DM-Ice17 and COSINE-100 NaI(Tl) Dark Mater Experiment: Testing DAMA's Claim for a Dark Matter Discovery

Jay Hyun Jo

Yale University

BNL Particle Physics Seminar

January 3, 2018

Wright Laboratory

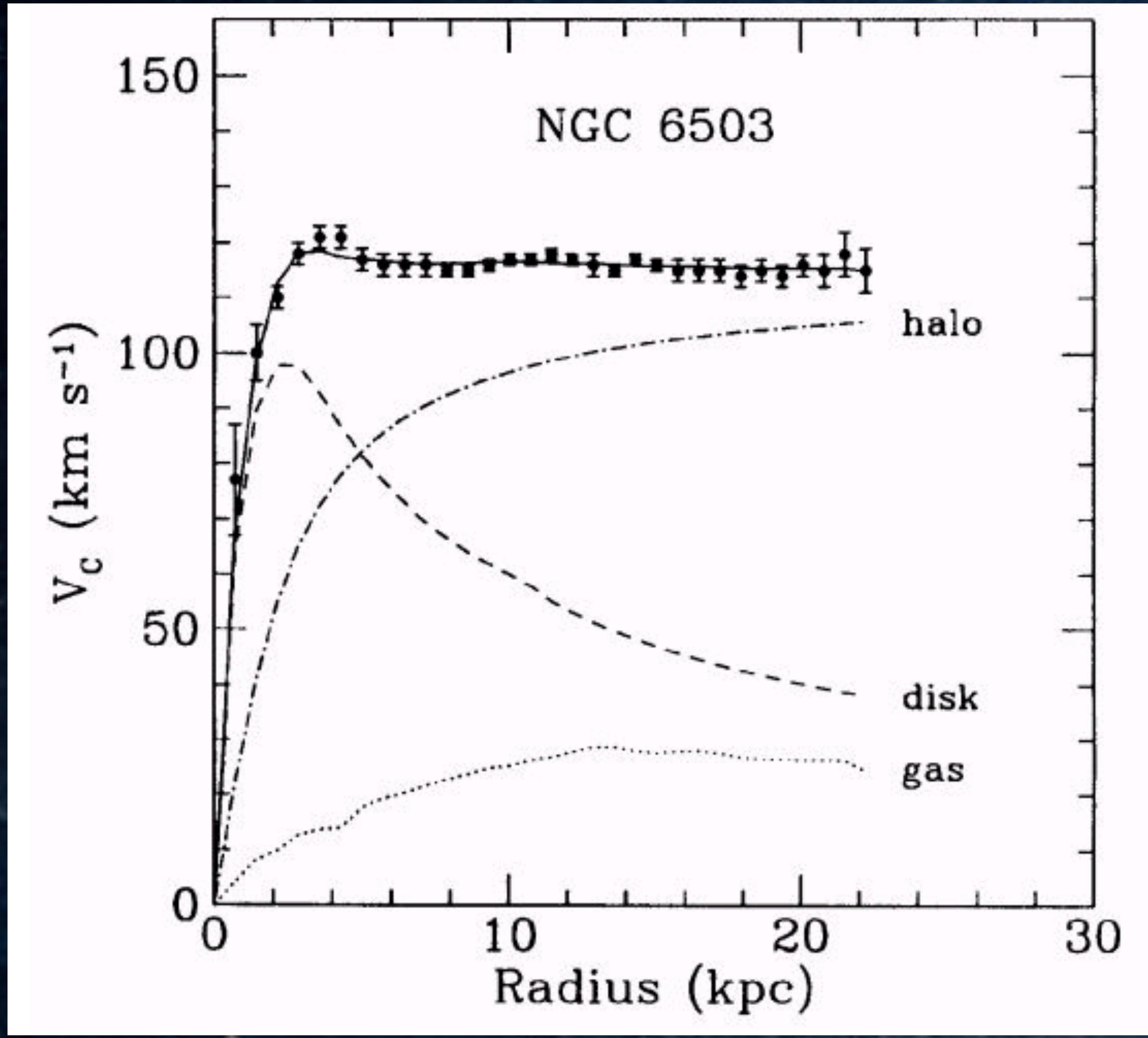
Yale

Content

- Introduction: Dark Matter, DAMA experiment, Global effort
- DM-Ice17: NaI(Tl) prototype experiment at South Pole
- COSINE-100: Full-scale NaI(Tl) experiment at Y2L
- What next?
- Summary

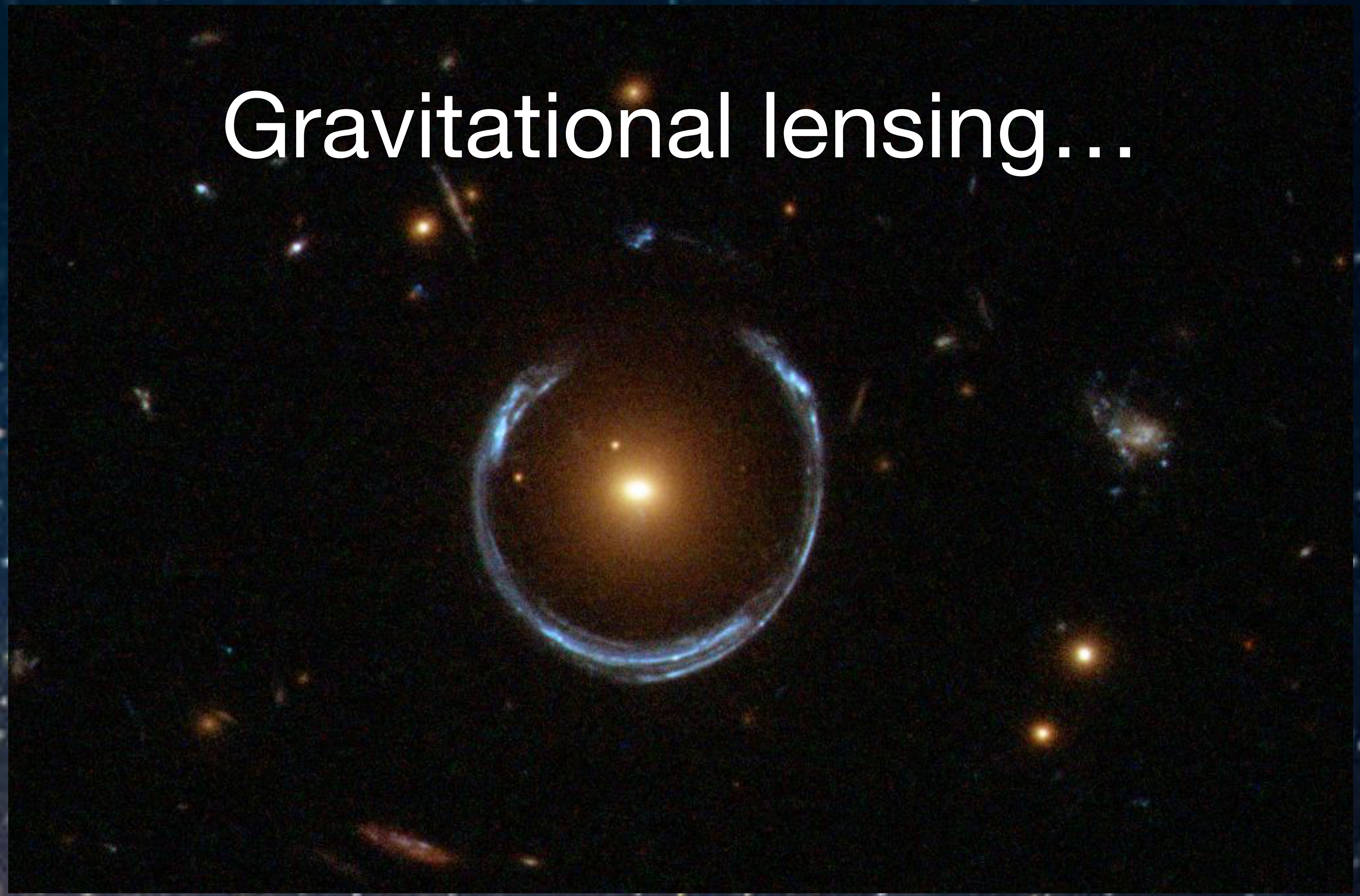
Evidence of Dark matter

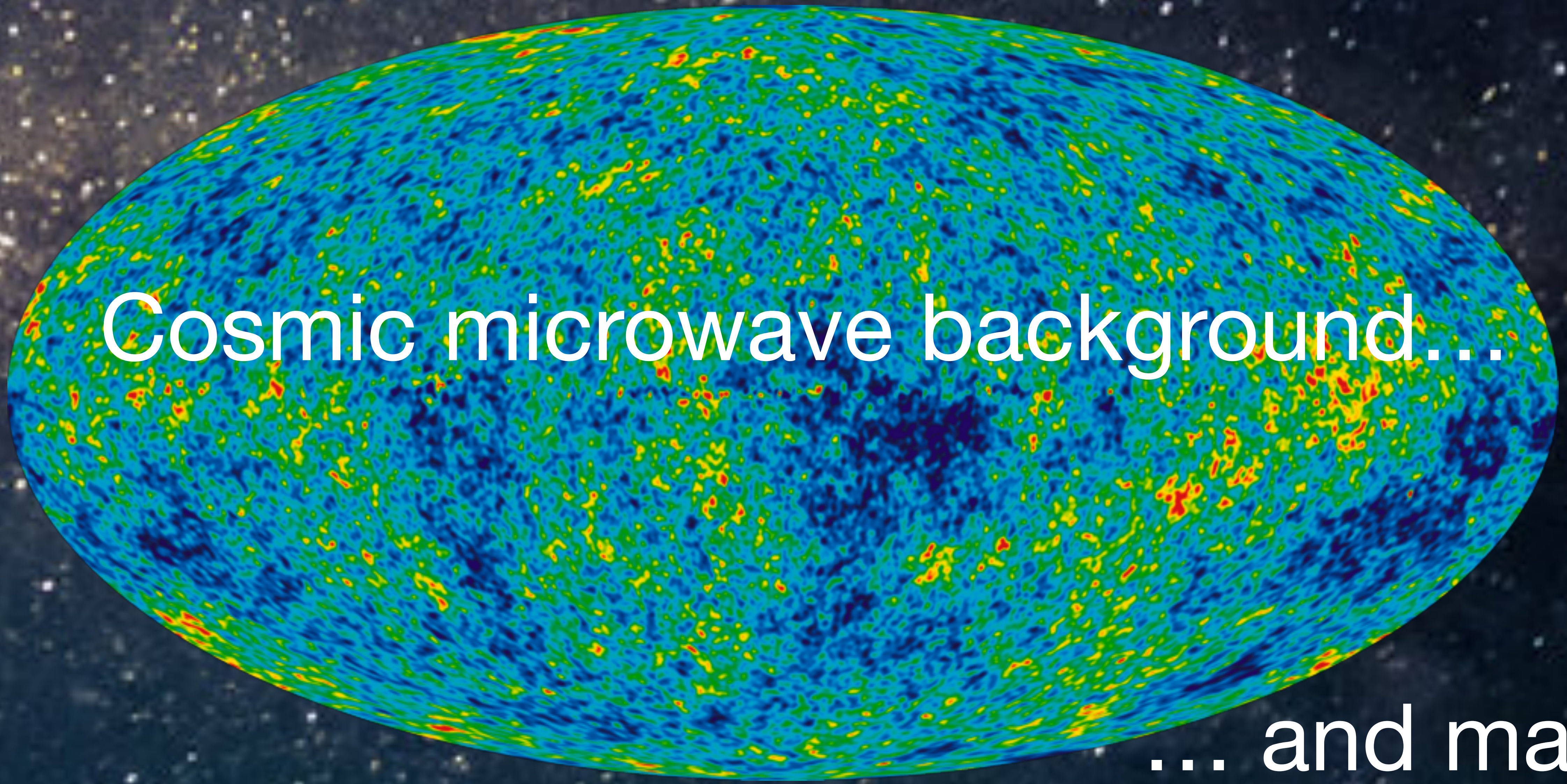
Cosmological observations give strong evidence of dark matter:



Galaxy rotation curves…

Gravitational lensing…

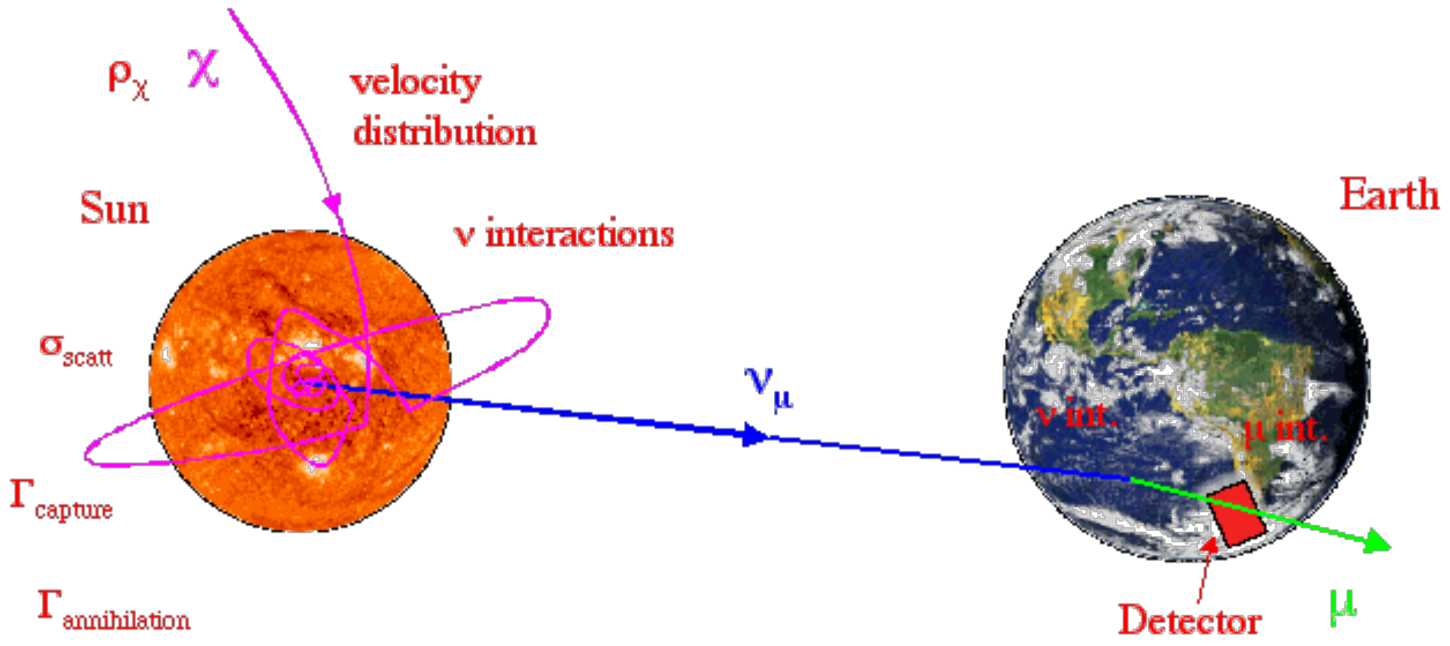


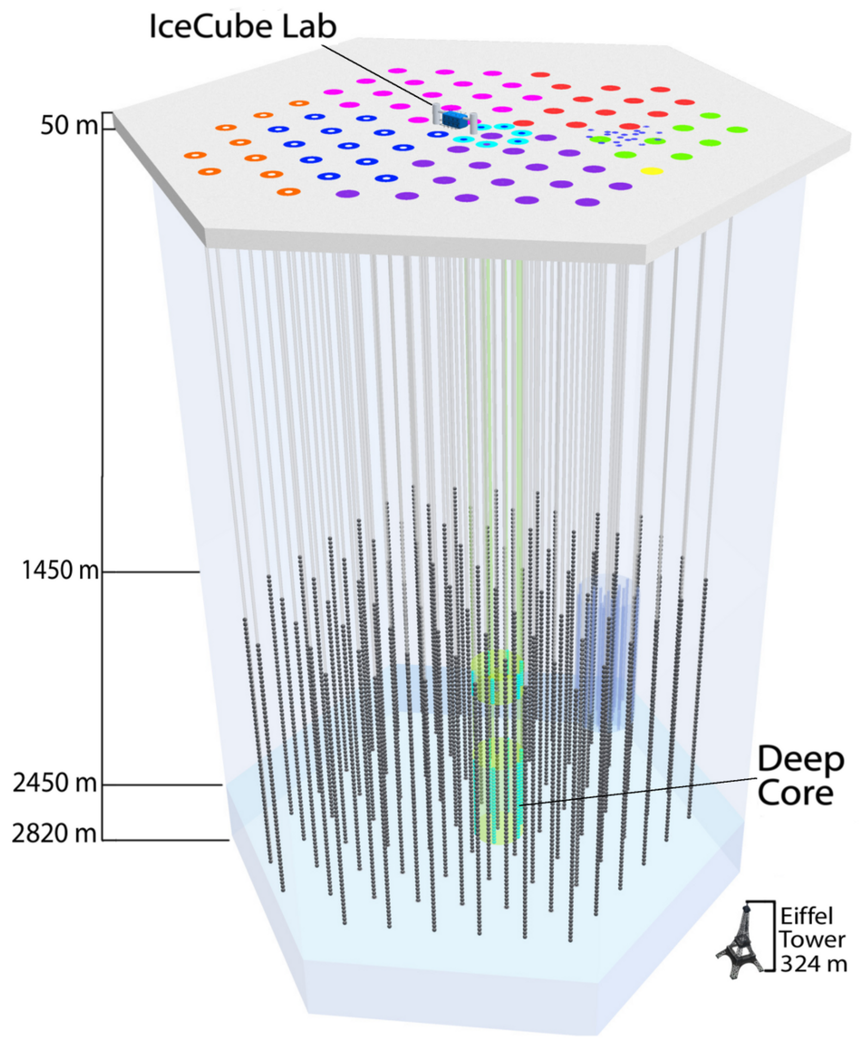


Cosmic microwave background…

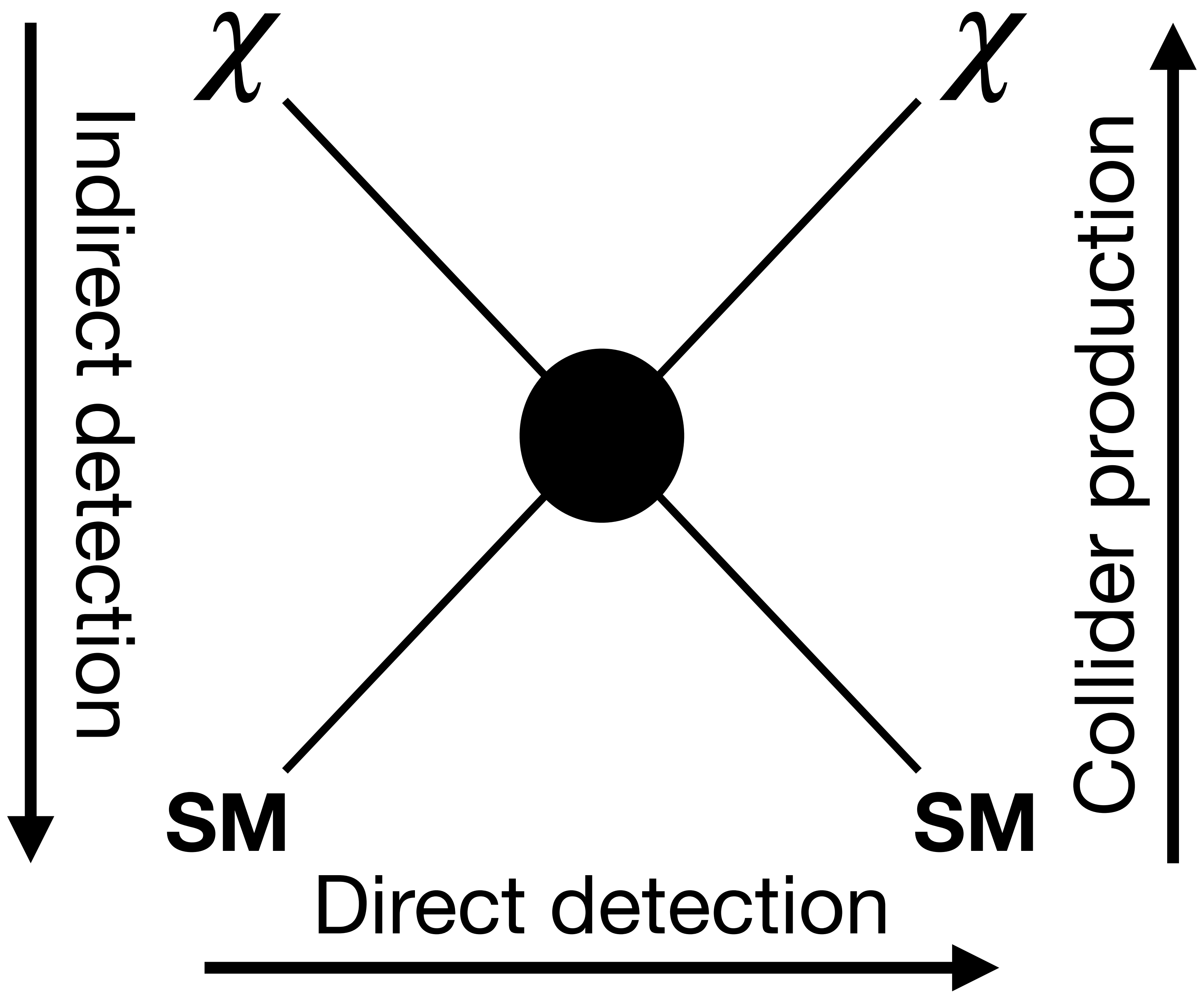
… and many others.

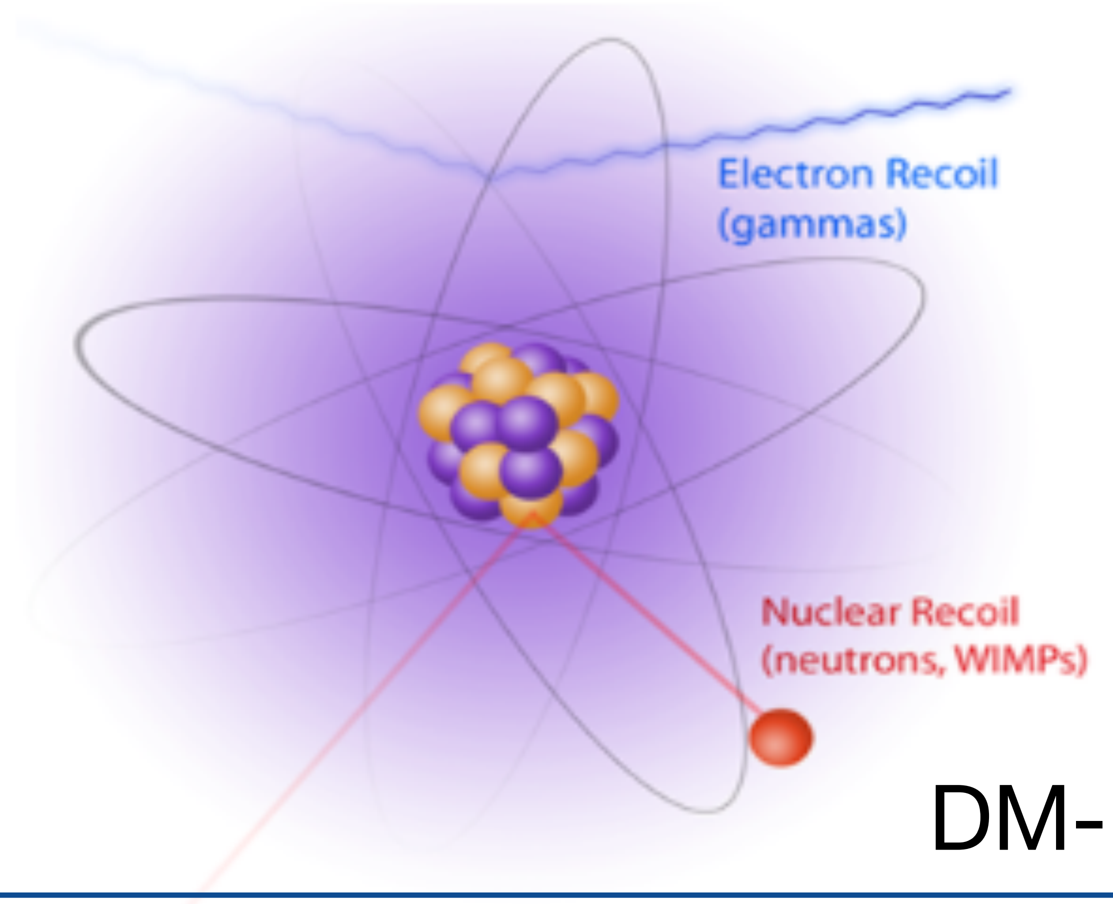
Dark matter detection



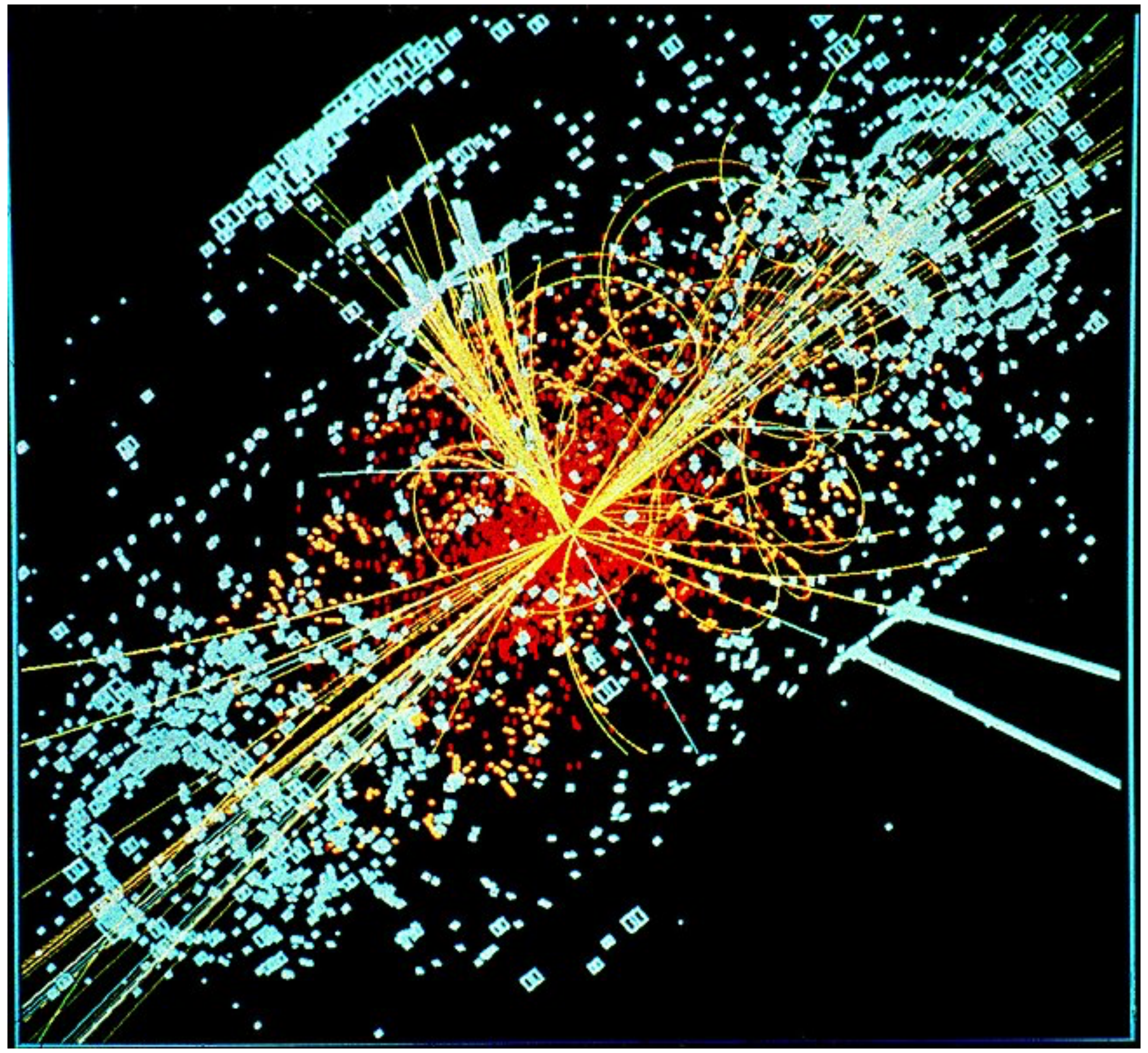


Annihilation or decay products from the Sun, Halo, etc.





DM-Nucleon scattering

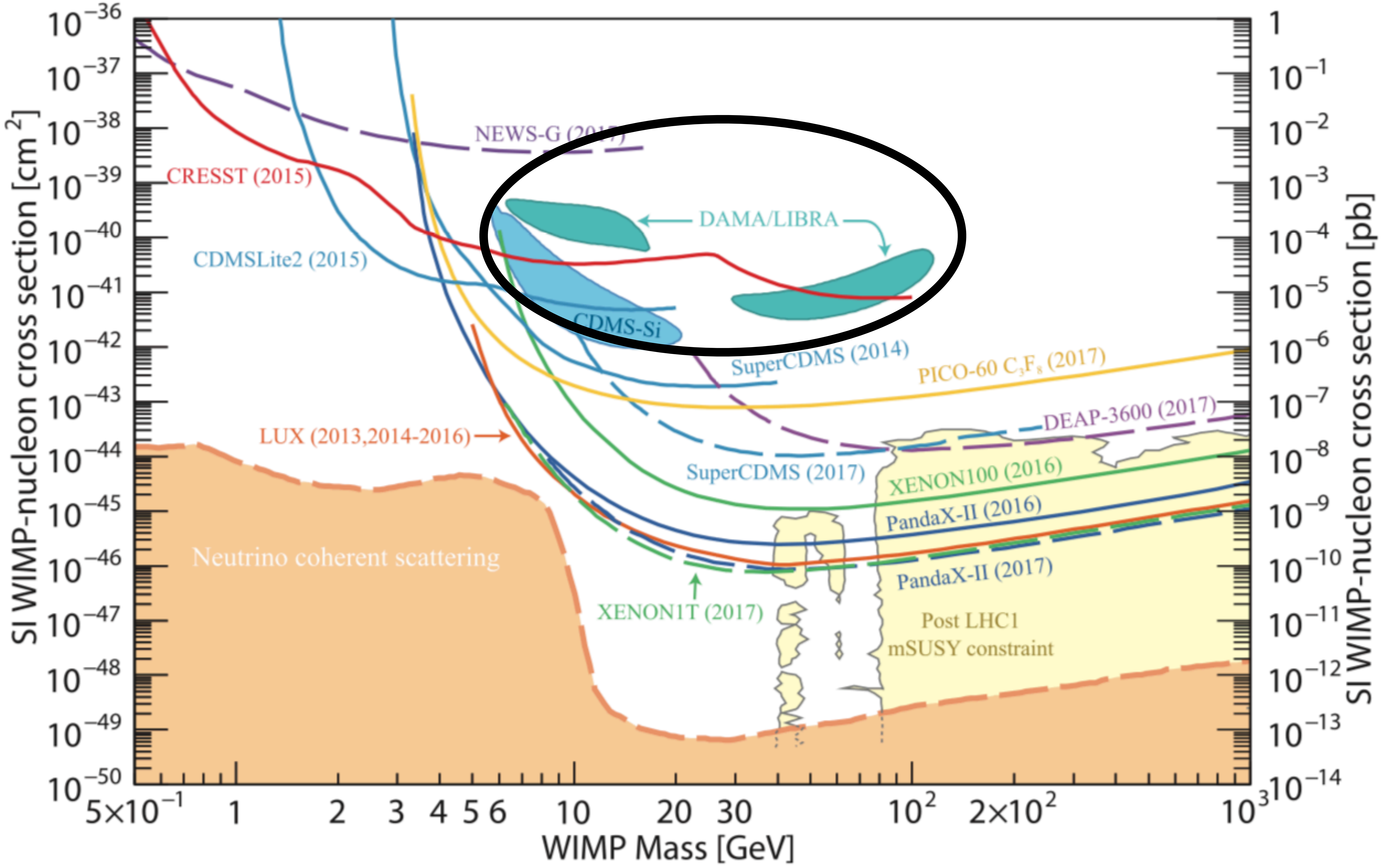


Search for missing energy

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)

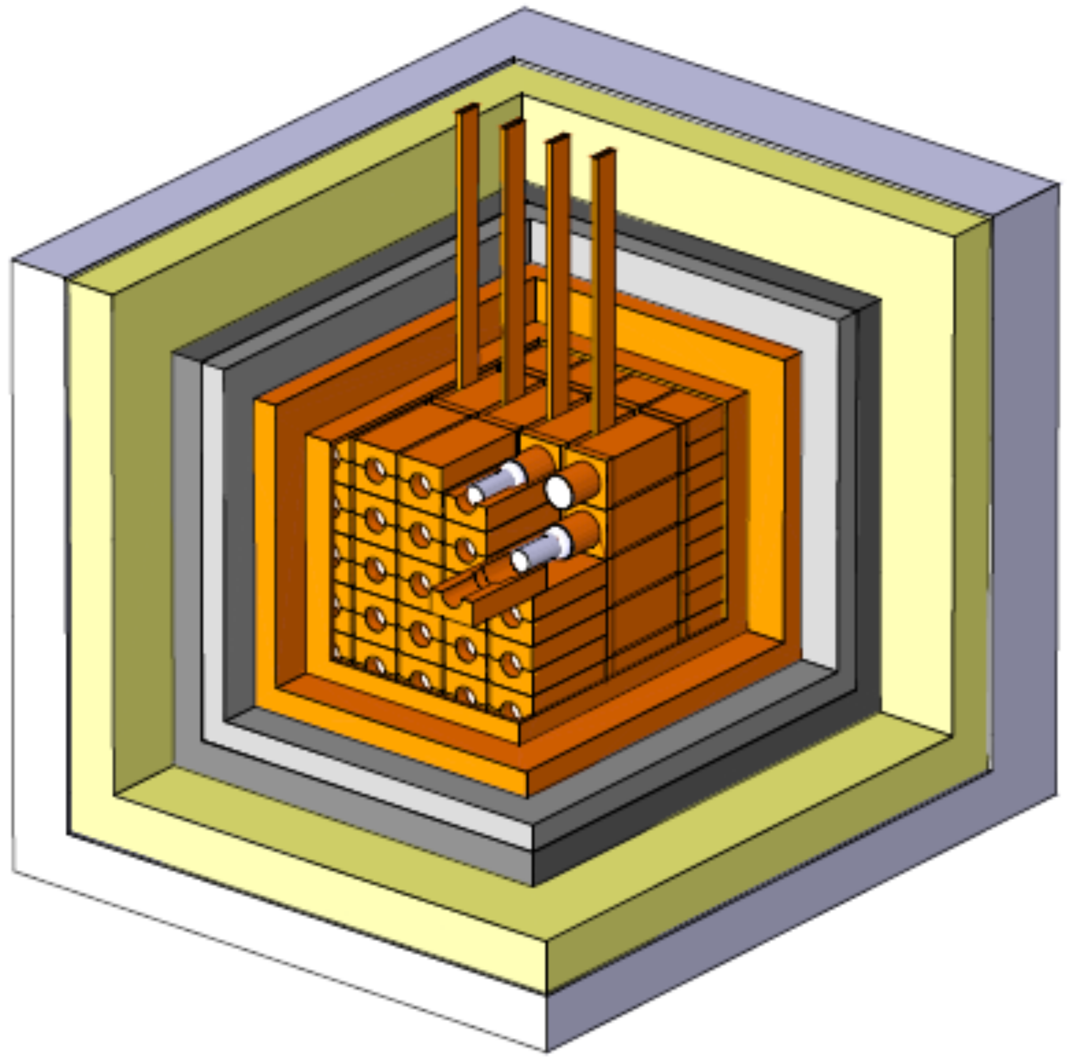
Annual Modulation of Dark Matter

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 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)

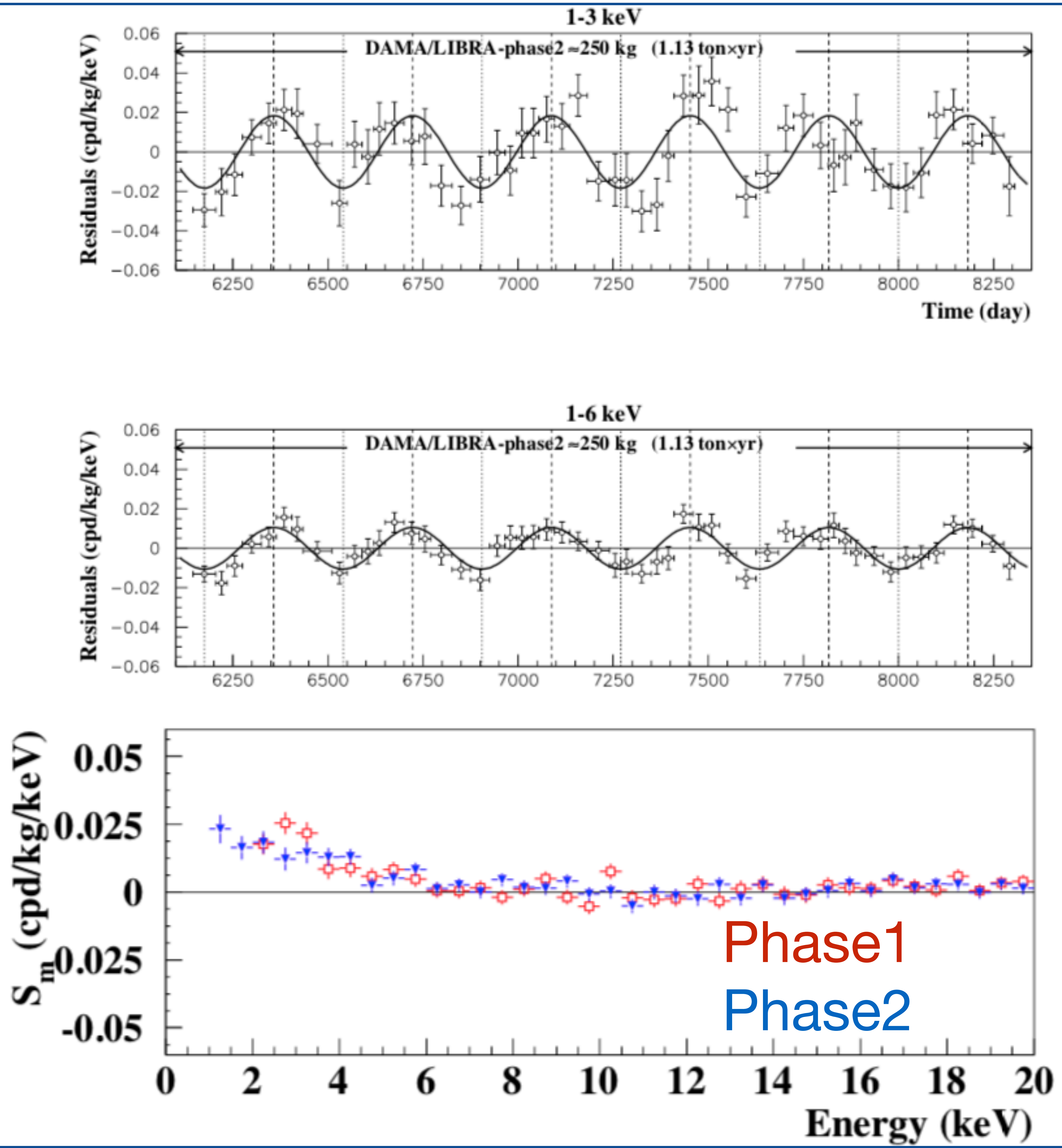


Bernabei *et al.*, NIM A (2008)

DAMA’s annual modulation

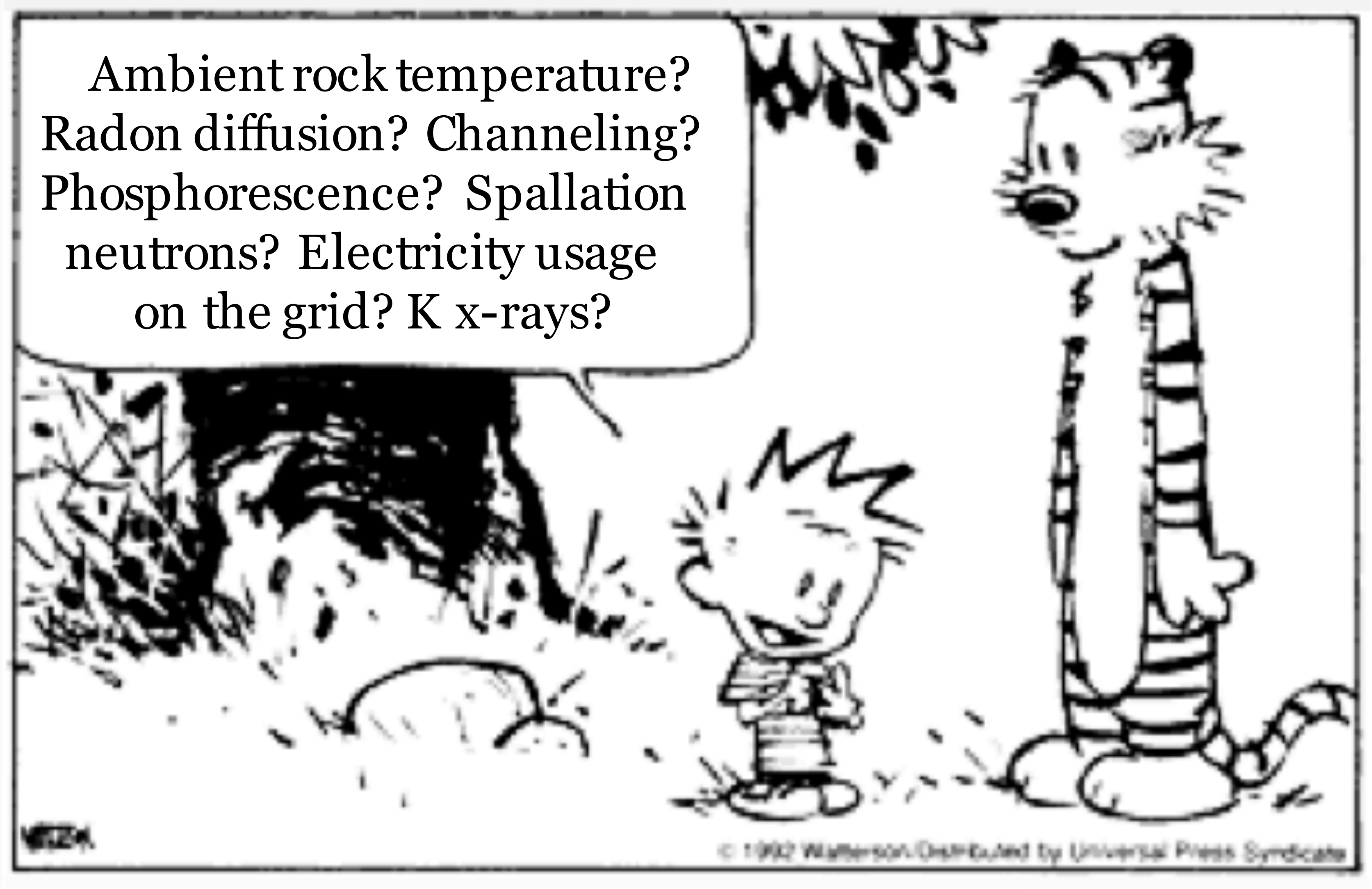
Bernabei *et al.*, arXiv:1805.10486

- DAMA/LIBRA-phase2 result announced with 1 keV threshold
  - (1-6) keV: 9.5 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

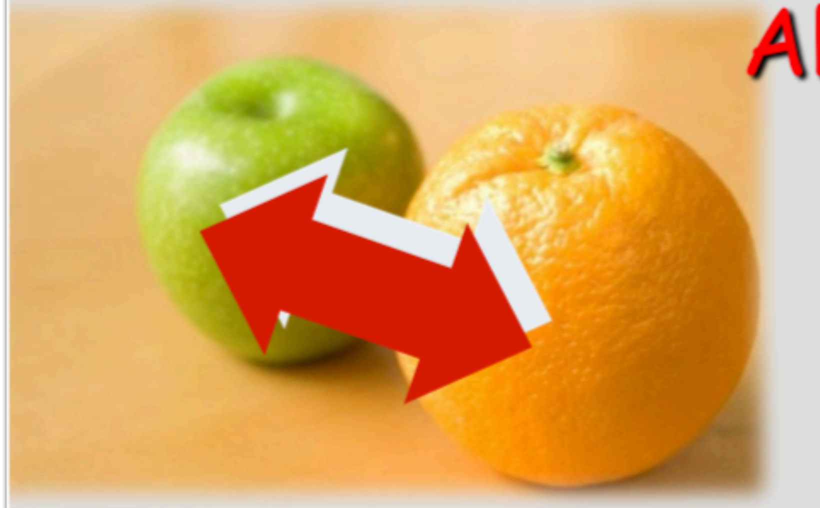
“What is causing DAMA’s modulation?
Could it be some backgrounds?”



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

Interpretation of the DAMA result

Bernabei, CSLNGS 2018



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?
- …

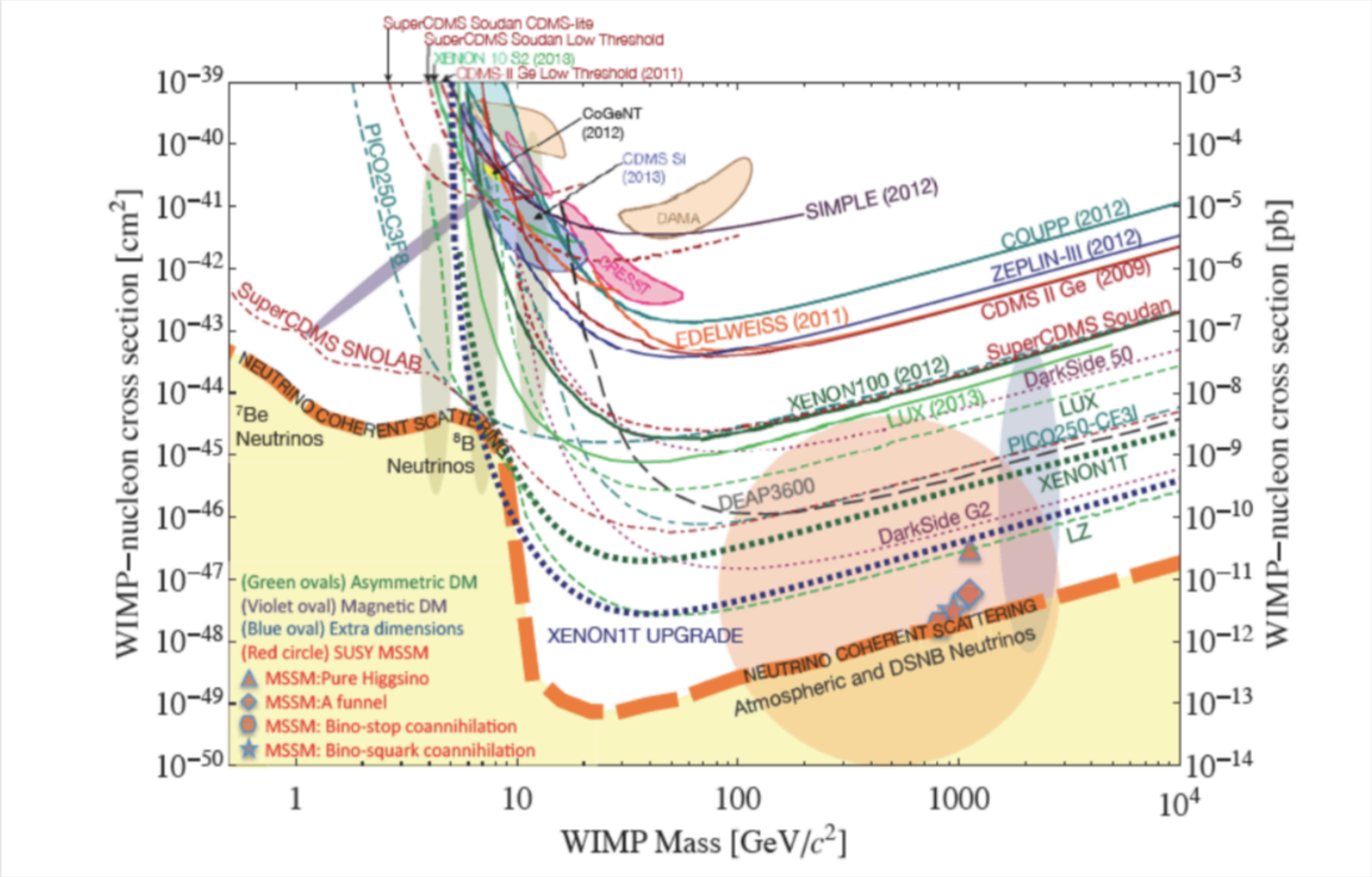
…and experimental aspects…

- 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

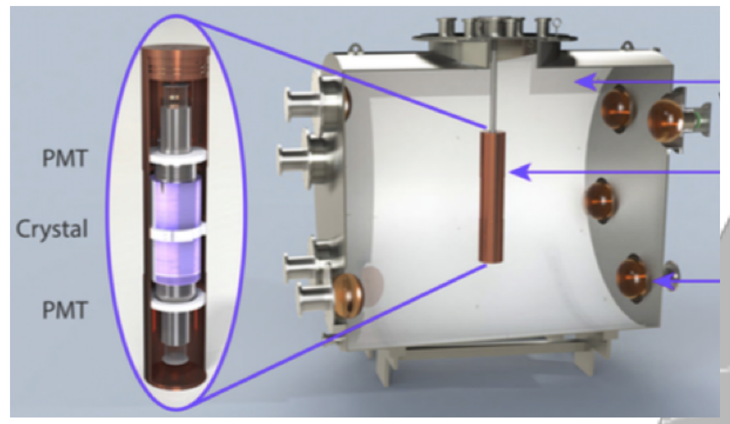
Is it an "universal" and "correct" way to approach the problem of DM and comparisons?

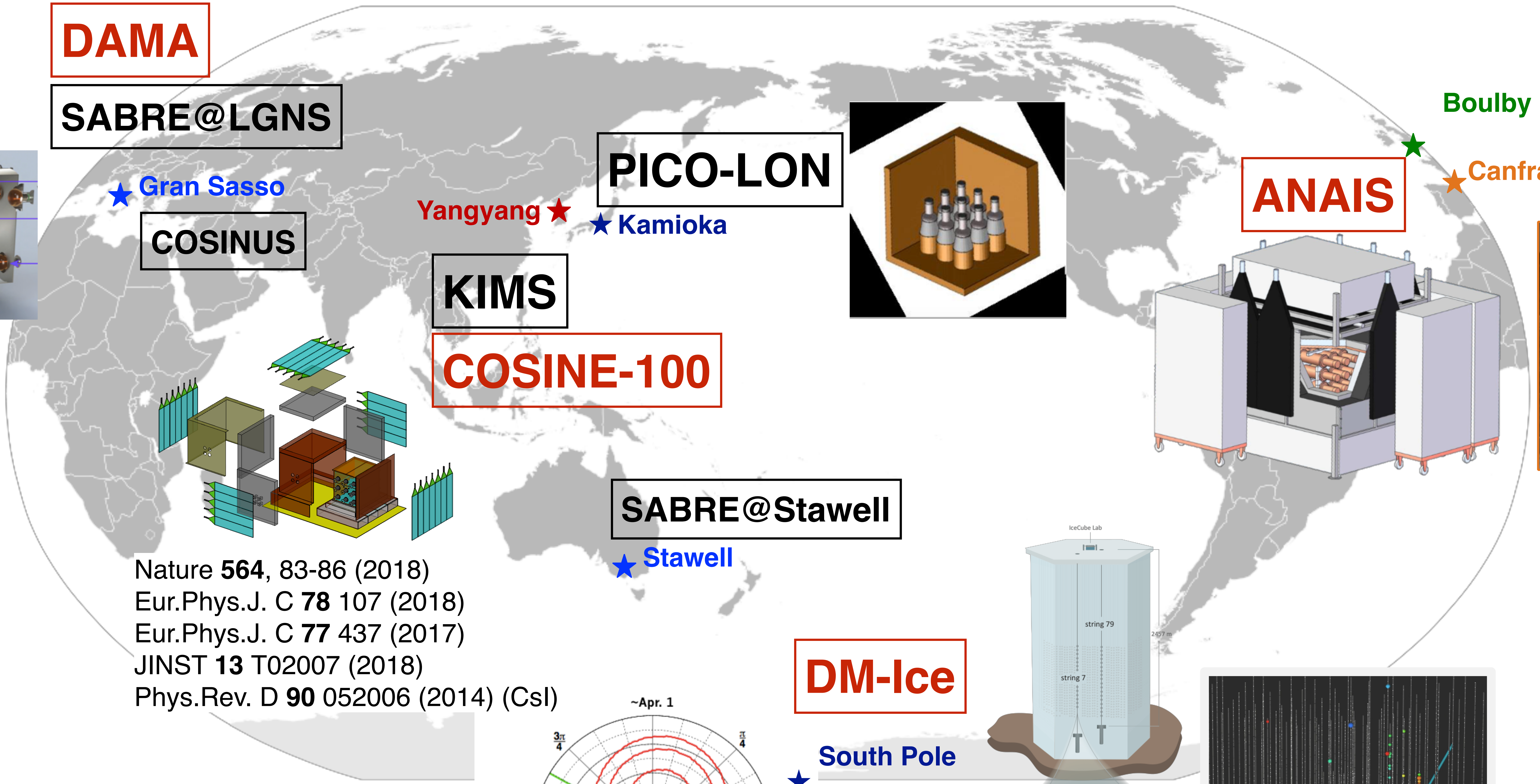


No, it isn't. This is just a largely arbitrary/partial/incorrect exercise

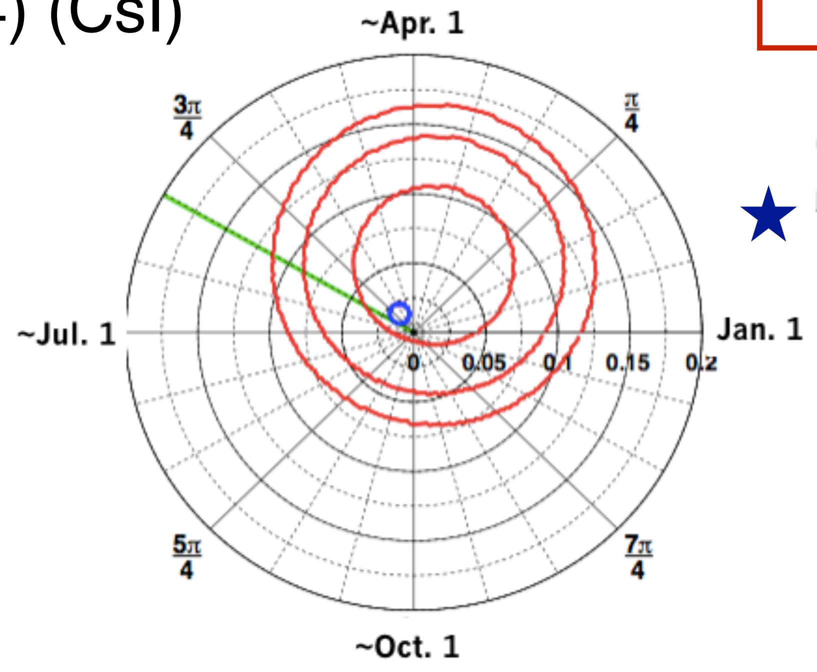
Need to directly test DAMA's result with the same target material

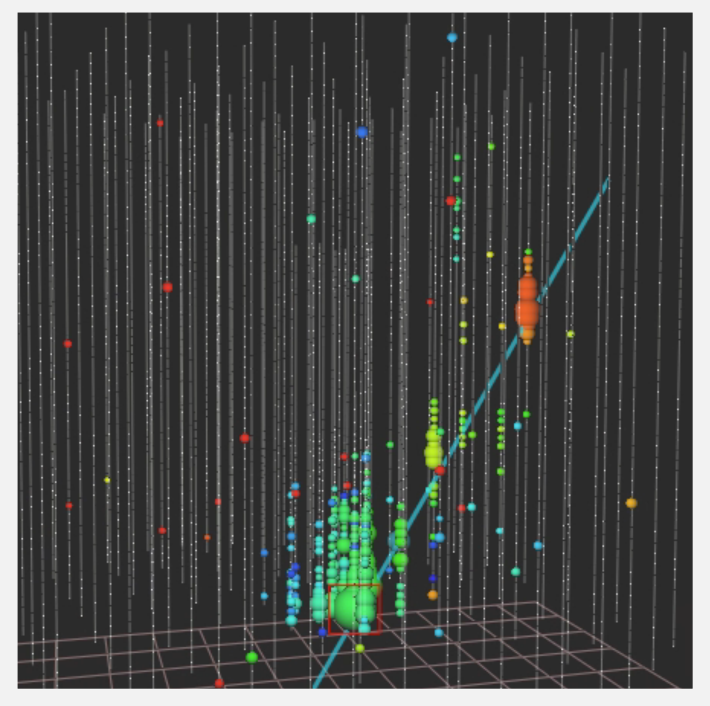
Global NaI(Tl) efforts





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)



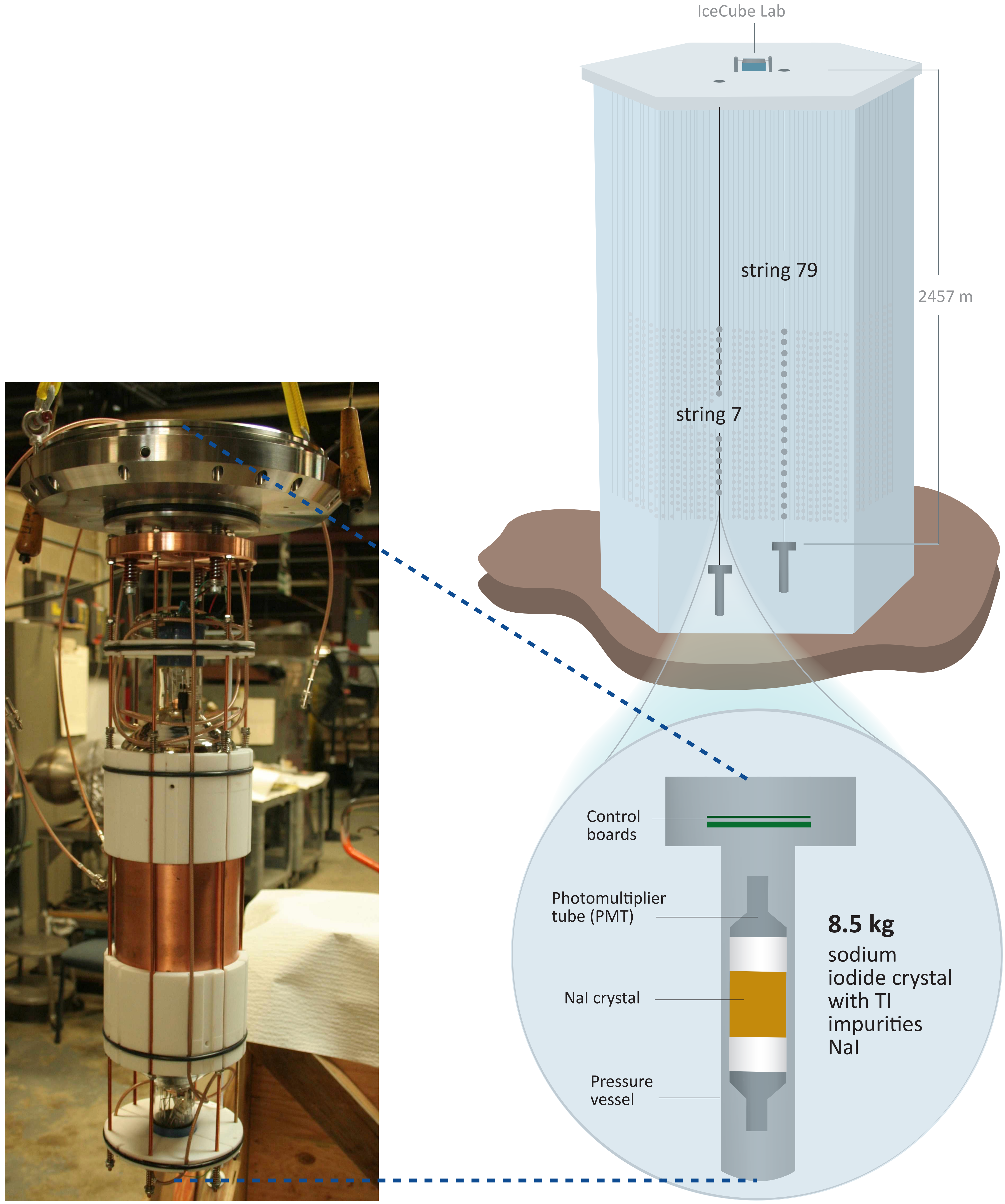


Astropart. Phys. **35** (2012) 749
Phys. Rev. D **90** 092005 (2014)
Phys. Rev. D **93** 042001 (2016)
Phys. Rev. D **95** 032006 (2017)

DM-Ice17: NaI(Tl) prototype experiment at South Pole

DM-Ice17 experiment

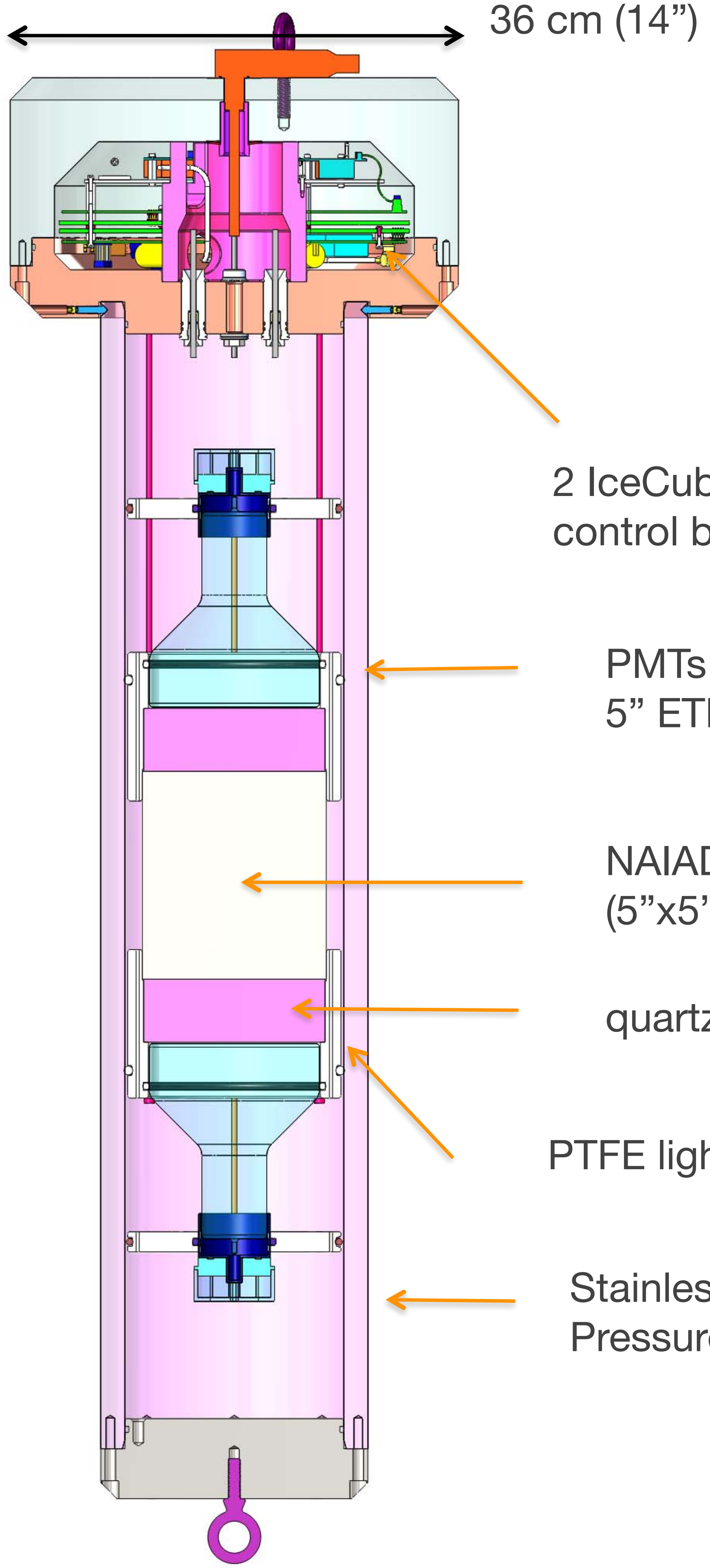
- Located at South Pole
- Two 8.5 kg NaI(Tl) crystals
- Installed: Dec. 2010, Physics run: Jun. 2011 - Jan. 2015
- Goals:
  - Demonstrate the feasibility of deploying and operating NaI(Tl) detectors in the Antarctic ice for a dark matter search
  - In situ measurement of the radiopurity of the Antarctic 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

DM-Ice17 detectors



2 IceCube mainboards + HV control boards

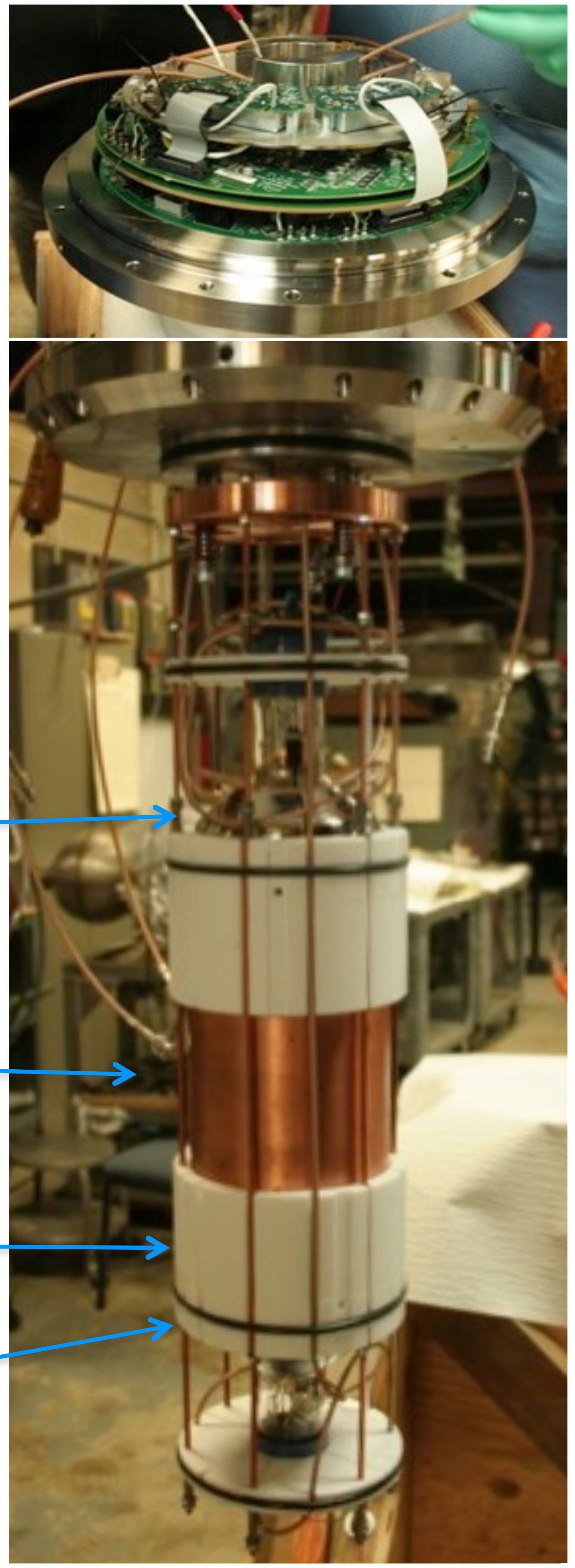
PMTs:
5" ETL 9390UKB

NAIAD NaI Crystal
(5"x5", 8.5 kg)

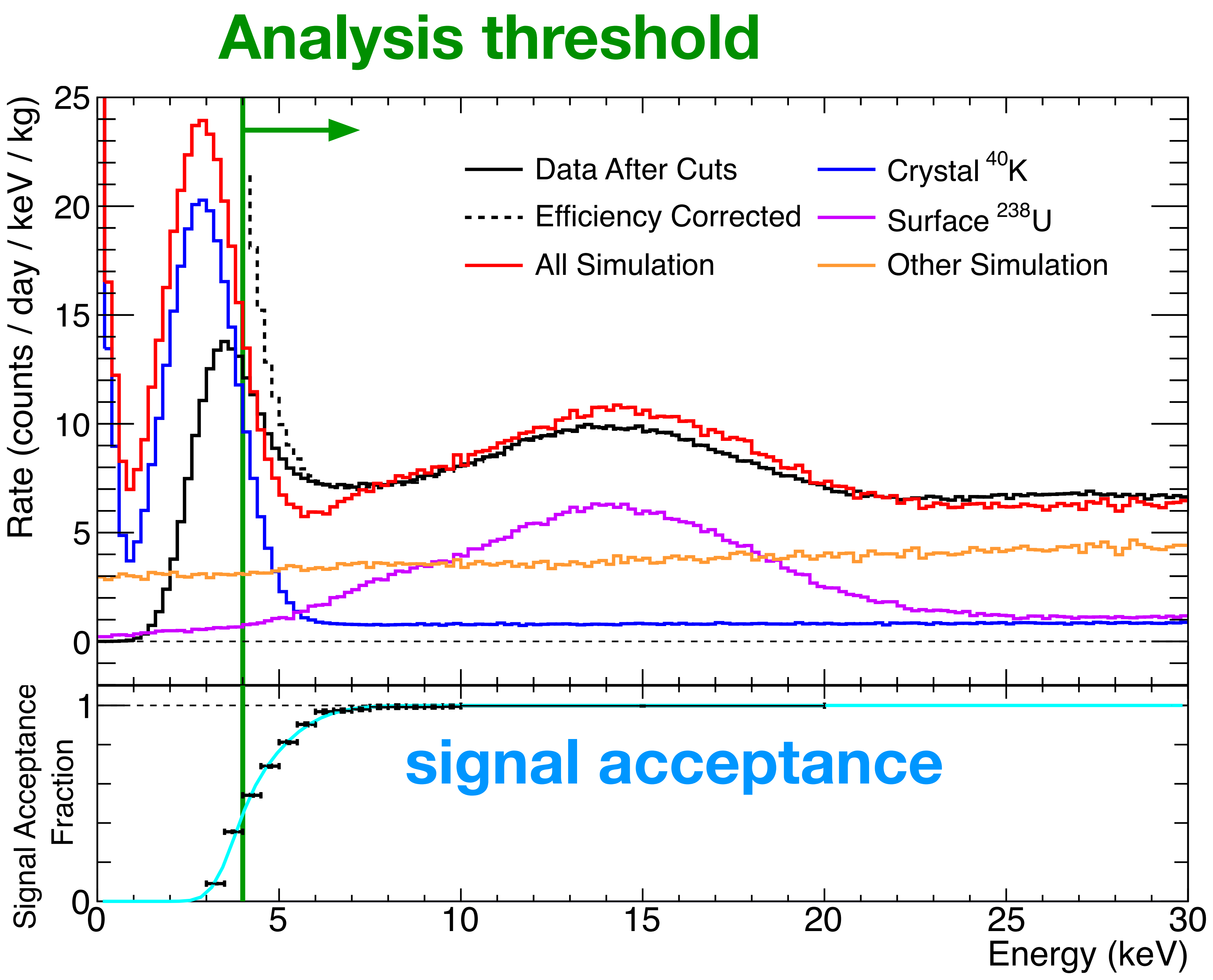
quartz light guides

PTFE light reflectors

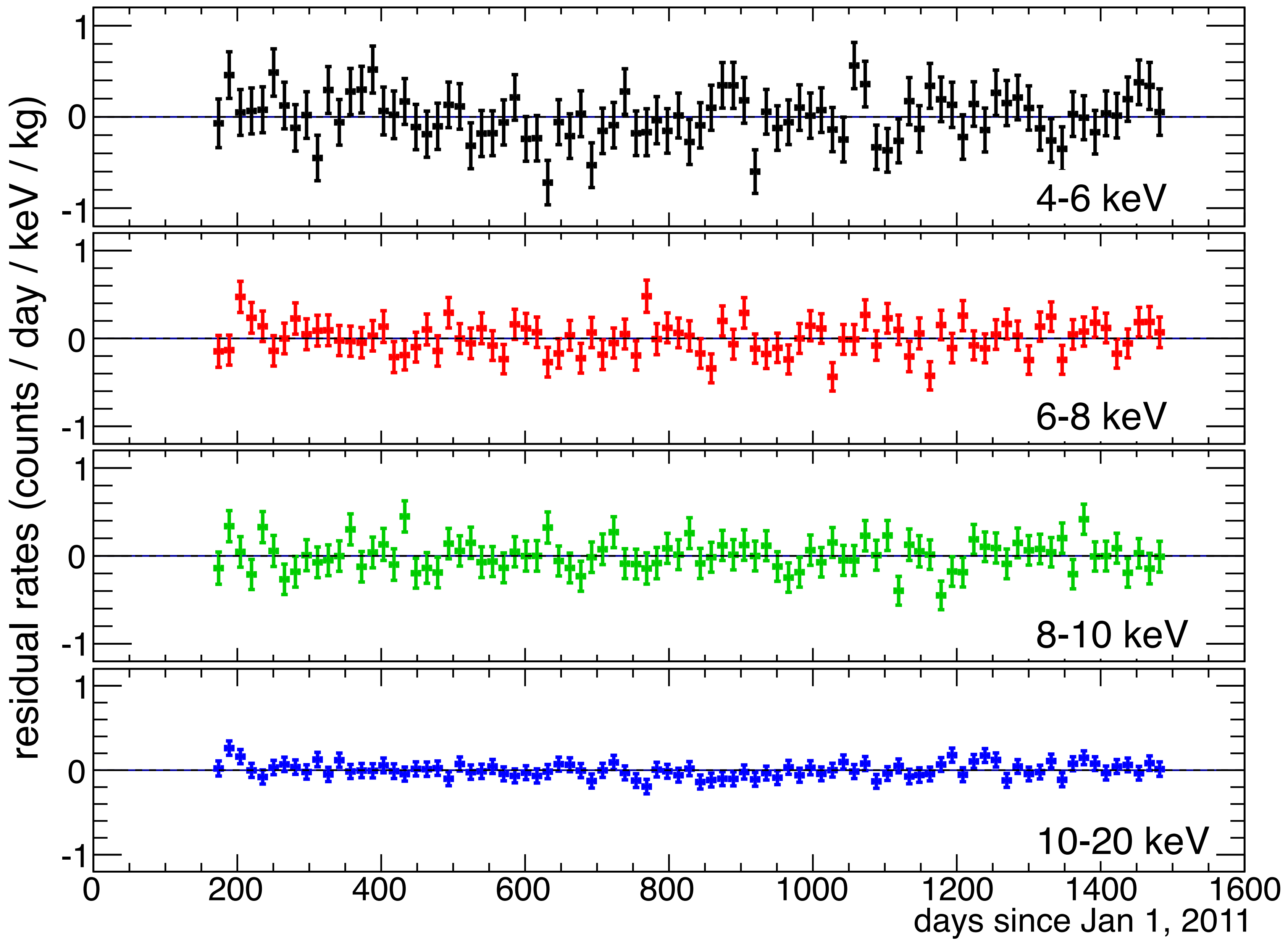
Stainless Steel
Pressure Vessel



- 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



Barbosa de Souza *et al*., Phys. Rev. D **95**, 032006 (2017)

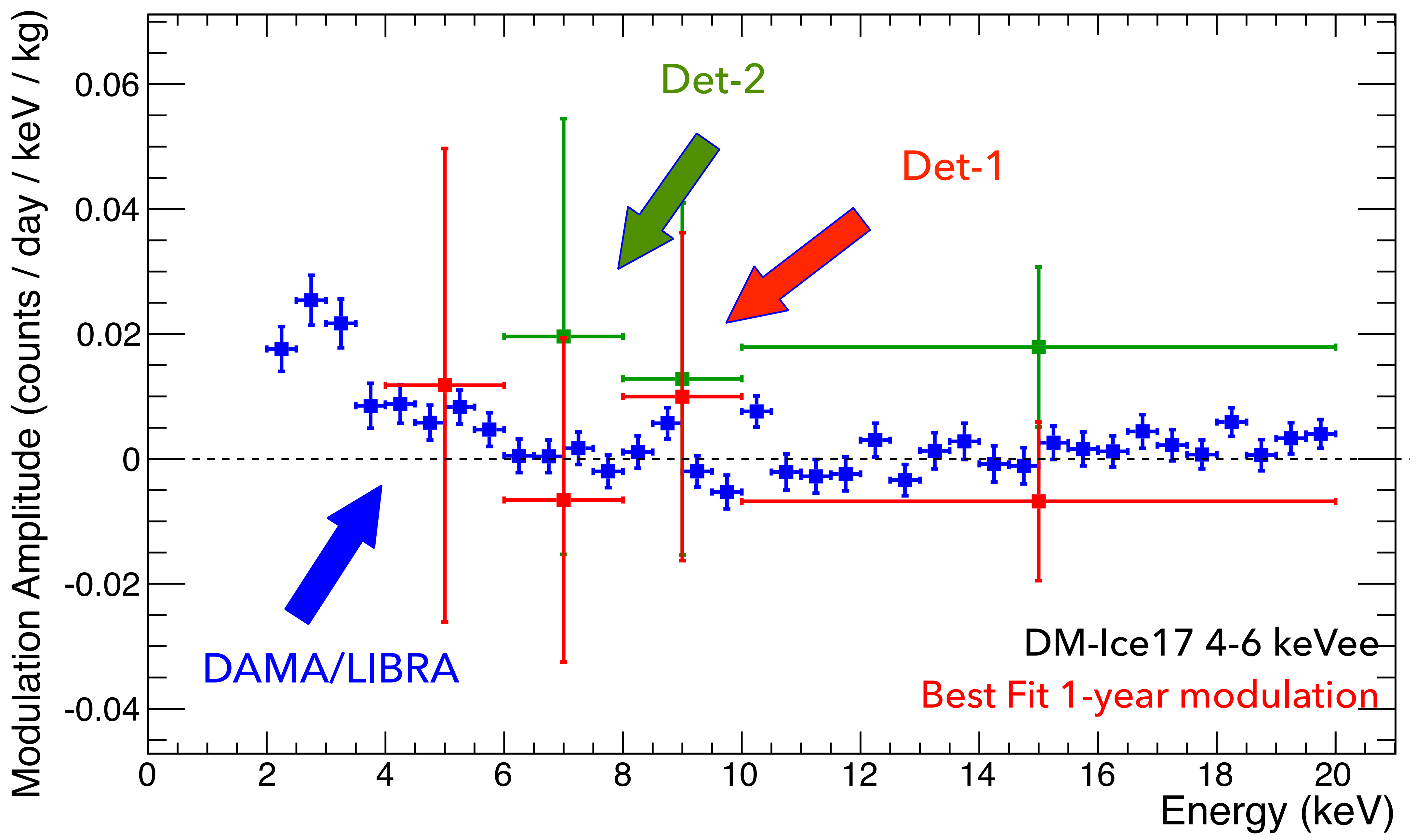


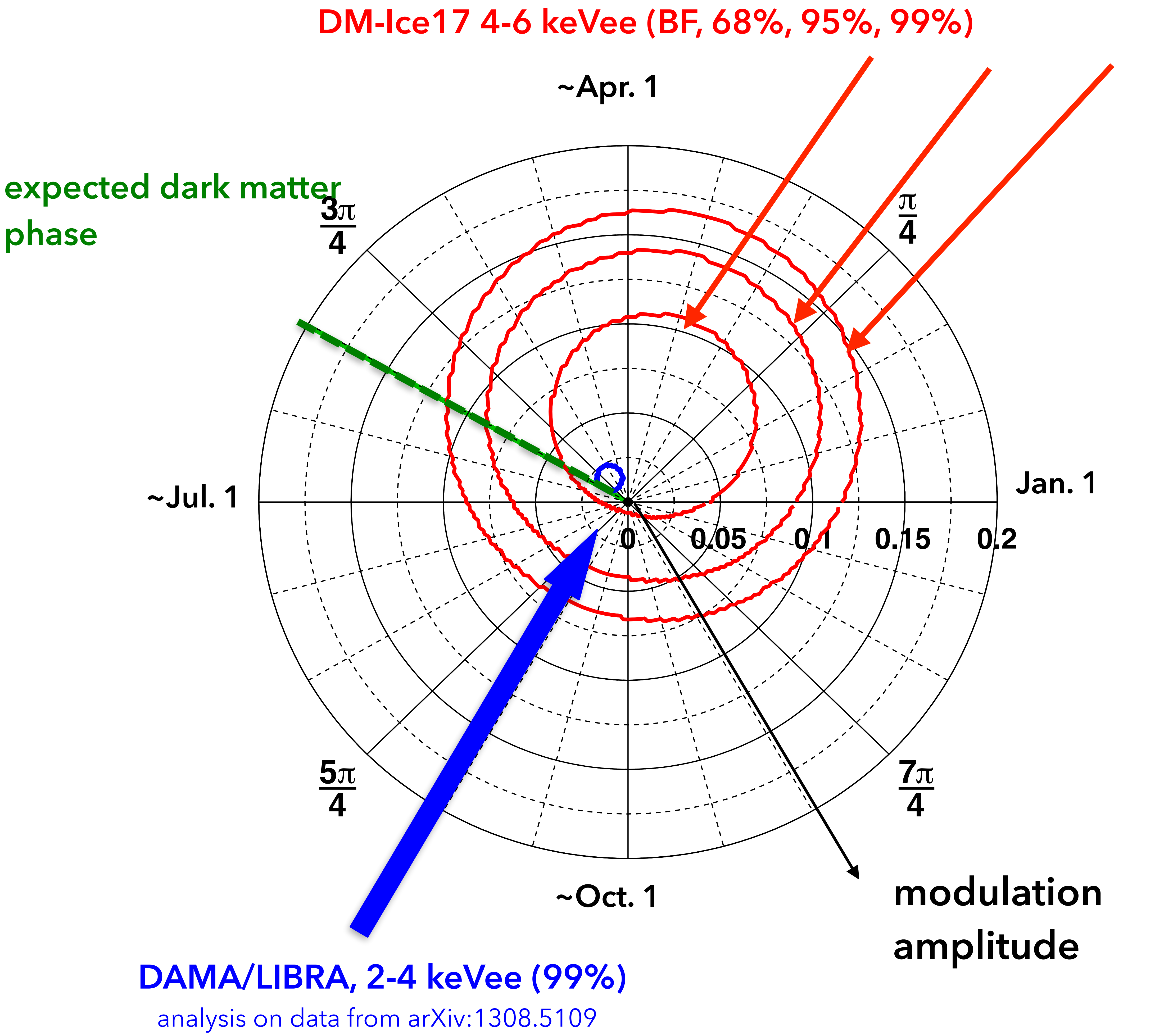
Annual modulation allowed region

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

Barbosa de Souza *et al.*, Phys. Rev. D **95**, 032006 (2017)

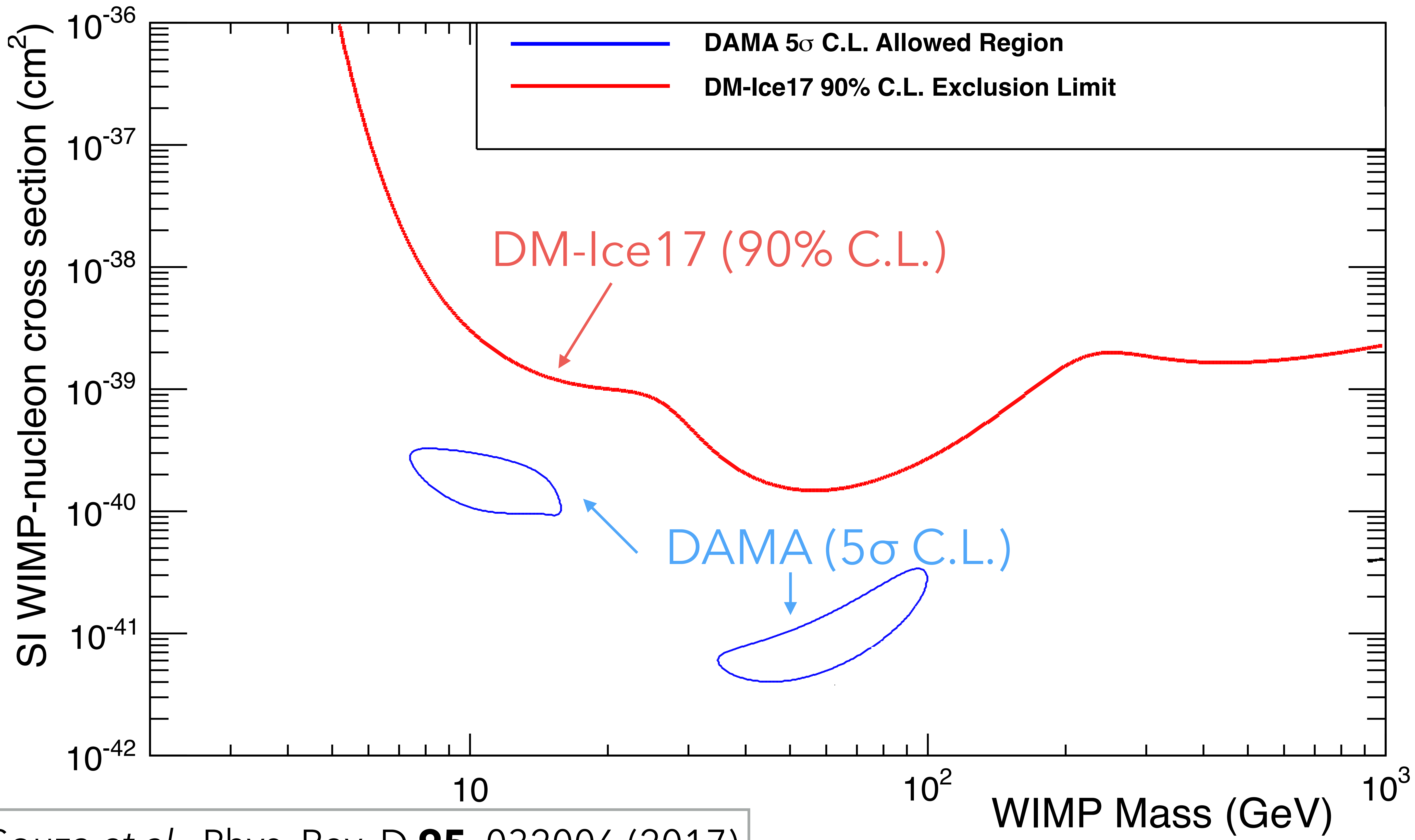




DM-Ice17 exclusion limit

DM-ICE

- The strongest exclusion limit in the Southern Hemisphere
- To test DAMA result, more mass, lower background, and lower analysis threshold are required

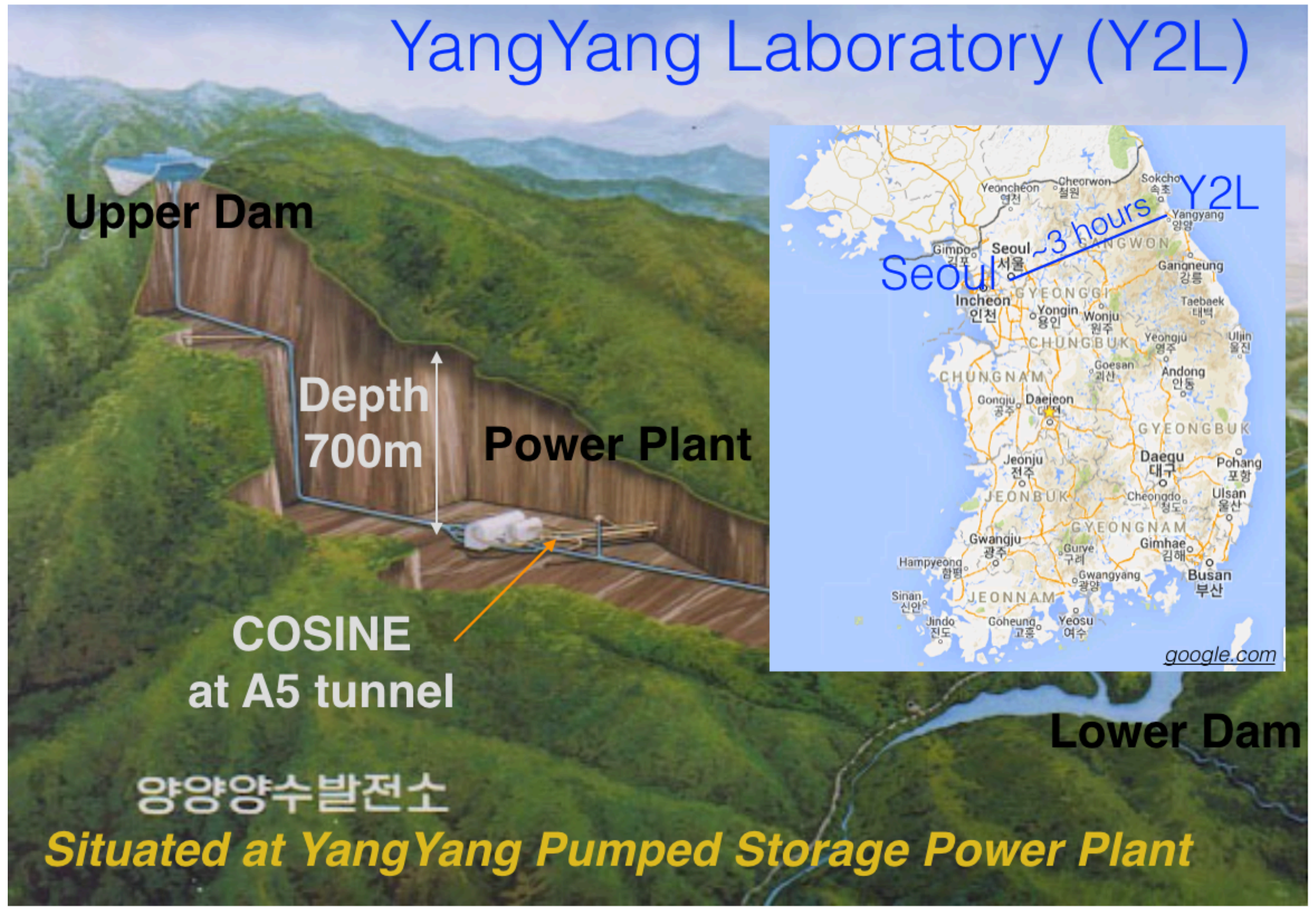


Barbosa de Souza *et al.*, Phys. Rev. D **95**, 032006 (2017)

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

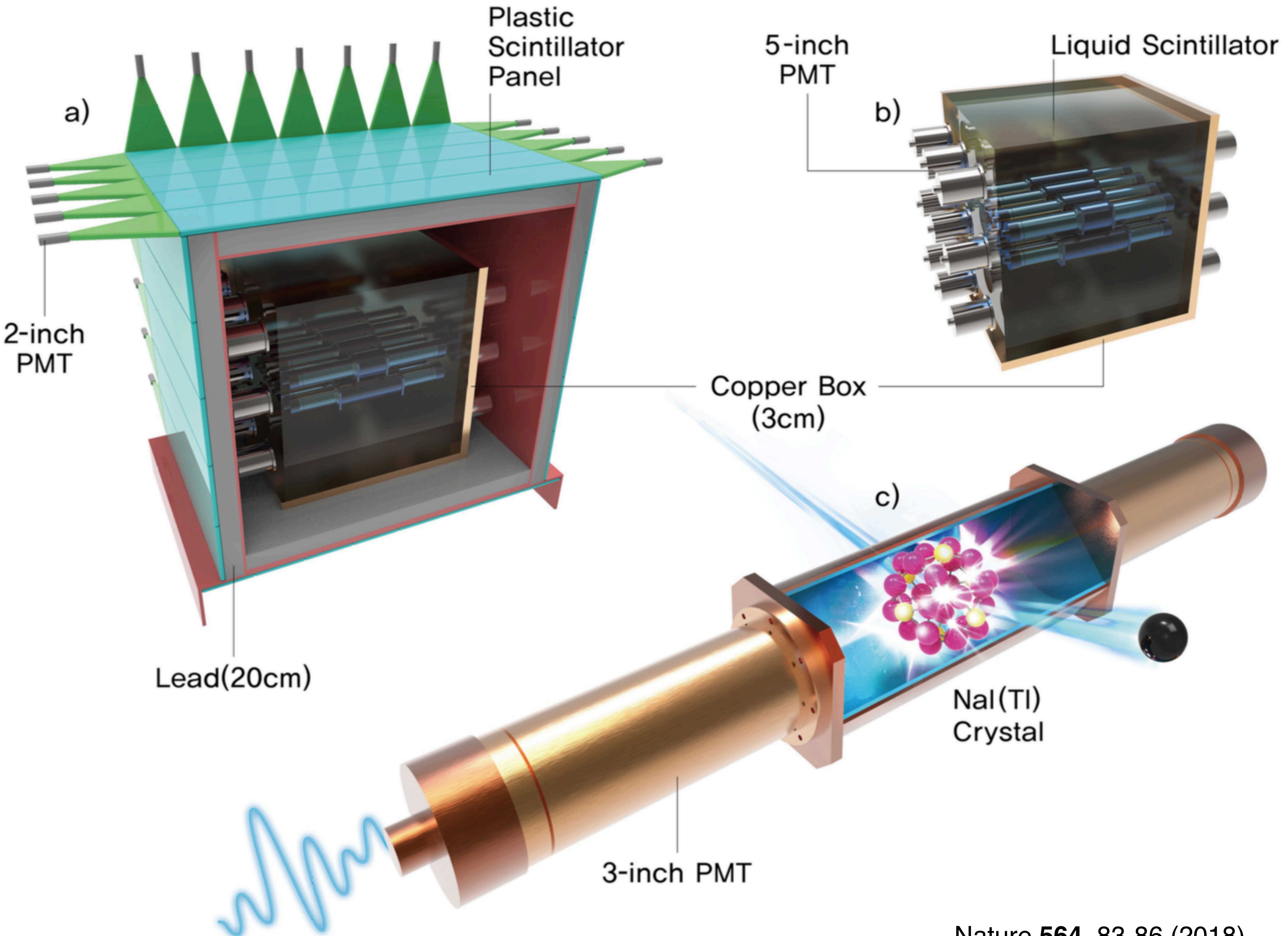
COSINE-100

- 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**



COSINE-100 detector configuration

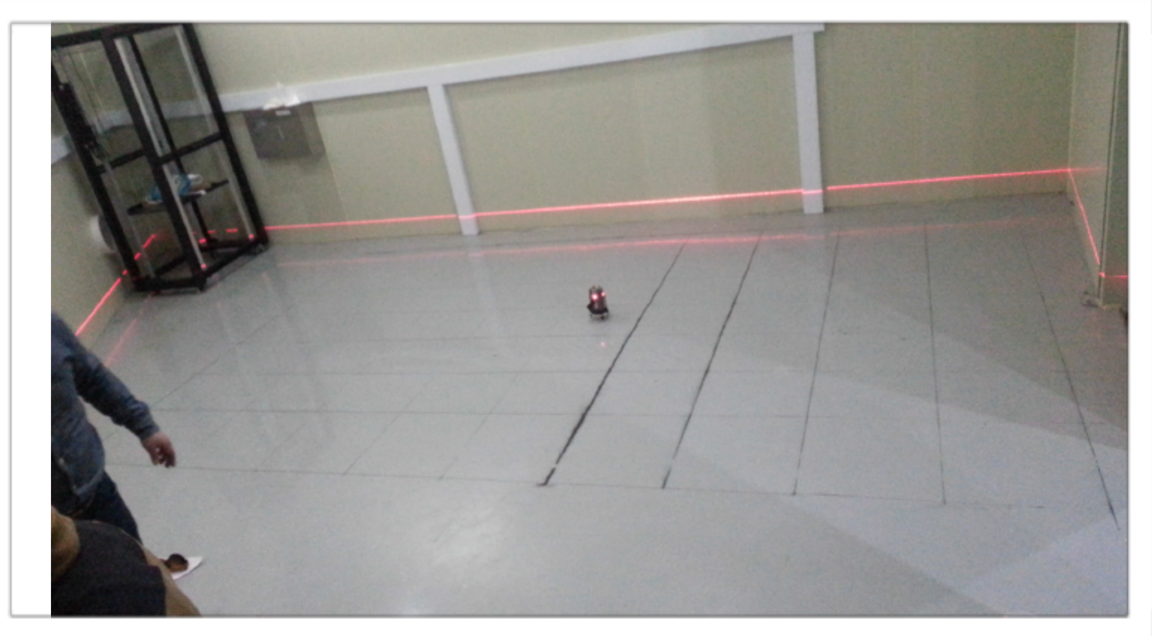
- 37 plastic scintillator panels to tag muons events
- 20cm thick lead shielding and 3cm thick copper box
- 2000L of liquid scintillator to tag internal/external background events
- 8 NaI(Tl) crystals



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

COSINE-100 construction timeline

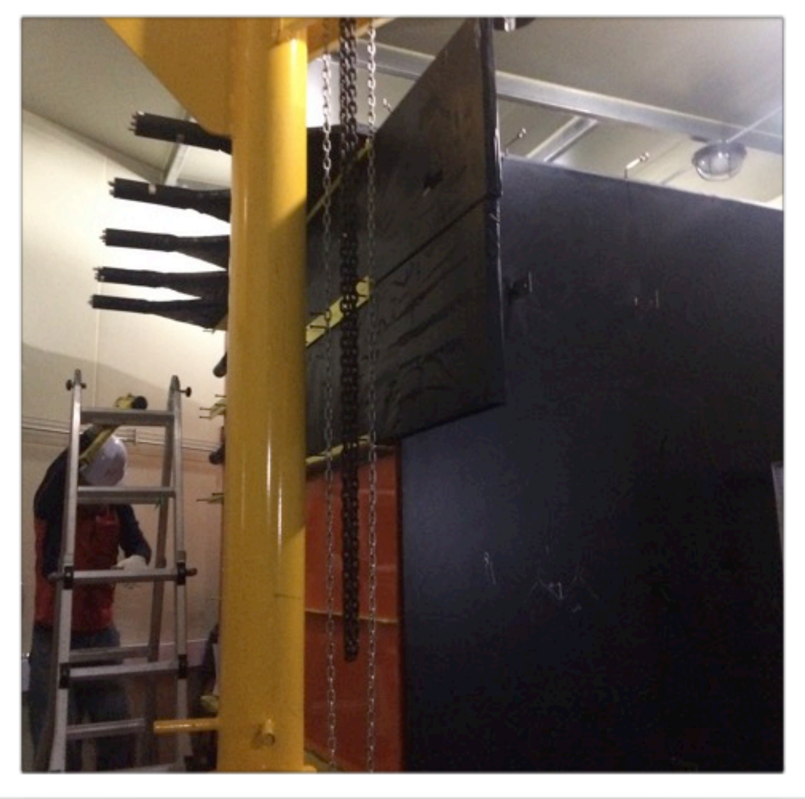
Dec. 2015

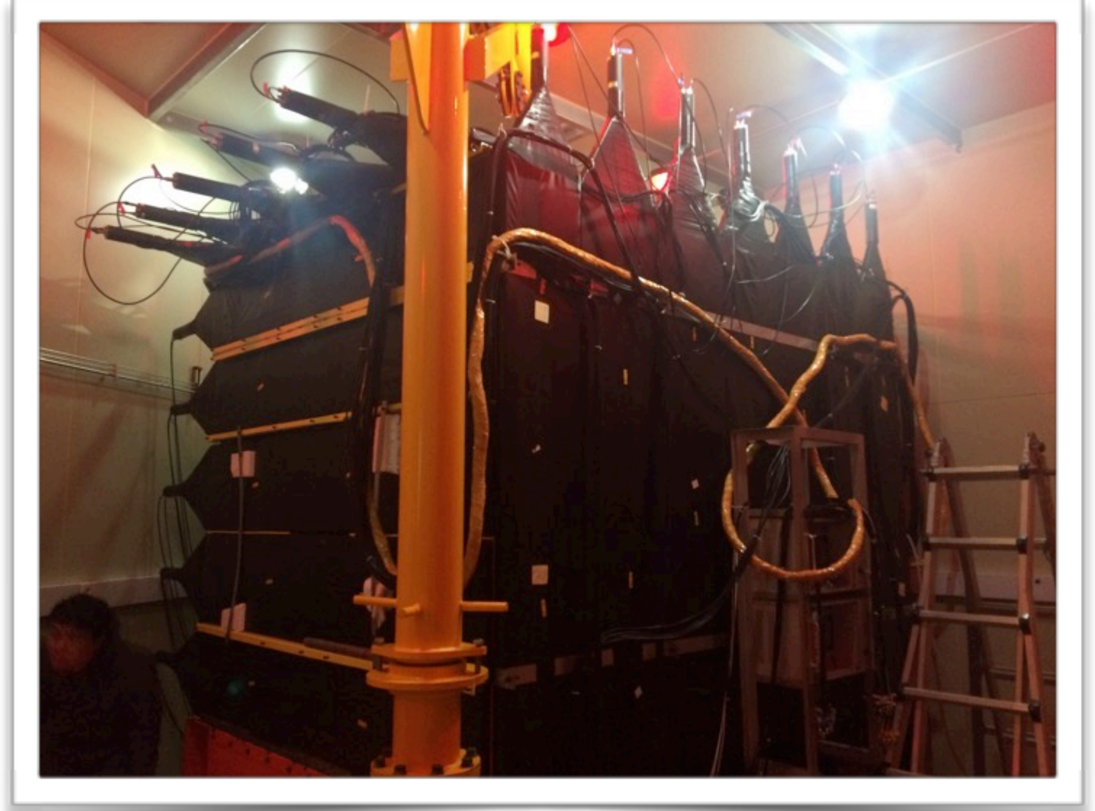


Jan. 2016

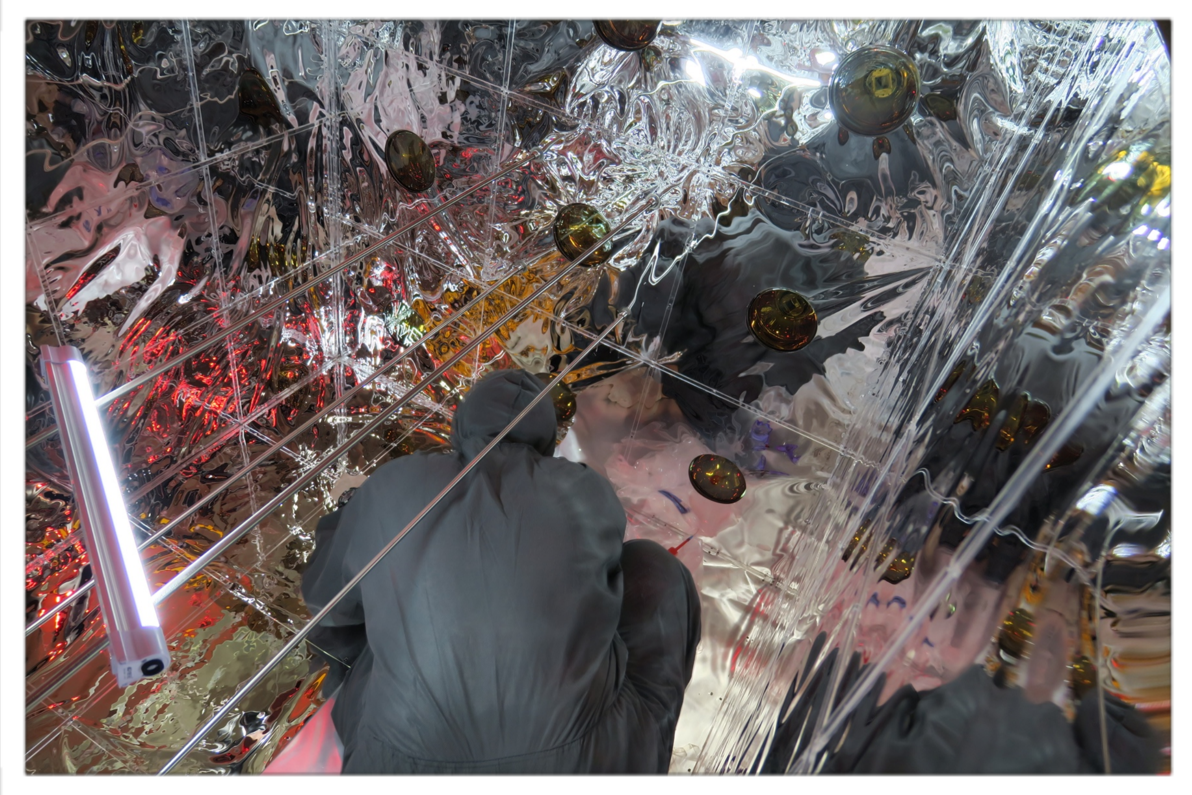
Feb. 2016

Mar. 2016

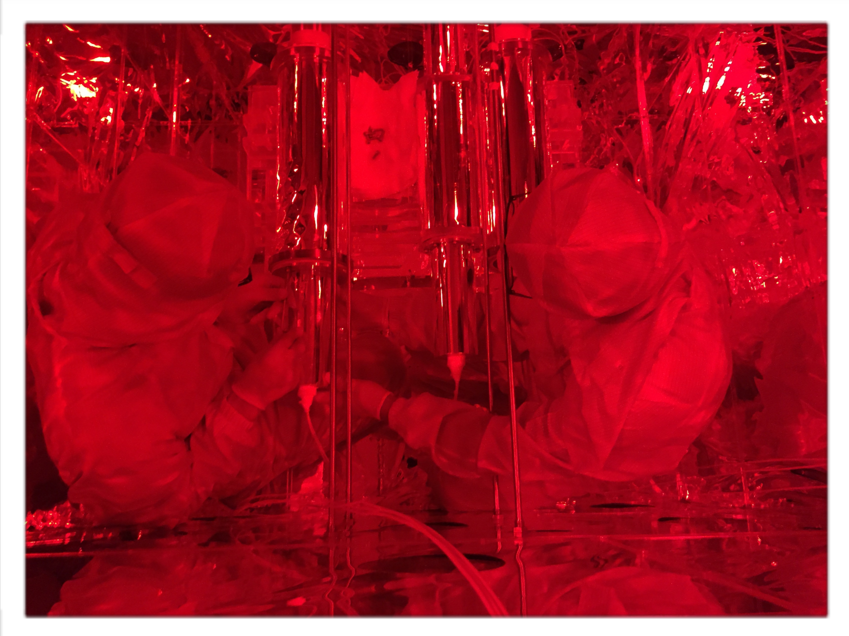




Apr. 2016

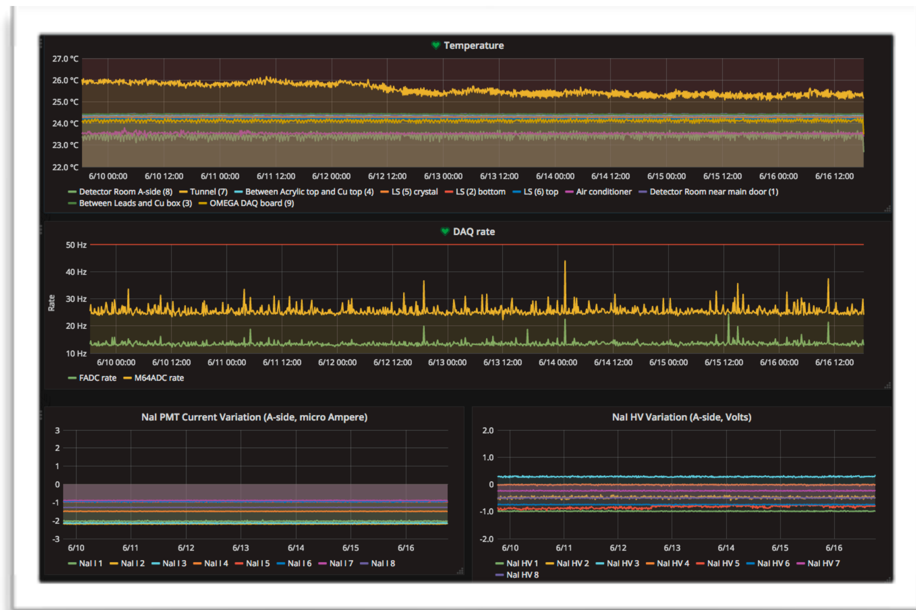


May. 2016

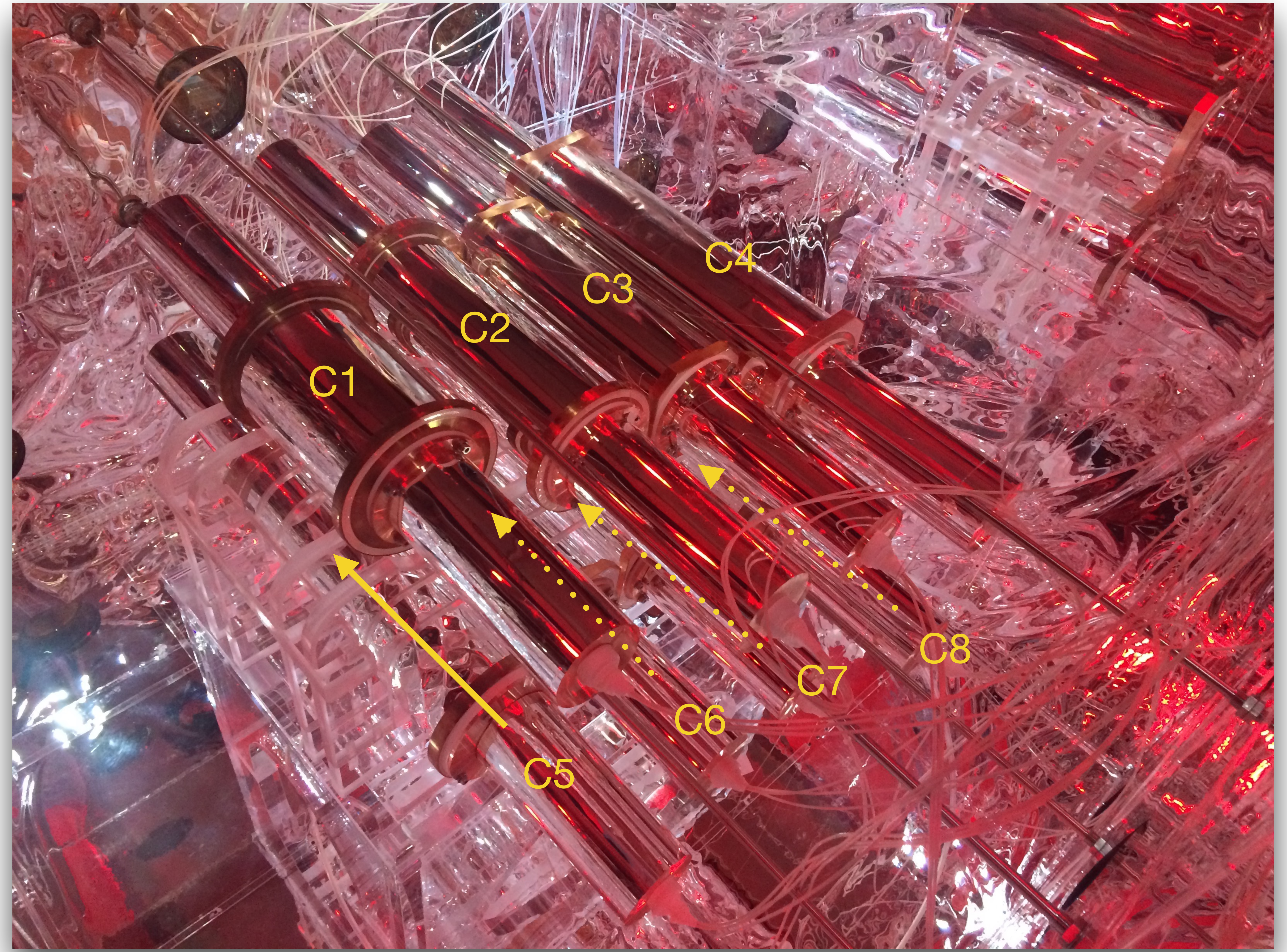


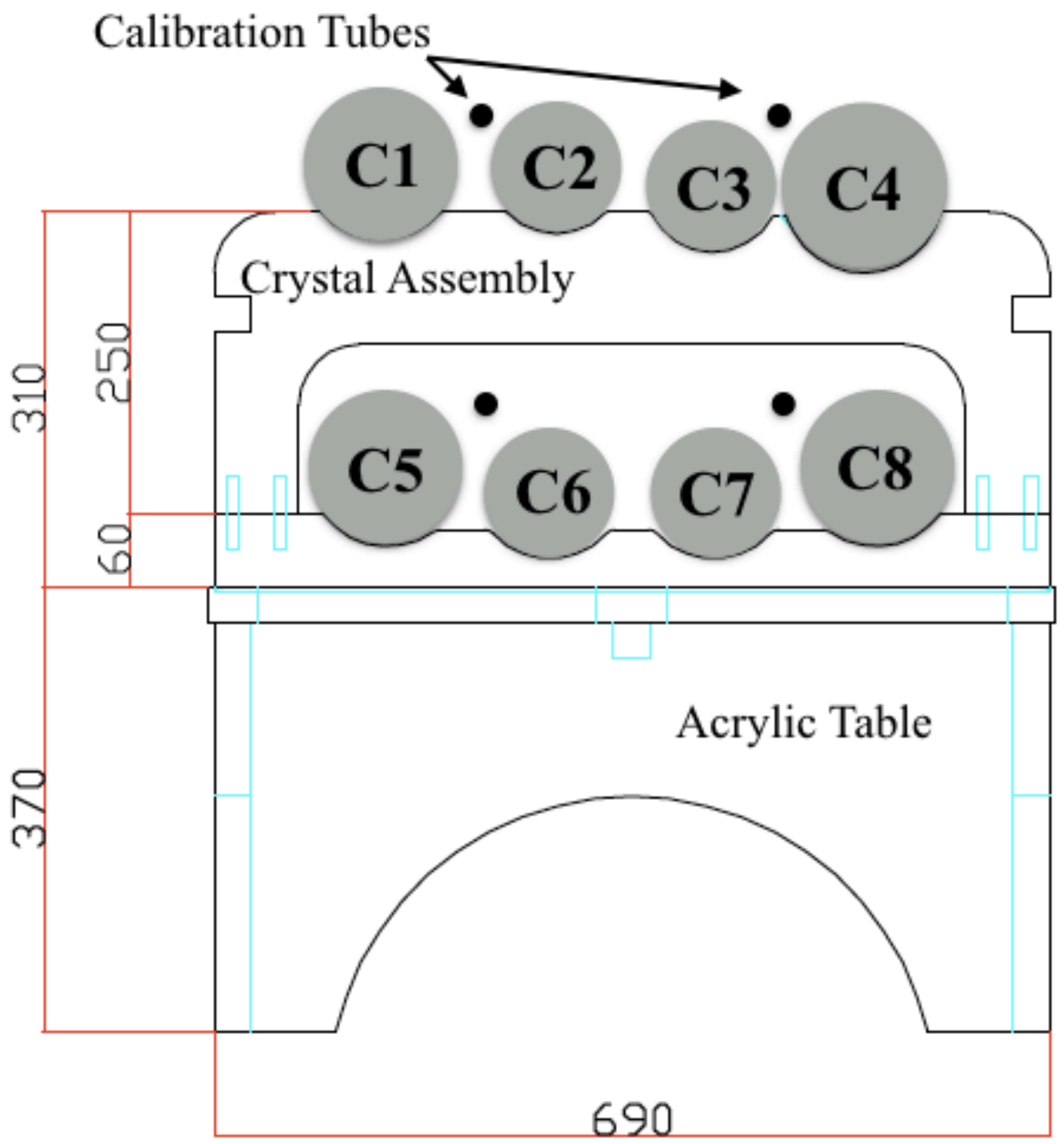
Jun. 2016

Sep. 2016



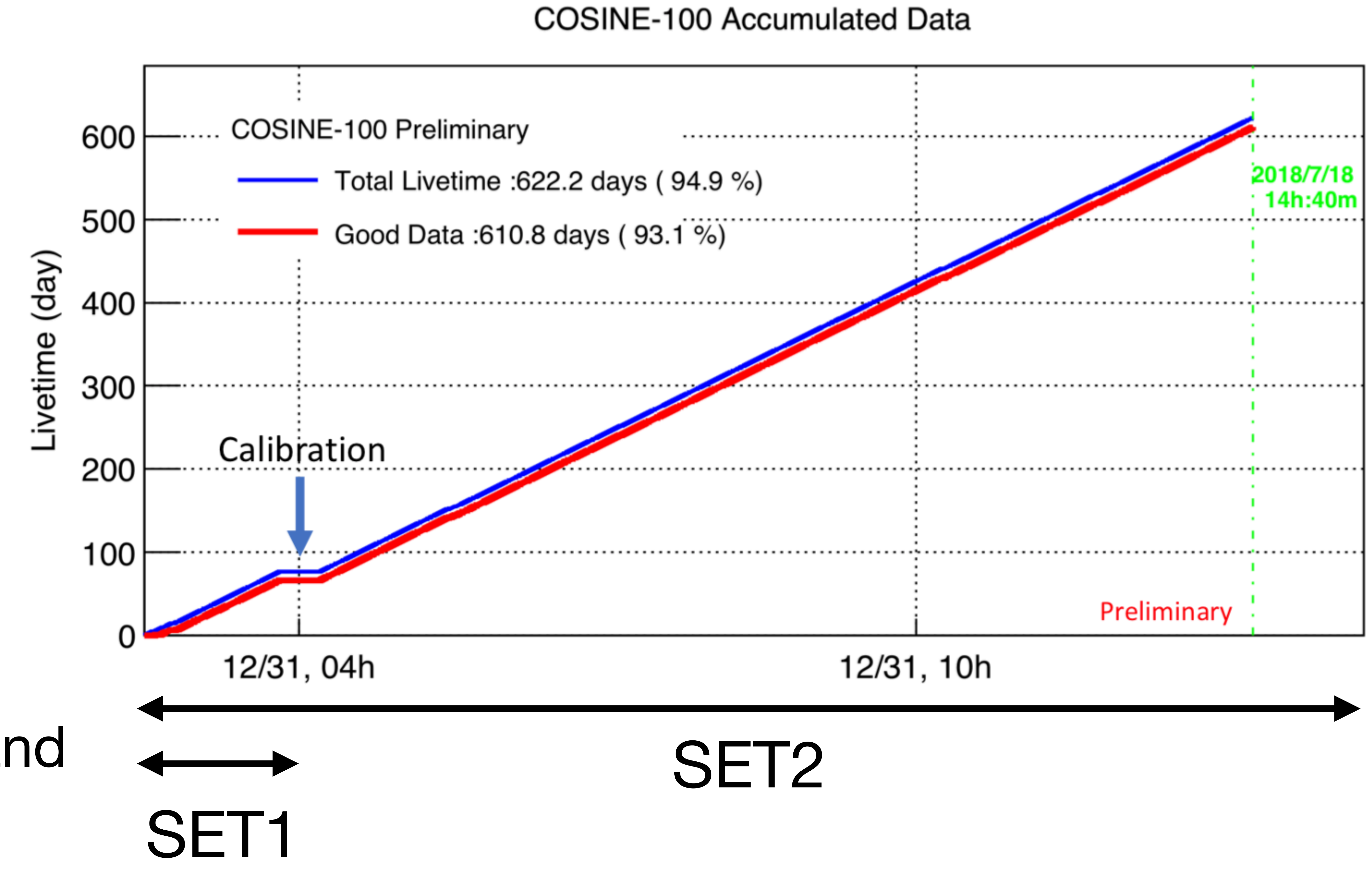
Crystal configuration





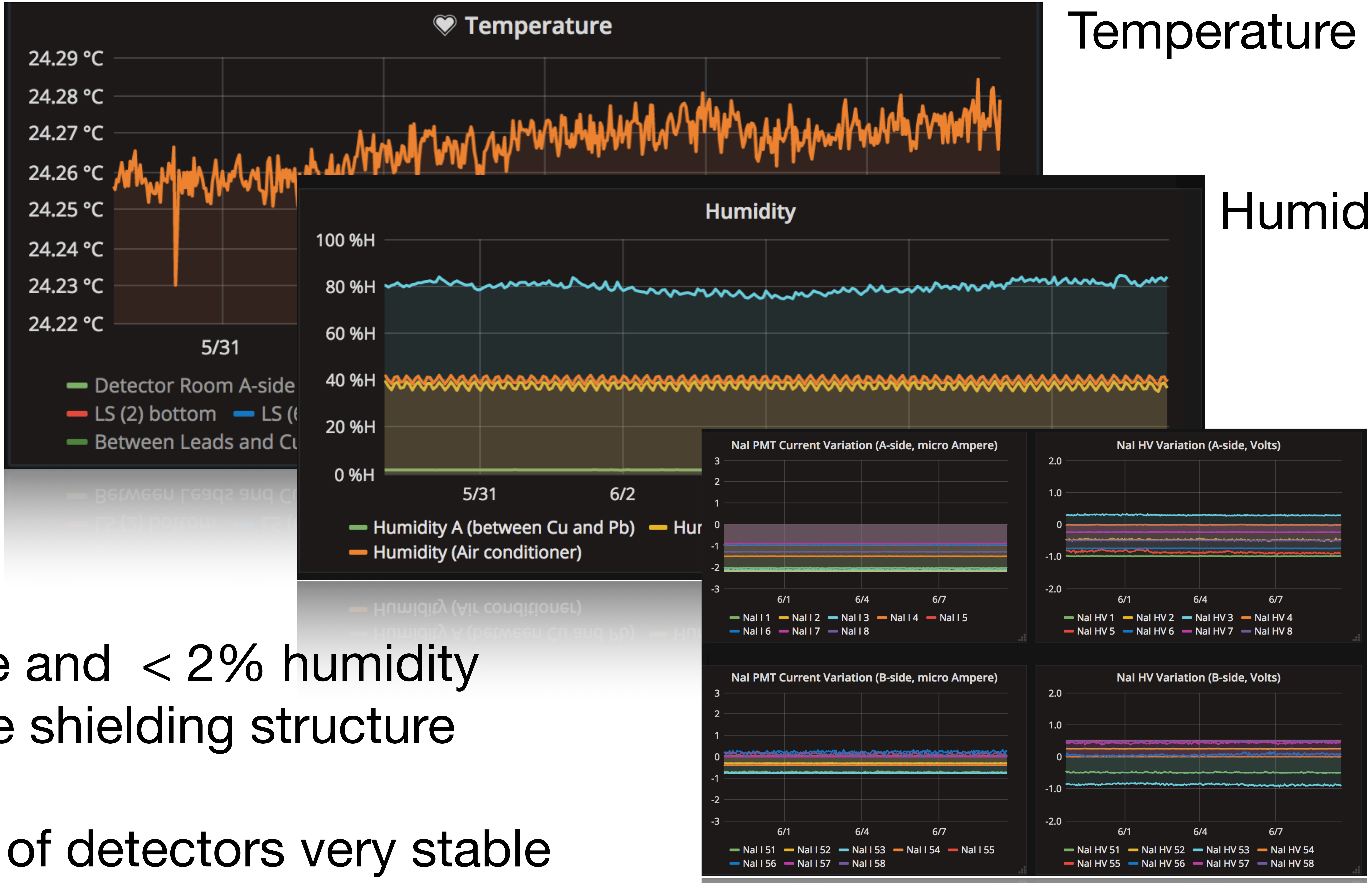
COSINE-100 operation

- Data taking since Sep. 2016
  - Stable operation
  - ~90% live time
  - Near 100% uptime outside of calibration
- > 22 months of data accumulation
  - SET1 data (59.5 days) - Background modeling, detector understanding, and WIMP analysis
  - SET2 data (> 720 days) - Annual modulation analysis



Environmental control/monitoring

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



Temperature

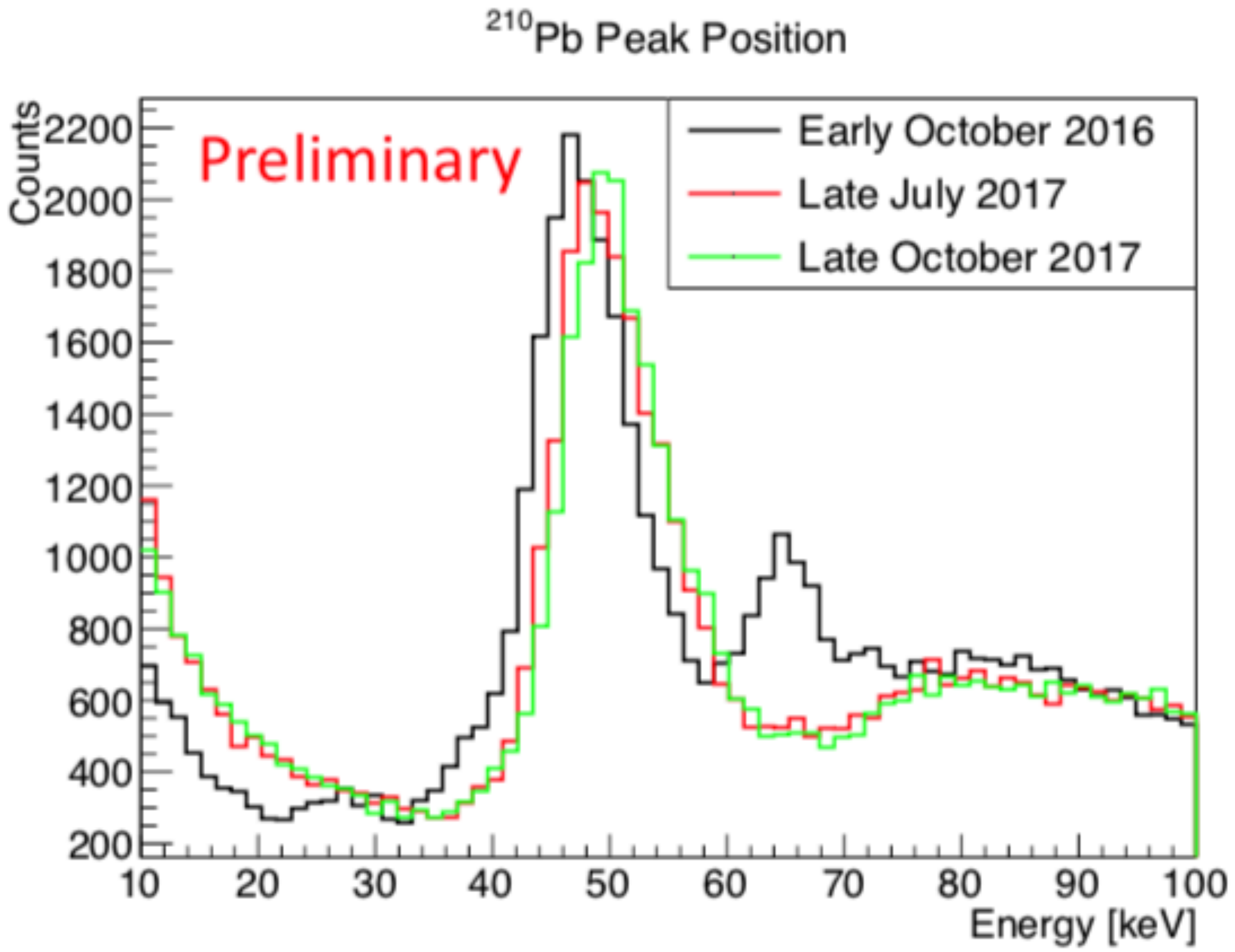
Humidity

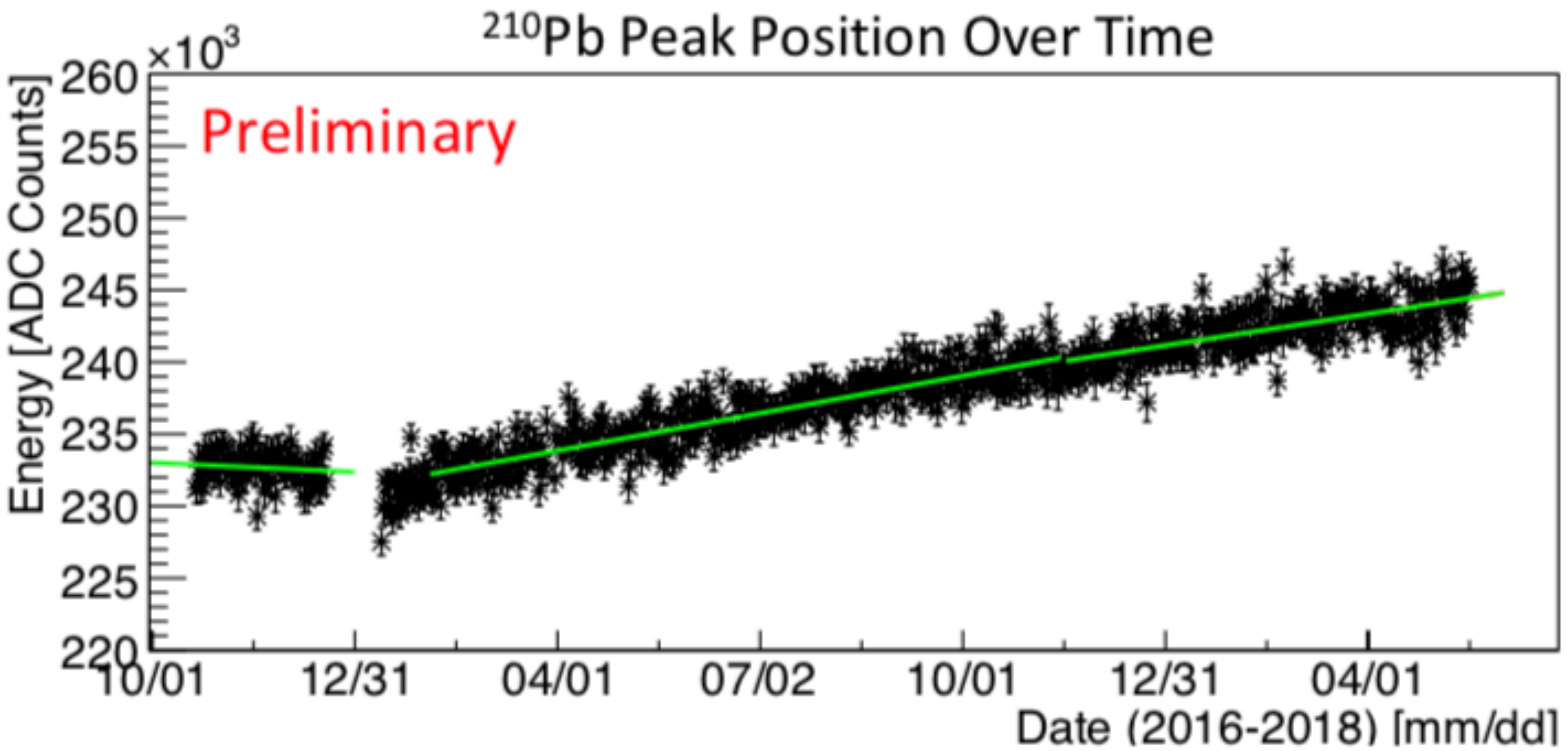
Current/Voltage

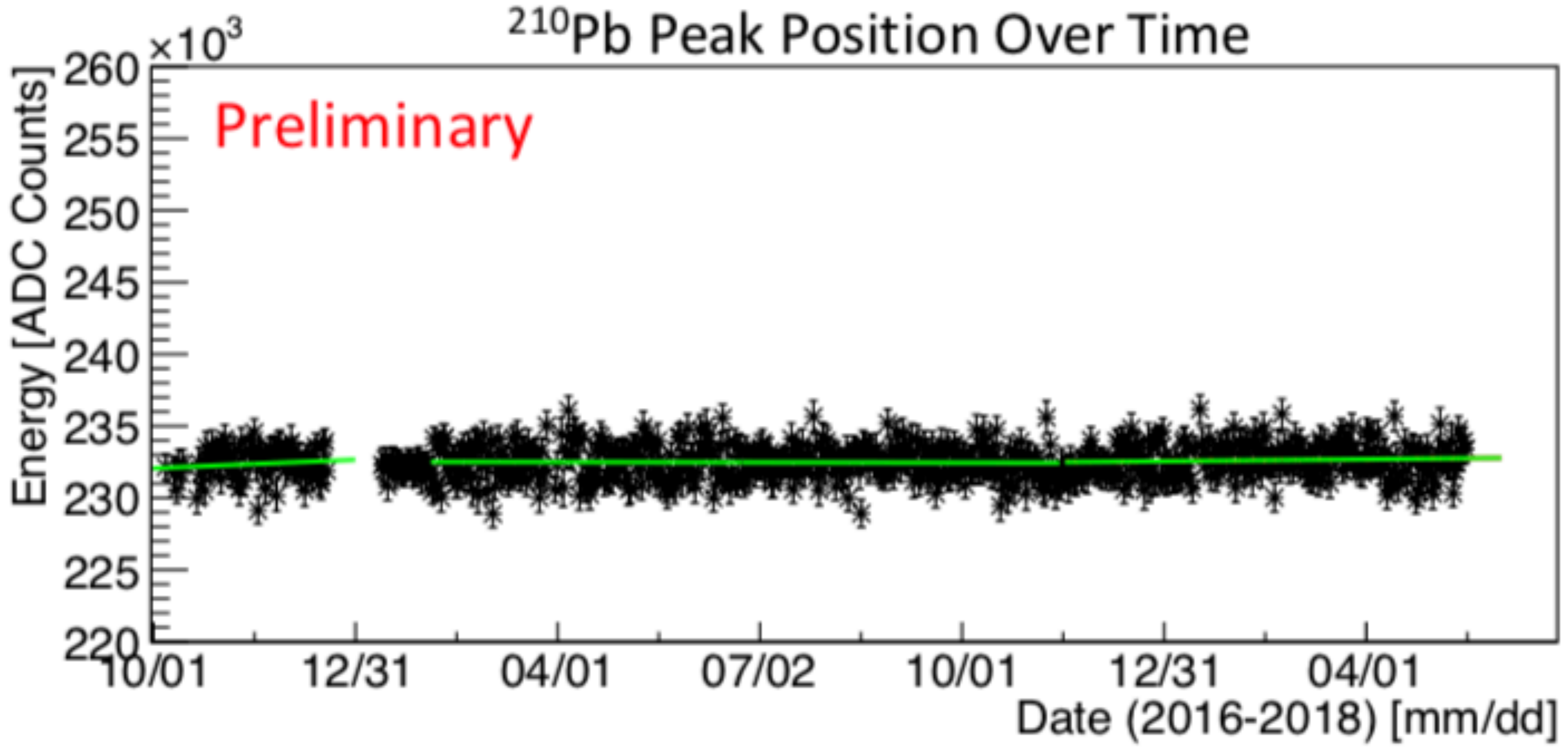
- < 0.5 ˚C temperature and < 2% humidity fluctuation inside the shielding structure
- Current and voltage of detectors very stable

Correcting for Gain Shifts

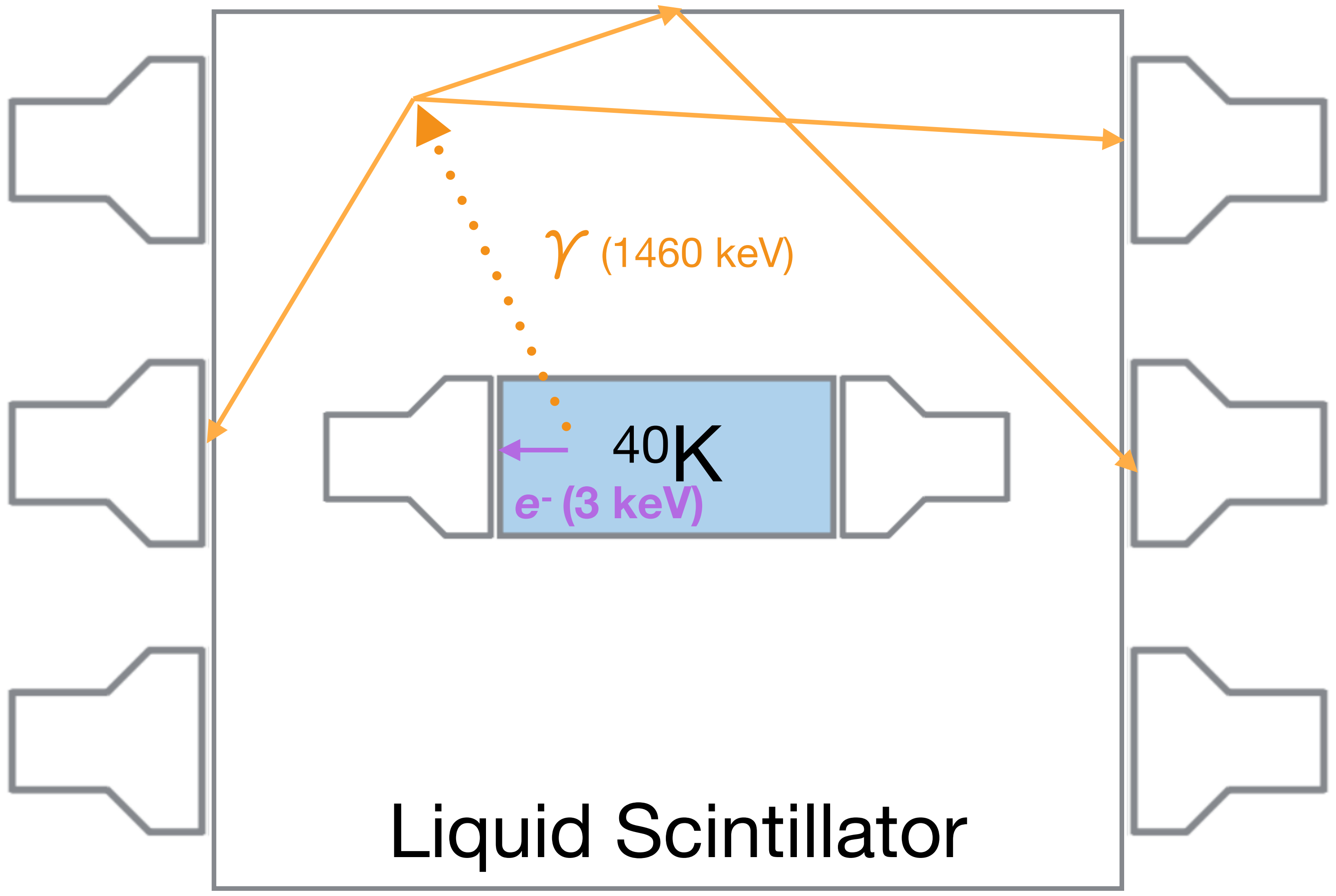
- Position of internal ^{210}Pb decays also monitored over time
- Gain shift corrected for by dividing out linear behavior

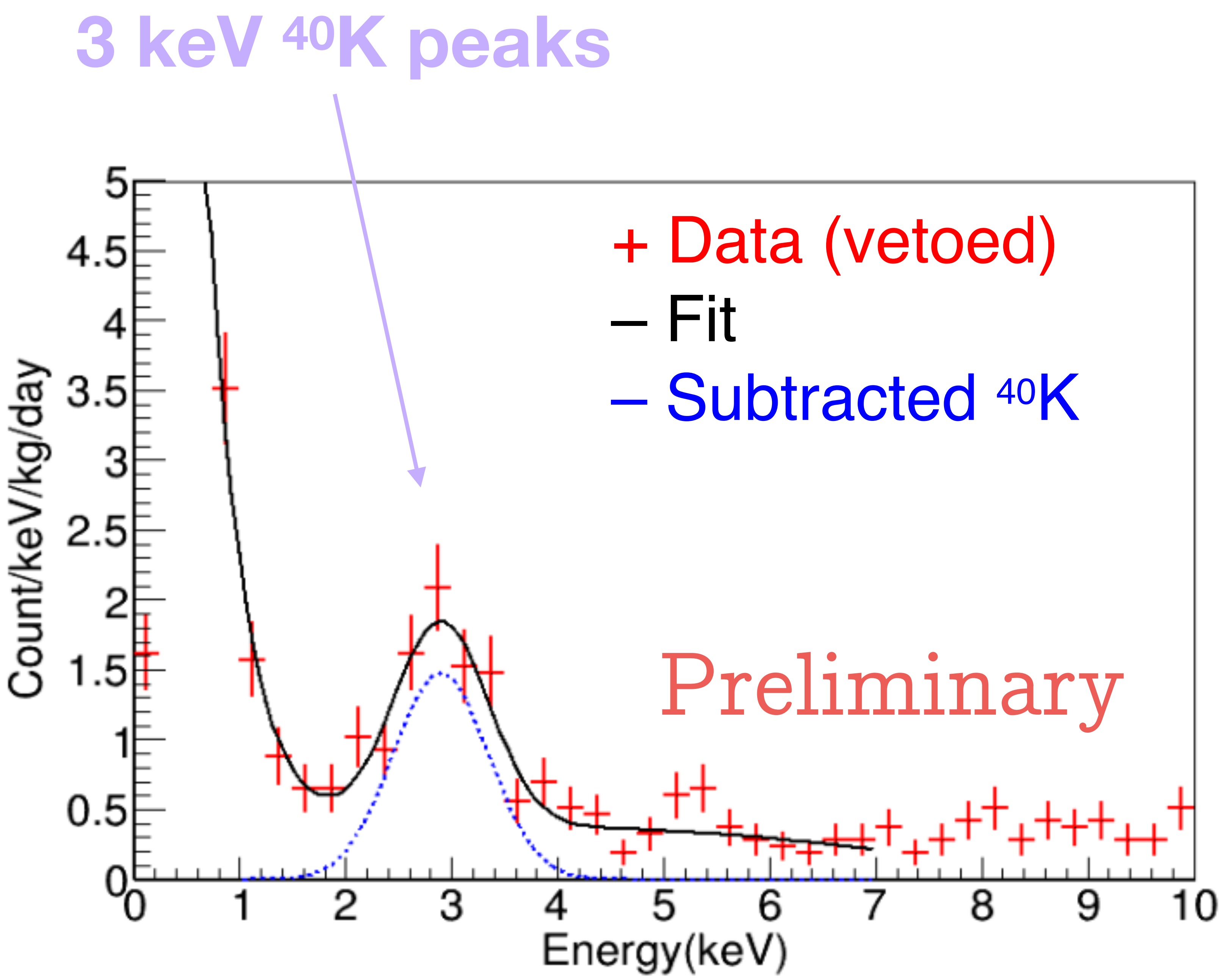


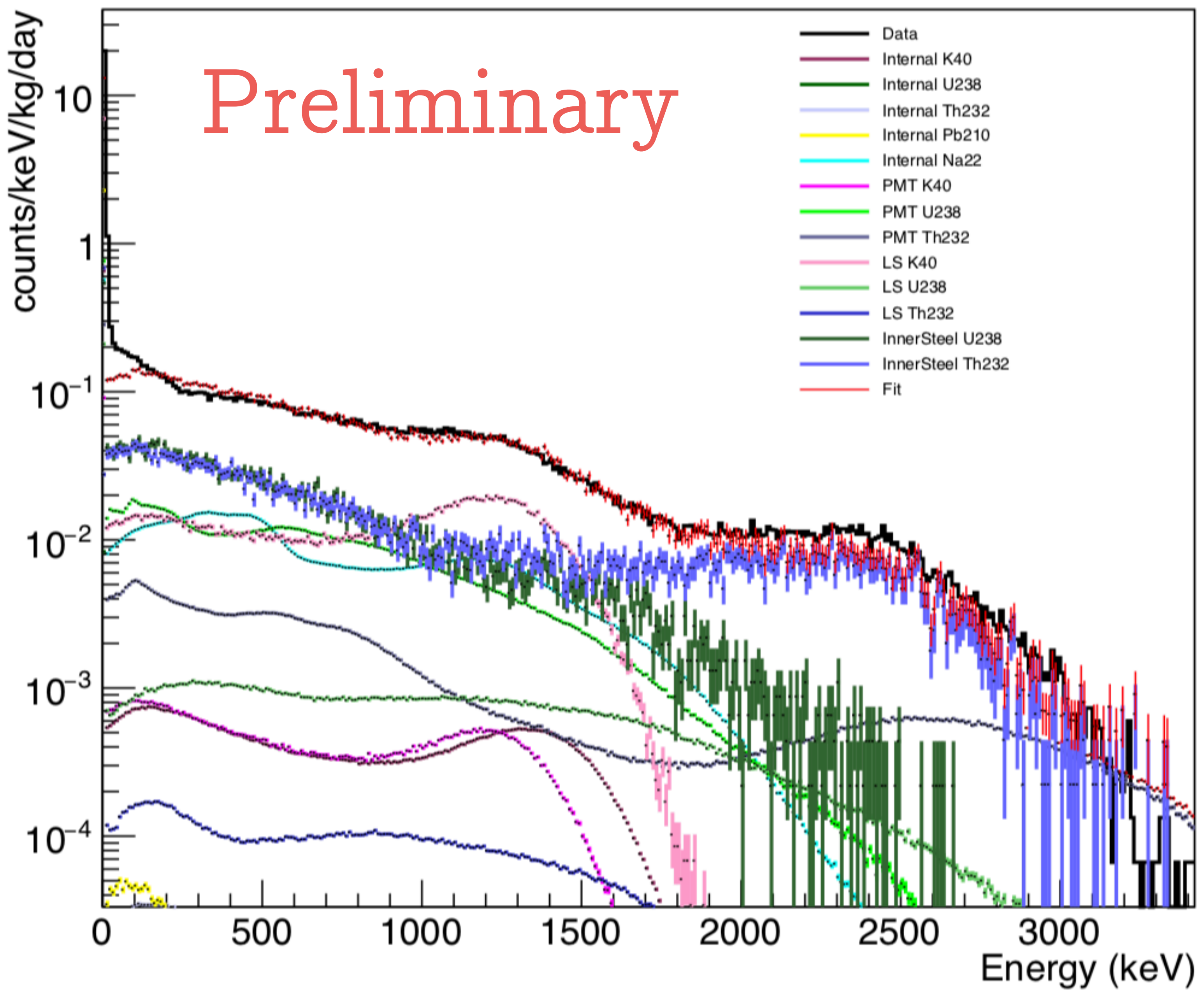




Liquid scintillator veto







- ^{40}K emits 1460 keV gamma with 3 keV Auger electron energy deposition in NaI crystal

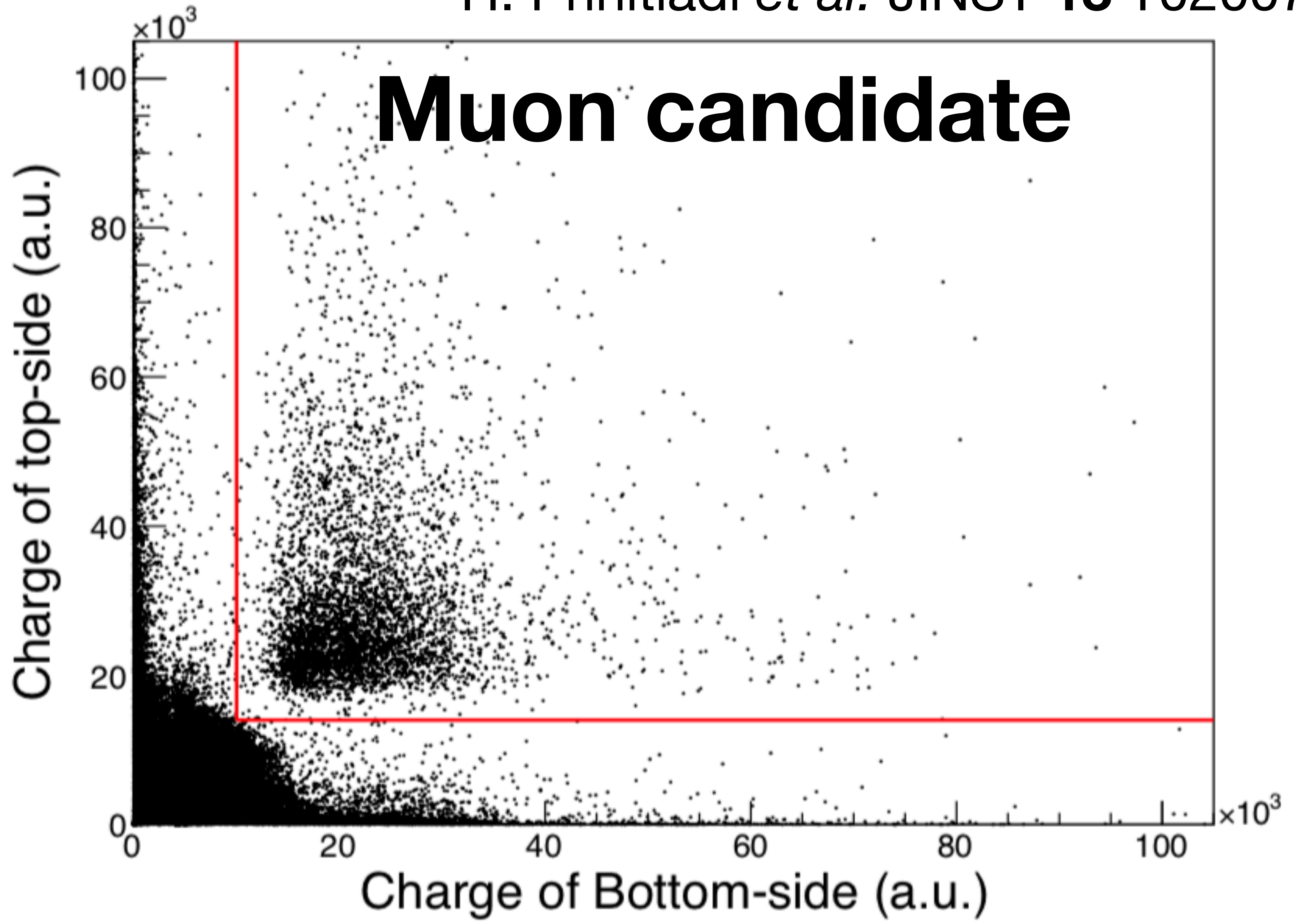
- Tagging 1460 keV events with LS enables **vetoing of 3 keV background events**

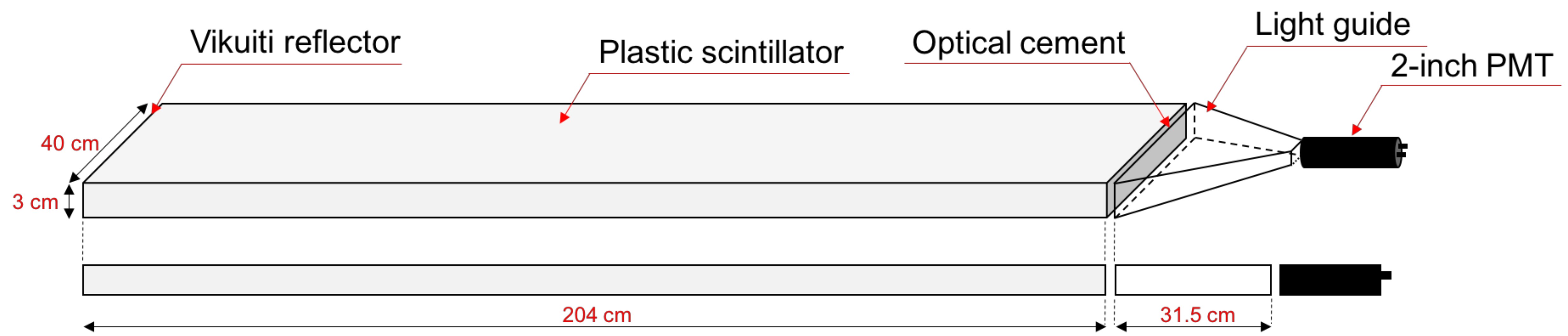
- Liquid scintillator internal contamination well modeled with simulation

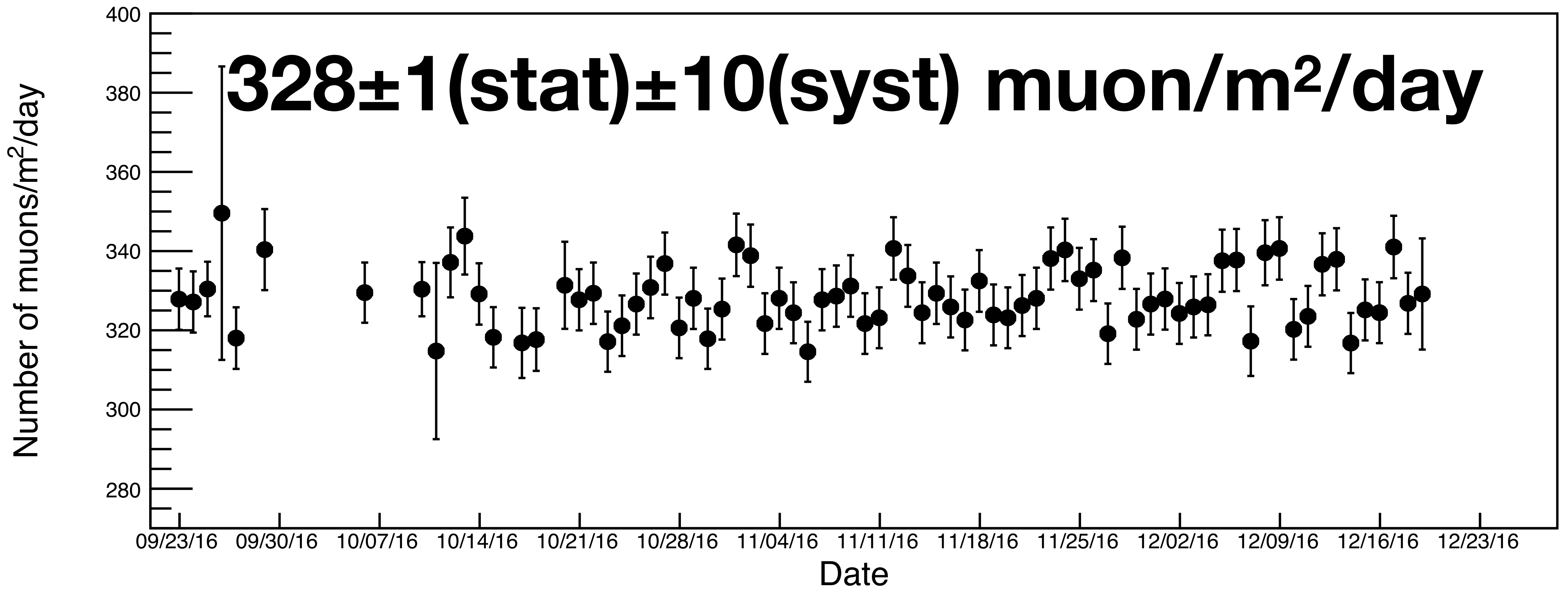
Muon detector

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

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



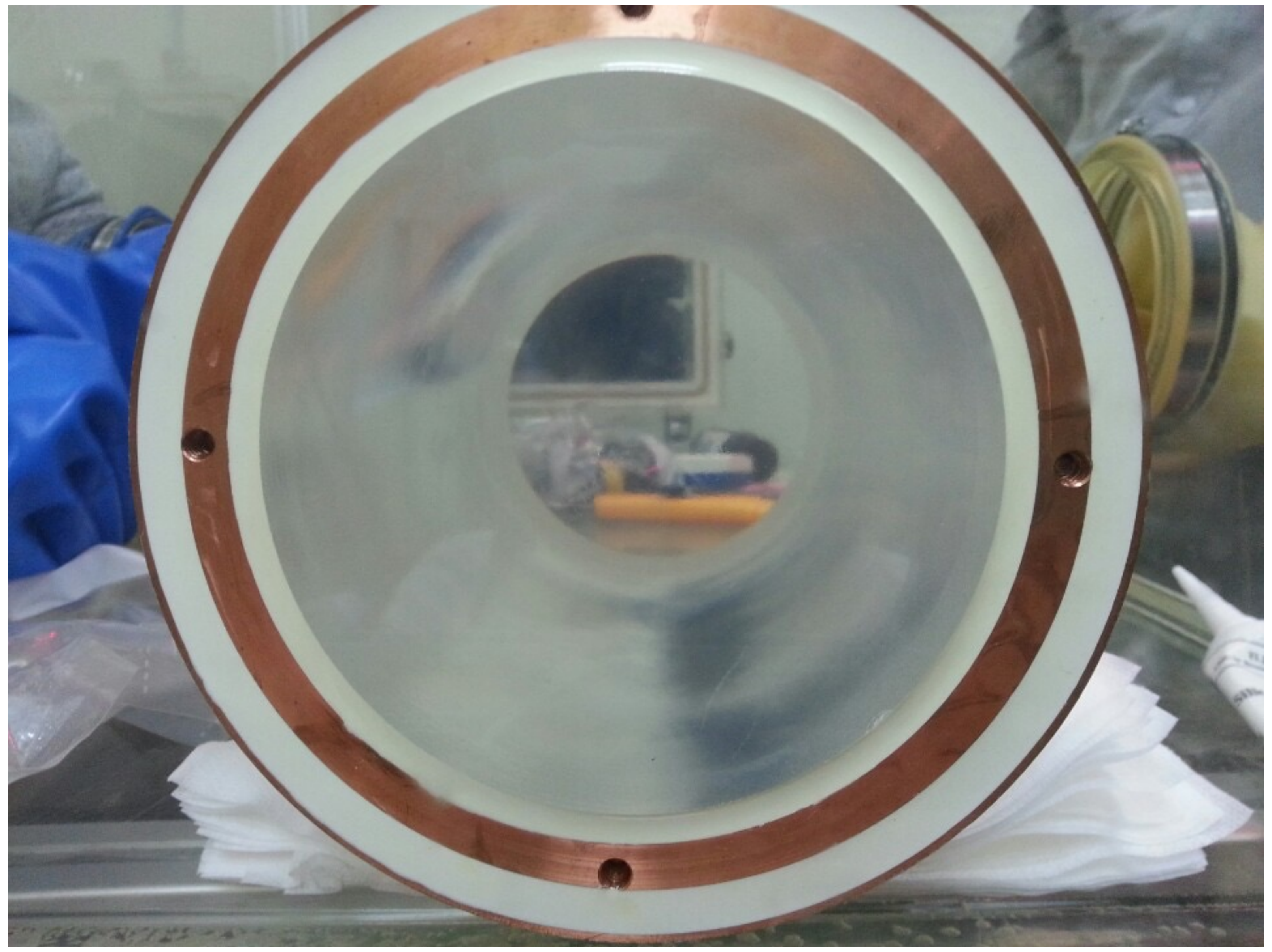


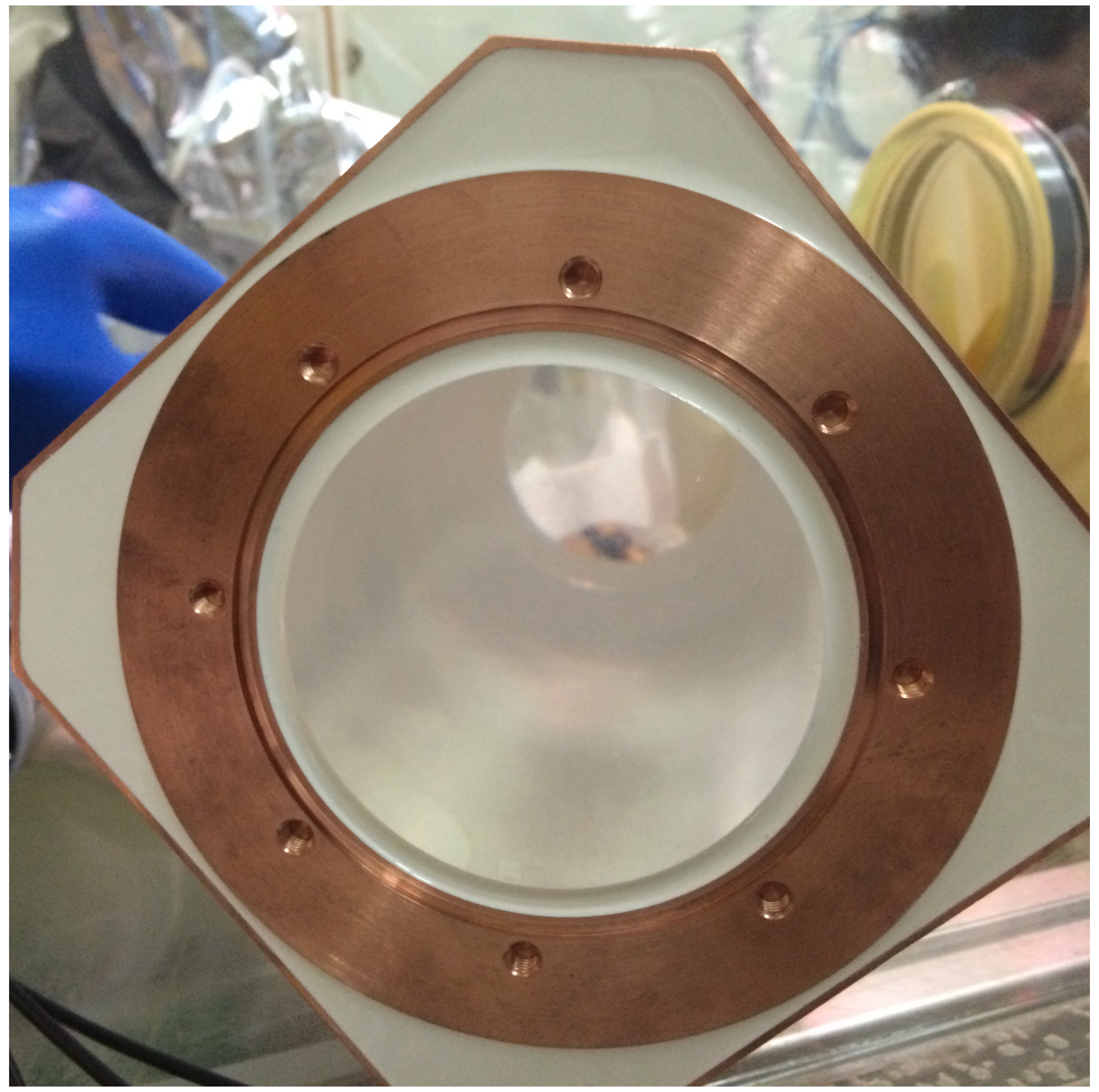


COSINE-100 NaI(Tl) crystals

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

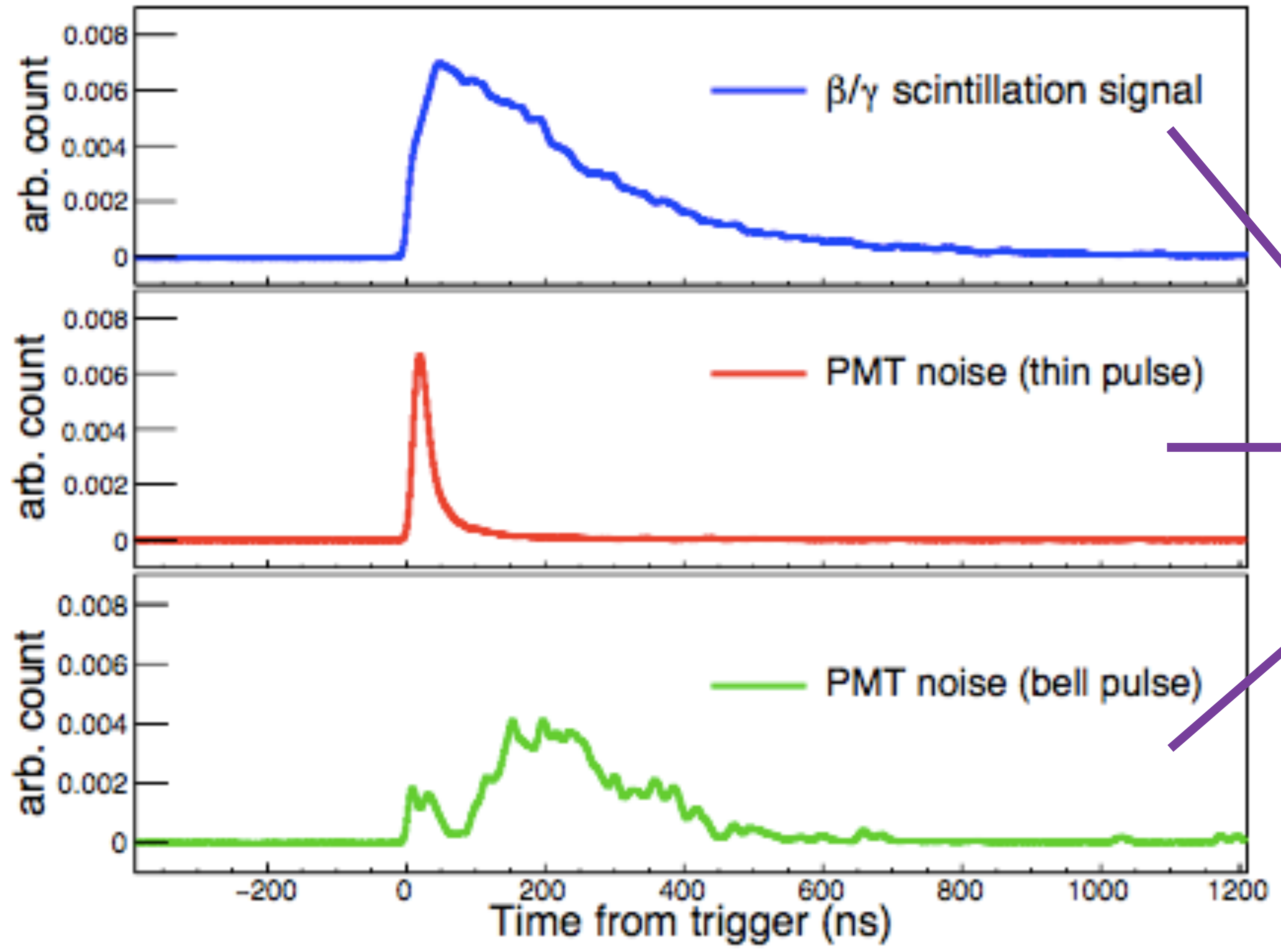


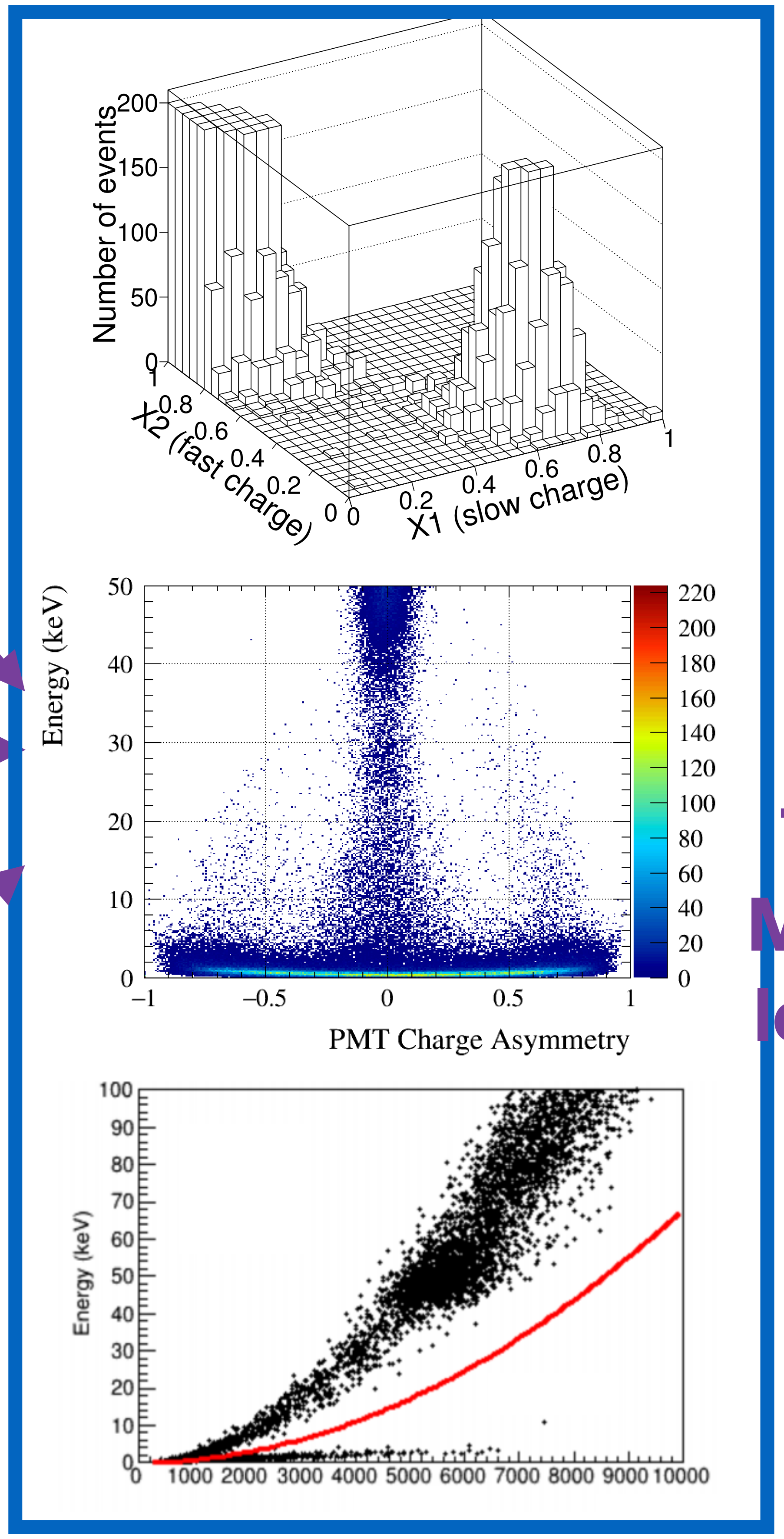


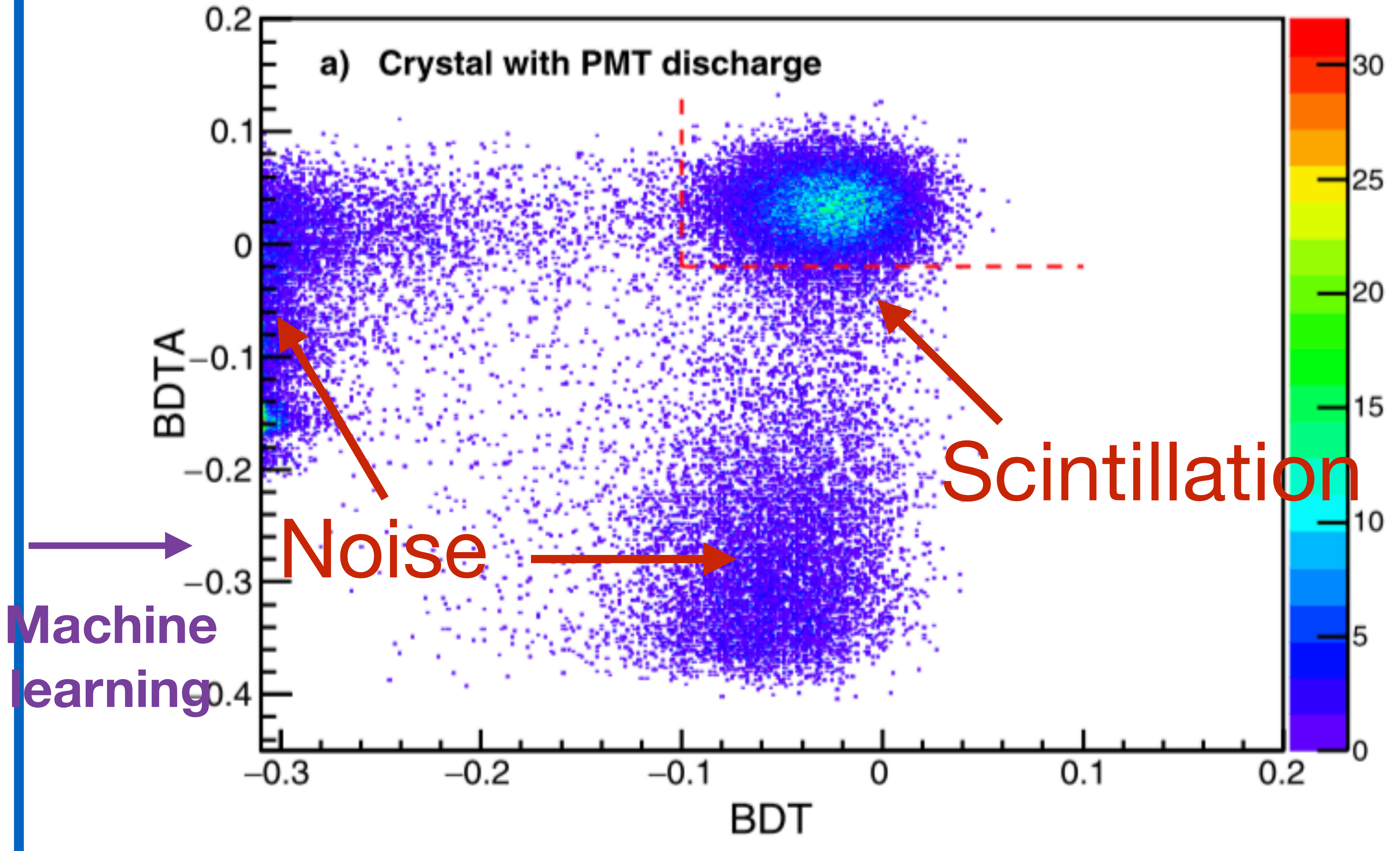
Crystal	Mass (kg)	Size (inches diameter×length)	Powder	α Rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light Yield (PEs/keV)
Crystal-1	8.3	5.0×7.0	AS-B	3.20 ± 0.08	43.4 ± 13.7	<0.02	1.3 ± 0.4	14.9 ± 1.5
Crystal-2	9.2	4.2×11.0	AS-C	2.06 ± 0.06	82.7 ± 12.7	<0.12	<0.6	14.6 ± 1.5
Crystal-3	9.2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

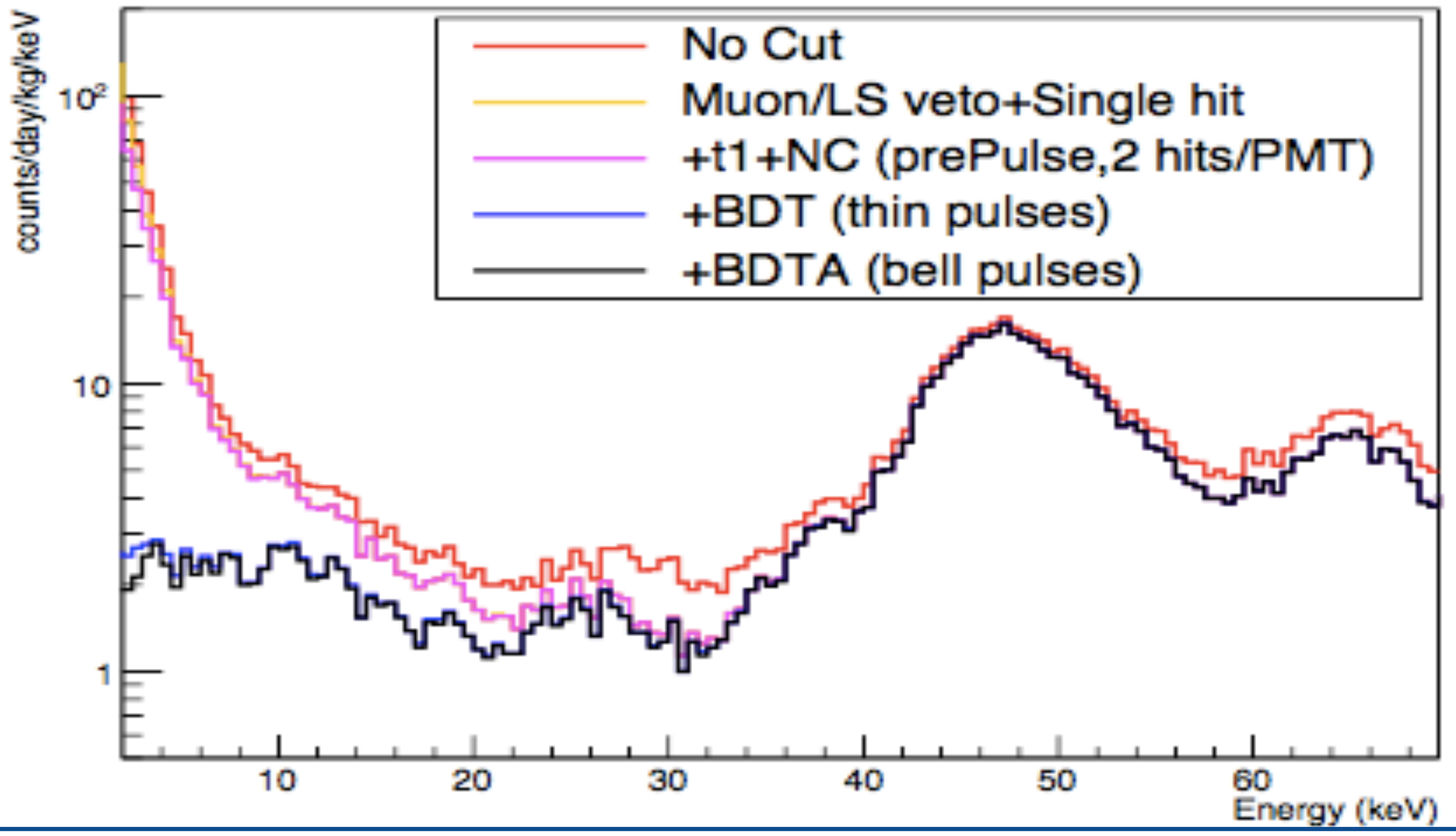
PMT noise rejection

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





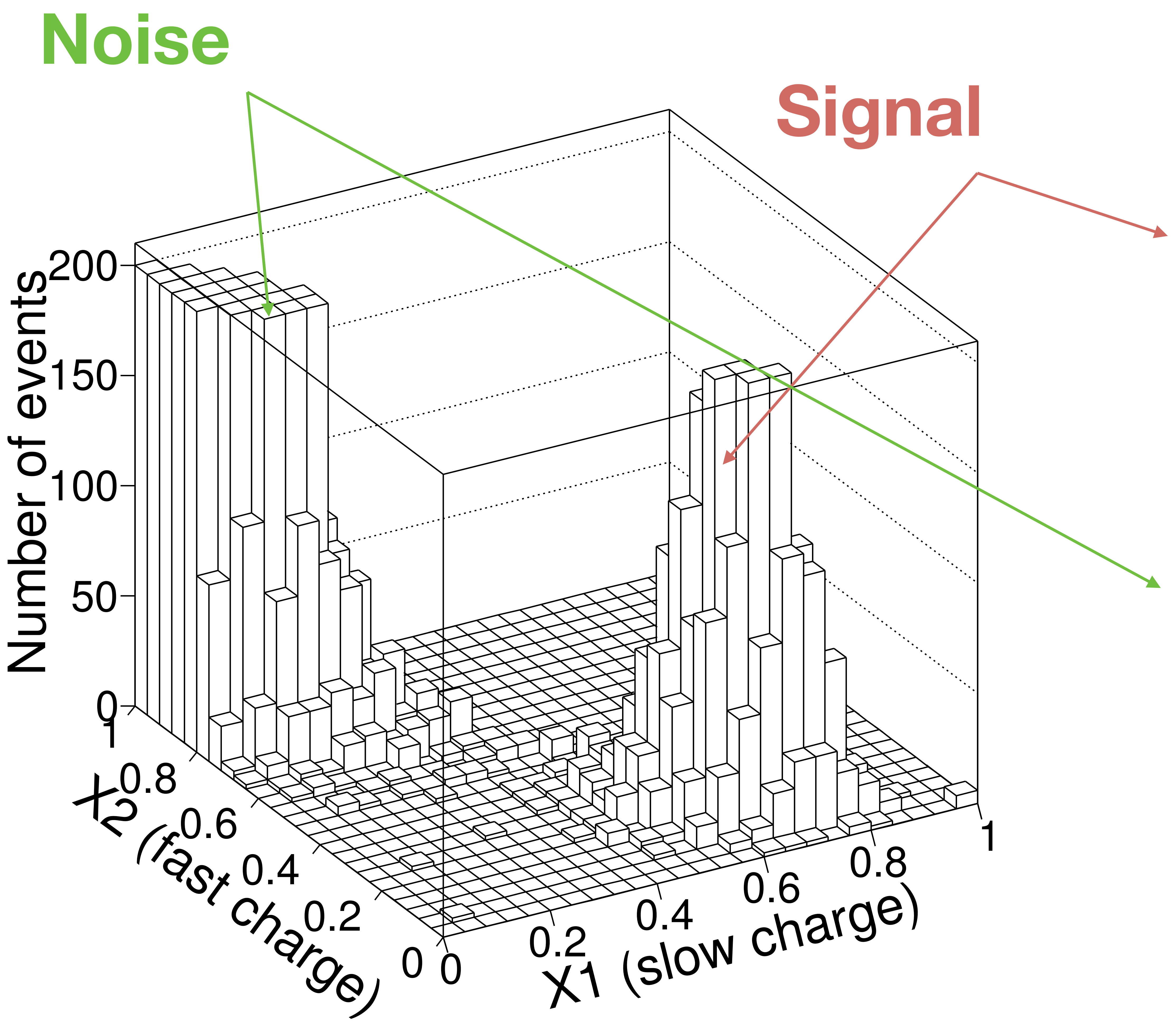


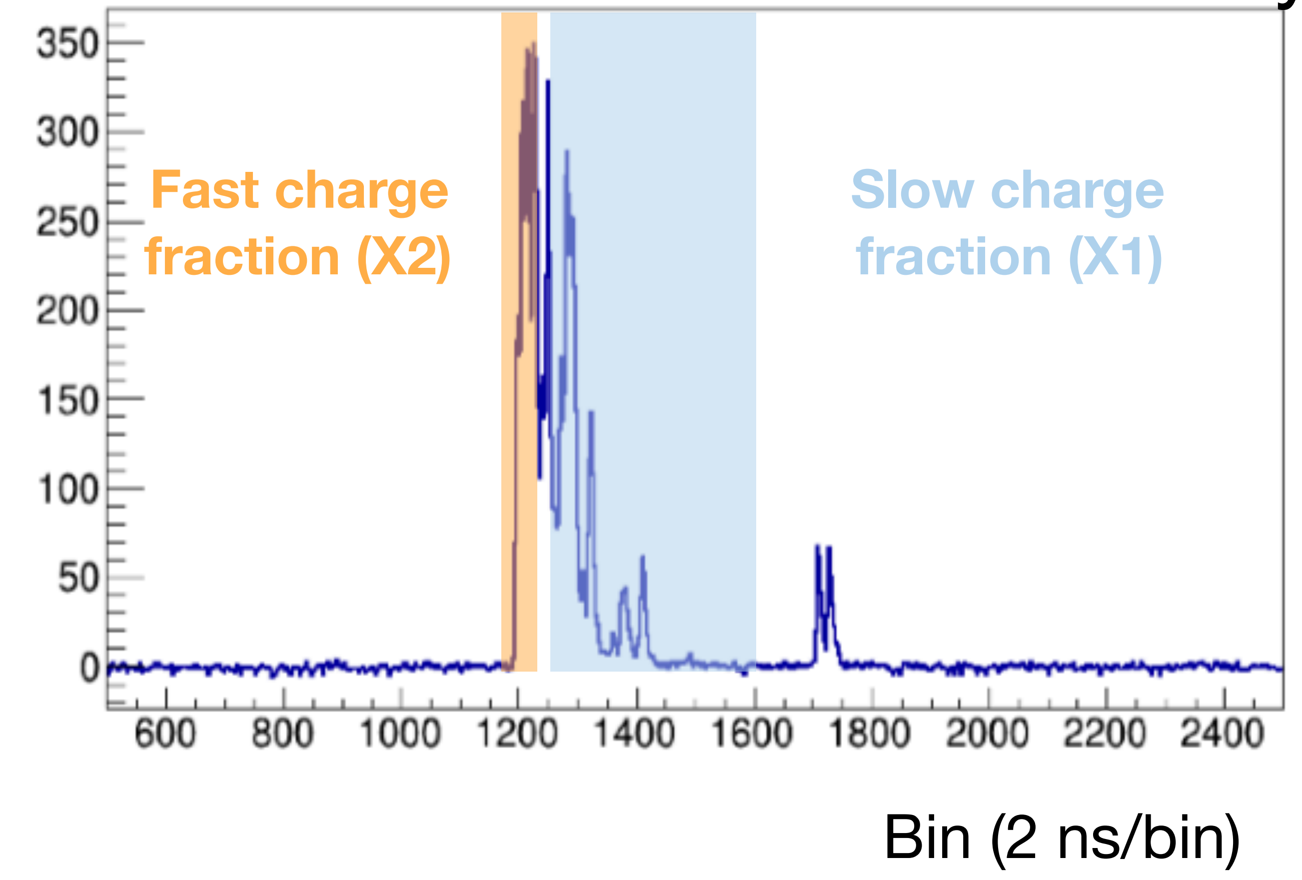


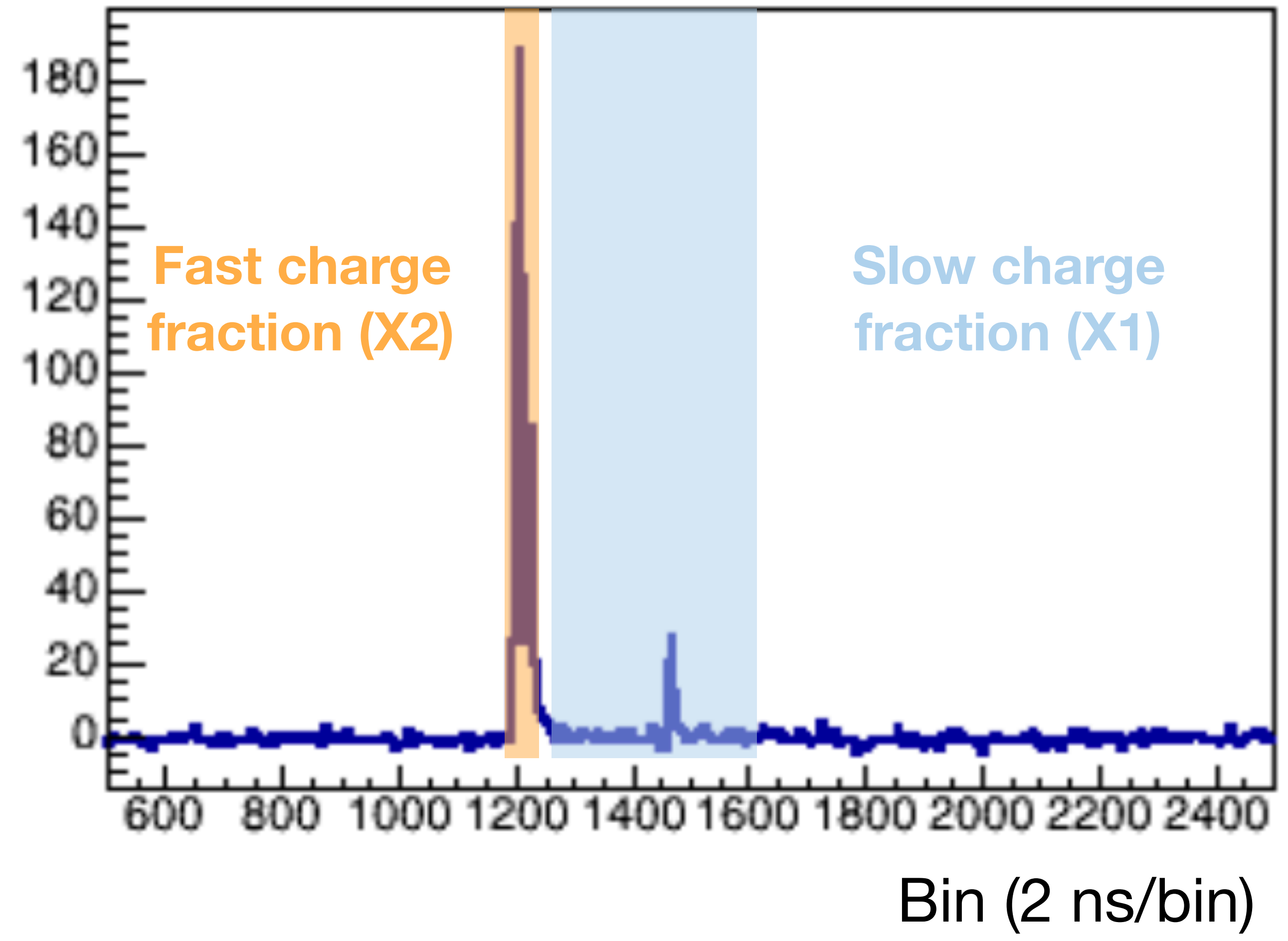
- Dominant source of noise events comes from PMT noise
- Boosted Decision Tree (BDT) was utilized to reject such noise events

PMT noise rejection: Charge Ratio

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

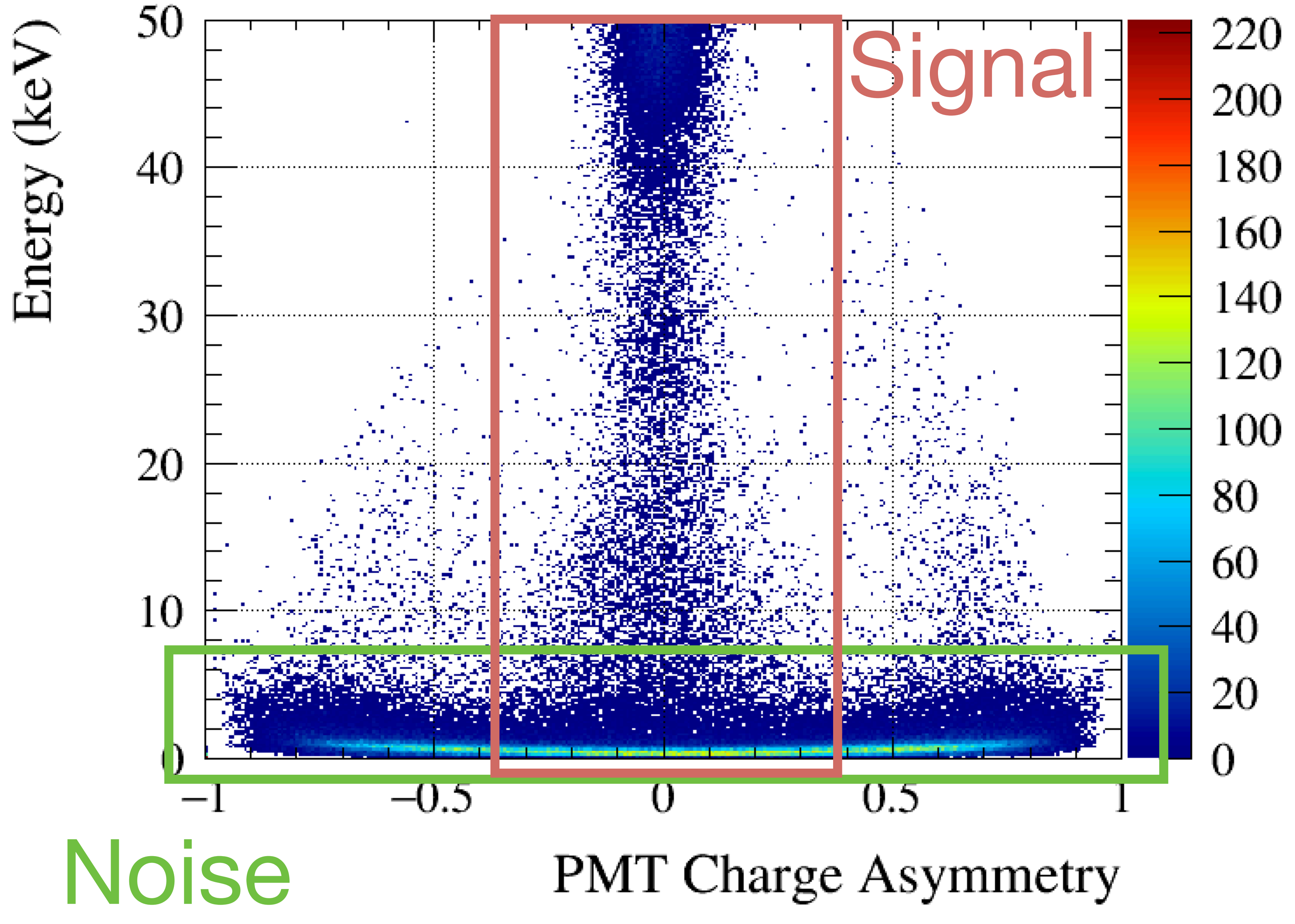


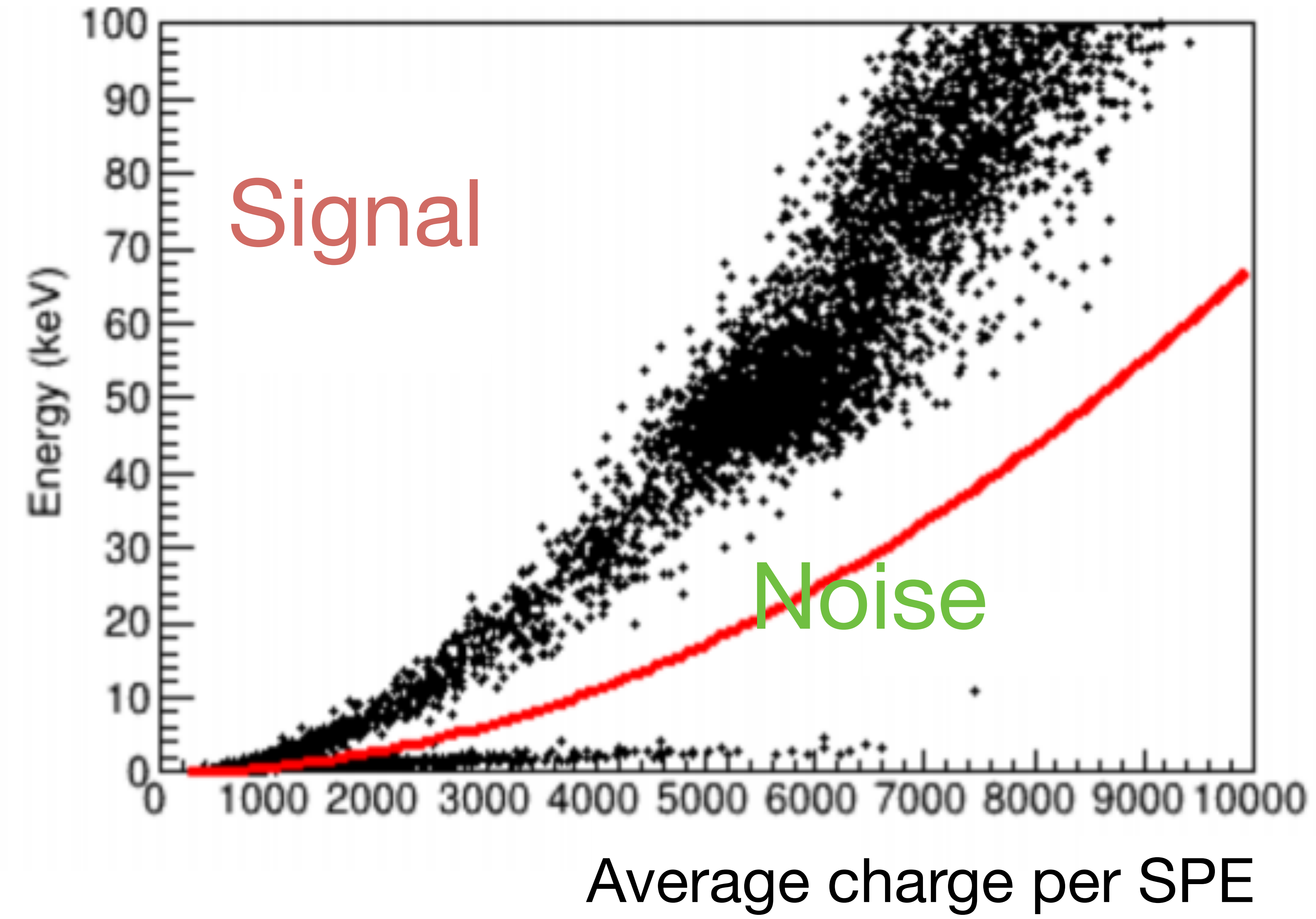




Looking at charge ratio between rising edge and falling edge of a pulse gives good noise separation power

PMT noise rejection: Asymmetry and Charge/Peak

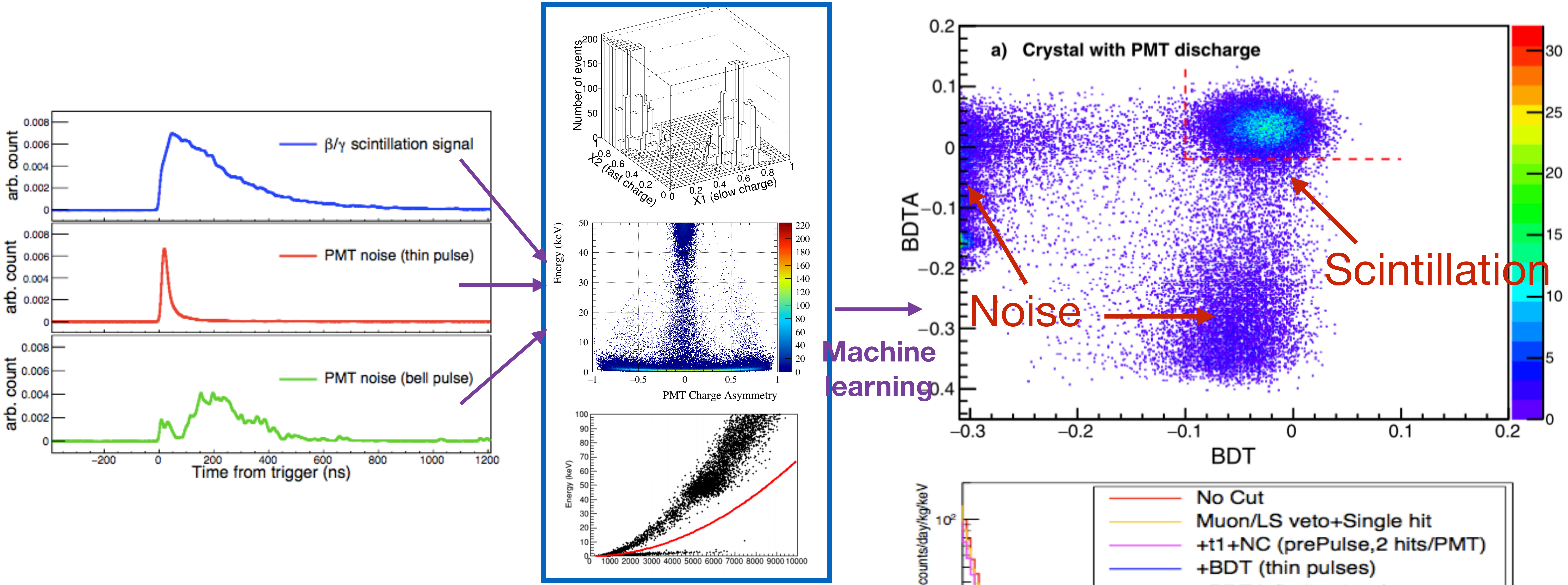


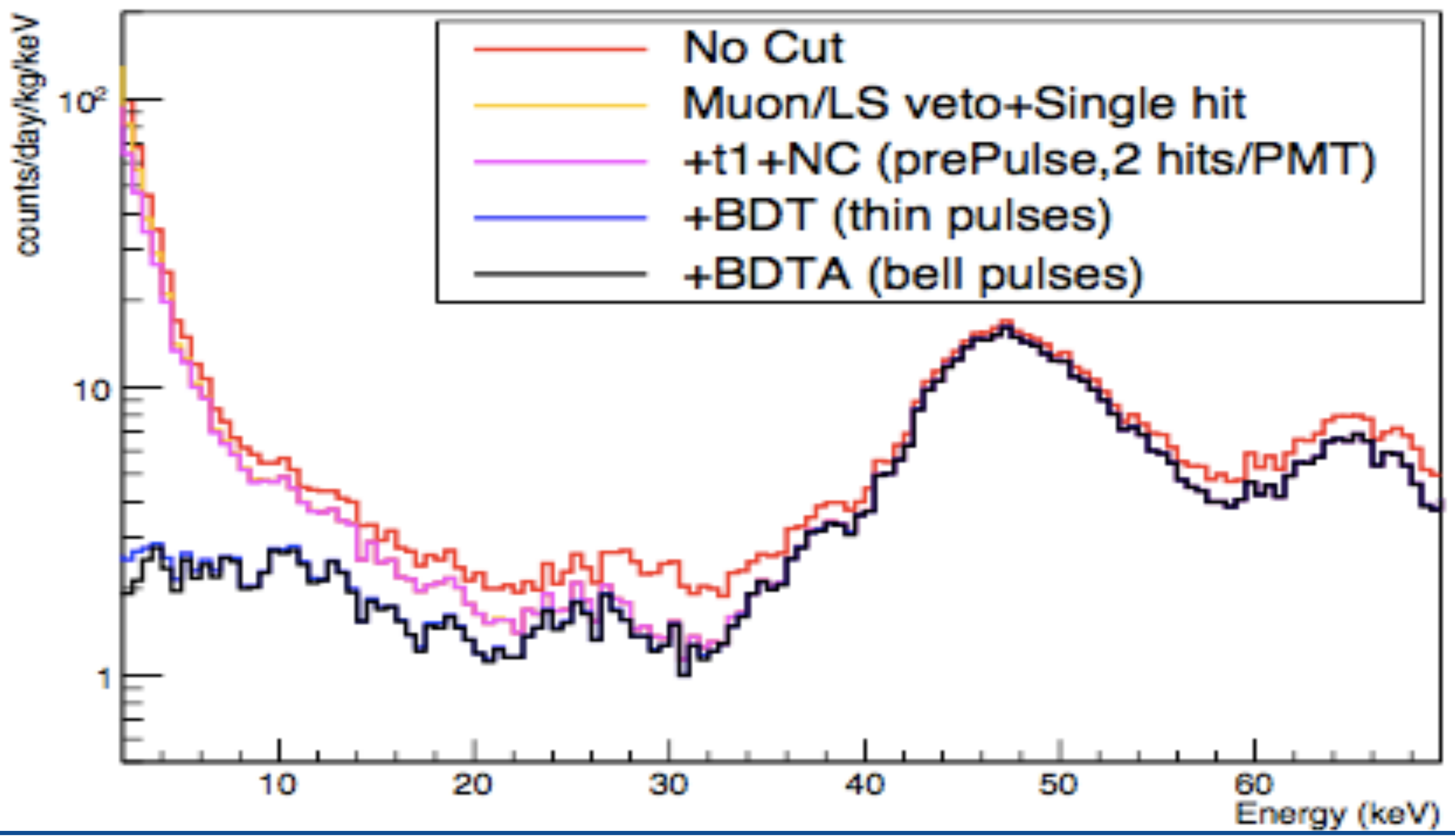


- Additional noise reduction cuts have been developed:
  - Charge asymmetry between 2 PMTs in each crystal
  - Charge/peak: Average charge per SPE

PMT noise rejection

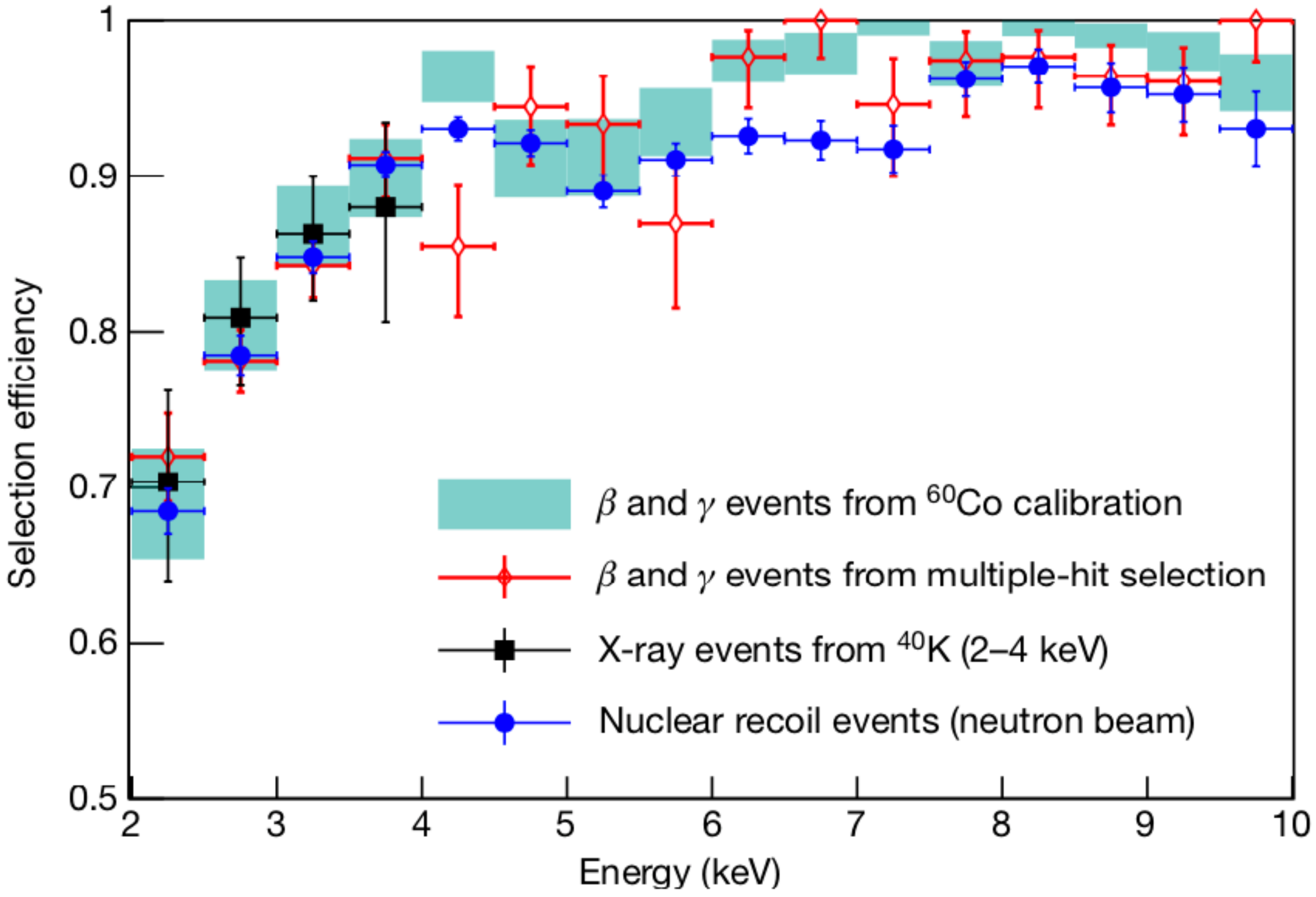
Nature **564**, 83-86 (2018)

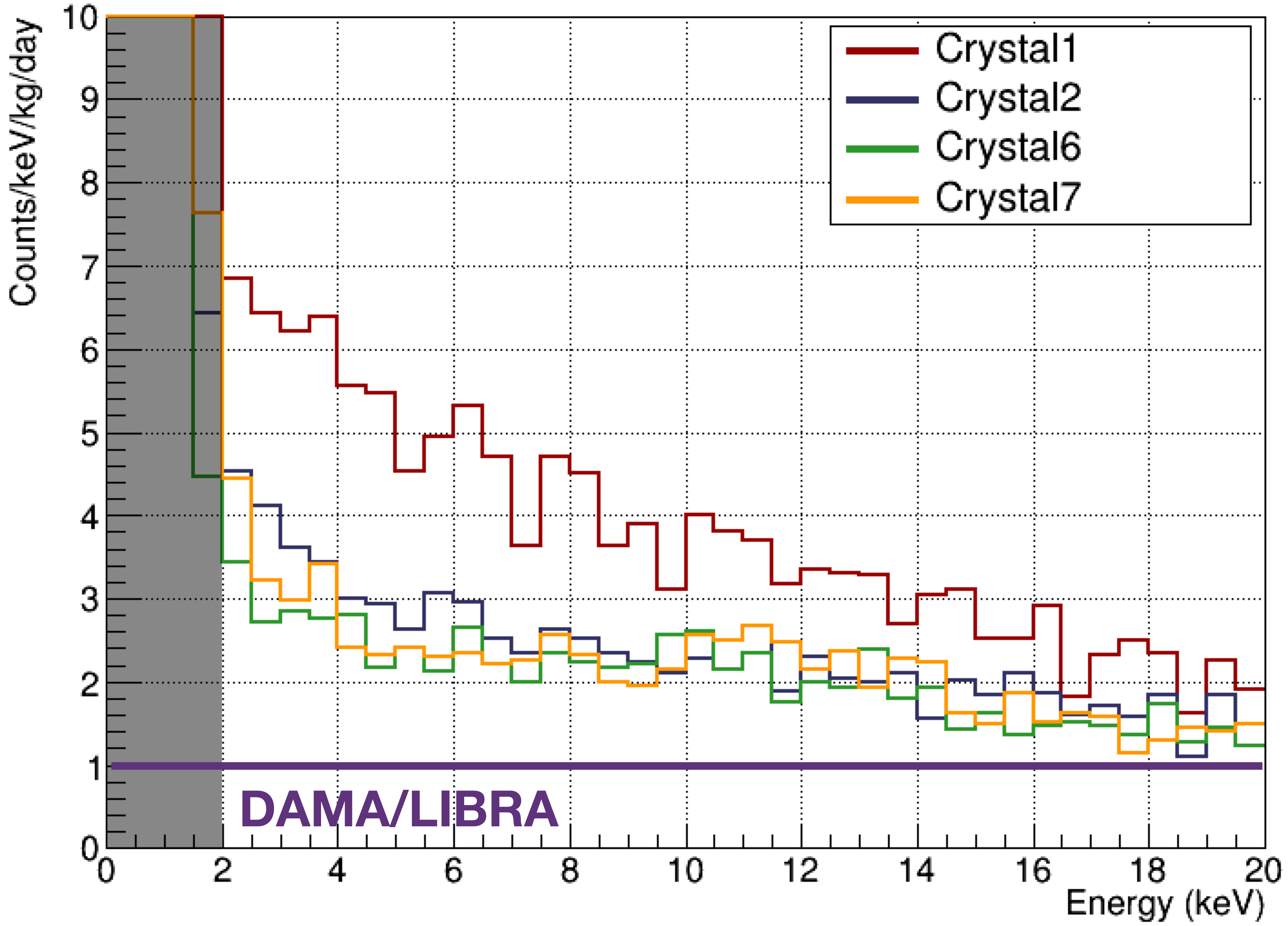




- Dominant source of noise events comes from PMT noise
- Boosted Decision Tree (BDT) was utilized to reject such noise events

Selection efficiency/Low energy spectrum

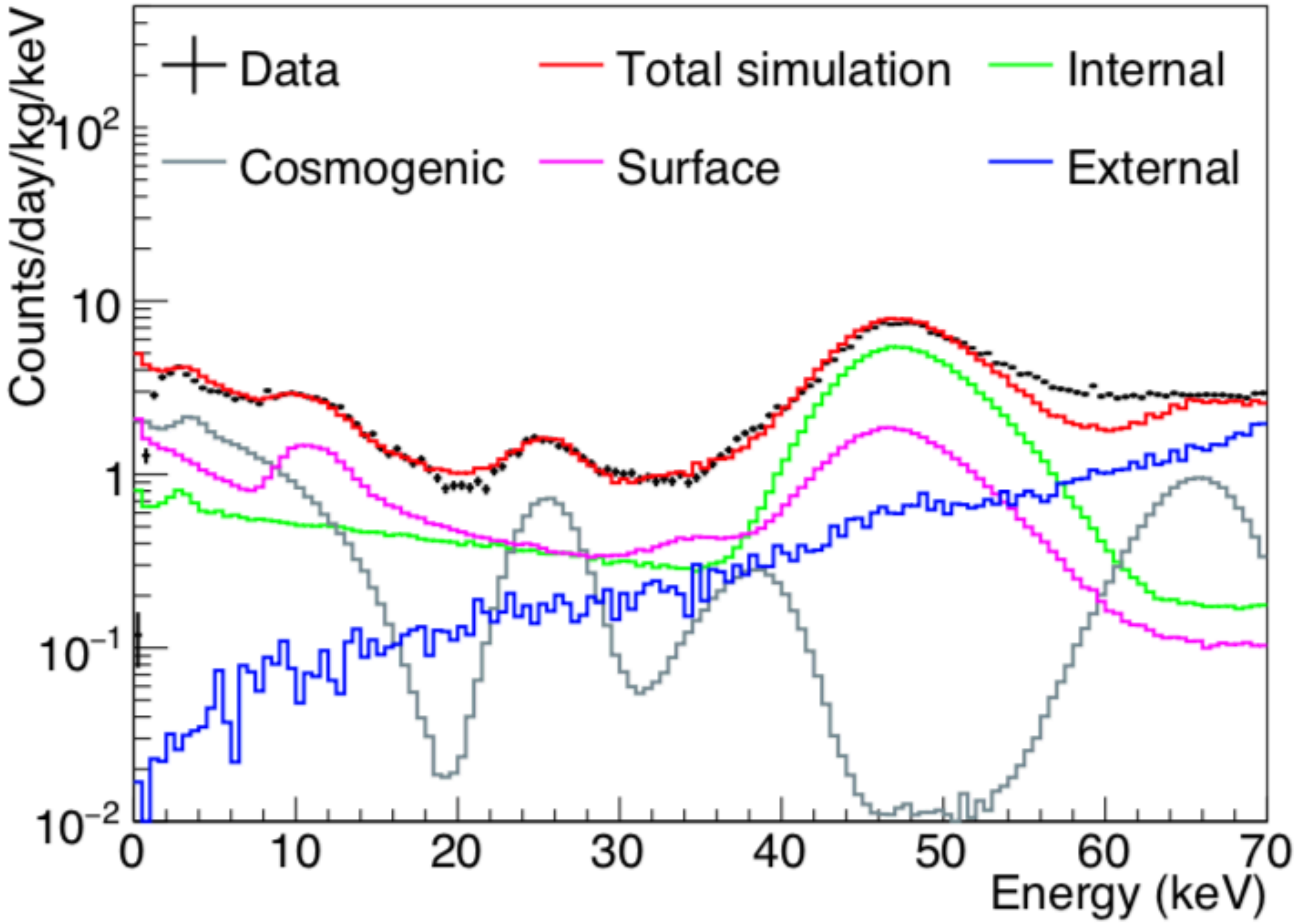


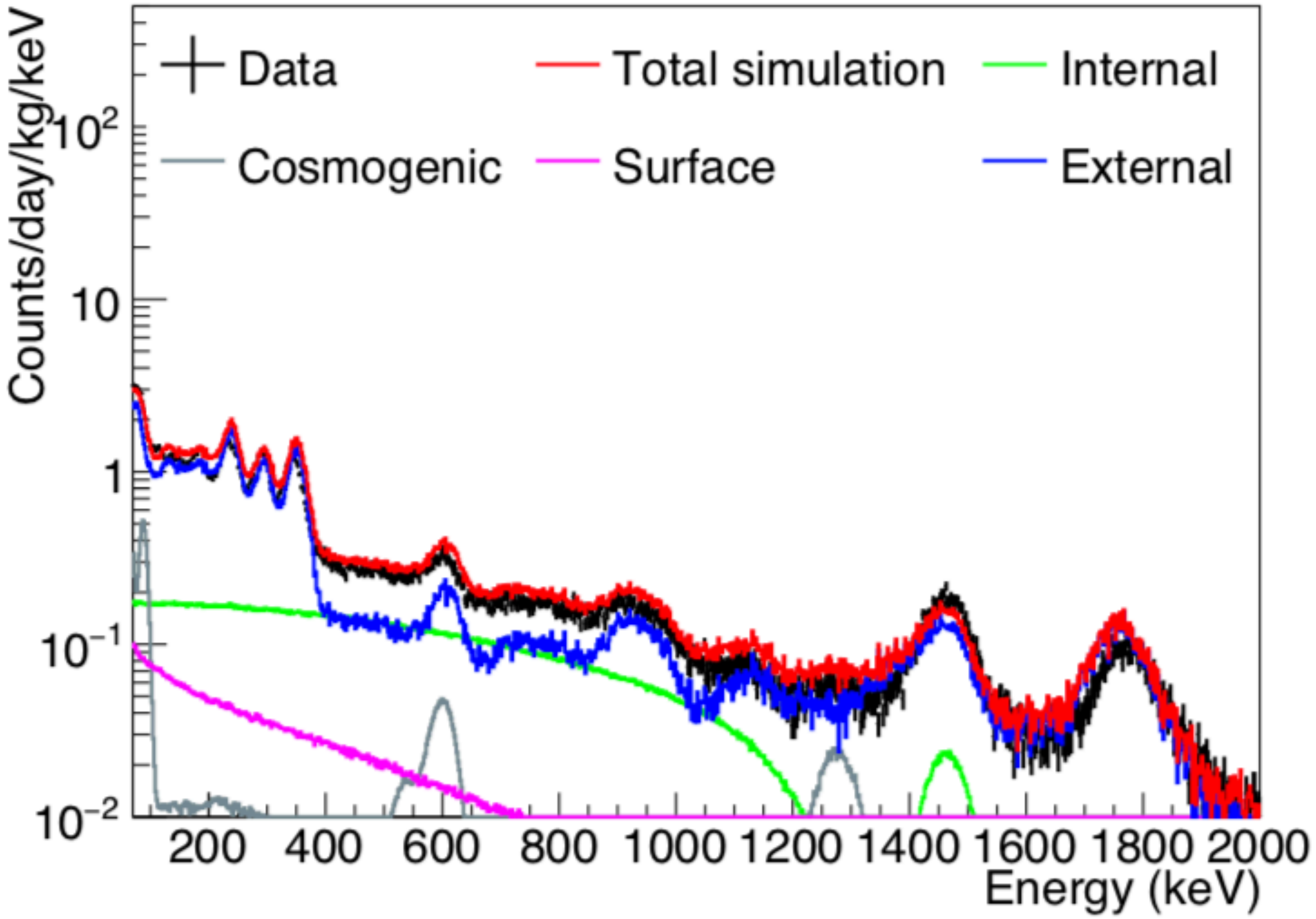


- ~70% efficiency at 2 keV
- 2 - 4 counts/keV/kg/day in region of interest depending on the crystal

Background in data vs. simulation

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





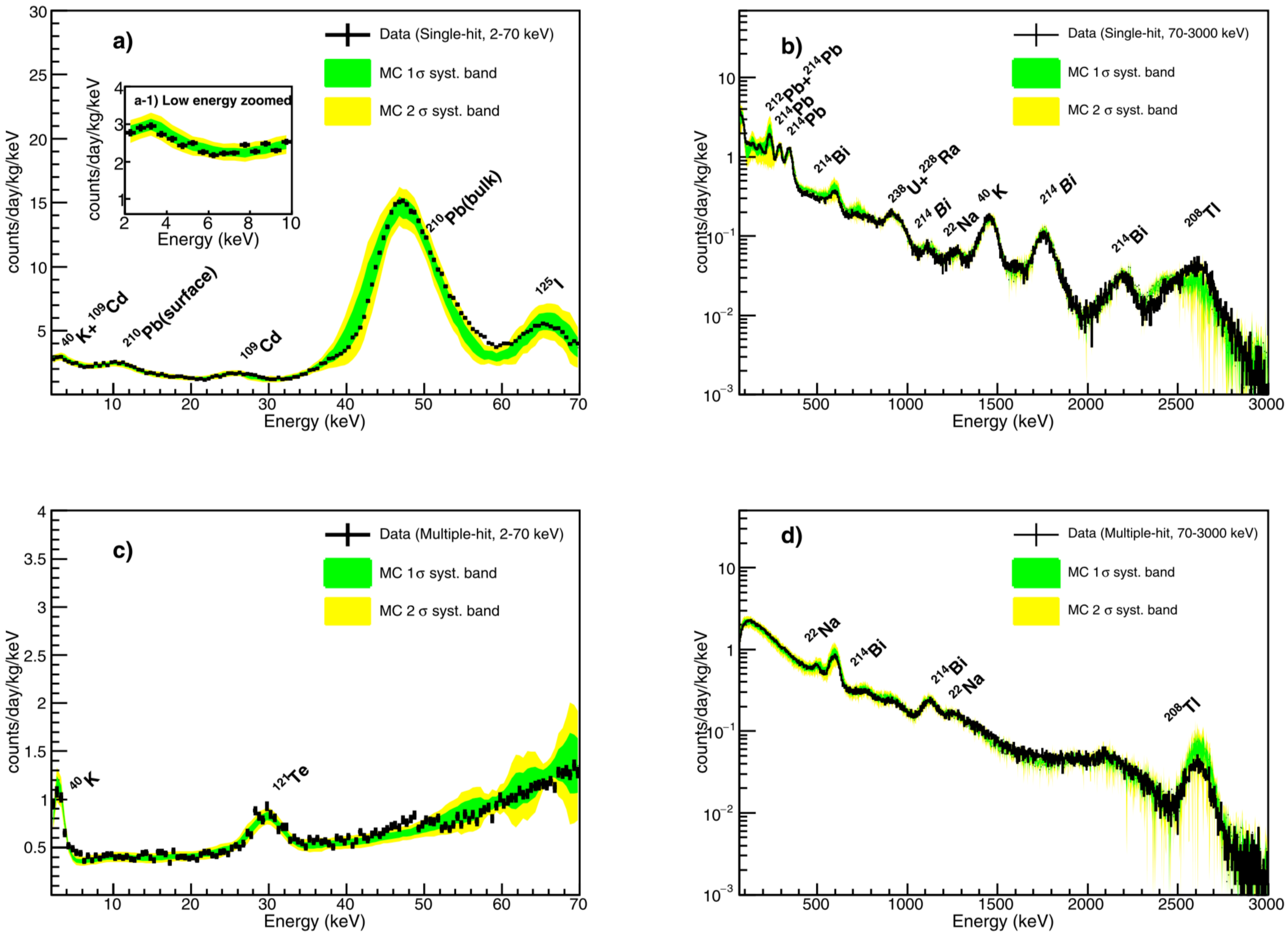
- Data reproduced well with GEANT4 simulation
- **Background well understood from 2 keV - 2000 keV**
- Dominant background from ^{210}Pb (internal, surface) and ^{40}K (internal), followed by cosmogenic ^{3}H

Background in data vs. simulation

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

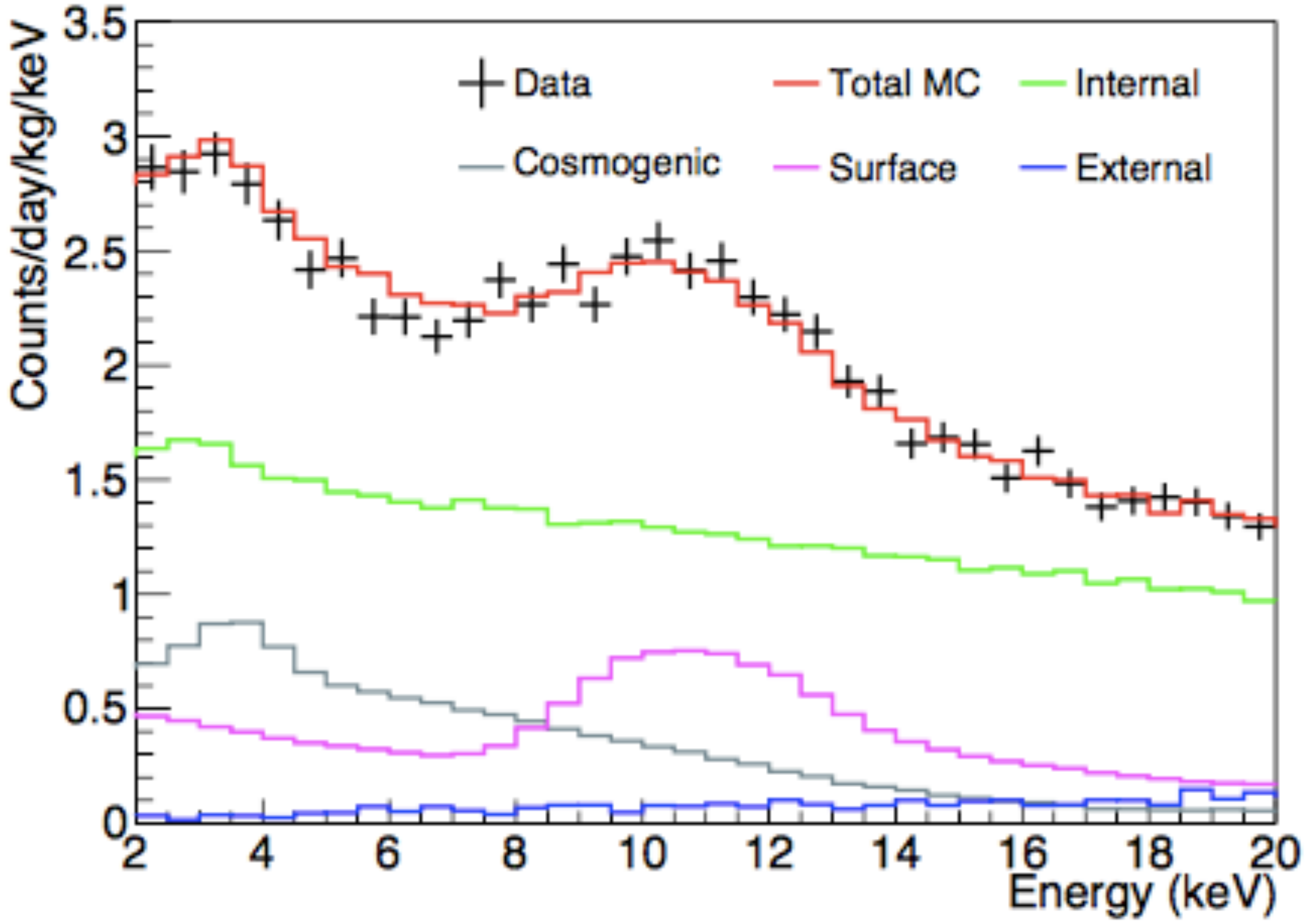
Single-hit

Multiple-hit

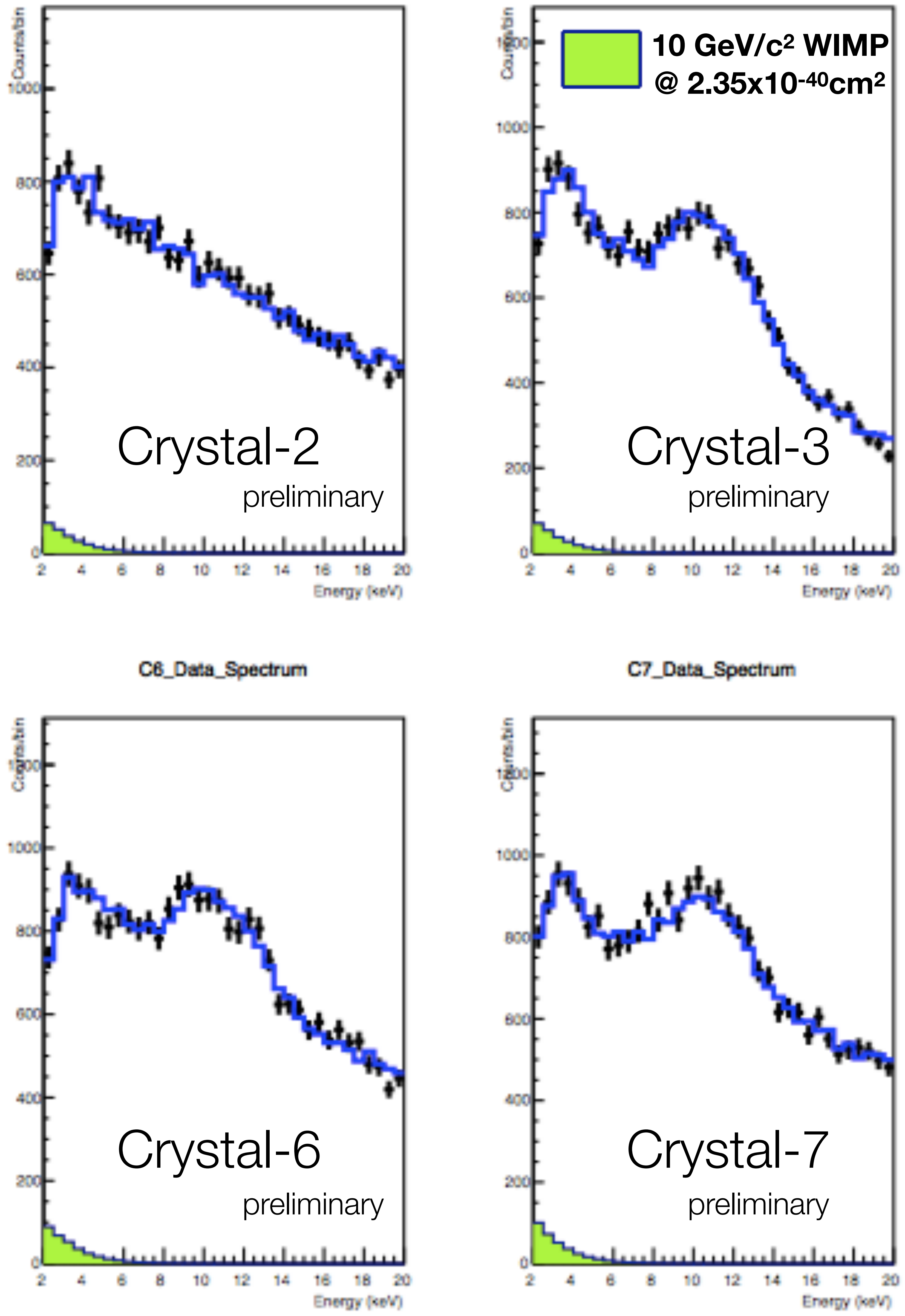


Physics analysis: WIMP analysis

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

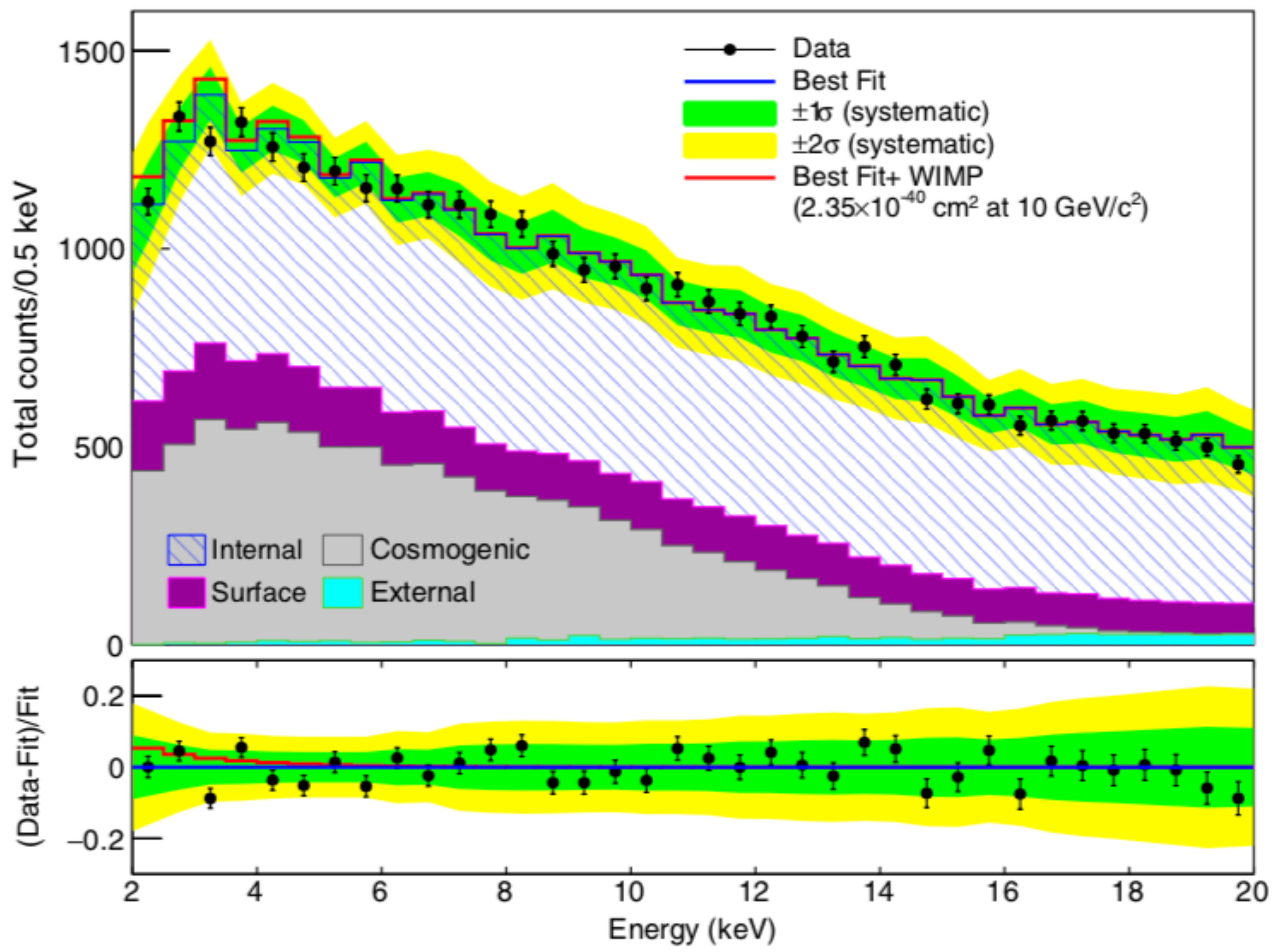


- Using 59.5 days of data: 6303.9 kg day exposure
- Spectrum fit for 2-20 keV including WIMP model
- Likelihood analysis to fit data using background model and WIMP signal model (SHM as described in Savage *et al*., JCAP 0904:010, 2009)
- Background understanding consideration from V. Kudryavtsev *et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

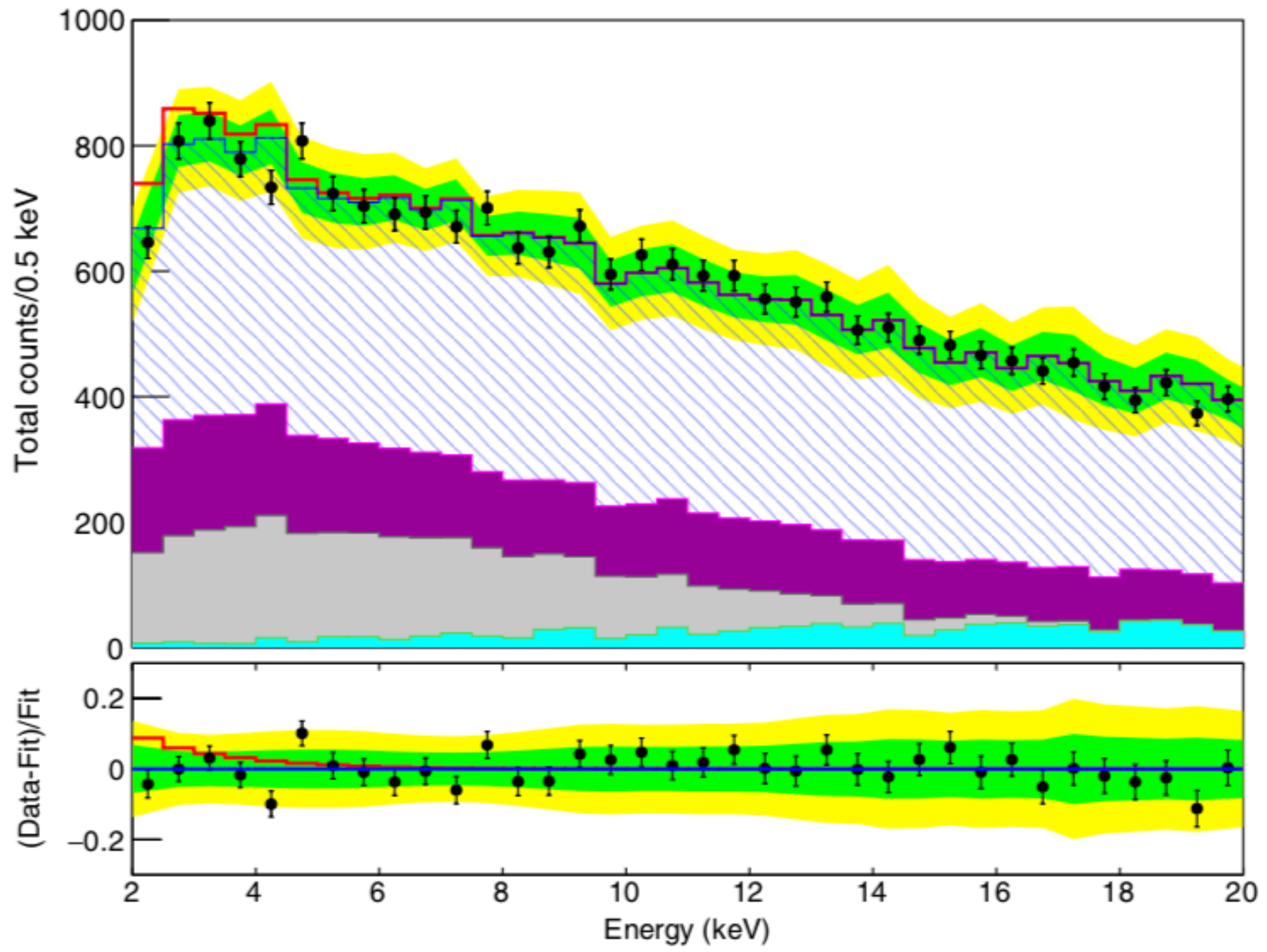


Physics analysis: WIMP analysis

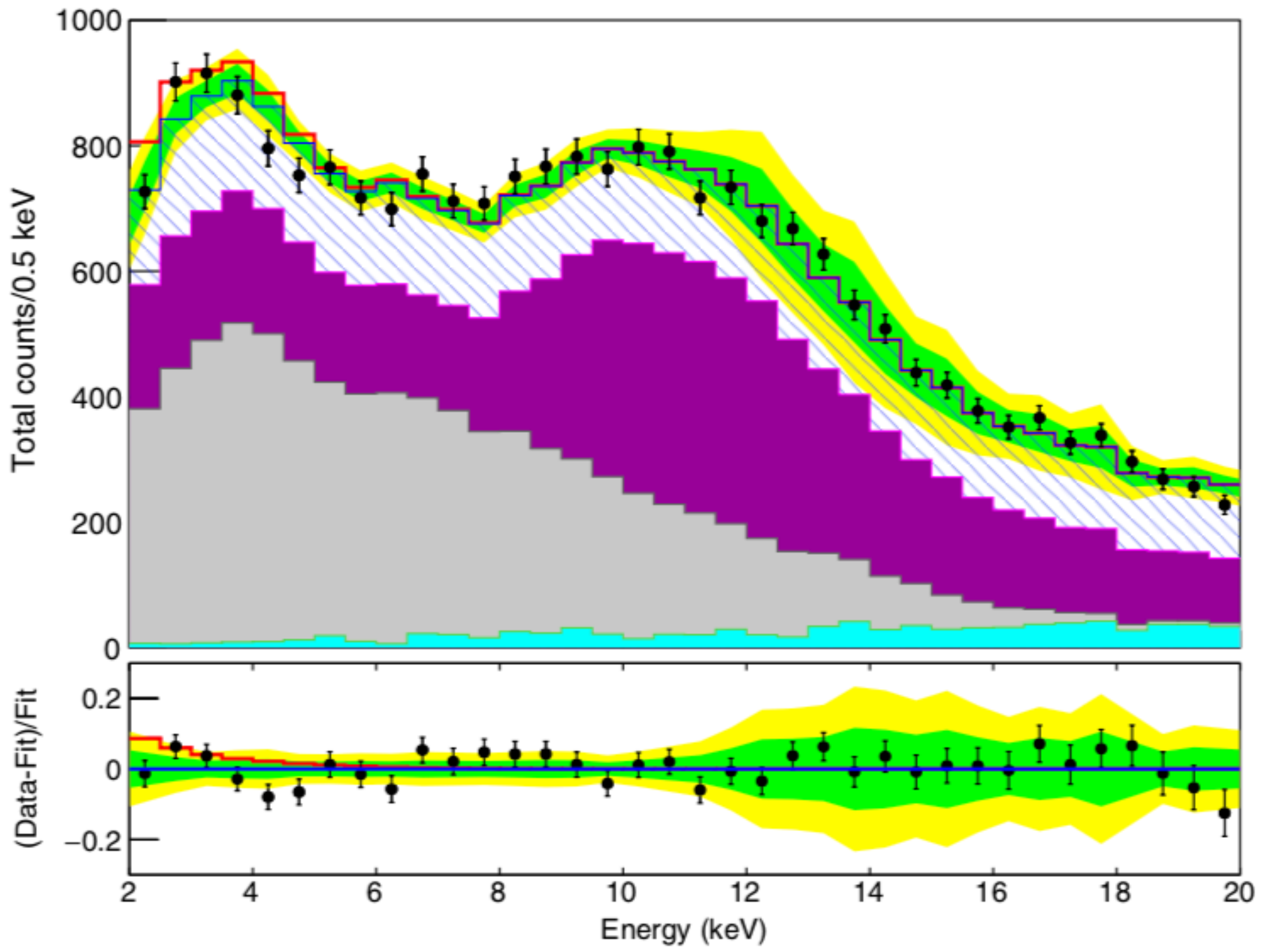
Nature **564**, 83-86 (2018)



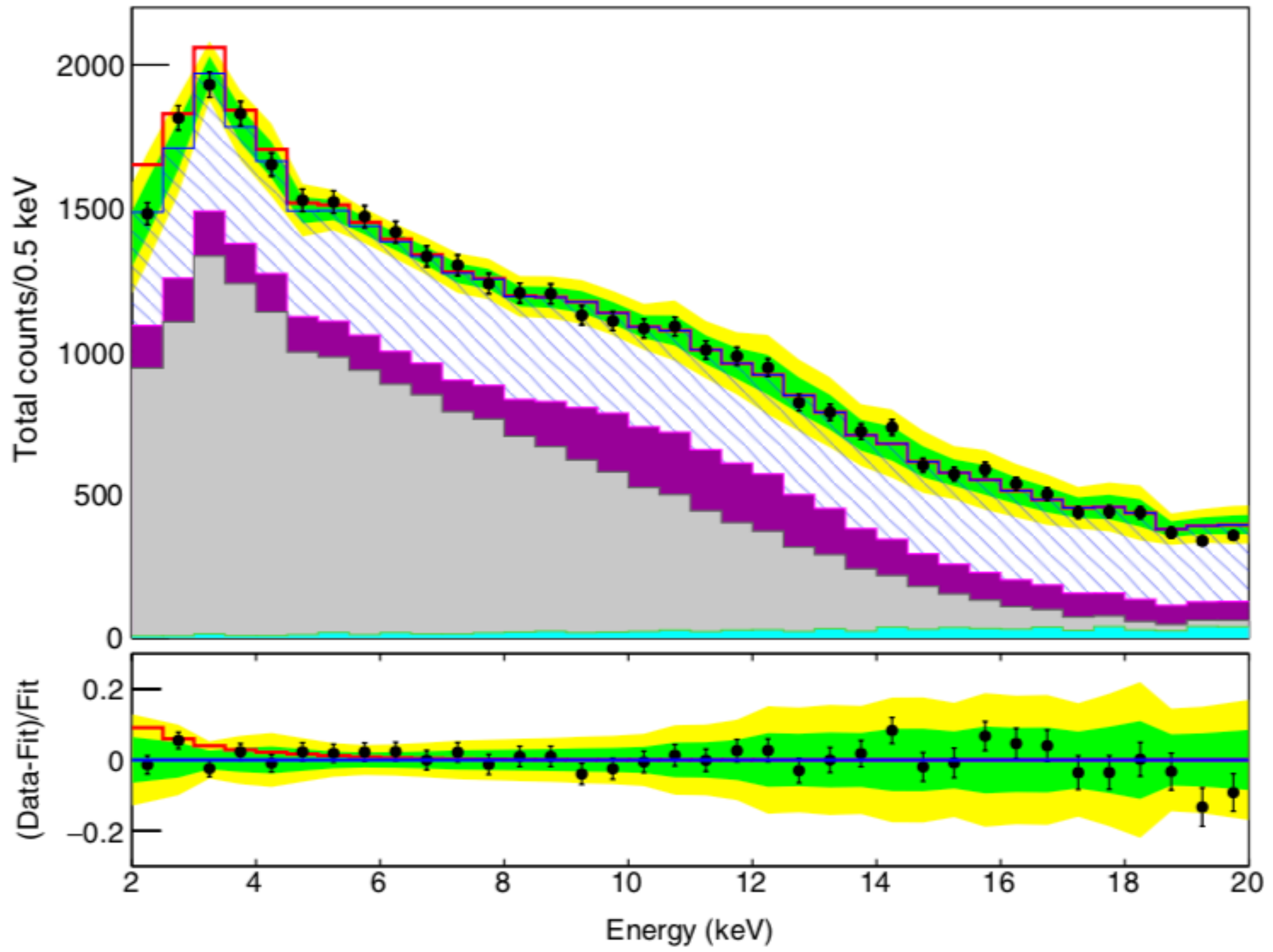
a) Crystal 1



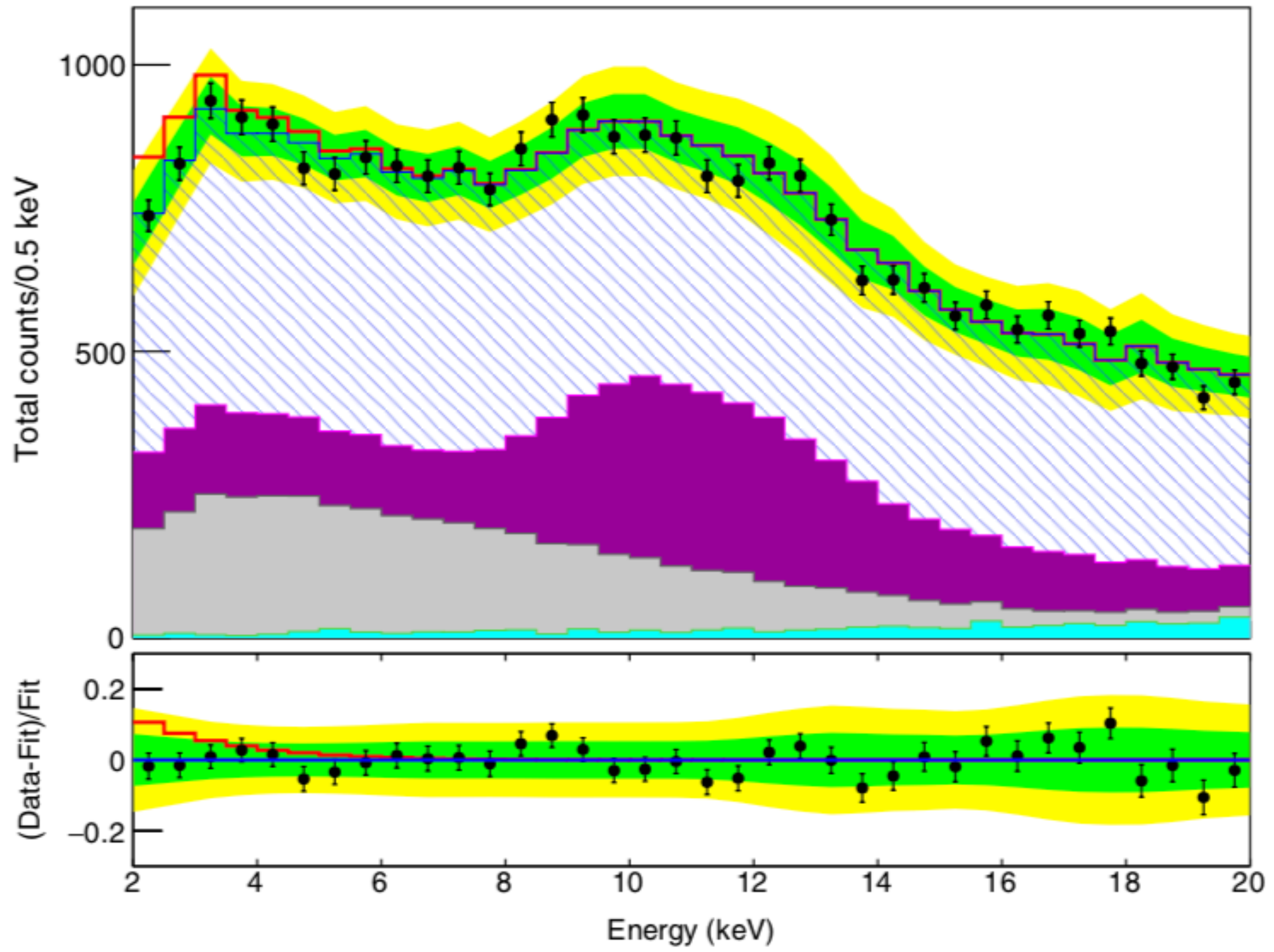
b) Crystal 2



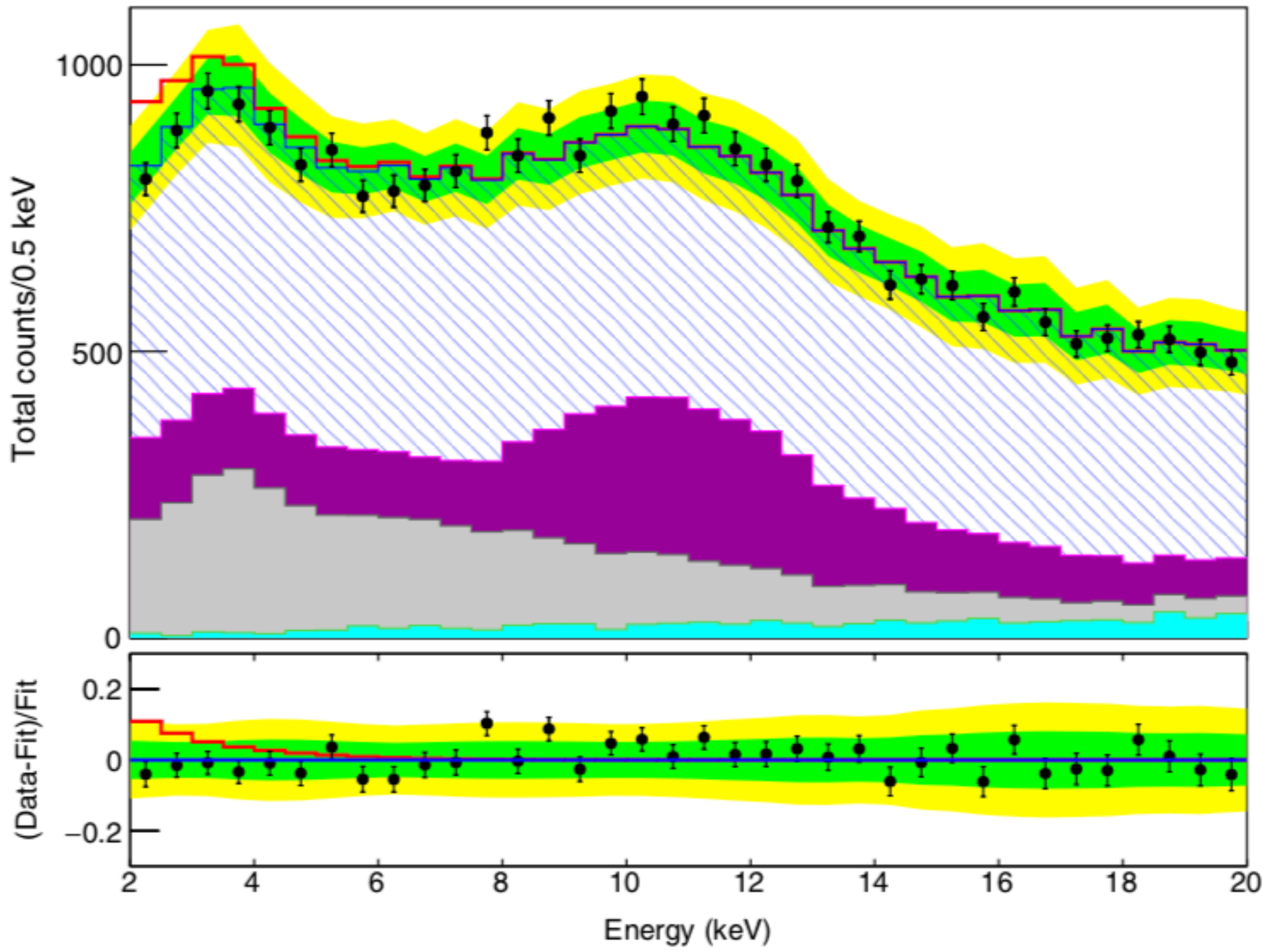
c) Crystal 3



d) Crystal 4

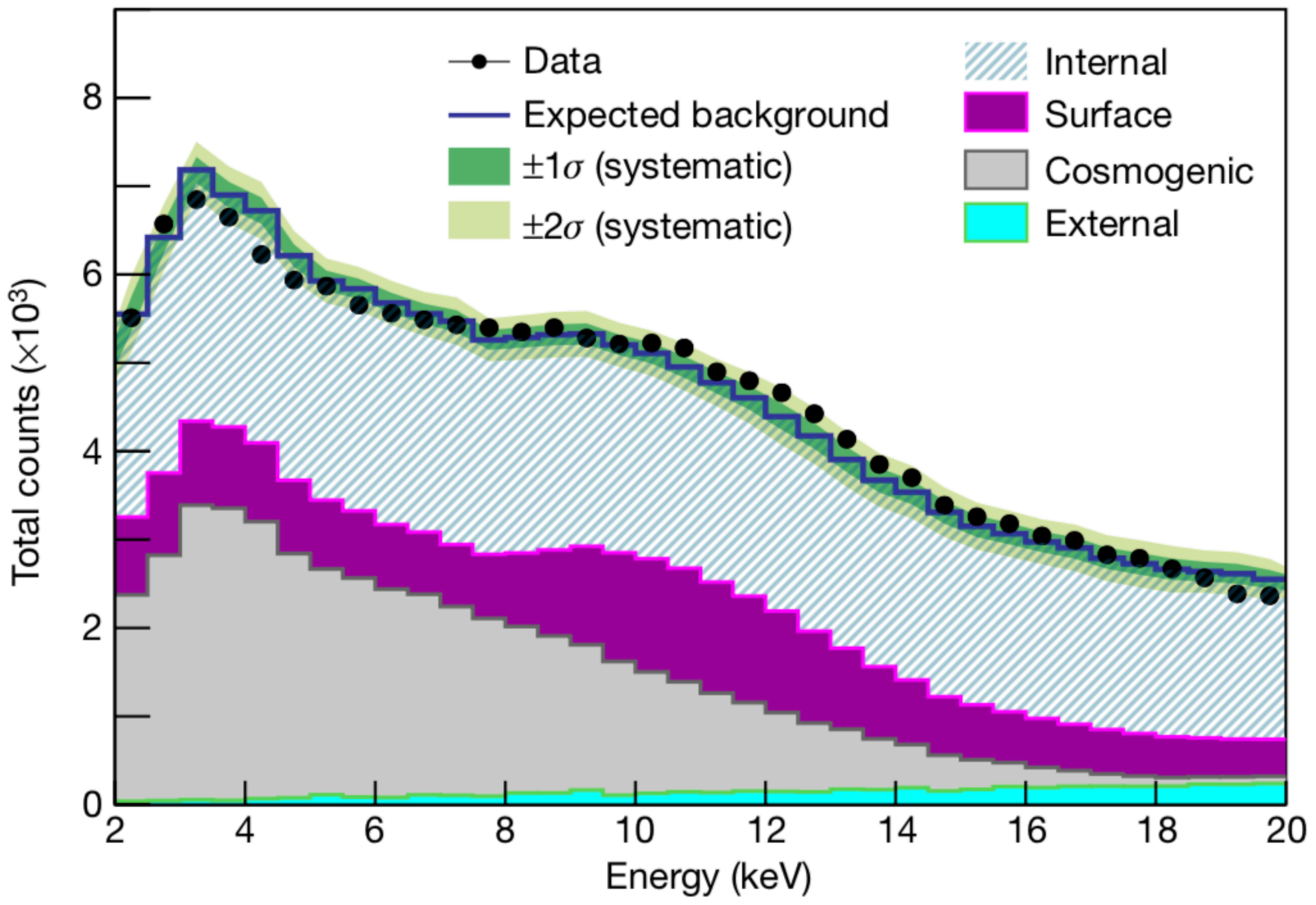


e) Crystal 6

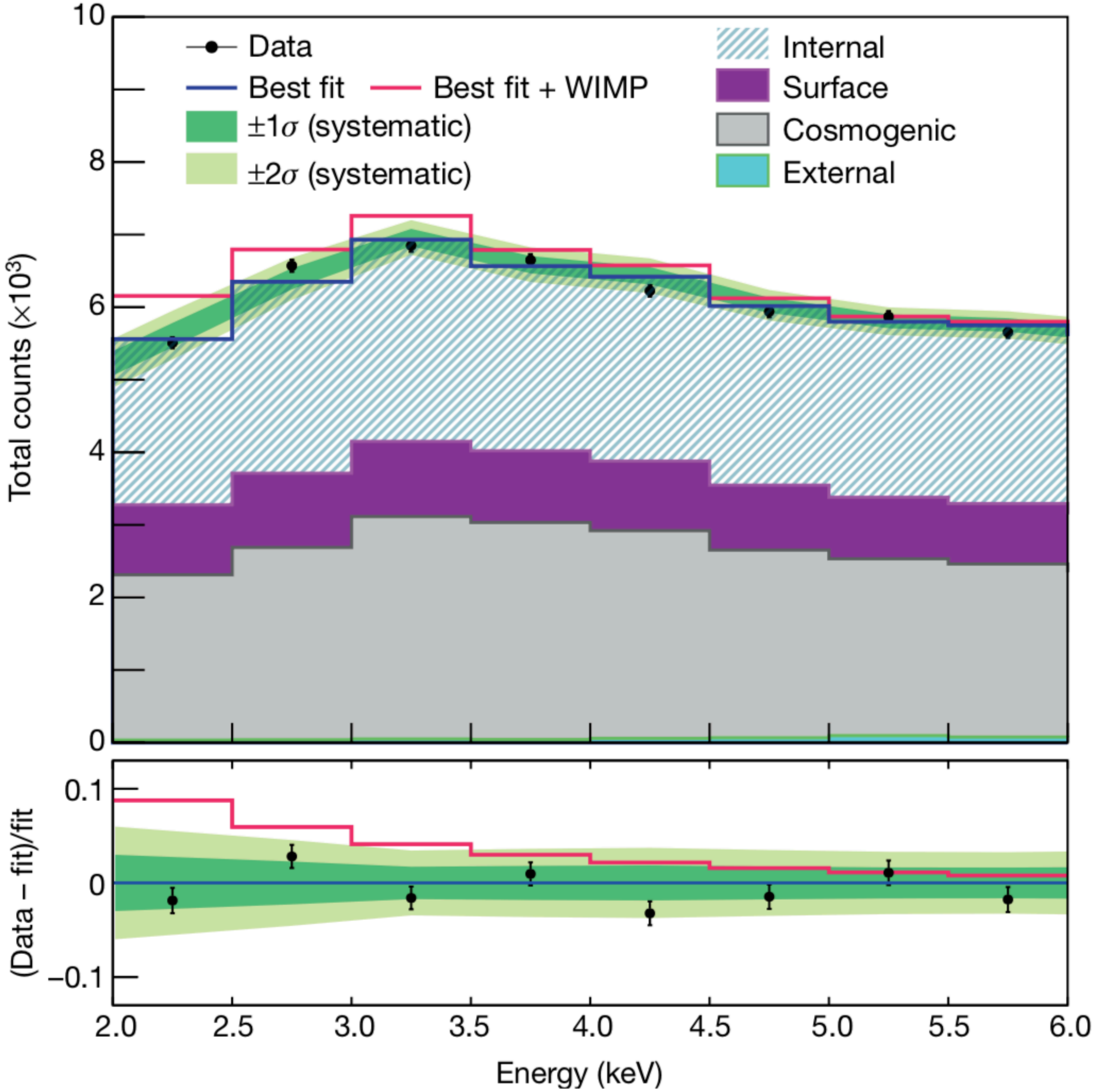


f) Crystal 7

Physics analysis: WIMP analysis



Measured and simulated energy spectra, summed for the six crystals

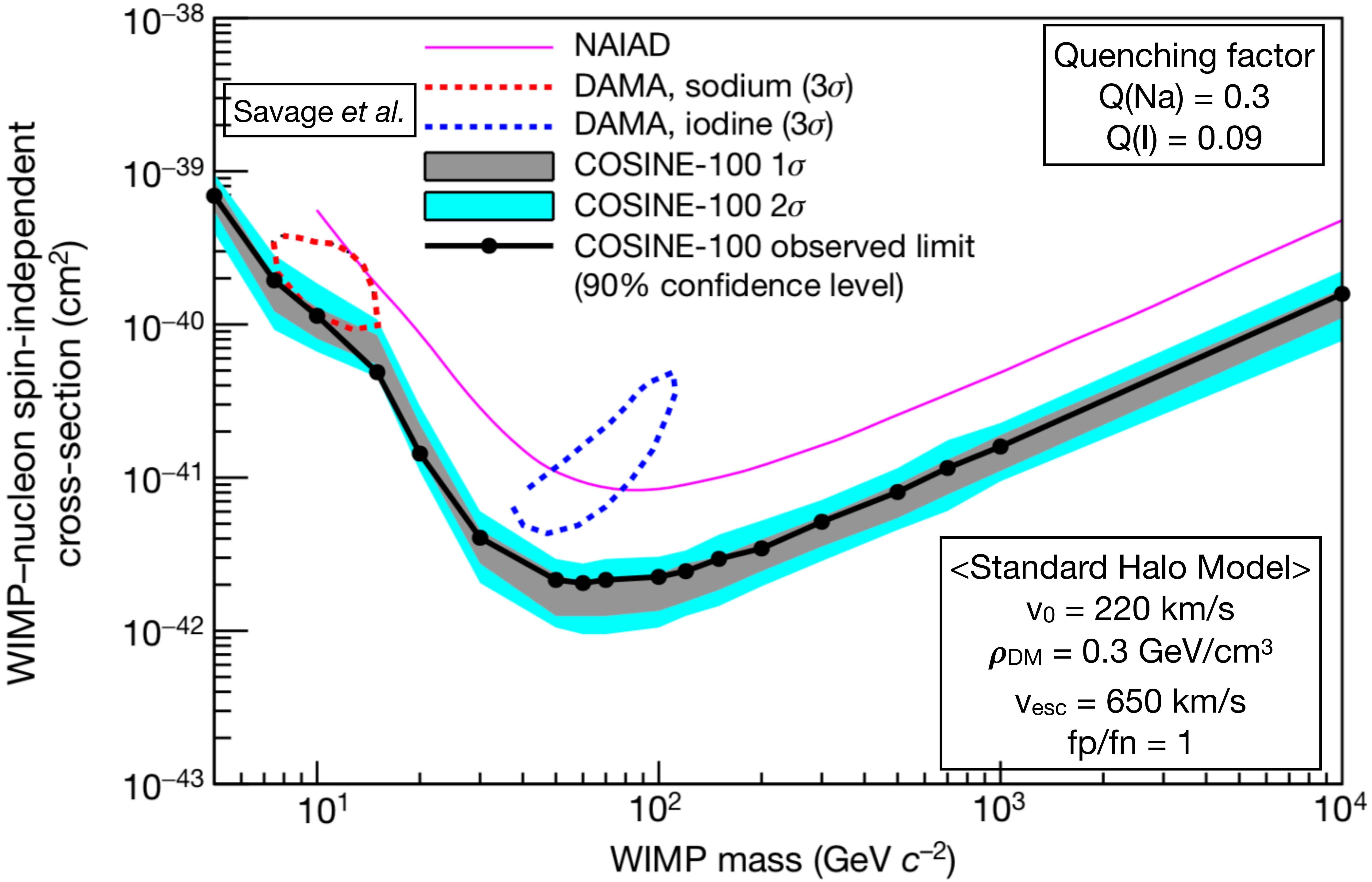


Fit result for a WIMP mass of 10 GeV c^{-2}, summed for the six crystals

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)

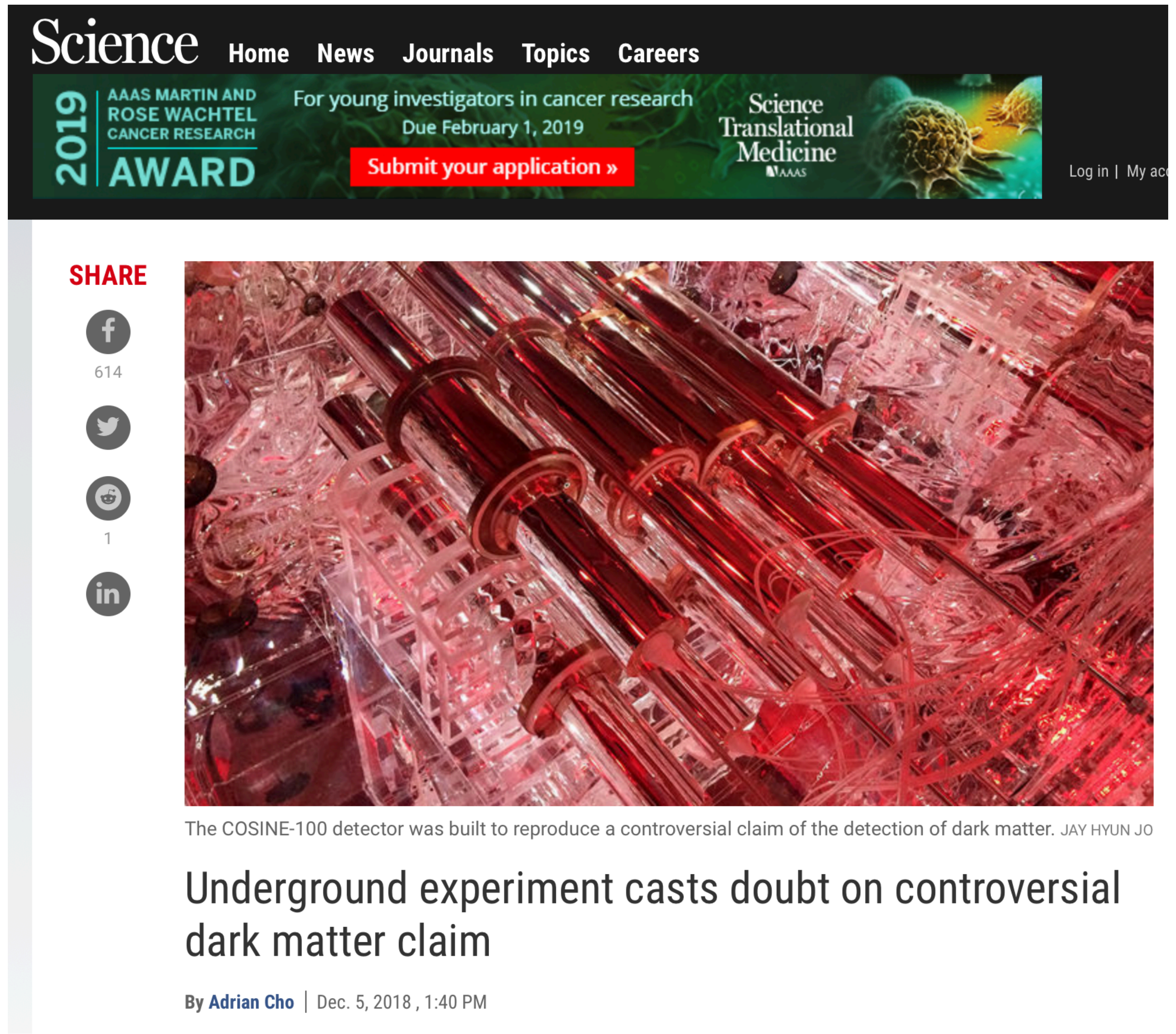


So…is DAMA dead?

- 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 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



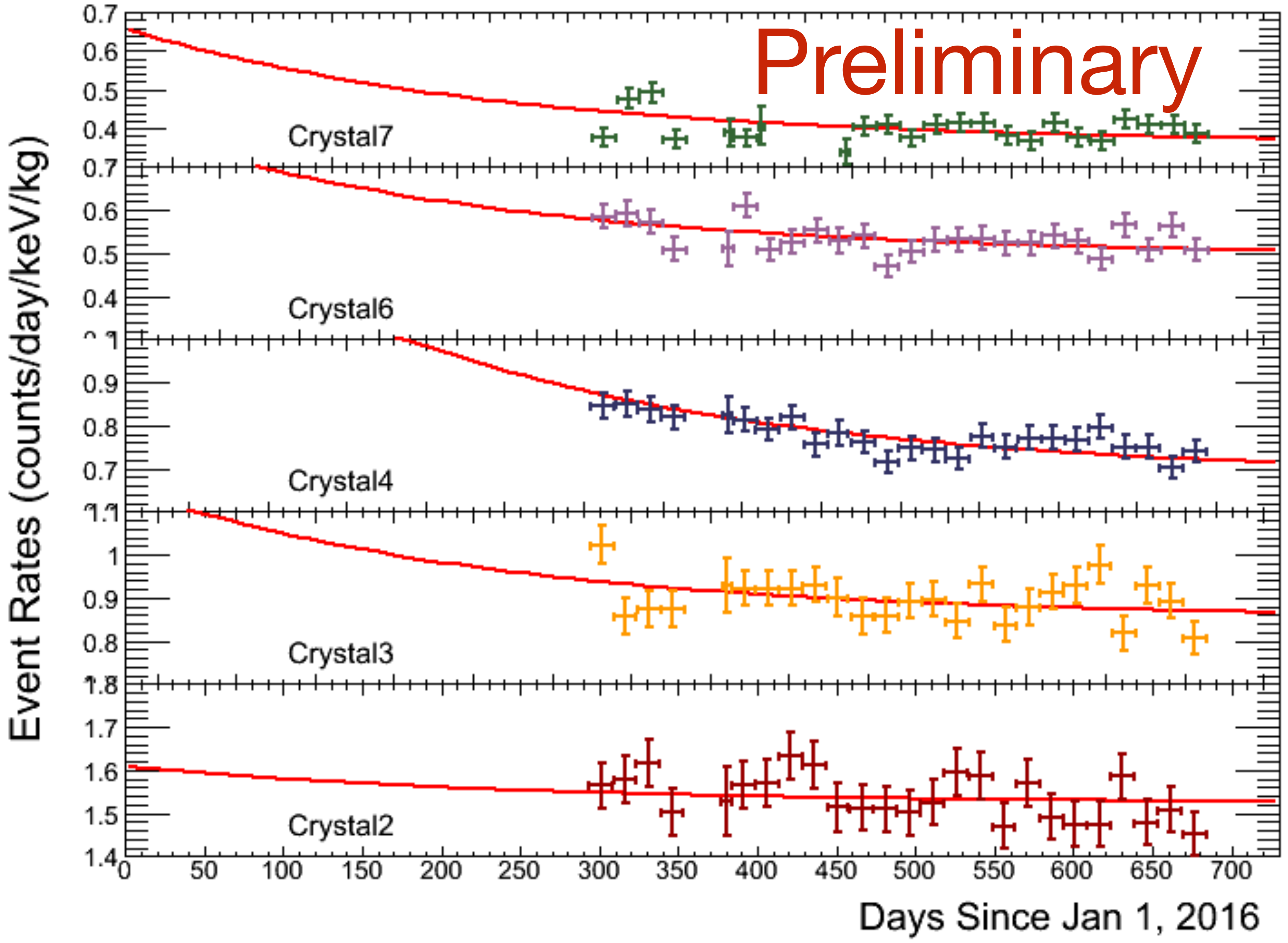
"COSINE-100 has no impact on the long-standing results obtained with the DAMA setups" - R. Bernabei

… 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"

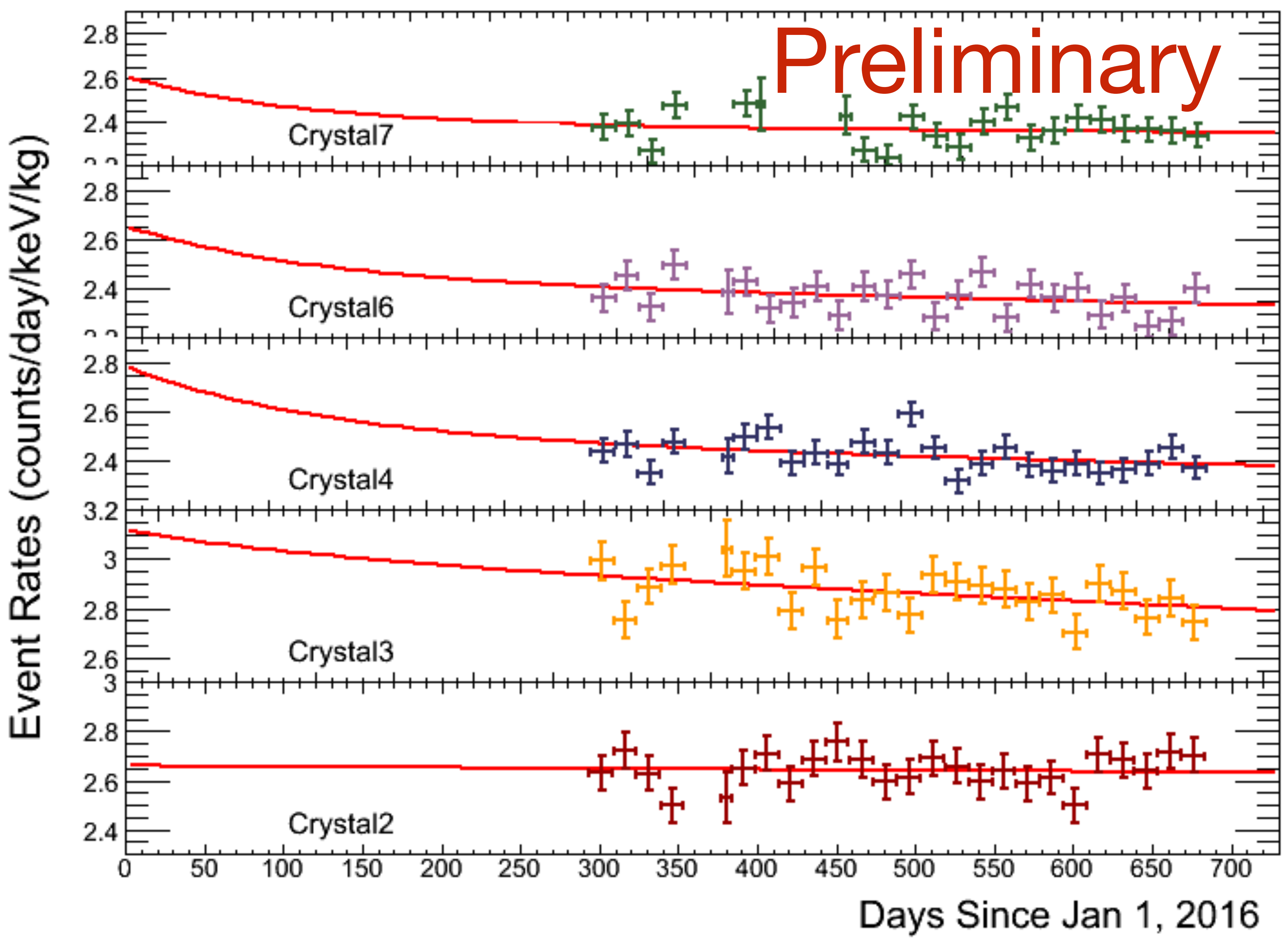
It is true that the COSINE-100 result only ruled out the simplest version of WIMPS, and for a complete test of DAMA, the annual modulation search is required

Physics analysis: Annual modulation analysis

Sideband sample: Multiple-hit 2-6 keV

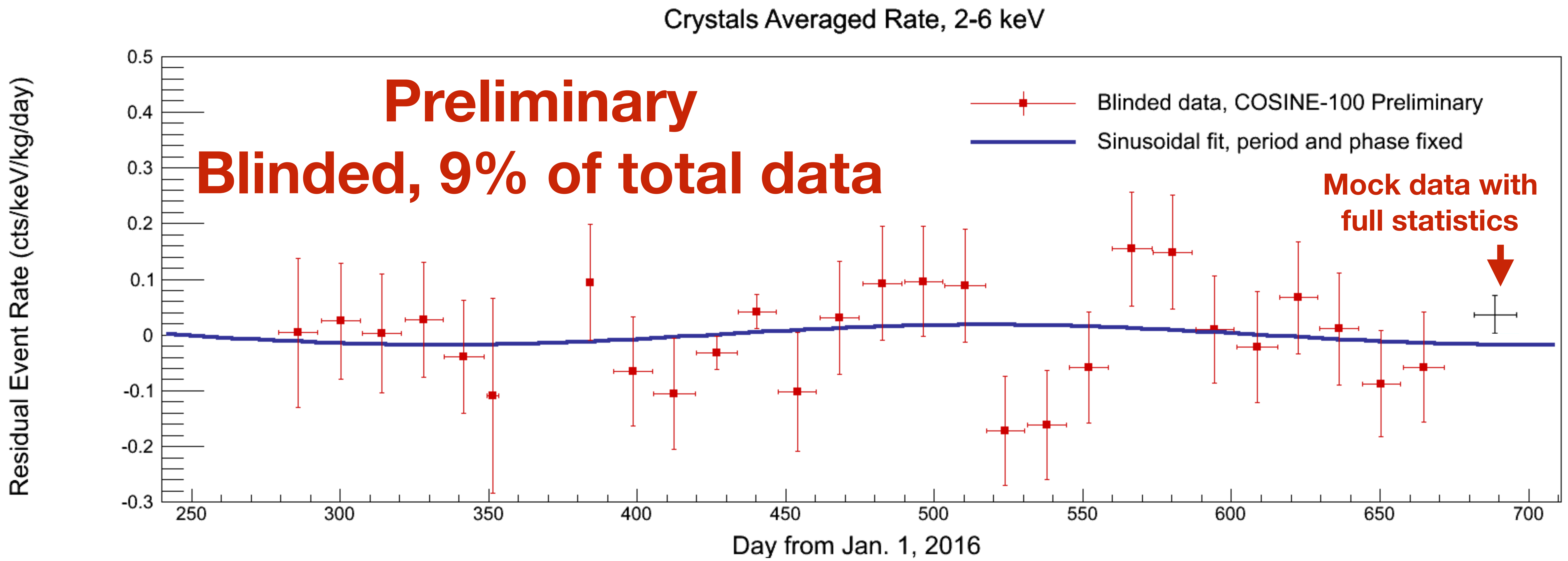


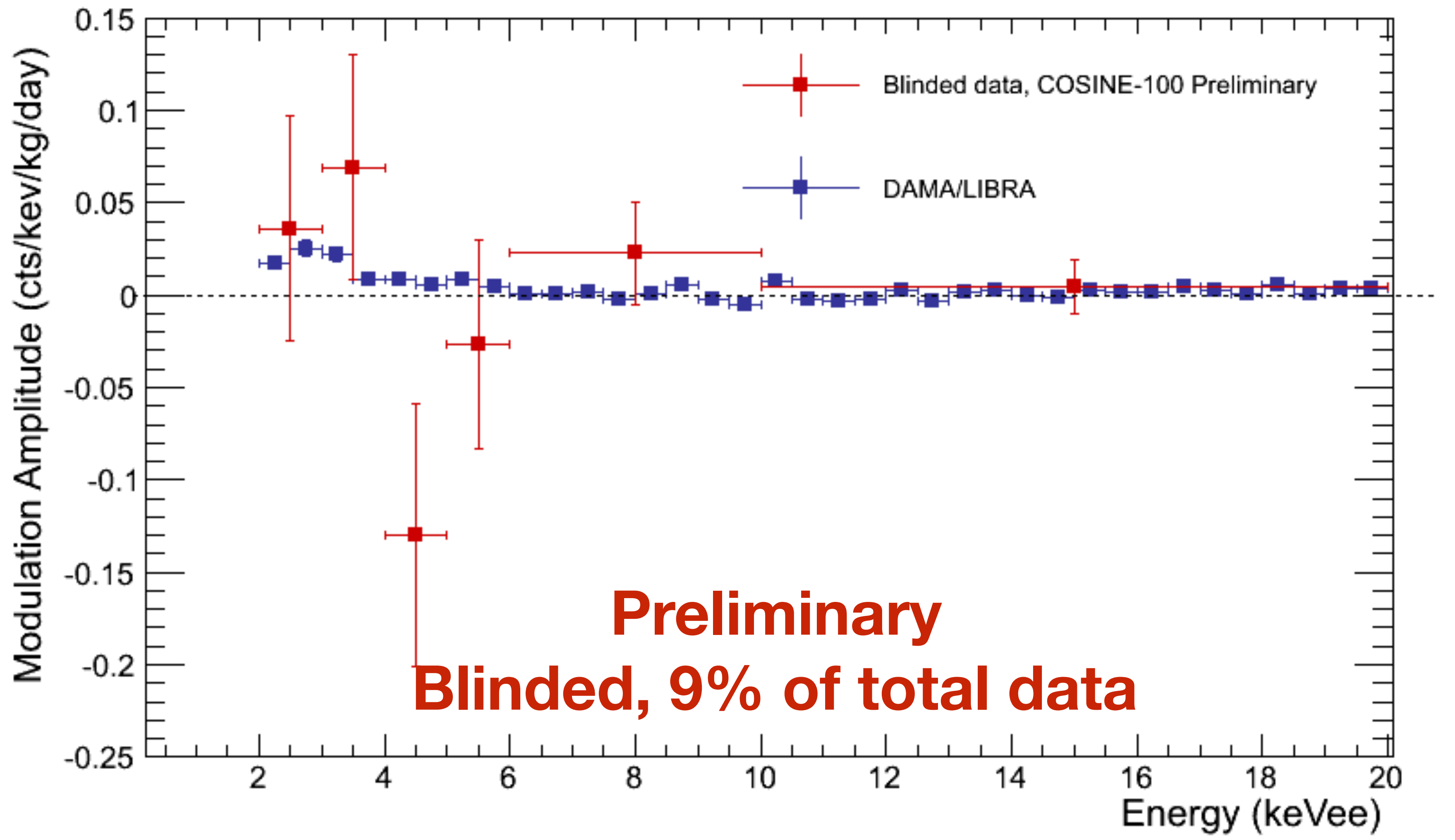
Sideband sample: Single-hit 6-10 keV



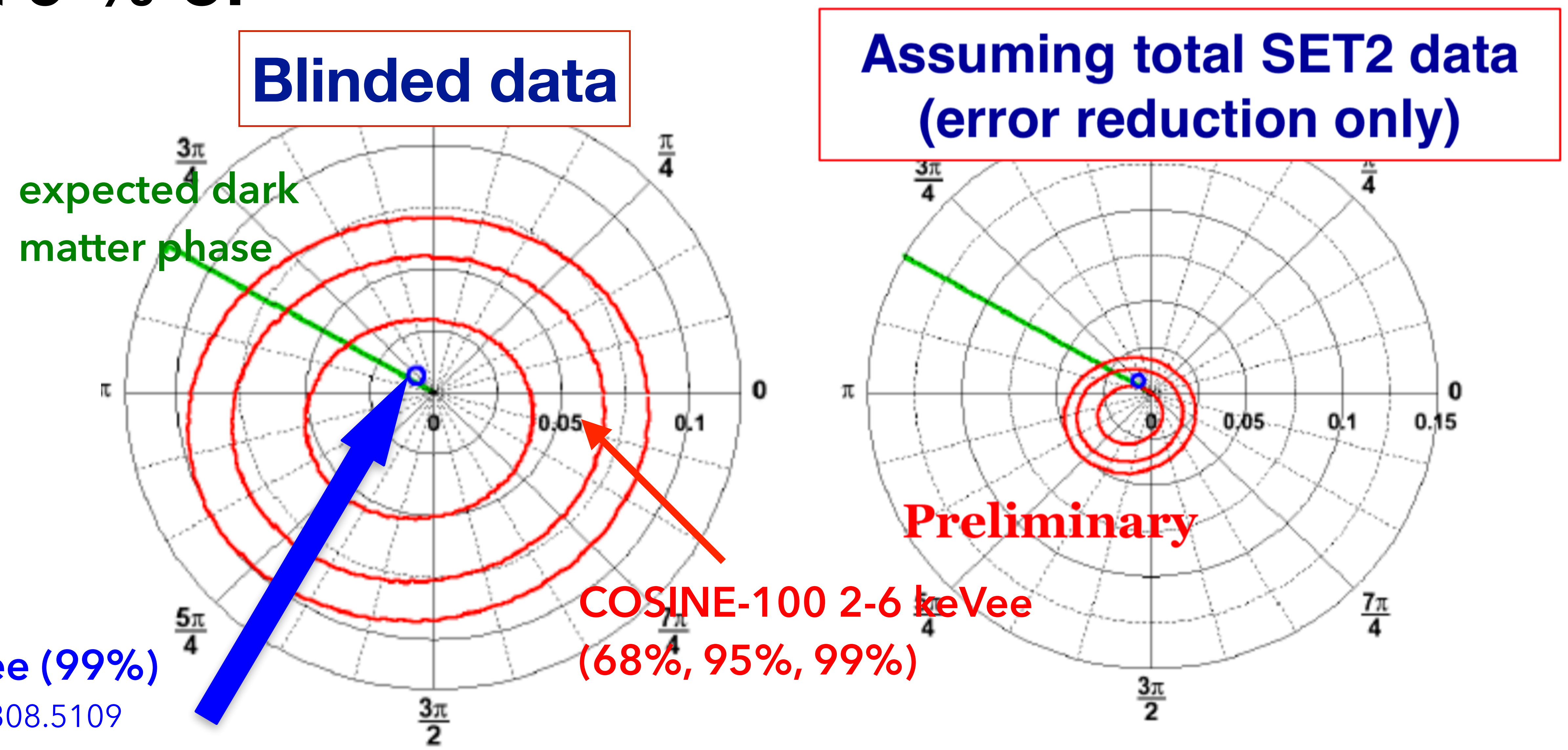
- Crystal 1, 5, and 8 are excluded in this analysis due to low light yield and excessive PMT noise
- Sideband data fits well with exponential models built with the known cosmogenic components

Physics analysis: Annual modulation analysis





- **Currently data in 2-6 keV is blinded, only using < 9 % of total data**
- Full data analysis will be using 720+ days of data
- Data quality, cosmogenic component subtraction, background modeling almost done
- **Stay tuned!**

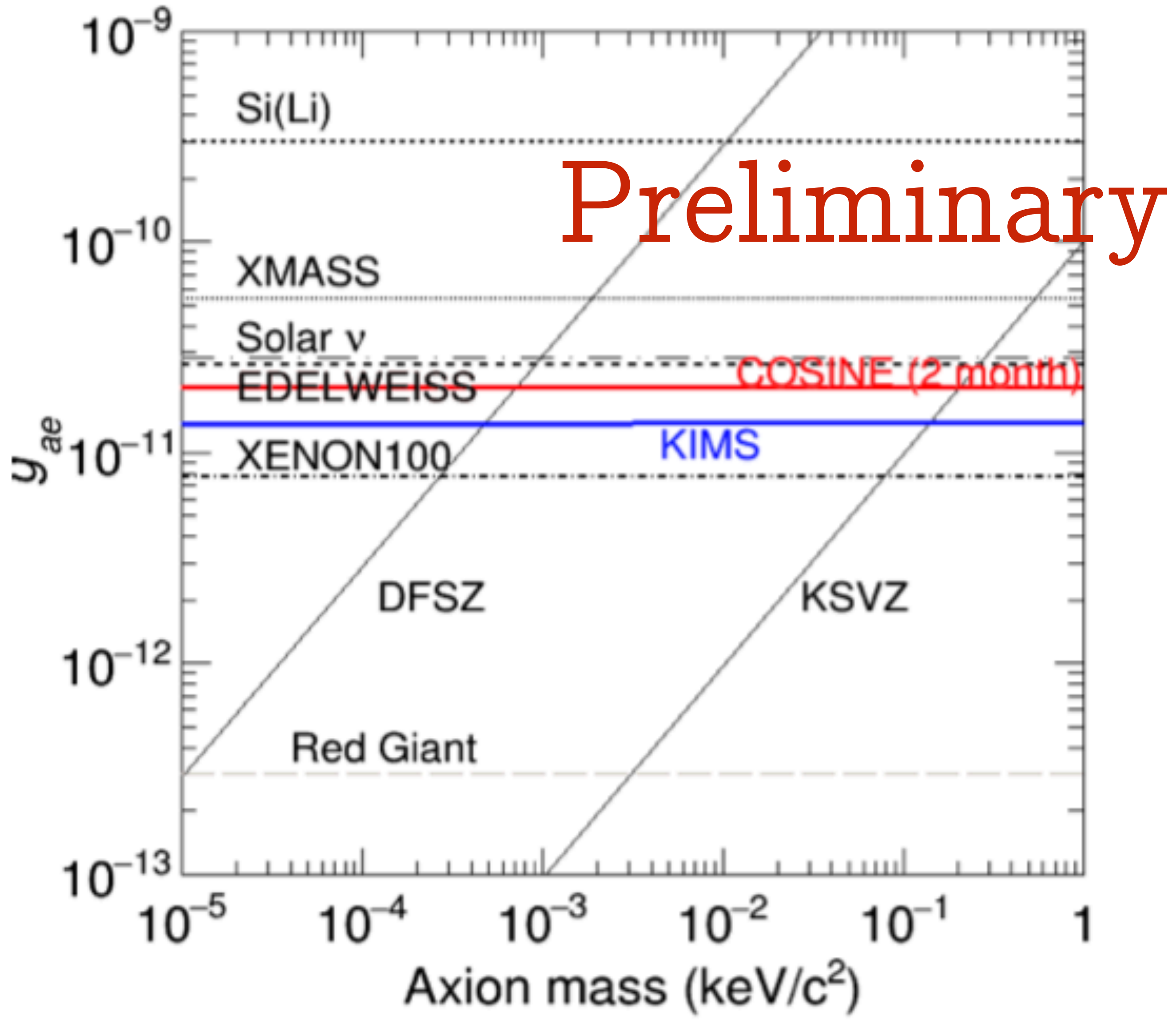


DAMA/LIBRA, 2-4 keVee (99%)
analysis on data from arXiv:1308.5109

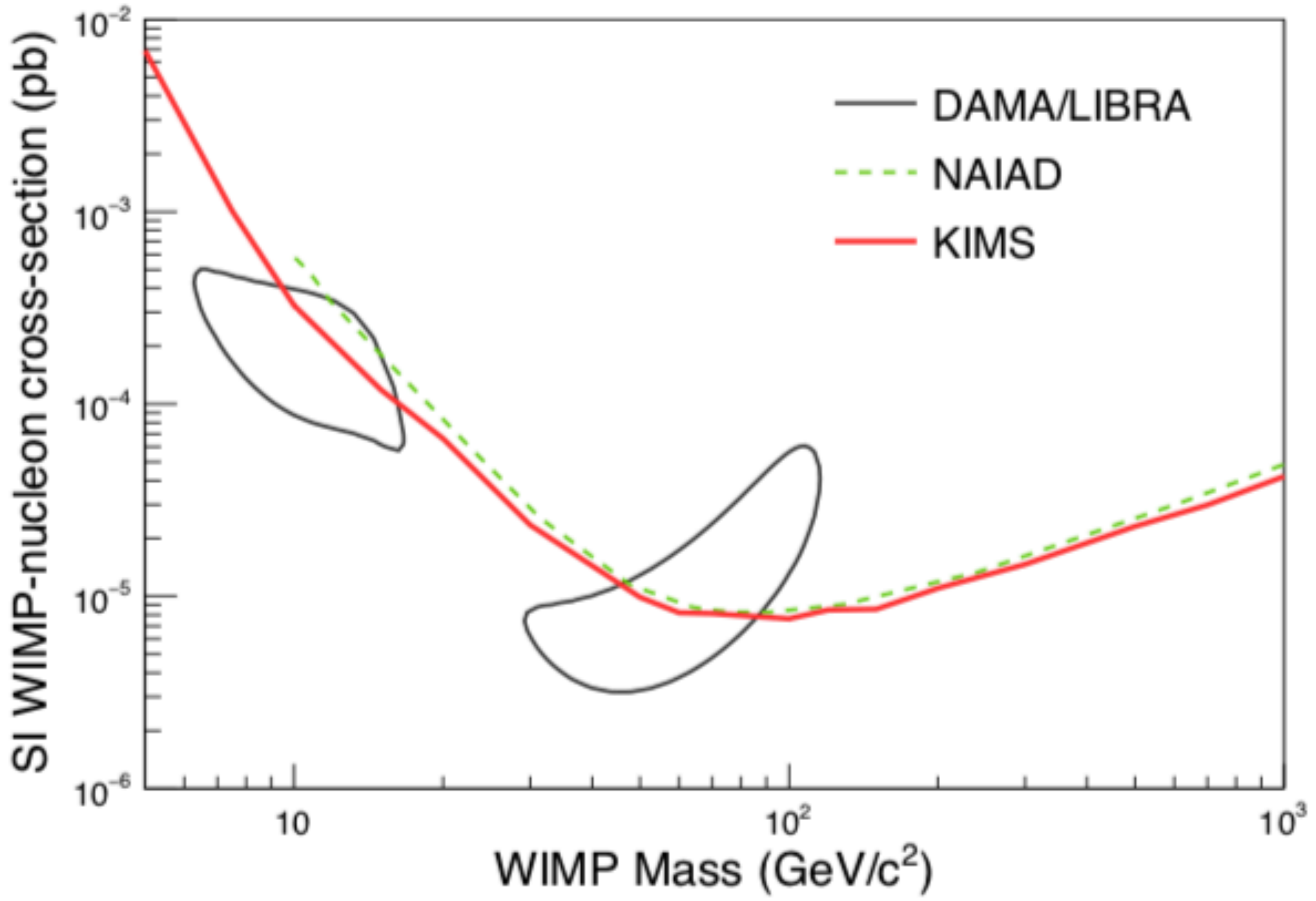
Other physics analyses

- 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, …

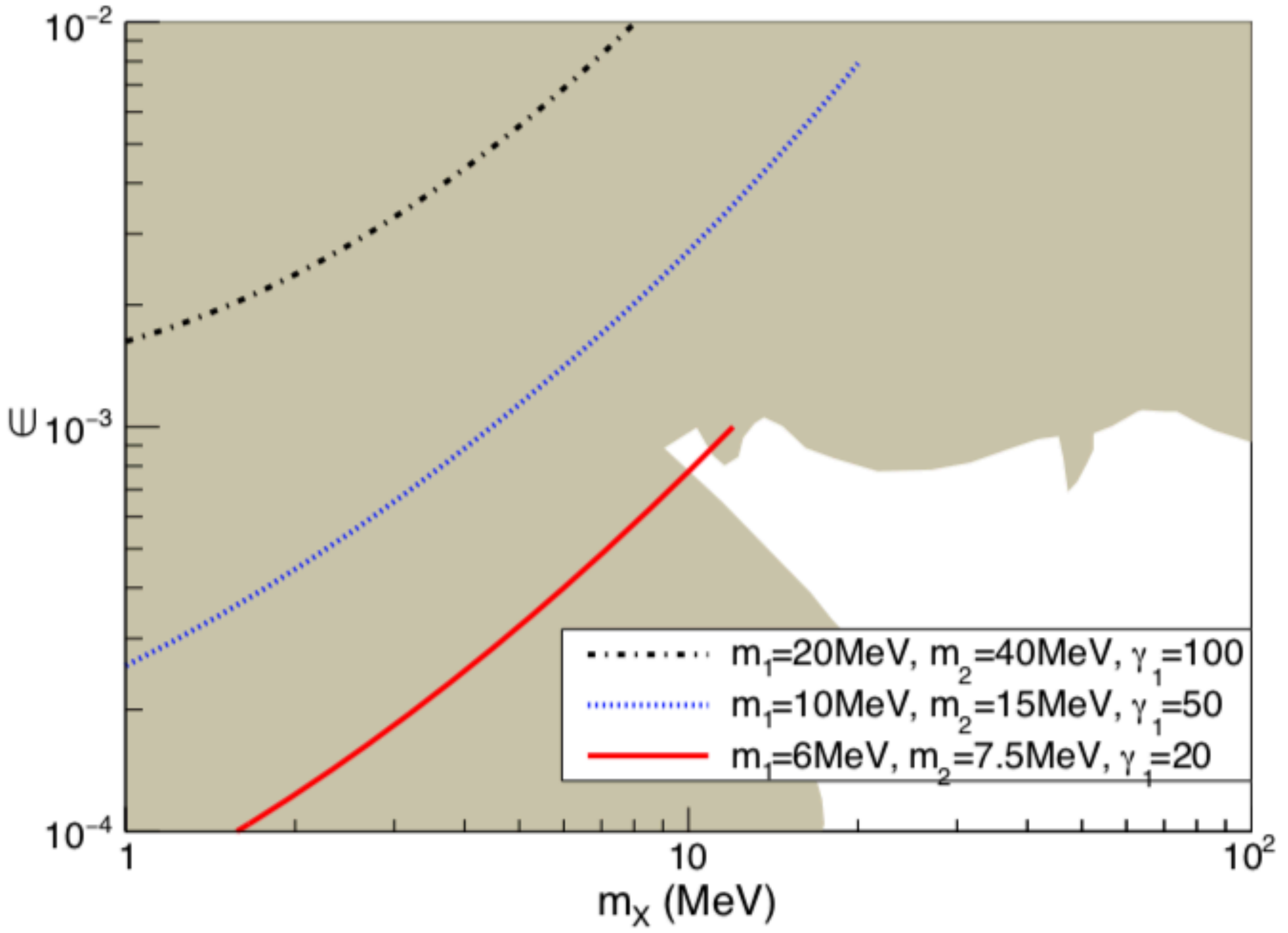
Solar Axion



PSD arXiv:1806.06499



iBDM arXiv:1811.09344

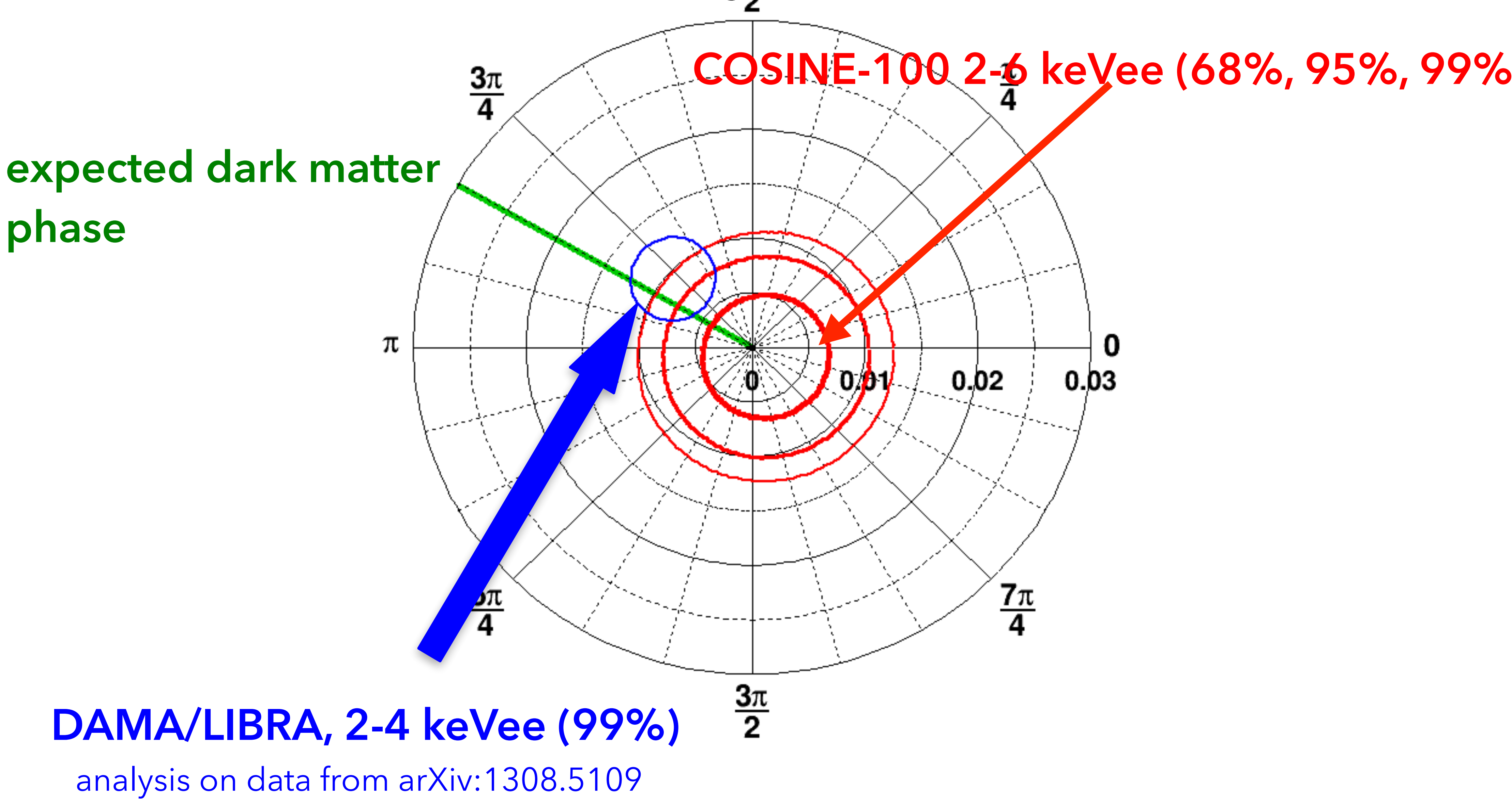


What next?

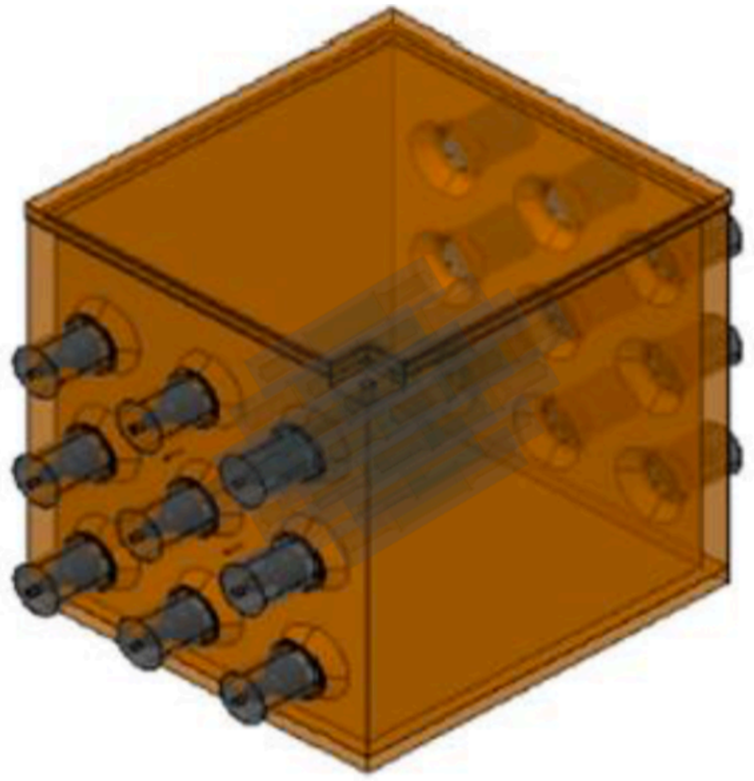
What next?

- 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)

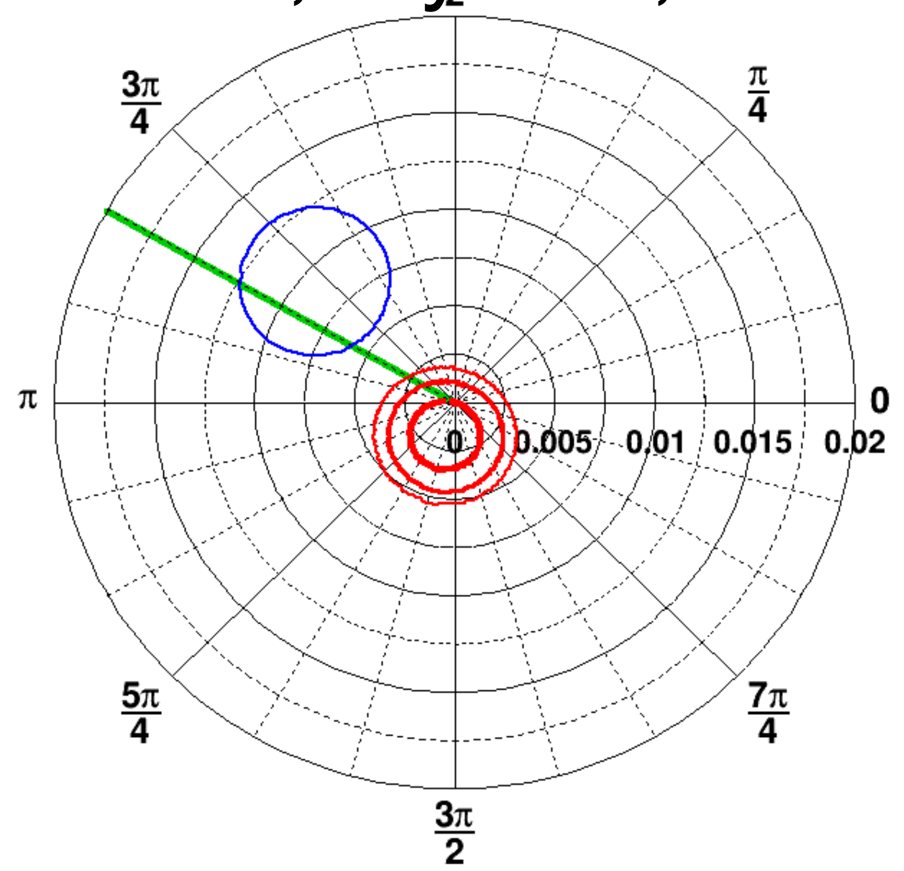
COSINE-100, 5 years, NULL case



COSINE-200 @ Y2L



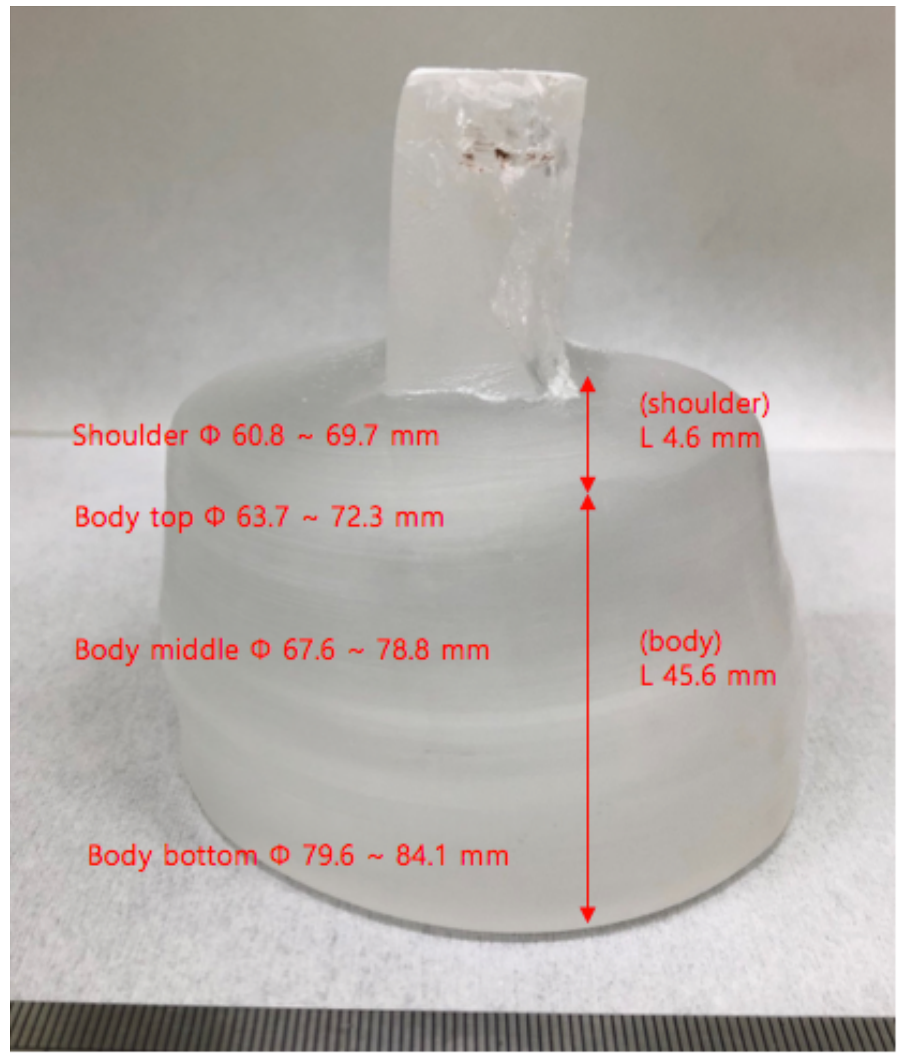
COSINE-200, 5 years, NULL case



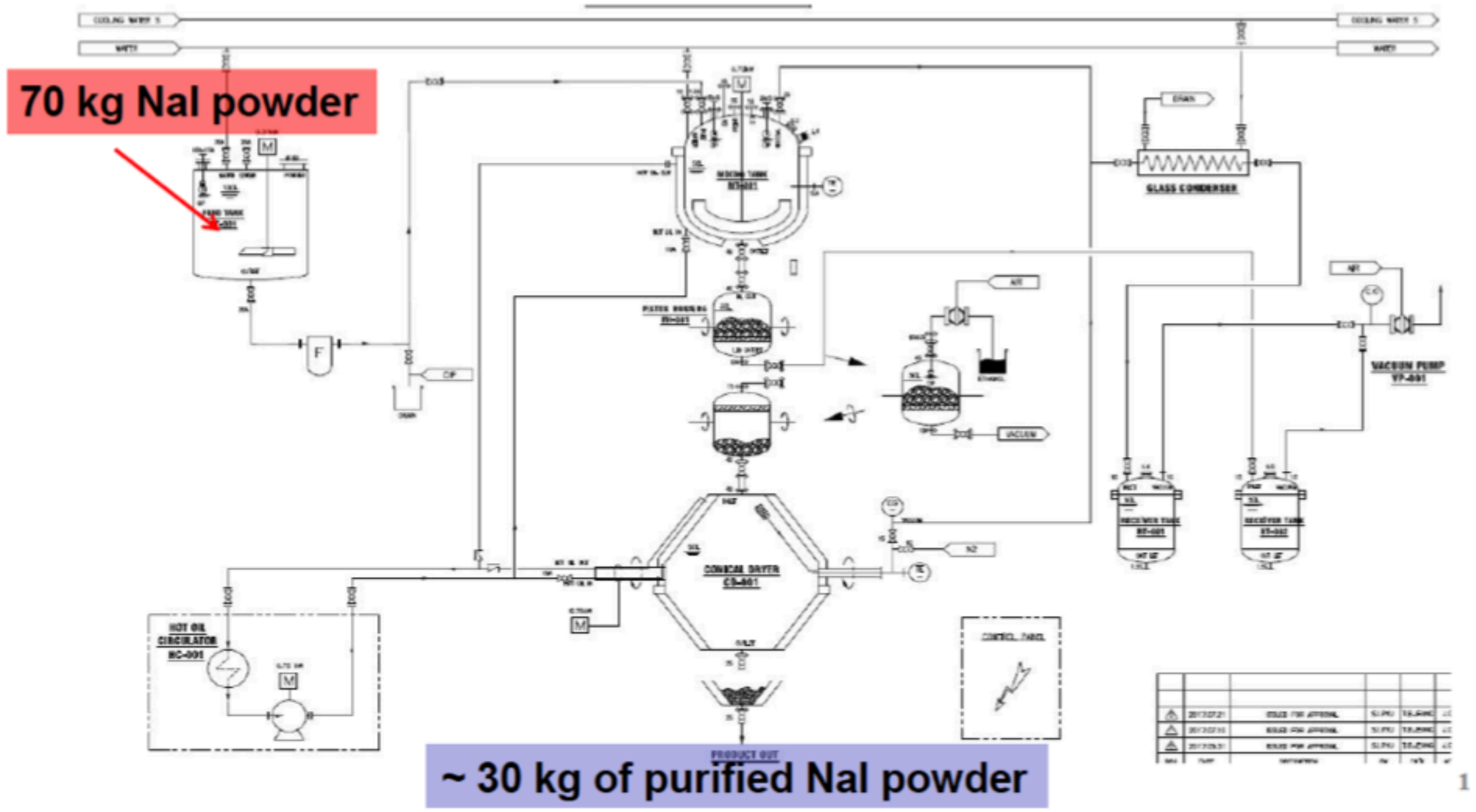
What next? (Crystal growing R&D)

- 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



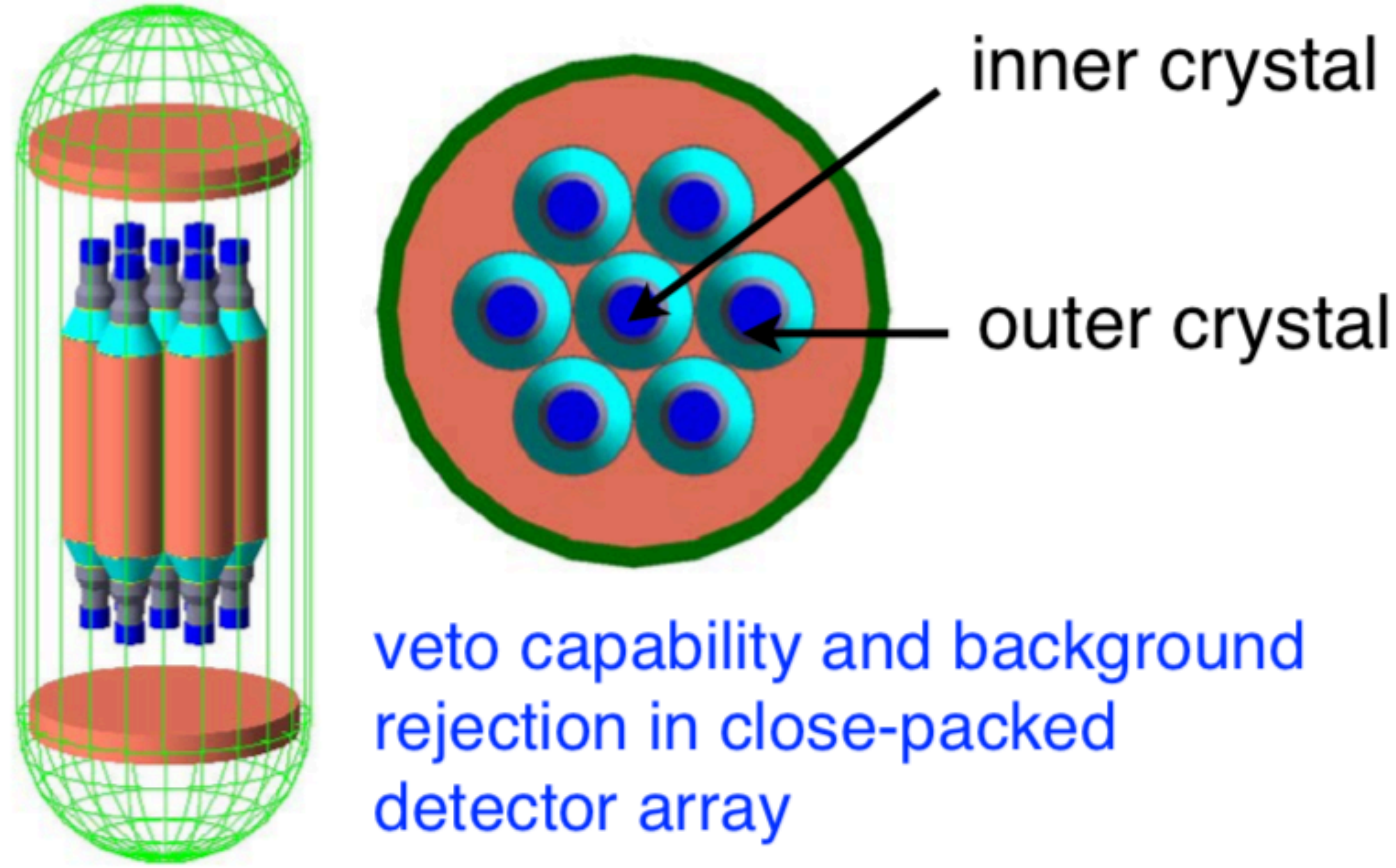
What next?

- **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

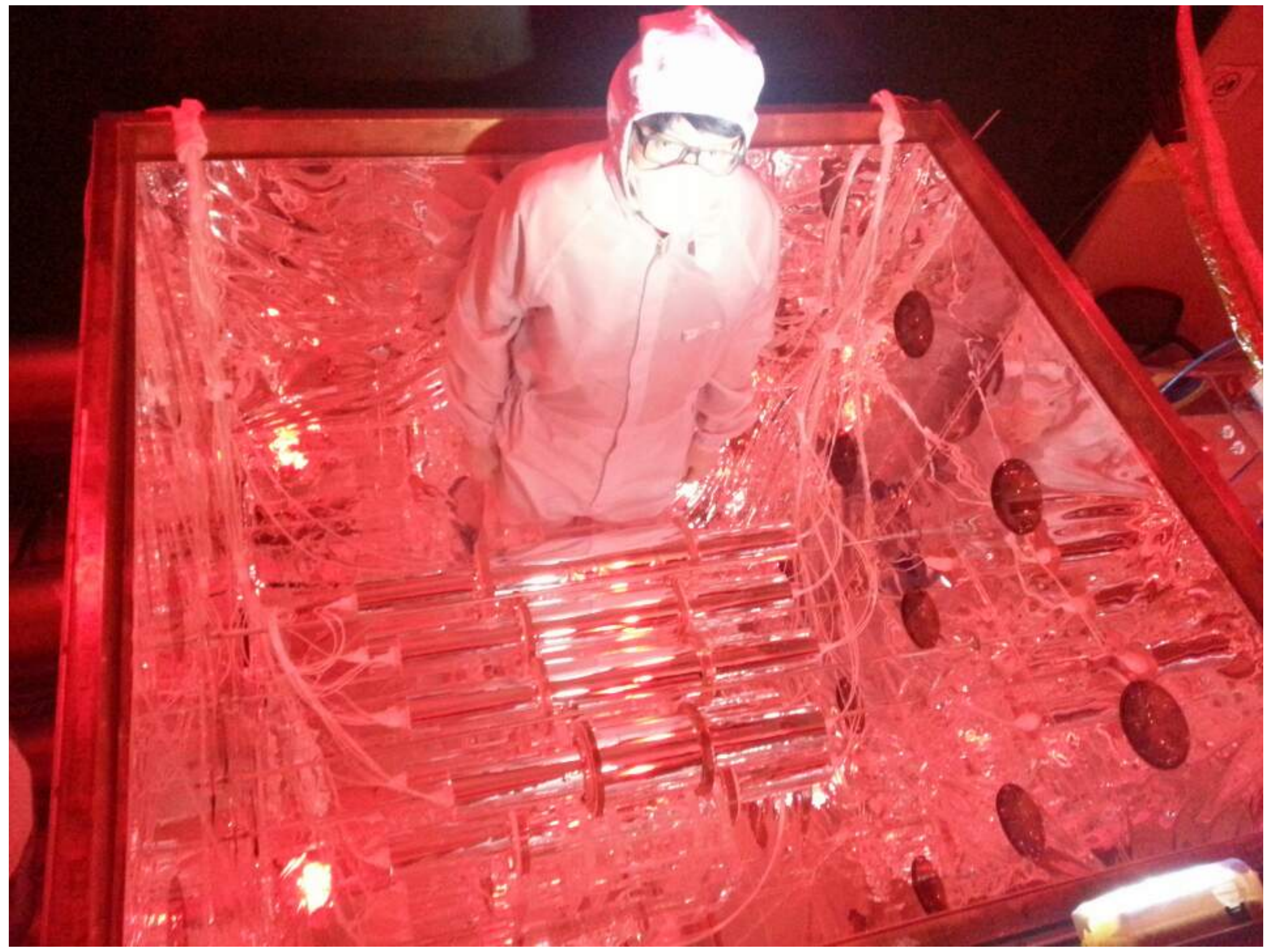
Close-Packed Detector Array



veto capability and background rejection in close-packed detector array

Summary and outlook





- DM-Ice17 and 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), the annual modulation analysis on-going
- 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!