Recent Results from the COSINE-100 Experiment

Jay Hyun Jo
Yale University

MultiDark Consolider Workshop
April 4, 2019

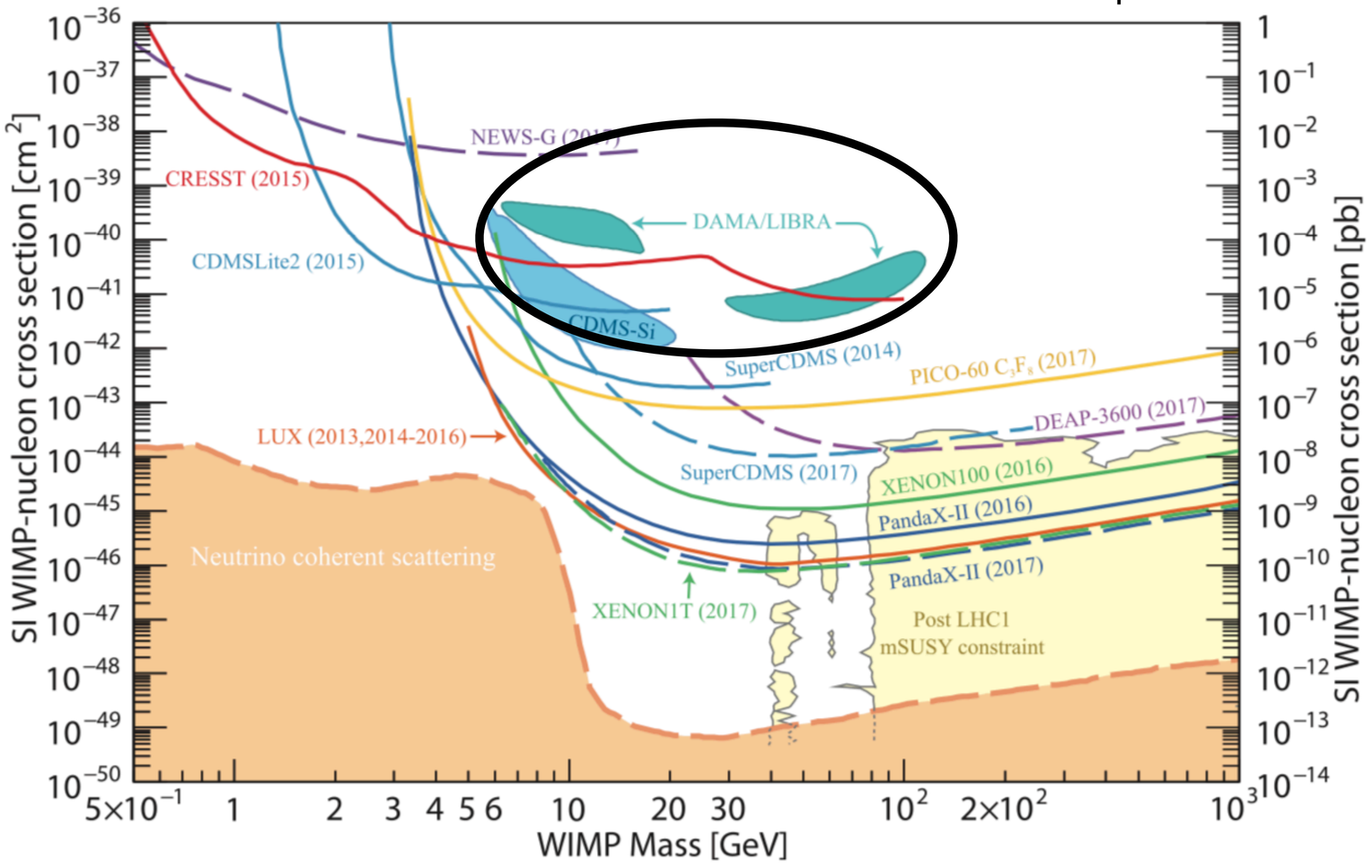
Wright Laboratory

Yale

Current status of direct dark matter searches

- No sign of WIMPs down to >10^{-46} cm^2 @ 30 GeV
- New experiments exploring low-mass dark matter
- DAMA's signal remains unresolved

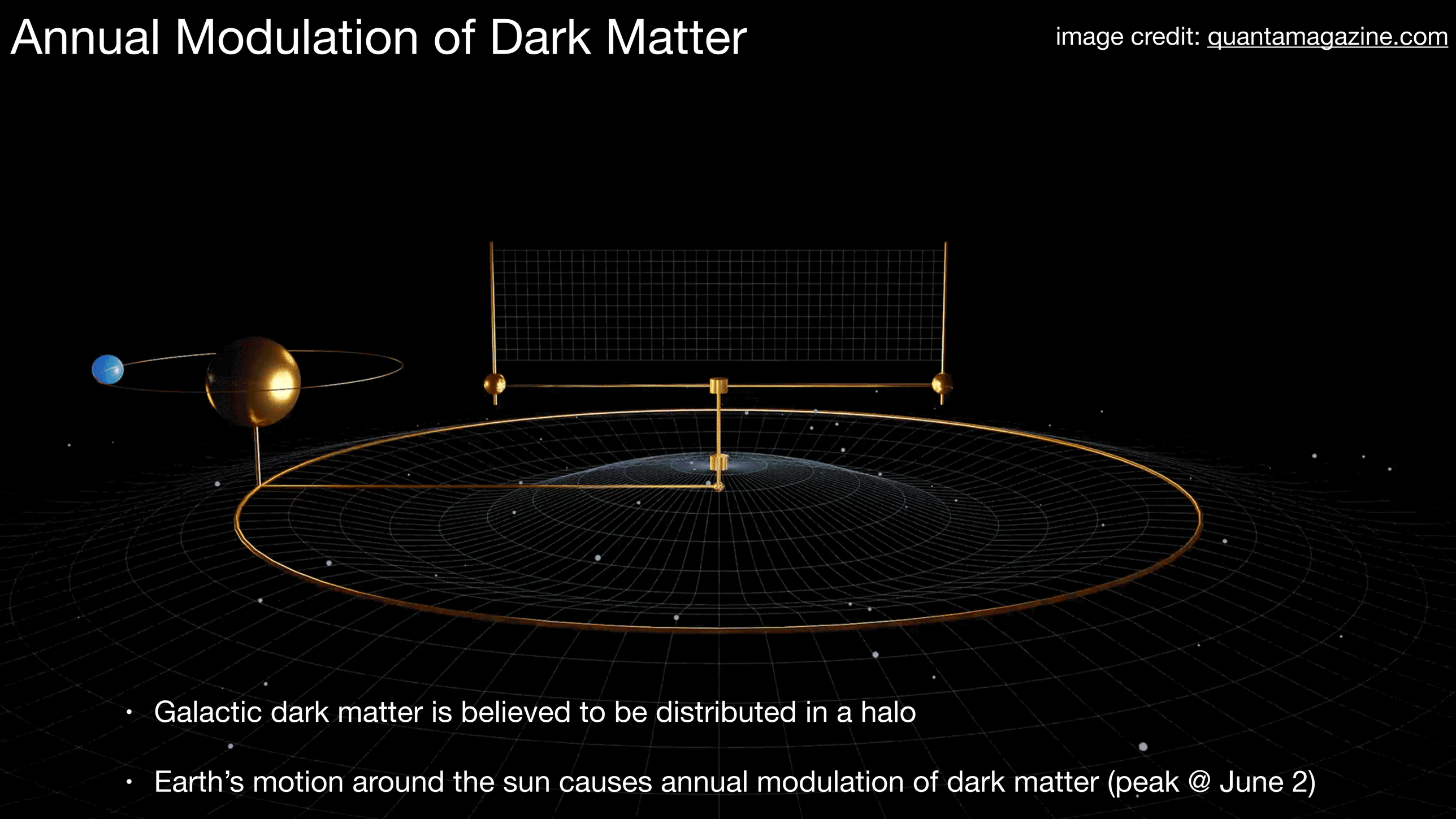
Particle Data Group 2018



Need to directly test DAMA's result with NaI(Tl)

Annual Modulation of Dark Matter

image credit: quantamagazine.com

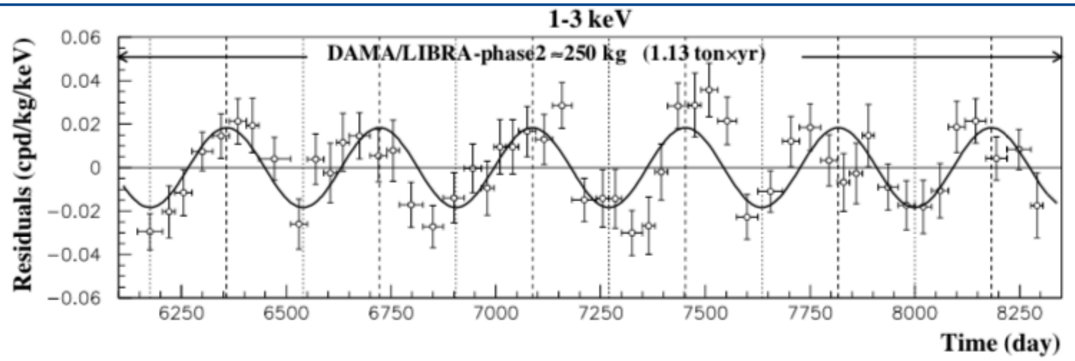


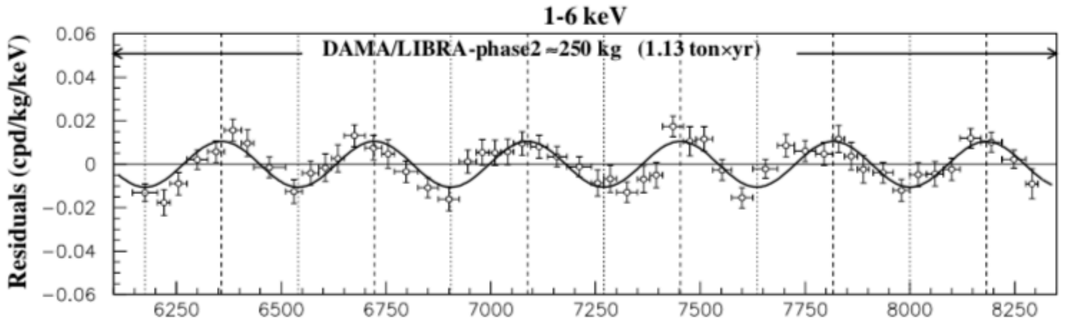
- Galactic dark matter is believed to be distributed in a halo
- Earth’s motion around the sun causes annual modulation of dark matter (peak @ June 2)

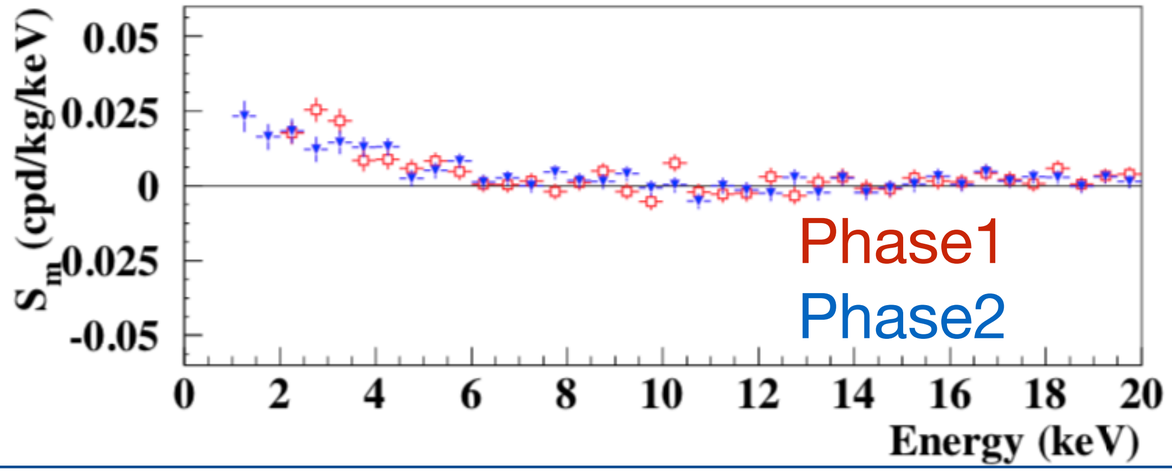
DAMA's annual modulation

Bernabei *et al.*, arXiv:1805.10486

- DAMA/LIBRA-phase2 result announced with 1 keV threshold
  - (1-6) keV: 9.5 σ from 1.13 ton-year
  - (2-6) keV: 12.9 σ from 2.46 ton-year
- **Modulation amplitude: (0.0103±0.0008) cpd/kg/keV in (2-6) keV**
- Phase: (145±5) days
- Period: (0.999±0.001) year

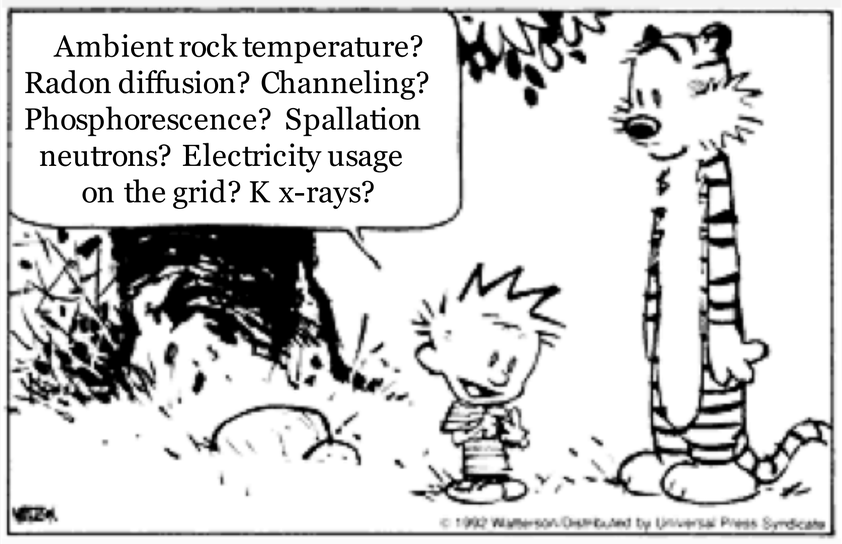






Interpretation of the DAMA result

"What is causing DAMA's modulation? Could it be some backgrounds?"



EPJC 56:333 (2008)
EPJC 72:2064 (2012)
EPJC 74:3196 (2014)

Interpretation of the DAMA result

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?
- ...

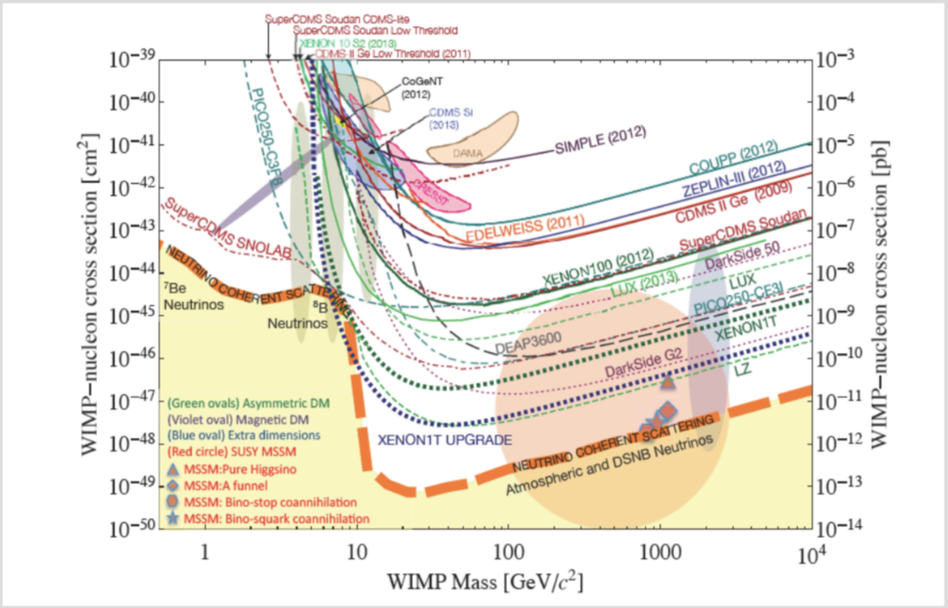
...and experimental aspects...

- 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

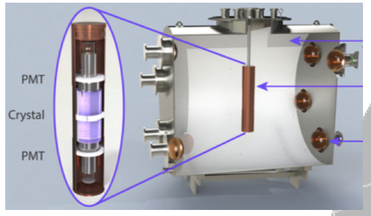
Is it an "universal" and "correct" way to approach the problem of DM and comparisons?



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

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

Global NaI(Tl) efforts



Currently running
Finished/Planned

DAMA

SABRE@LGNS

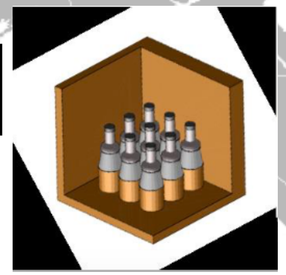
★ Gran Sasso

COSINUS

Yangyang ★

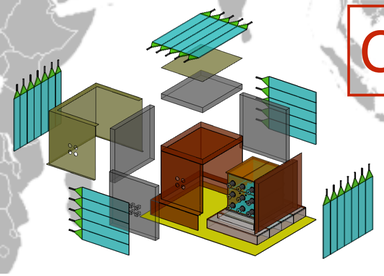
PICO-LON

★ Kamioka



KIMS

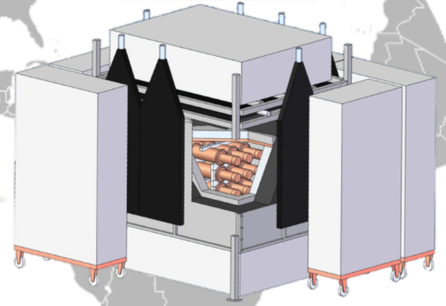
COSINE-100



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)

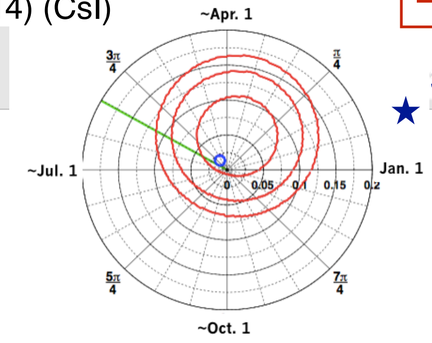
★ Boulby
★ Canfranc

ANAIS



SABRE@Stawell

★ Stawell



Astropart. Phys. **35** (2012) 749
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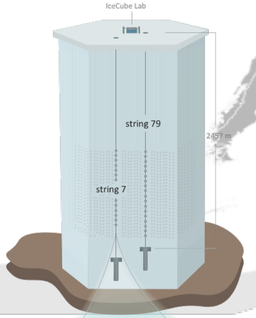
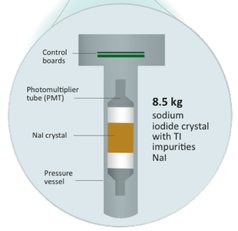
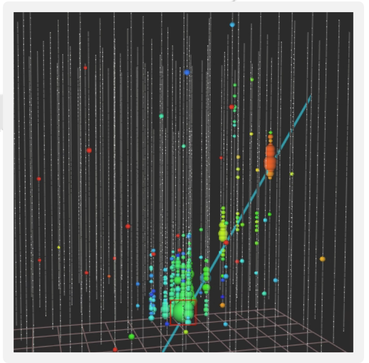
Phys. Rev. D **95** 032006 (2017)

DM-Ice

★ South Pole







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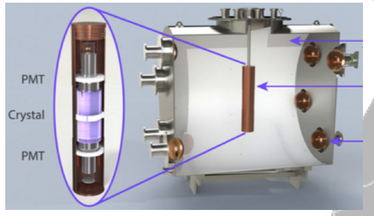

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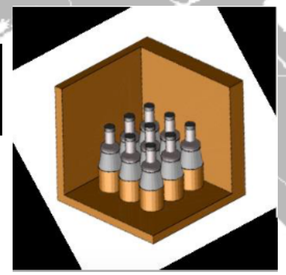

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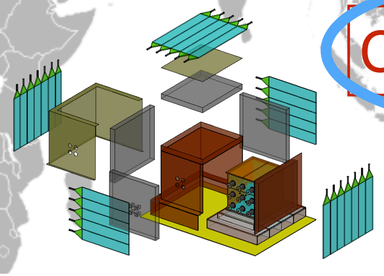
COSINE-100



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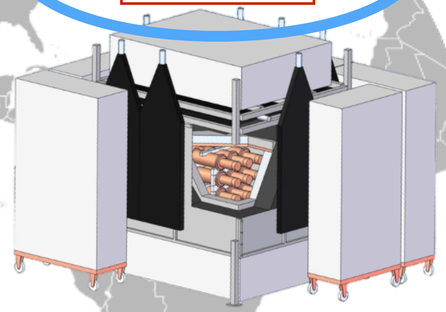

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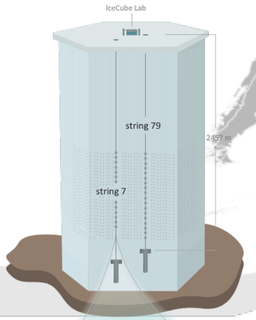

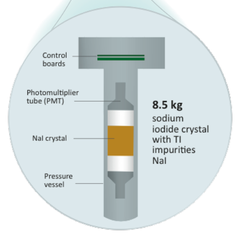

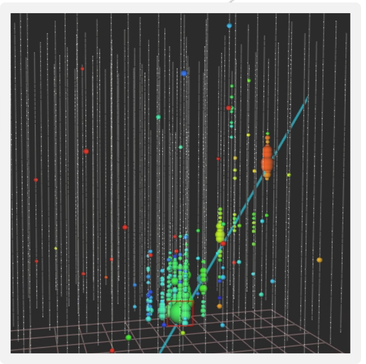

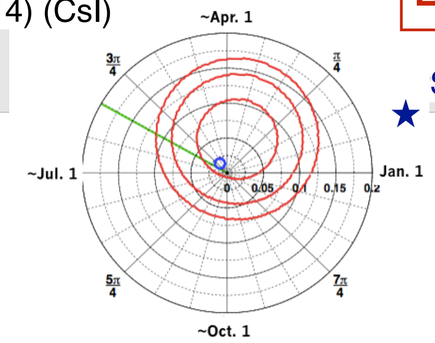

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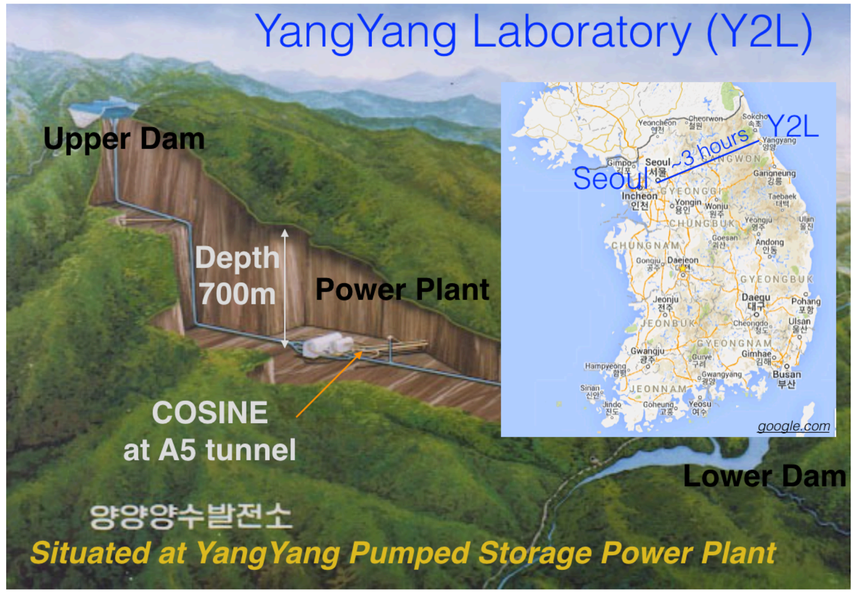
Phys. Rev. D **95** 032006 (2017)

COSINE-100

- A joint effort between DM-Ice and KIMS collaborations
- 8 NaI(Tl) crystals with 106 kg in total
- Located at Yangyang underground laboratory (Y2L), South Korea, with ~700 m rock overburden
- **Physics run started September 2016**



DM-ICE + KIMS Korea Invisible Mass Search Experiment

NSF

Institute for Basic Science ibs 기초과학연구원

KISTI www.kisti.re.kr

KRISS Korea Research Institute of Standards and Science

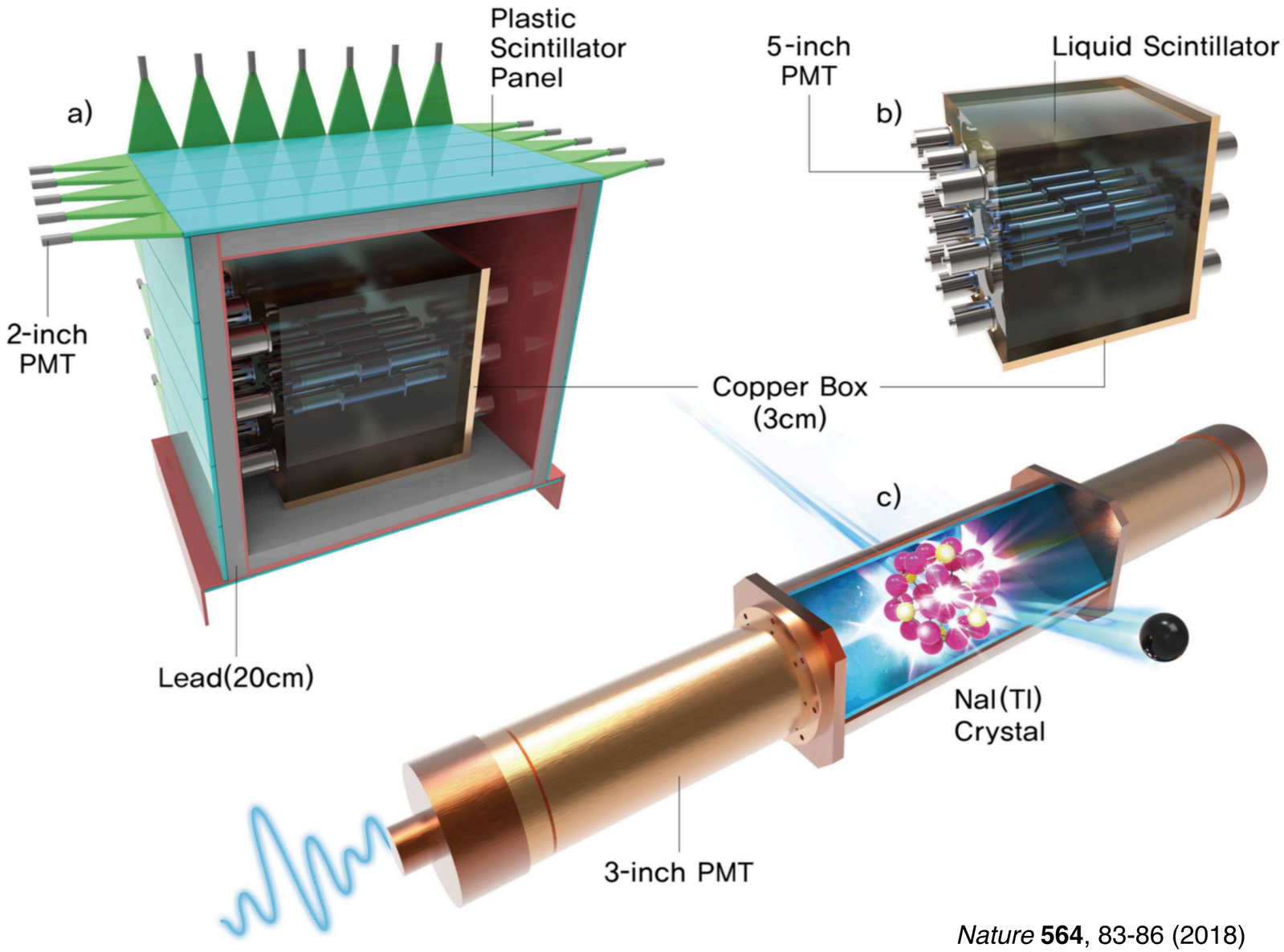
The University Of Sheffield.

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

Yale

COSINE-100 detector configuration

- 37 plastic scintillator panels to tag muons events
- 20cm thick lead shielding and 3cm thick copper box
- 2000L of liquid scintillator to tag internal/external background events
- 8 NaI(Tl) crystals



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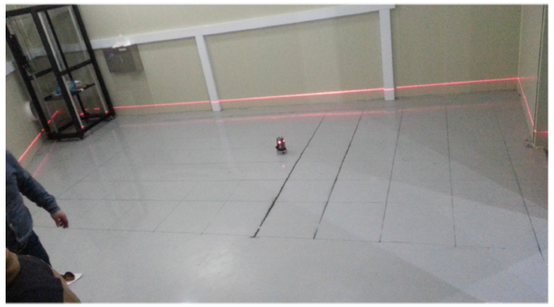
COSINE-100 construction timeline

Dec. 2015



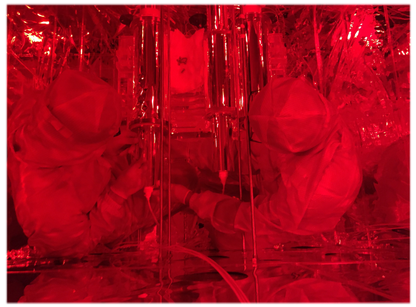
Jan. 2016

Feb. 2016

Mar. 2016

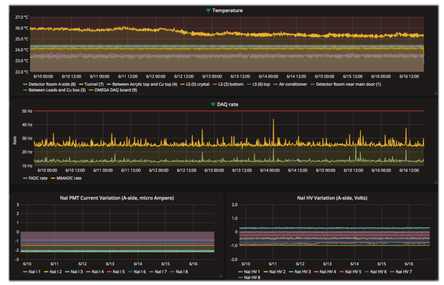
Apr. 2016

May. 2016

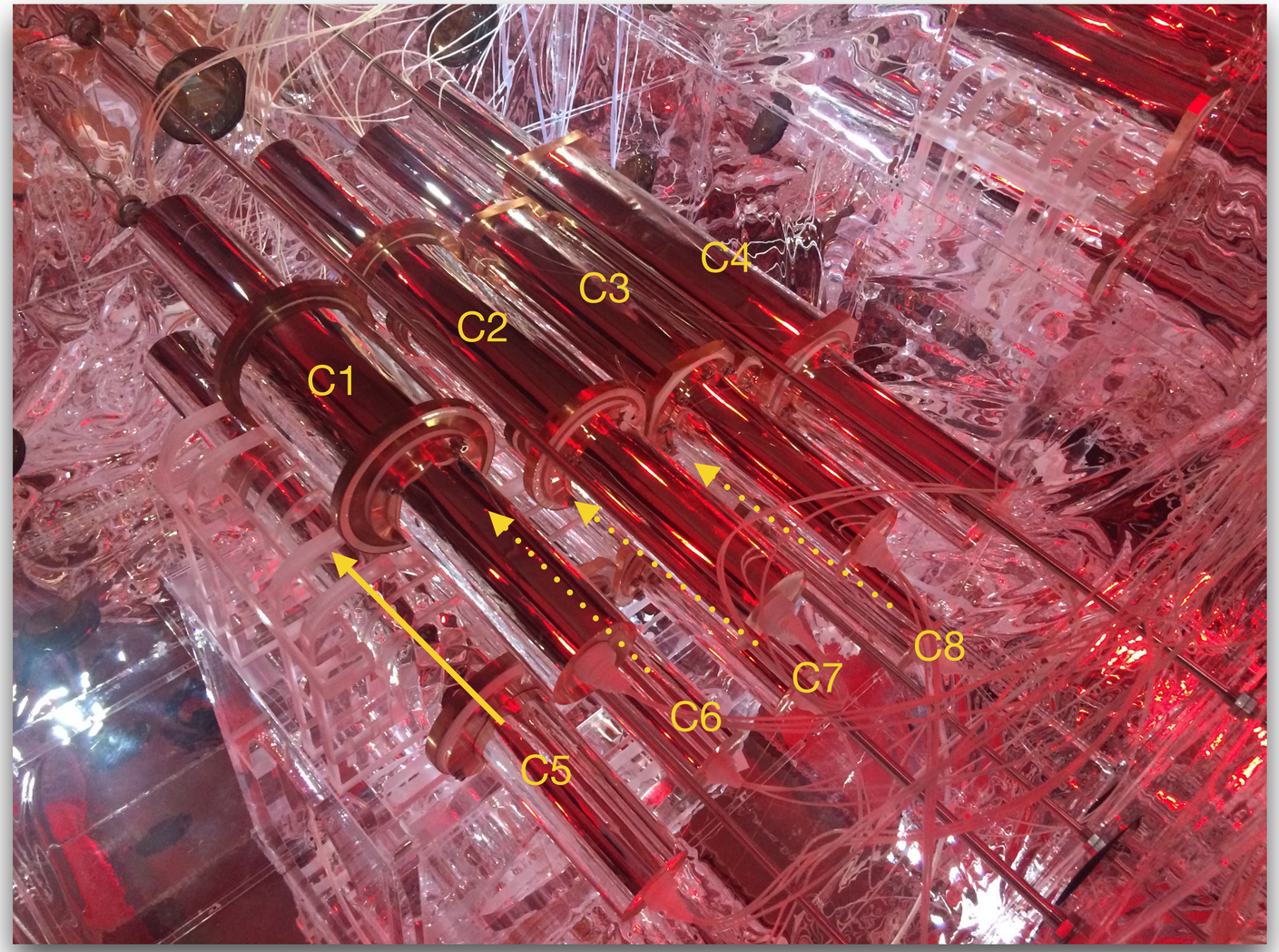


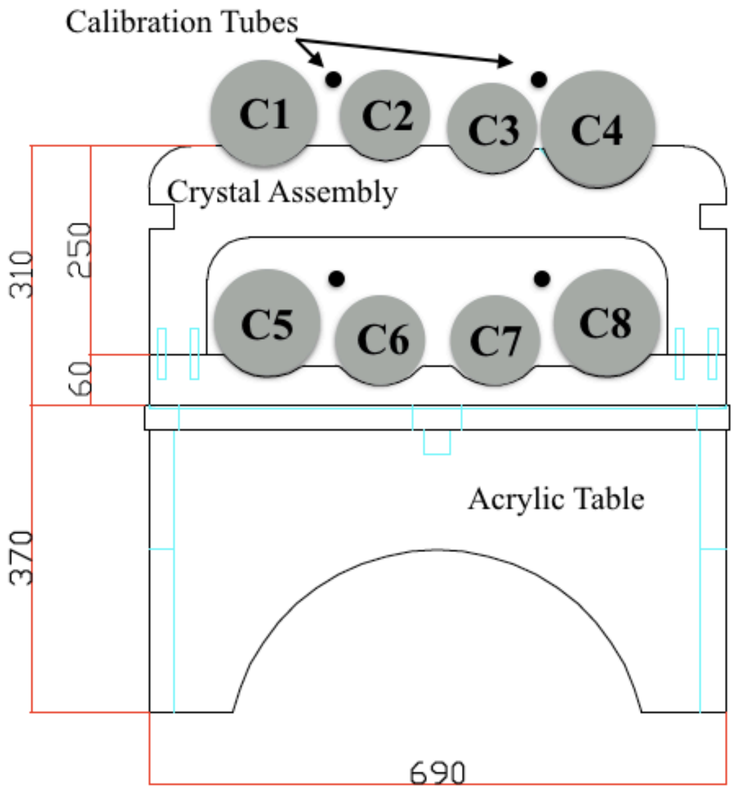
Jun. 2016

Sep. 2016



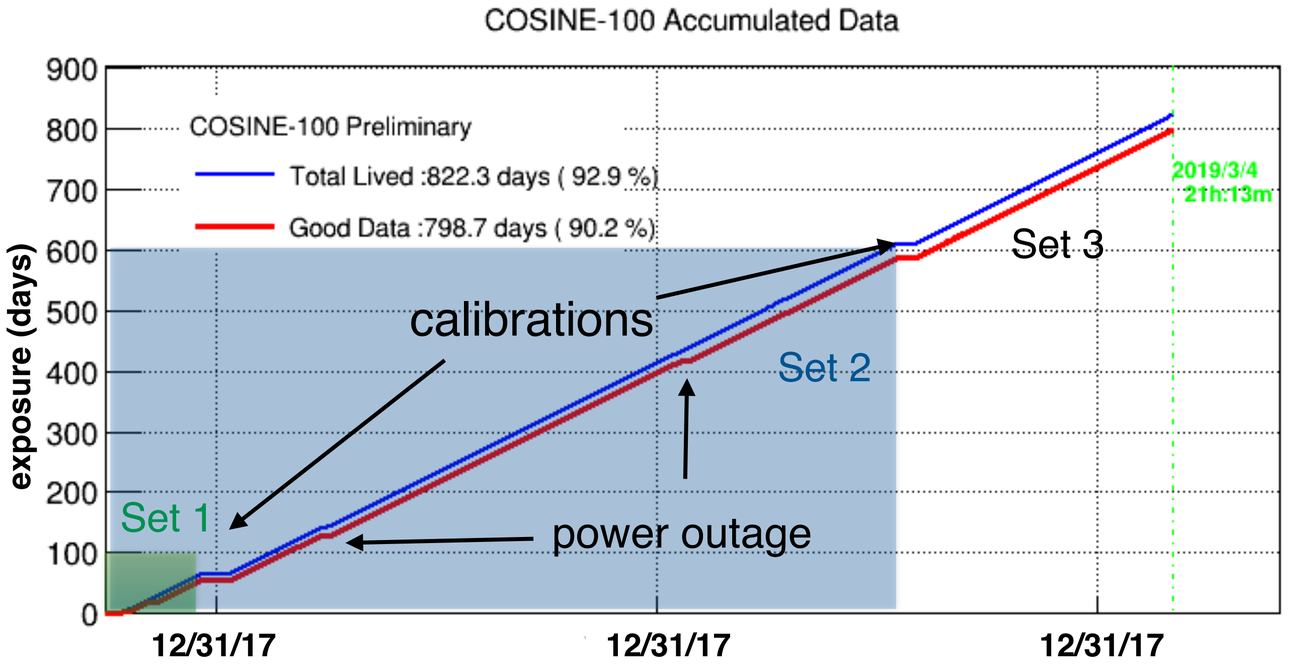
Crystal configuration





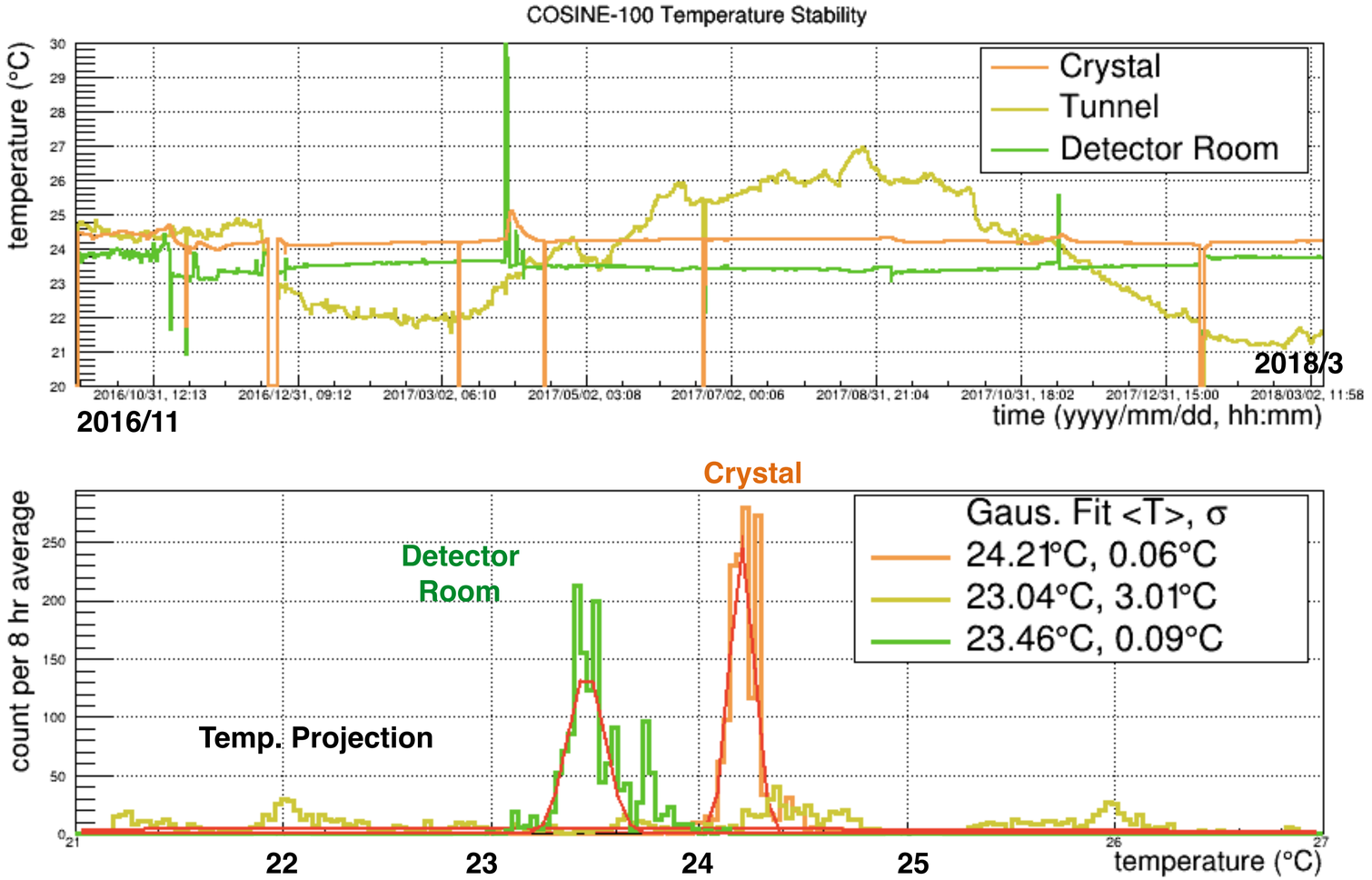
COSINE-100 operation

- Data taking since Sep. 2016
  - Stable operation
  - ~90% live time
  - Near 100% uptime outside of calibration
- > 2 years of data accumulation
  - SET1 data (59.5 days) - Background modeling, detector understanding, and WIMP analysis
  - SET2 data (621.0 days) - Annual modulation analysis



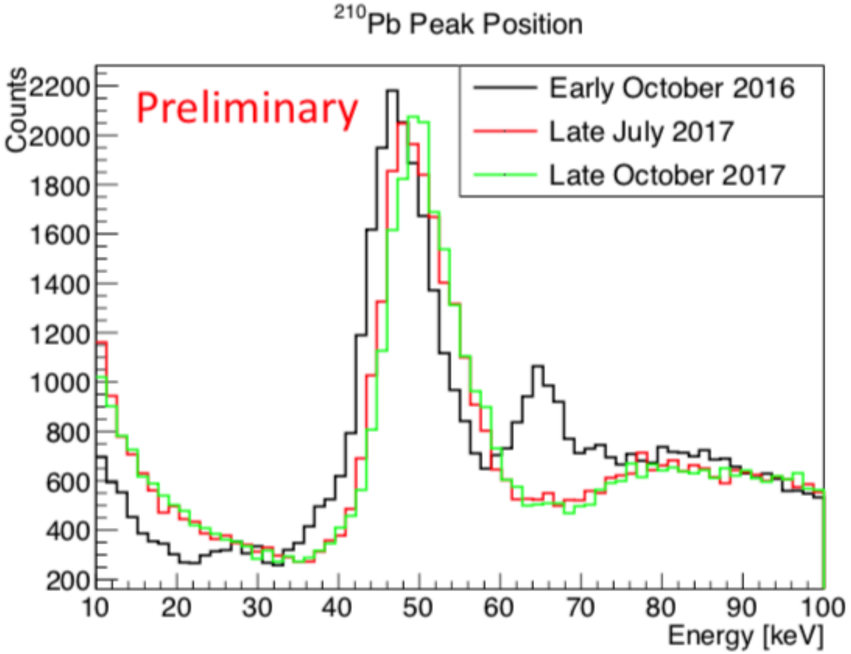
Environmental control/monitoring

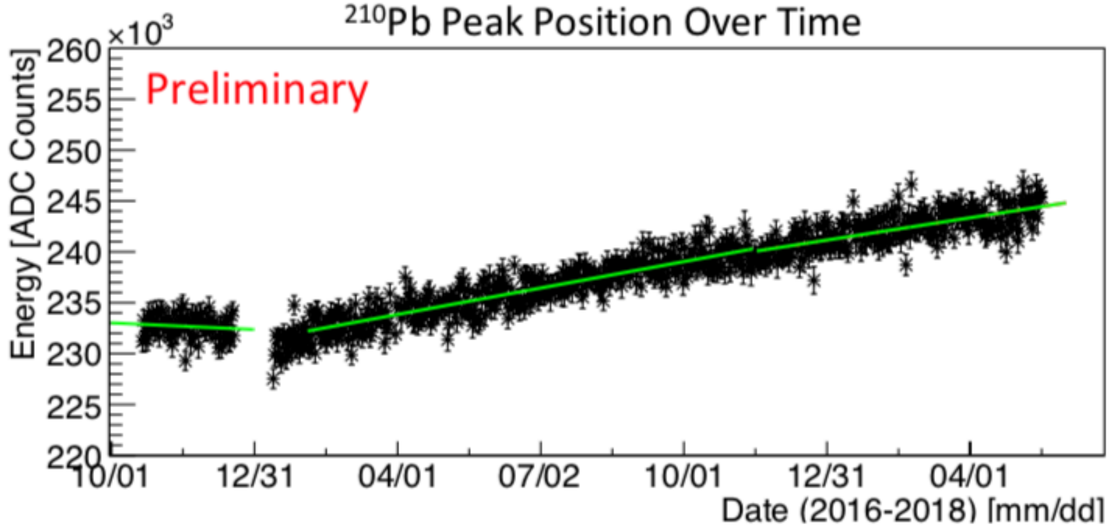
- Monitoring stability of temperature, humidity, current/voltage, etc.
- < 0.1 ℃ temperature and < 2% humidity fluctuation inside the shielding structure
- Current and voltage of detectors very stable

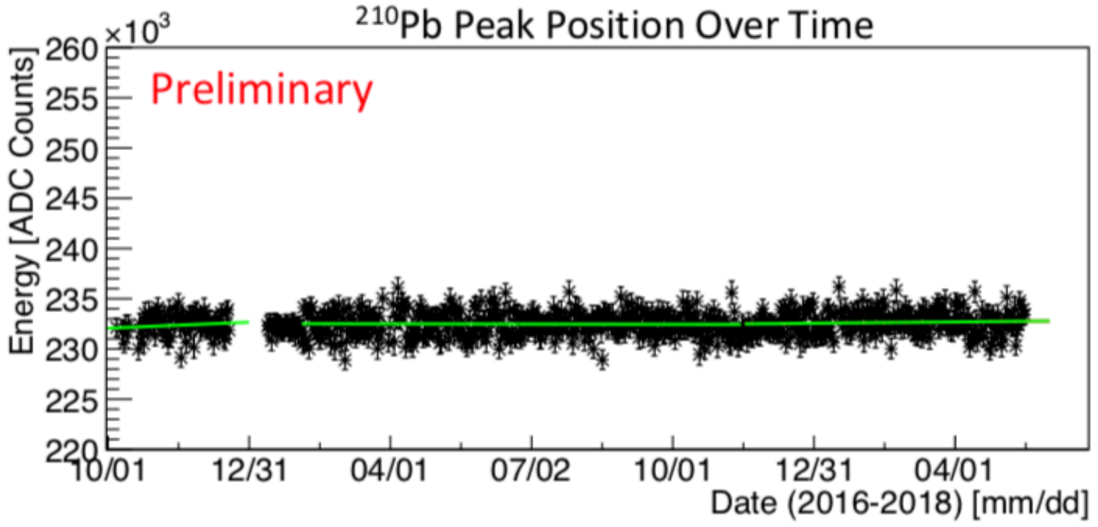


Correcting for Gain Shifts

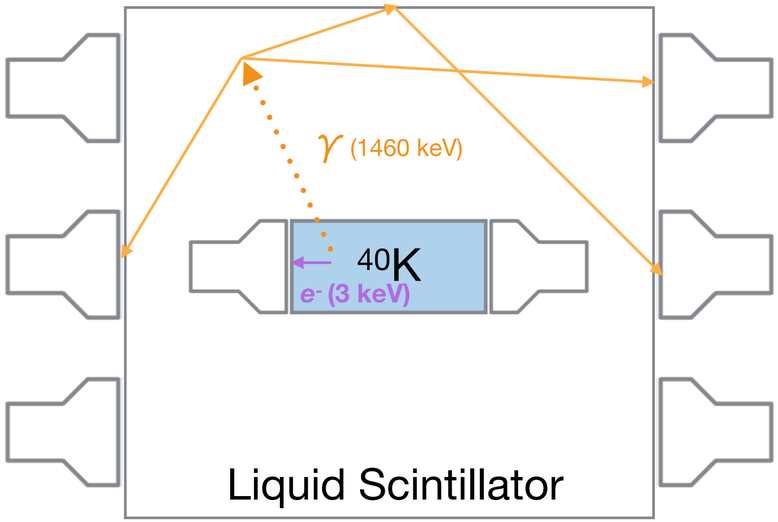
- Position of internal ^{210}Pb decays also monitored over time
- Gain shift corrected for by dividing out linear behavior

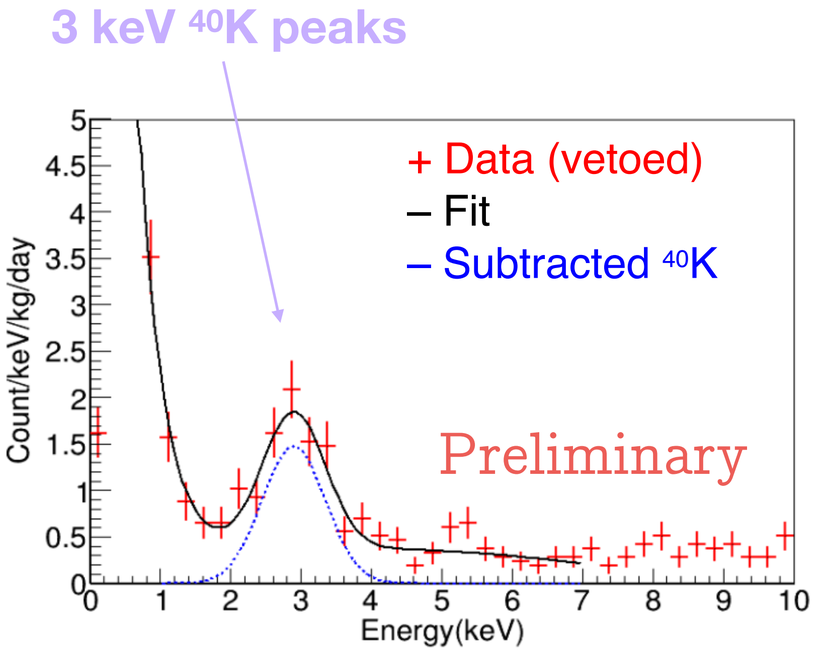


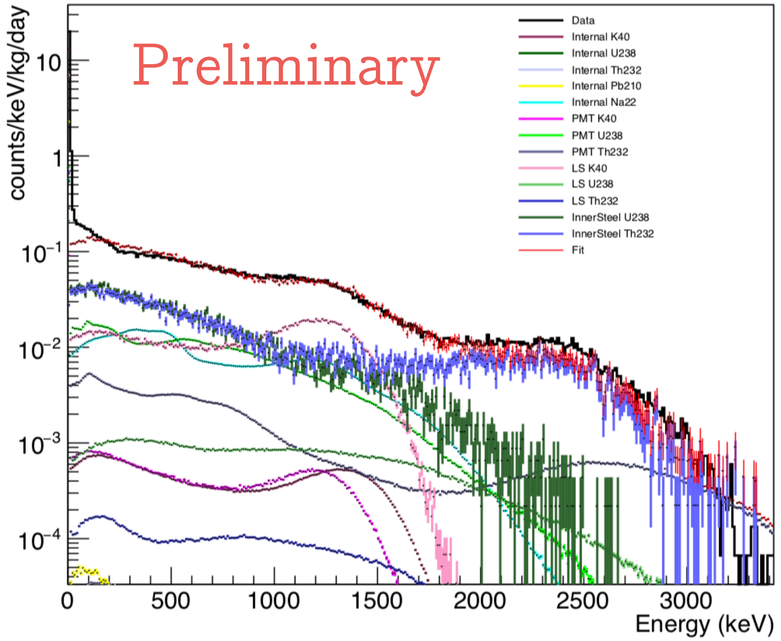




Liquid scintillator veto





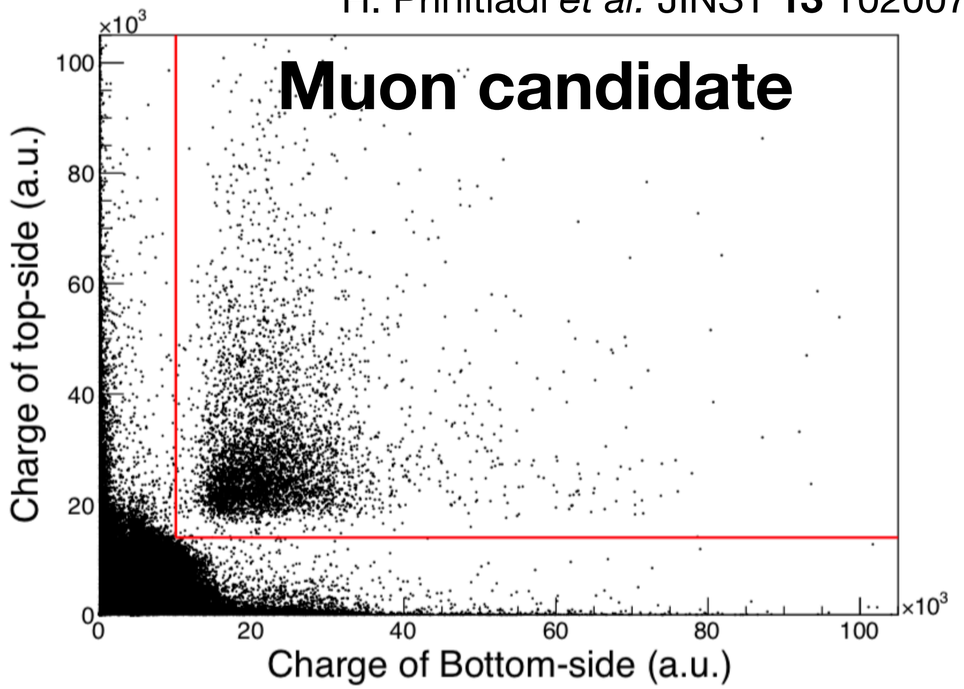


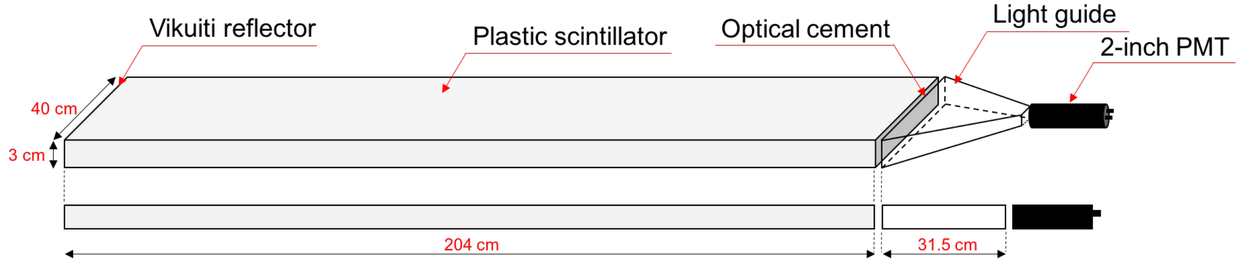
- ^{40}K emits 1460 keV gamma with 3 keV Auger electron energy deposition in NaI crystal
- **Tagging 1460 keV events with LS enables vetoing of 3 keV background events**
- Liquid scintillator internal contamination well modeled with simulation

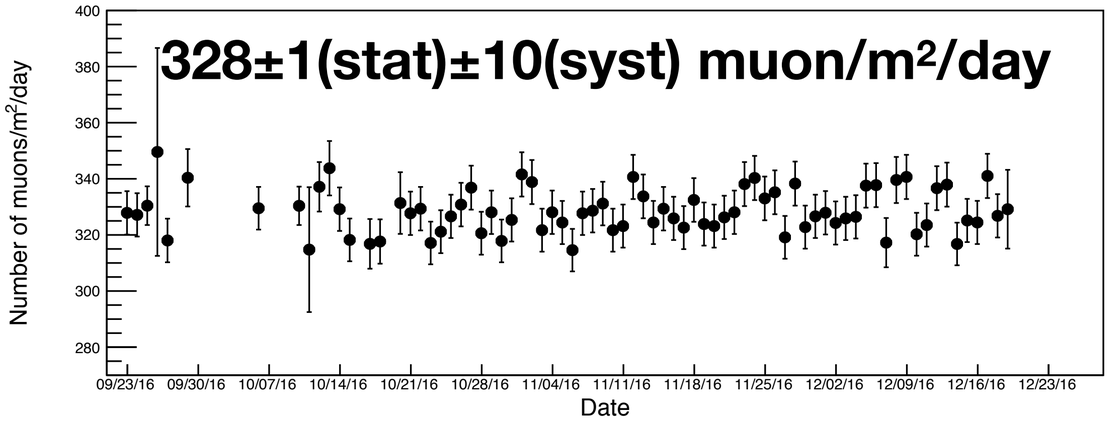
Muon detector

- Muon veto with 37 plastic scintillator panels with 2-inch PMTs
- Events correlated with muon tagged
- Muon-induced events in NaI(Tl) under investigation

H. Prihitiadi *et al.* JINST **13** T02007 (2018)



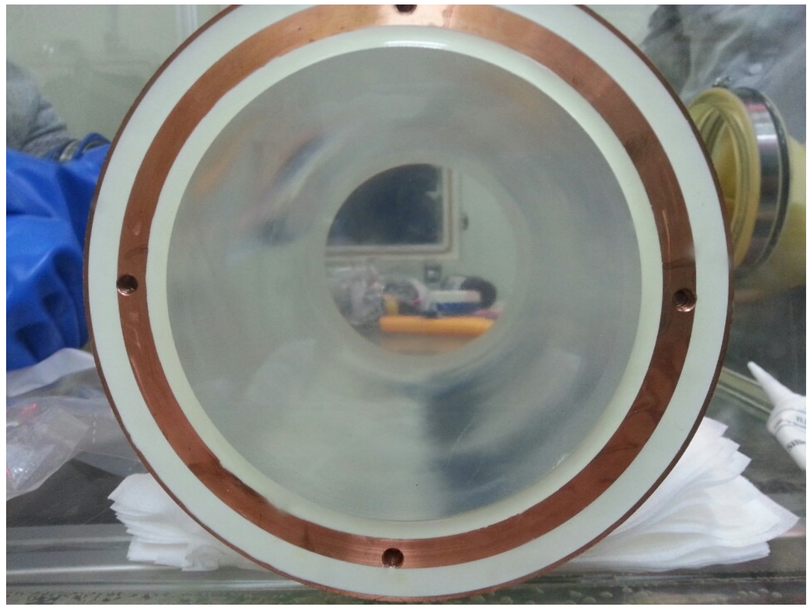


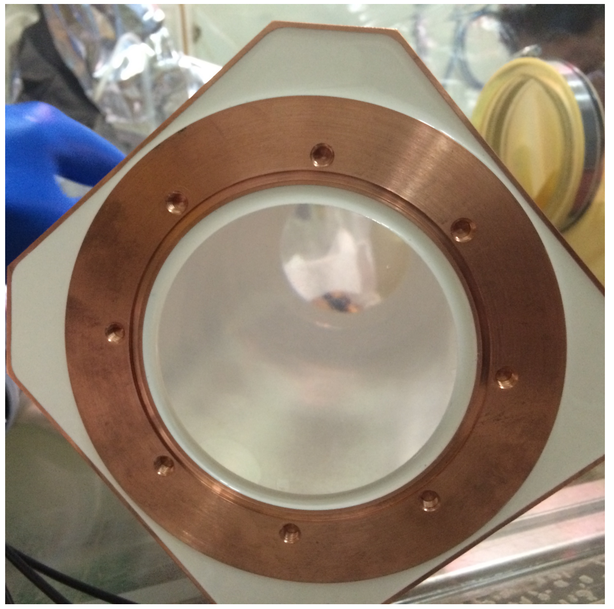


COSINE-100 NaI(Tl) crystals

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

- 8 Crystals, total 106 kg
- Culmination of R&D program with Alpha Spectra
- **U/Th/K below DAMA, ^{210}Po very close**
- High light yield
  - Crystal-5 & 8 used primarily for veto due to low light yield

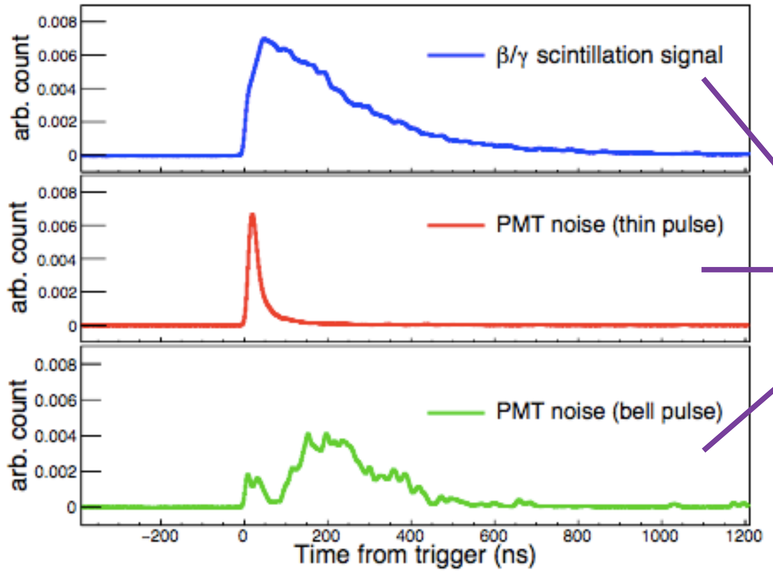


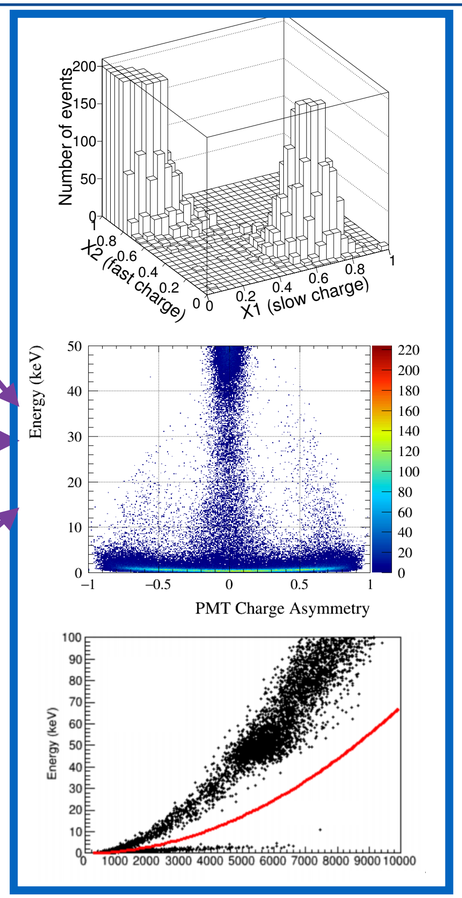


Crystal	Mass (kg)	Size (inches diameter×length)	Powder	α Rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light Yield (PEs/keV)
Crystal-1	8.3	5.0×7.0	AS-B	3.20 ± 0.08	43.4 ± 13.7	<0.02	1.3 ± 0.4	14.9 ± 1.5
Crystal-2	9.2	4.2×11.0	AS-C	2.06 ± 0.06	82.7 ± 12.7	<0.12	<0.6	14.6 ± 1.5
Crystal-3	9.2	4.2×11.0	AS-WSII	0.76 ± 0.02	41.1 ± 6.8	<0.04	0.4 ± 0.2	15.5 ± 1.6
Crystal-4	18.0	5.0×15.3	AS-WSII	0.74 ± 0.02	39.5 ± 8.3		<0.3	14.9 ± 1.5
Crystal-5	18.3	5.0×15.5	AS-C	2.06 ± 0.05	86.8 ± 10.8		2.4 ± 0.3	7.3 ± 0.7
Crystal-6	12.5	4.8×11.8	AS-WSIII	1.52 ± 0.04	12.2 ± 4.5	<0.02	0.6 ± 0.2	14.6 ± 1.5
Crystal-7	12.5	4.8×11.8	AS-WSIII	1.54 ± 0.04	18.8 ± 5.3		<0.6	14.0 ± 1.4
Crystal-8	18.3	5.0×15.5	AS-C	2.05 ± 0.05	56.2 ± 8.1		<1.4	3.5 ± 0.3
DAMA				< 0.5	< 20	0.7−10	0.5−7.5	5.5−7.5

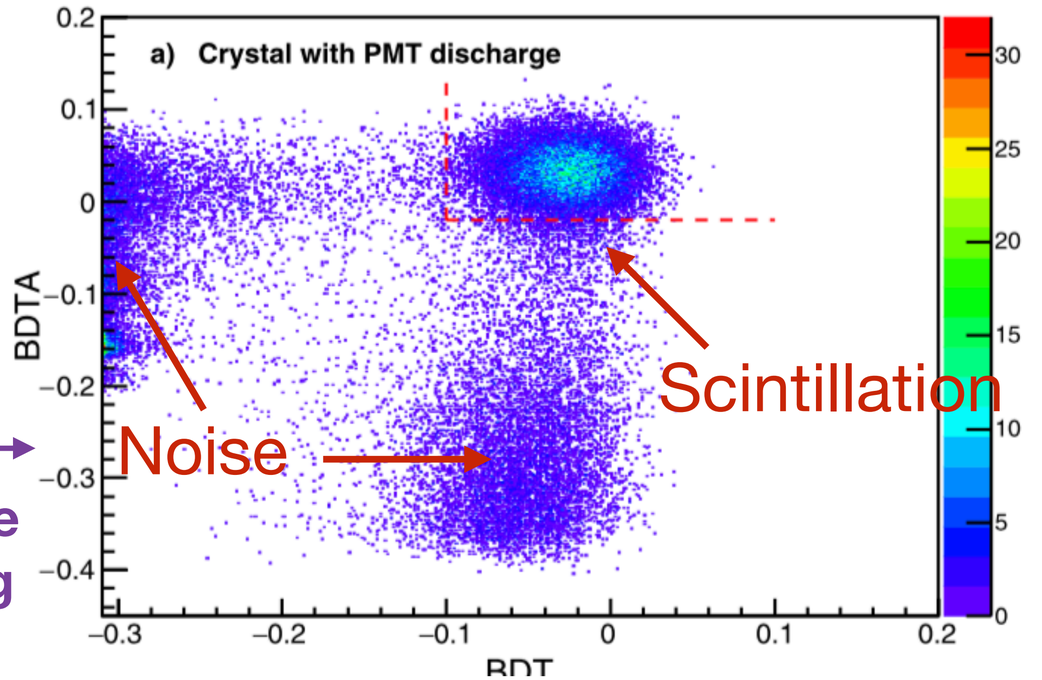
PMT noise rejection

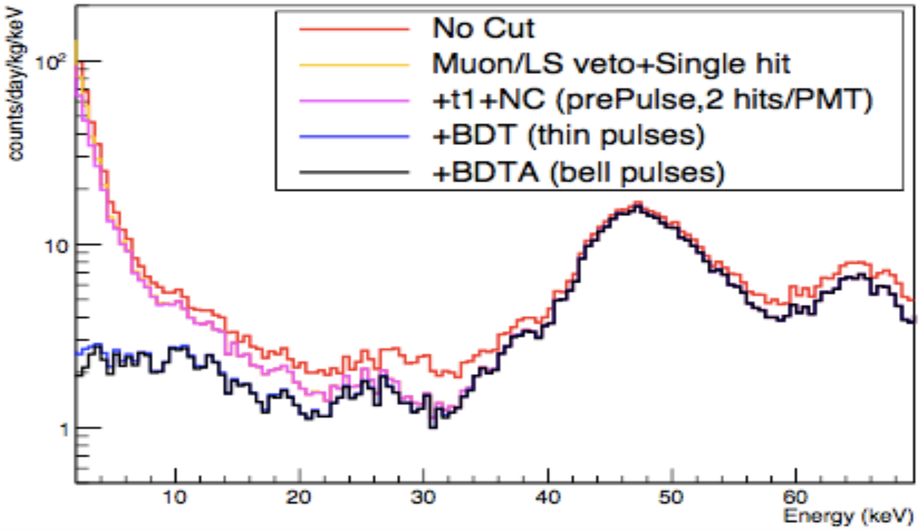
Nature **564**, 83-86 (2018)





Machine learning

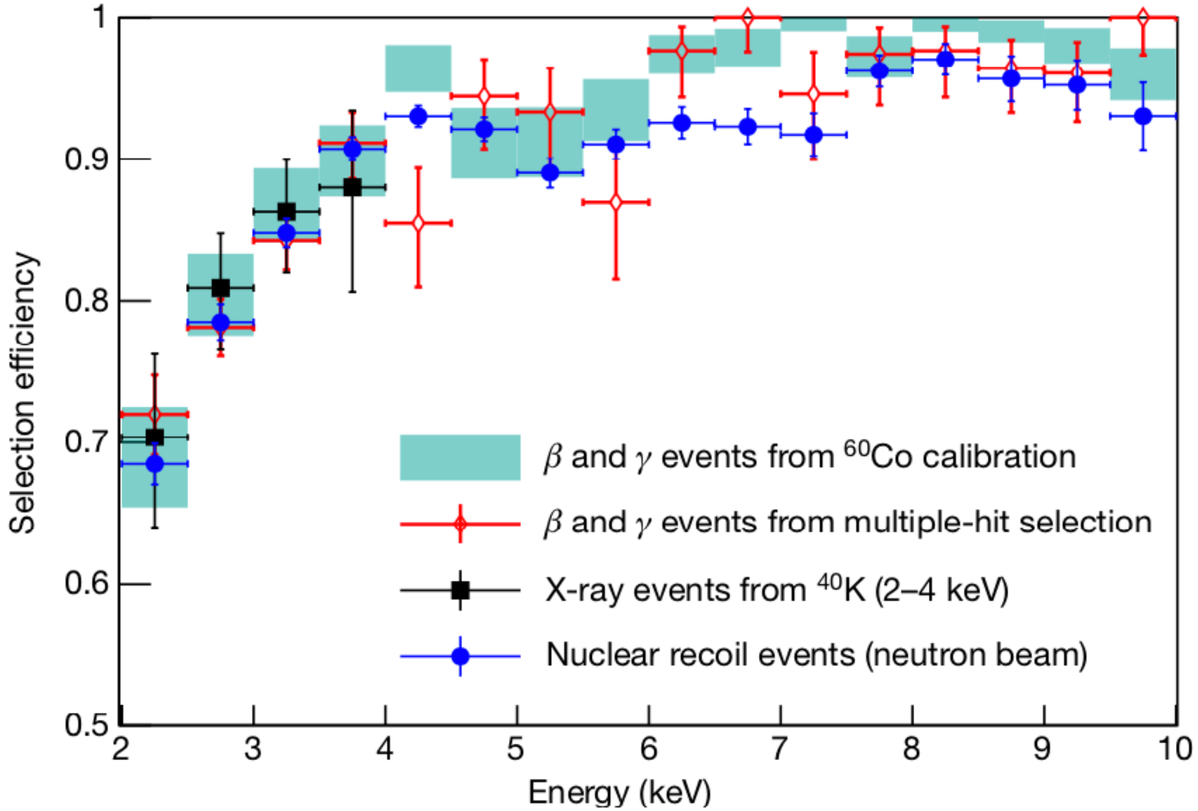


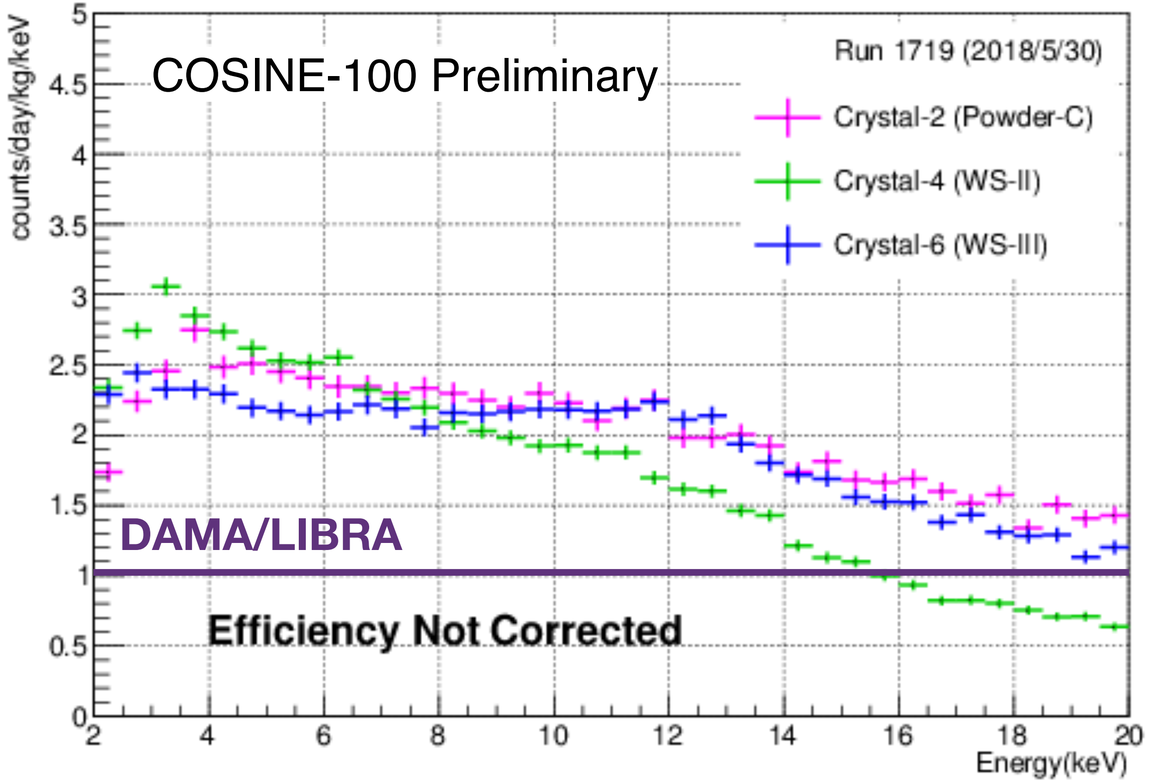


- Dominant source of noise events comes from PMT noise
- Boosted Decision Tree (BDT) was utilized to reject such noise events

Selection efficiency/Low energy spectrum

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

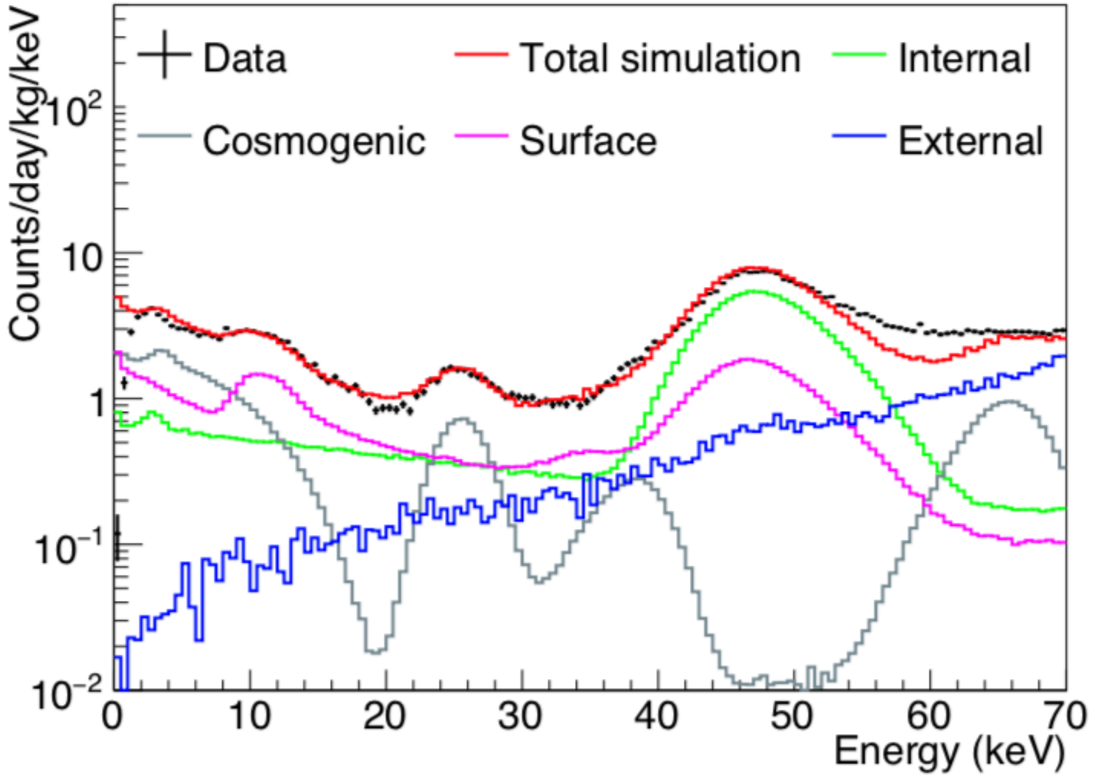


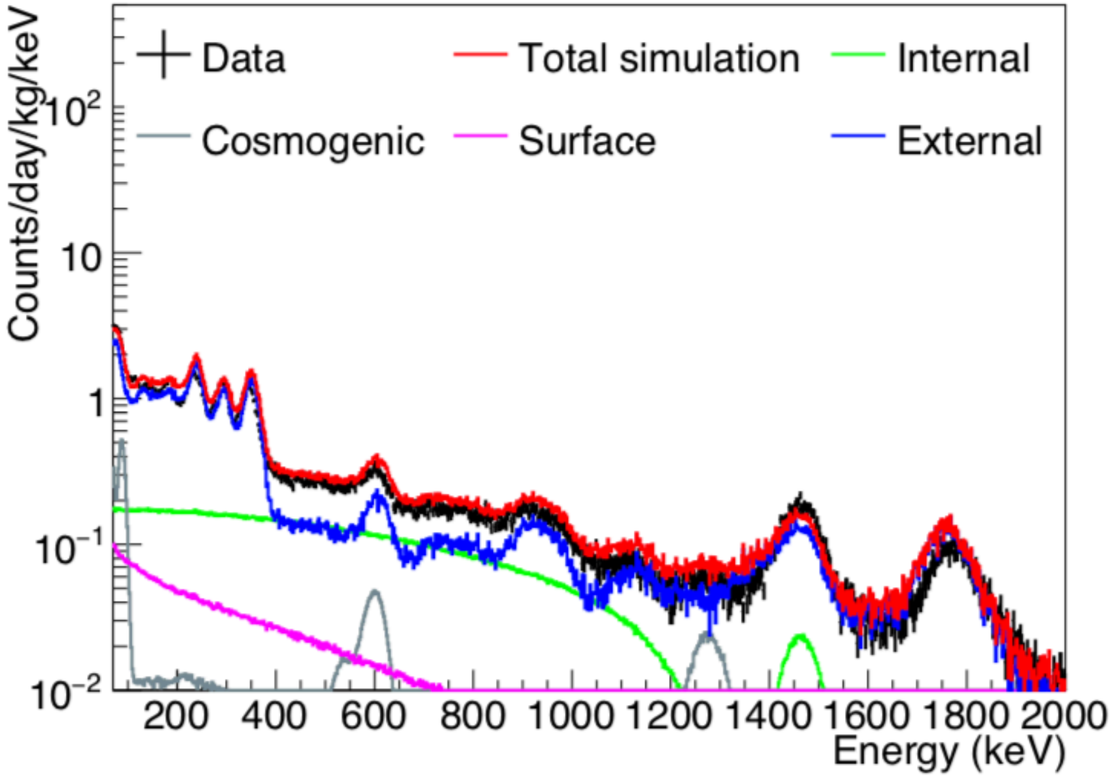


- ~70% efficiency at 2 keV
- 2 - 4 counts/keV/kg/day in region of interest depending on the crystal

Background in data vs. simulation

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



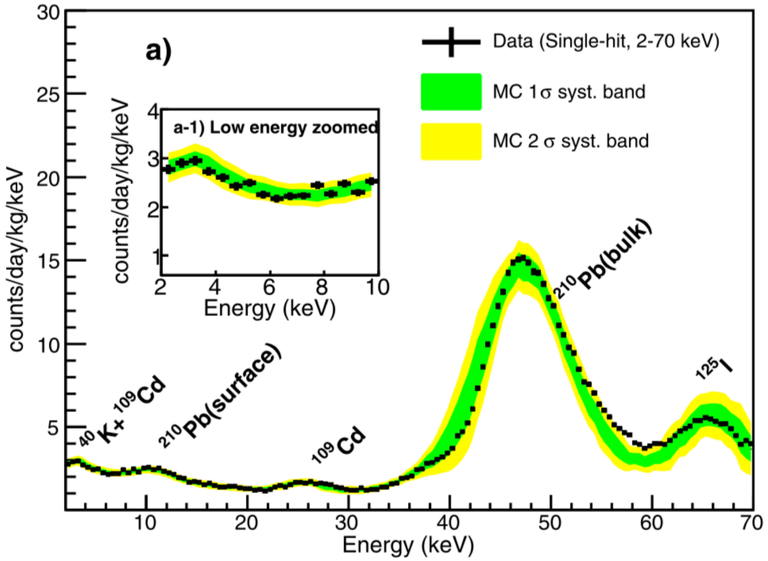


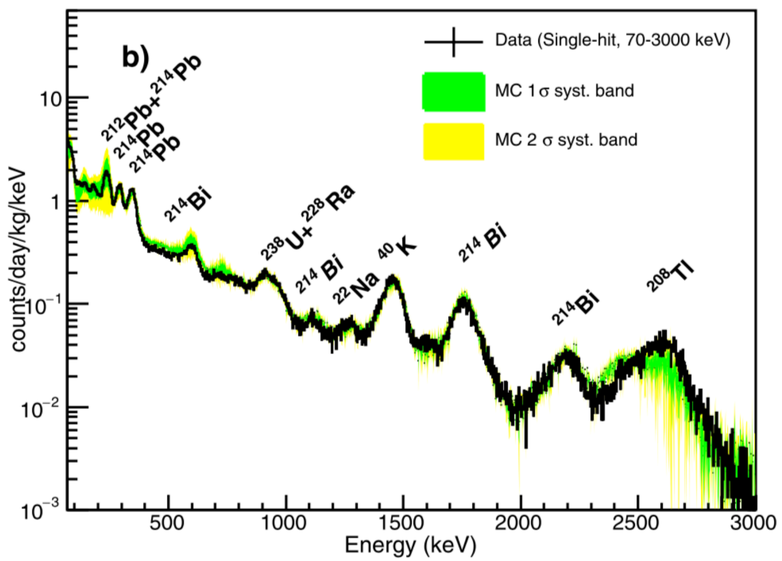
- Data reproduced well with Geant4 simulation
- **Background well understood from 2 keV - 2000 keV**
- Dominant background from ^{210}Pb (internal, surface) and ^{40}K (internal), followed by cosmogenic ^{3}H

Background in data vs. simulation

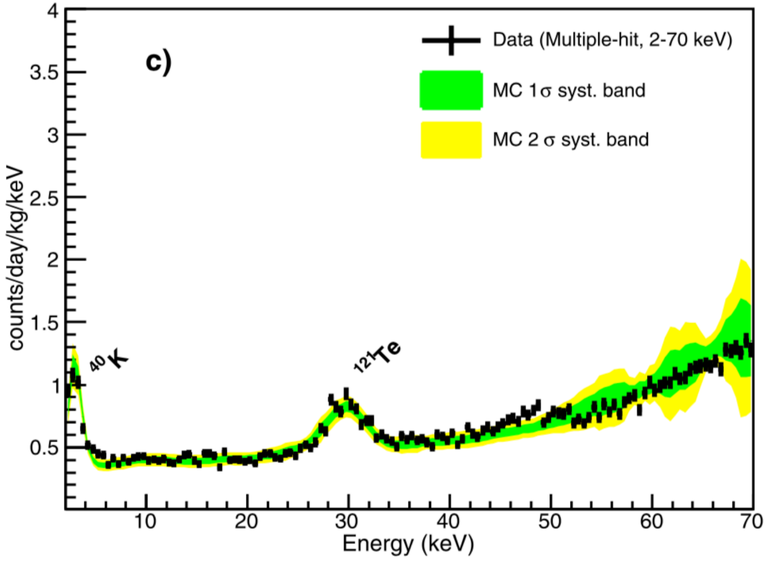
Nature **564**, 83-86 (2018)

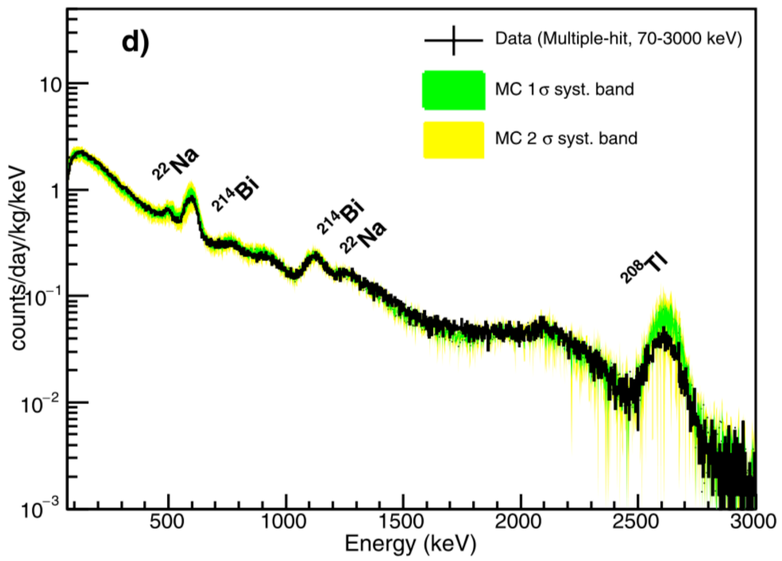
Single-hit





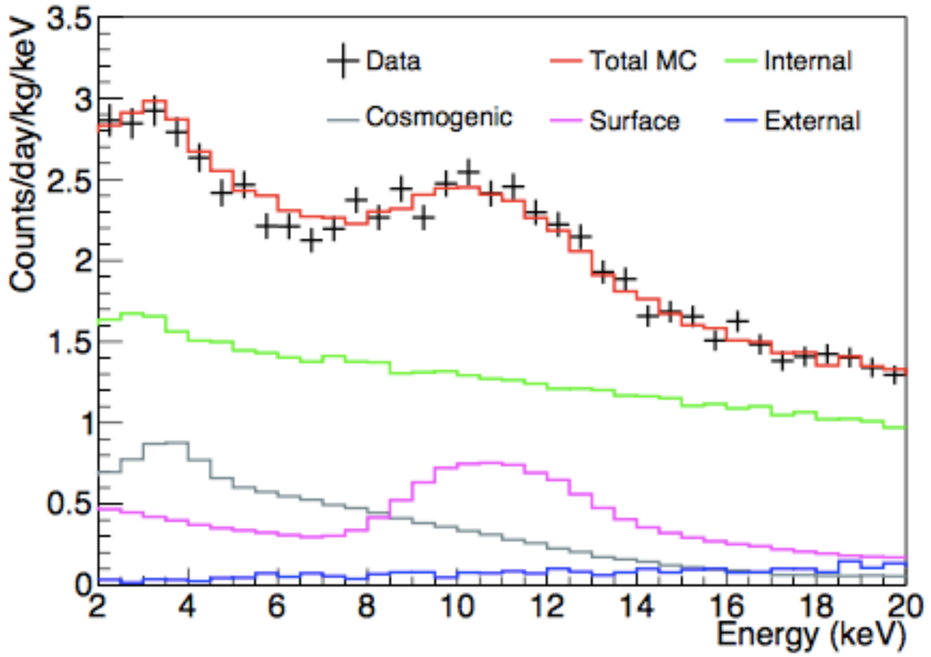
Multiple-hit

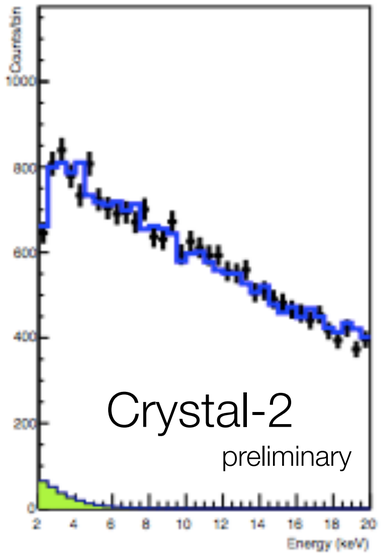


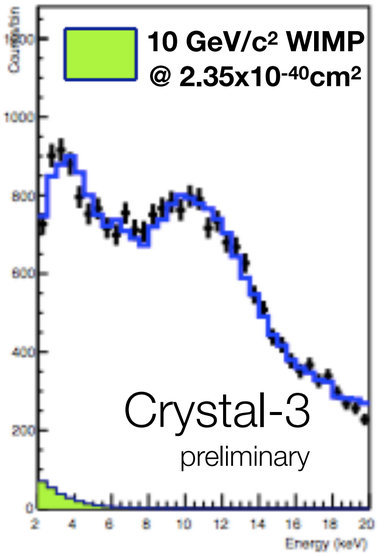


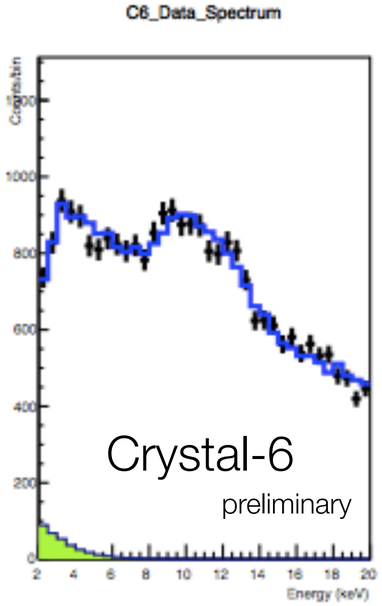
Physics analysis: WIMP analysis

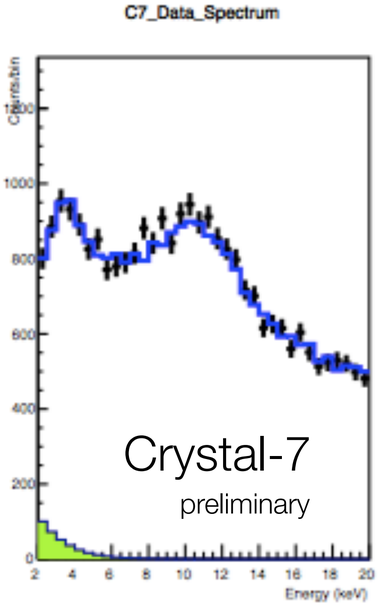
Eur. Phys. J. C **78** 490 (2018)







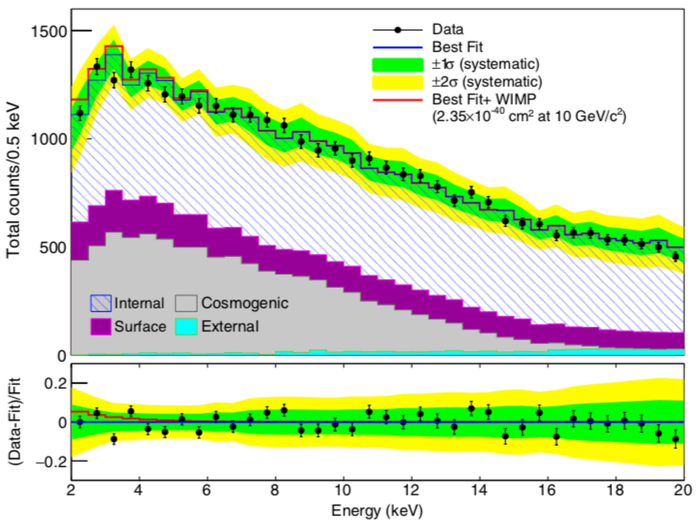




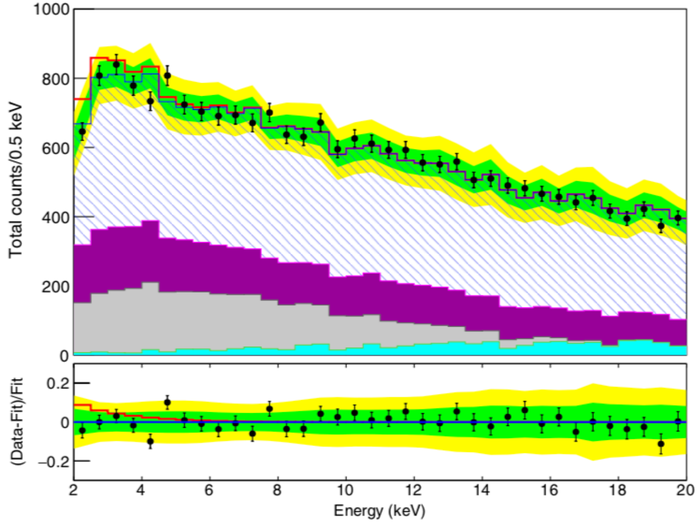
- Using 59.5 days of data: 6303.9 kg day exposure
- Spectrum fit for 2-20 keV including WIMP model
- Likelihood analysis to fit data using background model and WIMP signal model (SHM as described in Savage *et al*., JCAP 0904:010, 2009)
- Background understanding consideration from V. Kudryavtsev *et al*. Astropart. Phys. **33** (2010) 91

Physics analysis: WIMP analysis

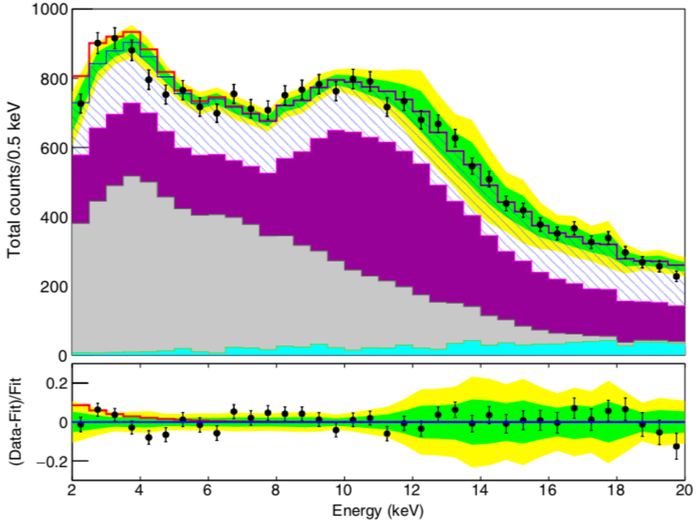
Nature **564**, 83-86 (2018)



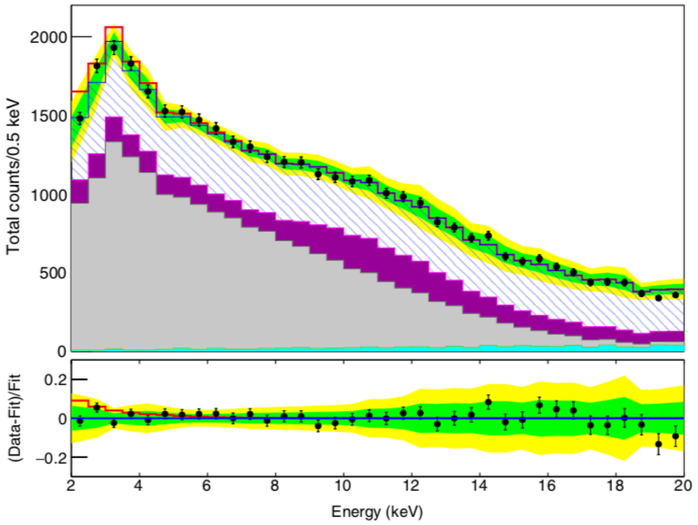
a) Crystal 1



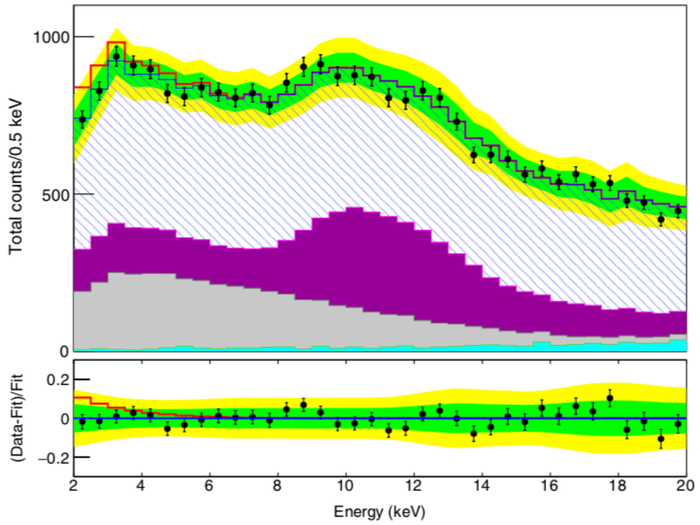
b) Crystal 2



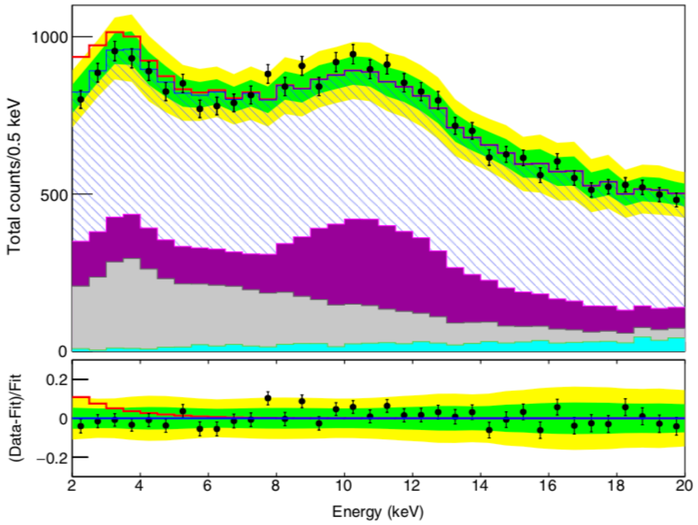
c) Crystal 3



d) Crystal 4



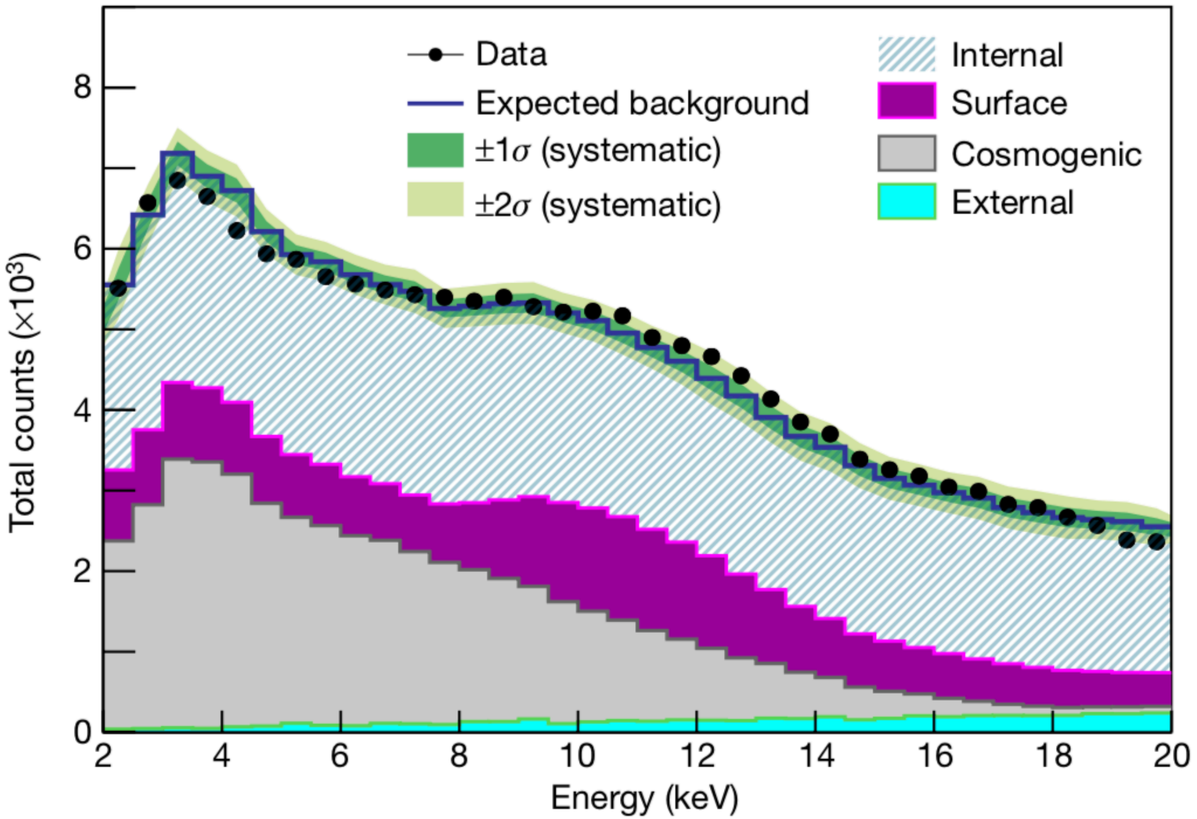
e) Crystal 6



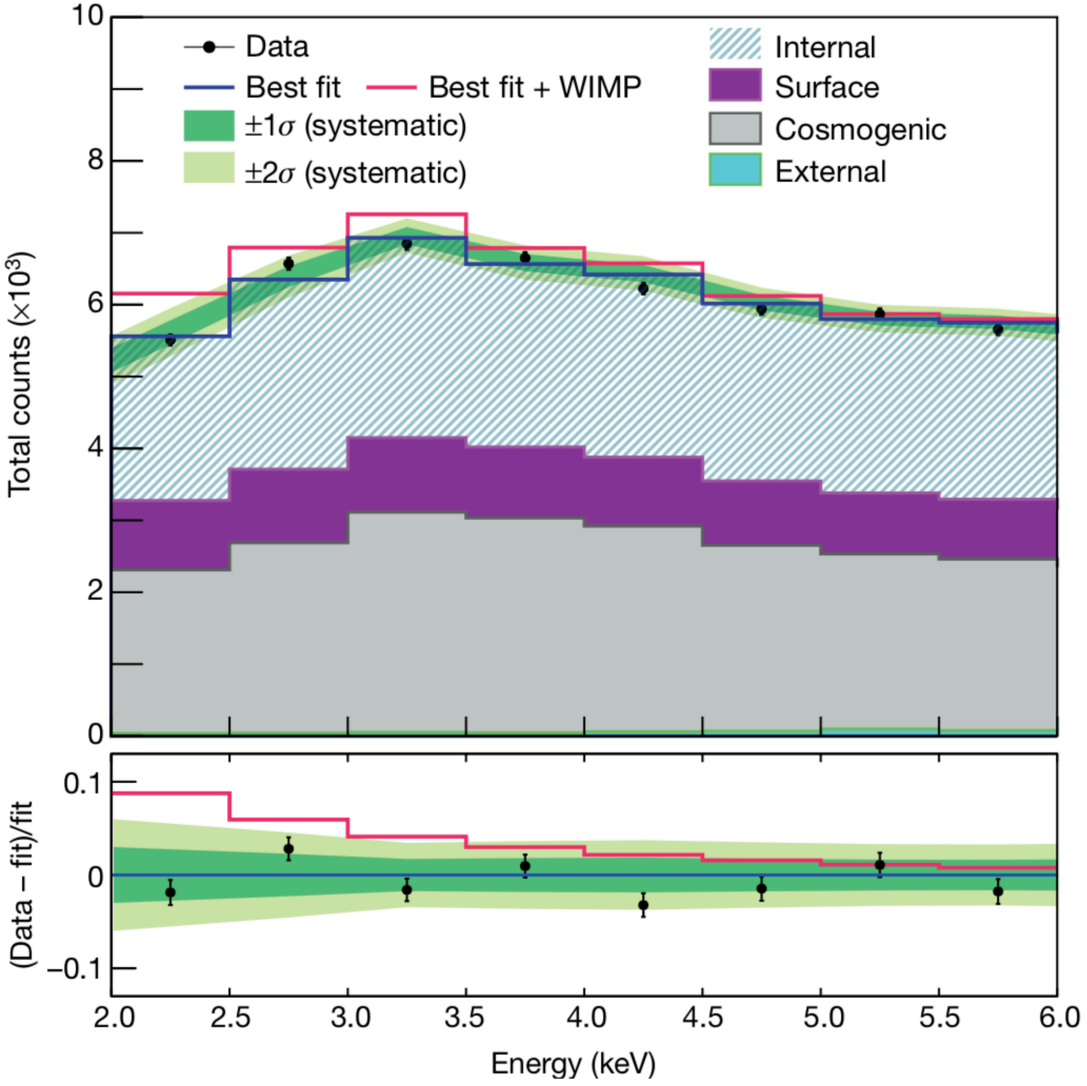
f) Crystal 7

Physics analysis: WIMP analysis

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



Measured and simulated energy spectra, summed for the six crystals

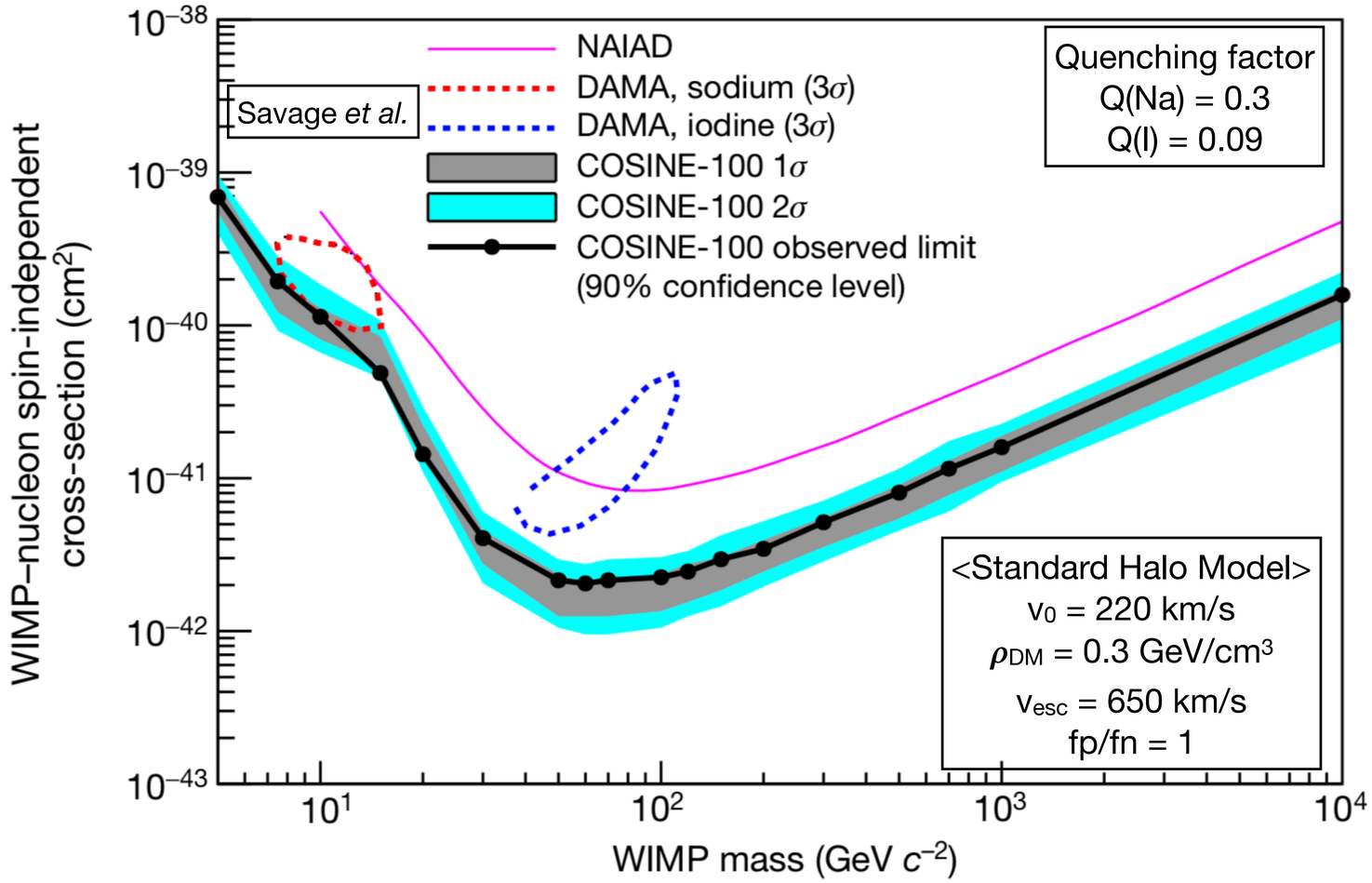


Fit result for a WIMP mass of 10 GeV c^{-2}, summed for the six crystals

Physics analysis: WIMP analysis

- Spectrum with known sources of backgrounds
- COSINE-100 excludes DAMA/LIBRA-phase1's signal as spin-independent WIMP with Standard Halo Model in NaI(Tl)
- Consistent with null results from other direct detect experiments with different target medium

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



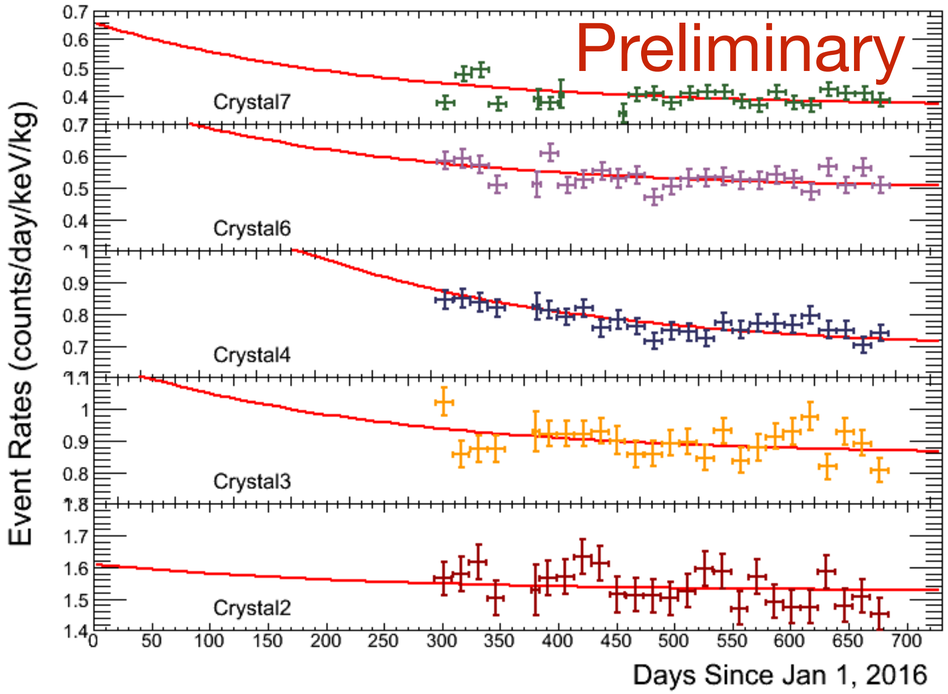
So…is DAMA dead?

- Unfortunately, not yet…
  - With the current spectral decomposition analysis, we can only reject a certain ‘model’ of the dark matter that can be interpreted from DAMA
  - We confirmed that DAMA’s modulation signal cannot be from standard WIMP in SHM with the same target material
    - “*I think this is one more nail in the coffin.*” - Dan Hooper

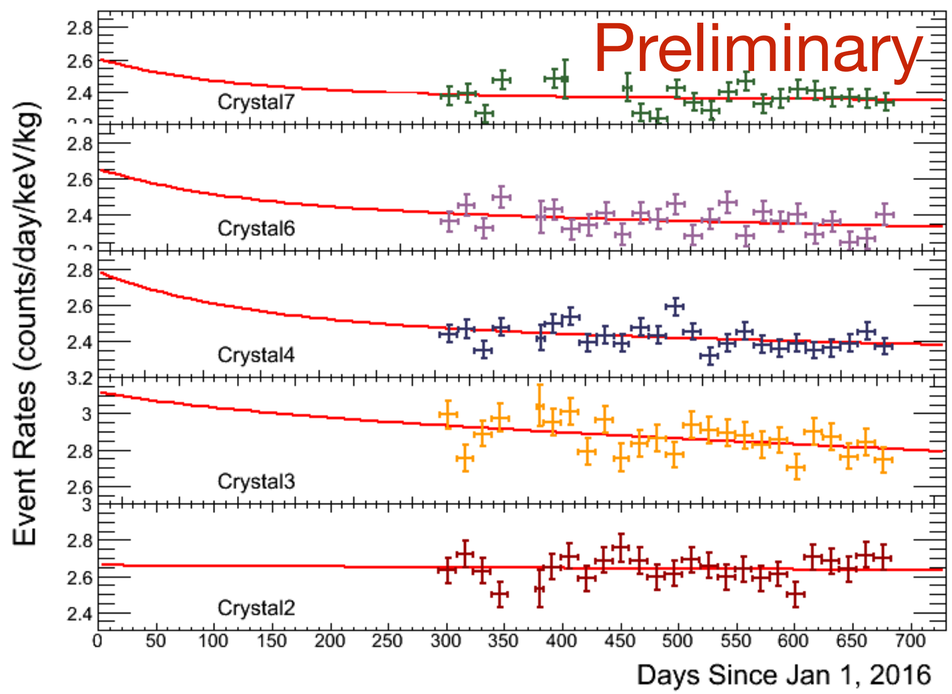
It is true that this COSINE-100 result only ruled out the simplest version of WIMPS, and for a complete test of DAMA, the annual modulation search is required

Physics analysis: Annual modulation analysis

Sideband sample: Multiple-hit 2-6 keV



Sideband sample: Single-hit 6-10 keV



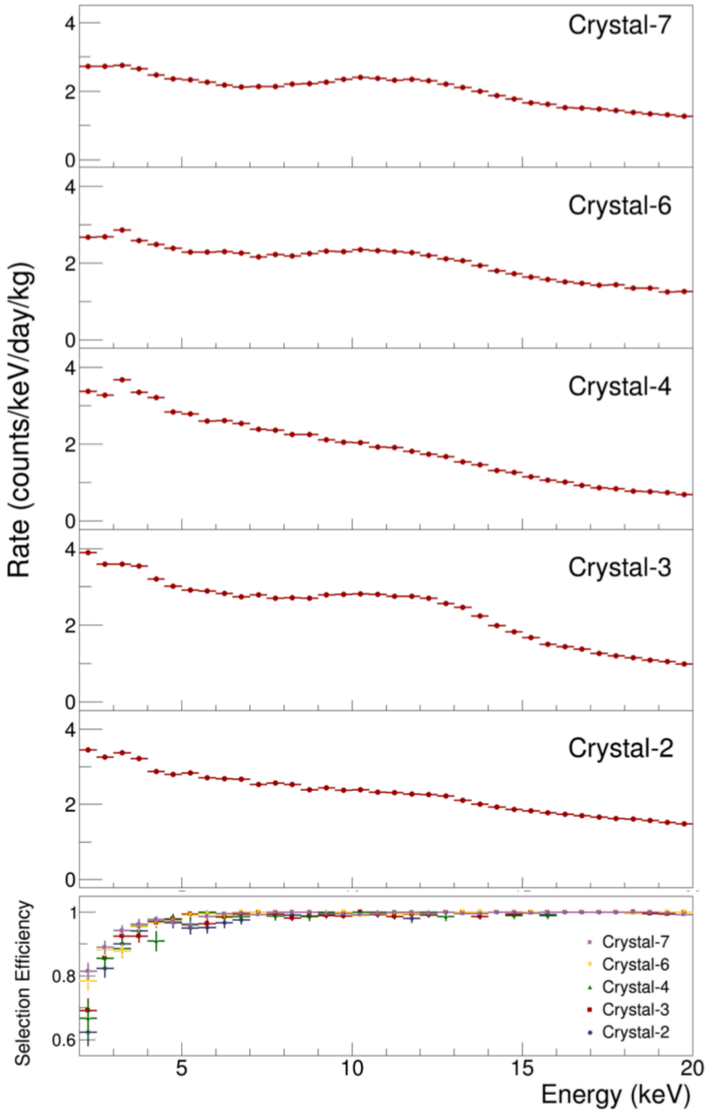
- Crystal 1, 5, and 8 are excluded in this analysis due to low light yield and excessive PMT noise
- Sideband data fits well with exponential models built with the known cosmogenic components

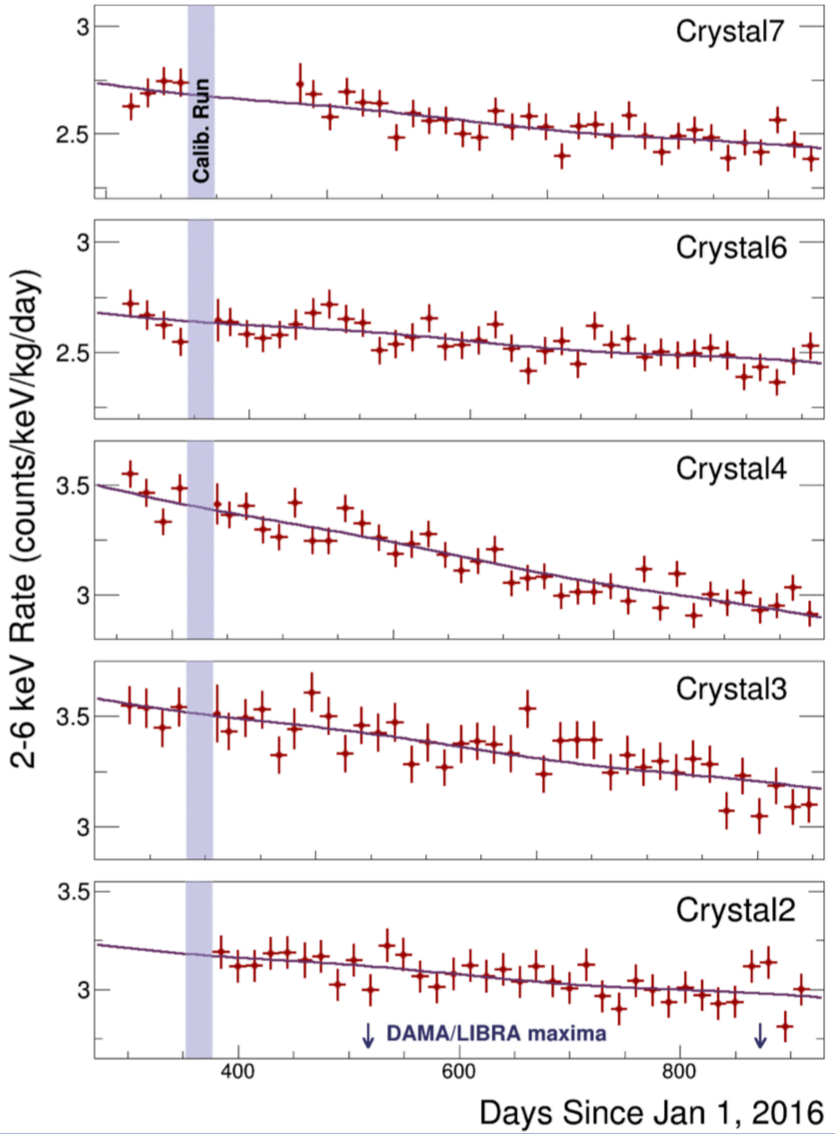
Physics analysis: Annual modulation analysis

arXiv:1903.10098

- Global fit using cosmogenic and sinusoidal components simultaneously for crystals
- Crystal-1, 5, and 8 excluded in this analysis due to low light yield and excessive PMT noise
- Sideband events decrease exponentially, agrees with known cosmogenic components

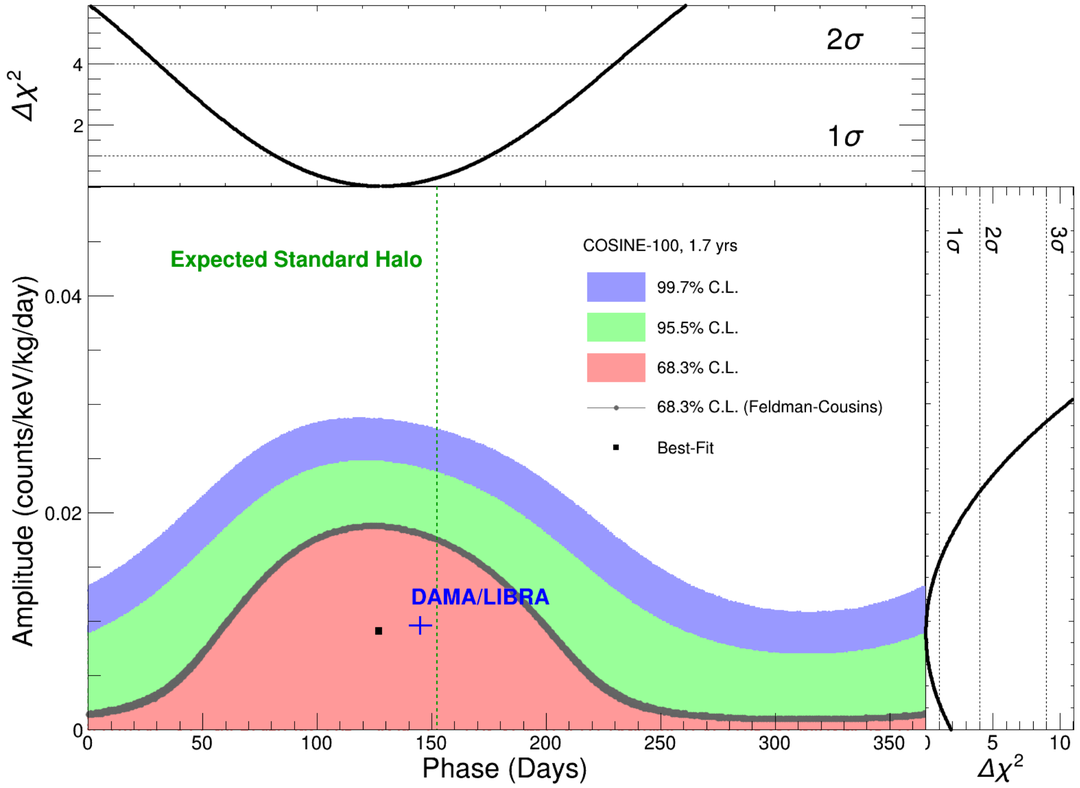
1.7 yrs, 97.7 kg yrs exposure

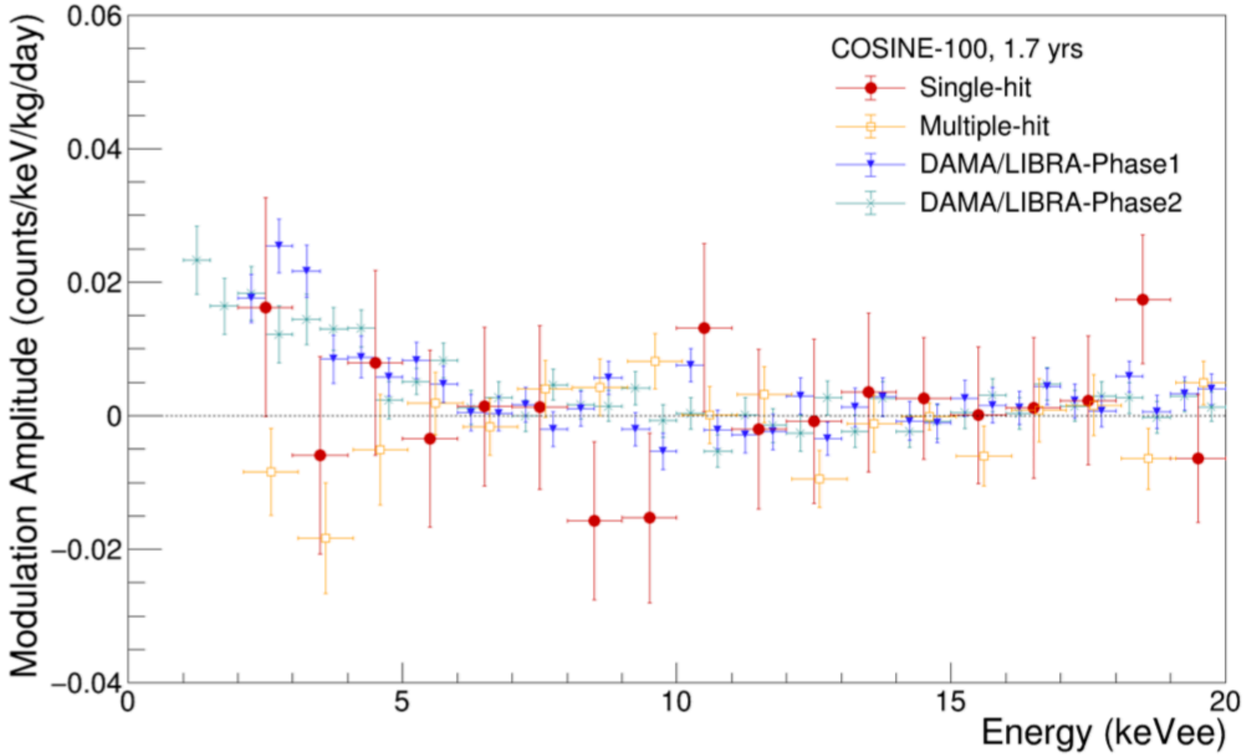




Physics analysis: Annual modulation analysis

arXiv:1903.10098



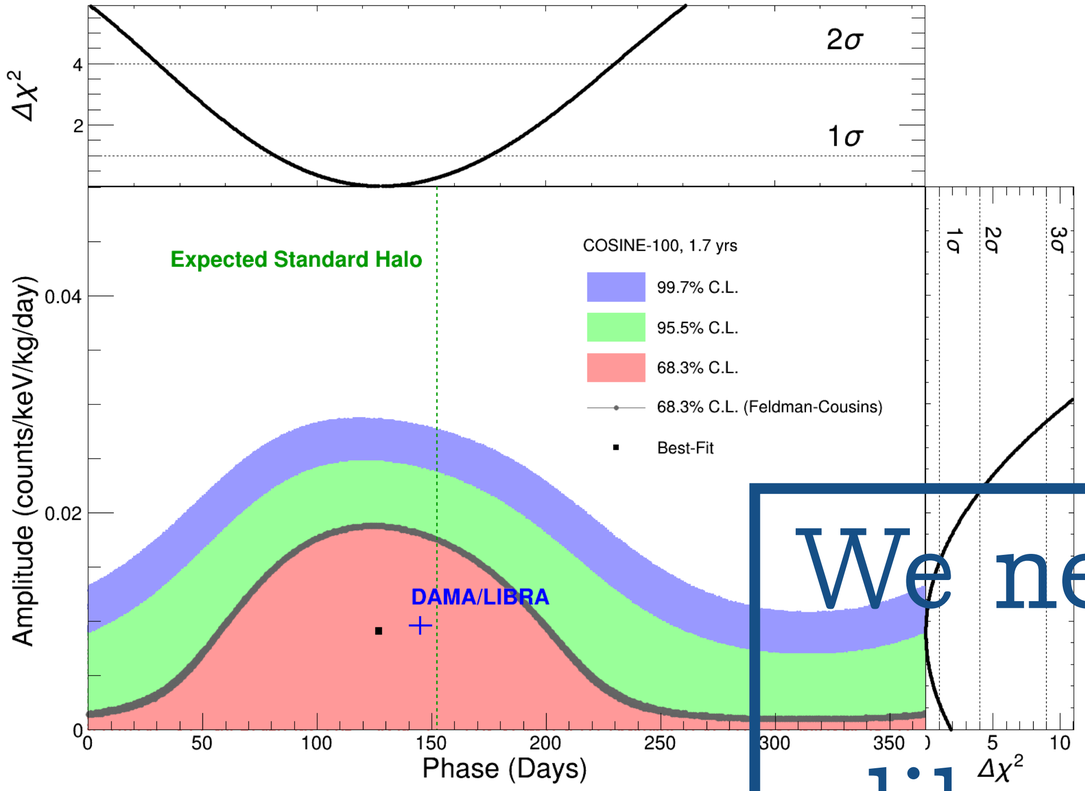


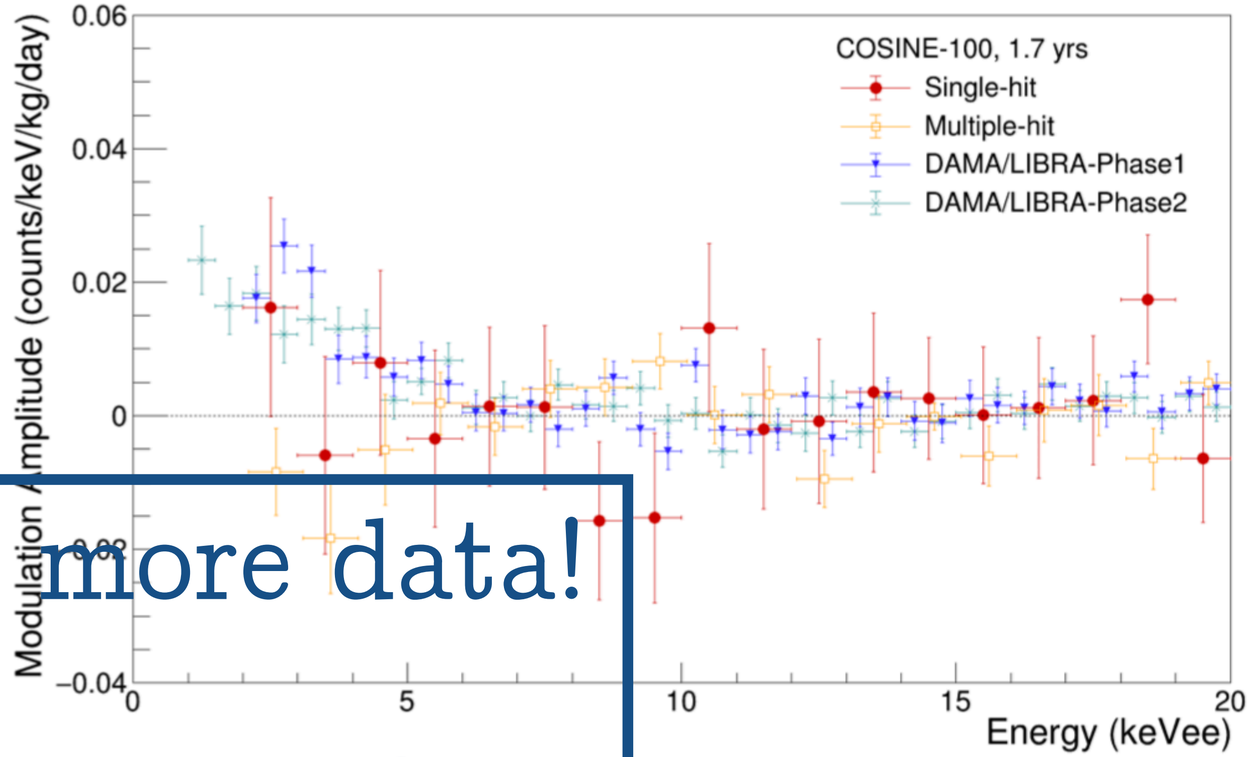
- Best fit amplitude for 2—6 keV
  - 0.0092 ± 0.0067 cpd/kg/keV
  - 127.2 ± 45.9 cpd/kg/keV
- Statistically limited, not yet able to distinguish DAMA/null

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)

Physics analysis: Annual modulation analysis

arXiv:1903.10098





We need more data!

...like everyone else...

- Best fit amplitude for 2—6 keV
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ANAIS-112 recent result

arXiv:1903.03973

ANAIS-112 annual modulation analysis

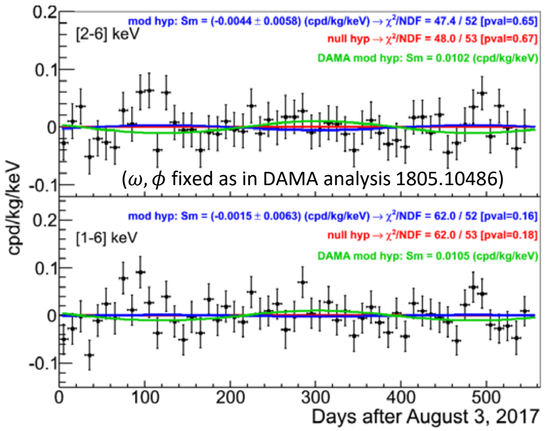
ArXiv:1903.03973

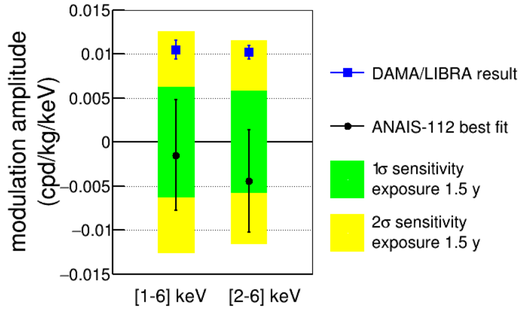
Exposure: 157.55 kg×y

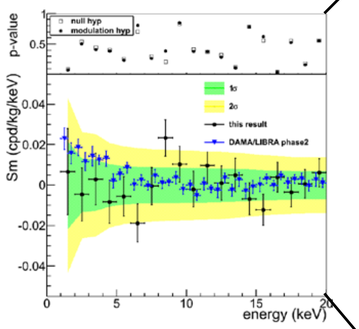
$$R(t) = R_0 + R_1 e^{-t/\tau} + S_m \cos[\omega(t+\phi)]$$

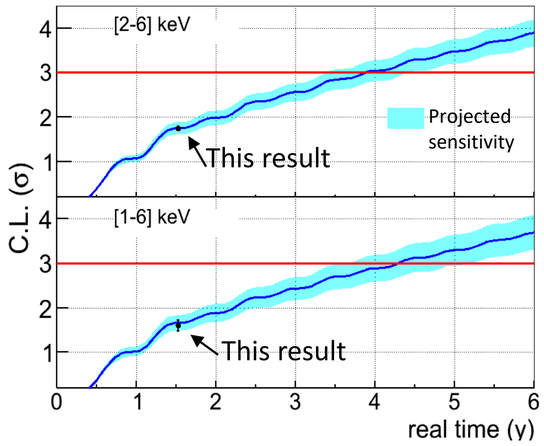
[2-6] keV → $S_m = -0.0044 \pm 0.0058$ cpd/kg/keV

[1-6] keV → $S_m = -0.0015 \pm 0.0063$ cpd/kg/keV



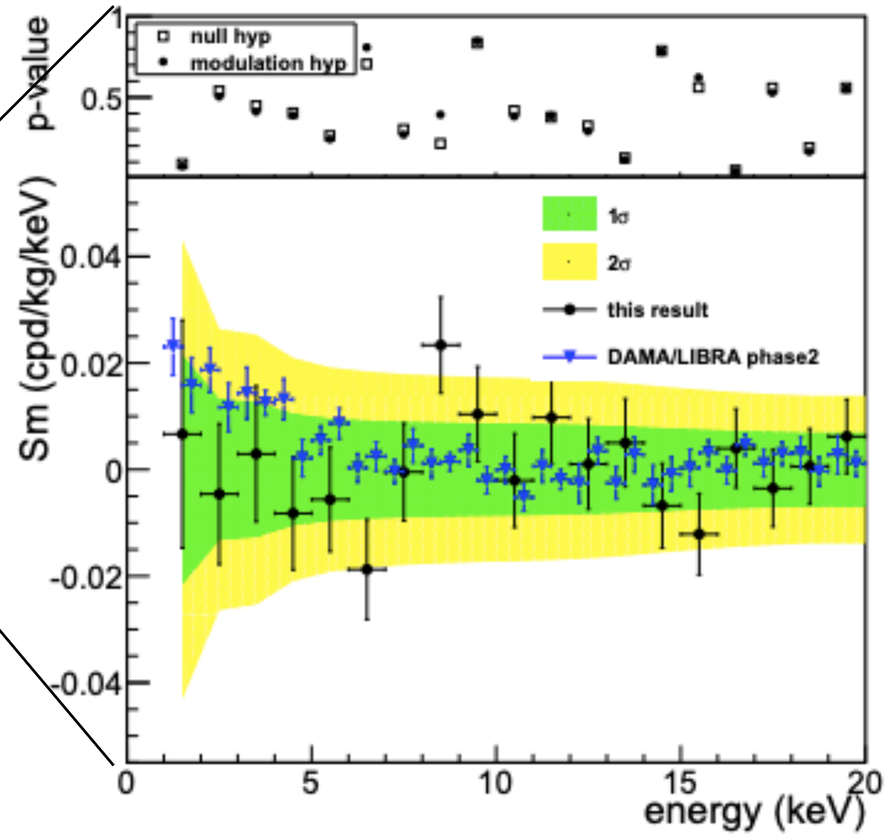






The result for 1.5 years confirms the estimated sensitivity for our background and exposure

Reaching 3σ sensitivity to DAMA/LIBRA result is possible in 2.5 - 3.5 more years of data-taking

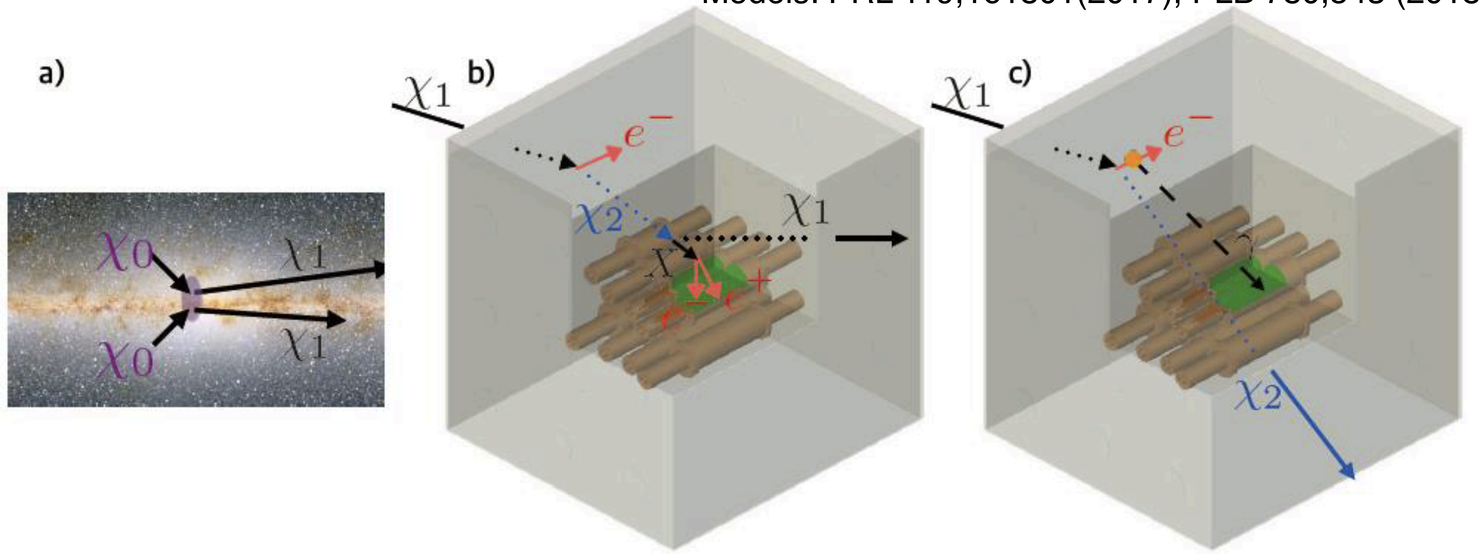


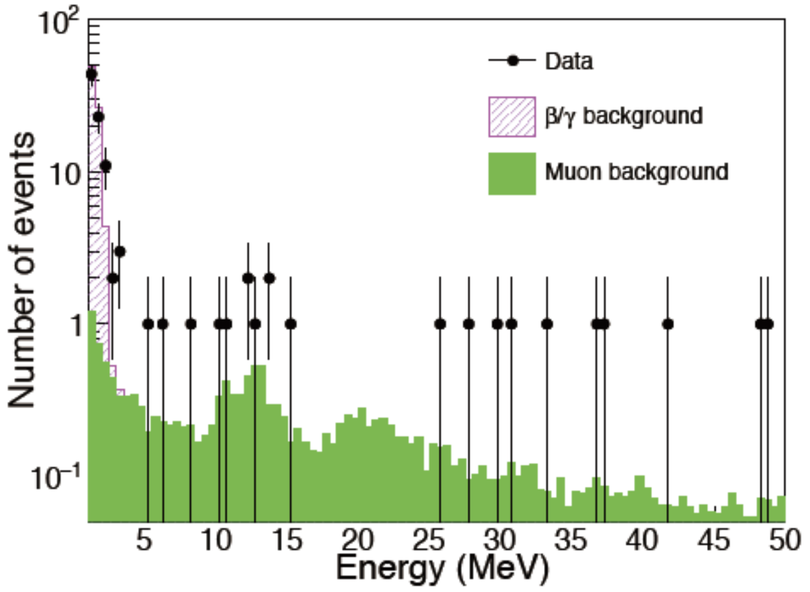
Moriond Conference

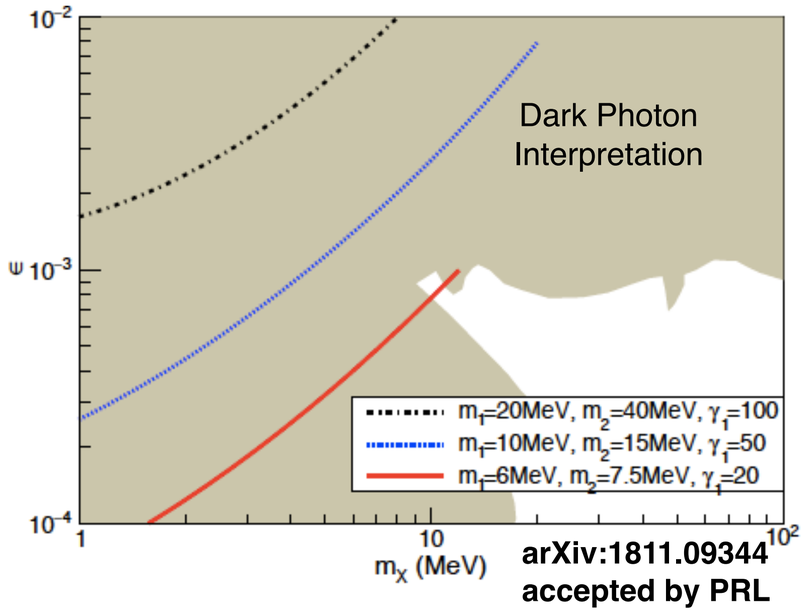
Other physics analysis: Boosted DM Search

Models: PRL 119,161801(2017), PLB 780,543 (2018)

- BDM: relativistic dark matter particle that is boosted by annihilation of heavier dark matter particles in the GC/Sun
- Taking advantage of effectively ton-scale liquid scintillator detector
- SET1 data (59.5 days) used for the analysis





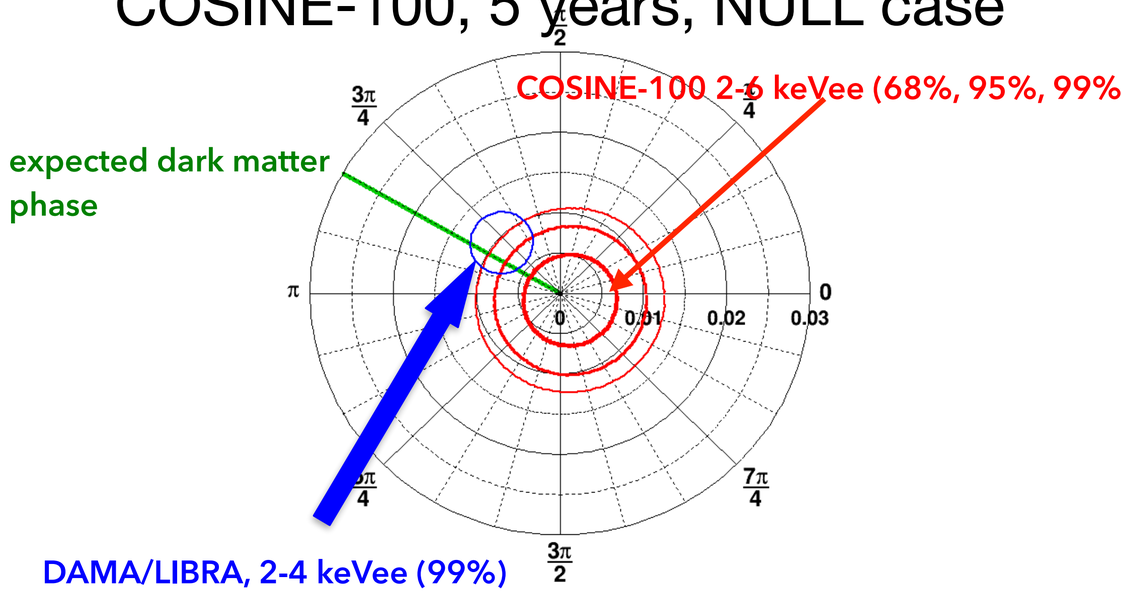


arXiv:1811.09344
accepted by PRL

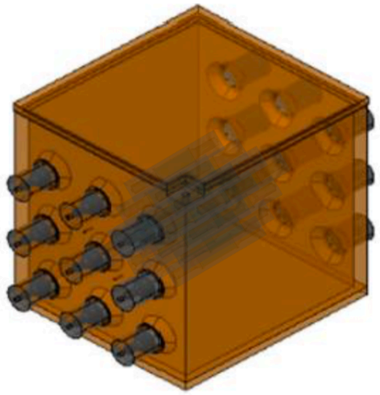
What next?

- Need to directly test DAMA with the annual modulation analysis
  - With the current background levels of COSINE-100 crystals, it takes **~3 years more exposure**
  - ANAIS has been running with 112 kg of NaI(Tl) crystals from the same manufacturer as COSINE-100, agreed to c**ombine the result** with COSINE soon
- The most critical factor for the sensitivity is the **crystal background level**, which is currently 2-4 times higher than DAMA's
  - In-house crystal growing is on going at IBS, Korea
  - Involves rigorous studies of NaI powder purification, growth optimization, and crystal encapsulation
  - Initial result promising: planning for upgrade (COSINE-200) with these lower background crystals (~1 DRU)

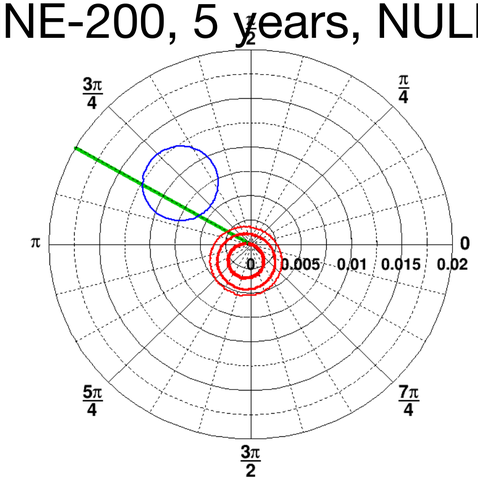
COSINE-100, 5 years, NULL case



COSINE-200 @ Y2L



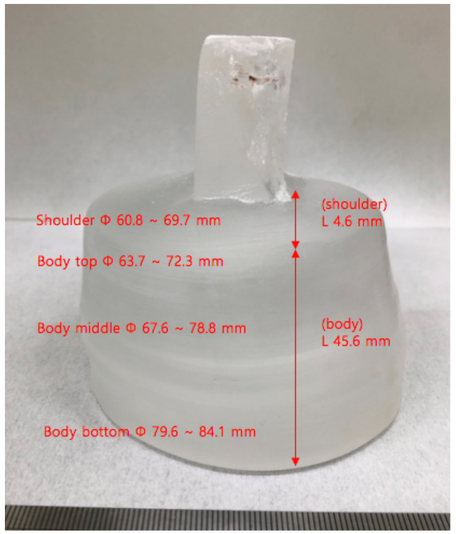
COSINE-200, 5 years, NULL case



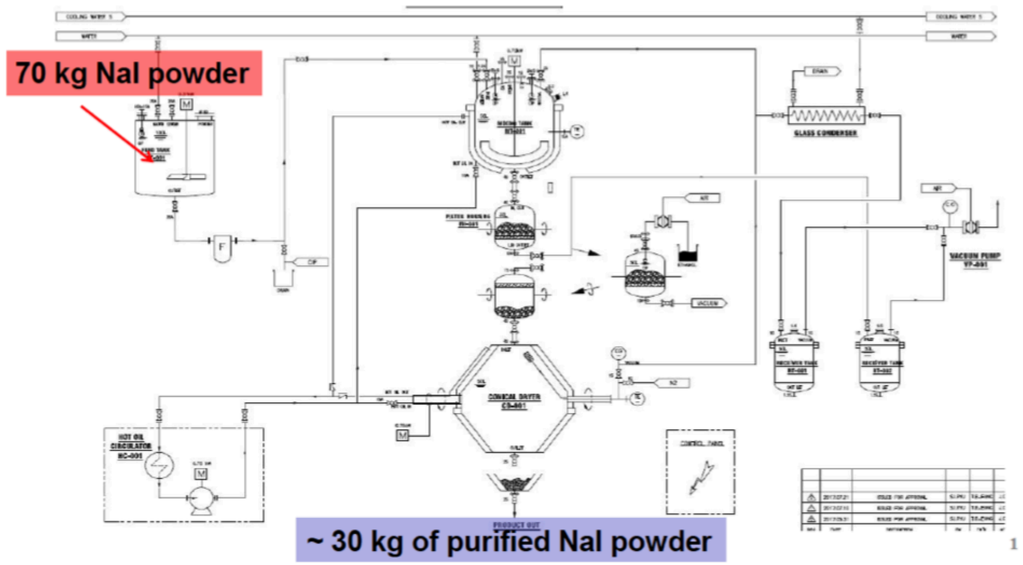
What next?

- Needs to grow our own crystal with low(er) background and better understanding of the crystal/assembly procedures
- Powder purification system and crystal growers are available at IBS facility
- Went through many trials and errors, found ways to reduce background contamination in powder & improve growth condition of NaI(Tl) crystals
- Current measurements show great improvements!

~ 100 kg NaI crystal (ingot) grower



Piping & Instrument Diagram

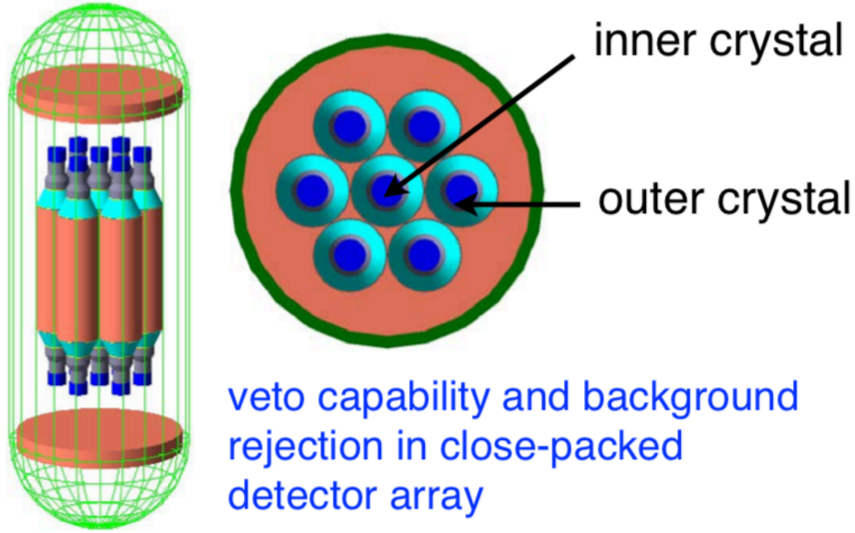


What next?

- **What if we do not see the modulation signal?**
  - We can refute DAMA's claim for dark matter discovery
  - DAMA's signal may be coming from the local effect (LNGS, shielding structure, etc.)
- **What if we do see the modulation signal?**
  - We need to understand the signal
  - The most straightforward idea is to repeat the same experiment in Southern Hemisphere (DM-Ice17, SABRE)
  - COSINE-200 in South Pole under consideration: IceCube upgrade is planned on 2022-2023

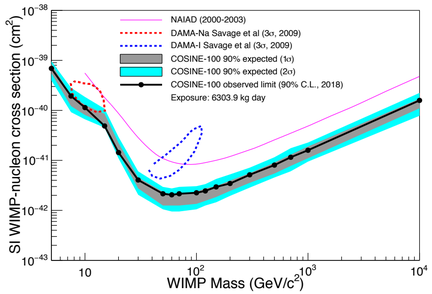
COSINE-200 @ South Pole

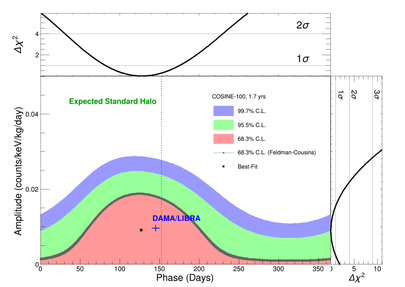
Close-Packed Detector Array

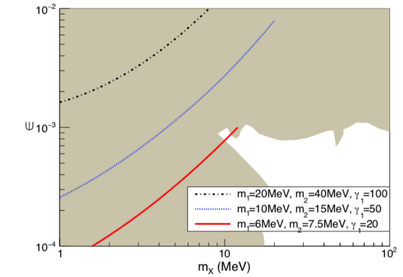


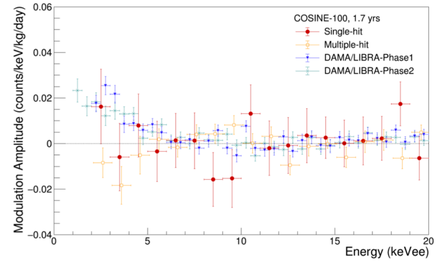
veto capability and background rejection in close-packed detector array

Summary and outlook









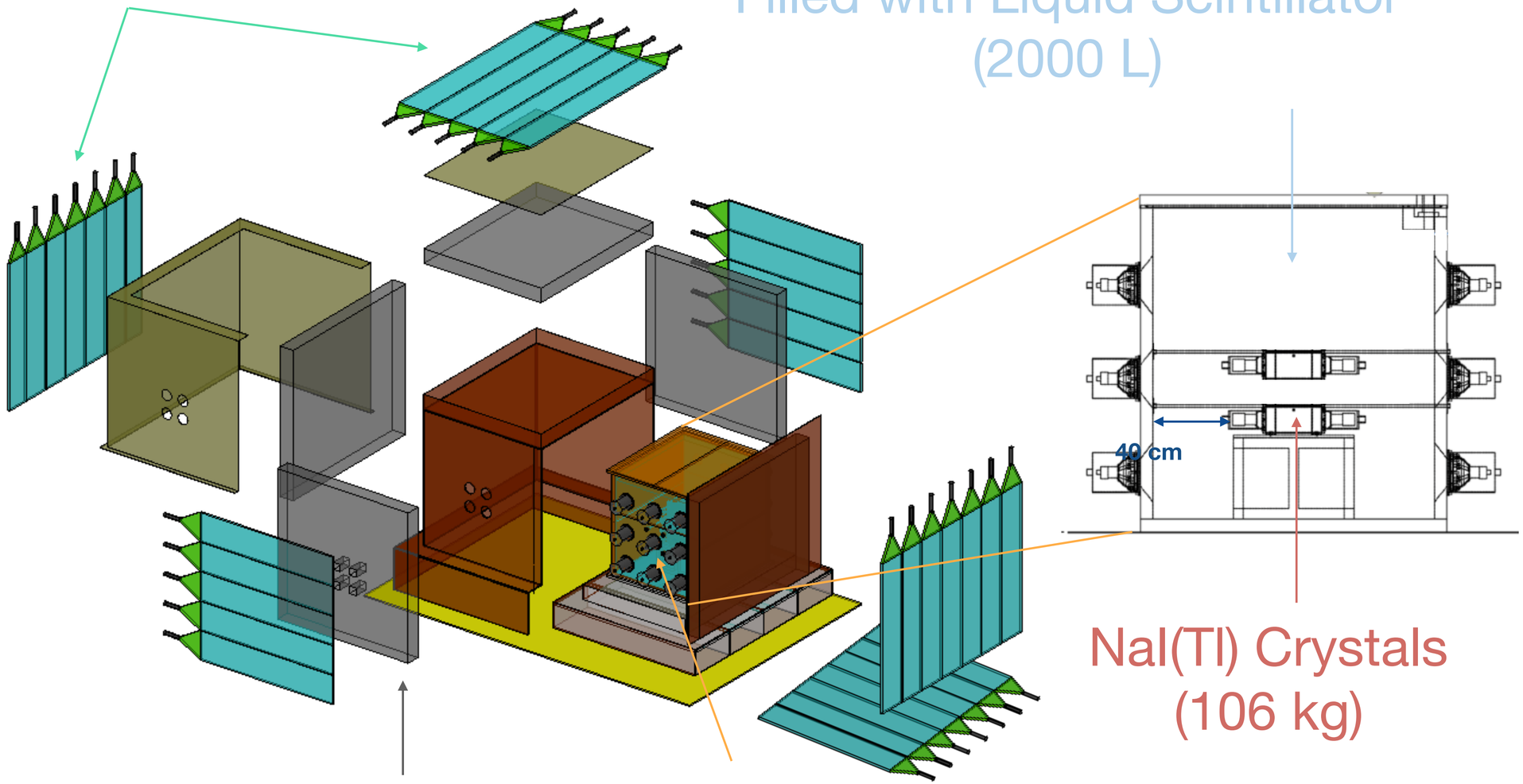
- COSINE-100: Goal is to test DAMA's claim for dark matter observation with the same target material
- COSINE-100 confirms that DAMA's modulation signal cannot be from standard WIMP & SHM with NaI(Tl)
- First modulation analysis with 1.7 years exposure shows consistent result with null hypothesis and DAMA signal, but statistics limited
- Upgrade plans for next phase of COSINE-100 developing: Crystal growing, lowering energy threshold, ANAIS-COSINE data combining, …
- Stay tuned for more exciting results to come!

Backup

COSINE-100 Detector Configuration

Plastic Scintillators

Filled with Liquid Scintillator
(2000 L)

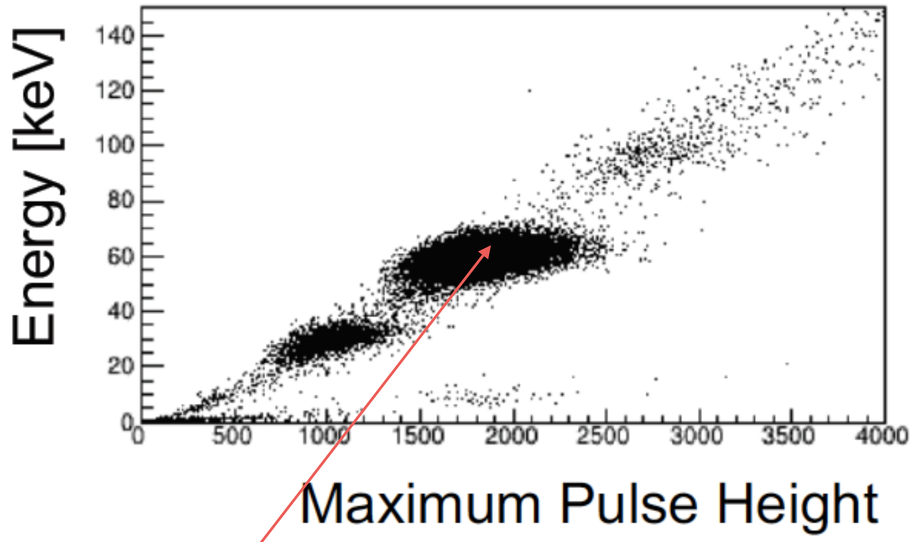


NaI(Tl) Crystals
(106 kg)

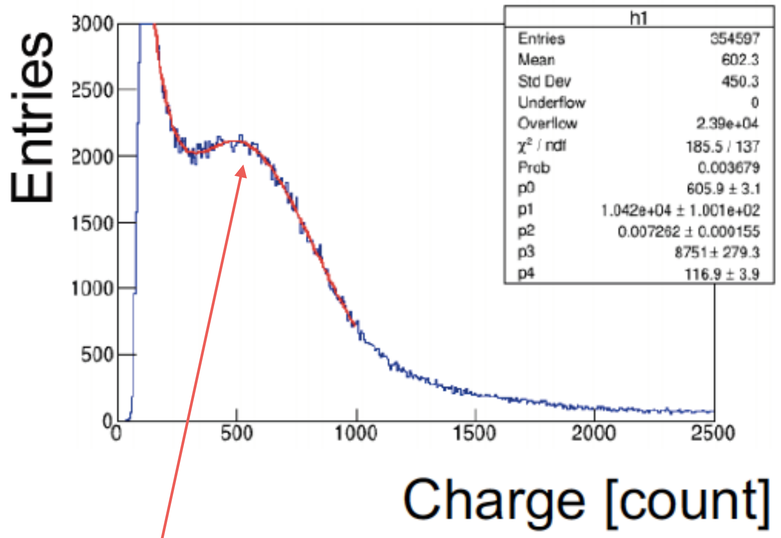
Lead Shielding (20 cm)

Cu Box (3 cm)

COSINE-100 Calibration/Light yield calculation



60 KeV gamma

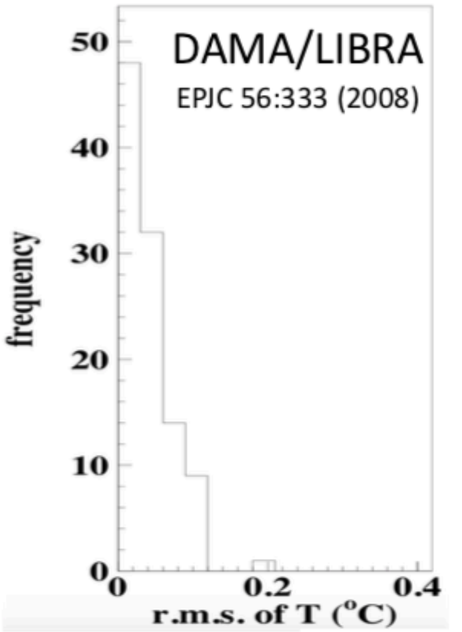


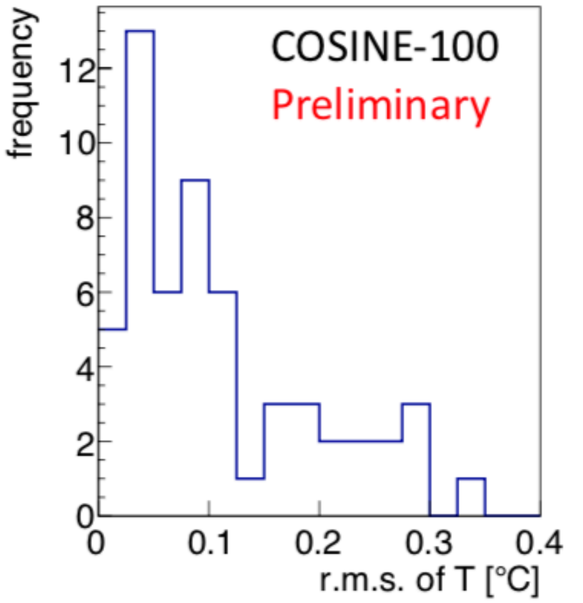
SPE

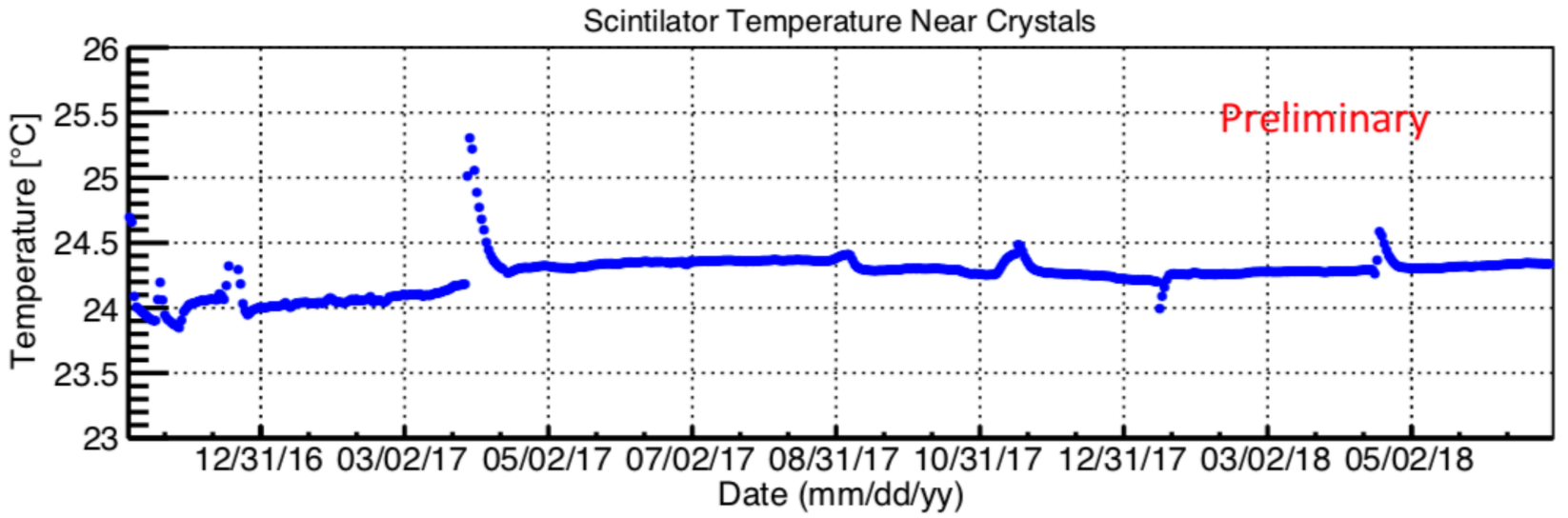
- ^{241}Am source (60 keV gamma) used to calibrate PMTs
- Gain is matched to have 60 keV peak at the mid-range of FADC dynamic range
- Single Photoelectron spectrum were fitted to calculate PMT light yield

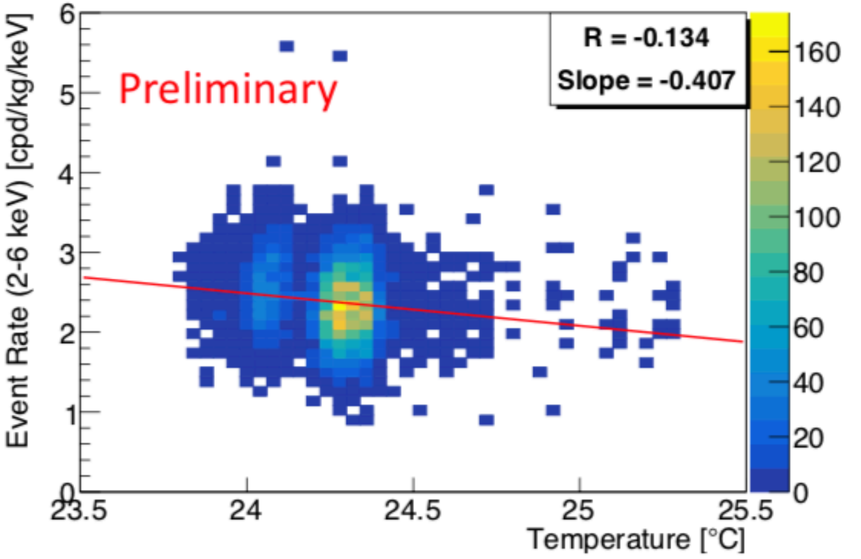
Temperature and Event Rate

- Mean RMS variation: 0.120 ℃
- Induces fluctuations of $\lesssim 10^{-4}$ cpd/kg/keV using DAMA-assumed change in light yield of $\lesssim$ -0.2%/℃



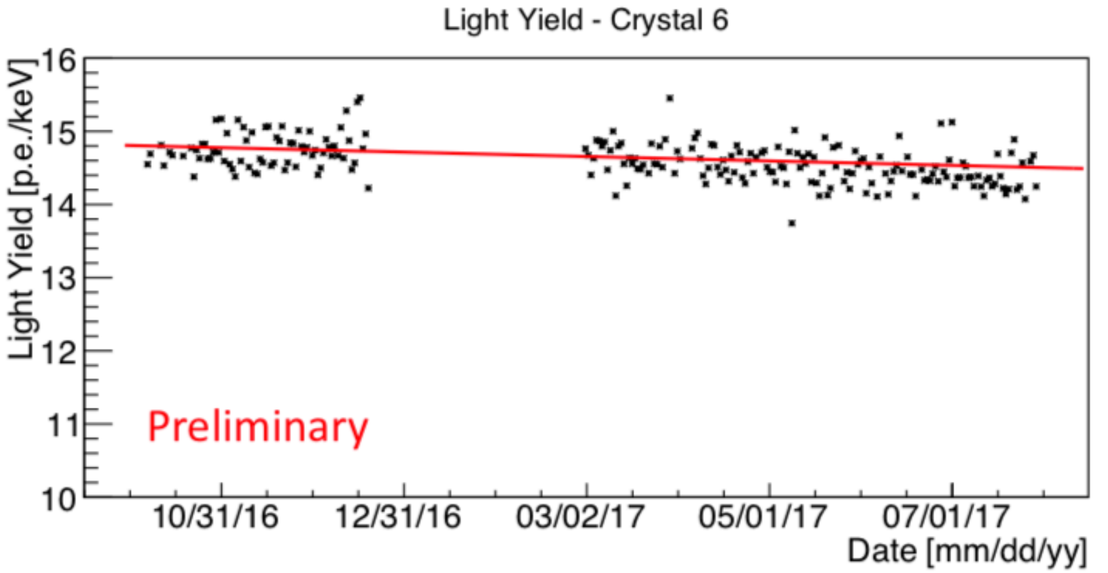


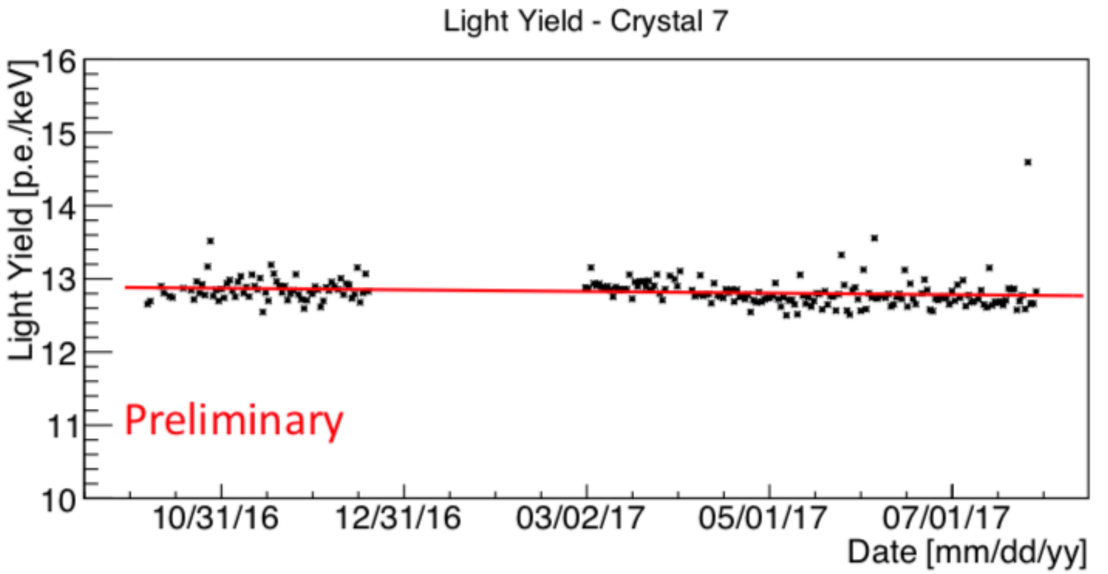




Observed Light Yields

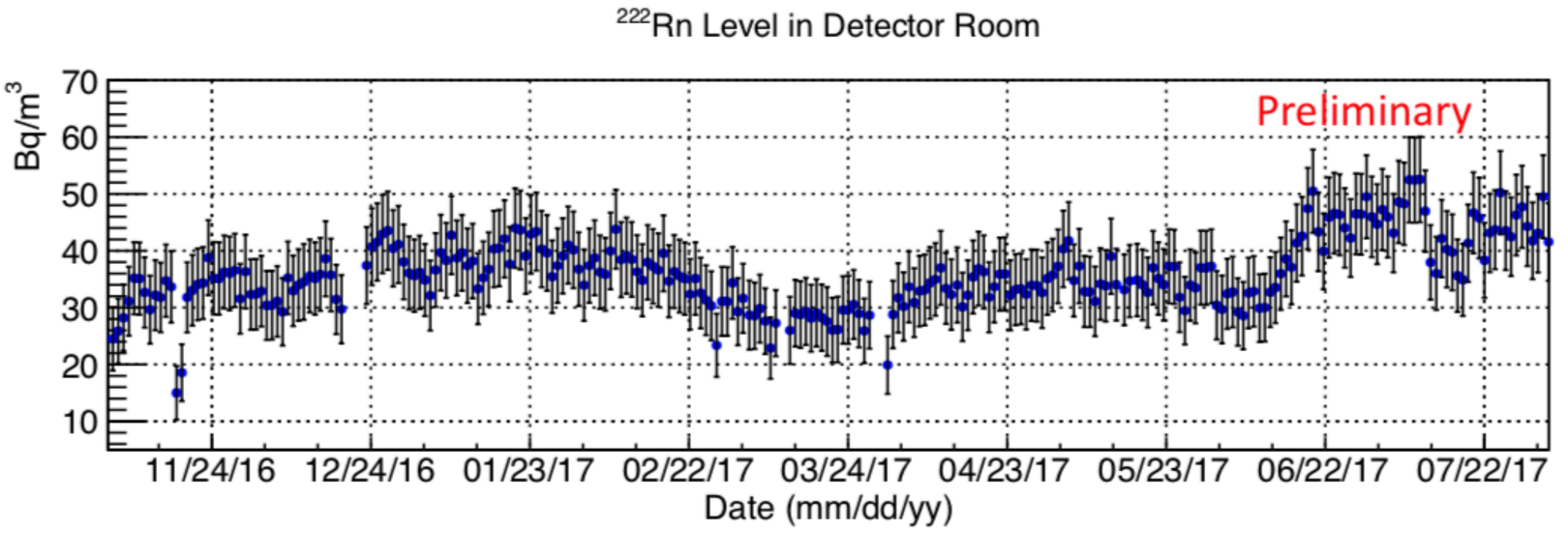
- Measurement of SPE and ^{210}Pb peaks allow determination of crystal light yields
  - Light yield: $\frac{E_{50\,keV}}{E_{SPE} \times 50keV}$
- Change of $\lesssim 1\ \frac{p.e.}{keV}$ per year in modulation analysis crystals
- Verified by calibration with ^{241}Am

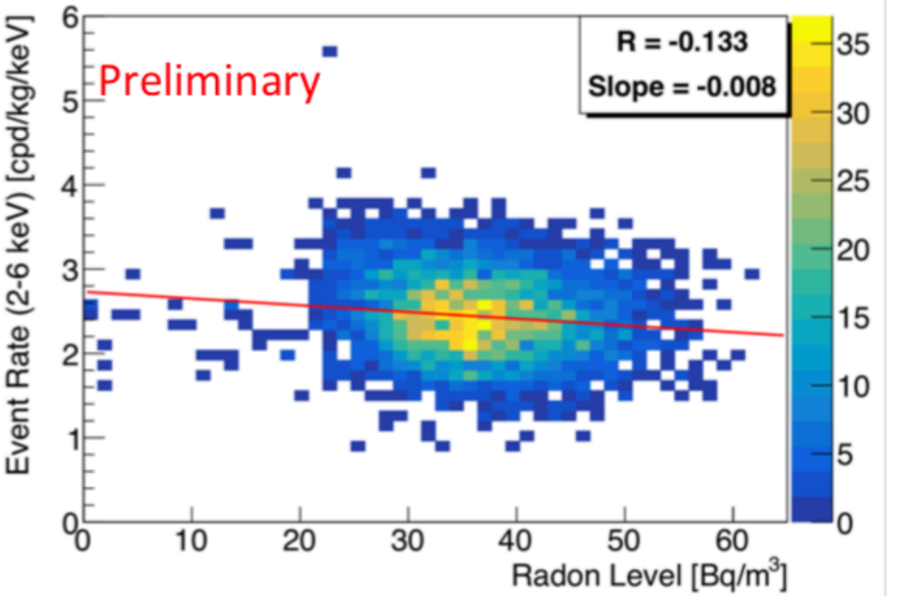


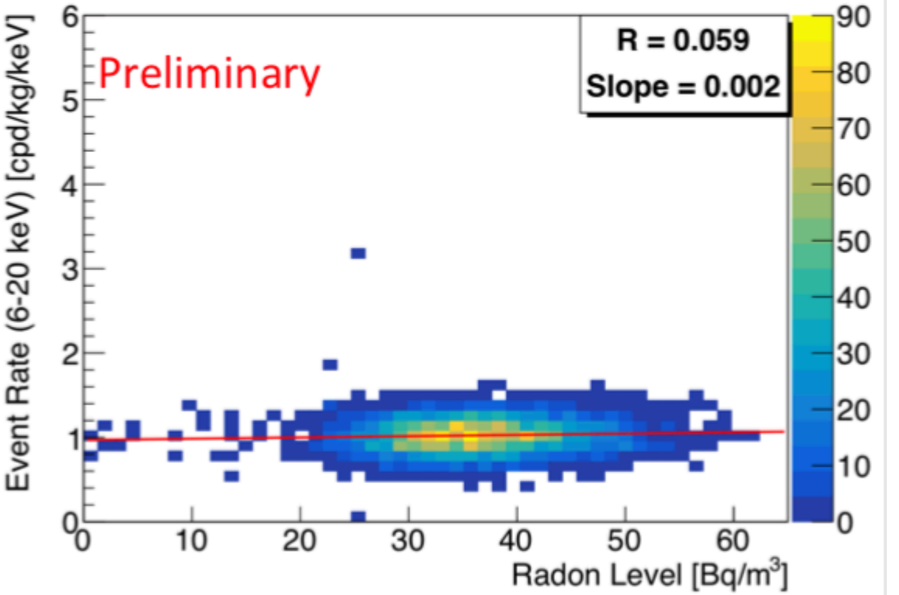


^{222}Rn and Event Rate

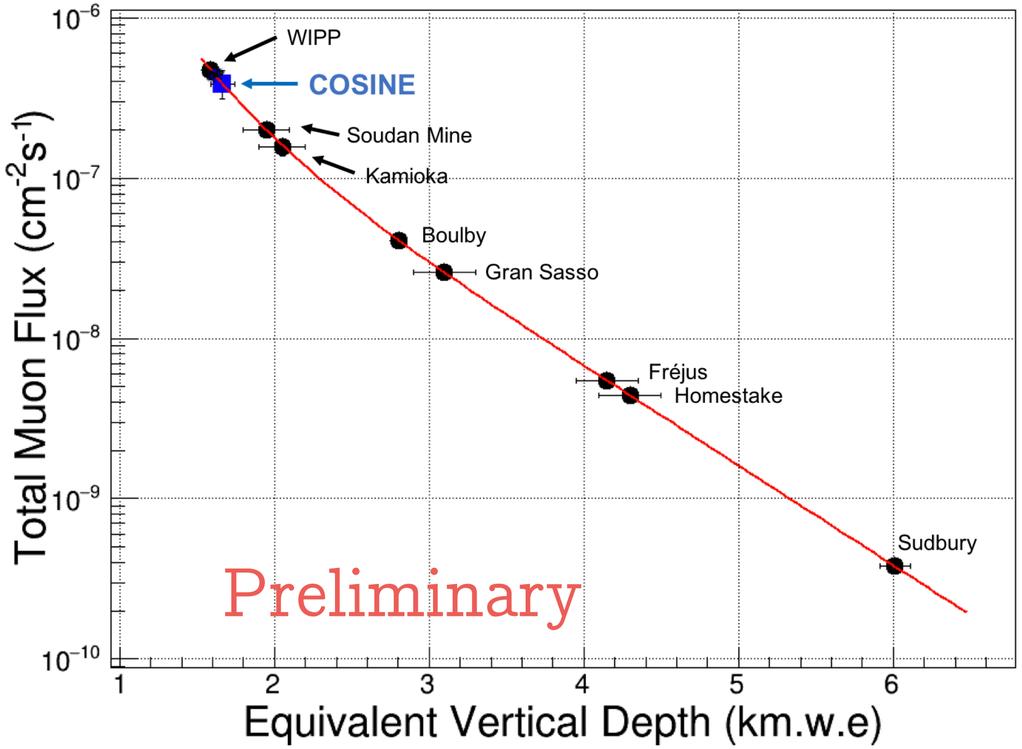
- Radon levels modulate in underground labs with period and phase similar to dark matter prediction
- Nitrogen cover gas significantly reduces radon in detector
- ^{222}Rn will similarly affect 2-6 keV and 6-20 keV regions

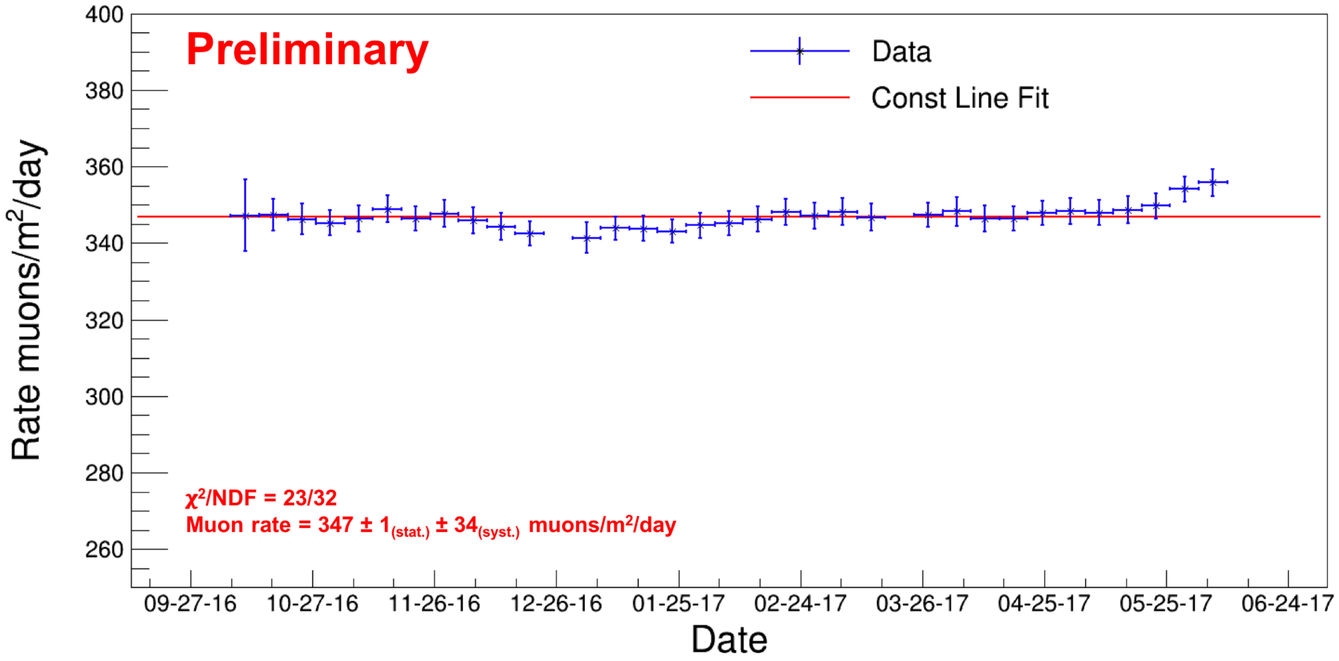






COSINE-100 Muon Background

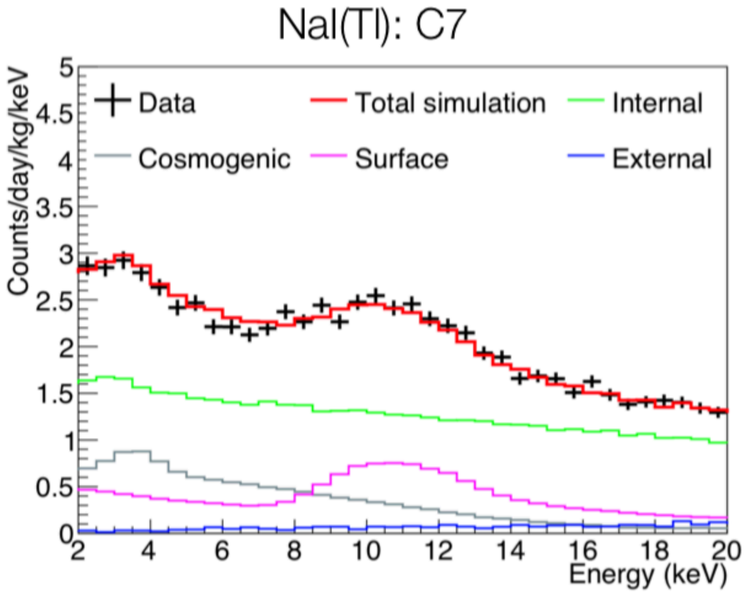


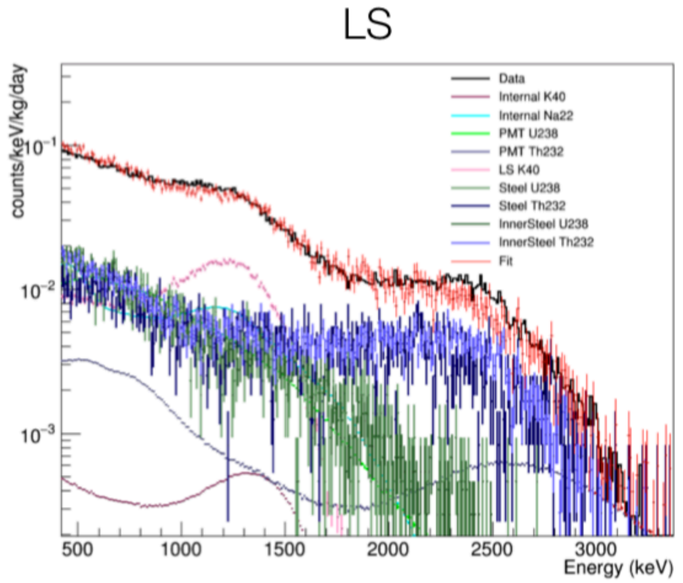


- Muon flux at COSINE-100 is ~3.98 x 10^{-7}/cm^2/s (344.29 muons/m^2/day)
- Rate has been consistent throughout the physics run
- Muon selection used to veto muon-induced crystal events

Background simulation

- Simulation of full detector using GEANT 4.9
  - NaI(Tl) crystal and LAB-based liquid scintillator
  - Dominant background in Crystal ROI (2-20 keV): ^{40}K, ^{210}Pb, ^{3}H
- Multi-channel fit: Low/high energy, single/multiple hit, multiple crystals, …
- Initial study is close to be finished, will continue to improve



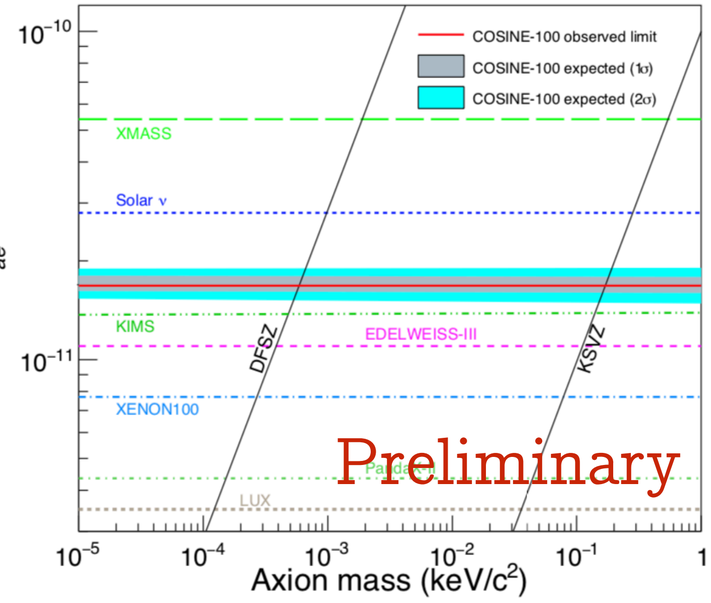


		Crystal-1	Crystal-2	Crystal-3	Crystal-4	Crystal-6	Crystal-7
Internal	^{40}K	0.10 ±0.02	0.20 ± 0.02	0.10 ± 0.01	0.10 ±0.01	0.05 ± 0.01	0.05 ±0.01
	^{210}Pb	2.50 ± 0.10	1.69 ± 0.09	0.57 ± 0.05	0.71 ± 0.05	1.46 ± 0.07	1.50 ± 0.07
	Other ($\times 10^{-4}$)	7.0±0.1	15±1	7.3±0.1	7.7±0.1	14±1	14±1
Cosmogenic	^{3}H	2.35 ± 0.90	0.81 ± 0.40	1.54 ± 0.77	1.97 ± 0.66	0.69 ± 0.67	0.58 ± 0.54
	^{109}Cd	0.05 ±0.04	0.009 ±0.009	0.13 ± 0.06	0.33 ± 0.16	0.09 ± 0.09	0.09 ± 0.09
	Other	-	-	0.02 ± 0.01	0.05 ± 0.02	0.05 ± 0.03	0.05 ± 0.03
Surface	^{210}Pb	0.64 ± 0.64	0.51 ± 0.51	1.16 ± 0.51	0.22 ± 0.16	0.34 ± 0.20	0.38 ± 0.21
External		0.03 ± 0.02	0.05 ± 0.04	0.03 ± 0.02	0.03 ± 0.02	0.04 ± 0.03	0.03 ± 0.02
Tolal simulation		5.68 ± 1.04	3.28 ± 0.67	3.57 ± 0.76	3.41 ± 0.75	2.74 ± 0.61	2.70 ± 0.51
Data		5.64 ± 0.10	3.27 ± 0.07	3.35 ± 0.07	3.19 ± 0.05	2.62 ± 0.05	2.64 ± 0.05

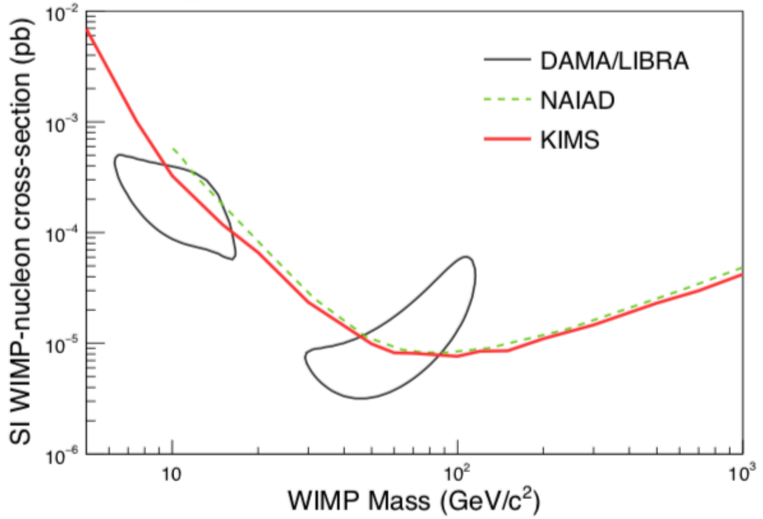
Other physics analyses

- From the background understanding, other interesting searches are actively on-going
- PSD analysis: looking at different decay time between electron/nuclear recoil within NaI(Tl) crystal
- Bosonic Super-WIMP, Solar axion, inelastic Boosted Dark Matter searches, …

Solar Axion



PSD arXiv:1806.06499



iBDM arXiv:1811.09344