

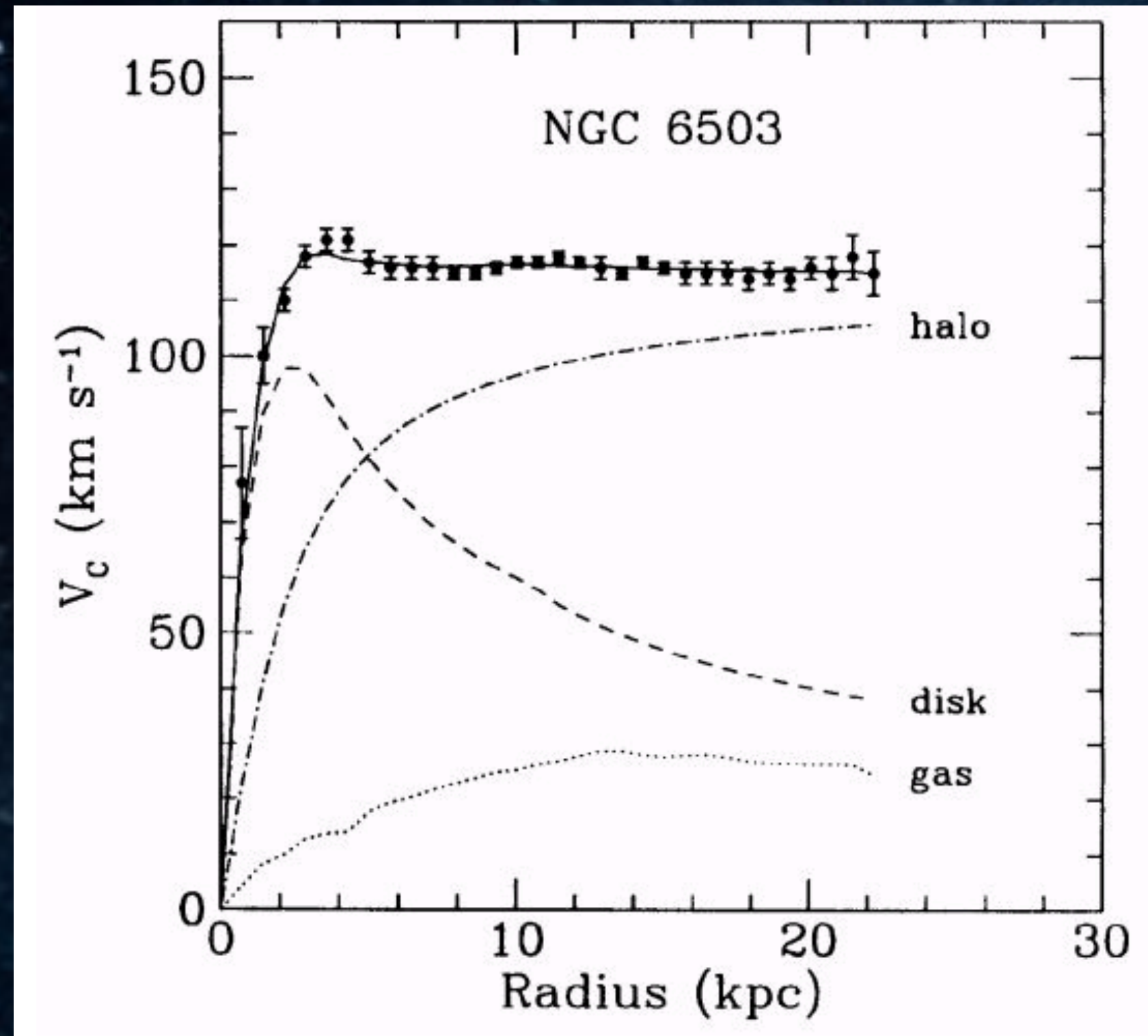
COSINE-100 NaI(Tl) Dark Matter Experiment: Testing DAMA's Claim for a Dark Matter Discovery

Jay Hyun Jo
Yale University

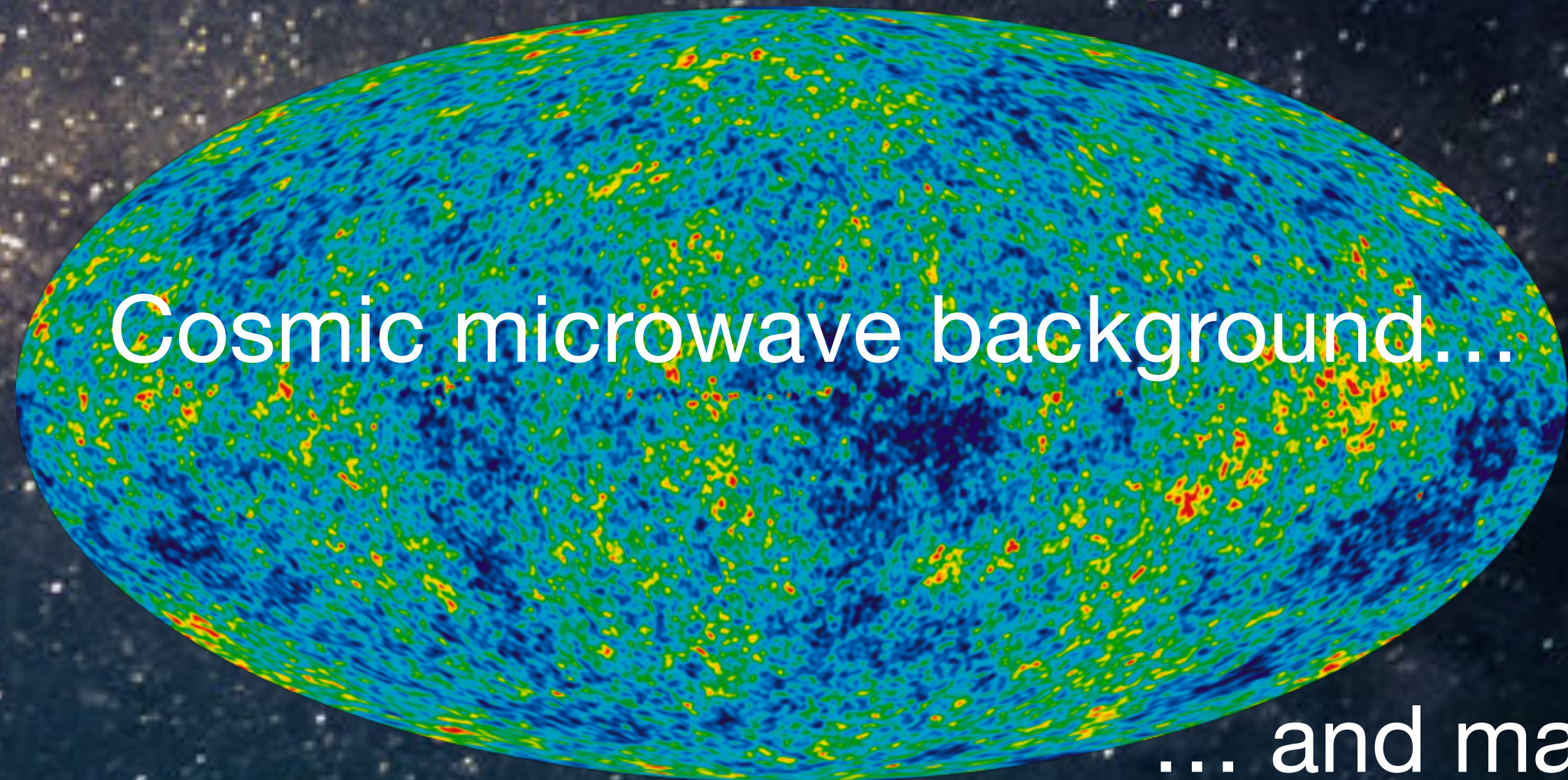
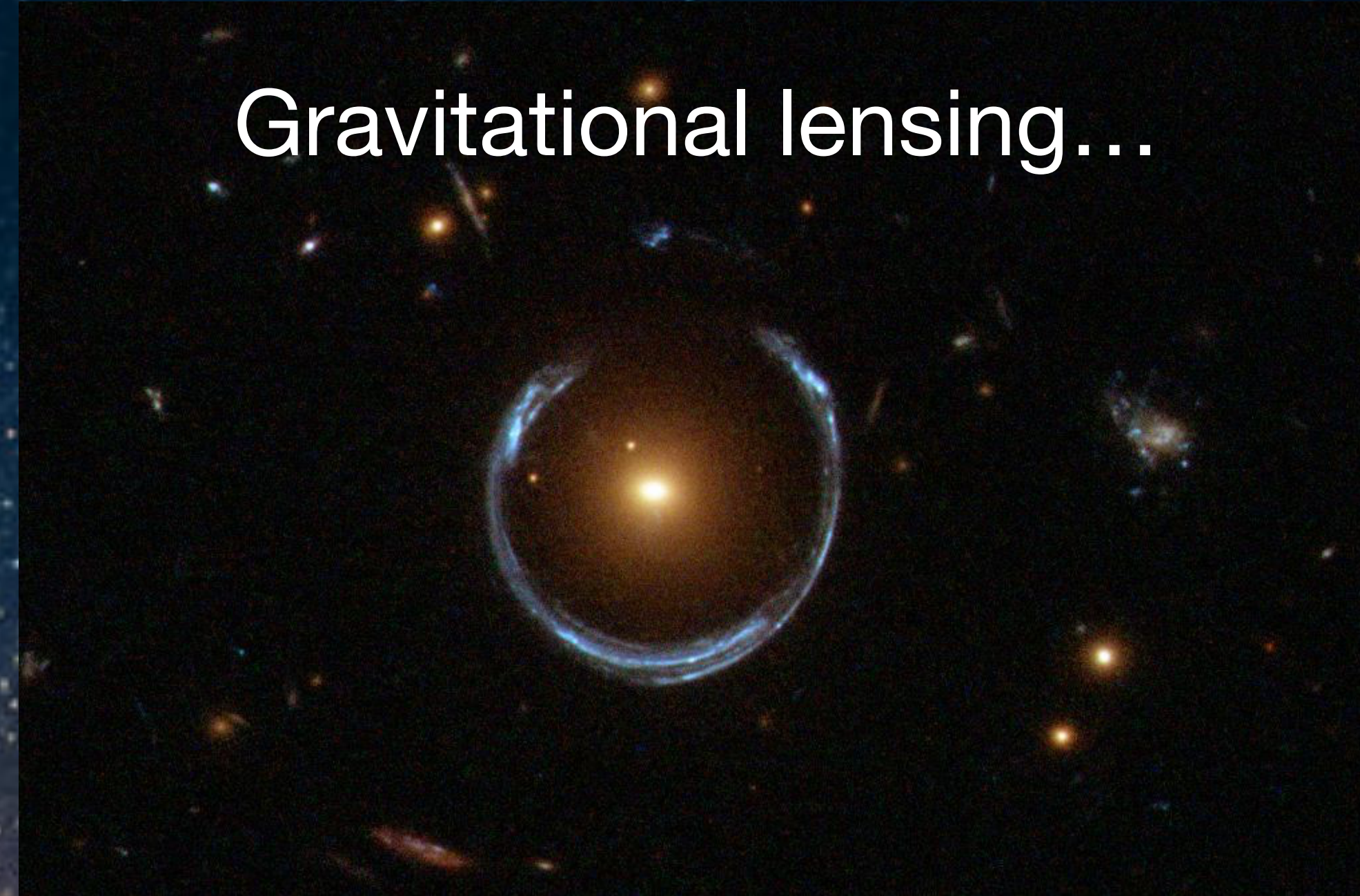
SLAC Experimental Seminar
March 26, 2019

Evidence of Dark matter

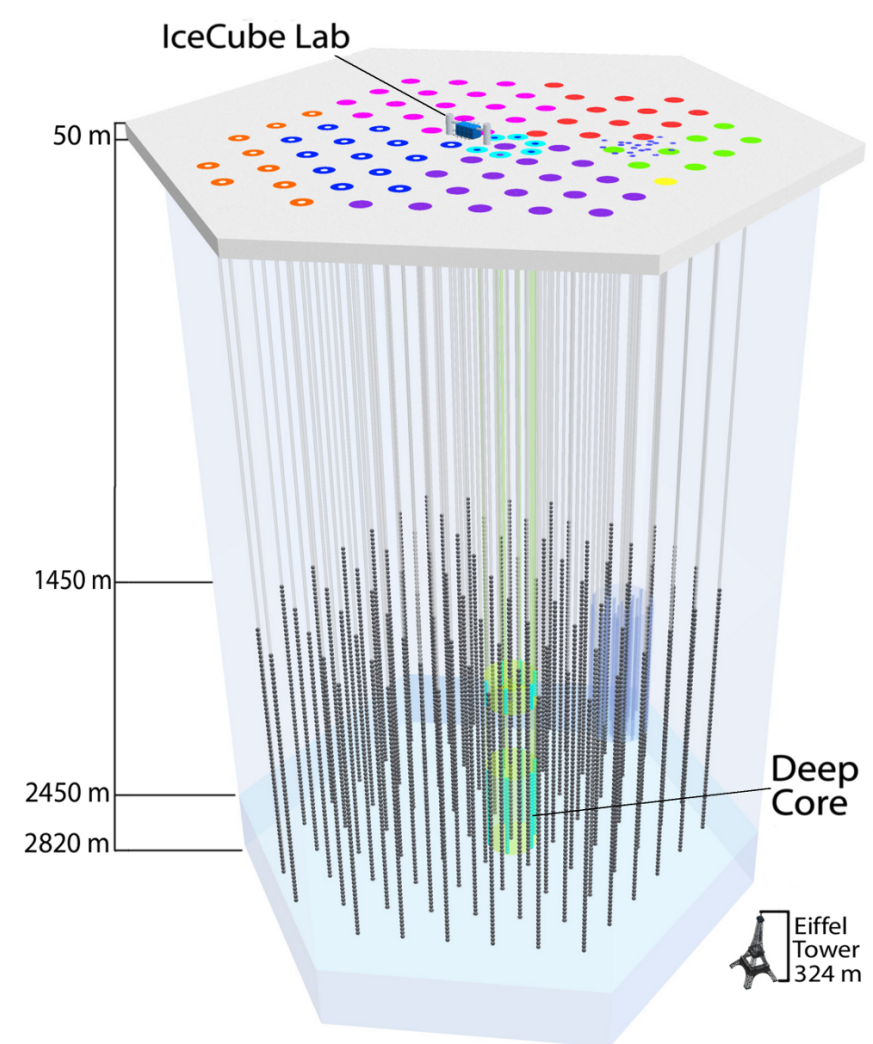
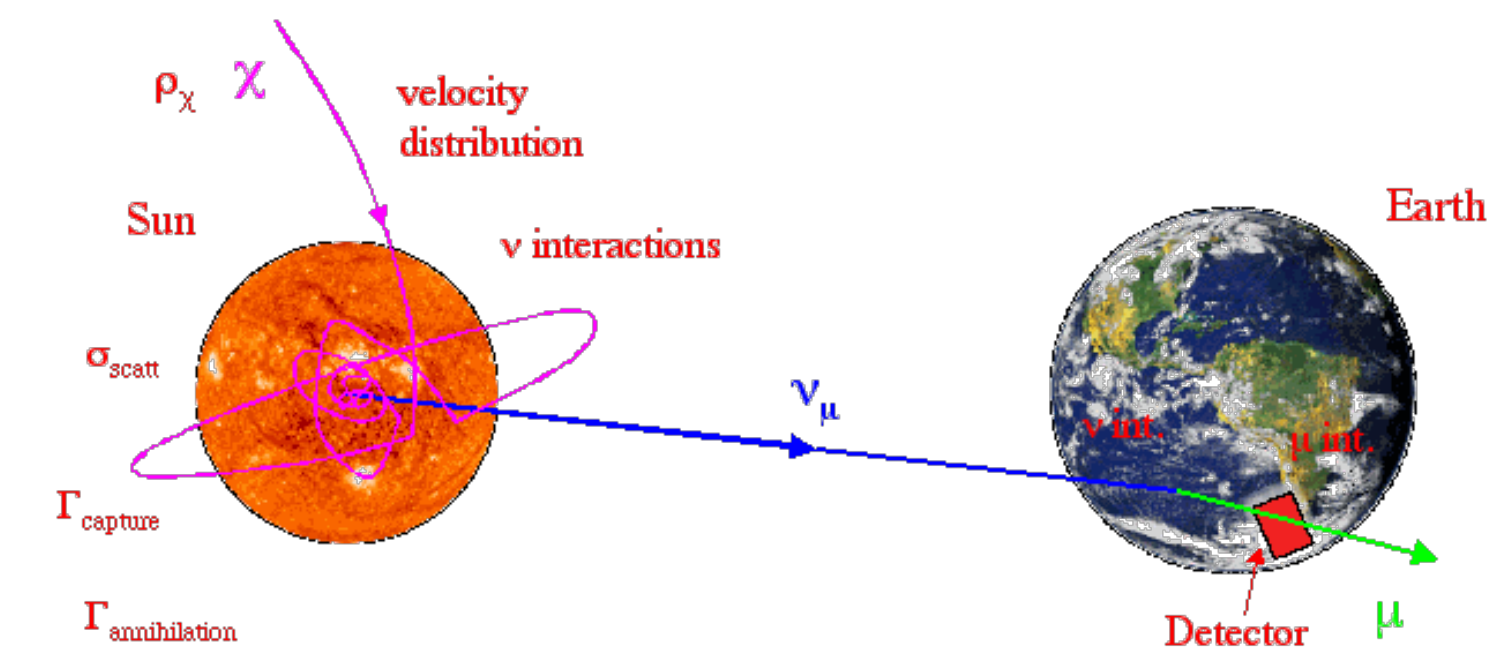
Cosmological observations give strong evidence of dark matter:



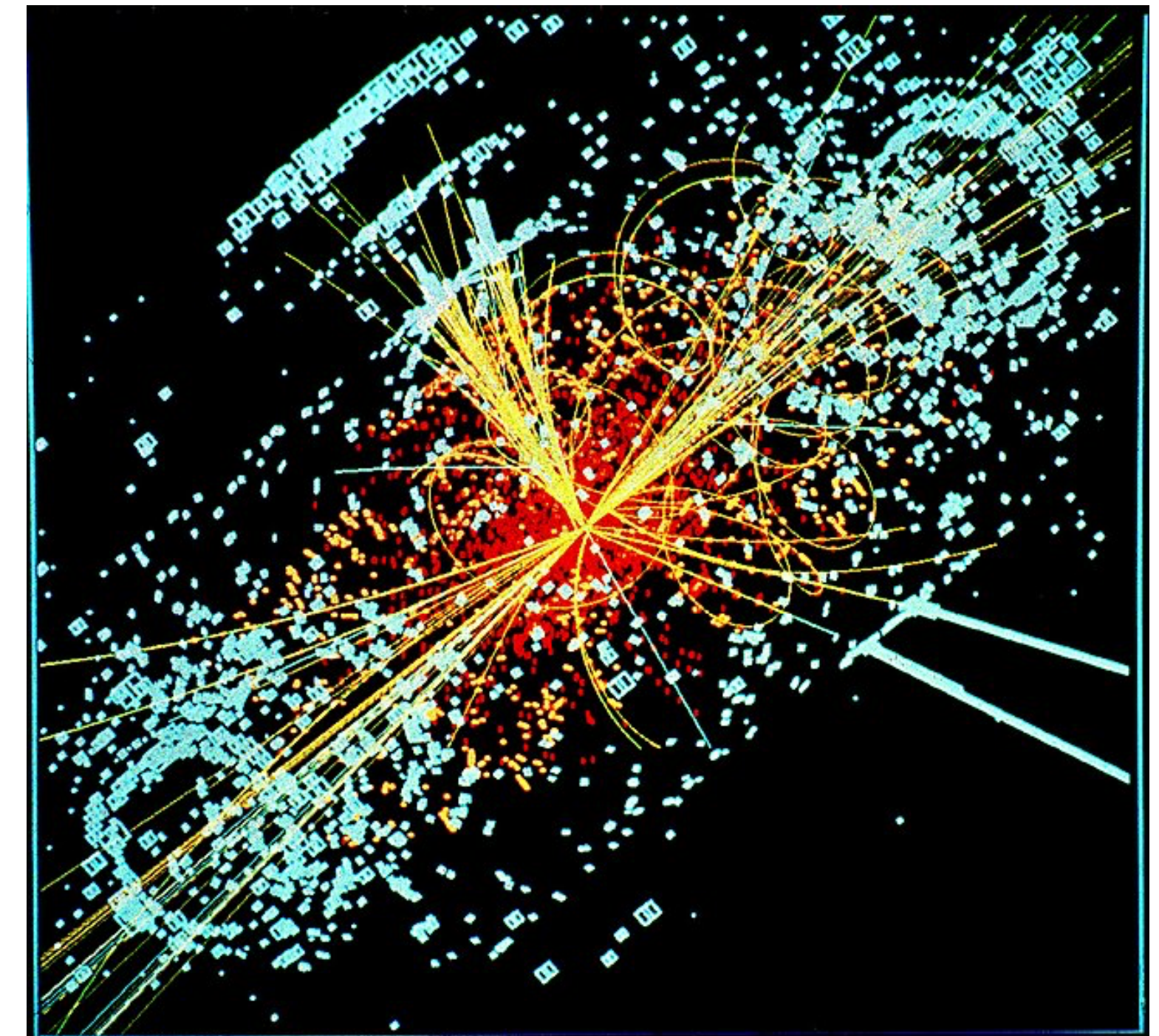
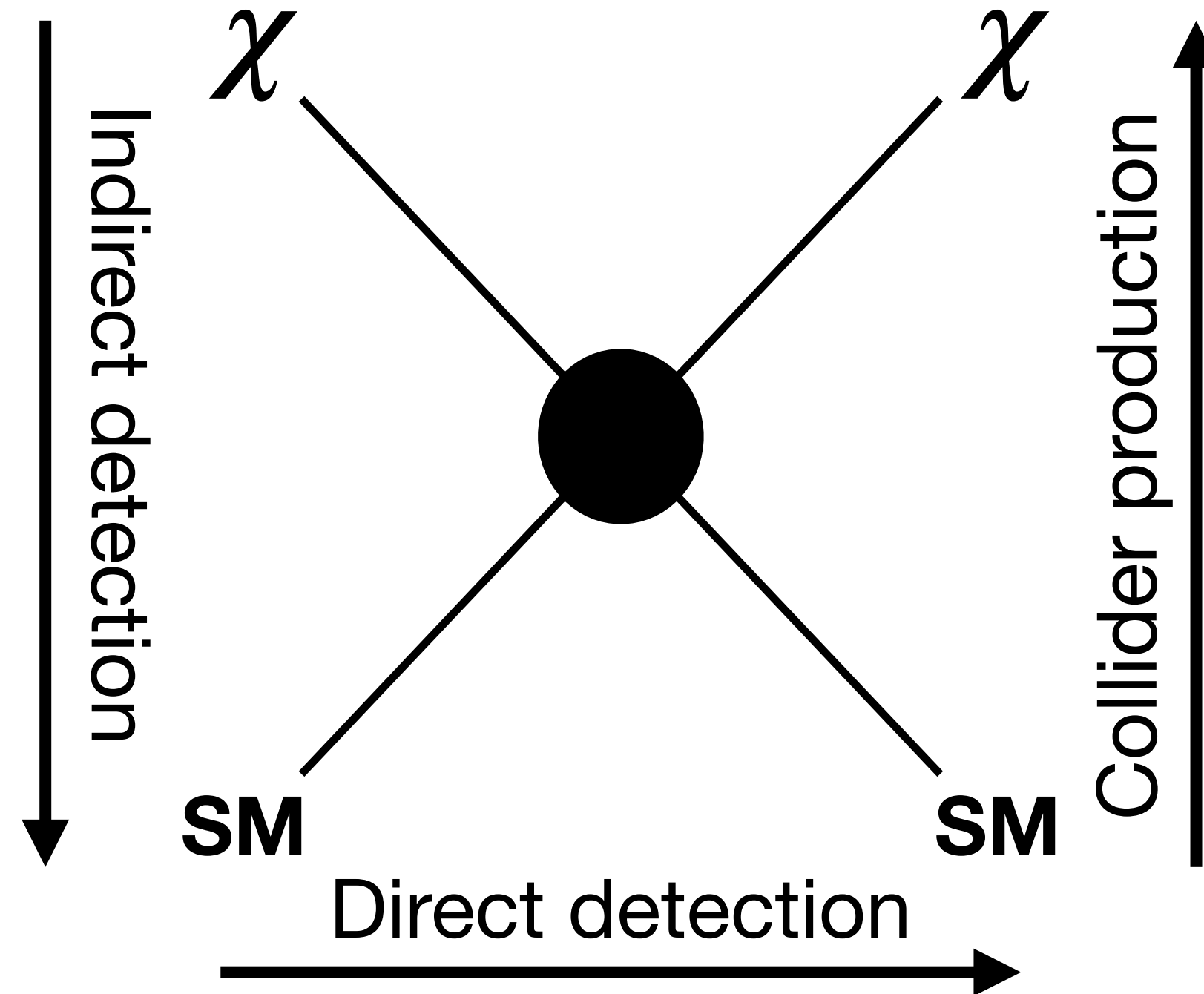
Galaxy rotation curves...



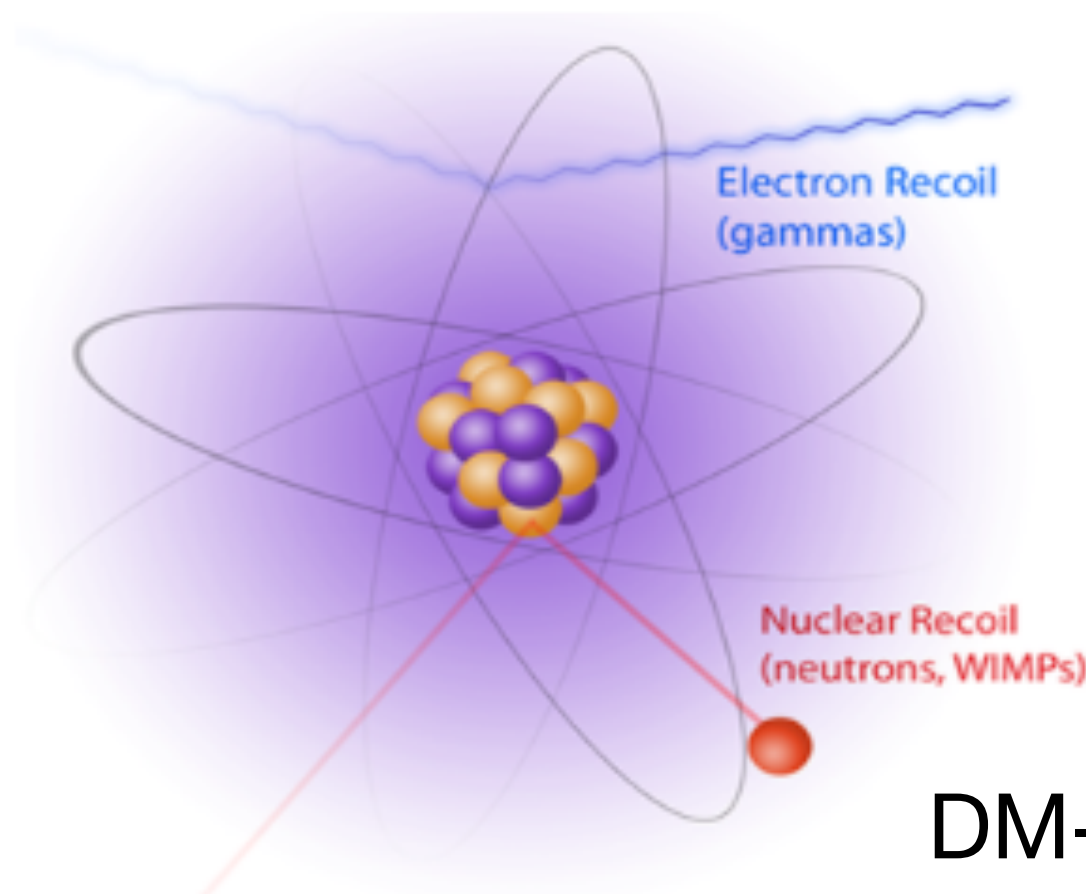
Dark matter detection



Annihilation or decay products from the Sun, Halo, etc.



Search for missing energy

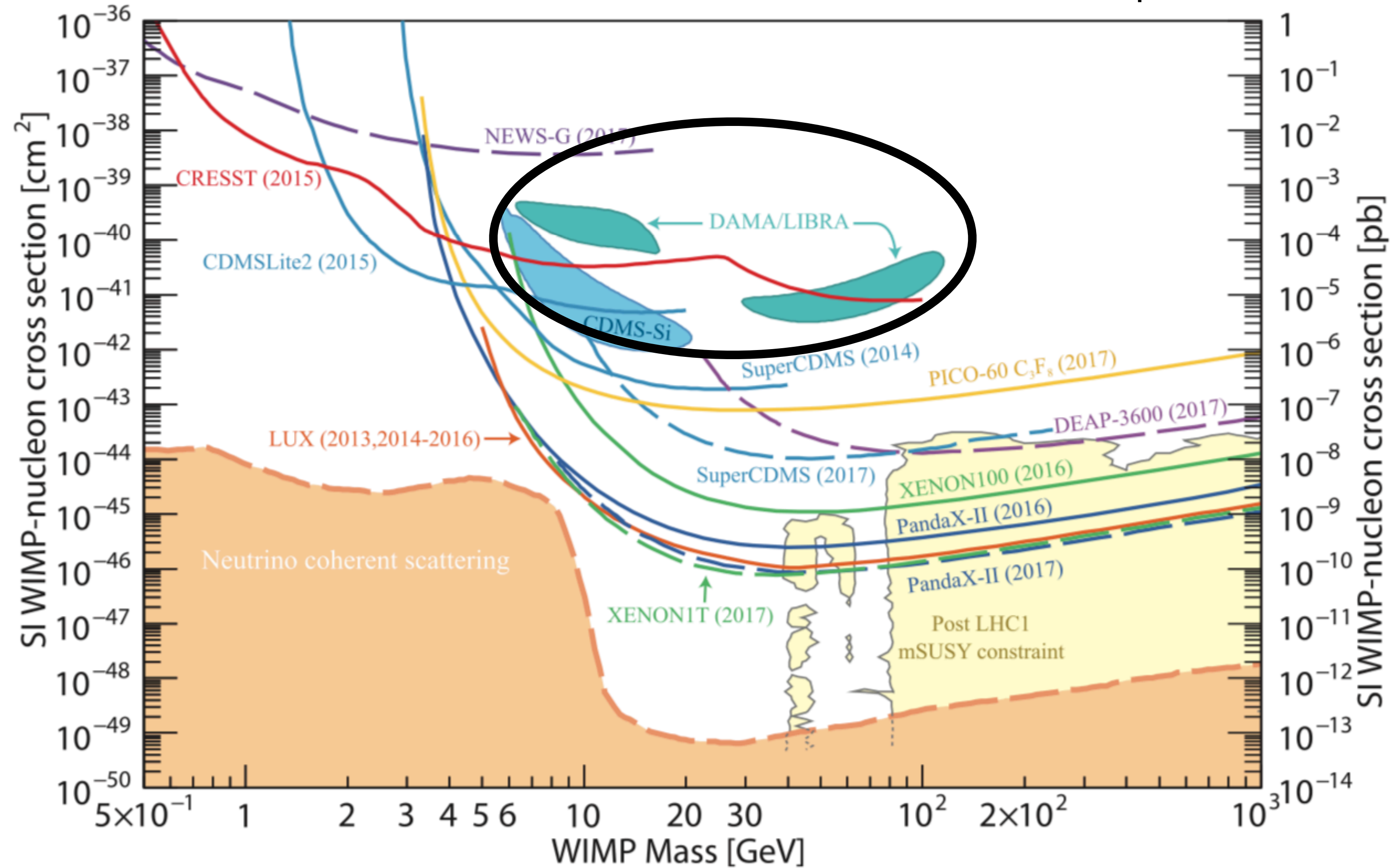


DM-Nucleon scattering

Current status of direct dark matter searches

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

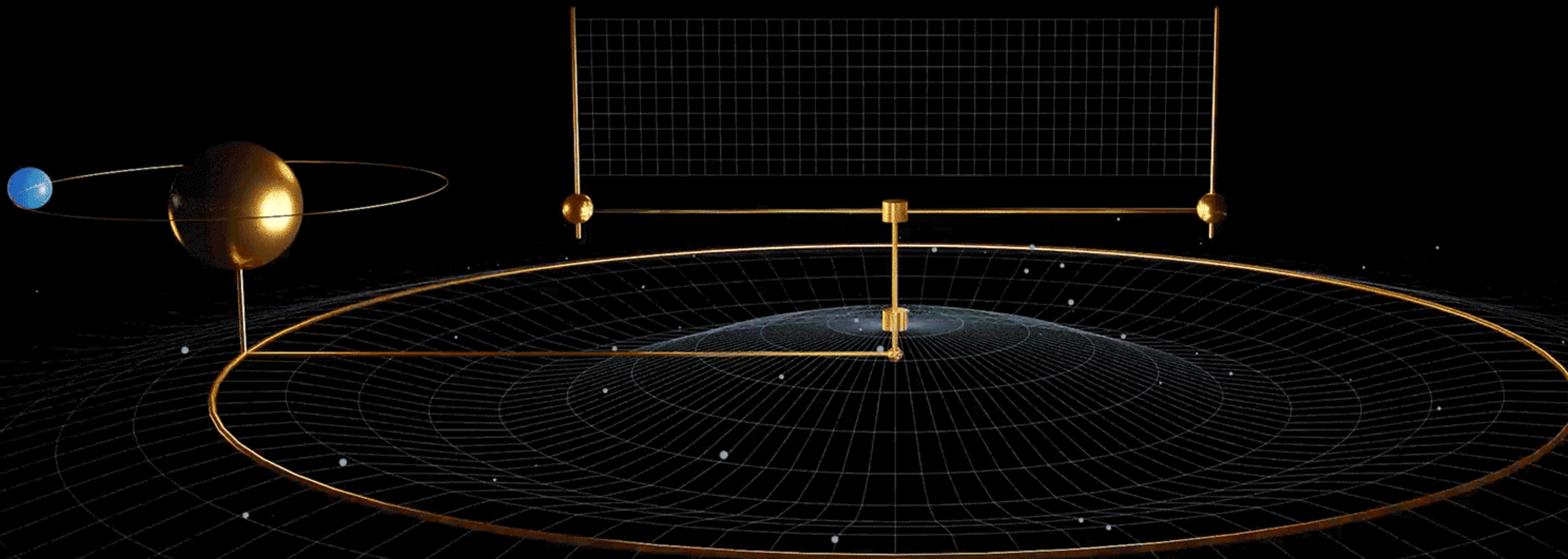
Particle Data Group 2018



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

Annual Modulation of Dark Matter

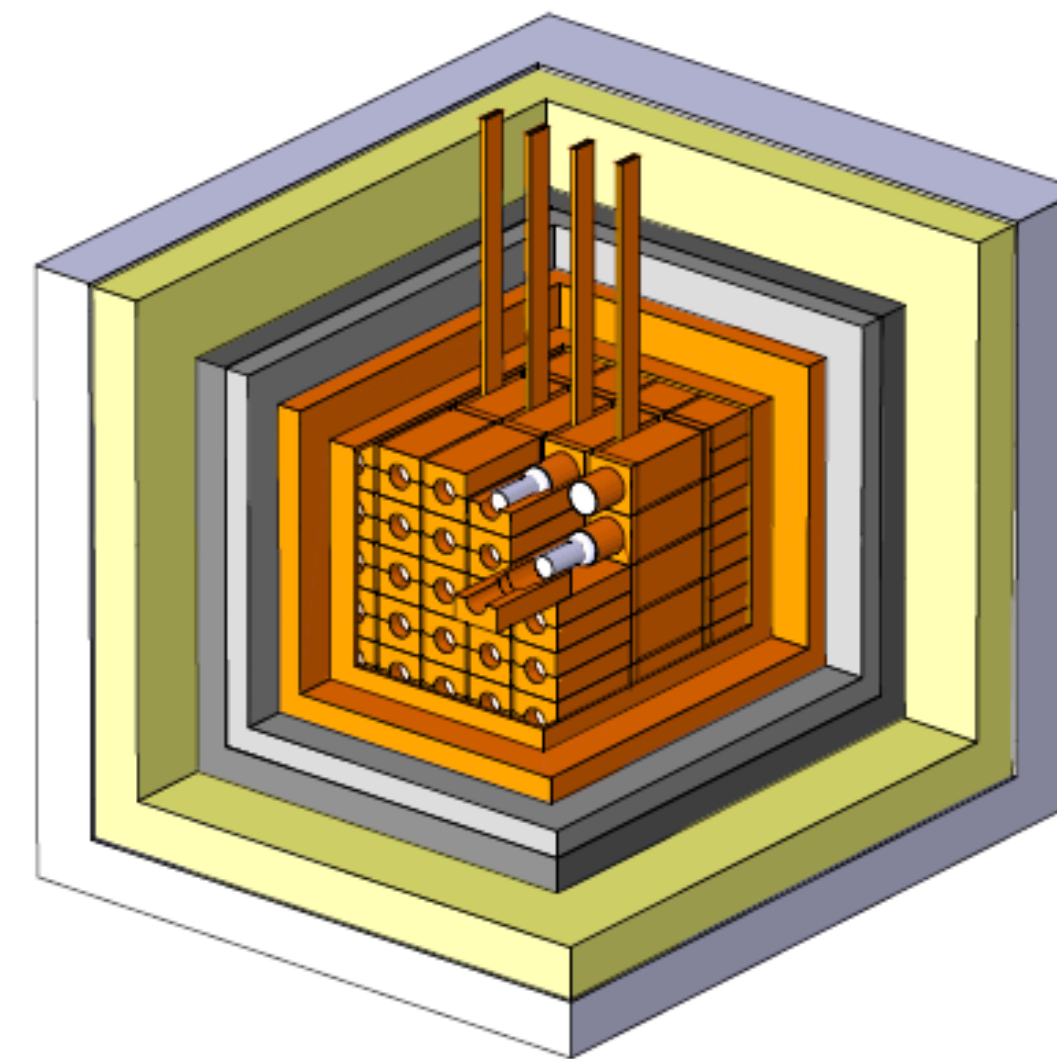
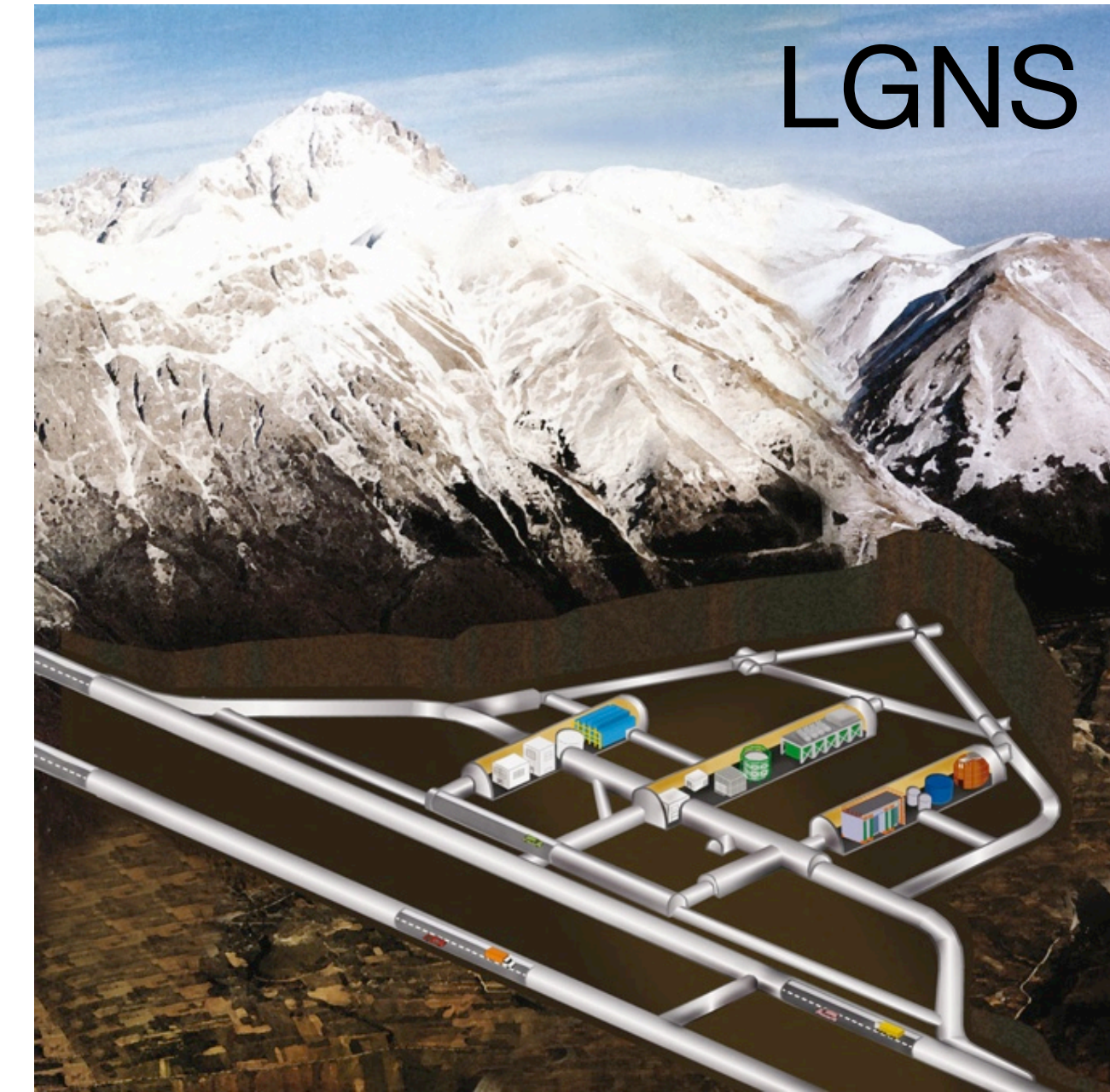
image credit: quantamagazine.com



- 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 experiment

- Located at LNGS, Italy
- 25 x 9.70 kg NaI(Tl) detectors
 - Crystals grown by Saint-Gobain
 - 0.85 - 1.3 cpd/kg/keV total background rate
- 2 PMTs/crystal
 - ~38.5% quantum efficiency
 - Light yield of 5.5 - 7.5 pe/keV
 - 10 cm quartz lightguides attached
- DAMA/NaI (100 kg 1996 - 2003),
DAMA/LIBRA phase 1 (250 kg, 2003-2010),
DAMA/LIBRA phase 2 (250 kg, 2010 - 2018)

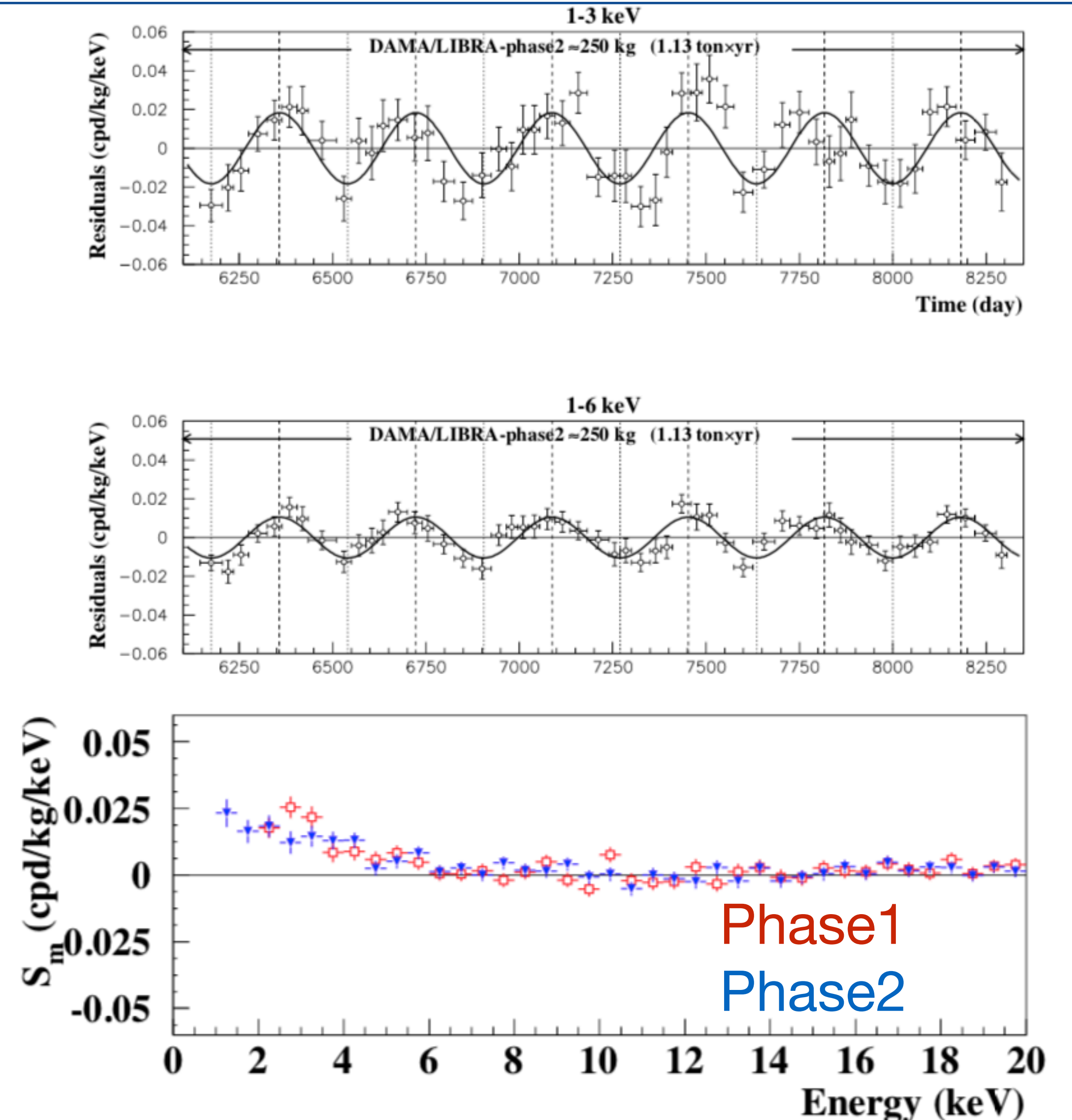


Bernabei *et al.*, NIM A (2008)

DAMA's annual modulation

Bernabei *et al.*, arXiv:1805.10486

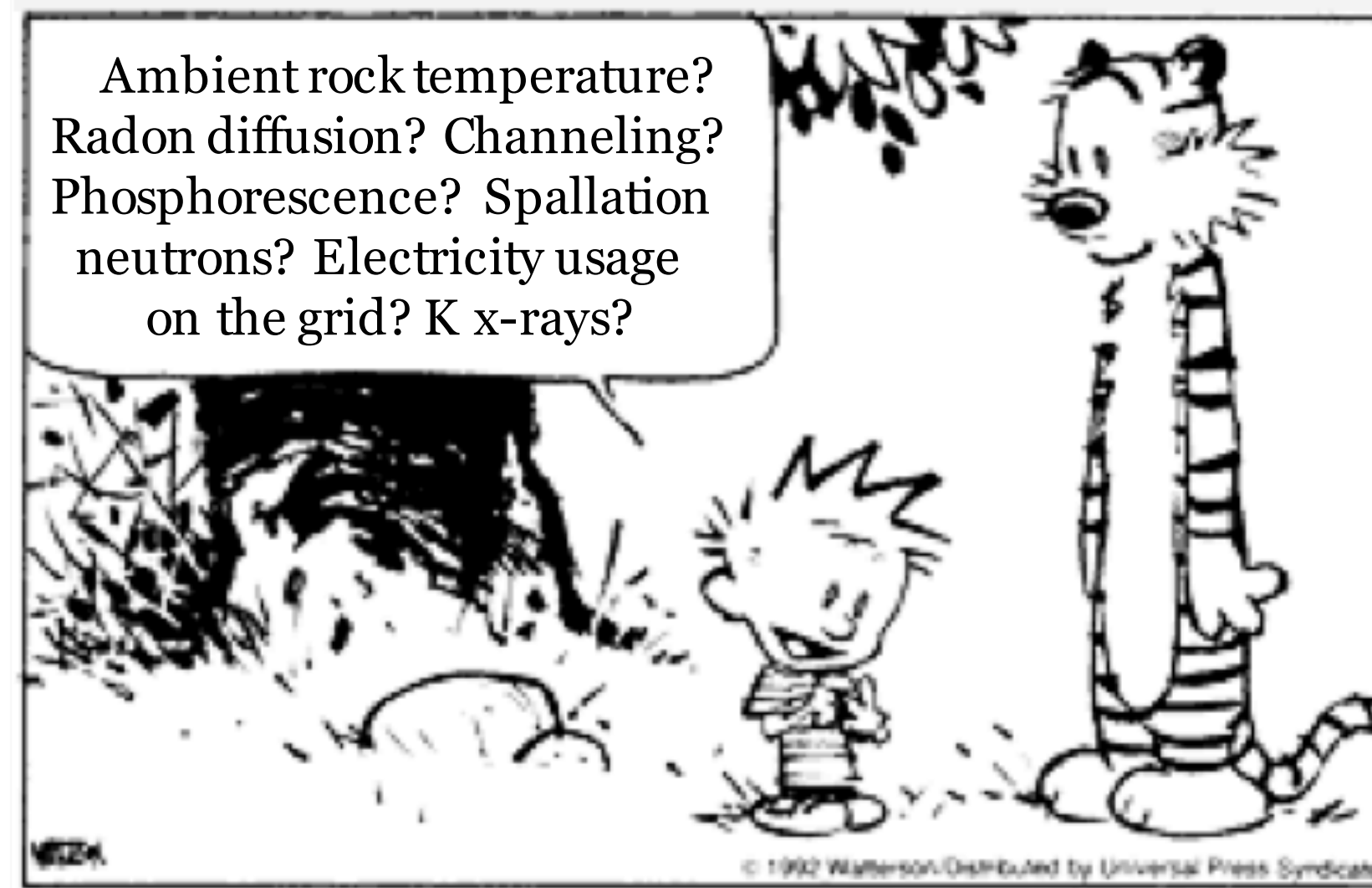
- DAMA/LIBRA-phase2 result announced with 1 keV threshold
 - (1-6) keV: 9.5σ from 1.13 ton-year
 - (2-6) keV: 12.9σ from 2.46 ton-year
- Modulation amplitude: (0.0103 ± 0.0008) cpd/kg/keV in (2-6) keV
- Phase: (145 ± 5) days
- Period: (0.999 ± 0.001) year



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)





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

...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
- ...

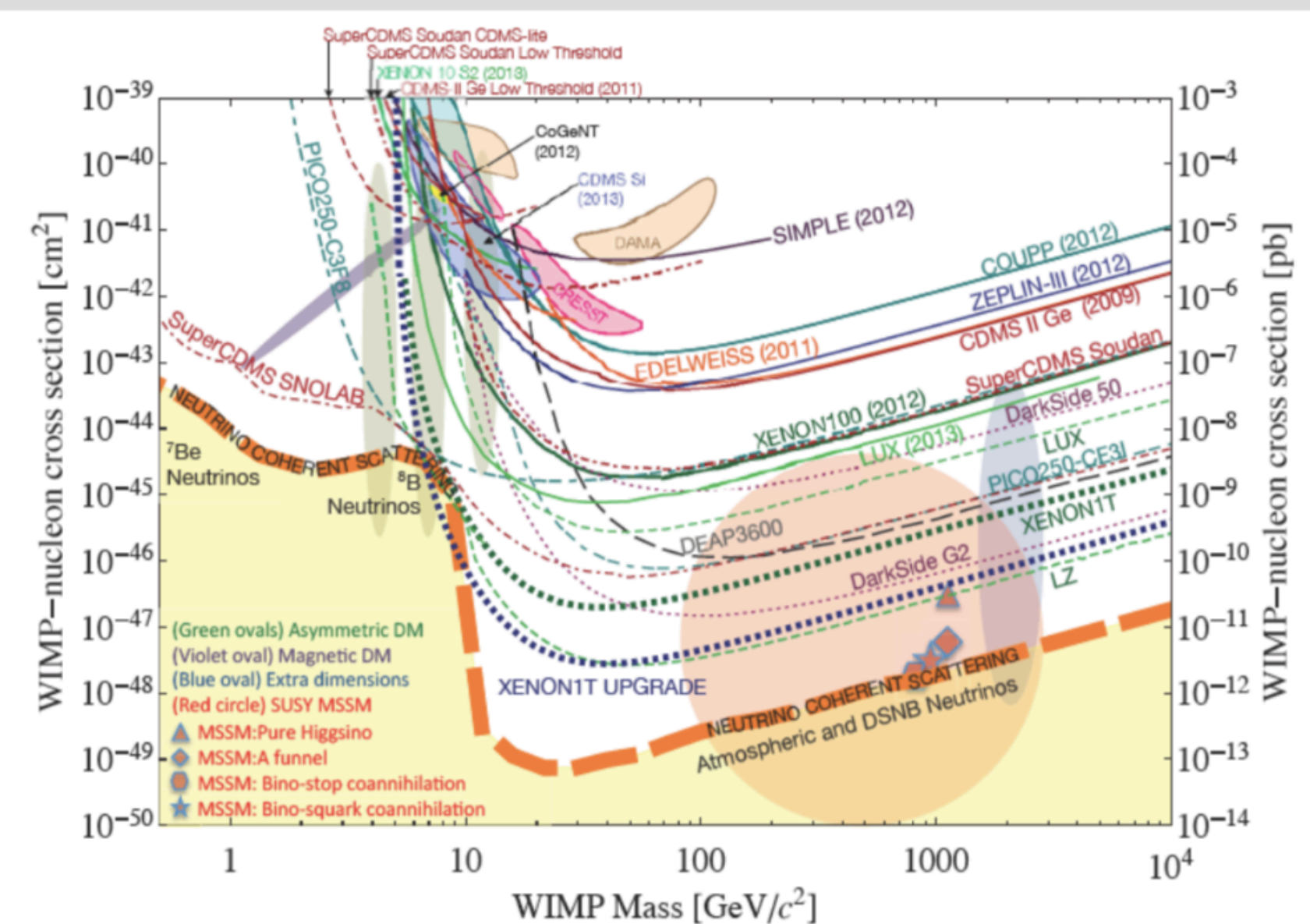
...models...

- 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?
- ...

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



DAMA

SABRE@LGNS

★ Gran Sasso

COSINUS

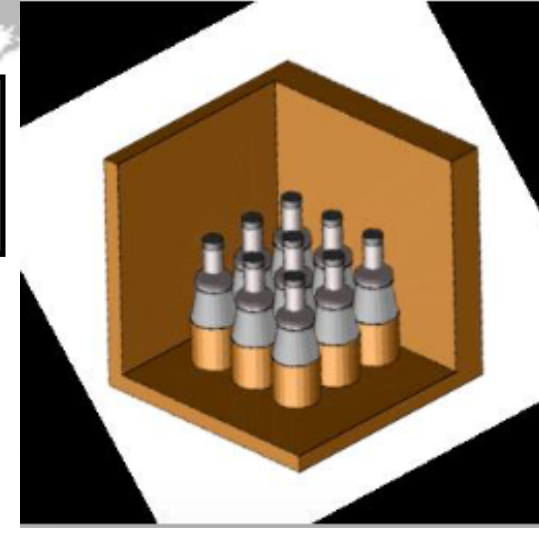
★ Yangyang

KIMS

COSINE-100

PICO-LON

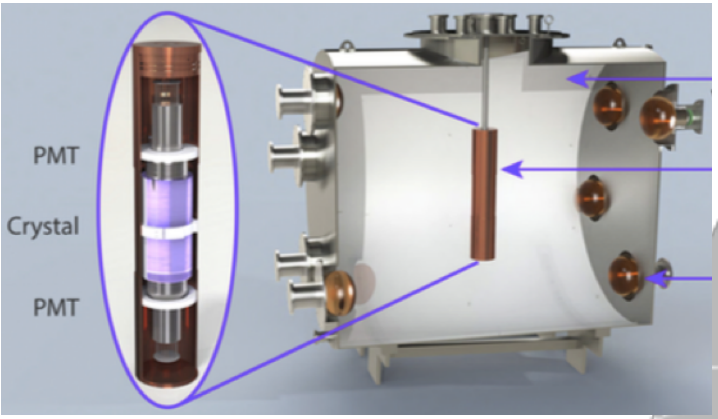
★ Kamioka



ANAIS

★ Boulby

★ Canfranc

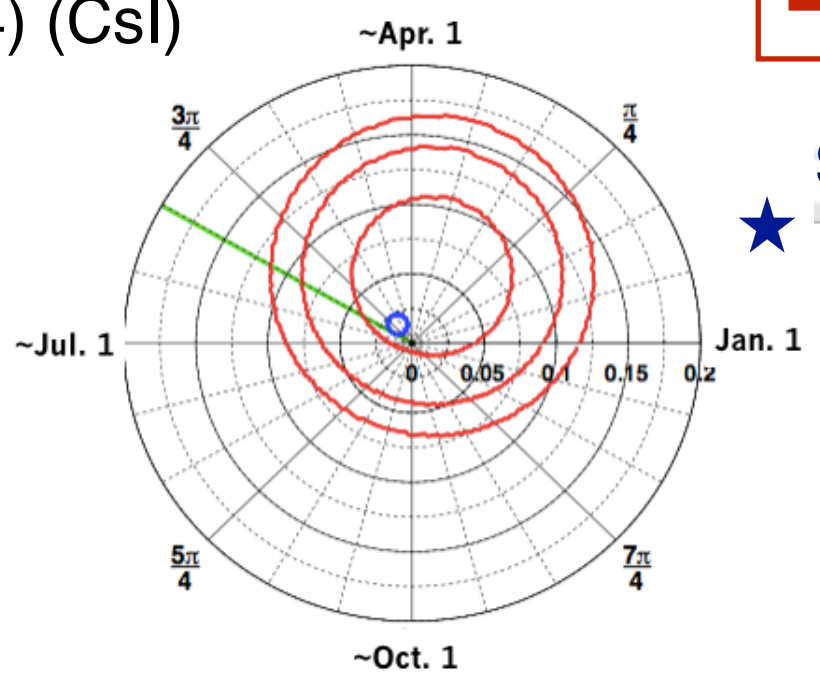


Nature **564**, 83-86 (2018)
 Eur.Phys.J. C **78** 107 (2018)
 Eur.Phys.J. C **77** 437 (2017)
 JINST **13** T02007 (2018)
 Phys.Rev. D **90** 052006 (2014) (Csl)

SABRE@Stawell

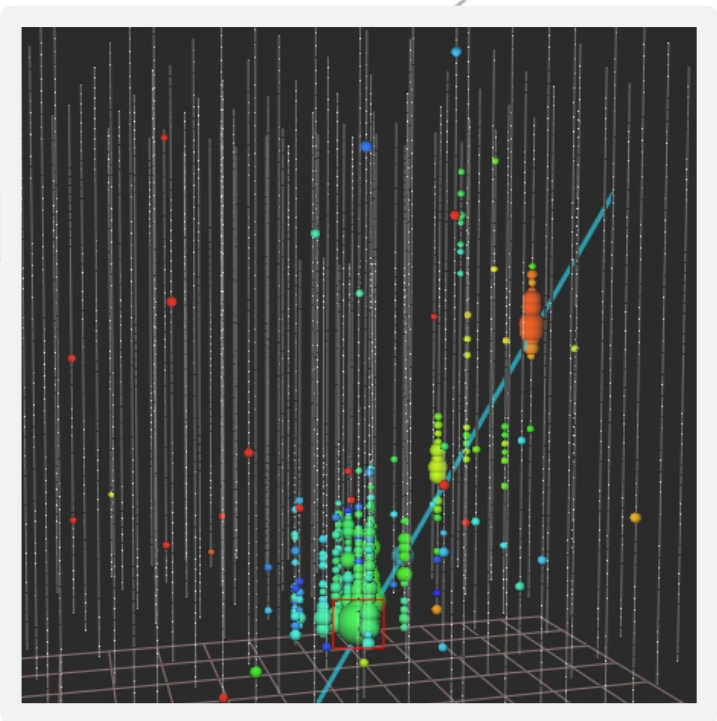
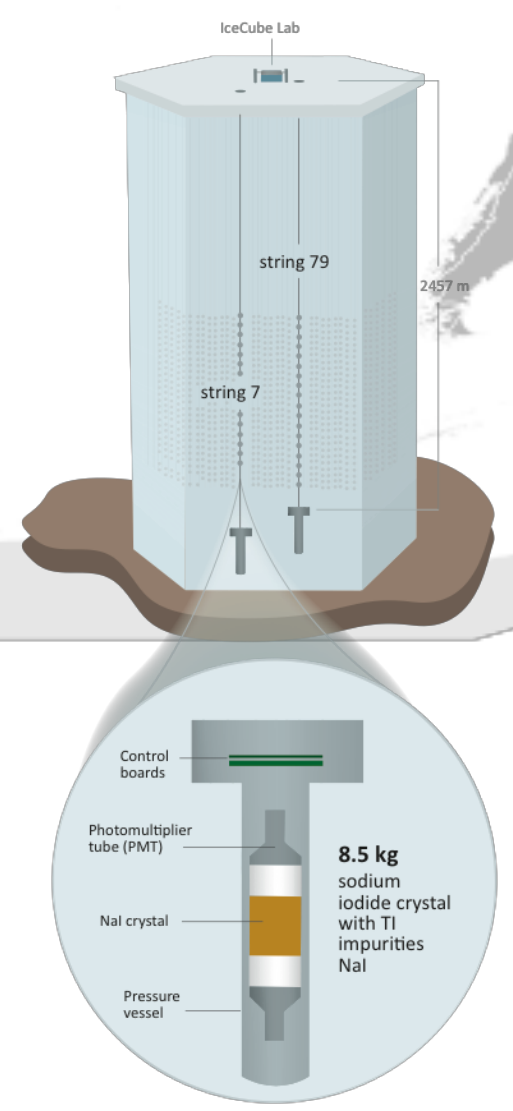
★ Stawell

Astropart. Phys. **35** (2012) 749
 Phys. Rev. D **90** 092005 (2014)
 Phys. Rev. D **93** 042001 (2016)
 Phys. Rev. D **95** 032006 (2017)



DM-Ice

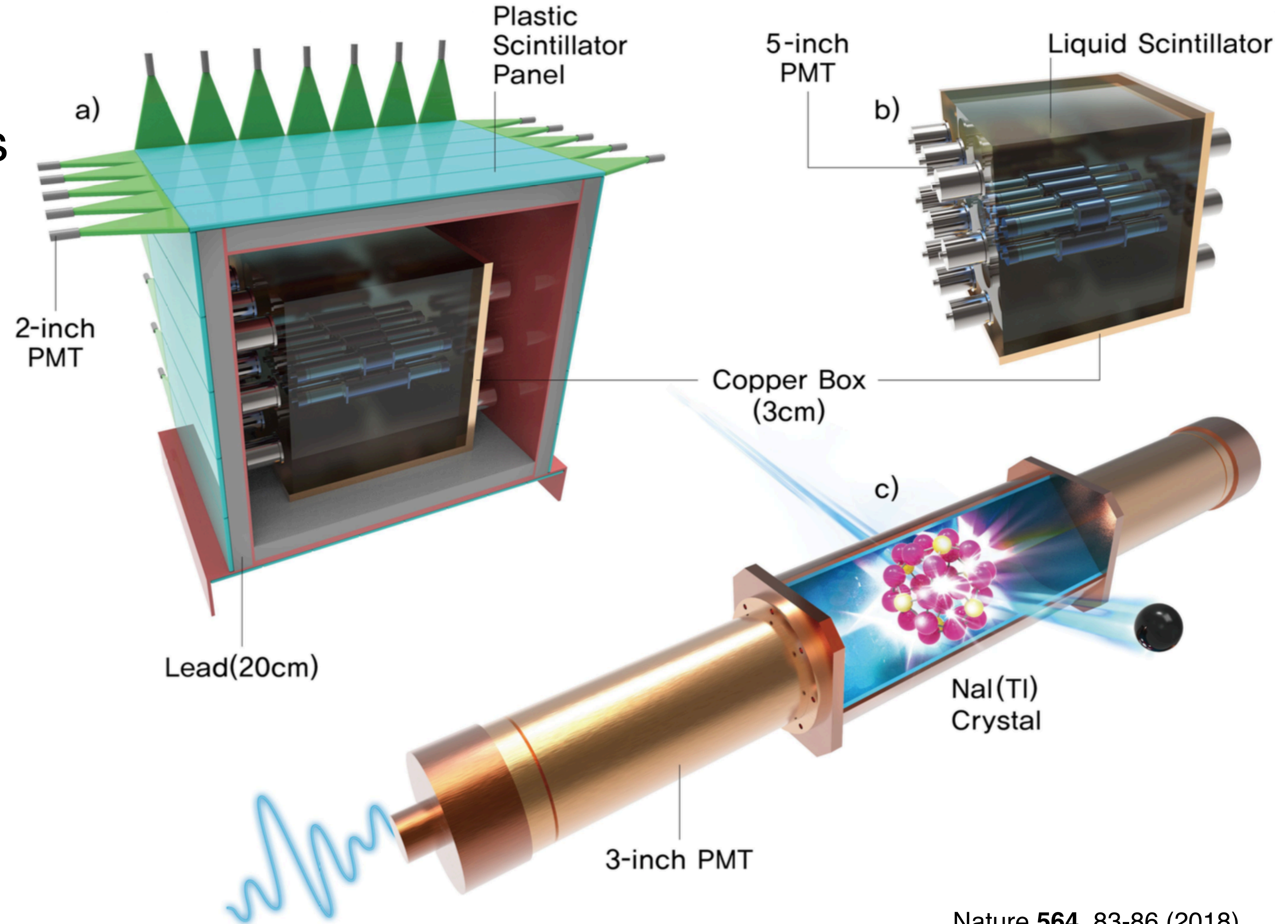
★ South Pole



COSINE-100: Full-scale NaI(Tl) experiment at Y2L

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



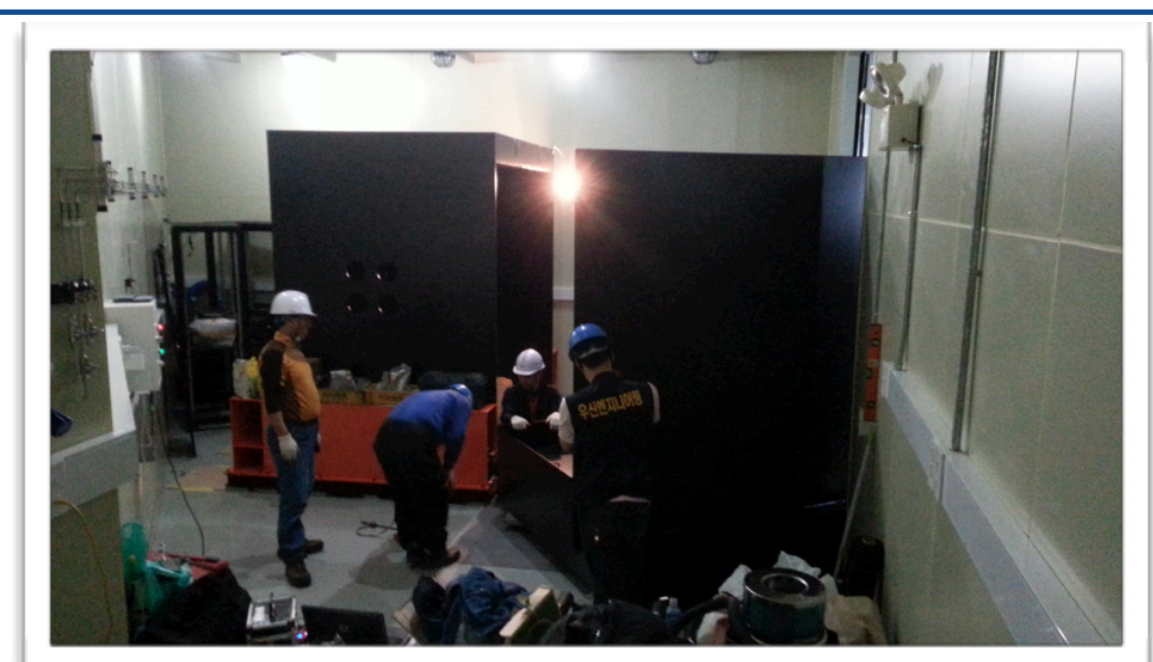
Nature **564**, 83-86 (2018)

COSINE-100 construction timeline

Dec. 2015



Jan. 2016

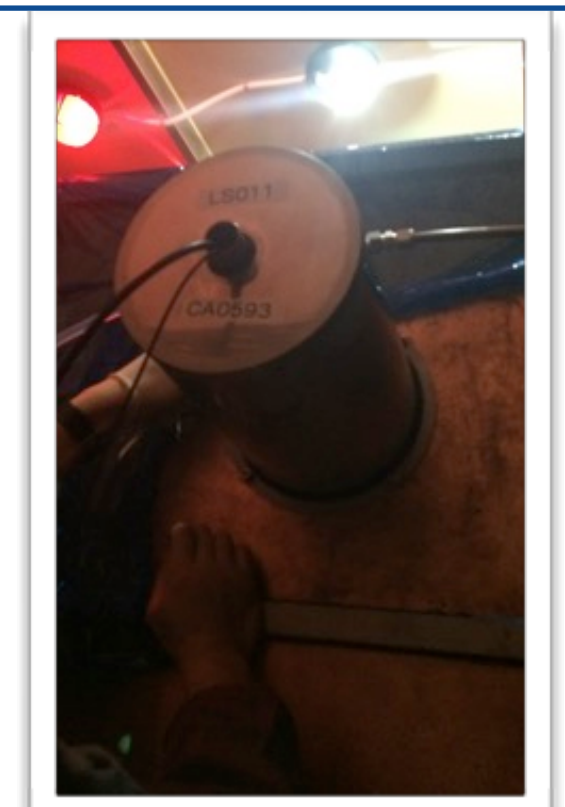
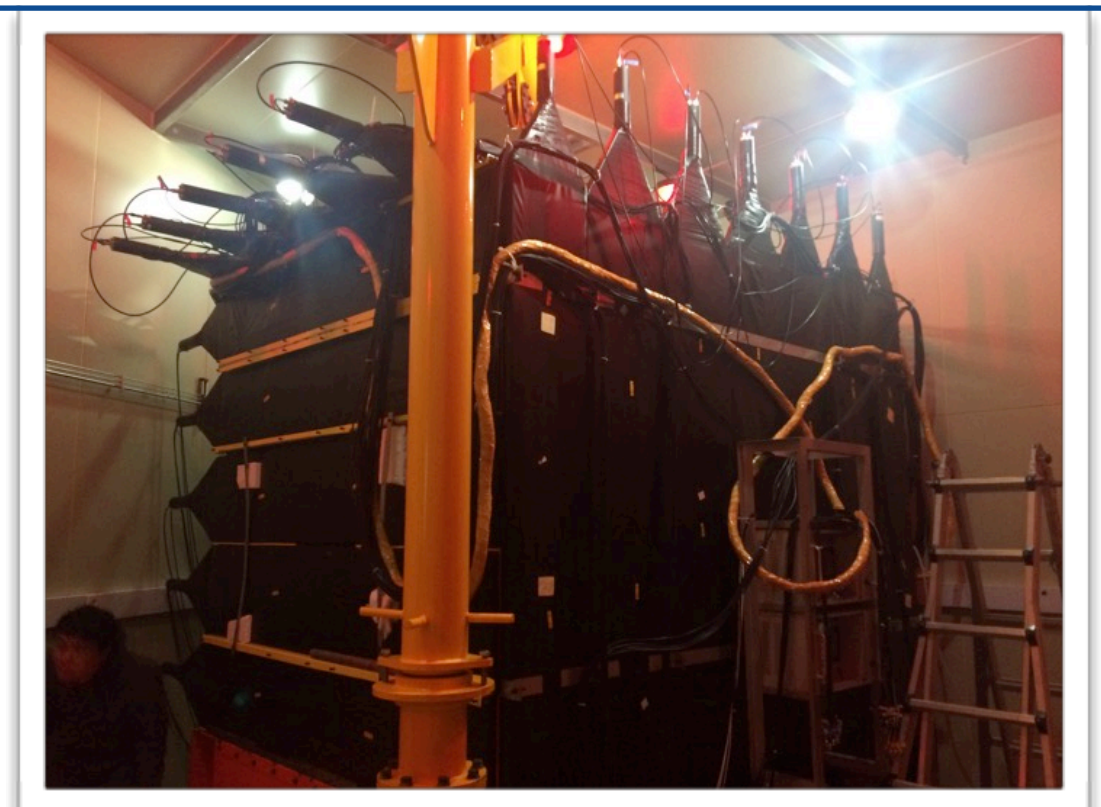
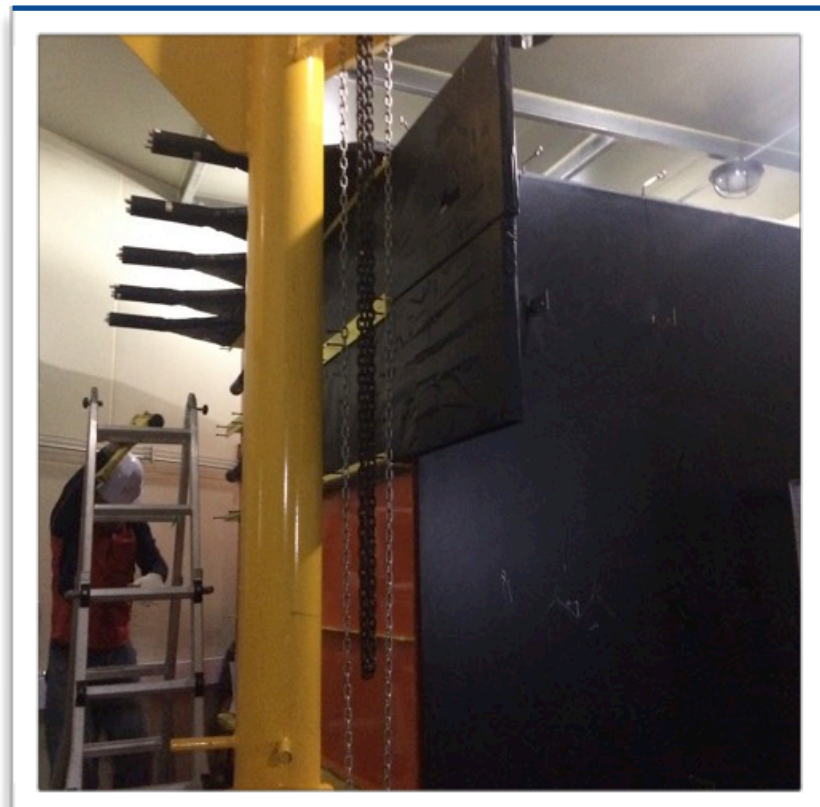


Feb. 2016



Mar. 2016

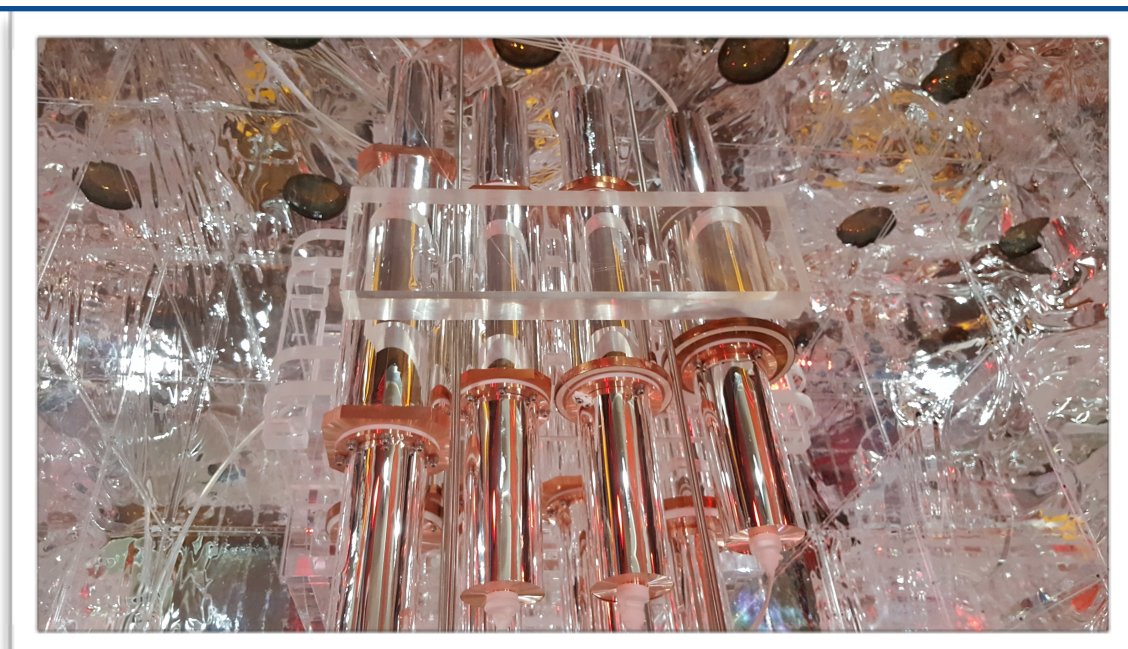
Apr. 2016



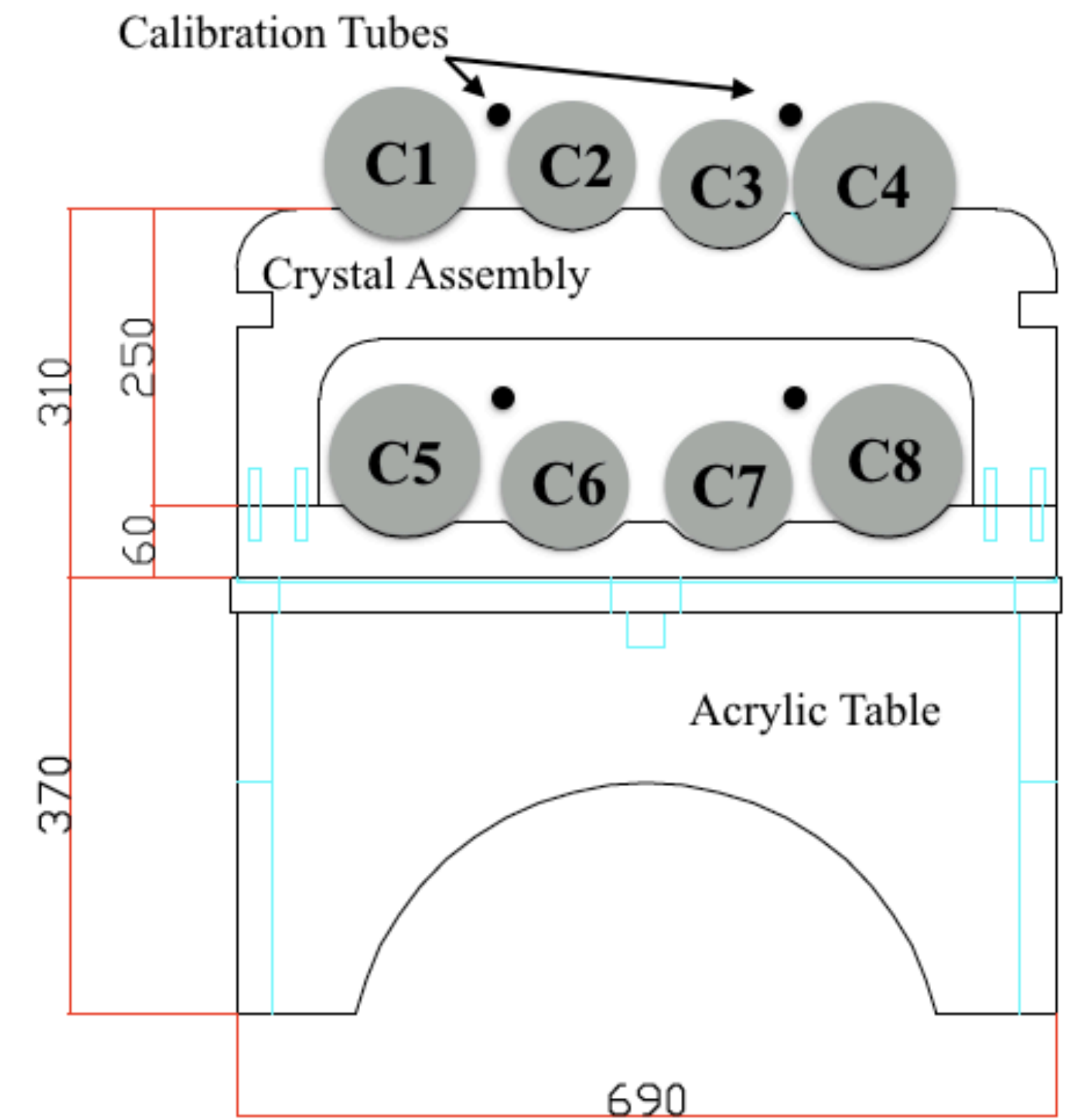
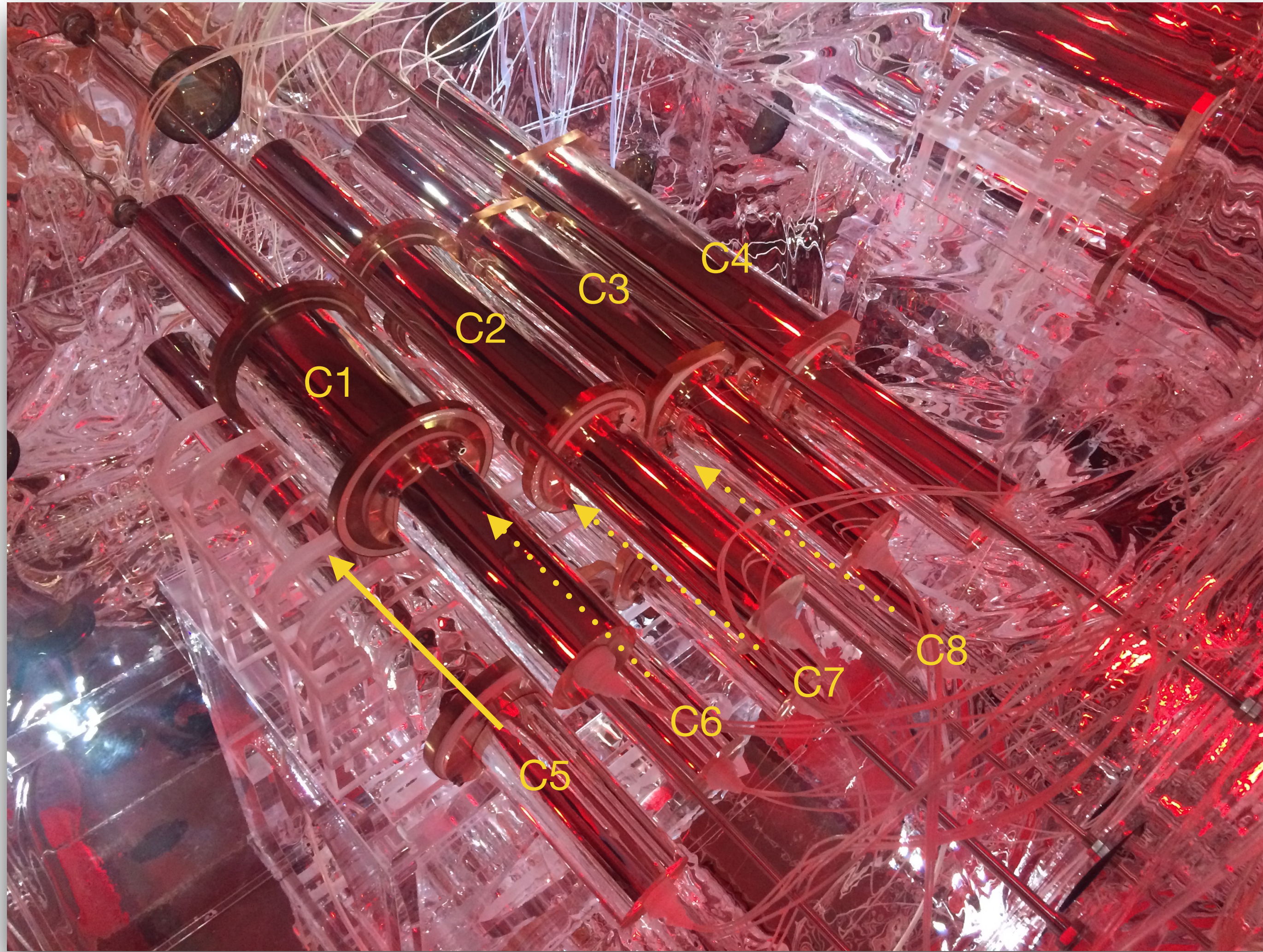
May. 2016

Jun. 2016

Sep. 2016

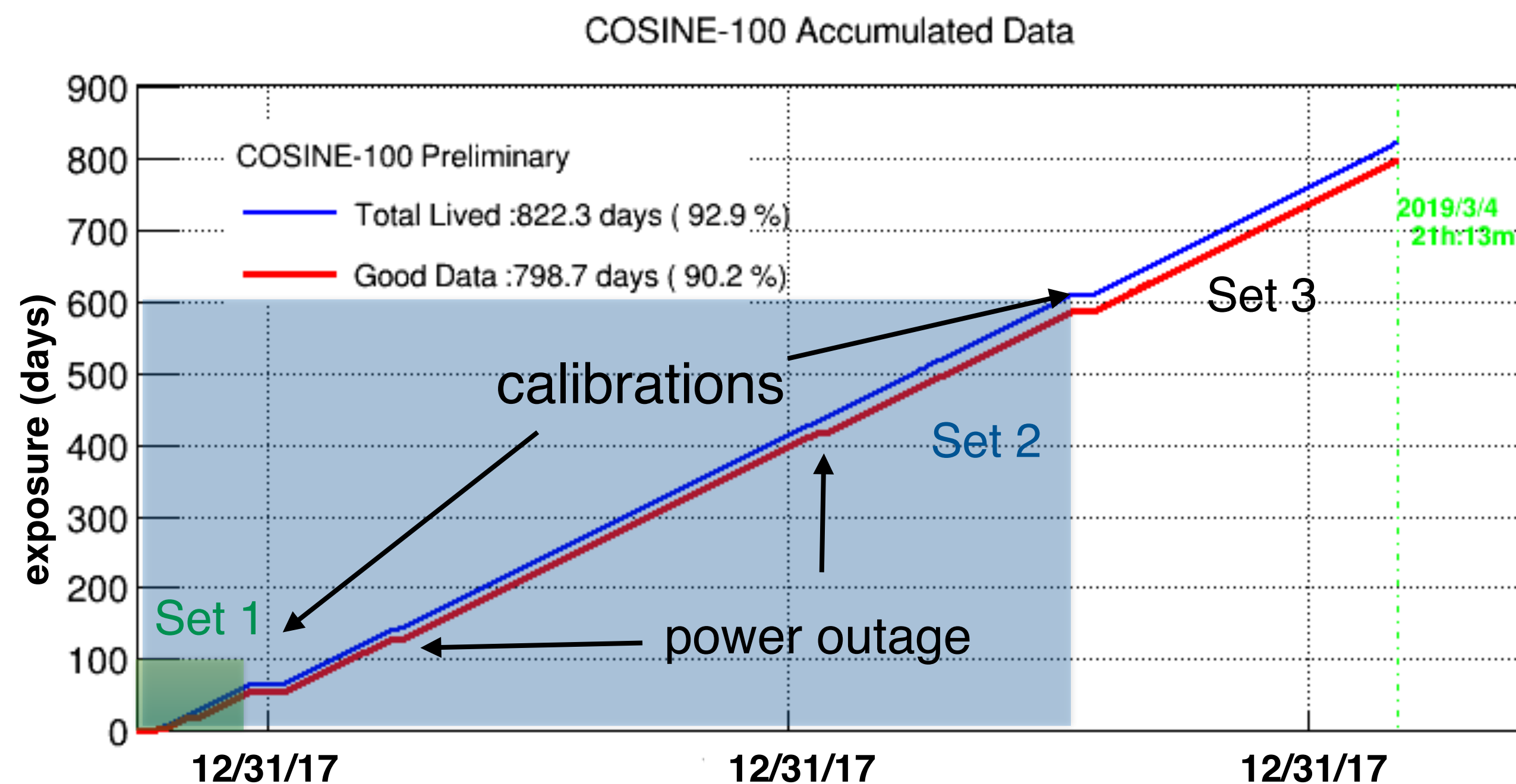


Crystal configuration



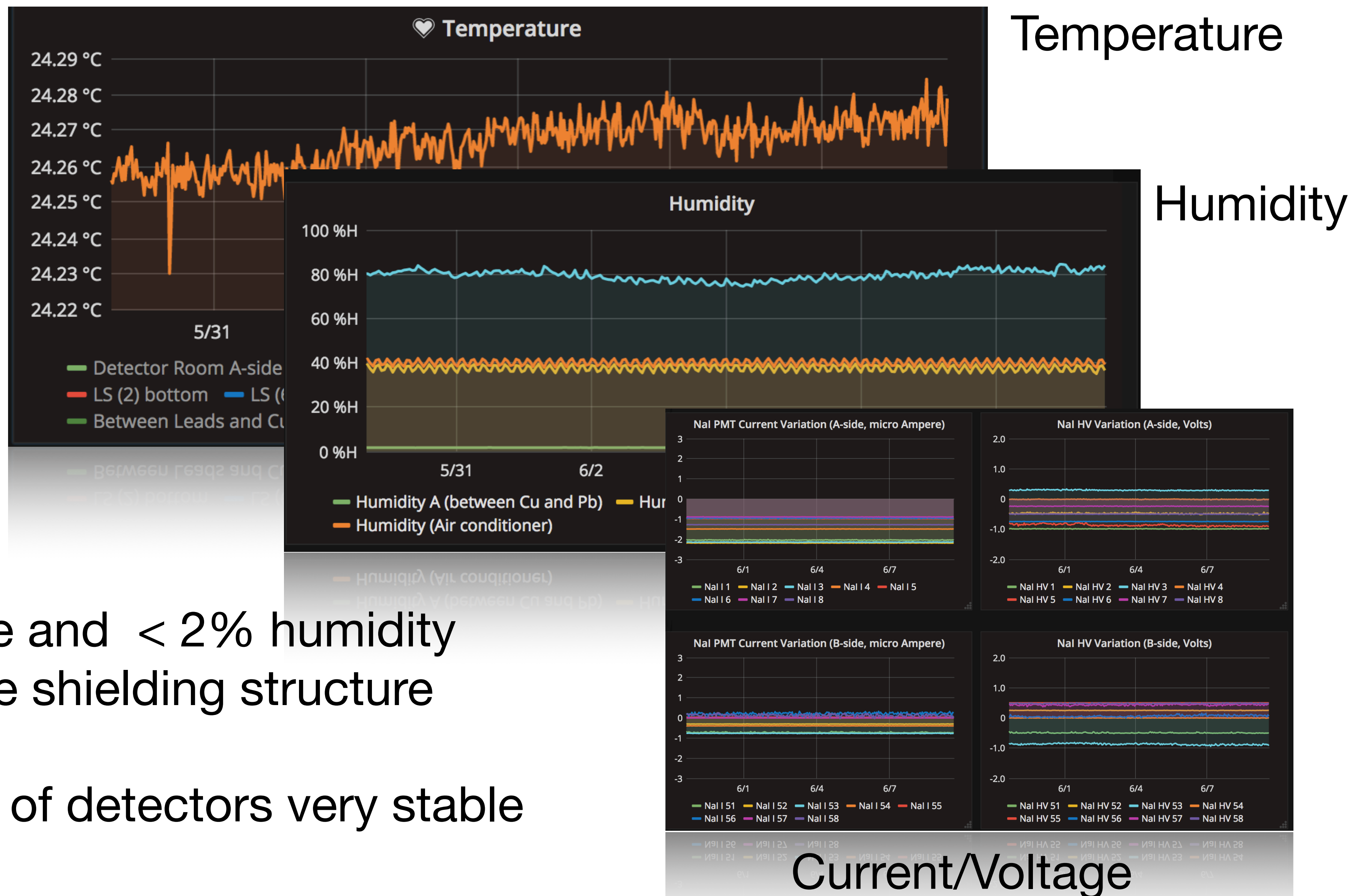
COSINE-100 operation

- Data taking since Sep. 2016
 - Stable operation
 - ~90% live time
 - Near 100% uptime outside of calibration
- > 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

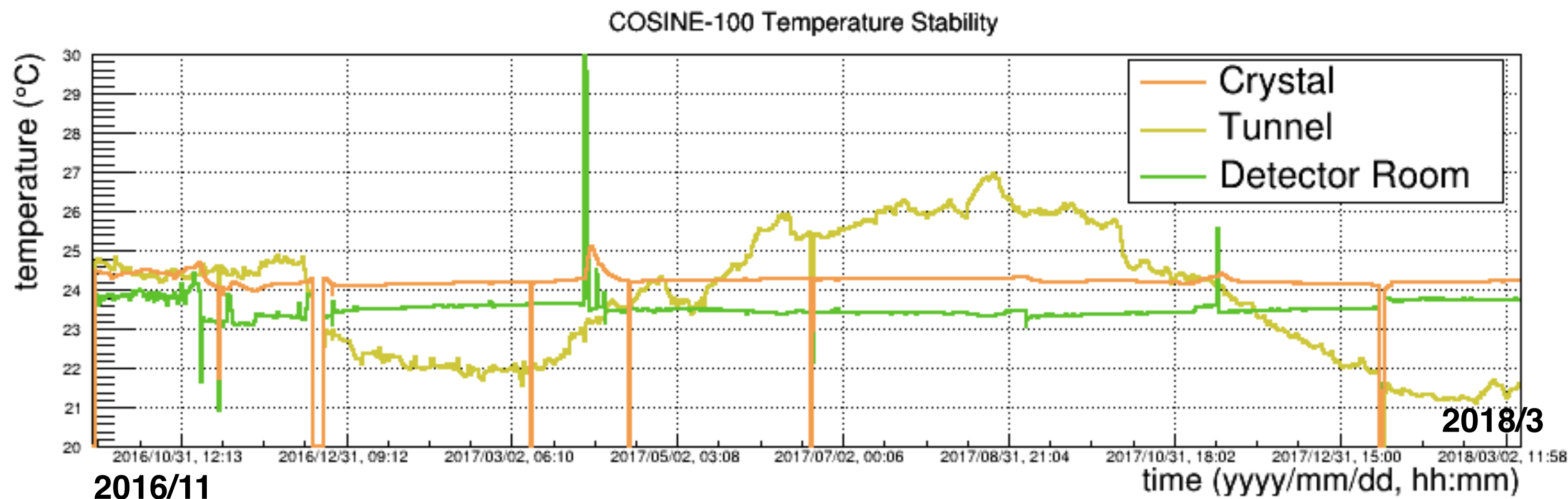
- Monitoring stability of temperature, humidity, current/voltage, etc.



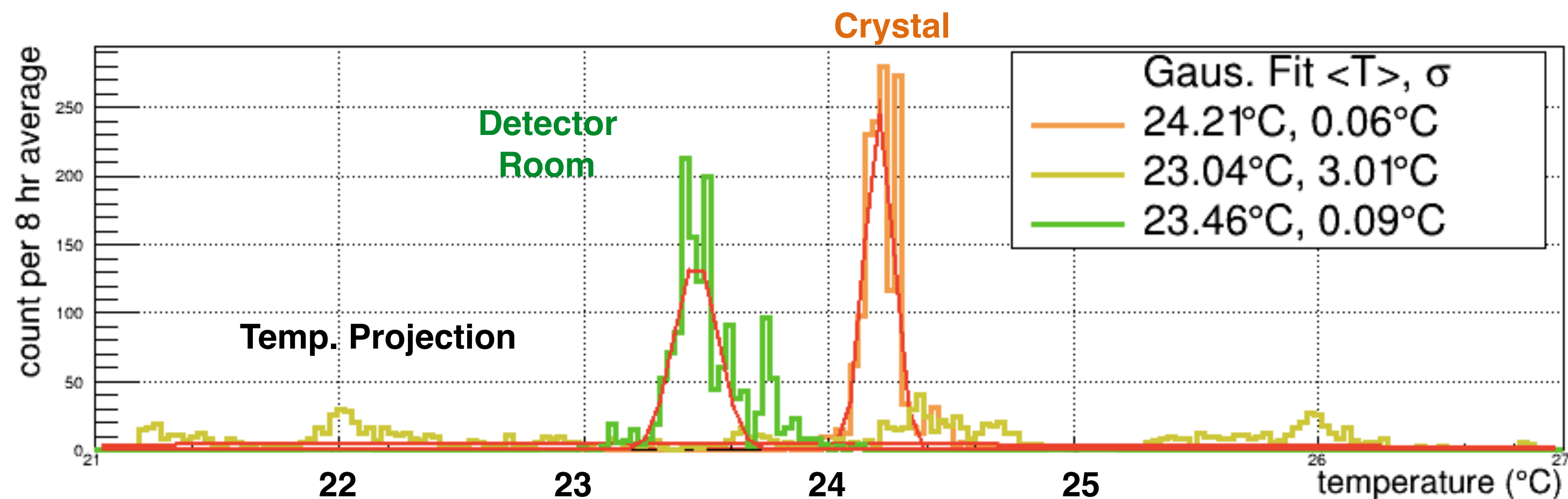
- $< 0.1 \text{ }^\circ\text{C}$ temperature and $< 2\%$ humidity fluctuation inside the shielding structure
- Current and voltage of detectors very stable

Environmental control/monitoring

- Monitoring stability of temperature, humidity, current/voltage, etc.



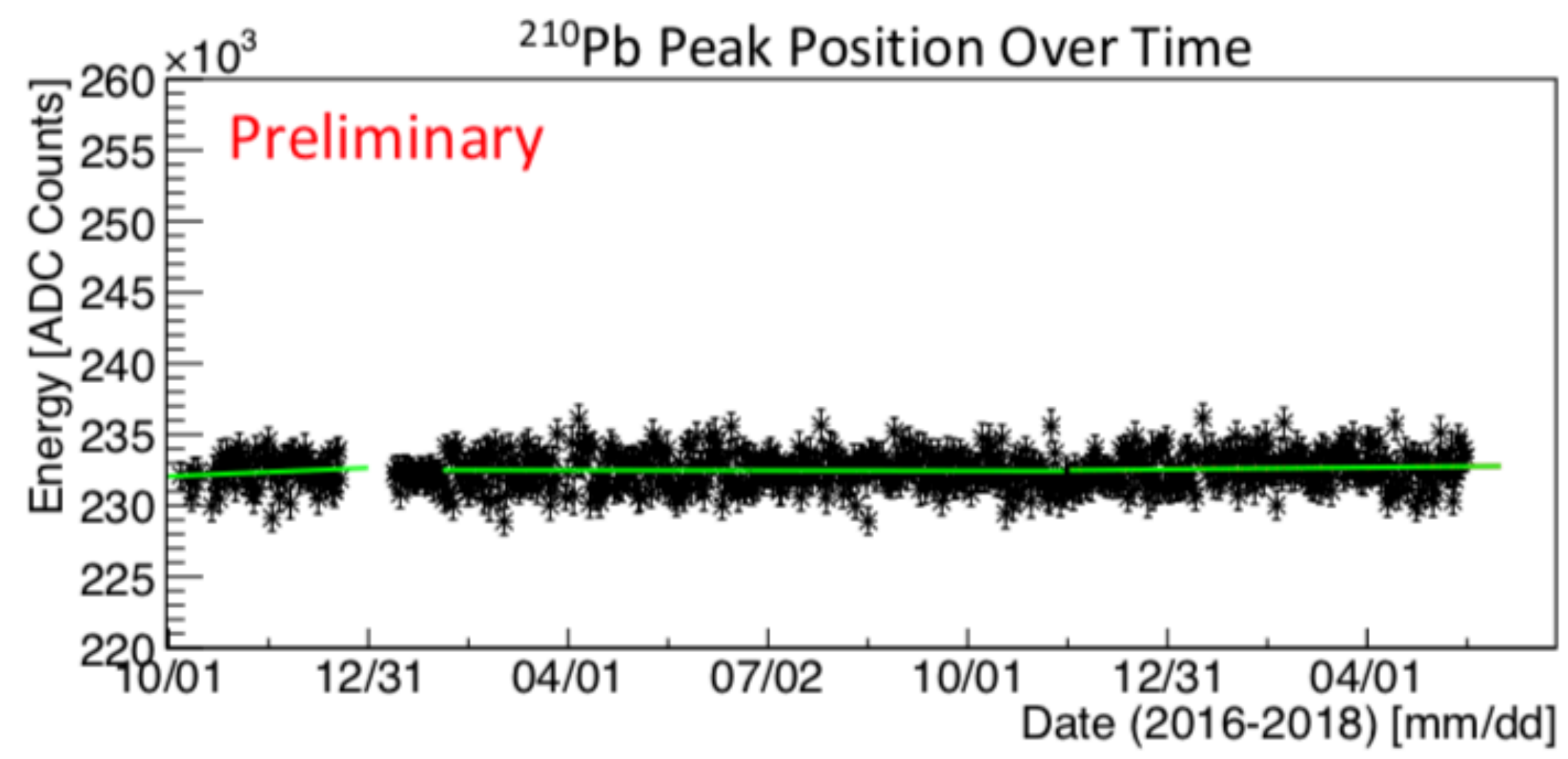
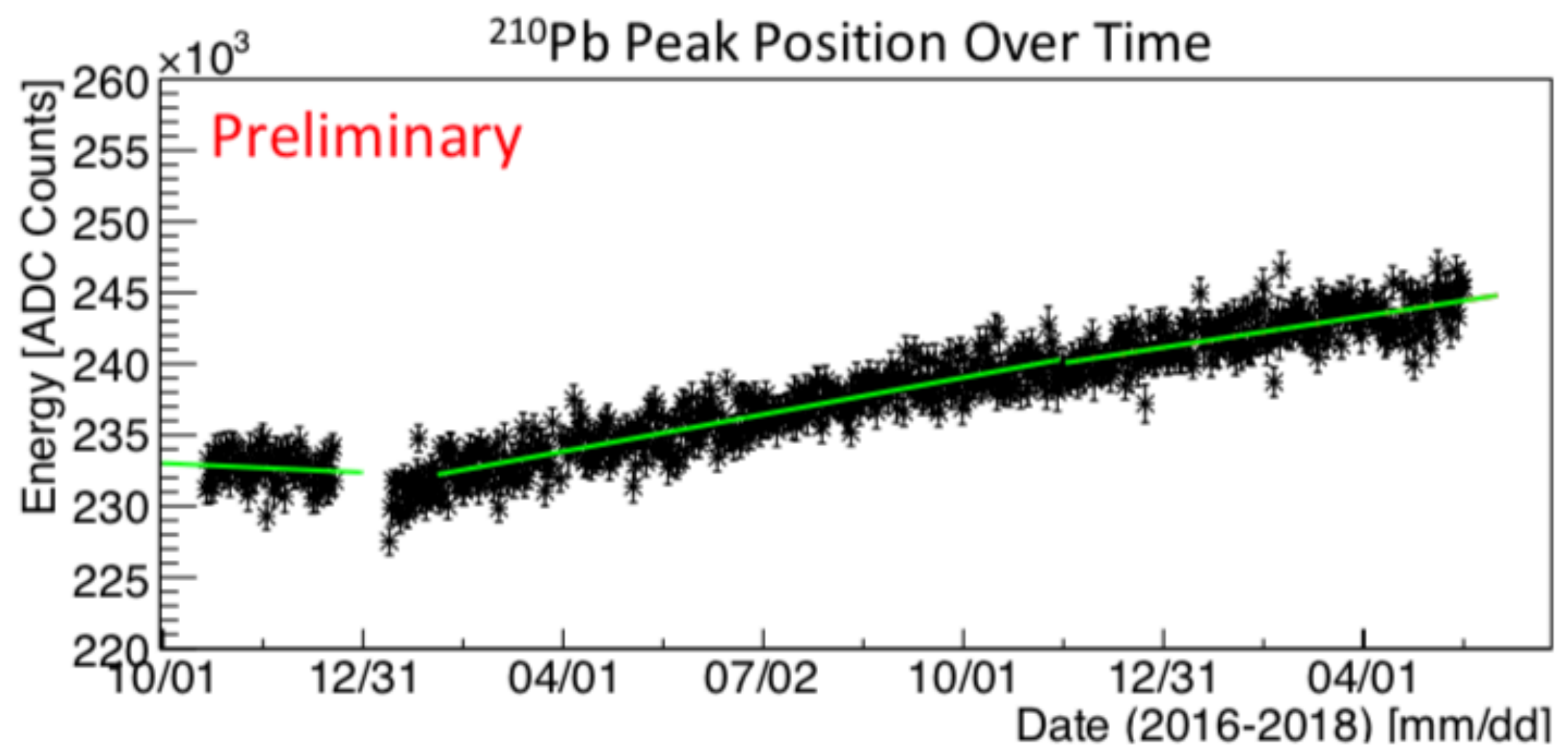
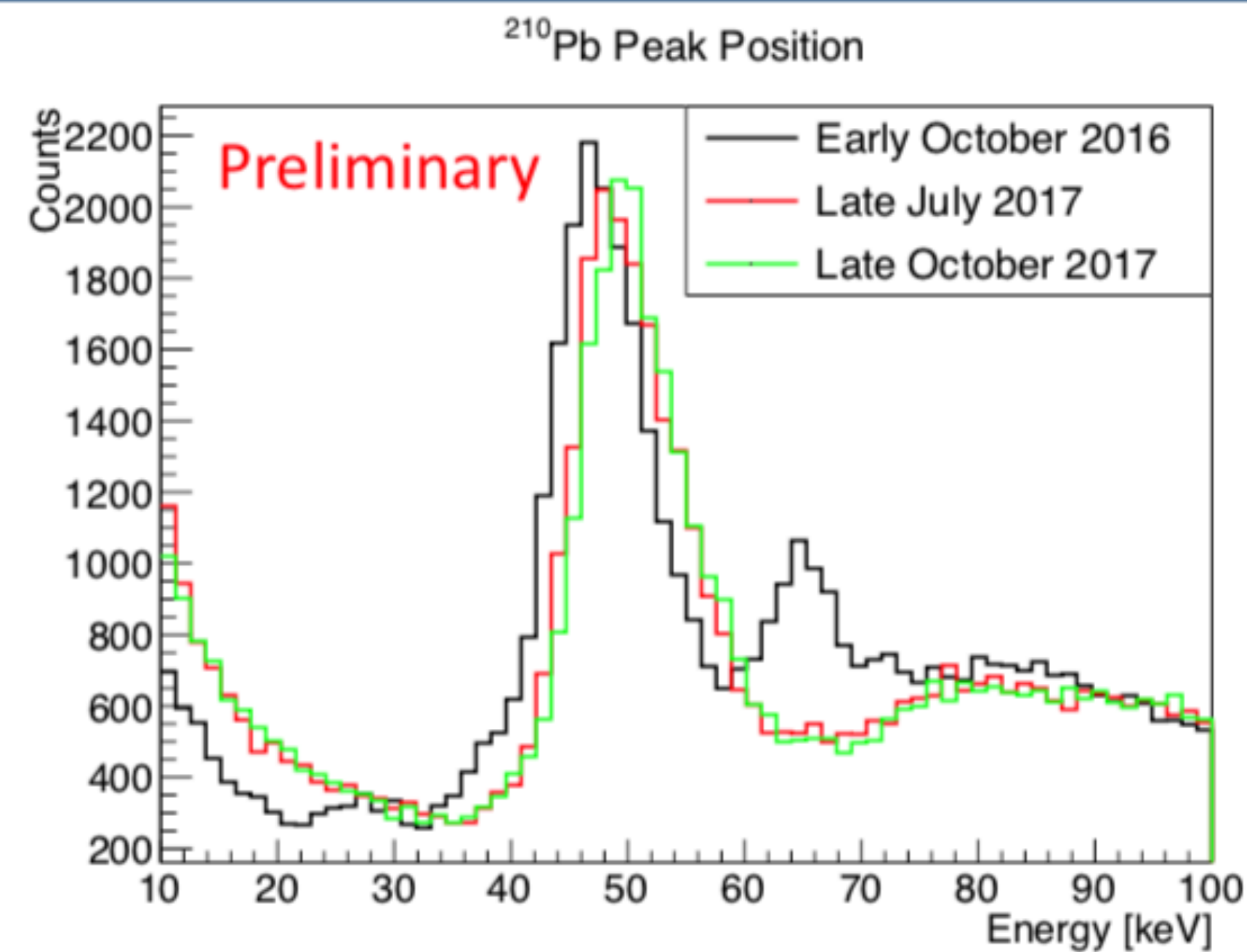
- < 0.1 °C temperature and < 2% humidity fluctuation inside the shielding structure



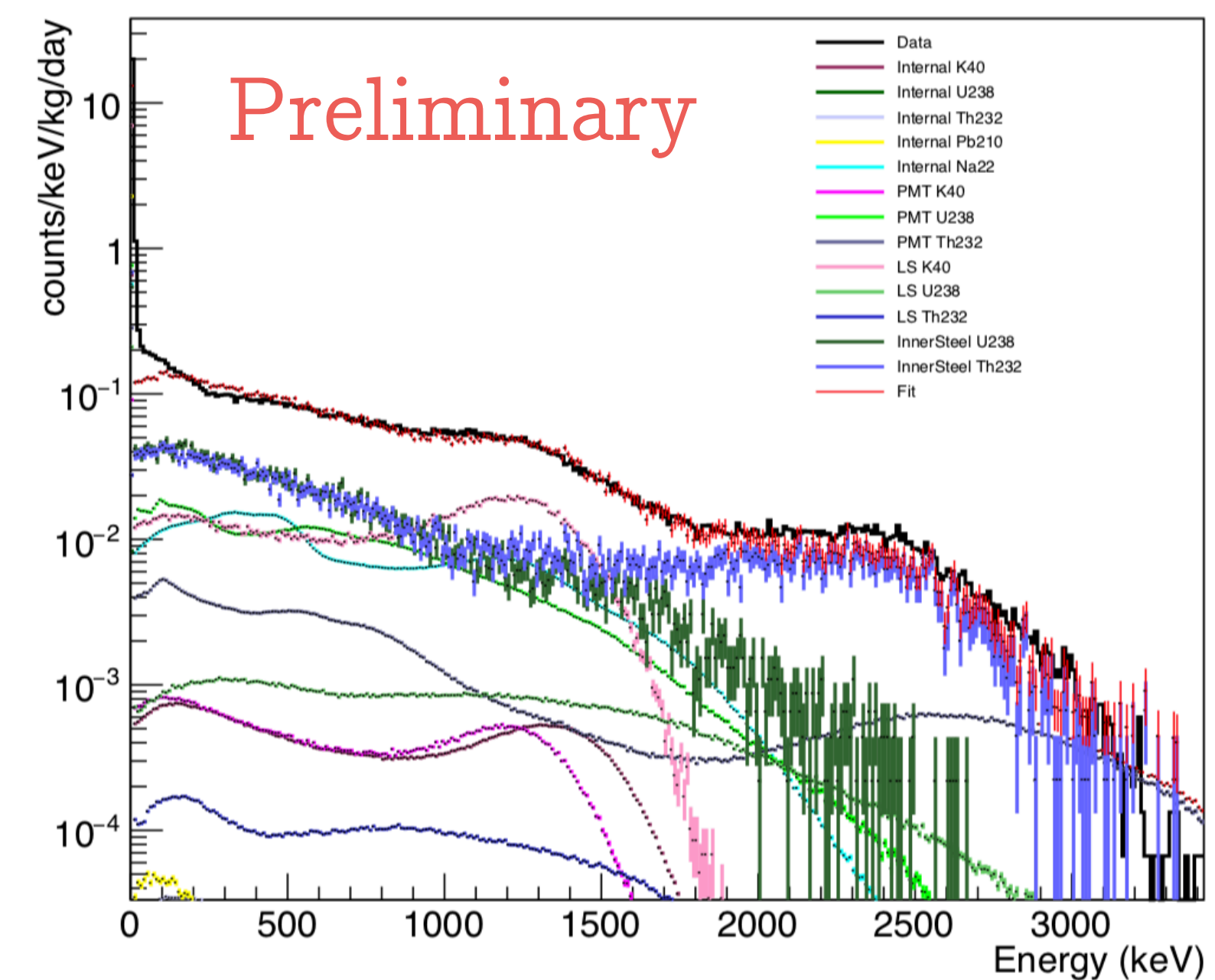
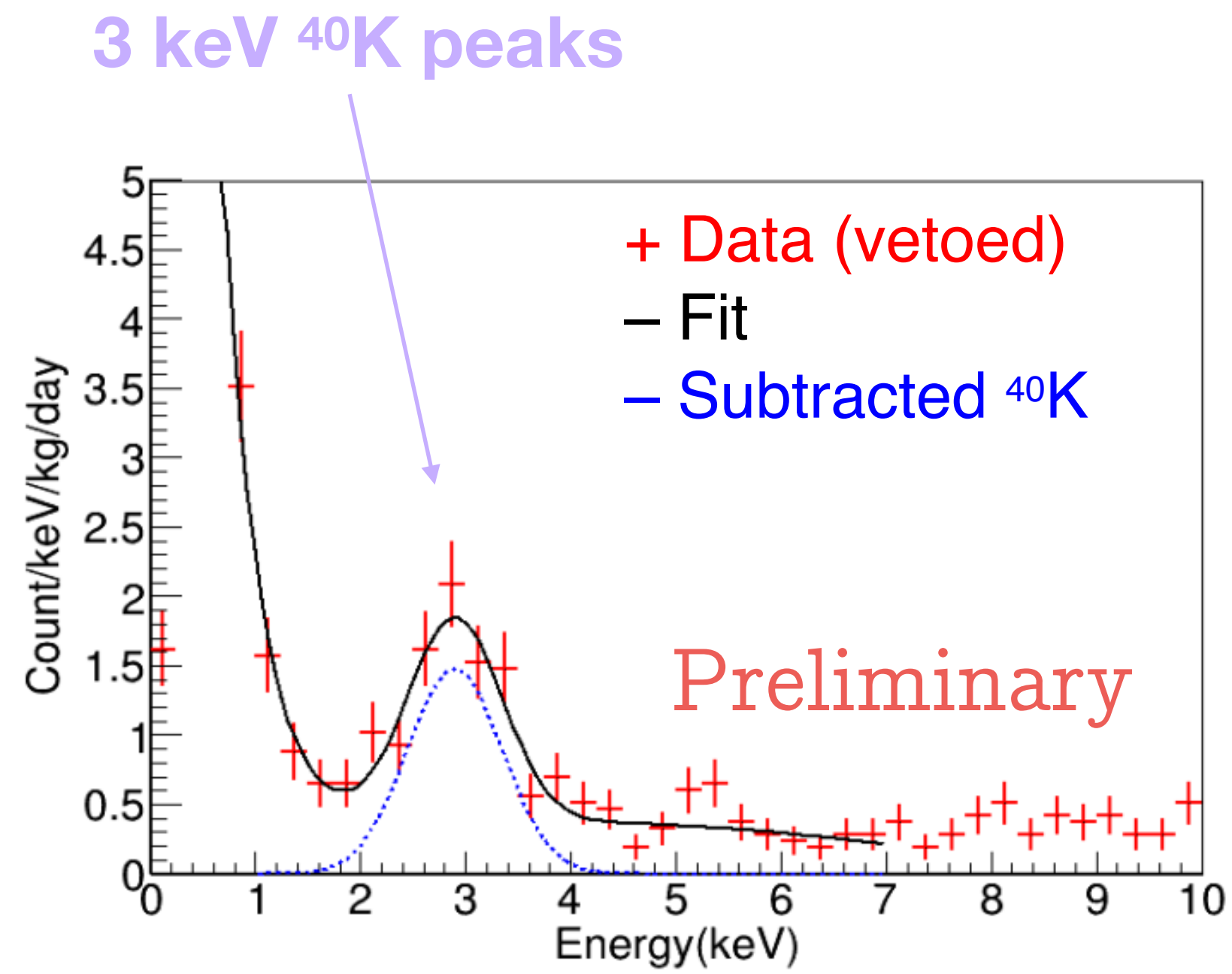
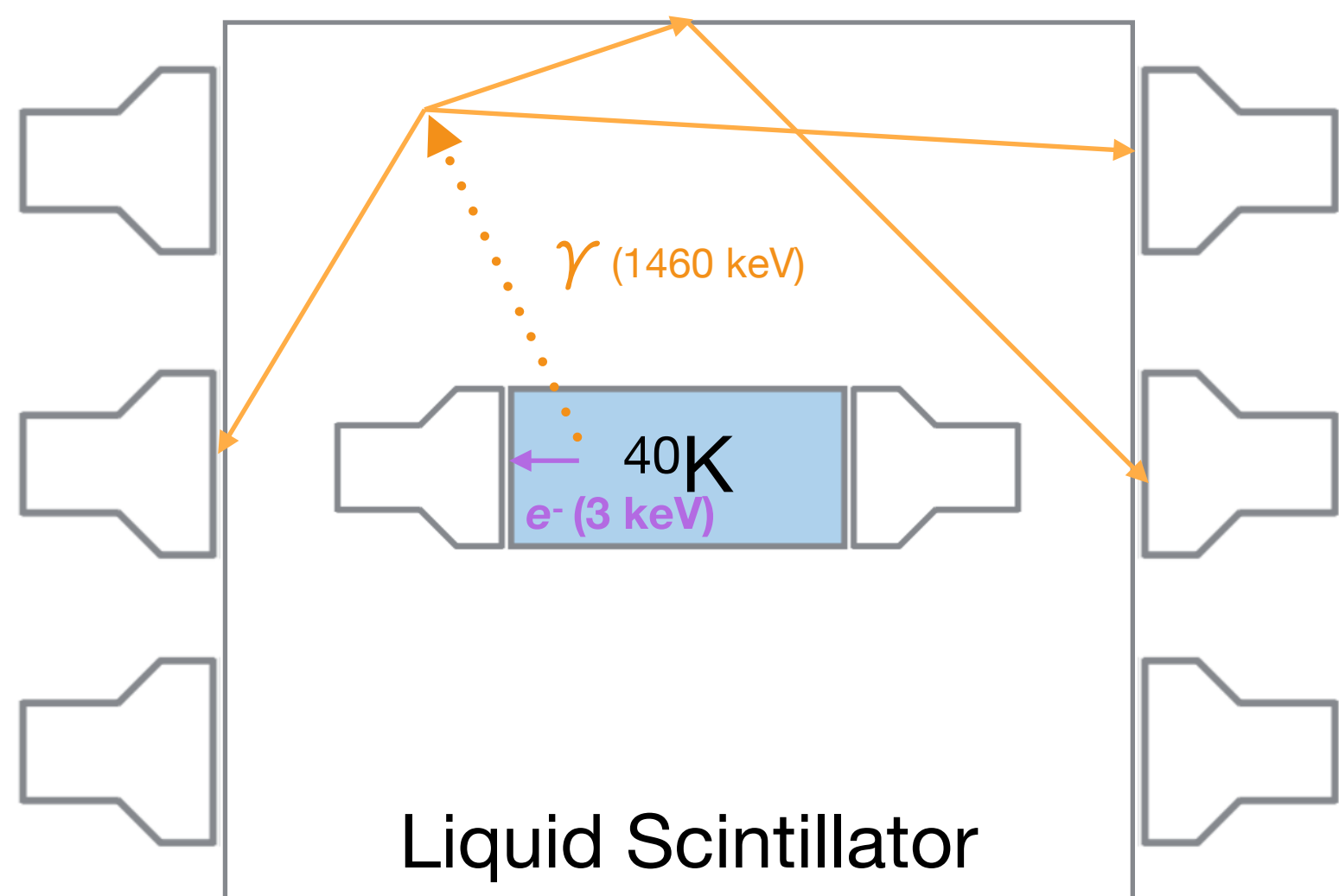
- Current and voltage of detectors very stable

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

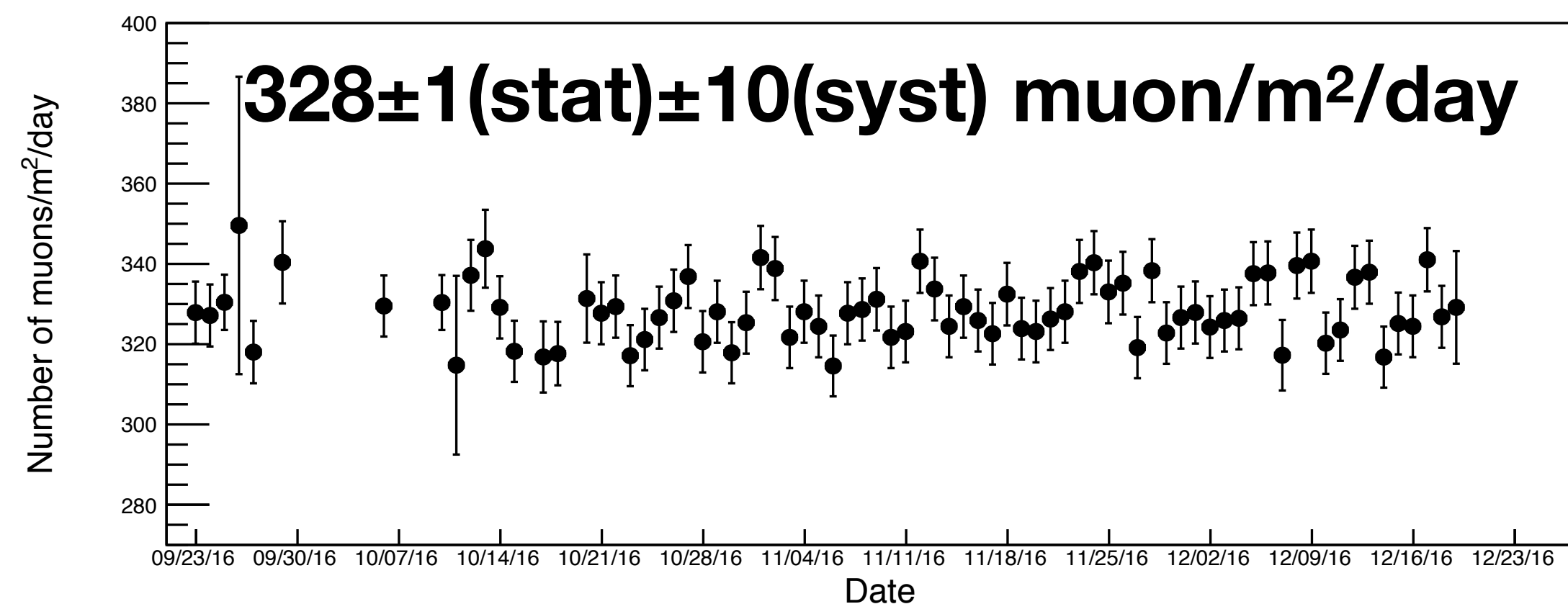
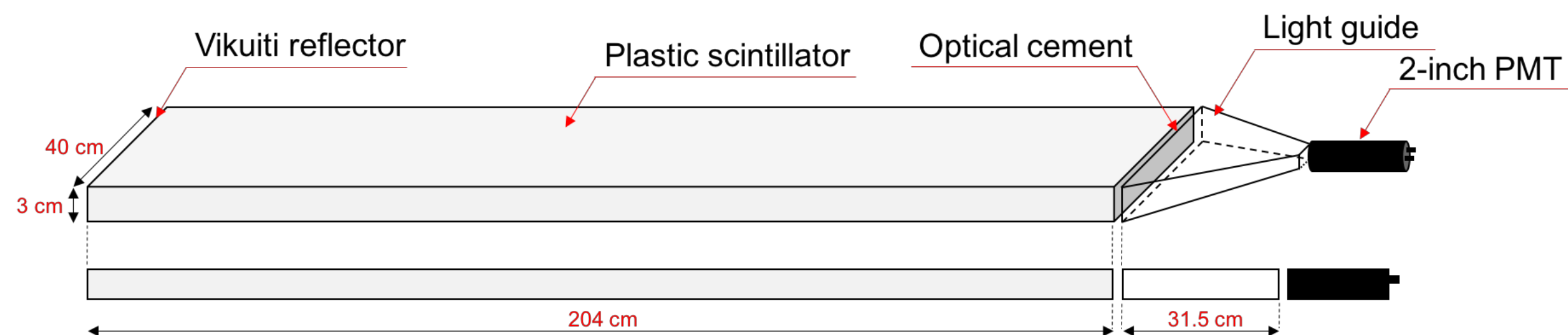
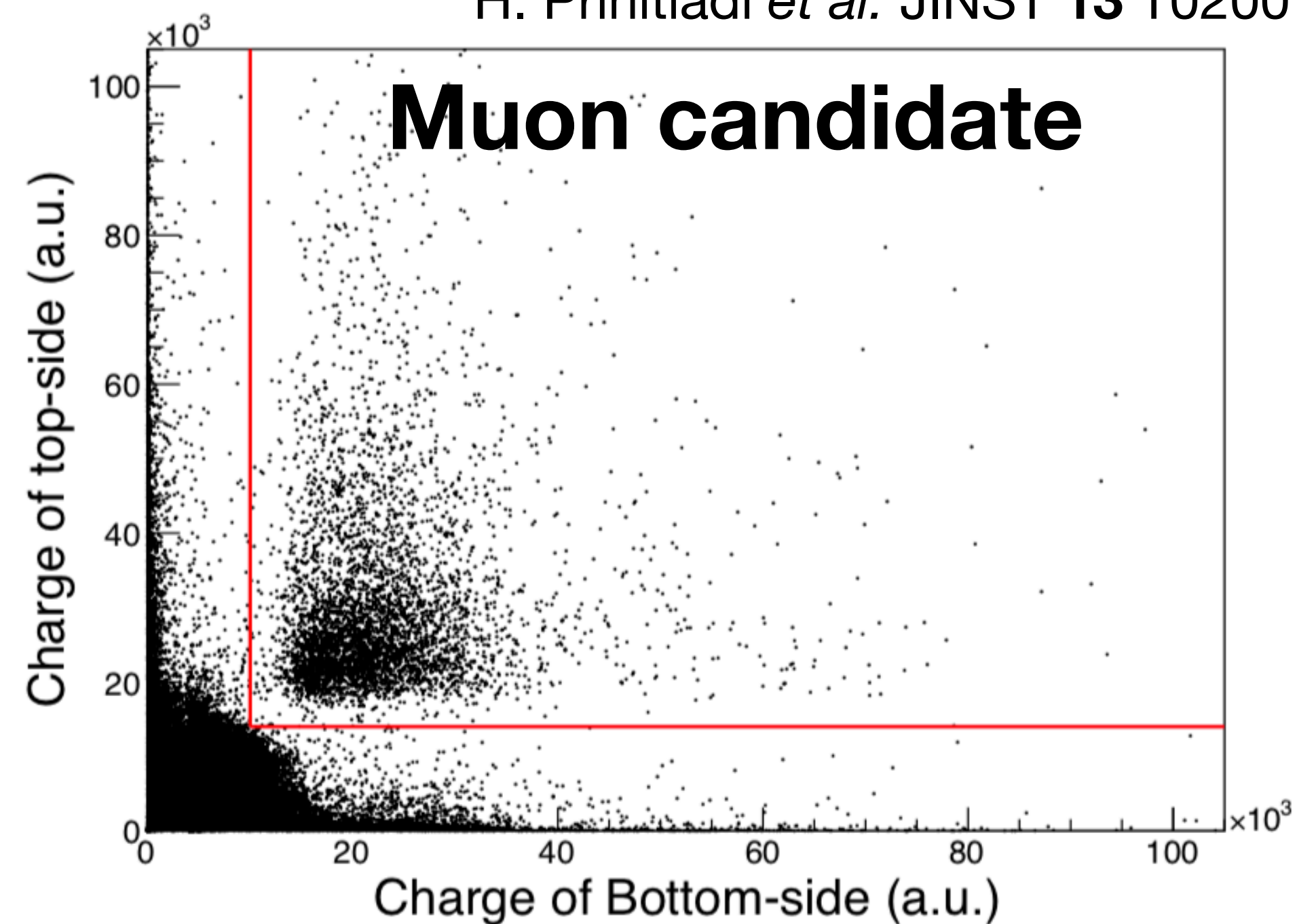


- ^{40}K emits 1460 keV gamma with 3 keV Auger electron energy deposition in NaI crystal
- Tagging 1460 keV events with LS enables **vetoing of 3 keV background events**
- Liquid scintillator internal contamination well modeled with simulation

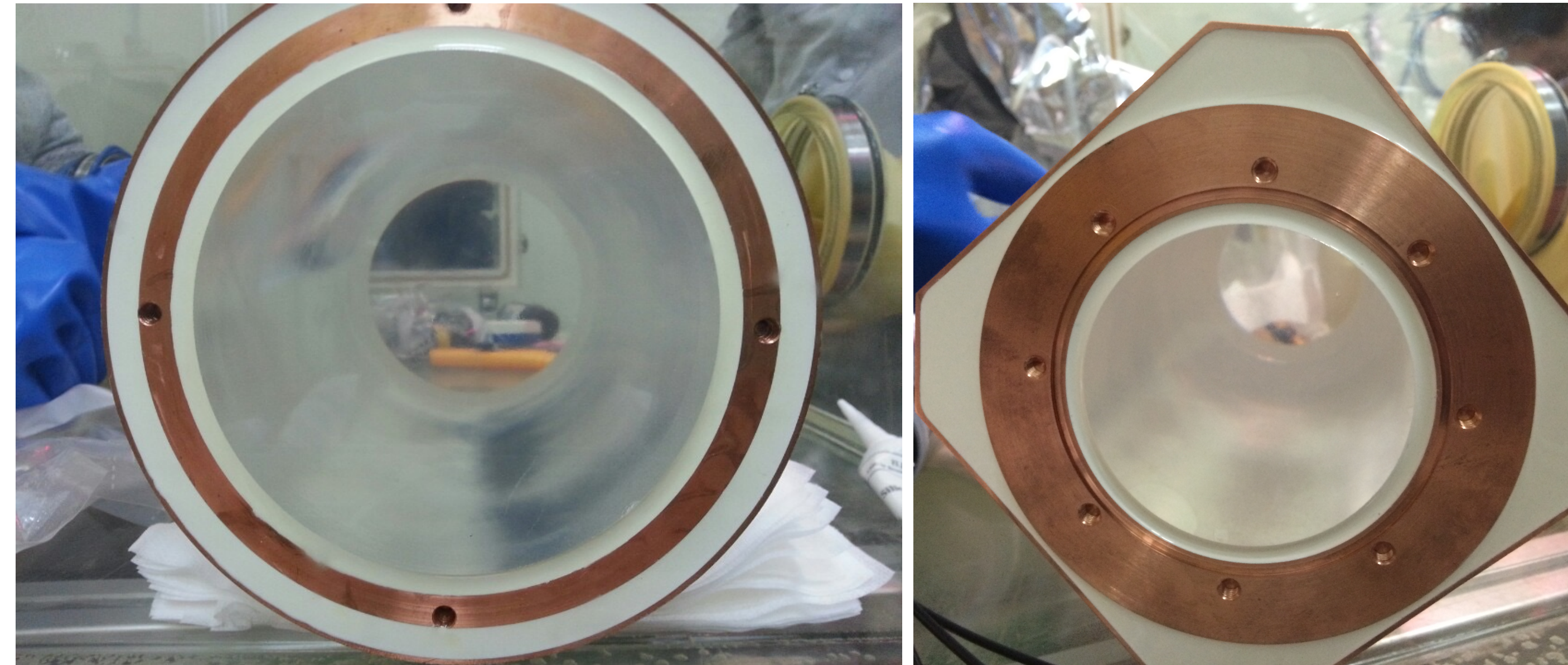
Muon detector

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

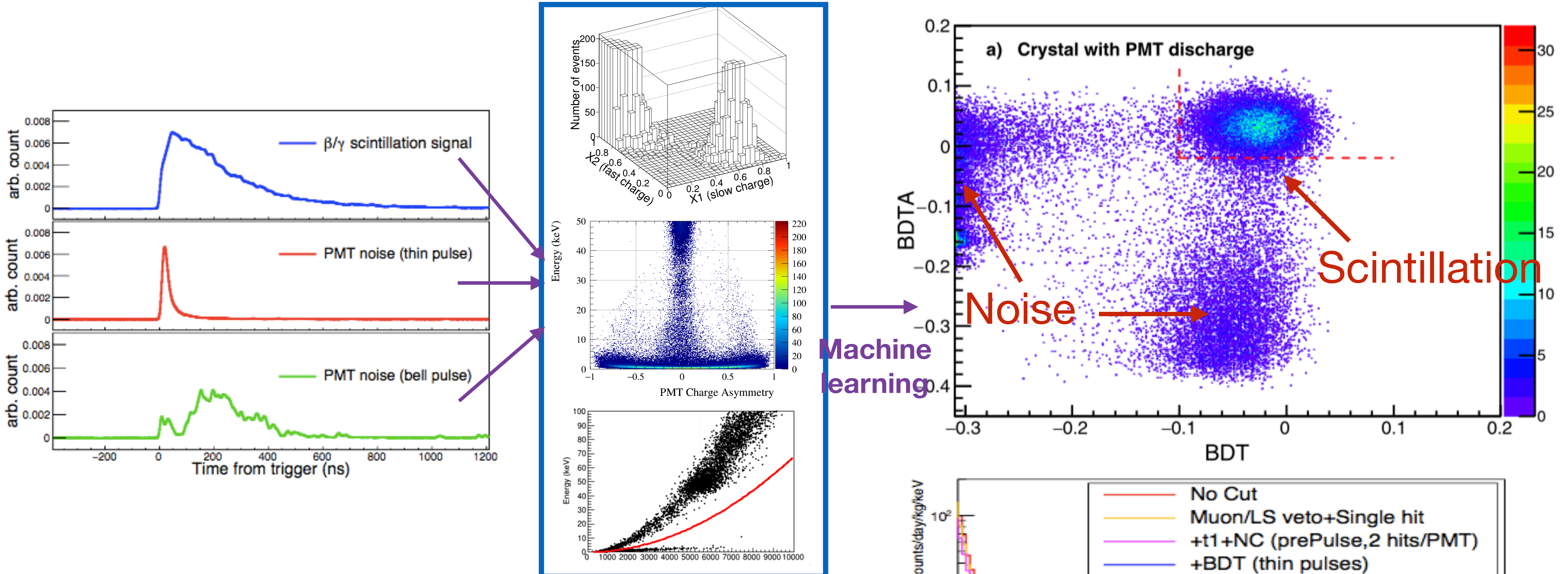
H. Prihitiadi *et al.* JINST **13** T02007 (2018)



- 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



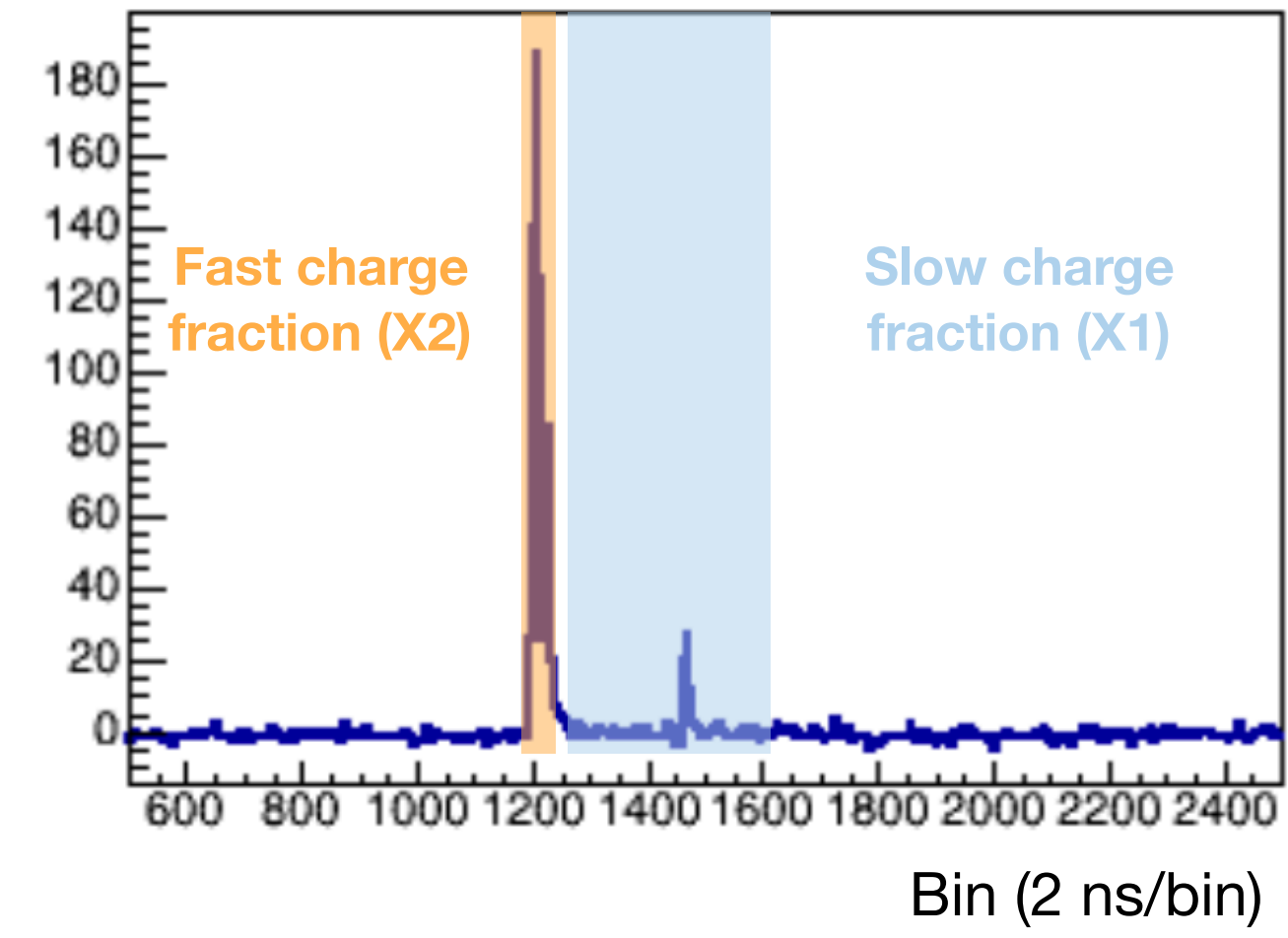
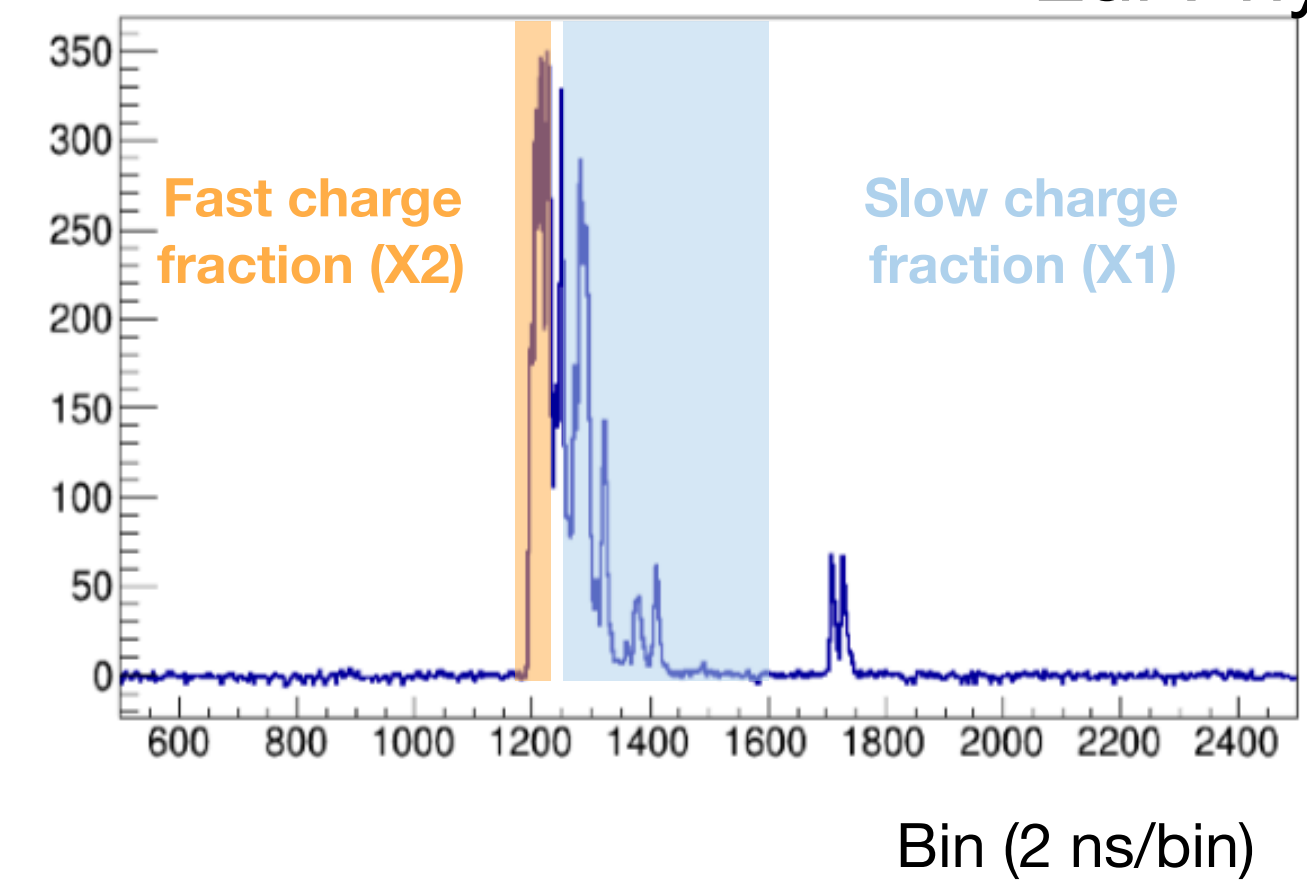
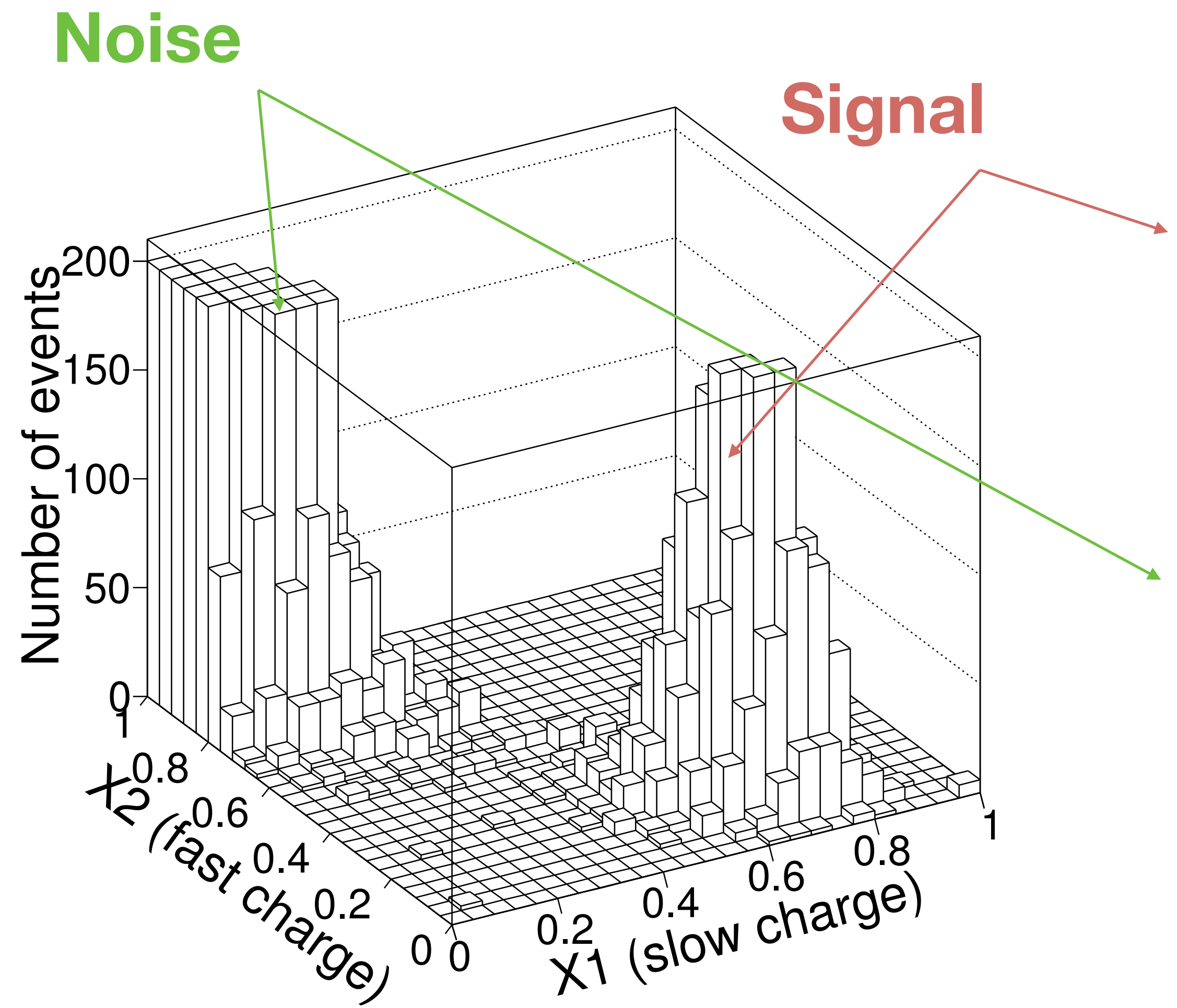
Crystal	Mass (kg)	Size (inches diameter × length)	Powder	α Rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light Yield (PEs/keV)
Crystal-1	8.3	5.0 × 7.0	AS-B	3.20 ± 0.08	43.4 ± 13.7	<0.02	1.3 ± 0.4	14.9 ± 1.5
Crystal-2	9.2	4.2 × 11.0	AS-C	2.06 ± 0.06	82.7 ± 12.7	<0.12	<0.6	14.6 ± 1.5
Crystal-3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



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

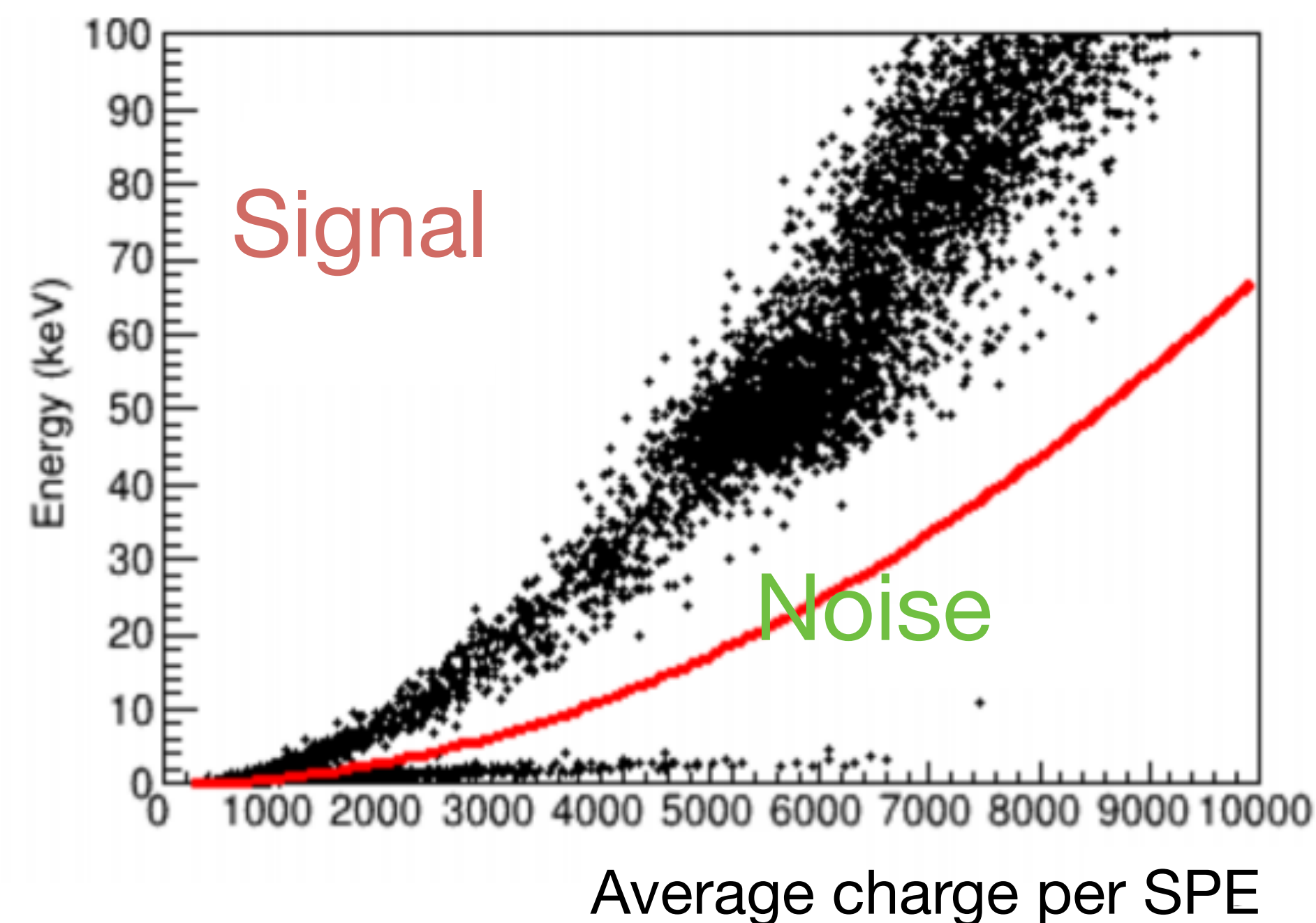
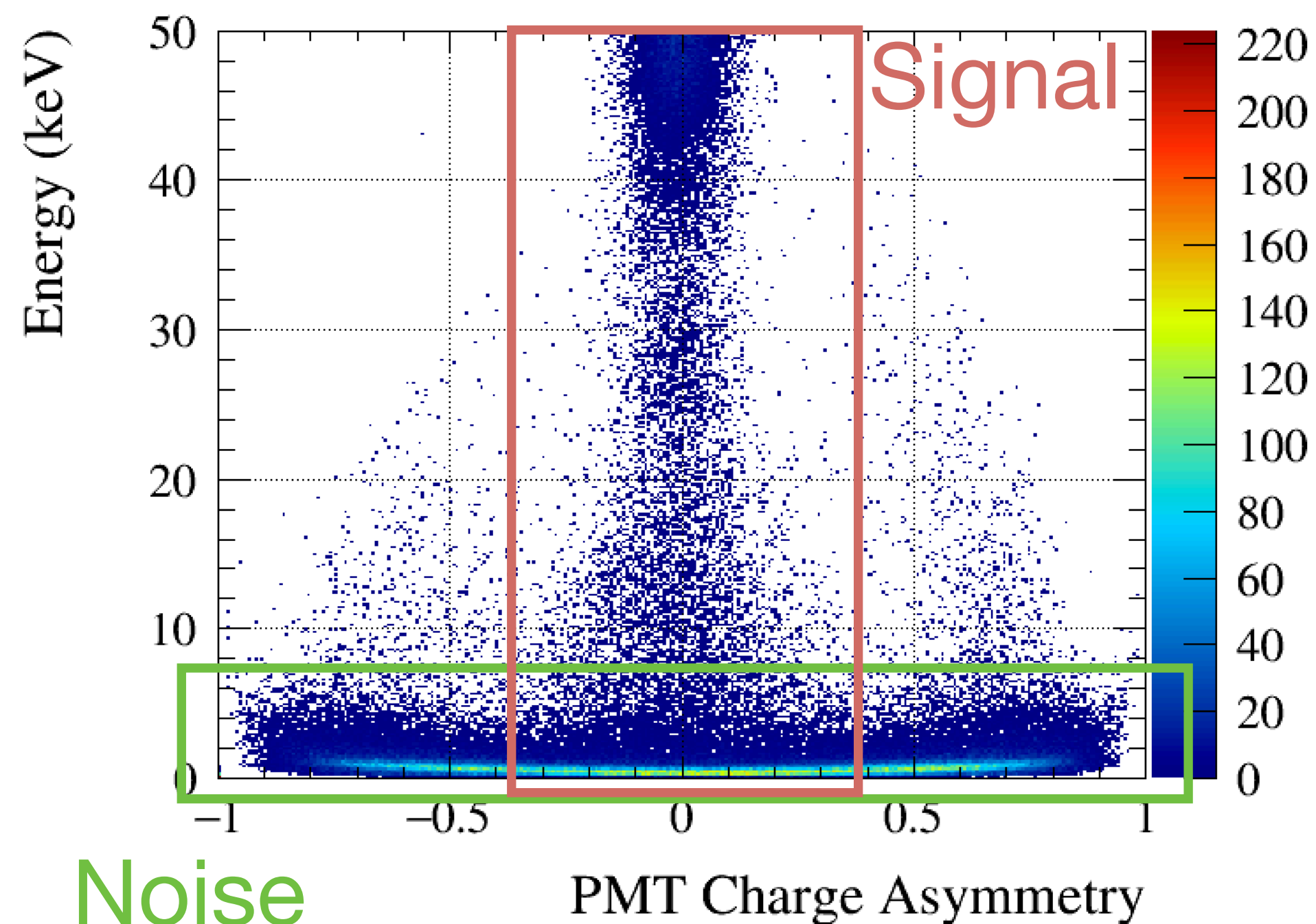
PMT noise rejection: Charge Ratio

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

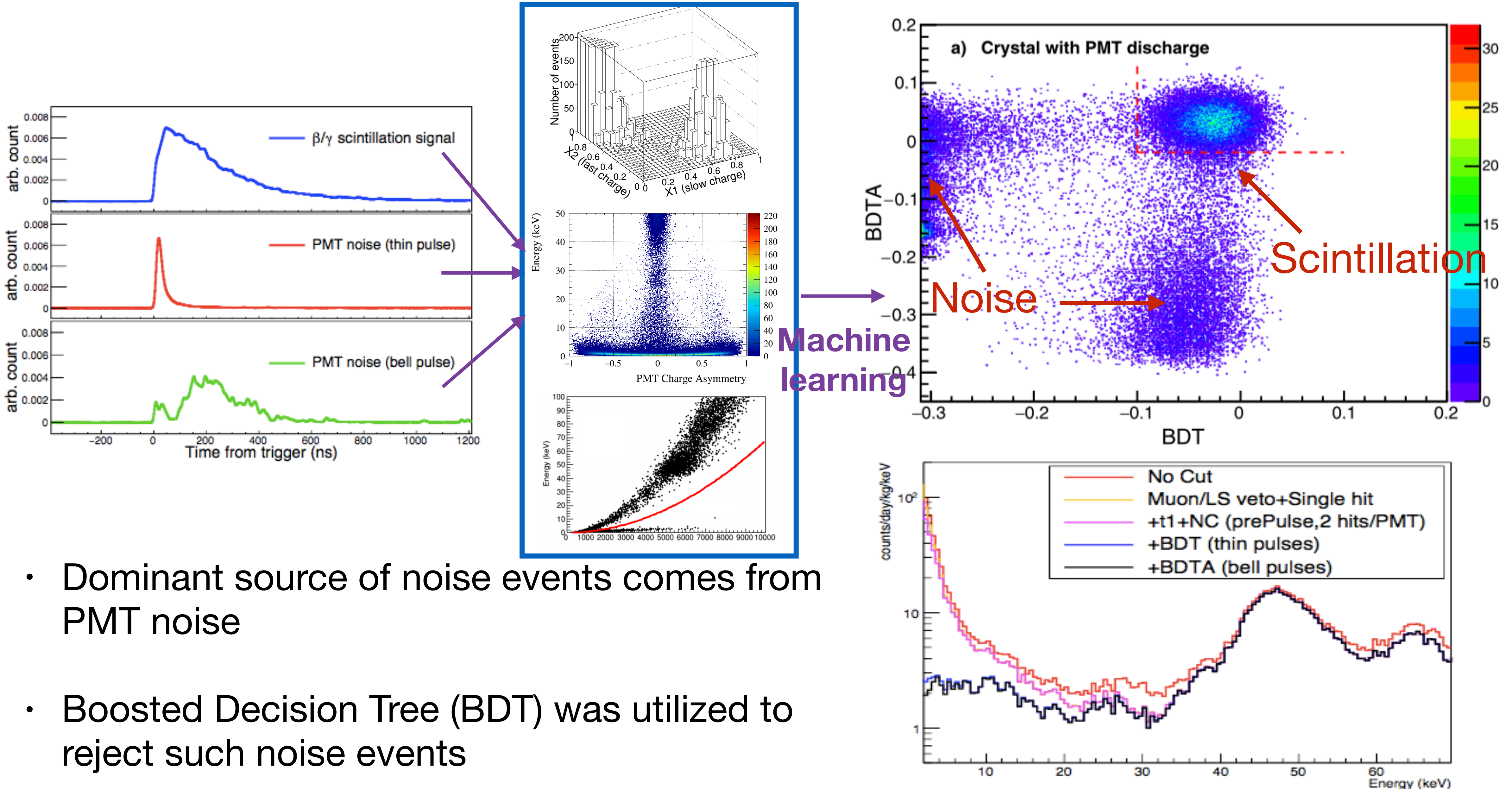


Looking at charge ratio between rising edge and falling edge of a pulse gives good noise separation power

PMT noise rejection: Asymmetry and Charge/Peak



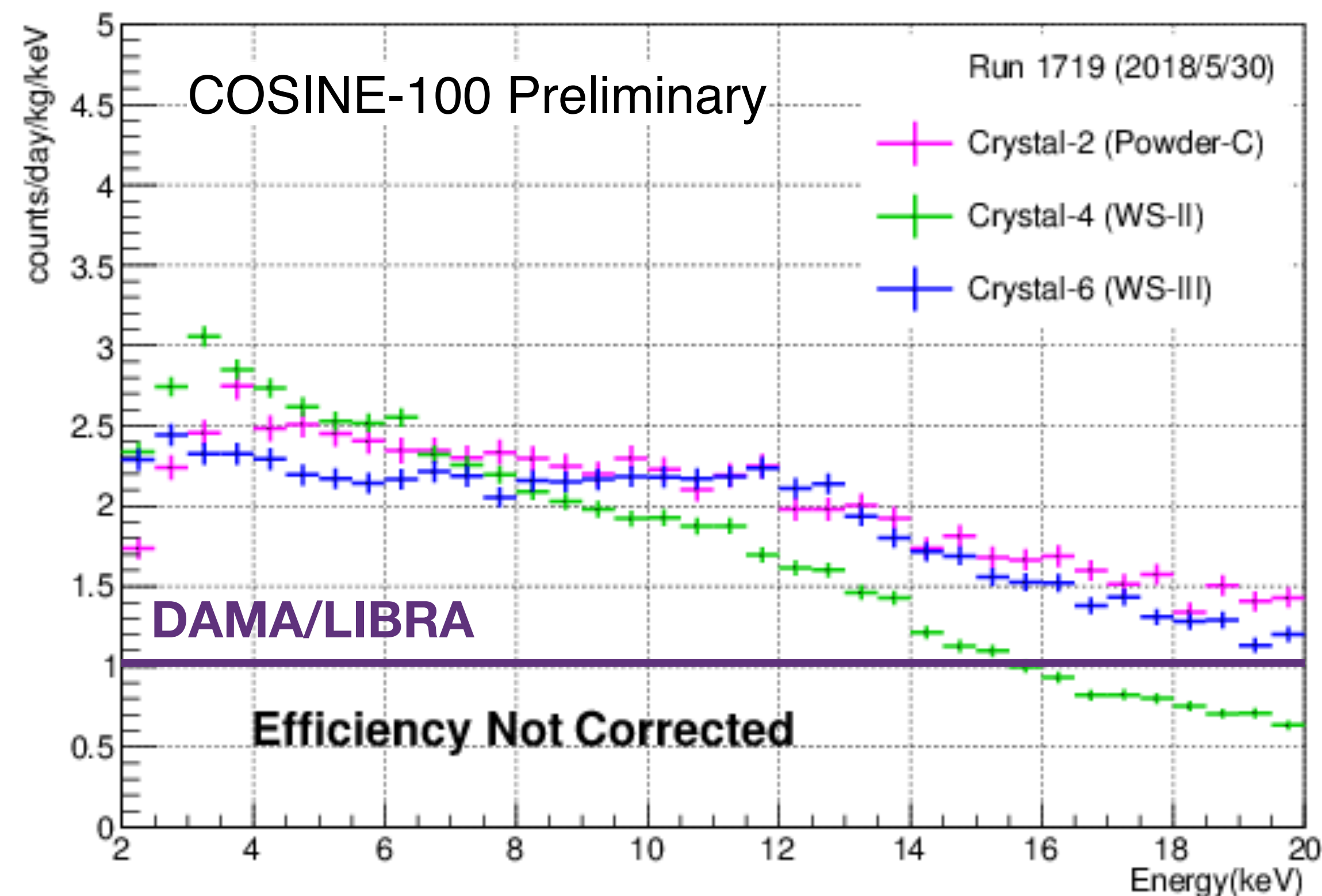
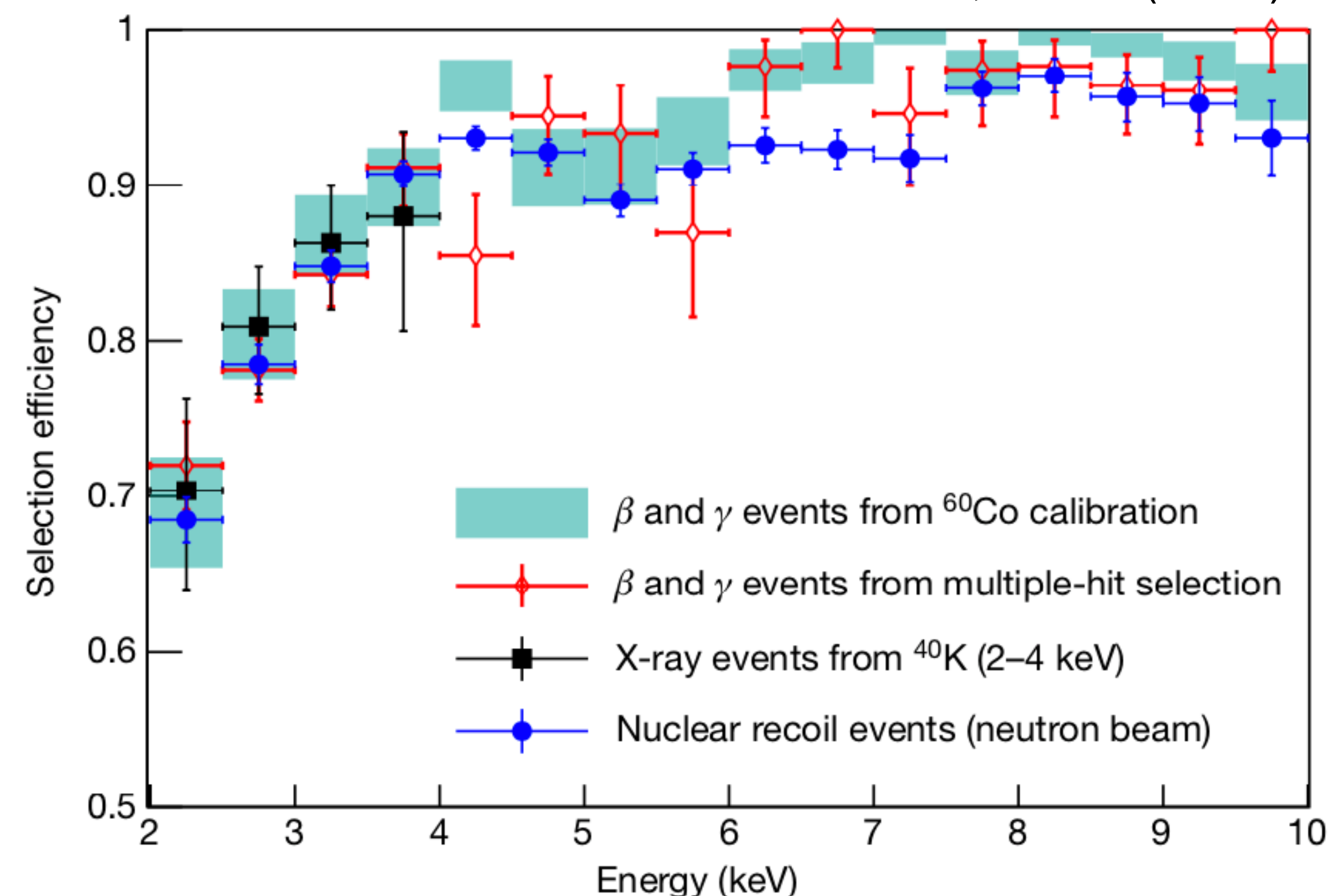
- Additional noise reduction cuts have been developed:
 - Charge asymmetry between 2 PMTs in each crystal
 - Charge/peak: Average charge per SPE



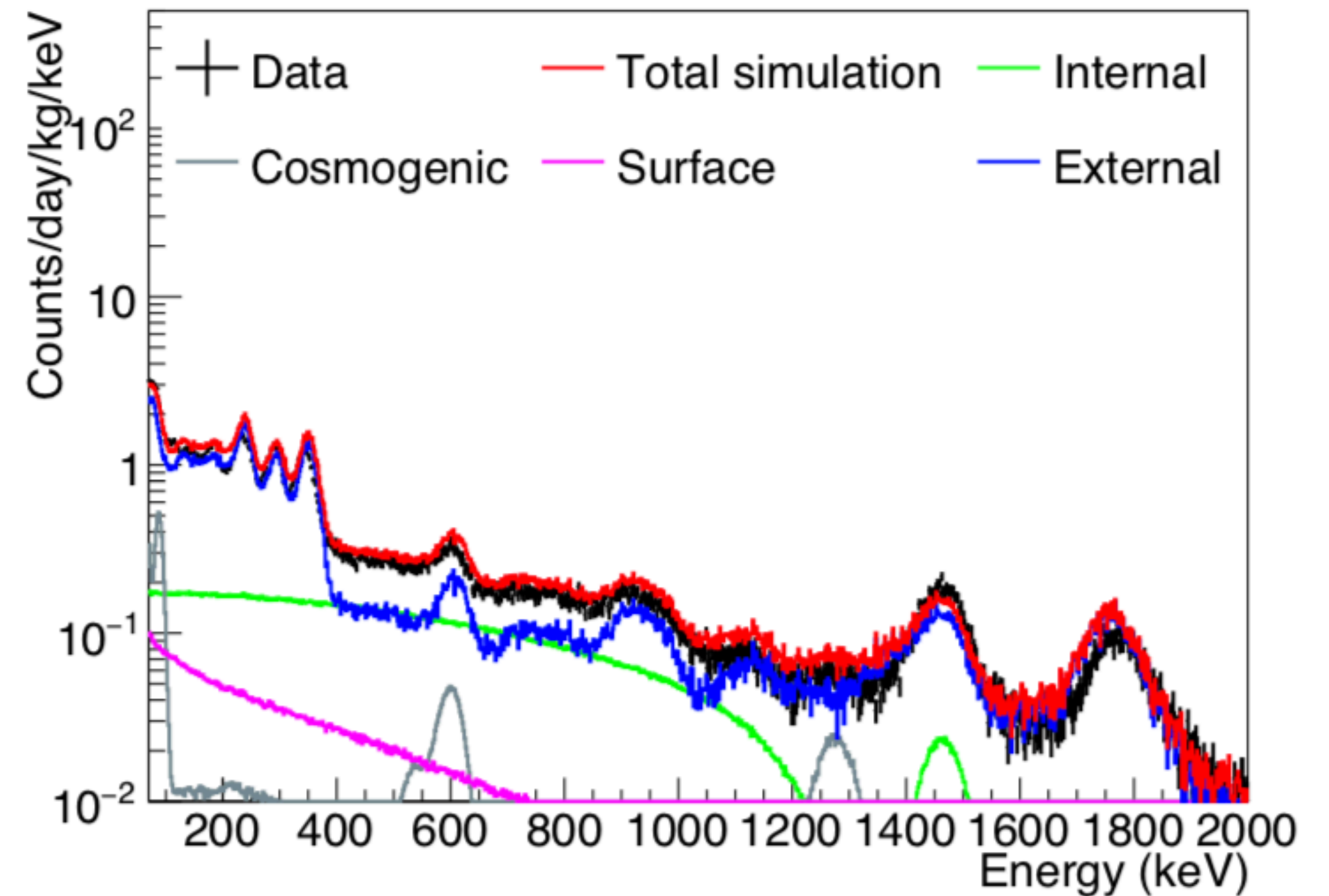
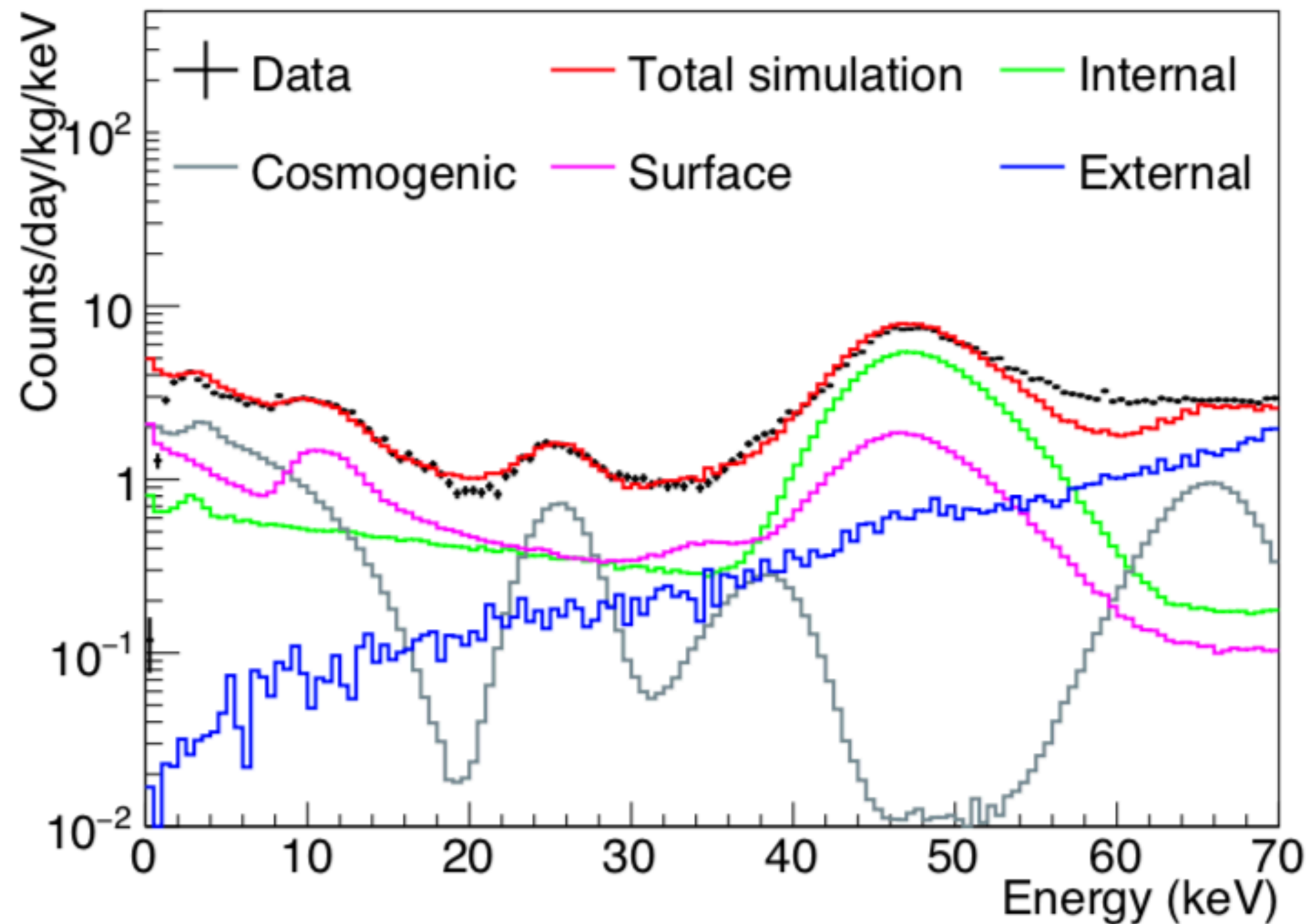
- Dominant source of noise events comes from PMT noise
- Boosted Decision Tree (BDT) was utilized to reject such noise events

Selection efficiency/Low energy spectrum

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

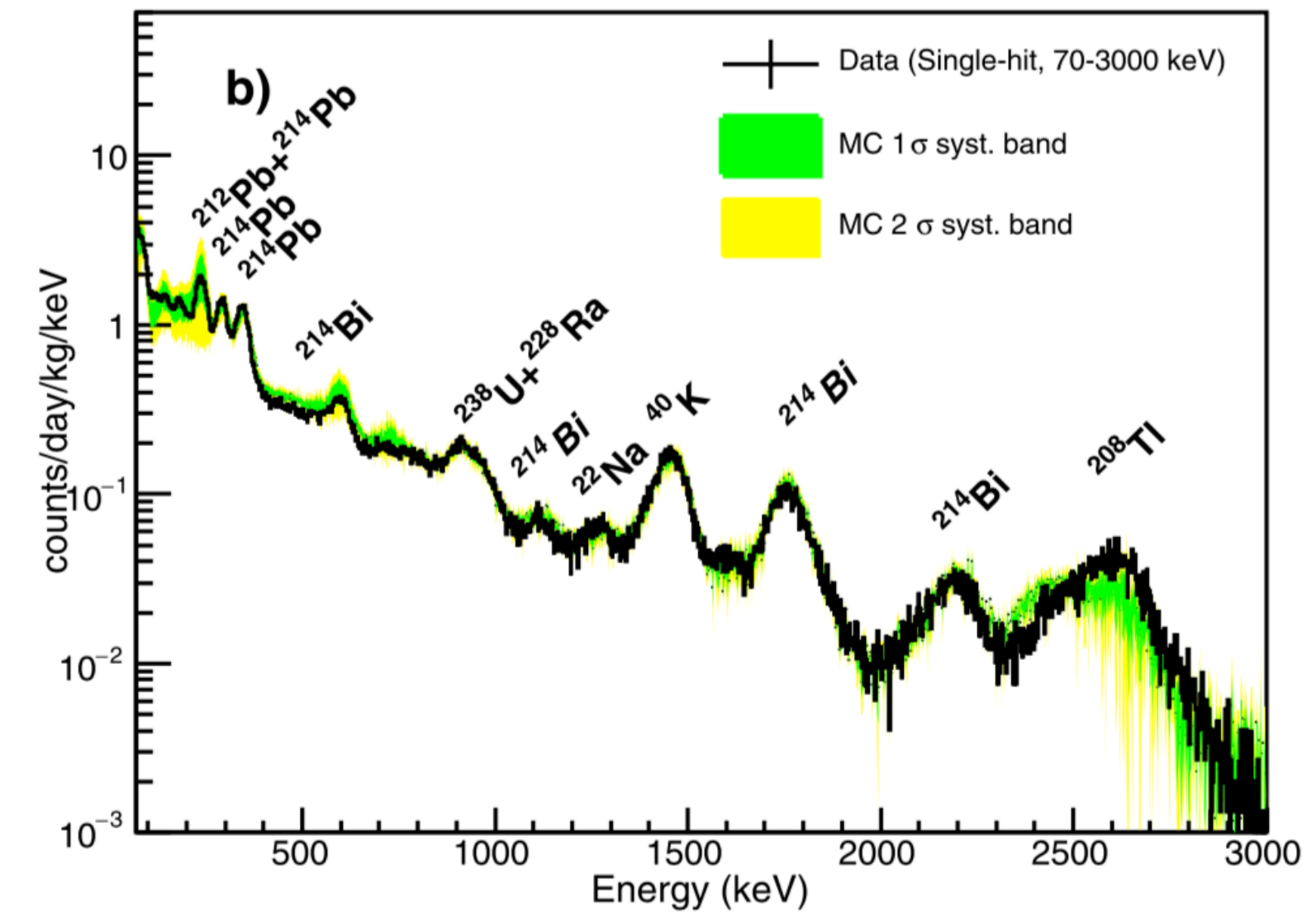
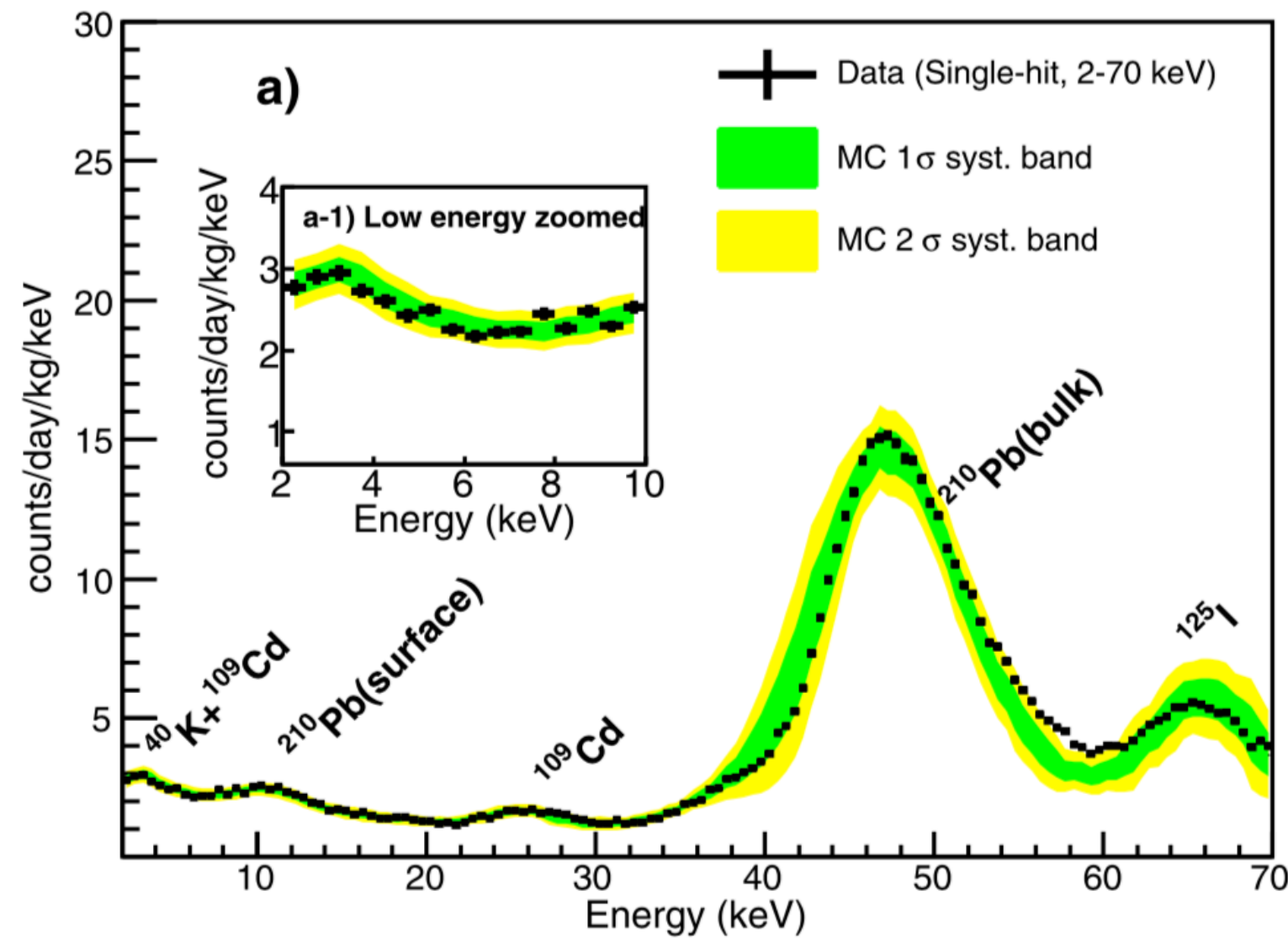


- ~70% efficiency at 2 keV
- 2 - 4 counts/keV/kg/day in region of interest depending on the crystal

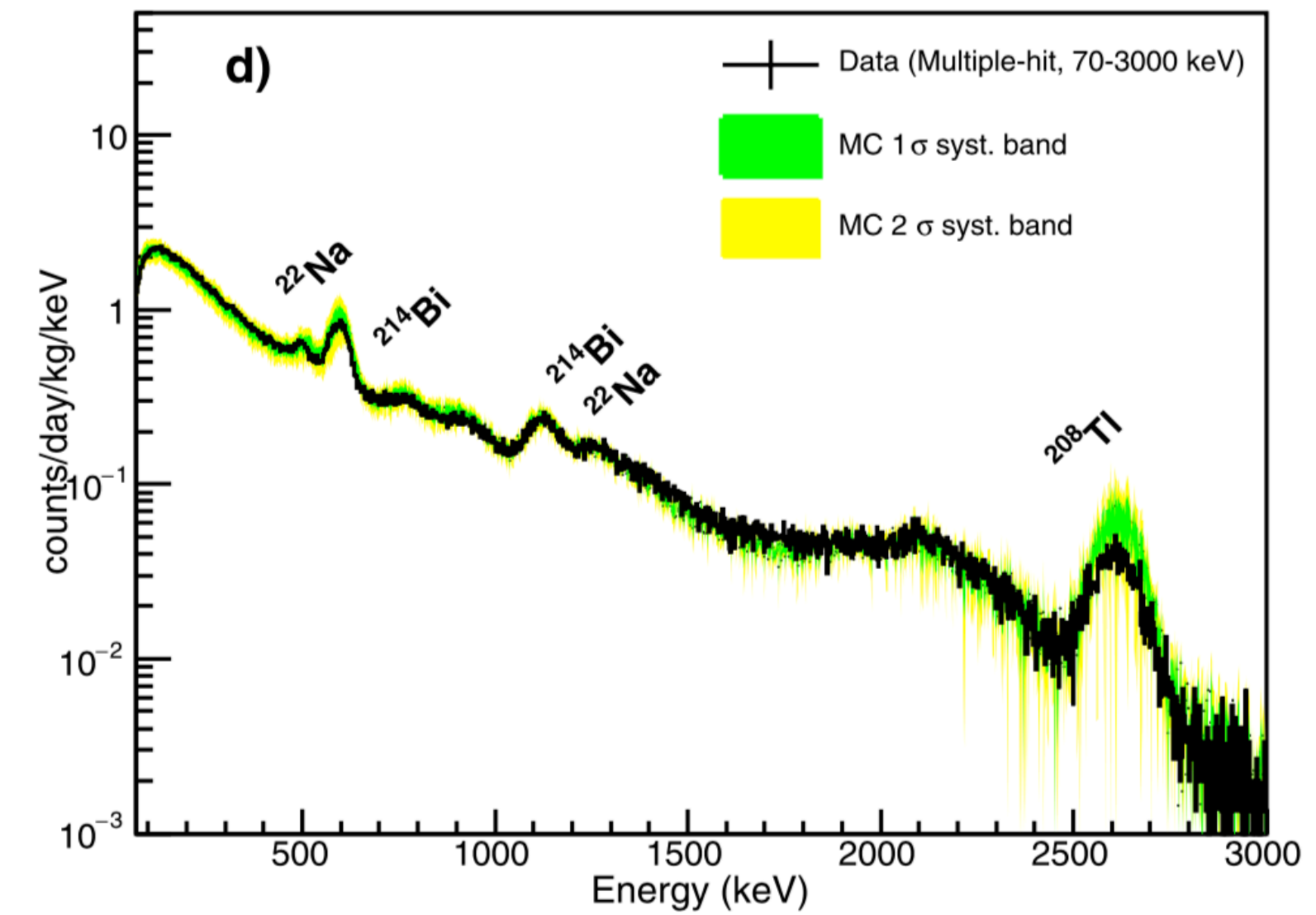
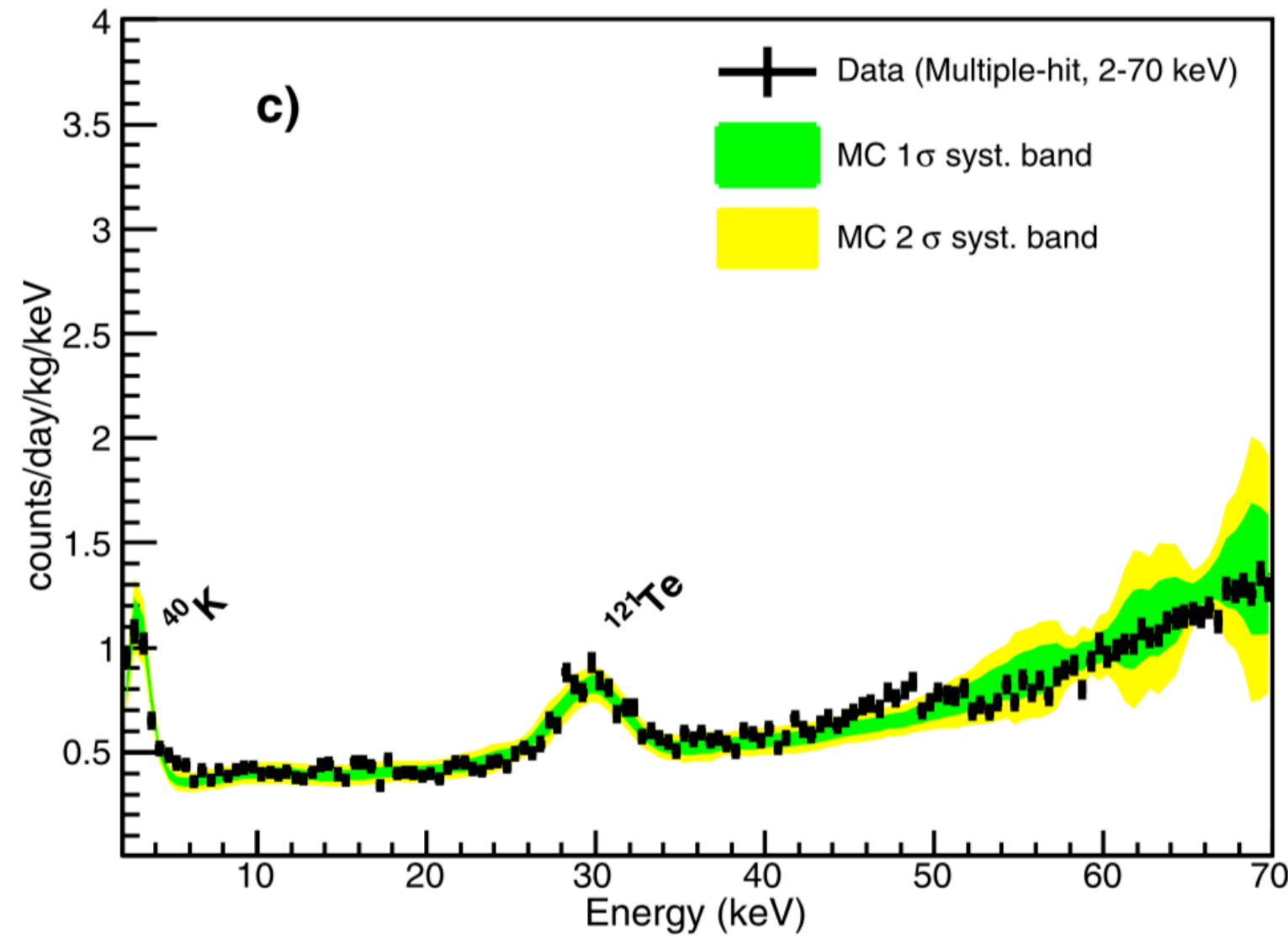


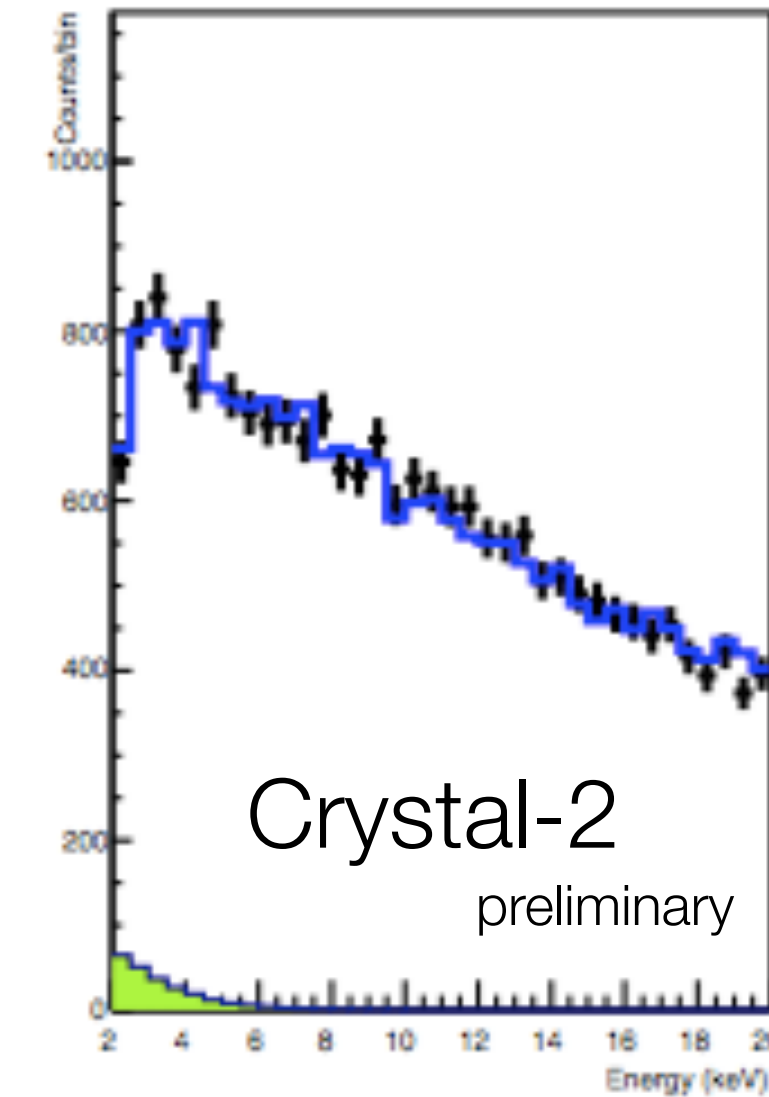
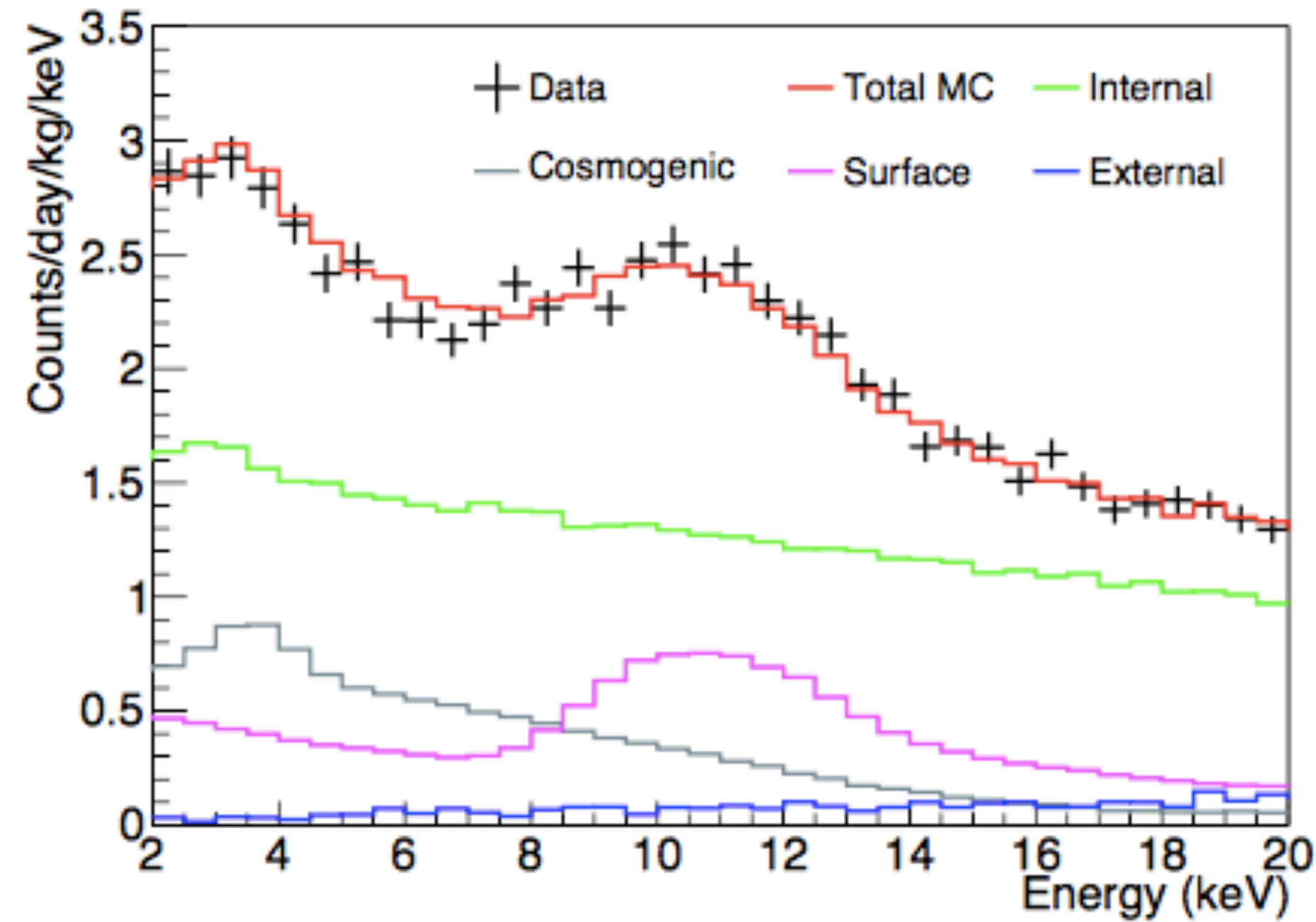
- Data reproduced well with Geant4 simulation
- **Background well understood from 2 keV - 2000 keV**
- Dominant background from ^{210}Pb (internal, surface) and ^{40}K (internal), followed by cosmogenic ^3H

Single-hit

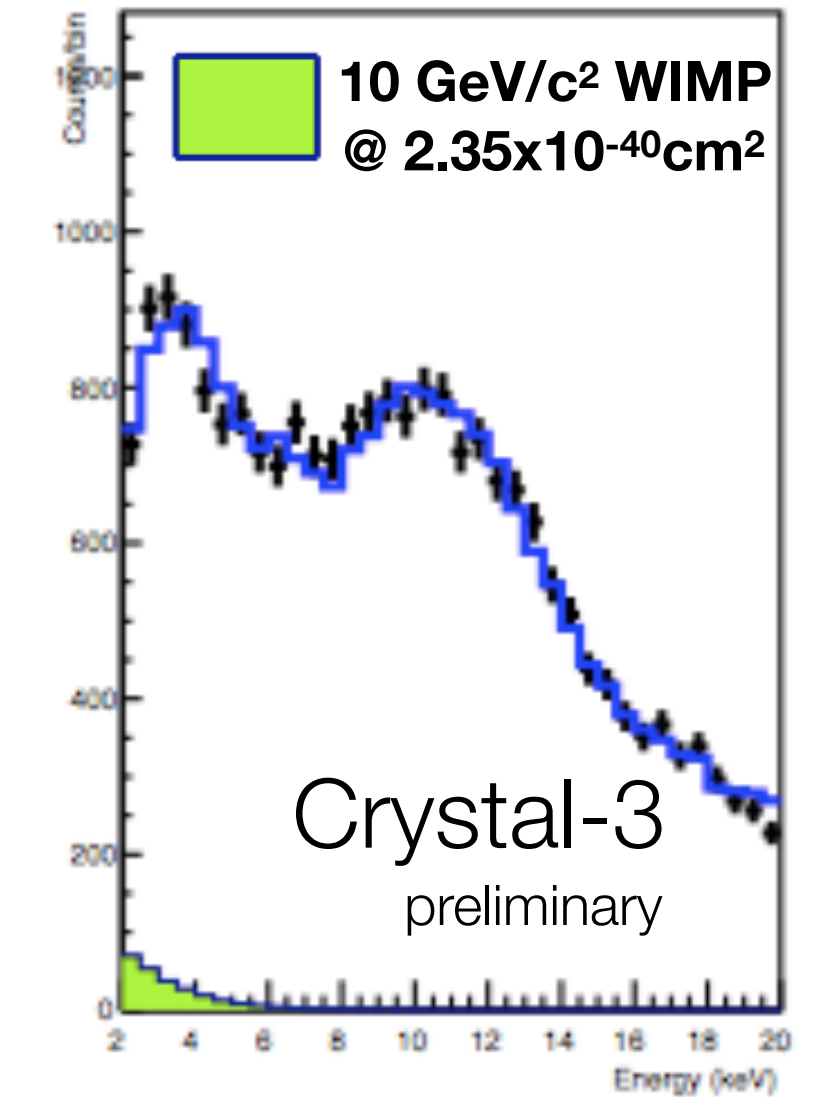


Multiple-hit

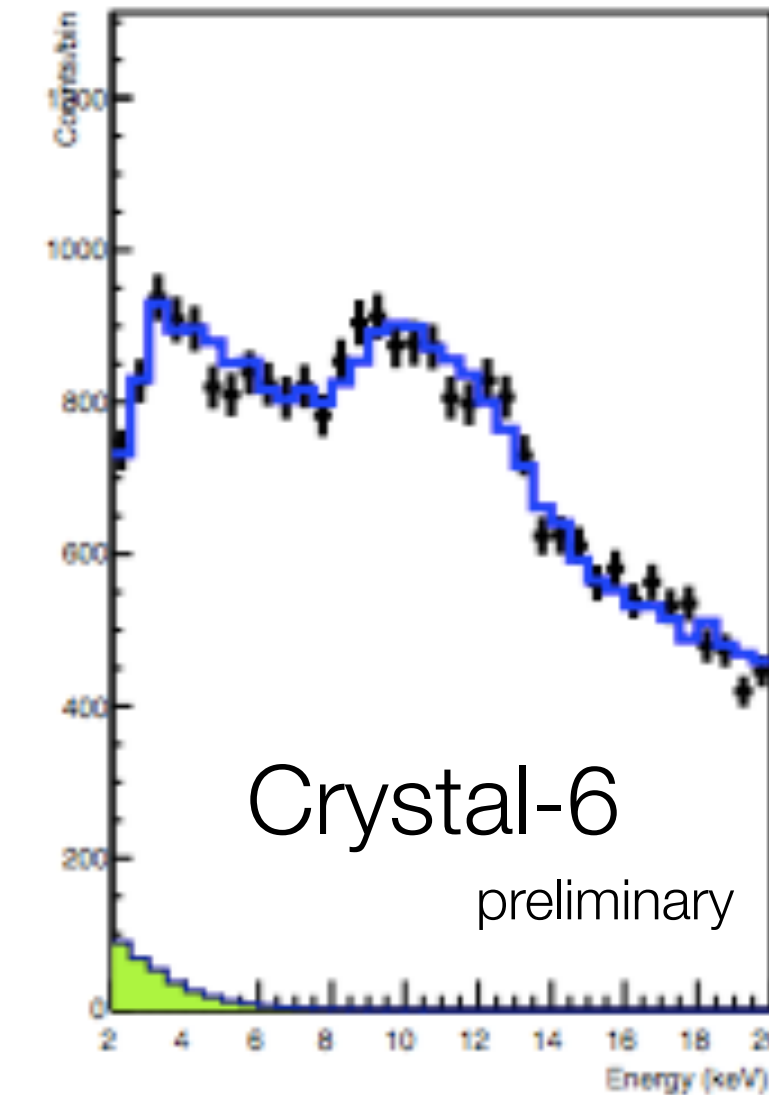




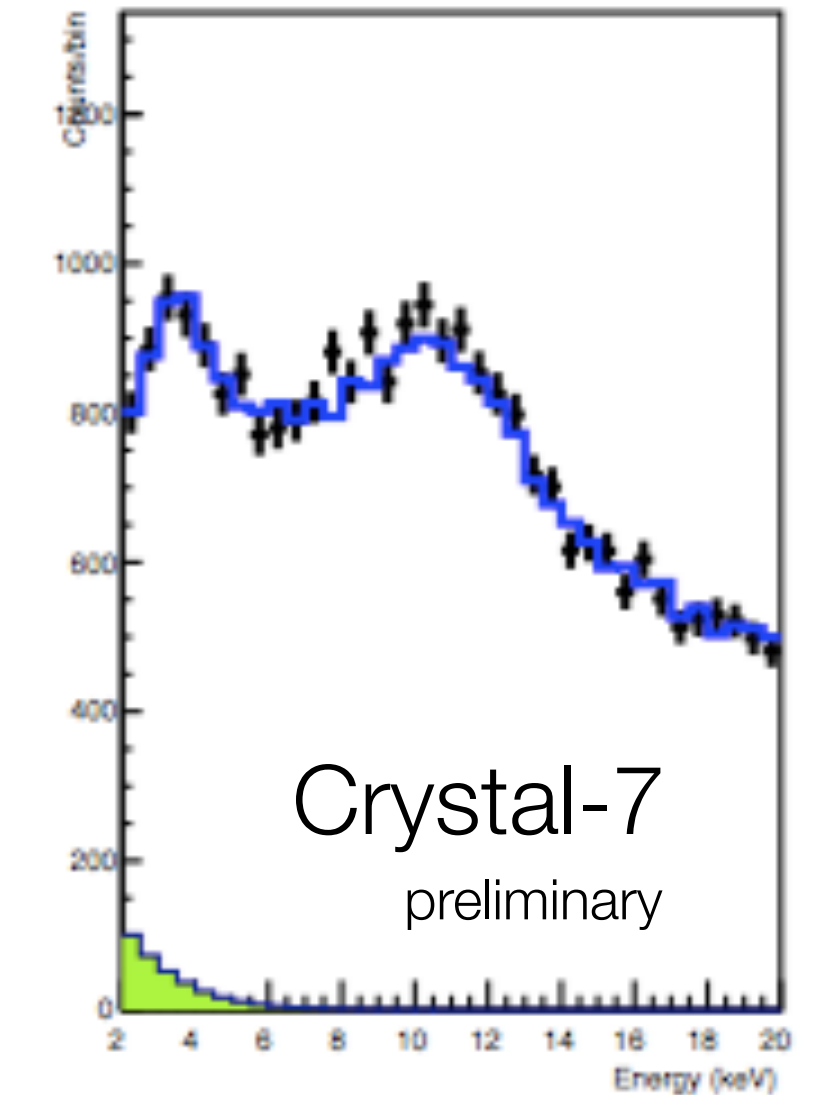
C6_Data_Spectrum



C7_Data_Spectrum



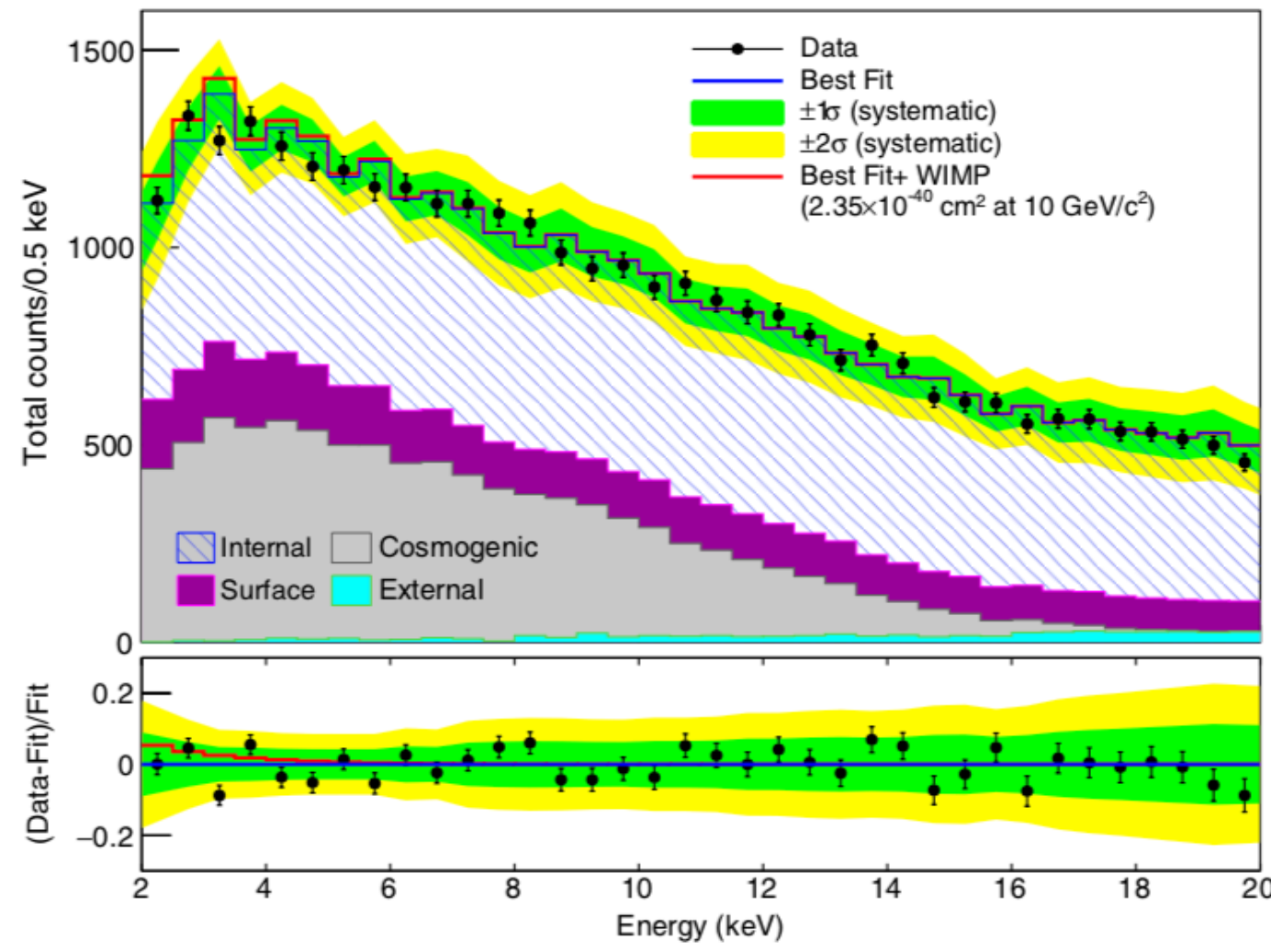
Crystal-6 preliminary



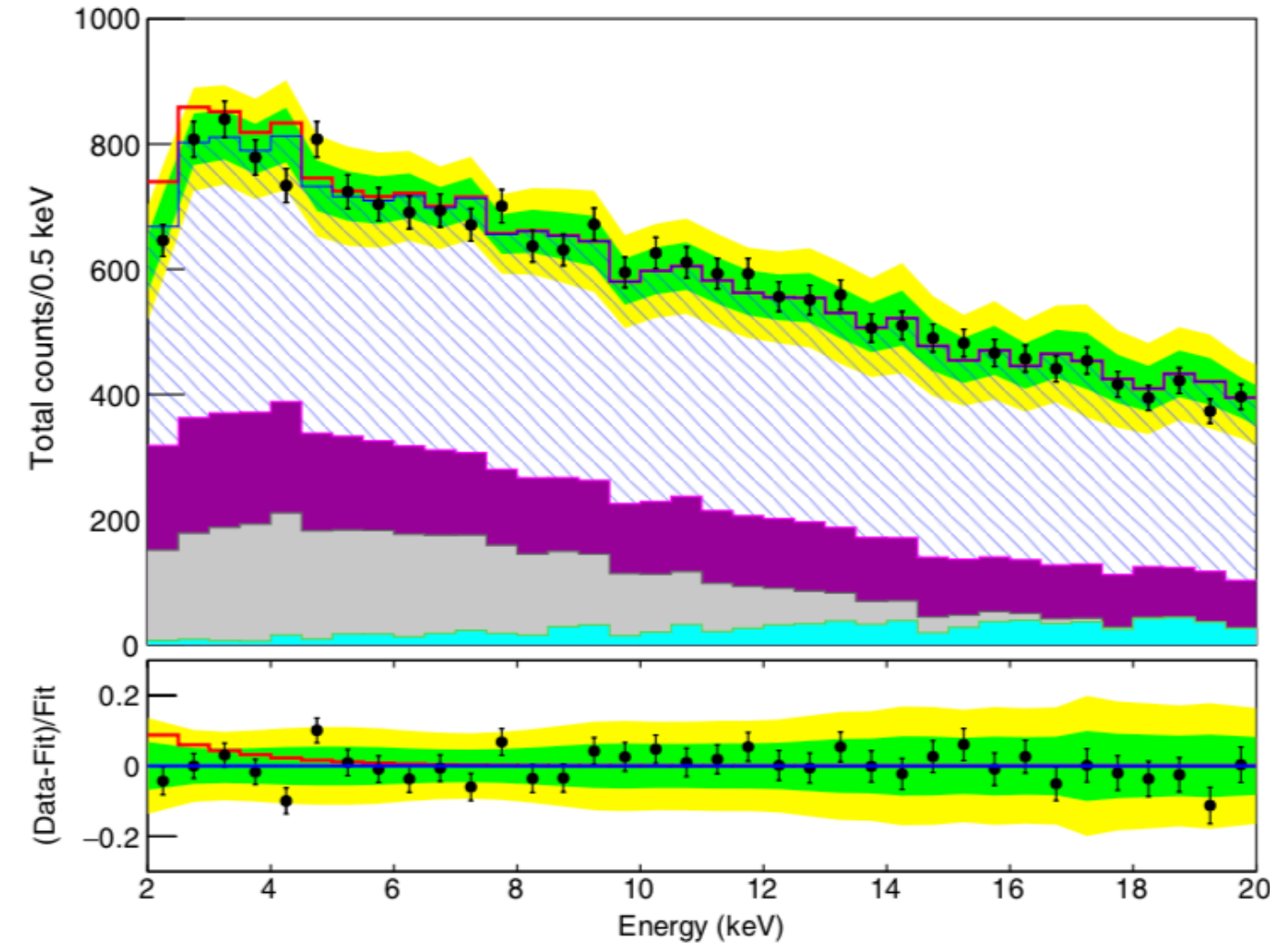
Crystal-7 preliminary

10 GeV/c² WIMP
@ 2.35x10⁻⁴⁰cm²

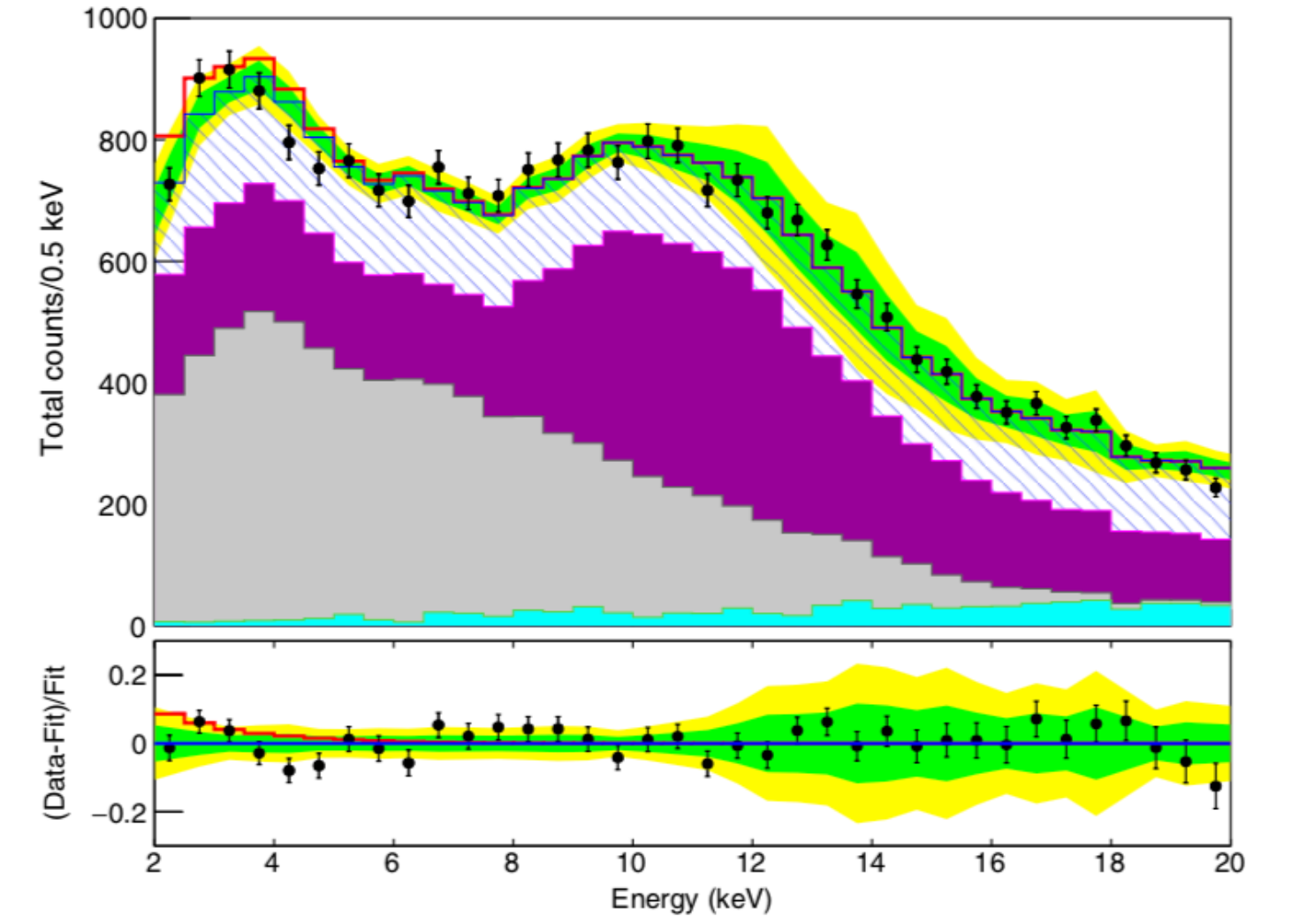
- Using 59.5 days of data: 6303.9 kg day exposure
- Spectrum fit for 2-20 keV including WIMP model
- Likelihood analysis to fit data using background model and WIMP signal model (SHM as described in Savage *et al.*, JCAP 0904:010, 2009)
- Background understanding consideration from V. Kudryavtsev *et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



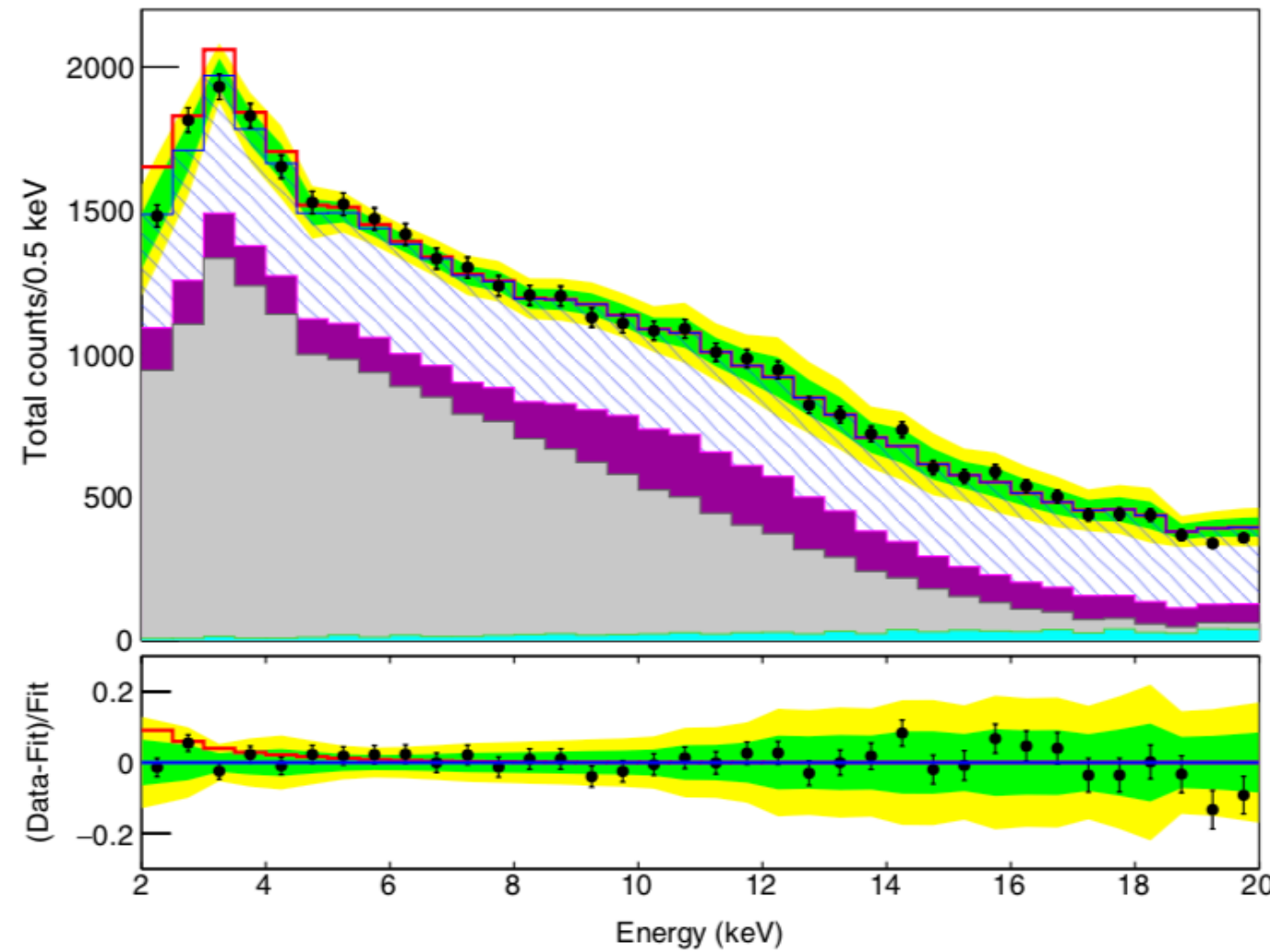
a) Crystal 1



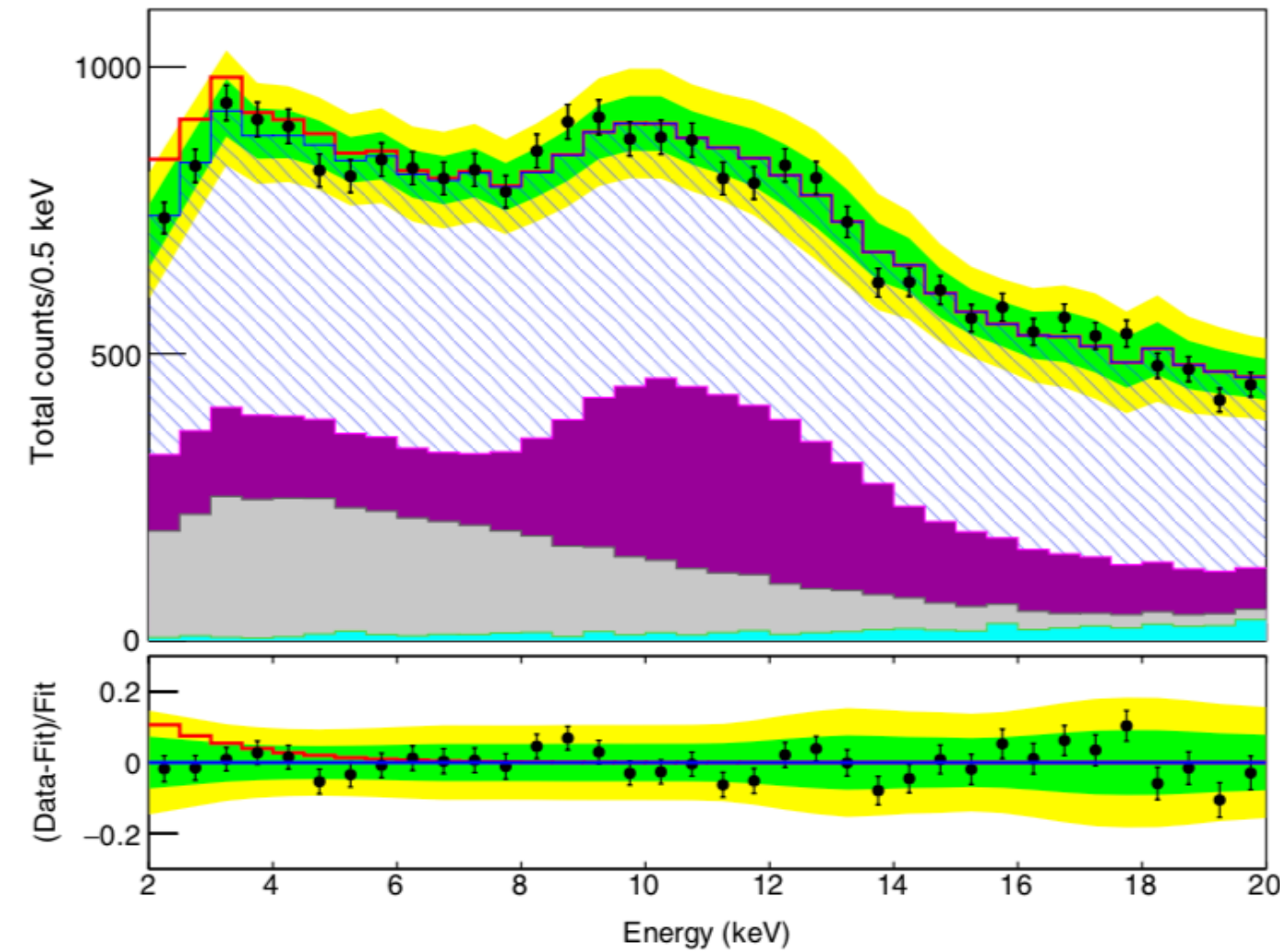
b) Crystal 2



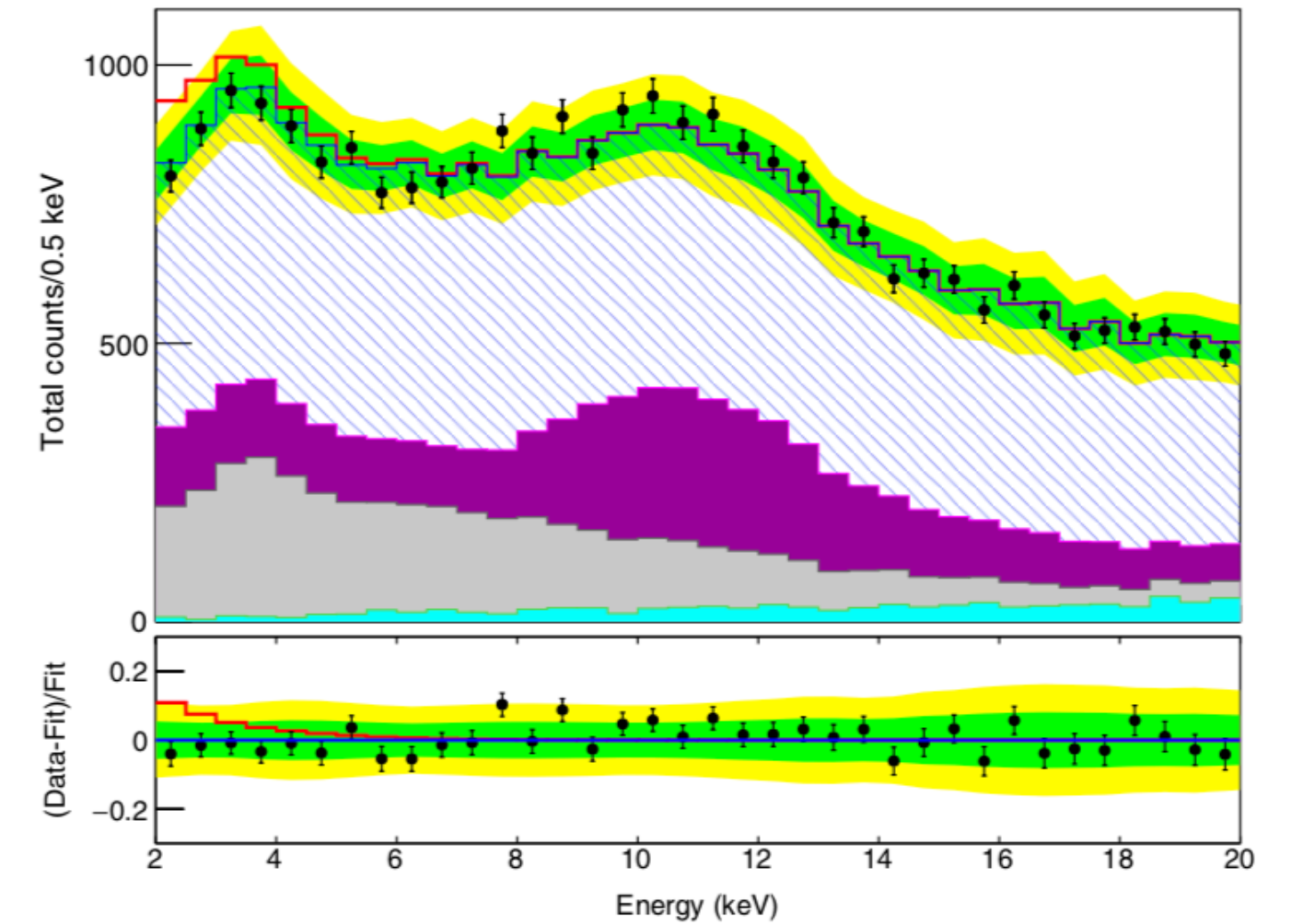
c) Crystal 3



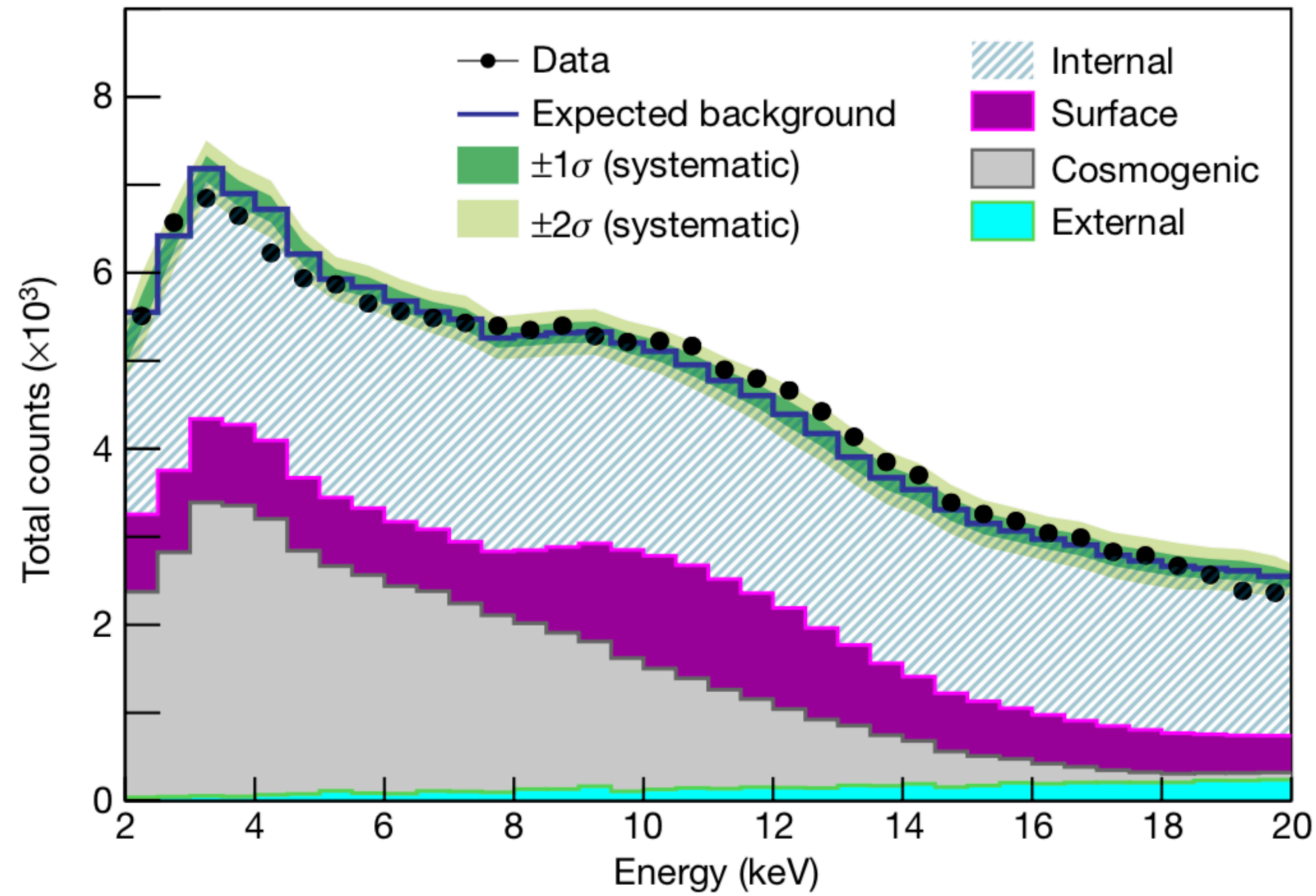
d) Crystal 4



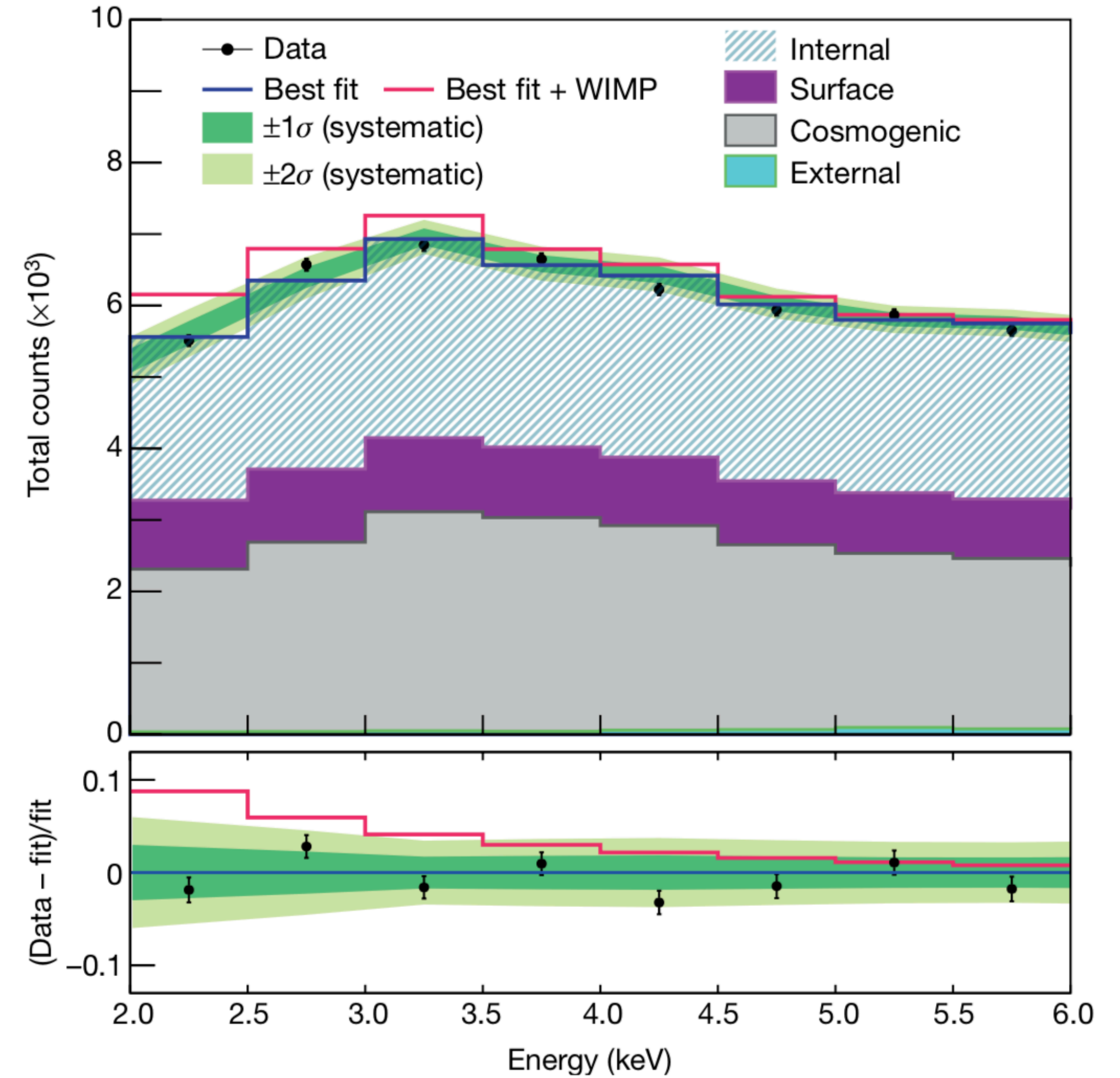
e) Crystal 6



f) Crystal 7



Measured and simulated energy spectra, summed for the six crystals

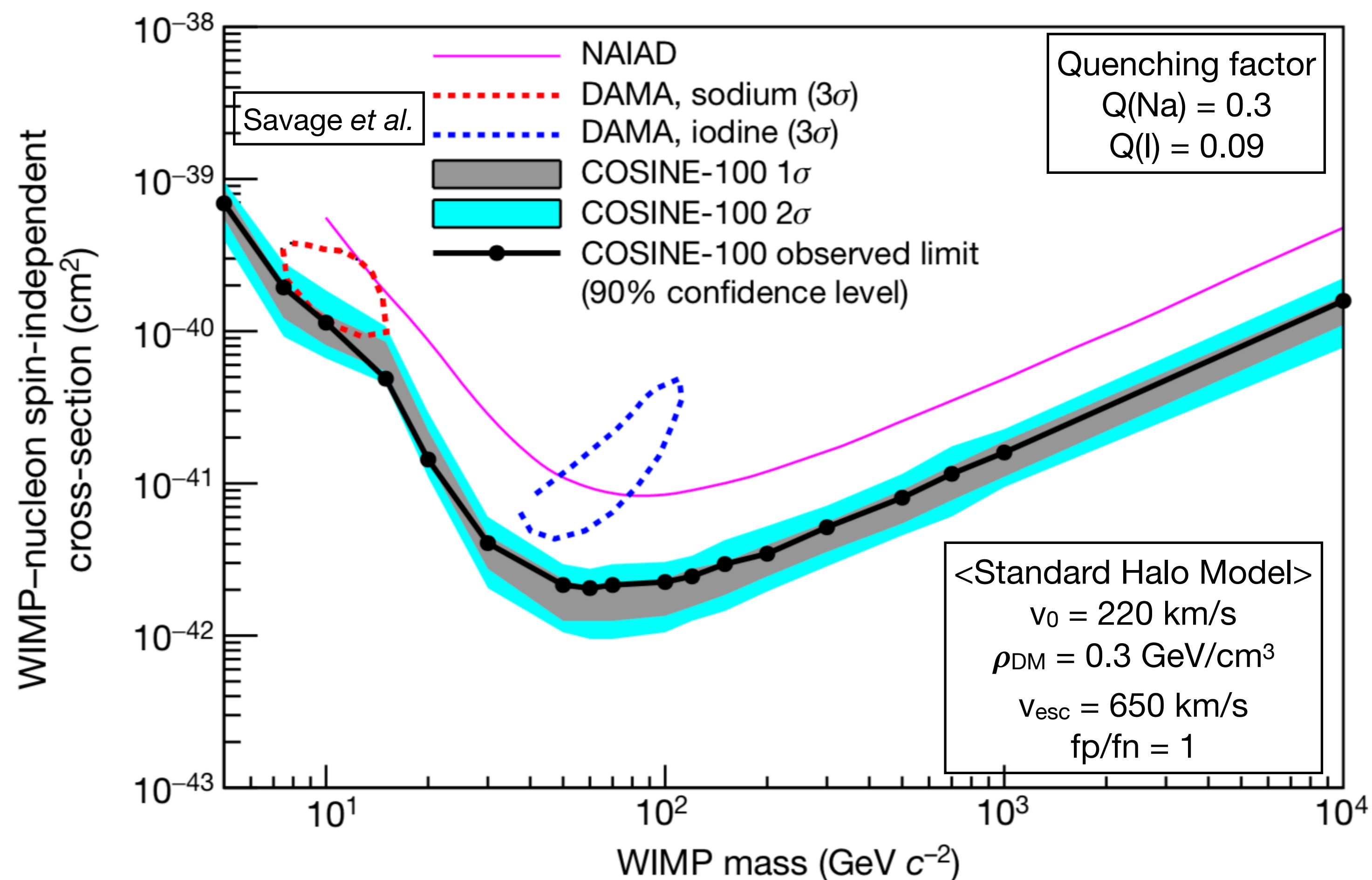


Fit result for a WIMP mass of $10 \text{ GeV } c^{-2}$, summed for the six crystals

Physics analysis: WIMP analysis

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

- 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



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

So...is DAMA dead? Quotes from DAMA

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A controversial sighting of dark matter is looking even shakier

The COSINE-100 experiment finds no evidence of the evasive subatomic particles
BY EMILY CONOVER 1:00PM, DECEMBER 5, 2018

DAMA DRAMA The COSINE-100 dark matter detector (pictured) found no signs of the mysterious subatomic particles interacting in sodium iodide crystals, casting doubt on the earlier DAMA experiment.

JAY HYUN JO

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The COSINE-100 detector was built to reproduce a controversial claim of the detection of dark matter. JAY HYUN JO

Underground experiment casts doubt on controversial dark matter claim

By Adrian Cho | Dec. 5, 2018, 1:40 PM

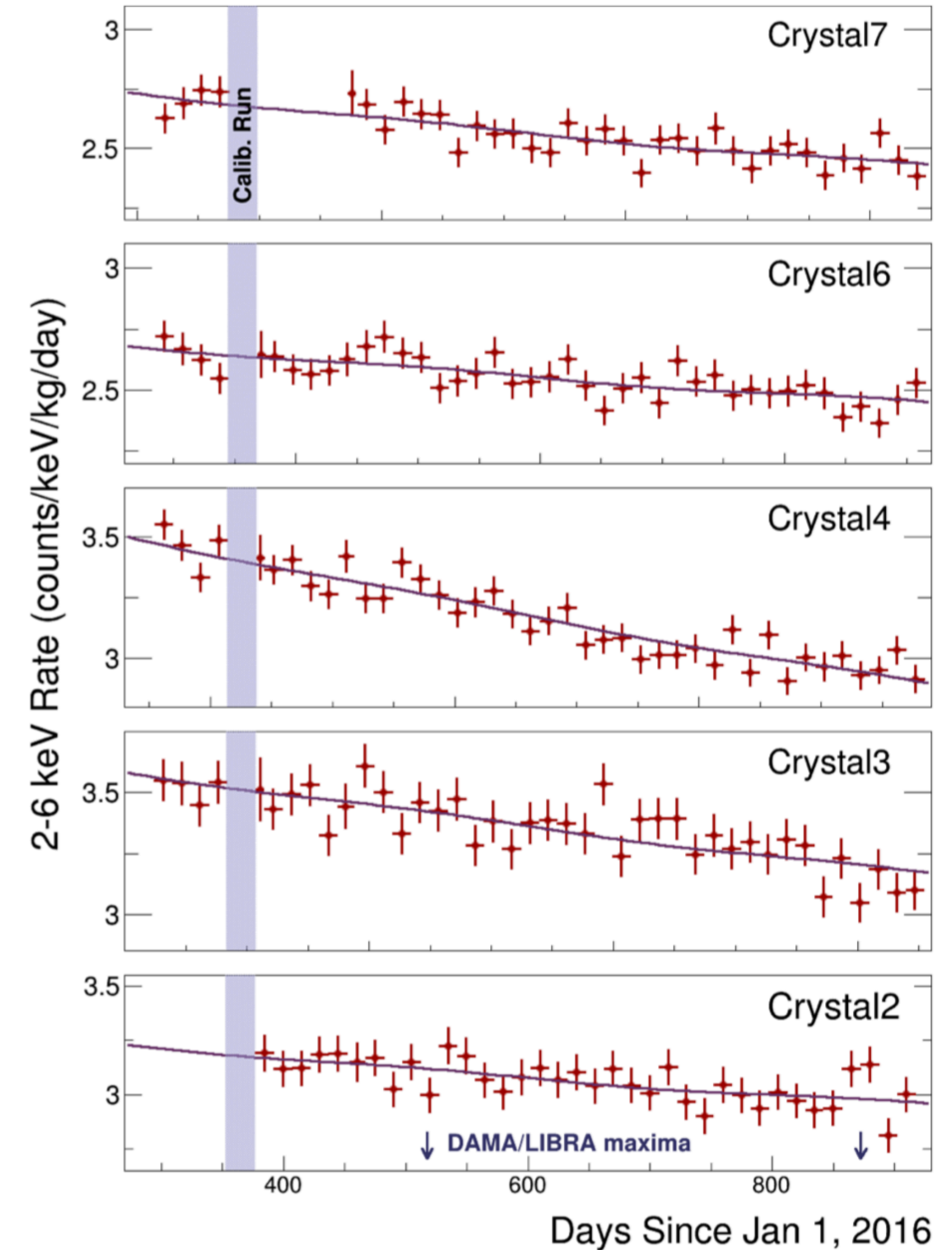
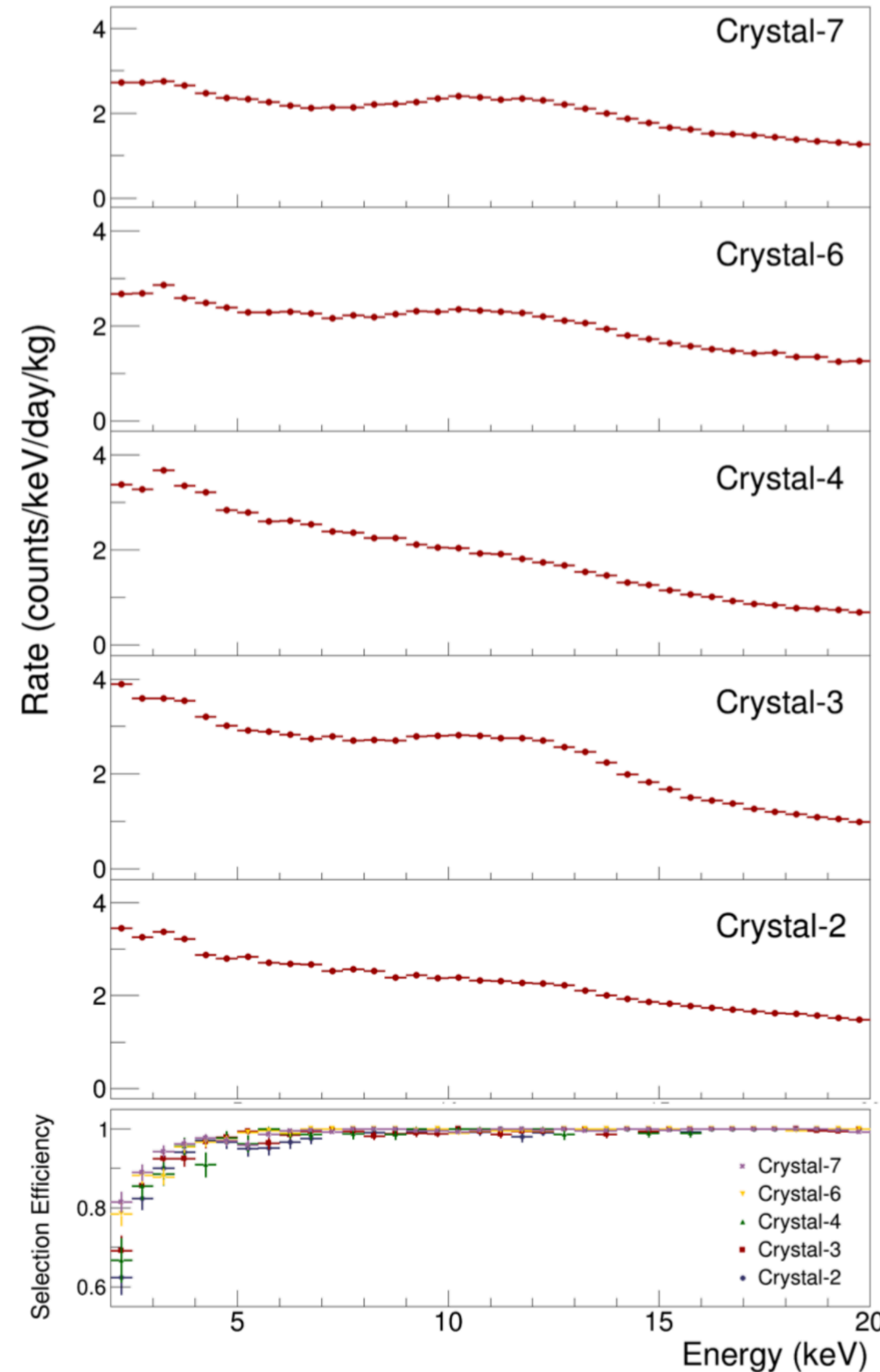
“COSINE-100 has no impact on the long-standing results obtained with the DAMA setups” - R. Bernabei

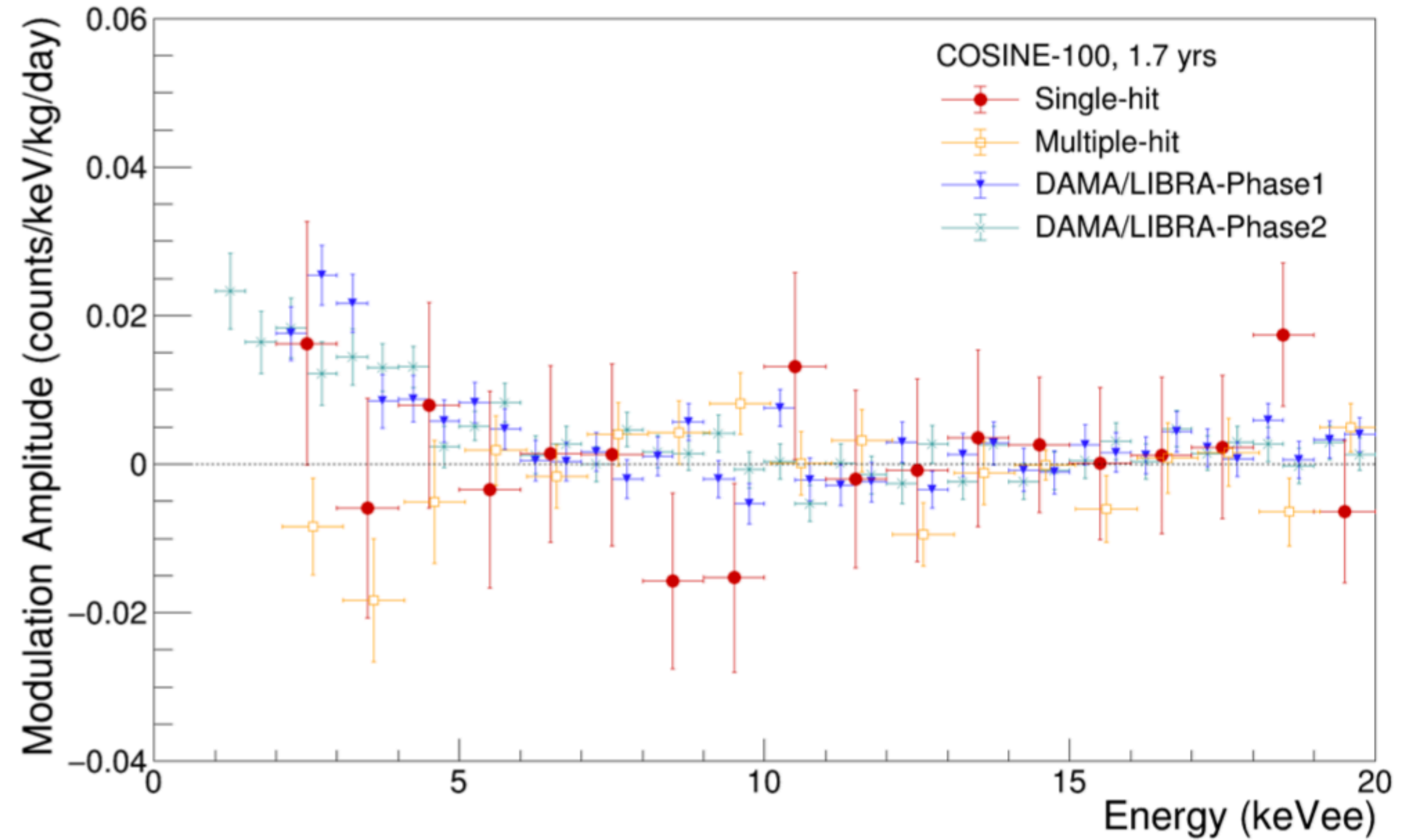
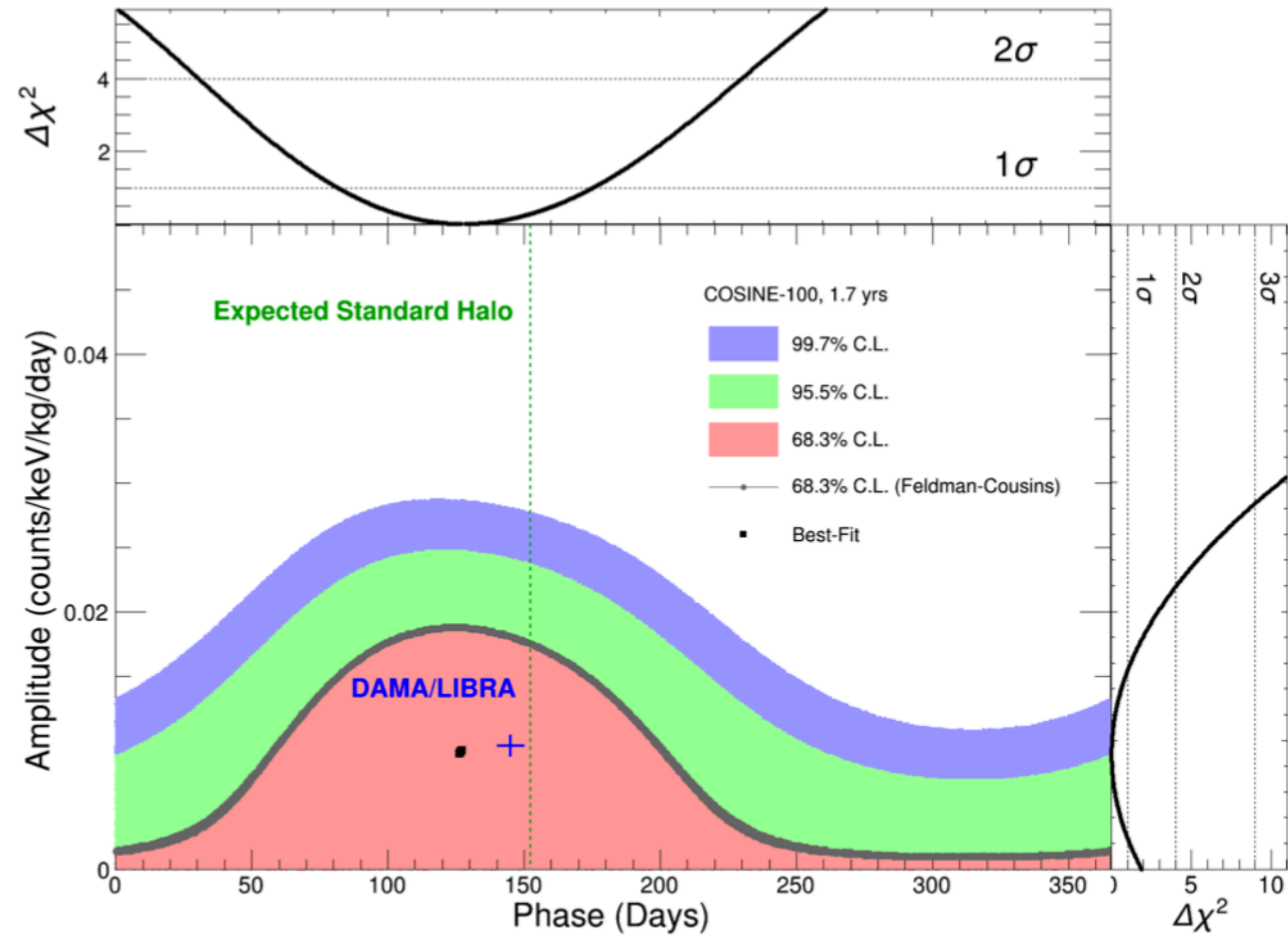
... But Bernabei says the test is too weak to do that. “The modeling of a background is a quite uncertain procedure and at low energy is in general not reliable”

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

1.7 yrs, 97.7 kg yrs exposure

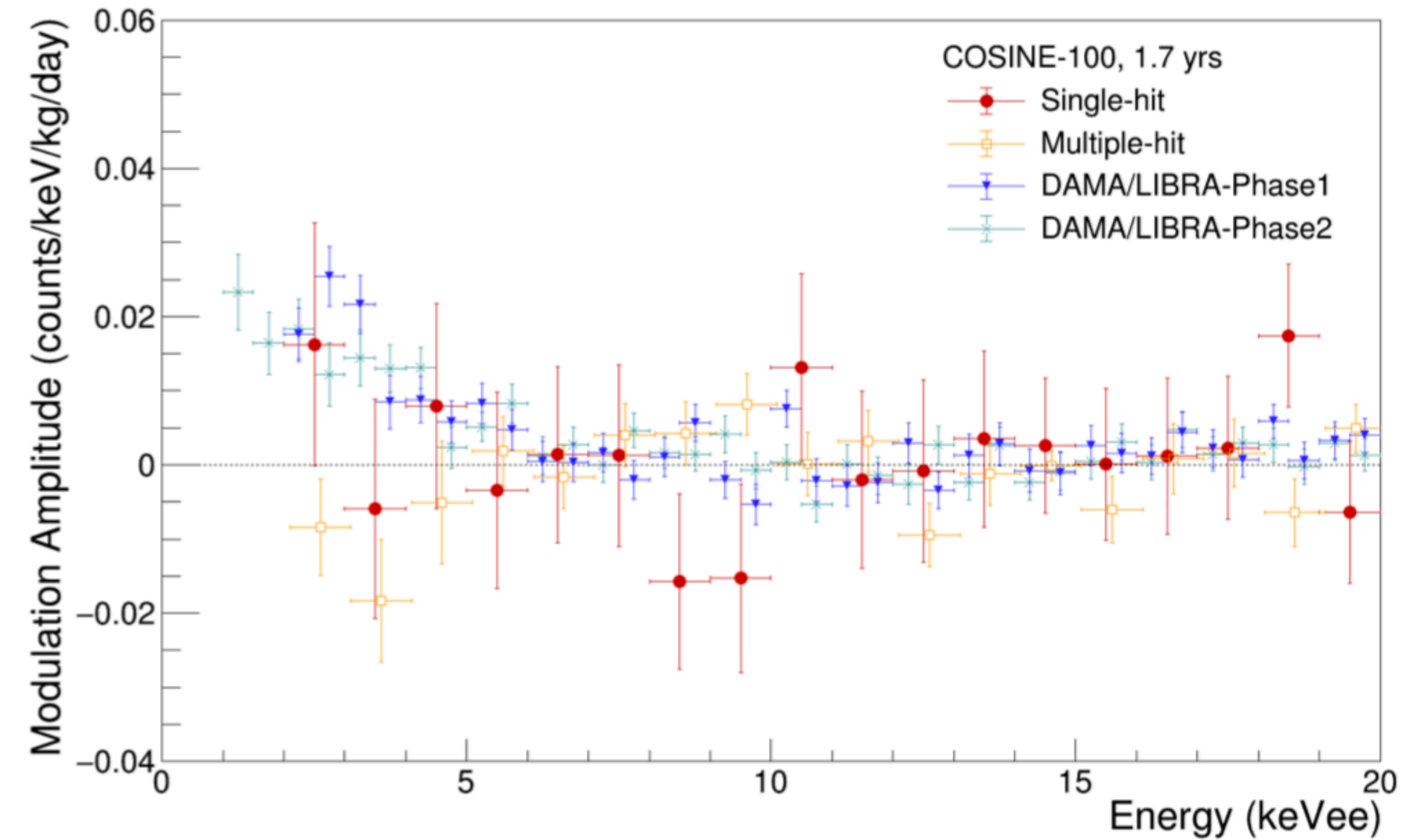
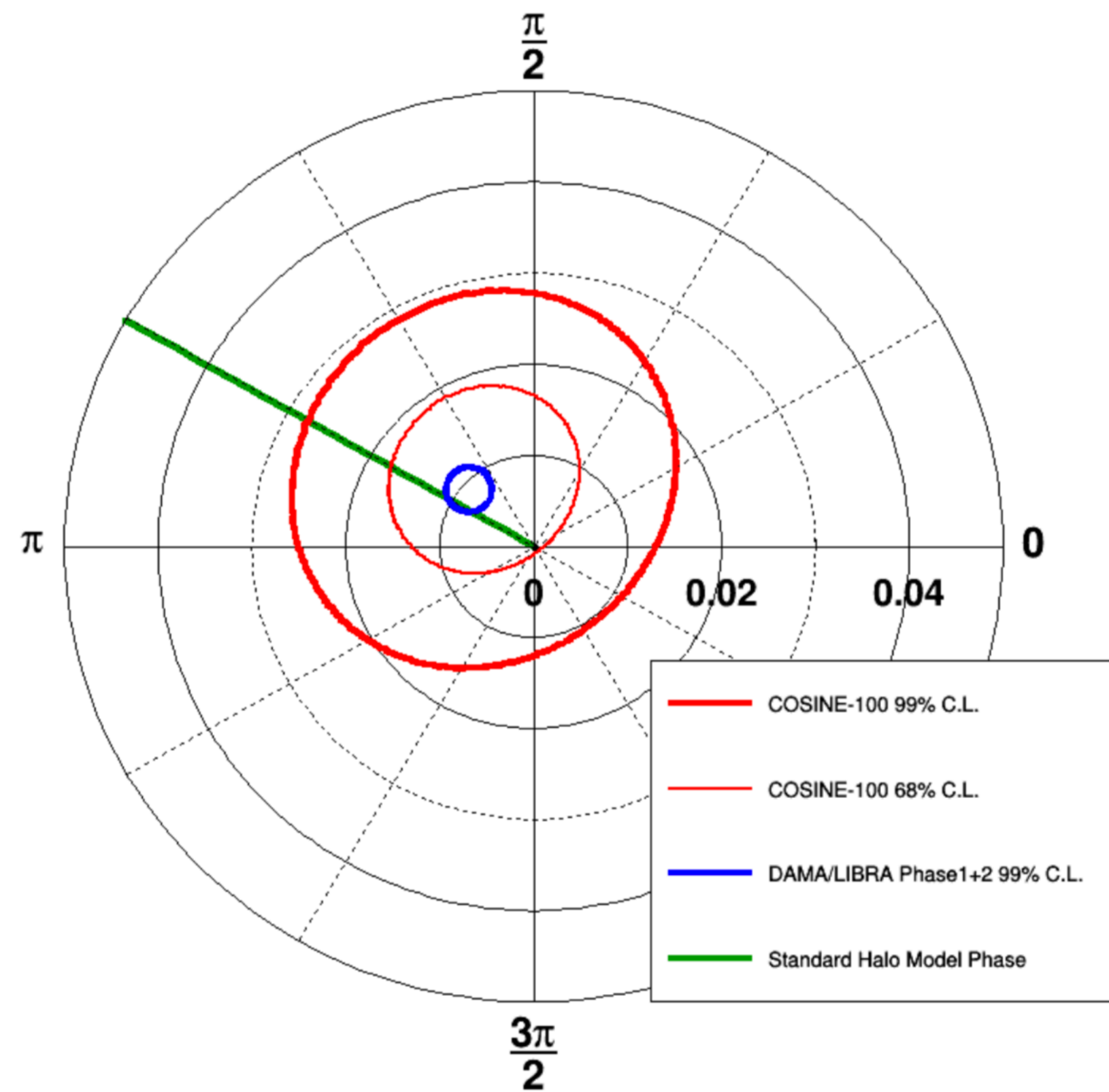
- Global fit using cosmogenic and sinusoidal components simultaneously for crystals
- Crystal-1, 5, and 8 excluded in this analysis due to low light yield and excessive PMT noise
- Sideband events decrease exponentially, agrees with known cosmogenic components





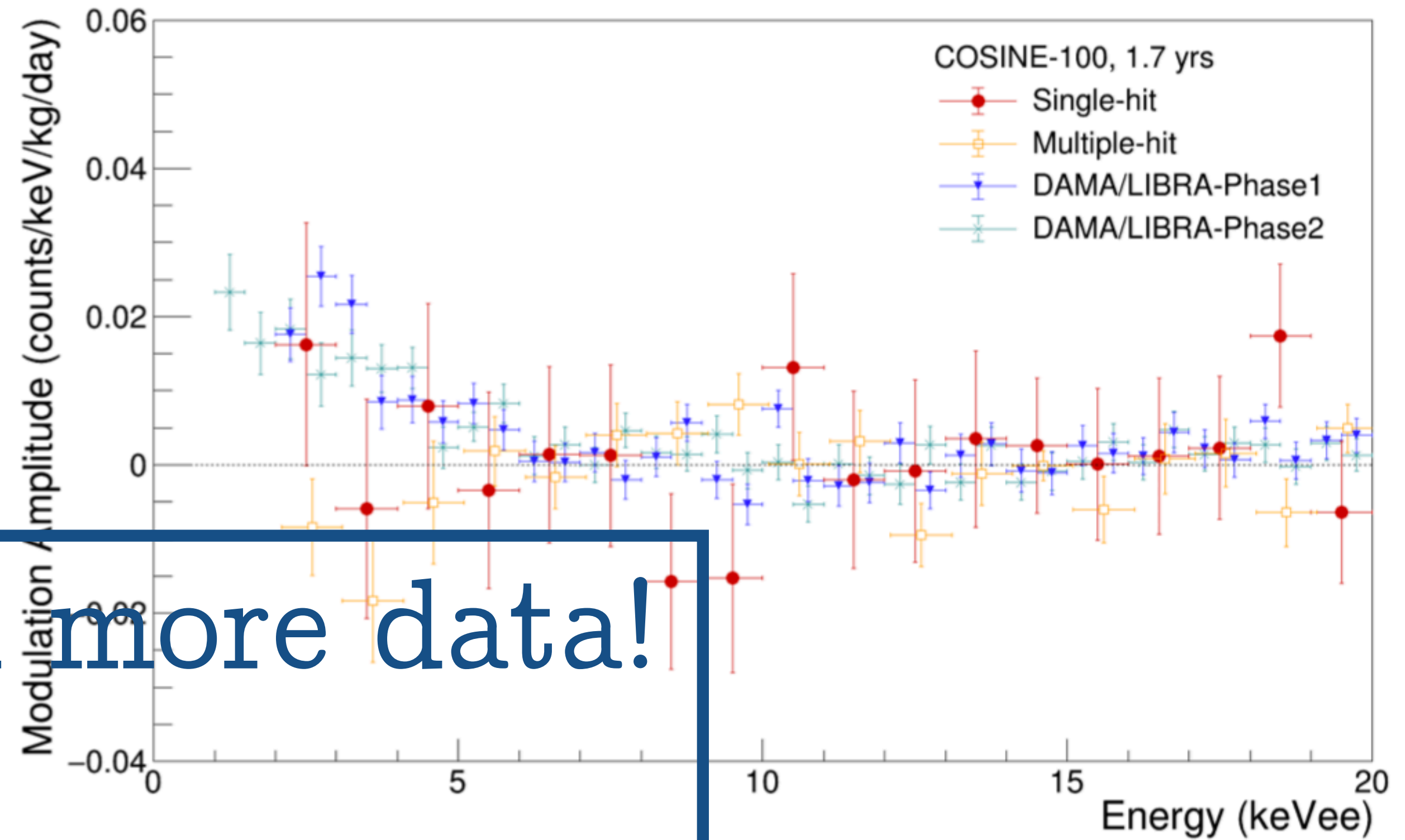
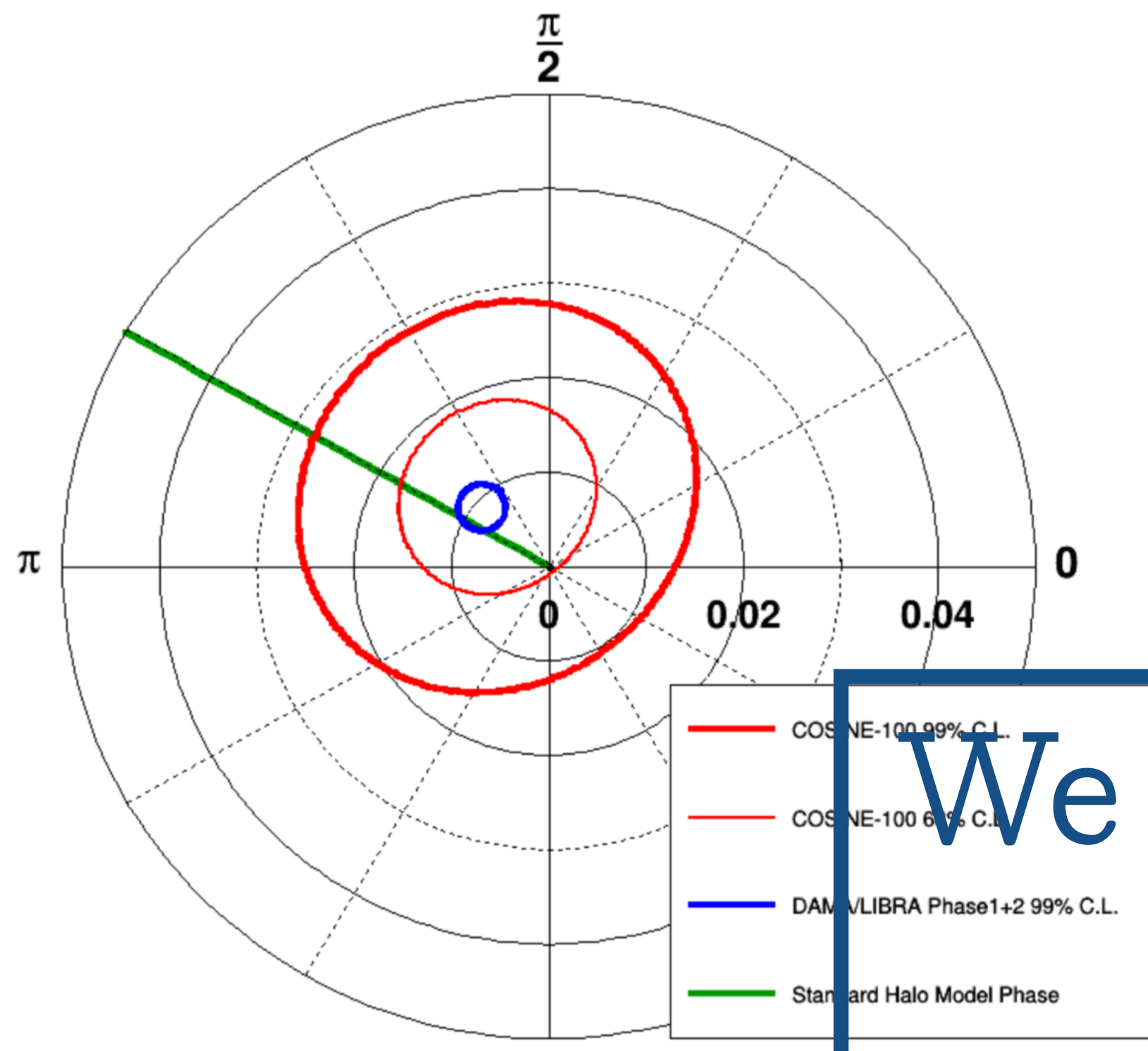
- Best fit amplitude for 2–6 keV
 - 0.0092 ± 0.0067 cpd/kg/keV
 - 127.2 ± 45.9 cpd/kg/keV
- Statistically limited, not yet able to distinguish DAMA/null

Configuration	χ^2	<i>d.o.f.</i>	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)



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We need more data!
 ...like everyone else...

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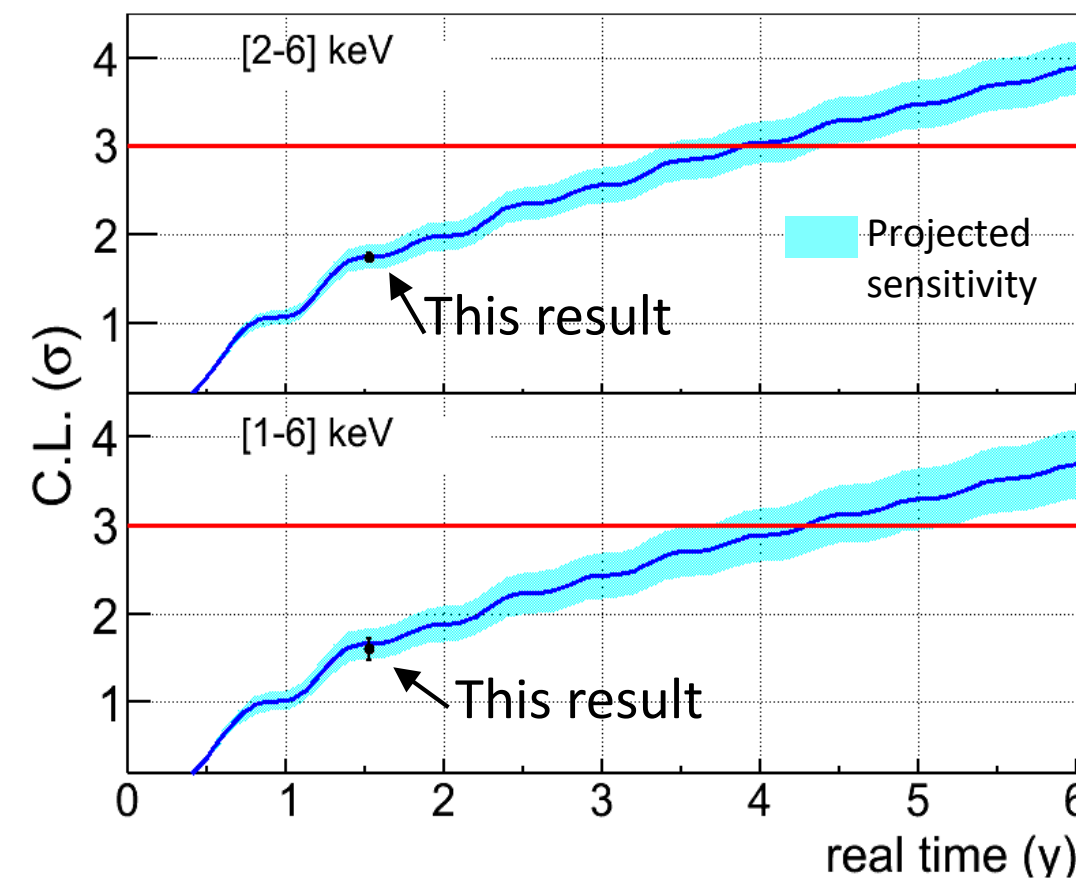
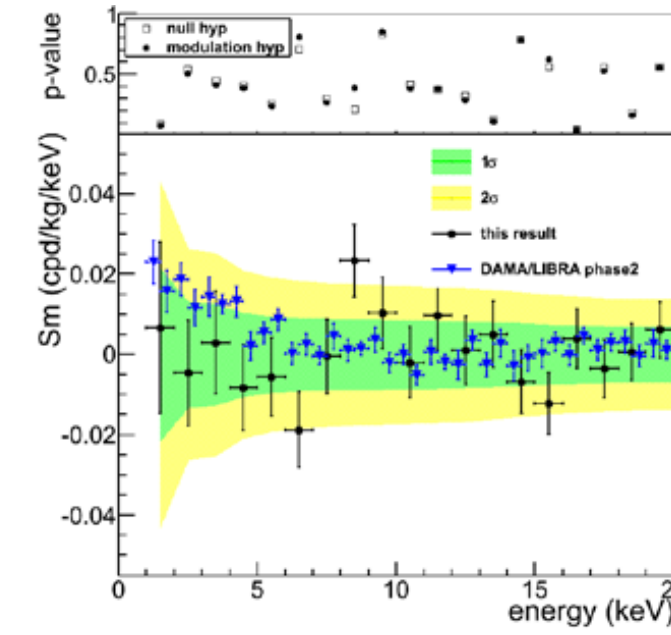
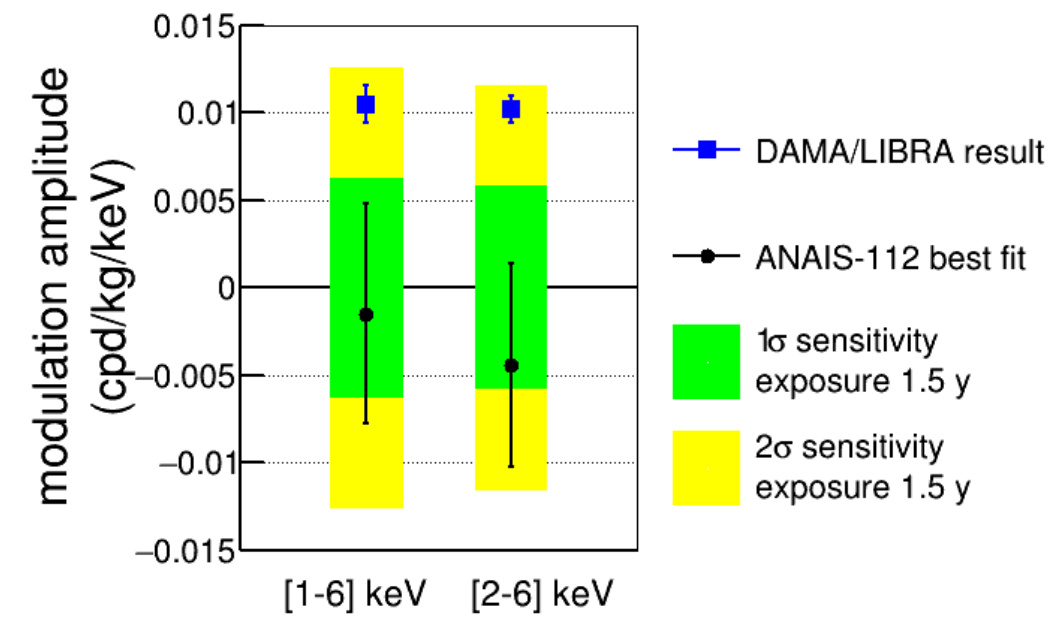
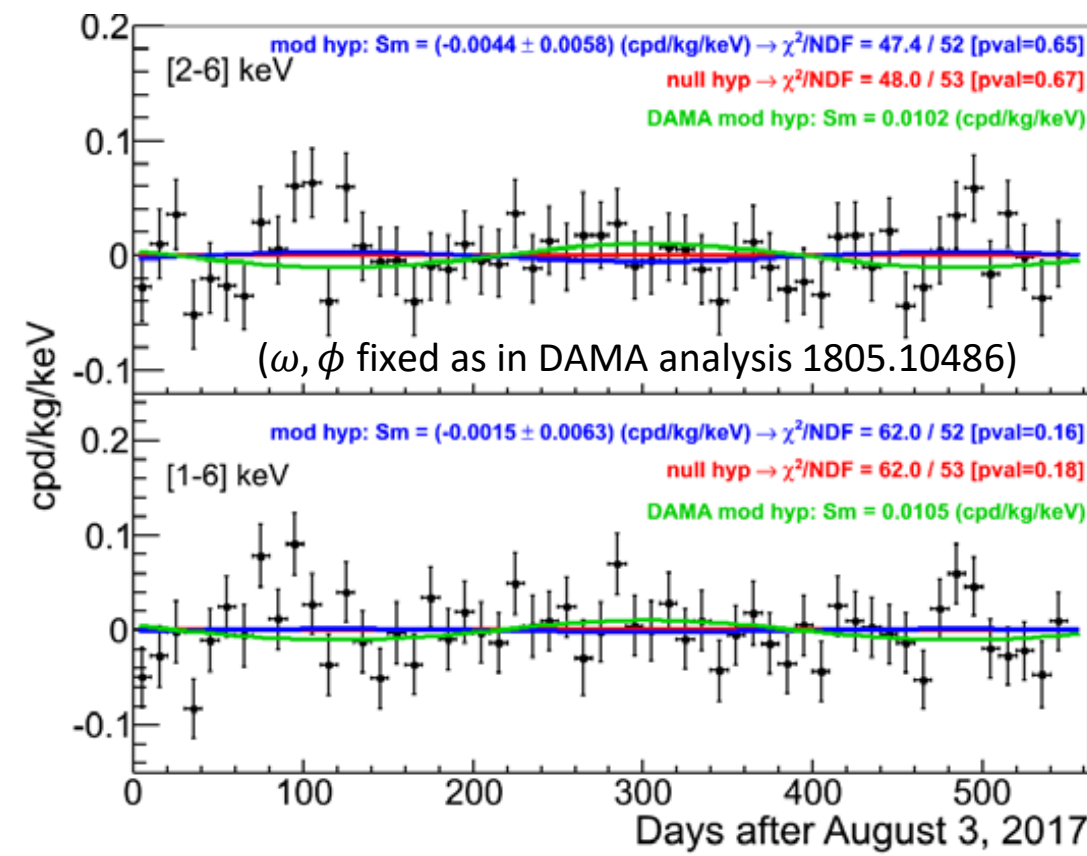
ANAIS-112 annual modulation analysis

[ArXiv:1903.03973](https://arxiv.org/abs/1903.03973)

Exposure: 157.55 kg×y

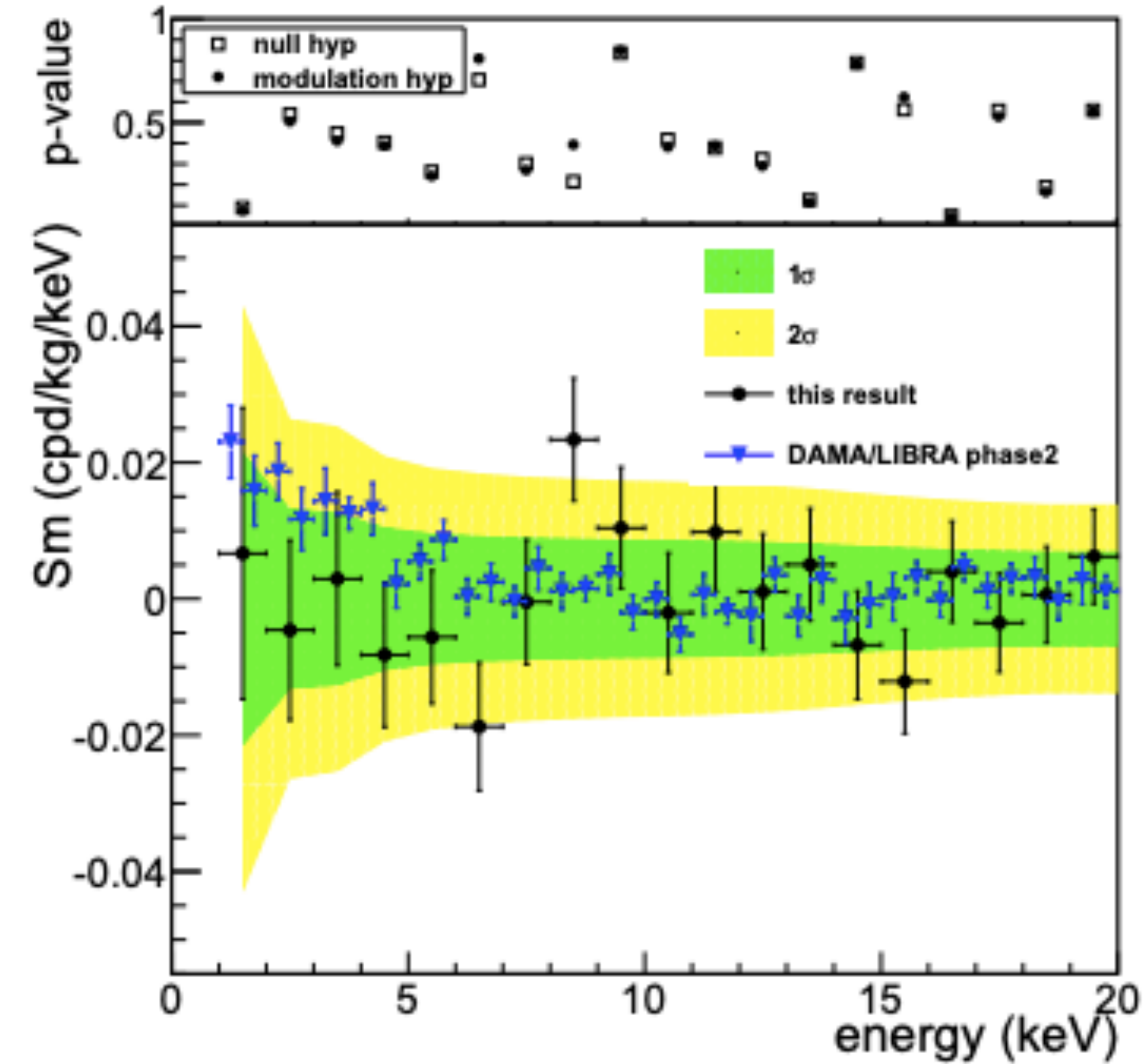
$$R(t) = R_0 + R_1 e^{-t/\tau} + S_m \cos[\omega(t + \phi)]$$

[2-6] keV $\rightarrow S_m = -0.0044 \pm 0.0058$ cpd/kg/keV
 [1-6] keV $\rightarrow S_m = -0.0015 \pm 0.0063$ cpd/kg/keV



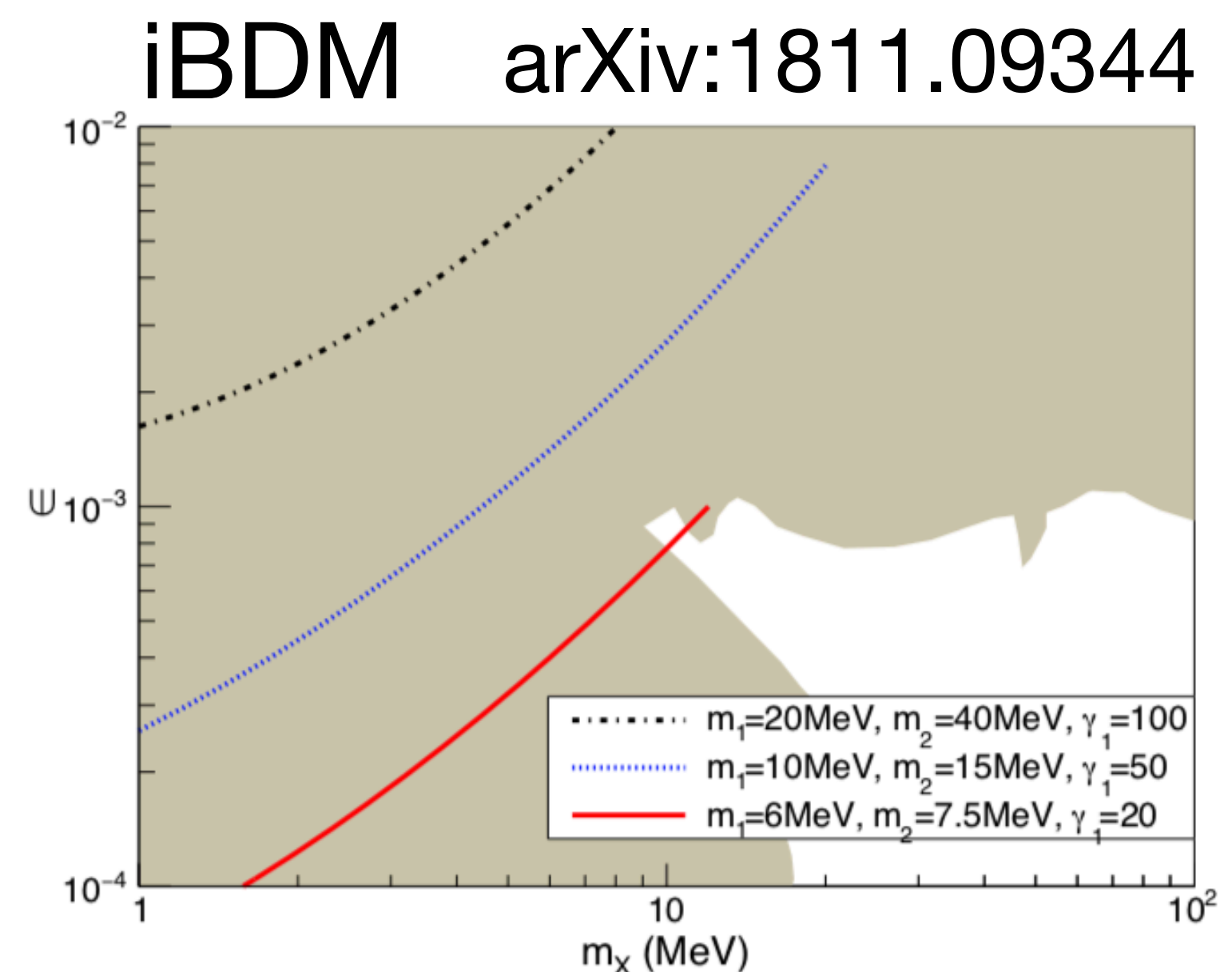
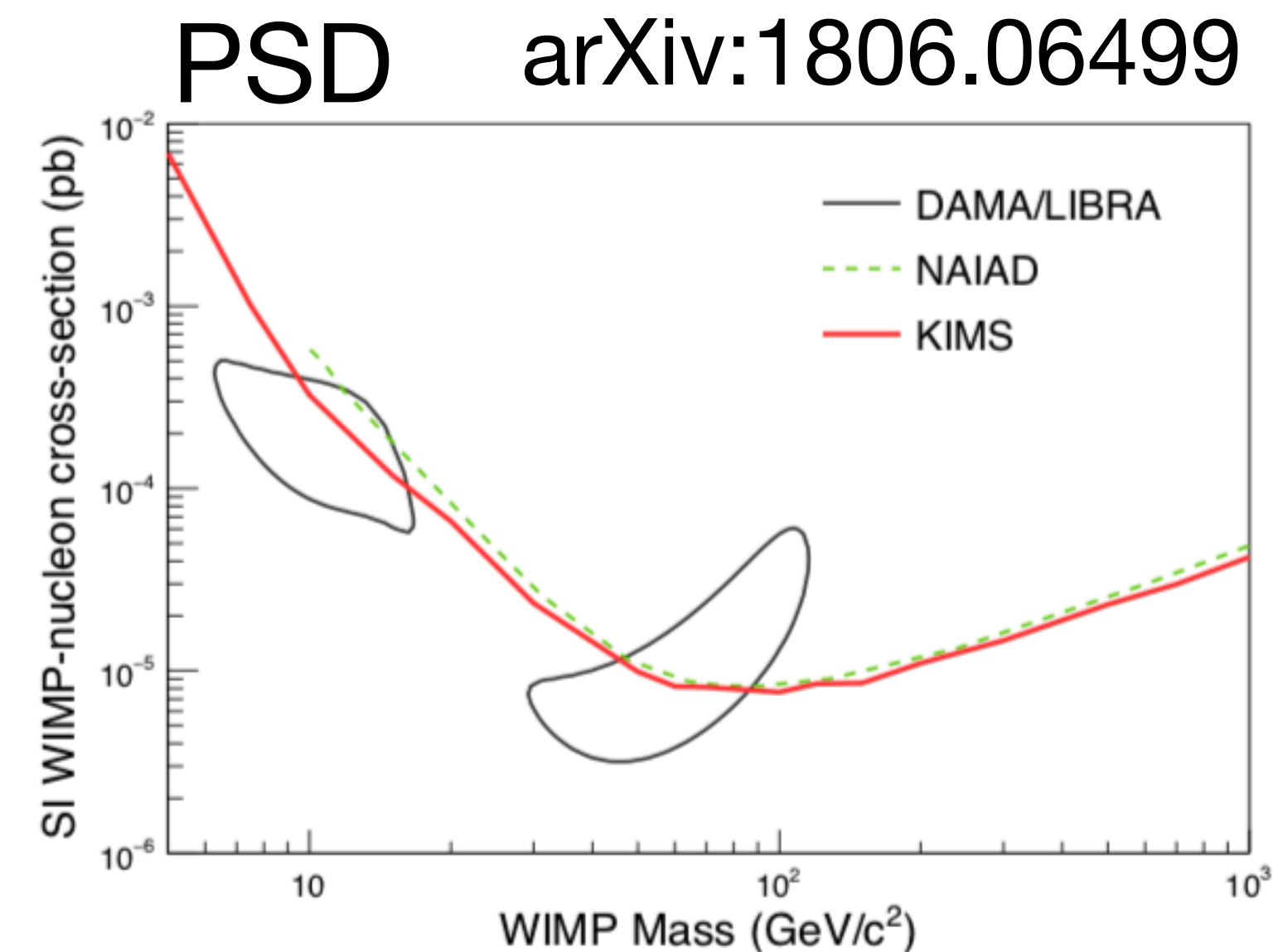
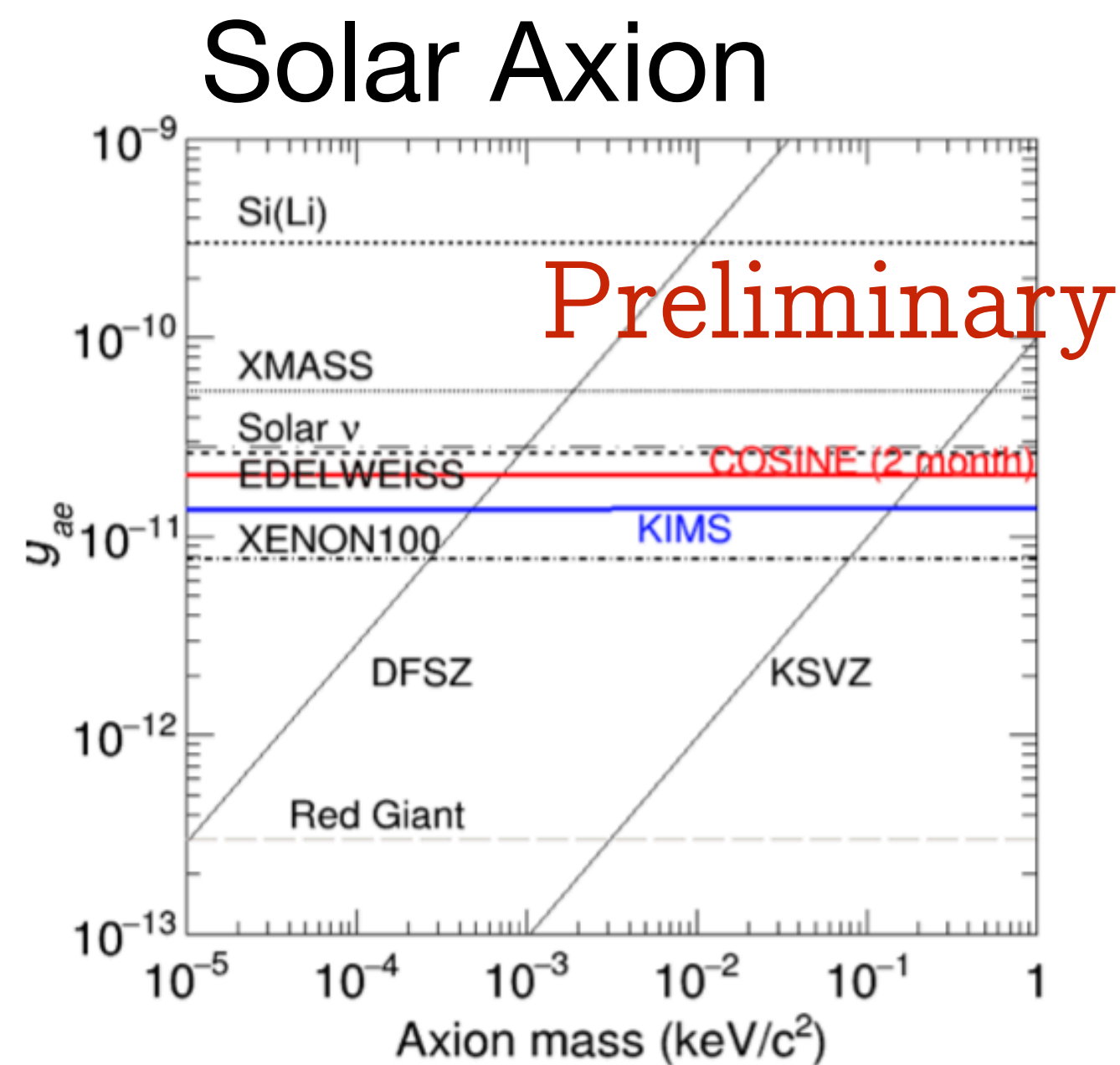
The result for 1.5 years confirms the estimated sensitivity for our background and exposure

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



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, ...

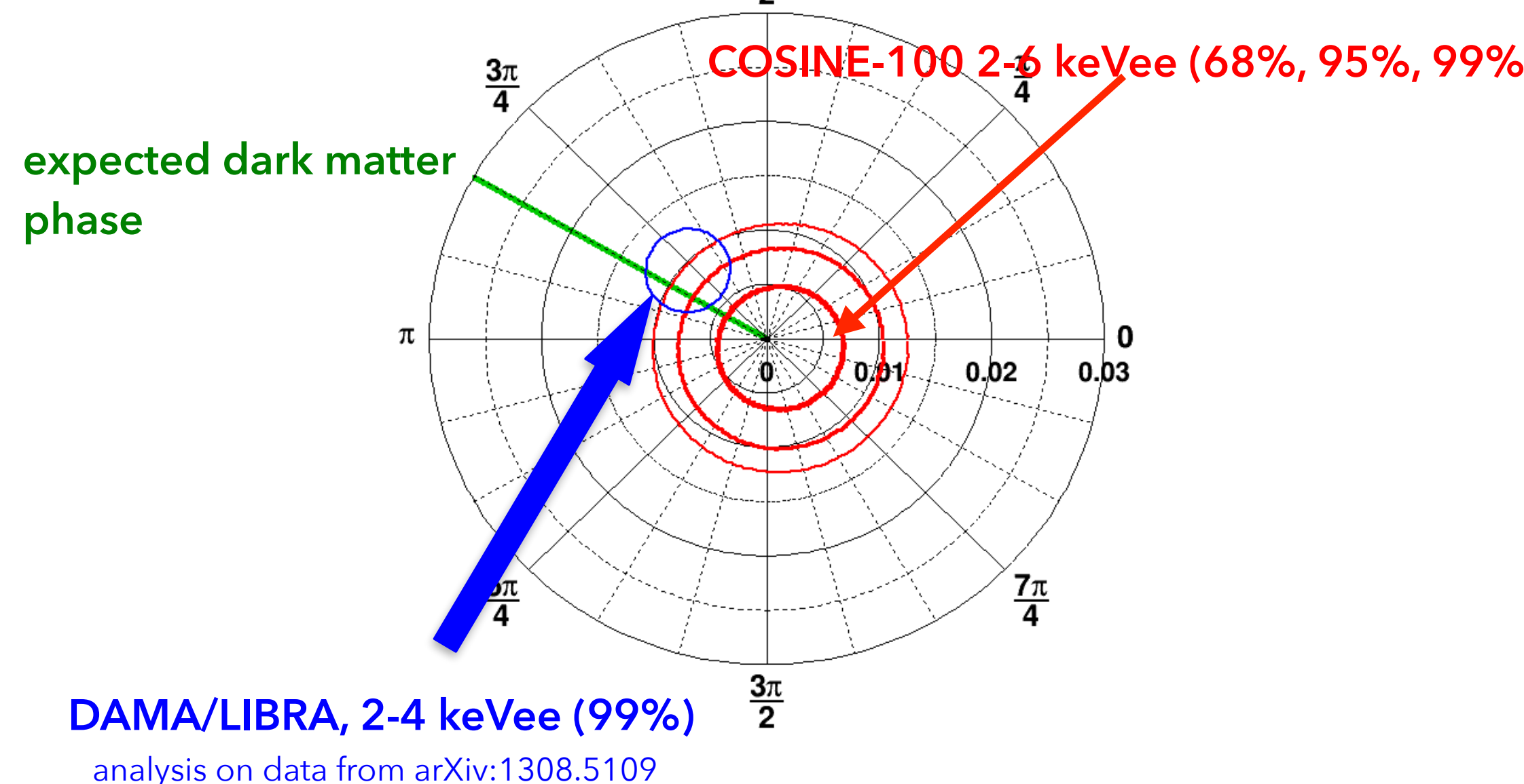


What next?

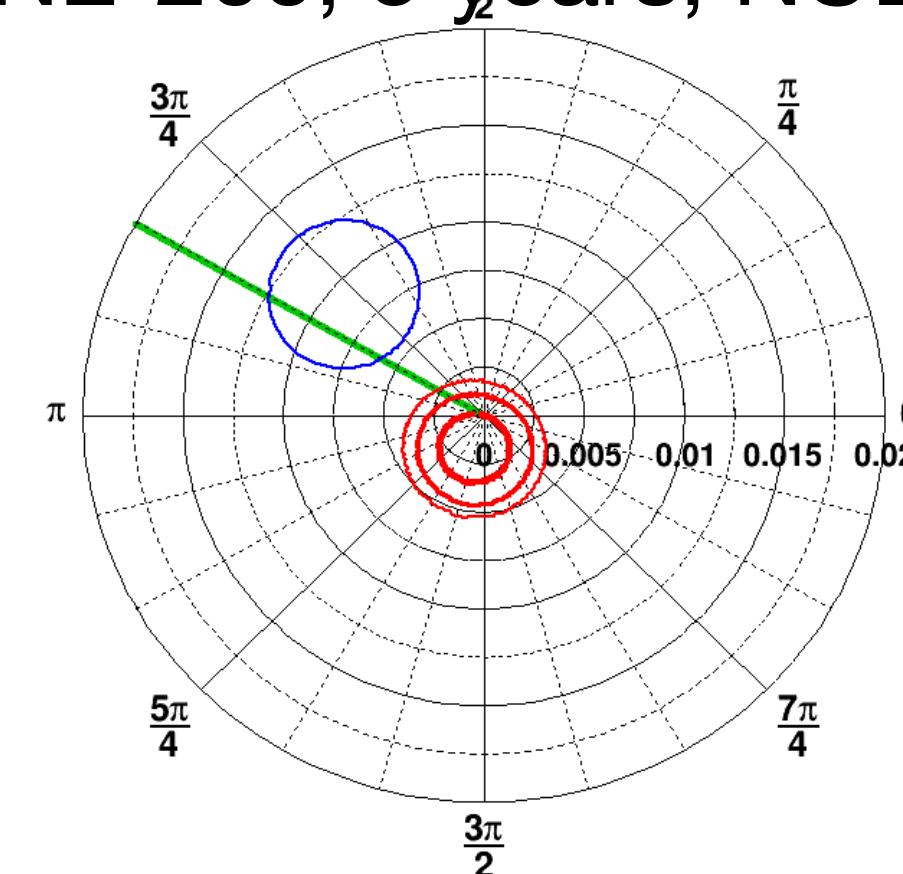
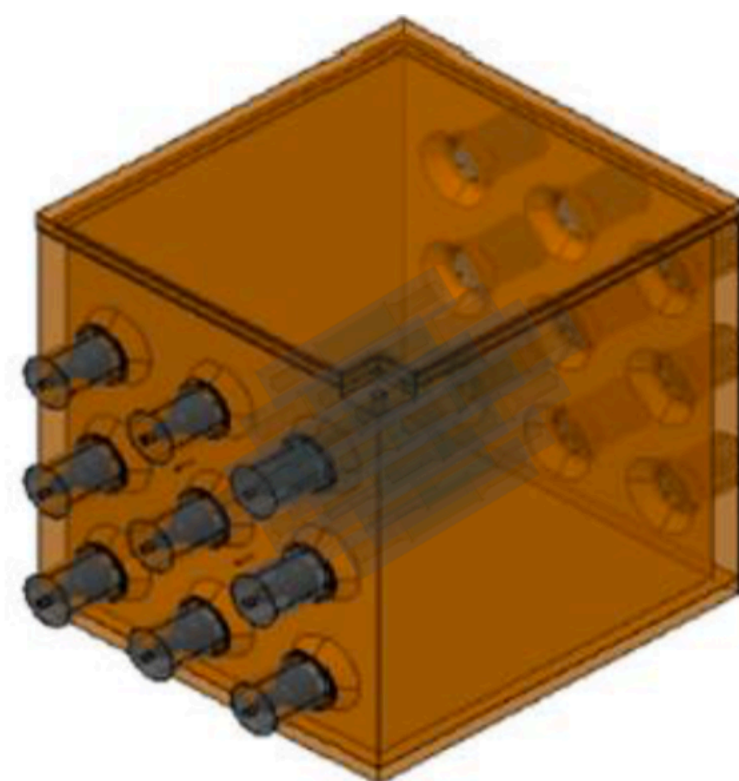
What next?

- 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 **combine 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



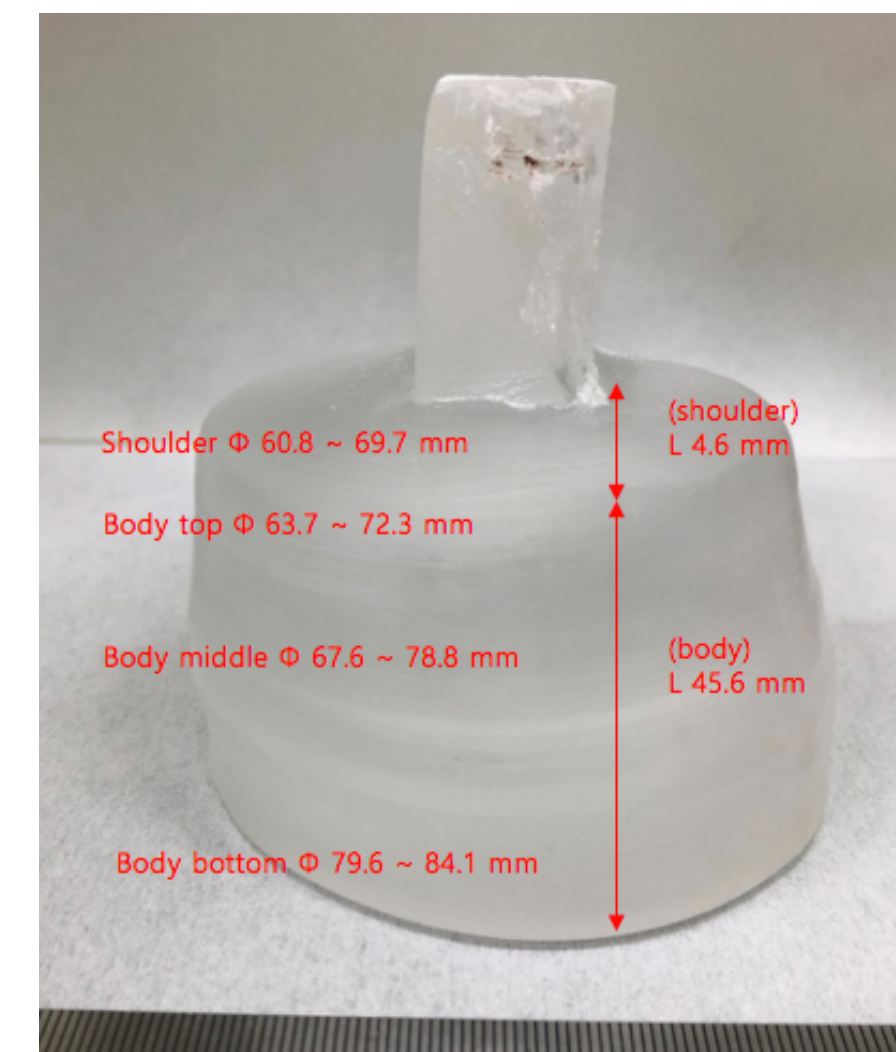
COSINE-200 @ Y2L COSINE-200, 5 years, NULL case



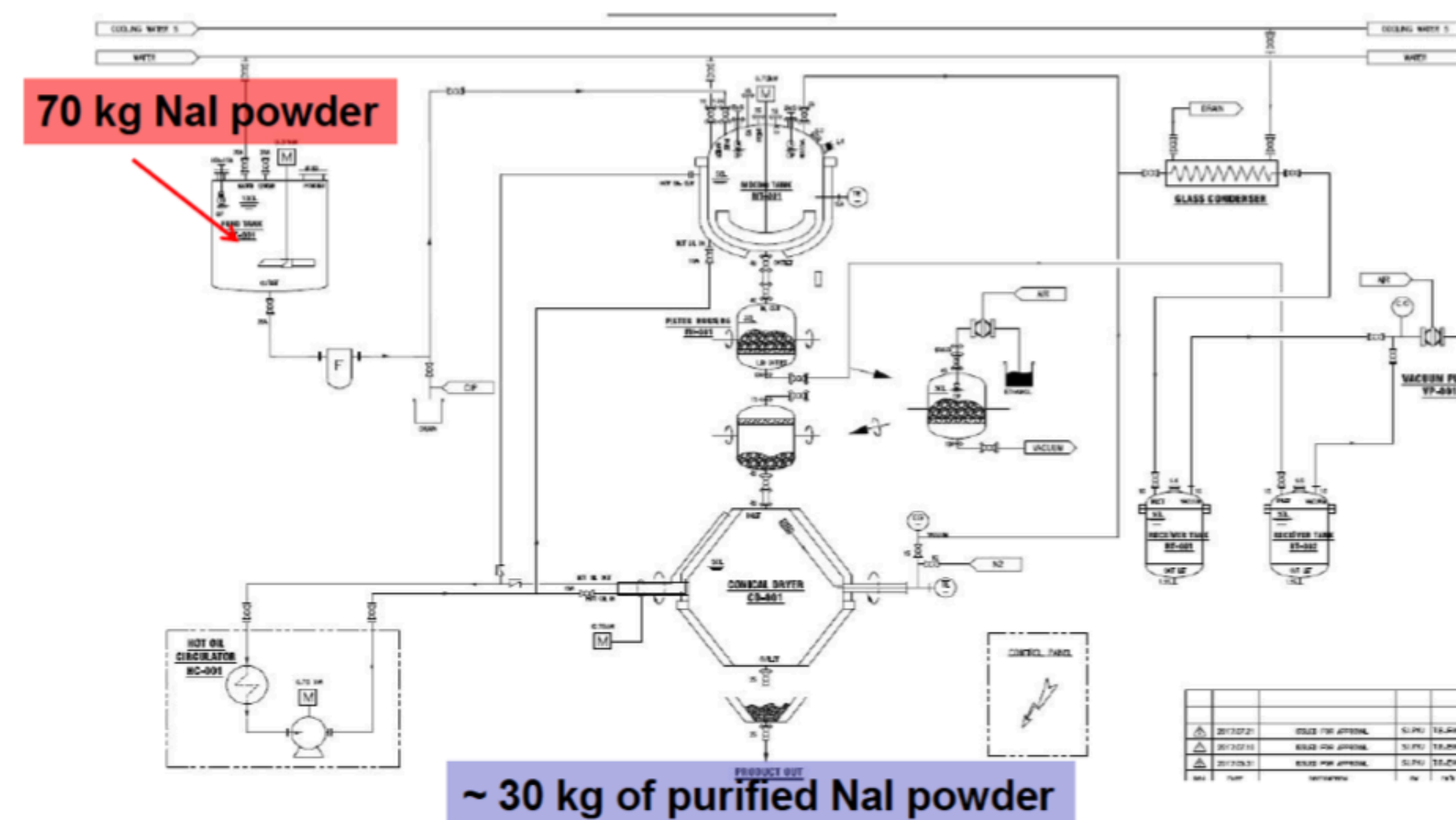
What next? (Crystal growing R&D)

- 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

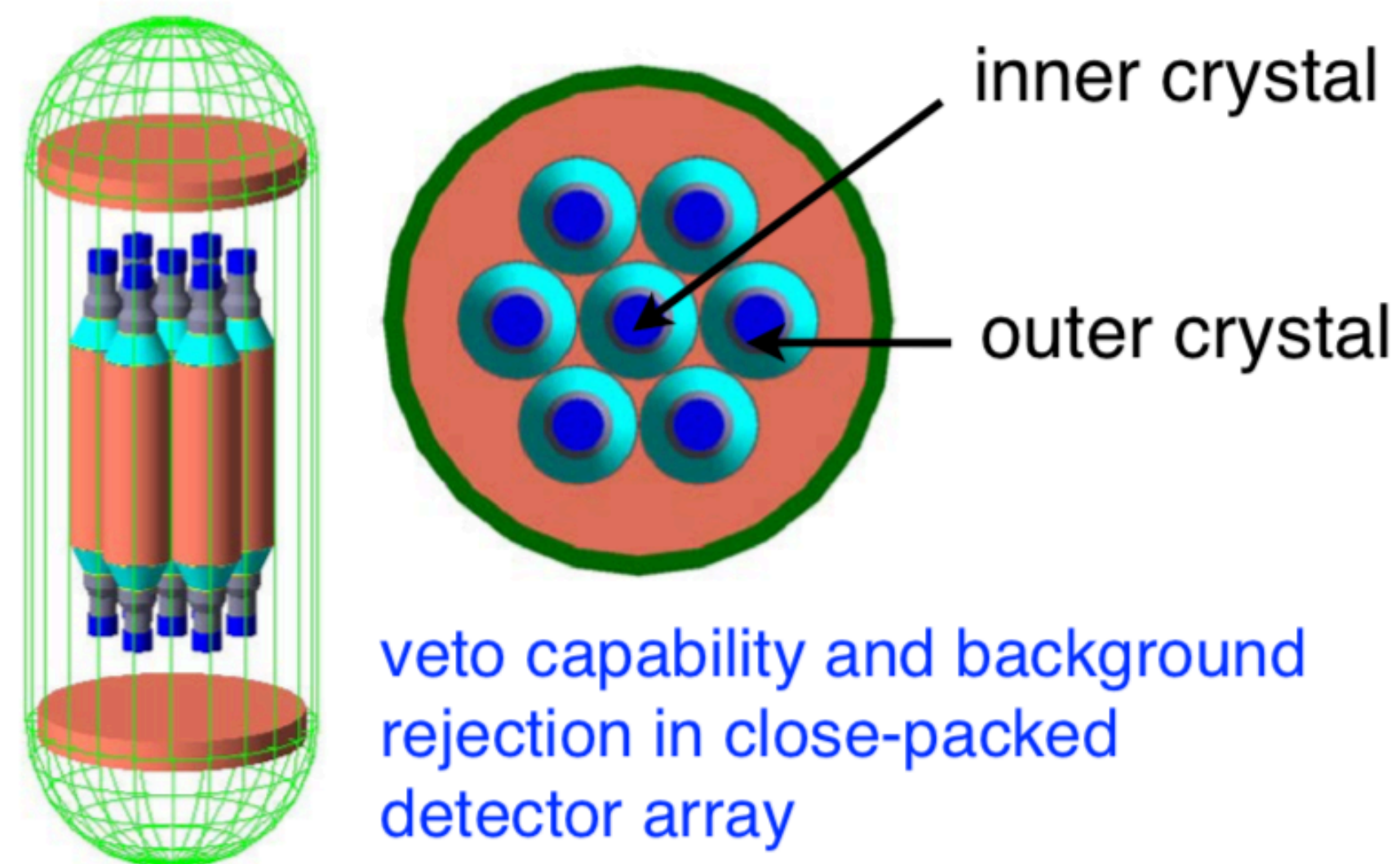


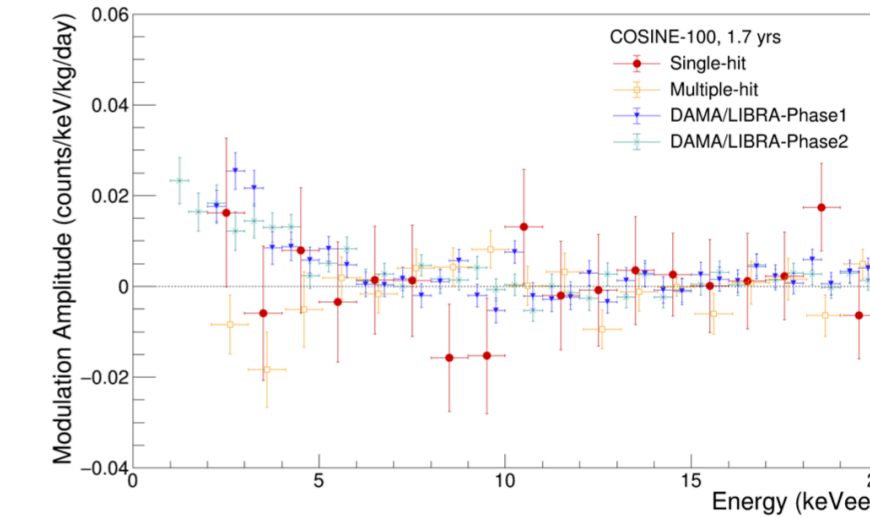
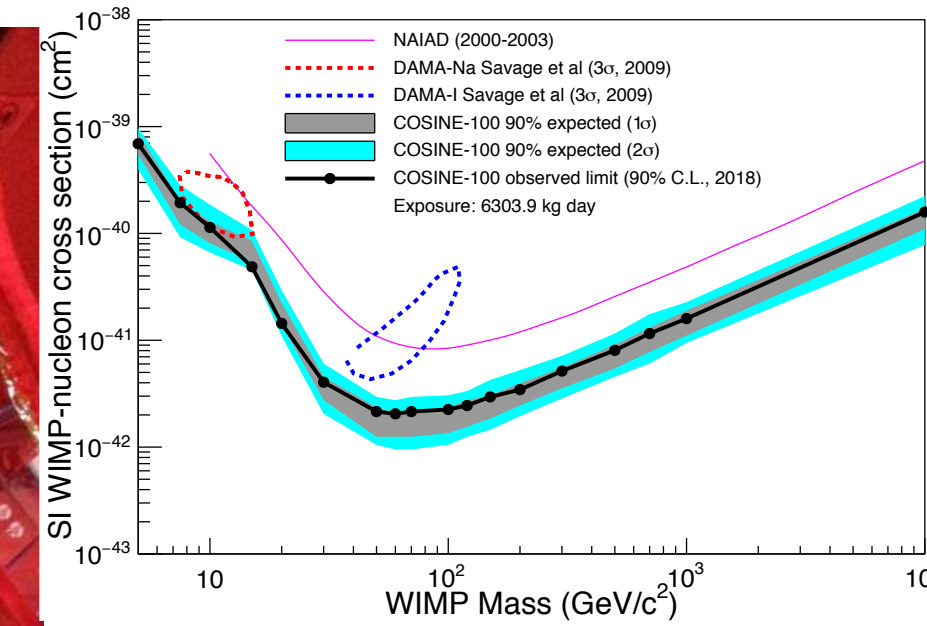
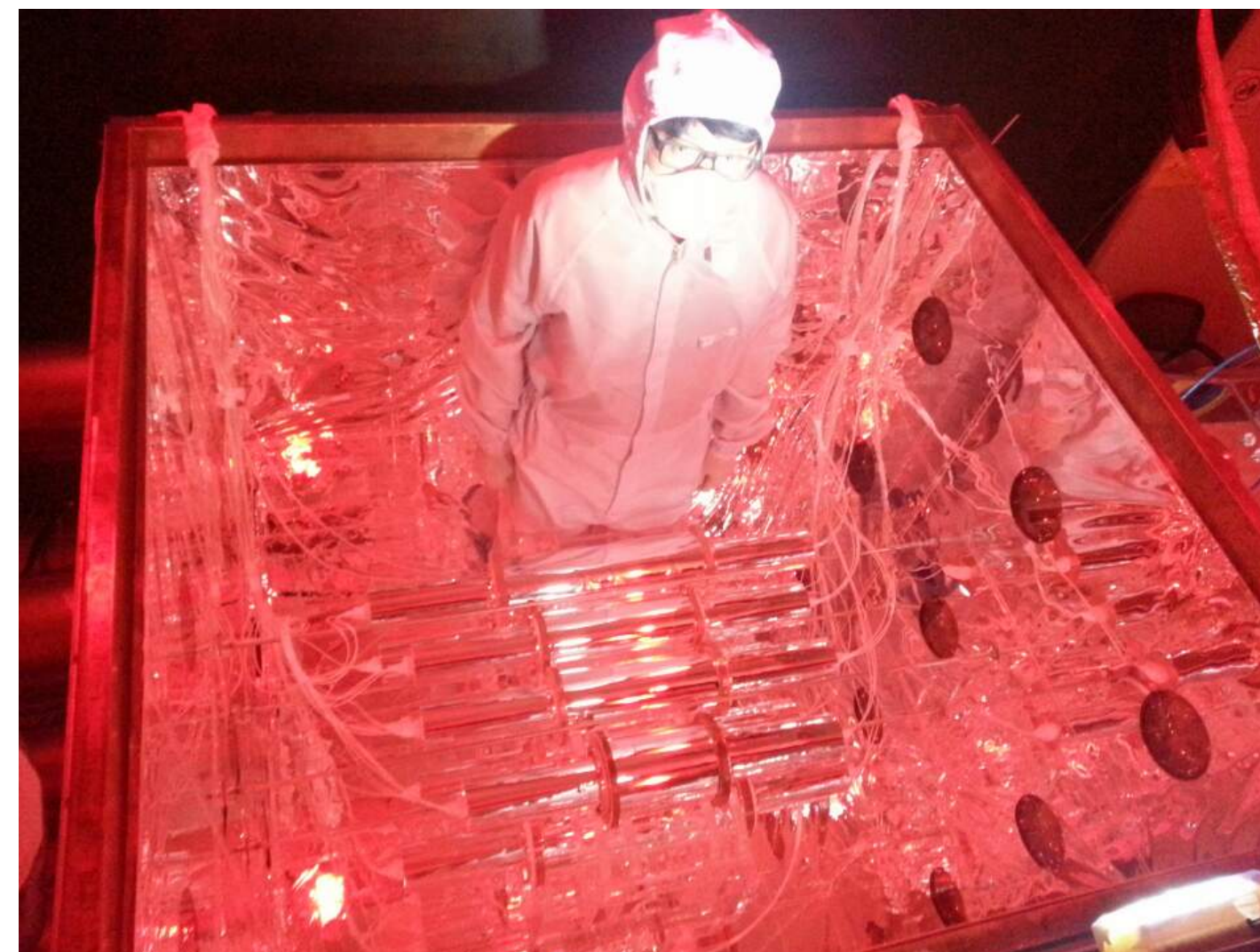
What next?

- **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





- 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!