

# Recent Results from the COSINE-100 Experiment

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*on behalf of the COSINE-100 Collaboration*

Yale University

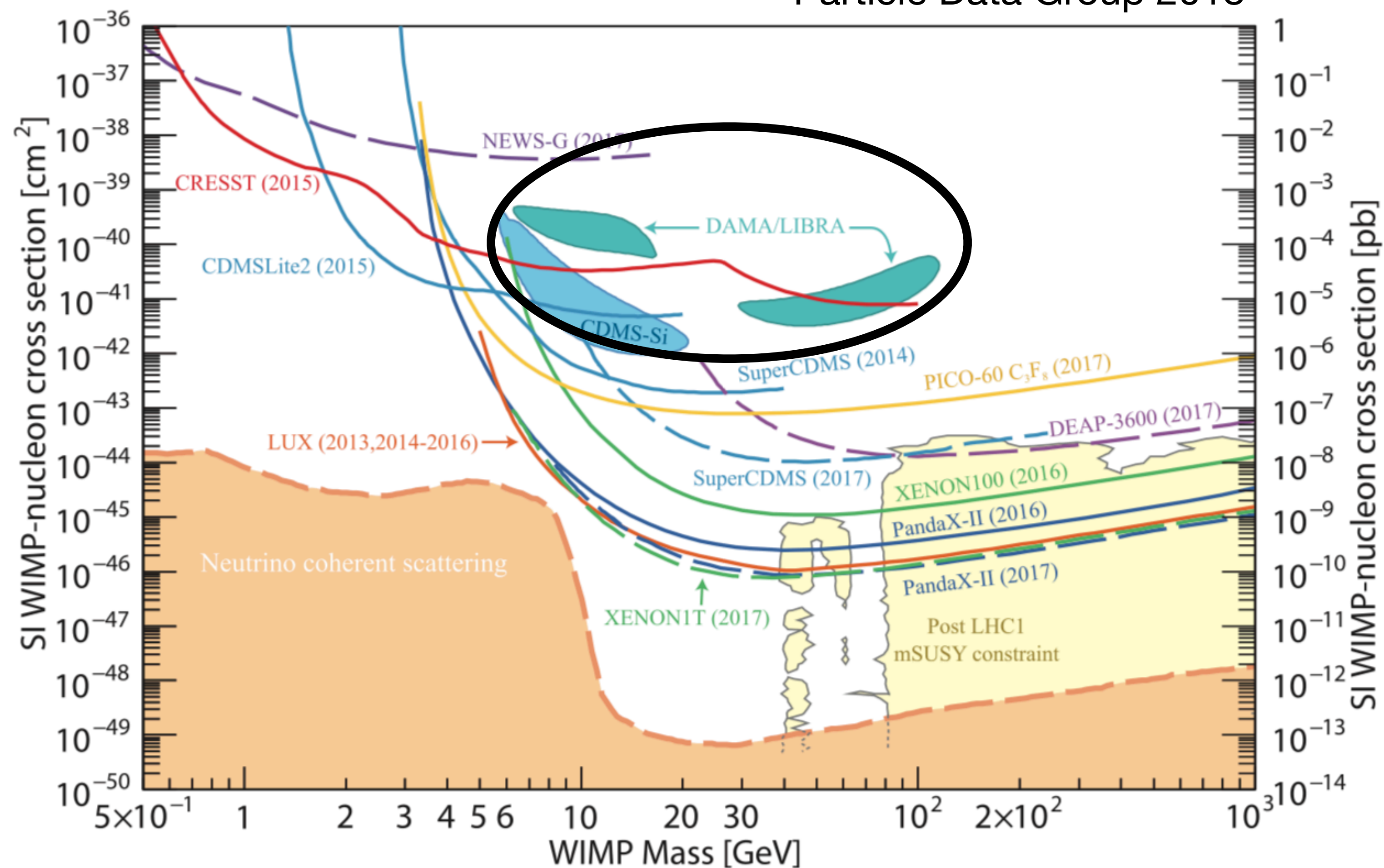
IDM 2018  
July 23 - 27, 2018



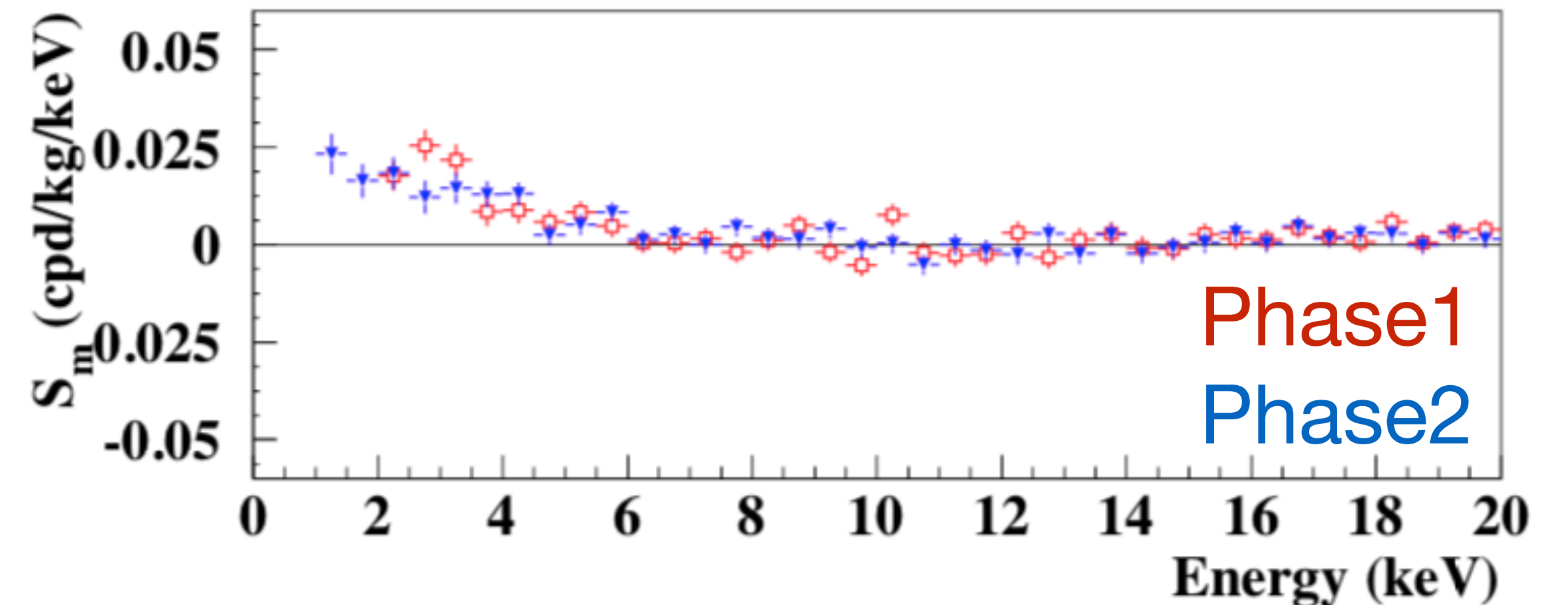
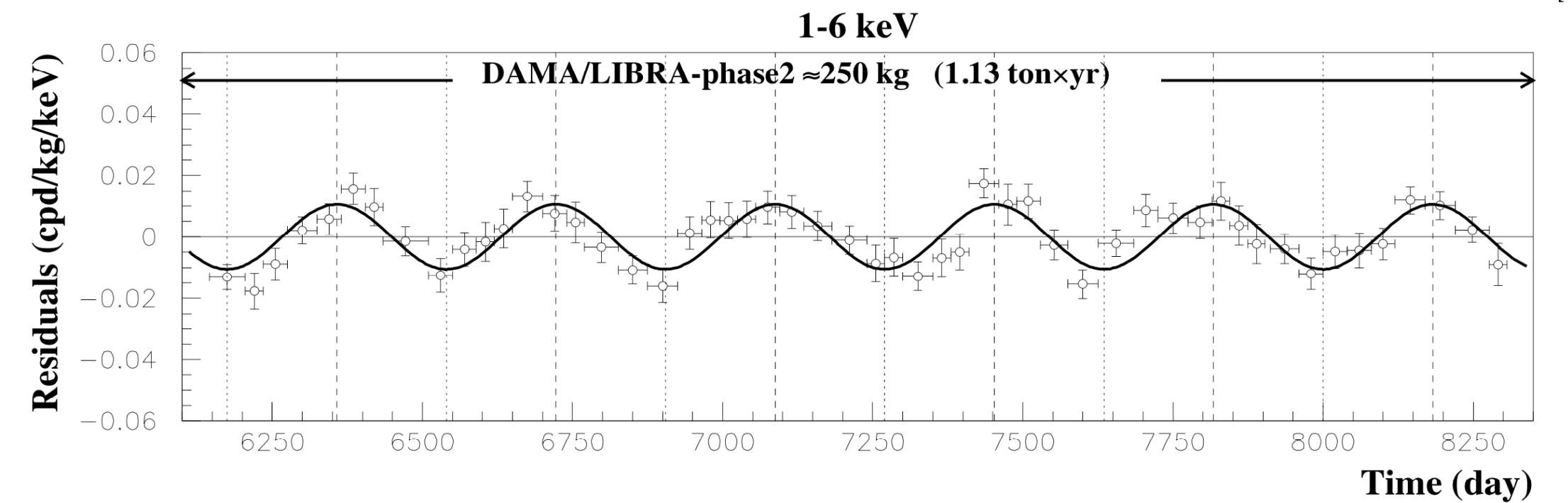
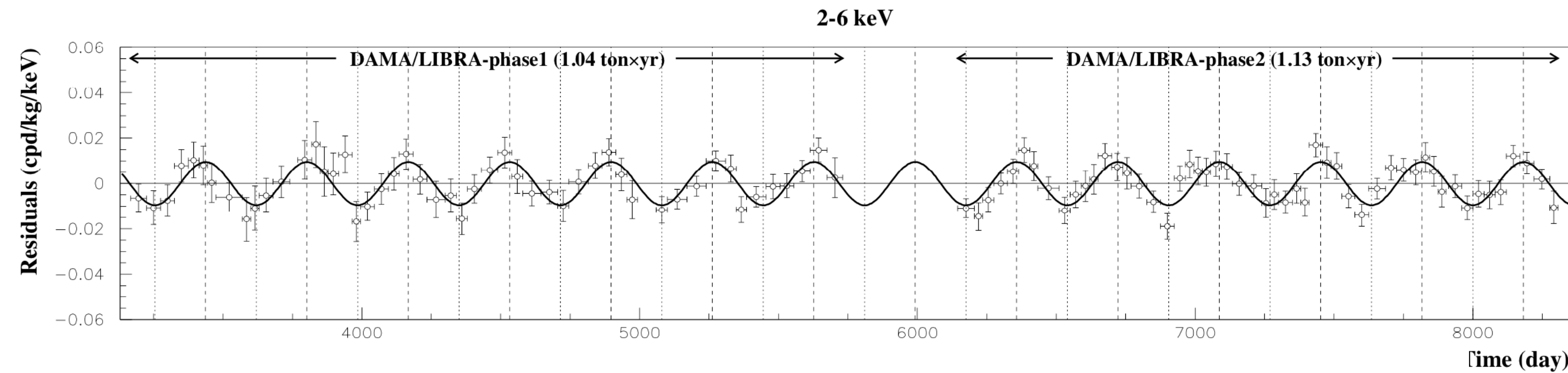
# Current Status of Direct Dark Matter Searches

- 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



- DAMA/LIBRA-phase2 result with 1 keV threshold
  - (2-6) keV:  $12.9 \sigma$  from 2.46 ton-year
  - (1-6) keV:  $9.5 \sigma$  from 1.13 ton-year
- Modulation amplitude:  $(0.0103 \pm 0.0008)$  cpd/kg/keV in (2-6) keV
- Phase:  $(145 \pm 5)$  days
- Period:  $(0.999 \pm 0.001)$  year
- Long-standing conflict with other experiments using different target material





# Global NaI Efforts



**DAMA**

**SABRE**

**COSINUS**

★ Gran Sasso + Australia

**KIMS (+ DM-Ice)**

**COSINE-100**

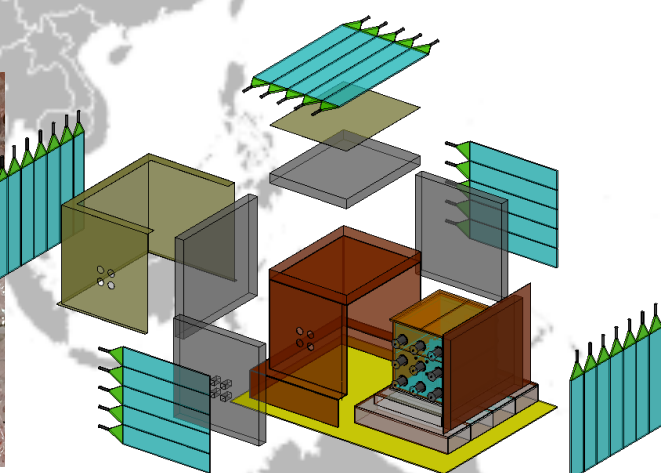
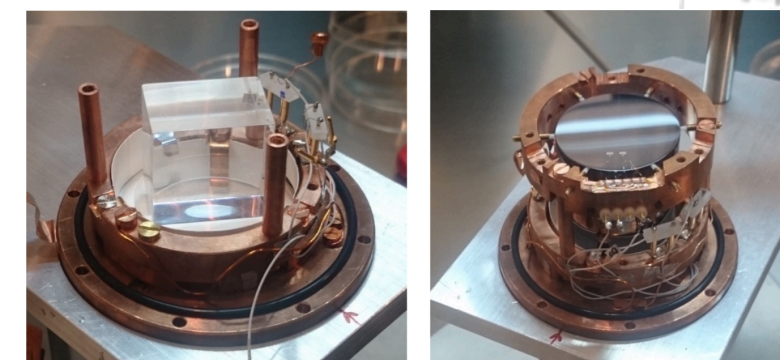
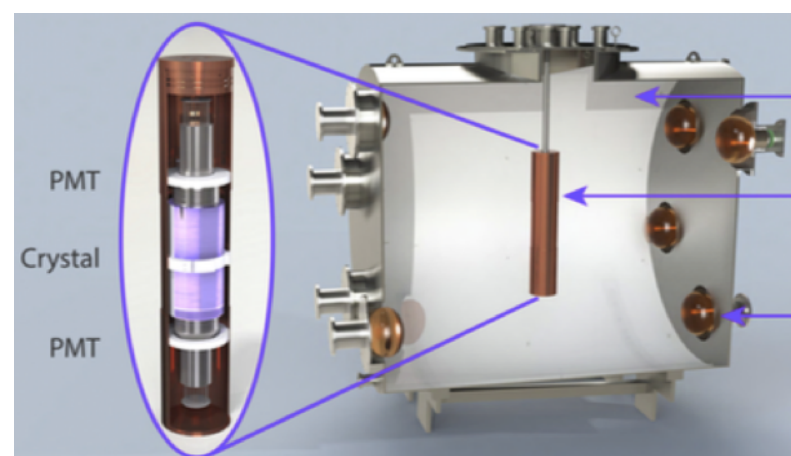
★ Yangyang  
★ Kamioka

**PICOLON**

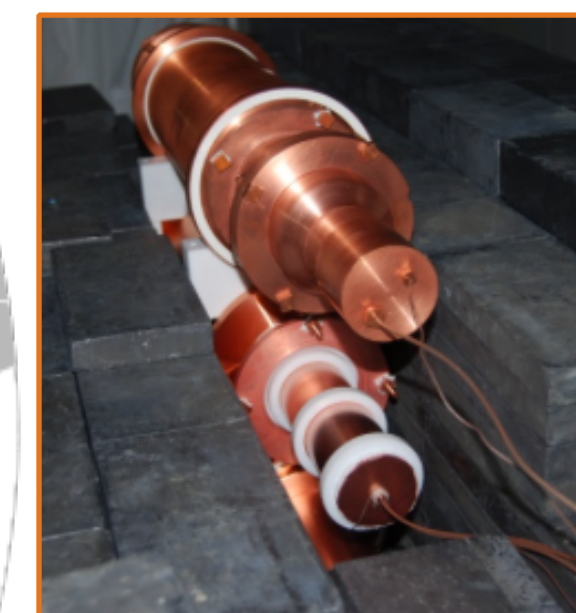
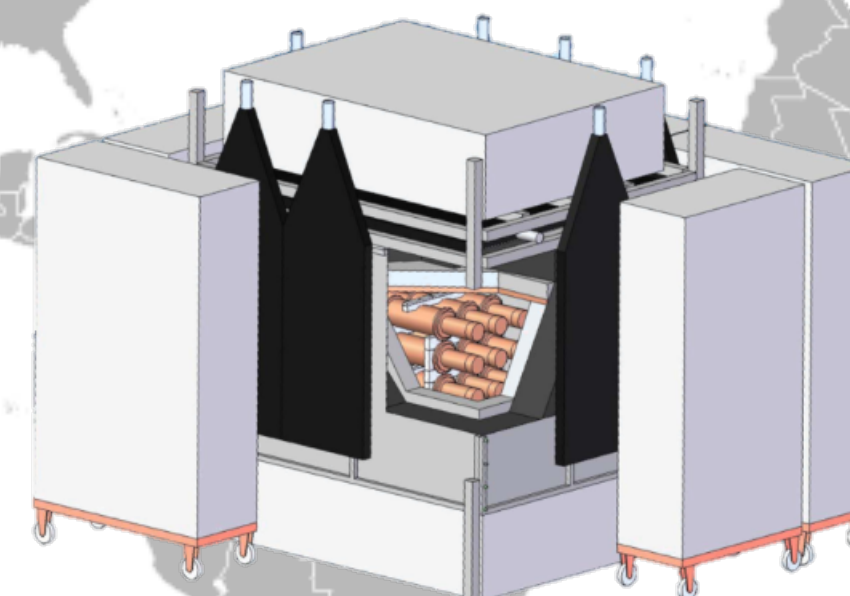
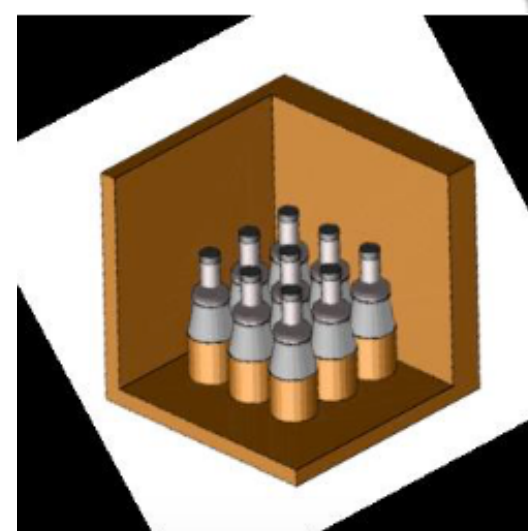
**ANAIS**

★ Boulby

★ Canfranc

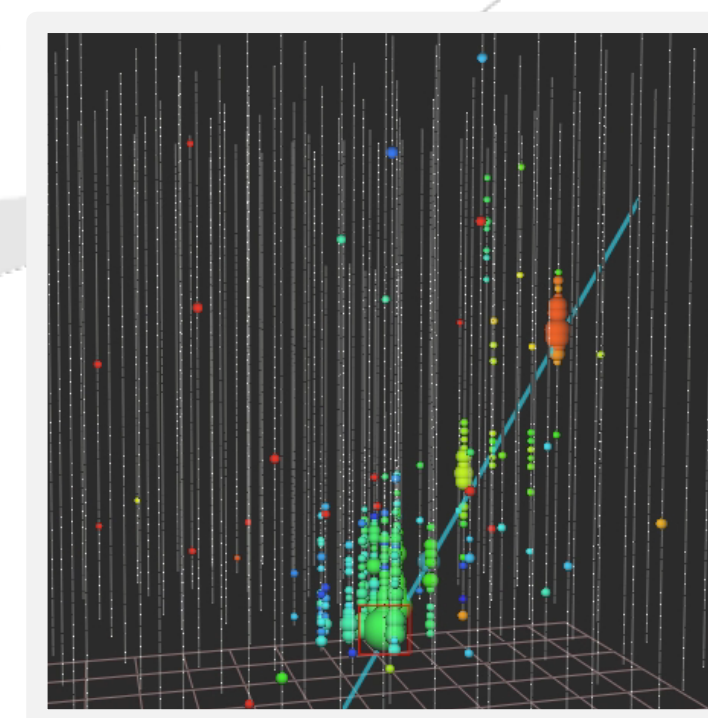
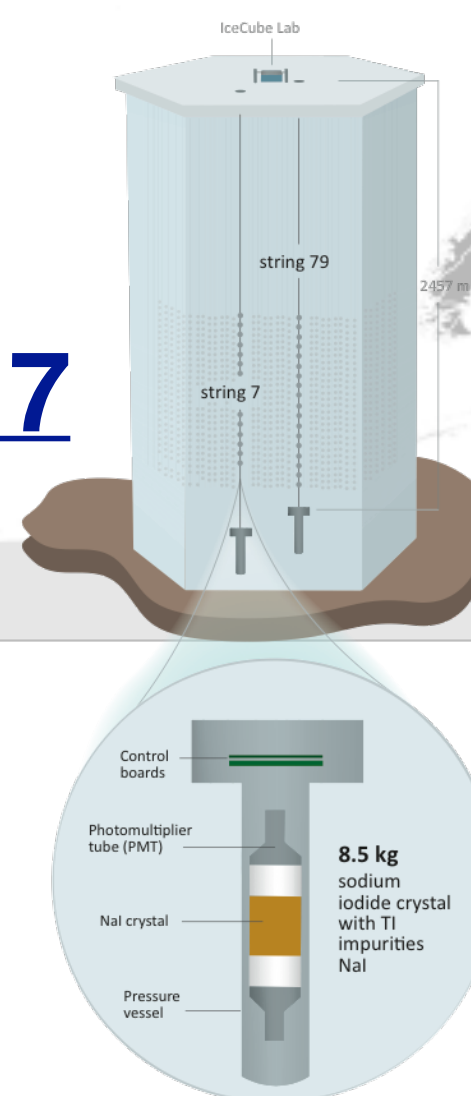


Eur.Phys.J. C **78** 107 (2018)  
Eur.Phys.J. C **77** 437 (2017)  
JINST **13** T02007 (2018)  
Phys.Rev. D **90** 052006 (2014) (Csl)

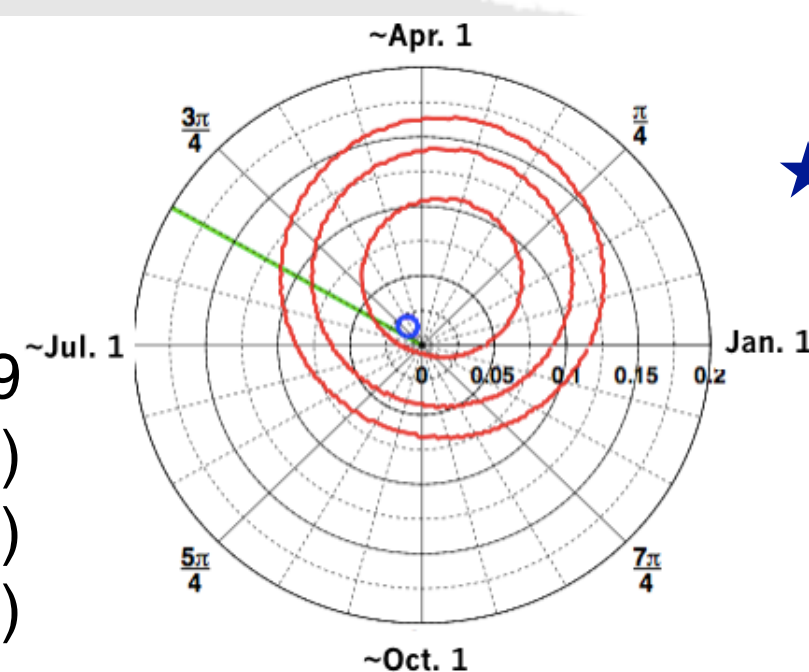


**DM-Ice17**

★ South Pole

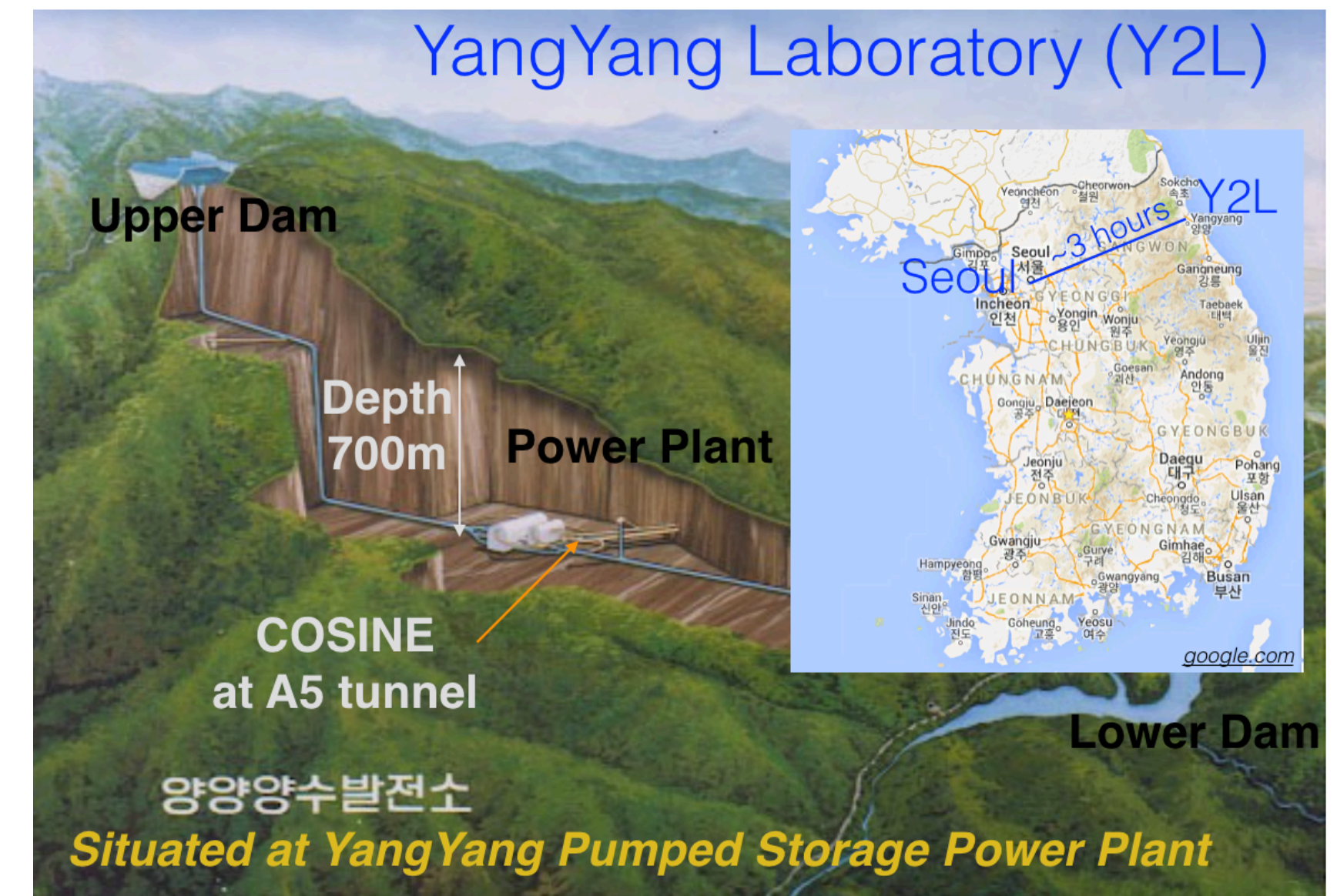


Astropart. Phys. **35** (2012) 749  
Phys. Rev. D **90** 092005 (2014)  
Phys. Rev. D **93** 042001 (2016)  
Phys. Rev. D **95** 032006 (2017)



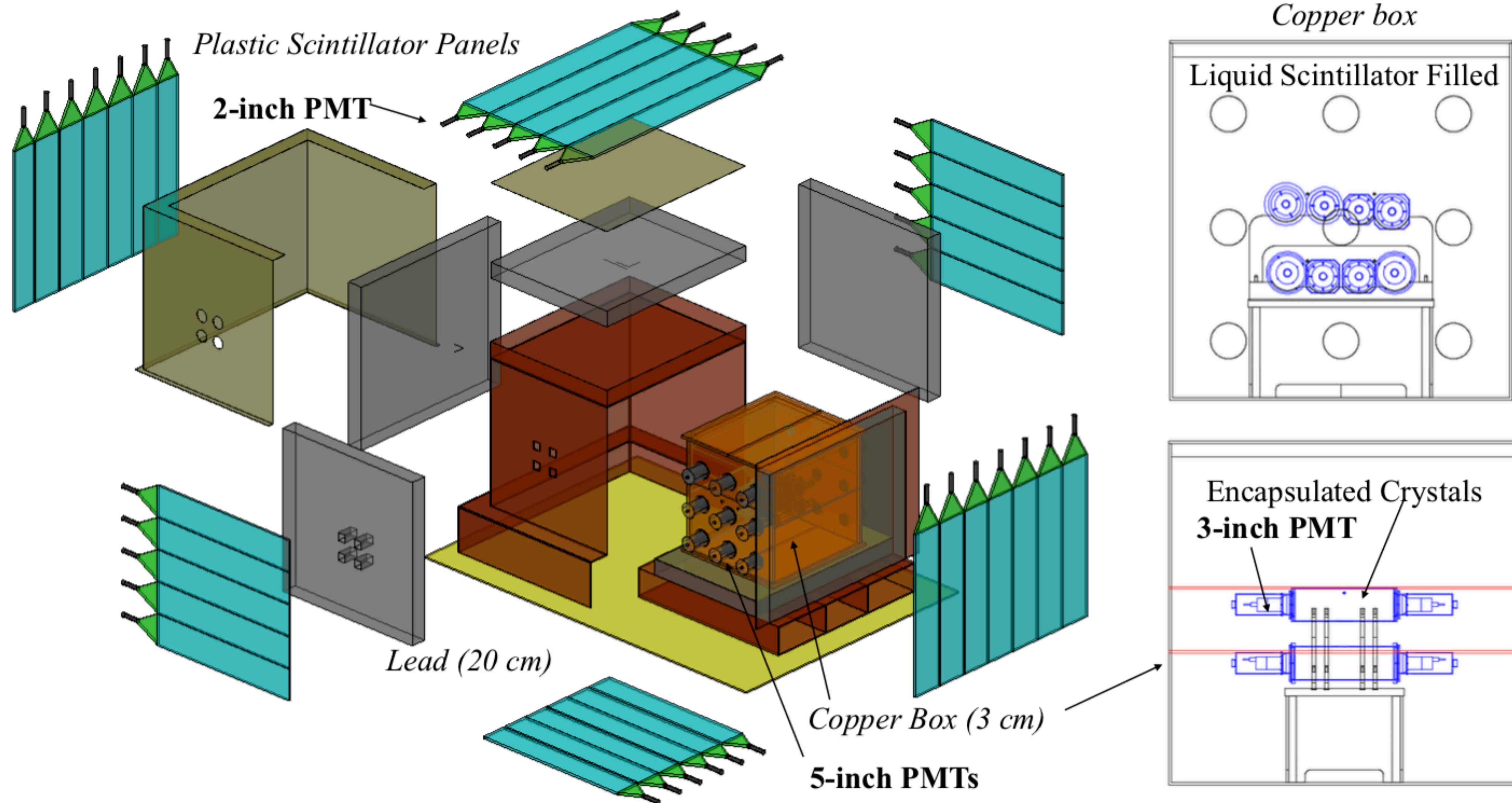


- A joint effort between DM-Ice and KIMS collaborations
- 8 NaI(Tl) crystals with 106 kg in total
- Located at Yangyang underground laboratory (Y2L), South Korea, with ~700 m rock overburden
- **Physics run started September 2016**





# COSINE-100 Detector Configuration





# COSINE-100 Construction Timeline



Dec. 2015



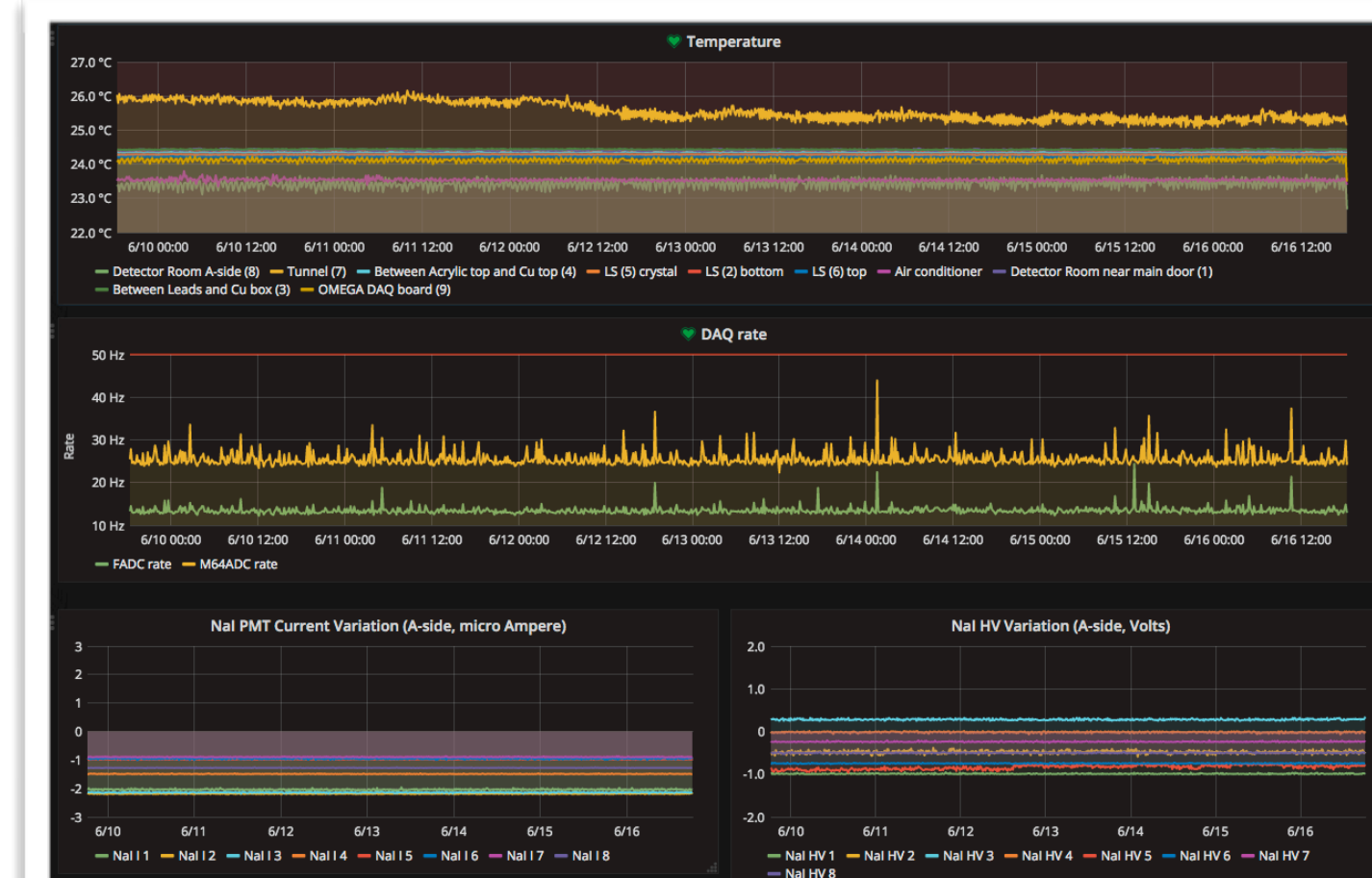
Mar. 2016



Jun. 2016



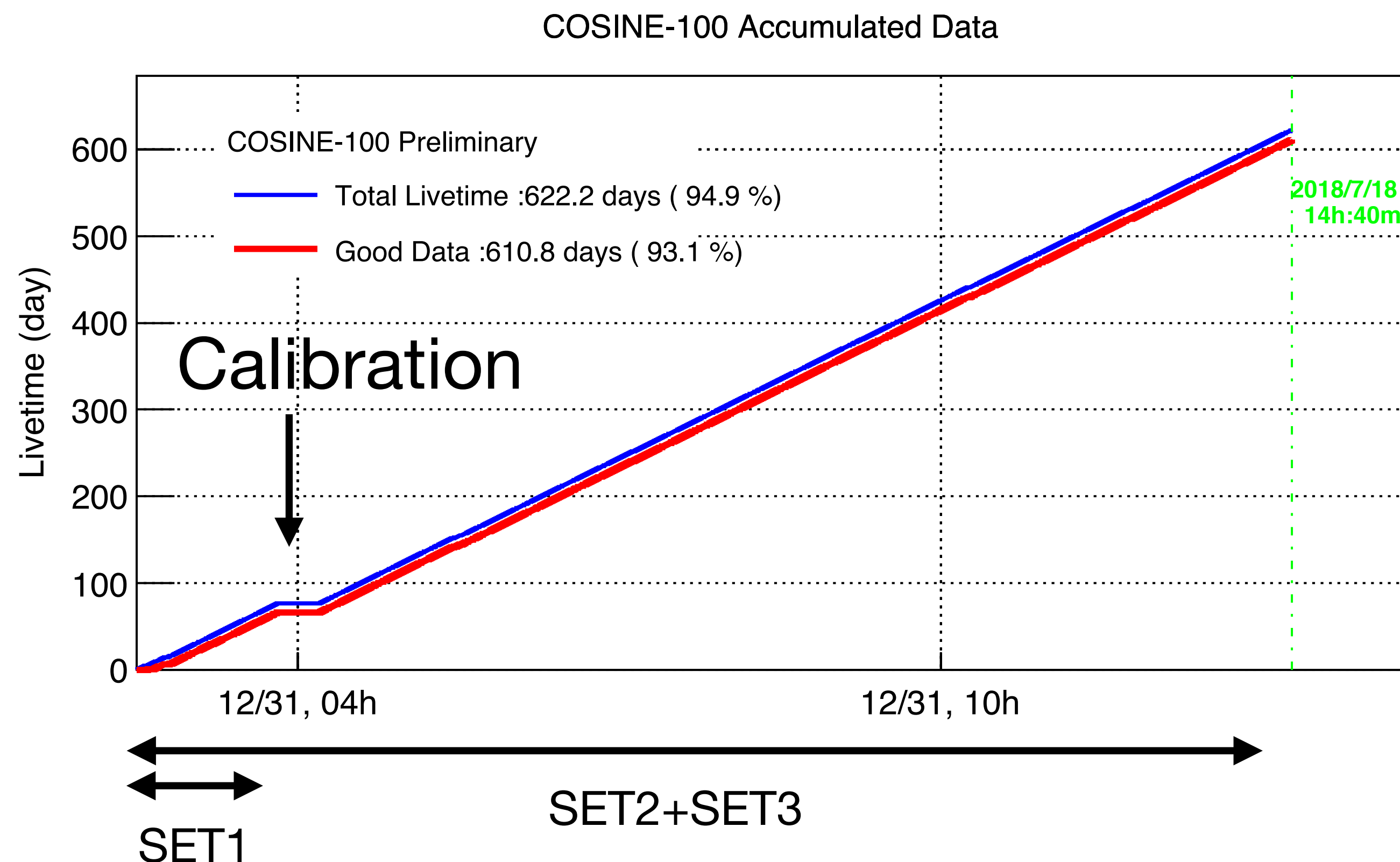
Sep. 2016





# COSINE-100 Operation

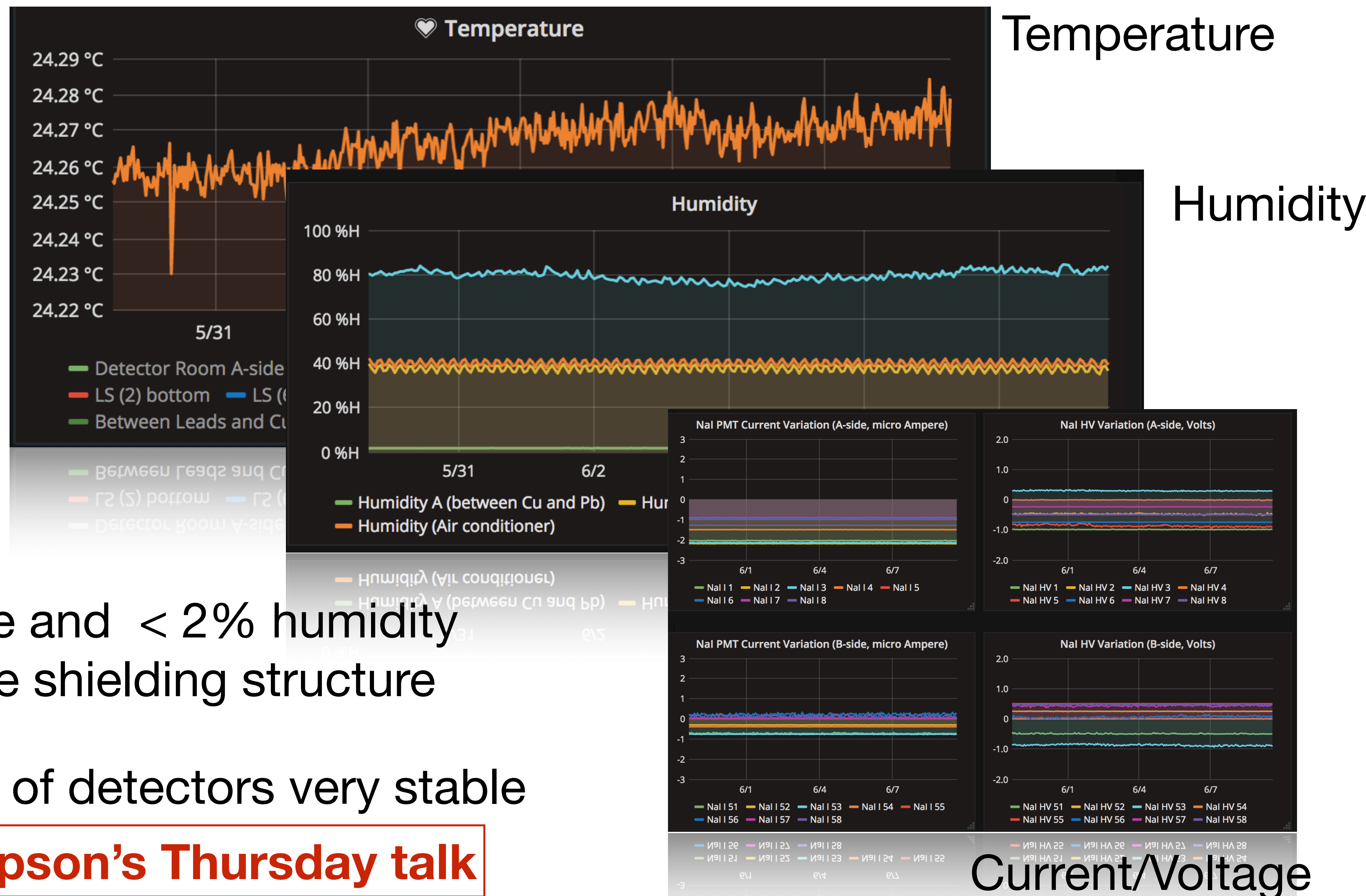
- Data taking since Sep. 2016
  - Stable operation
  - ~95% live time
  - Near 100% uptime outside of calibration
- 21.6 months of data accumulation
  - SET1 data (59.5 days) - Background modeling, detector understanding, and WIMP analysis
  - SET2+SET3 data (585 days) - Annual modulation analysis





# Environmental Control/Monitoring

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

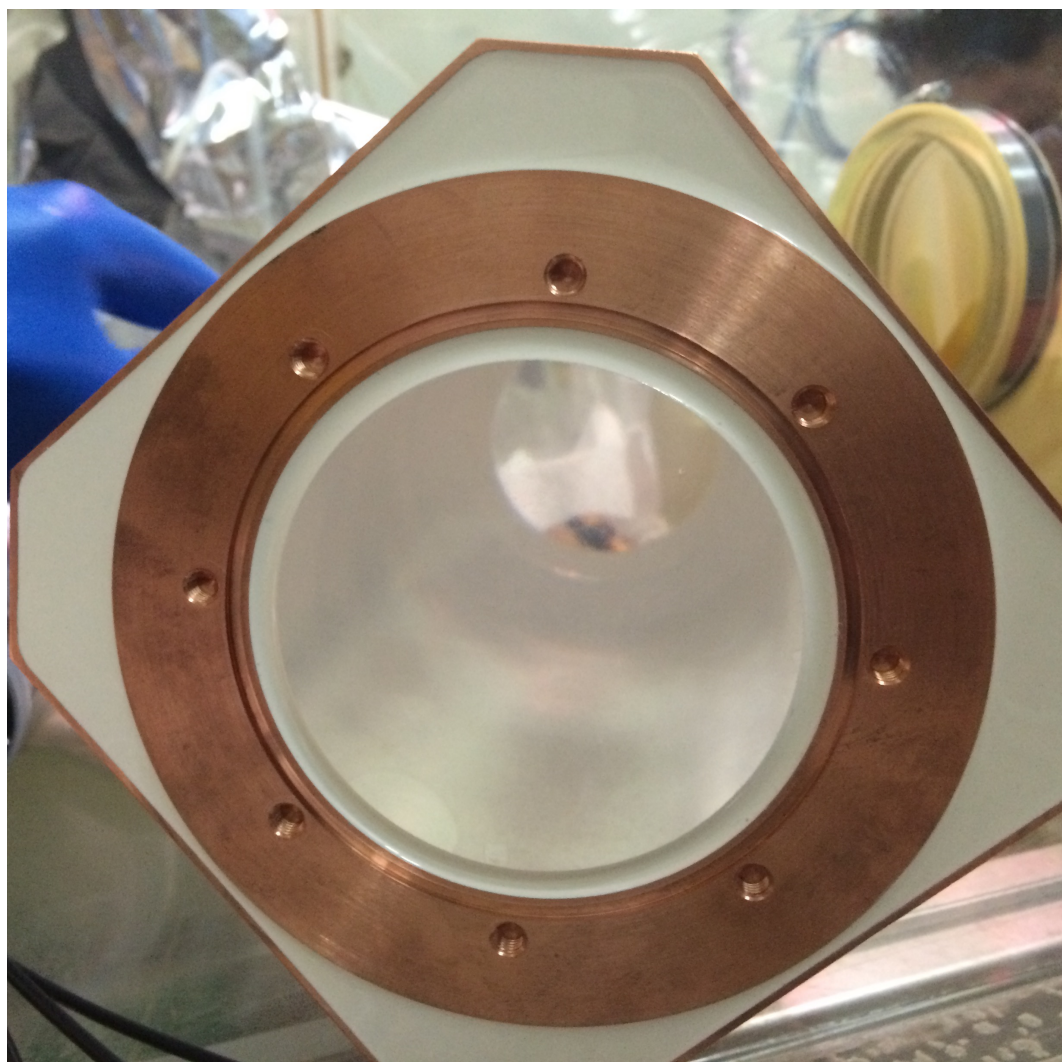
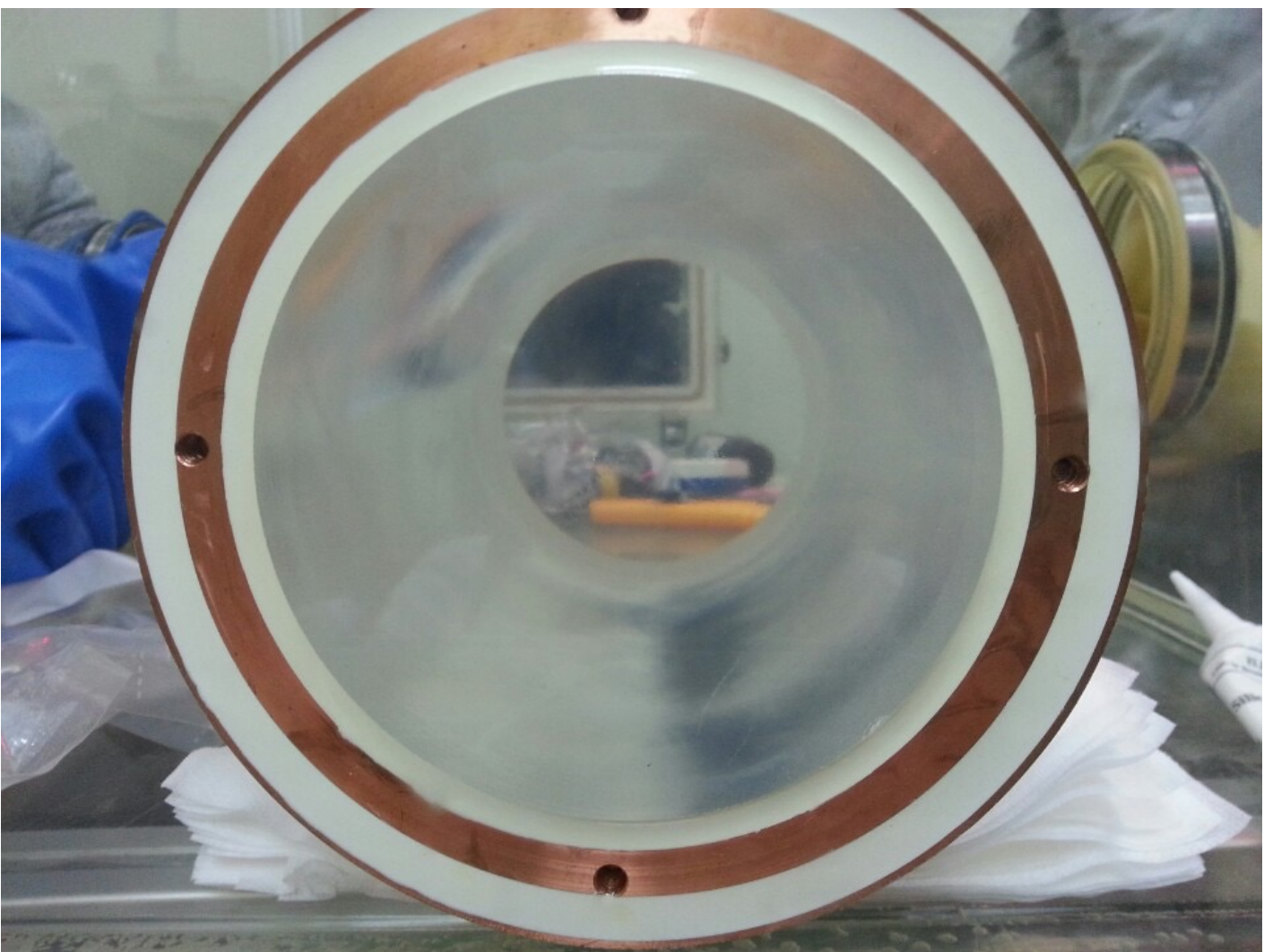


- $< 0.5$  °C temperature and  $< 2\%$  humidity fluctuation inside the shielding structure
- Current and voltage of detectors very stable





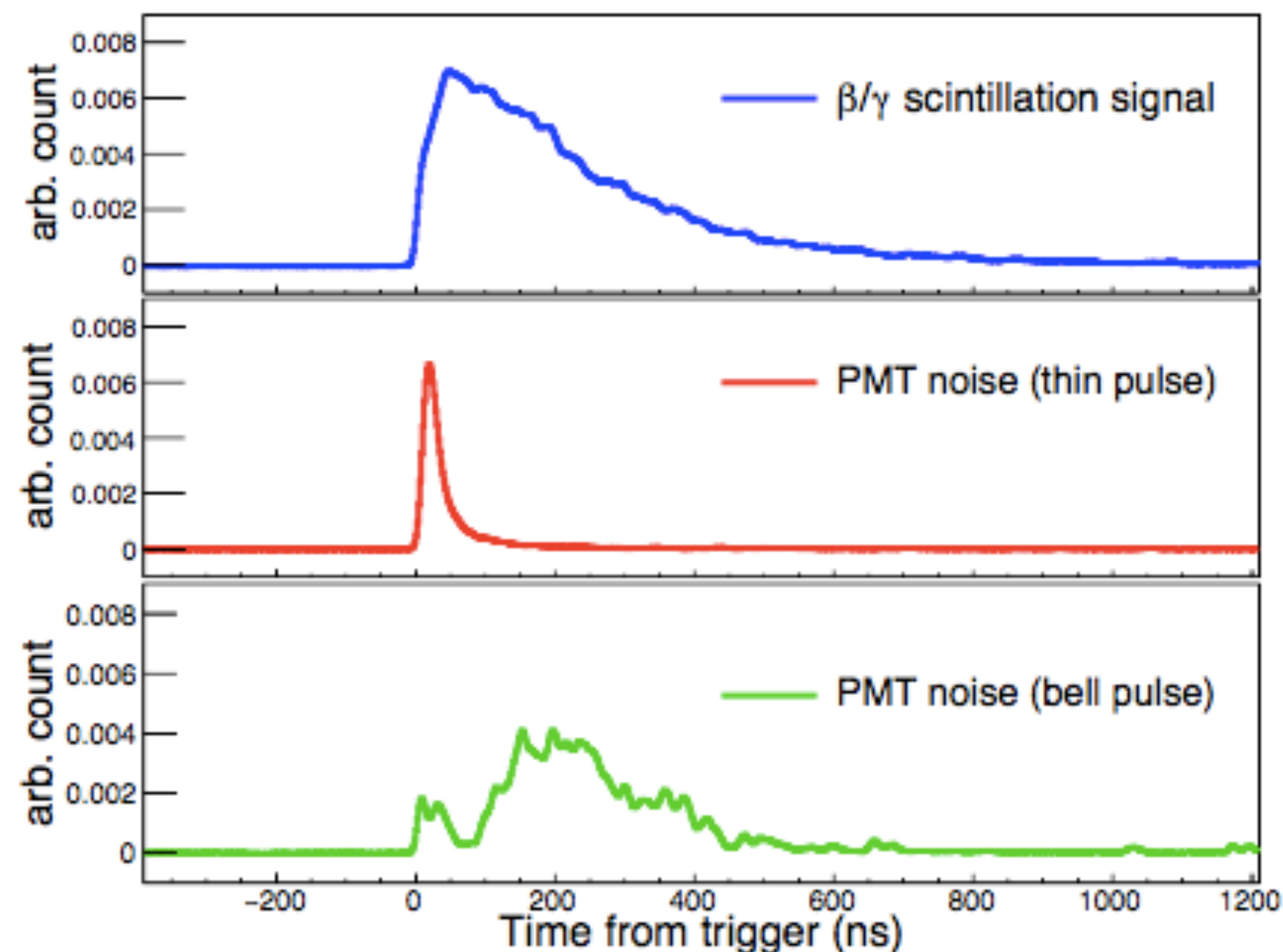
- 8 Crystals, total 106 kg
- Culmination of R&D program with Alpha Spectra
- U/Th/K below DAMA,  $^{210}\text{Po}$  very close
- High light yield
  - Crystal-5 & 8 used primarily for veto due to low light yield



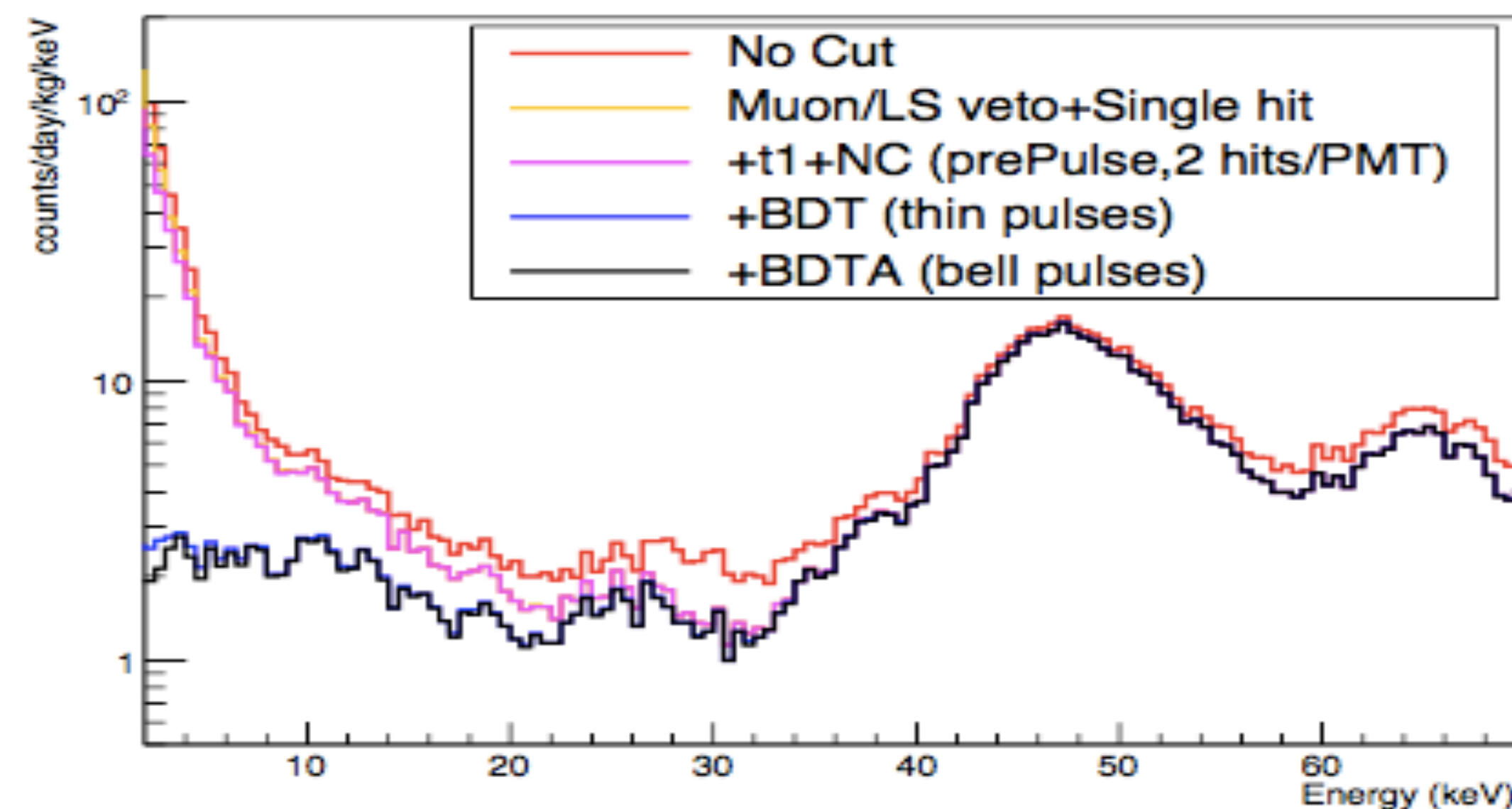
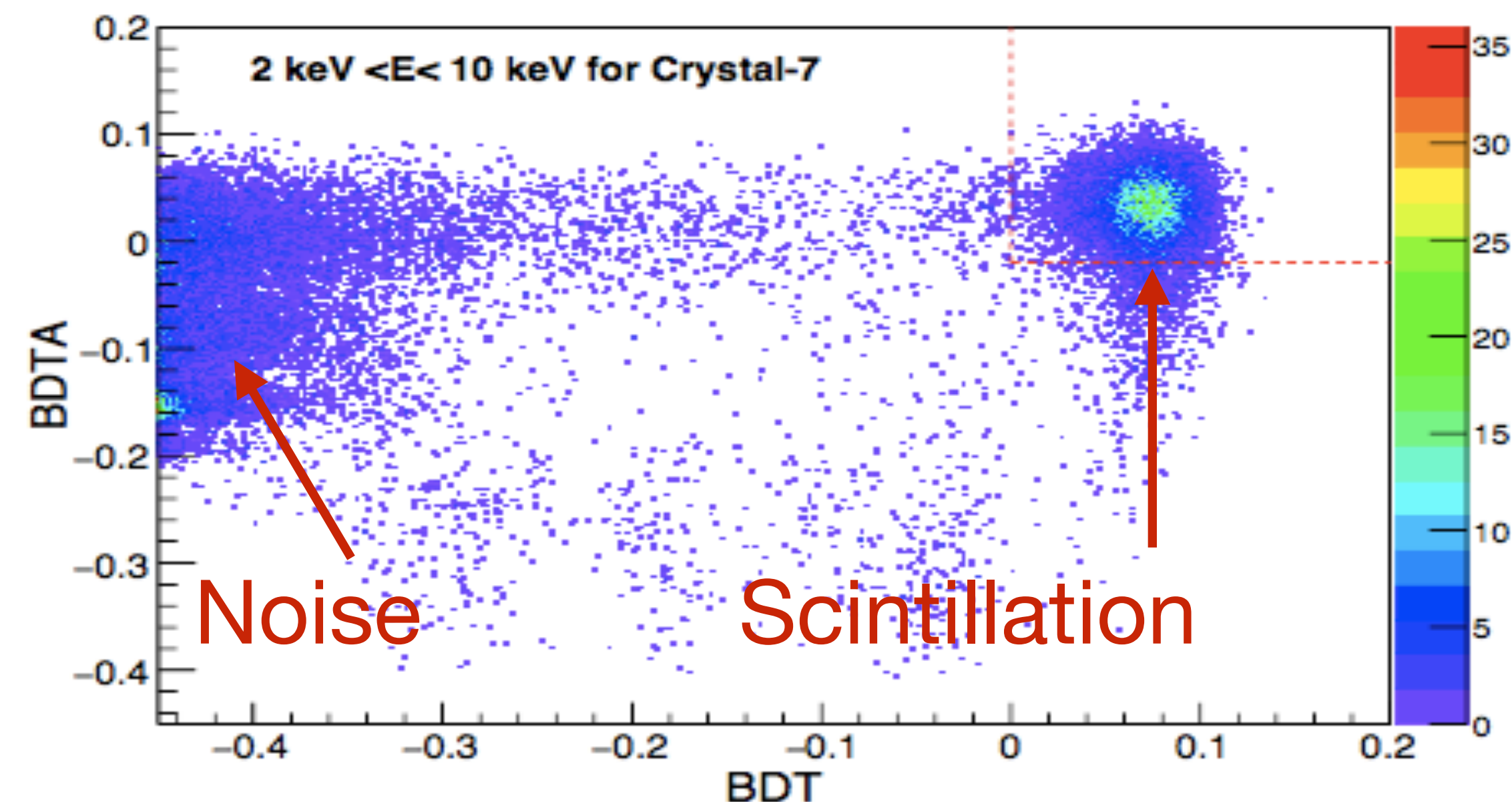
| Crystal   | Mass<br>(kg) | Size (inches<br>diameter×length) | Powder   | $\alpha$ Rate<br>(mBq/kg) | $^{40}\text{K}$<br>(ppb) | $^{238}\text{U}$<br>(ppt) | $^{232}\text{Th}$<br>(ppt) | Light Yield<br>(PEs/keV) |
|-----------|--------------|----------------------------------|----------|---------------------------|--------------------------|---------------------------|----------------------------|--------------------------|
| 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

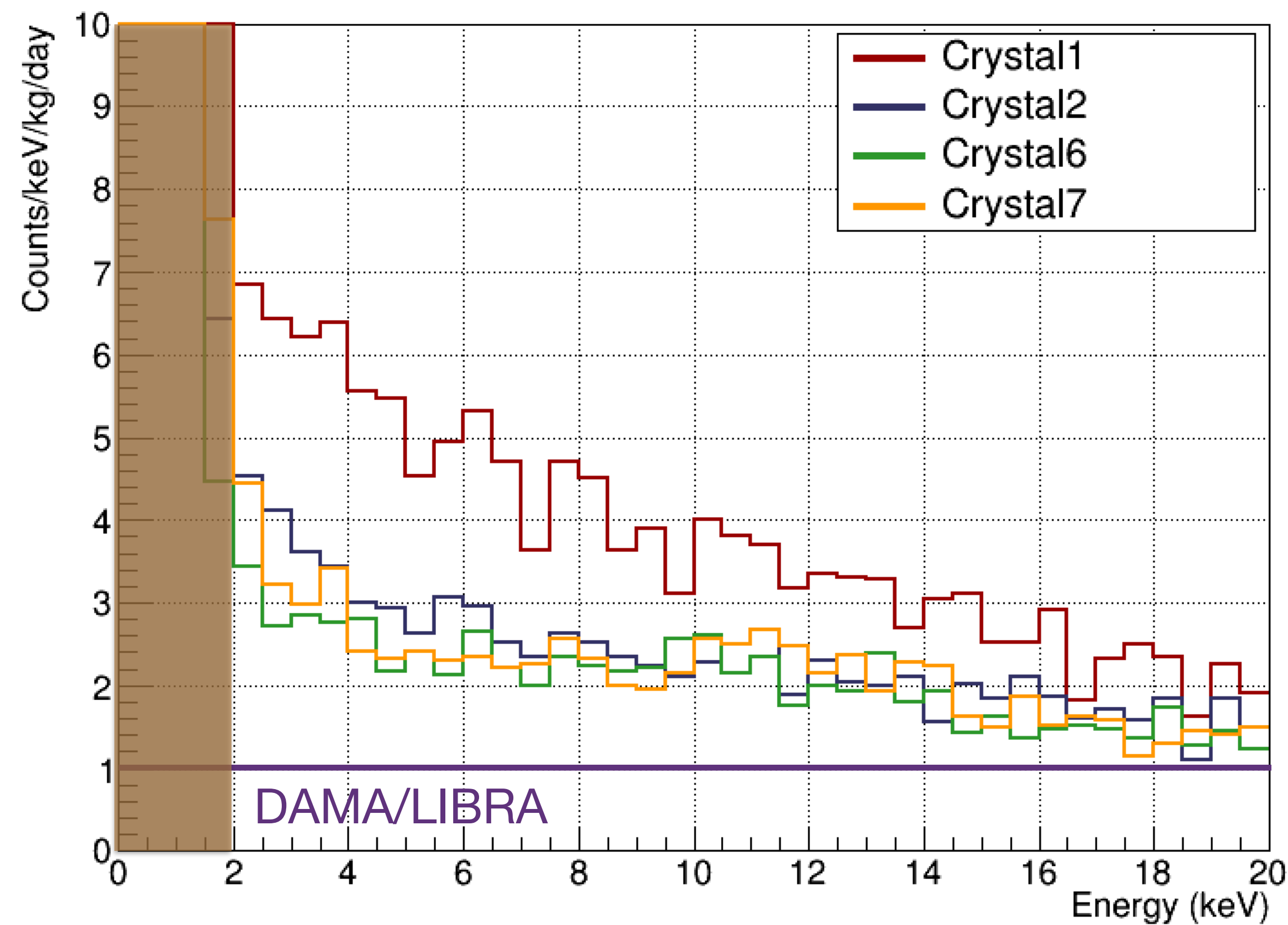
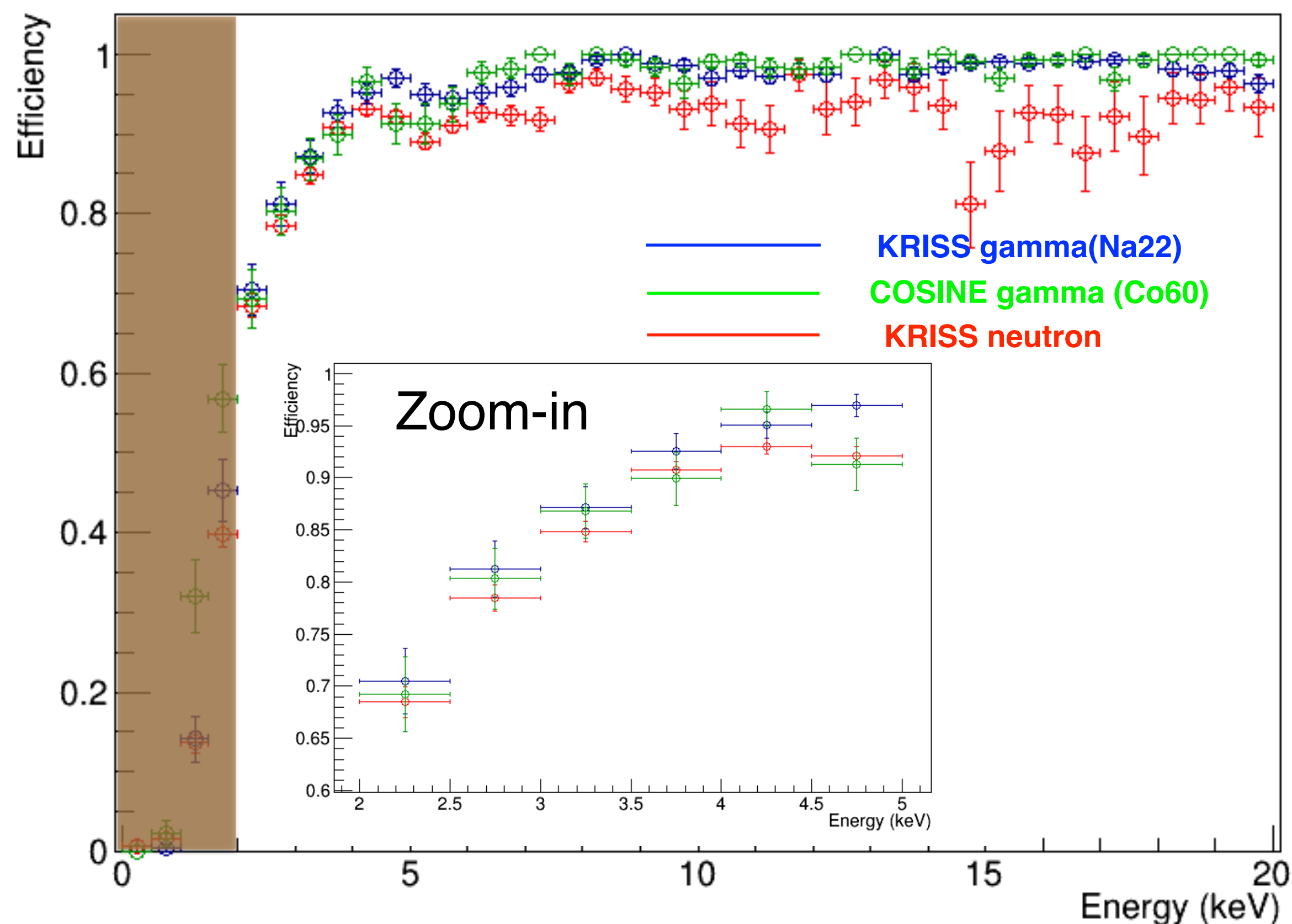


- Dominant source of noise events comes from PMT noise
- Boosted Decision Tree (BDT) was utilized to reject such noise events



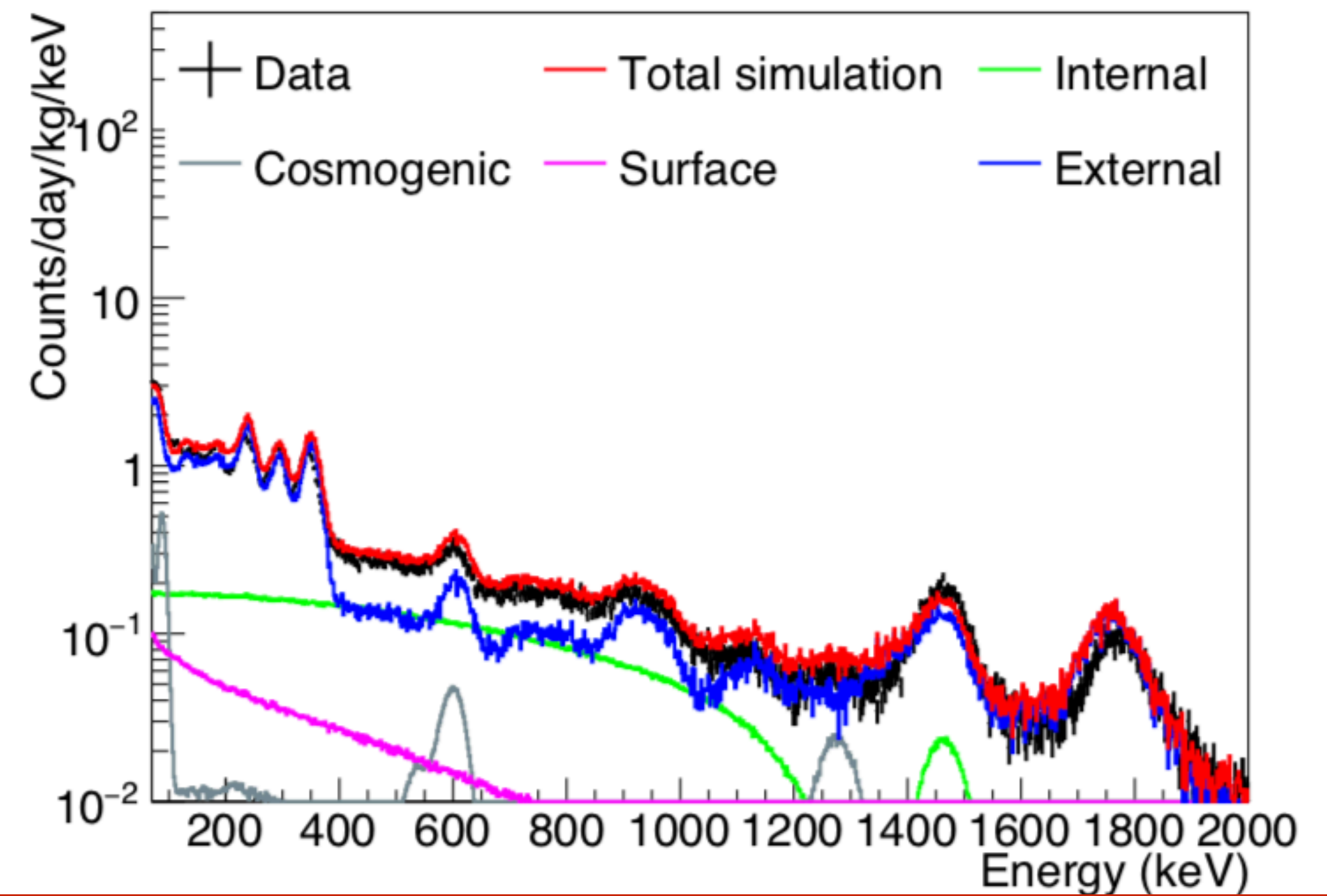
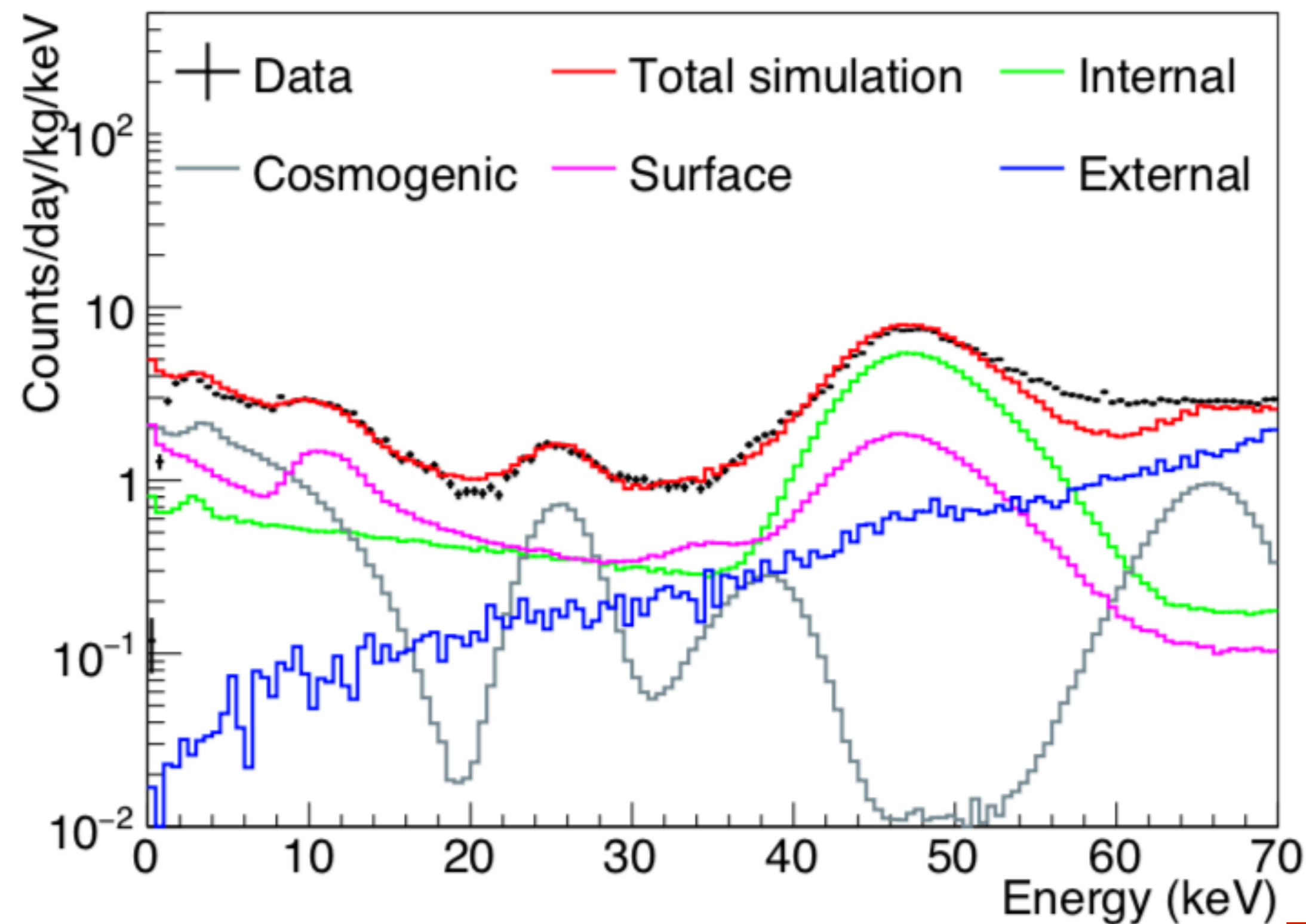


# Selection Efficiency/Low Energy Spectrum



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



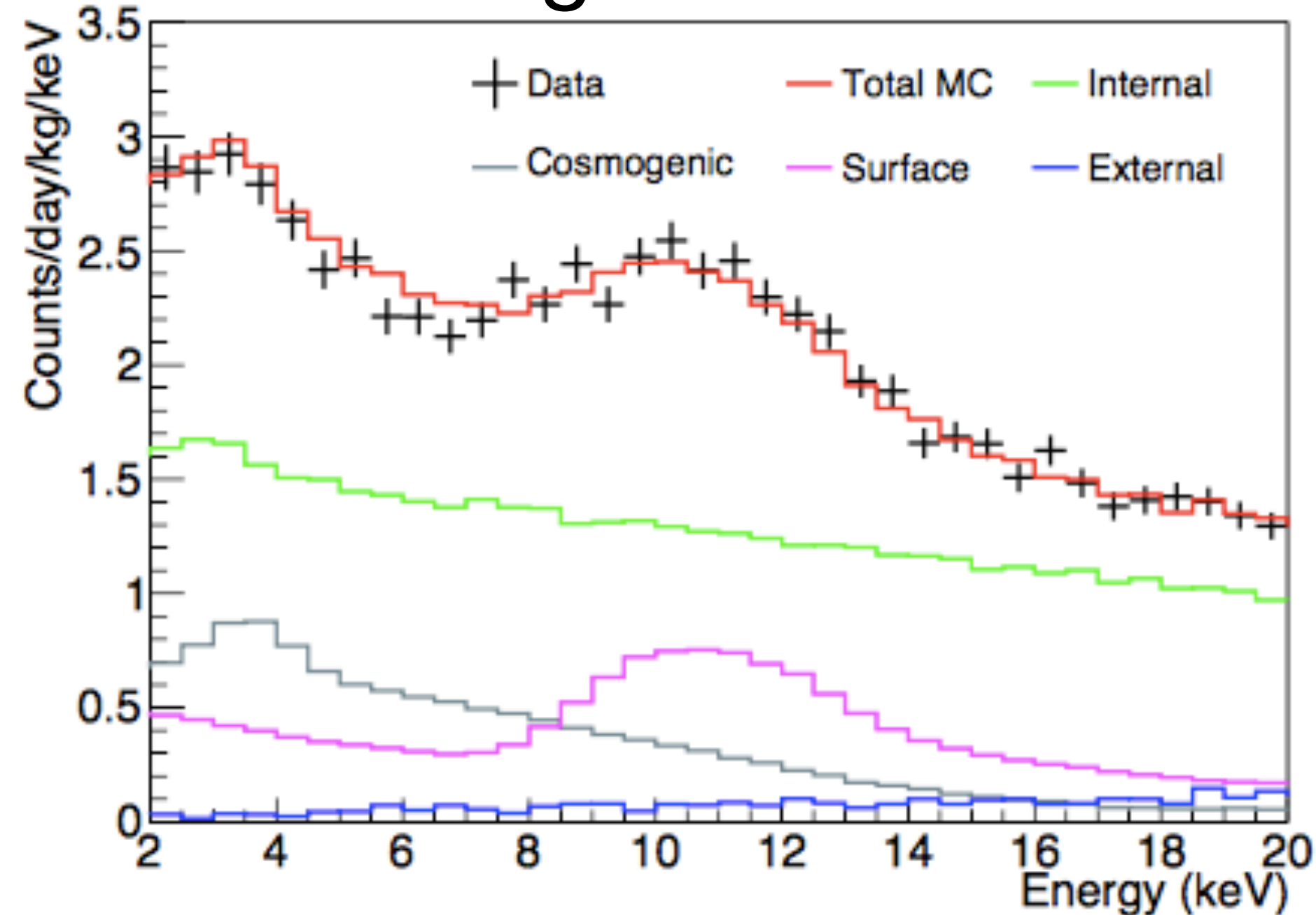


**See Estella Barbosa de Souza's talk today**

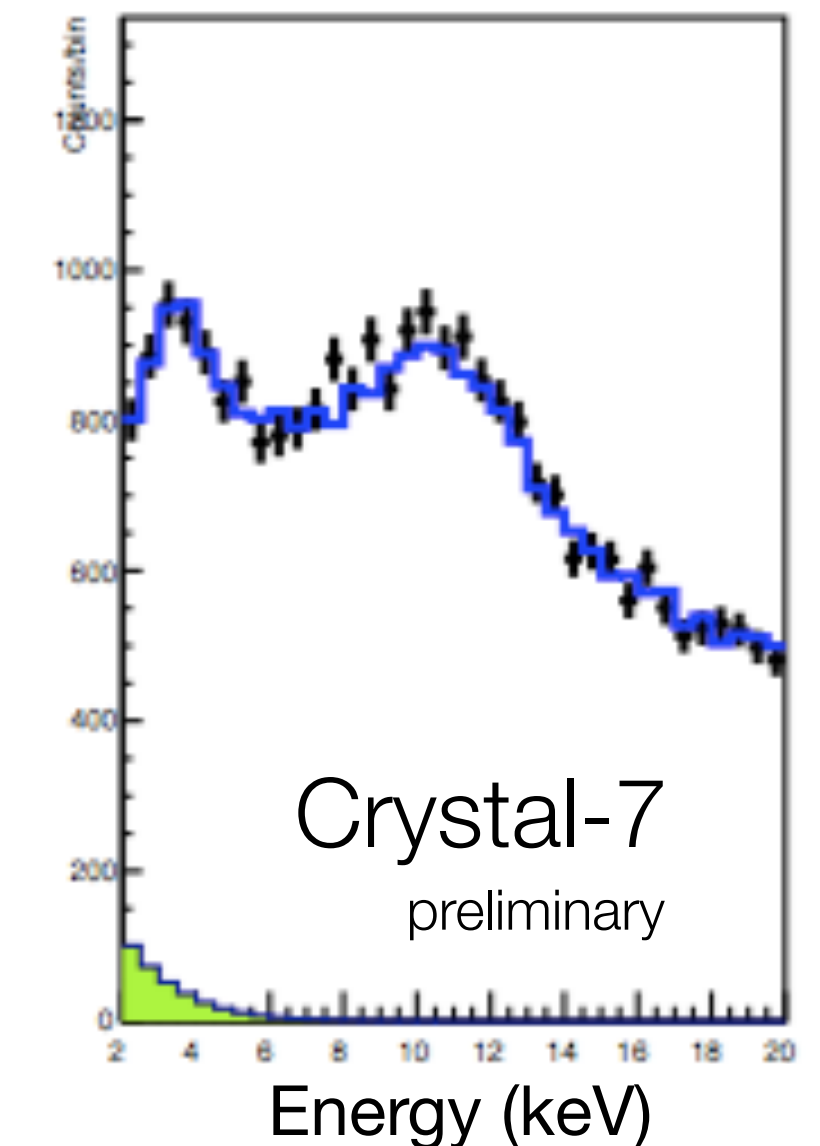
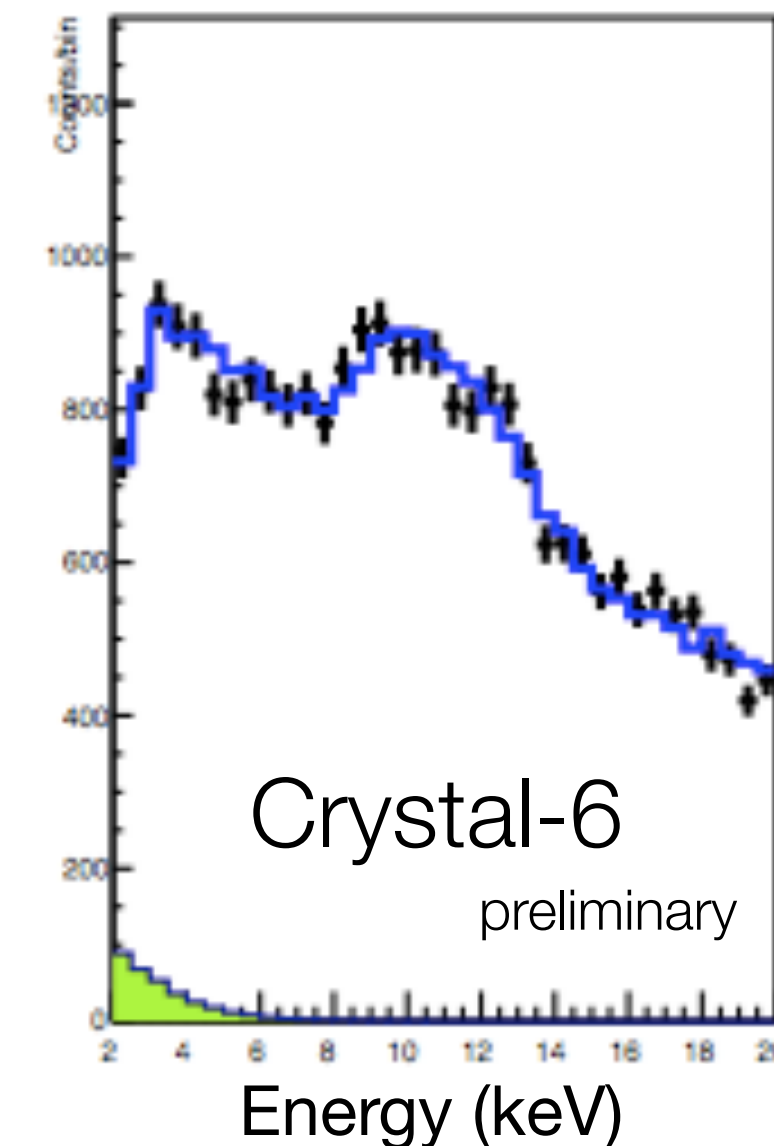
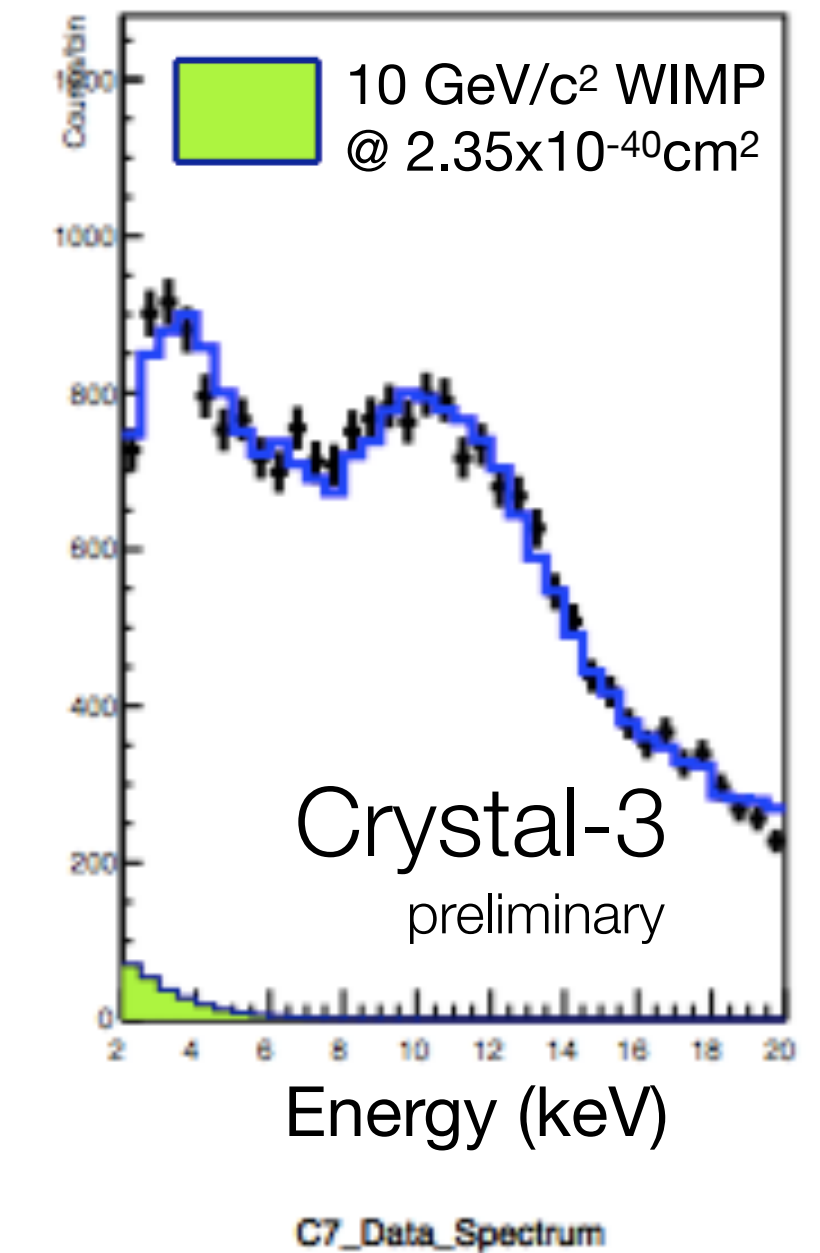
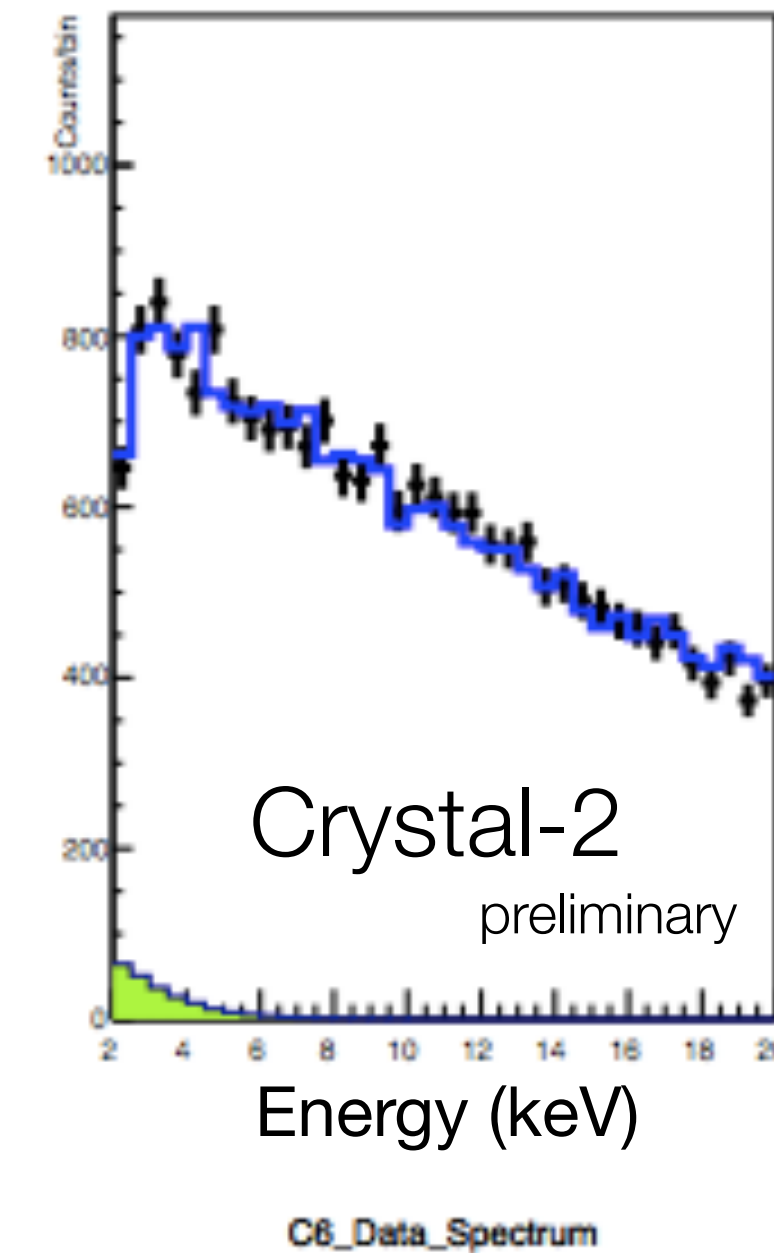
- Data reproduced well with GEANT4 simulation
- **Background well understood from 2 keV - 2000 keV**
- Dominant background from  $^{210}\text{Pb}$  and  $^{40}\text{K}$ , followed by cosmogenic  $^3\text{H}$



## Background model



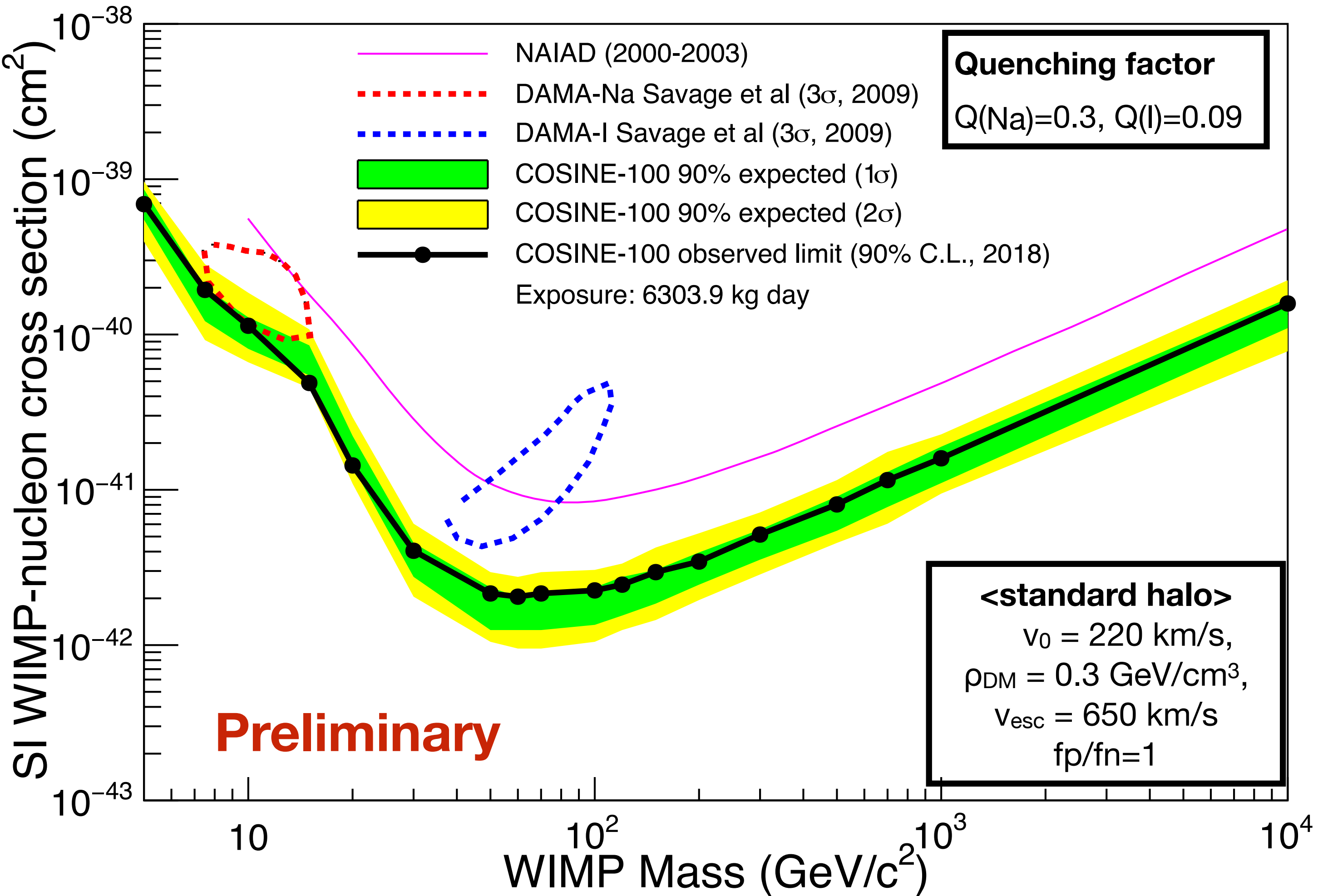
- Using 59.5 days of data: 6303.9 kg·day exposure
- Spectrum fit for 2-20 keV including WIMP model
  - Likelihood analysis to fit data using background model and WIMP signal model (SHM as described in Savage *et al.*, JCAP 0904:010 (2009))
  - Background understanding consideration from V. Kudryavtsev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





# Physics Analysis: WIMP Analysis

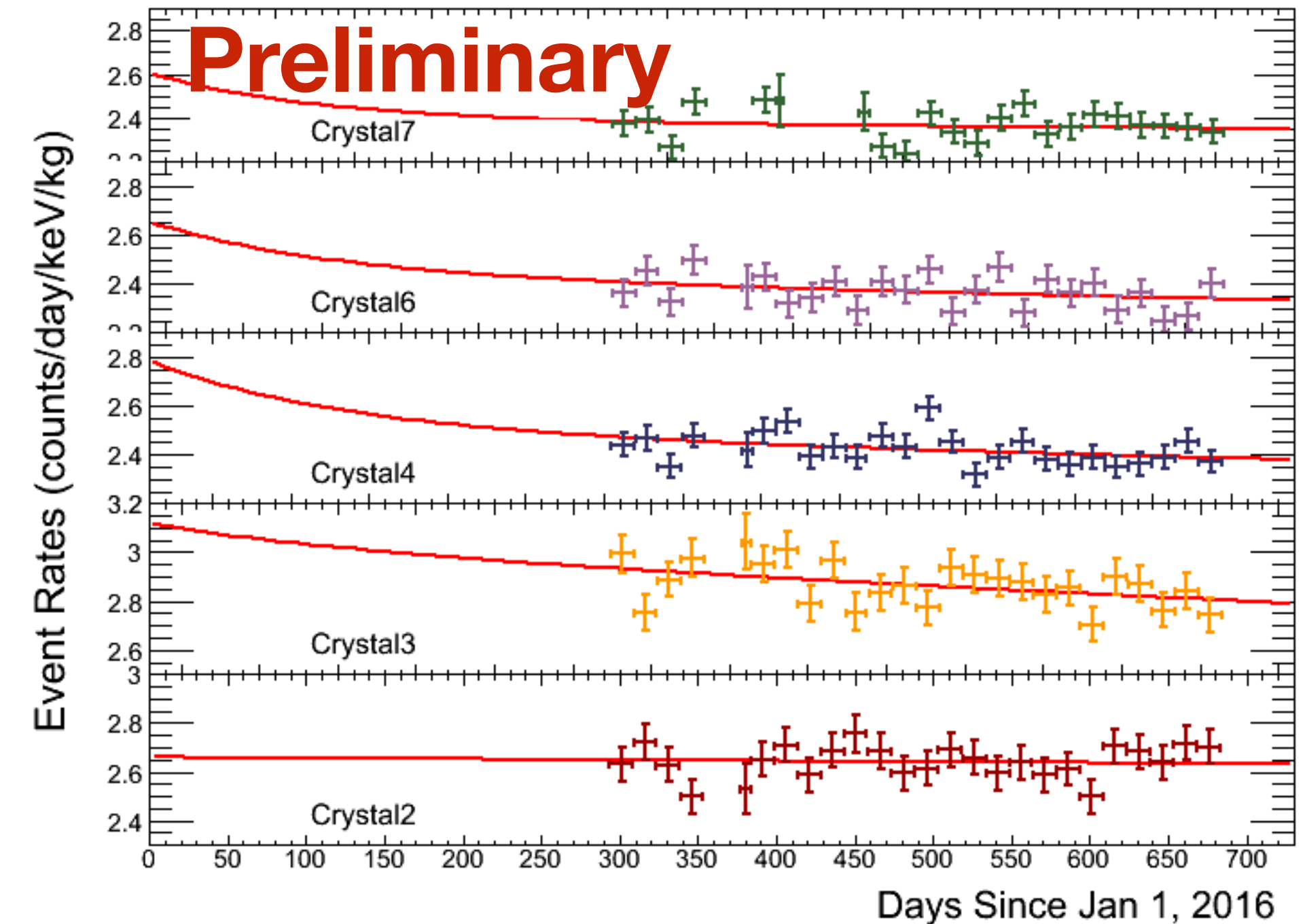
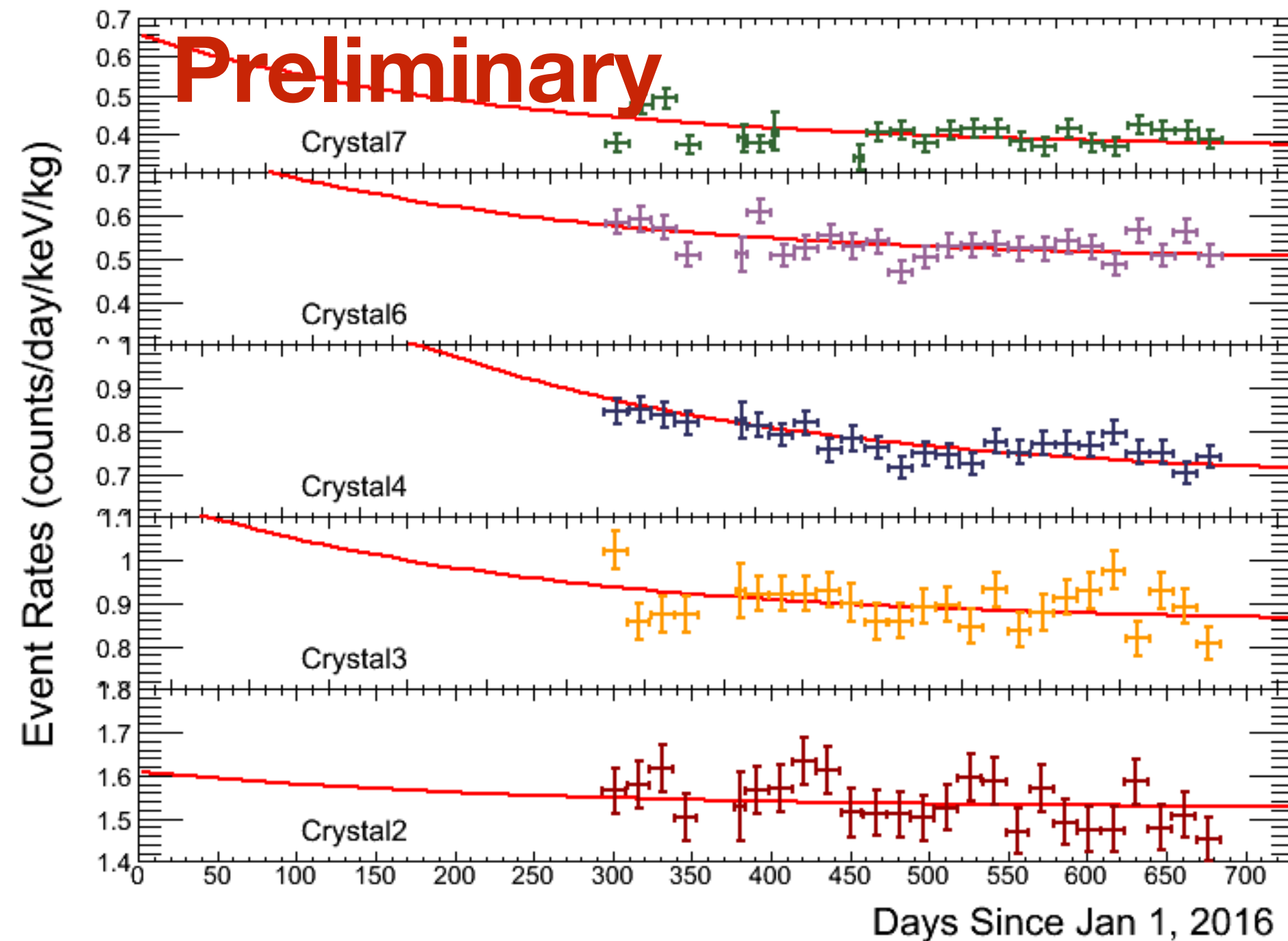
- Spectrum with known sources of backgrounds
- Excludes DAMA/LIBRA-phase1 w/ NaI(Tl) (as spin-independent WIMP with Standard Halo Model)
- Consistent with null results from other direct detect experiments with different target medium





Sideband sample: Multiple-hit 2-6 keV

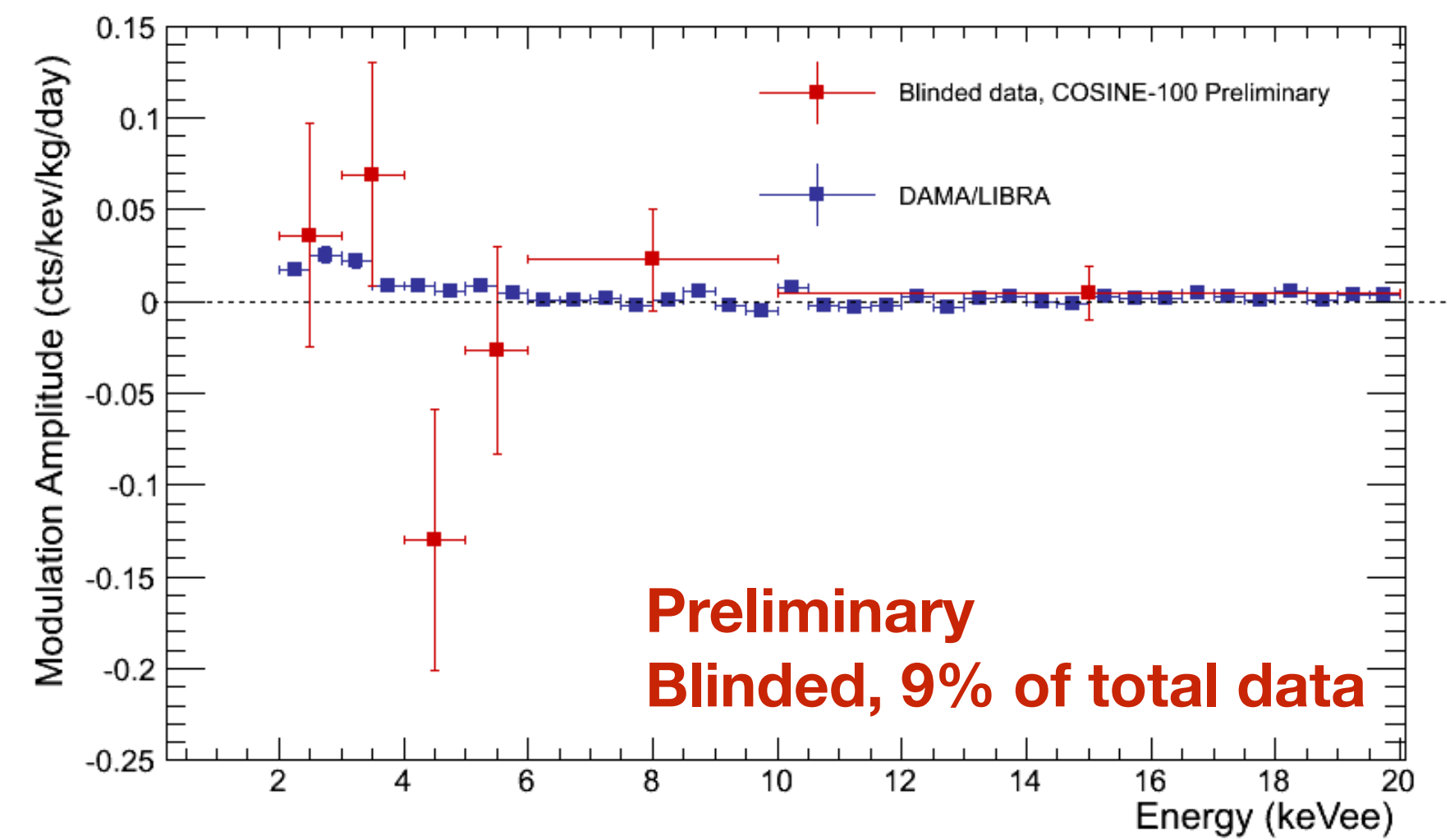
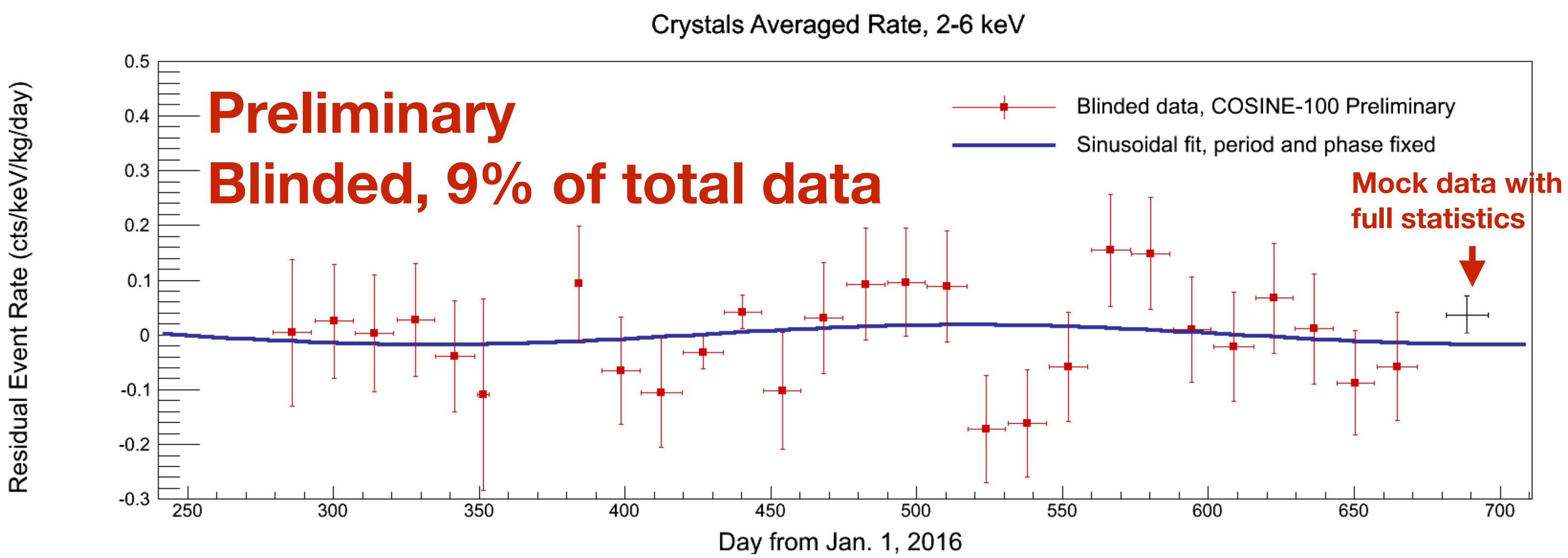
Sideband sample: Single-hit 6-10 keV



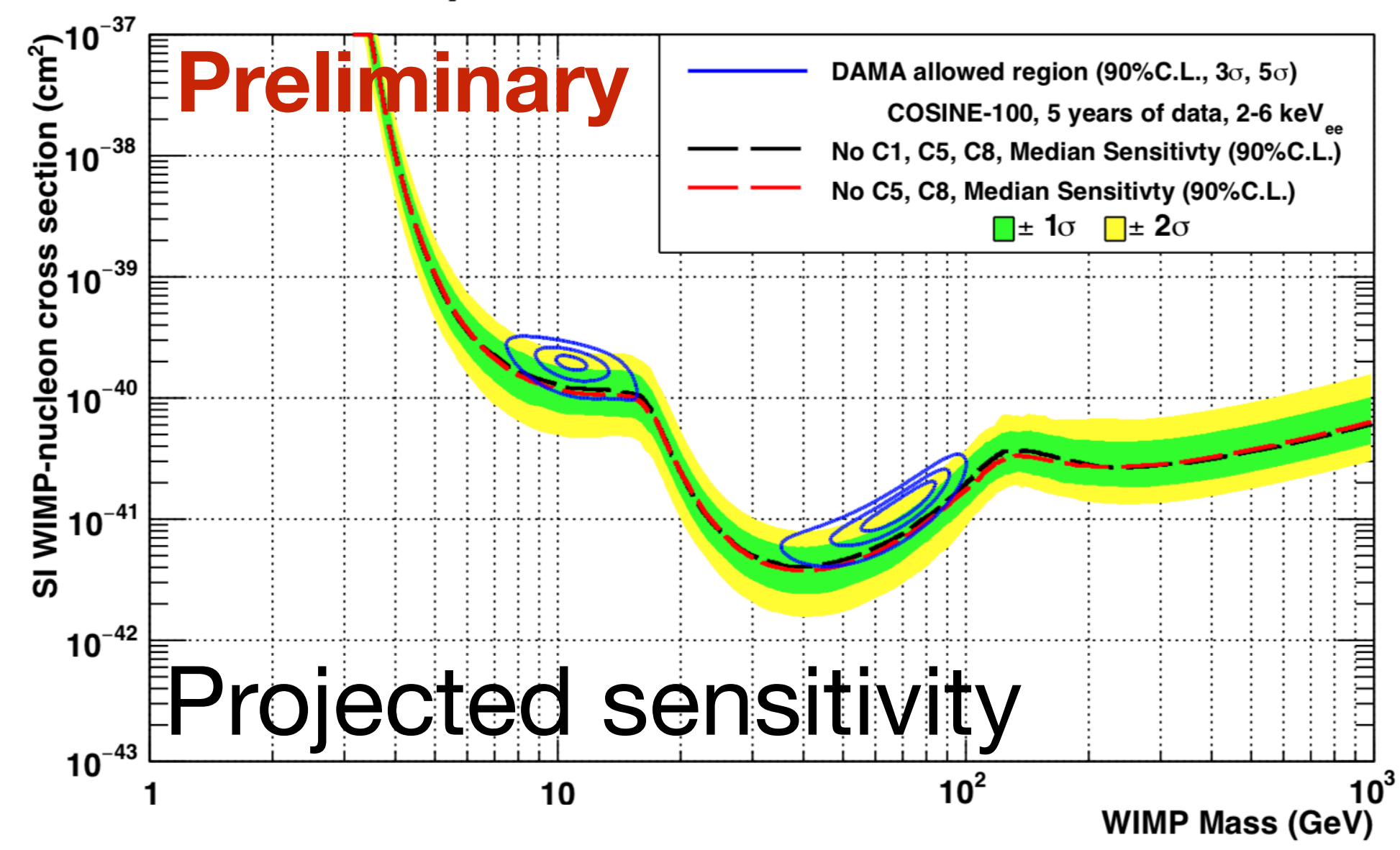
- Crystal 1, 5, and 8 are excluded in this analysis due to low light yield and excessive PMT noise
- Sideband data fits well with exponential models built with the known cosmogenic components



# Physics Analysis: Annual Modulation Analysis

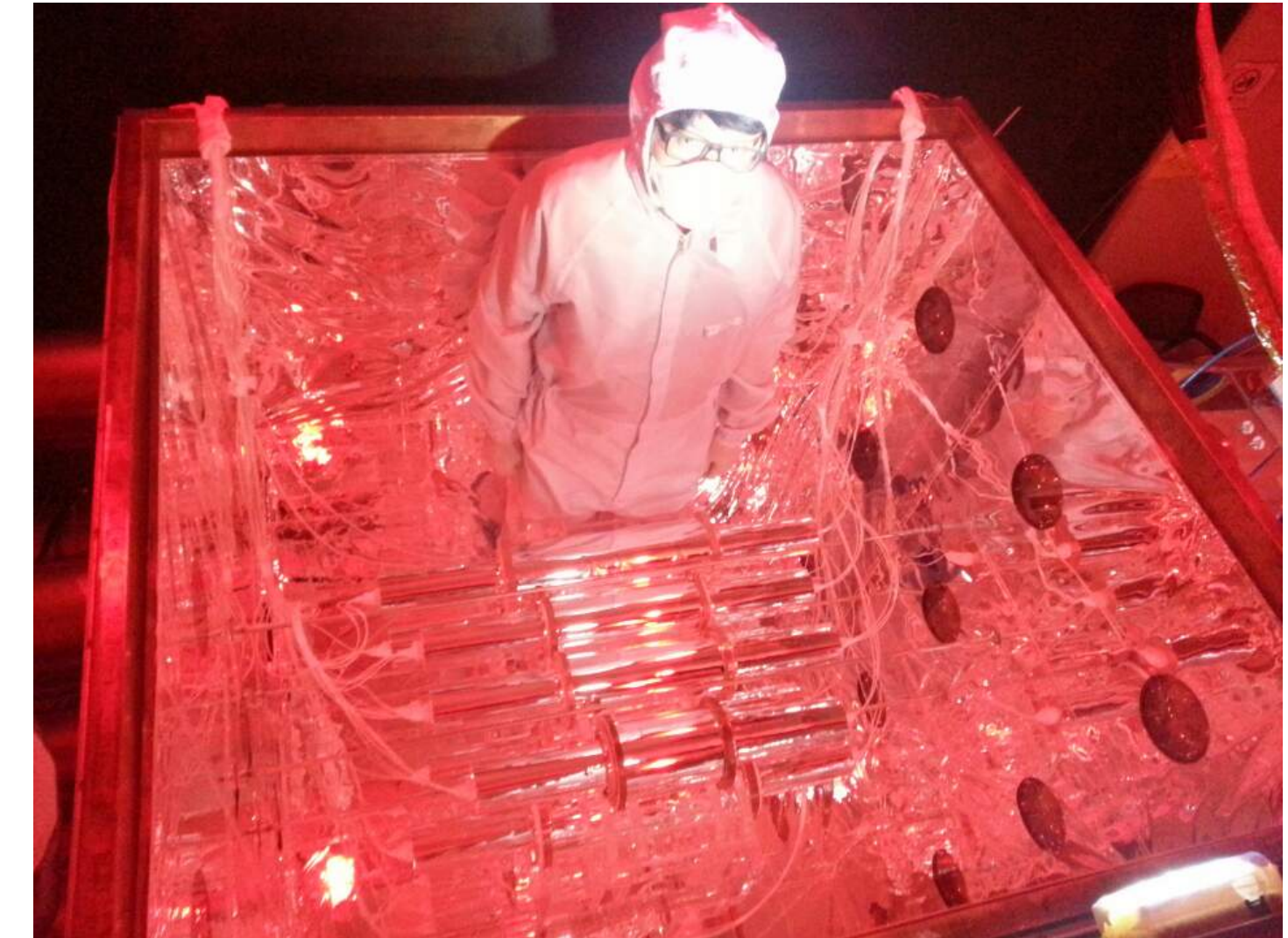
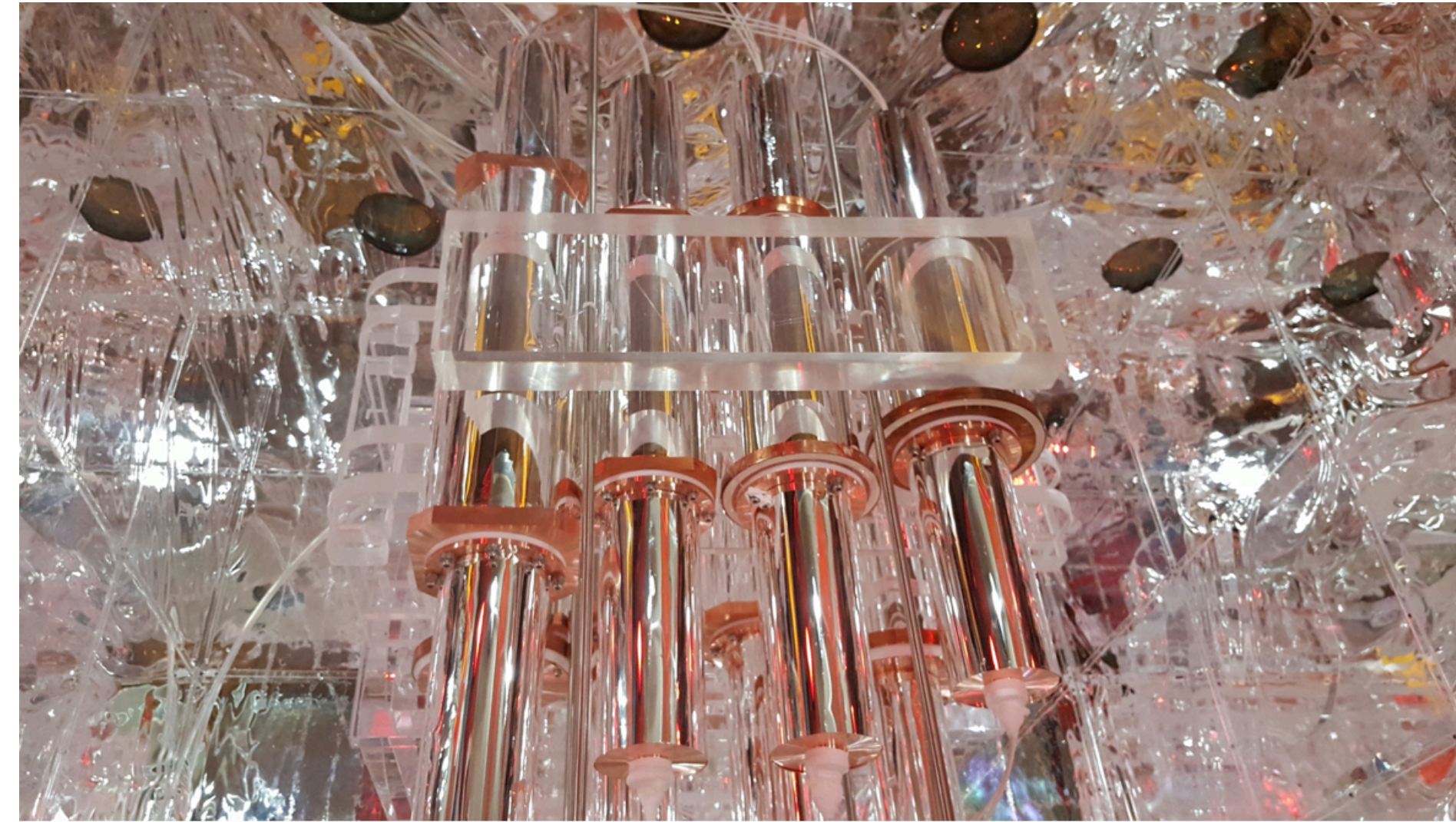


- **Currently data in 2-6 keV is blinded, only using 9 % of total data**
- Full data analysis will be using 585+ days of data
- Data quality, cosmogenic component estimation, background trend understanding almost done: **Stay tuned!**
- **5 years of running can rule out DAMA**
- Agreed to combine data with ANAIS





# Summary and Outlook



- COSINE-100: Goal is to test DAMA's claim for dark matter observation; running very smoothly since Sept. 2016
- COSINE-100 confirms that DAMA's modulation signal cannot be from standard WIMP & SHM with NaI(Tl)
- Model independent annual modulation analysis is ongoing
- Crystal growing R&D is being developed in IBS, and looks promising
- Stay tuned for more exciting results to come!

See William Thompson's talk (yesterday): Detector Stability of COSINE-100  
See Estella Barbosa de Souza's talk (today): Background Assessment of the COSINE-100 Experiment

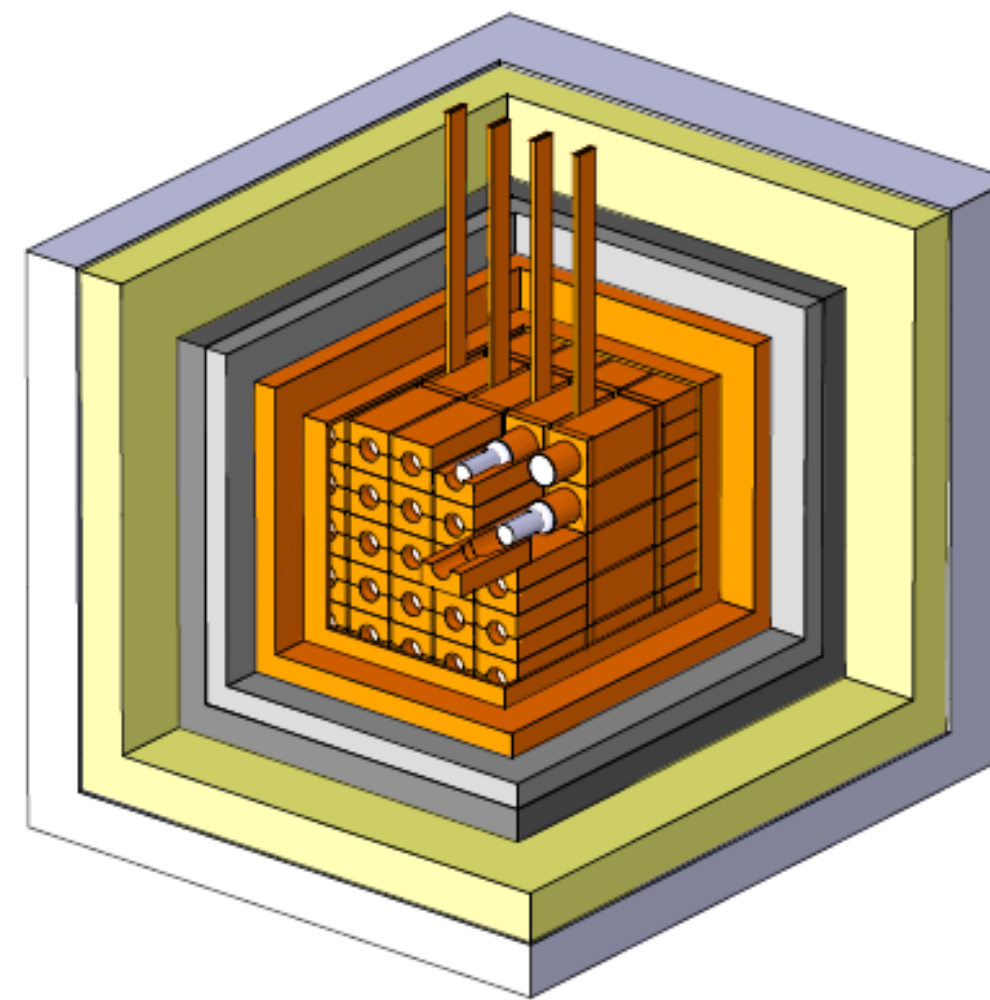
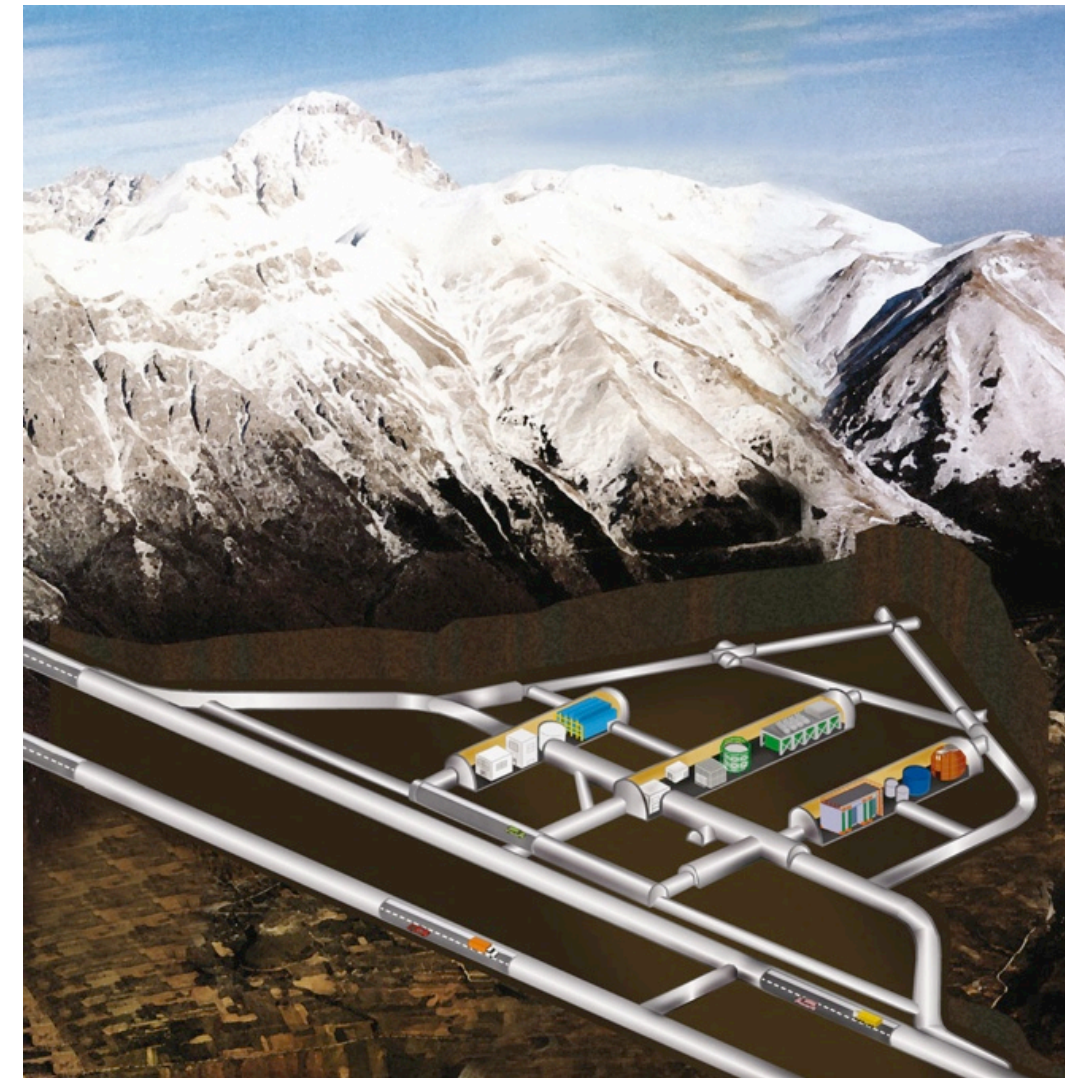


# Backup



- Located at LNGS, Italy
- 25 x 9.70 kg NaI (TI) detectors
  - Grown by Saint-Gobain
  - 0.85 - 1.3 cpd/kg/keV total background rate
- 2 PMTs/crystal
  - ~38.5% QE
  - 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)

LNGS



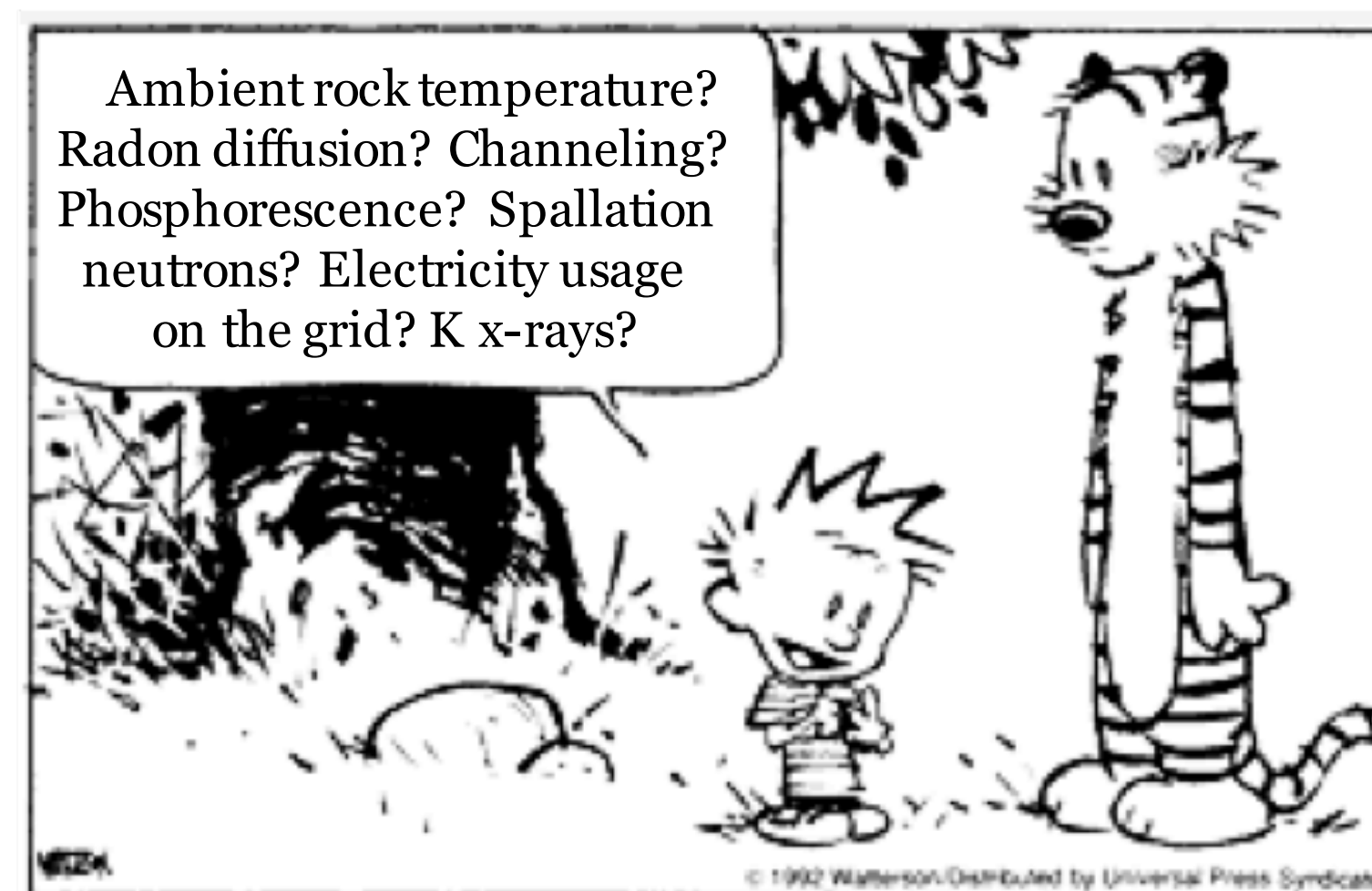
Bernabei *et al.*, NIM A (2008)



# Interpretation of the DAMA Result

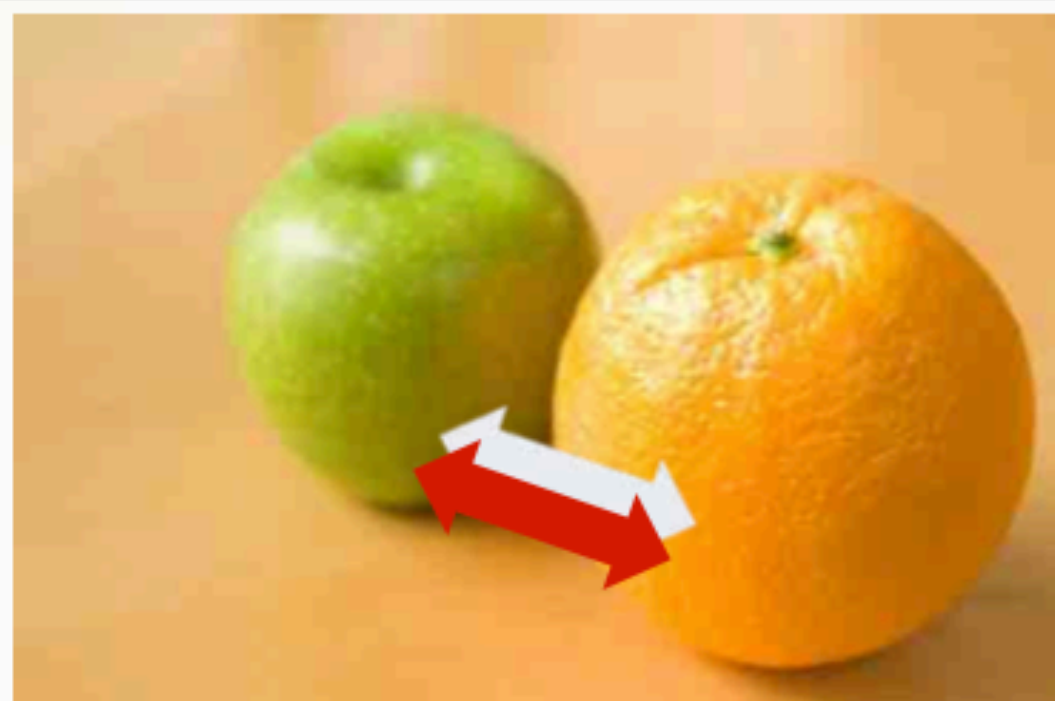


*“What is causing DAMA’s modulation?  
Could it be some backgrounds?”*





# Interpretation of the DAMA Result



## About interpretation

See e.g.: Riv.N.Cim.26 n.1(2003)1, JIMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, IJMPA28(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...

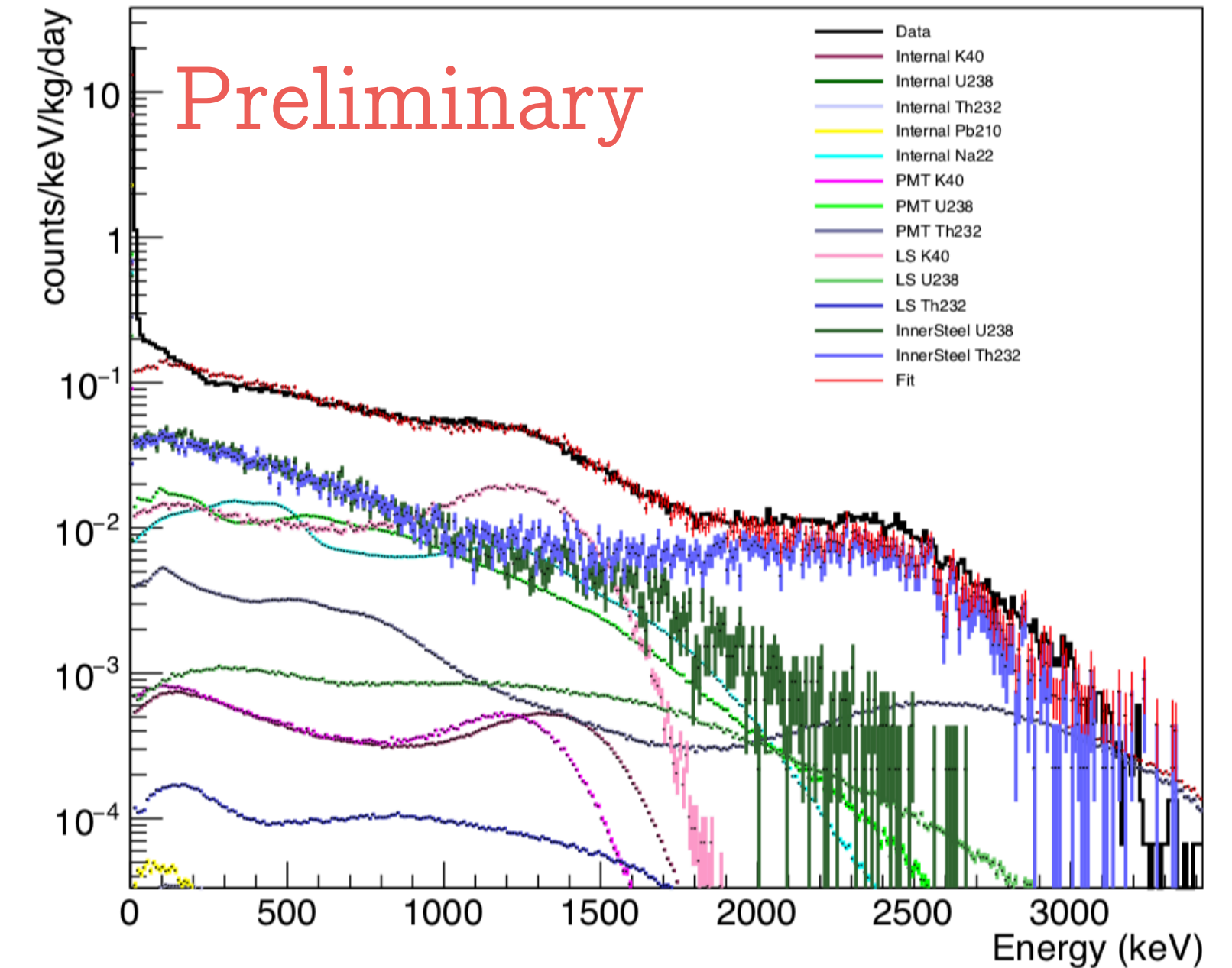
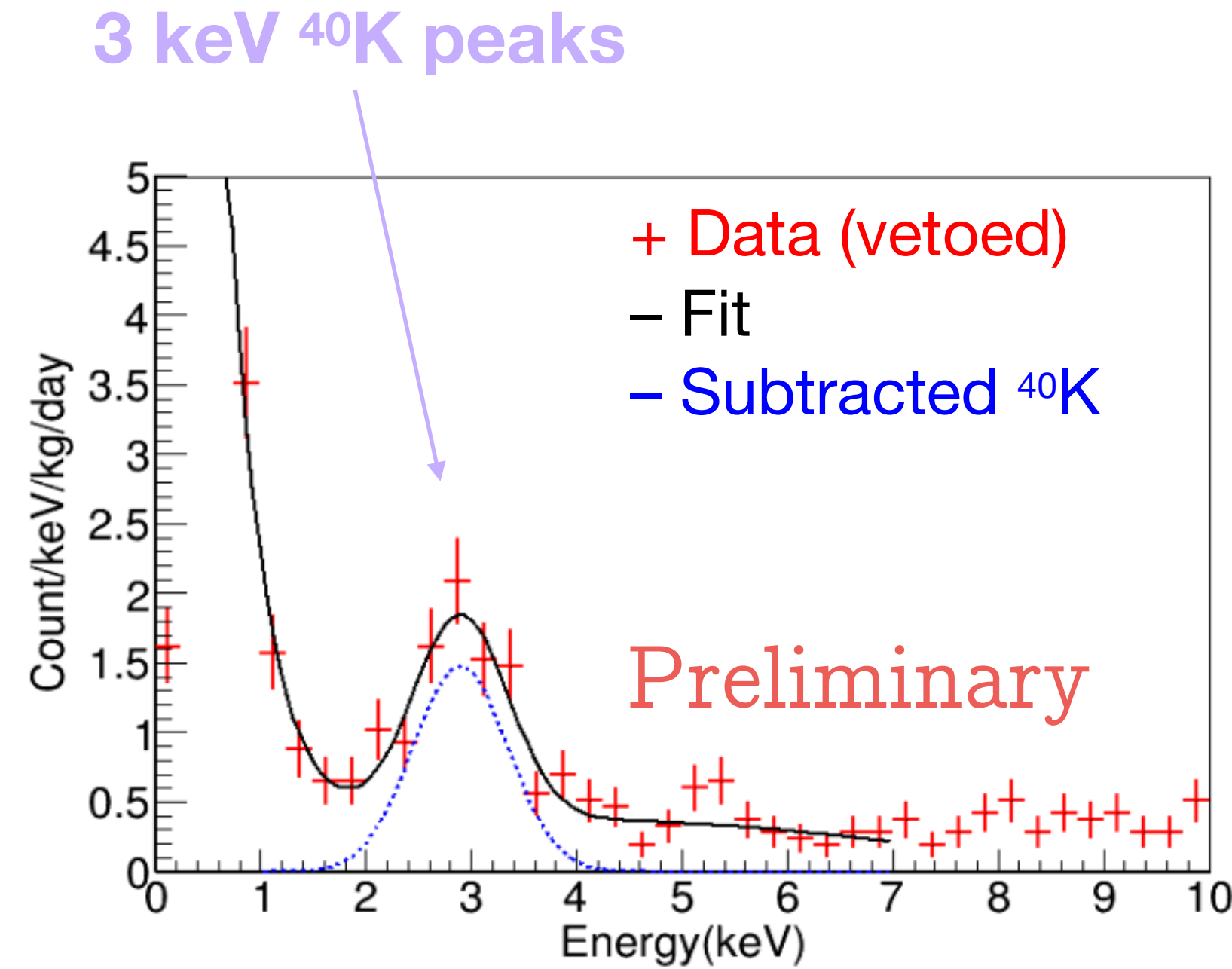
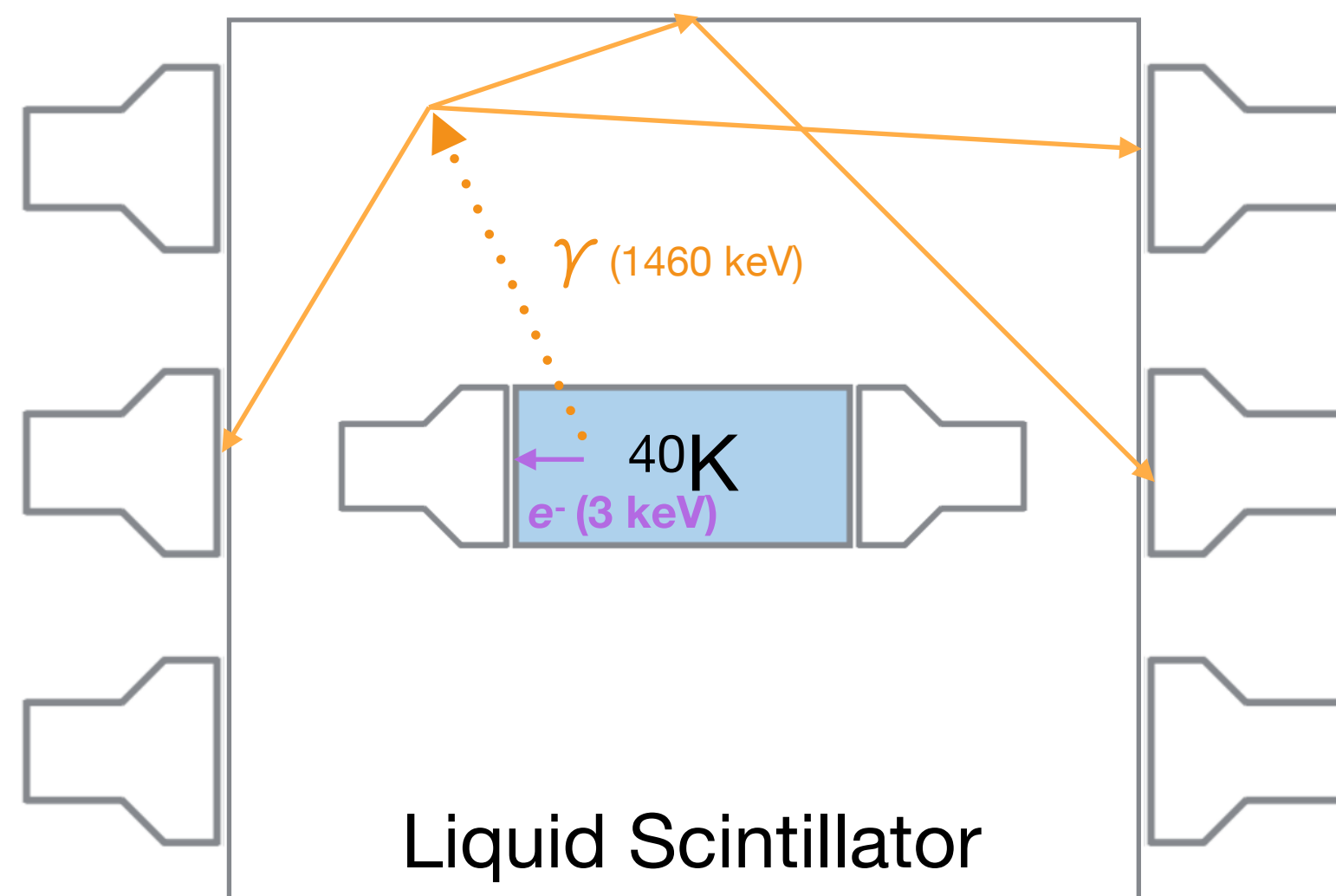
- Which particle?
- Which interaction coupling?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- ...

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 be directly compared in model independent way with DAMA**

P. Belli,  
IDM2016

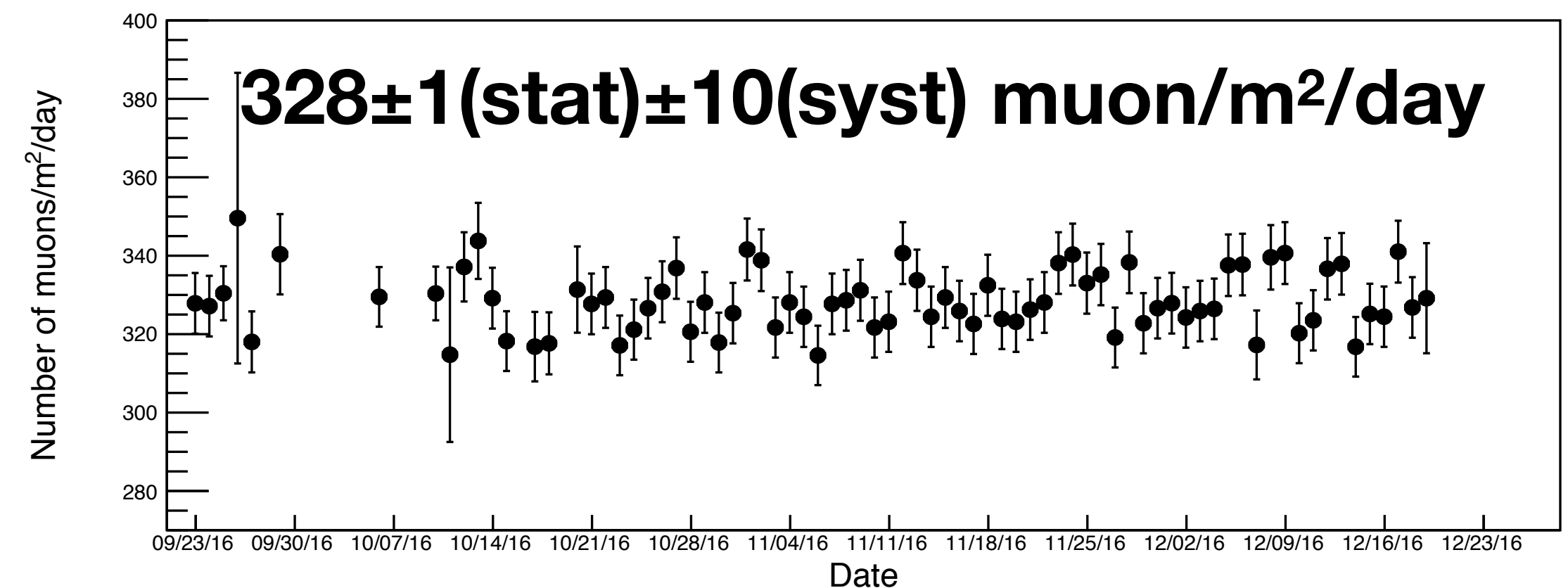
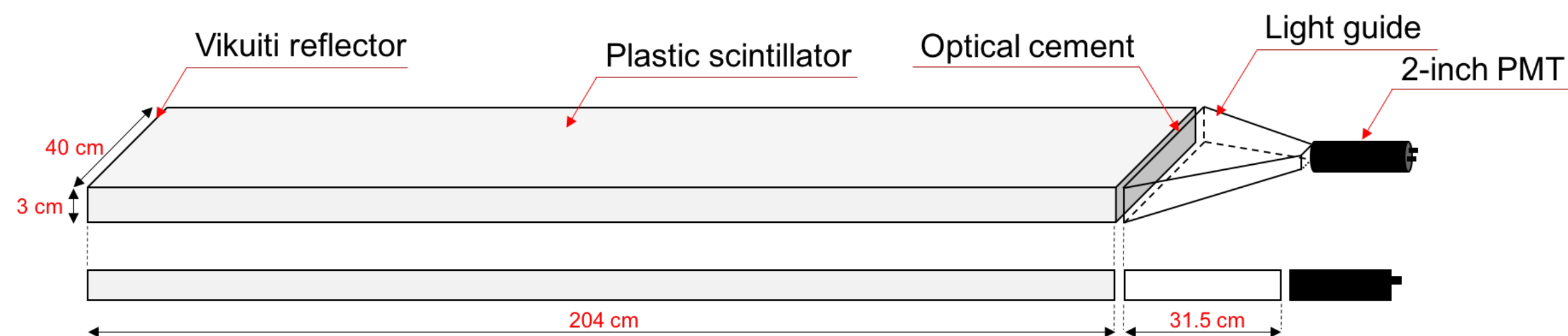
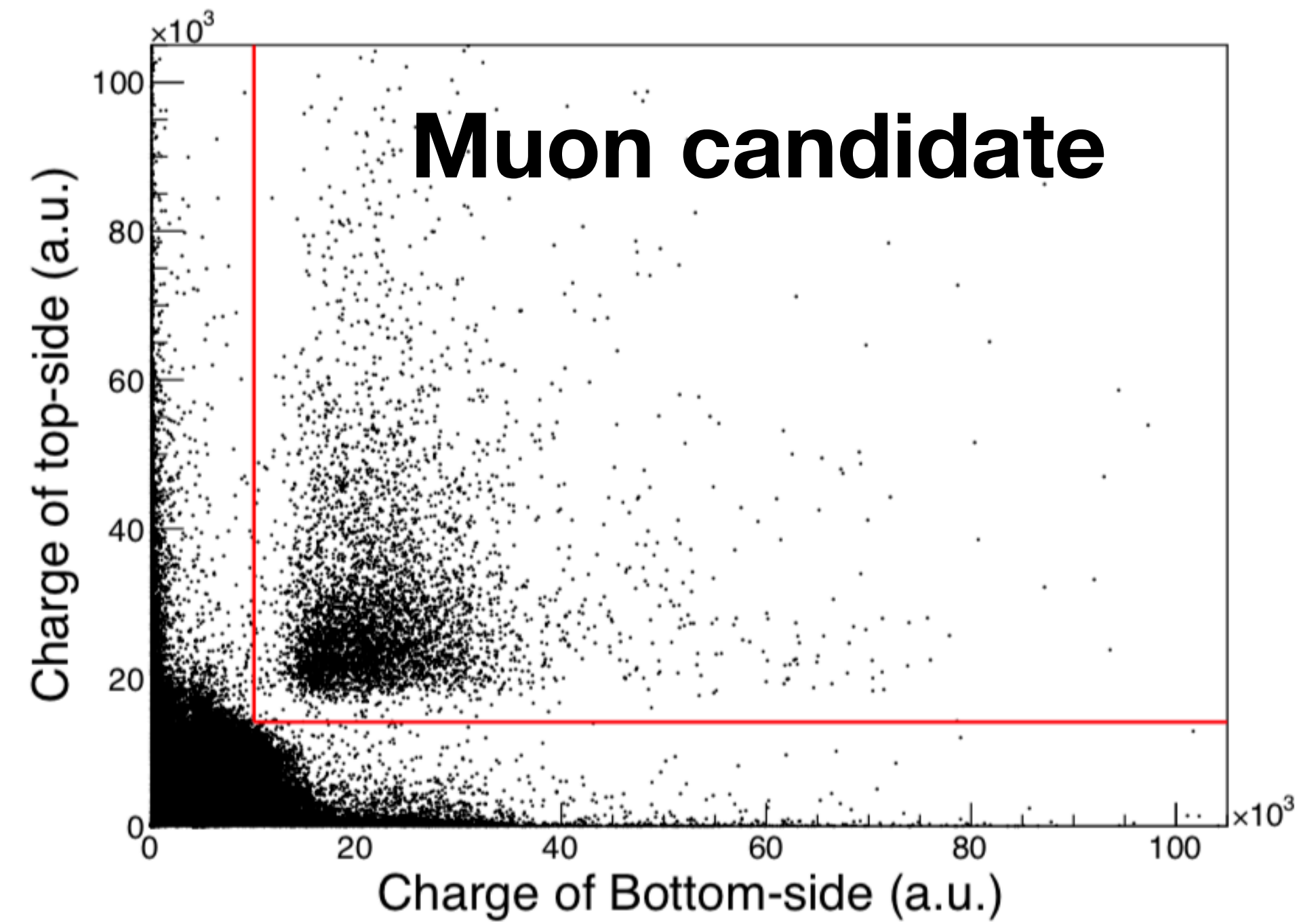




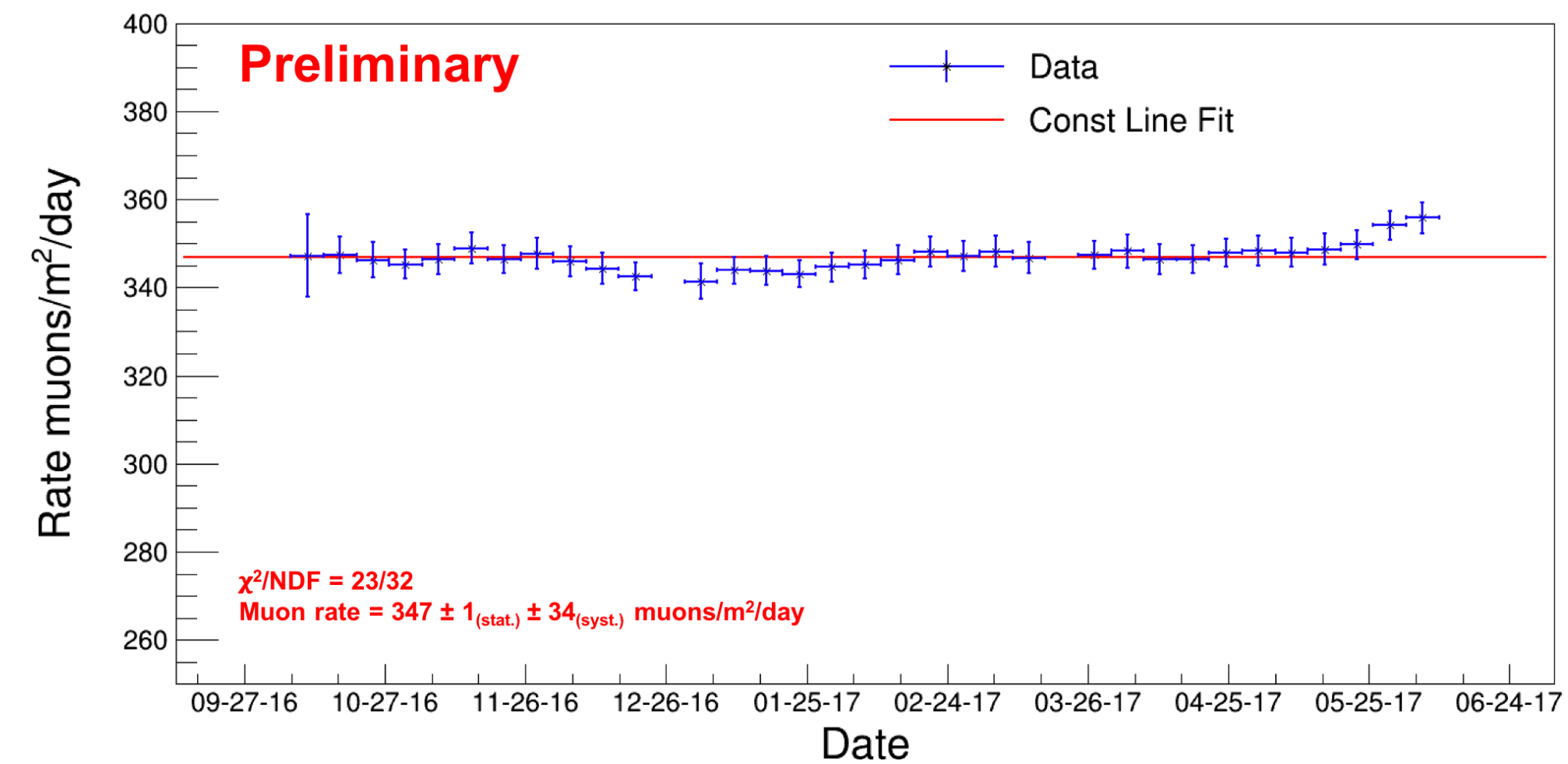
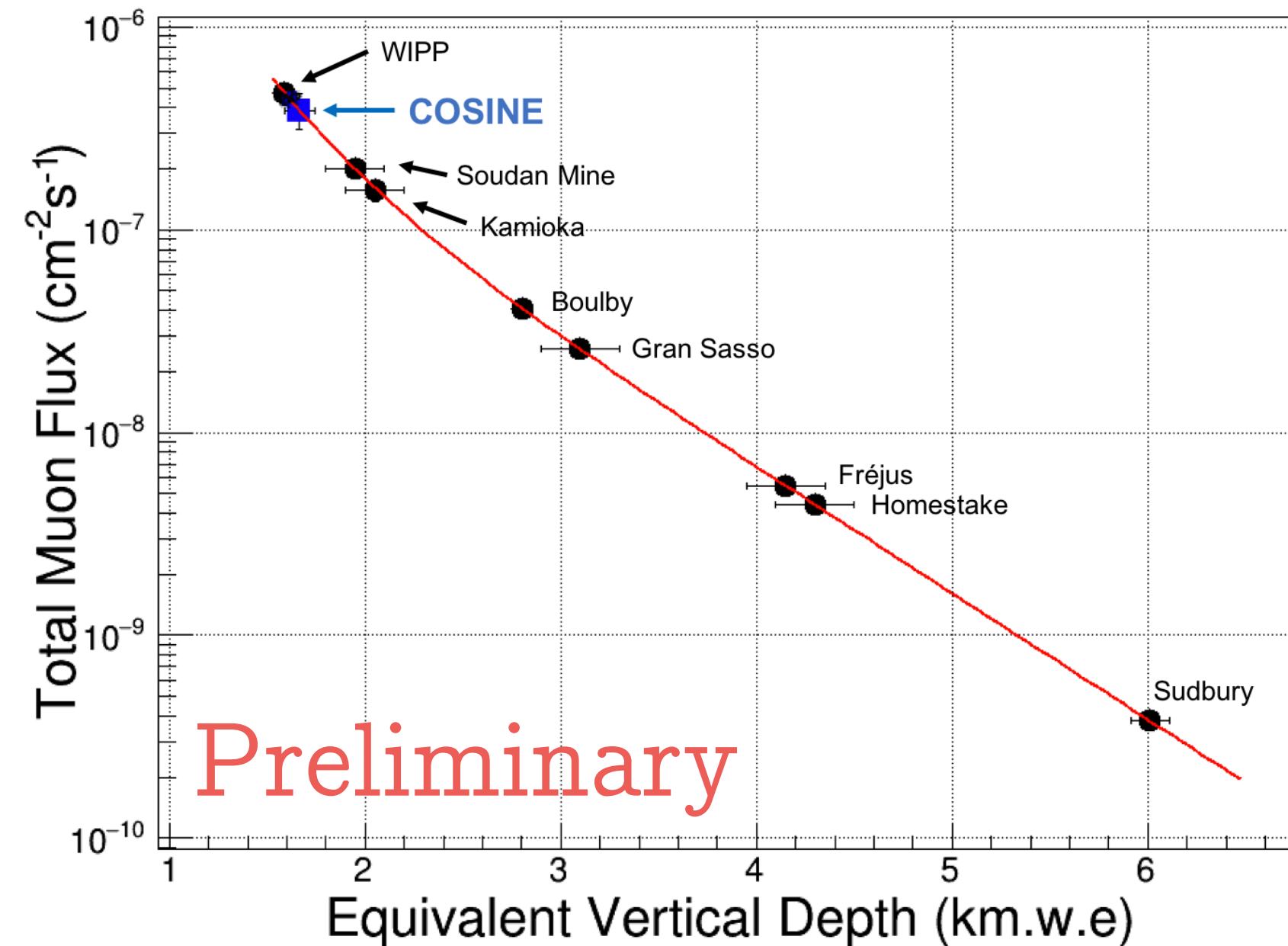
- $^{40}\text{K}$  emits 1460 keV gamma with 3 keV Auger electron energy deposition in NaI crystal
- Tagging 1460 keV events with LS enables **vetoing of 3 keV background events**
- Liquid scintillator internal contamination well modeled with simulation



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





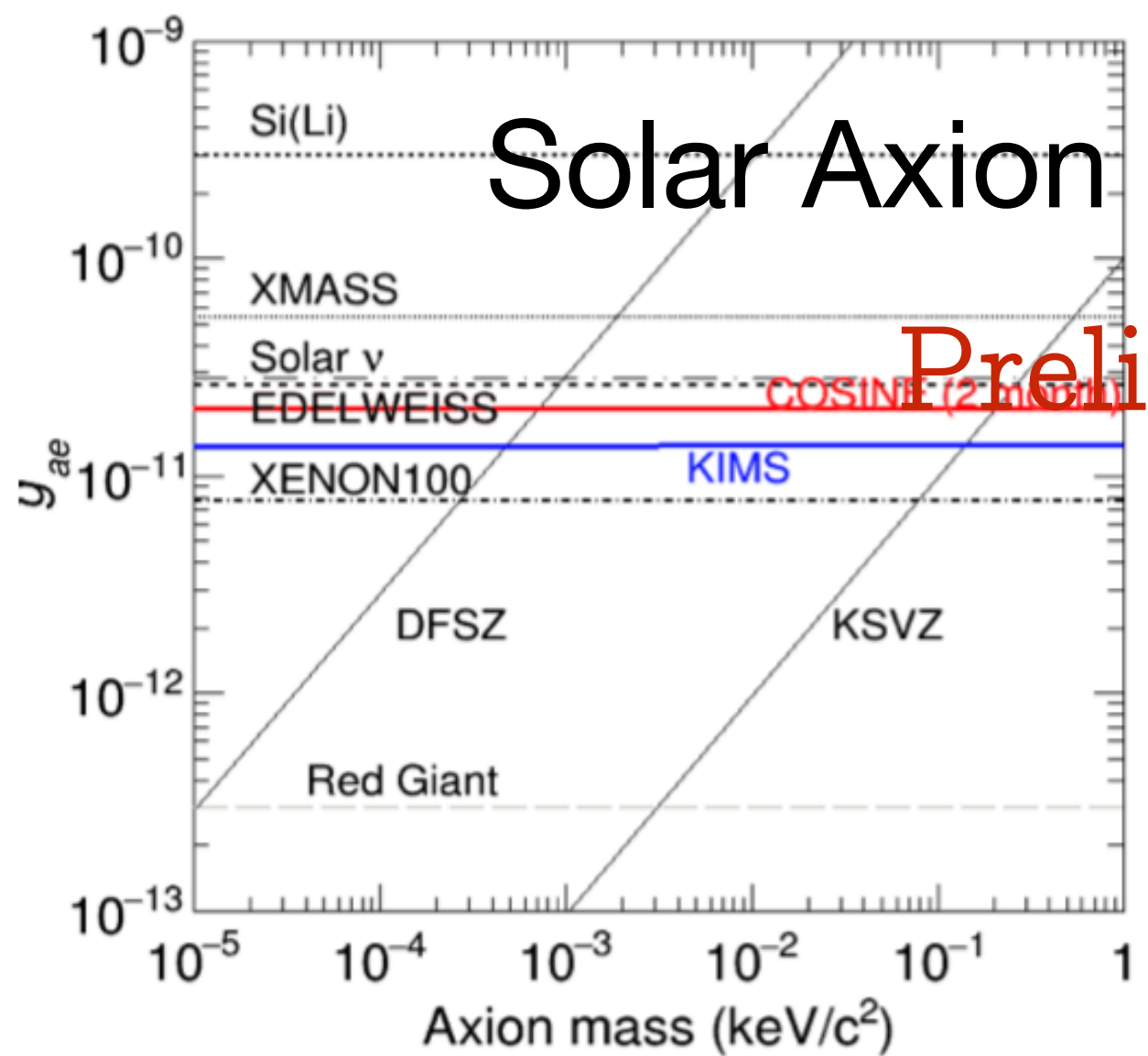


- Muon flux at COSINE-100 is  $\sim 3.98 \times 10^{-7}/\text{cm}^2/\text{s}$  (344.29  $\text{muons/m}^2/\text{day}$ )
- Rate has been consistent throughout the physics run
- Muon selection used to veto muon-induced crystal events

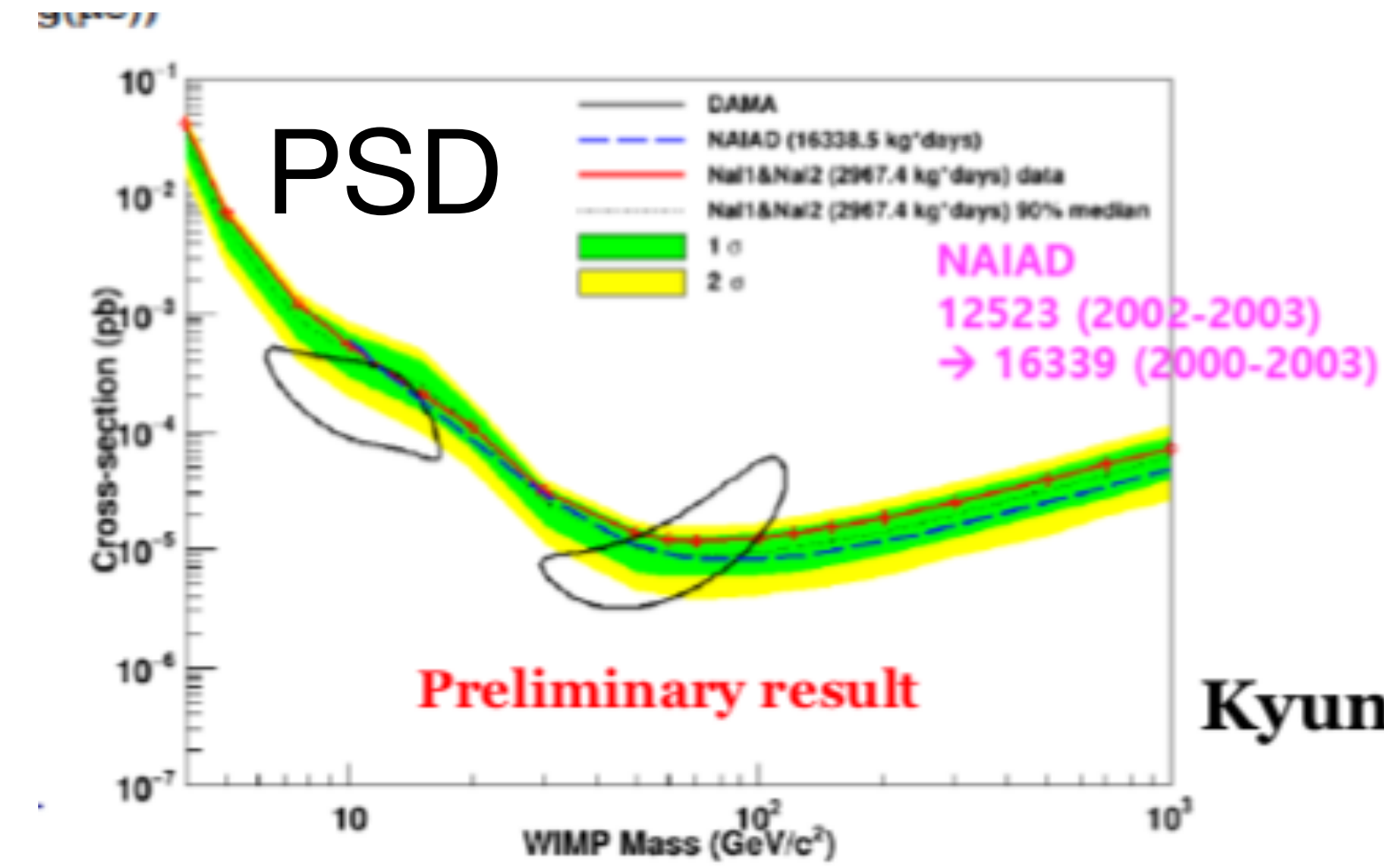


# COSINE-100 Other physics analysis

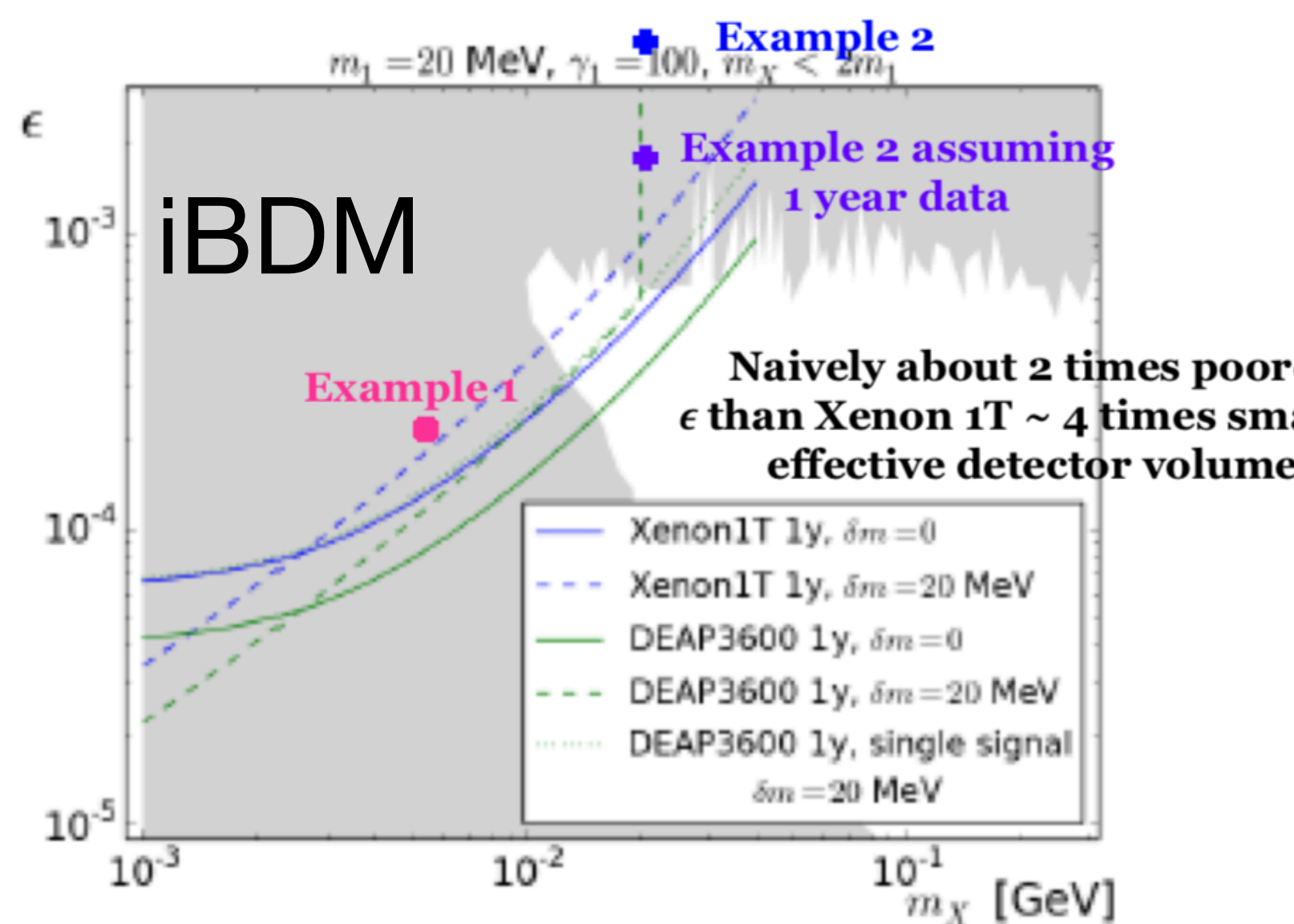
- From the background understanding, other interesting searches are actively on-going
- PSD analysis: looking at different decay time between electron/nuclear recoil within NaI(Tl) crystal
- Bosonic Super-WIMP, Solar axion, inelastic Boosted Dark Matter searches, ...



Preliminary



Kyun

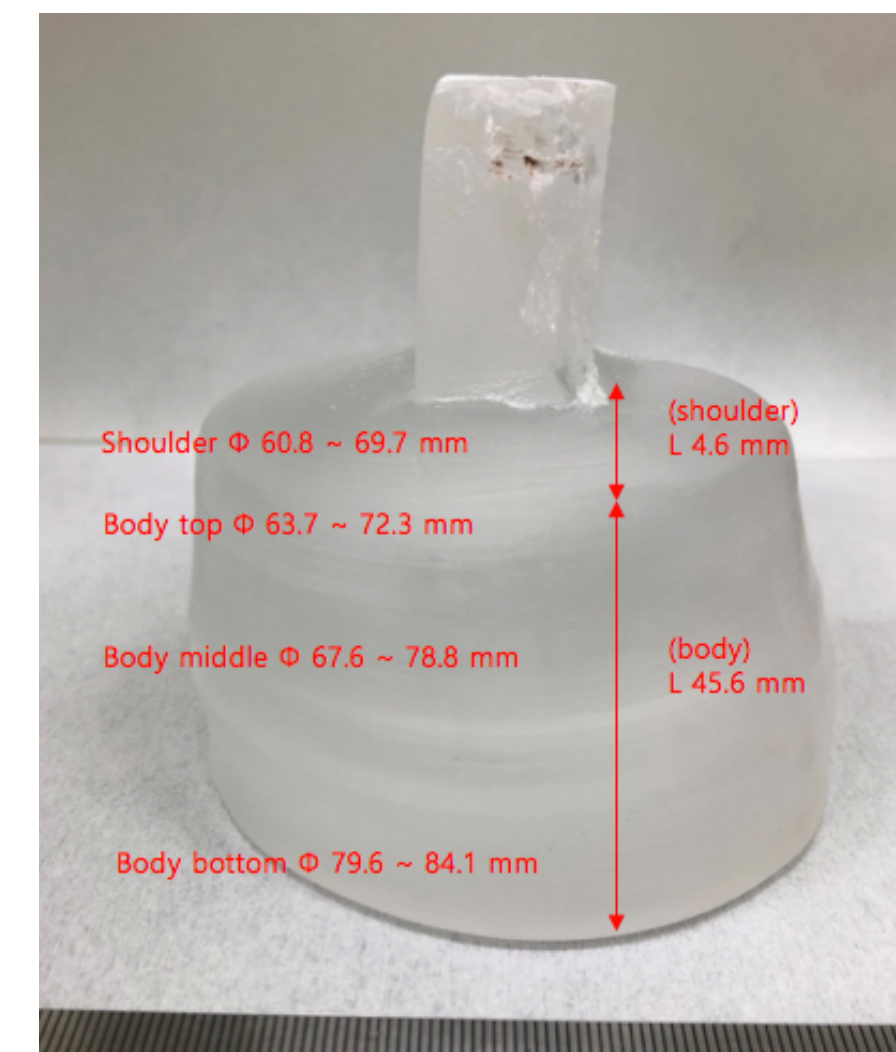




# COSINE-100 Crystal growing R&D

- 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 Korean 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

