# Status of COSINE-100 Experiment

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DBD2016
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Yale

Wright Laboratory

# Contents

- Introduction: COSINE-100 Dark Matter Experiment
- COSINE-100 Hardware Construction
- Data Taking and Monitoring
- Initial Performance
- Conclusion and Outlook

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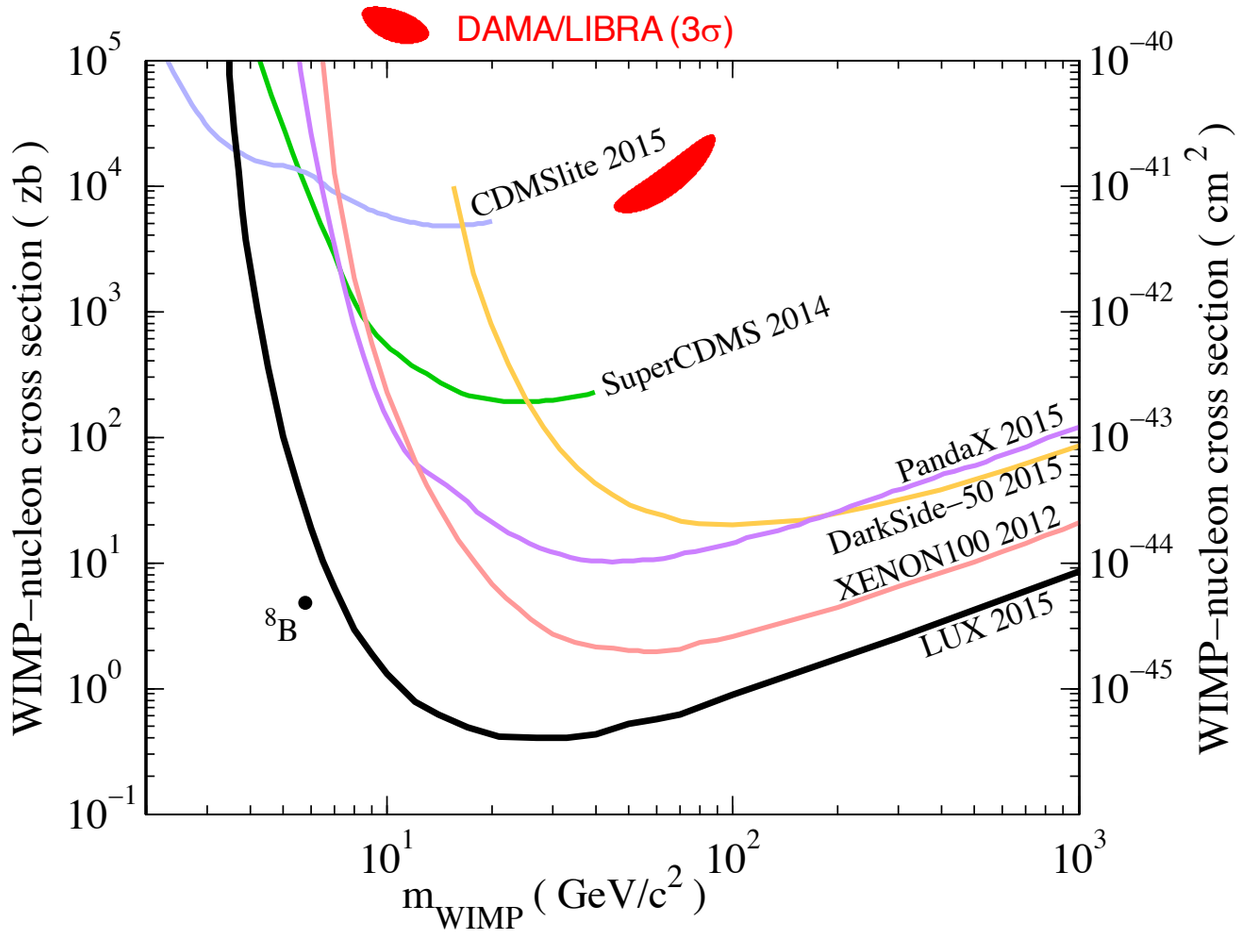
# Current Dark Matter Search Status

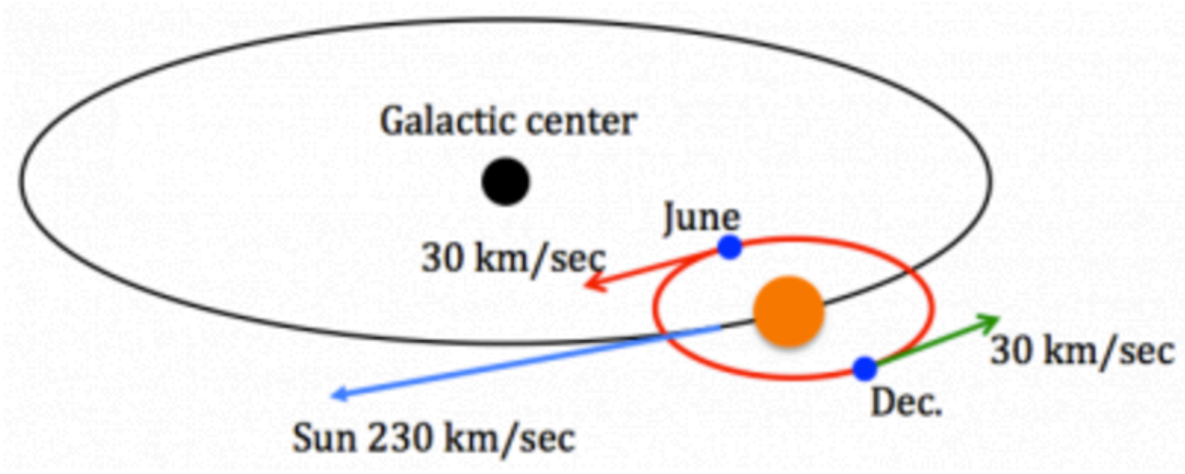



LUX Collaboration,
arXiv:1512.03506

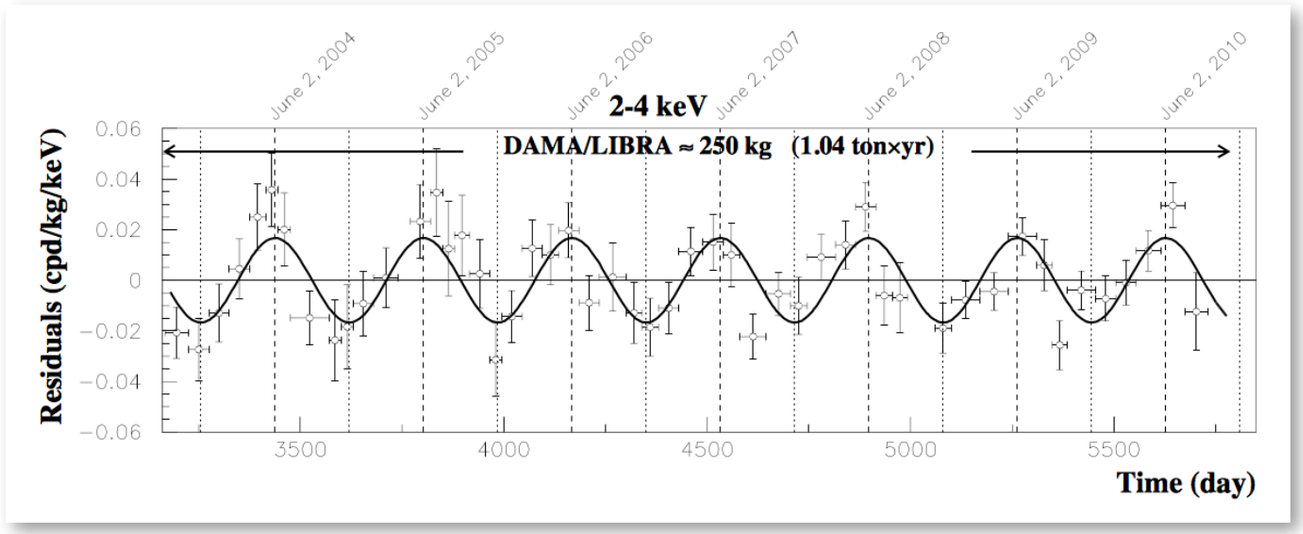
- Liquid Xenon detectors provide currently the best sensitivity to spin-independent WIMP scattering

- Signal excesses in other experiments in tension under standard interaction models

# Annual Modulation and DAMA




Barnabei *et al*, Eur. Phys. J. C (2013)




- 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)
- 9.3 σ modulation observed by DAMA/NaI, DAMA/LIBRA
  - Is it dark matter or something else?
  - More exclusion limits *cannot* answer this question

# Global Efforts with NaI(Tl)

- **DM-Ice**:
  17 kg prototype detectors @ South Pole

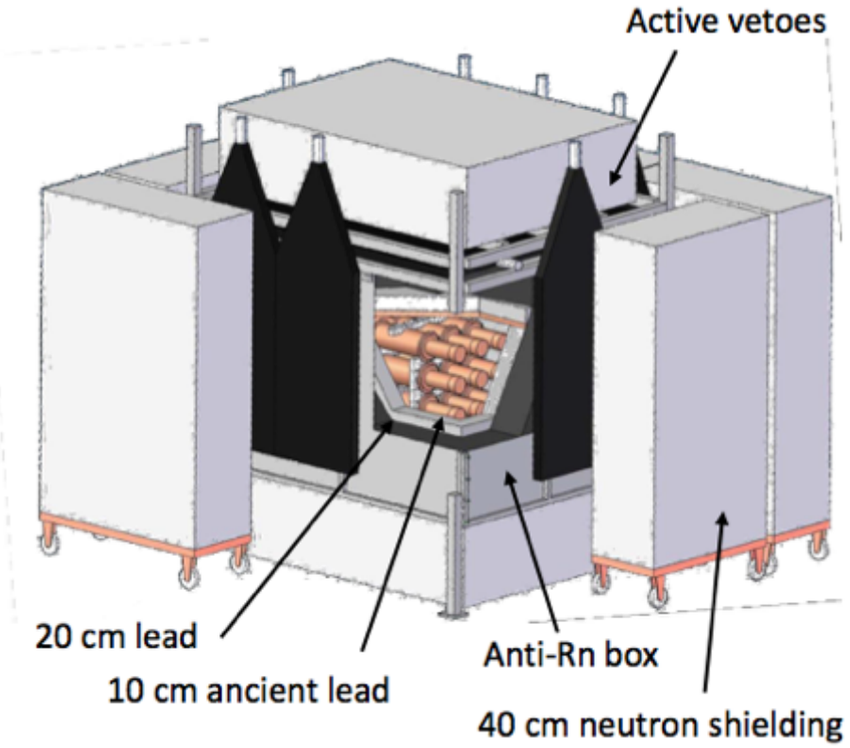
- **KIMS-NaI**:
  Various NaI crystal R&D in CsI array @ Yangyang

- **ANAIS**:
  112.5 kg total crystal mass @ Canfranc

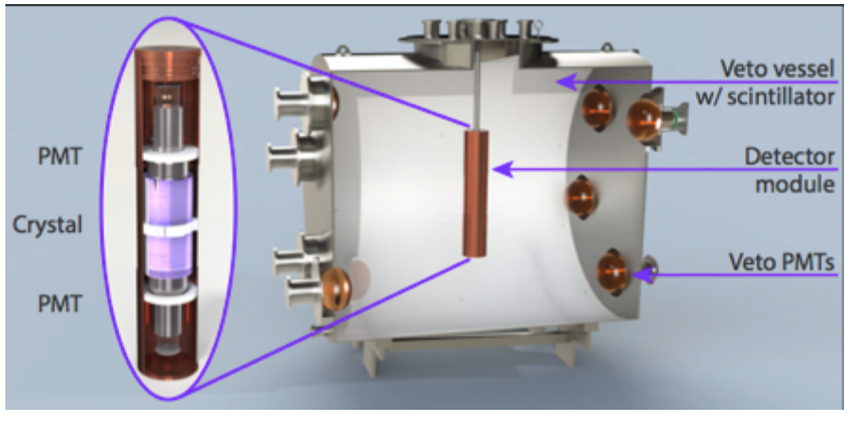
- **SABRE**:
  Ultra-pure crystal (30-50 kg) in liquid scintillator veto @ LNGS & Stawell

- **PICO-LON**:
  Low-background crystal R&D setup @ Kamioka

ANAIS




SABRE

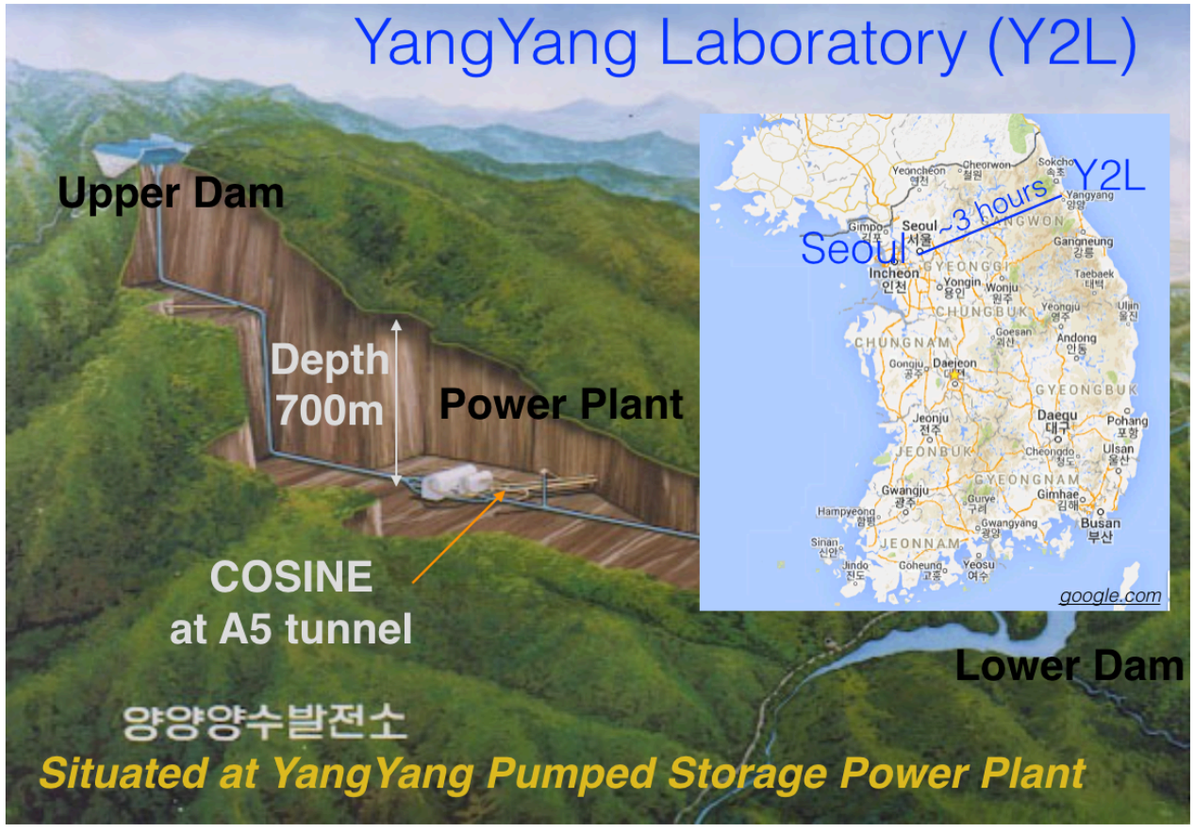


# COSINE-100 Dark Matter Experiment

- A joint effort between **DM-Ice** and **KIMS** collaboration

- 14 institutes with ~50 members

- Located at Yangyang underground laboratory (Y2L), South Korea, with ~700 m rock overburden



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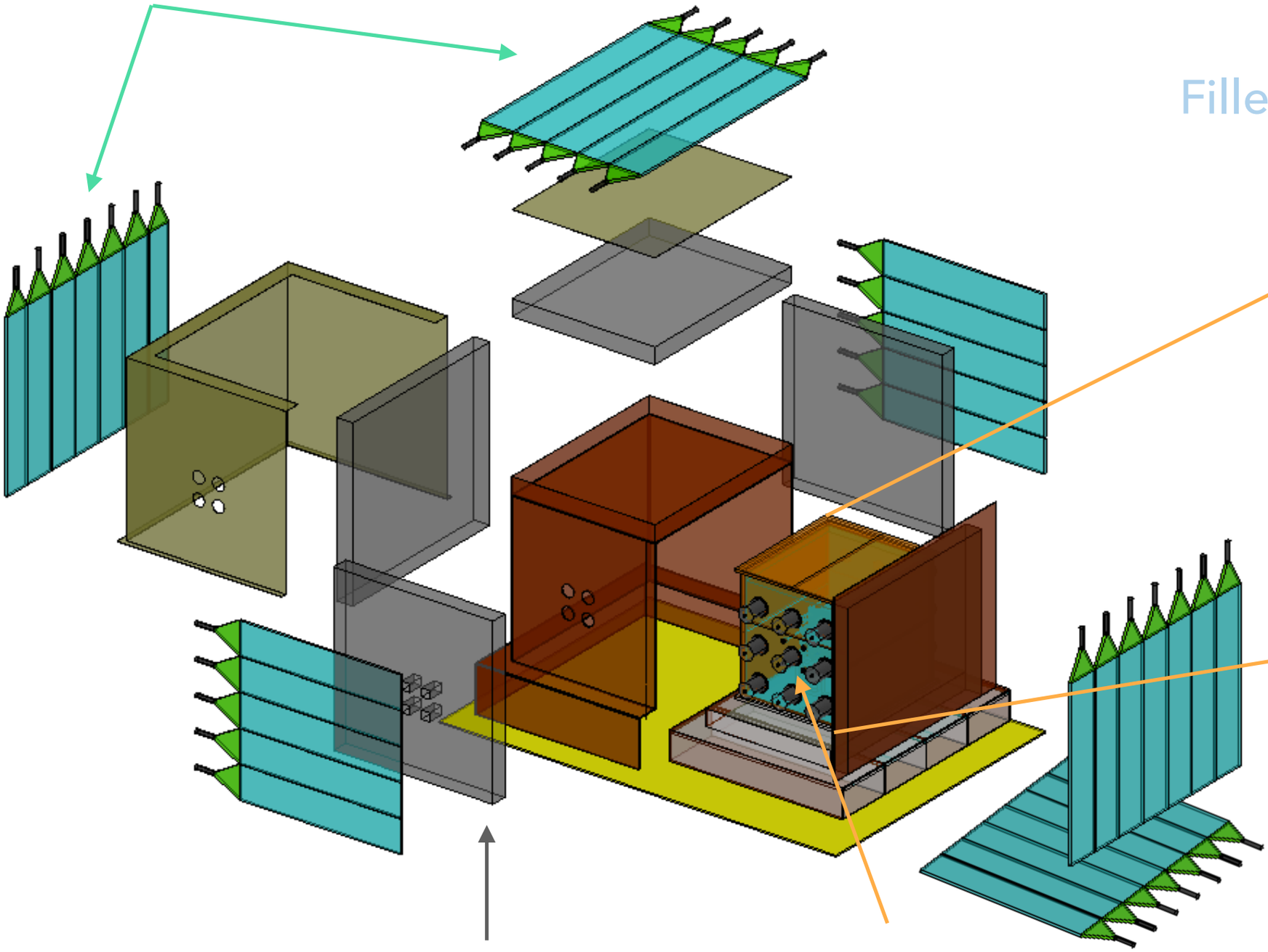
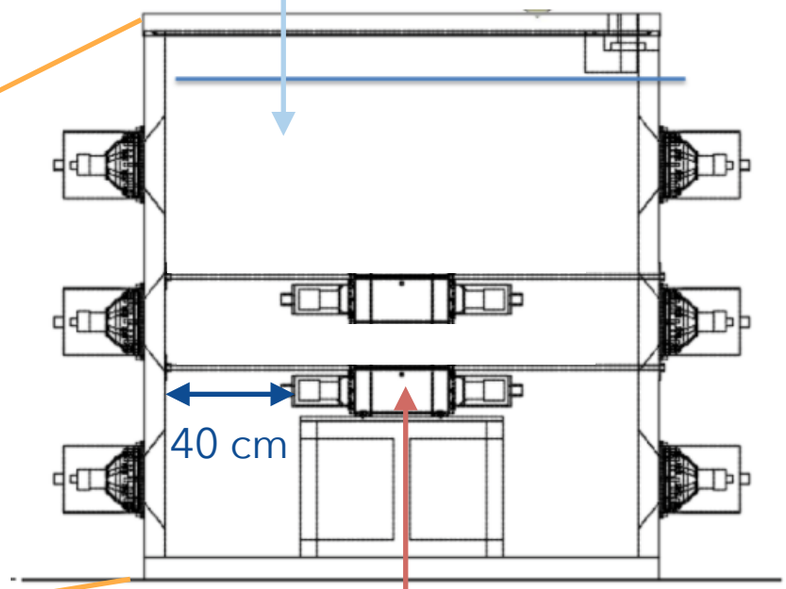
# COSINE-100 Shielding Structure

Plastic Scintillators

Filled with Liquid Scintillator






NaI(Tl) Crystals

Lead Shielding (20 cm)

Cu Box (3 cm)

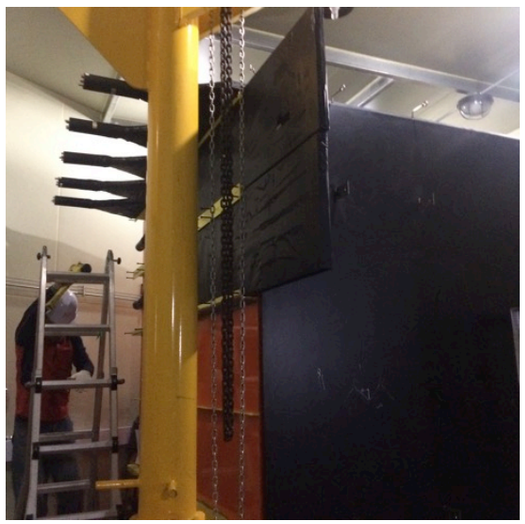
# COSINE-100 Construction Timeline

Dec. 2015

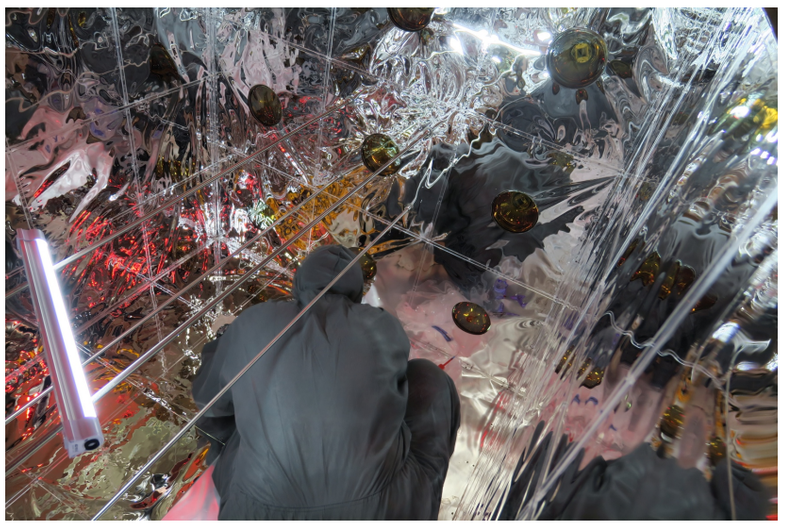
Jan. 2016

Feb. 2016

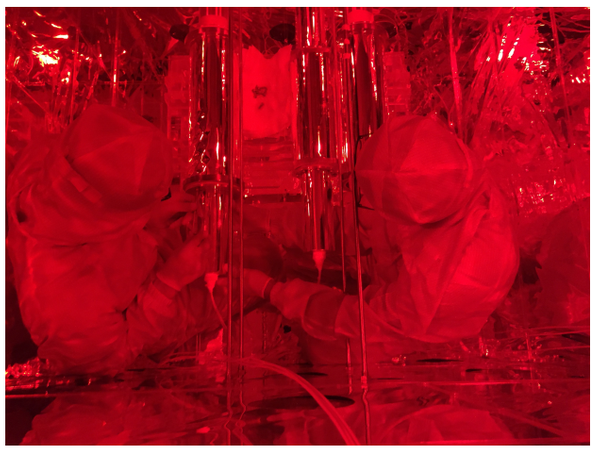
Mar. 2016



Apr. 2016

May. 2016




Jun. 2016

Sep. 2016

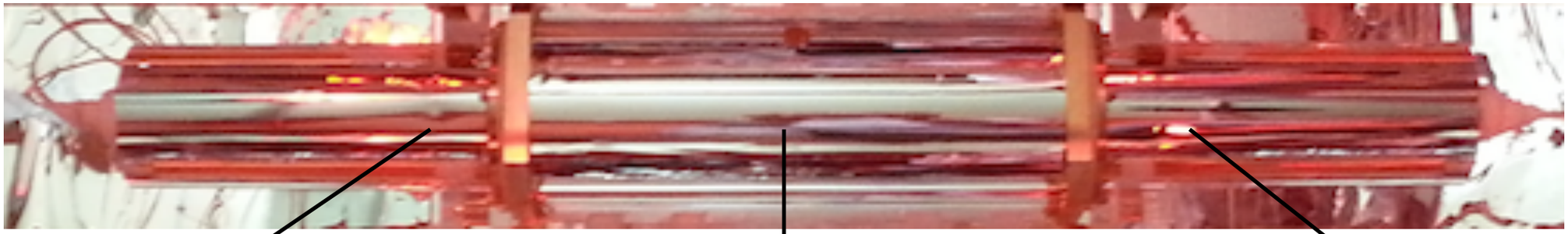
# COSINE-100 NaI(Tl) Crystals

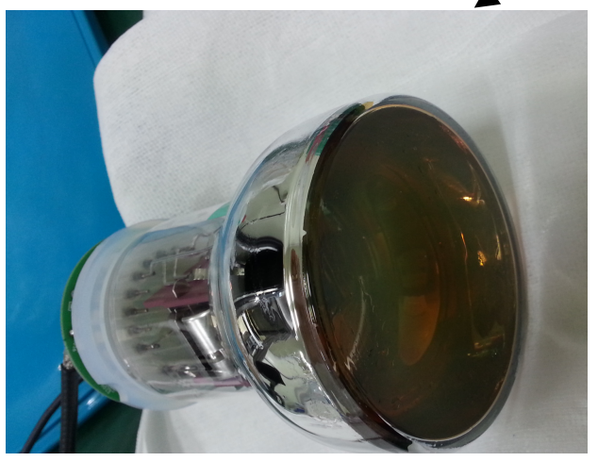
Preliminary

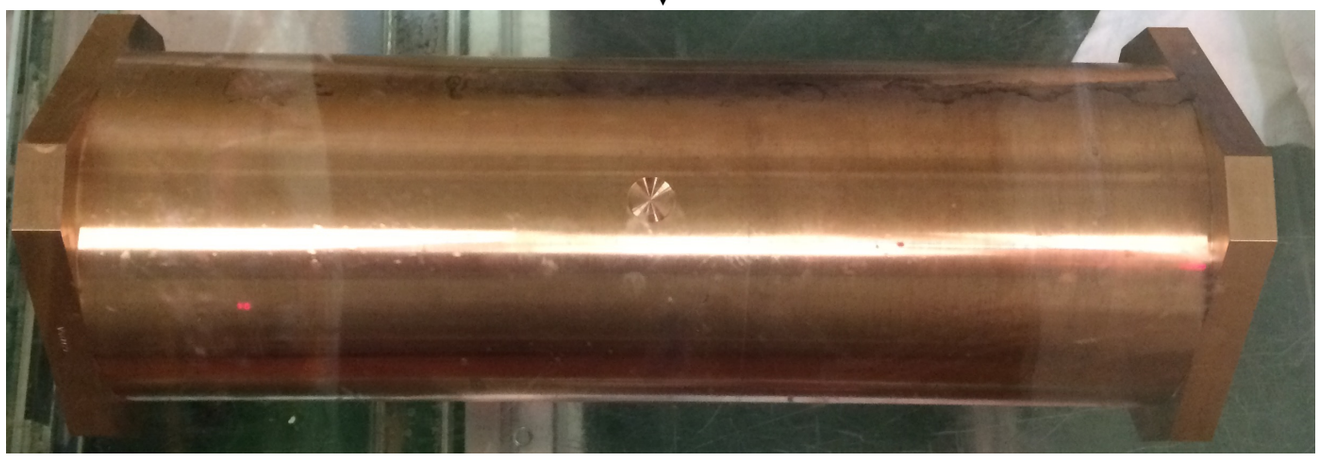
| | Mass (kg) | Powder Type | $^{40}$K (ppb) | $^{238}$U (ppt) | $^{232}$Th (ppt) | $^{210}$Po (mBq/kg) |
|---|---|---|---|---|---|---|
| Crystal 1 | 8.26 | Powder B | 43.4±13.7 | <0.02 | 1.31±0.35 | 3.20±0.04 |
| Crystal 2 | 9.15 | Powder C | 82.7±12.1 | <0.12 | <0.63 | 2.06±0.03 |
| Crystal 3 | 9.16 | WIMPScint-II | 41.1±6.8 | <0.04 | 0.44±0.19 | 0.76±0.02 |
| Crystal 4 | 18.01 | WIMPScint-II | 39.5±8.3 | | <0.3 | 0.74±0.01 |
| Crystal 5 | 18.28 | Powder C | 86.8±10.8 | | 2.35±0.31 | 2.06±0.02 |
| Crystal 6 | 12.5 | WIMPScint-III | 12.2±4.5 | <0.018 | 0.56±0.19 | 1.52±0.02 |
| Crystal 7 | 12.5 | WIMPScint-III | 18.8±5.3 | | <0.6 | 1.54±0.02 |
| Crystal 8 | 18.28 | Powder C | 56.15±8.1 | | <1.4 | 2.05±0.02 |
| DAMA | | | <20 | 0.7 - 10 | 0.5 - 7.5 | <0.5 |

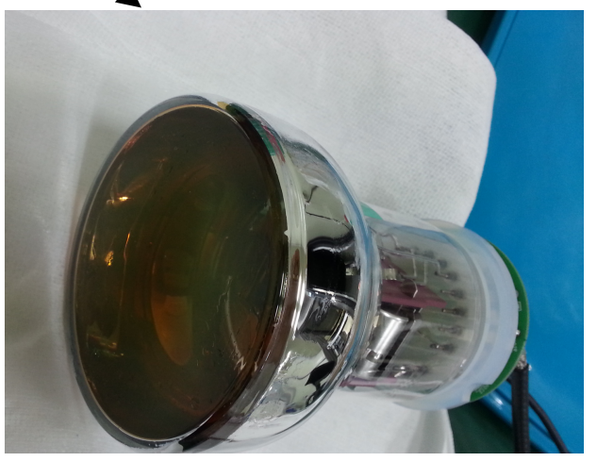
- 8 crystals with total mass of ~106 kg
- Preliminary background values estimated both at R&D and COSINE setup
- Average light yield ~15 p.e./keV

# Crystal-PMT Assembly



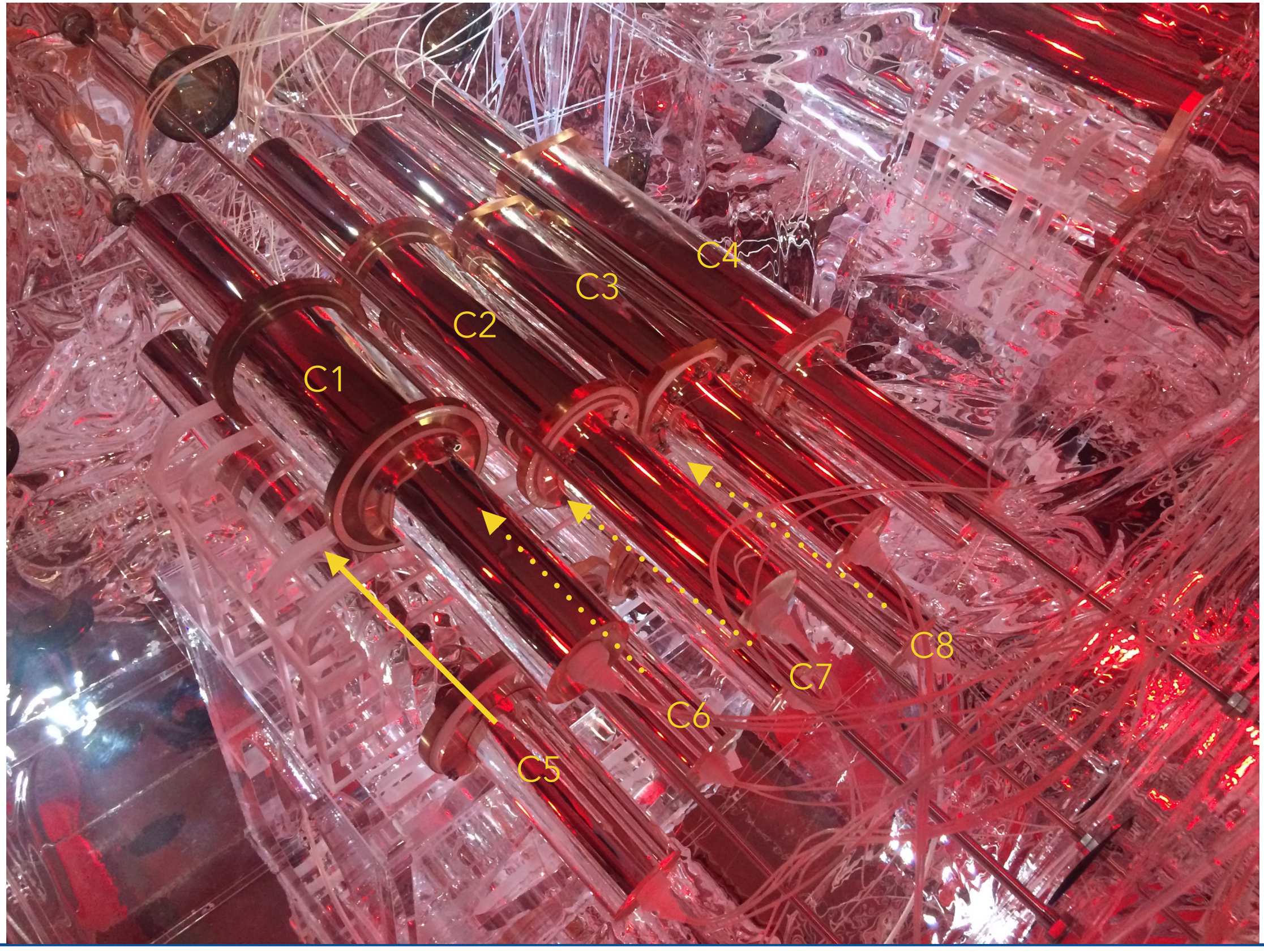




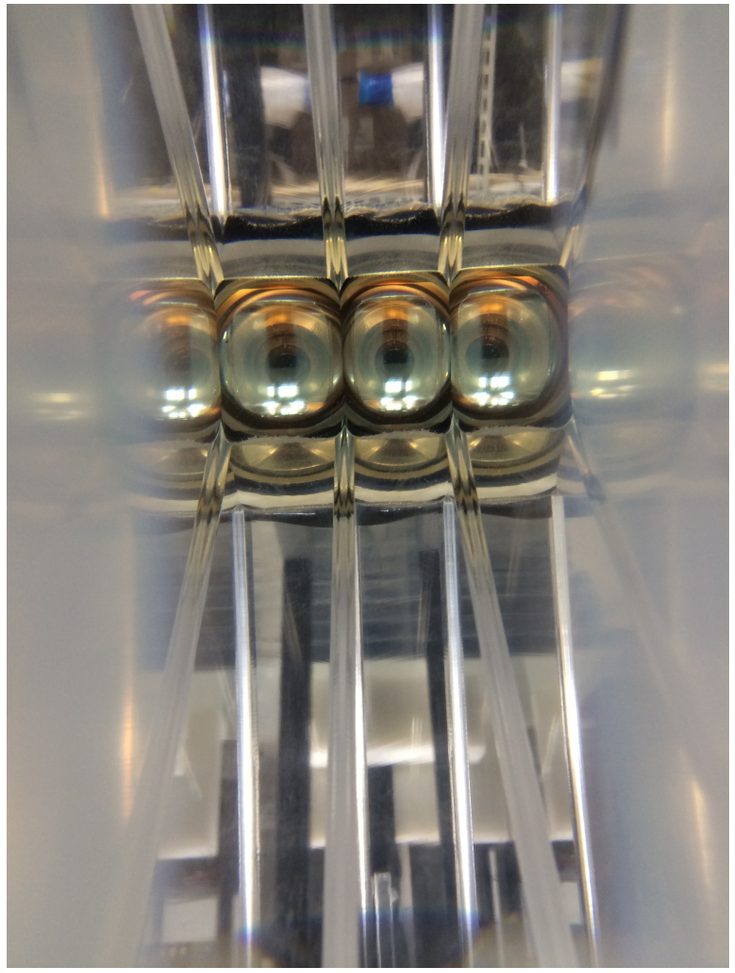


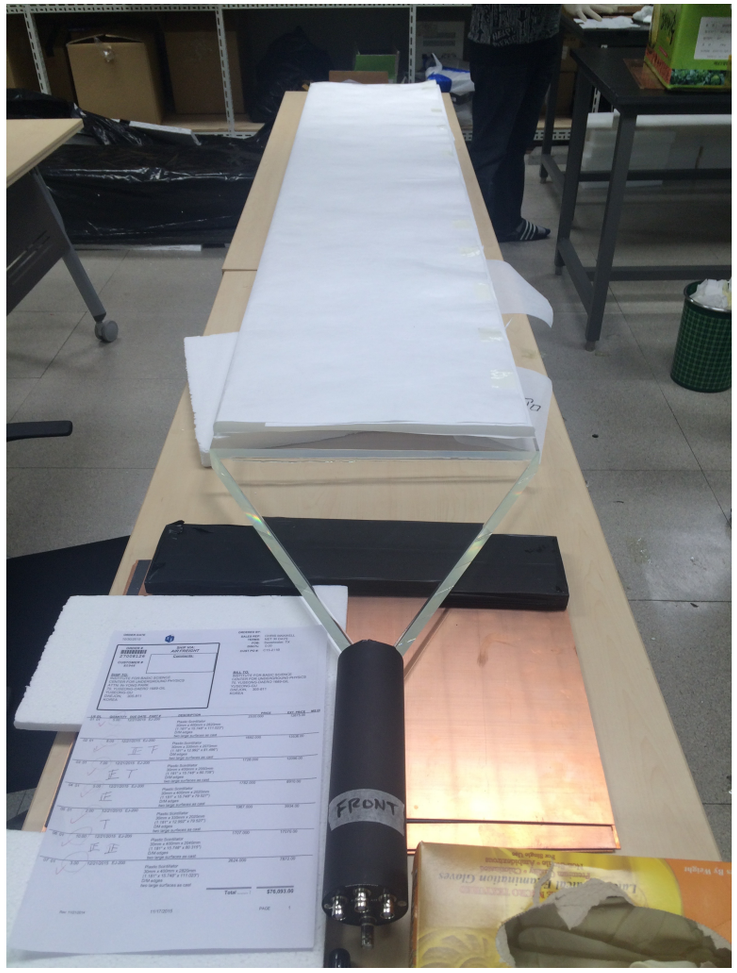
- OFE Cu-encapsulated NaI crystal is attached with two 3-inch PMTs
- PMT: R12669 from Hamamatsu, 35% Quantum Efficiency at 420 nm
- Outer surface of crystal and PMT cap is wrapped with Vikuiti reflective films

# Crystal Installation



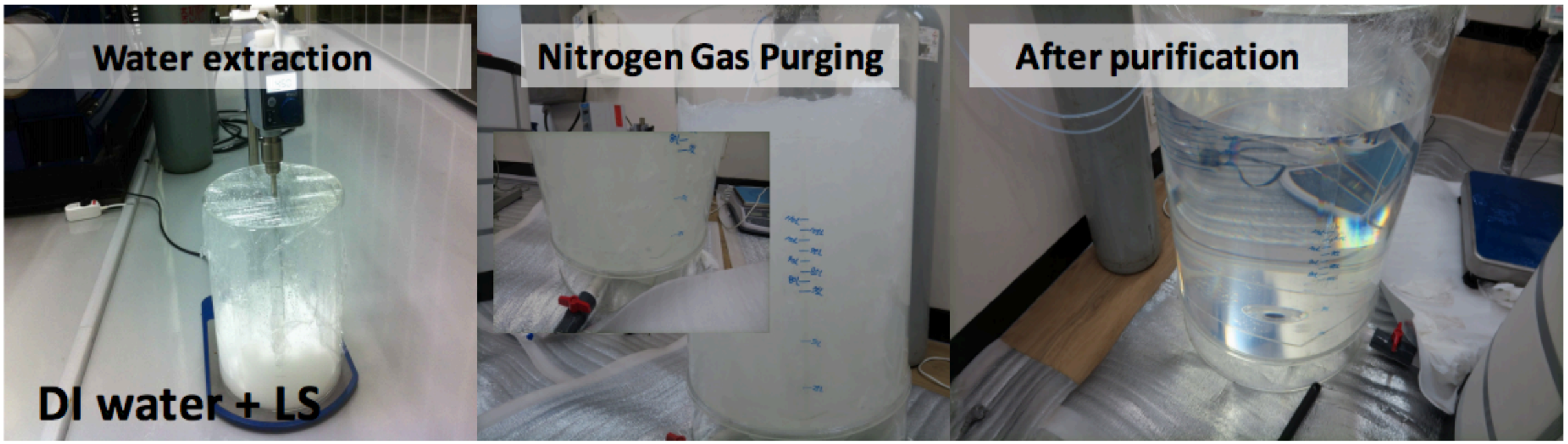
# Plastic Scintillator





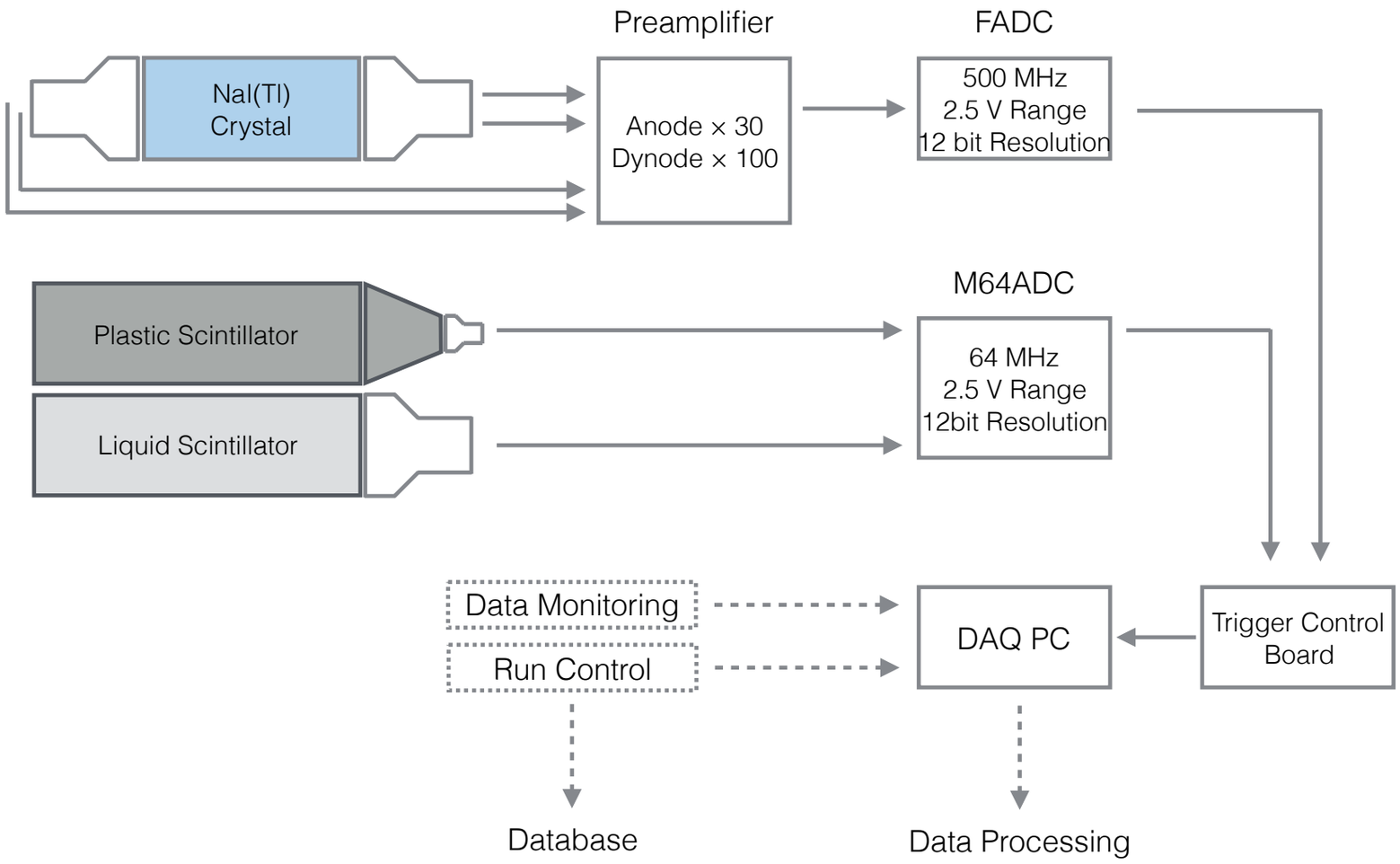

- Purpose: To tag cosmic ray muon events
- 37 panels of plastic scintillator (EJ-200), 3 cm thick
- Attached with light guides and 2-inch PMT, wrapped with diffuse reflector

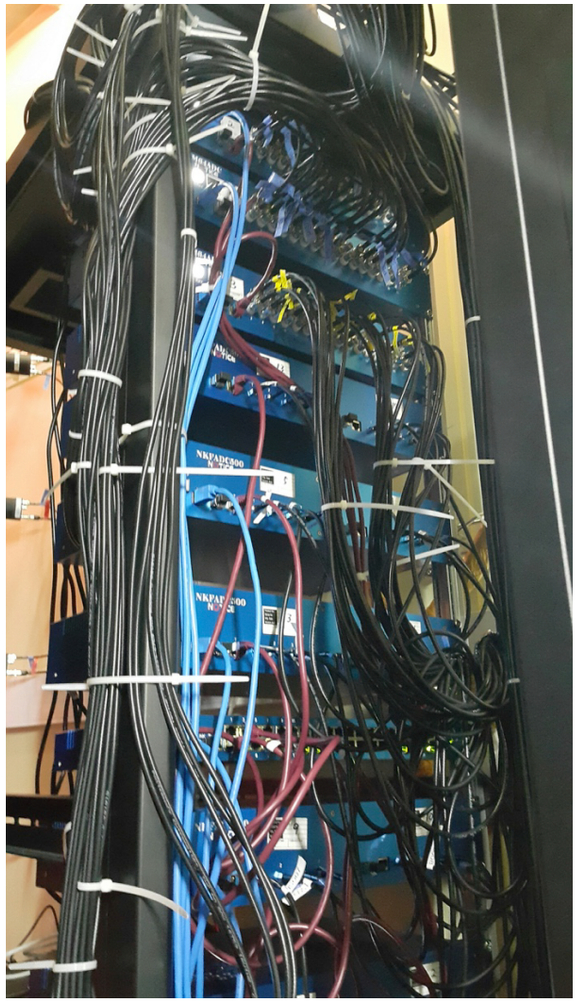
# Liquid Scintillator




- Purpose: Tag and veto 3 keV $^{40}$K (and 0.9 keV $^{22}$Na), also works as shielding for external backgrounds and neutron
- LAB-based liquid scintillator
- ~2000 liters filled inside of Cu box
- Shown to contain less than 7 ppt of $^{238}$U and 4 ppt of $^{232}$Th
- Expected background contribution less than 0.01 counts/day/keV/kg

# Data Acquisition System



- Crystal data taken with FADC 500 Mega samples/sec waveform digitizer
- M64ADC data taken with M64ADC 64 MHz waveform digitizer
  - Plastic and liquid scintillator data

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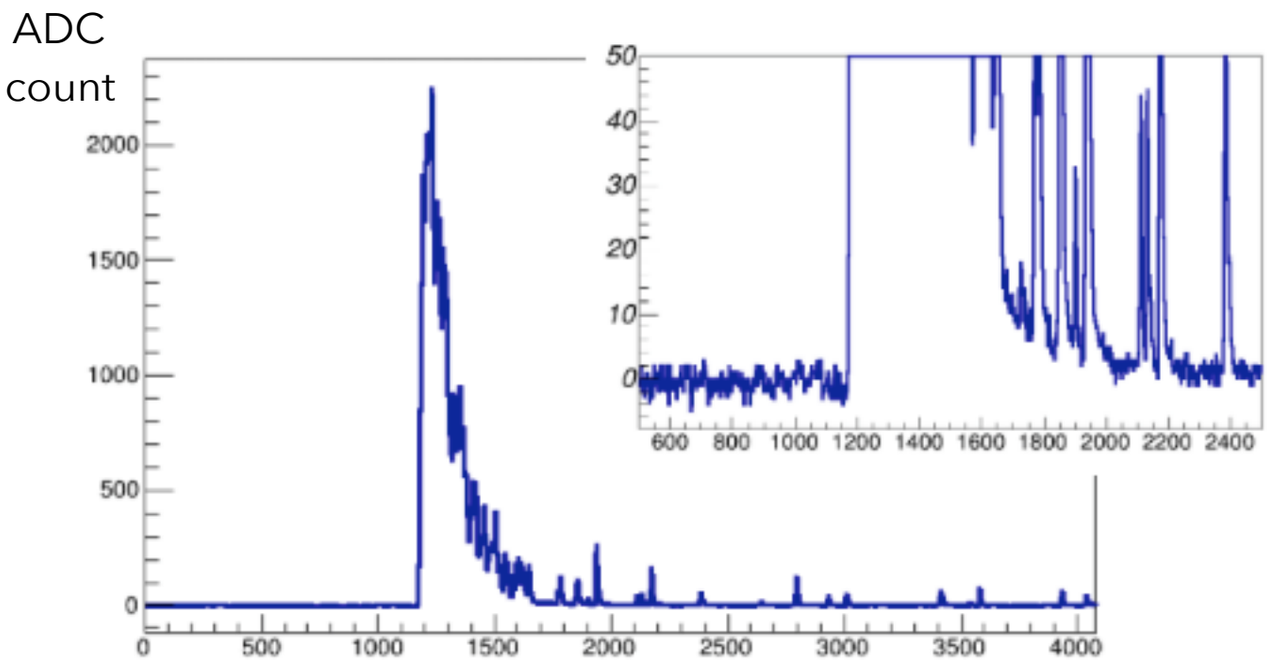
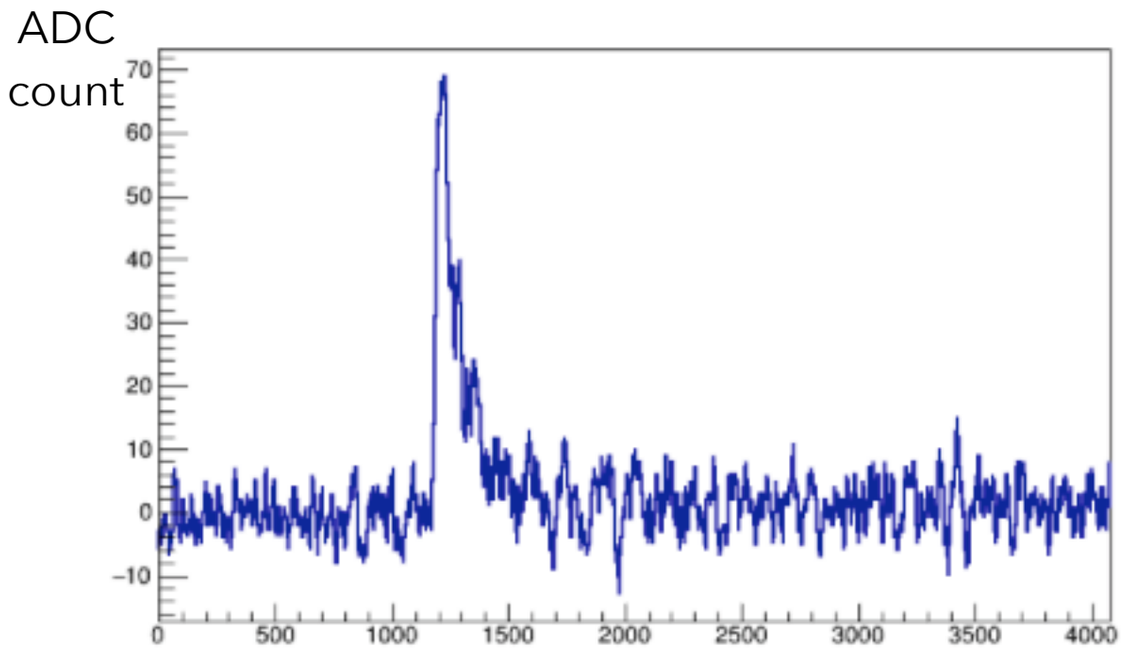
# Crystal PMT Waveforms

Anode Waveform
(0-120 keV)

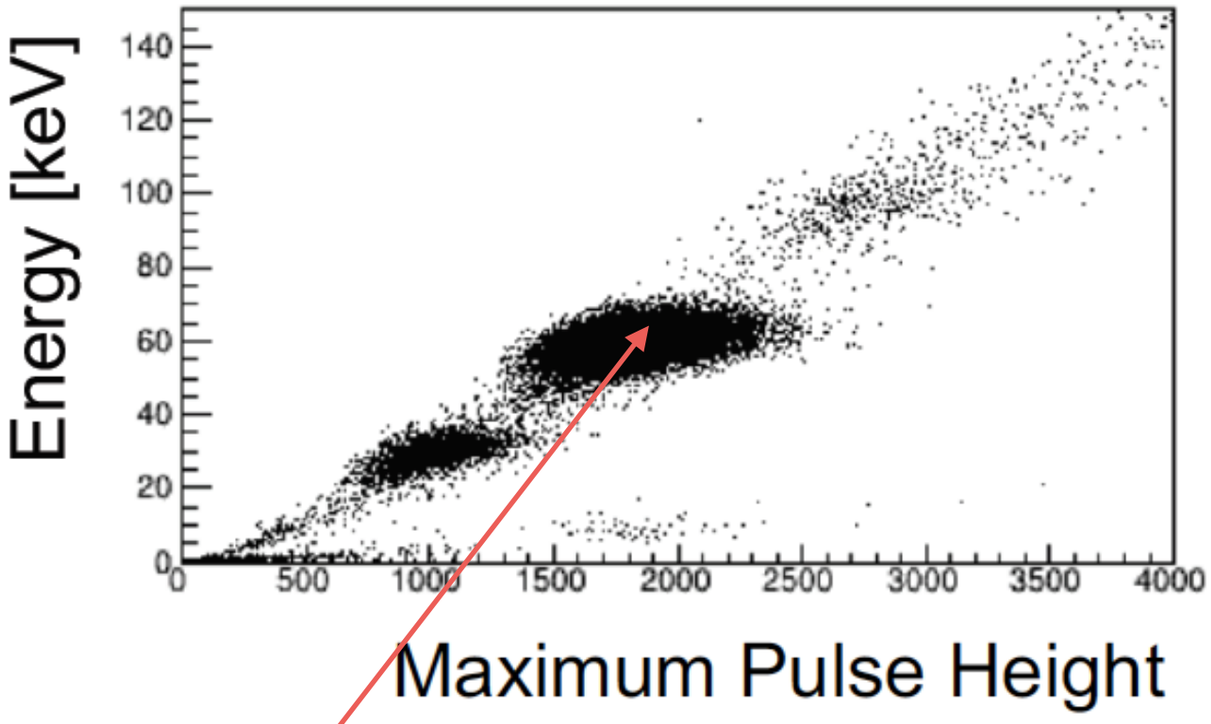


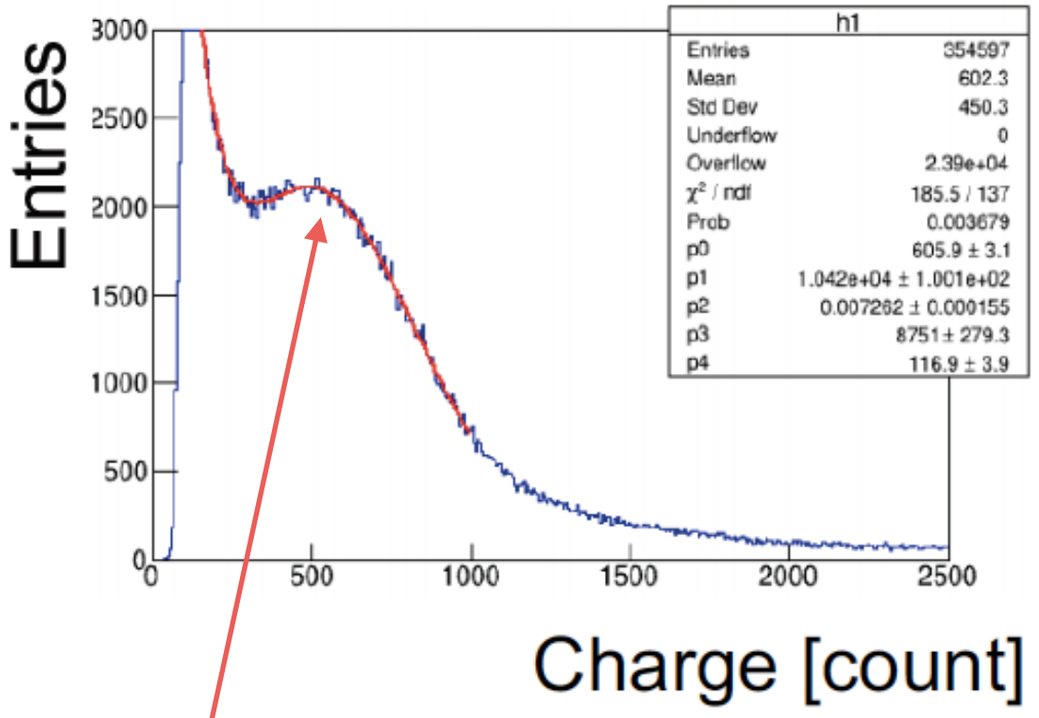

Dynode Waveform
(50-10,000 keV)




- The same events read in two channels: Anode and Dynode
  - **Anode** signal with waveform sensitivity at single-photon level: Primary channel for dark matter search
  - **Dynode** signal for high energy events: helps in understanding better the internal backgrounds in the crystals

# Calibration/Light yield calculation




60 KeV gamma

SPE

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

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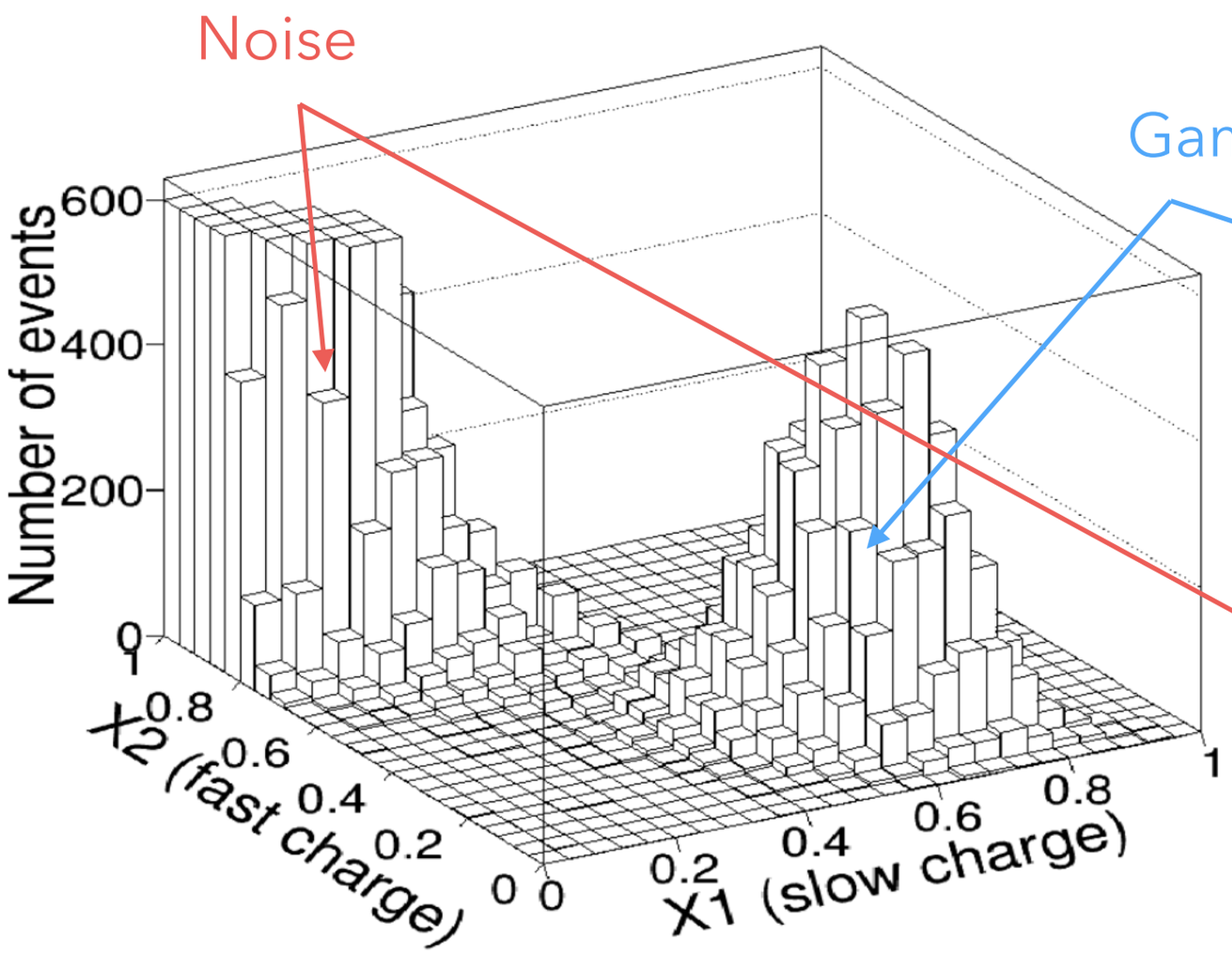
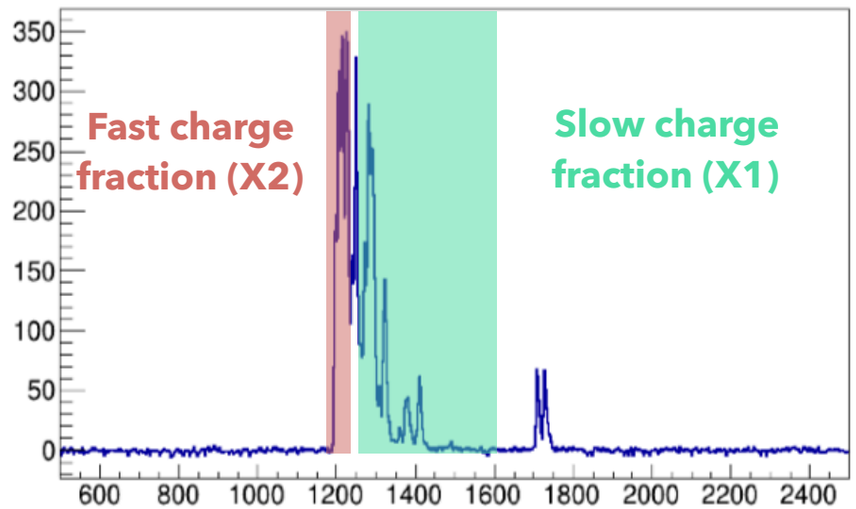
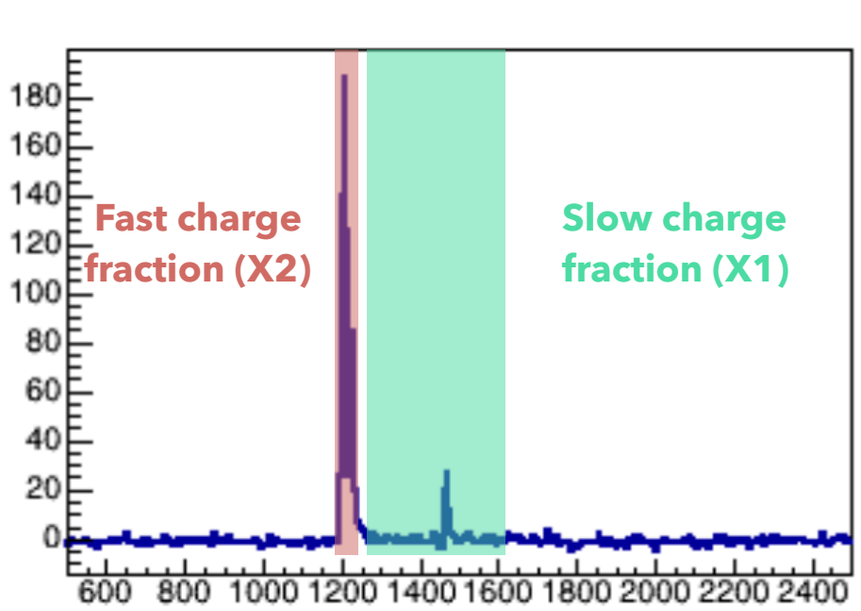
# Event Selection: Fast Event Rejection

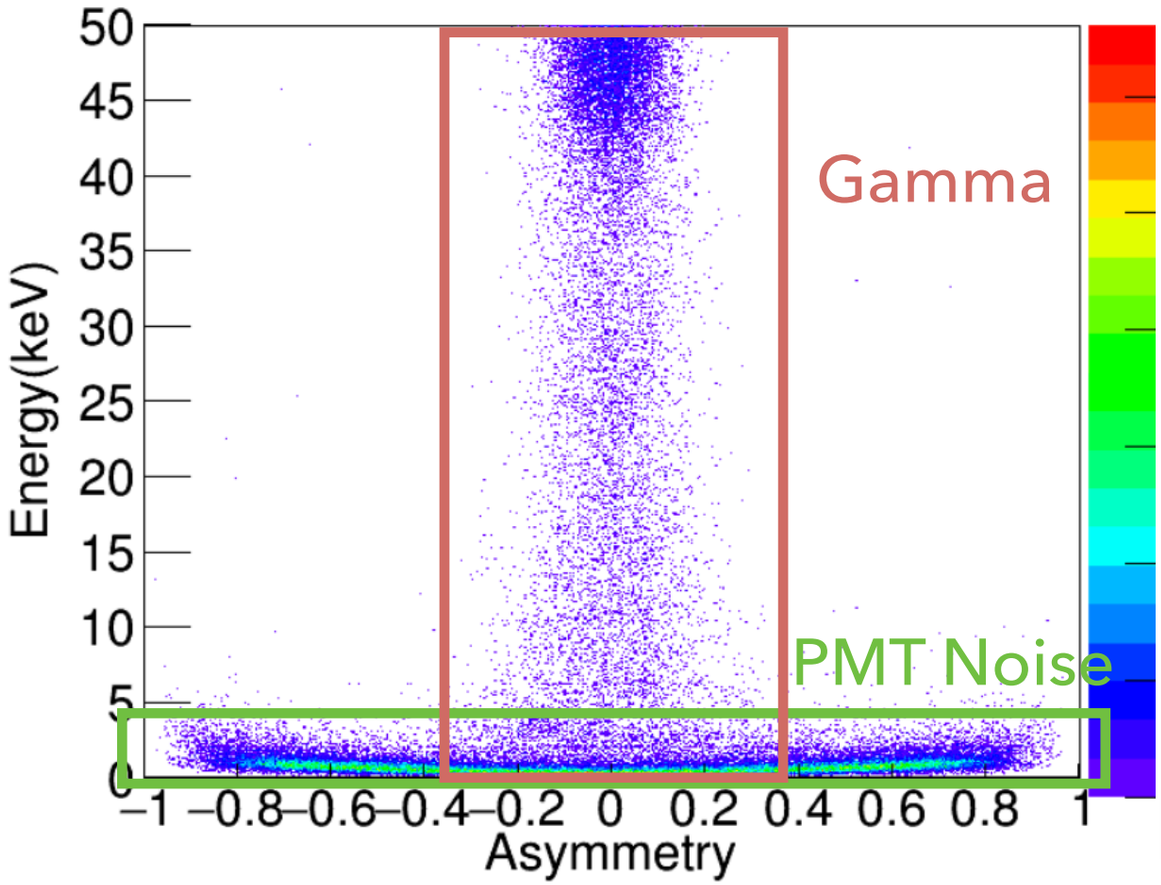


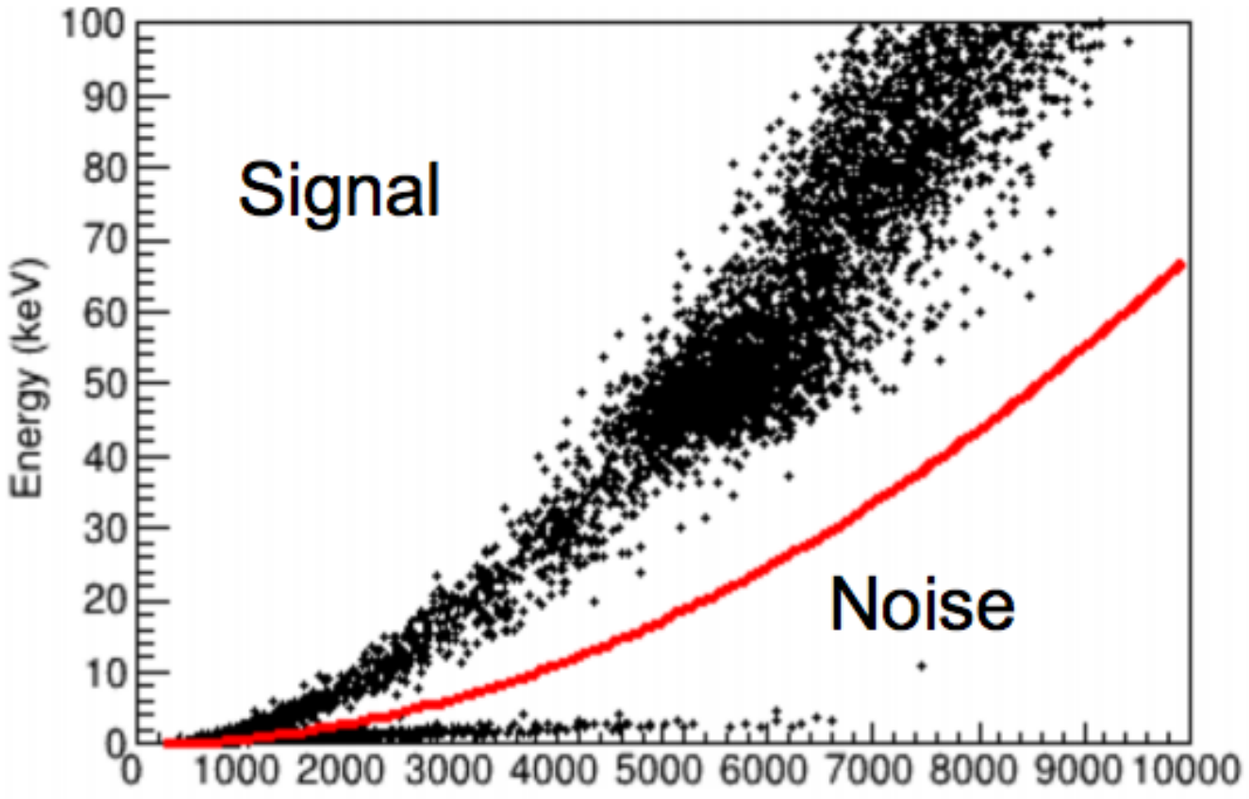




- Looking at charge ratio between rising edge and falling edge of a pulse gives good noise separation power

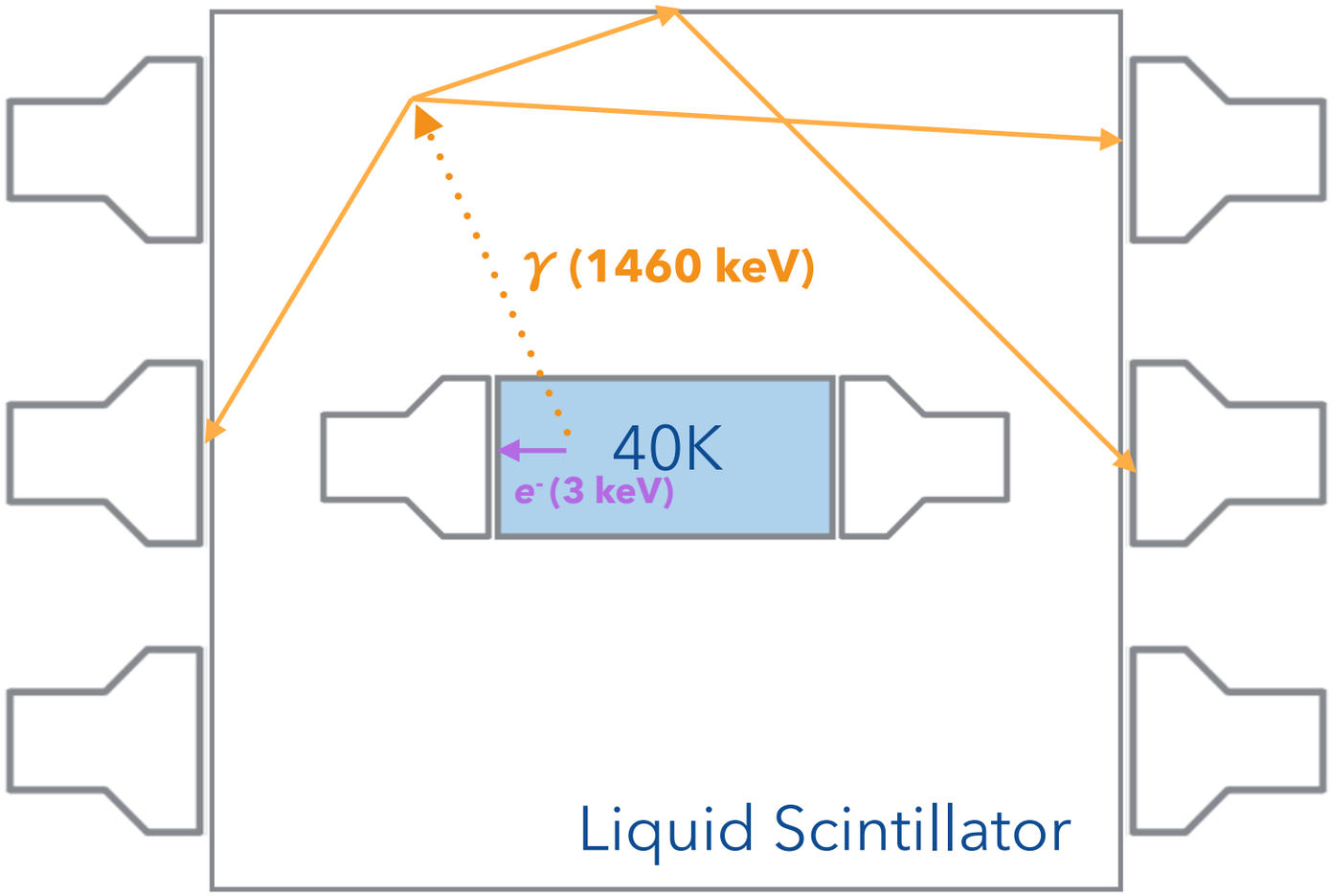
# Event Selection: Asymmetry between PMTs & Charge/Peak




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

# Crystal-LS Coincidence Events

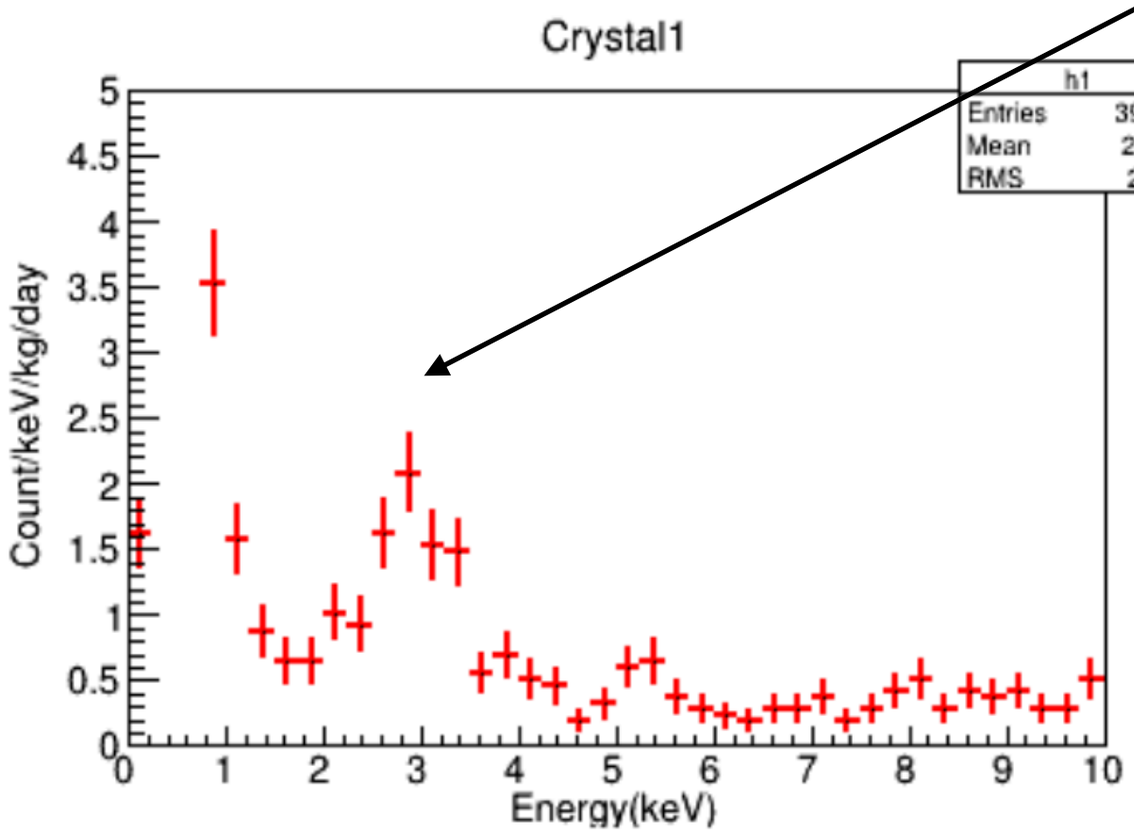


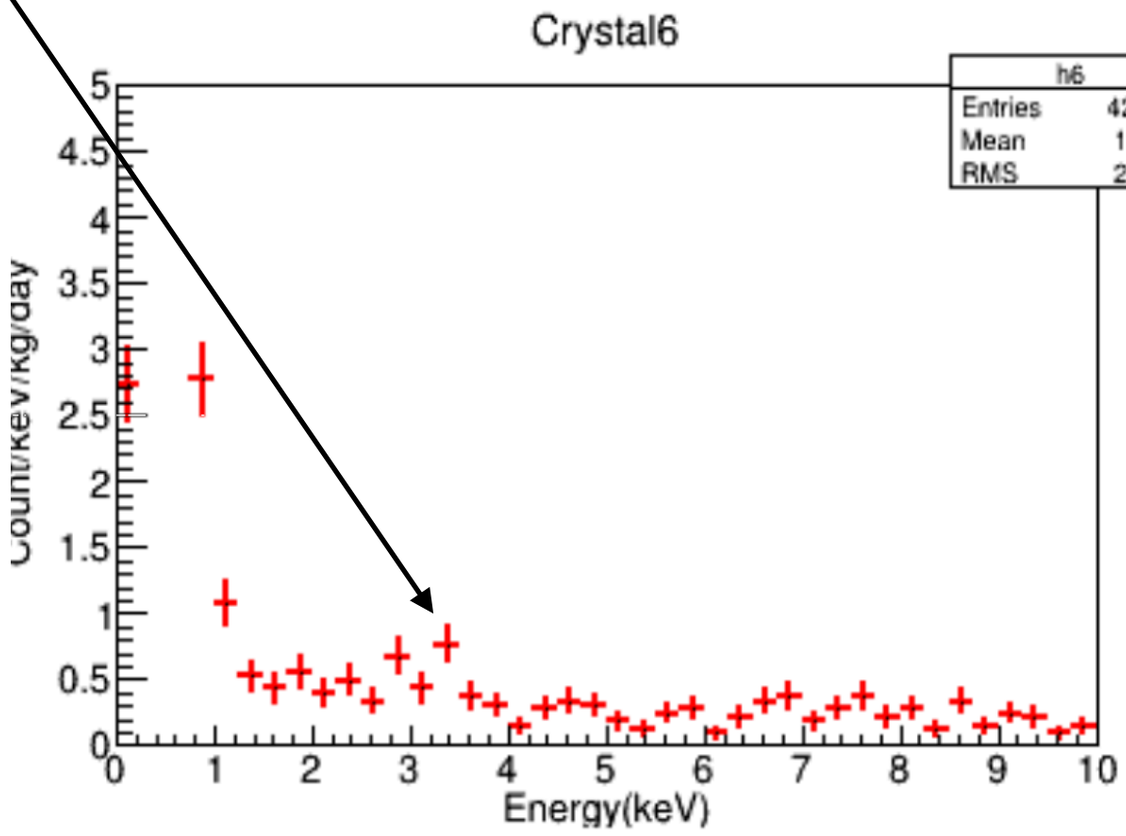

- $^{40}$K emits 1460 keV gamma with 3 keV Auger electron energy deposition in NaI crystal
- Tagging 1460 keV events with LS enables to veto 3 keV background events

# Crystal-LS Coincidence Events

3 keV $^{40}$K peaks

Preliminary




- $^{40}$K emits 1460 keV gamma with 3 keV energy deposition in NaI crystal
- Tagging 1460 keV events with LS enables to veto 3 keV background events
- With event selection, 3 keV peak

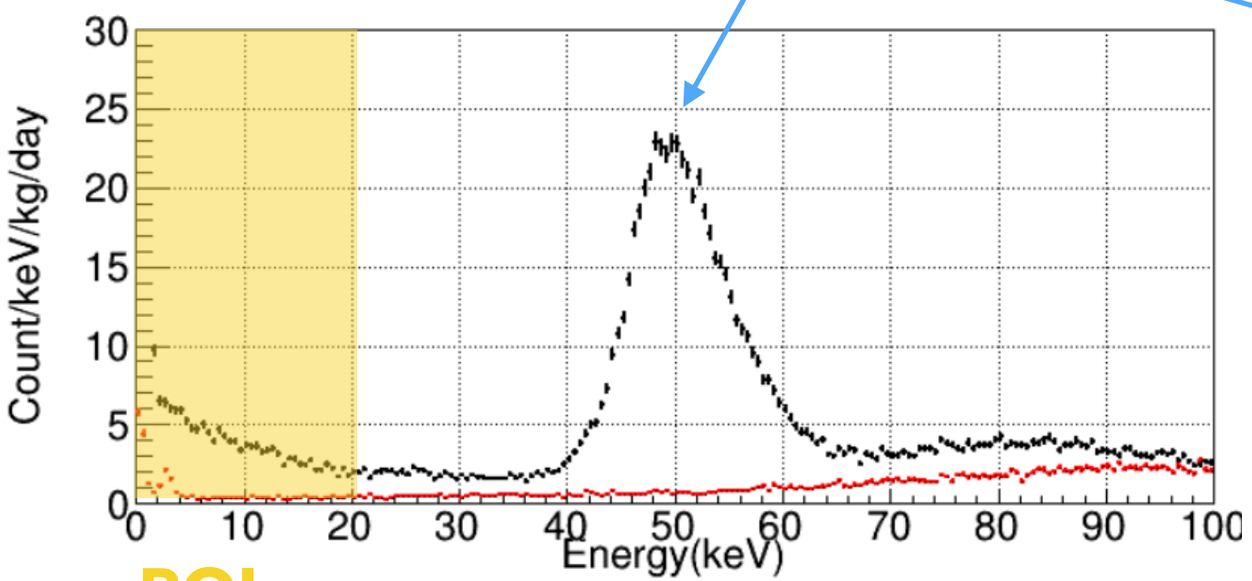
# Low Energy Spectrum

## Preliminary

$^{210}$Pb

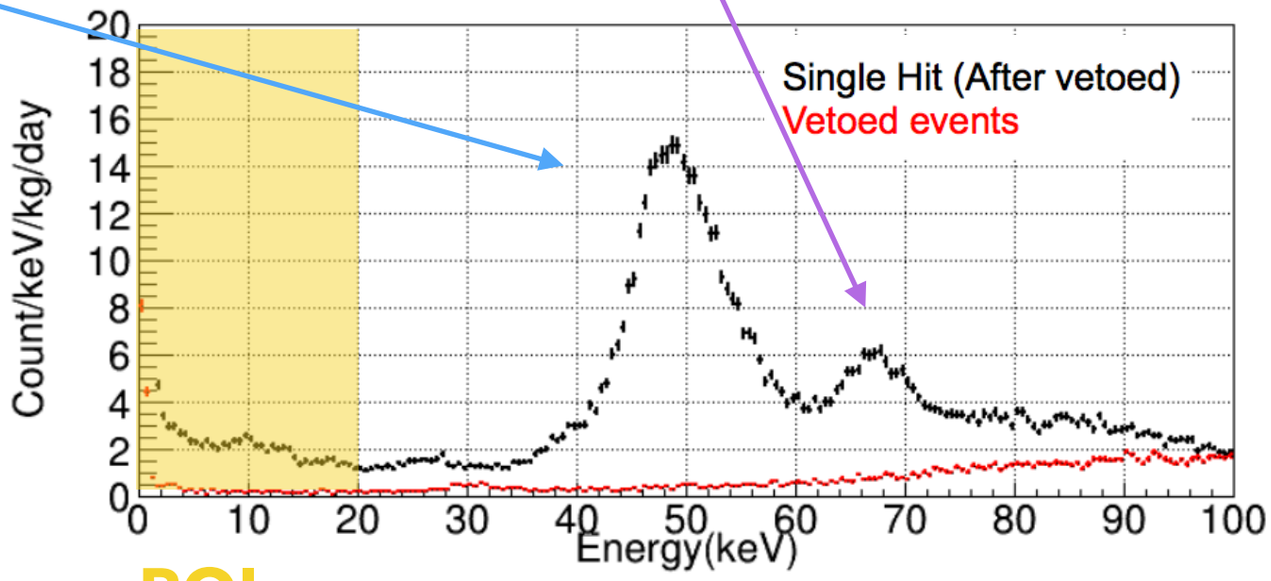
$^{125}$I

Crystal 1




ROI

Crystal 6

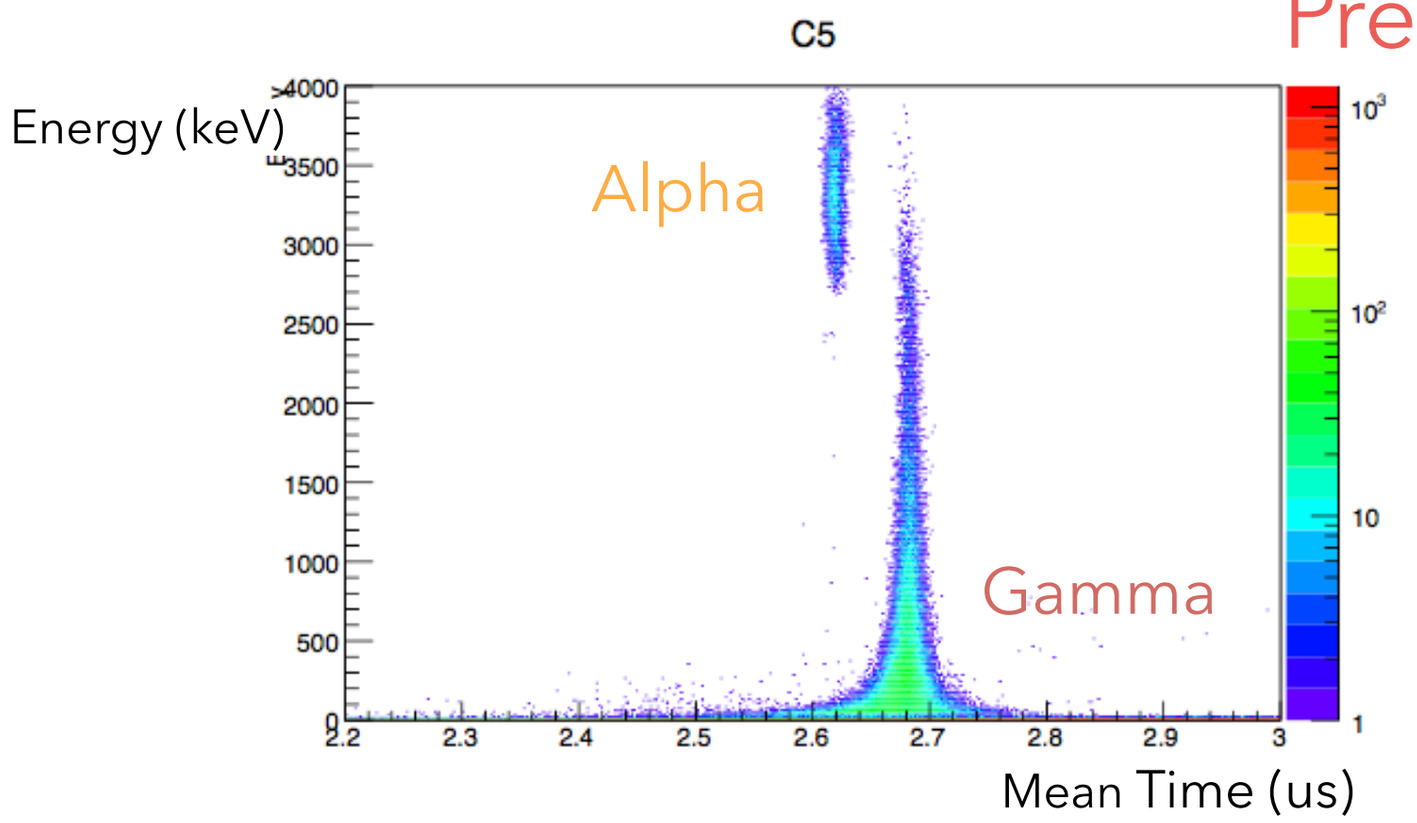



ROI

- 10 days of data, current set of event selection applied (not final!)
- Depending on crystal, background level ~3 dru at the region of interest
- Cosmogenic peaks remain in certain crystals
- There are still room for improvements

# Pulse Shape Discrimination for Alpha

Preliminary

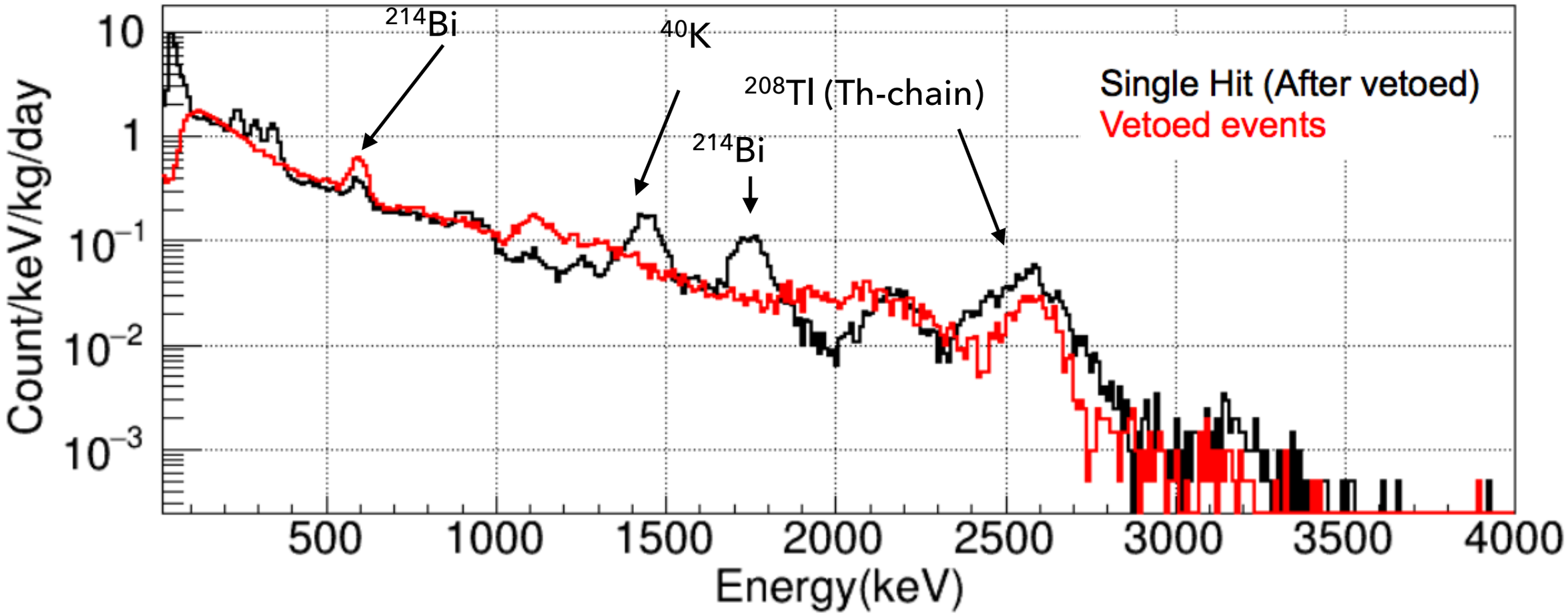



- Pulse Shape Discrimination technique works well for alpha separation
- Using charge-weighted mean time
- With separated alpha events, estimation of $^{210}$Po background can be performed
  - 0.5~3 mBq/kg for COSINE-100 crystals

# High Energy Spectrum

Preliminary

Crystal 6

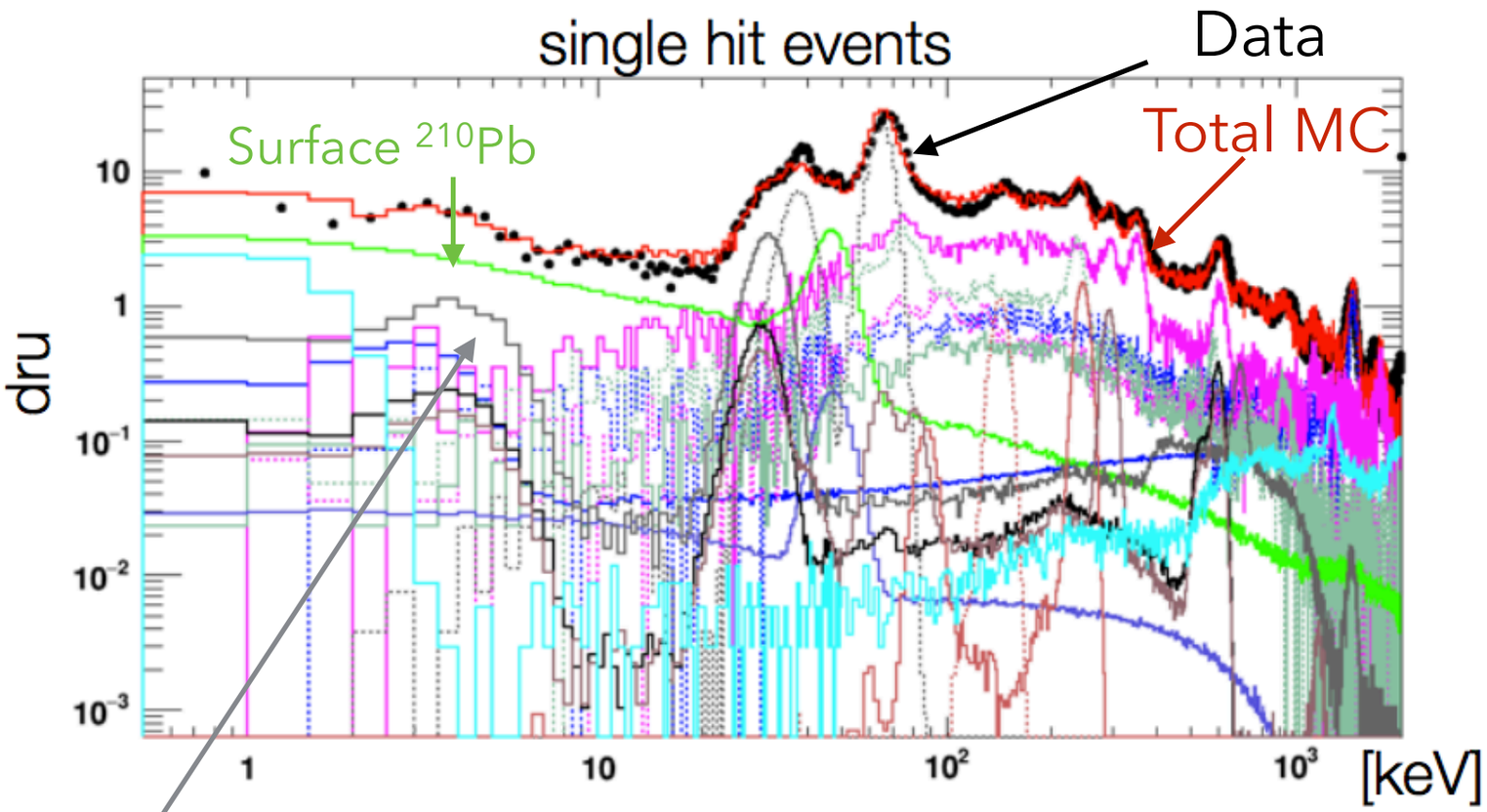



- Gamma spectrum shows pronounce background peaks including 1460 keV from $^{40}$K

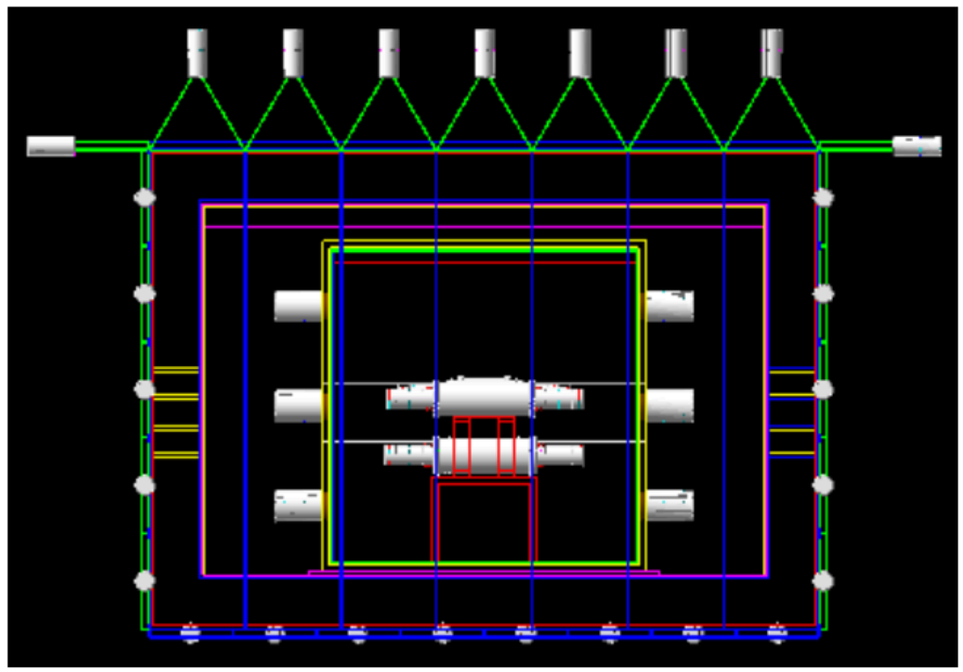
- Dynamic range for high energy signals is > 5 MeV

# NaI Crystal Simulation

Preliminary



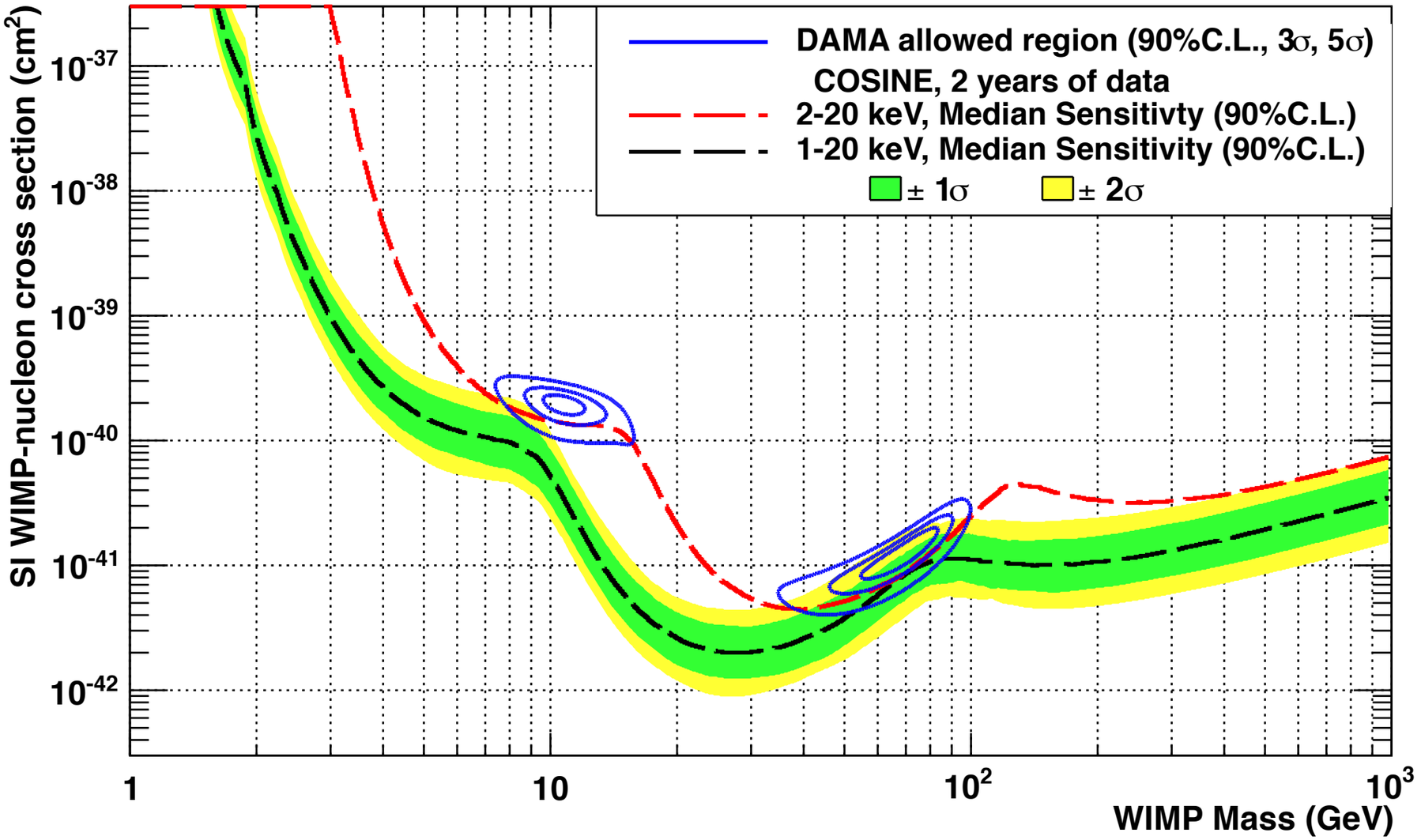

Simulation within R&D array (C3)



Detector Geometry at COSINE-100

- Work in progress, Geant4 framework
- Using NaI energy spectrum in R&D setup for the first step
- Surface $^{210}$Pb is suspected to be the dominant background, followed by $^{40}$K internal to crystal

# Projected Sensitivity of COSINE-100




- 2-4 dru flat background is assumed

- 2 years of data with 1 keV analysis threshold will give comparable sensitivity with DAMA's 90% C.L allowed region

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# What Next?

- To have stronger exclusion limit, there are 2 things to be done: lowering analysis energy threshold, and background reduction

- **Lowering energy threshold**

  - More sophisticated event selection

  - Good simulation

- **Background reduction**

  - Ultra-low background crystal growing

  - Low background PMTs

  - Low-temperature detectors

# Conclusion and Outlook

- COSINE-100 is a joint effort between DM-Ice and KIMS collaborations to search for dark matter interaction in NaI(Tl) crystals

- COSINE-100 consists of 8 crystals with total mass of 106 kg, 2000 liters of LAB-based liquid scintillator to tag low energy backgrounds, and 37 plastic scintillators to tag muon events

- Initial performance of COSINE-100 is promising, yet there is still room for improvements

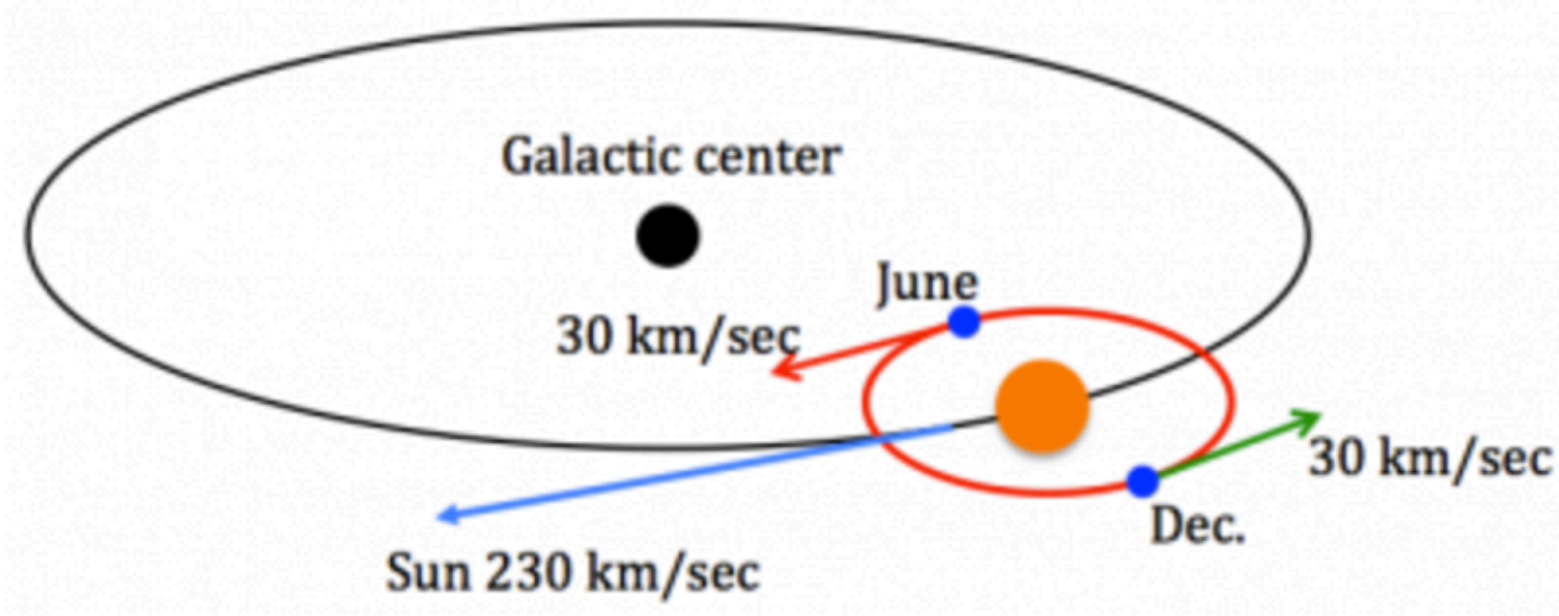
- Physics run has started on September 2016

- COSINE-100 has the capacity to directly test DAMA within time period of ~2 years…Stay tuned!

# Thank you!

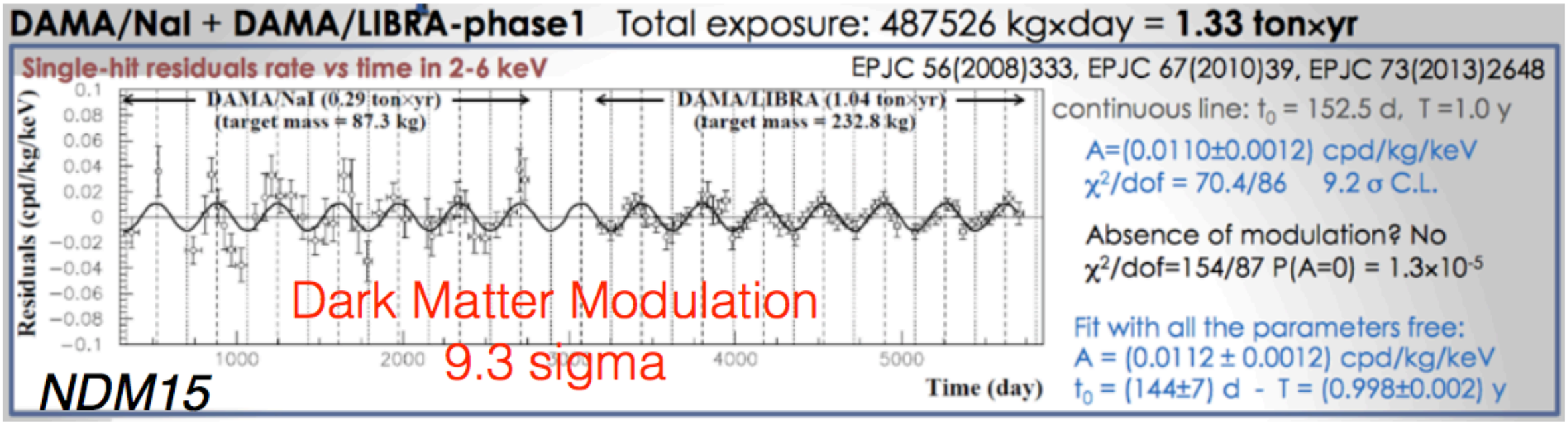
# Backups

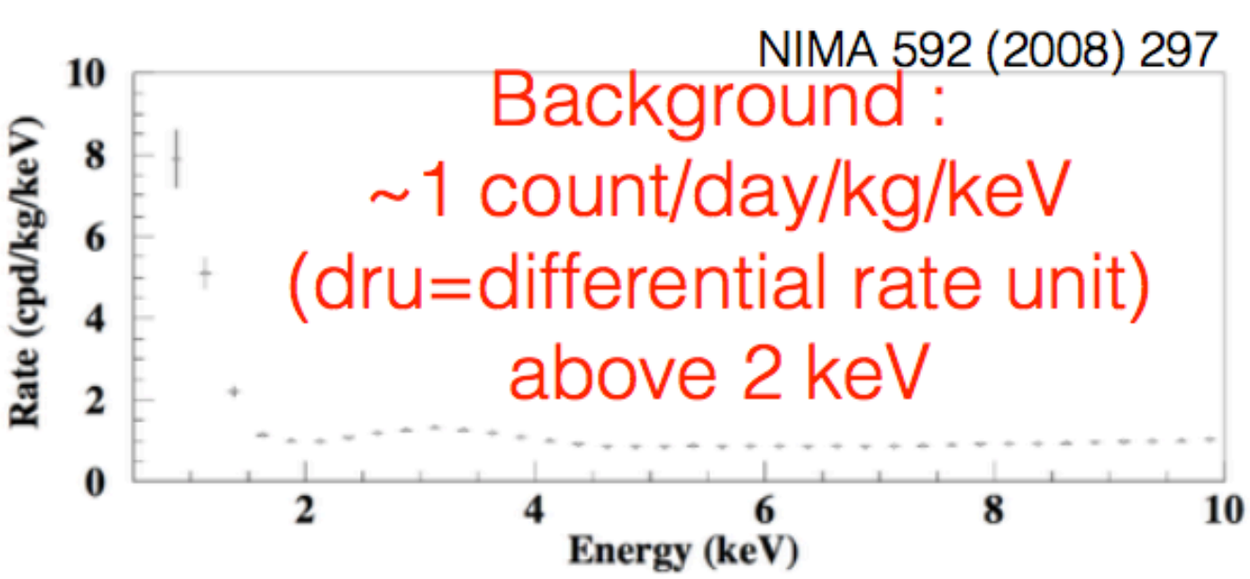
# Annual Modulation of Dark Matter

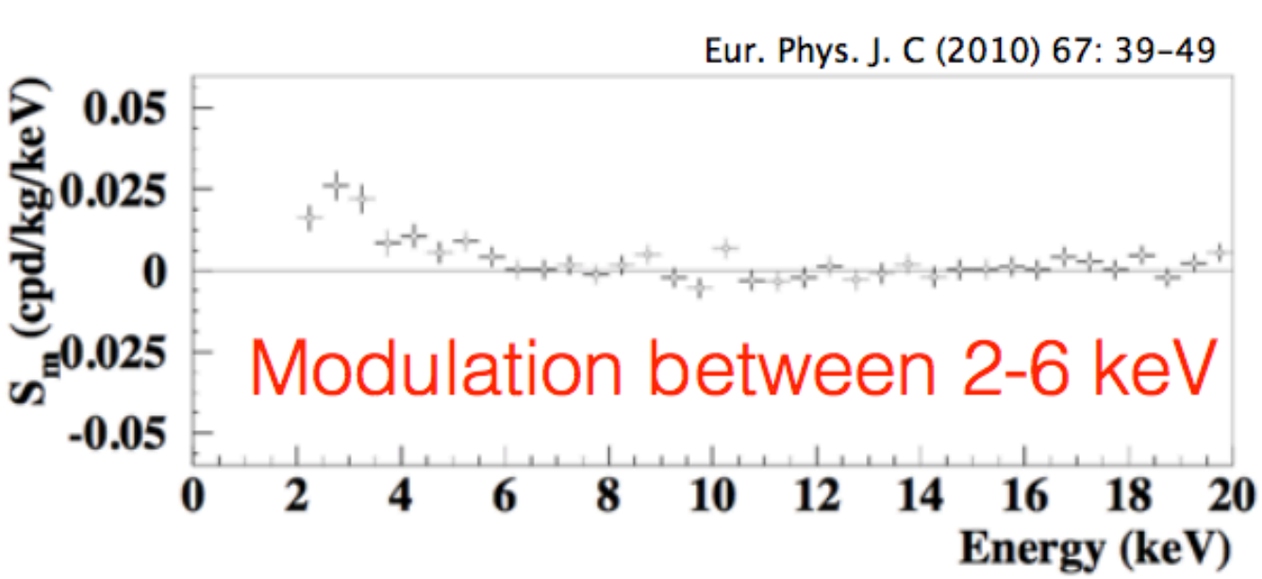



- Galactic dark matter is believed to be distributed in a halo
- Relative velocity of the detector with respect to the dark matter depends on the time of the year, shows a sinusoidal dependence with time; Annual Modulation

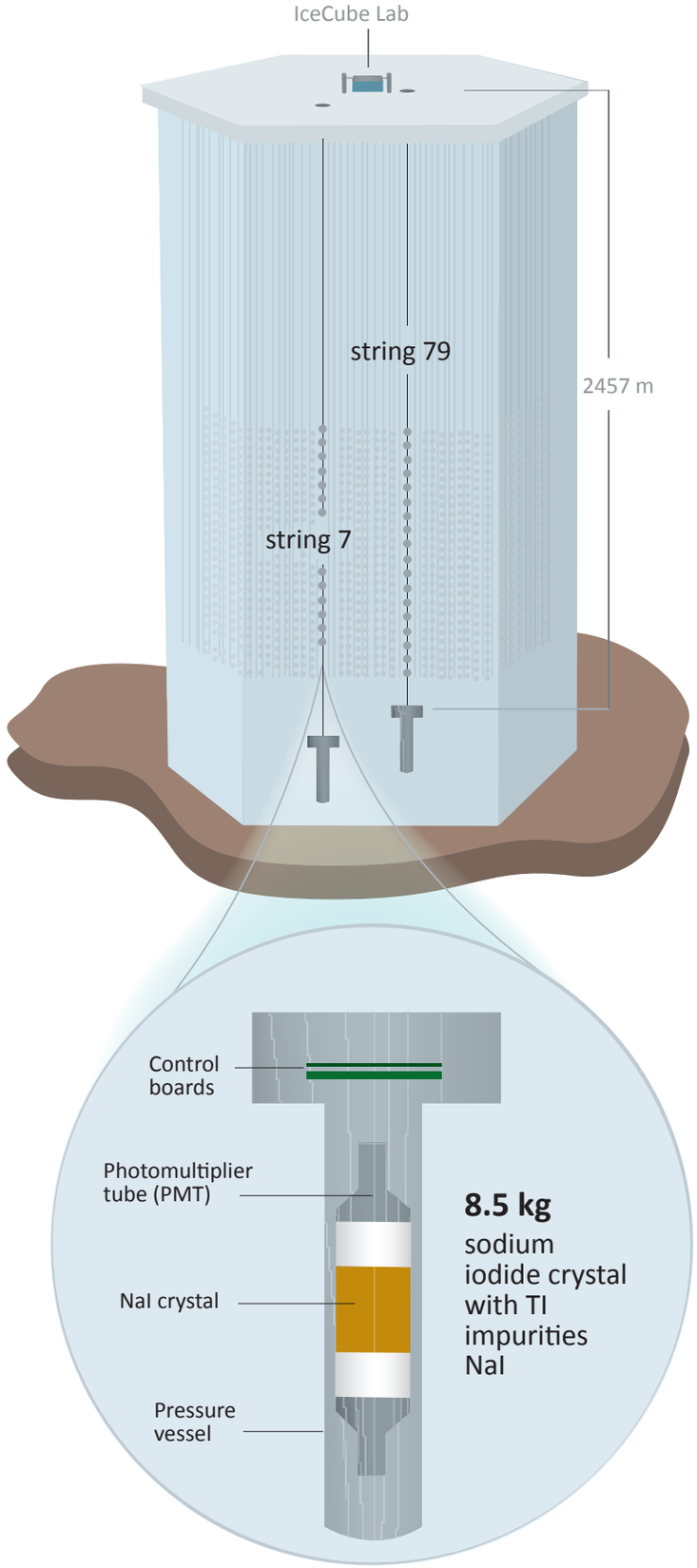
# DAMA

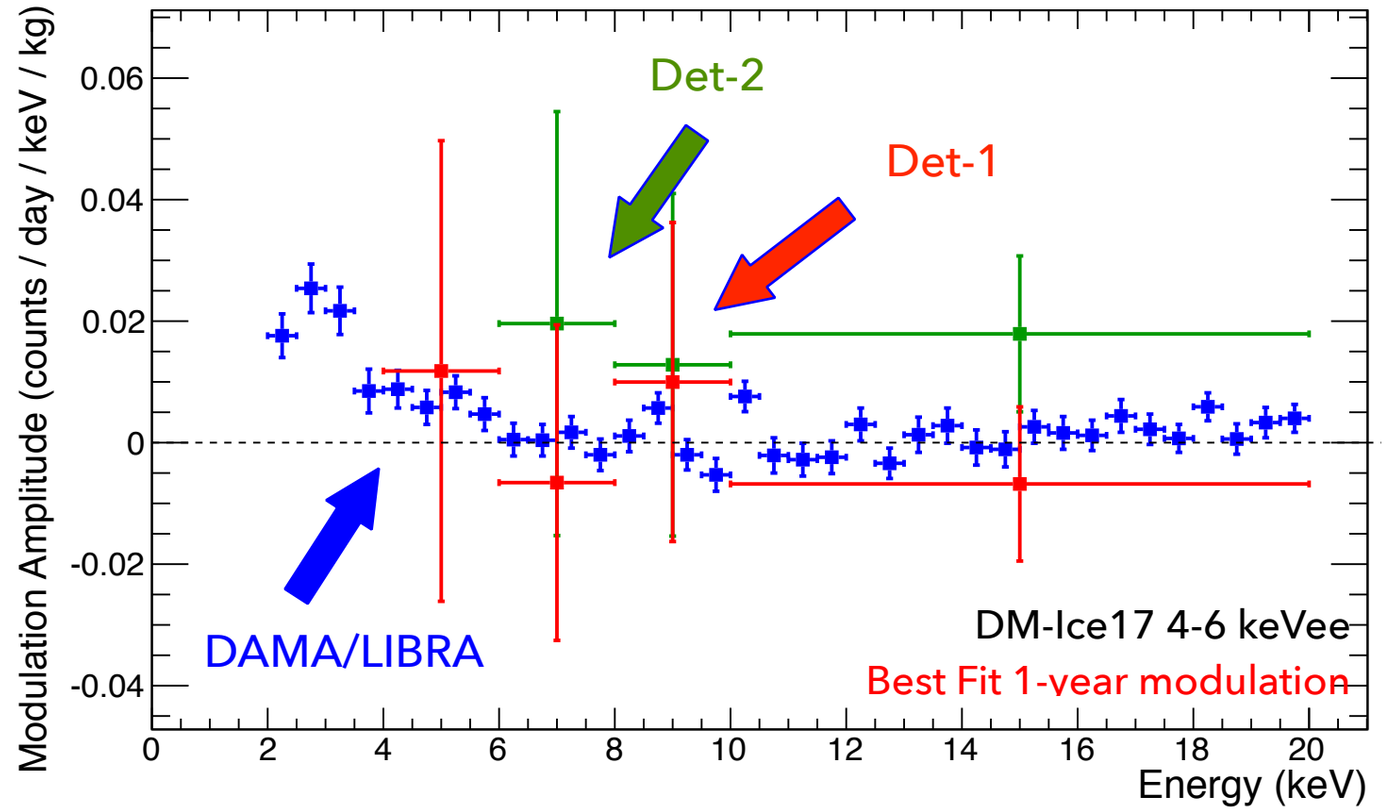

DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = 1.33 ton×yr
Single-hit residuals rate vs time in 2-6 keV
EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648
DAMA/NaI (0.29 ton×yr)
(target mass = 87.3 kg)
DAMA/LIBRA (1.04 ton×yr)
(target mass = 232.8 kg)
Residuals (cpd/kg/keV)
Time (day)
Dark Matter Modulation
9.3 sigma
NDM15
continuous line: t0 = 152.5 d, T =1.0 y
A=(0.0110±0.0012) cpd/kg/keV
χ2/dof = 70.4/86 9.2 σ C.L.
Absence of modulation? No
χ2/dof=154/87 P(A=0) = 1.3×10-5
Fit with all the parameters free:
A = (0.0112 ± 0.0012) cpd/kg/keV
t0 = (144±7) d - T = (0.998±0.002) y

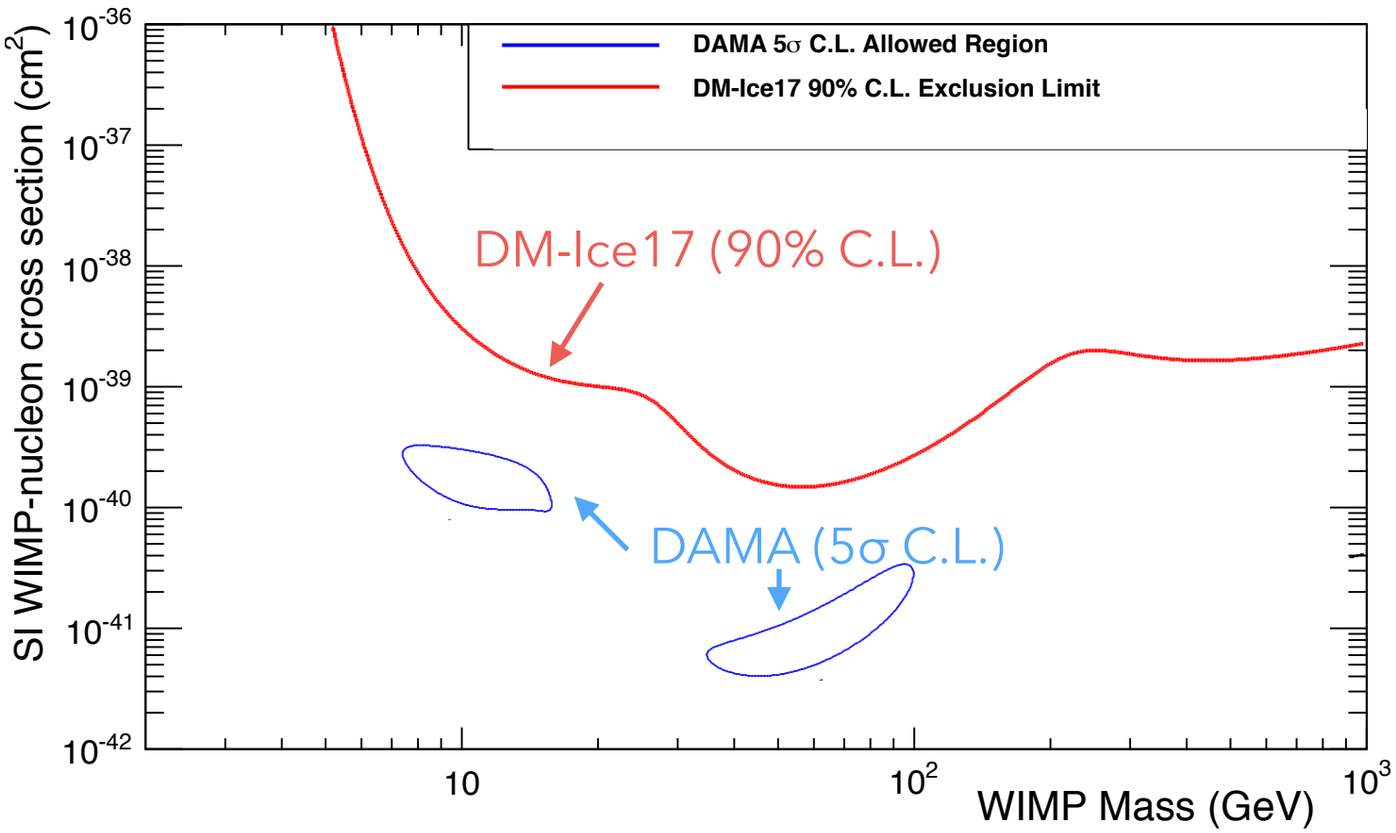

NIMA 592 (2008) 297
Background :
~1 count/day/kg/keV
(dru=differential rate unit)
above 2 keV
Rate (cpd/kg/keV)
Energy (keV)


Eur. Phys. J. C (2010) 67: 39–49
Modulation between 2-6 keV
Sm (cpd/kg/keV)
Energy (keV)

# DM-Ice17

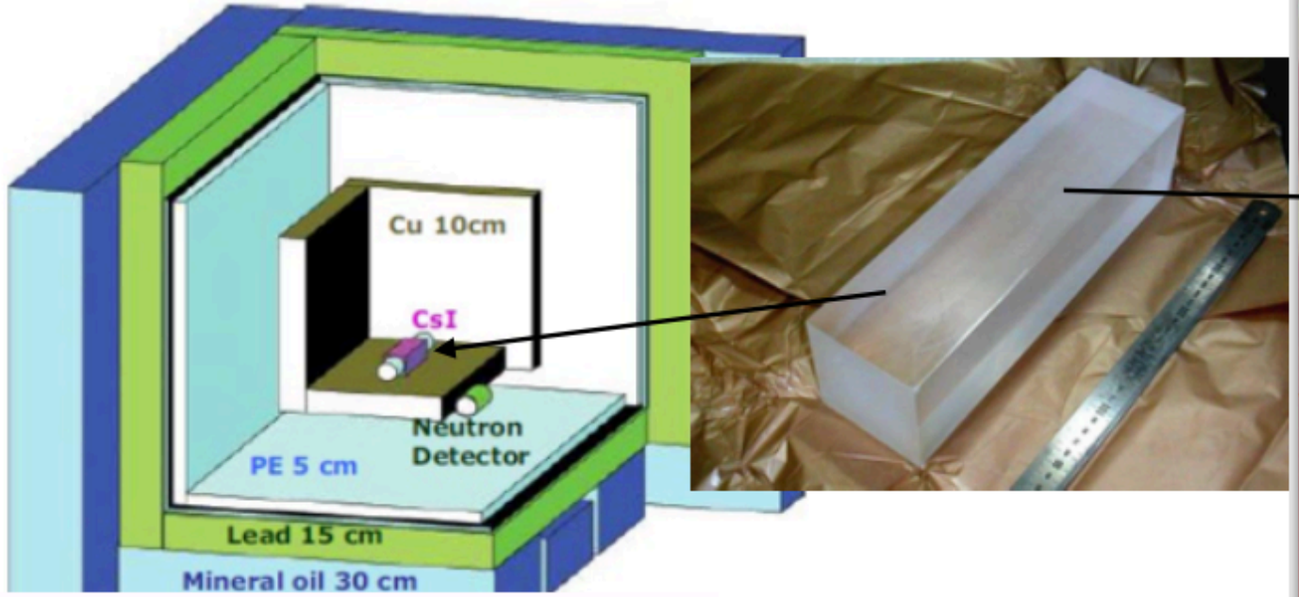

IceCube Lab
string 79
string 7
2457 m
Control boards
Photomultiplier tube (PMT)
NaI crystal
Pressure vessel
8.5 kg
sodium iodide crystal with Tl impurities
NaI


Det-2
Det-1
DAMA/LIBRA
DM-Ice17 4-6 keVee
Best Fit 1-year modulation
Modulation Amplitude (counts / day / keV / kg)
Energy (keV)

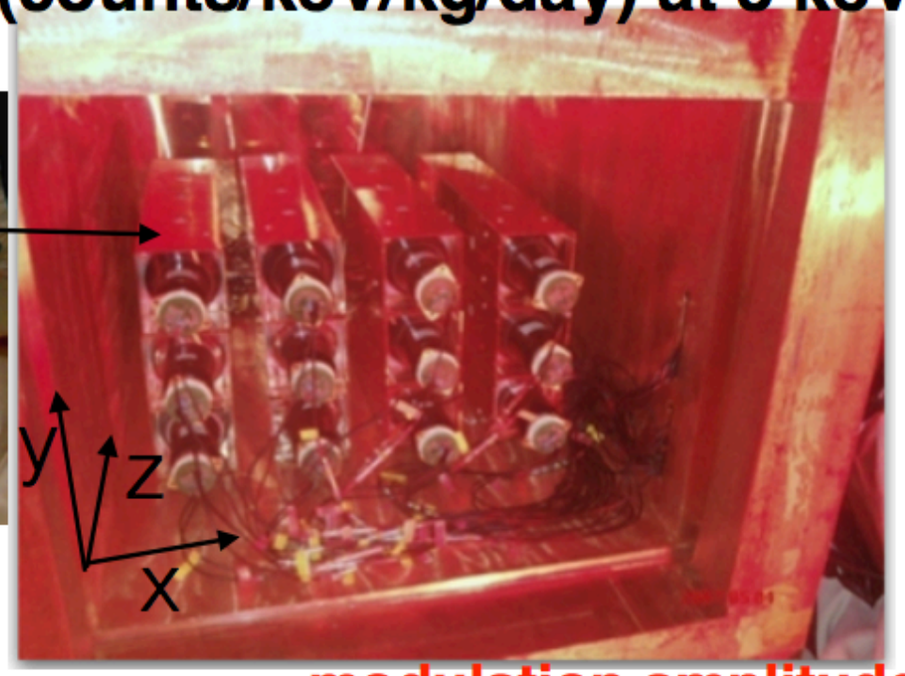

DAMA 5σ C.L. Allowed Region
DM-Ice17 90% C.L. Exclusion Limit
DM-Ice17 (90% C.L.)
DAMA (5σ C.L.)
SI WIMP-nucleon cross section (cm²)
WIMP Mass (GeV)

# KIMS-CsI

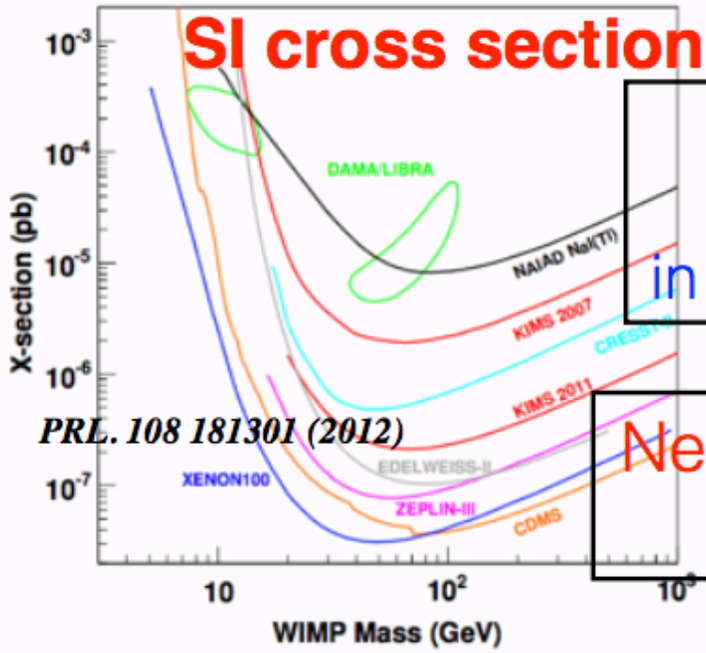
**12 CsI(Tl) 8.7 kg crystals (103 kg total)**
**Background level achieved at ~3 dru (counts/keV/kg/day) at 3 keV**





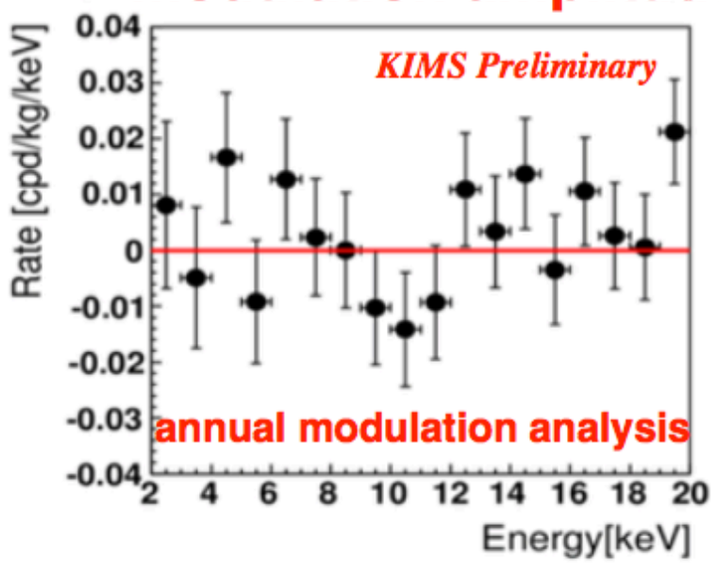

**SI cross section limit**




KIMS-CsI results
rejects DAMA signal
in WIMP-Iodine interactions

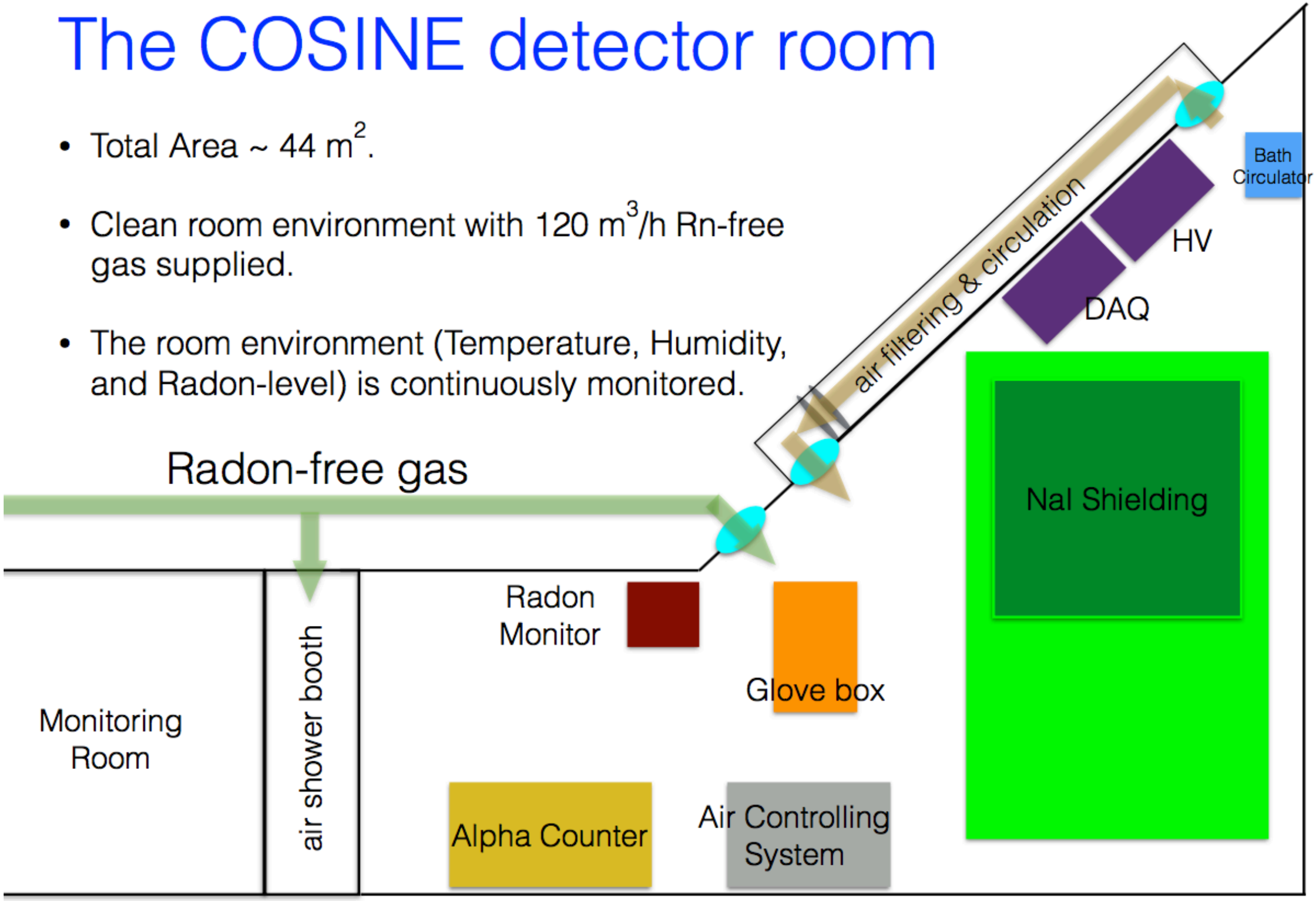
Need to investigate WIMP-Sodium interactions

**modulation amplitude**



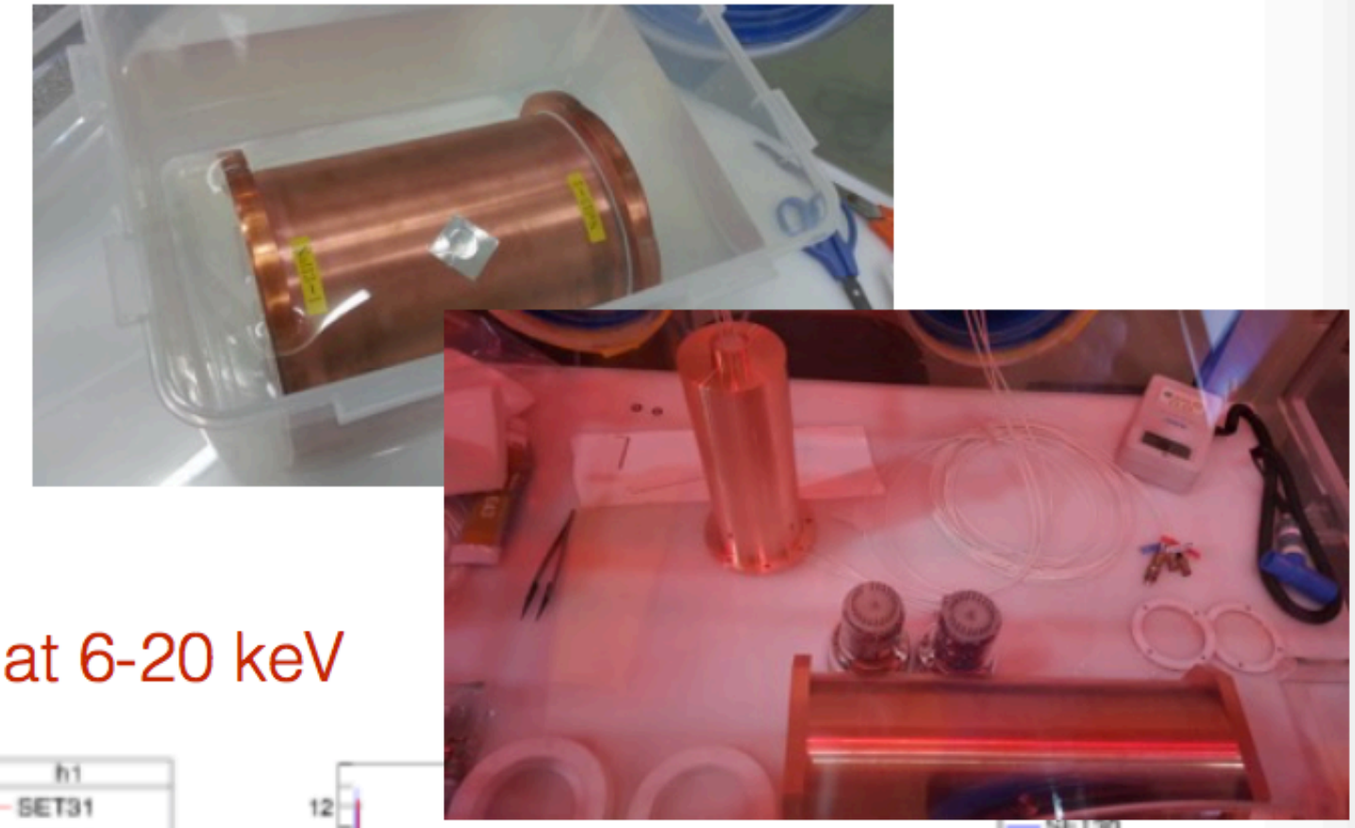
# The COSINE detector room

- Total Area ~ 44 $m^2$.
- Clean room environment with 120 $m^3$/h Rn-free gas supplied.
- The room environment (Temperature, Humidity, and Radon-level) is continuously monitored.



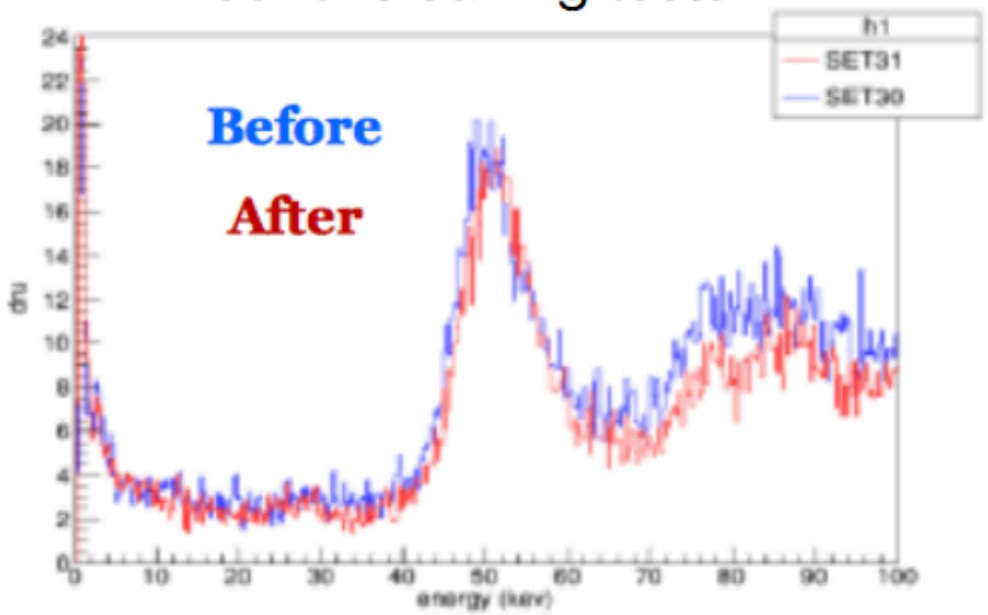
# Cleaning of Xtals and Parts

Cleaning in an ultrasonic bath with radiac wash and high grade ethanol.

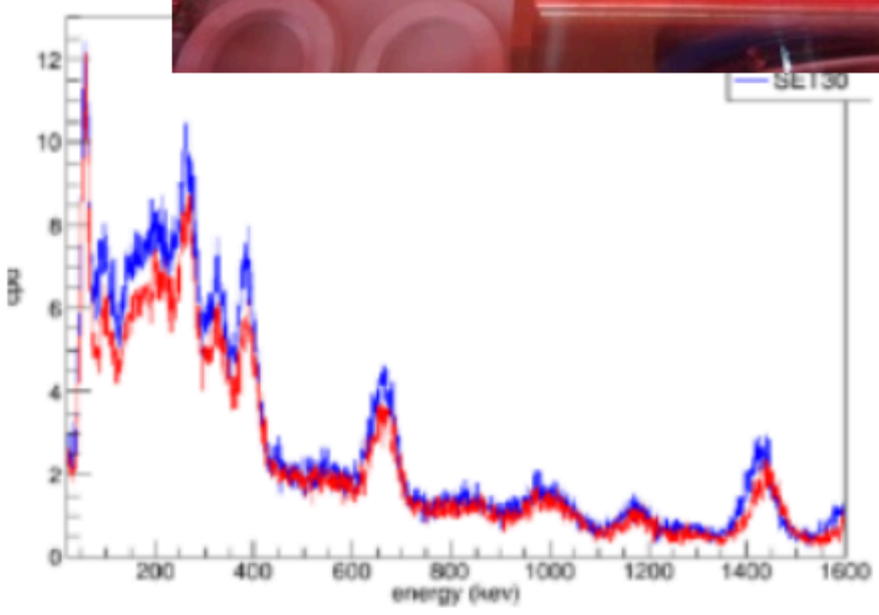


Previously, 0.3 dru reduction at 6-20 keV

Alcohol cleaning tests

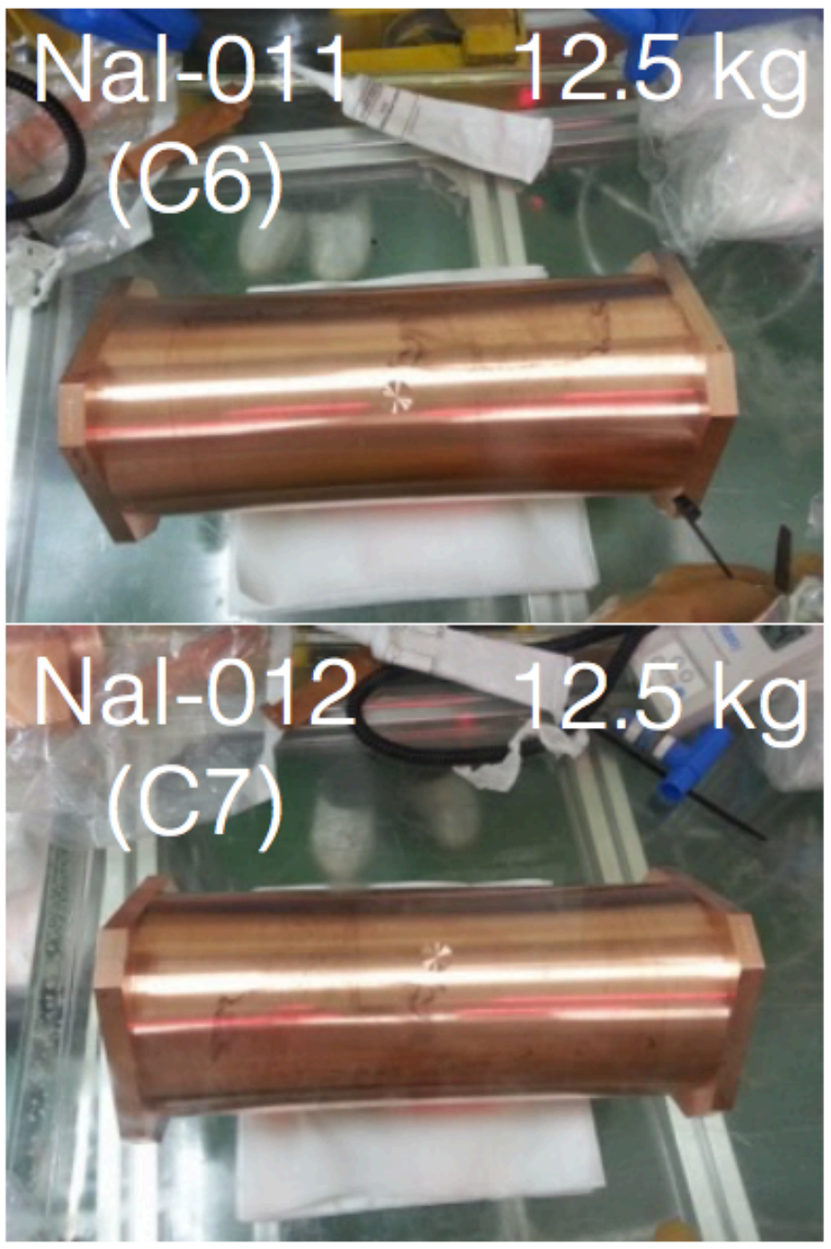


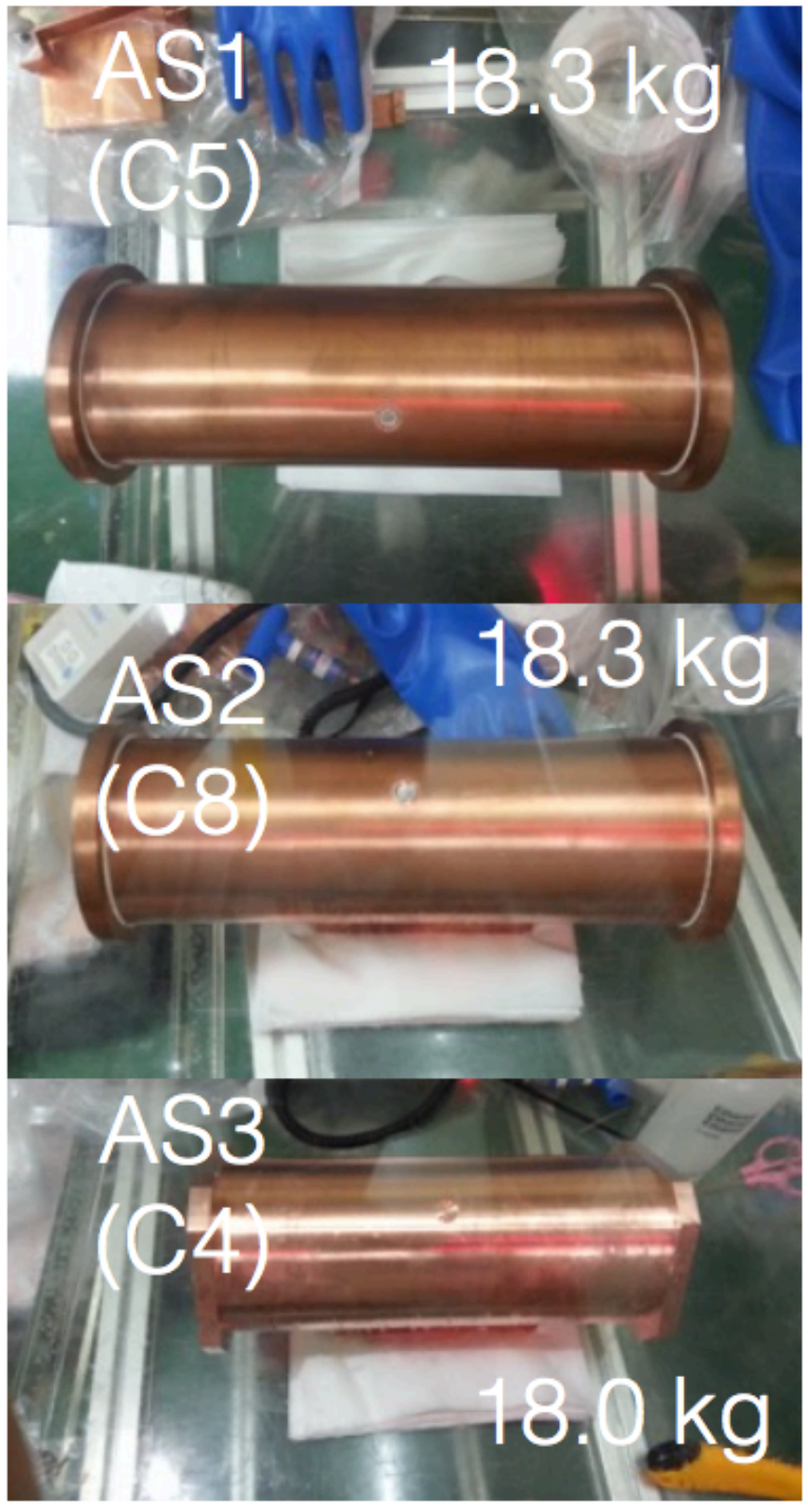

Low Energy




High Energy

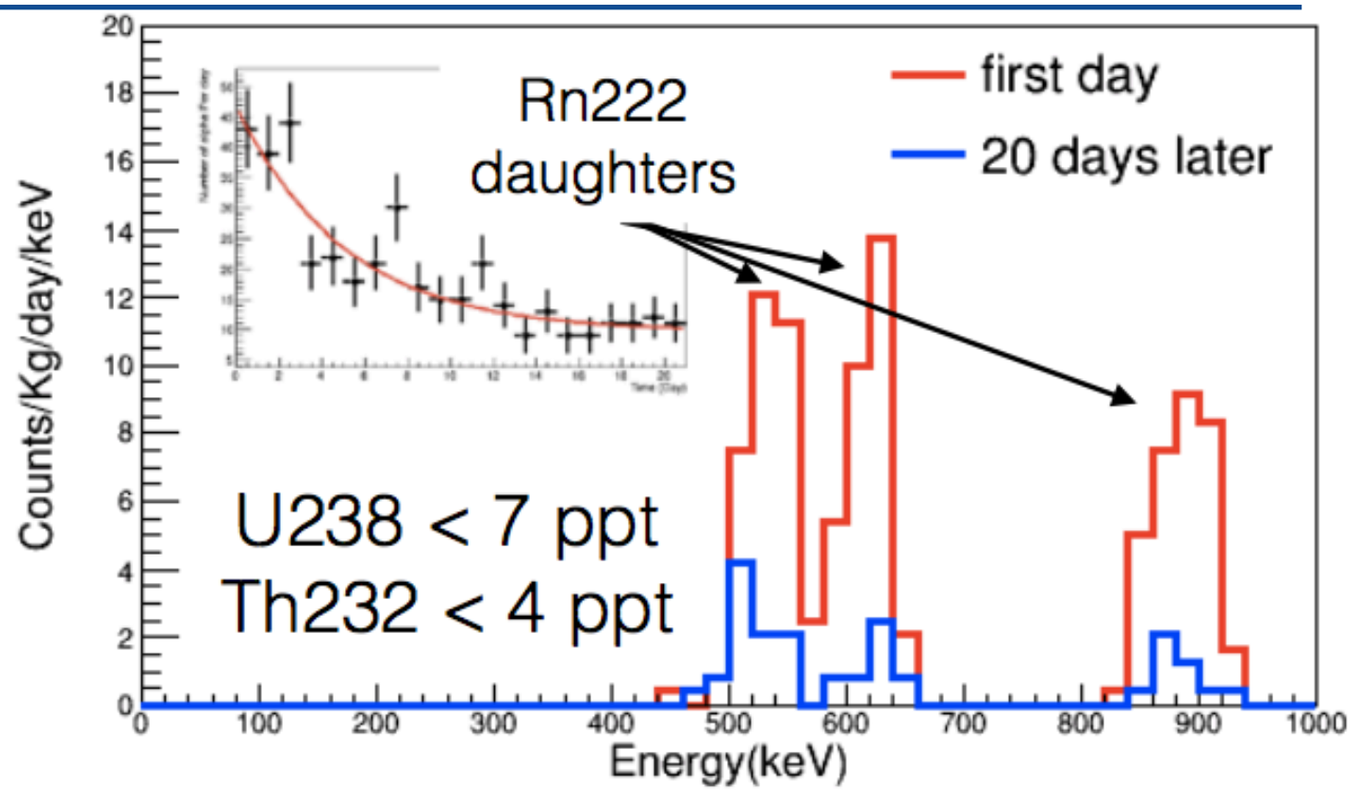
# COSINE-100 Crystals

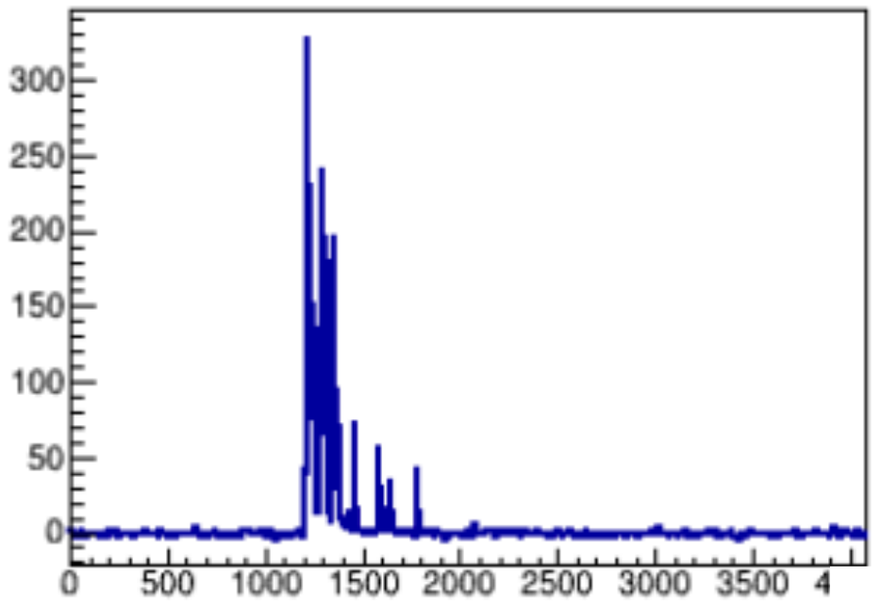



# LS for COSINE-100

Linear alkylbenzene (LAB) :
Good optical/radioactive properties
2,5-Diphenyloxazole (PPO) :
fluor, scintillator/wavelength shifter
p-bis-(o-methylstyryl)-benzene (bis-MSB) : wavelength shifter

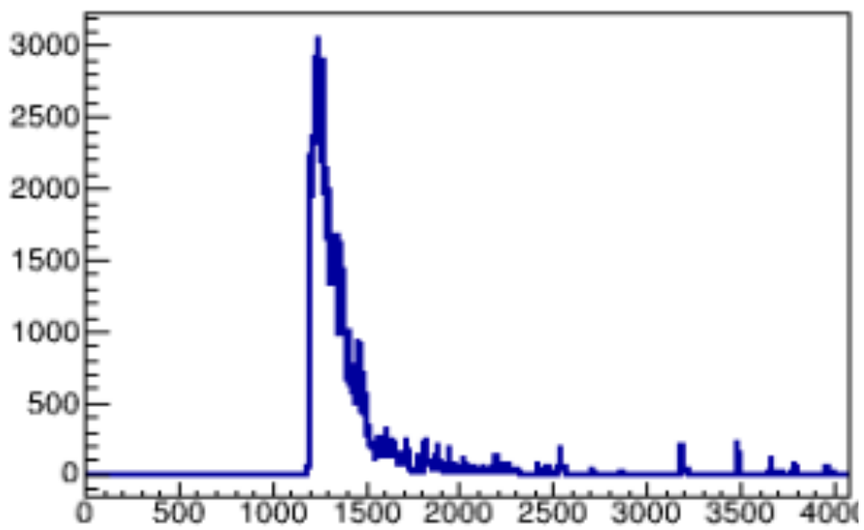




# Examples of Signal Events

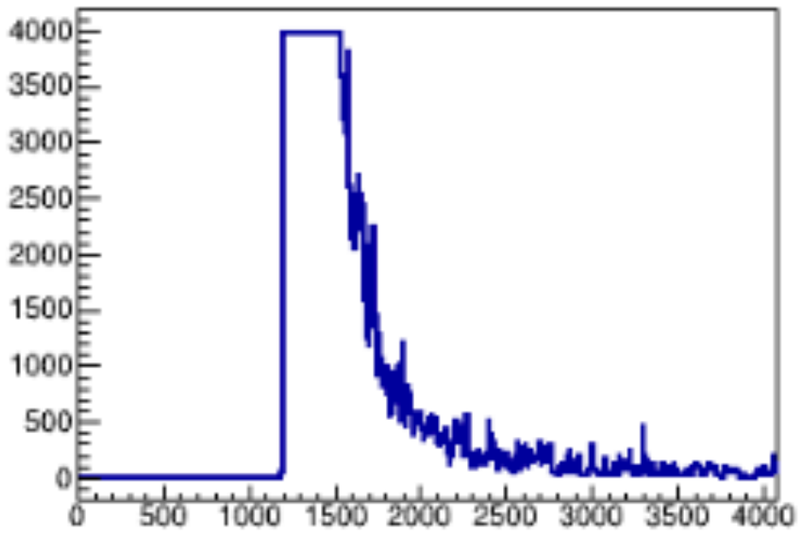



3 keV

100 keV

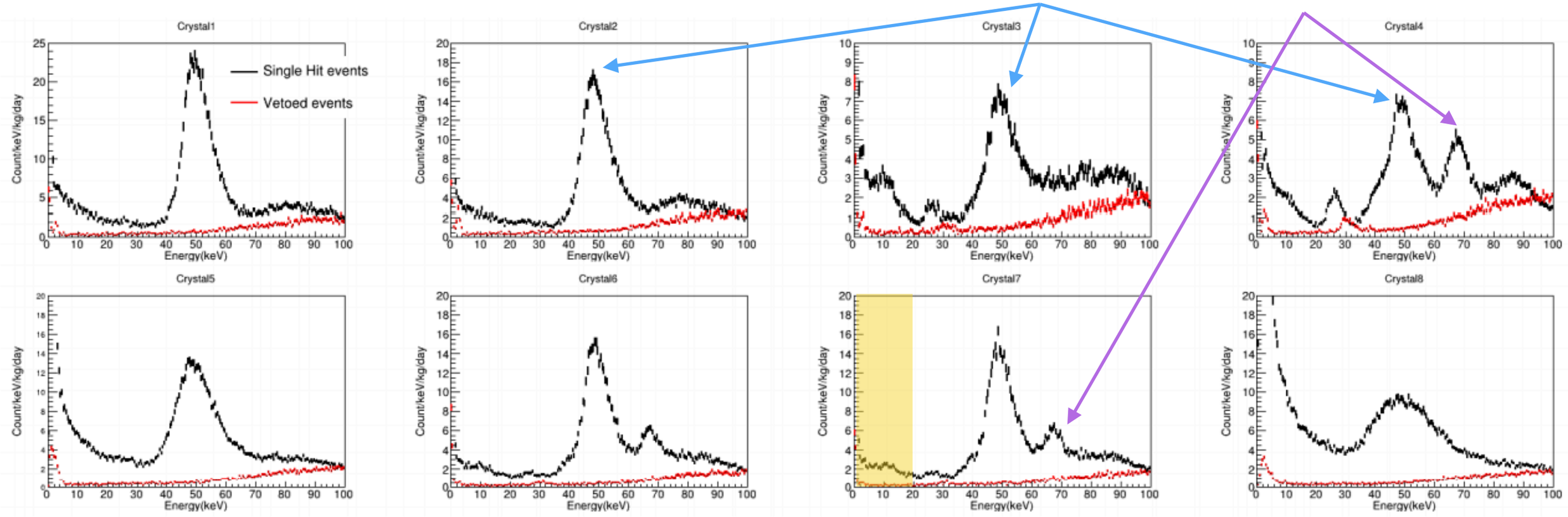



> 1 MeV



# Low Energy Spectrum

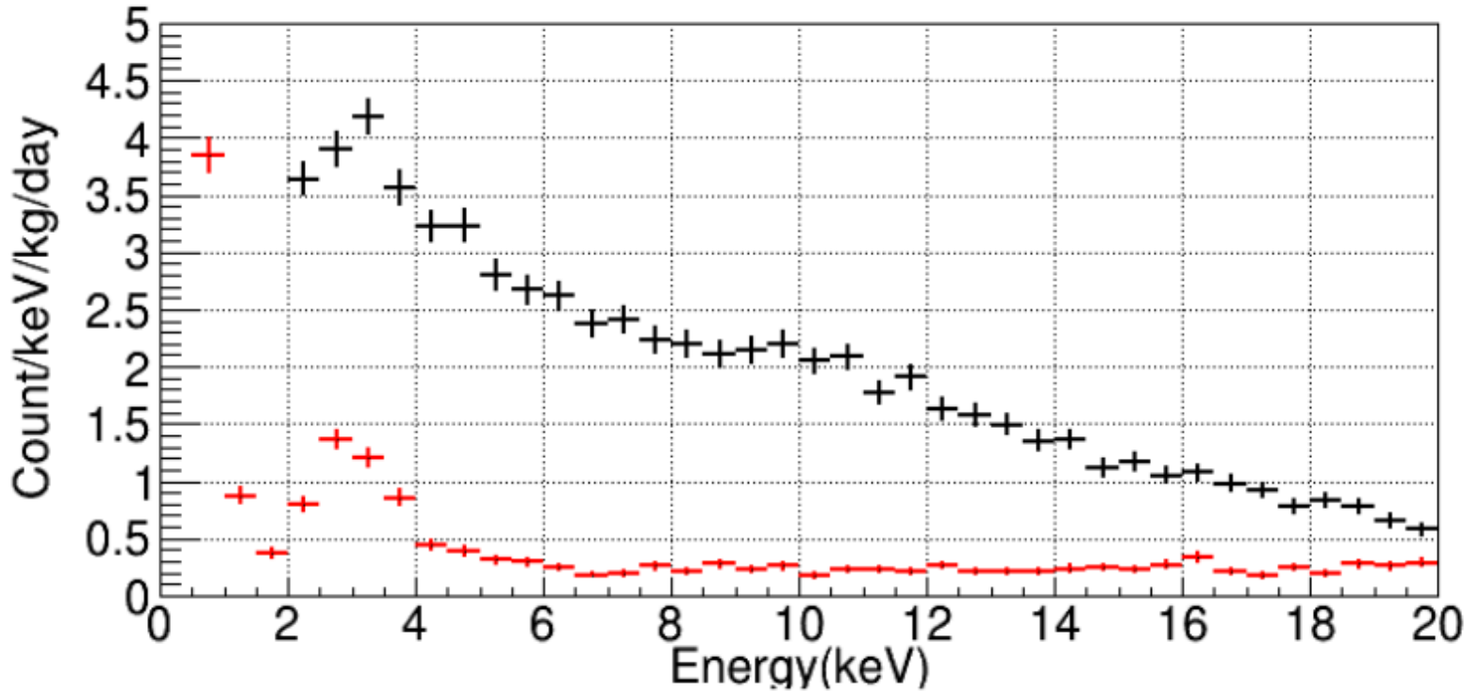
## Preliminary



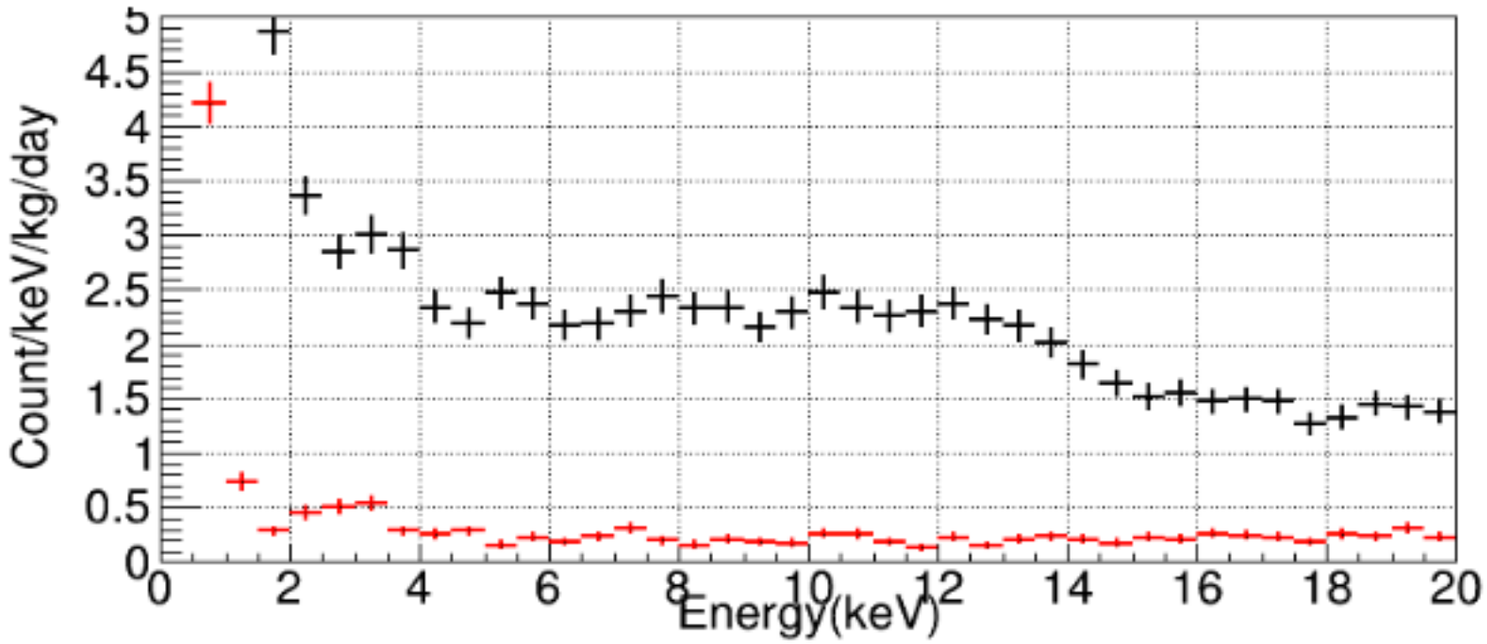

- 10 days of data, current set of event selection applied (not final!)
- Depending on crystal, background level ~3 dru at the region of interest
- Cosmogenic peaks remain in certain crystals
- There are still room for improvements

# Low Energy Spectrum (< 20 keV)

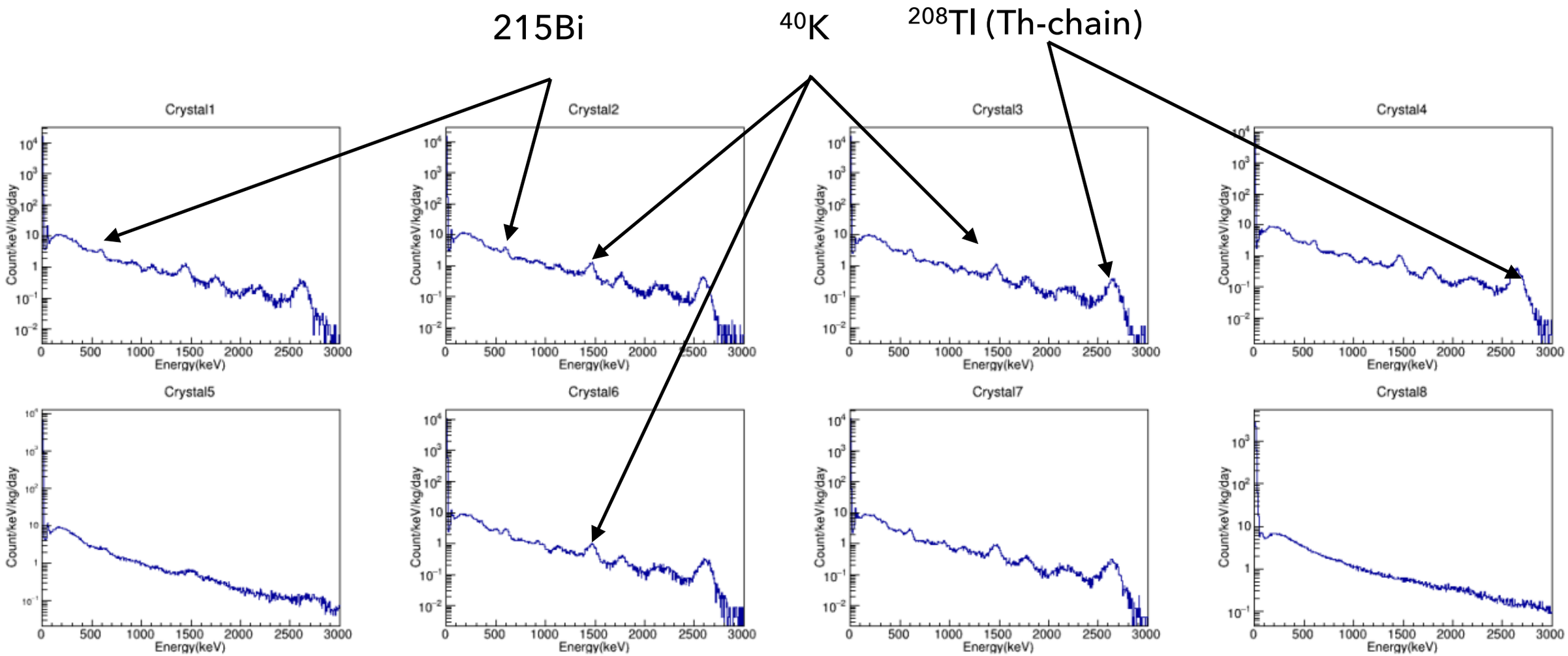
**Crystal 4**



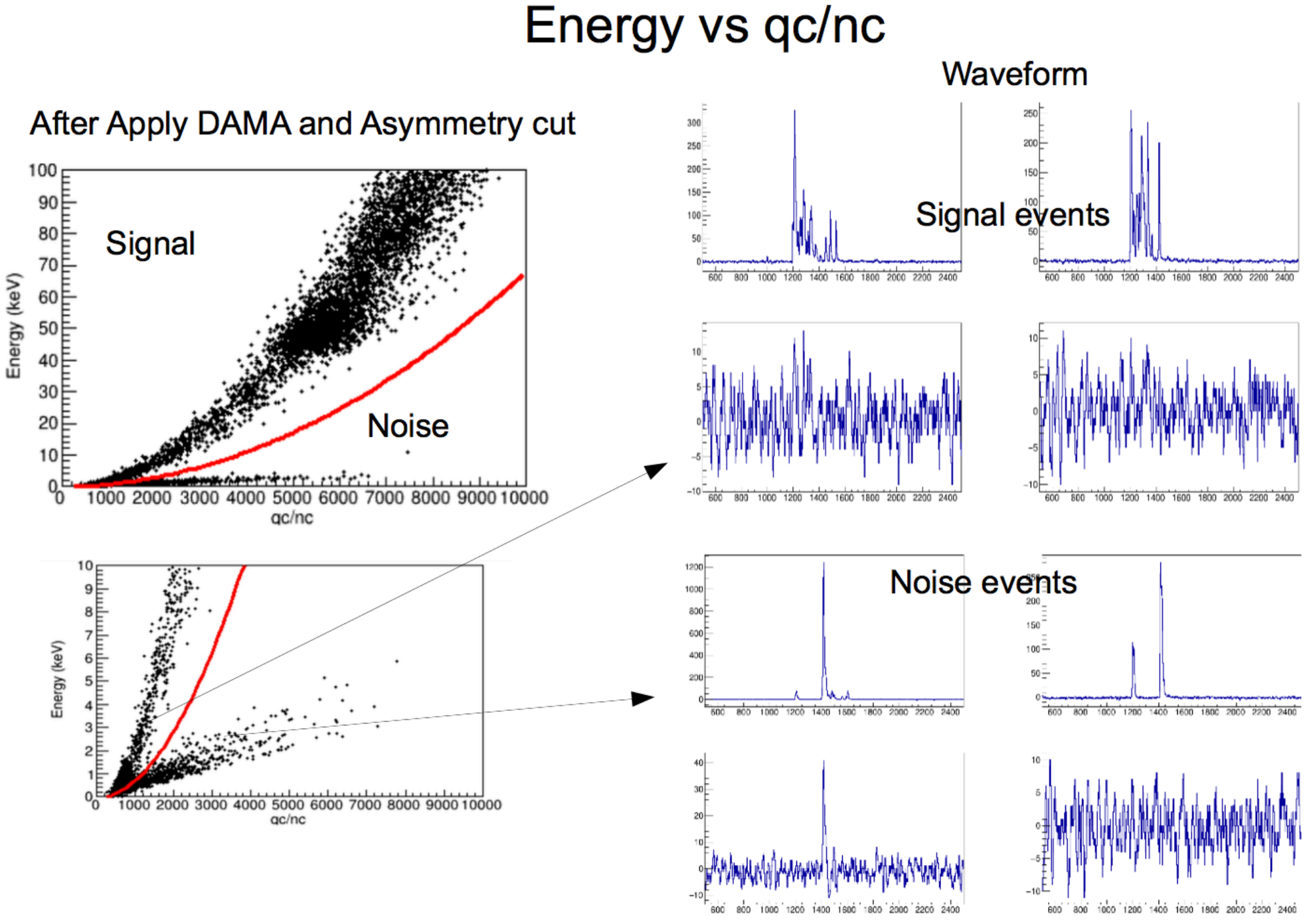

**Crystal 7**



# HE spectrum


215Bi
40K
208Tl (Th-chain)
Crystal1
Crystal2
Crystal3
Crystal4
Crystal5
Crystal6
Crystal7
Crystal8
Count/keV/kg/day
Energy(keV)

# Average charge/SPE cut



# Observation

Eur. Phys. J. C (2016) 76:185