NaI(Tl) Dark Matter Experiment: Status of Effort to Confirm or Deny DAMA

Jay Hyun Jo
Yale University

Berkeley Workshop on the Direct Detection of Dark Matter
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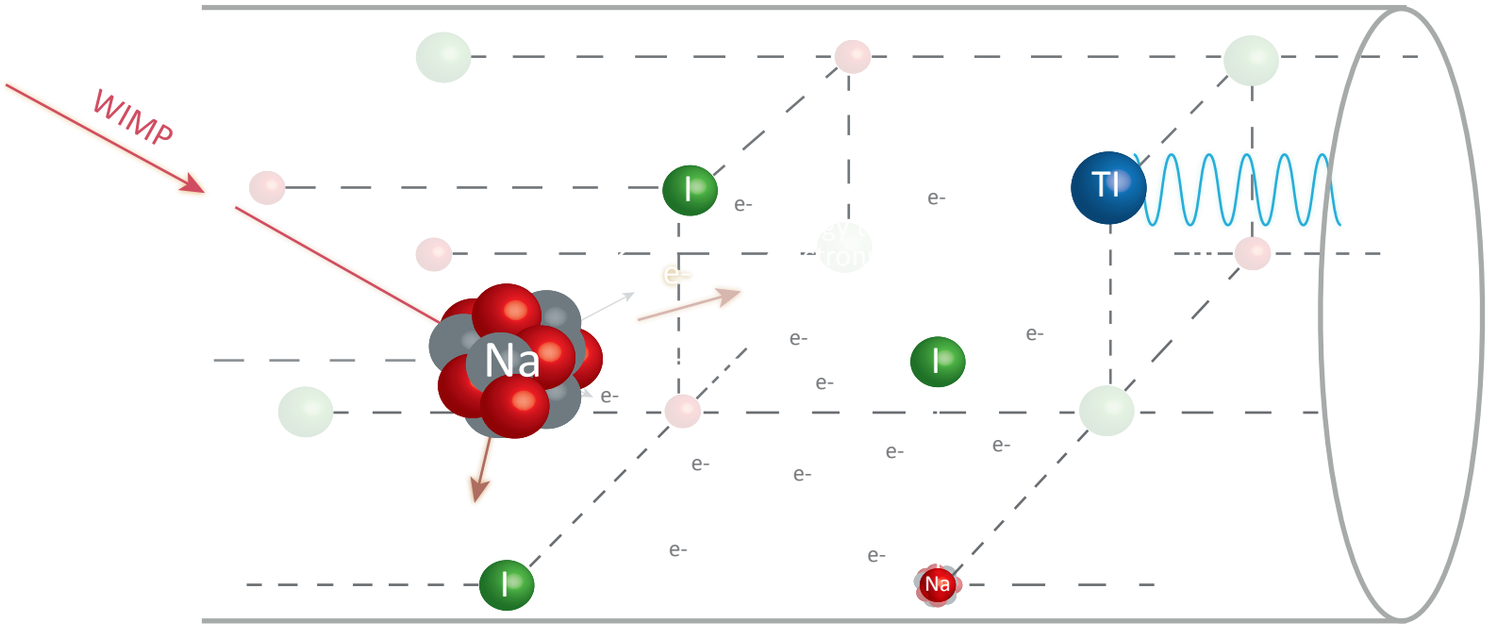
Yale

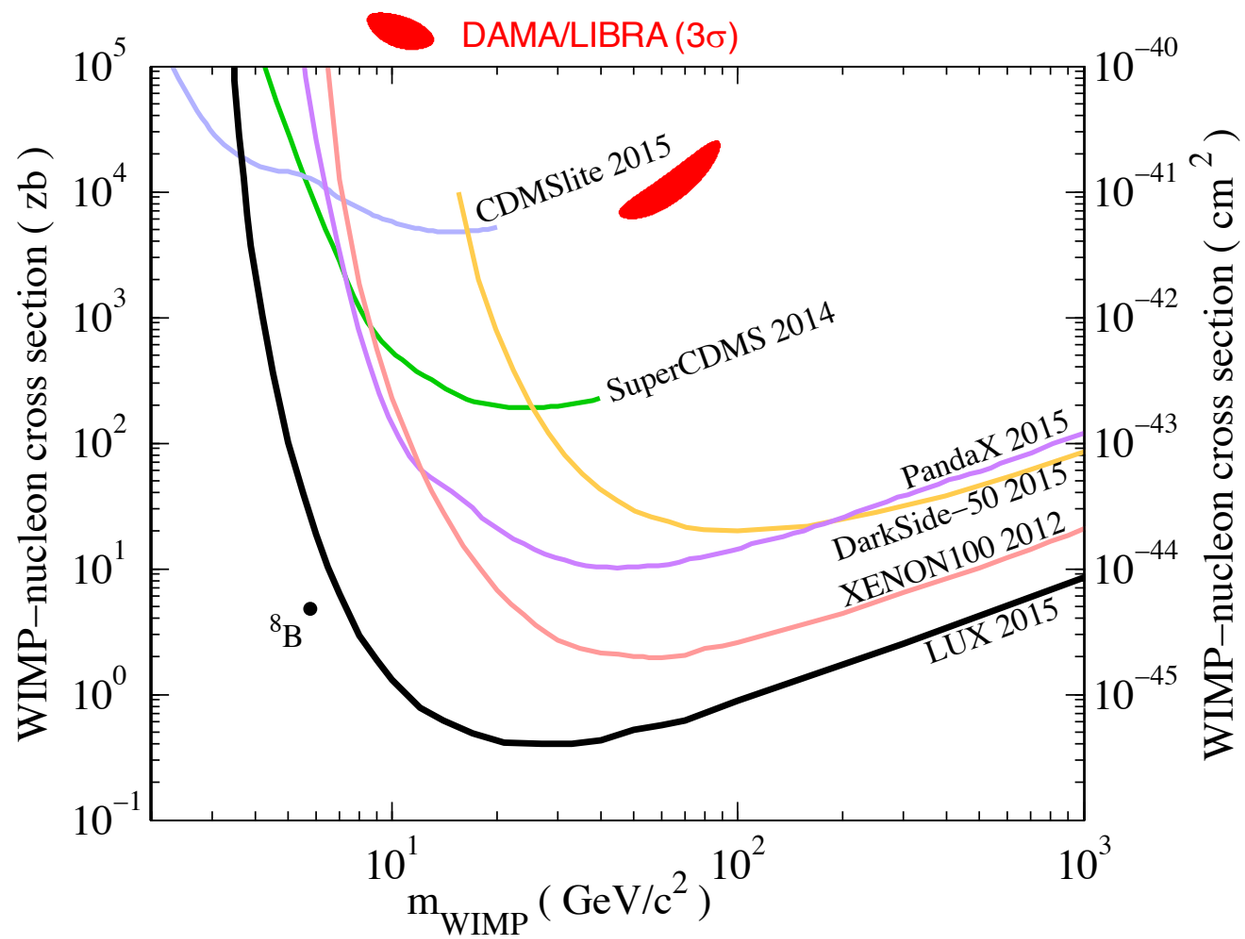
Wright Laboratory

Contents



- Introduction: DAMA Experiment, Results, and Interpretation
- COSINE-100 Experiment
- Global Efforts with NaI(Tl) Detector
- Prospect and Conclusion

Current Dark Matter Field

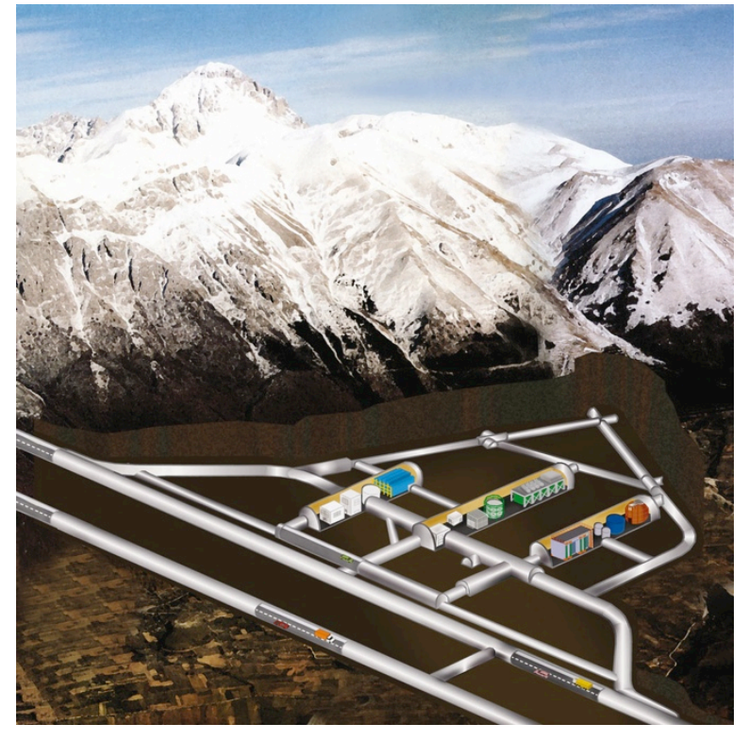


LUX Collaboration, arXiv:1512.03506

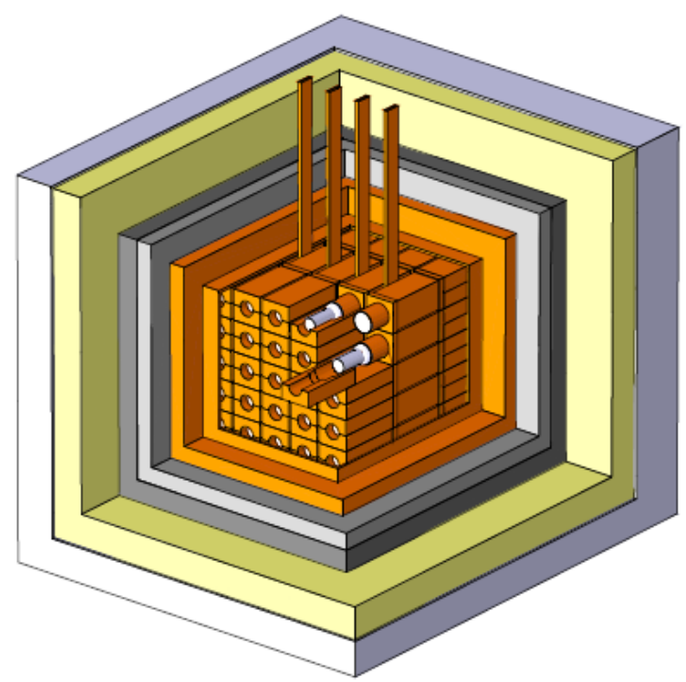
- Liquid Xenon detectors provide currently the best sensitivity to spin-independent WIMP scattering
- No other experiments could confirm the dark matter signal: tension with the DAMA result
- More exclusion limits cannot answer this question

DAMA Experiment

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



LNGS

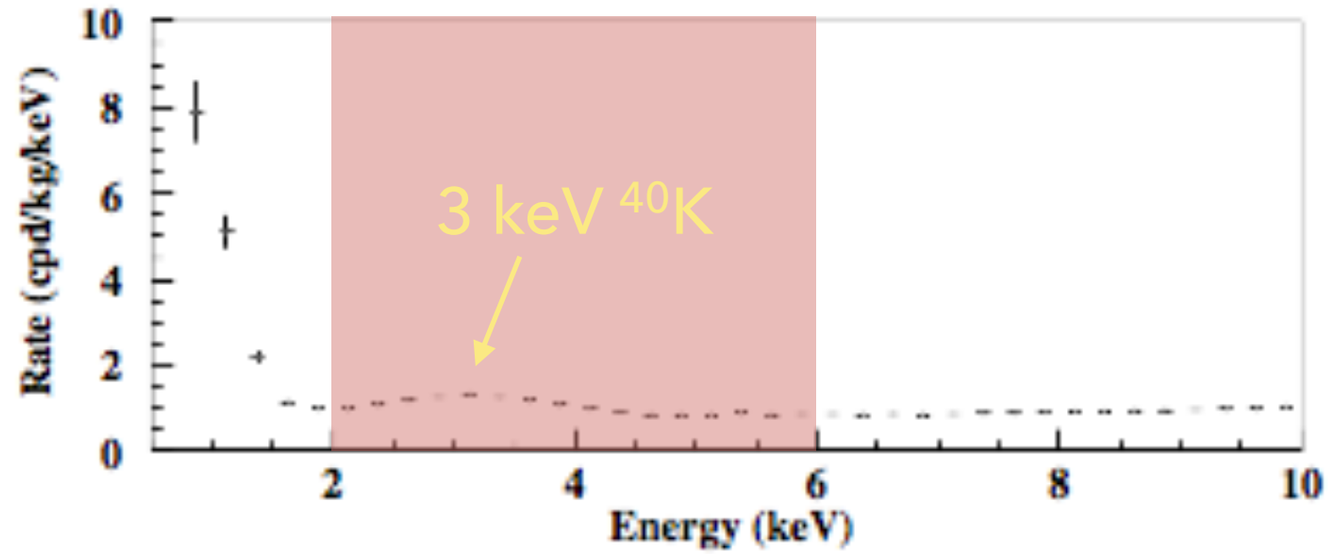


Bernabei *et al.*, NIM A (2008)

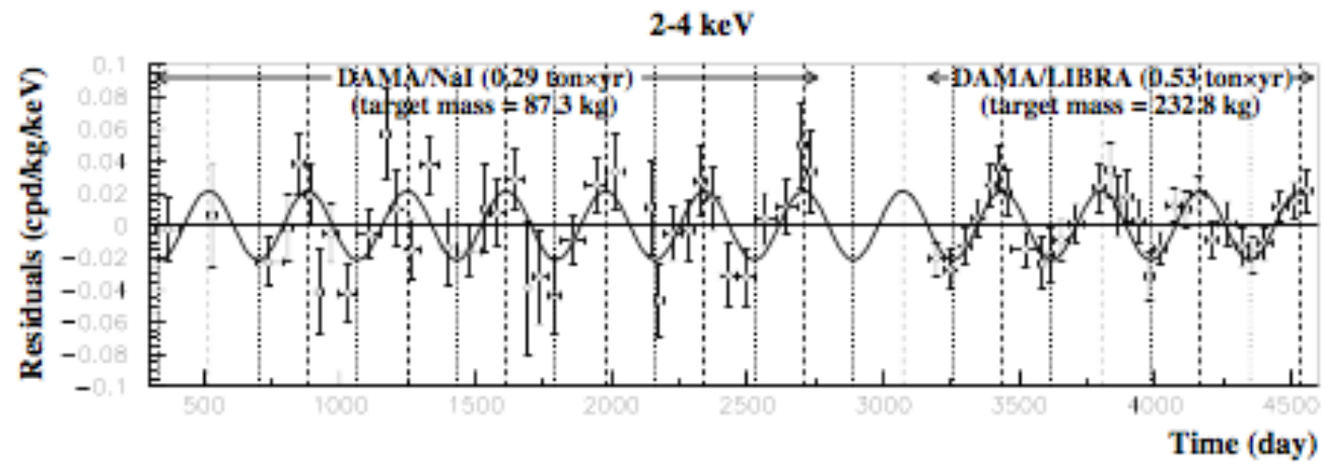
Results from DAMA

Bernabei *et al.*, arxiv:0804.2741

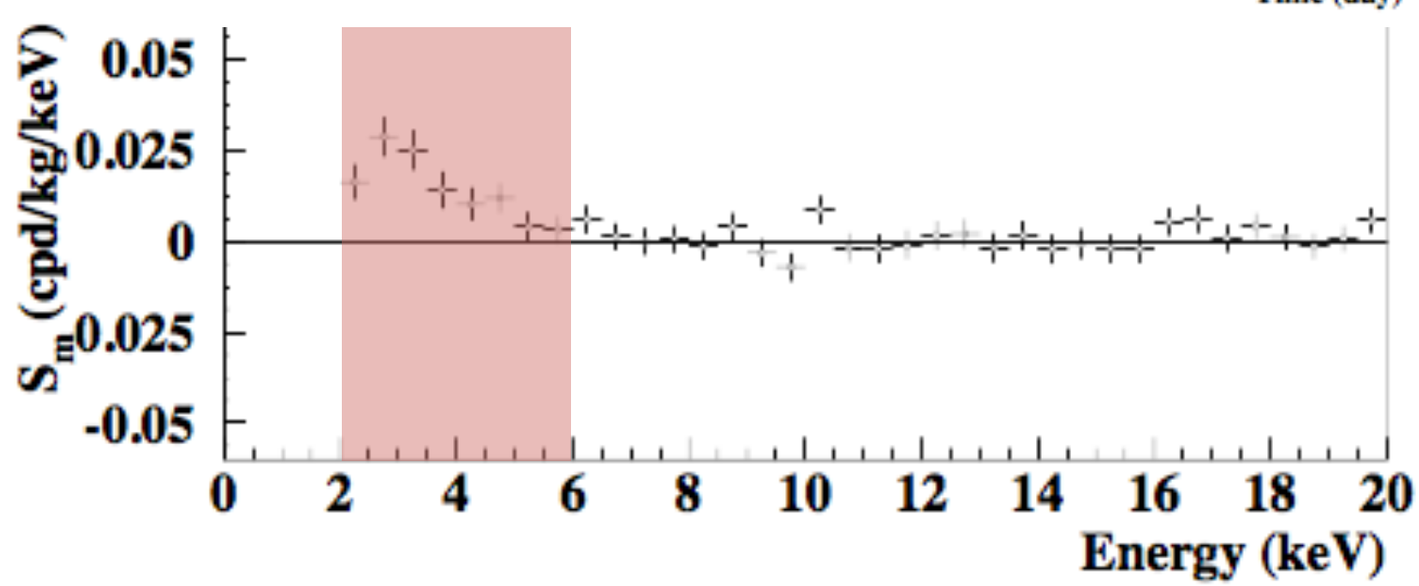
- ~1 cpd/kg/keV background above 2 keV



- Modulation between 2-6 keV over 14 annual cycles

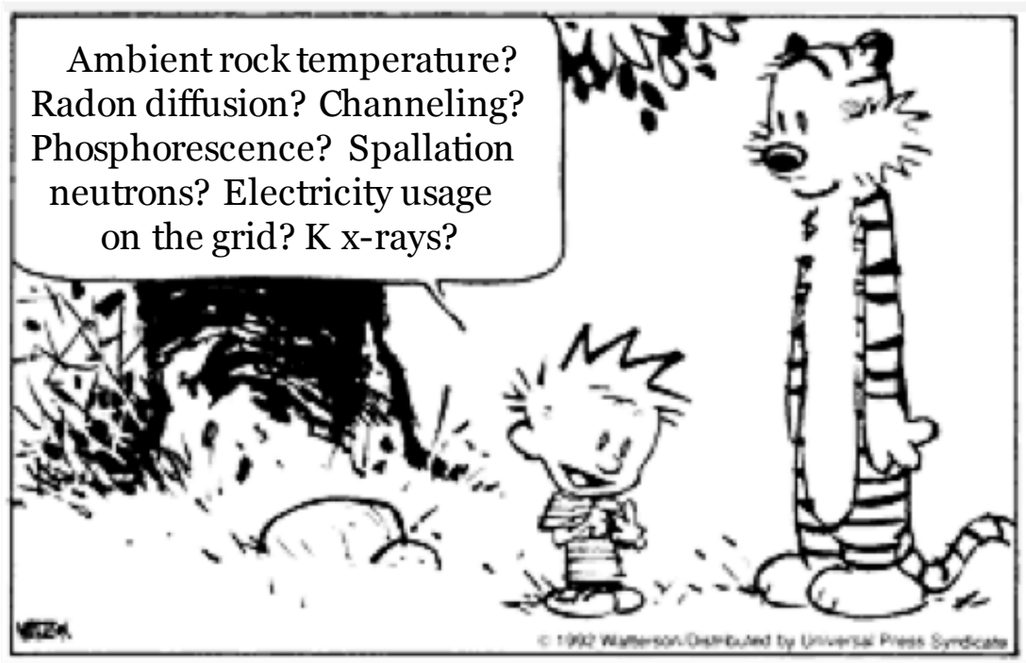


- Dark matter modulation with 9.3 σ

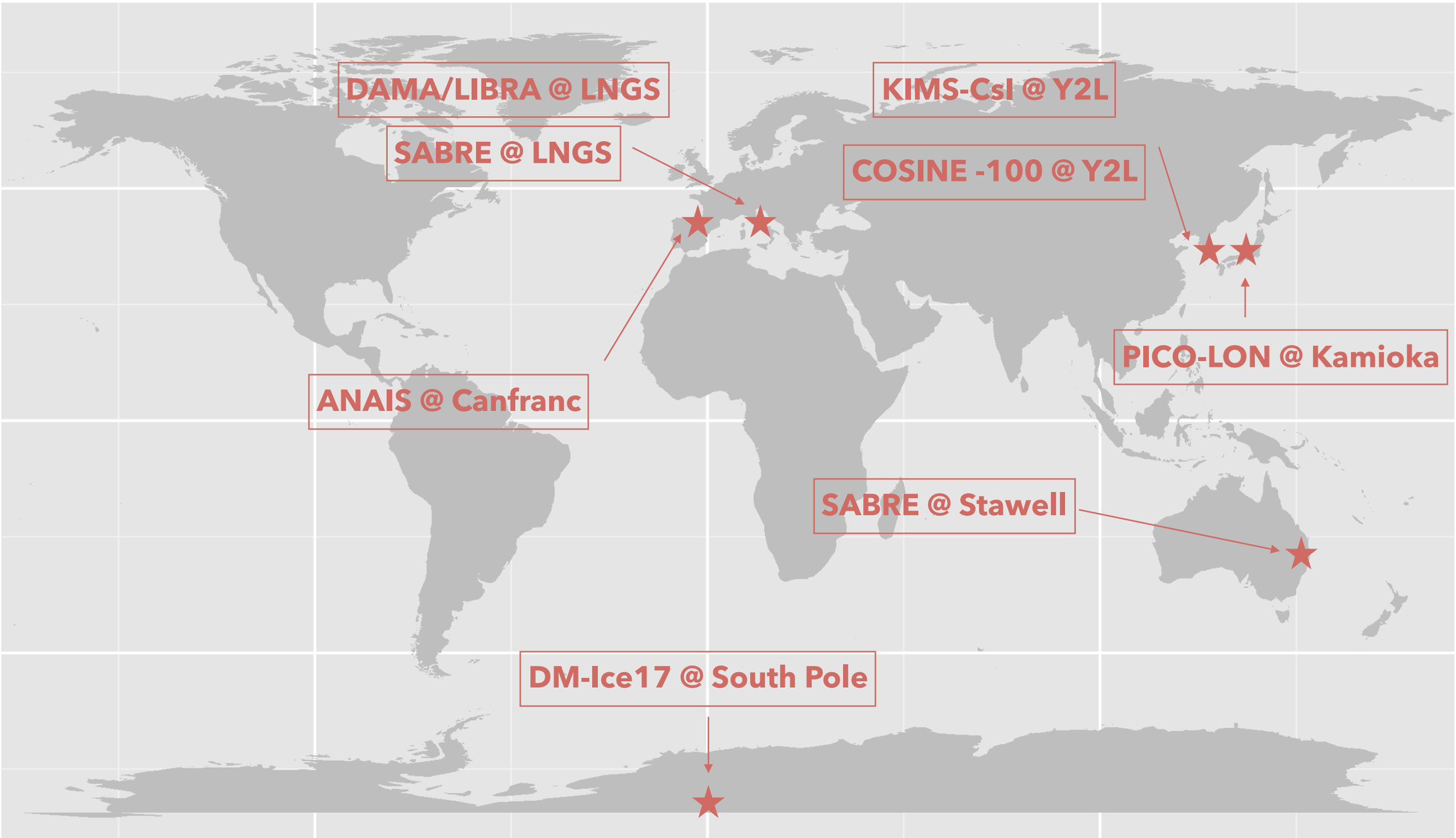


Interpretation of the DAMA Result

"What is causing DAMA's modulation? Could it be some backgrounds?"

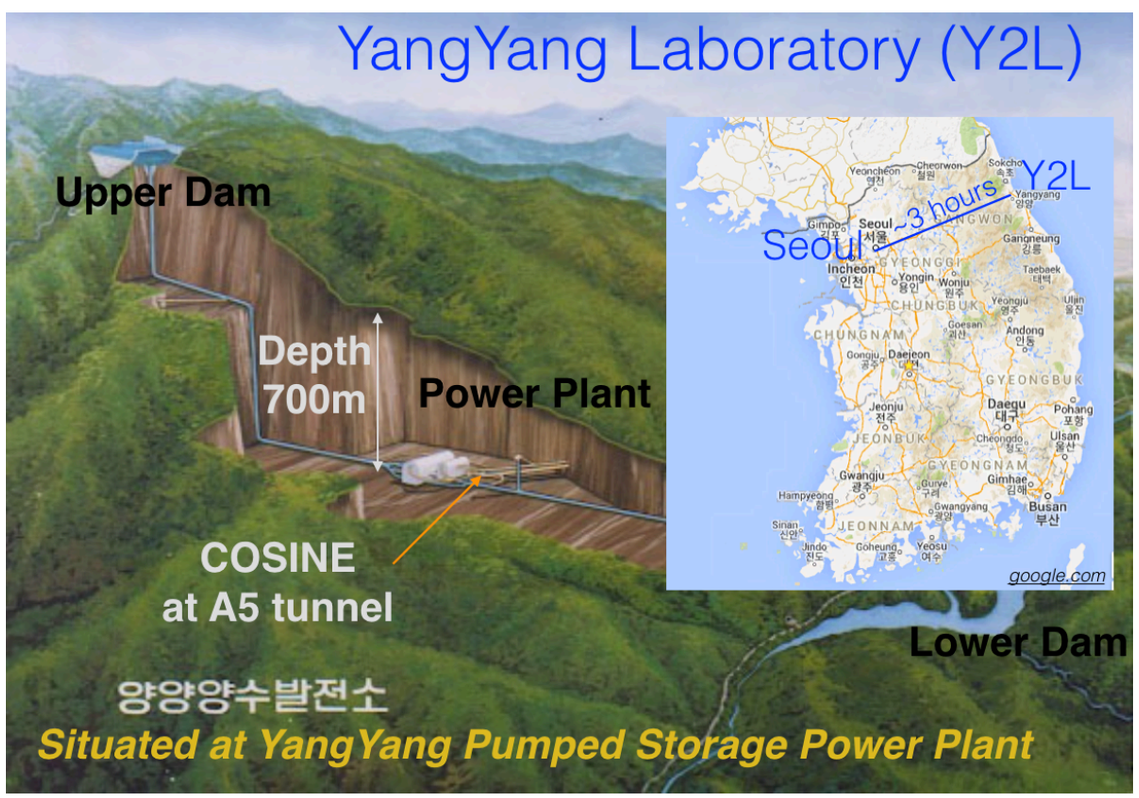


Global NaI(Tl) Efforts

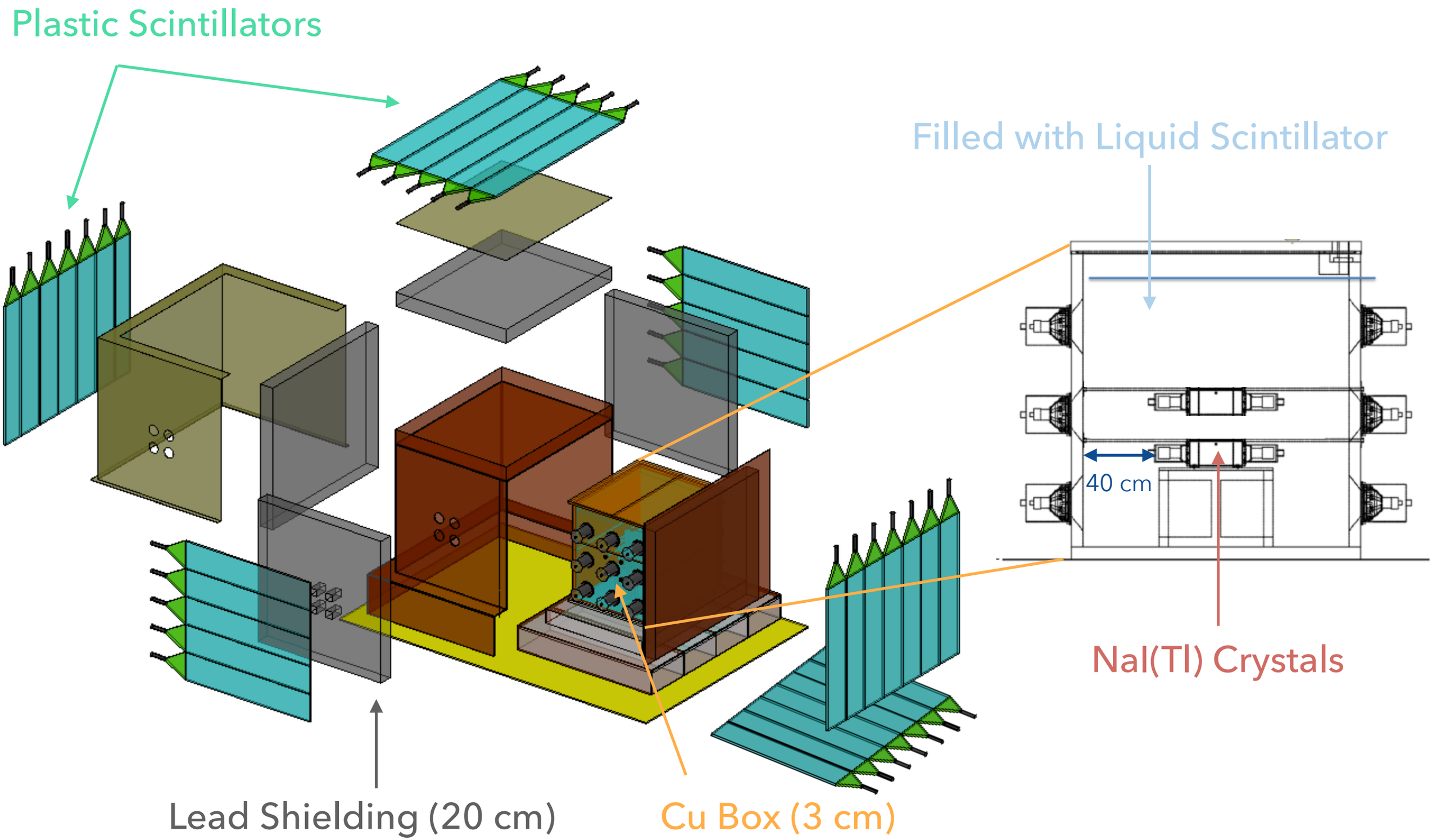


COSINE-100

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

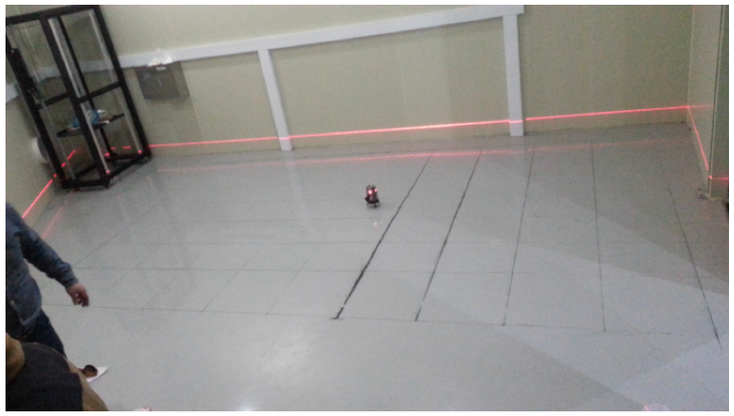


COSINE-100 Shielding Structure



COSINE-100 Construction Timeline

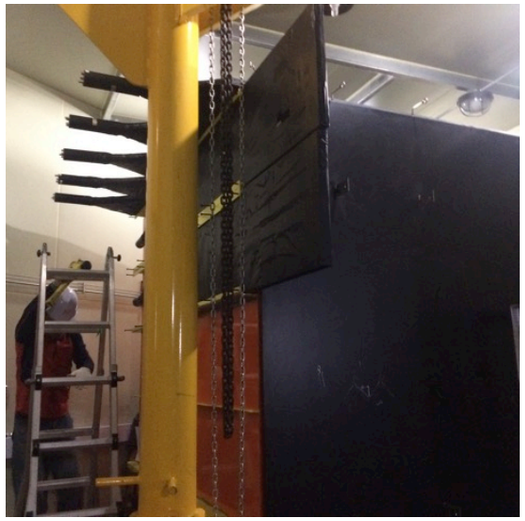
Dec. 2015



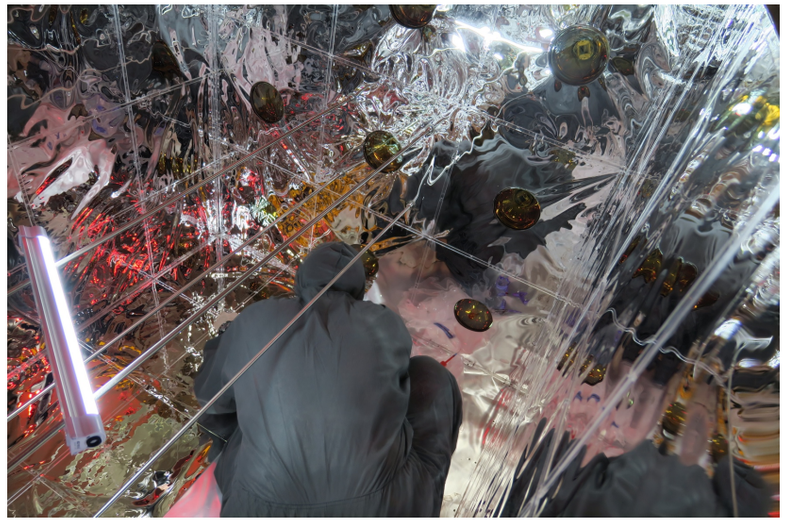
Jan. 2016

Feb. 2016

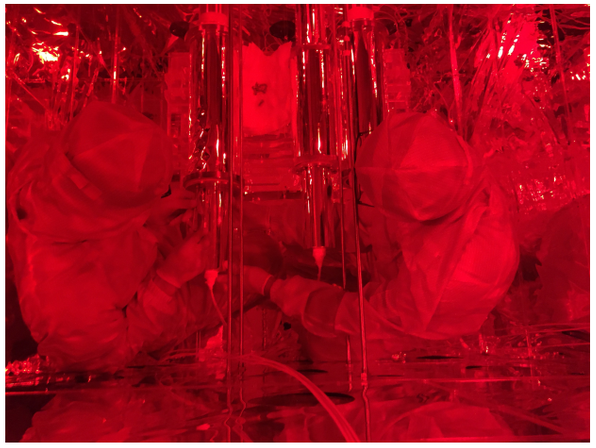
Mar. 2016



Apr. 2016



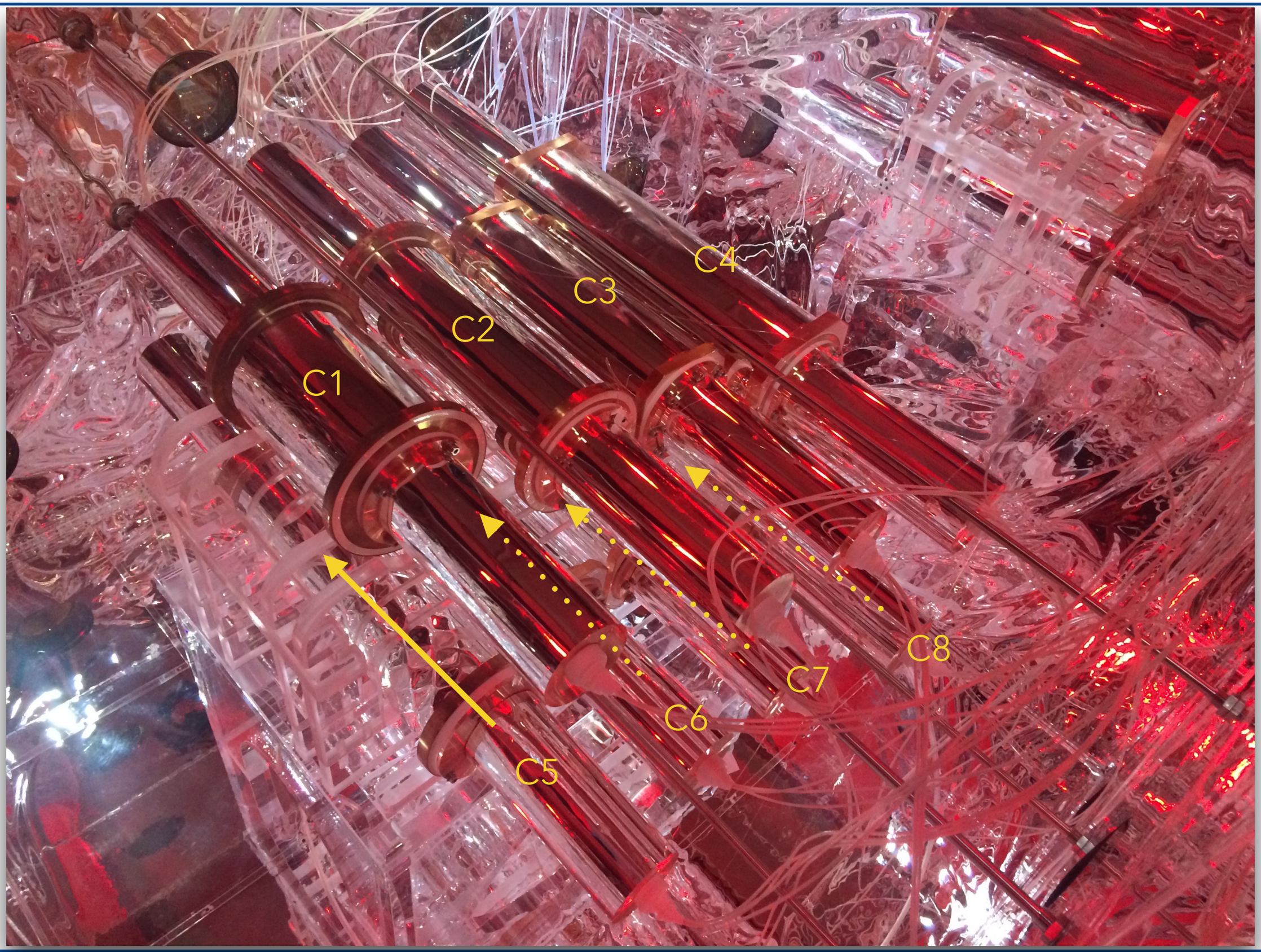
May. 2016



Jun. 2016

Sep. 2016

Crystal Installation



COSINE-100 NaI(Tl) Crystals

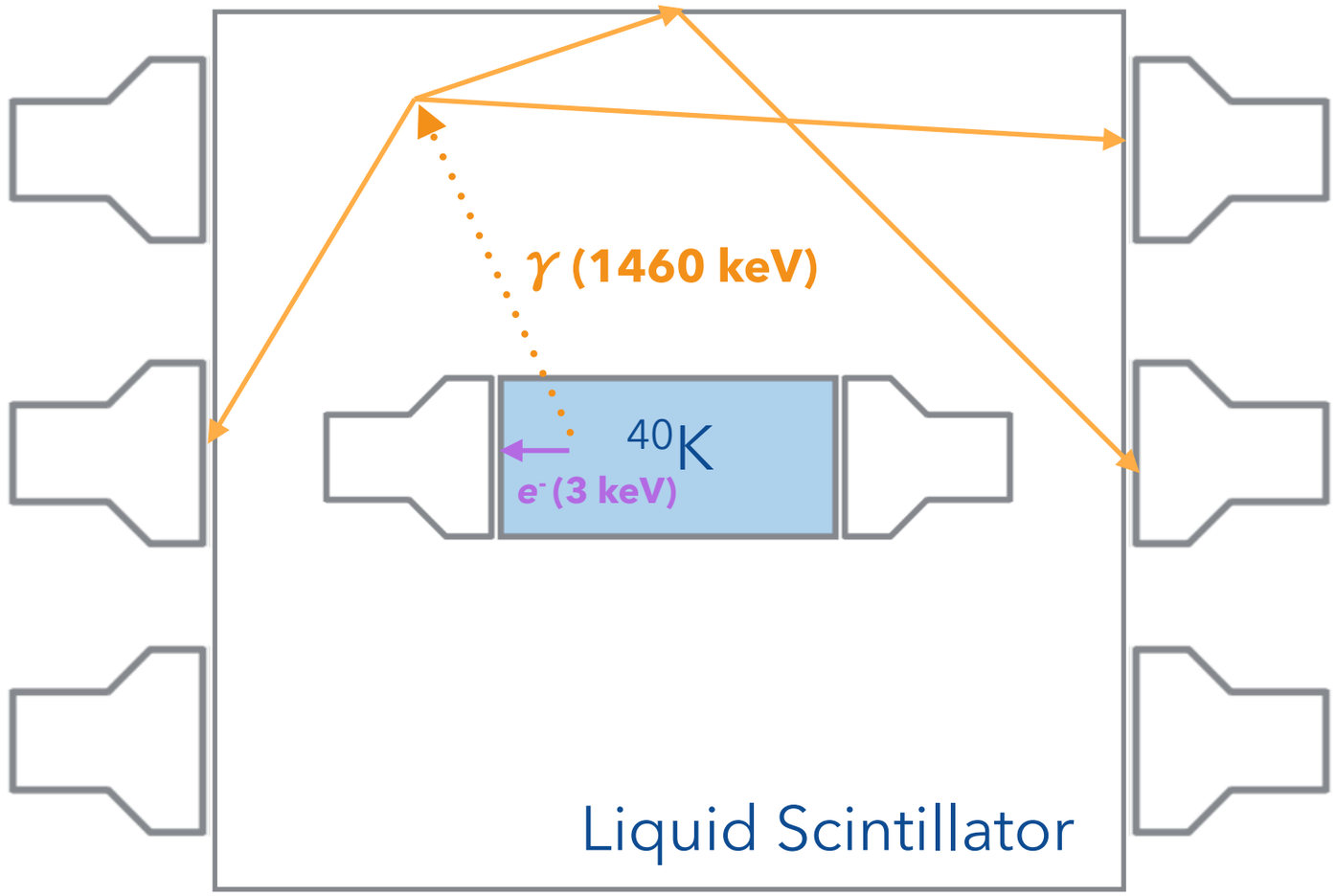
Preliminary

	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

JHJ , DBD2016

- 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-LS Coincidence Events

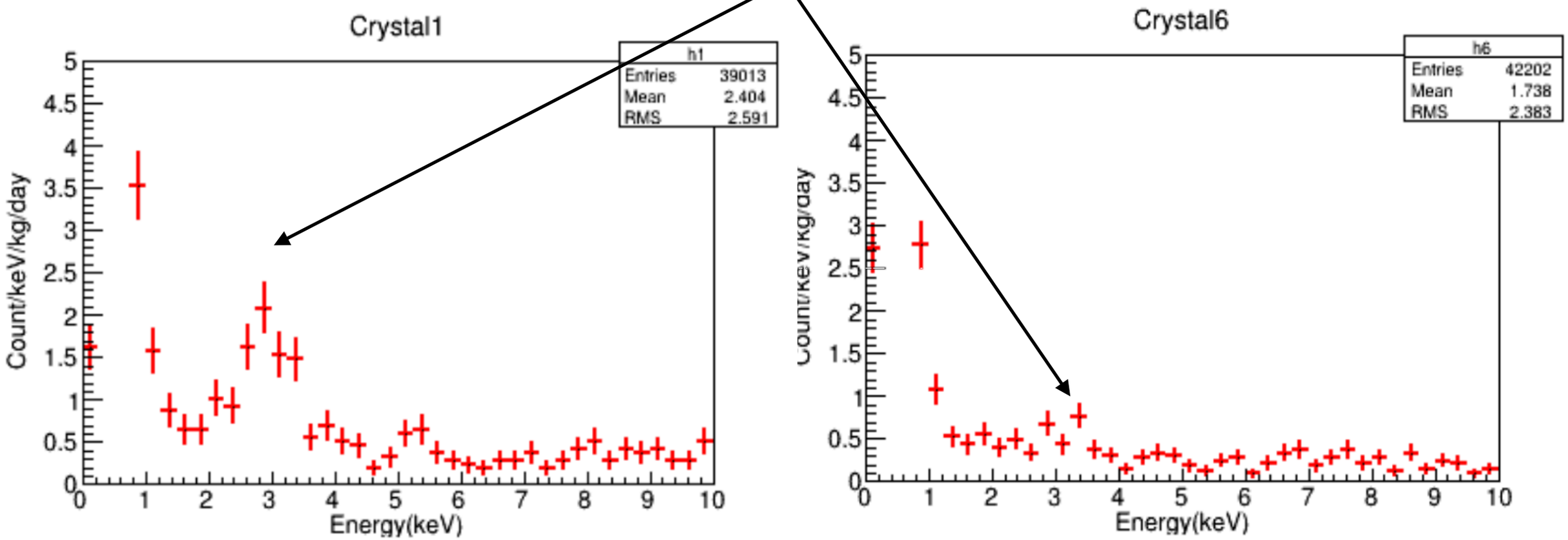


- ^{40}K emits 1460 keV gamma with 3 keV Auger electron energy deposition in NaI crystal
- Tagging 1460 keV events with LS enables to veto 3 keV background events

Crystal-LS Coincidence Events

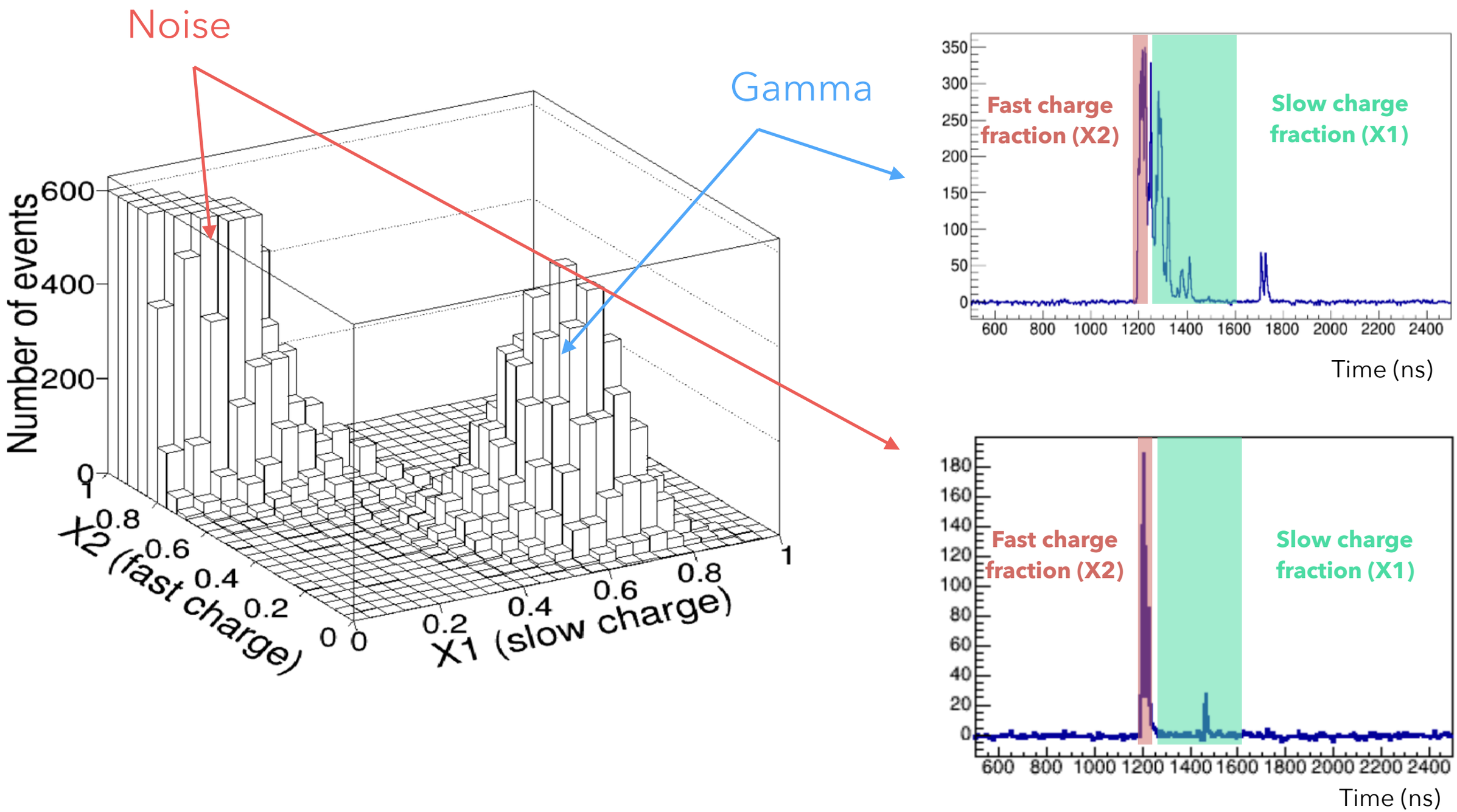
3 keV ^{40}K peaks

Preliminary



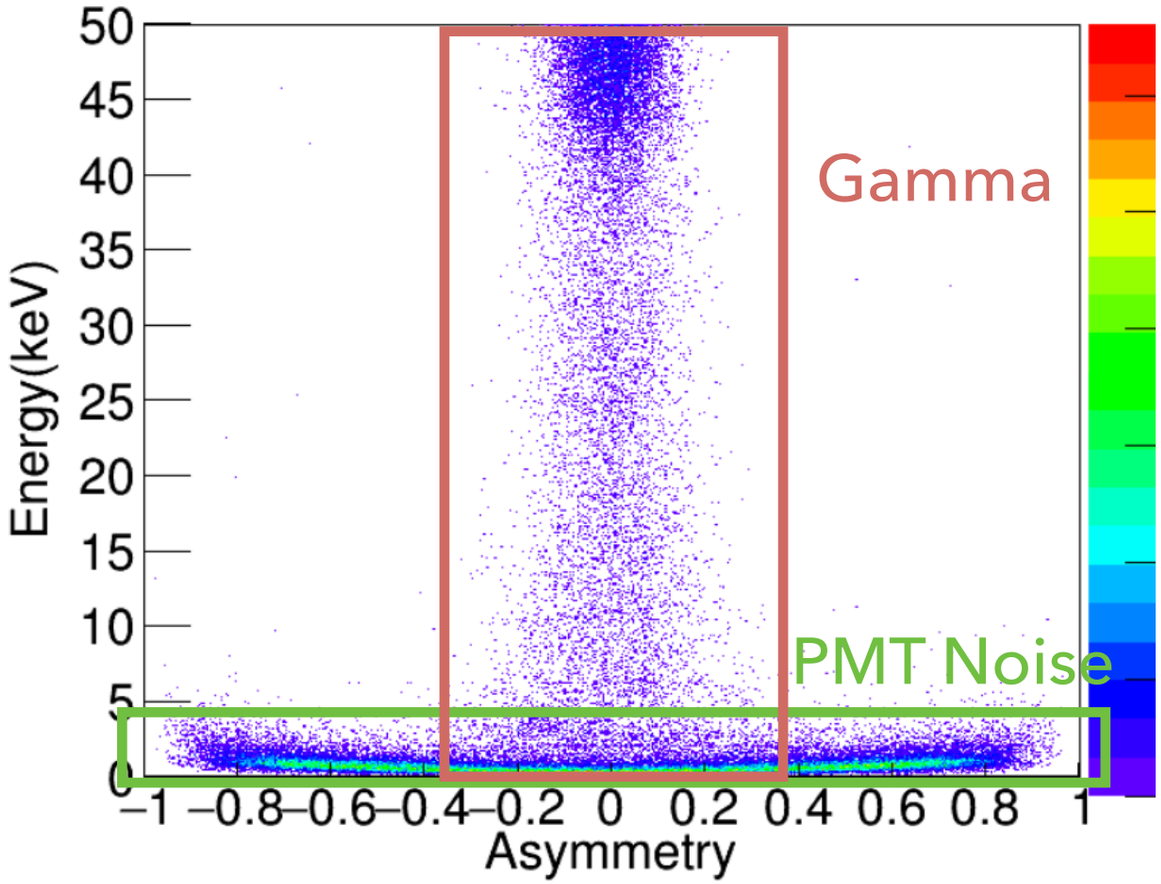
- ^{40}K emits 1460 keV gamma with 3 keV energy deposition in NaI crystal
- Tagging 1460 keV events with LS enables to veto 3 keV background events

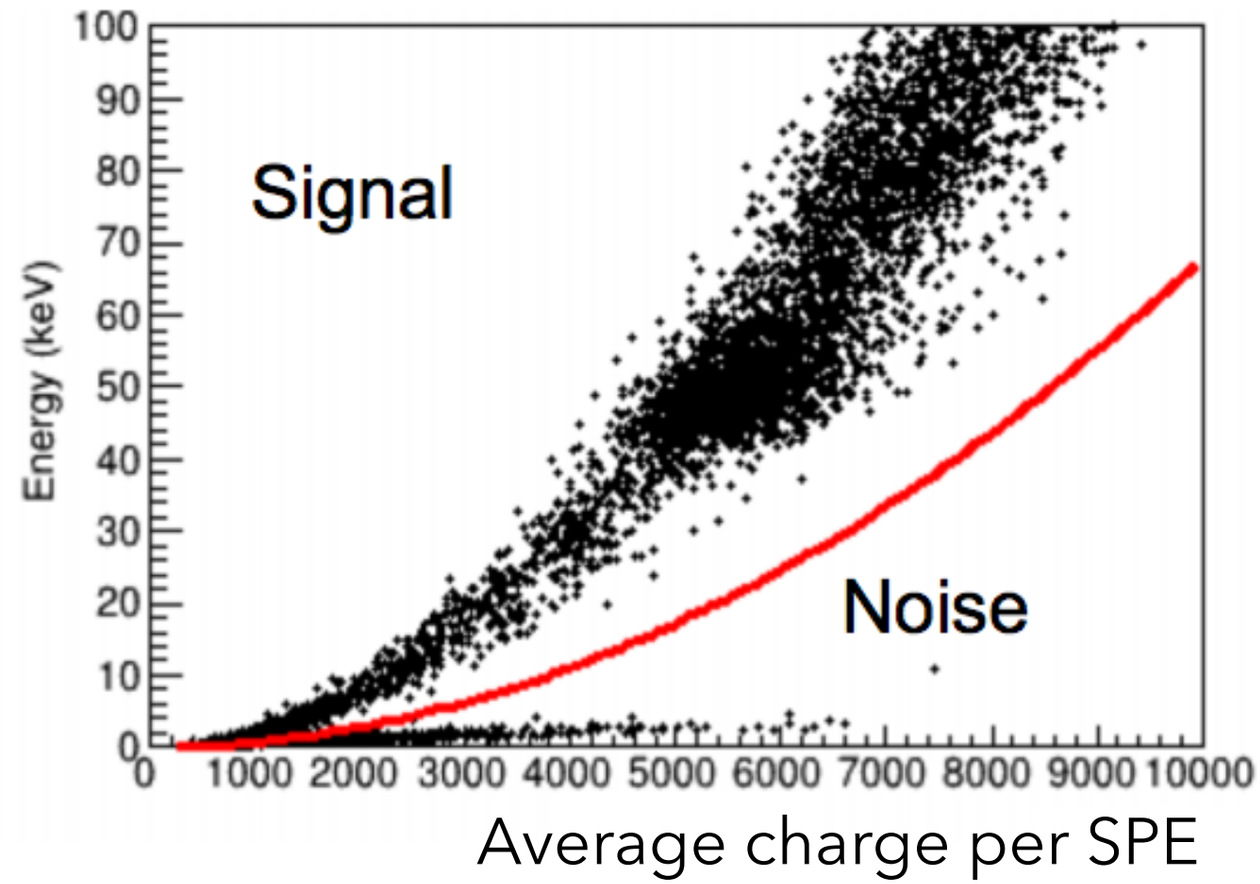
COSINE-100 Event Selection



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

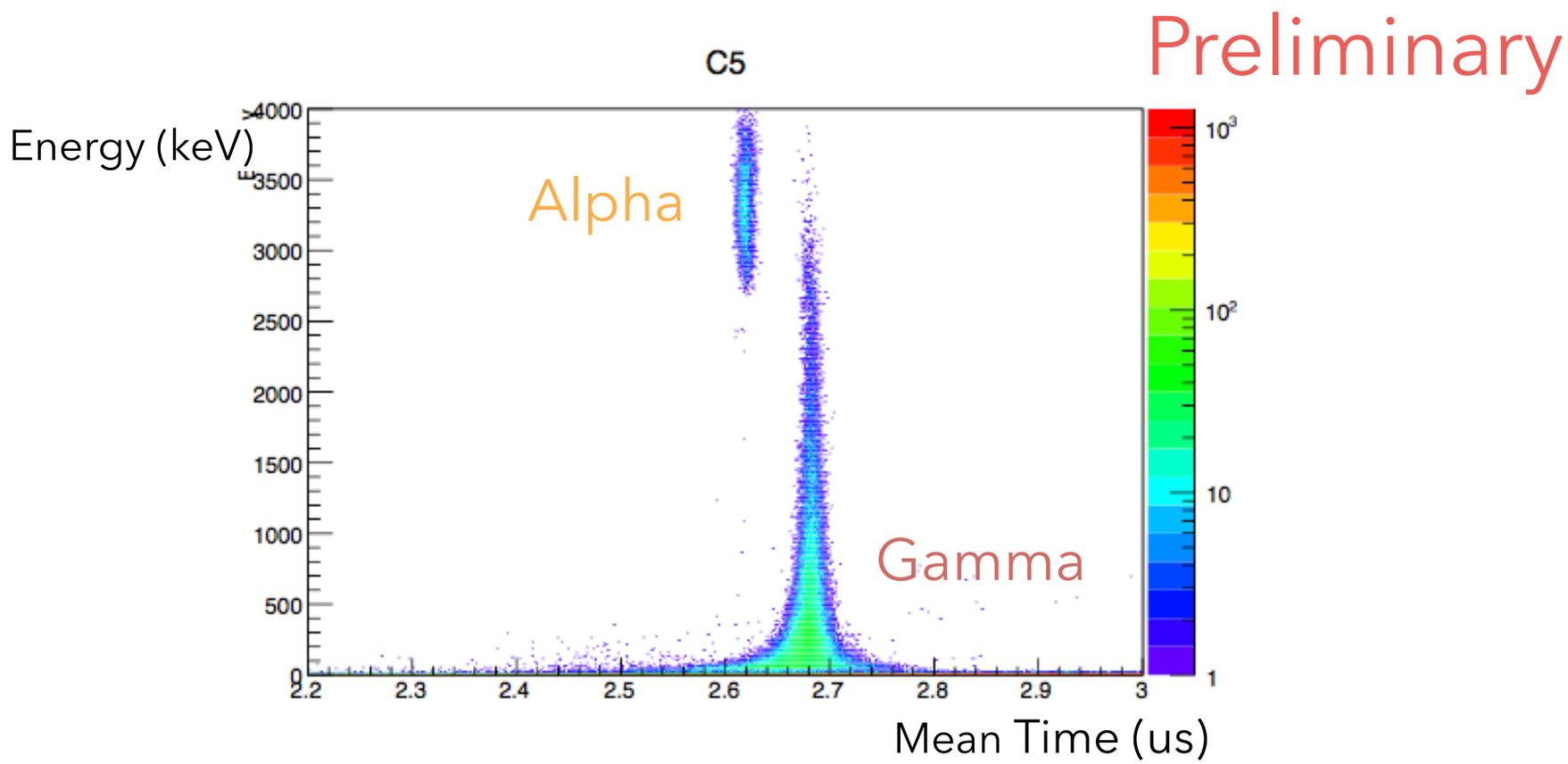
COSINE-100 Event Selection





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

Pulse Shape Discrimination for Alpha

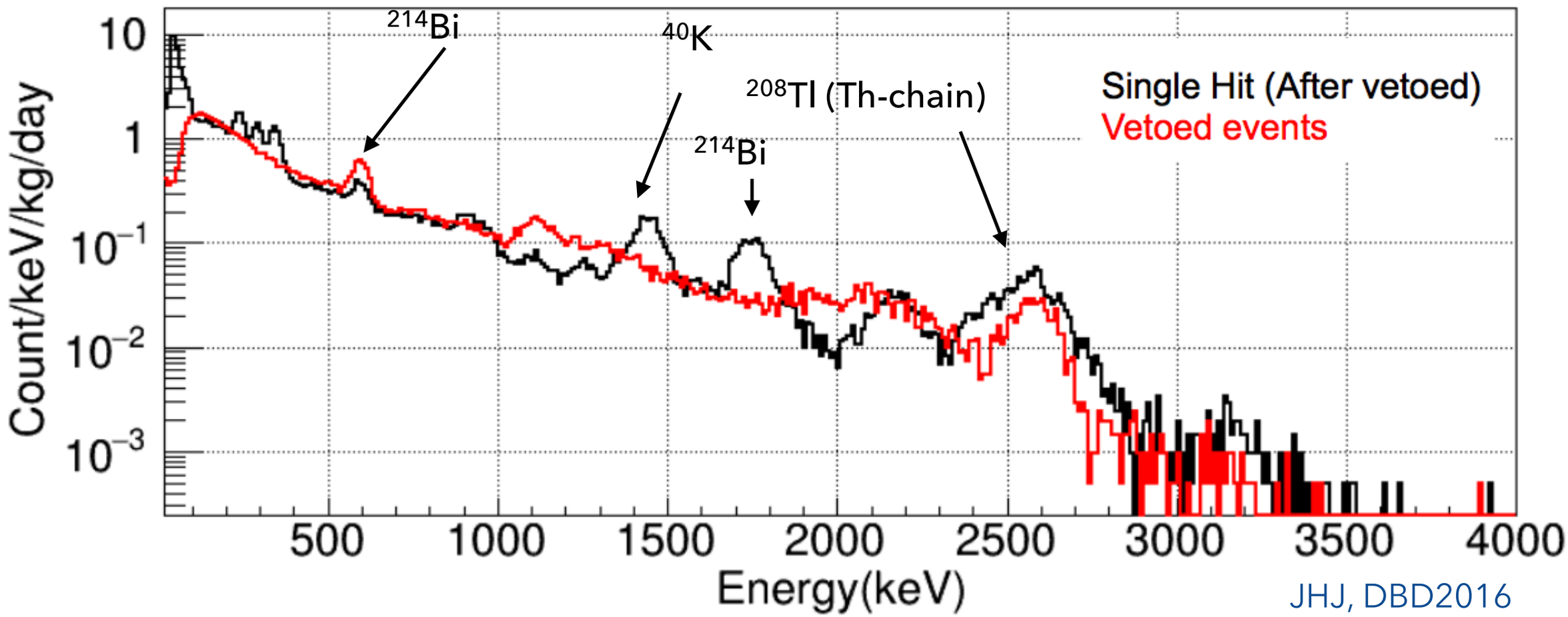


- Pulse Shape Discrimination technique works well for alpha separation
- Using charge-weighted mean time
- With separated alpha events, estimation of ^{210}Po background can be performed
  - 0.5~3 mBq/kg for COSINE-100 crystals

COSINE-100 High Energy Spectrum

Preliminary

Crystal 6



JHJ, DBD2016

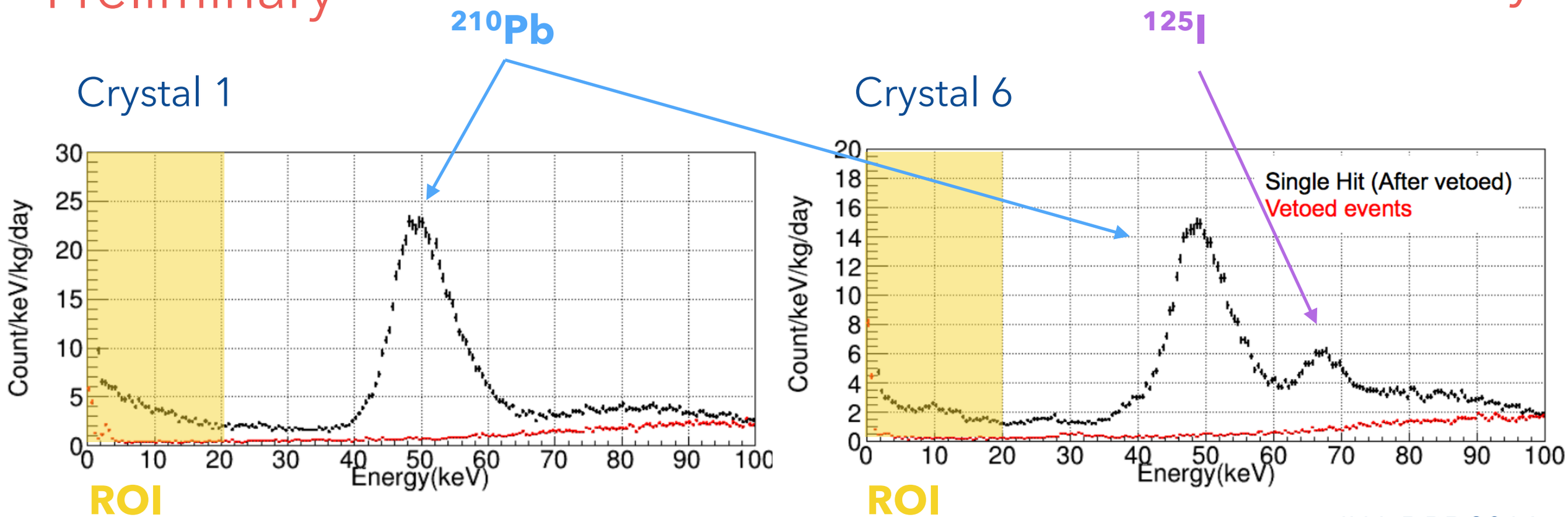
- Gamma spectrum shows pronounce background peaks including 1460 keV from ^{40}K

- Dynamic range for high energy signals is > 5 MeV

COSINE-100 Low Energy Spectrum

Preliminary

Preliminary

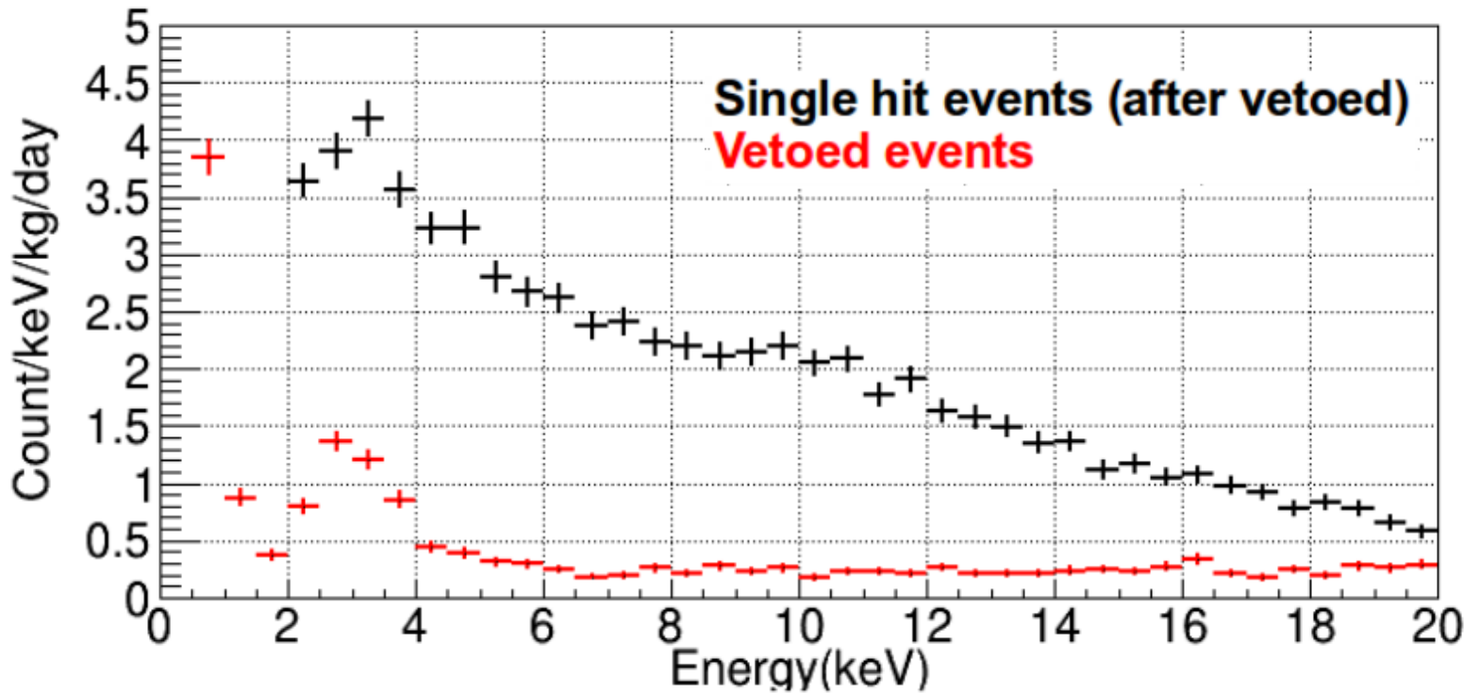


JHJ, DBD2016

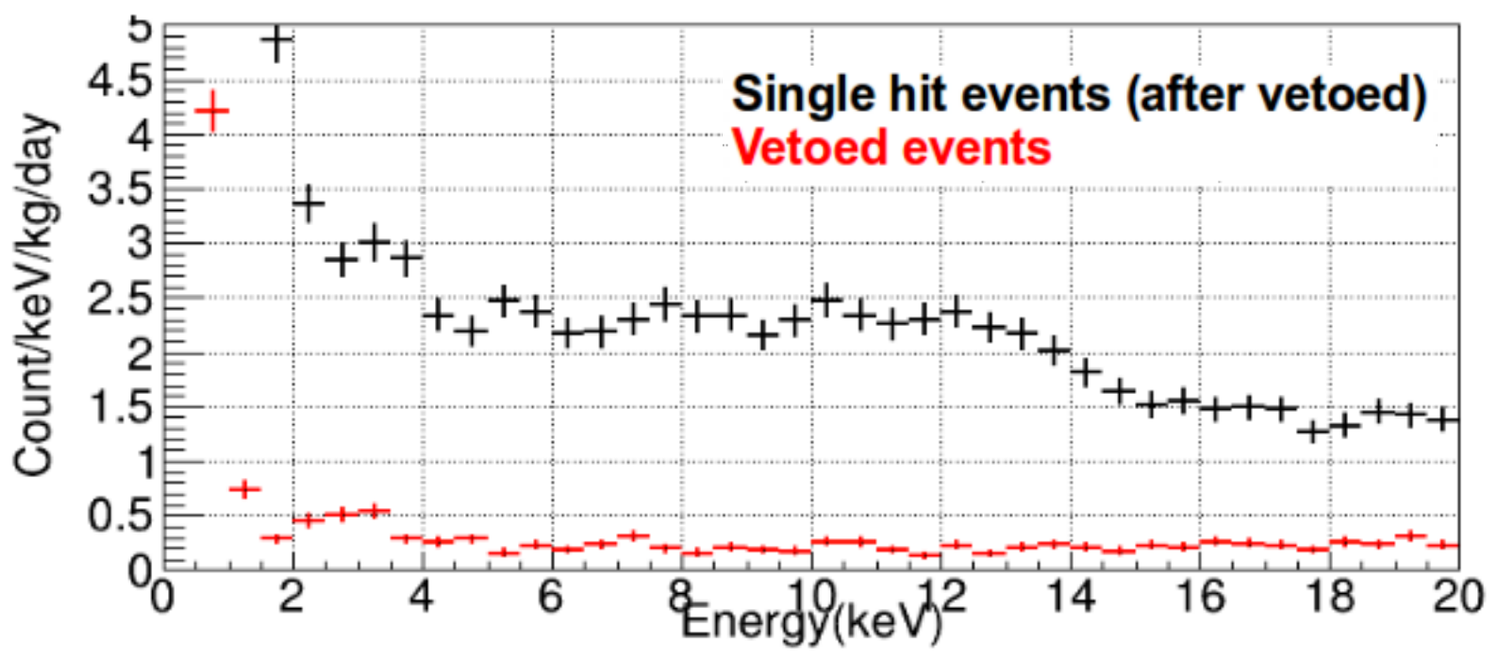
- 10 days of data, current set of event selection applied (not final!)
- Depending on crystal, background level ~3 dru at the region of interest
- Cosmogenic peaks remain in certain crystals
- There are still room for improvements

COSINE-100 Low Energy Spectrum (< 20 keV)

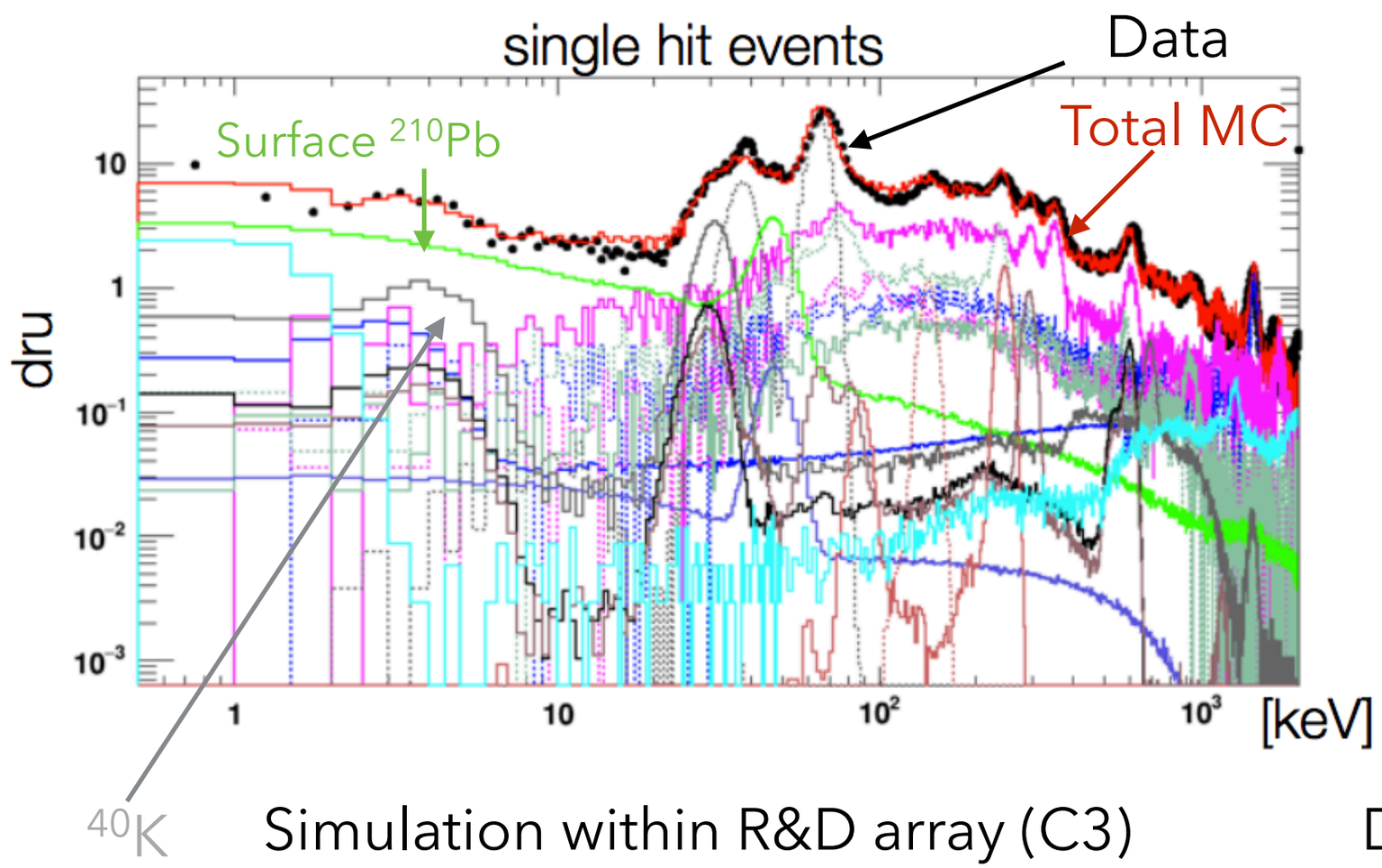
Crystal 4



Crystal 7

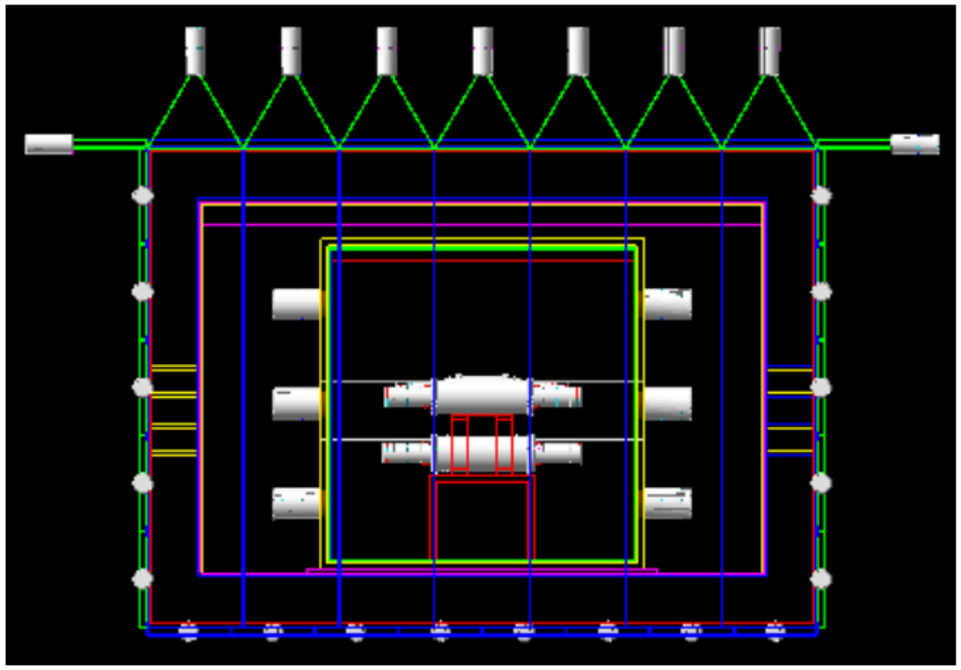


COSINE-100 NaI Crystal Simulation



Simulation within R&D array (C3)

Preliminary

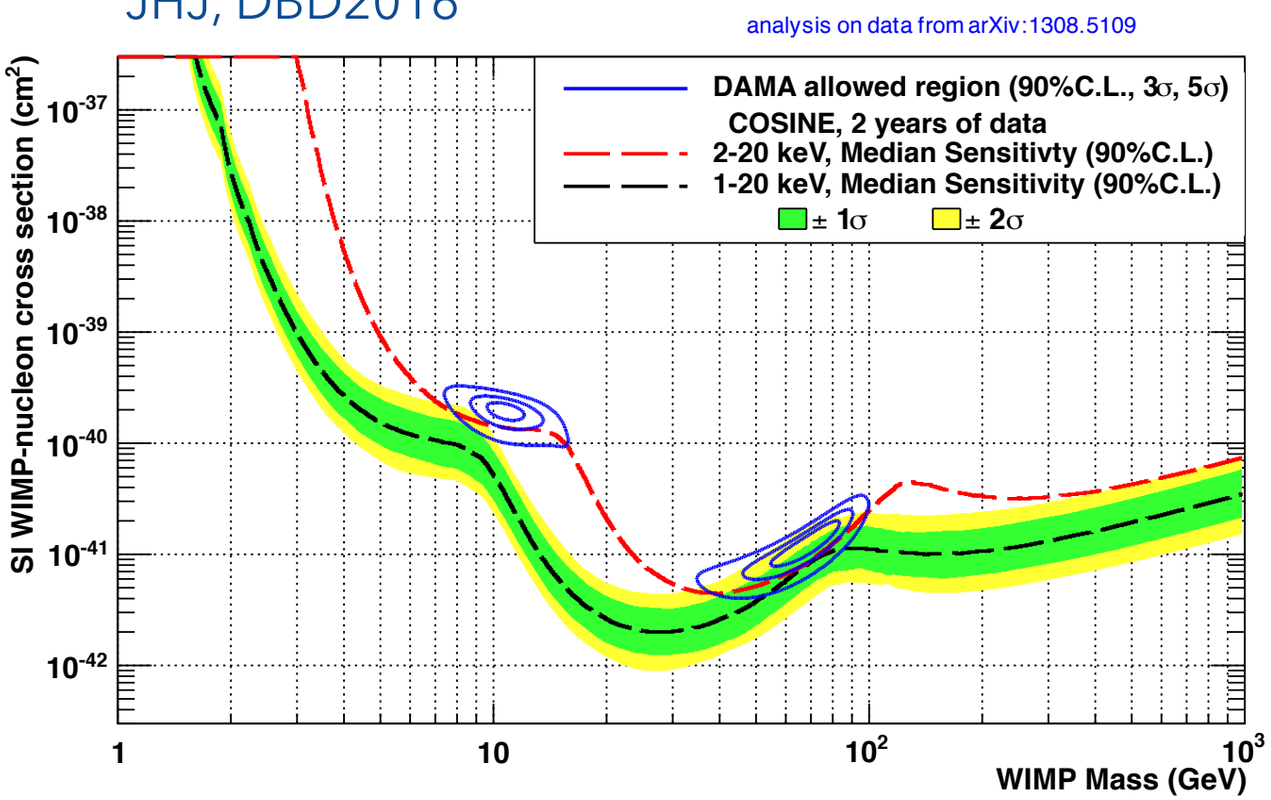


Detector Geometry at COSINE-100

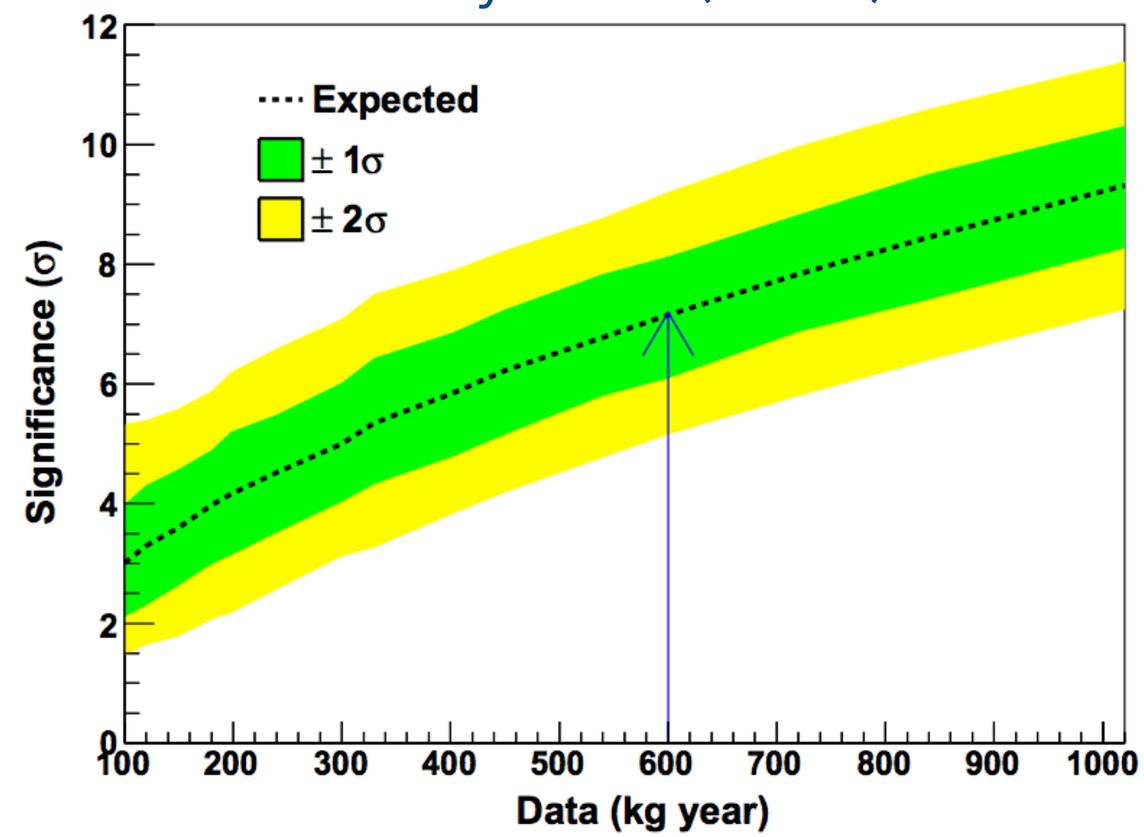
- Work in progress, Geant4 framework
- Using NaI energy spectrum in R&D setup for the first step
- Surface ^{210}Pb is suspected to be the dominant background, followed by ^{40}K internal to crystal

COSINE-100 Projected Sensitivity

JHJ, DBD2016



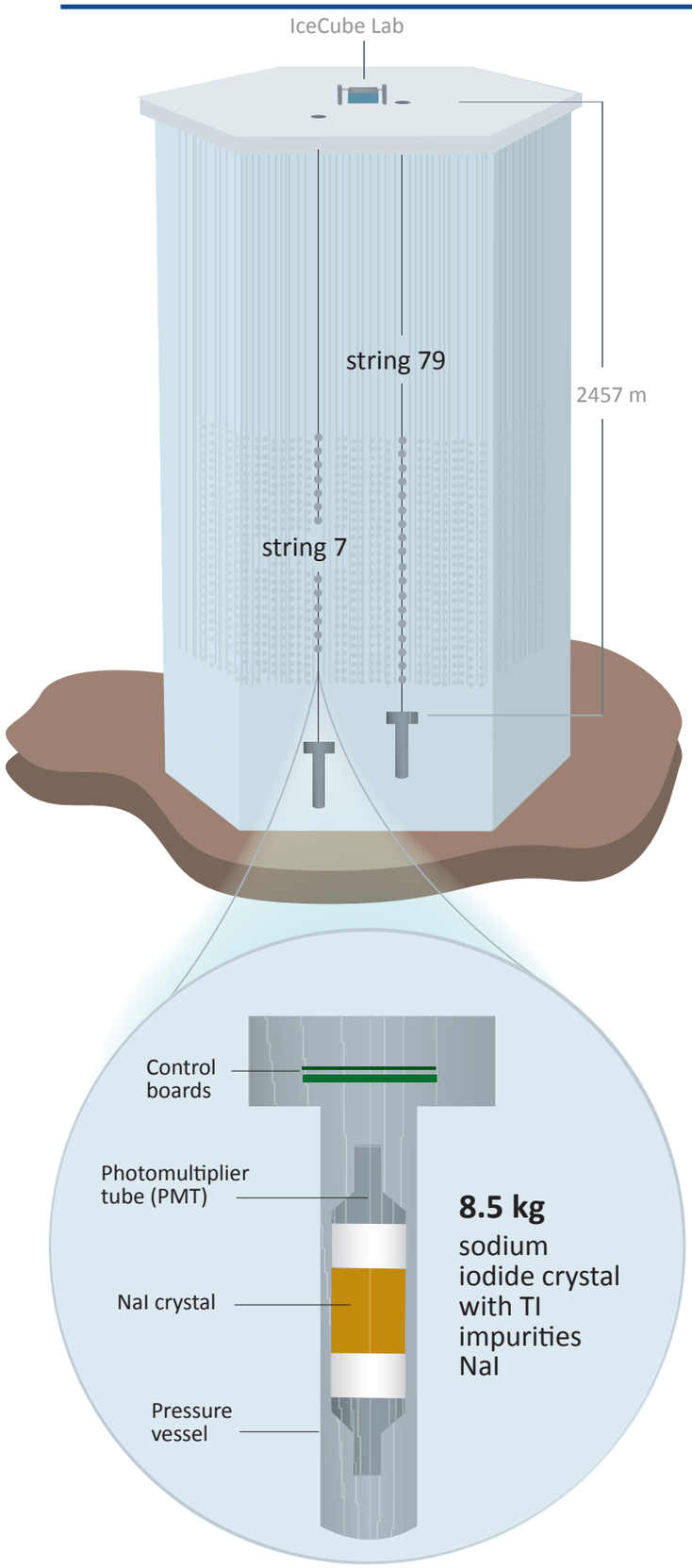
Eur. Phys. J. C (2016) 76:185

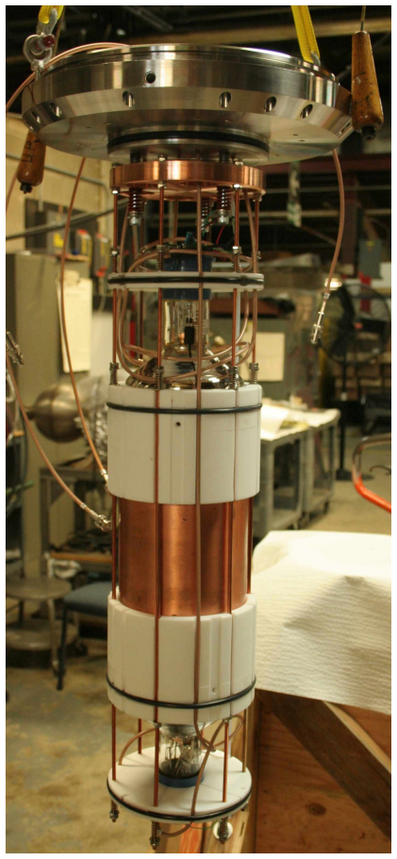


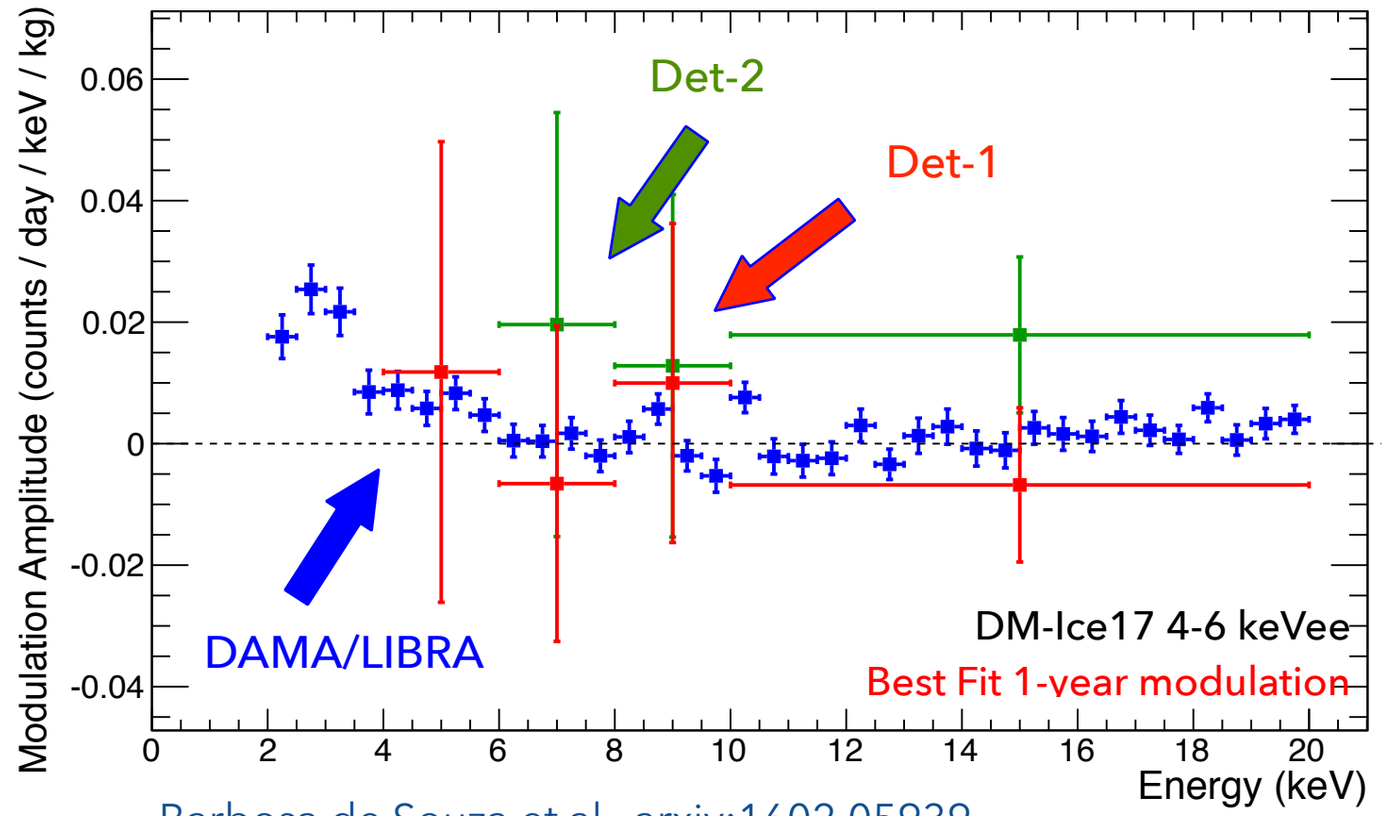
- 2-4 dru flat background is assumed
- 2 years of data with 1 keV analysis threshold will give comparable sensitivity with DAMA's 90% C.L allowed region
- If observed, 600 kg·years of data will give ~7 sigma result (2 dru bkg assumed)

DM-Ice17

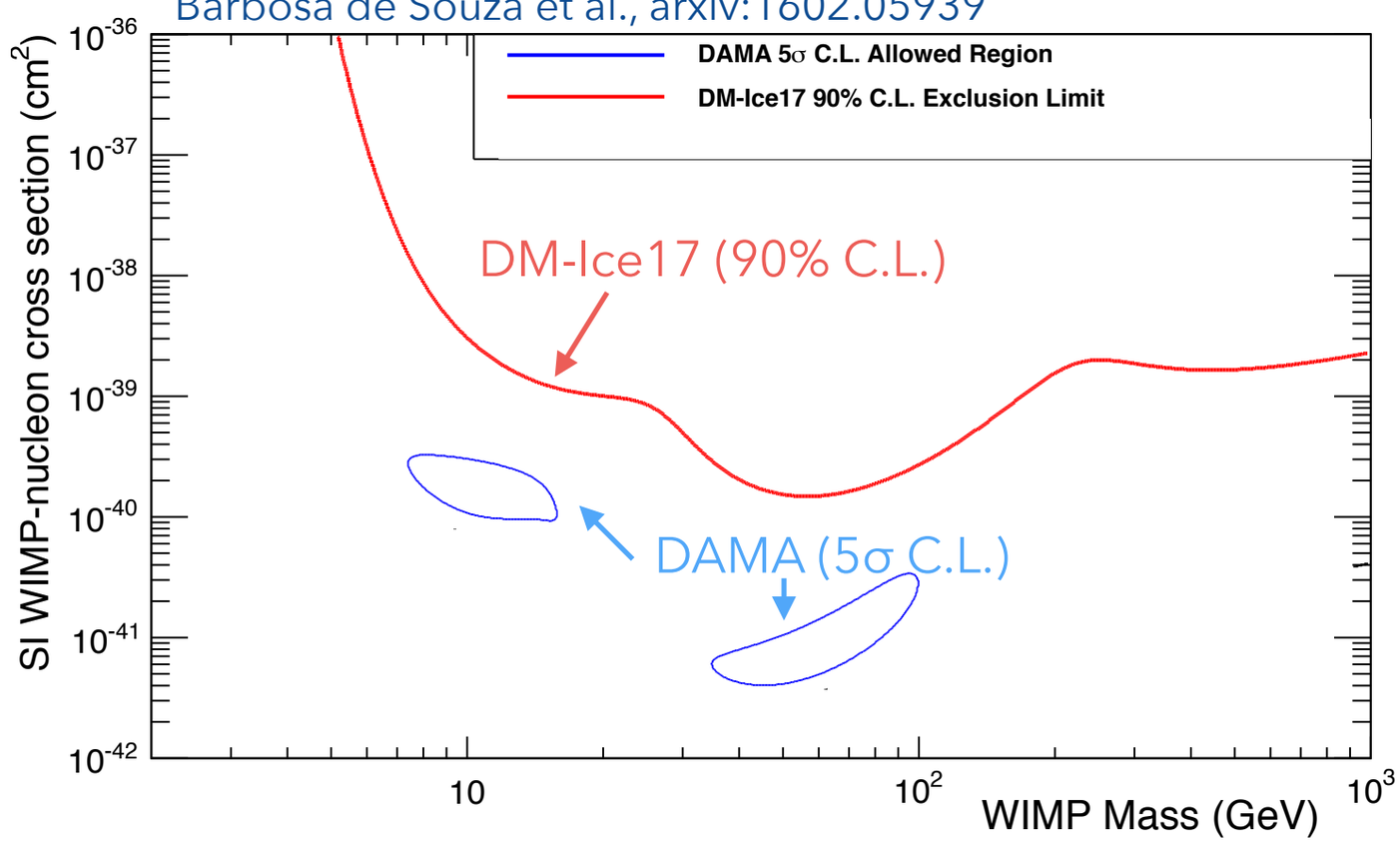
DM-ICE







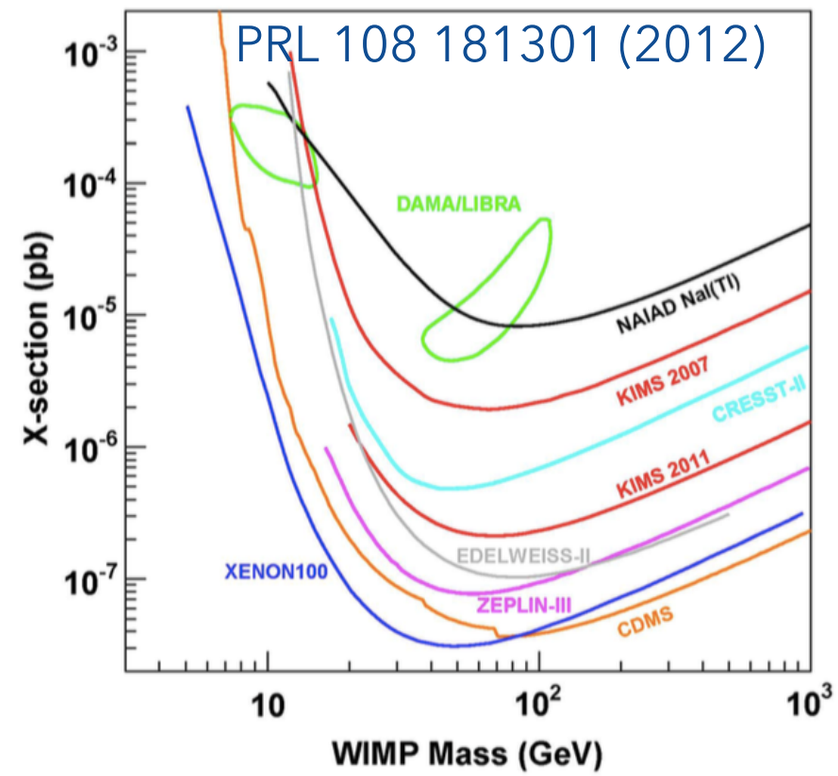
Barbosa de Souza et al., arxiv:1602.05939

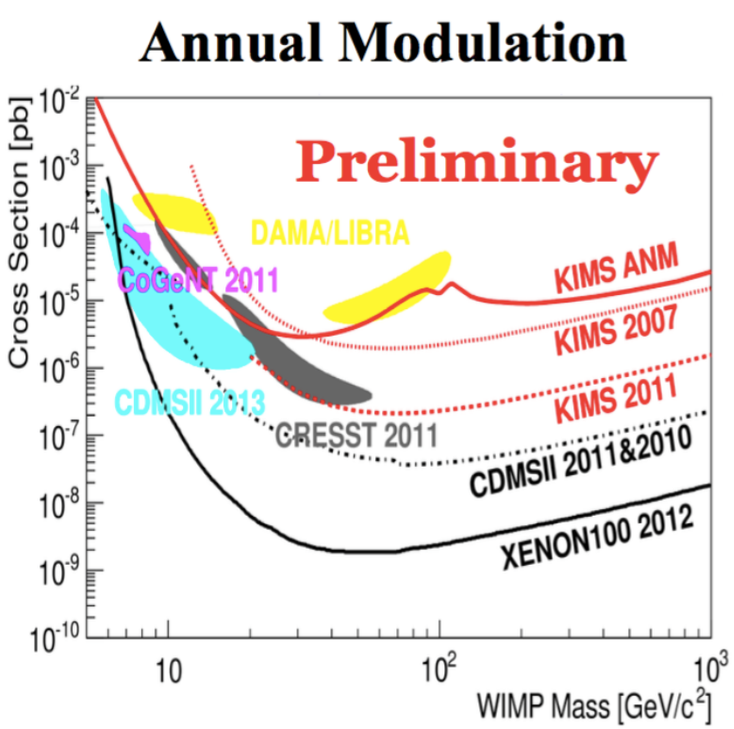


KIMS-CsI

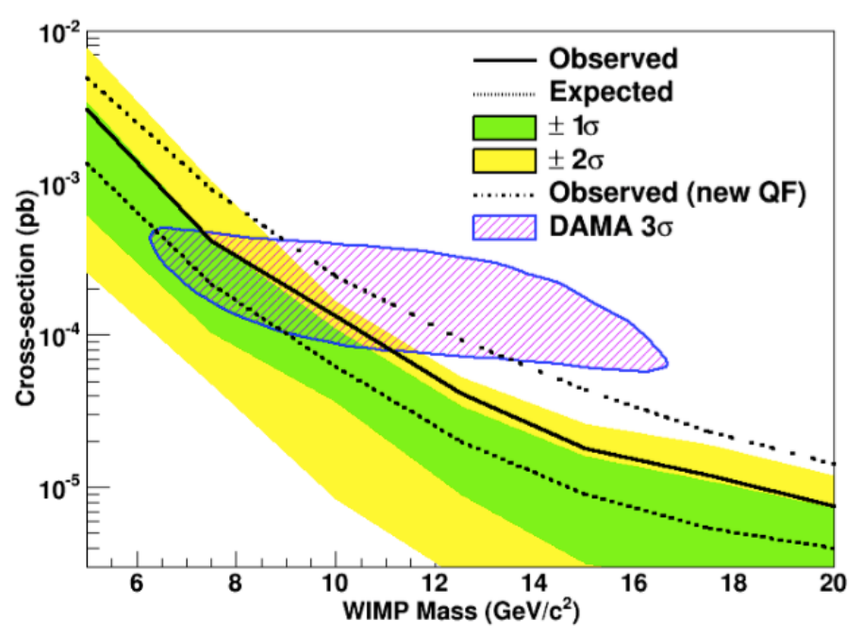
H. Lee, IDM2016

- 12 CsI crystals with 104.4 kg
- 2.5 years data (2009 - 2012)
- 2~3 cpd/kg/keV background
- Model-independent rejection for WIMP-Iodine interaction



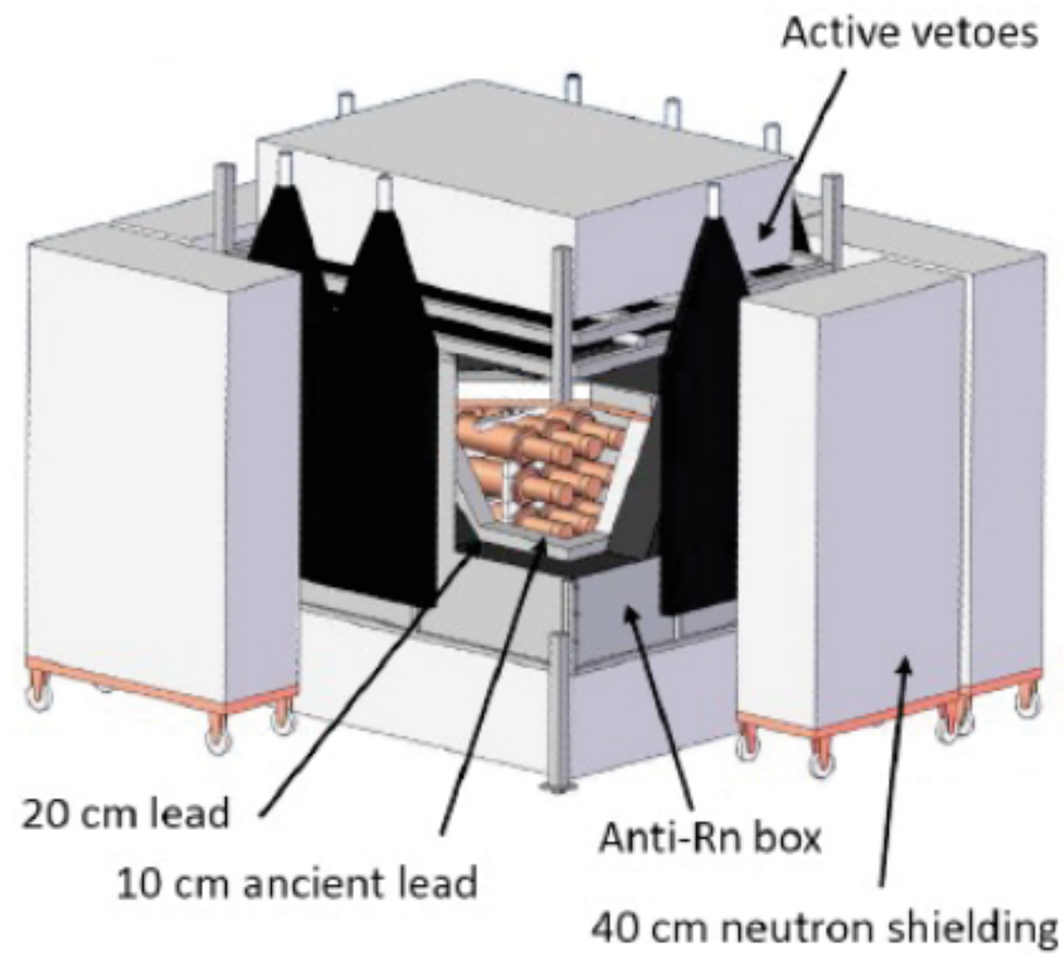


PRD 90 052006 (2014)



ANAIS

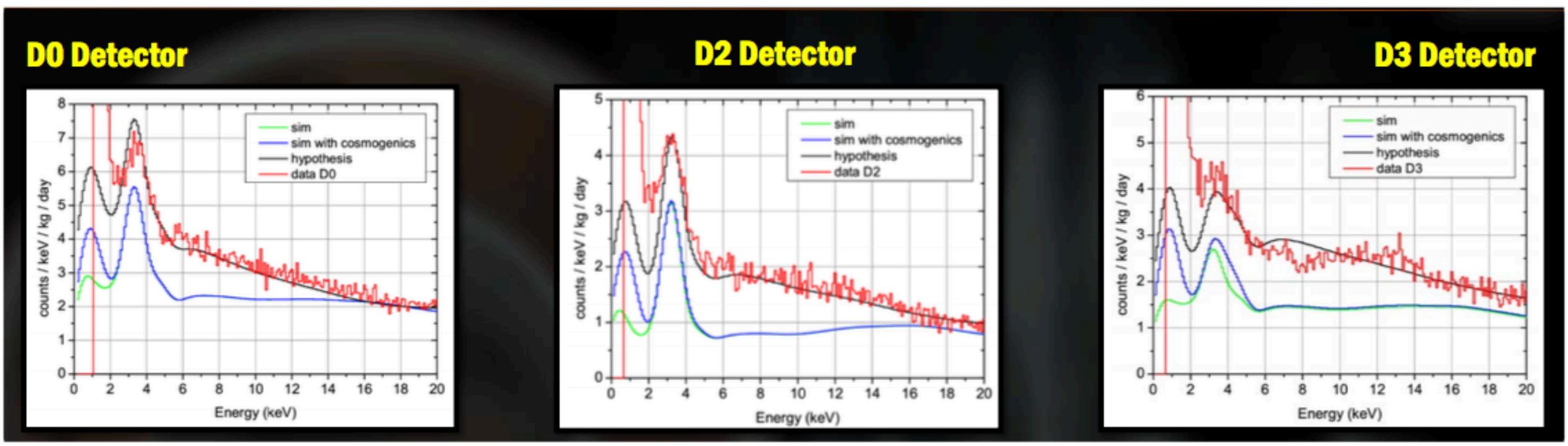
- 112.5 Kg in a 3 x 3 array configuration
  - Crystals grown by Alpha Spectra
- Located at Canfranc Lab, Spain
- 37 kg currently installed in R&D setup, secured 5 crystals so far (4 more coming)
- Possible combined-analysis with COSINE in future



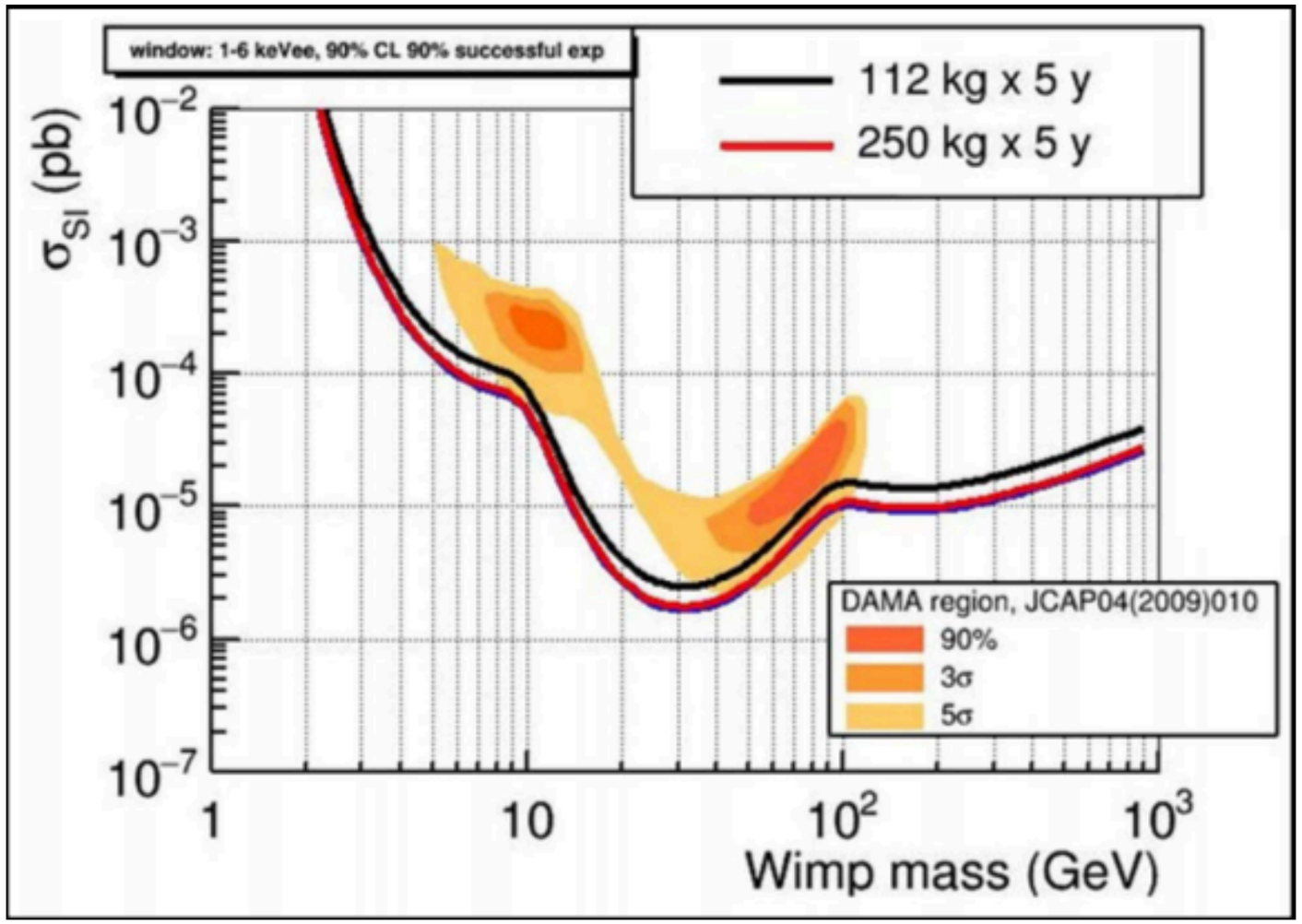
ANAIS: Background

P. Vilar, RENATA 2016

	^{40}K	^{238}U	^{210}Pb	^{232}Th
D0	1.4 mBq/kg (45 ppb K)	9 μBq/kg	3.15 mBq/kg	5 μBq/kg (^{220}Rn-^{216}Po) 3 μBq/kg (^{212}Bi-Po)
D1	1.1 mBq/kg (34 ppb K)	9 μBq/kg	3.15 mBq/kg	4 μBq/kg (^{220}Rn-^{216}Po)
D2	1.1 mBq/kg (34 ppb K)	2.7 μBq/kg	0.70 mBq/kg	≈1 μBq/kg (^{220}Rn-^{216}Po) ≈1 μBq/kg (^{212}Bi-Po)
D3	0.6 mBq/kg (19 ppb K)	~4 μBq/kg	~1.8 mBq/kg	≈0,6 μBq/kg (^{220}Rn-^{216}Po) ≈0,6 μBq/kg (^{212}Bi-Po)



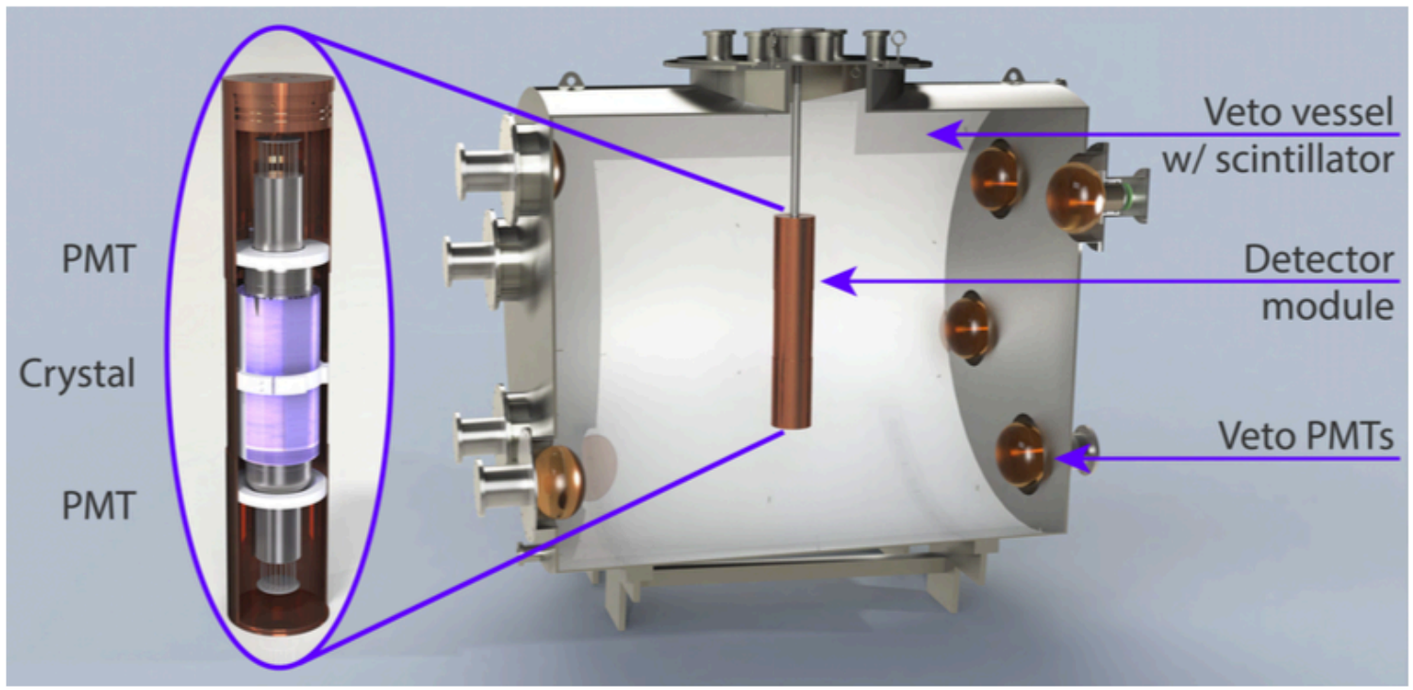
ANAIS: Plan and Sensitivity



P. Vilar, RENATA 2016

- Expected to run by March 2017
- Sensitivity comparable to DAMA signal with 5 years of running
  - 1-6 keV region
  - D2 background level

SABRE



F. Forborg, IDM2016

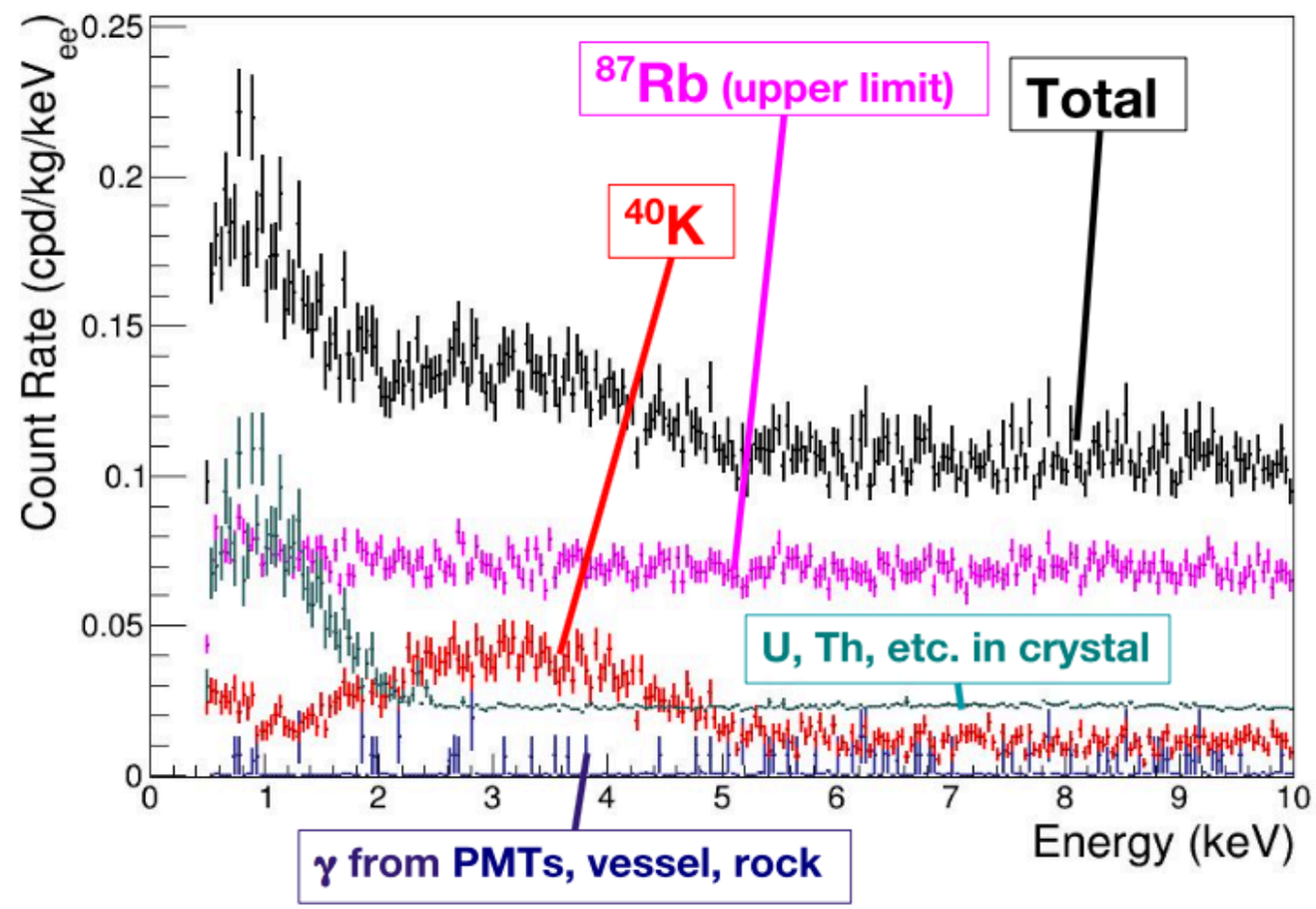
- ~50 kg of ultra pure crystals with *liquid scintillator veto*
  - SAFHC-Hitech and Sigma-Aldrich
- Plan to install both at LNGS (Italy) and SUPL (Australia)
- Proof-of-Principle: 2 kg of crystal grown

SABRE: Background Expectation

F. Forborg, IDM2016

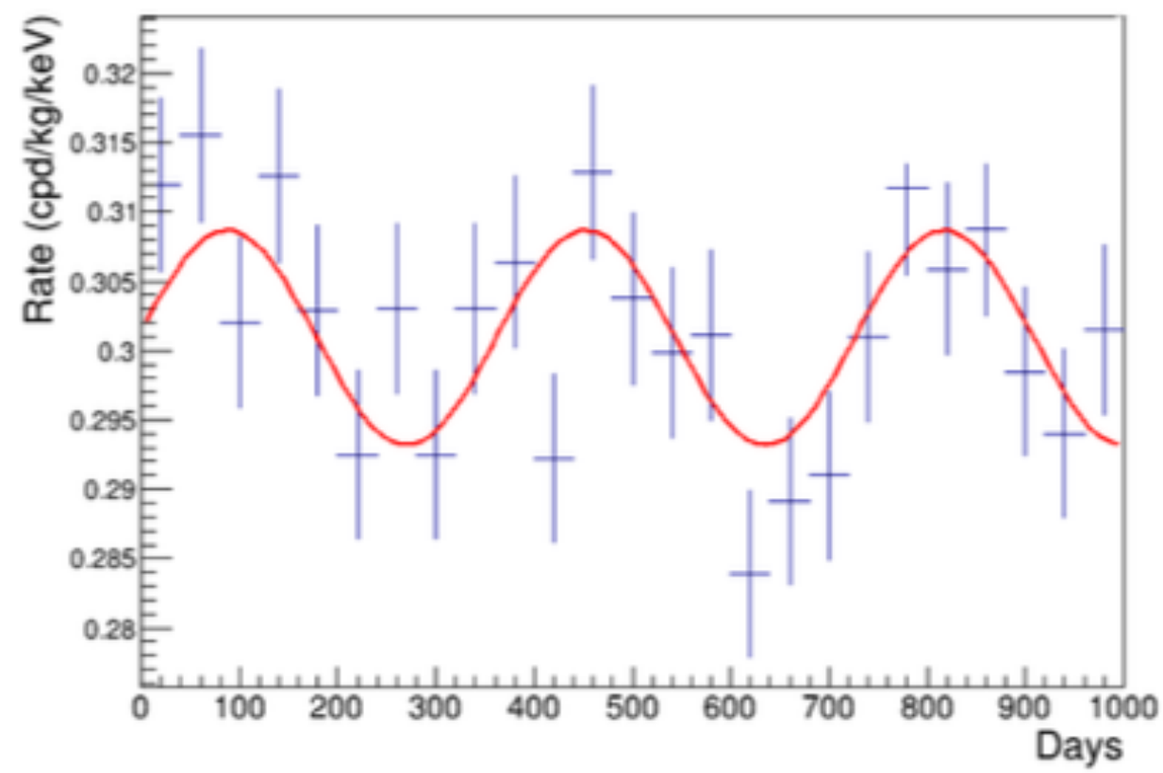
- Focusing on lowering K background from a powder level
- With new NaI power purification, < 10 ppb was achieved
  - Not yet instrumented, only ICPMS assay
  - No ^{210}Pb measurement yet
- Simulated background shows ~0.13 cpd/kg/keV in 2-6 keV region

^{39}K [ppb]	Seastar	PNNL	DAMA
A	9 ± 1	10.0 ± 0.7	
B	7 ± 1	9.1 ± 0.3	
D	11 ± 1	9.7 ± 0.4	
E	9 ± 1	9.8 ± 0.4	
Average	9	9.6	13



SABRE: Plan and Sensitivity

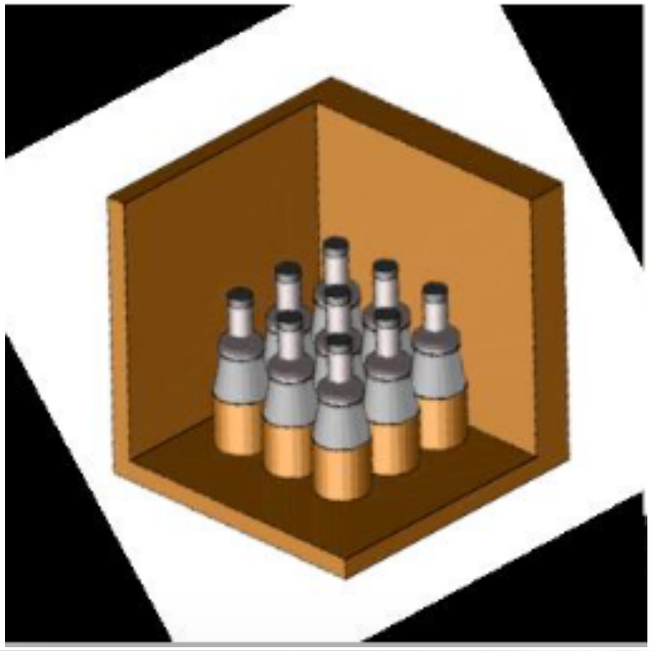
- R&D setup for 1-2 crystals nearly completed
- Full detectors construction at LNGS and SUPL start in 2017
- Goal
  - 50 kg crystals with 3 years of running
  - ROI: 2-6 keV
  - Expect to have 0.13 cpd/kg/keV total background in ROI

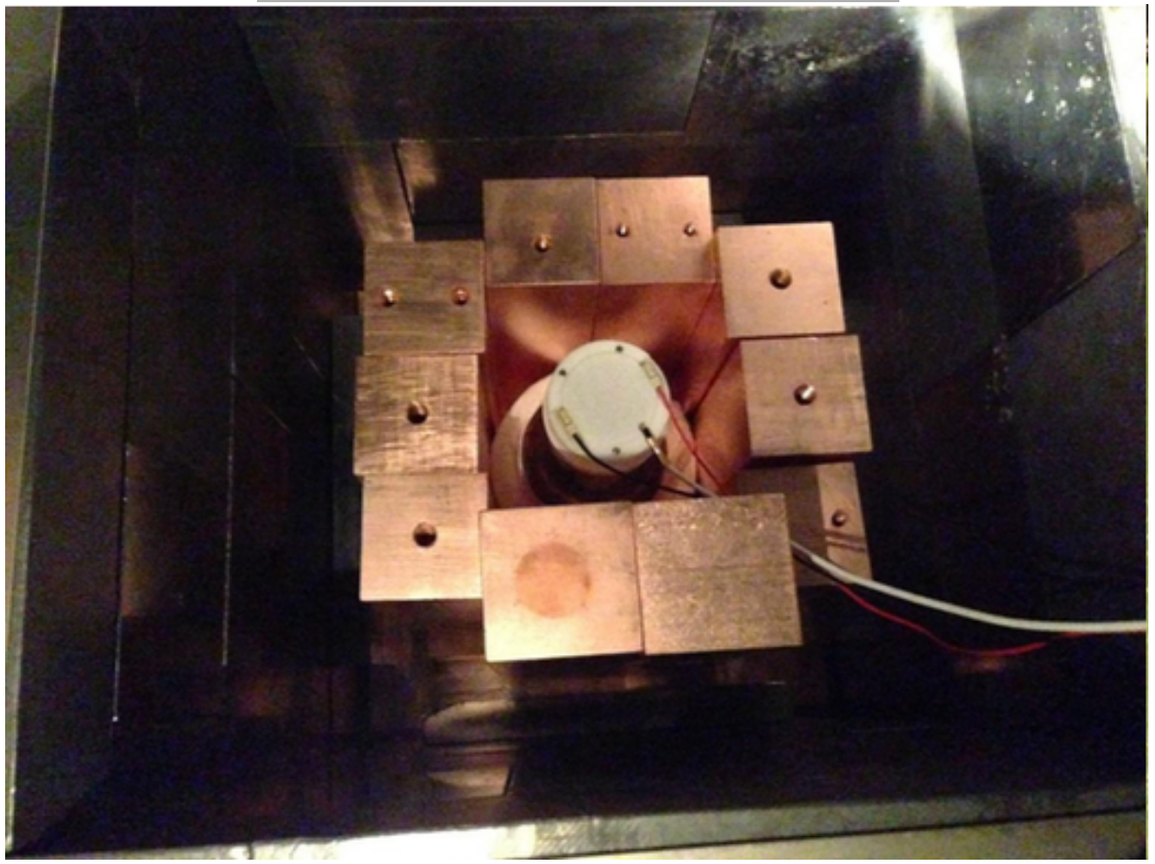


F. Forborg, IDM2016

PICO-LON

- 54 kg of ultra radiopure NaI(Tl)
  - Grown by the collaboration itself
- Located at Kamioka
- Successfully grown 2.3 kg of low background crystal
- R&D setup running

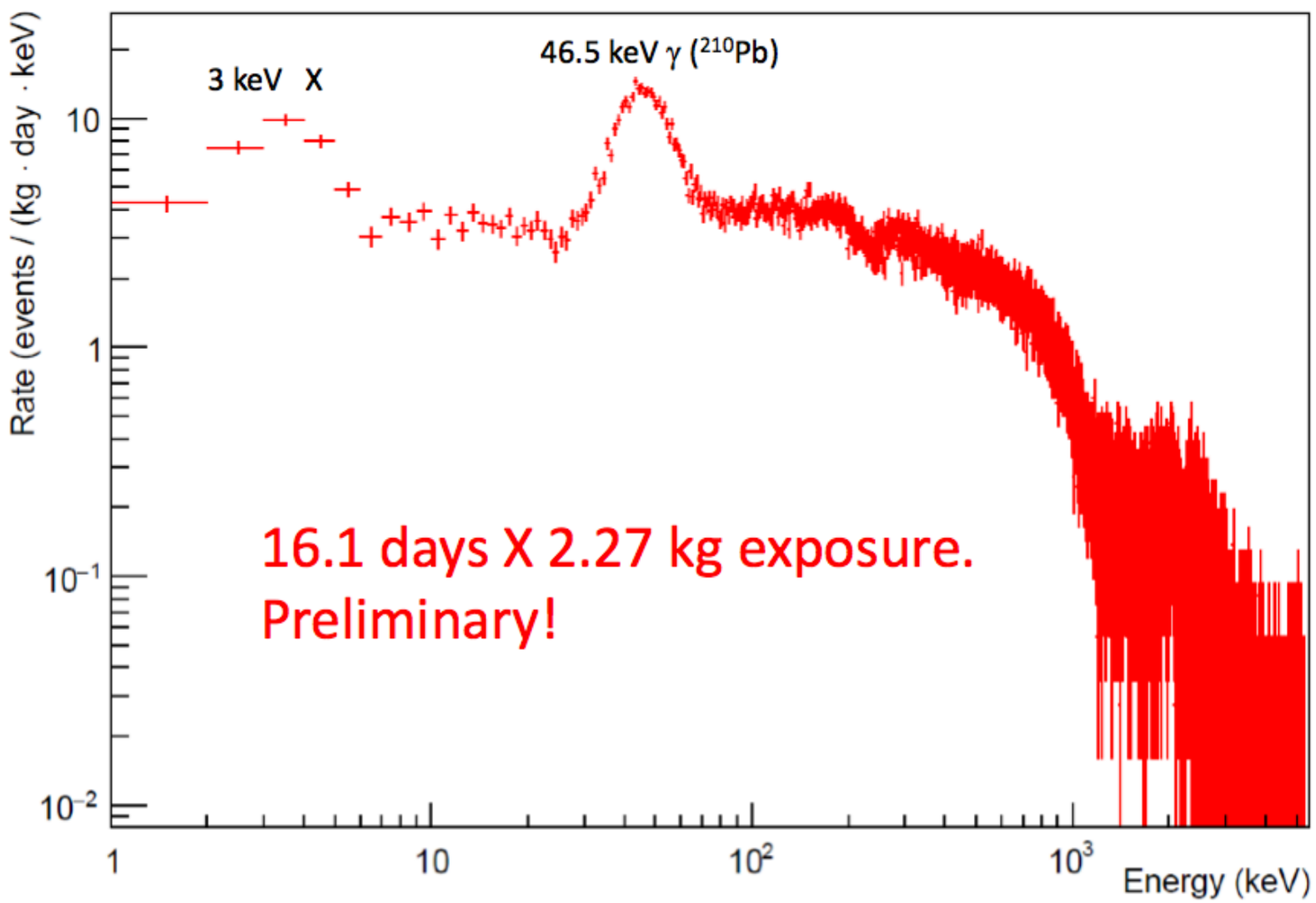




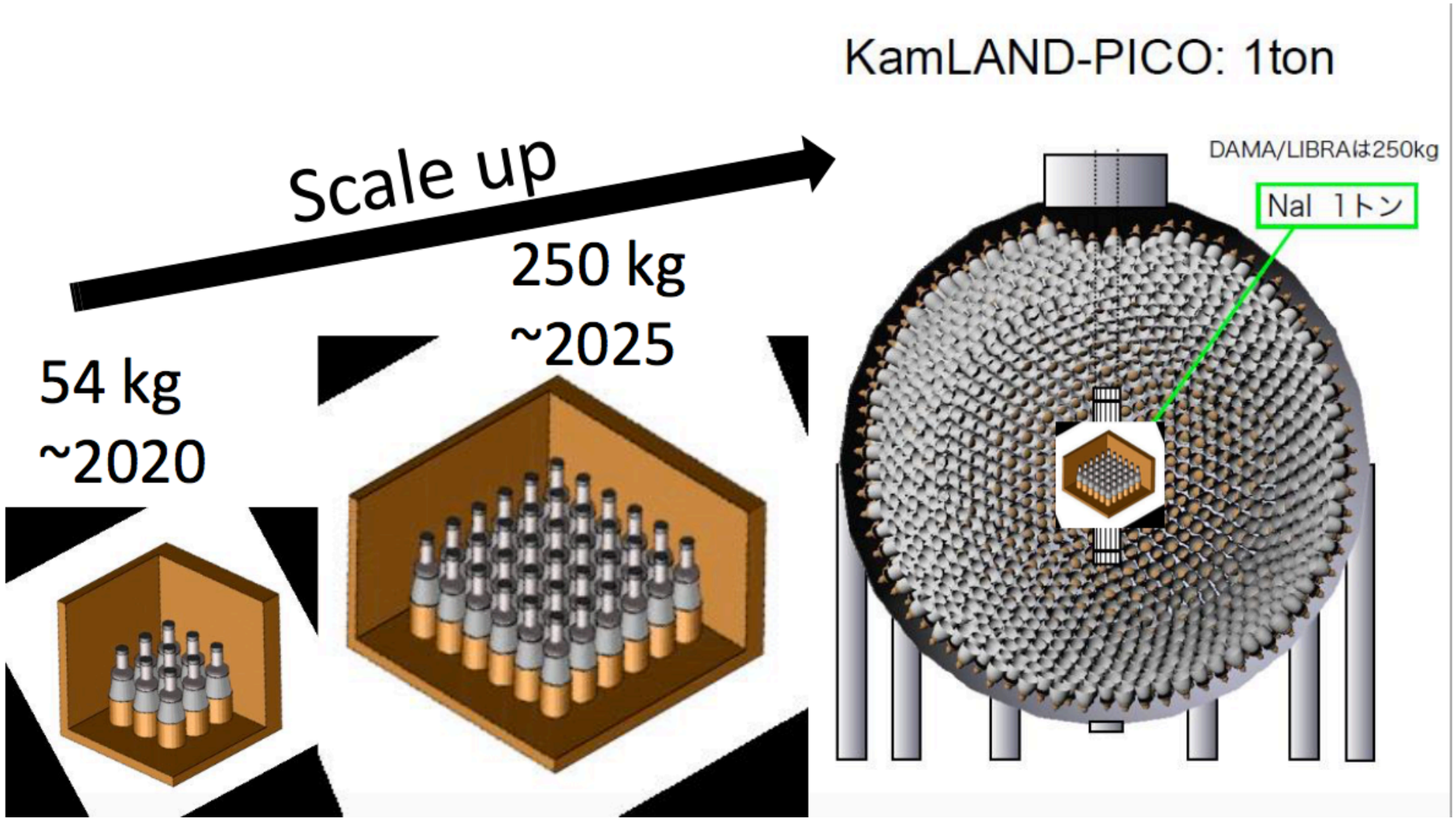
PICO-LON: Background

K. Fushimi, DBD2016

	DAMA	DM-Ice	Ingot 26~37 (2016)	Goal of PICO-LON
^{nat}K (ppb)	<20	660	< 1	<20
^{232}Th(ppt)	0.5-0.7	2.5	0.3±0.5	<4
^{238}U(ppt)	0.7-10	1.4	4.7±0.3	<10
^{210}Pb (μBq/kg)	5-30	1470	29.4±6.6	< 5



PICO-LON: Plan



- Plan to reduce background further

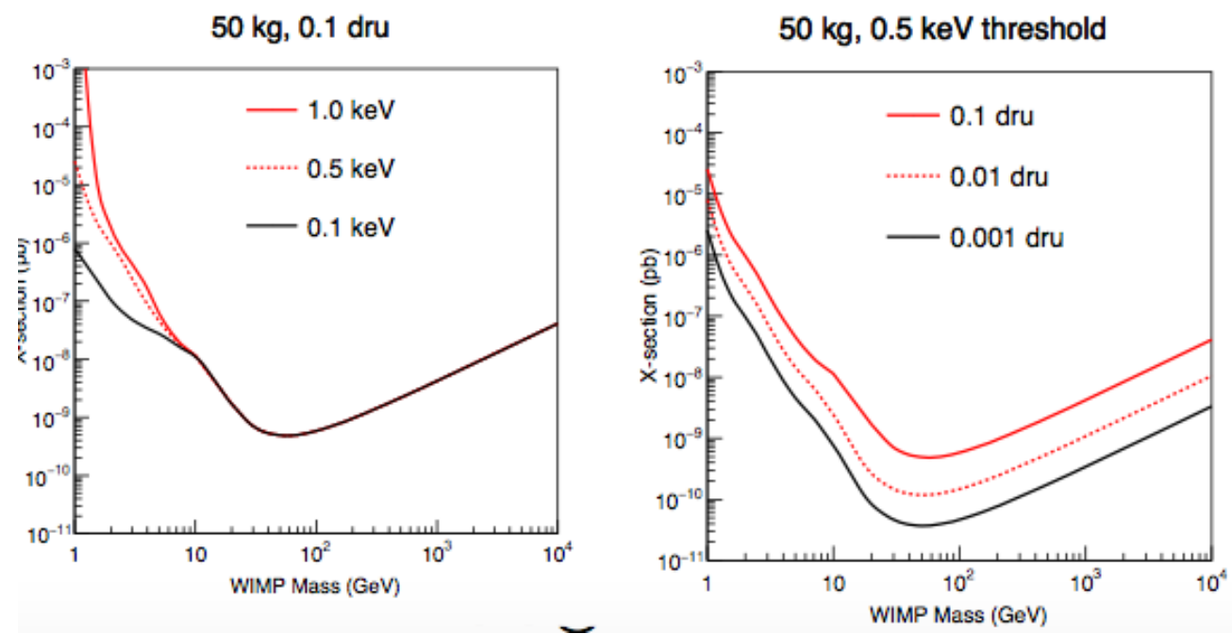
K. Fushimi, DBD2016

- Physics run with 56 kg will start 2017~2018
- Future phases include installation in KamLAND

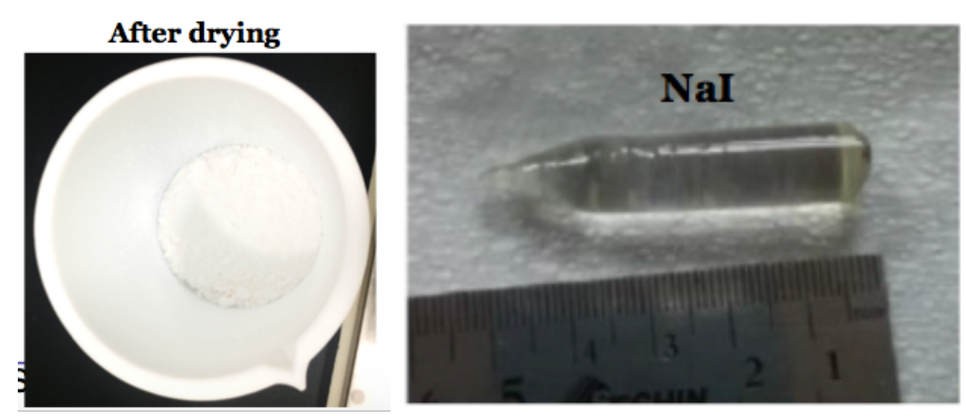
How can we improve sensitivity

- 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:
    Powder purification, growing process underground…
  - Low background PMTs: Metal body PMT?
  - Low-temperature detectors: Higher light yield & lower PMT noise



What if we do see signal?

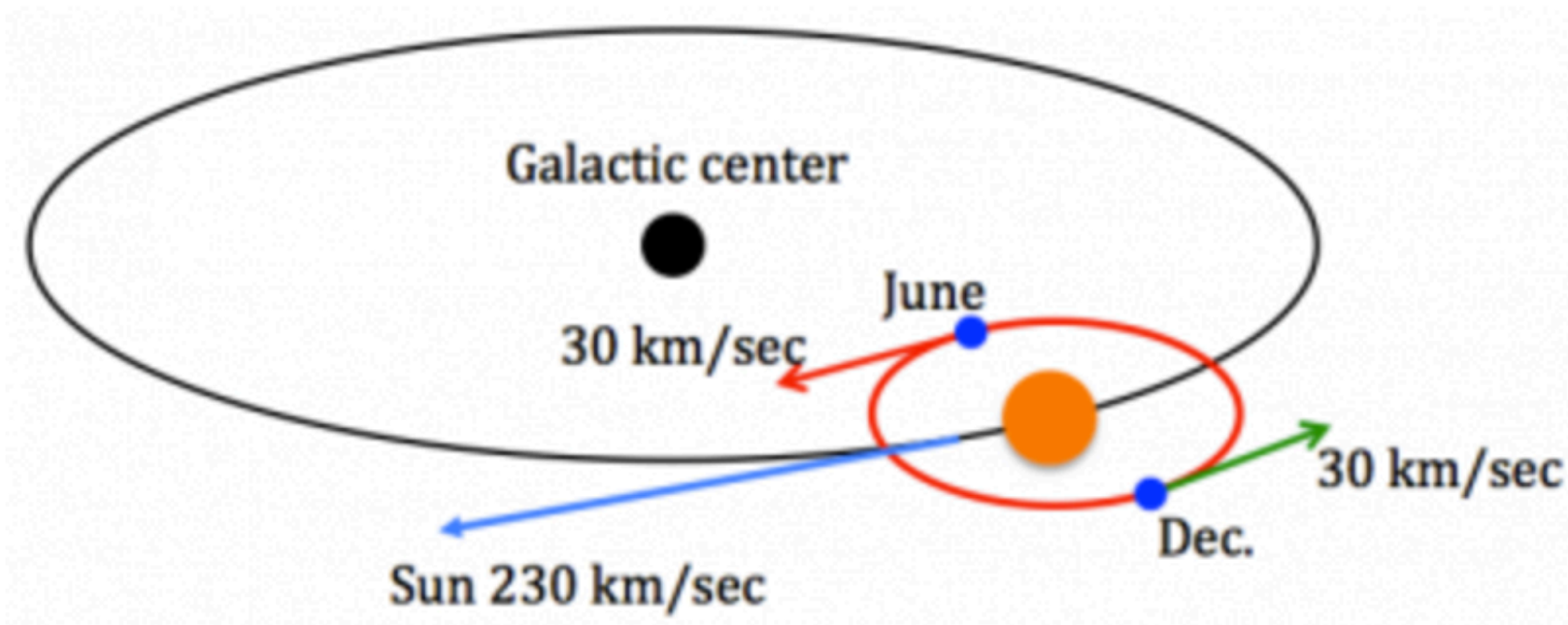
- Need to find out what is causing it!
- Intensive follow-up study will be required…
- Operating the same type of experiment at Southern Hemisphere helps to disentangle seasonal effect
  - SABRE, DM-Ice, COSINE-Phase N, …
- As we lower our background level (< modulation amplitude?), more we can learn about the signal…

Conclusion

- WIMP interpretation of DAMA signal in tension with other experiment: Independent NaI(Tl) experiments are needed
- COSINE-100 is running with 108 kg of NaI(Tl) crystals, expecting to have DAMA-comparable sensitivity in ~2 years
- Global efforts with NaI detectors on-going, including ANAIS, SABRE, PICO-LON, etc.
- For stronger limit, lowering the analysis threshold as well as growing ultra low background crystal needed
- Very exciting time for NaI dark matter search…stay tuned!

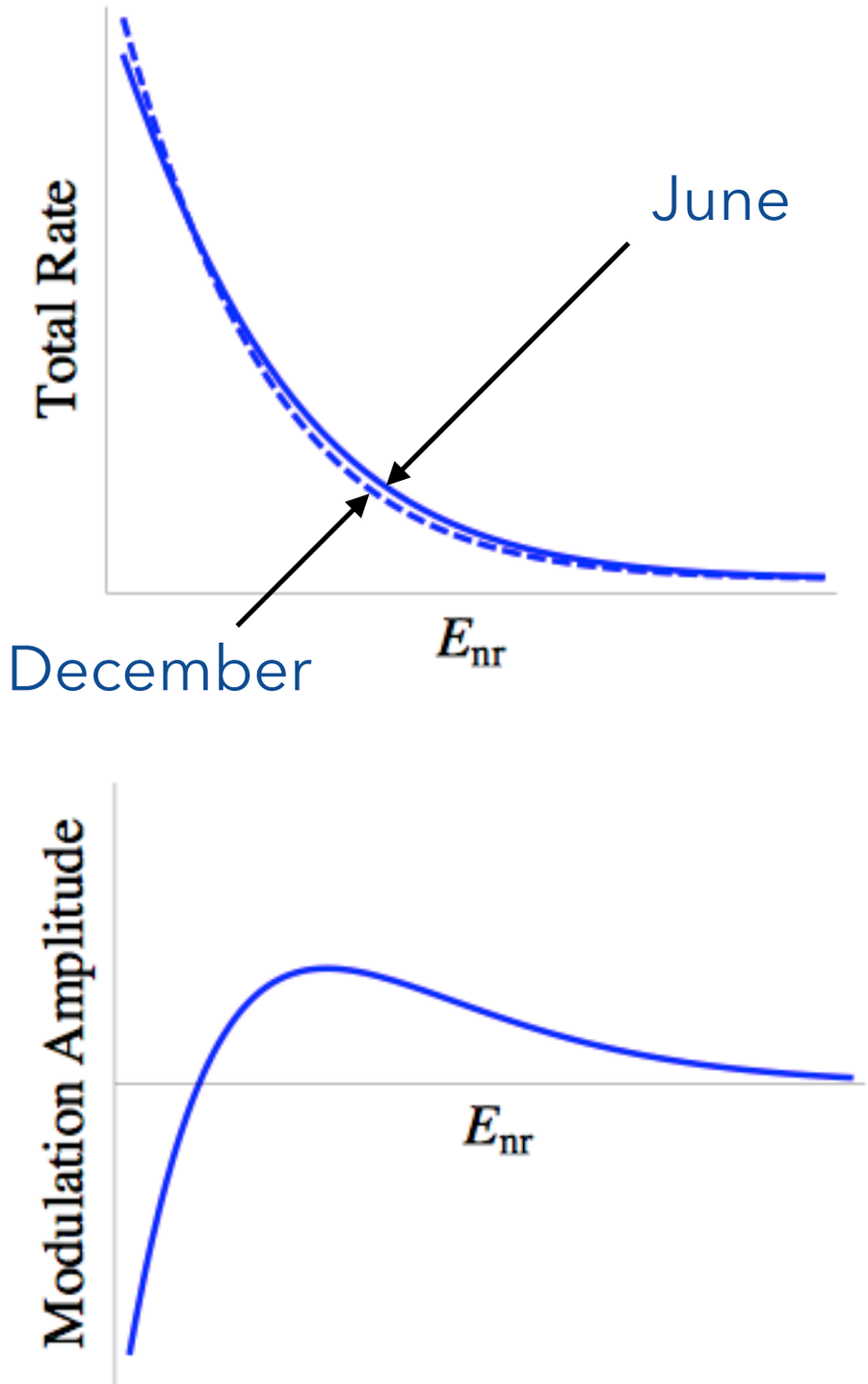
Backups

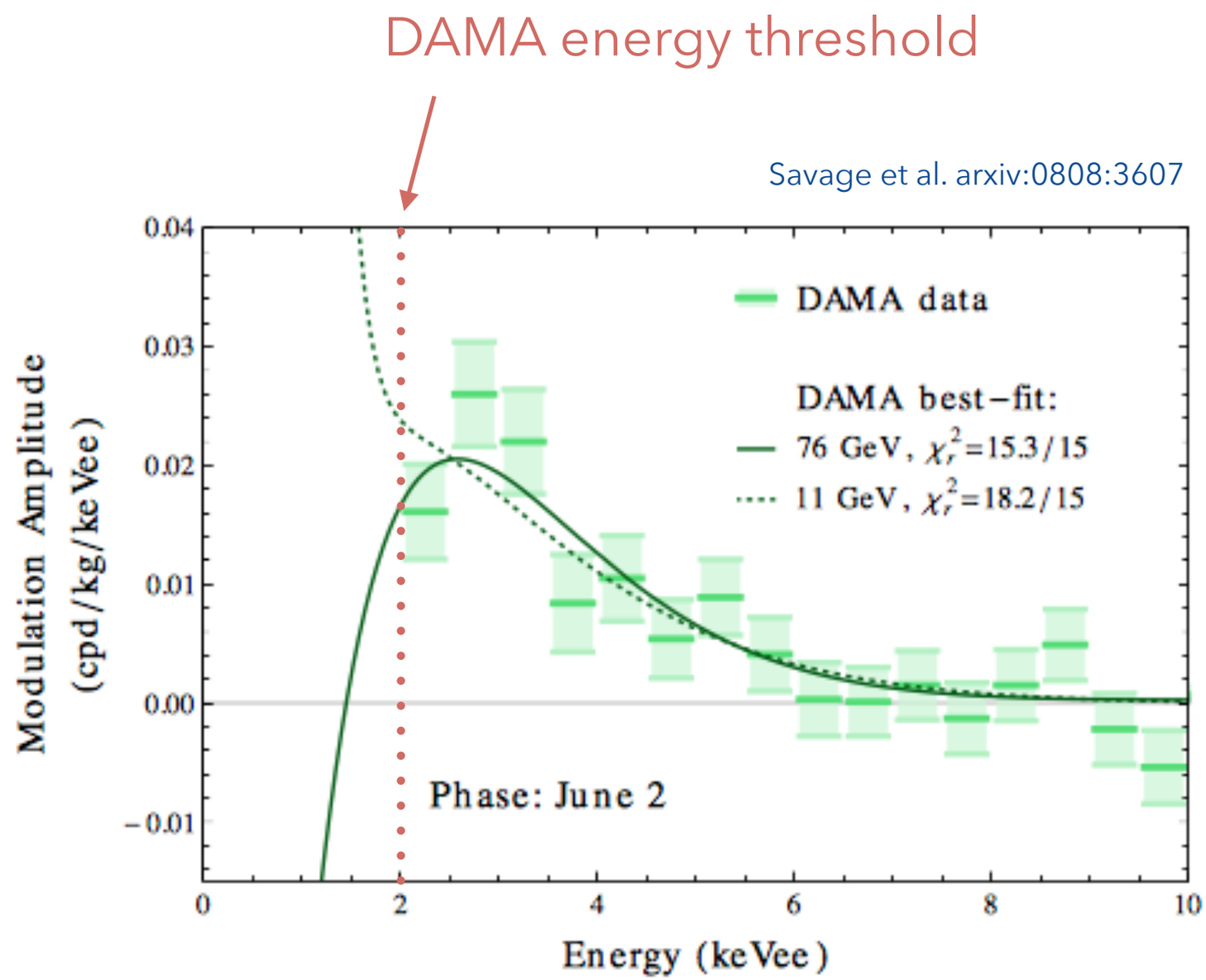
Annual Modulation



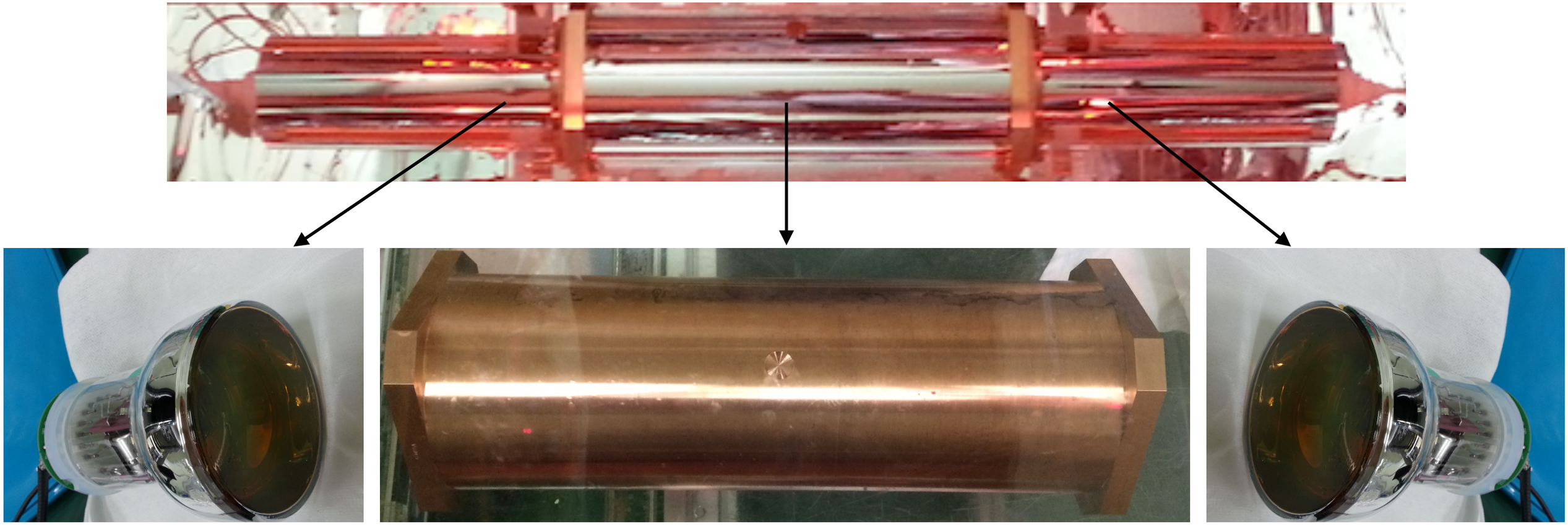
- Galactic dark matter is believed to be distributed in a halo
- Earth's motion around the sun causes annual modulation of dark matter (with a 1 year period and peak @ June 2)

Interpretation of the DAMA Result



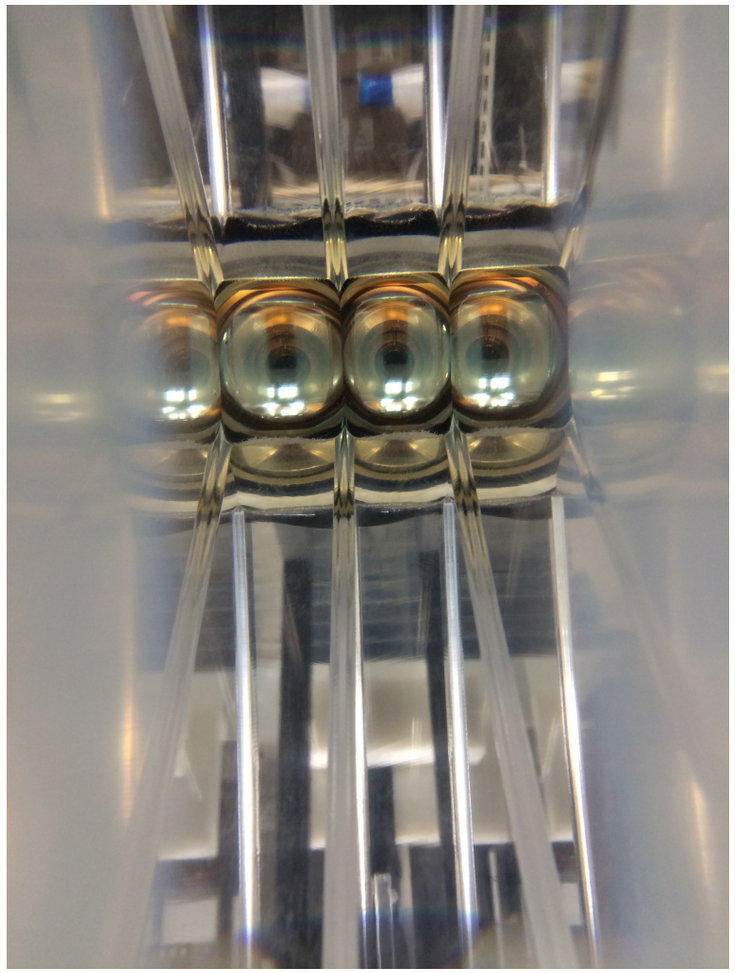


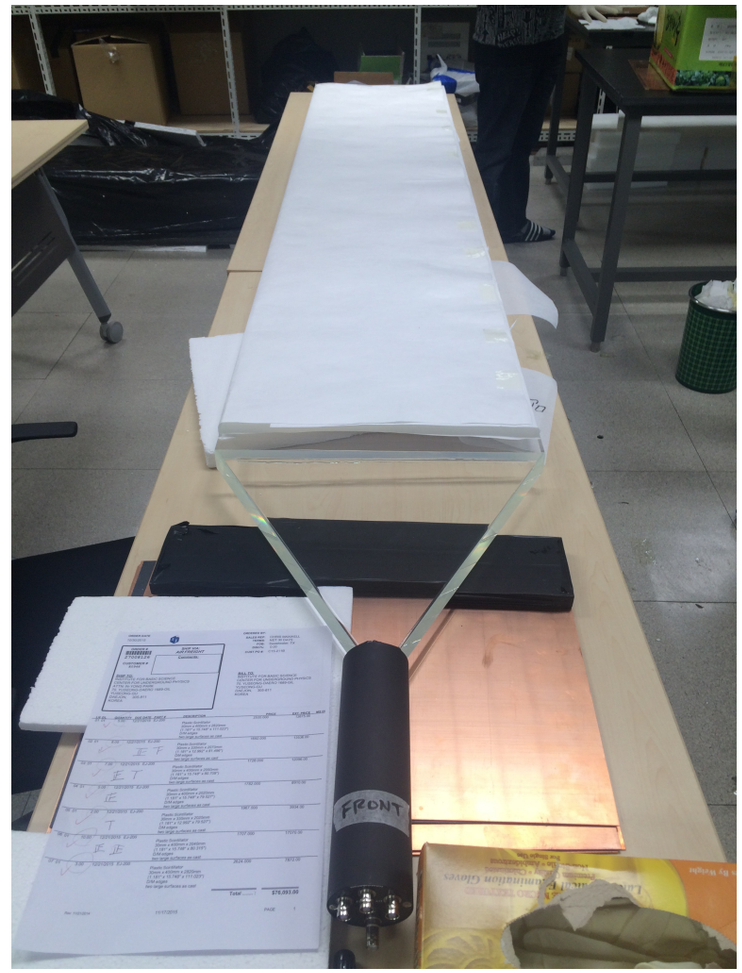
Crystal-PMT Assembly



- 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

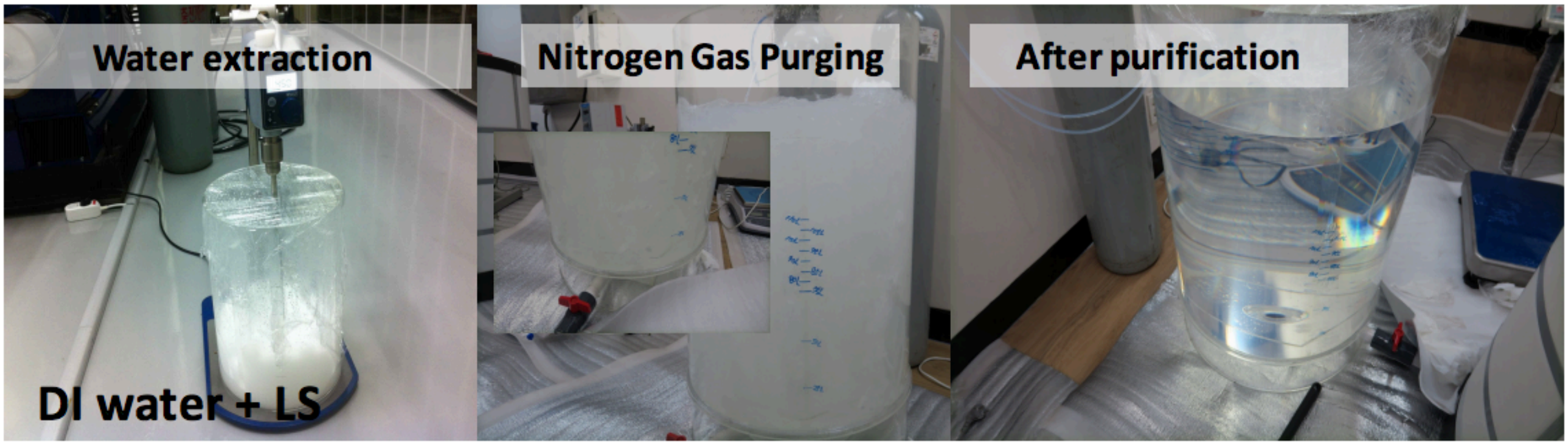
Plastic Scintillator





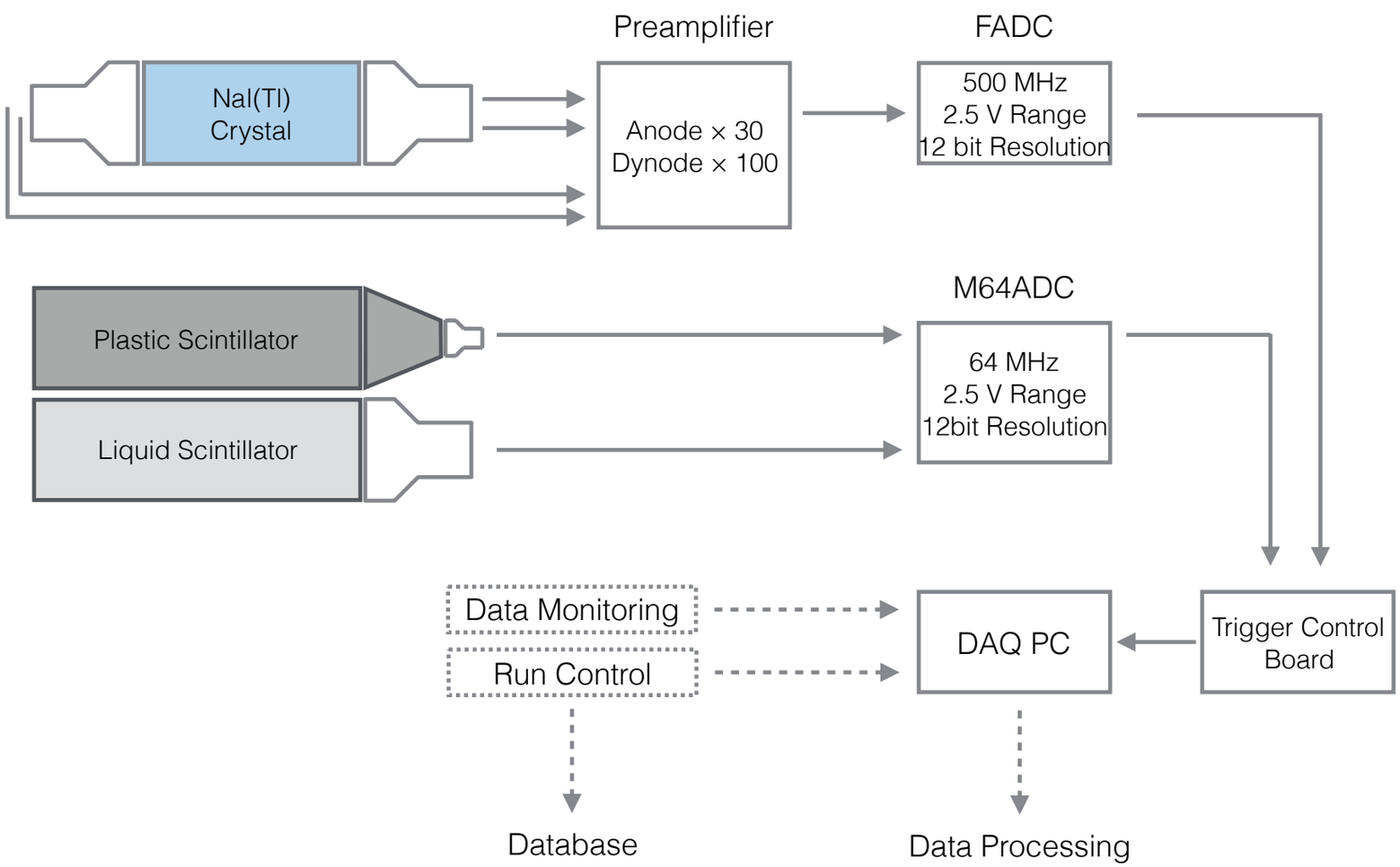
- Purpose: To tag cosmic ray muon events
- 37 panels of plastic scintillator (EJ-200), 3 cm thick
- Attached with light guides and 2-inch PMT, wrapped with diffuse reflector

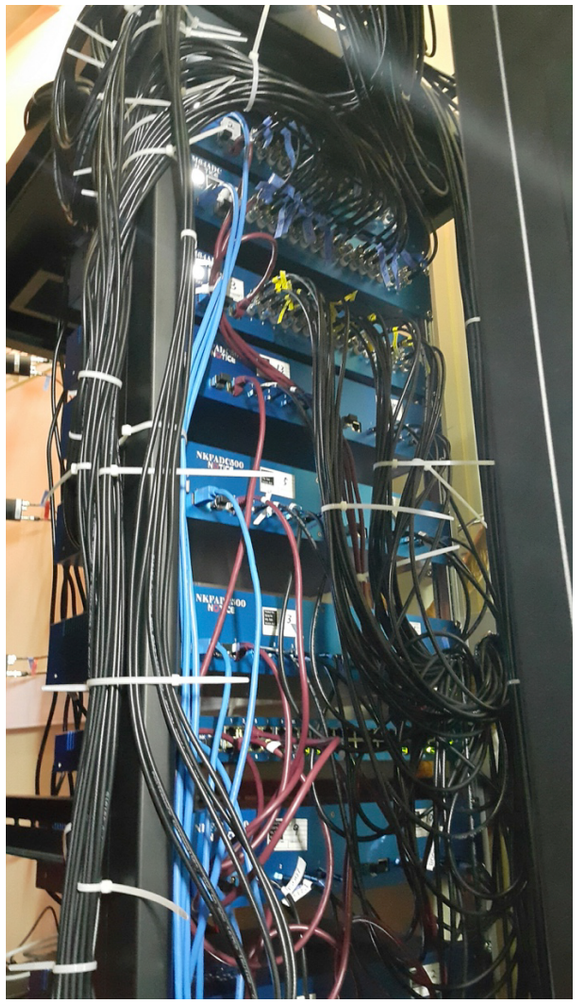
Liquid Scintillator



- 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

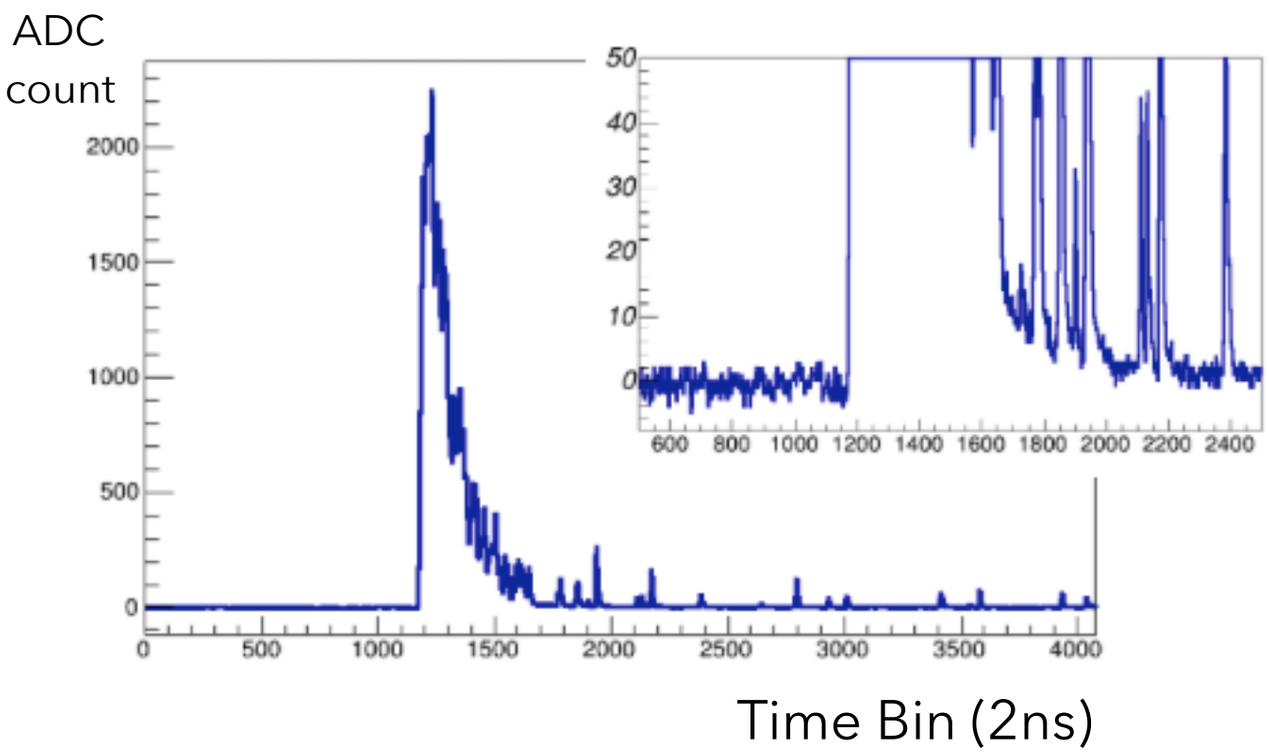




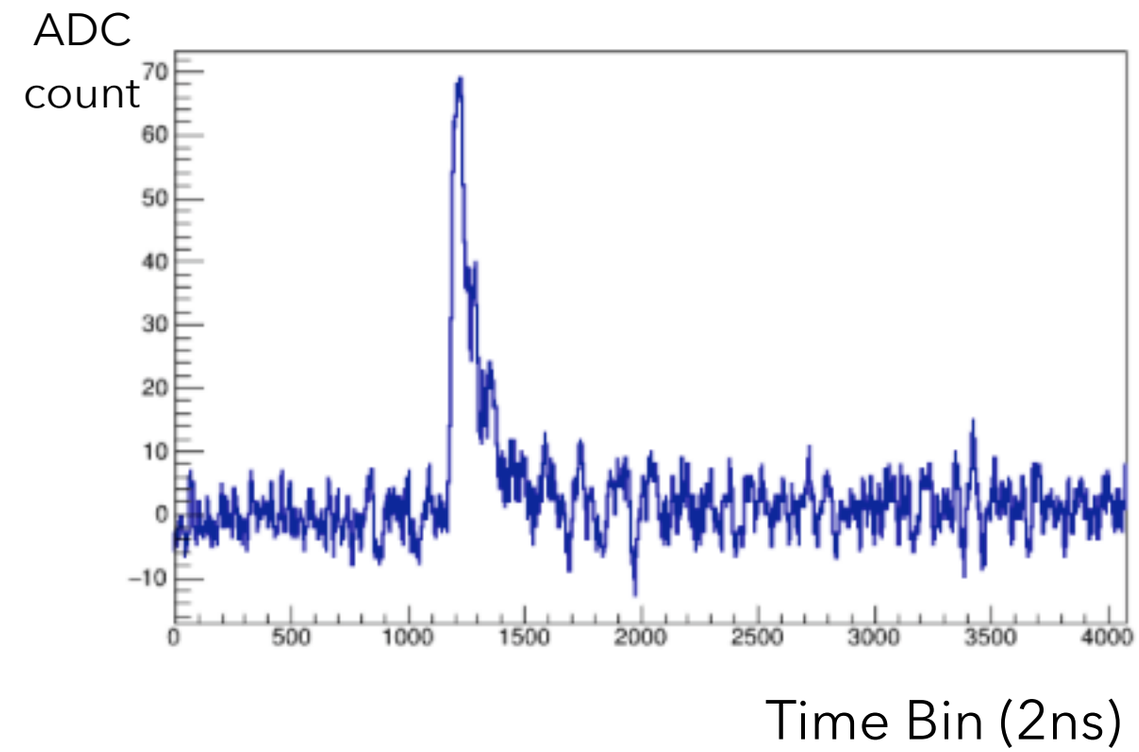
- Crystal data taken with FADC 500 Mega samples/sec waveform digitizer
- M64ADC data taken with M64ADC 64 MHz waveform digitizer
  - Plastic and liquid scintillator data

Crystal PMT Waveforms

Anode Waveform
(0-120 keV)



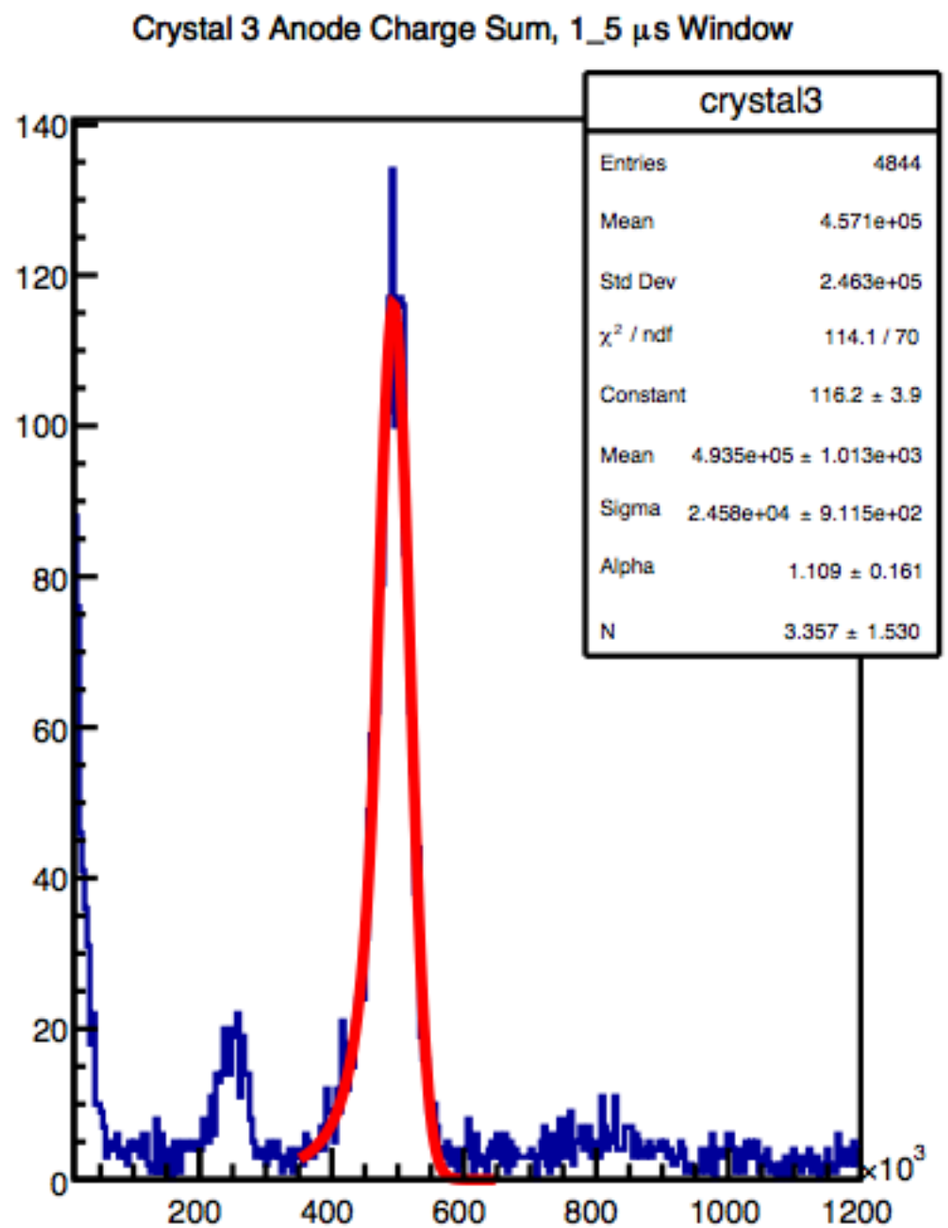
Dynode Waveform
(50-10,000 keV)



- 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

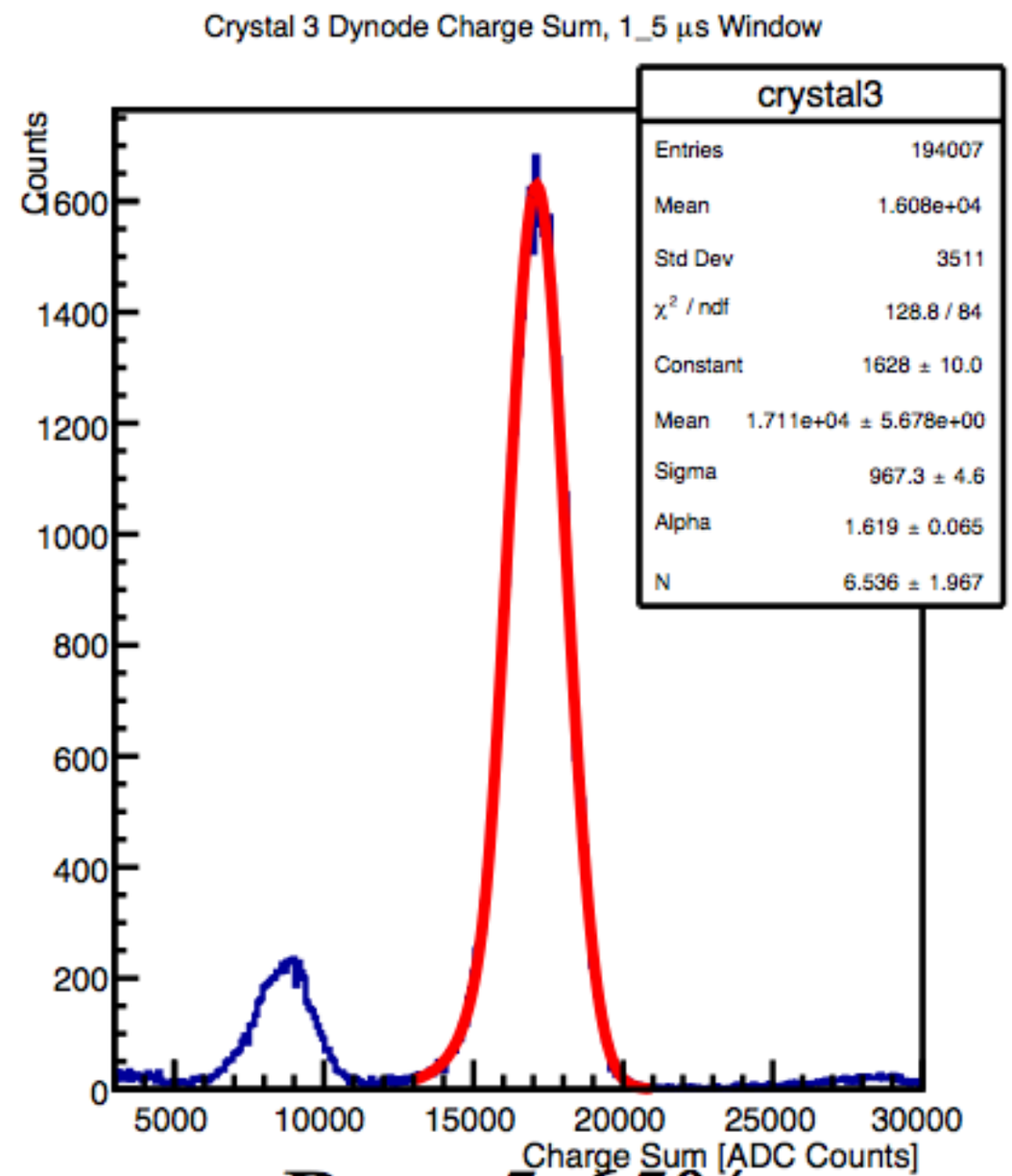
Resolution @ 60 keV

Am-241 ADC sum (Anode)



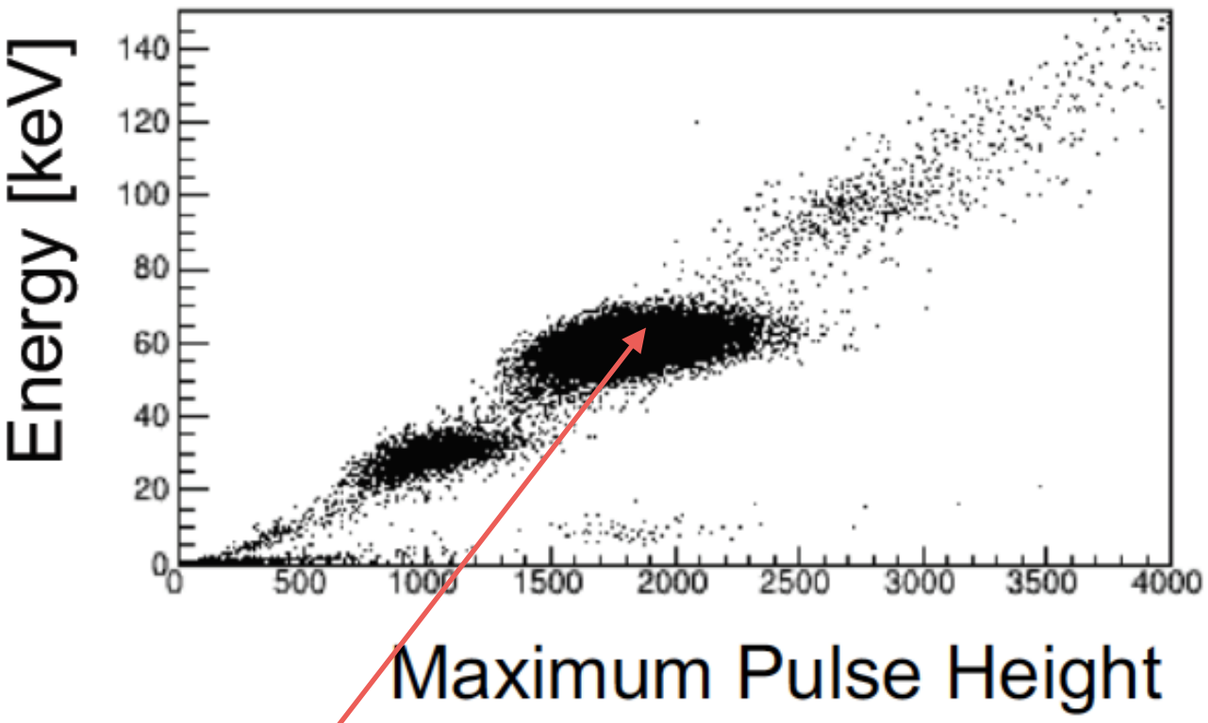
Res: 4.98%

Am-241 ADC sum (Dynode)

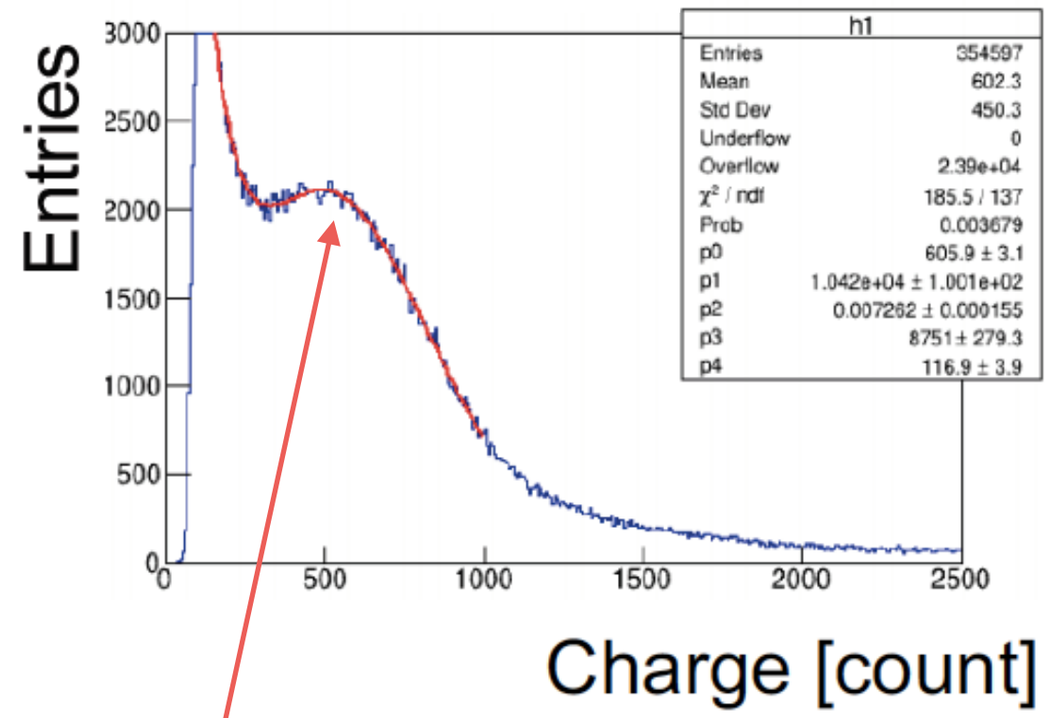


Res: 5.65%

Calibration/Light yield calculation



60 KeV gamma

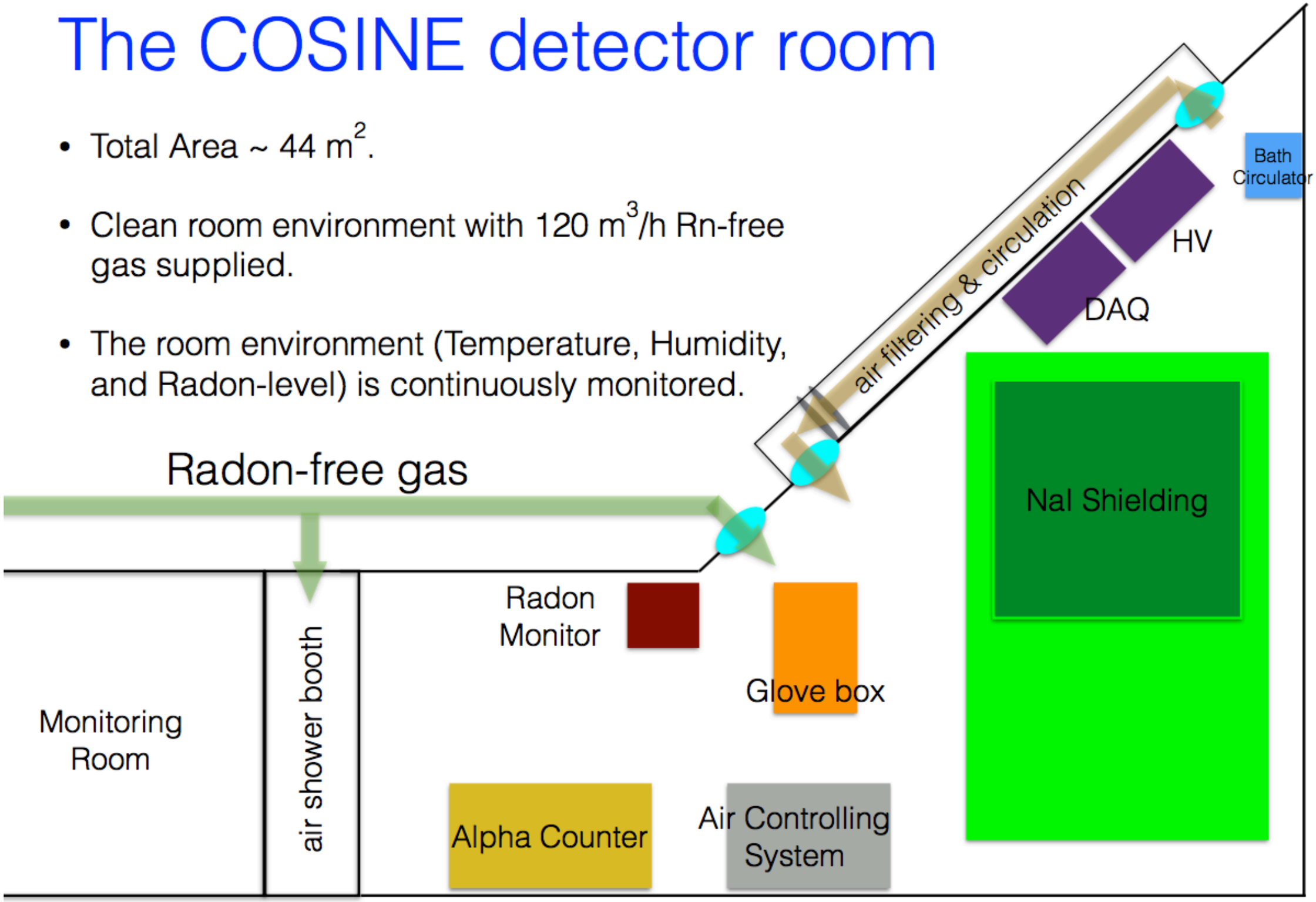


SPE

- ^{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

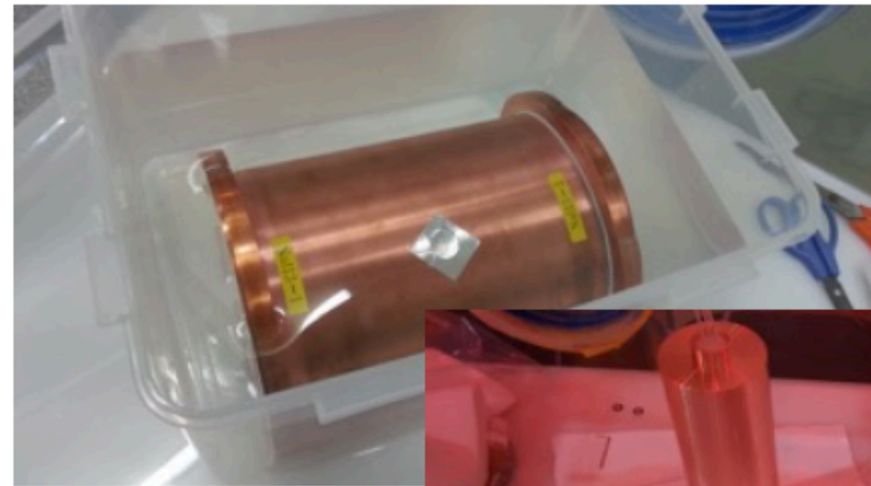
The COSINE detector room

- 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.



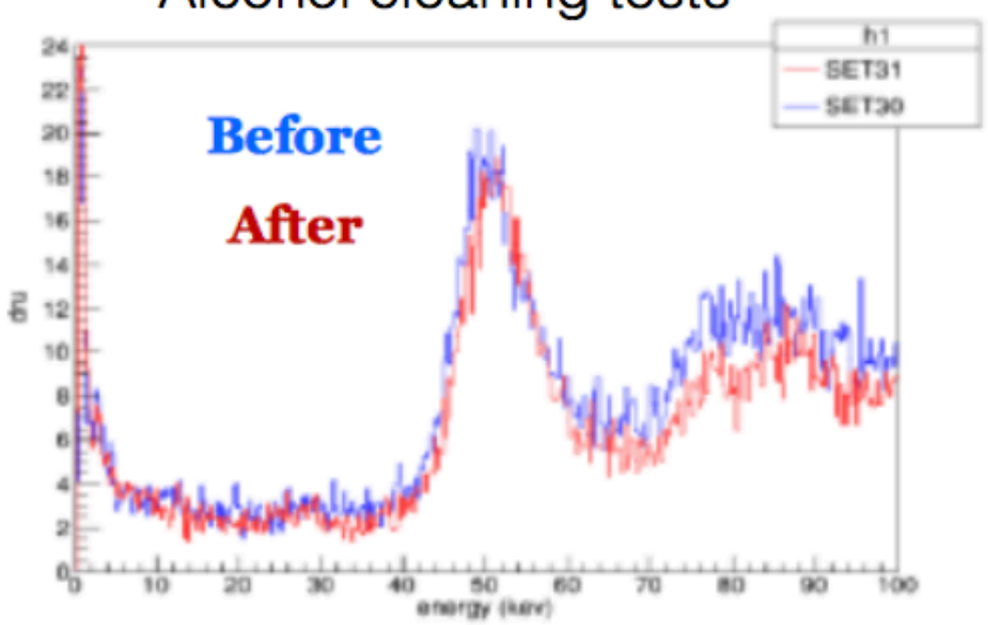
Cleaning of Crystals and Parts

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

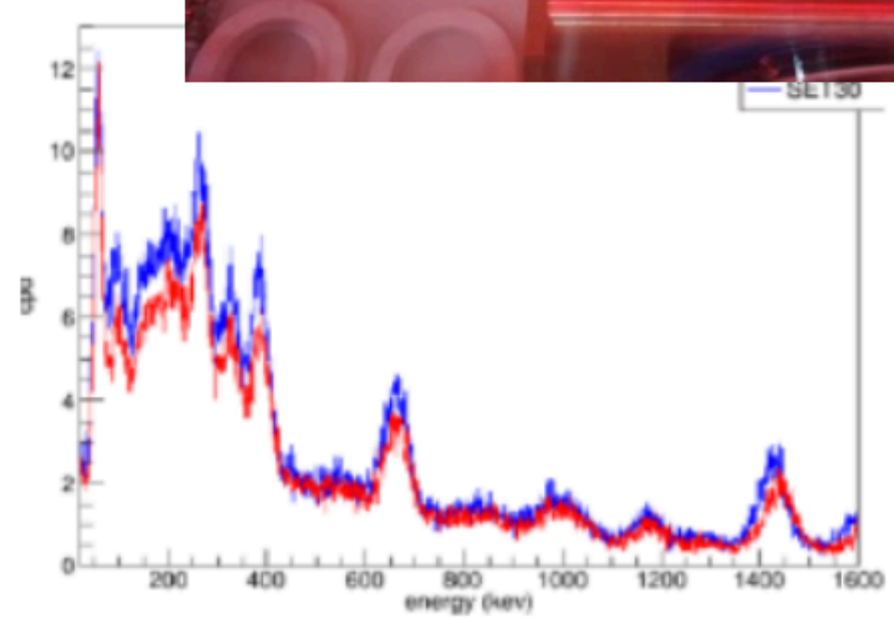


Previously, 0.3 dru reduction at 6-20 keV

Alcohol cleaning tests

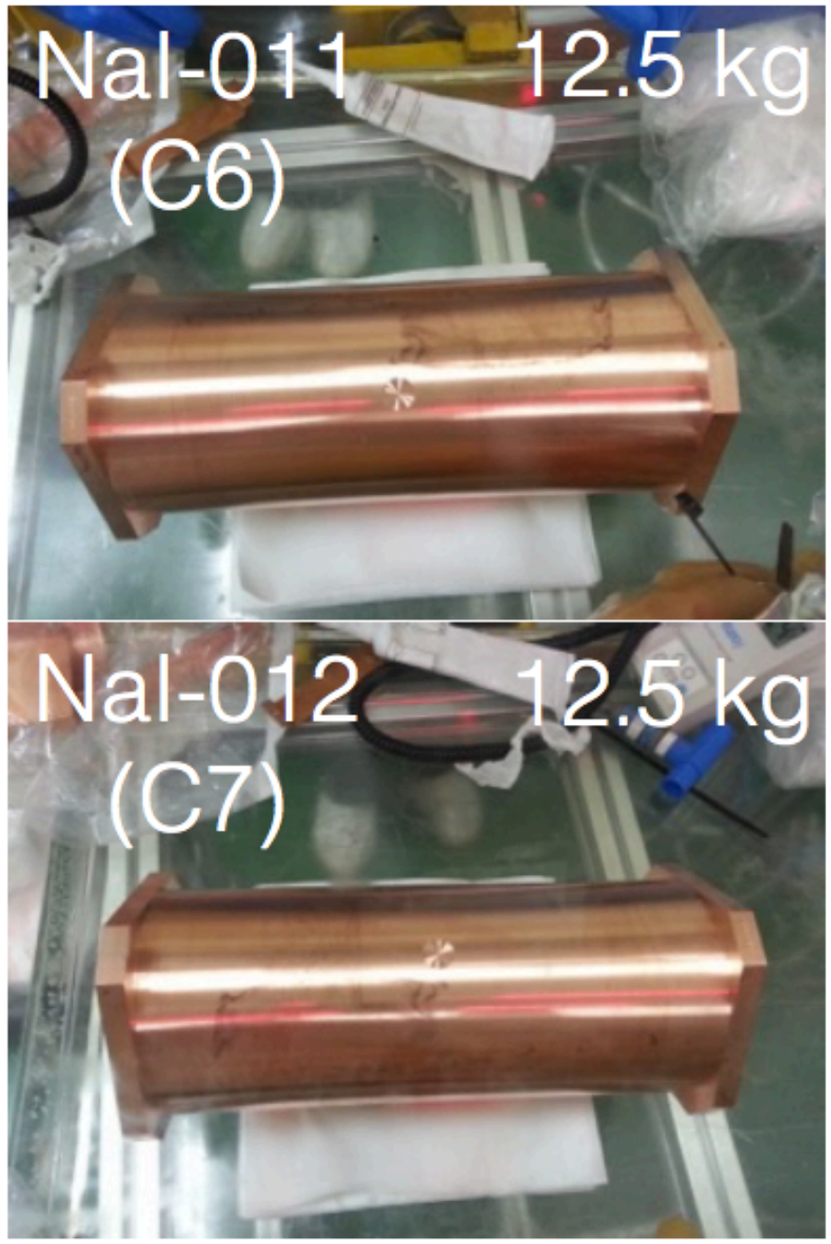


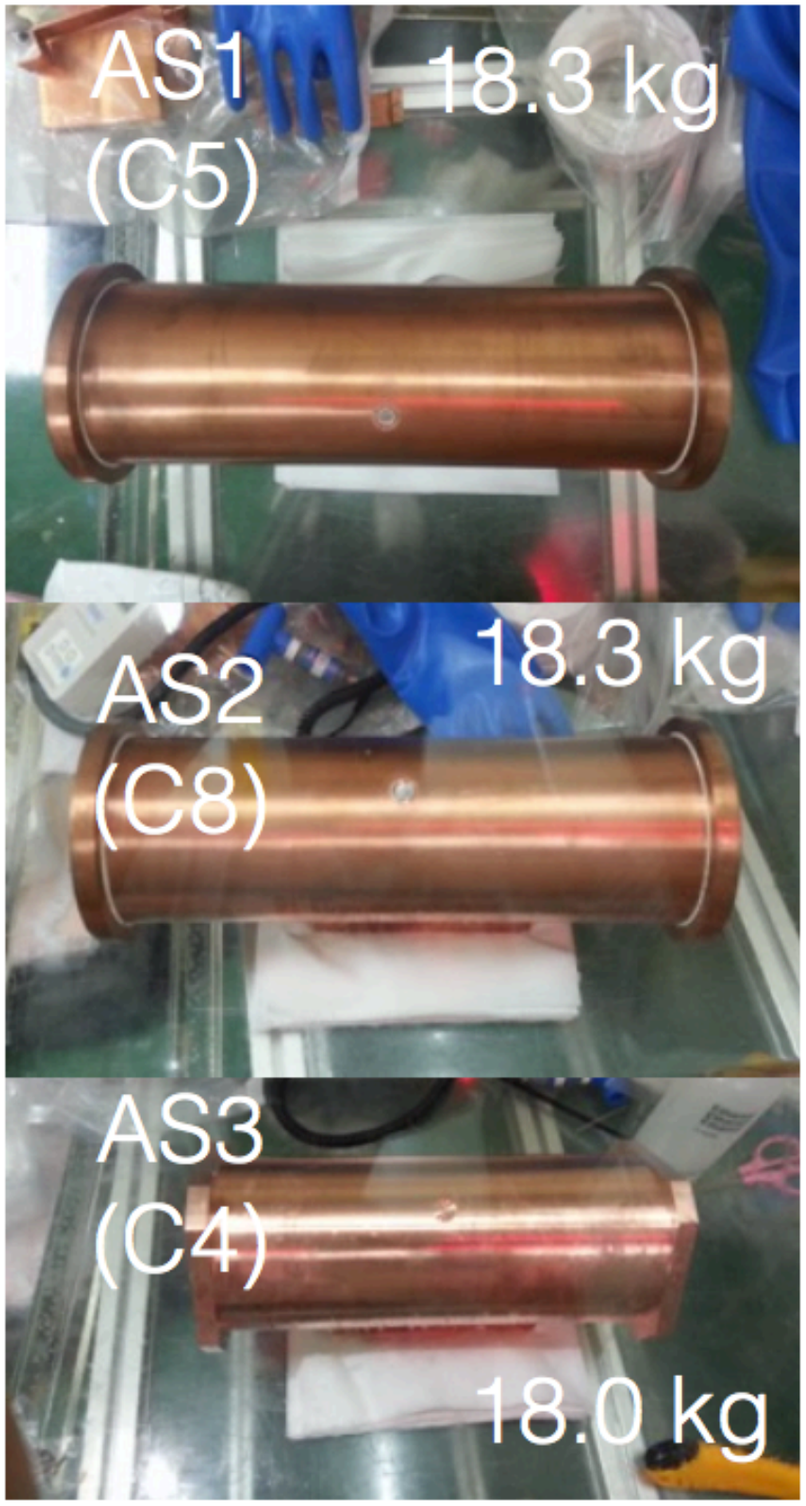
Low Energy



High Energy

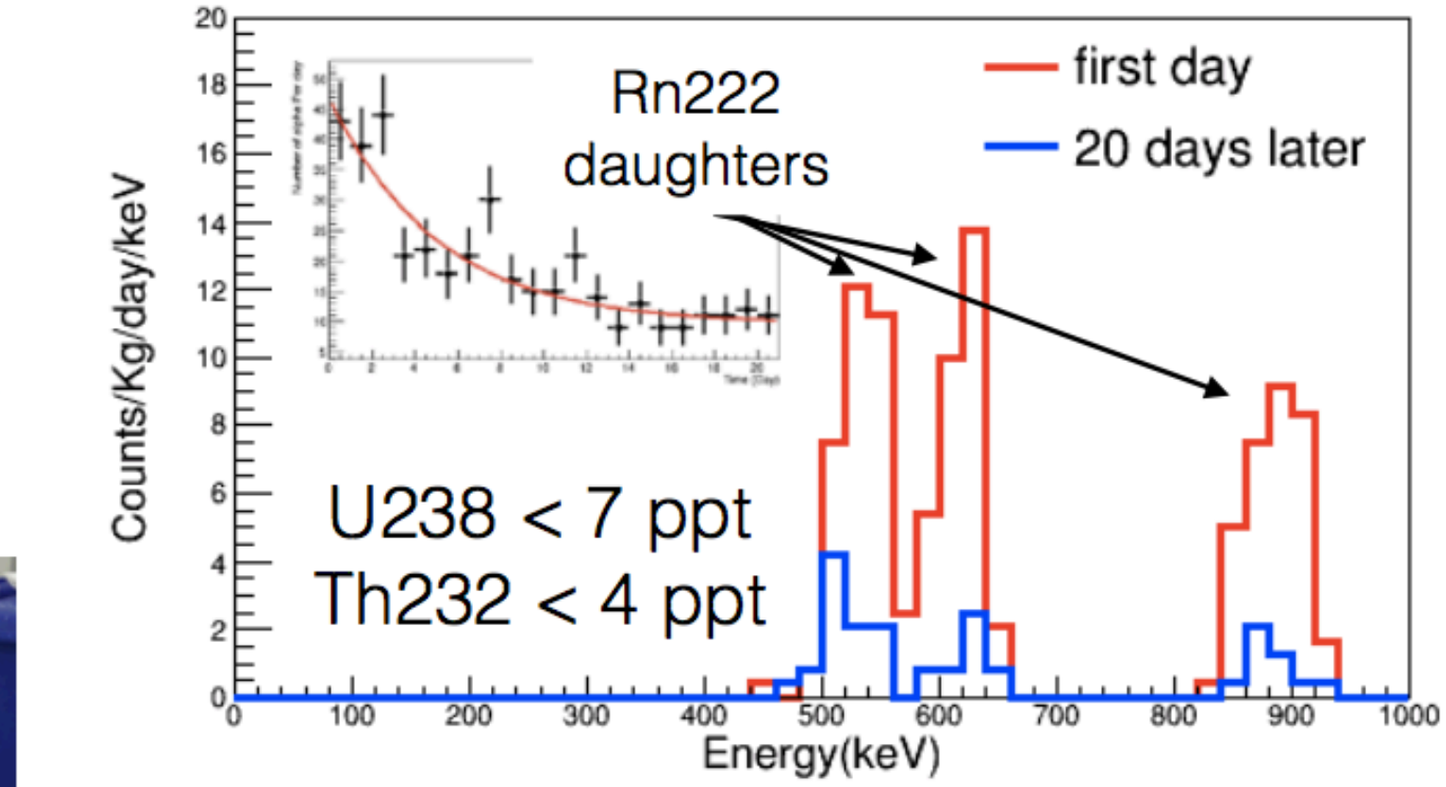
COSINE-100 Crystals

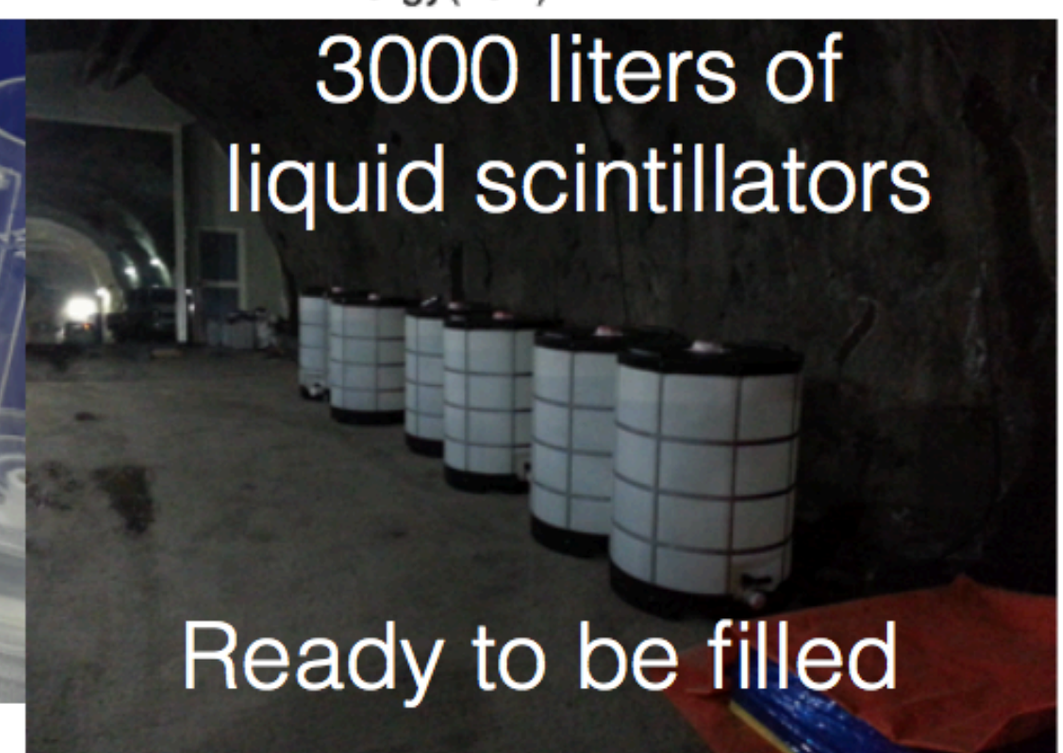




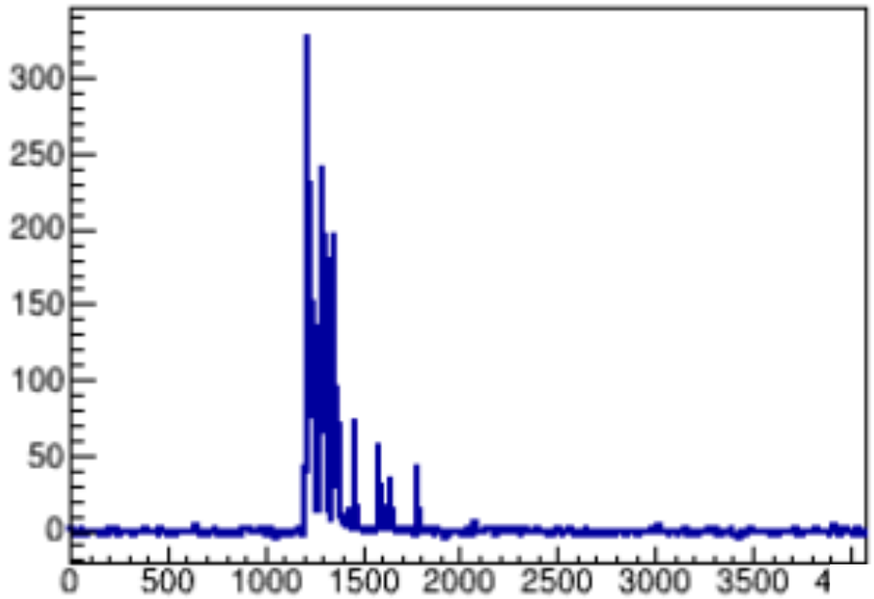
LS for COSINE-100

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



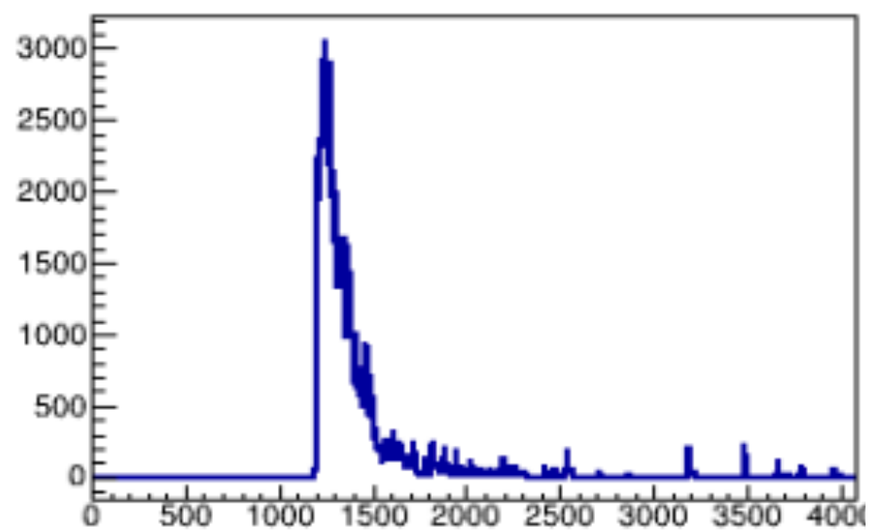


Examples of Signal Events

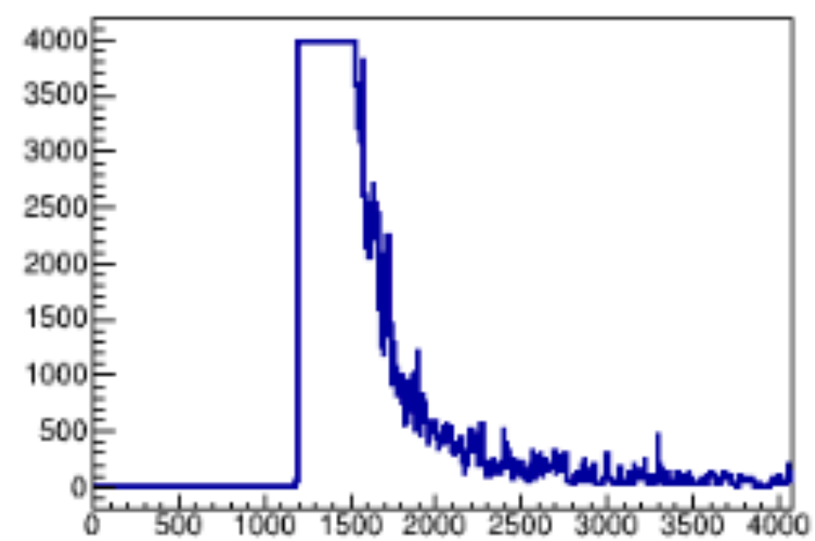


3 keV

100 keV

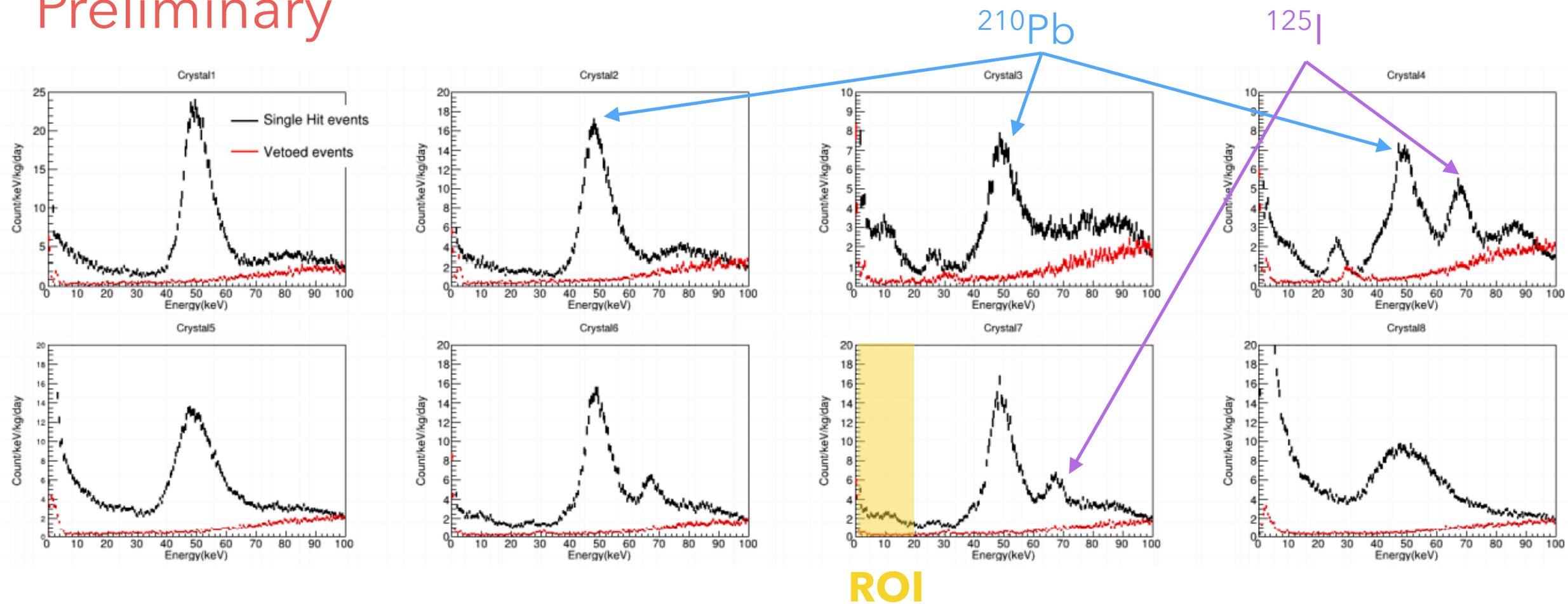


> 1 MeV



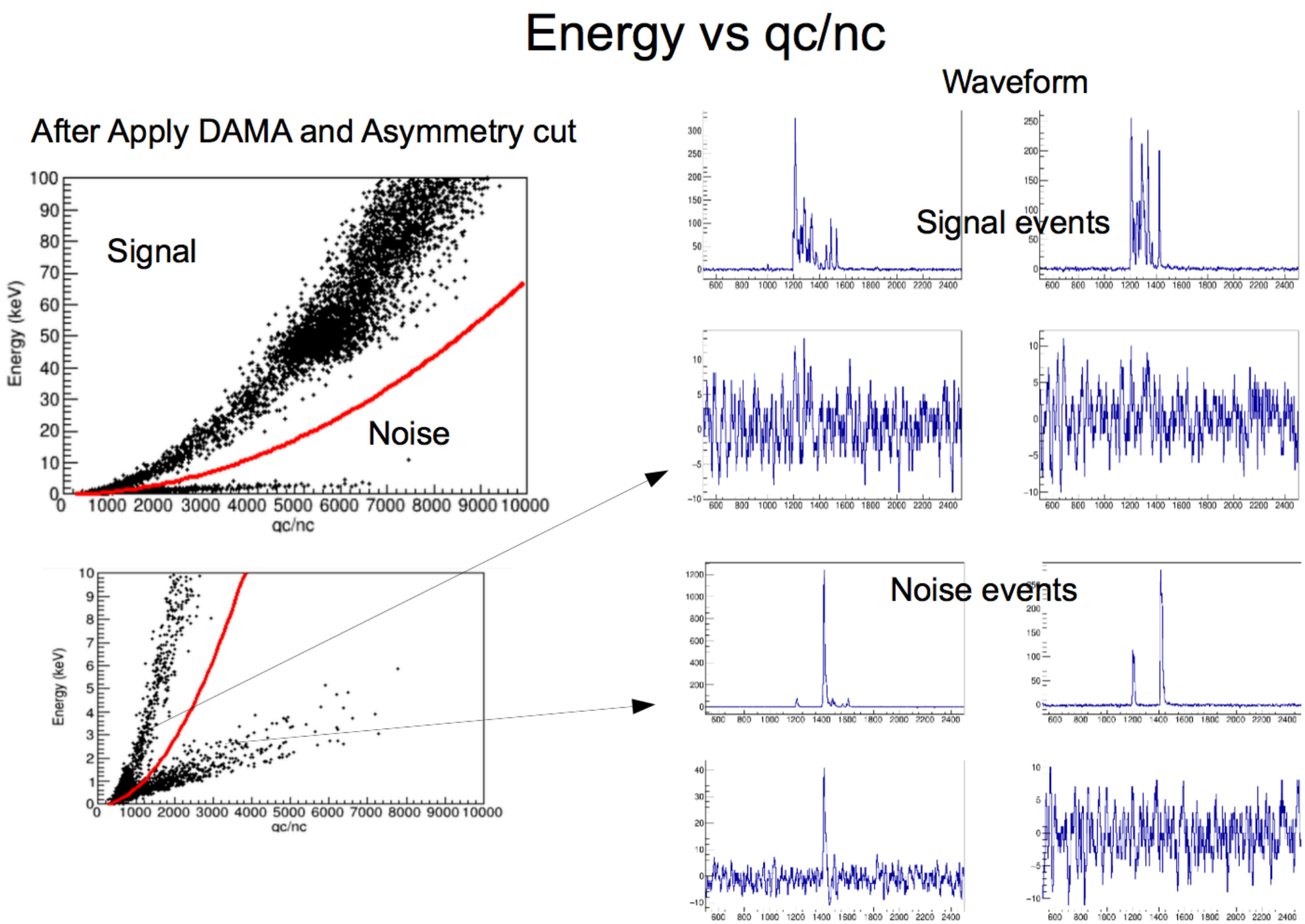
Low Energy Spectrum

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

Average charge/SPE cut



Crystal growing in Korea

Under development

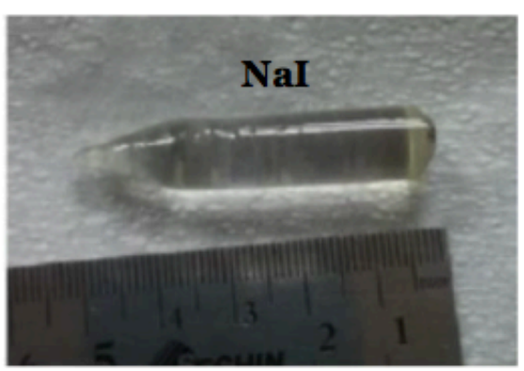
Czochralski Furnace

Bridgman Furnace

1st crystal (Sapphire) grown ~ 30kg !

Kyropoulos Furnace

Bridgman



- A small NaI was grown in Korea
- We will try to grow **larger crystals**
  - ❖ A special Kyropoulos machine is under consideration

- Whole procedure can be done by ourselves
  - ❖ Speed up the R&D of background reduction

H. Lee, IDM2016