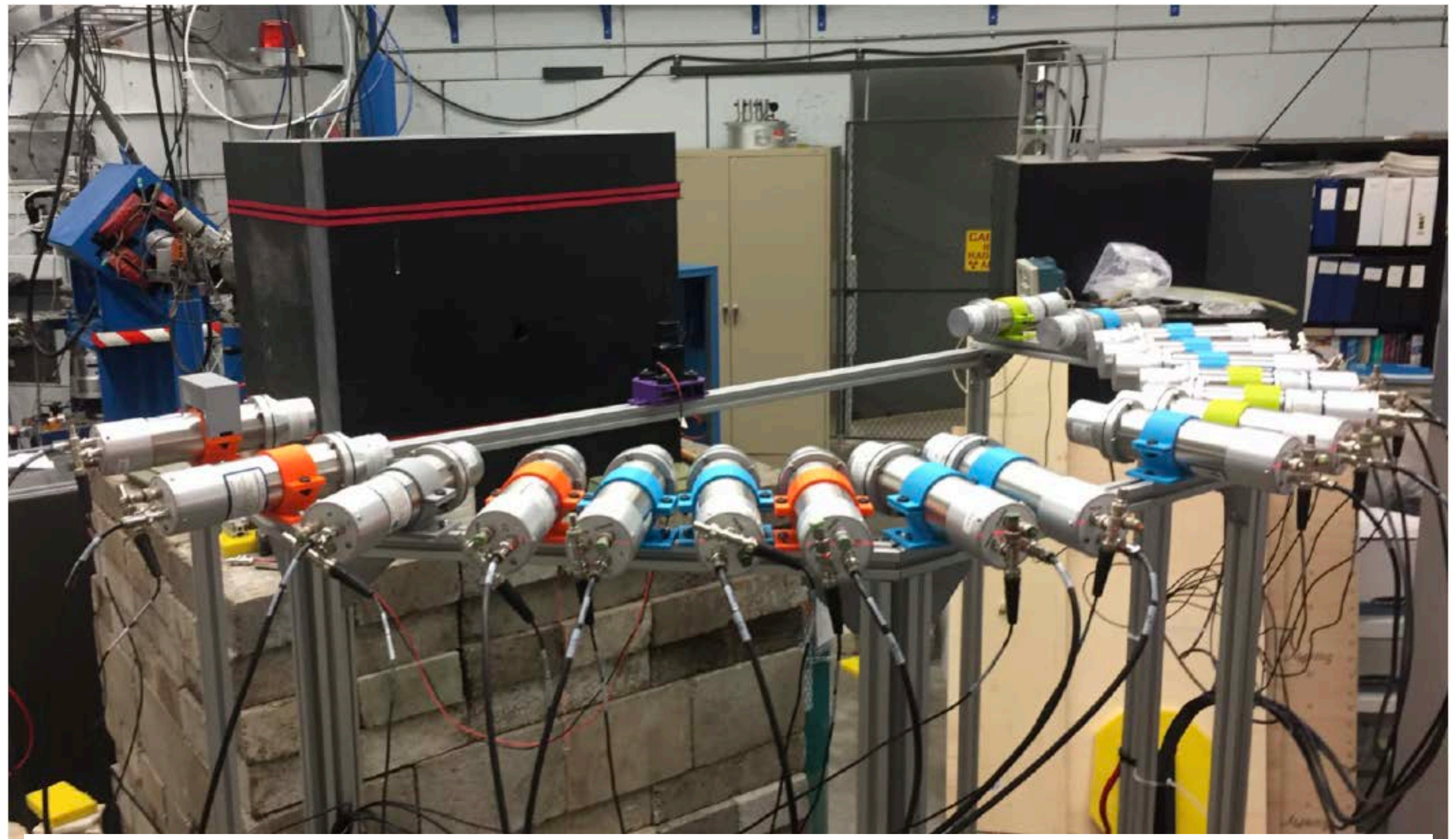




Detector effects

- e.g. quenching factor & channeling
  - Potential variation among crystals

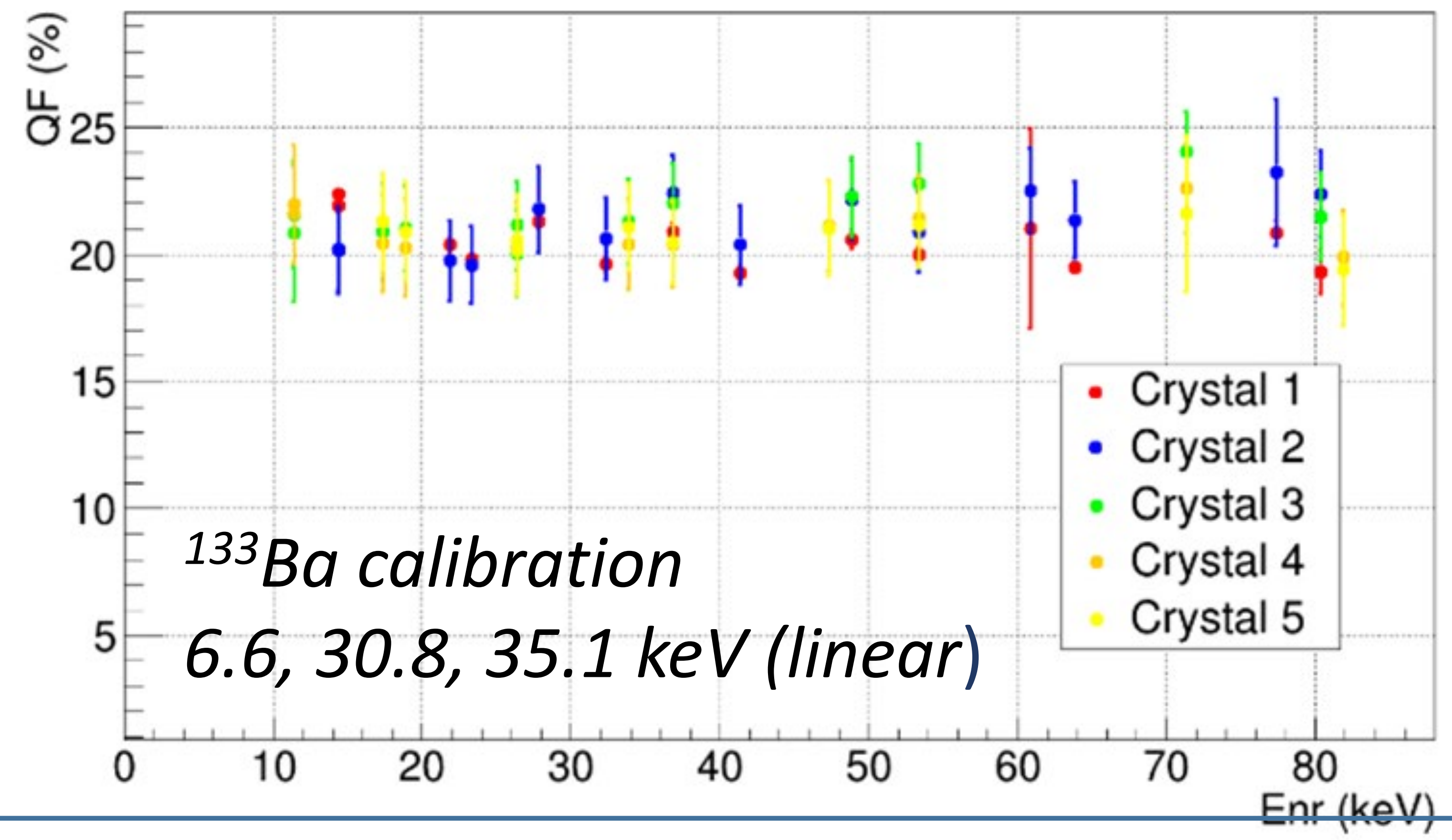
Measurement @ TUNL in collaboration w/ ANAIS

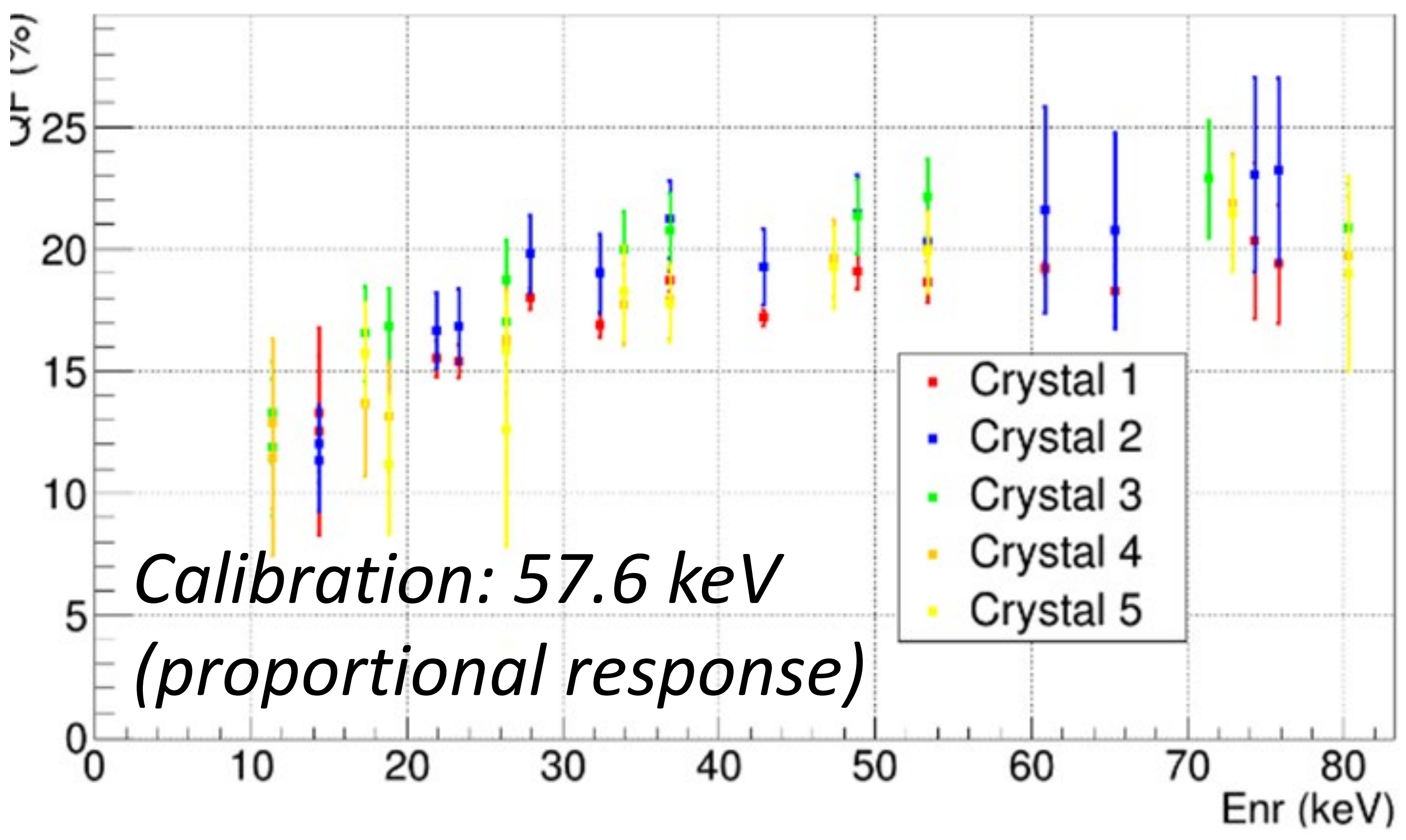


J. Physics (Conference series) 2156 (2022) 012065

Results for Na:

- No differences among different crystals
- QF_{Na}~20% @ 30 keVNR, but energy calibration method changes the energy dependence (non-linearity!)





Results for I:

- Lower energy threshold needed for this measurement
- Only upper limits for two of the crystals

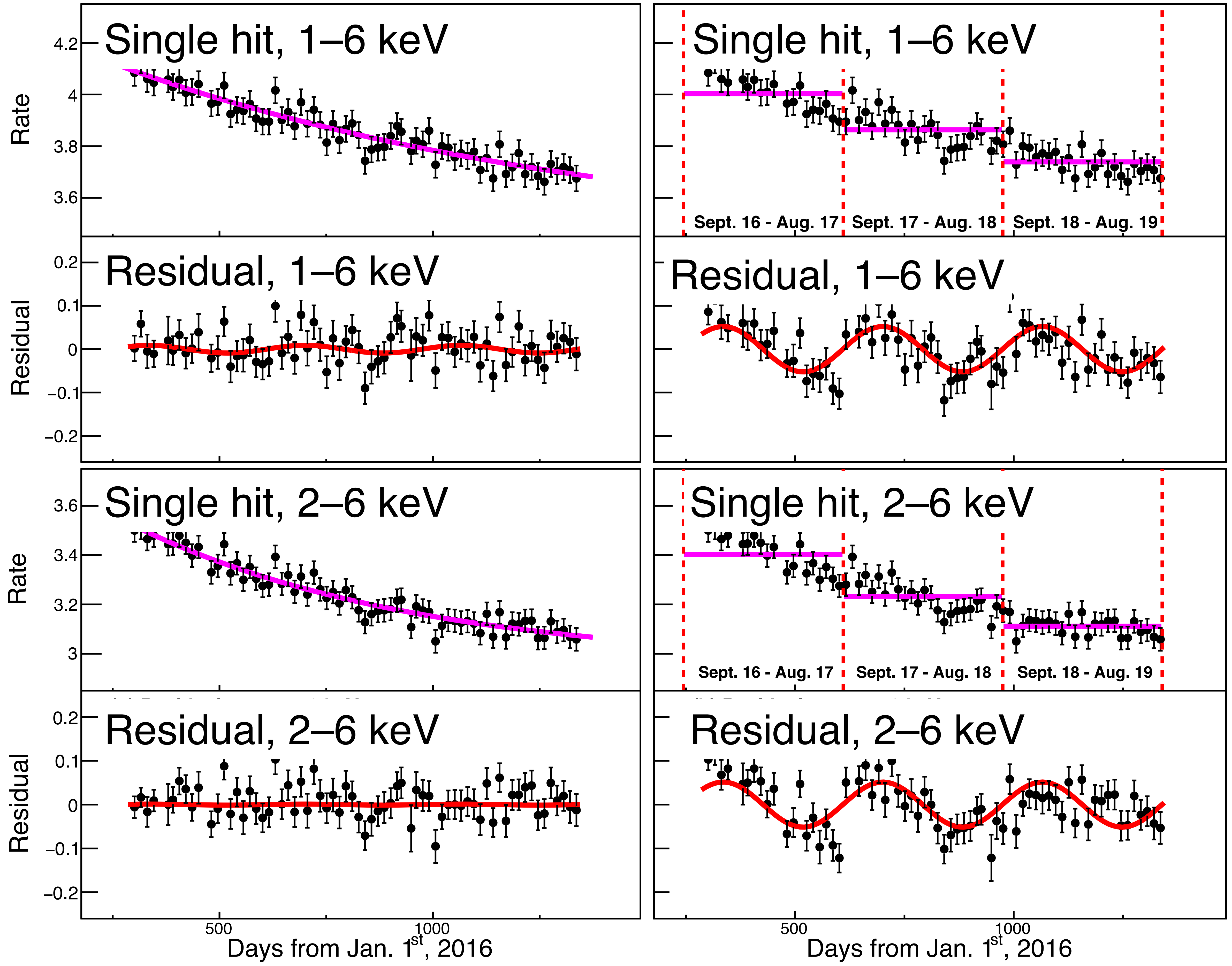
QF_I < 9.4 % @ 11.5 keV
QF_I < 8.2 % @ 13.6 keV

Curtesy of M. Martinez

Lee, et al. Astrop. Phys. 108 (2019) 50

Modulation introduced with DAMA-like analysis

COSINE-100 data



COSINE-like analysis

Fit for background,
7 exponentials

Fit residual for modulation

1–6 keV

2–6 keV

DAMA-like analysis

Subtract single average per dataset

Fit residual for modulation

~7σ modulation
opposite phase

Impossible to confirm without rate vs. time

Talk by G. Adhikari, Poster by S. Hollick et.al.

Future of NaI

Prisca Cushman, Wednesday

Summary of Spin-dependent target opportunities

Couples to net nuclear spin J_N

$$\sigma_{SD} = \frac{32}{\pi} G_F^2 \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2} \frac{J_N + 1}{J_N} \left(a_p \langle S_p \rangle + a_n \langle S_n \rangle \right)^2$$

neutron coupling

^{73}Ge (7.73%)	$\langle S_n \rangle = .46$	CDMS, EDELWEISS
^{29}Si (4.68%)	$\langle S_n \rangle = .13$	DAMIC/SENSEI, CDMS
^{17}O (0.037%)	$\langle S_n \rangle = .5$	CRESST ($CaWO_4$)
^{129}Xe (26%)	$\langle S_n \rangle = .33$	LXe TPCs
^{131}Xe (21%)	$\langle S_n \rangle = -.27$	

proton coupling

^{7}Li (92.4%)	$\langle S_p \rangle = .5$	CRESST($LiAlO_2$, Li_2MoO_4)
^{127}I (100%)	$\langle S_p \rangle = .31$	
^{23}Na (100%)	$\langle S_p \rangle = .25$	NaI (and CsI) DAMA, SABRE, ANAIS, COSINE-100, COSINUS
^{133}Cs (100%)	$\langle S_p \rangle = -.37$	
^{1}H (100%)	$\langle S_p \rangle = .5$	Snowball (H_2O)

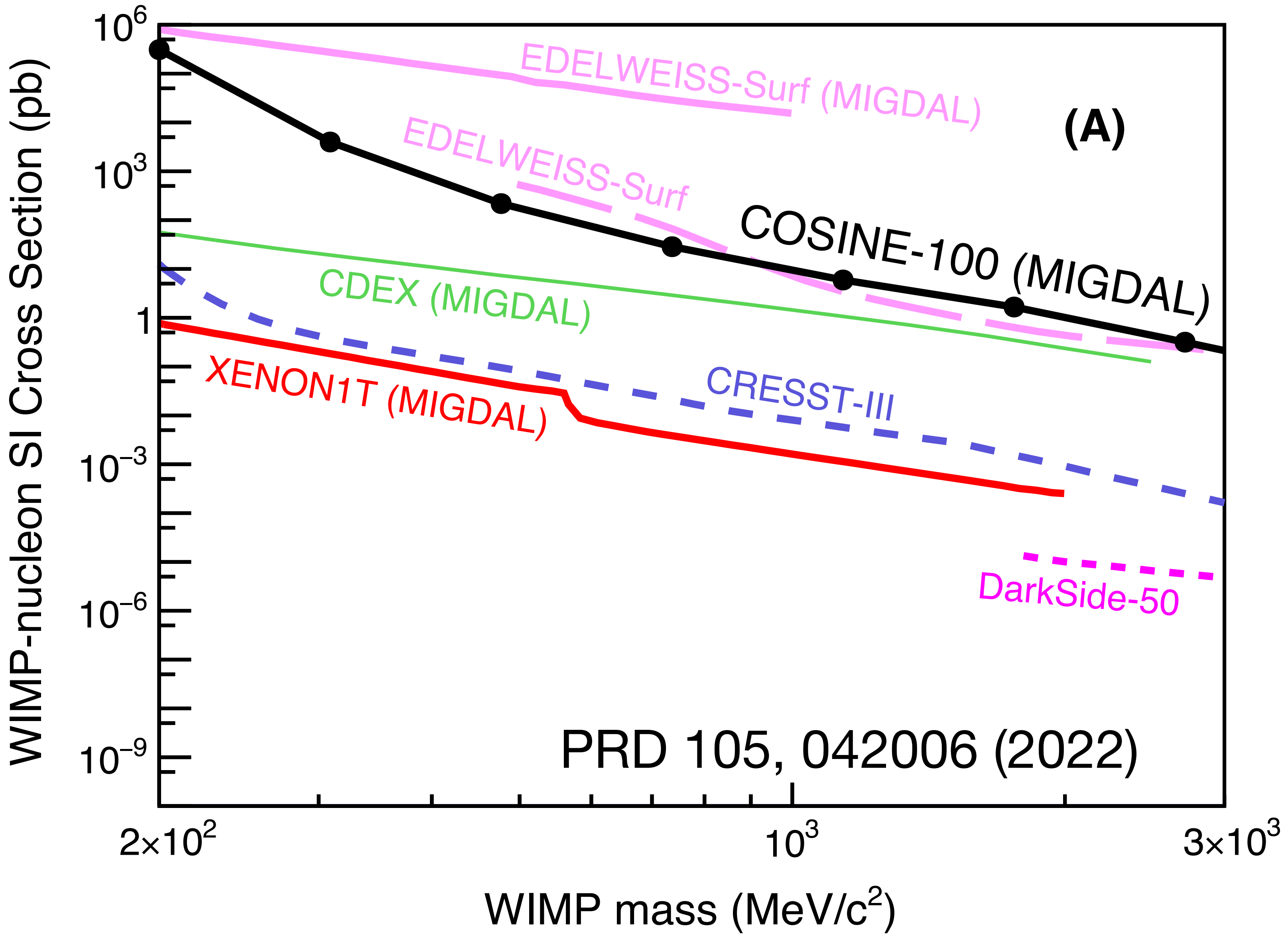
proton & neutron coupling

^{19}F (% depends on fluorocarbon)	$\langle S_n \rangle = -.11$	$\langle S_p \rangle = .44$	PICO (CF_3I, C_3F_8)
^{6}Li (7.6%)	$\langle S_n \rangle = .472$	$\langle S_p \rangle = .472$	CRESST ($LiAlO_2$, Li_2MoO_4)

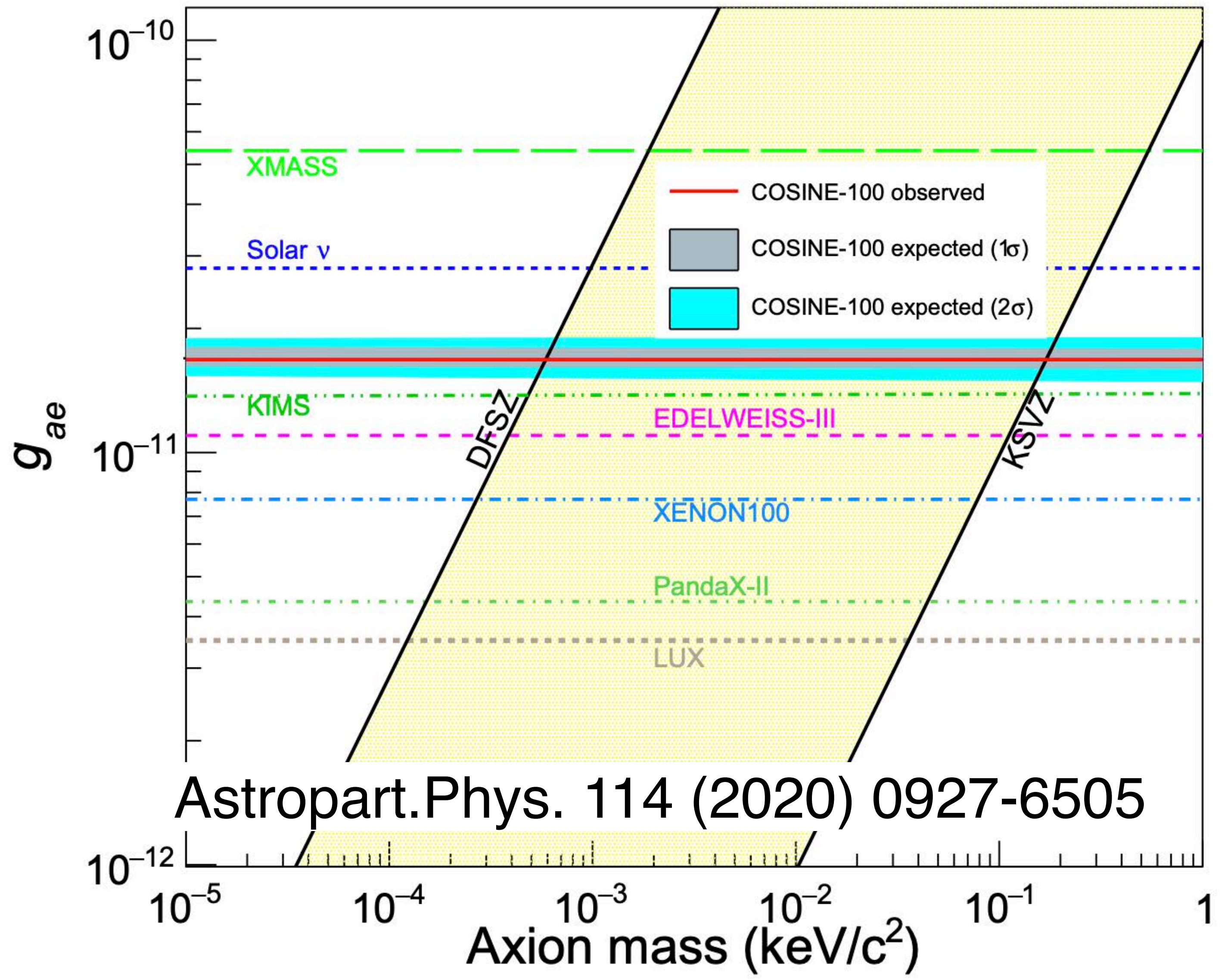
11

Dark Matter searches with NaI

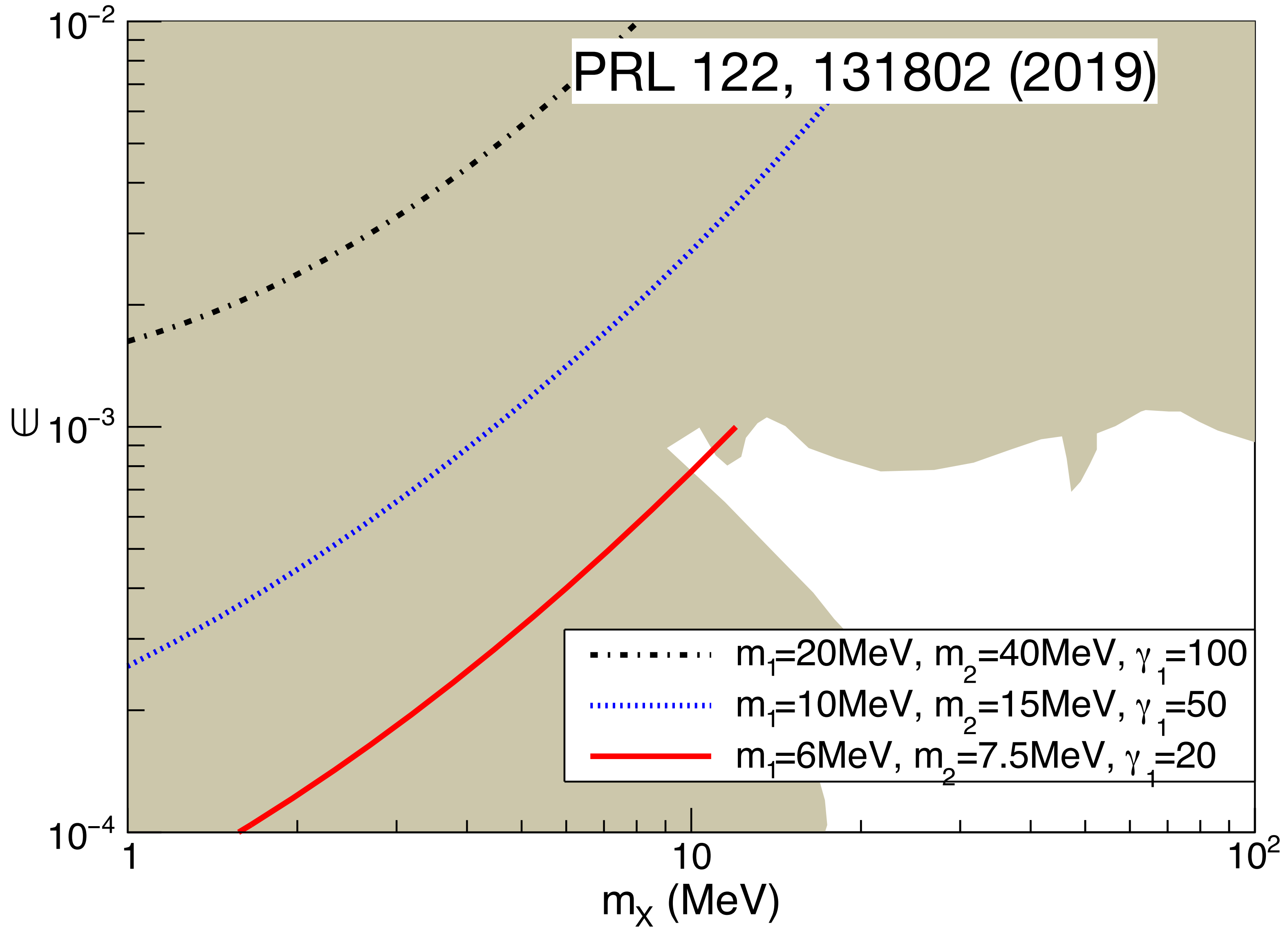
Migdal effect



Solar axion

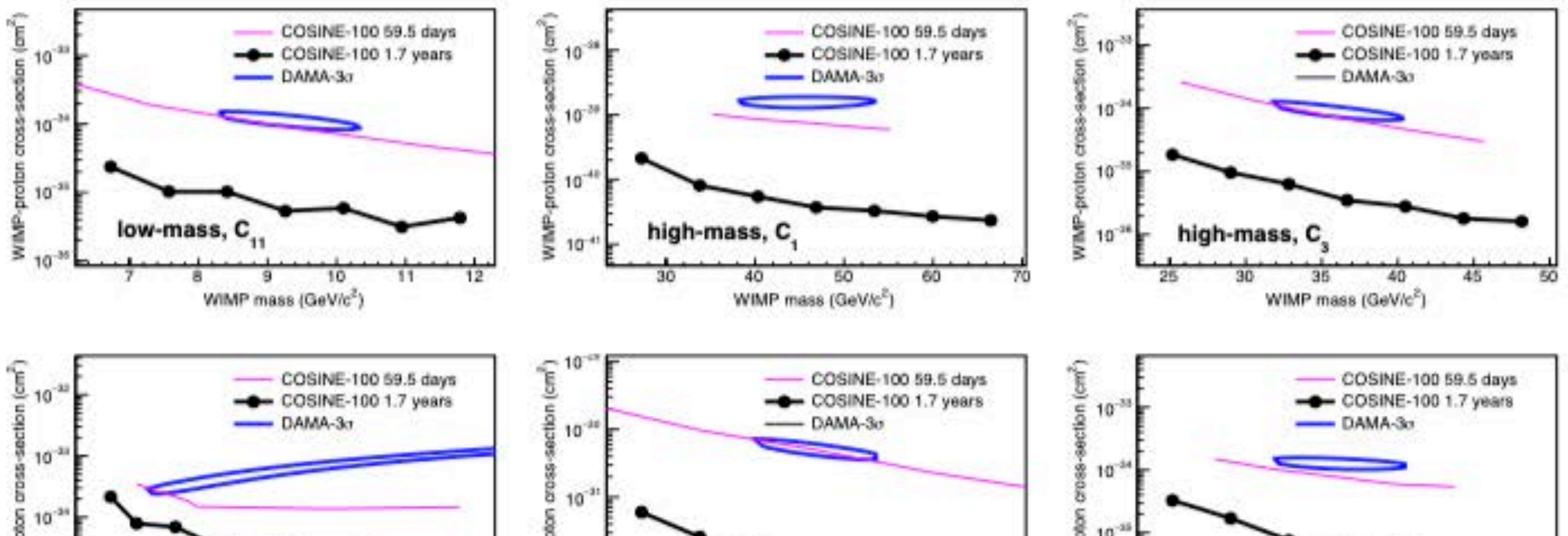


Inverse boosted DM



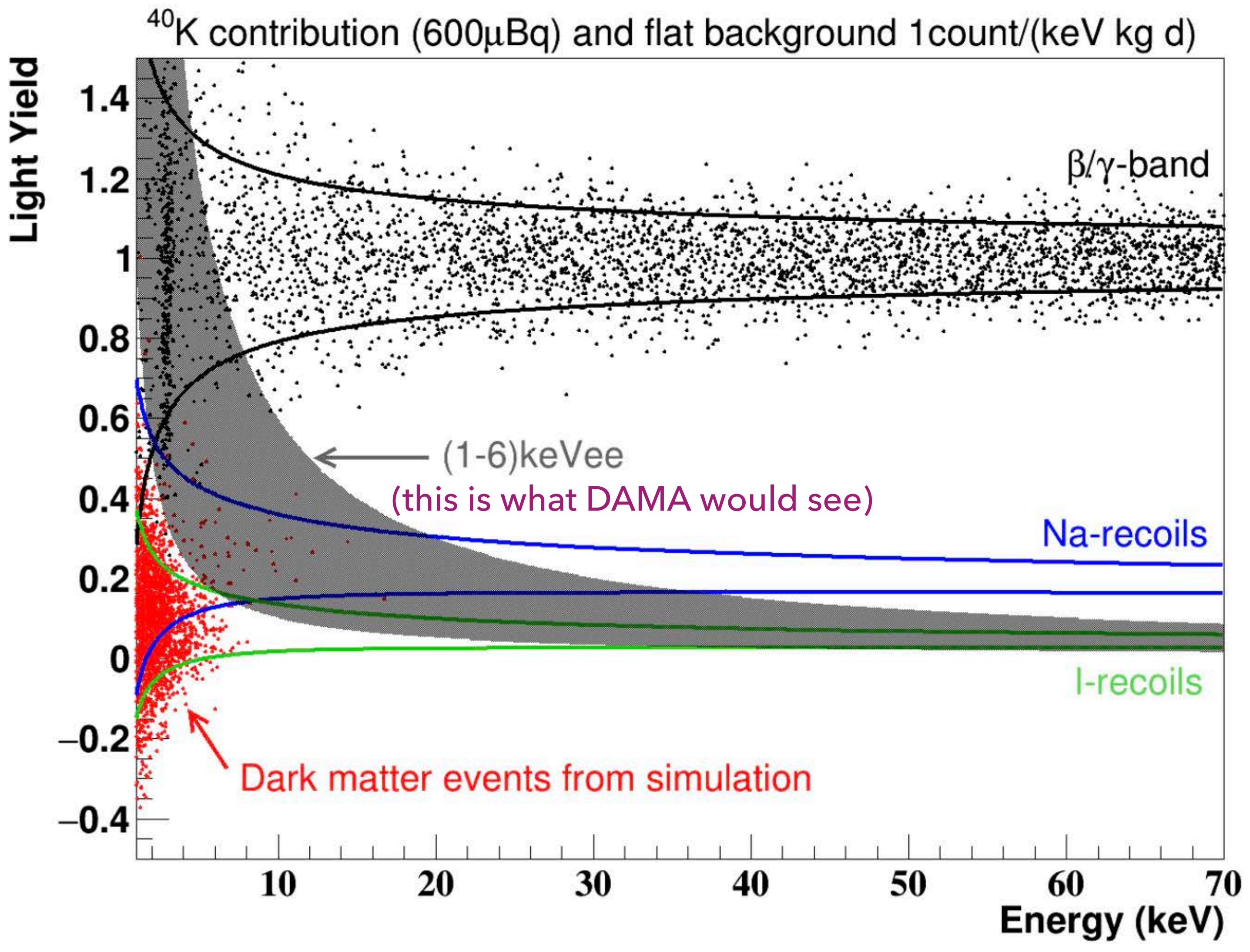
EFT Operators

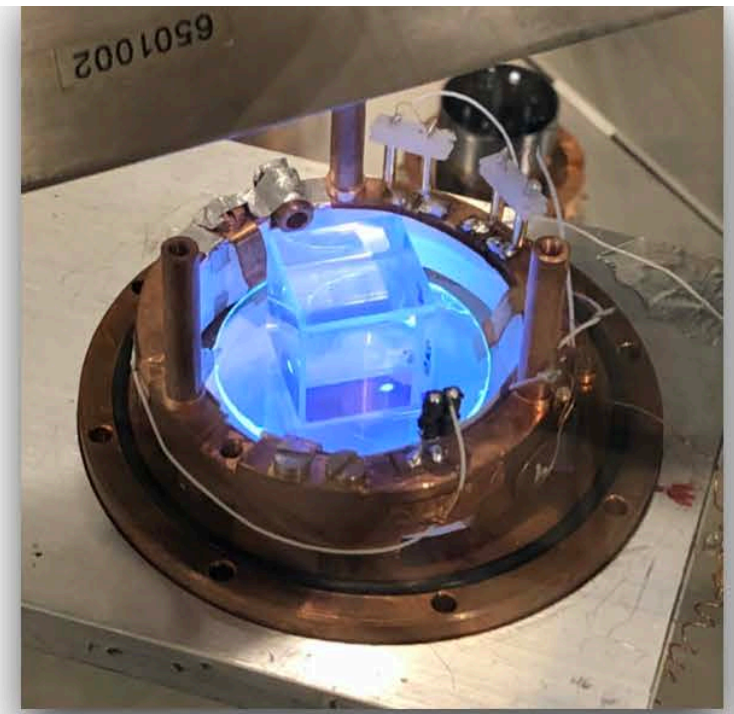
Sci Adv. 2021 Nov 12;7(46):eabk2699

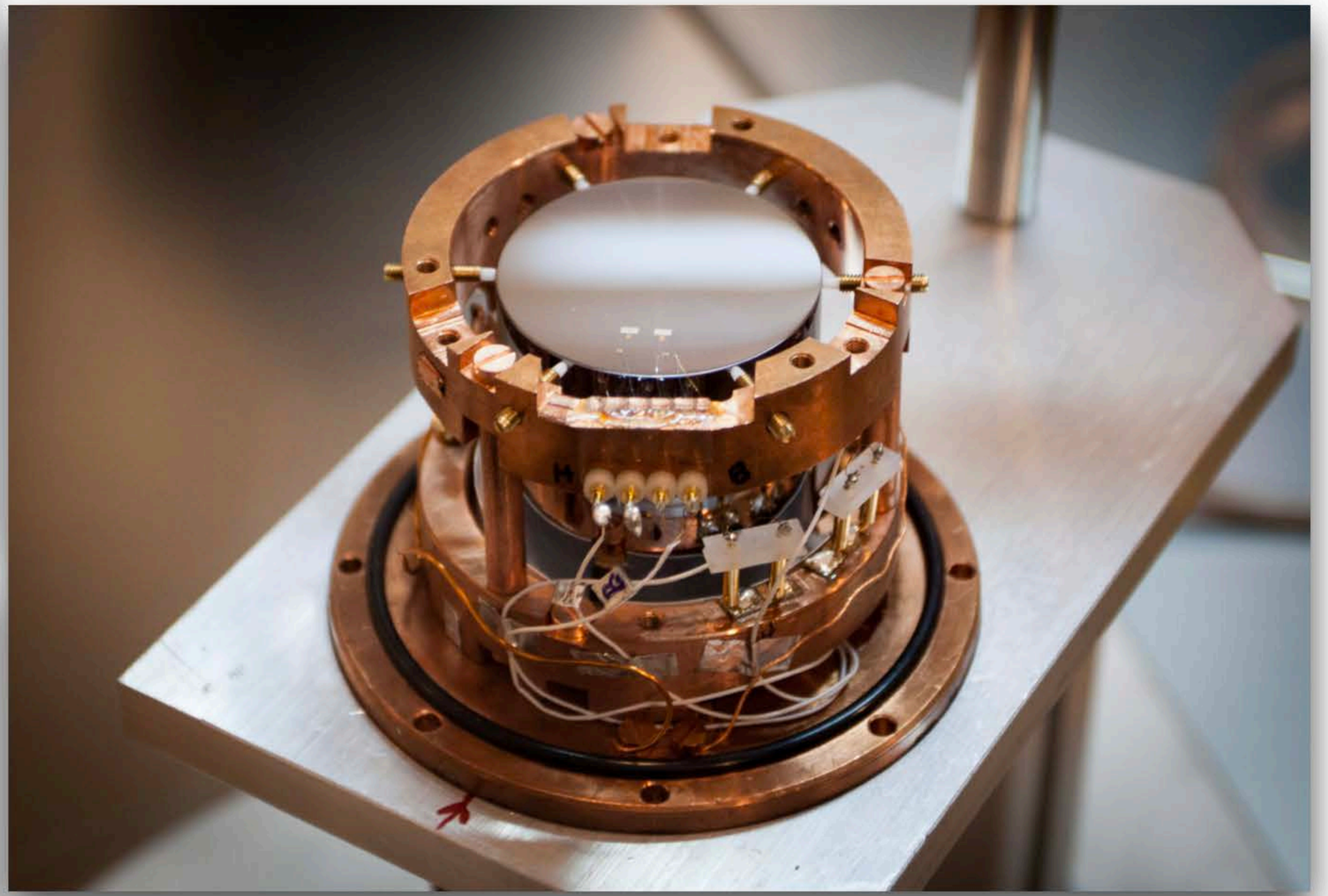


COSINUS

- NaI crystals as cryogenic detectors
- NR vs ER via TES sensors + SQUIDs:
- - Heat (phonons) + scintillation





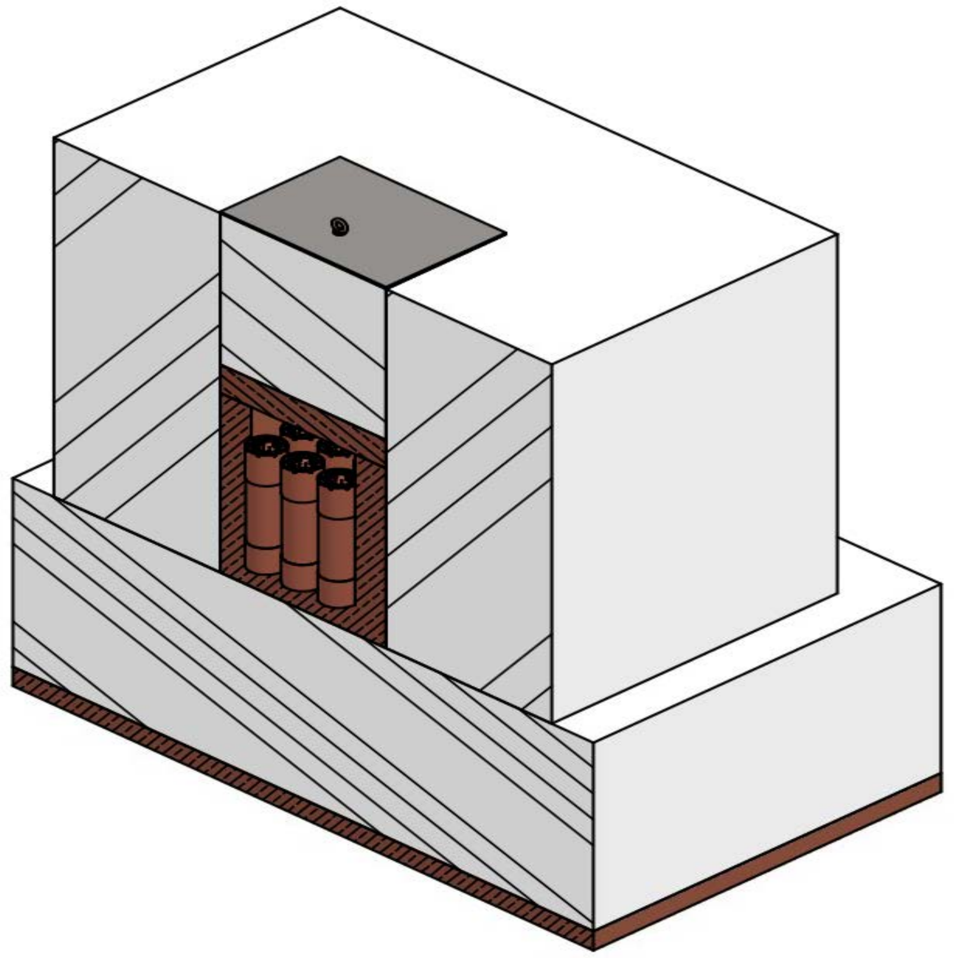


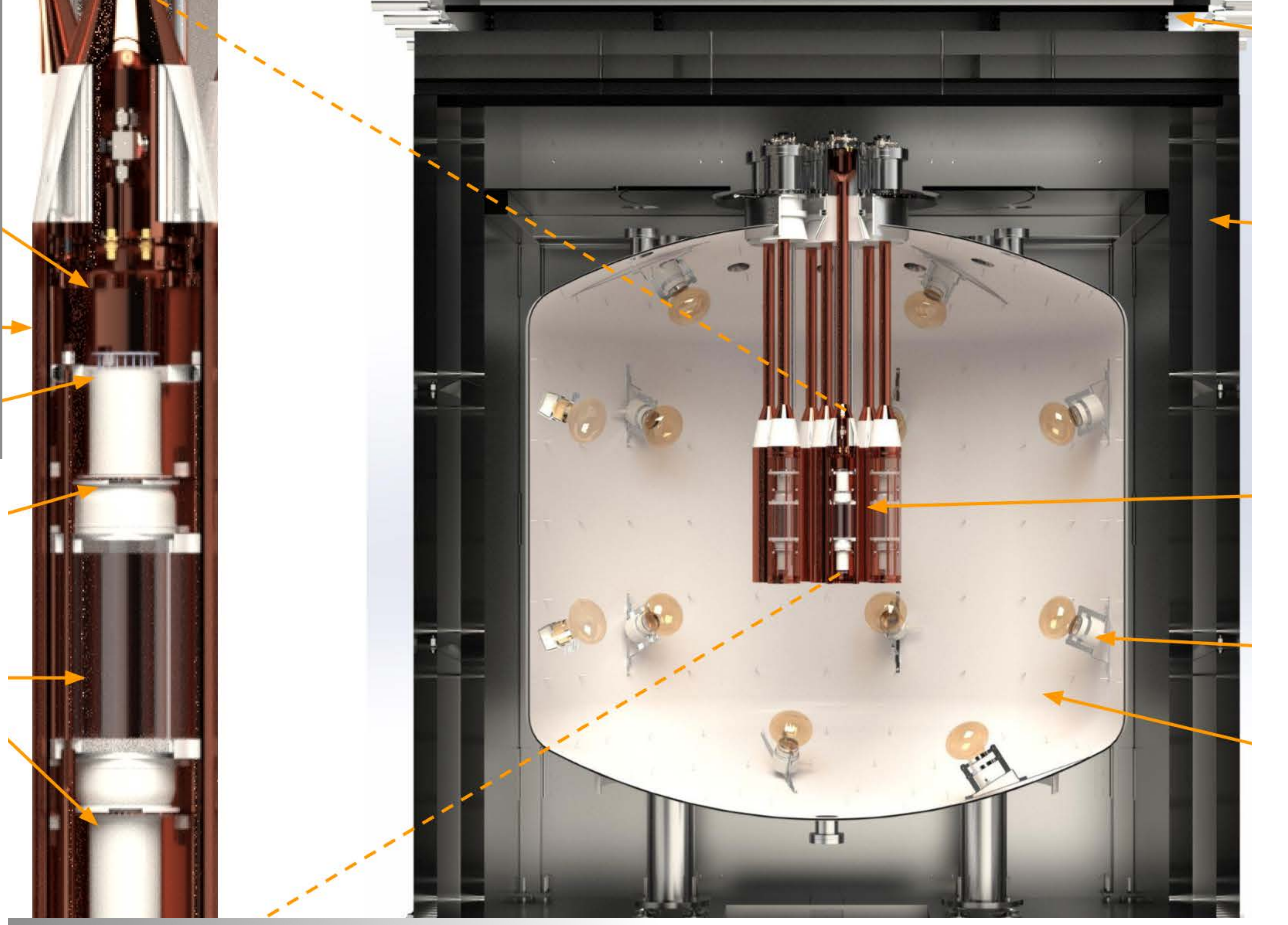
COSINUS

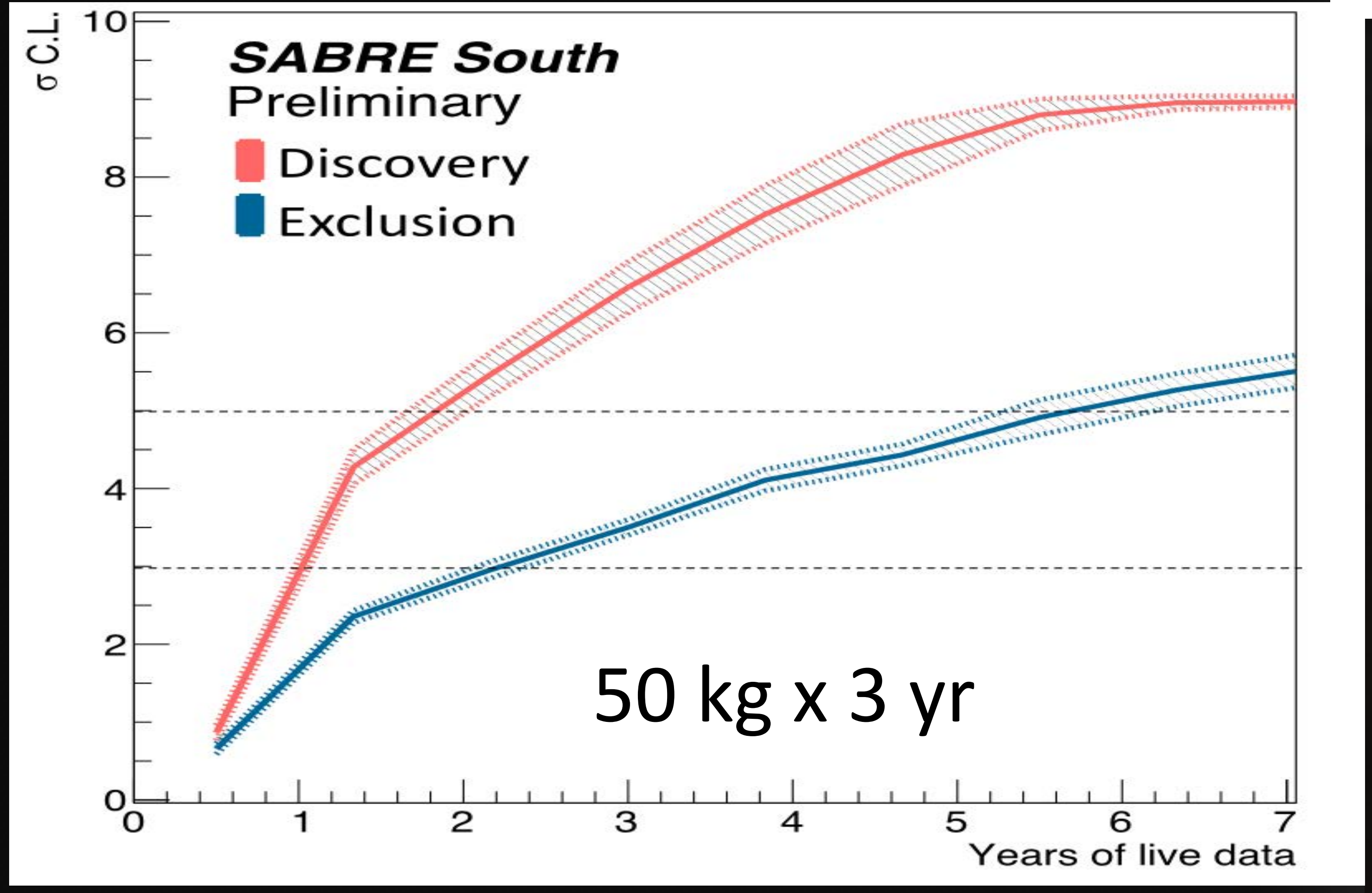
SABRE-North/South

Goal: ~0.1 dru background

Unambiguous test by running in both hemispheres

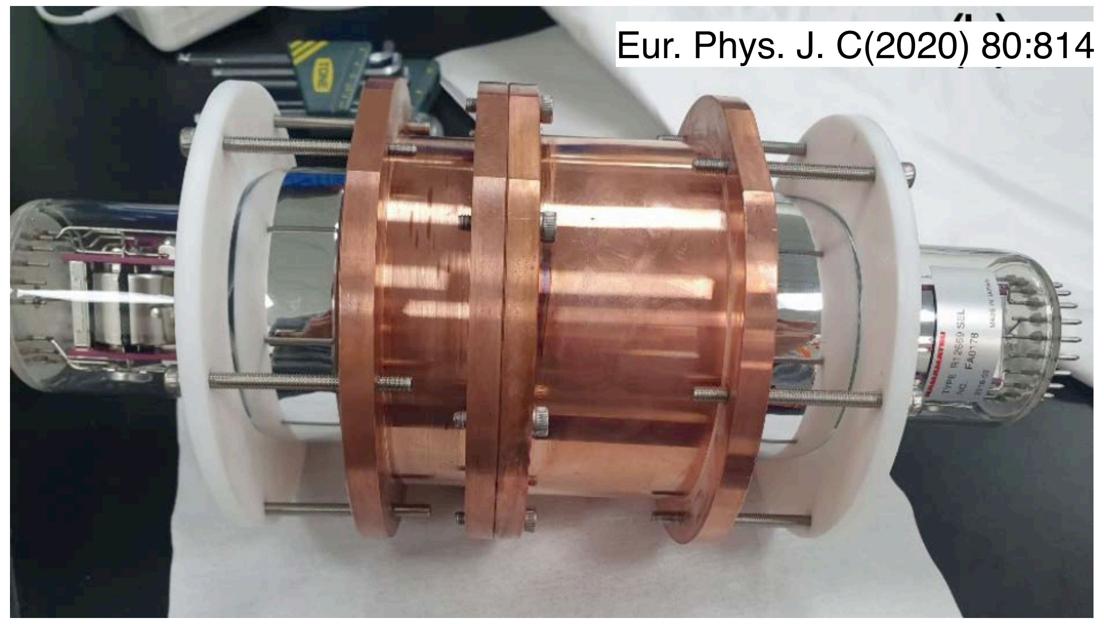






Conclusions





- DAMA sees annual modulation
- No signal from other direct detection experiments
- ANAIS-112 & COSINE-100 offer direct test, no clear observation of modulation
- However, no explanation for DAMA's signal
  - SABRE & COSINUS may offer new information
- NaI to continue with dark matter searches (see G. Adhikari's talk)