Results of the DM-Ice17 and COSINE-100 experiment

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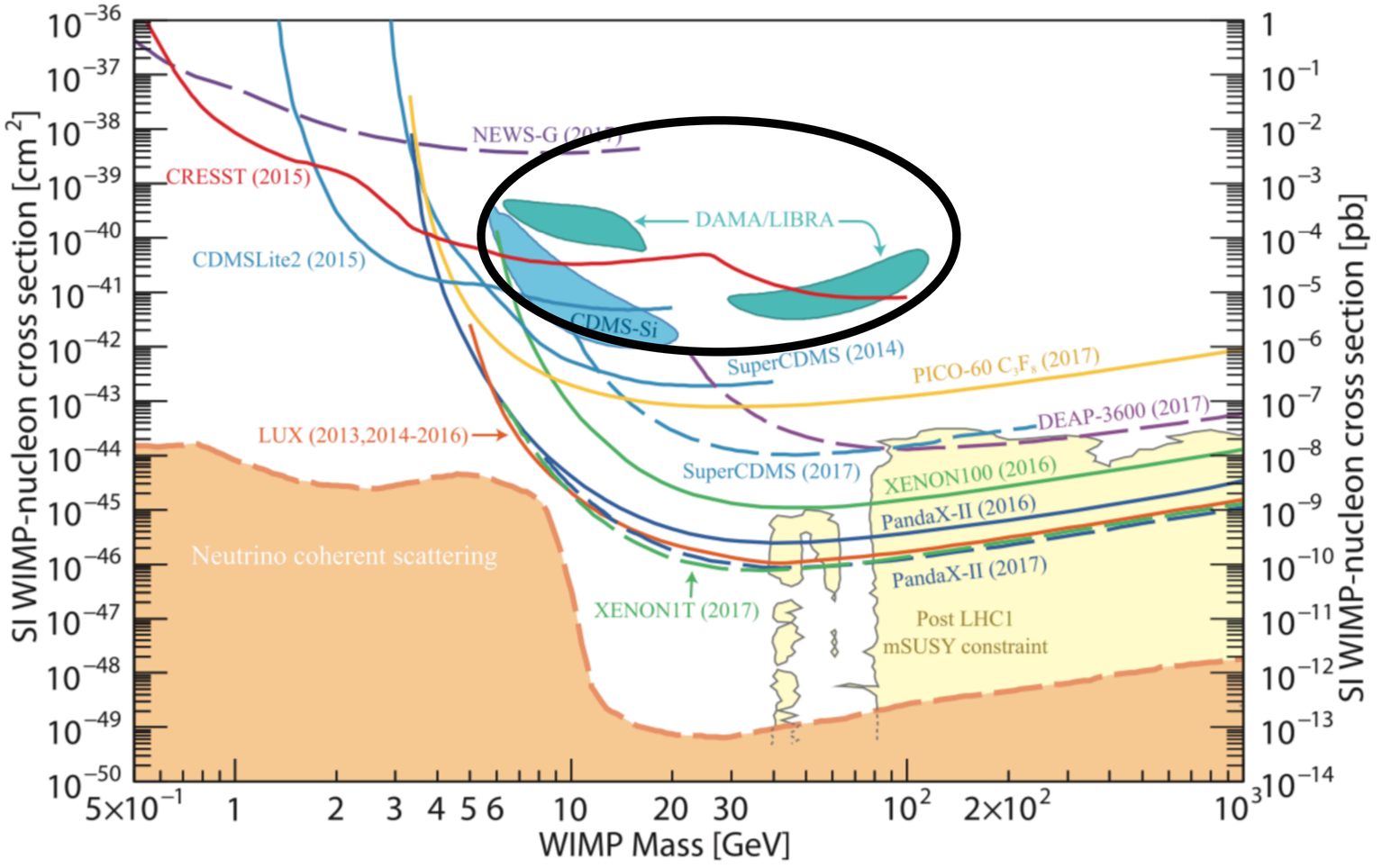
Wright Laboratory

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

Phys. Rev. D **98**, 030001 (2018)



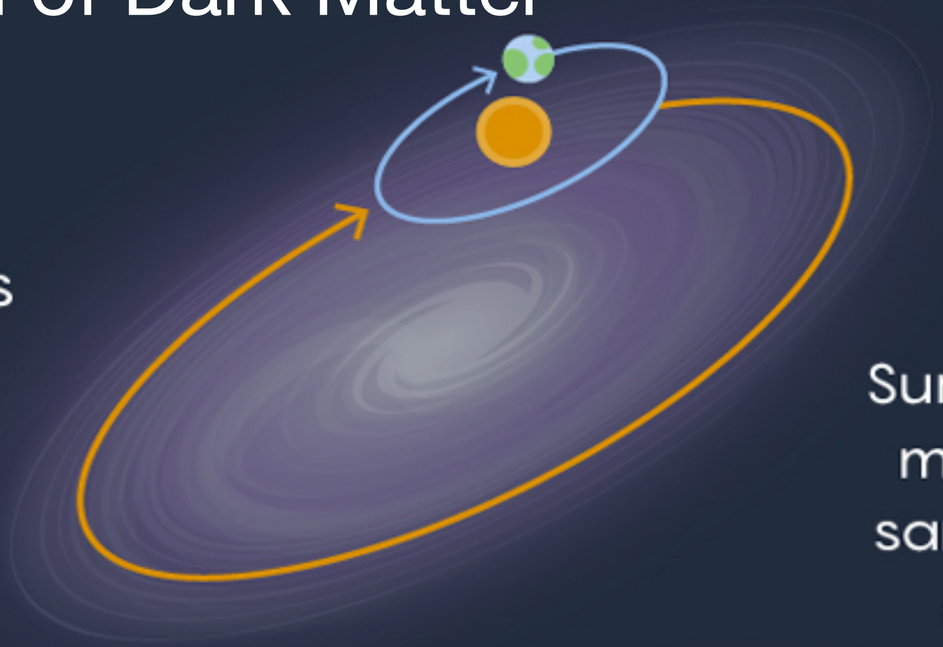
Need to directly test DAMA's result with NaI(Tl)

Annual Modulation of Dark Matter

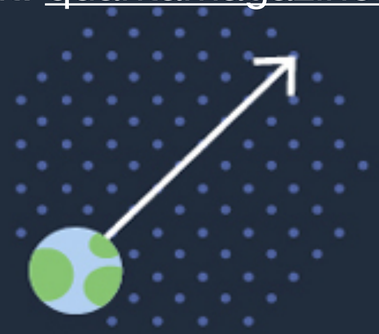
image credit: quantamagazine.com

The Highs

In June, Earth moves at its fastest speed through the dark matter halo.



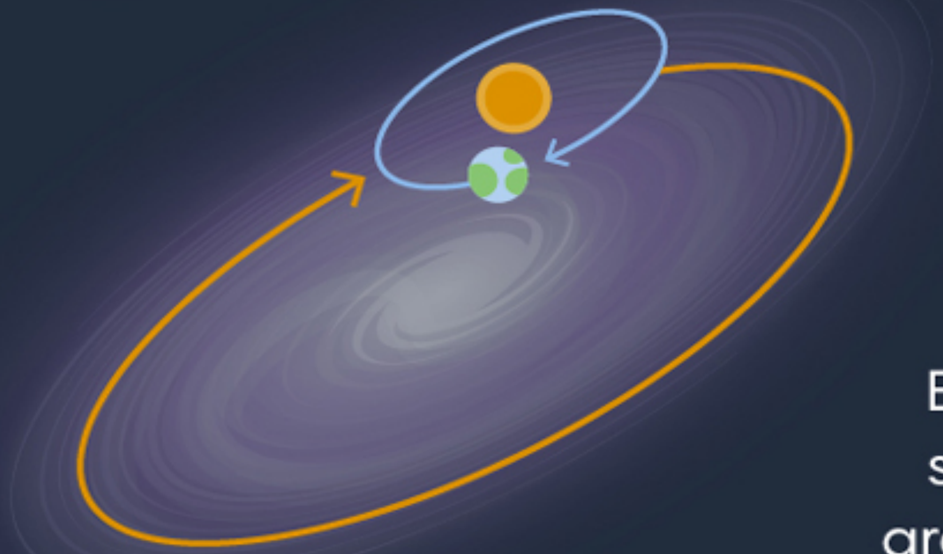
Sun and Earth move in the same relative direction



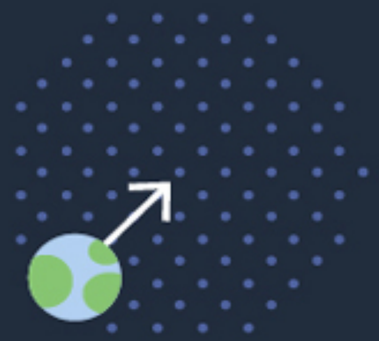
Earth passes through many dark matter particles

The Lows

In December, Earth moves at its slowest speed.



Earth and sun orbits are opposed

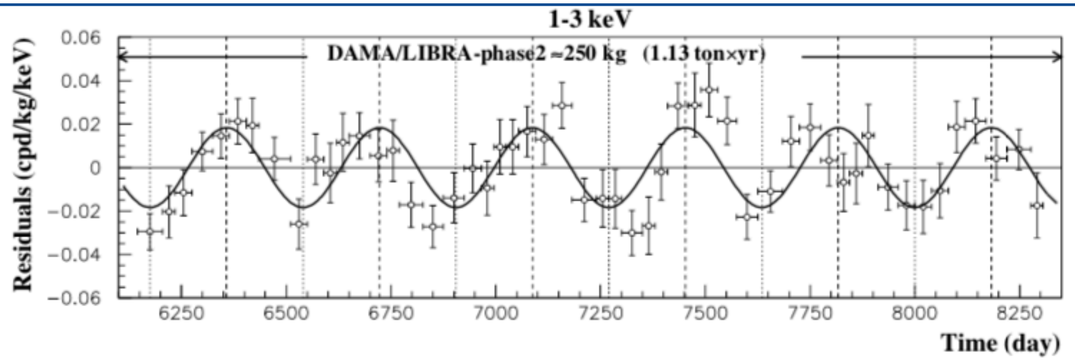


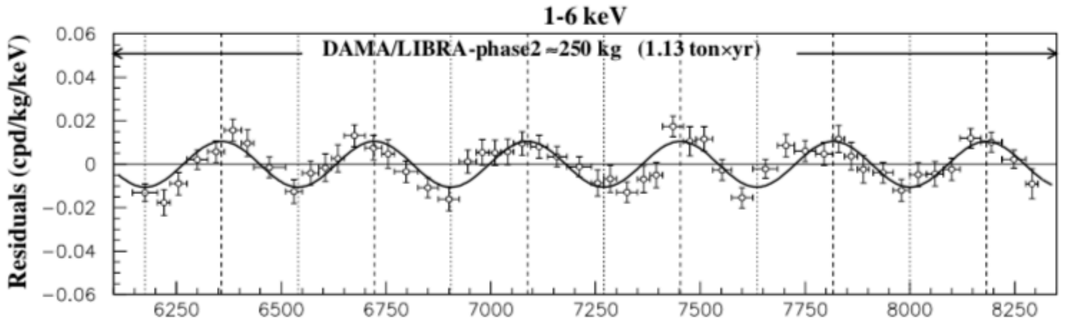
Earth encounters fewer particles

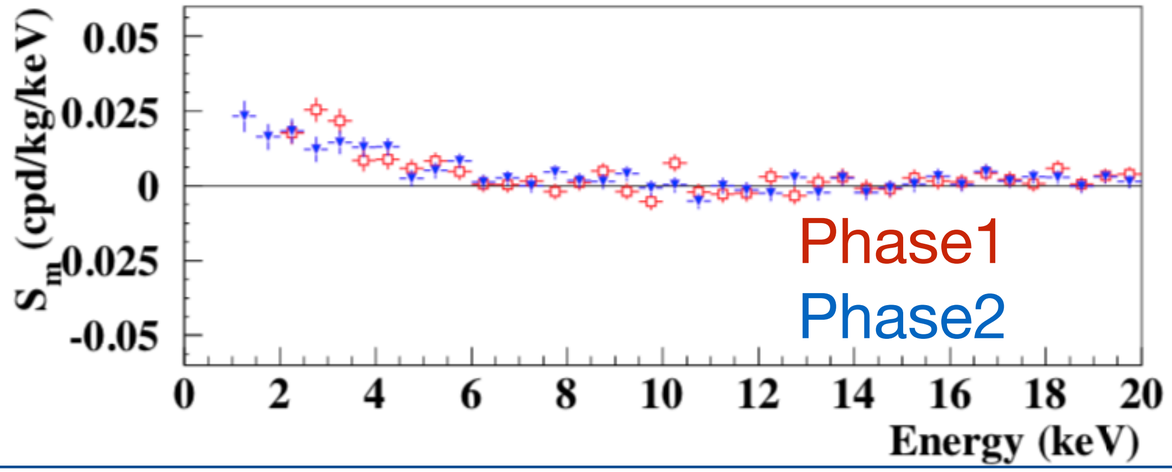
DAMA's annual modulation

Nucl. Phys. At. Energy **19**, 307 (2019)

- 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



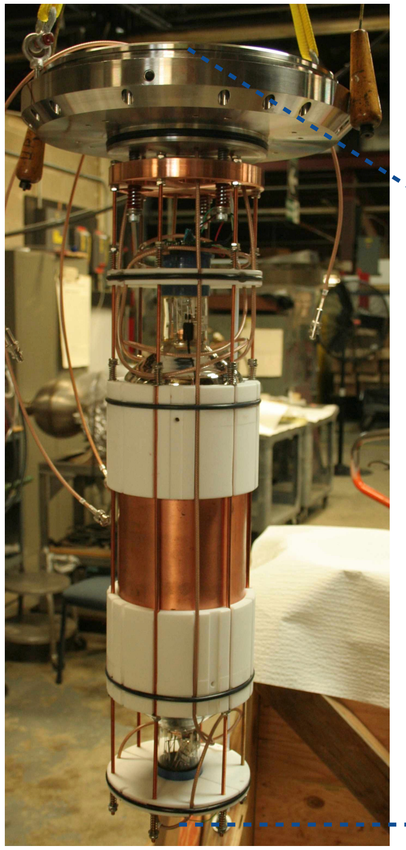


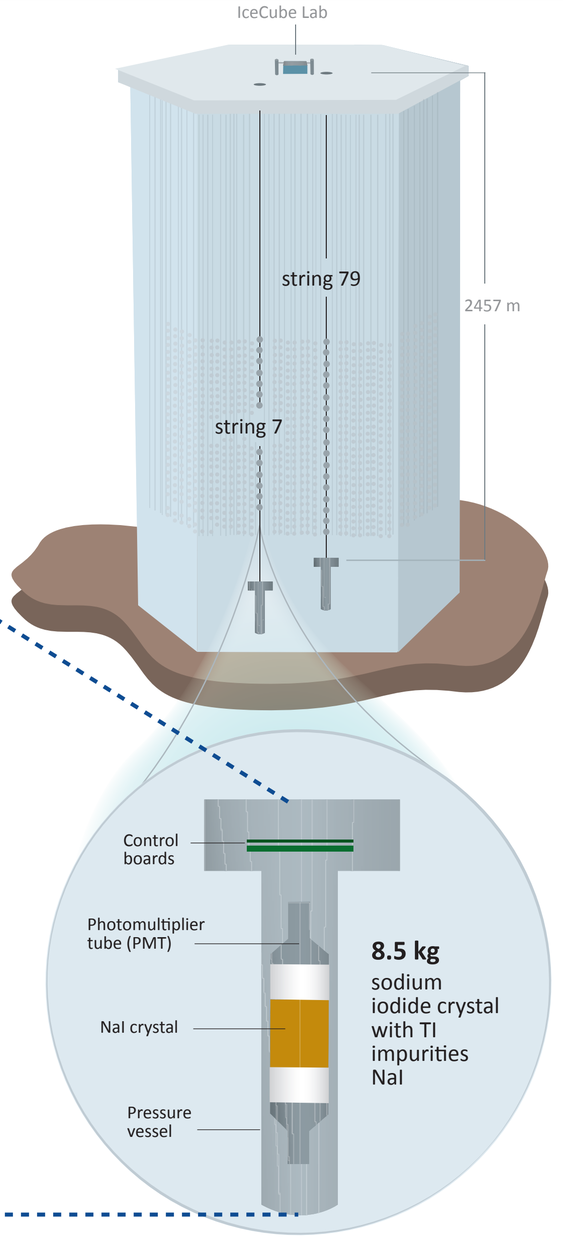


DM-Ice17 experiment

DM-ICE

- Located at South Pole
- Two 8.5 kg NaI(Tl) crystals
- Installed: Dec. 2010, Physics run: Jun. 2011 - Jan. 2015
- Goals:
  - Demonstrate the feasibility of deploying and operating NaI(Tl) detectors in the Antarctic ice for a dark matter search
  - In situ measurement of the radiopurity of the Antarctic ice at 2450 m depth
  - Study environmental stability
  - First search for annual modulation with NaI(Tl) in the Southern Hemisphere





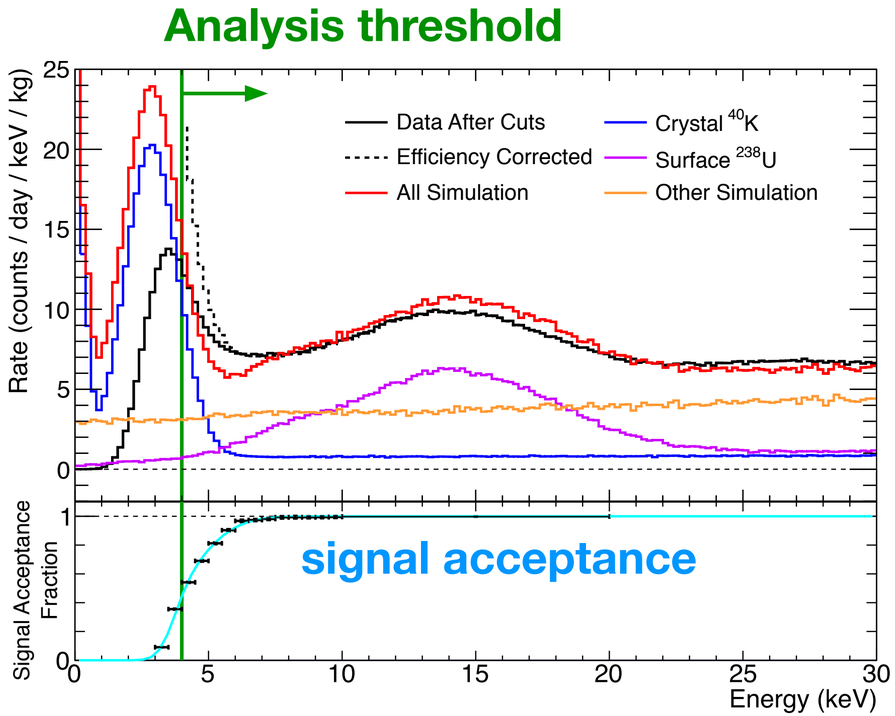
Why the South Pole?

- If found, the same dark matter signal in both hemispheres
- **Seasonal variation reversed in phase**
  - Opposite muon rate, tagging of muons verified by IceCube/DeepCore
- Overburden from 2450 m ice (2200 m.w.e.)
  - Negligible environmental radioactivity: ppt ^{238}U/^{232}Th, ppb ^{40}K
  - Stable temperature under ice
- Support infrastructure of Amundsen-Scott South Pole Station

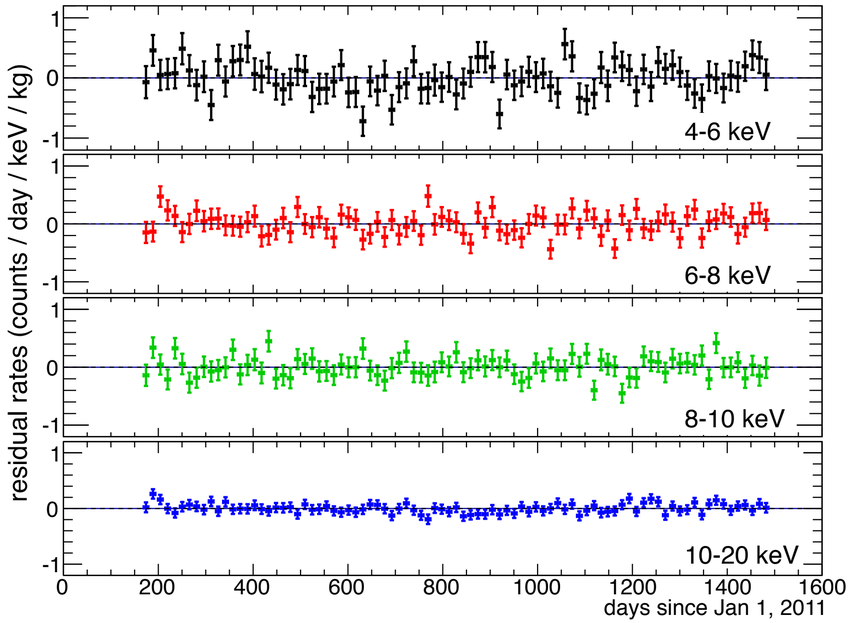
Low energy event rate

DM-ICE

- Analysis threshold at 4 keV
- 3 keV peak from ^{40}K contamination in the crystals, ~15 keV feature from surface ^{238}U contamination on the copper encapsulation
- The data are consistent with the null hypothesis in each energy bin



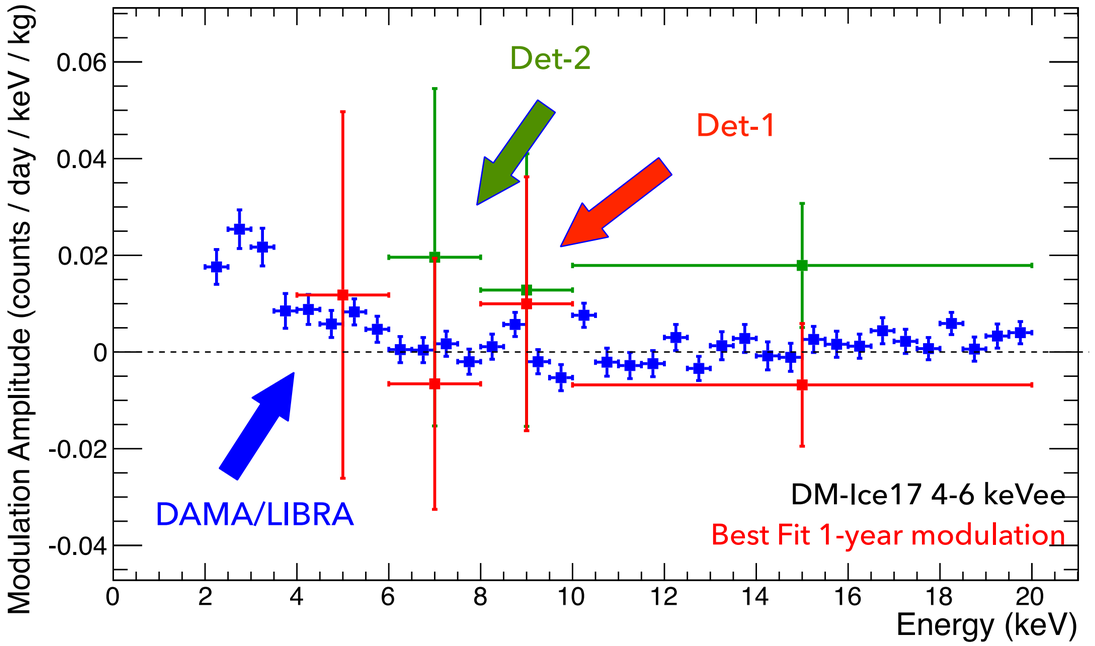
Phys. Rev. D **95**, 032006 (2017)



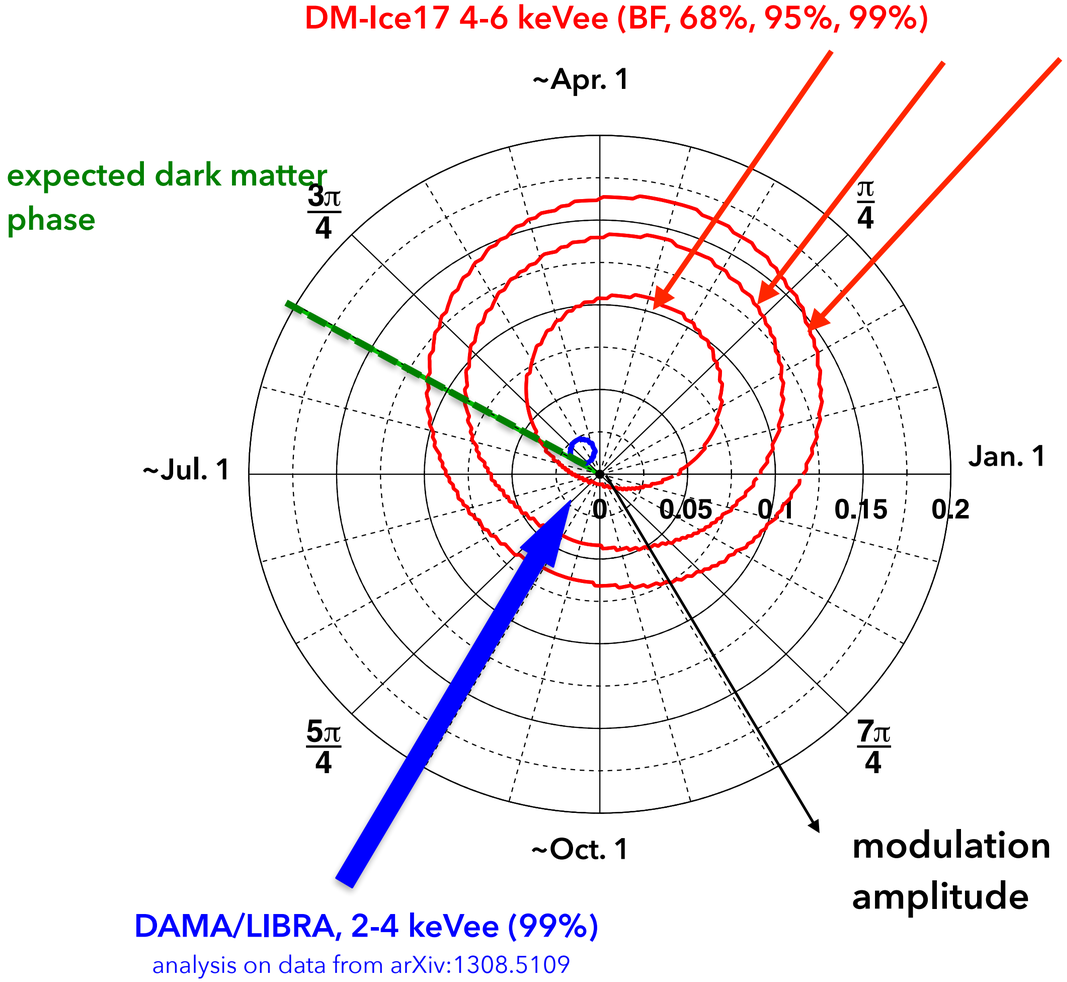
Annual modulation allowed region

DM-ICE

- Comparing sinusoidal modulation to background subtracted event rates
- Maximum likelihood fits for DAMA and DM-Ice17
- Period/phase fixed with 1 year/June 2
- Dark matter modulation amplitudes are consistent at all energies with both **no modulation** and the DAMA signal

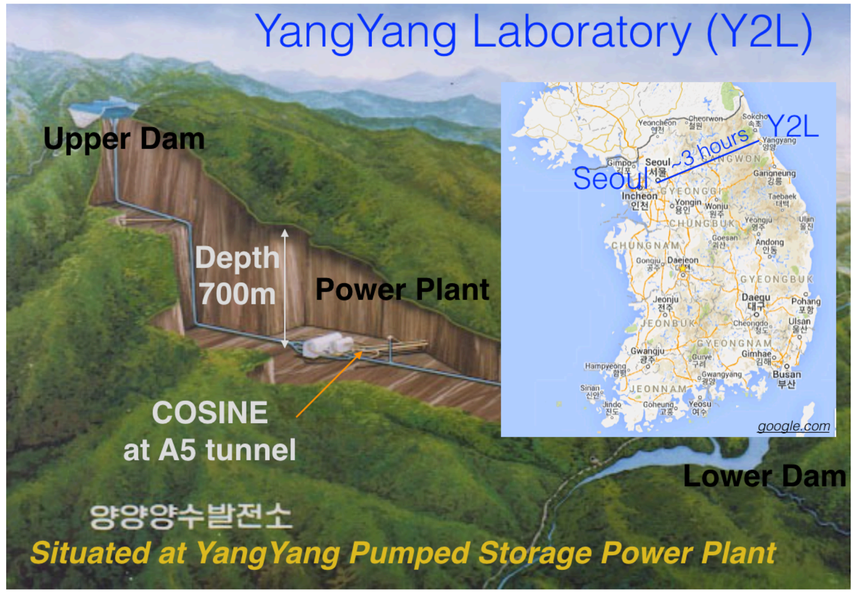


Phys. Rev. D **95**, 032006 (2017)



COSINE-100 experiment

- 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

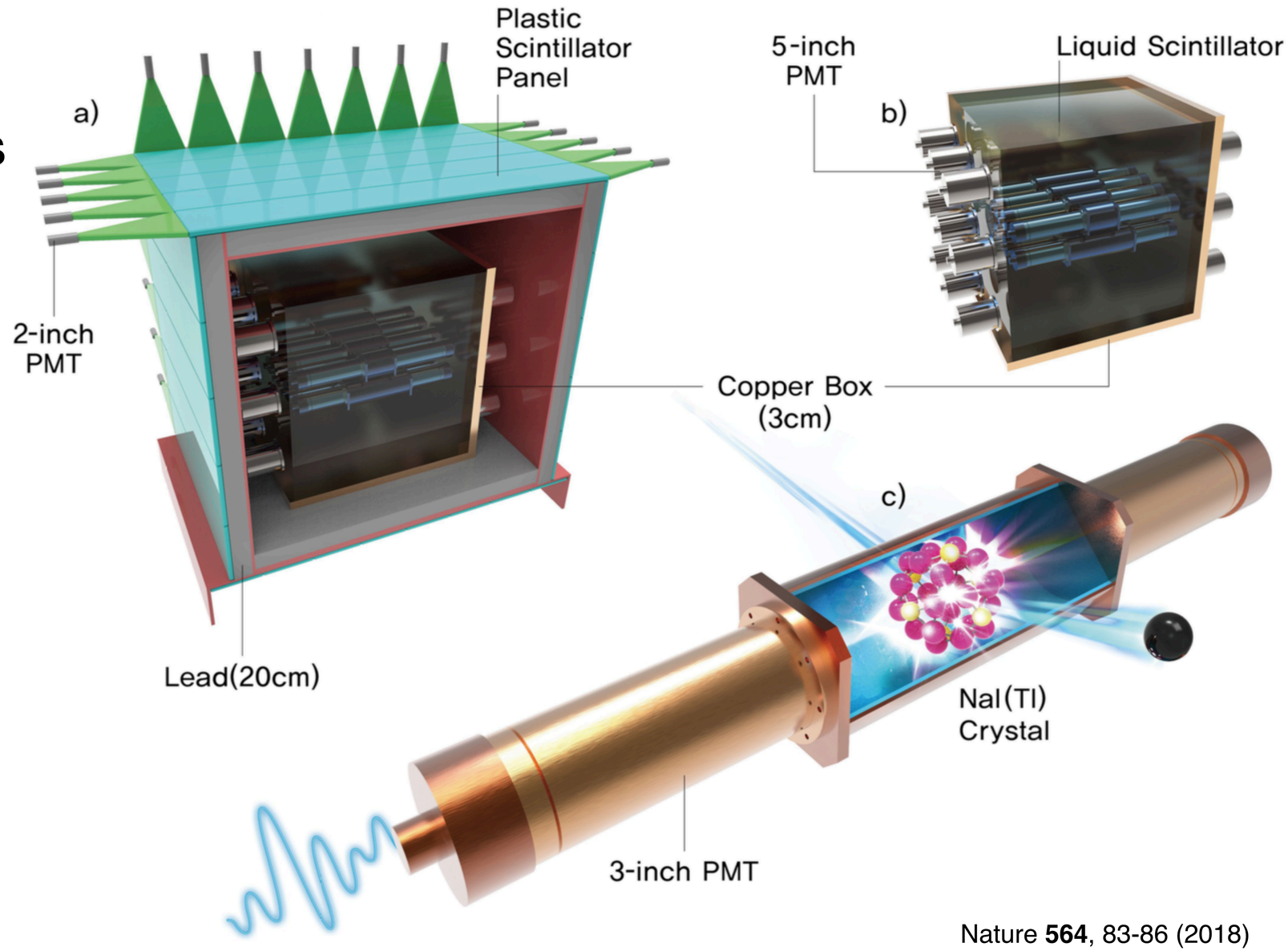
The University Of Sheffield.

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

Yale

COSINE-100 detector configuration

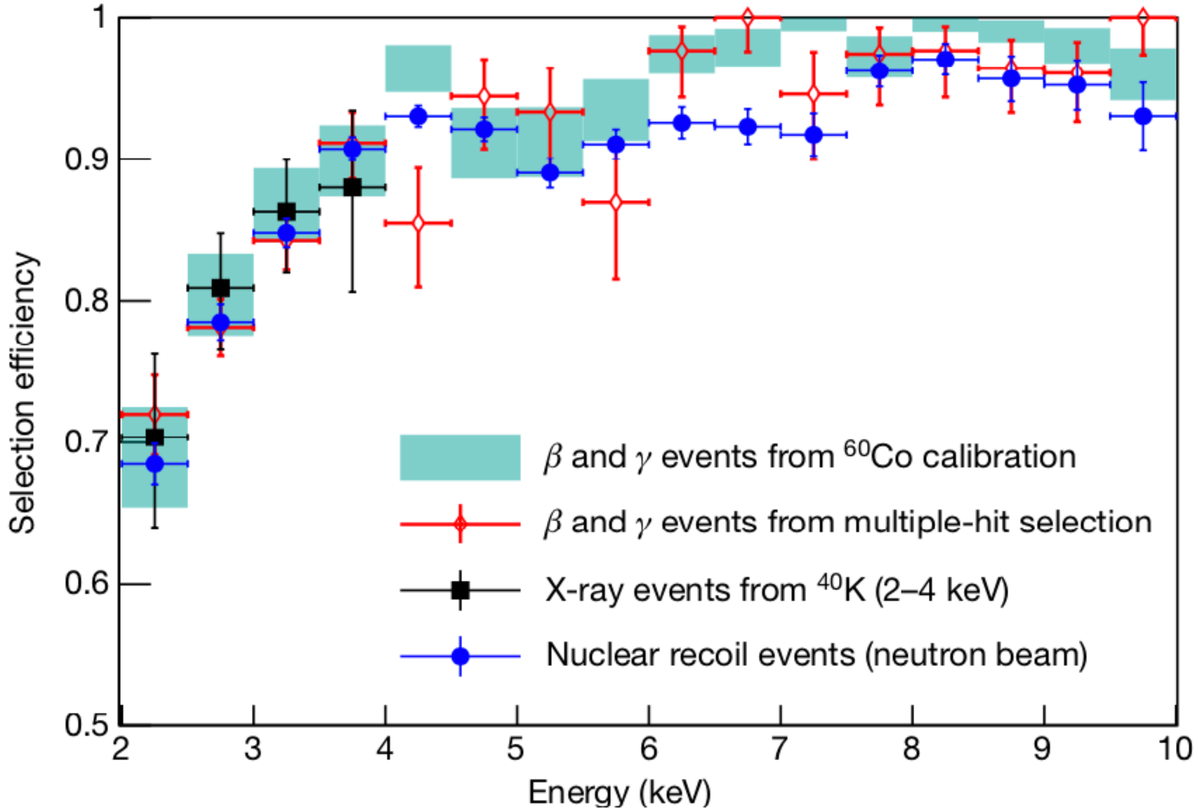
- 37 plastic scintillator panels to tag muons events
- 20cm thick lead shielding and 3cm thick copper box
- 2000L of liquid scintillator to tag internal/external background events
- 8 NaI(Tl) crystals

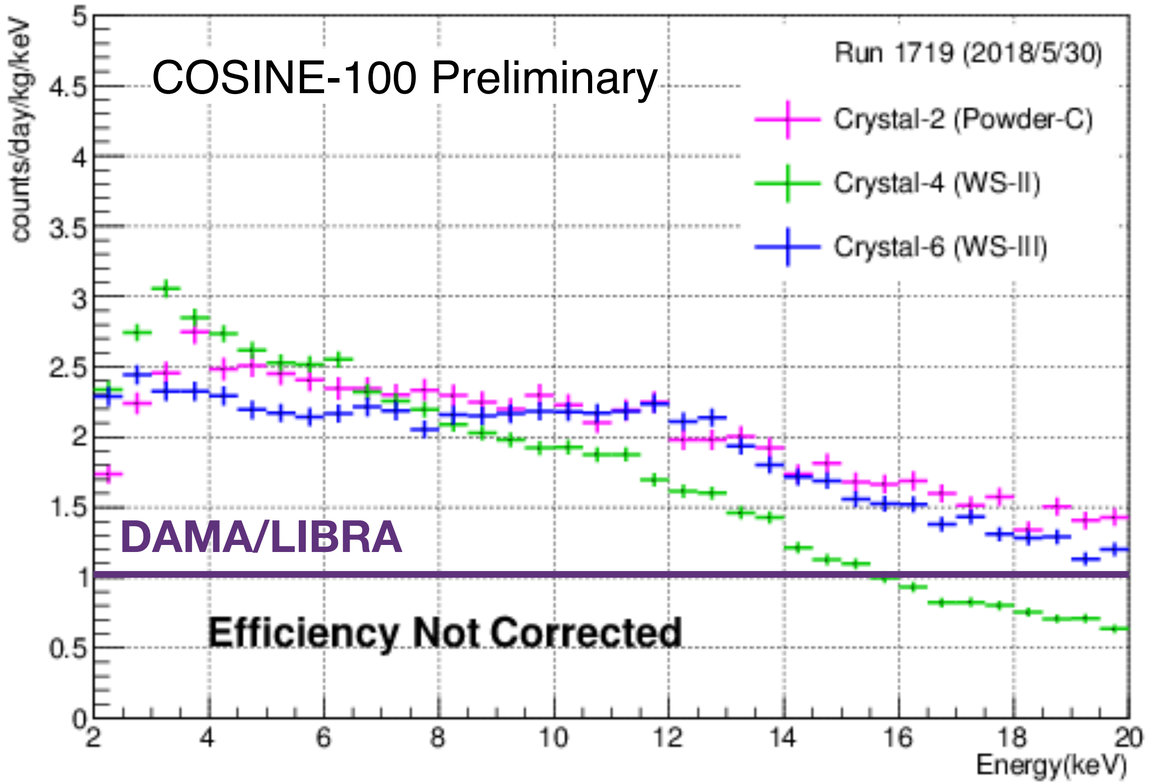


Nature **564**, 83-86 (2018)

Selection efficiency/Low energy spectrum

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

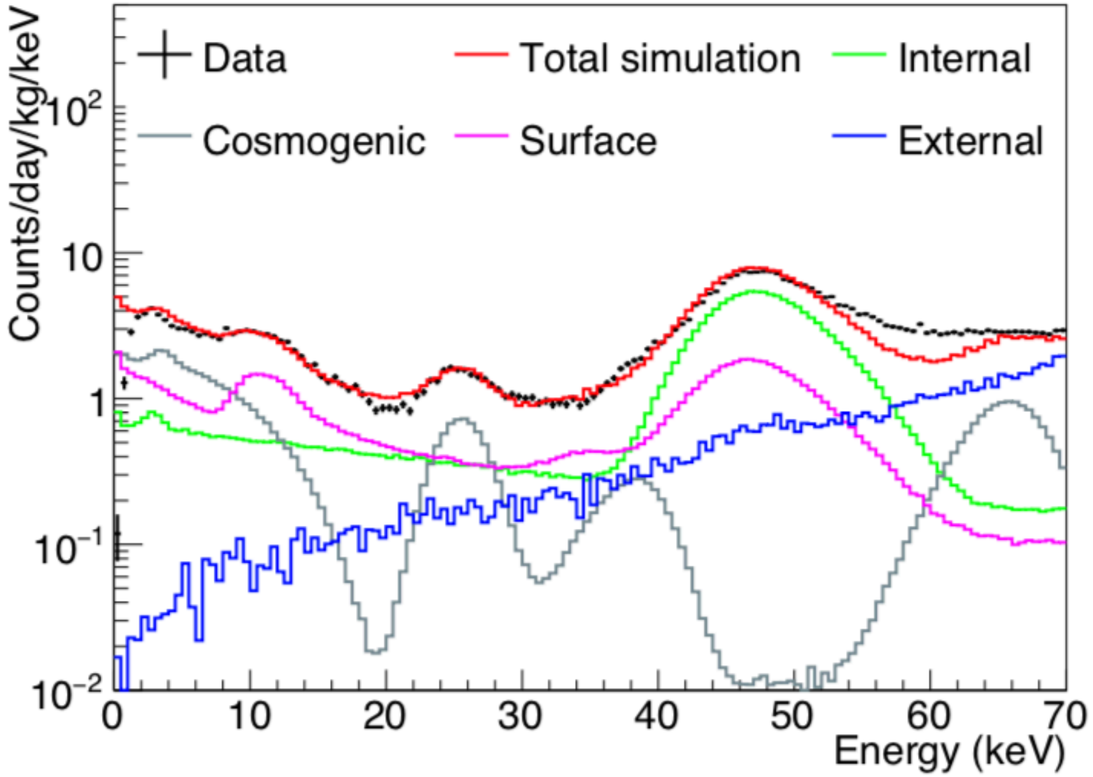


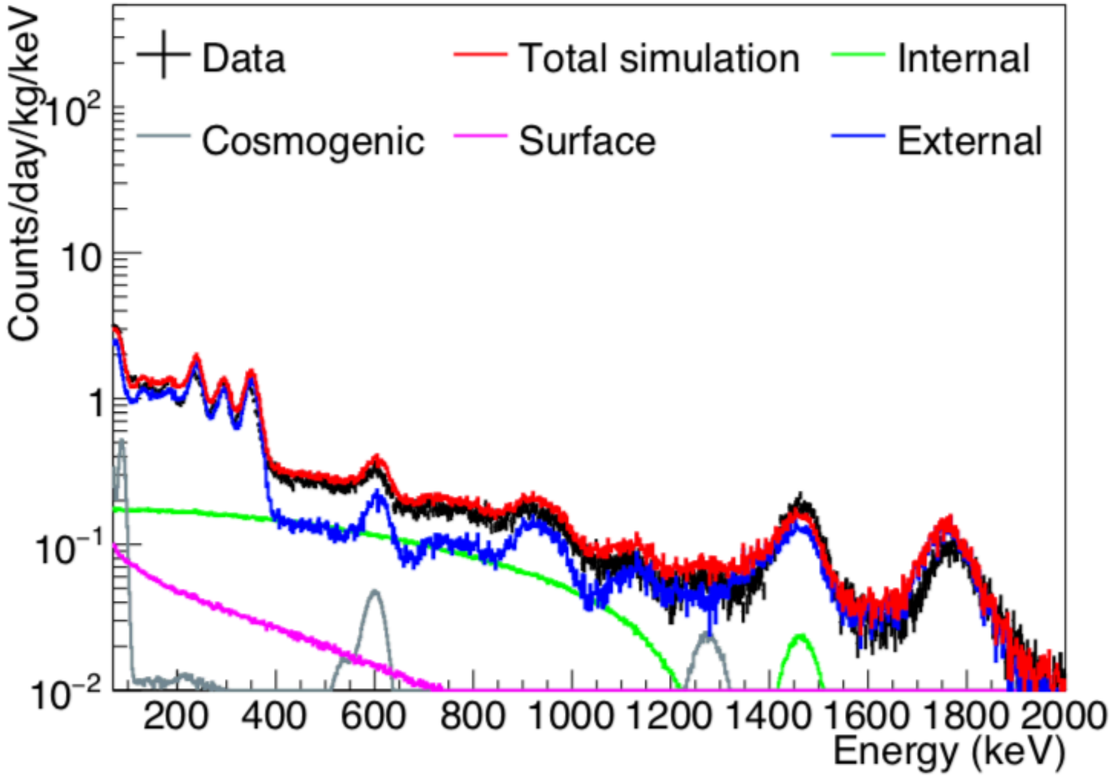


- ~70% efficiency at 2 keV
- 2 - 4 counts/keV/kg/day in region of interest depending on the crystal

Background in data vs. simulation

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

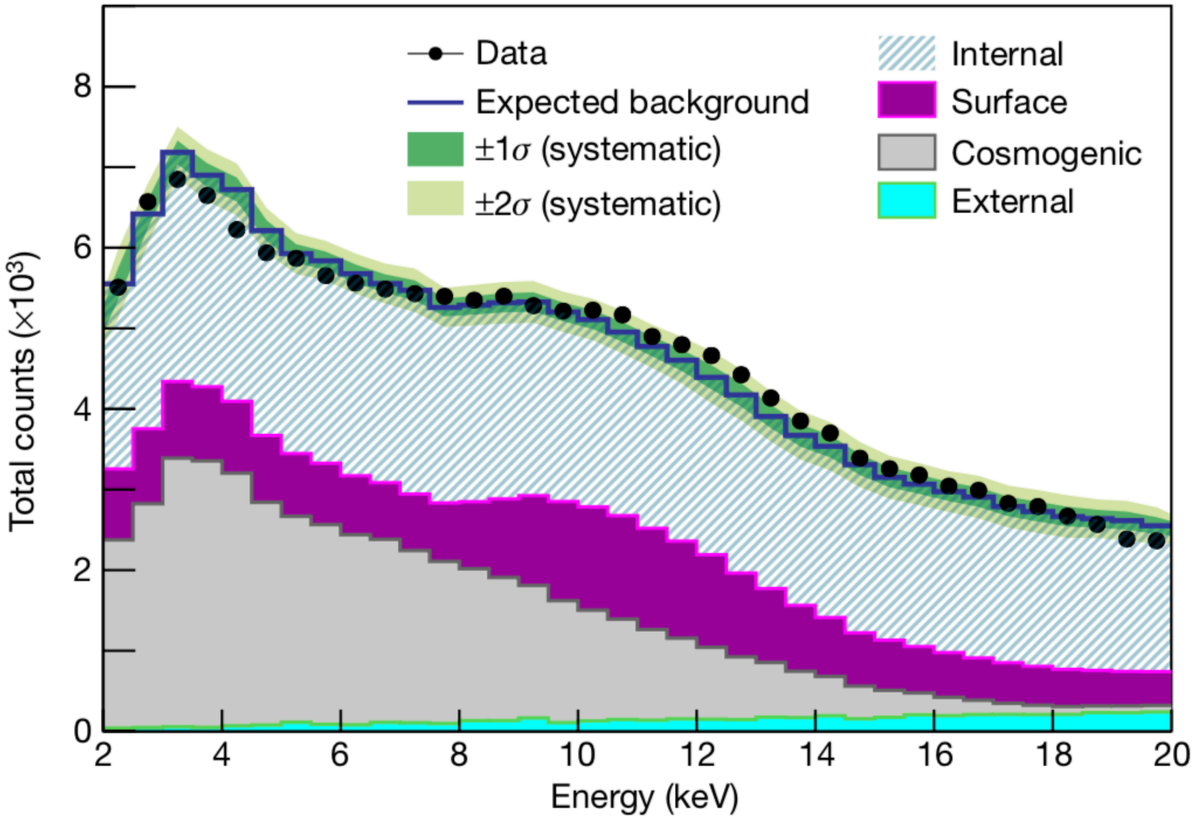




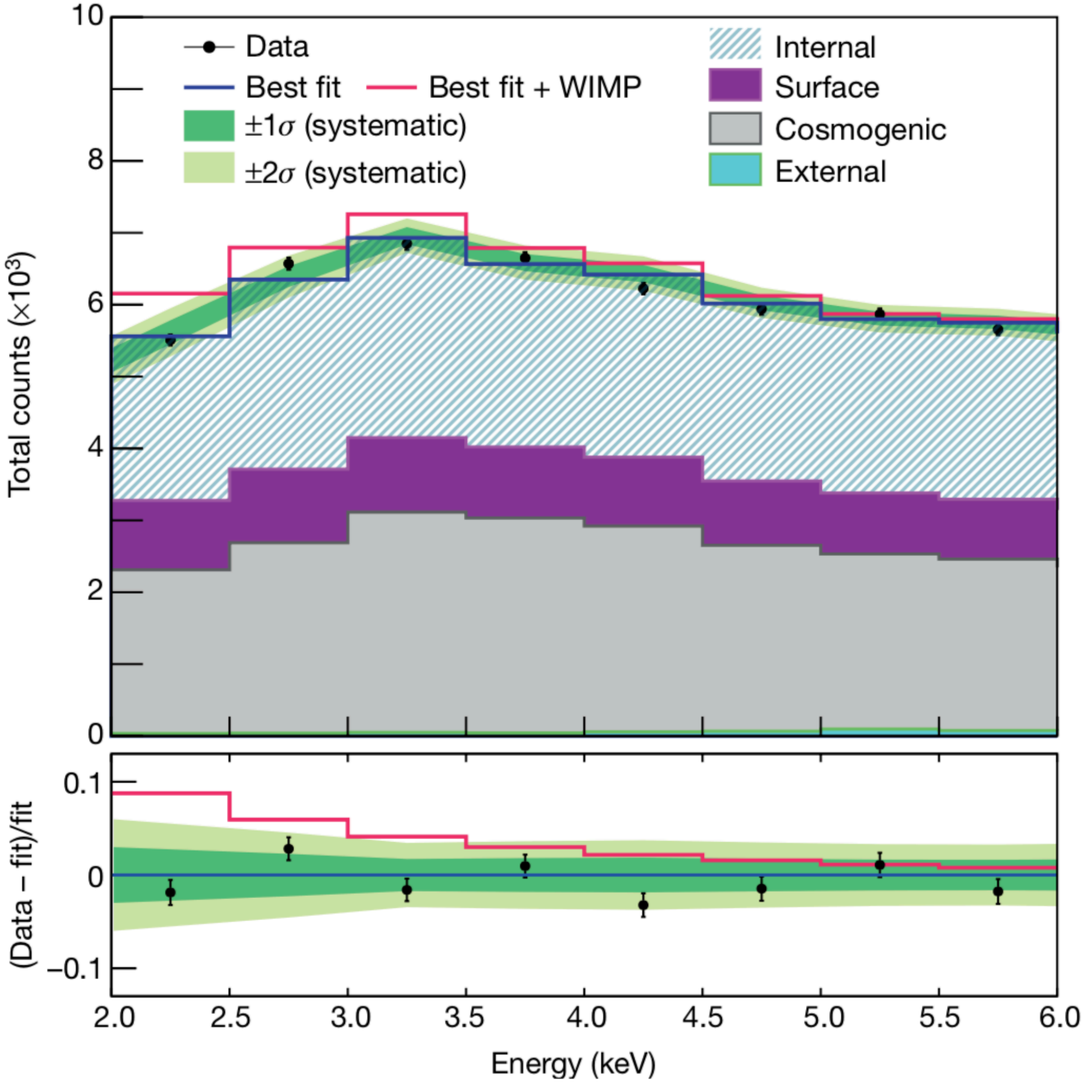
- Data reproduced well with Geant4 simulation
- **Background well understood from 2 keV - 2000 keV**
- Dominant background from ^{210}Pb (internal, surface) and ^{40}K (internal), followed by cosmogenic ^{3}H

WIMP analysis: Backgrounds+WIMP

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



Measured and simulated energy spectra, summed for the six crystals

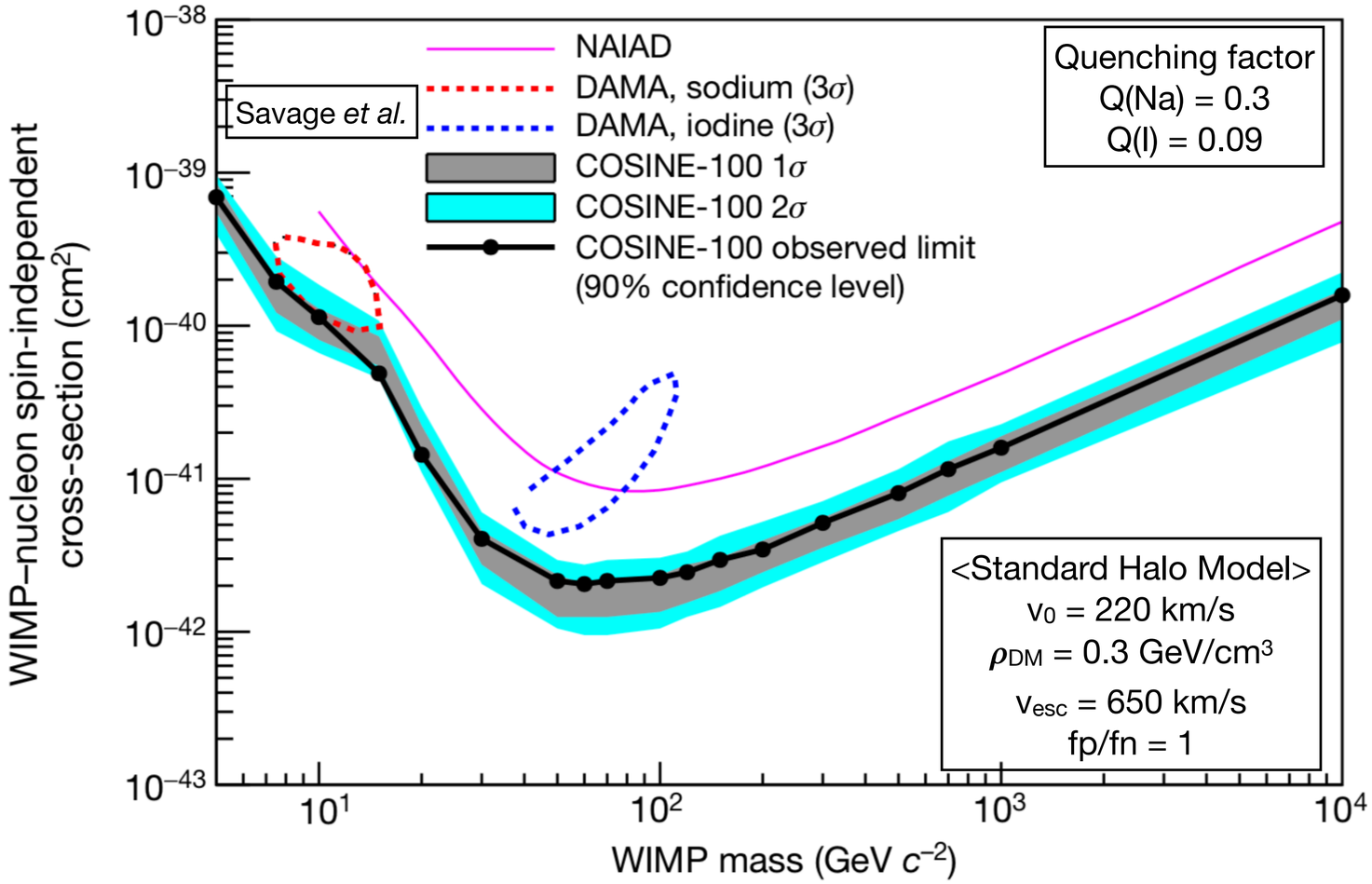


Fit result for a WIMP mass of 10 GeV c^{-2}, summed for the six crystals

WIMP analysis: Result

- 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)



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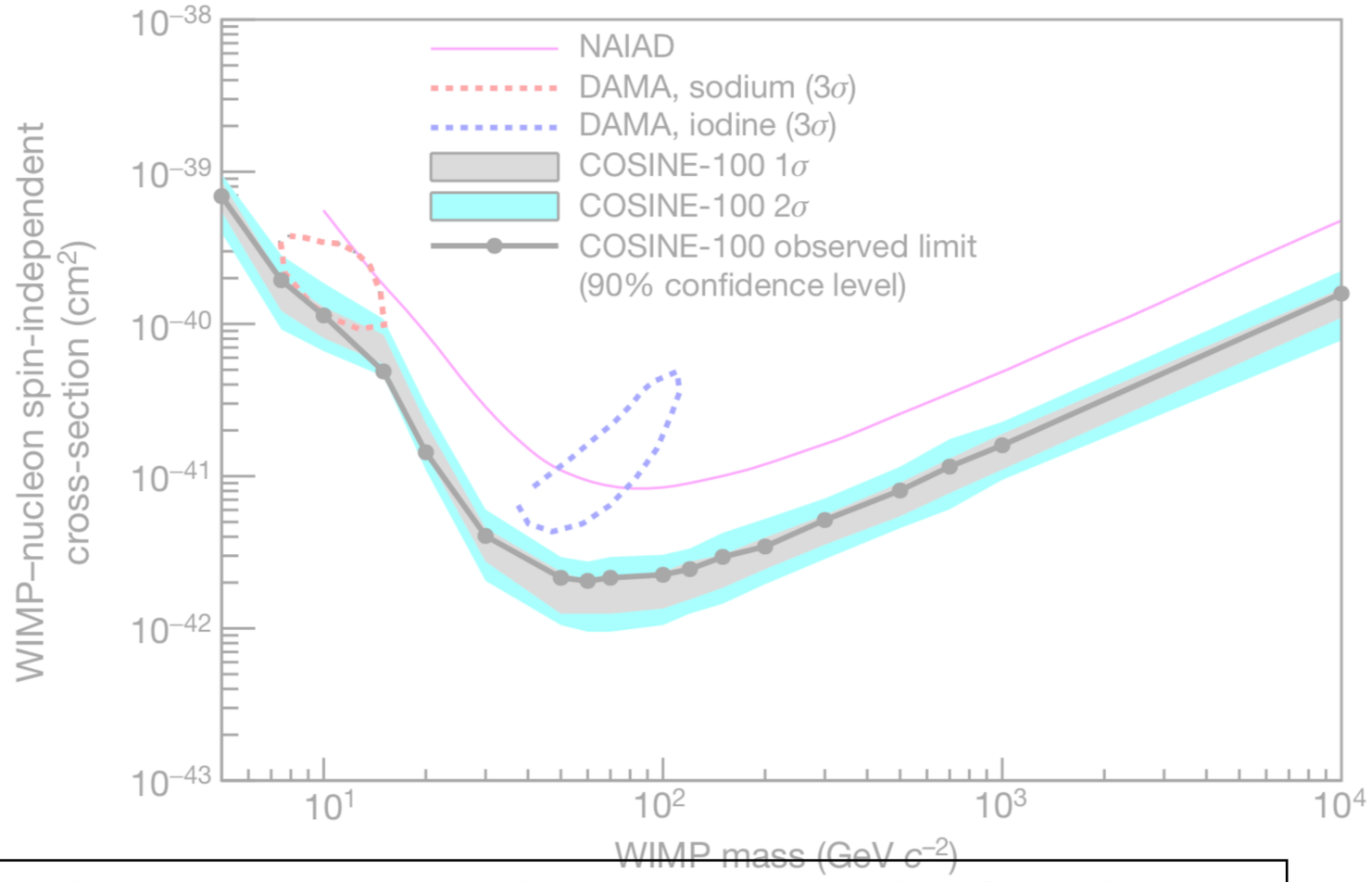
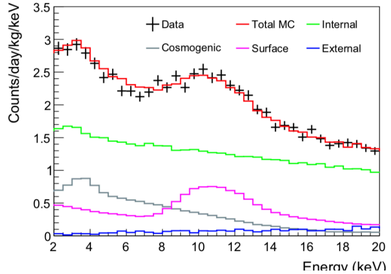
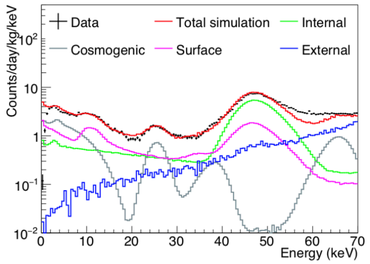
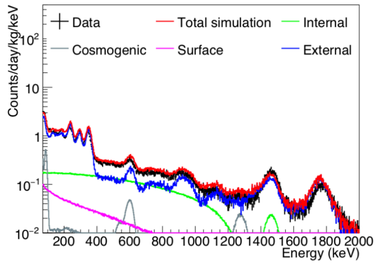


The COSINE-100 result ruled out the simplest version of WIMPS, but for a complete test of DAMA, the annual modulation search is required

Annual modulation analysis: Fitting strategy





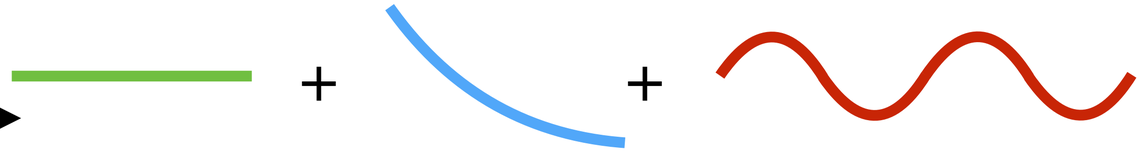


Eur. Phys. J. C **78** 490 (2018)

	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	0.29 ± 0.15	0.08 ± 0.08	0.09 ± 0.09
Other	–	–	0.02 ± 0.01	0.09 ± 0.04	0.06 ± 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

Backgrounds, constrained:
Different for each crystal

Signal, floated:
Same for all the crystals



$$\text{Rate} = C + p_0 \cdot \exp\left(-\frac{ln2 \cdot t}{p_1}\right) + A \cdot \cos\frac{2\pi(t - t_0)}{T}$$

- **C**: Constant offset constrained by backgrounds
- **p_0, p_1**: amplitude and decay time for exponentially decaying background as a model for cosmogenically activated backgrounds
- **A, T, t_0**: Modulation amplitude, period (fixed to 365.25 days), phase
- Global fit using cosmogenic and sinusoidal components simultaneously for crystals

Annual modulation analysis: Result

Phys. Rev. Lett. **123,** 031302 (2019)

Backgrounds, constrained:
Different for each crystal

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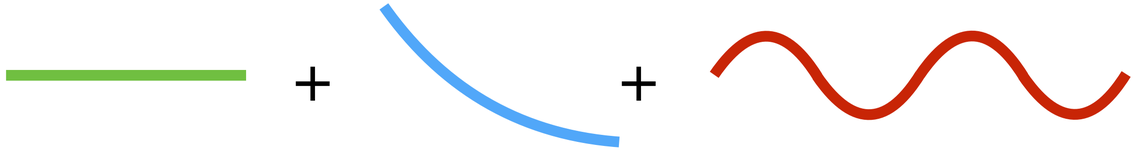
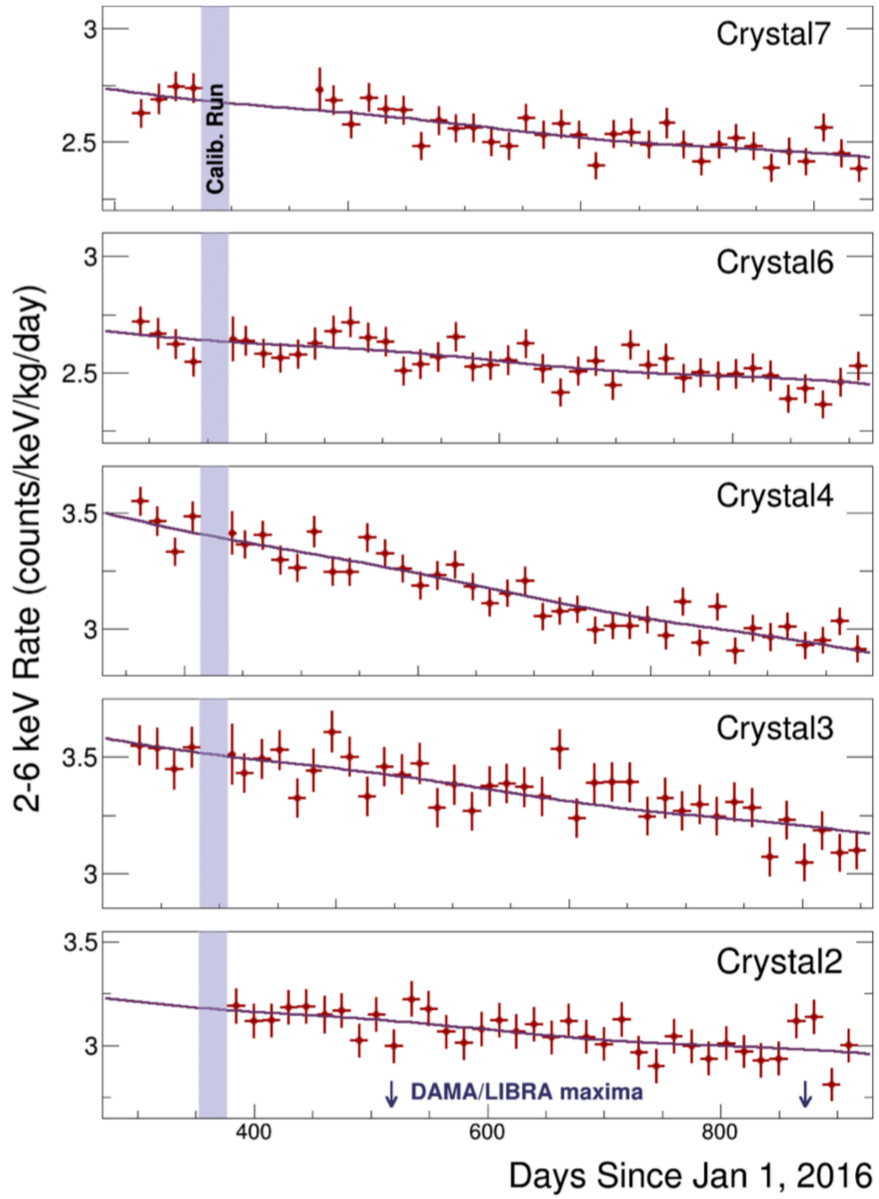
Same for all the crystals



$$\text{Rate} = C + p_0 \cdot \exp\left(-\frac{ln2 \cdot t}{p_1}\right) + A \cdot \cos\frac{2\pi(t - t_0)}{T}$$

- 1.7 years of data with a total exposure of 97.7 kg·yrs
- 15-day interval for binning
- 670 events/day or 2.7 cpd/keV/kg on average in 2-6 keV energy interval



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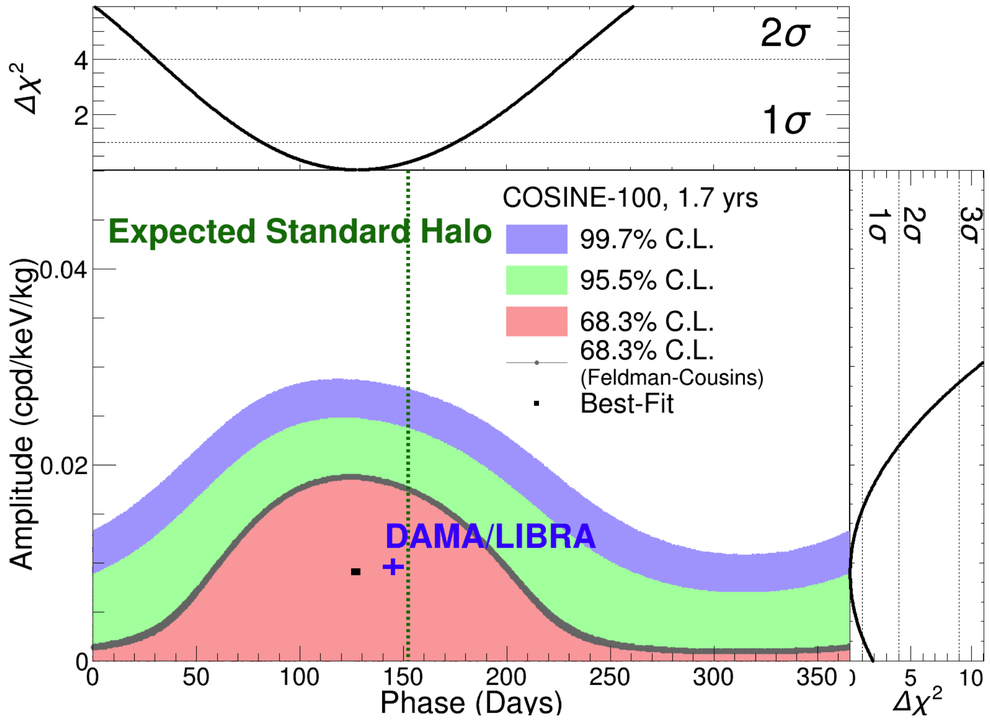
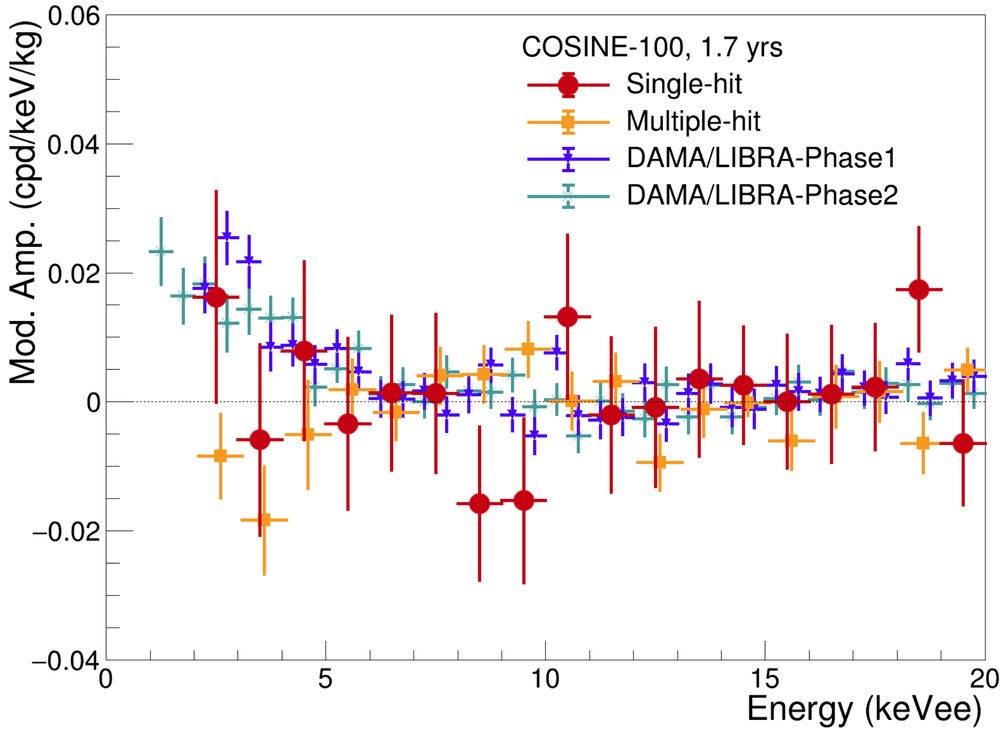


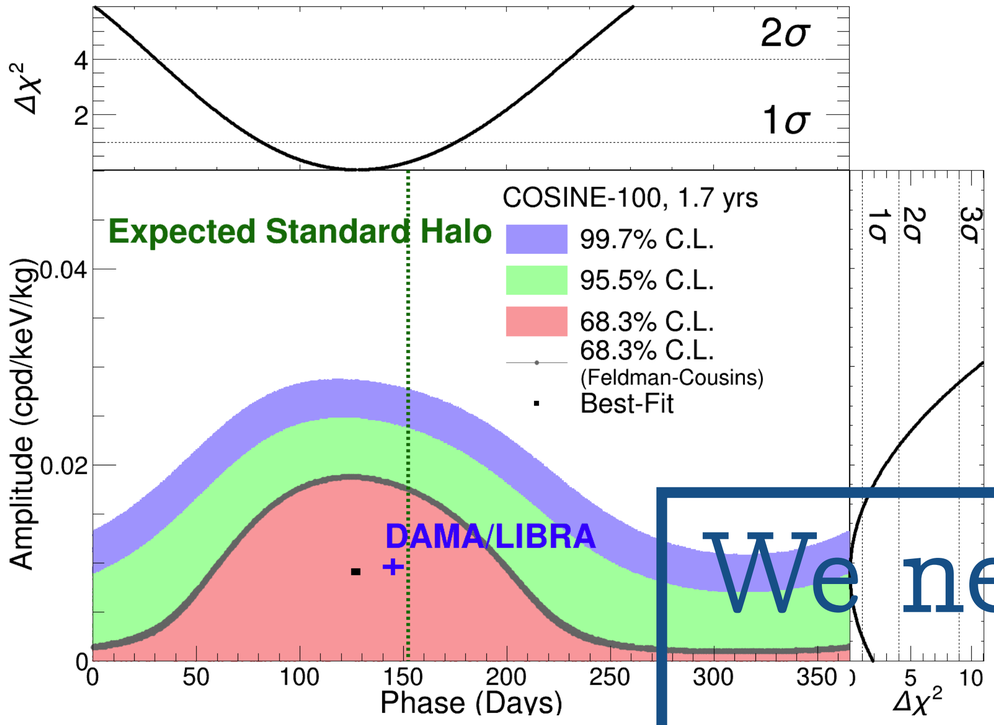


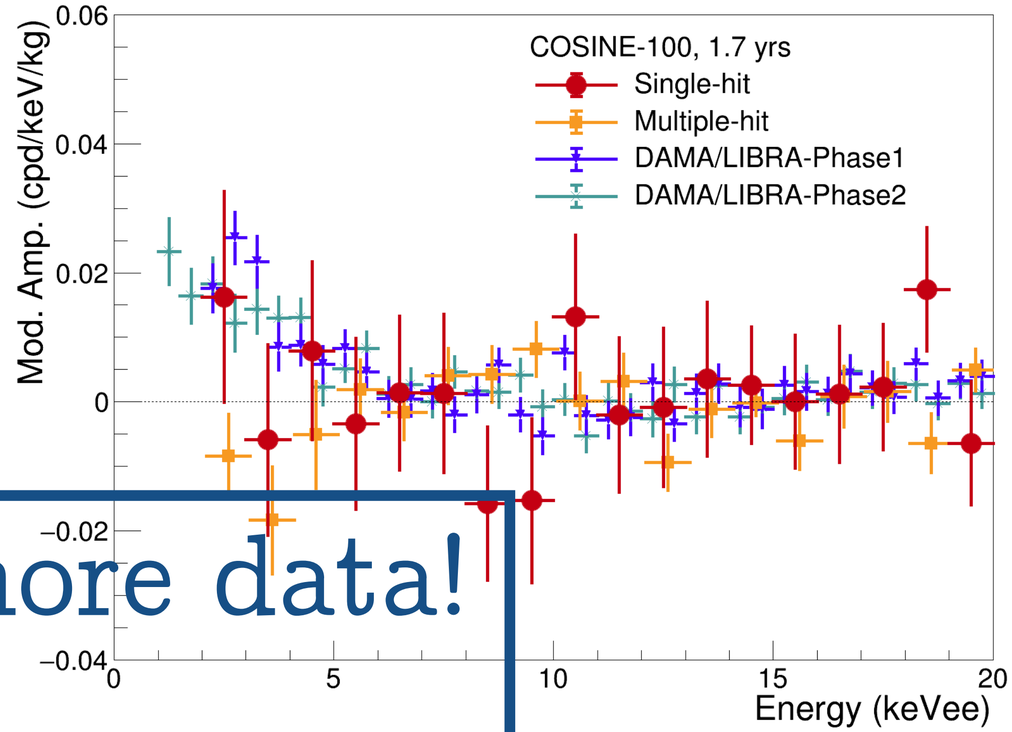
- Best fit amplitude and phase for 2–6 keV
  - 0.0092 ± 0.0067 cpd/kg/keV
  - 127.2 ± 45.9 days
- Feldman-Cousins method used to cross-check, returns consistent C.L.
- **Small positive modulation signal in low energy, but statistically limited: not yet able to distinguish DAMA/null**

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)

Annual modulation analysis: Result

Phys. Rev. Lett. **123,** 031302 (2019)





We need more data!

...like everyone else...

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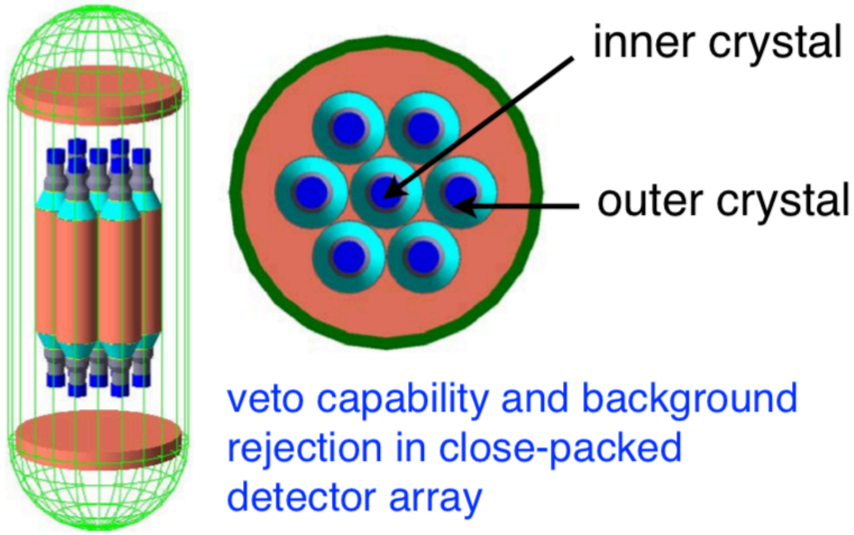
What next?

- **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)
  - DM-Ice250 in South Pole under consideration: IceCube upgrade is planned on 2022-2023

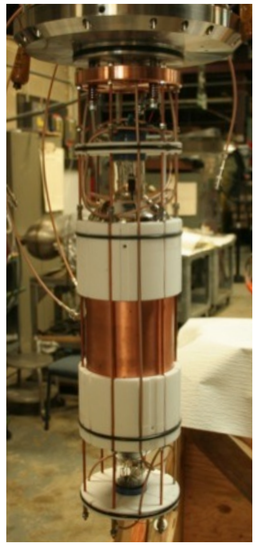
DM-Ice250 @ South Pole

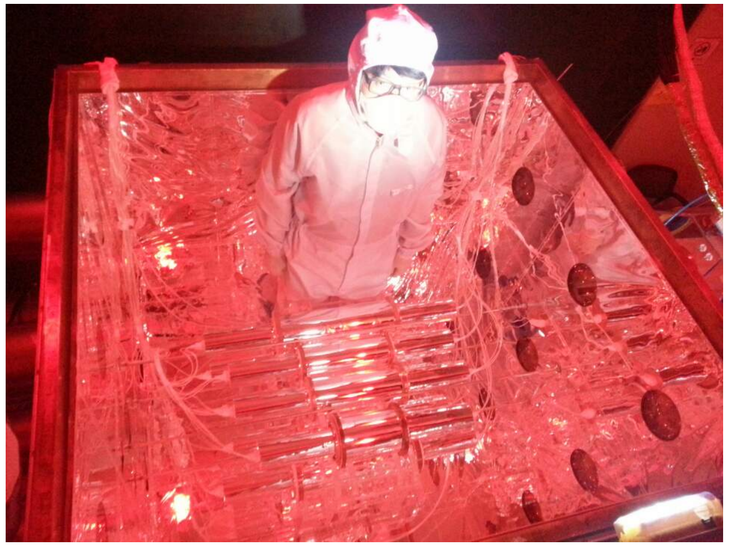
Close-Packed Detector Array

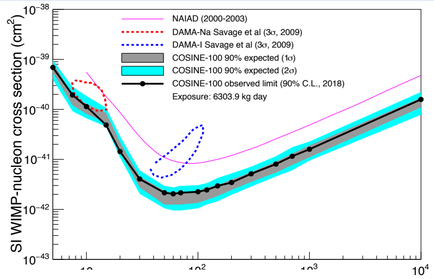


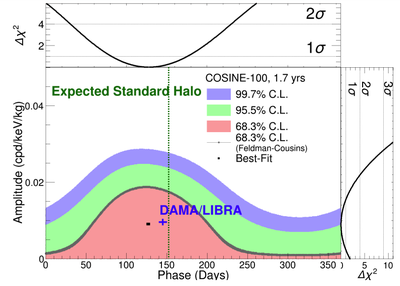
veto capability and background rejection in close-packed detector array

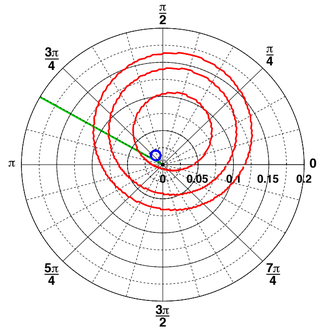
Summary and outlook

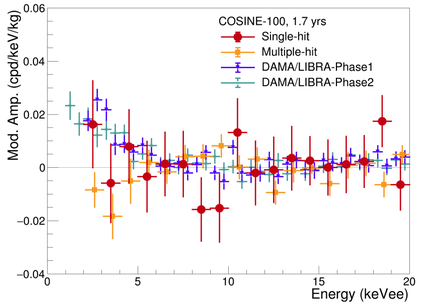












- DM-Ice17 & COSINE-100: Goal is to test DAMA's claim for dark matter observation with the same target material
- DM-Ice17 demonstrated the South Pole as viable underground location for dark matter searches
- COSINE-100 confirms that DAMA's modulation signal cannot be from standard WIMP & SHM with NaI(Tl)
- First modulation analysis with 1.7 years exposure shows consistent result with null hypothesis and DAMA signal, but statistics limited
- Stay tuned for more exciting results to come!

Backup

ANAIS-112 recent result

arXiv:1903.03973

ANAIS-112 annual modulation analysis

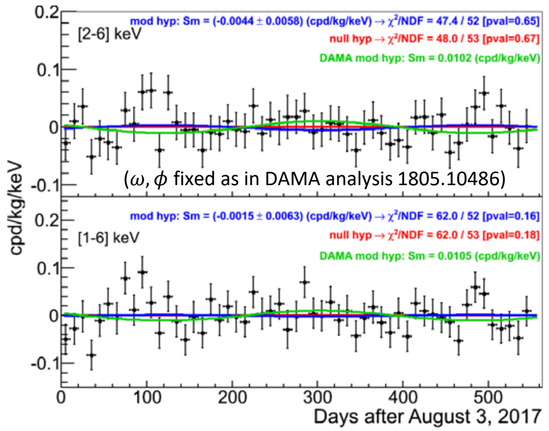
ArXiv:1903.03973

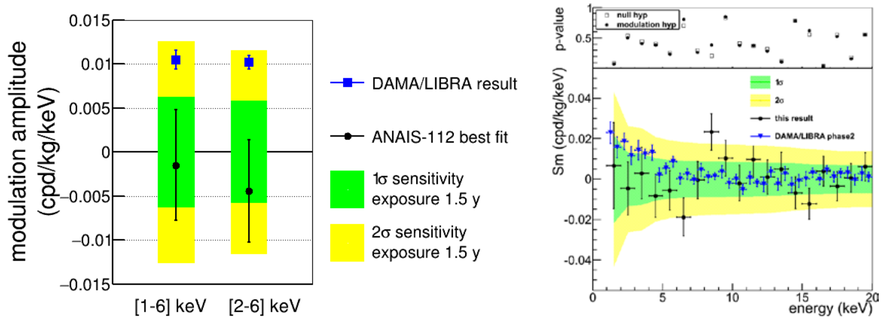
Exposure: 157.55 kg×y

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

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

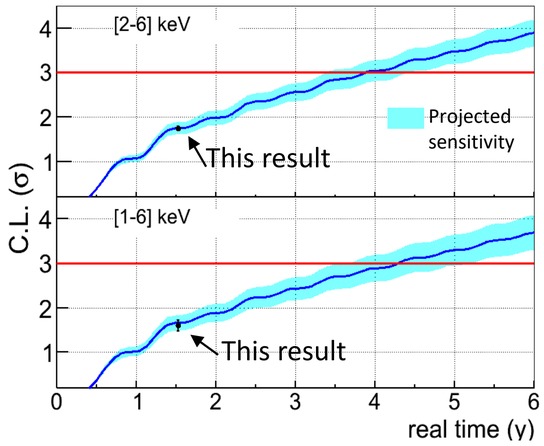
[1-6] keV → $S_m = -0.0015 \pm 0.0063$ cpd/kg/keV

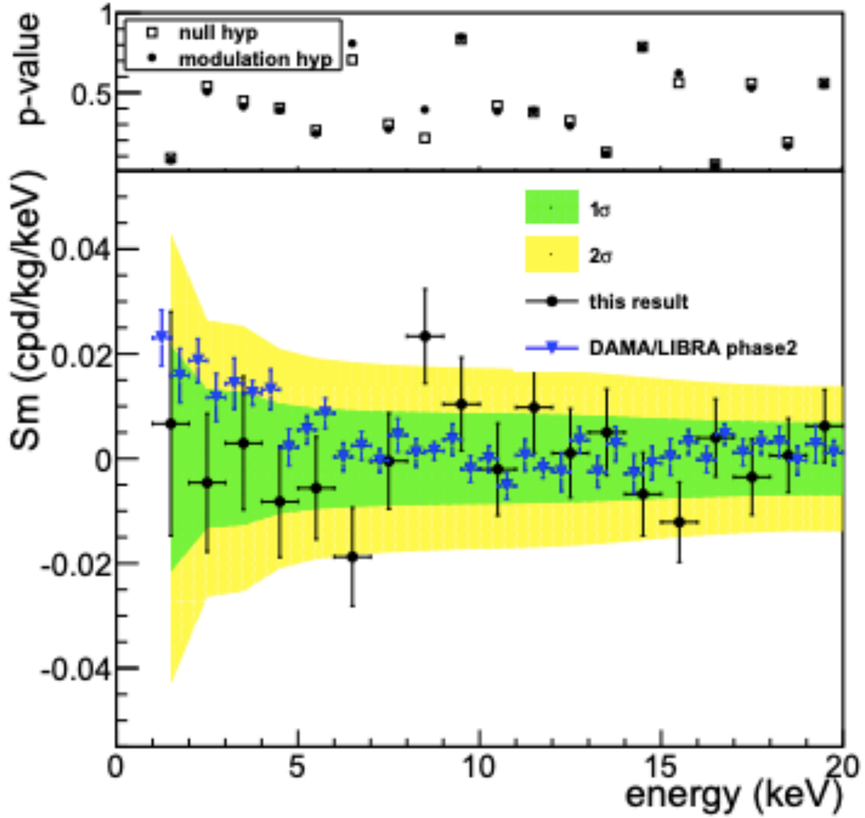




The result for 1.5 years confirms the estimated sensitivity for our background and exposure

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



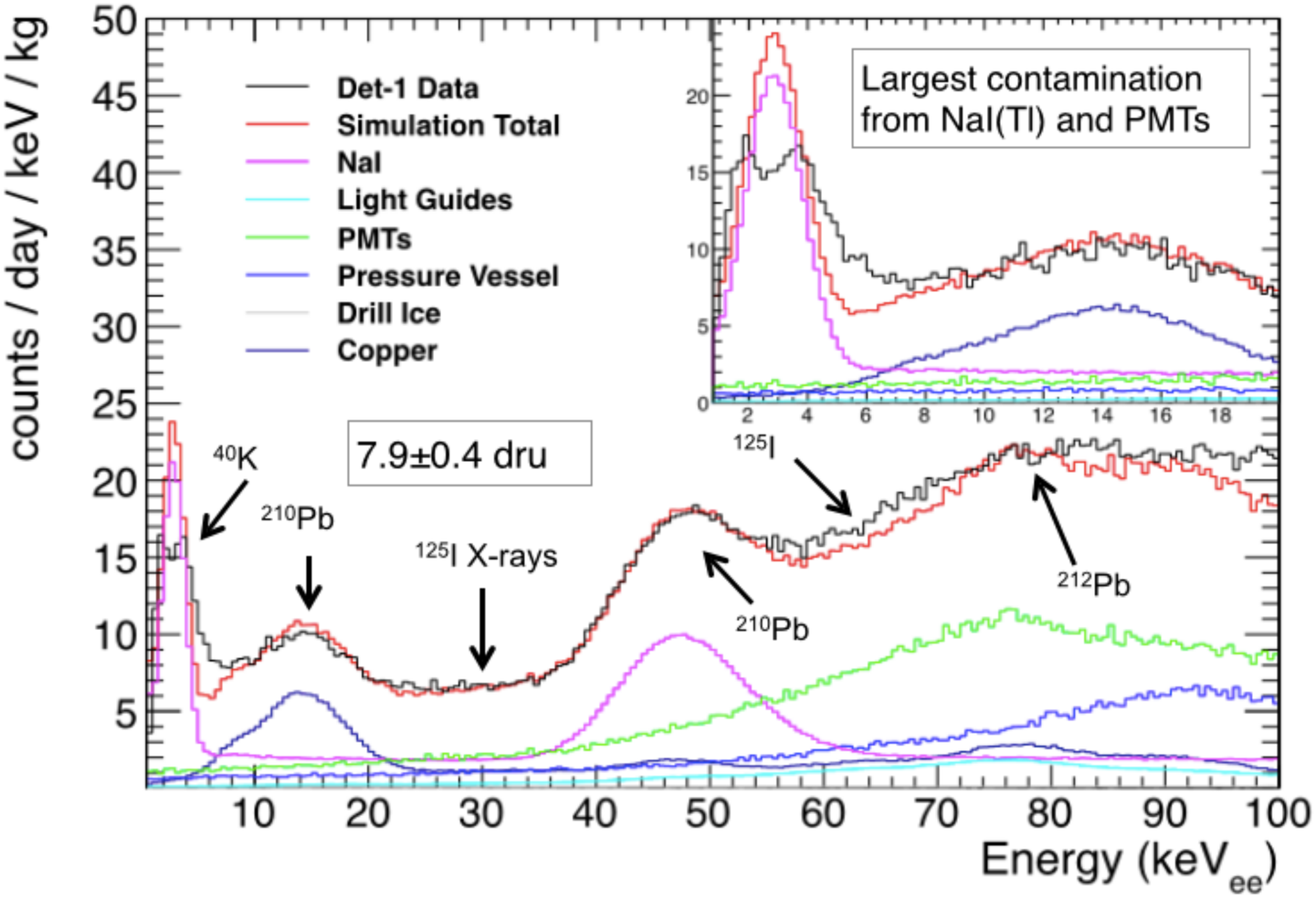


Moriond Conference

DM-Ice17 Background Model: Low Energy Region

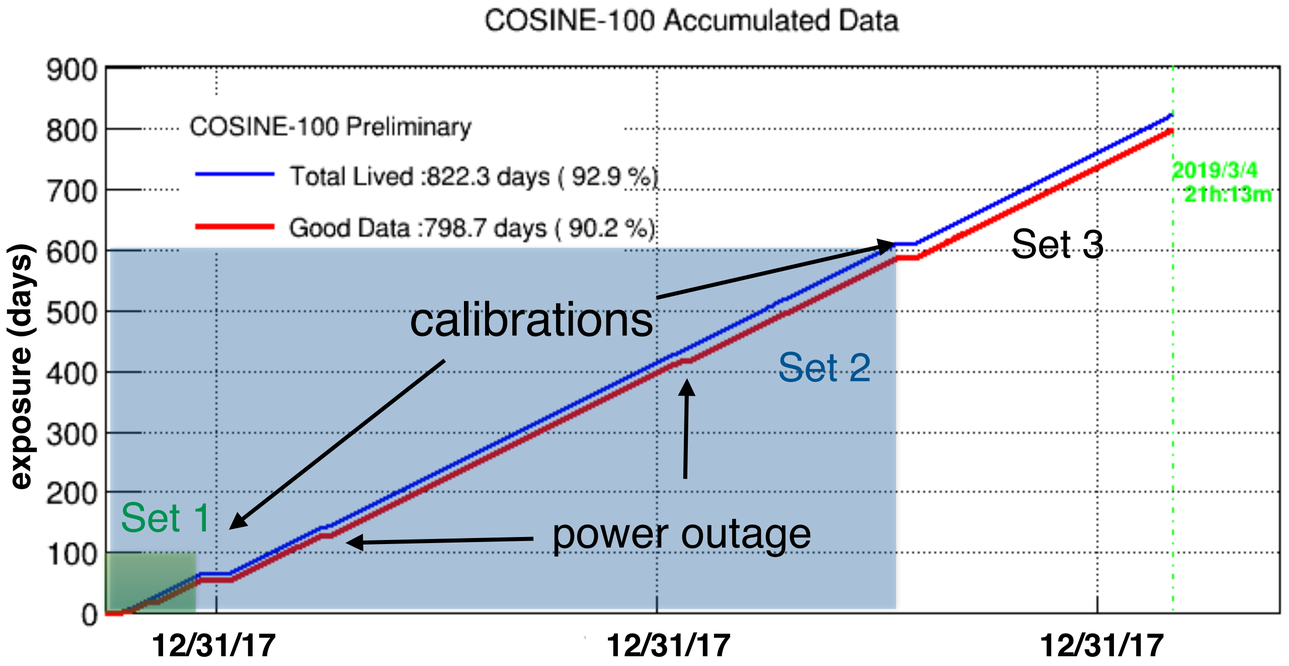
Cherwinka *et al.*, Phys. Rev. D **90** (2014) 092005

- Below 5 keV, background is dominated by
  - ^{40}K and ^{210}Pb in NaI(Tl)
  - PMTs
  - Surface ^{210}Pb and Light guides
- 7.9±0.4 dru observed between 6.5-8 keV



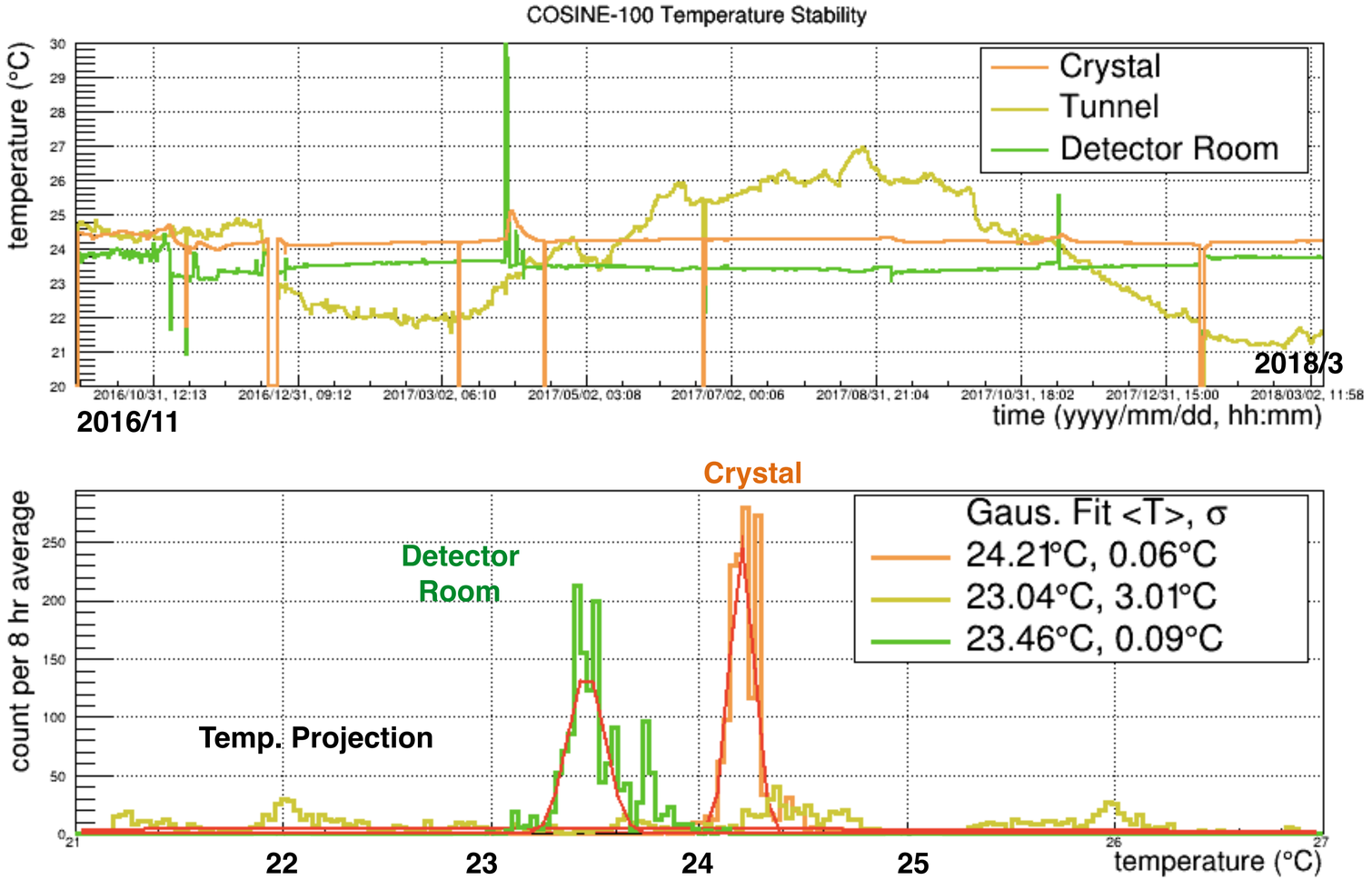
COSINE-100 operation

- Data taking since Sep. 2016
  - Stable operation
  - ~90% live time
  - Near 100% uptime outside of calibration
- > 23 months of data accumulation
  - SET1 data (59.5 days) - Background modeling, detector understanding, and WIMP analysis
  - SET2 data (621.0 days) - Annual modulation analysis



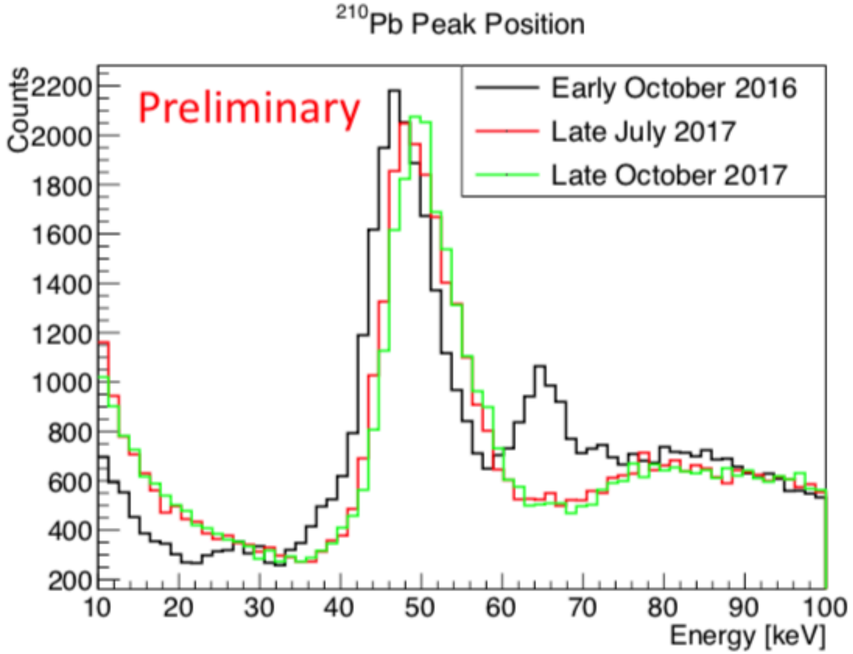
Environmental control/monitoring

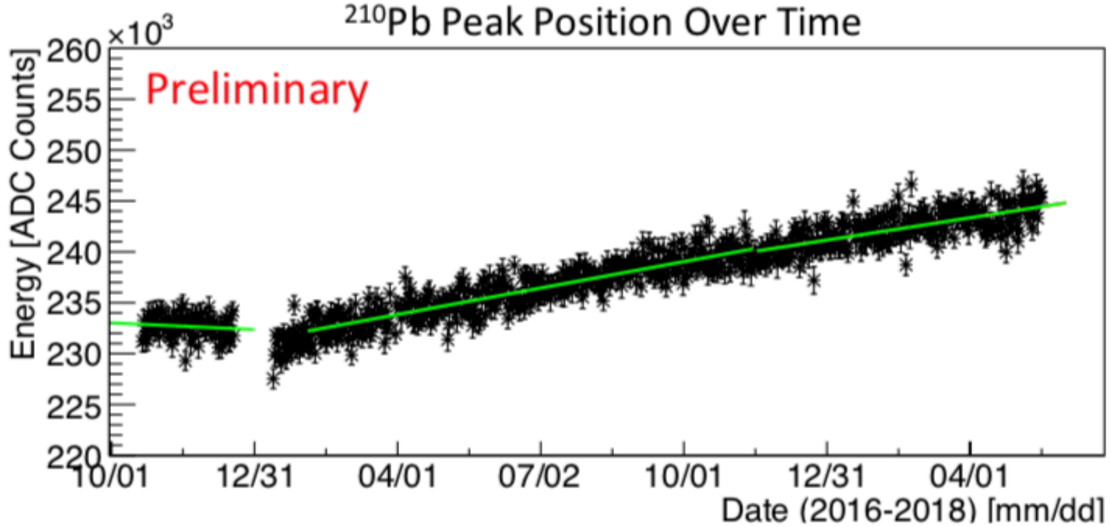
- Monitoring stability of temperature, humidity, current/voltage, etc.
- < 0.1 ℃ temperature and < 2% humidity fluctuation inside the shielding structure
- Current and voltage of detectors very stable

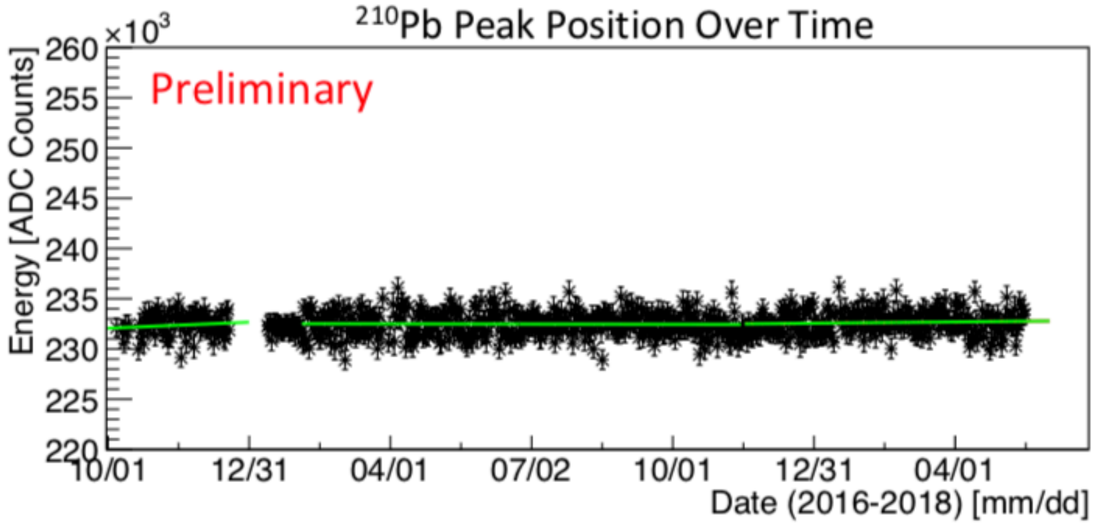


Correcting for Gain Shifts

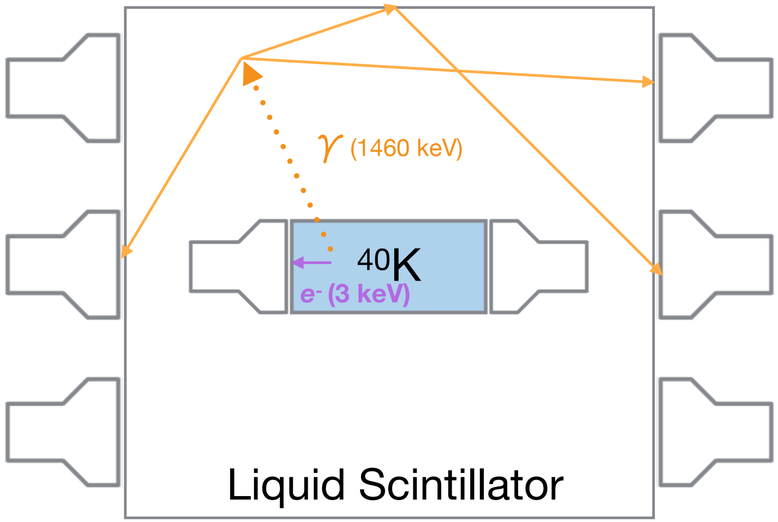
- Position of internal ^{210}Pb decays also monitored over time
- Gain shift corrected for by dividing out linear behavior

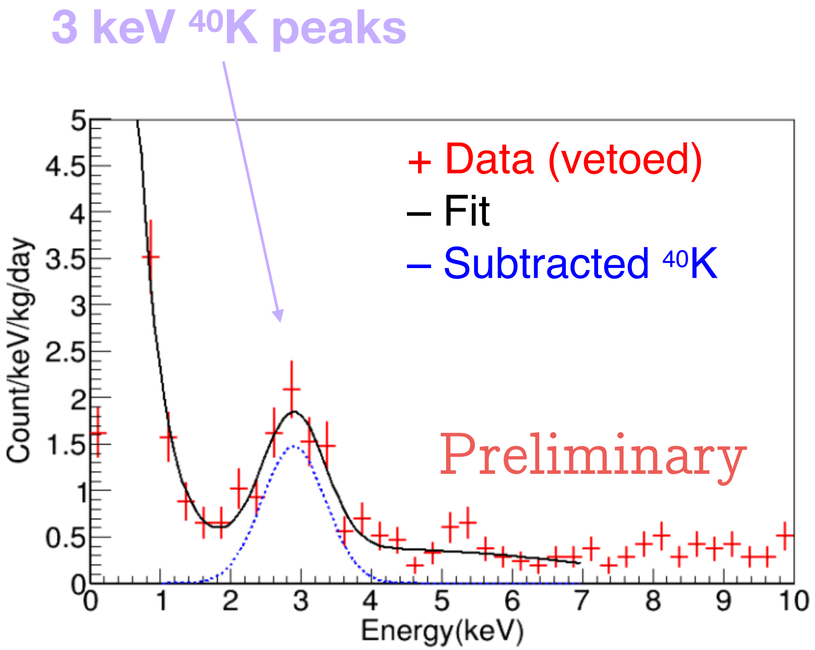


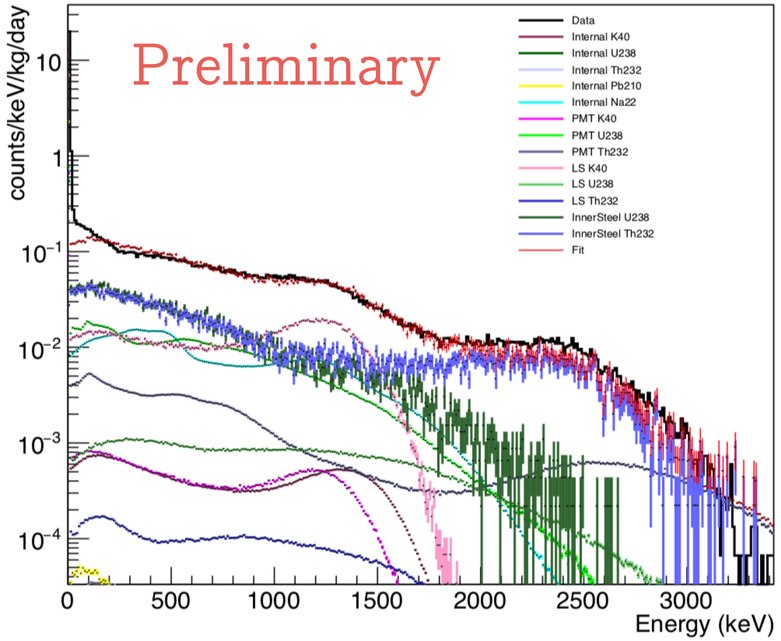




Liquid scintillator veto





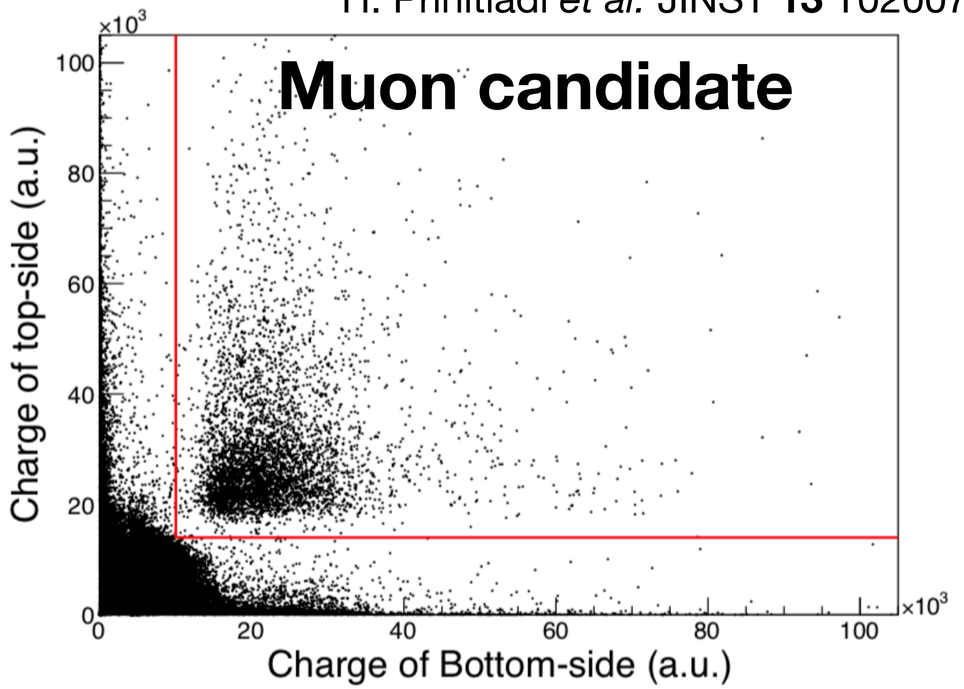


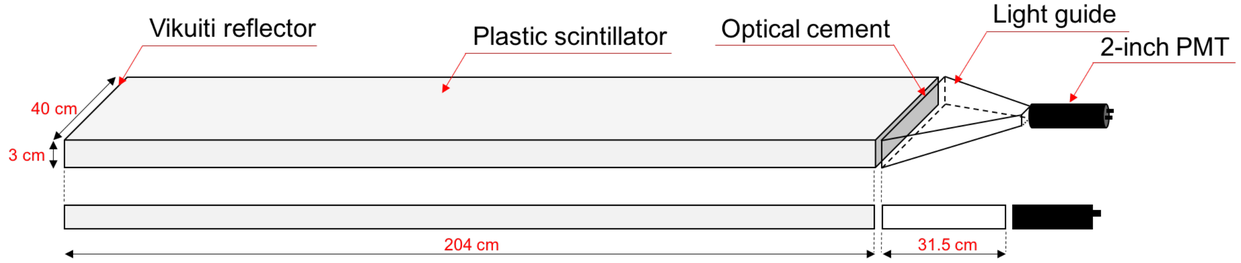
- ^{40}K emits 1460 keV gamma with 3 keV Auger electron energy deposition in NaI crystal
- Tagging 1460 keV events with LS enables **vetoing of 3 keV background events**
- Liquid scintillator internal contamination well modeled with simulation

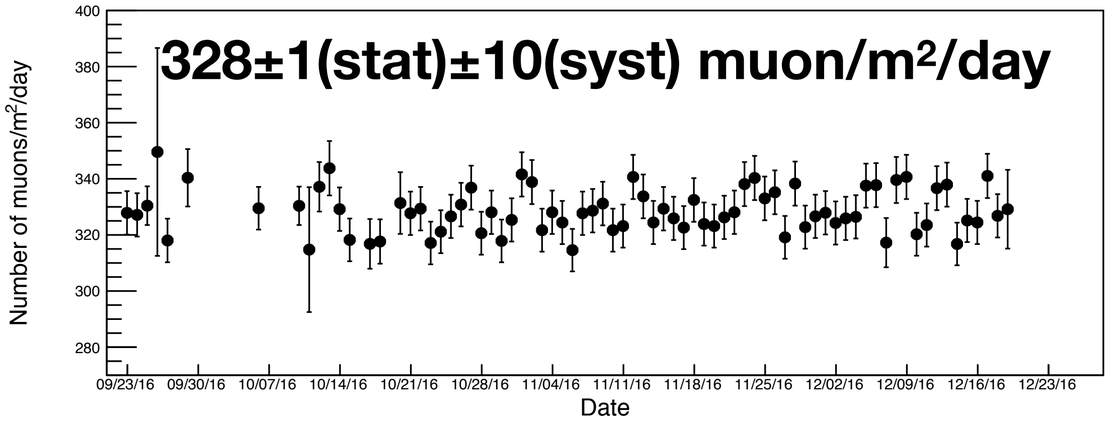
Muon detector

- 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)



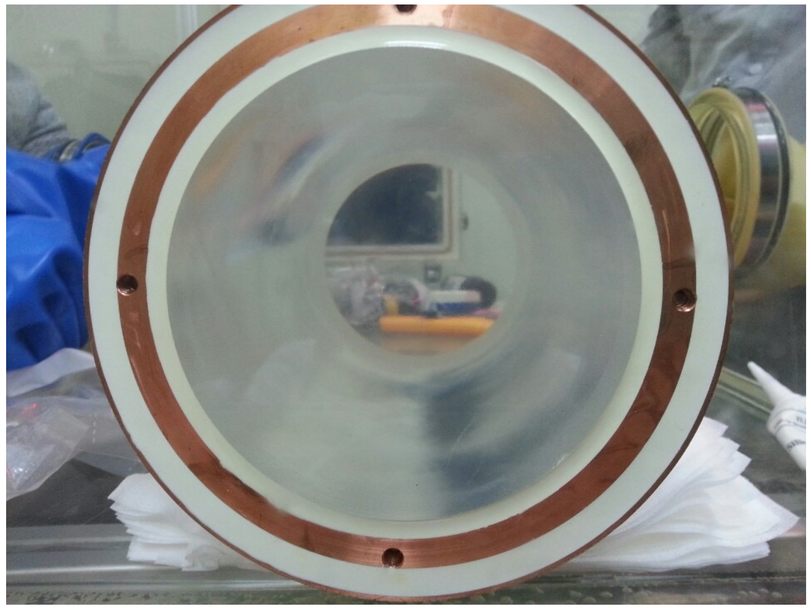


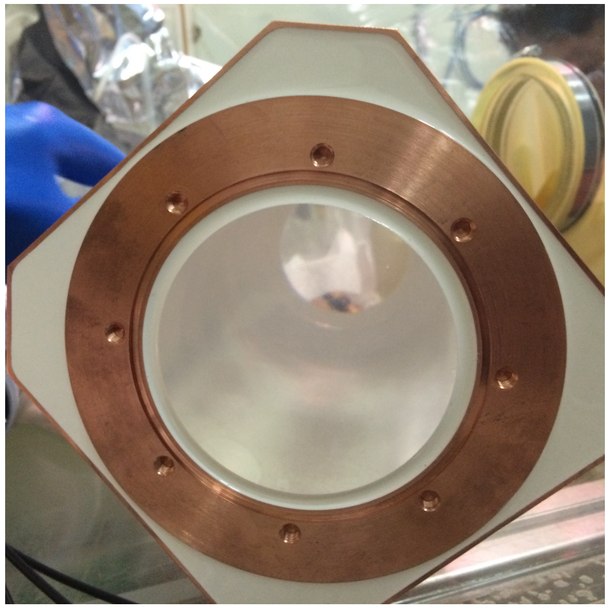


COSINE-100 NaI(Tl) crystals

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

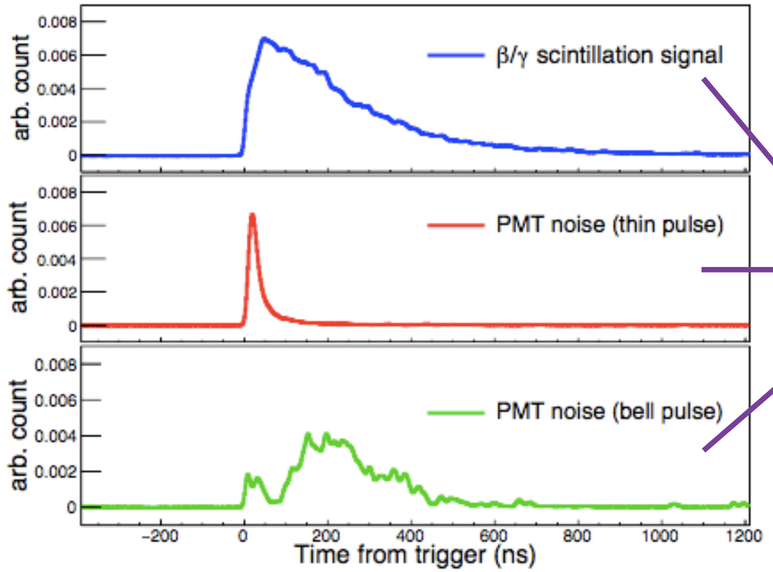


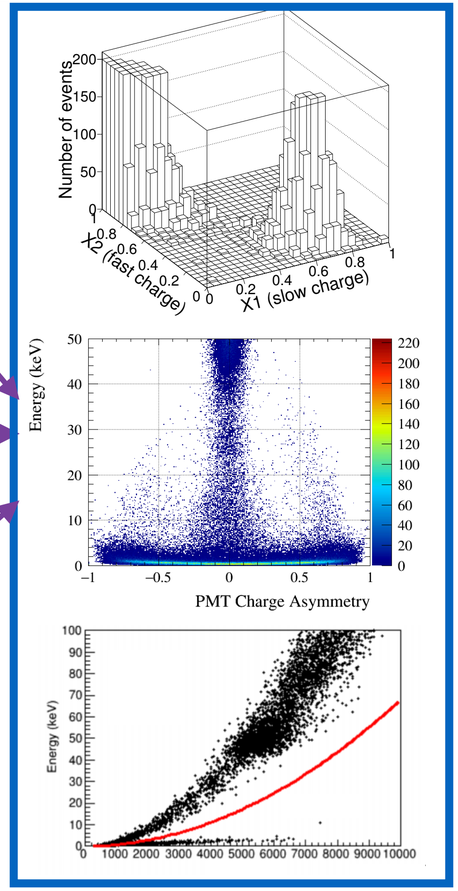


Crystal	Mass (kg)	Size (inches diameter×length)	Powder	α Rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light Yield (PEs/keV)
Crystal-1	8.3	5.0×7.0	AS-B	3.20 ± 0.08	43.4 ± 13.7	<0.02	1.3 ± 0.4	14.9 ± 1.5
Crystal-2	9.2	4.2×11.0	AS-C	2.06 ± 0.06	82.7 ± 12.7	<0.12	<0.6	14.6 ± 1.5
Crystal-3	9.2	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

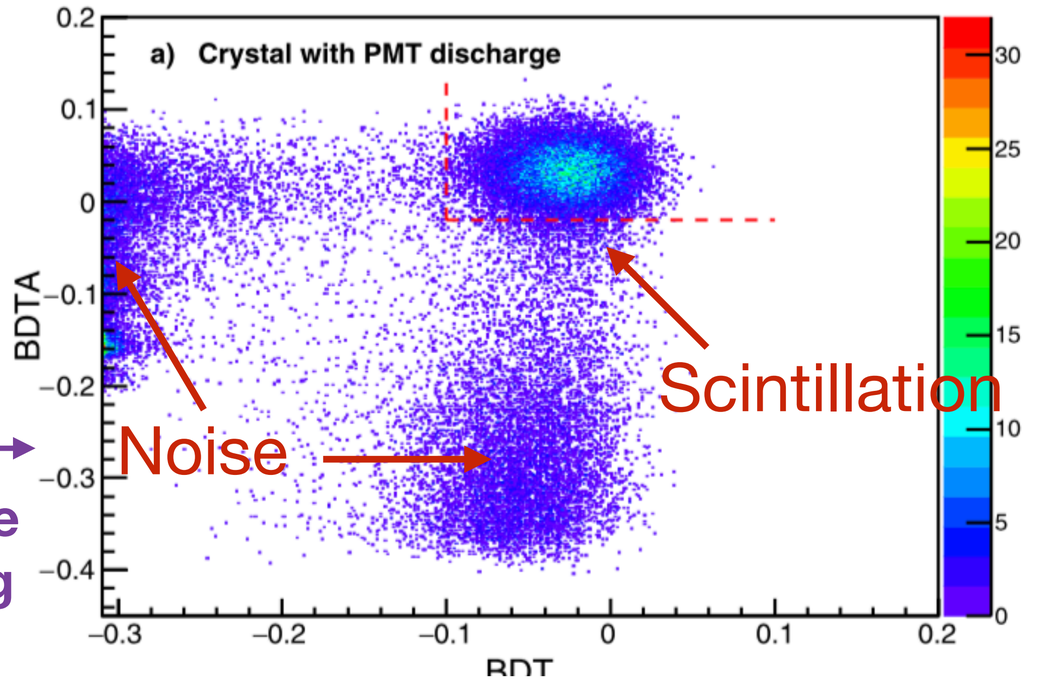
PMT noise rejection

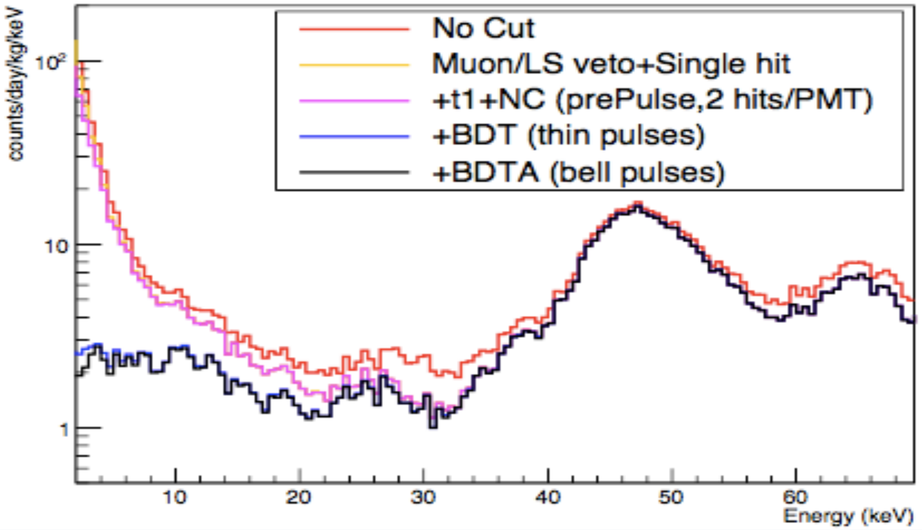
Nature **564**, 83-86 (2018)





Machine learning



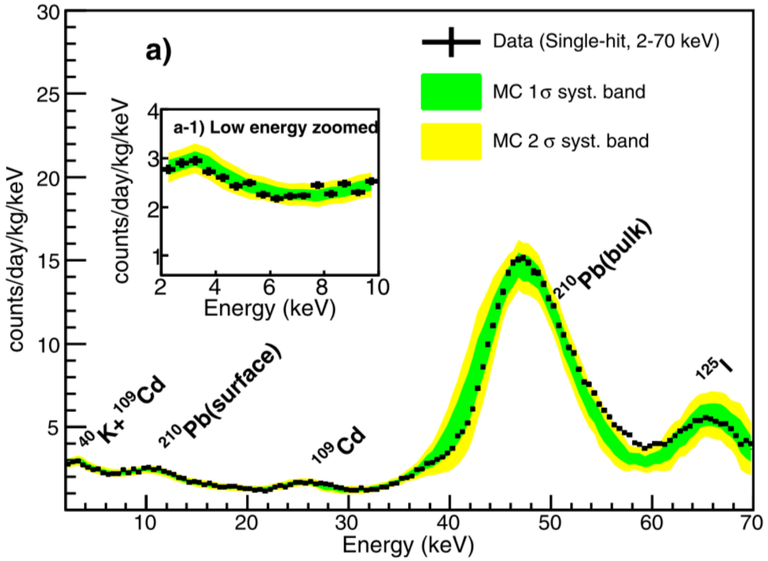


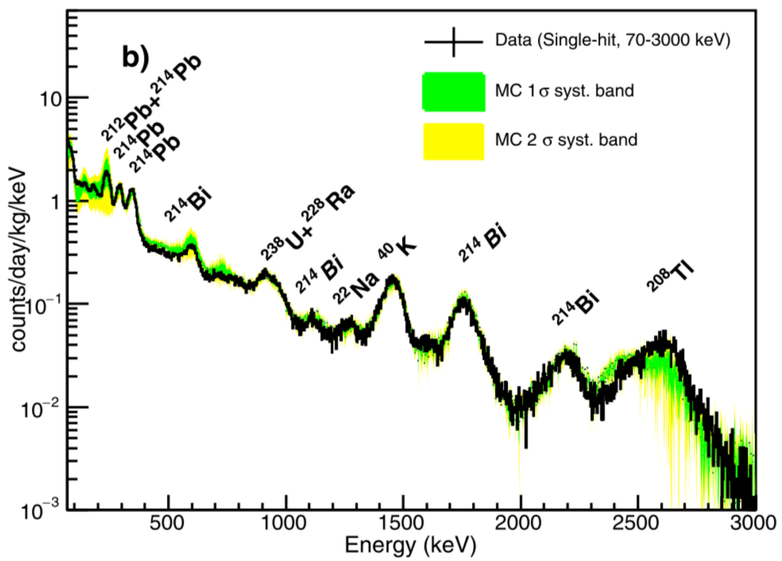
- Dominant source of noise events comes from PMT noise
- Boosted Decision Tree (BDT) was utilized to reject such noise events

Background in data vs. simulation

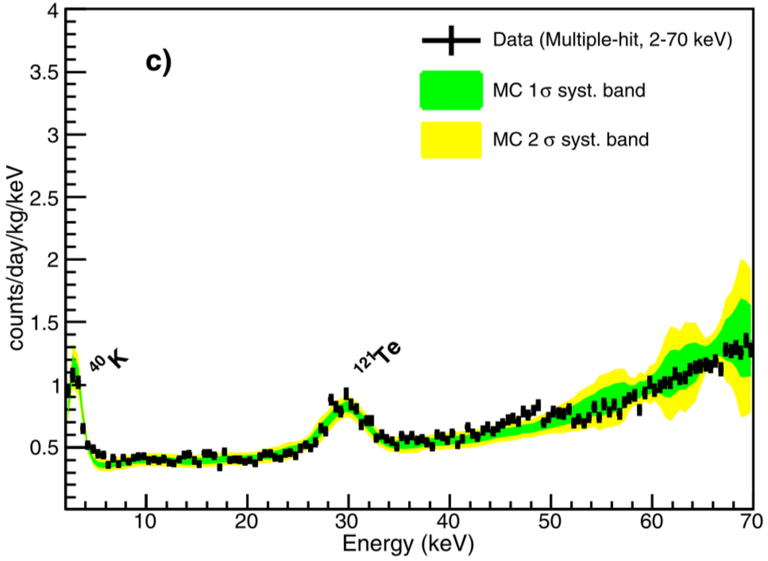
Nature **564**, 83-86 (2018)

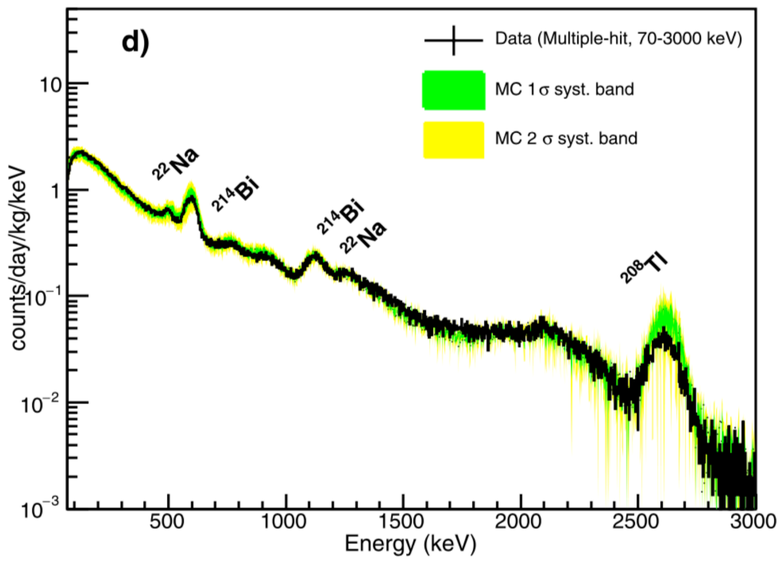
Single-hit





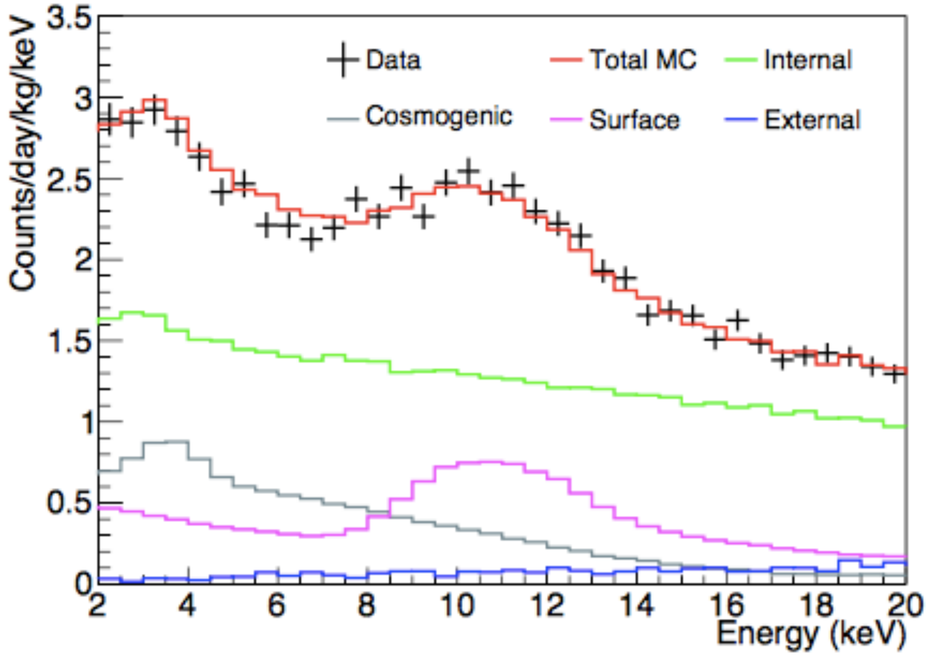
Multiple-hit

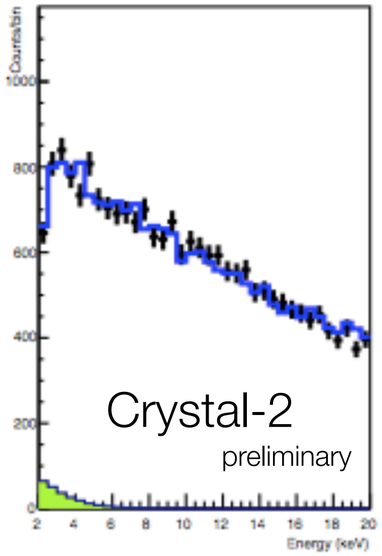


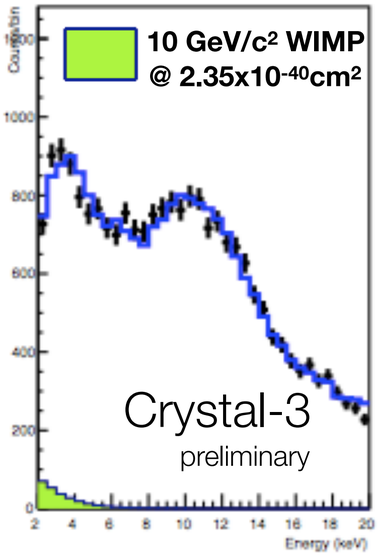


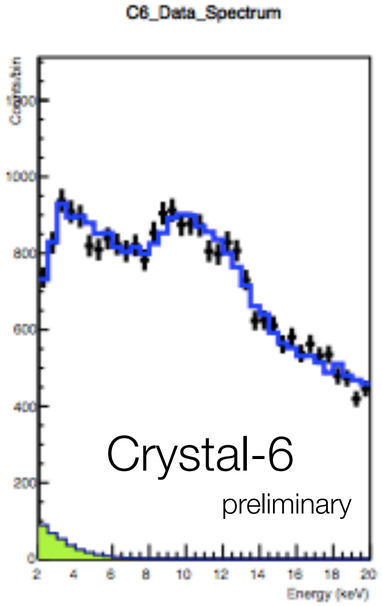
WIMP analysis: Backgrounds+WIMP

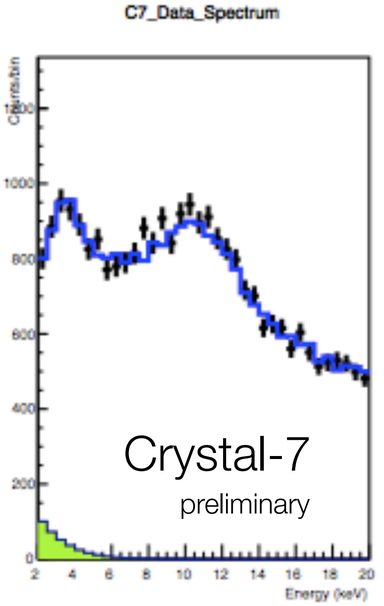
Eur. Phys. J. C **78** 490 (2018)







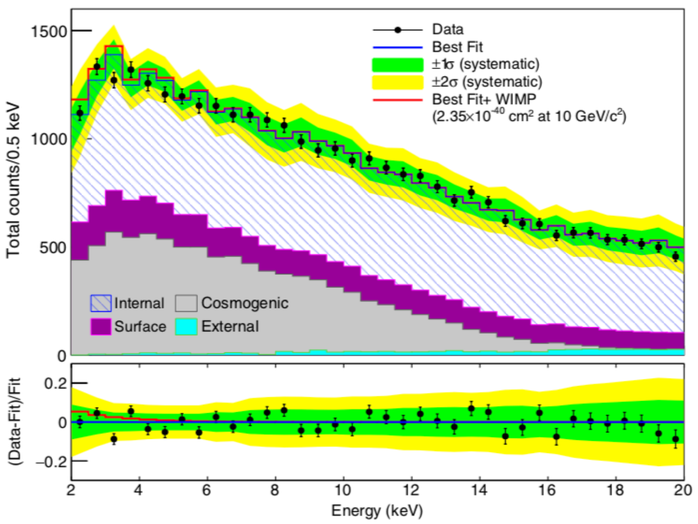




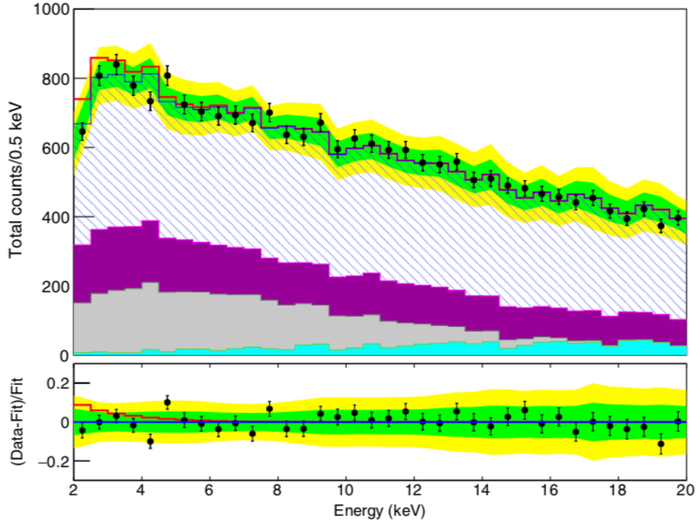
- Using 59.5 days of data: 6303.9 kg day exposure
- Spectrum fit for 2-20 keV including WIMP model
- Likelihood analysis to fit data using background model and WIMP signal model (SHM as described in Savage *et al*., JCAP 0904:010, 2009)
- Background understanding consideration from V. Kudryavtsev *et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

WIMP analysis: Backgrounds+WIMP

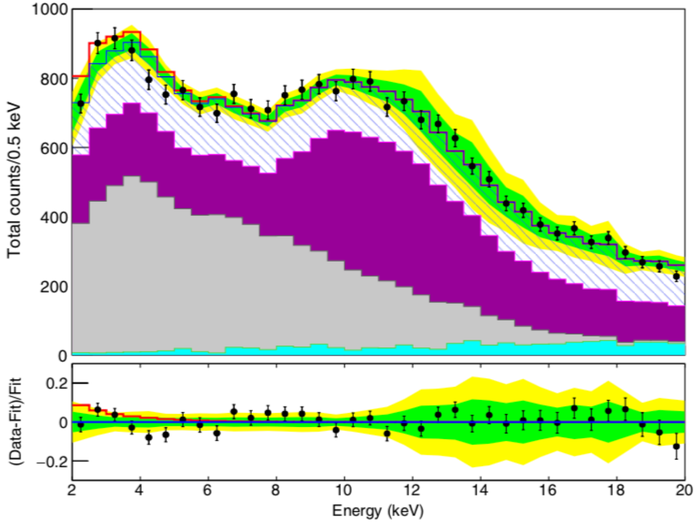
Nature **564**, 83-86 (2018)



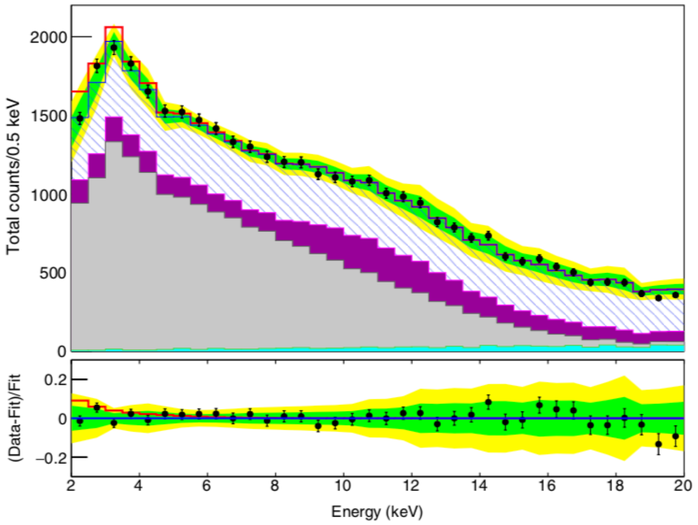
a) Crystal 1



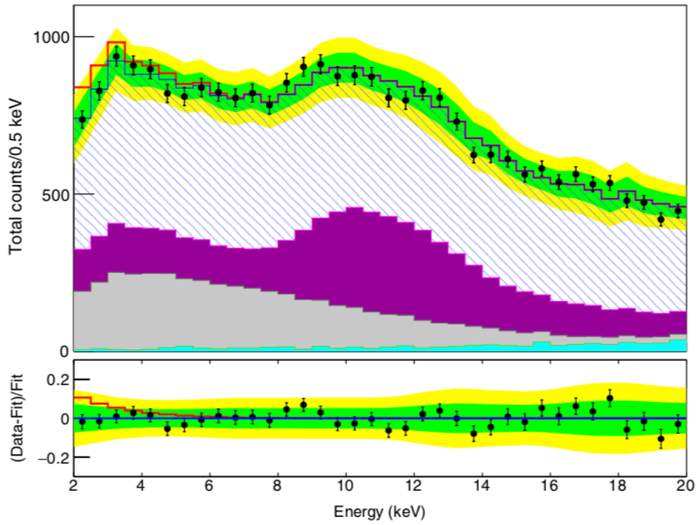
b) Crystal 2



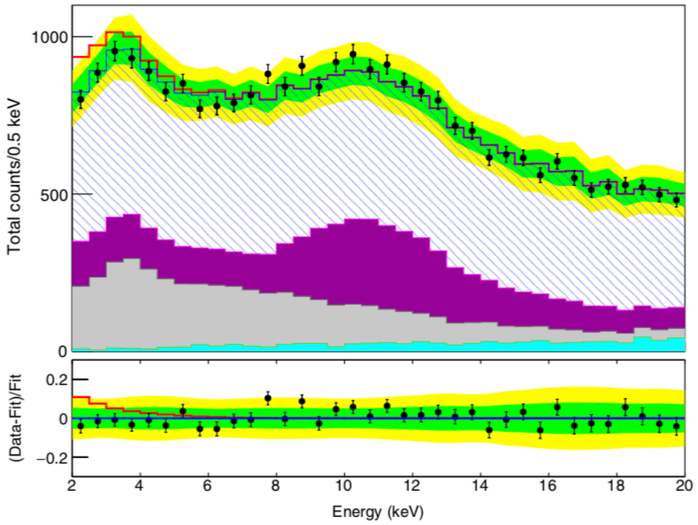
c) Crystal 3



d) Crystal 4



e) Crystal 6

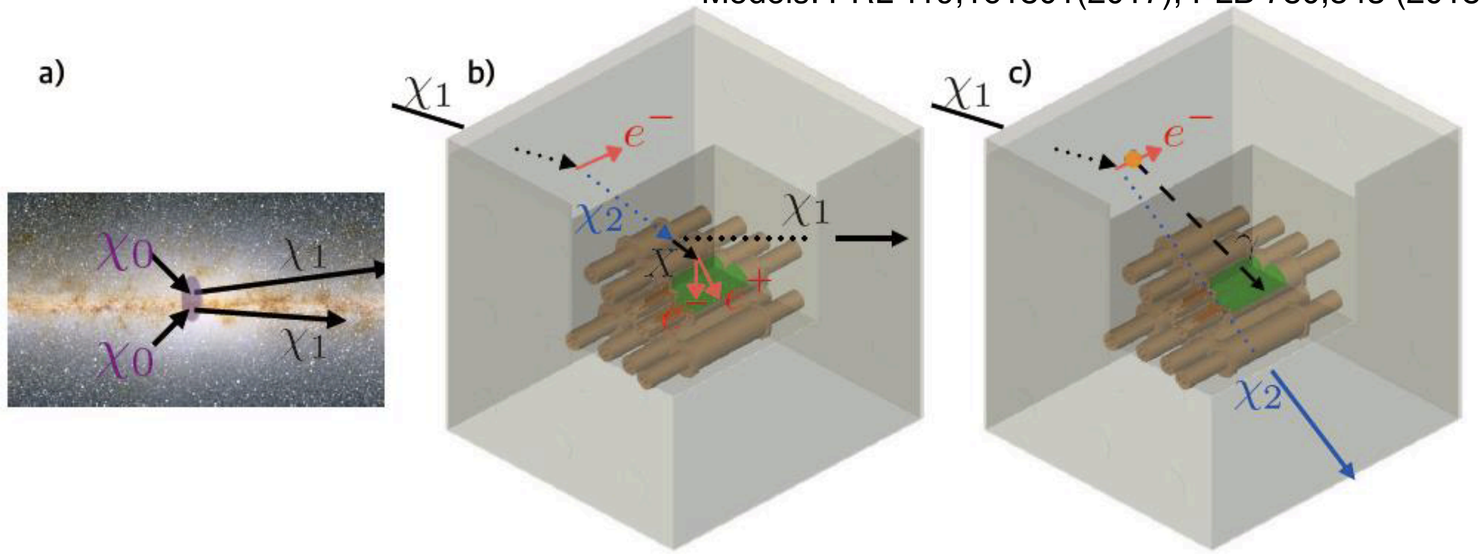


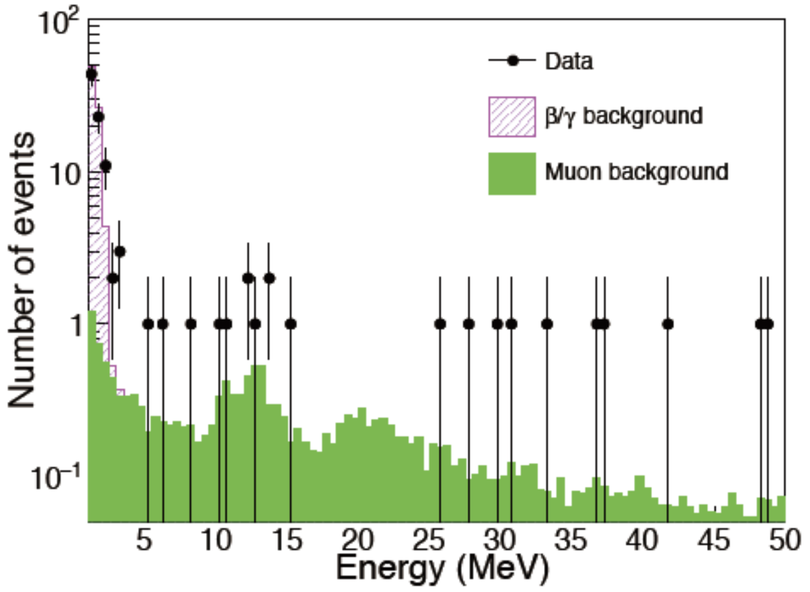
f) Crystal 7

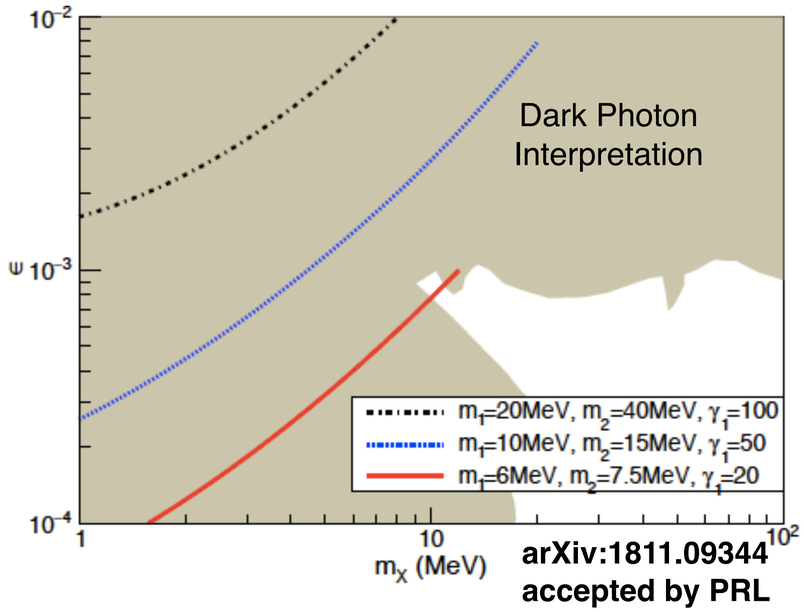
Other physics analysis: Boosted DM Search

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? (Crystal growing R&D)

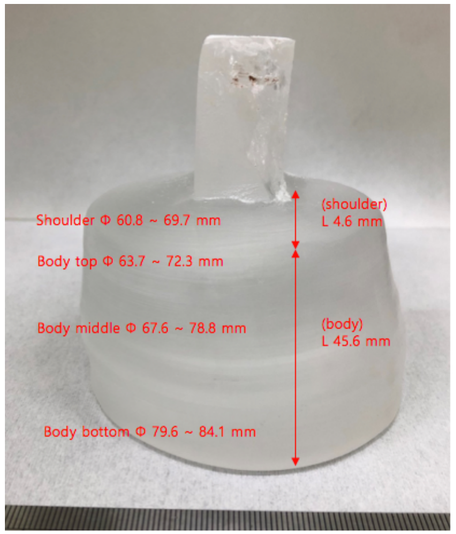
- Needs to grow our own crystal with low(er) background and better understanding of the crystal

- 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