The Status of the COSINE-100 Dark Matter Experiment

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Yale University

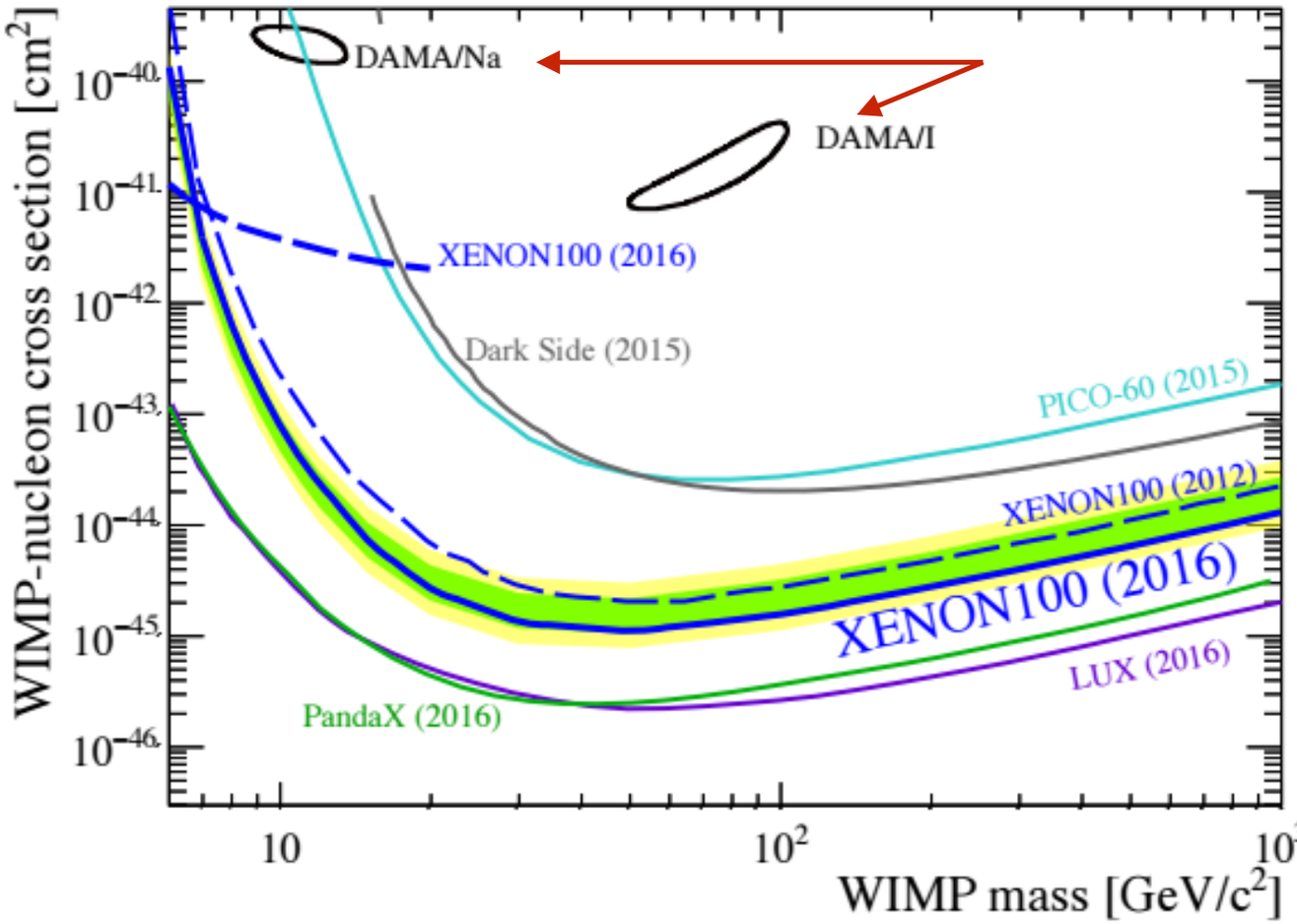
WIN 2017

June 23, 2017

Wright Laboratory

Yale

Current Status of WIMP Searches



XENON100 Collaboration, Phys. Rev. D **94**, 122001

- Liquid xenon detectors currently provide the best sensitivity to spin-independent WIMP scattering
- Tension with the DAMA/NaI and DAMA/LIBRA results: no other experiment have been able to confirm the dark matter signal claim
- More stringent exclusion limits cannot answer this question

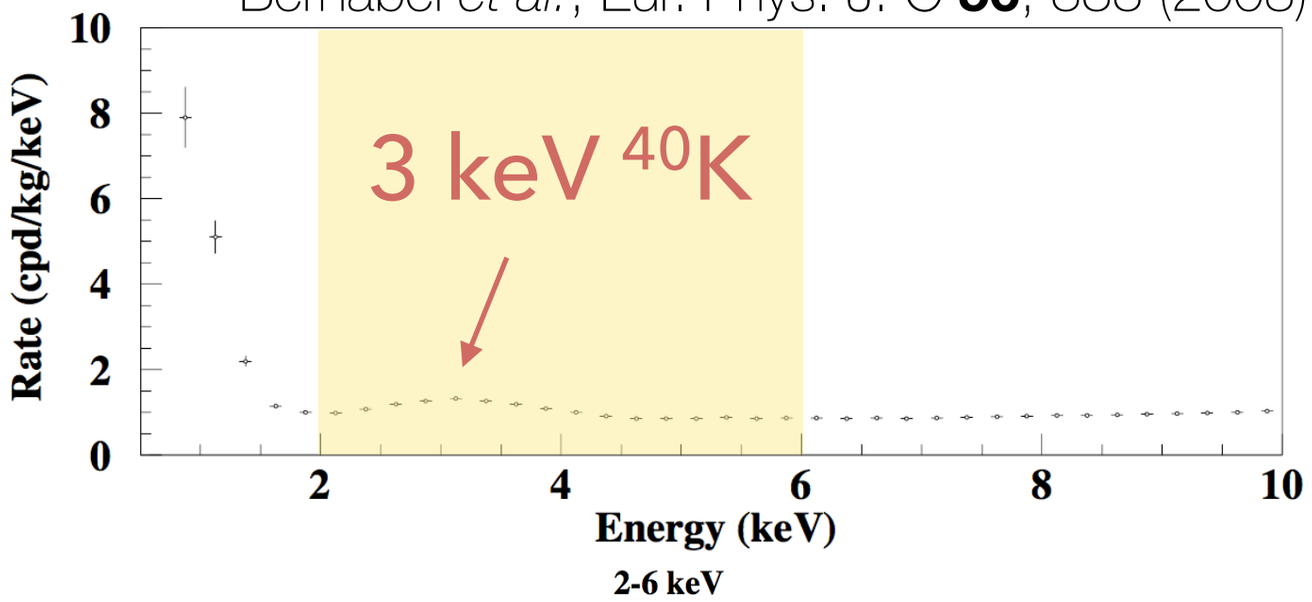
Results from DAMA/NaI and DAMA/LIBRA

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

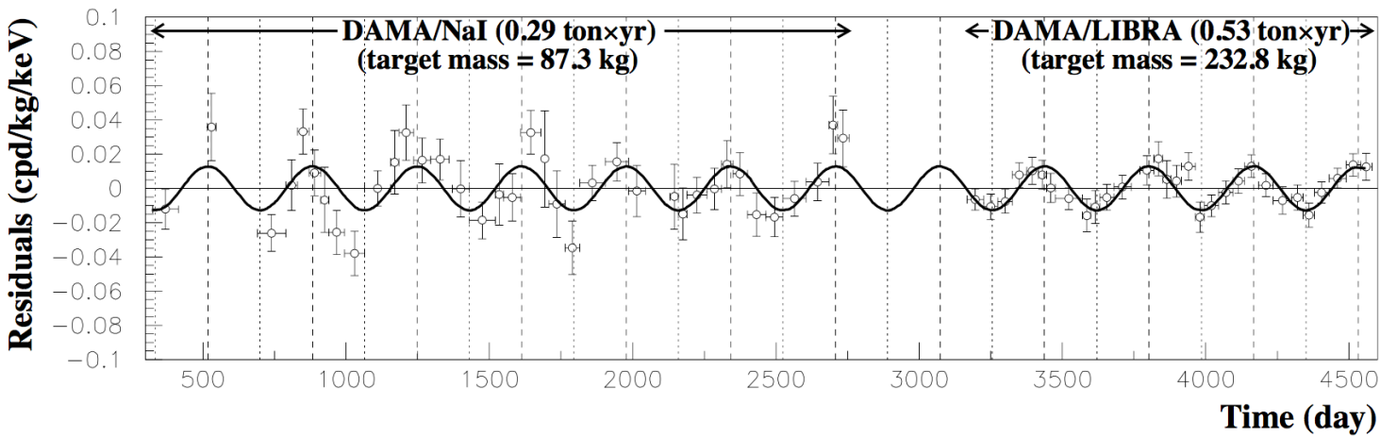
- Modulation between 2-6 keV over 14 annual cycles

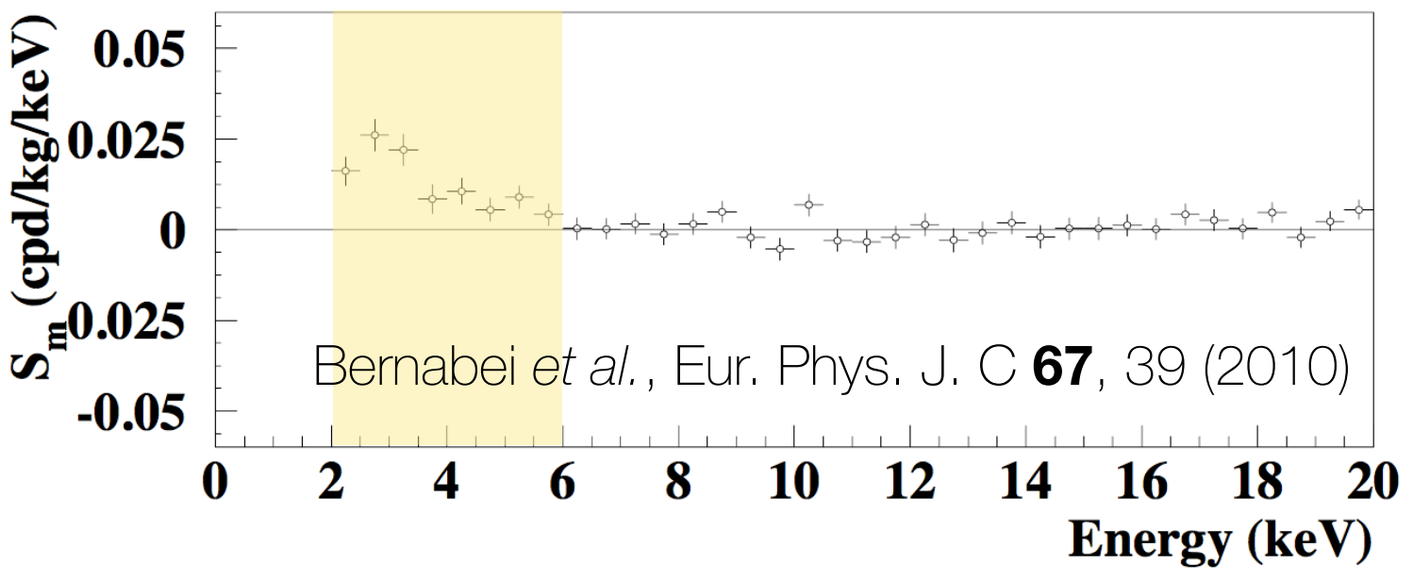
- Dark matter modulation with 9.3 σ

Bernabei *et al.*, Eur. Phys. J. C **56**, 333 (2008)



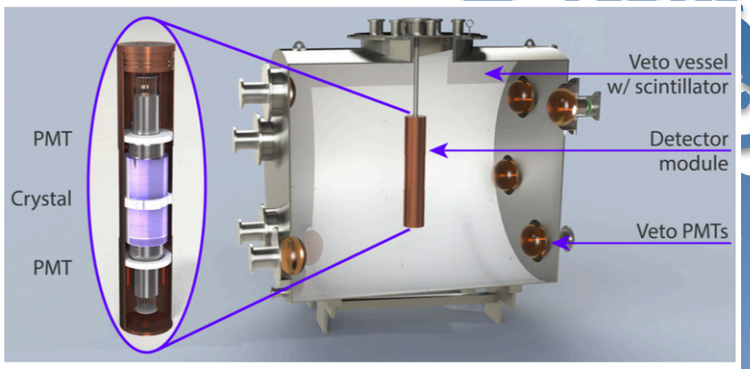
2-6 keV





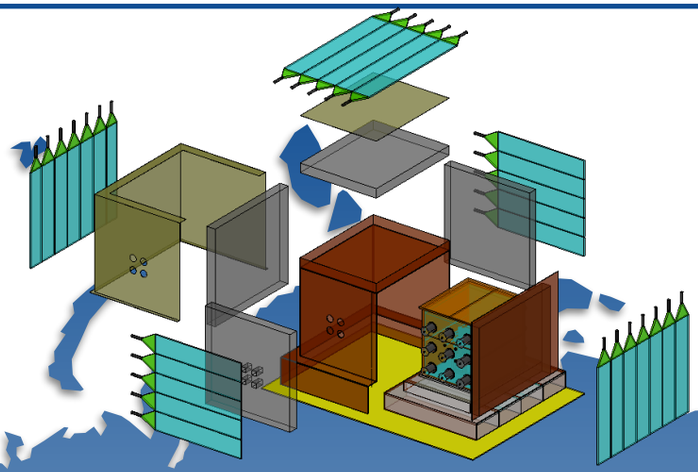
Bernabei *et al.*, Eur. Phys. J. C **67**, 39 (2010)

Global NaI(Tl) Efforts

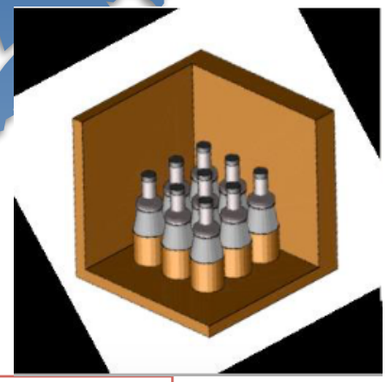


DAMA/LIBRA @ LNGS

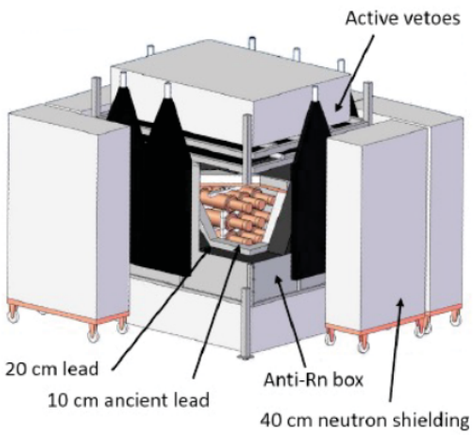
SABRE @ LNGS



COSINE-100 @ Y2L

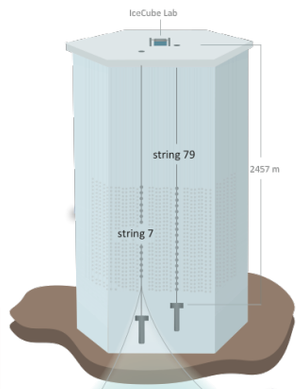


PICO-LON @ Kamioka

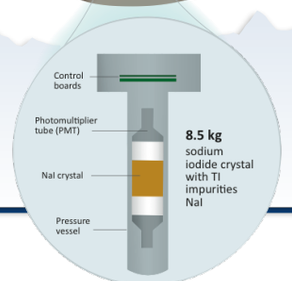


ANAIS @ Canfranc

SABRE @ Stawell



DM-Ice17 @ South Pole



COSINE-100

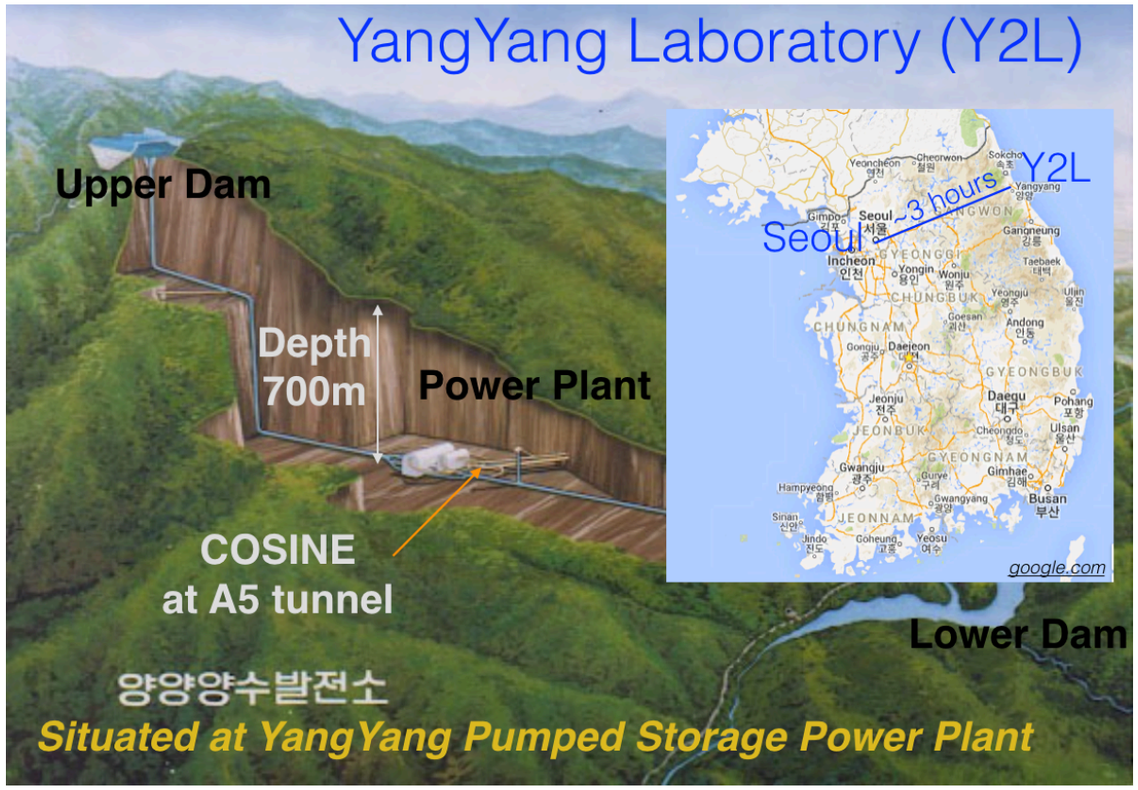
- Joint effort between DM-Ice and KIMS collaborations

DM-ICE + KIMS Korea Invisible Mass Search Experiment

- 8 crystals with 106 kg in total, ~2000 L of liquid scintillator veto

- Located at Yangyang Underground Laboratory (Y2L), South Korea, with ~700 m rock (~2100 m.w.e.) overburden

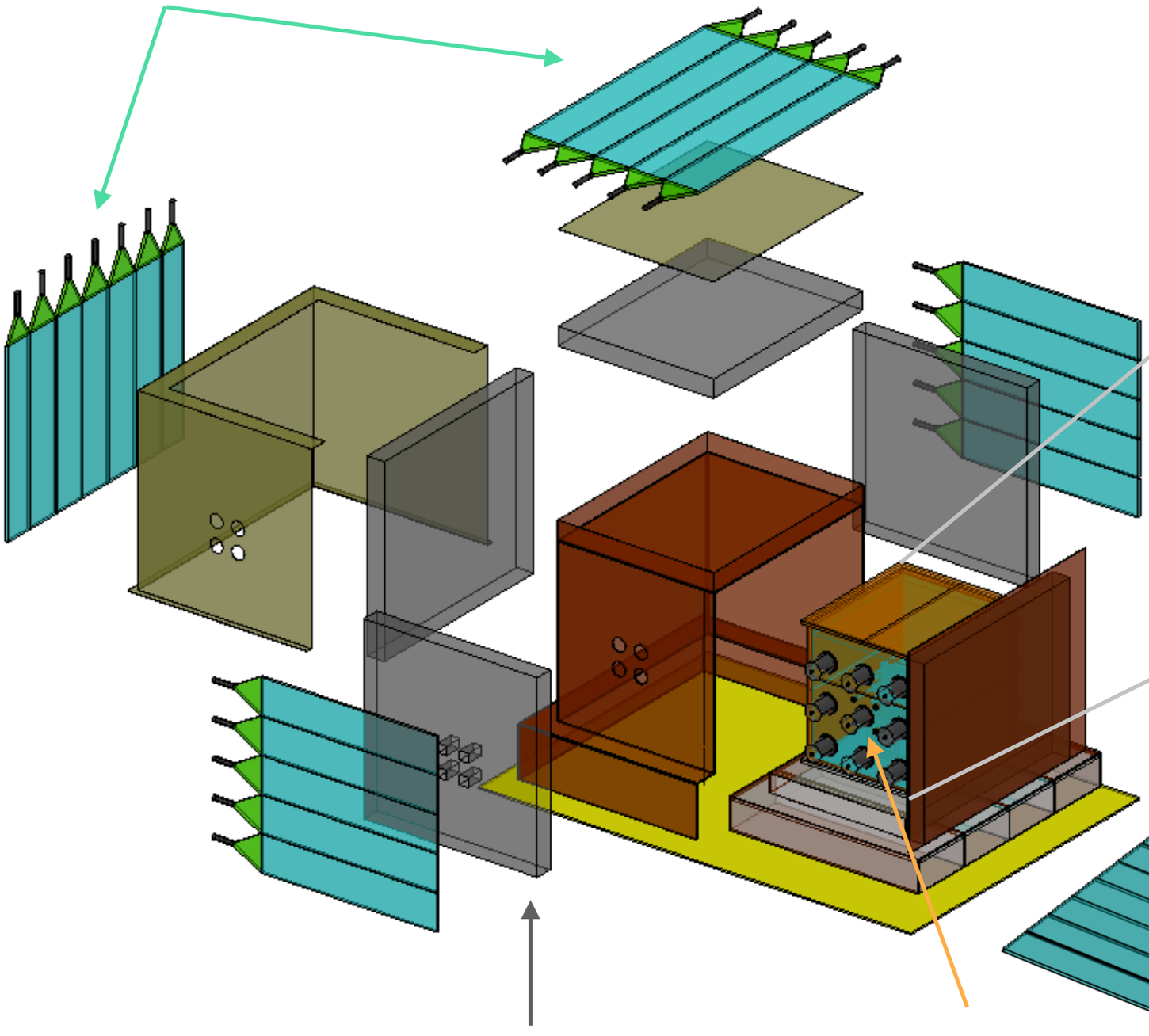
- Physics run started September 2016

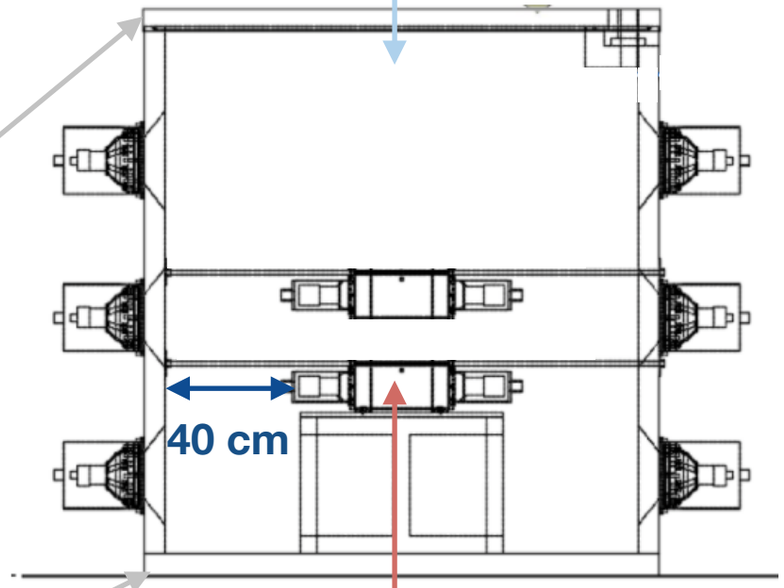


COSINE-100 Shielding Structure

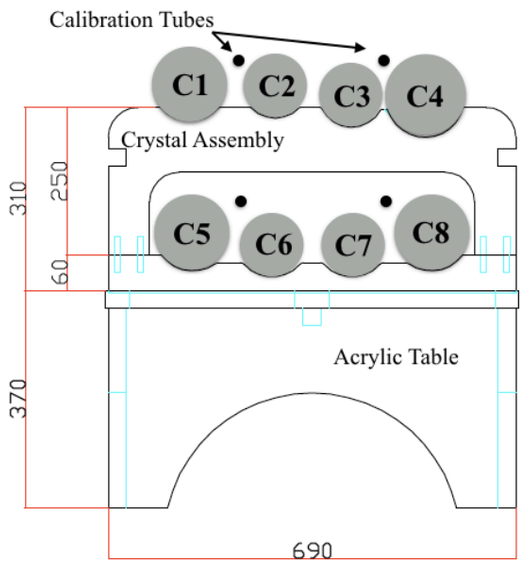
Plastic Scintillators

Filled with Liquid Scintillator (2000 L)





NaI(Tl) Crystals (106 kg)



Lead Shielding (20 cm)

Cu Box (3 cm)

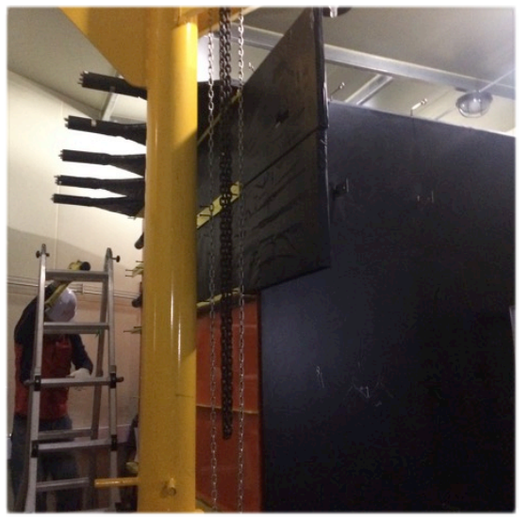
COSINE-100 Construction Timeline

Dec. 2015

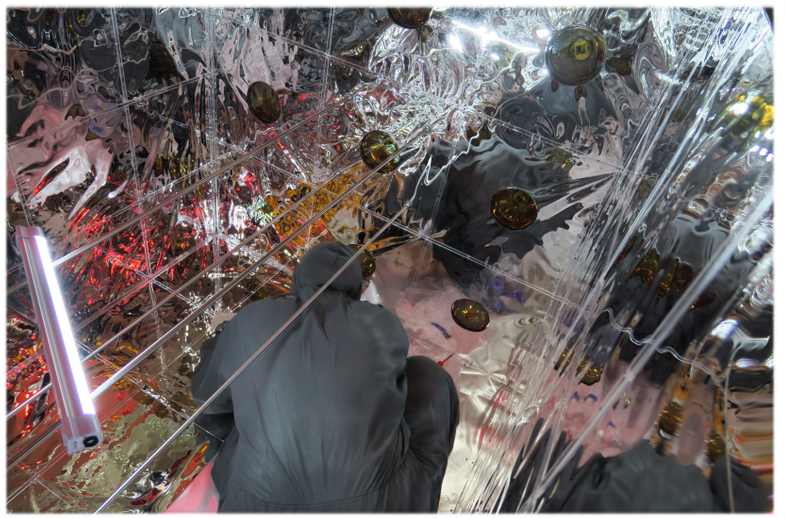
Jan. 2016

Feb. 2016

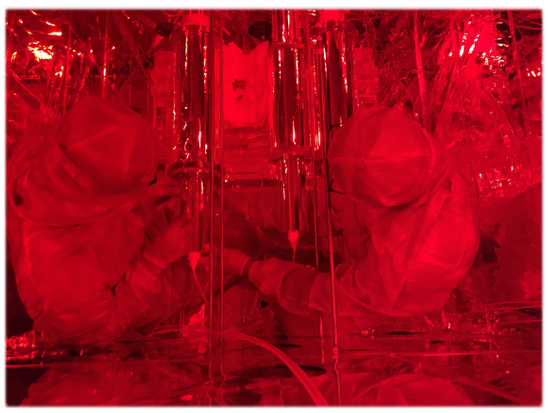
Mar. 2016



Apr. 2016

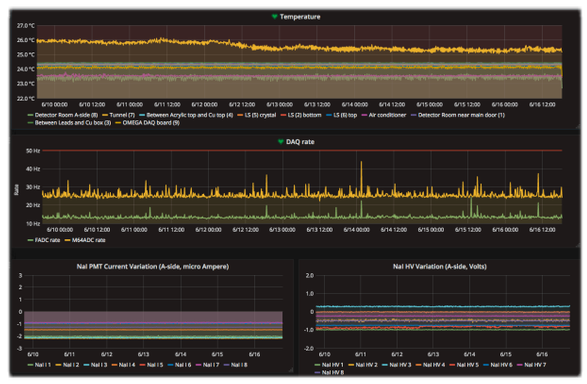


May. 2016

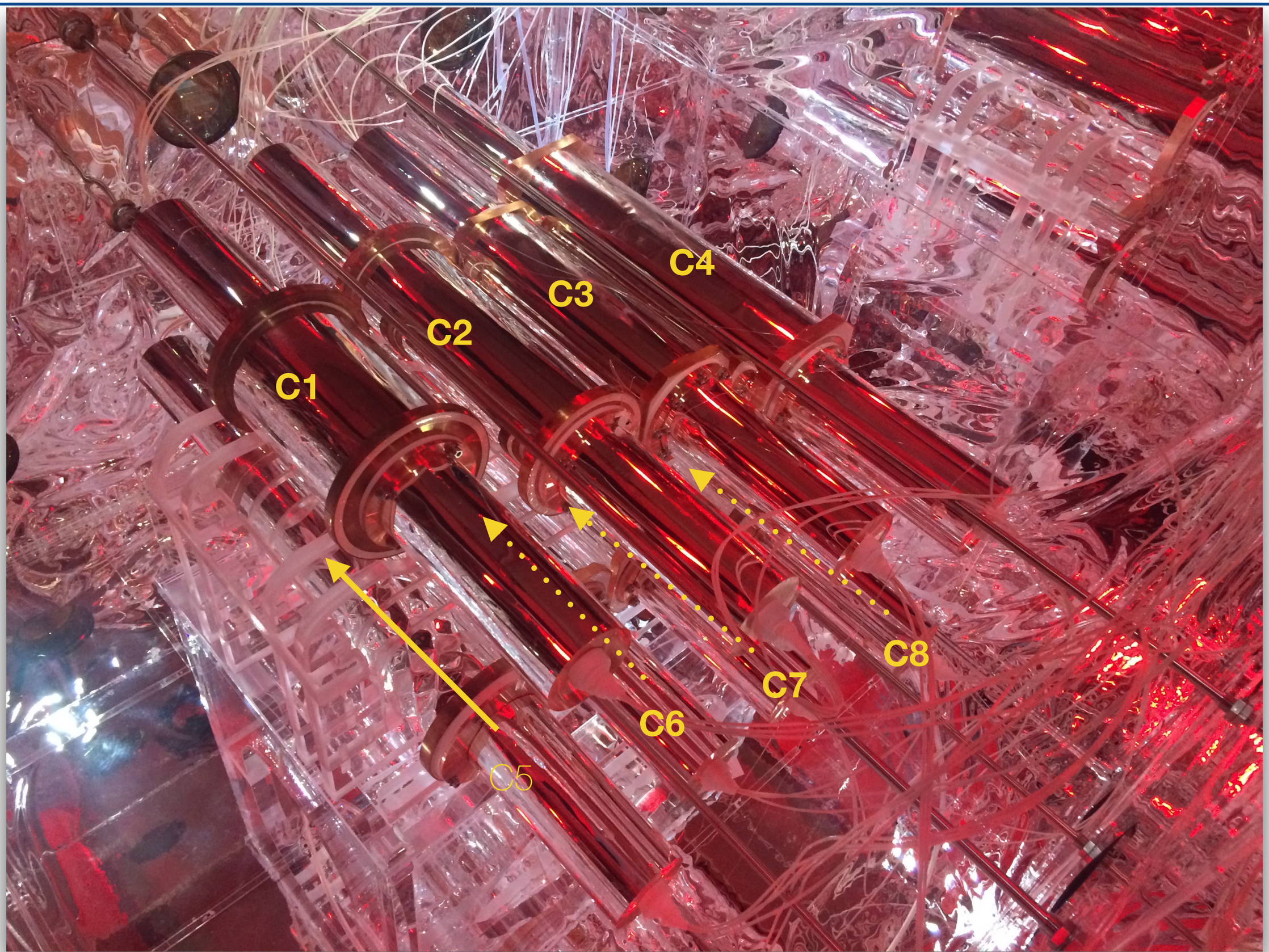


Jun. 2016

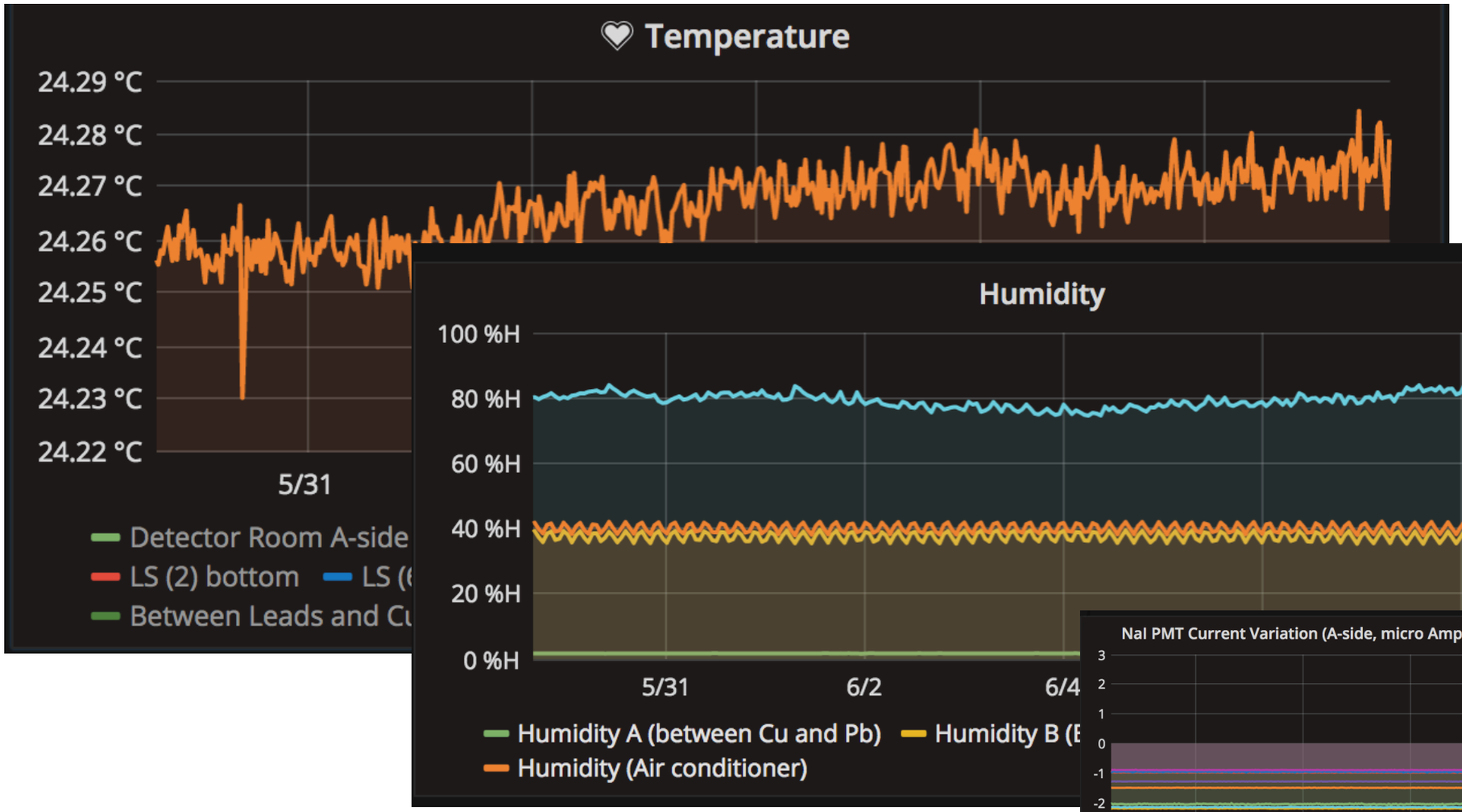
Sep. 2016



Crystal Installation

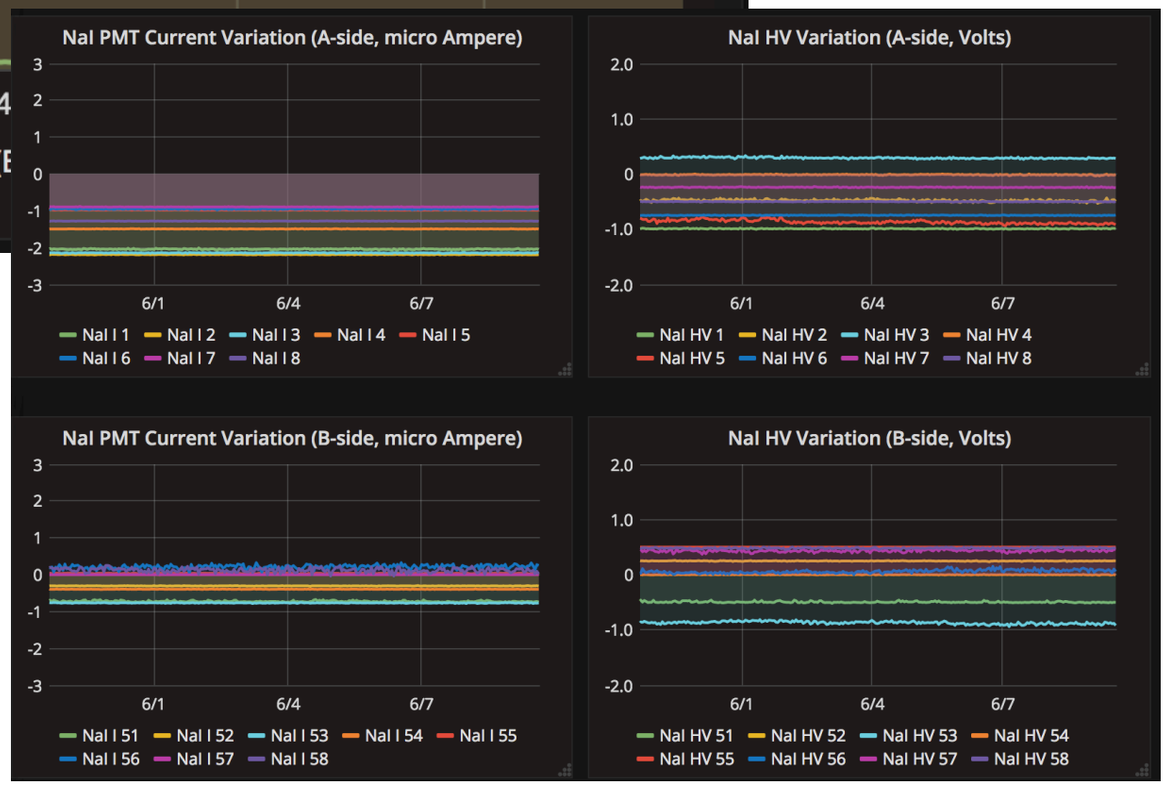


Environmental Control/Monitoring



Temperature

Humidity



Current/Voltage

- Monitoring stability of temperature, humidity, current/voltage, etc.
- < 1℃ temperature fluctuation inside the shielding structure

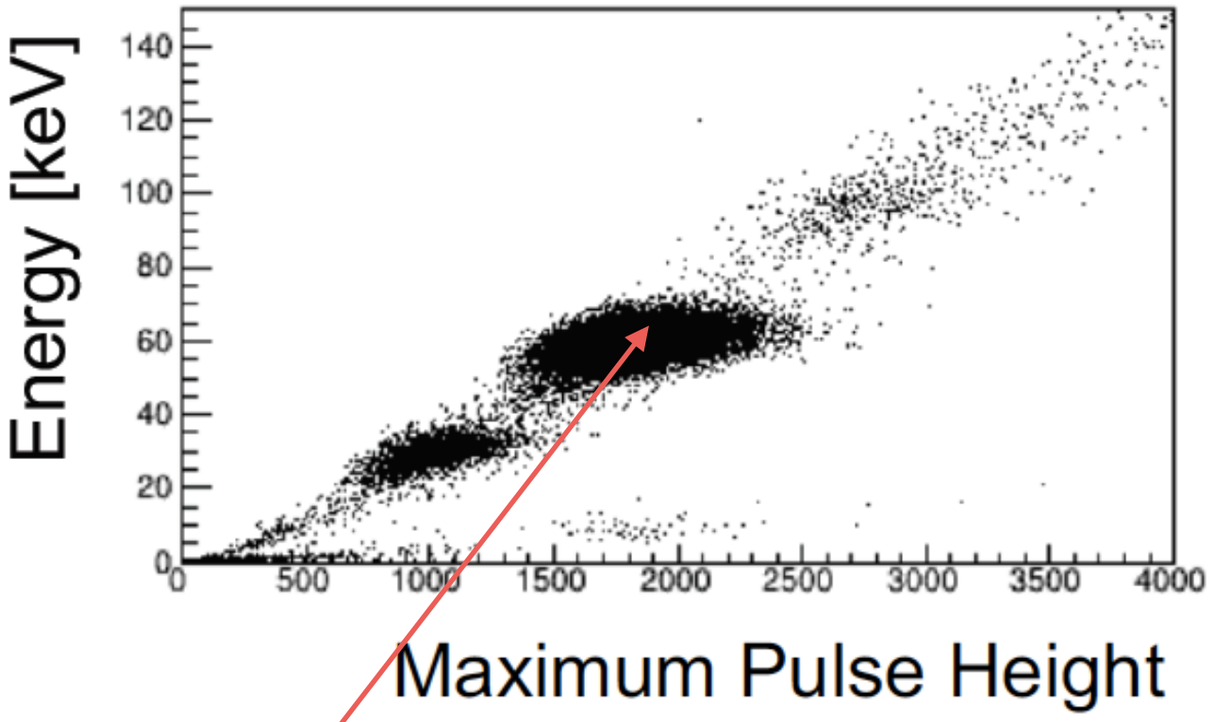
COSINE-100 NaI(Tl) Crystals

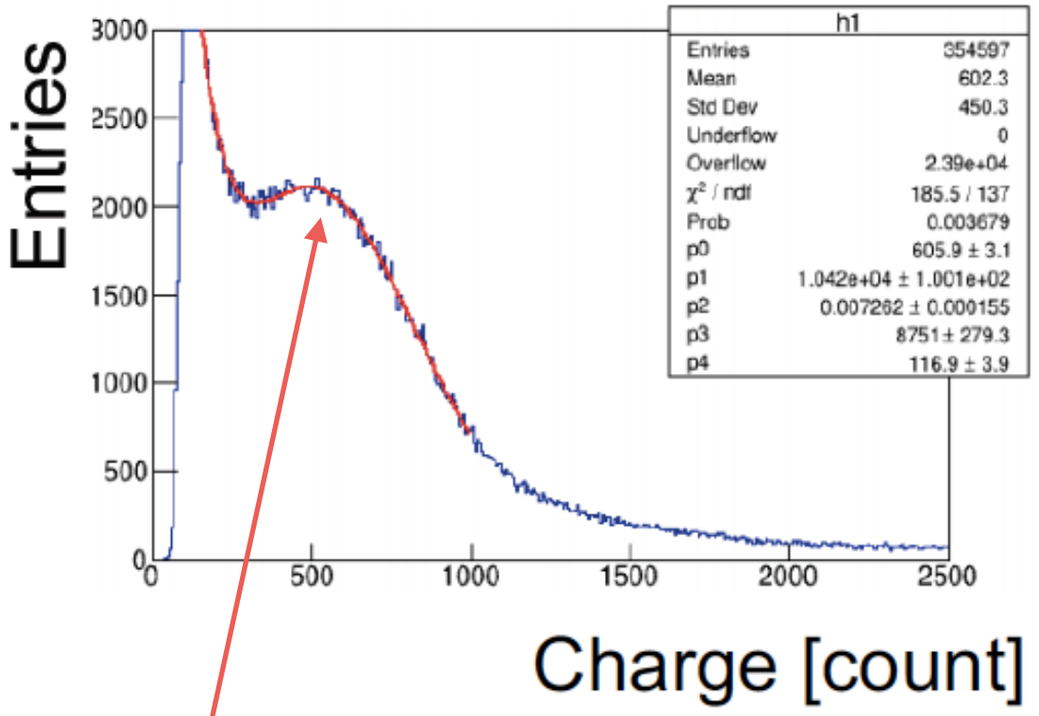
Preliminary

	Mass (kg)	Powder Type	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	^{210}Po (mBq/kg)	Light Yield (npe/keV)
Crystal 1	8.26	Powder B	34.74±4.74	<0.02	1.31±0.35	3.20±0.04	14.67±0.62
Crystal 2	9.15	Powder C	60.64±4.64	<0.12	<0.63	2.06±0.03	14.56±0.54
Crystal 3	9.16	WIMPScint-II	34.34±3.10	<0.04	0.44±0.19	0.76±0.02	15.75±0.76
Crystal 4	18.01	WIMPScint-II	33.32±3.50		<0.3	0.74±0.02	14.69±0.46
Crystal 5	18.28	Powder C	82.33±5.49		2.35±0.31	2.06±0.03	6.26 ±0.34
Crystal 6	12.5	WIMPScint-III	16.79±2.46	<0.018	0.56±0.19	1.52±0.02	14.52±0.51
Crystal 7	12.5	WIMPScint-III	18.69±2.79		<0.6	1.54±0.02	14.41±0.50
Crystal 8	18.28	Powder C	54.25±3.82		<0.9	2.05±0.02	3.27 ±0.20
DAMA			<20	0.7 - 10	0.5 - 7.5	<0.5	5.5 - 7.5

- 8 crystals with a total mass of ~106 kg
- Preliminary background values estimated both at R&D and COSINE-100 setups
- Average light yield ~15 p.e./keV

Calibration/Light yield calculation

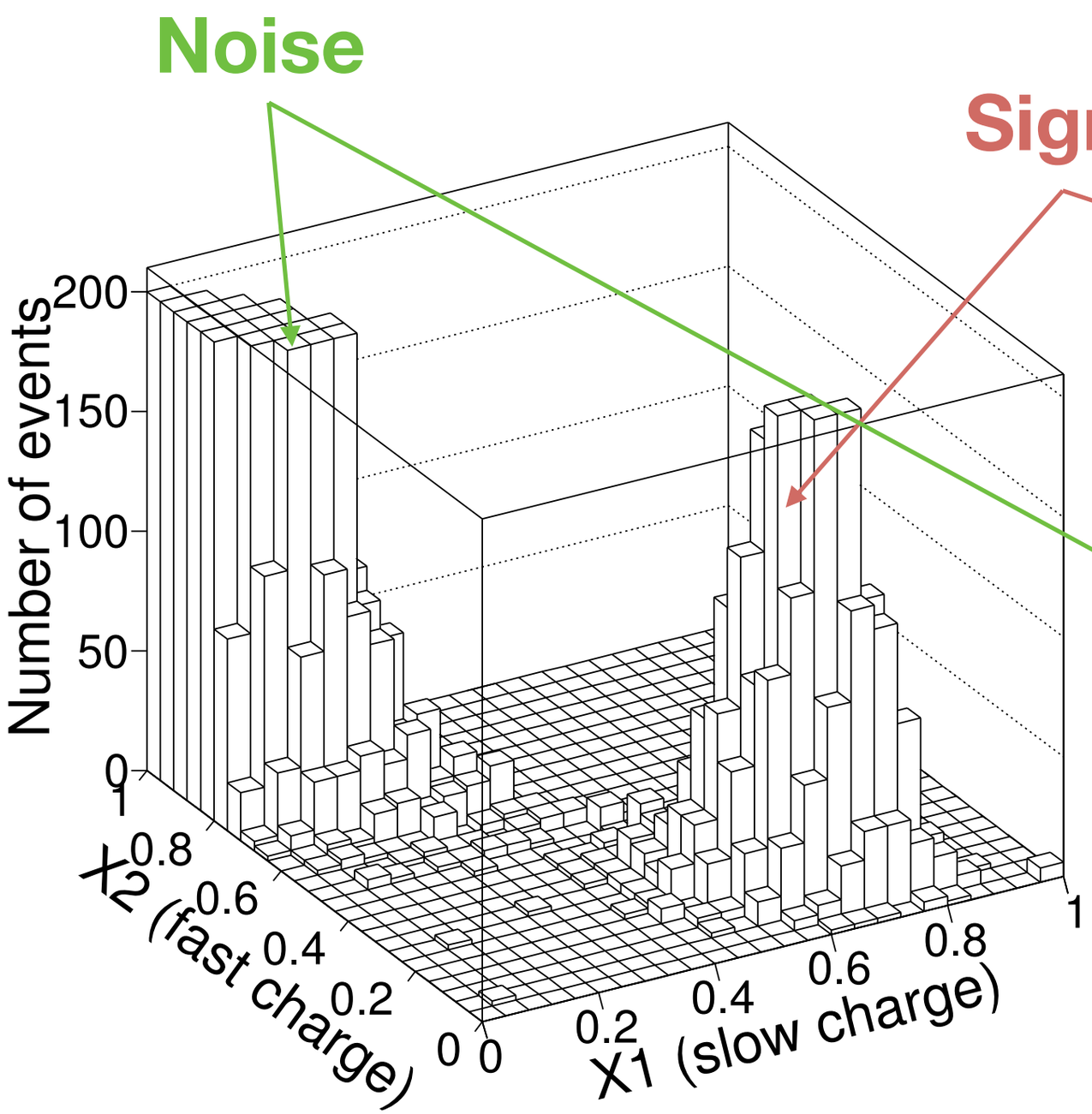


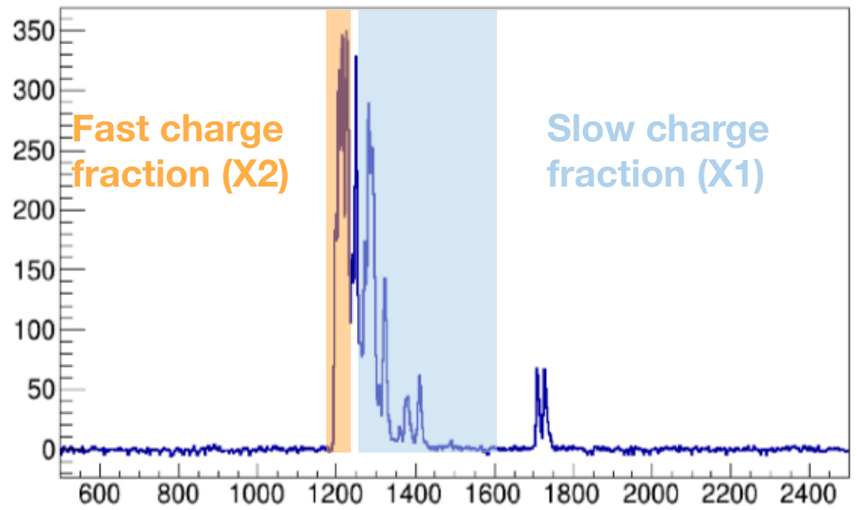


60 KeV gamma SPE

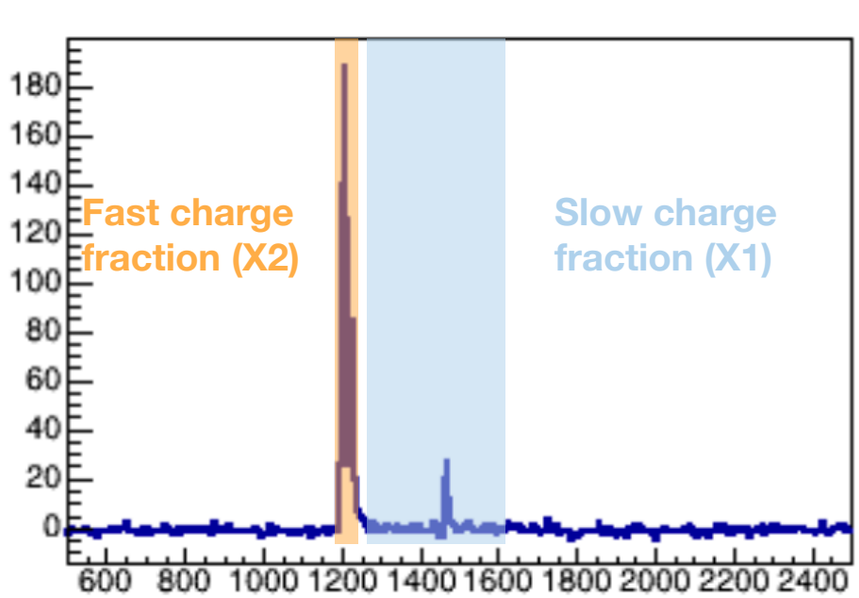
- ^{241}Am source (60 keV gamma) used to calibrate PMTs
- Gain is matched to have 60 keV peak at the mid-range of FADC dynamic range
- Single Photoelectron spectrum were fitted to calculate PMT light yield

Event Selection: Charge Ratio





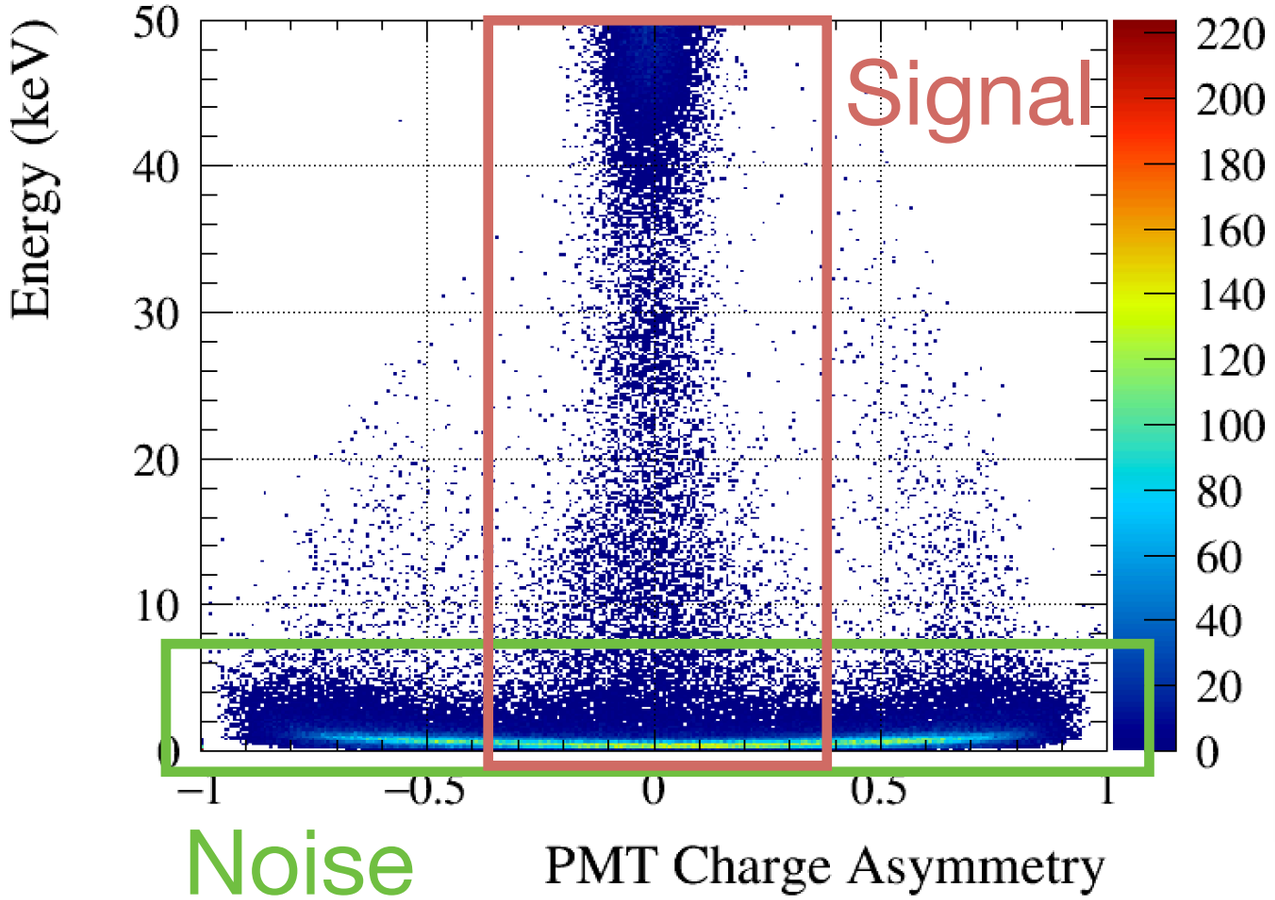
Bin (2 ns/bin)

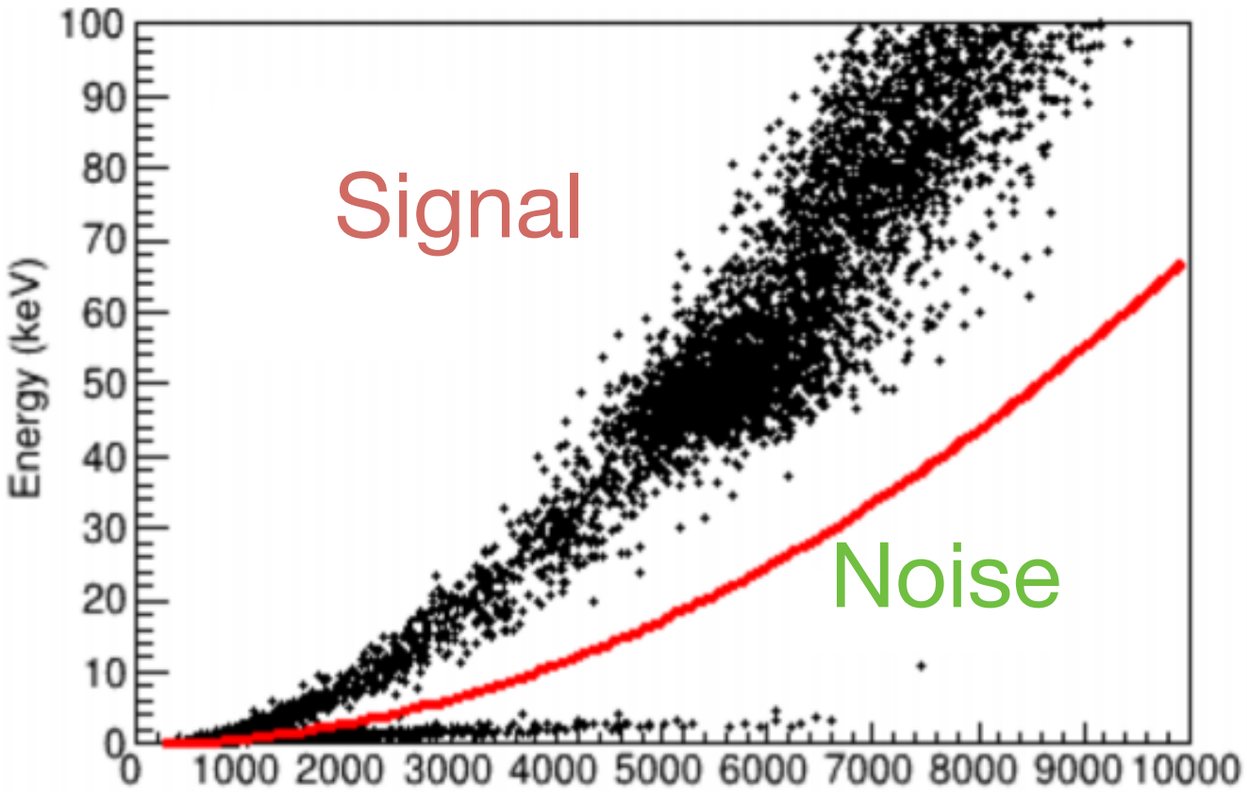


Bin (2 ns/bin)

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

Event Selection: Asymmetry and Charge/Peak

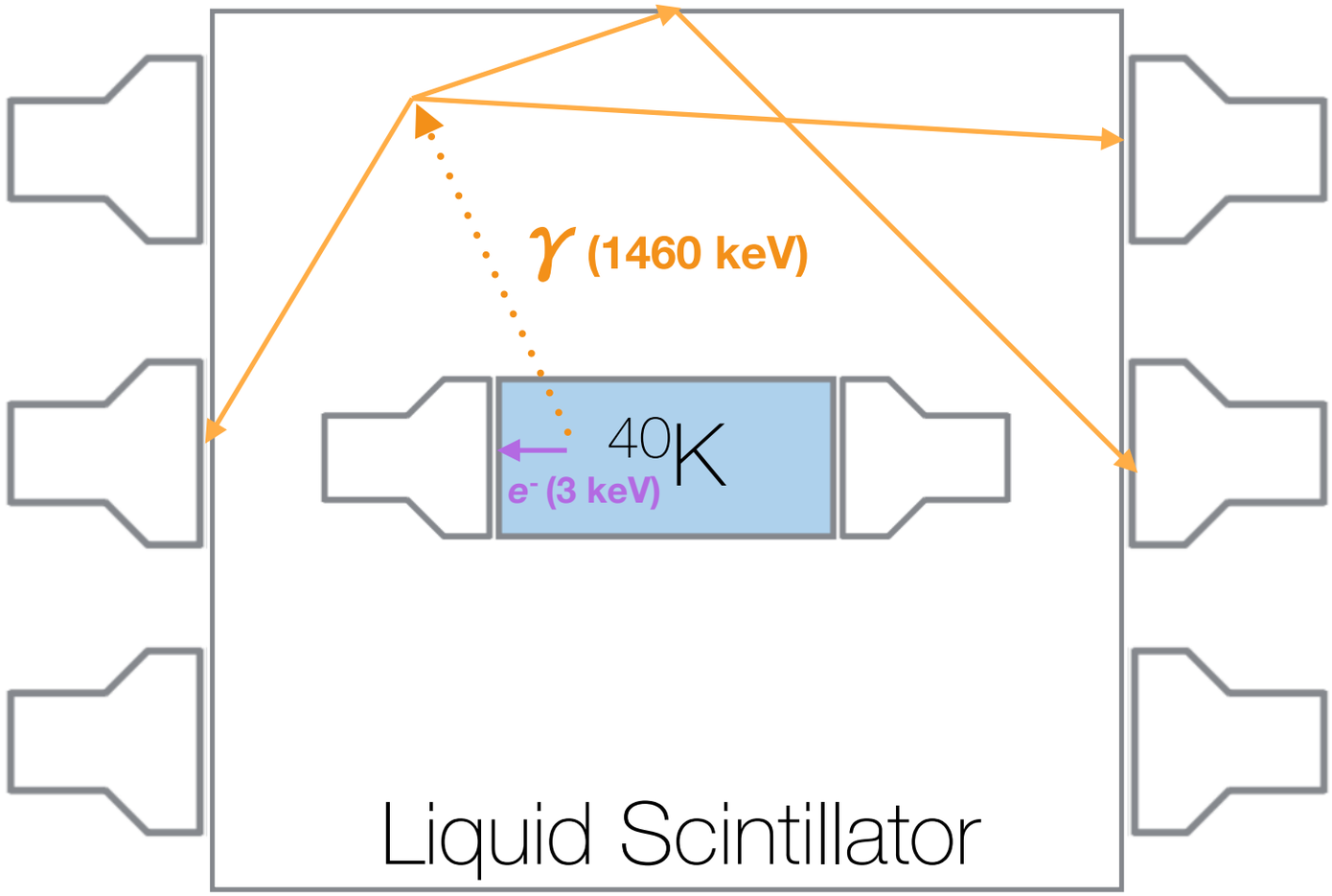


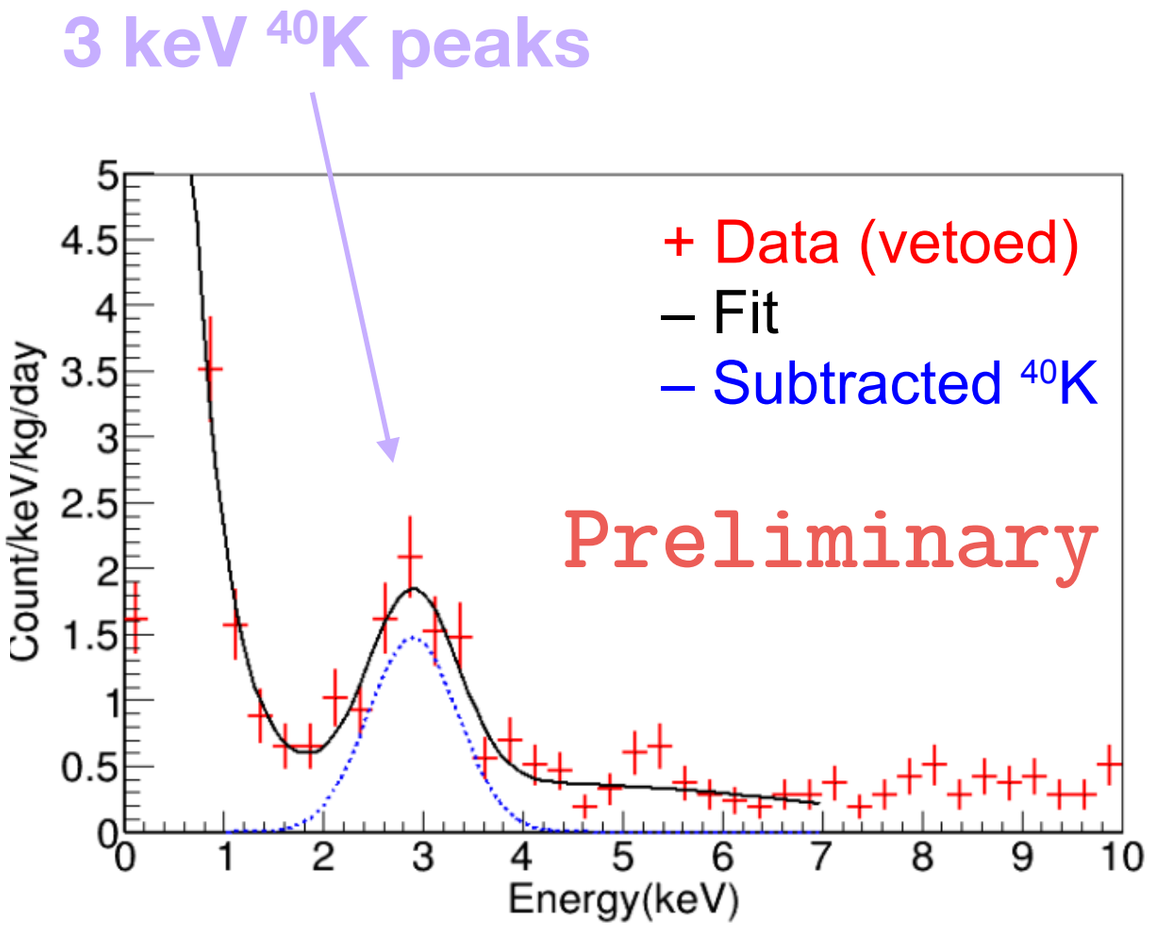


Average charge per SPE

- Additional noise reduction cuts have been developed:
  - Charge asymmetry between 2 PMTs in each crystal
  - Charge/peak: Average charge per SPE
- New development of event selection criteria based on multivariate analysis on going

Crystal-LS Coincidence Events

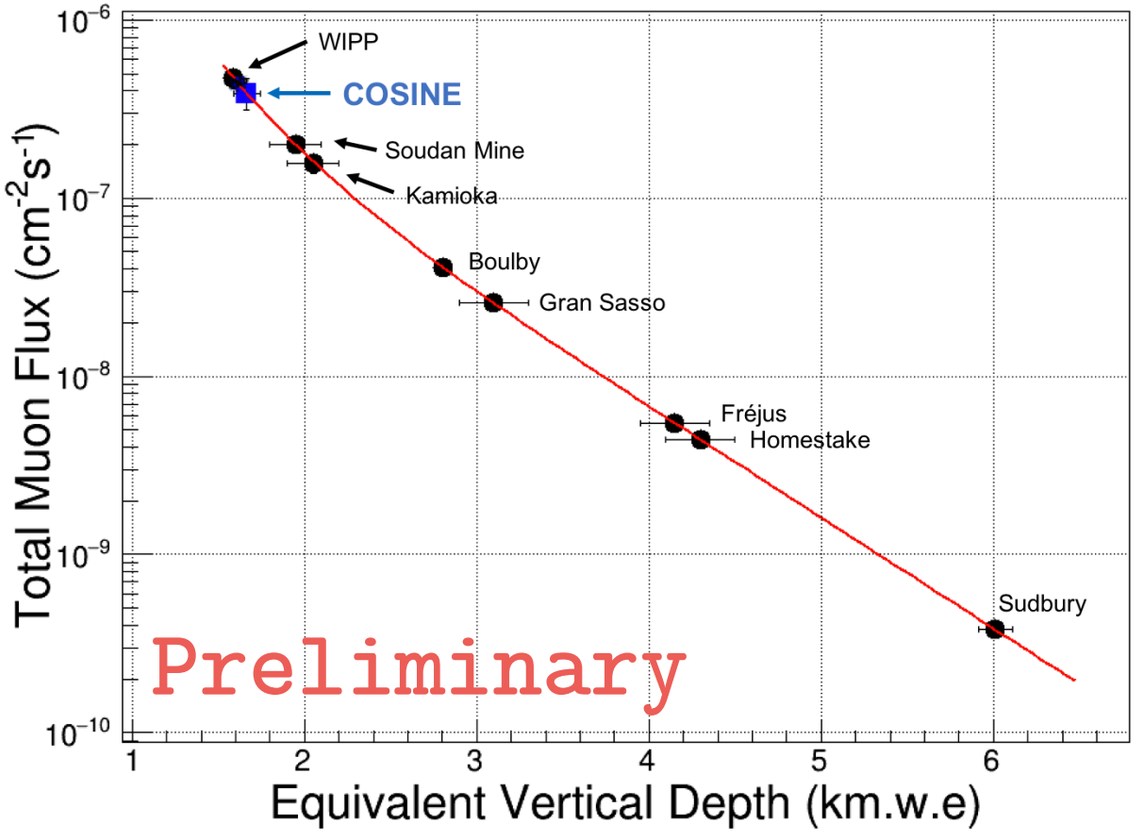


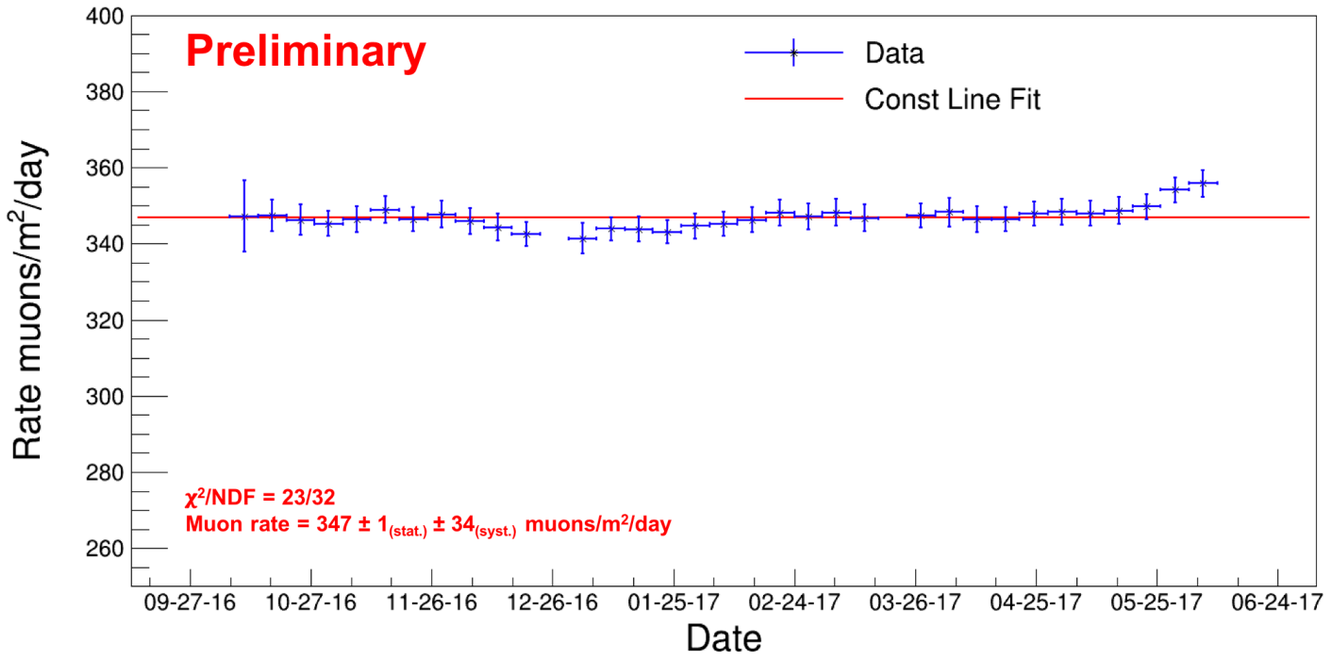


- ^{40}K emits 1460 keV gamma with 3 keV Auger electron energy deposition in NaI crystal

- Tagging 1460 keV events with LS enables to veto 3 keV background events

COSINE-100 Muon Background

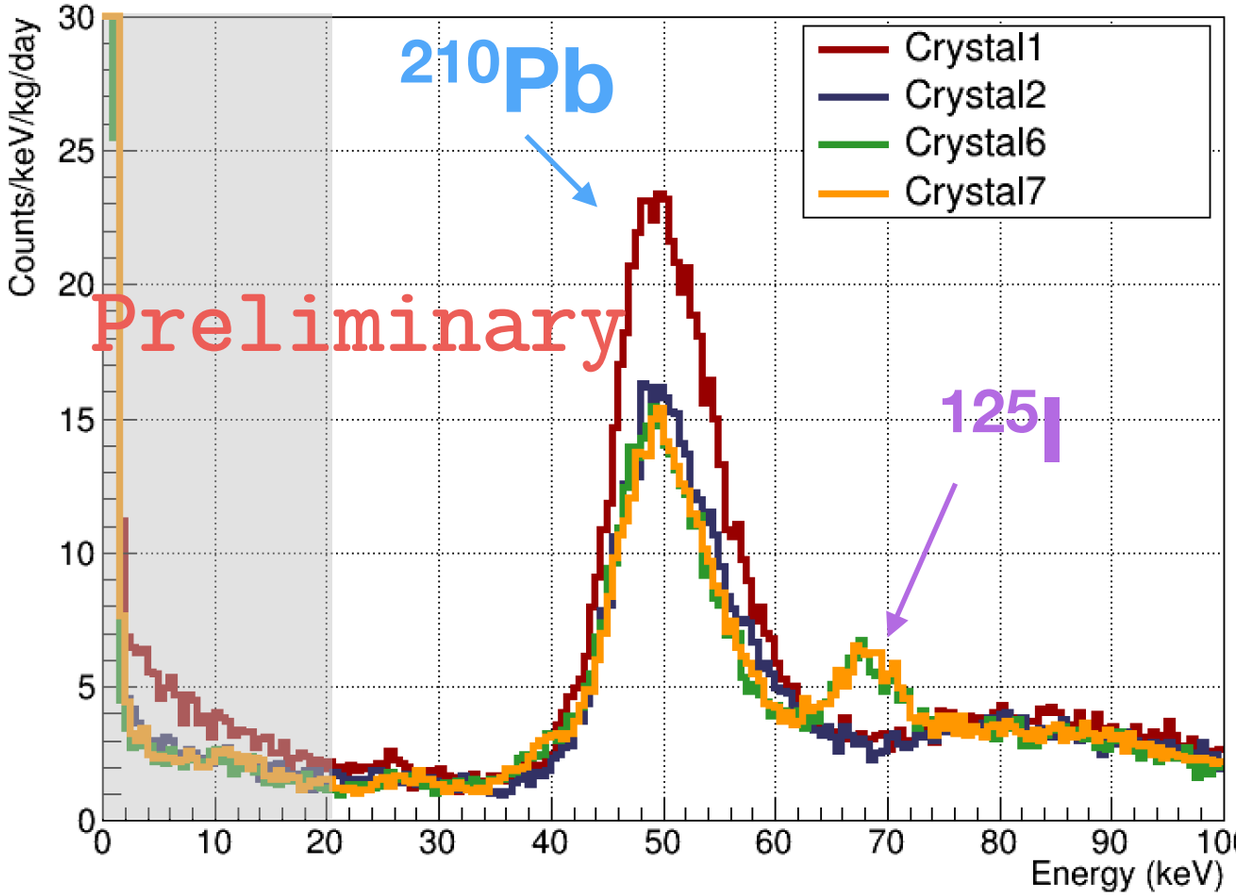


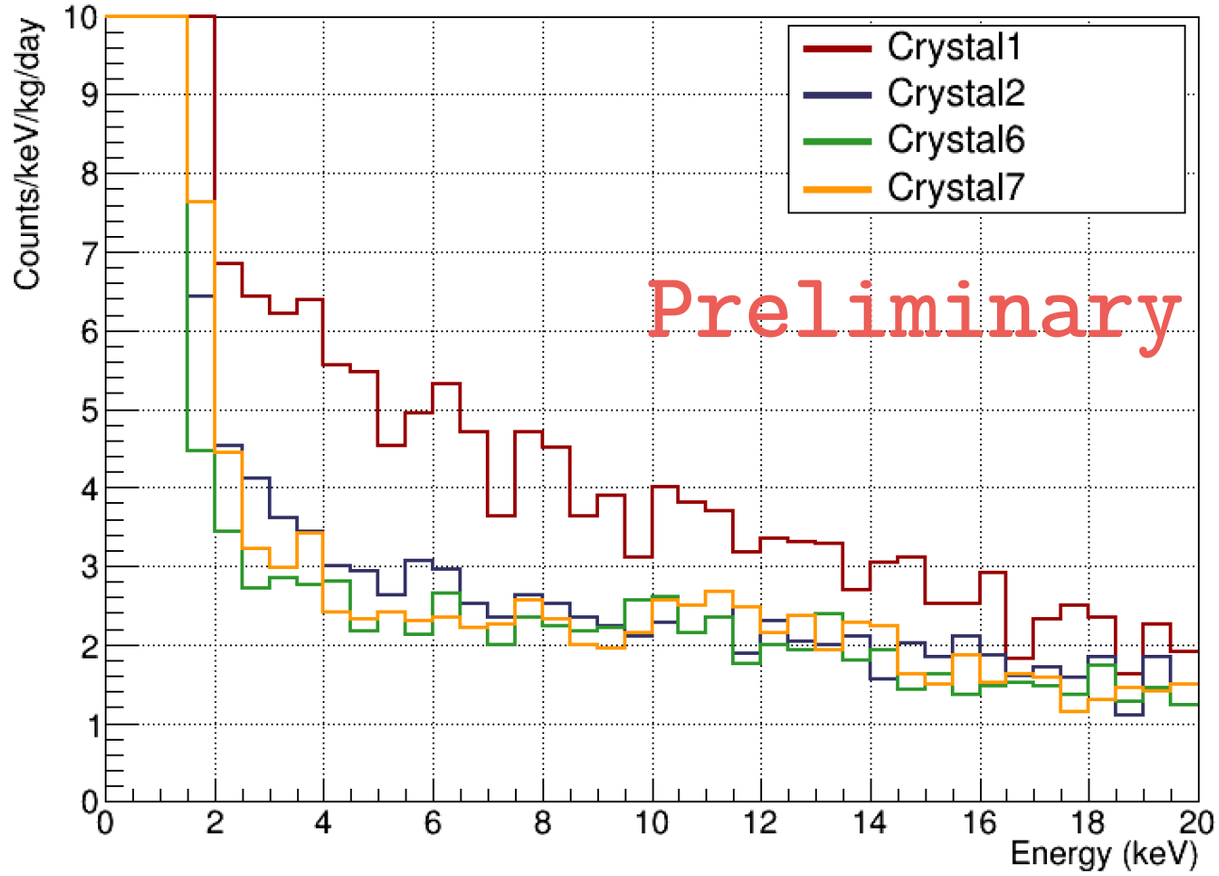


- Muon flux at COSINE-100 is ~3.98 x 10^{-7}/cm^2/s (344.29 muons/m^2/day)
- Rate has been consistent throughout the physics run
- Muon selection used to veto muon-induced crystal events

Low Energy Spectrum

ROI

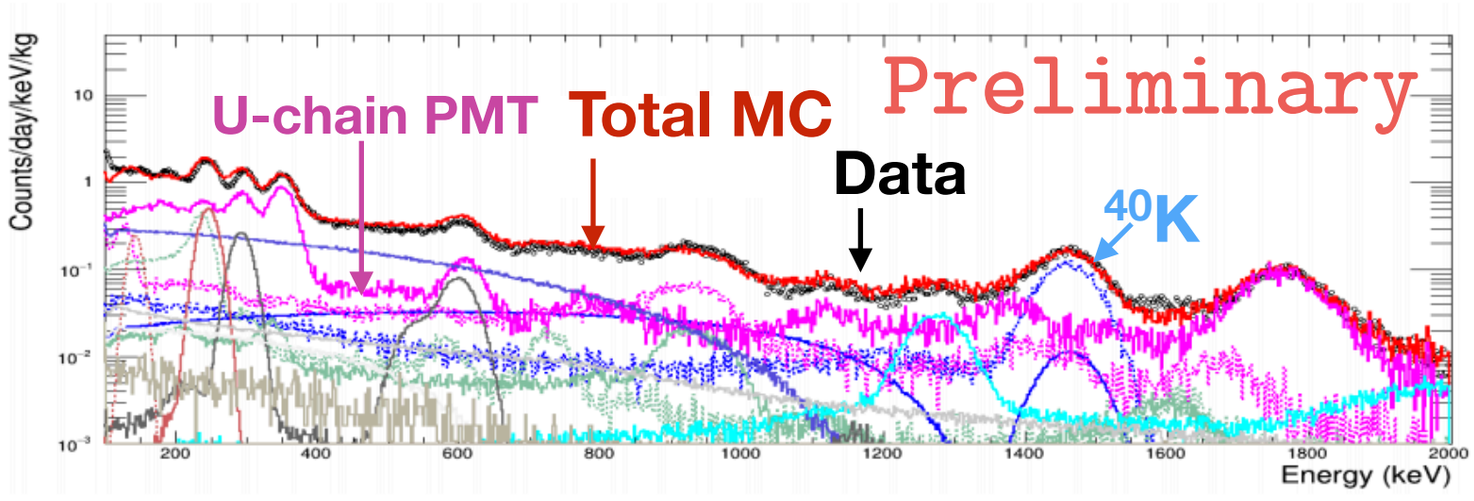


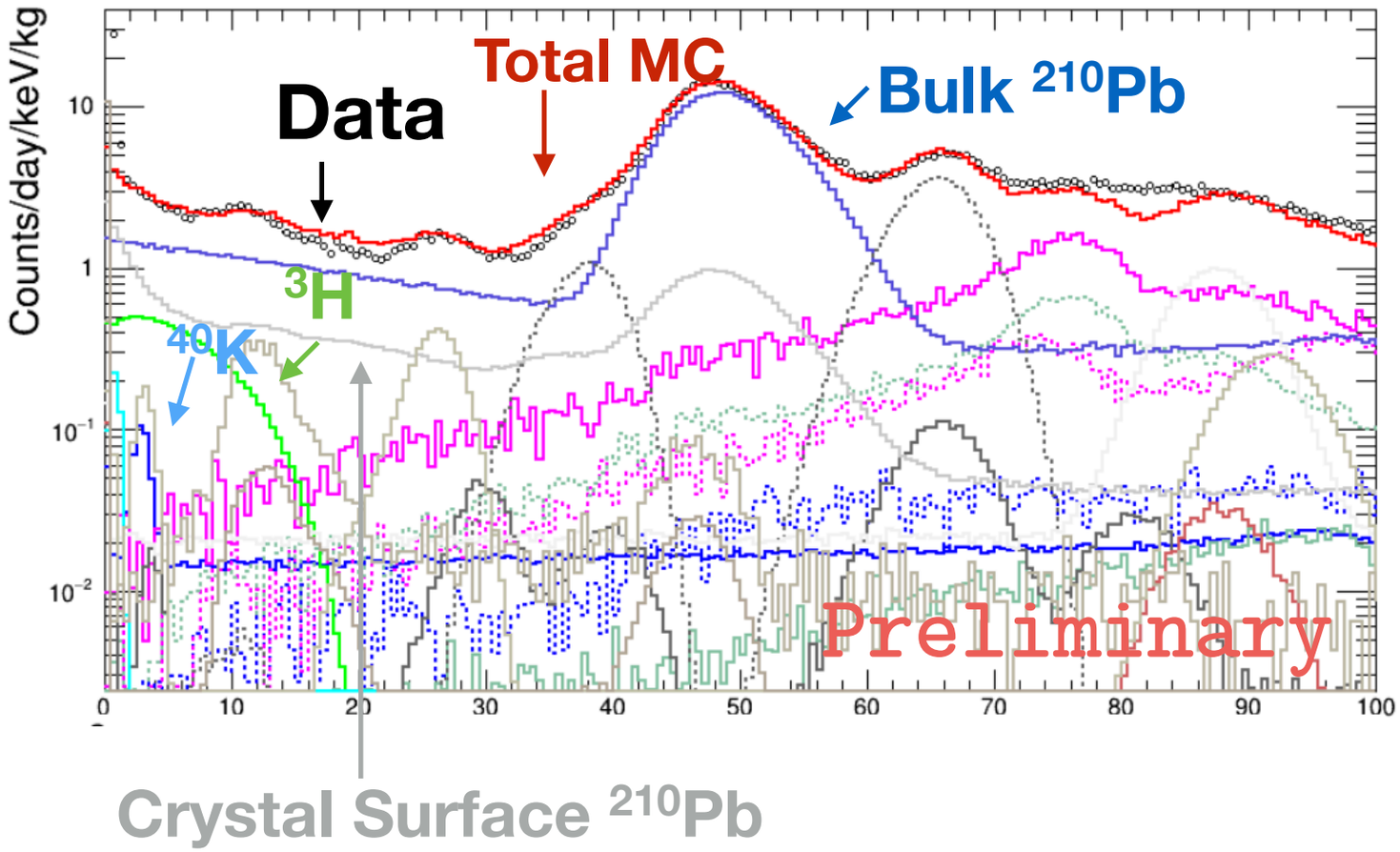


- 10 days of data, preliminary set of event selection applied
- Cosmogenic ^{125}I ($T_{1/2}$ = 59 days) peaks remain in newer crystals
- Depending on crystal, background level 2 to 4 dru in the region of interest
- There is still room for improvement!

COSINE-100 NaI Crystal Simulation

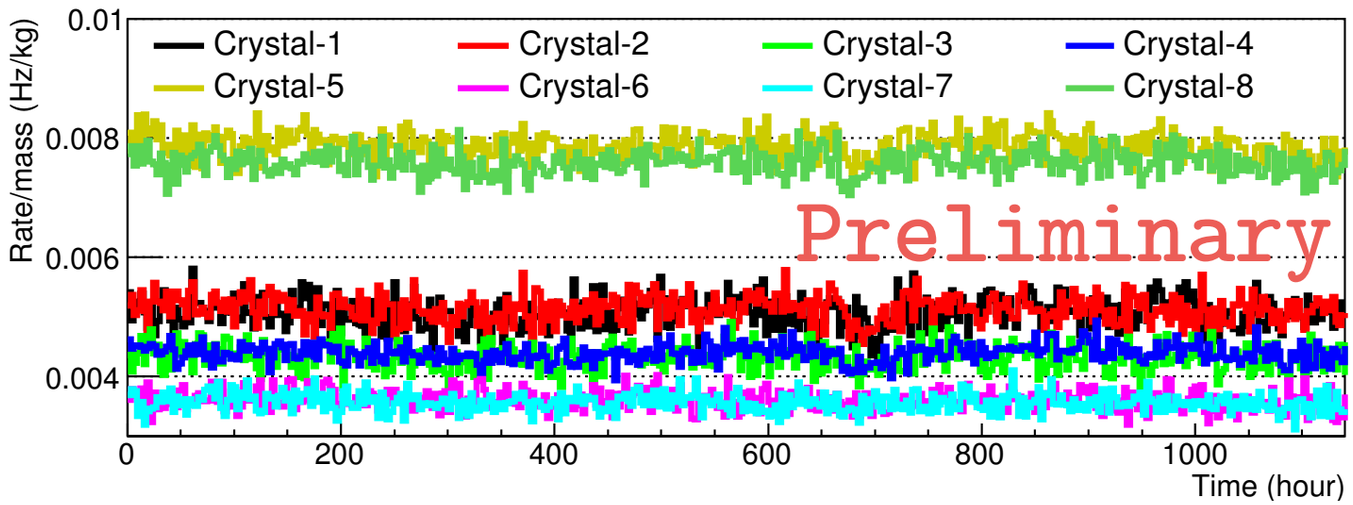
- Work in progress, Geant4 framework
- Some discrepancy still remains in low energy region
- Bulk/Surface ^{210}Pb is suspected to be the dominant background in the ROI, followed by cosmogenic ^{3}H





Stable Operation and Data Accumulation

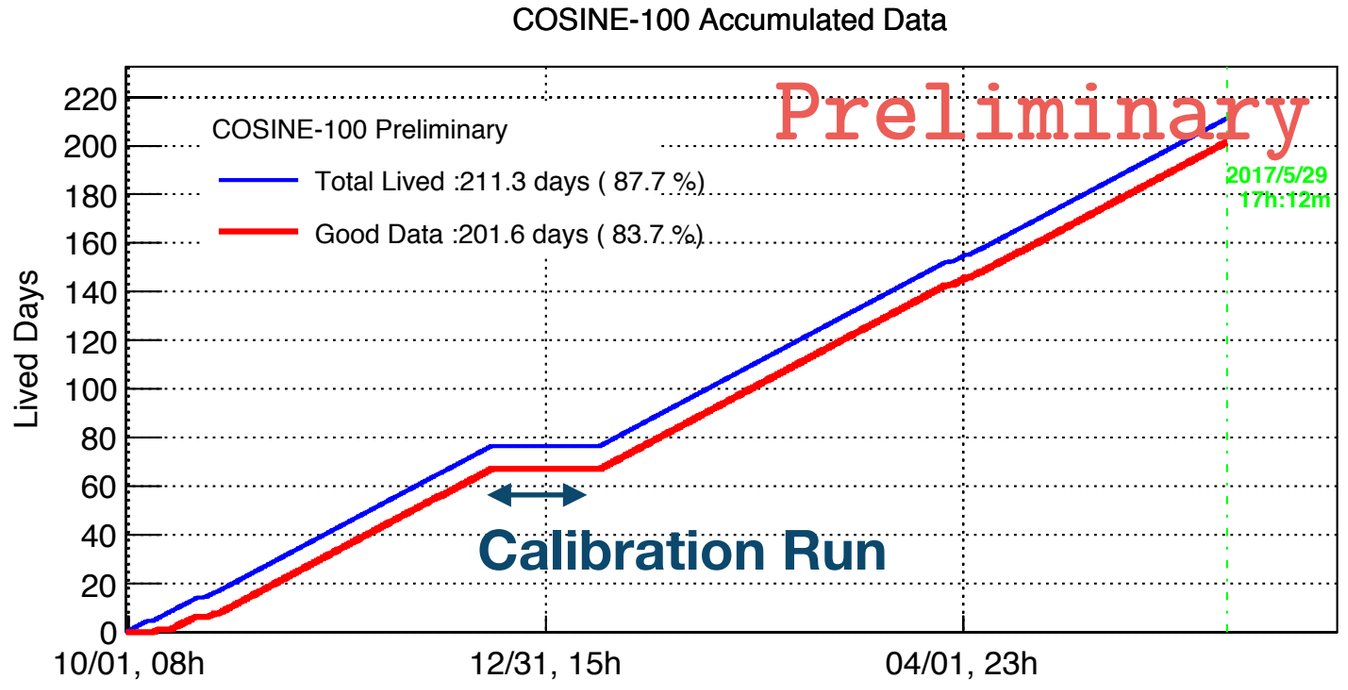
- Stable crystal trigger rates throughout the physics run



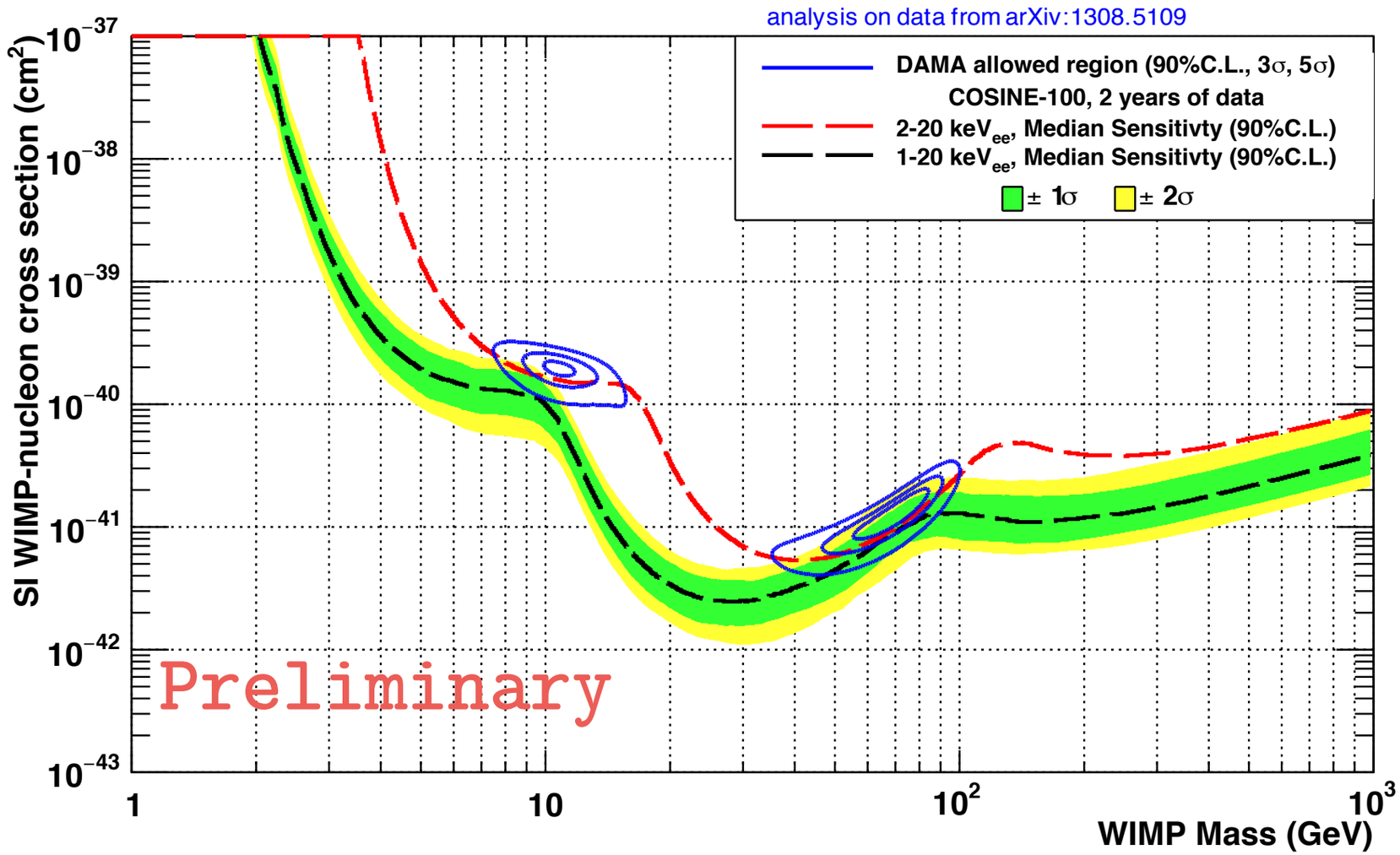
- 78% live time with 71% good-quality data

  - Accumulated more than 6 months of data

  - Downtime mostly due to calibration campaign



COSINE-100 Projected Sensitivity



- ~4 cpd/kg/keV flat background is assumed

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

Conclusions

- WIMP interpretation of DAMA signal is in tension with other experiments: Independent NaI(Tl) experiments are needed

- COSINE-100 is running with 106 kg of NaI(Tl) crystals, with lower backgrounds and better technology than its predecessor experiments; physics run started on September 2016

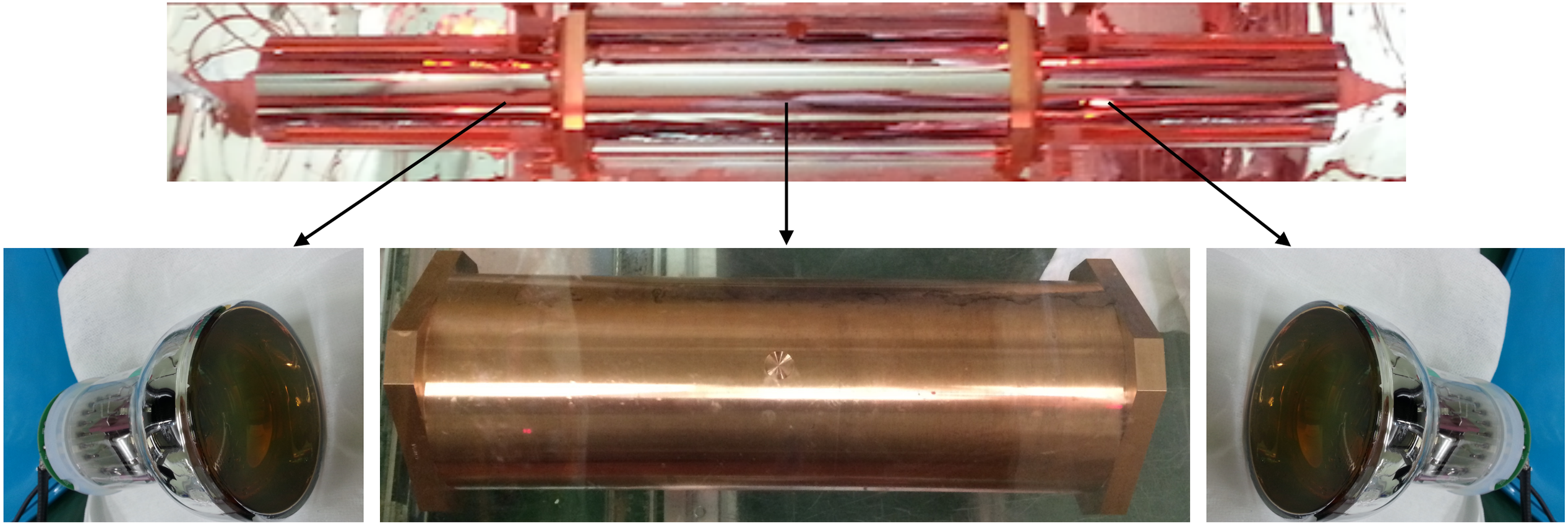
- Initial performance of COSINE-100 is promising, expect to have DAMA-comparable sensitivity in ~2 years

- Continued R&D for higher purity crystals

- Very exciting time for NaI dark matter search…stay tuned!

Backups

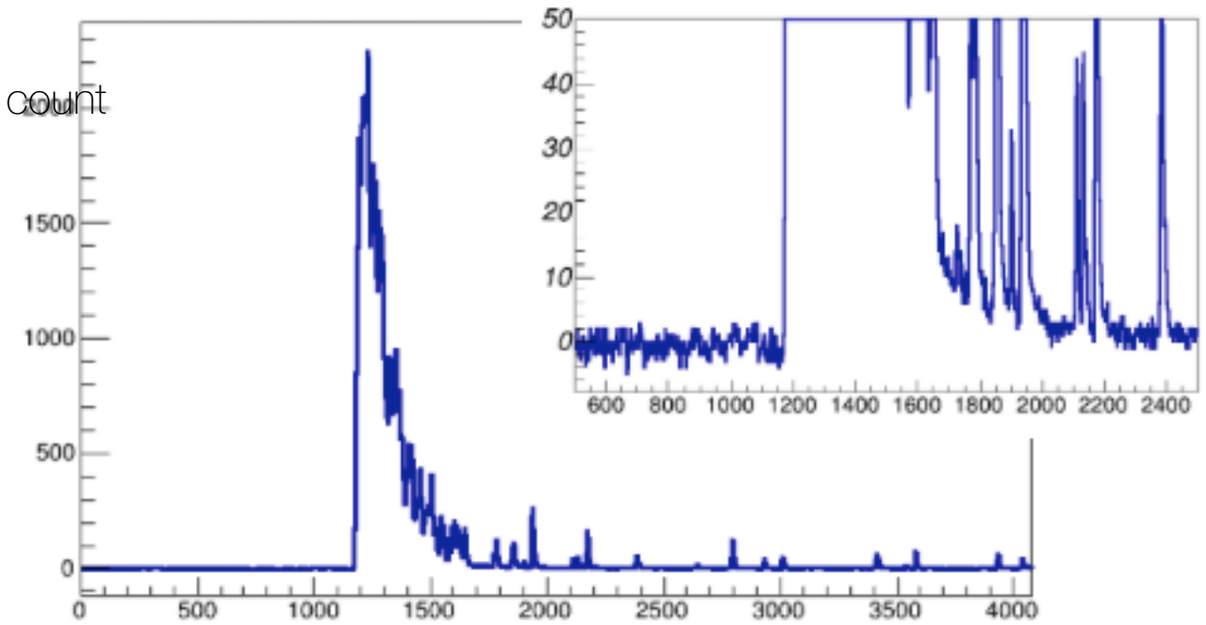
COSINE-100 Crystal-PMT Assembly



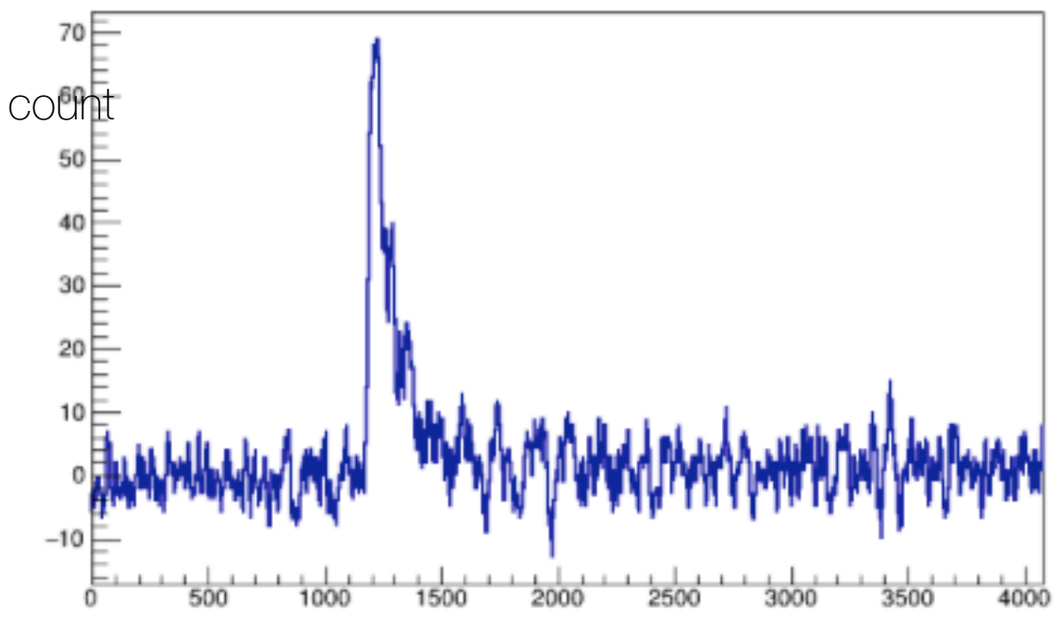
- OFE Cu-encapsulated NaI crystal is attached with two 3-inch PMTs
- PMT: R12669 from Hamamatsu, 35% Quantum Efficiency at 420 nm
- Outer surface of crystal and PMT cap is wrapped with Vikuiti reflective films

Crystal PMT Waveforms

Anode Waveform (0-120 keV)



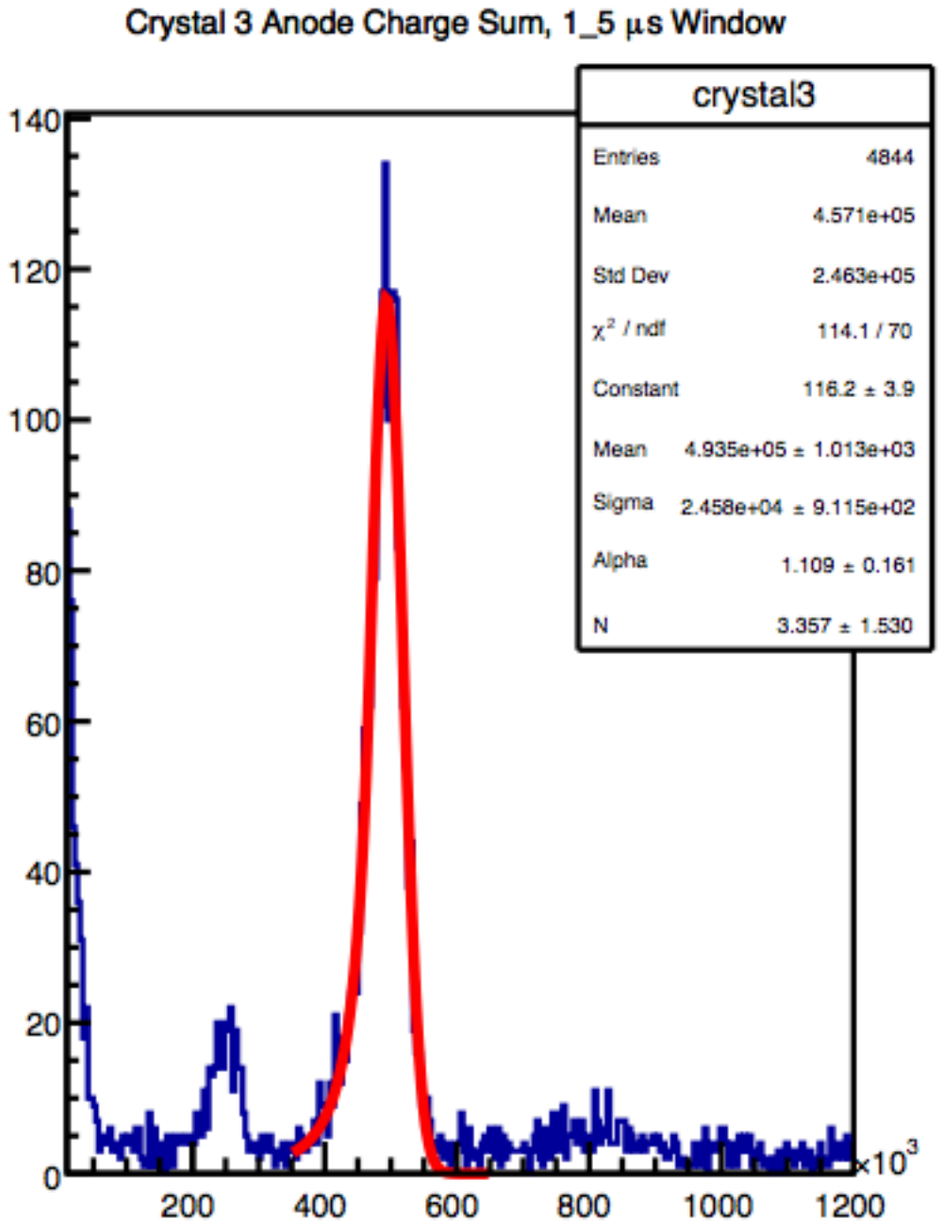
Dynode Waveform (50-10,000 keV)



- 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

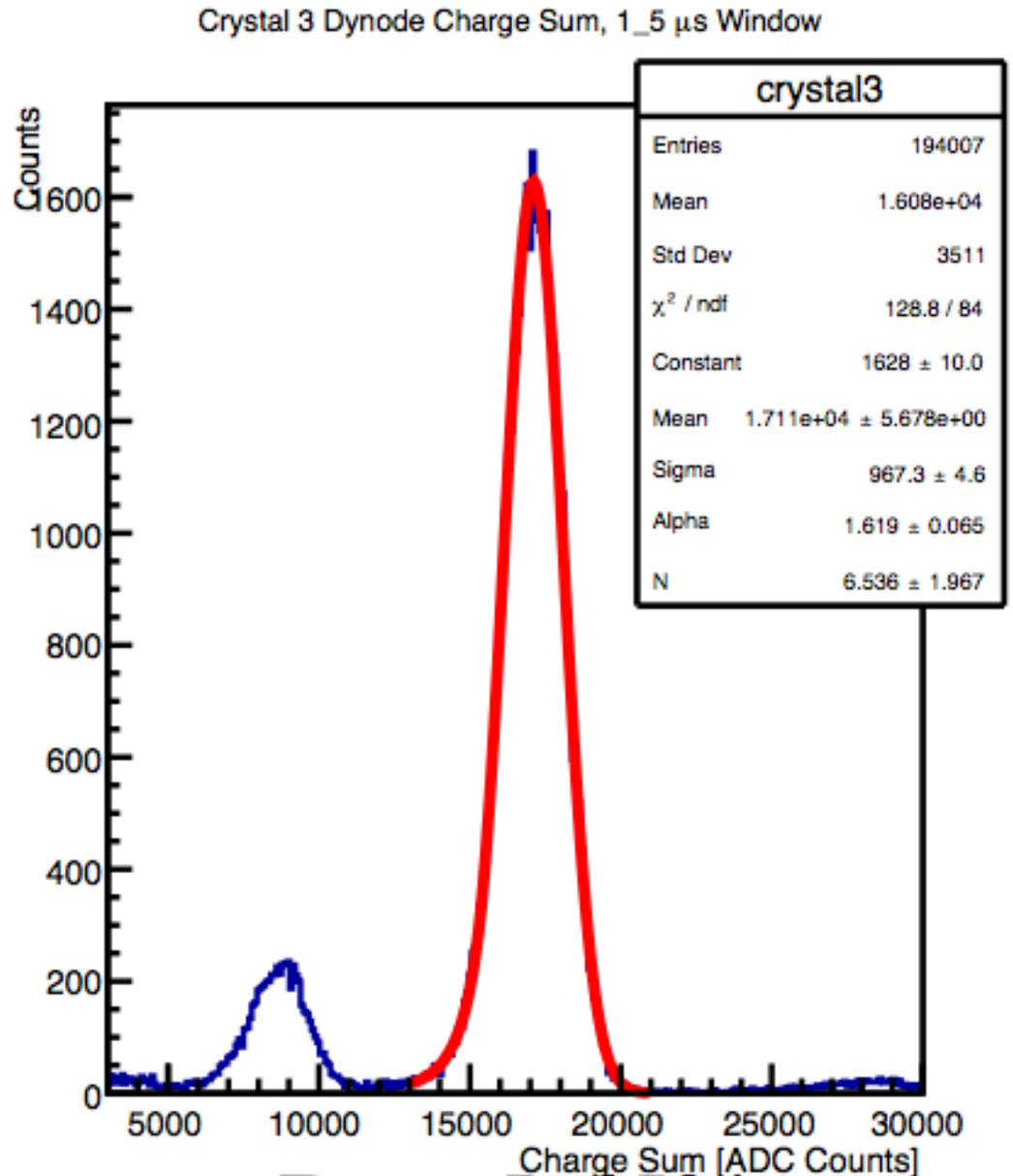
Resolution @ 60 keV

Am-241 ADC sum (Anode)



Res: 4.98%

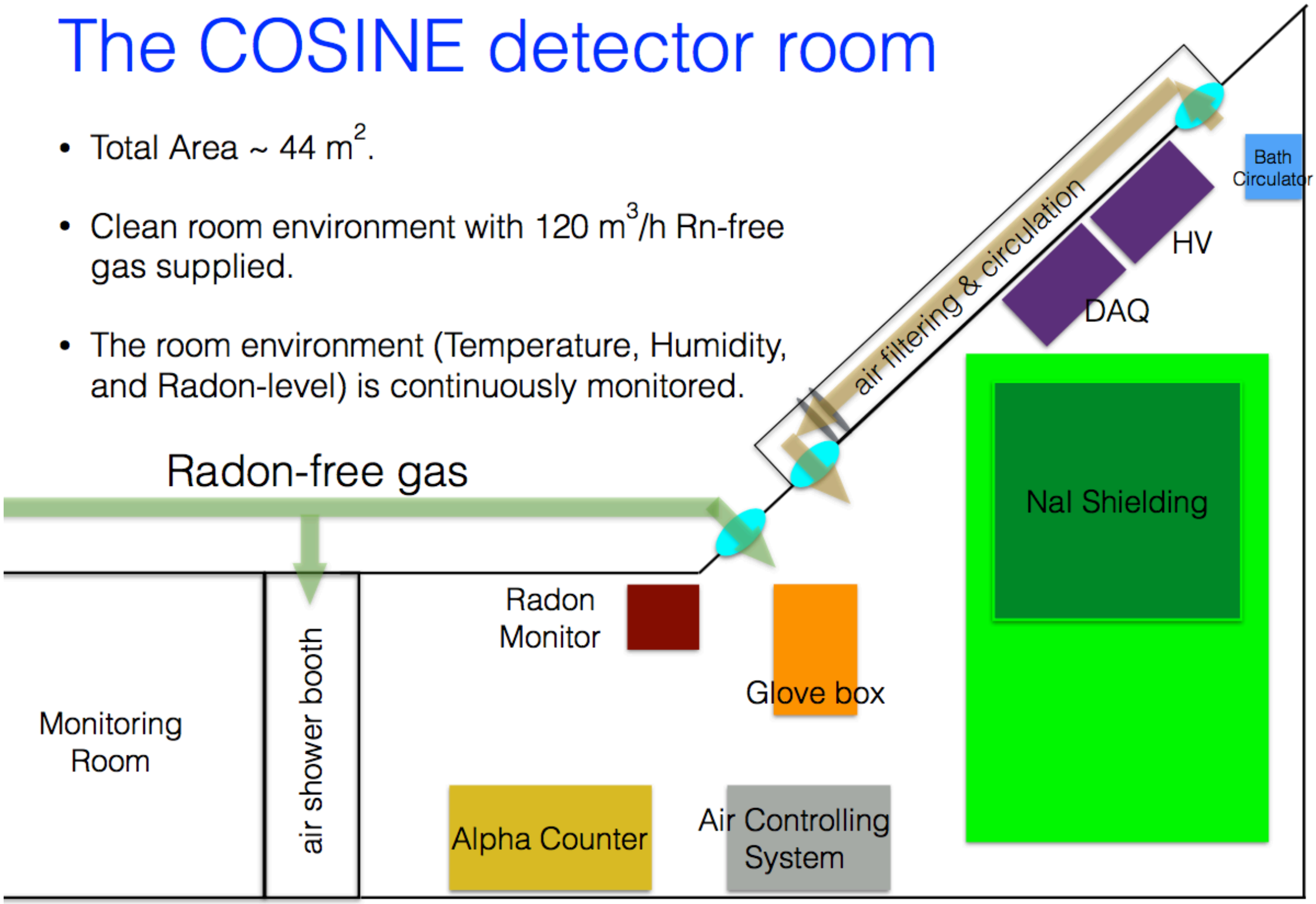
Am-241 ADC sum (Dynode)



Res: 5.65%

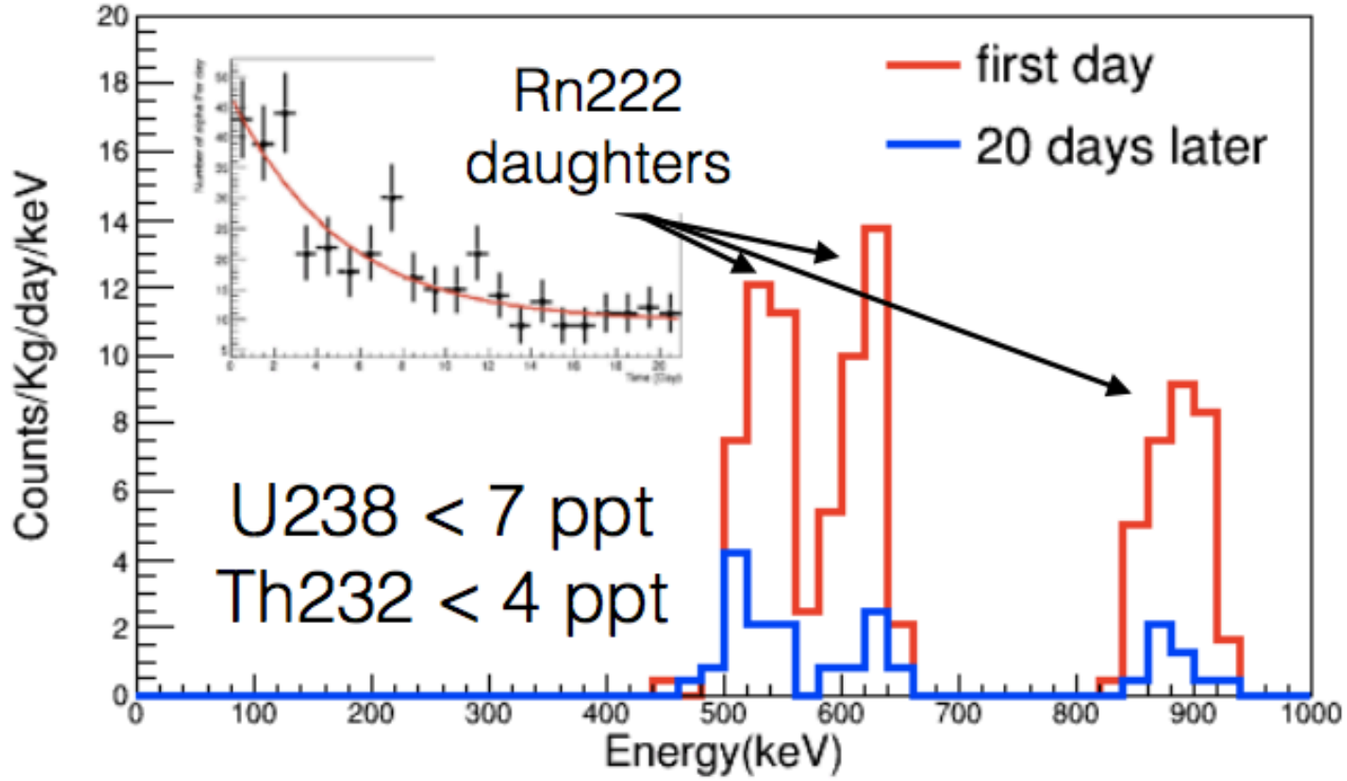
The COSINE detector room

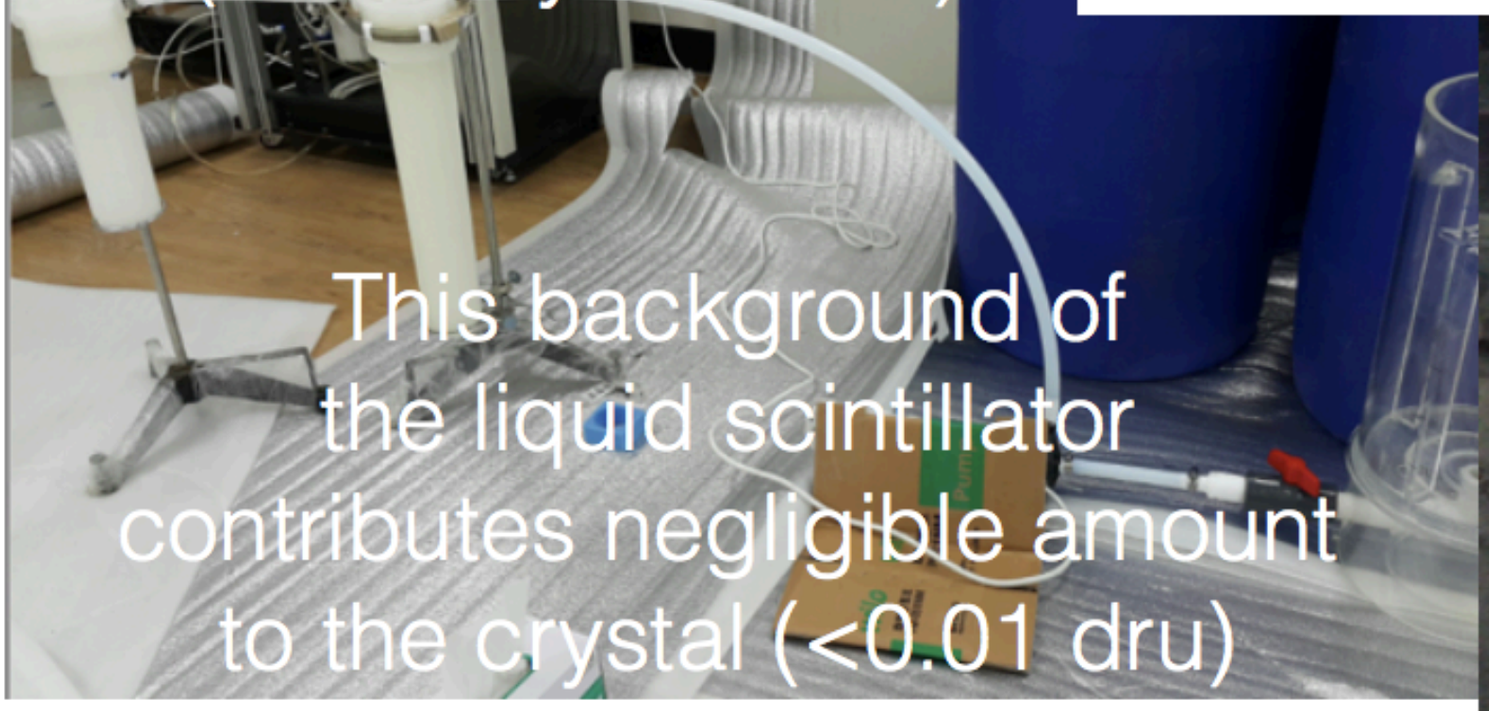
- Total Area ~ 44 m^2.
- Clean room environment with 120 m^3/h Rn-free gas supplied.
- The room environment (Temperature, Humidity, and Radon-level) is continuously monitored.

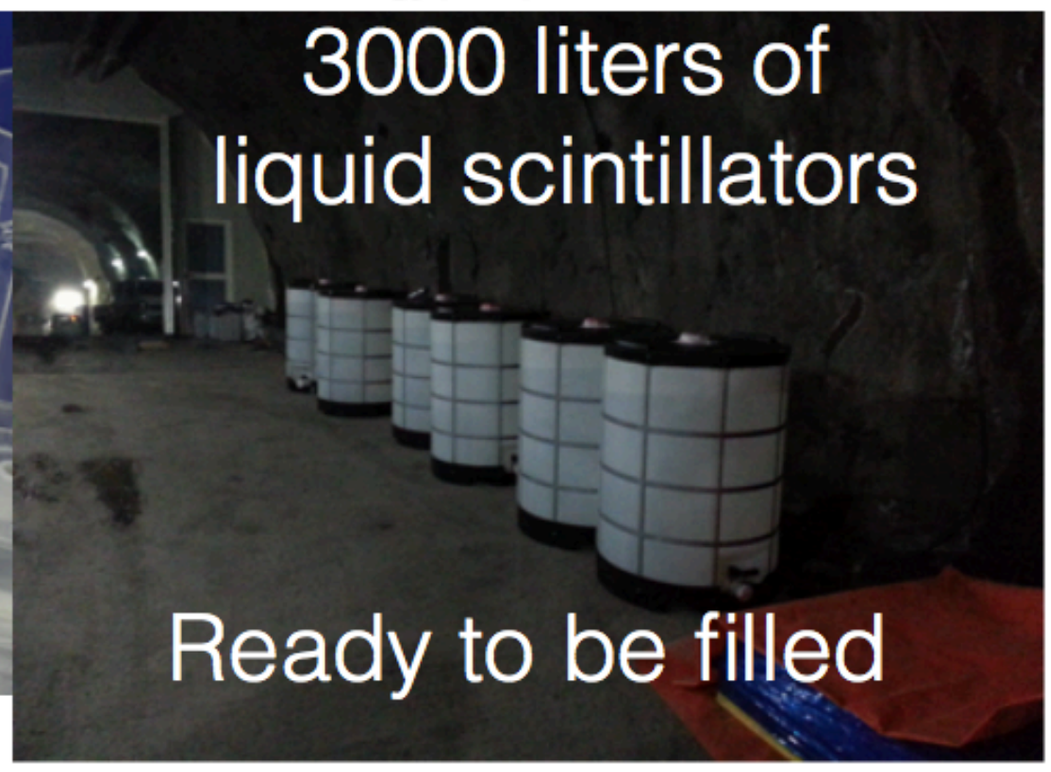


LS for COSINE-100

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

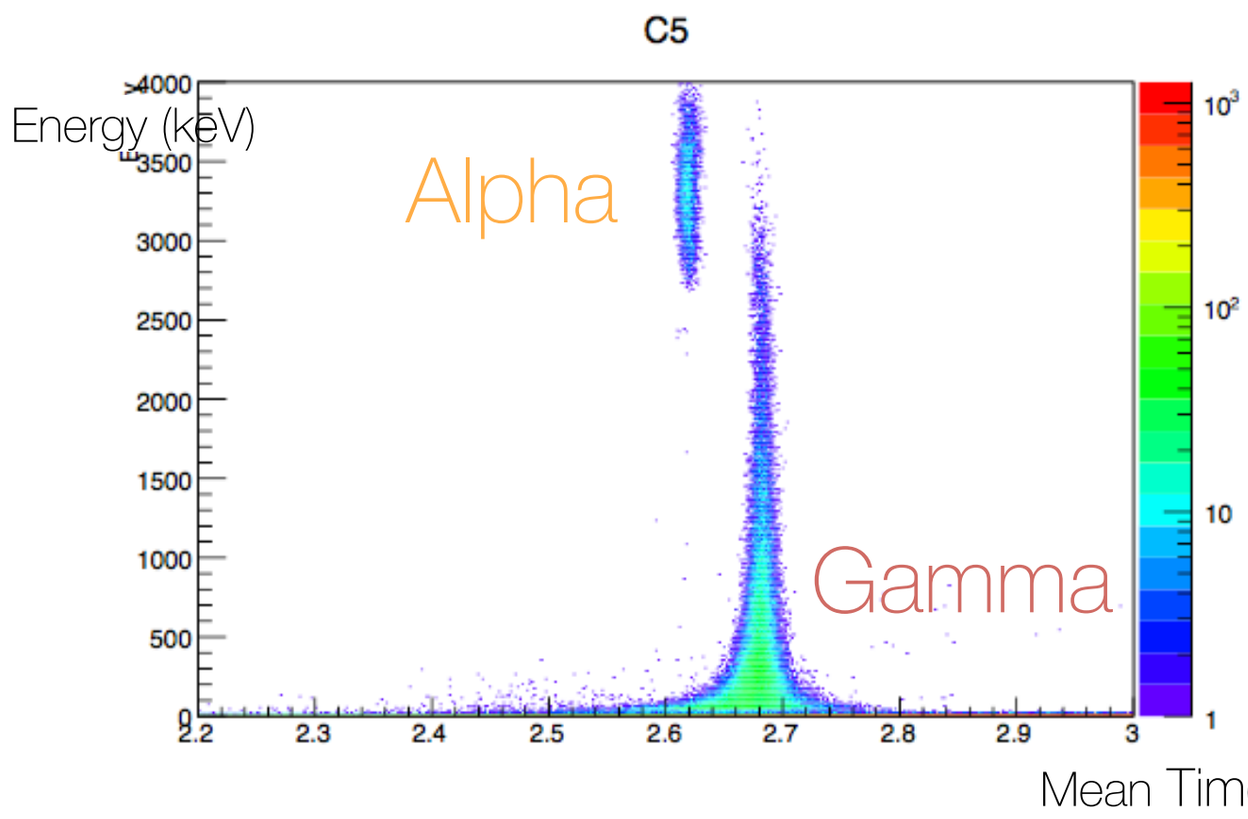






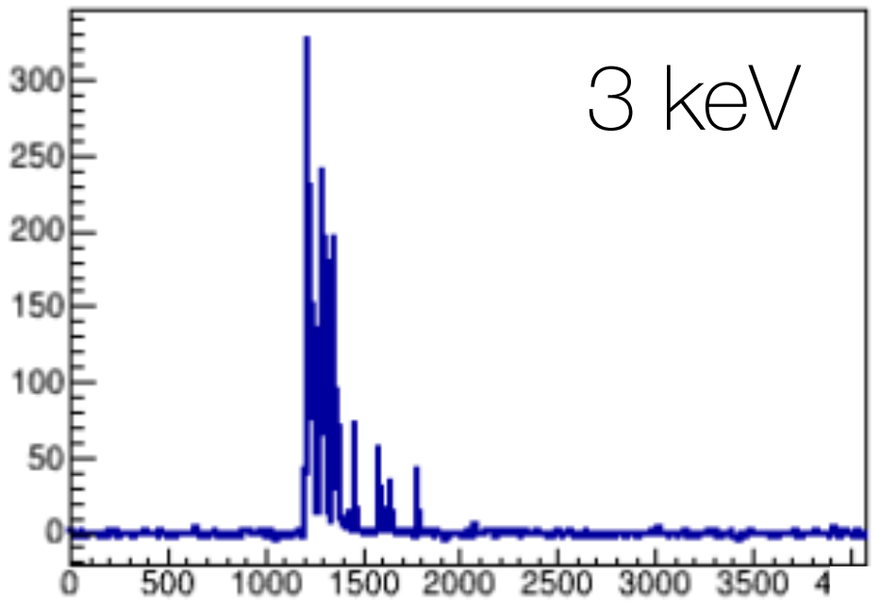
Pulse Shape Discrimination for Alpha

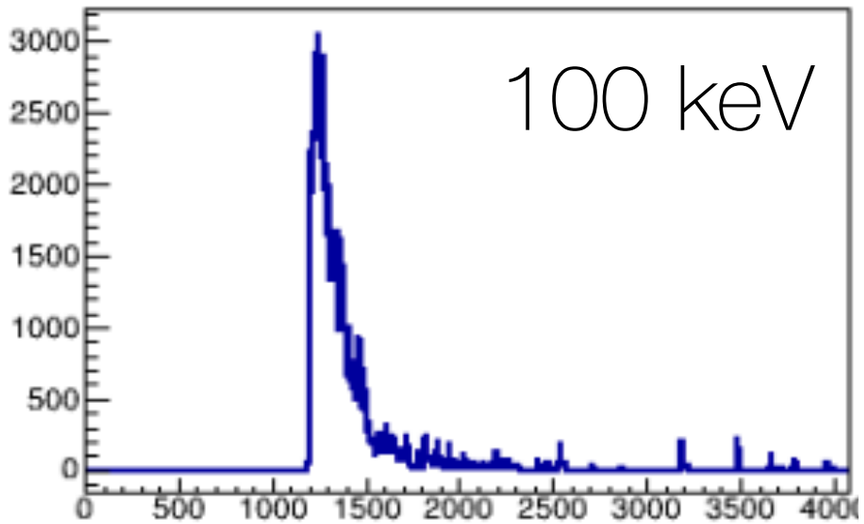
Preliminary

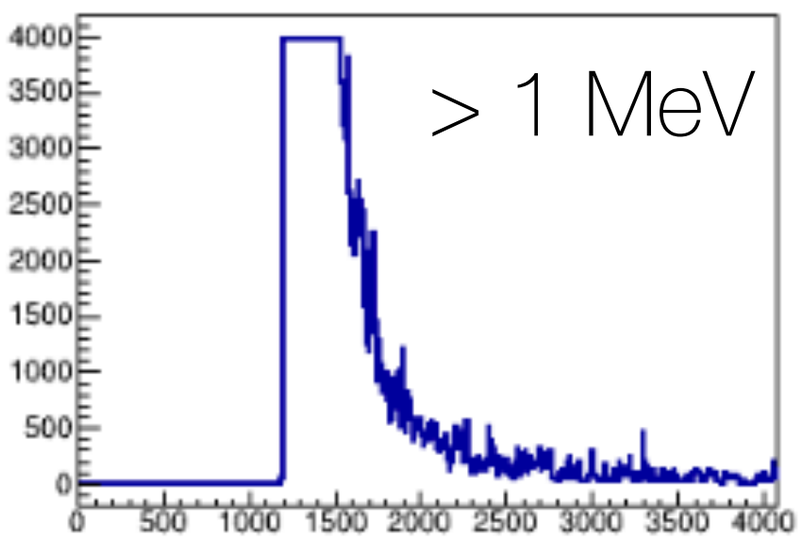


- Pulse Shape Discrimination technique works well for alpha separation
- Using charge-weighted mean time
- With separated alpha events, estimation of ^{210}Po background can be performed
  - 0.5~3 mBq/kg for COSINE-100 crystals

Examples of Signal Events (Anode Channel)





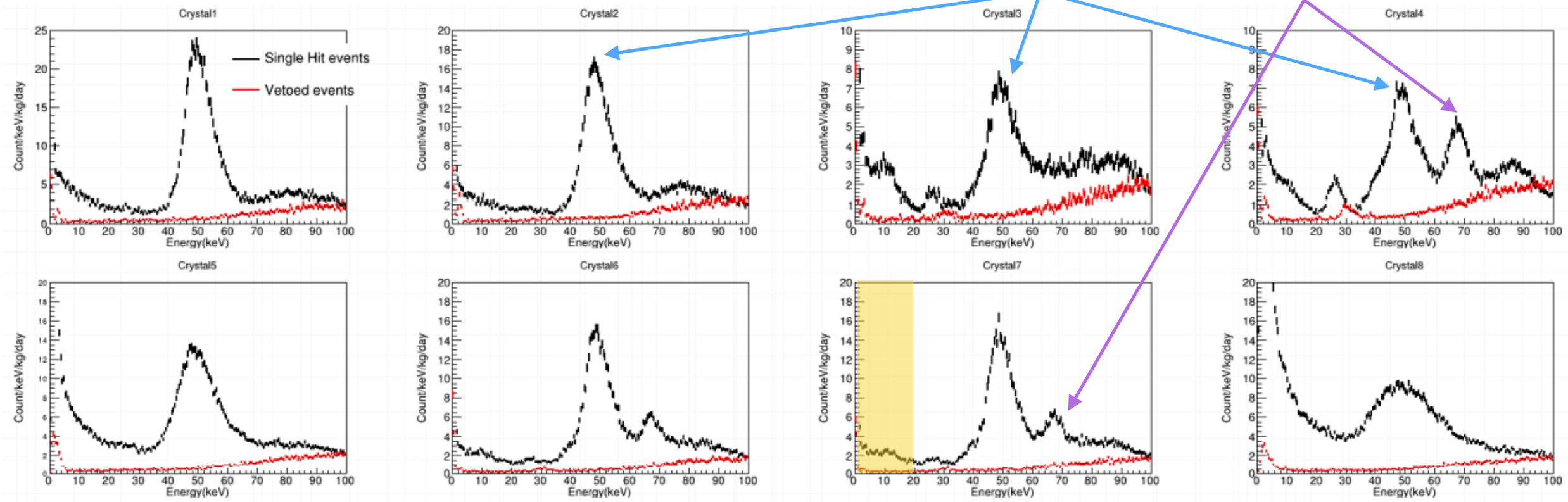


Low Energy Spectrum

Preliminary

^{210}Pb

^{125}I



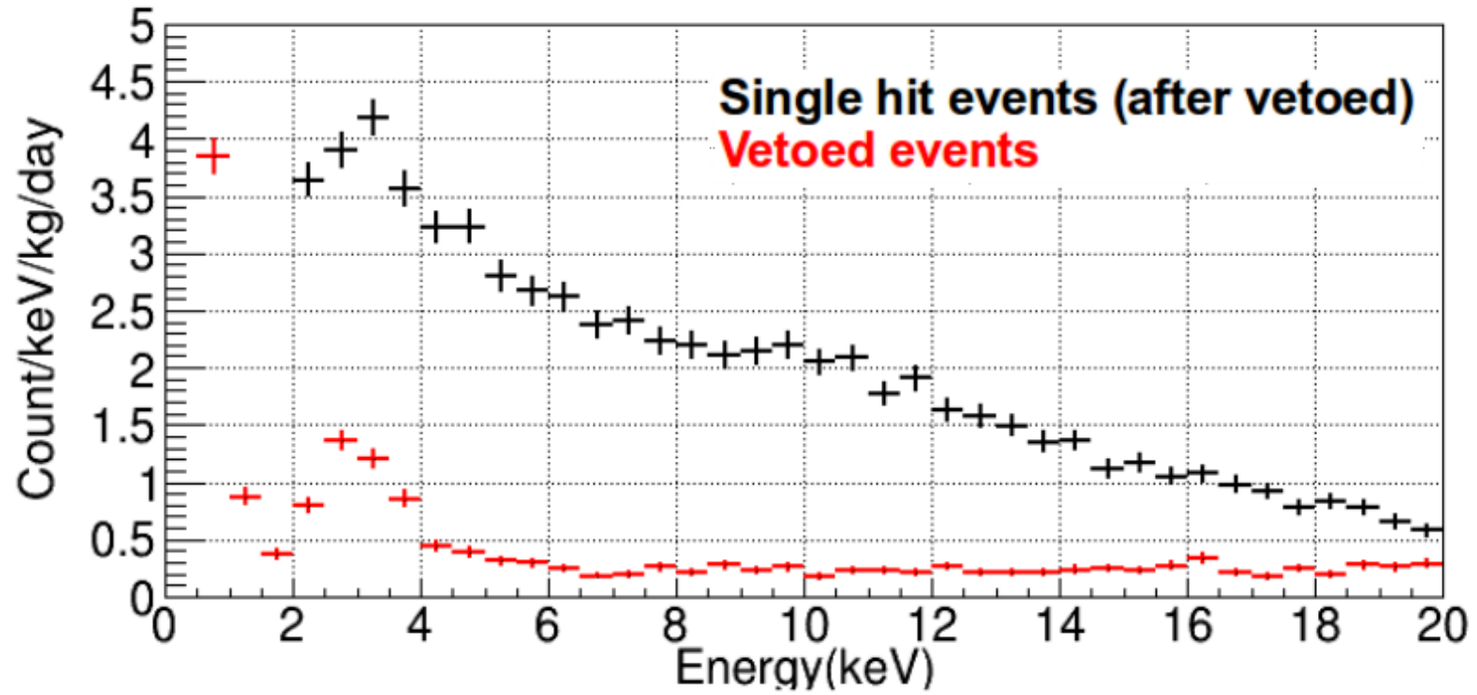
ROI

- 10 days of data, preliminary set of event selection applied
- Depending on crystal, background level 2 to 4 dru in the region of interest
- Cosmogenic peaks remain in certain crystals
- There are still room for improvements

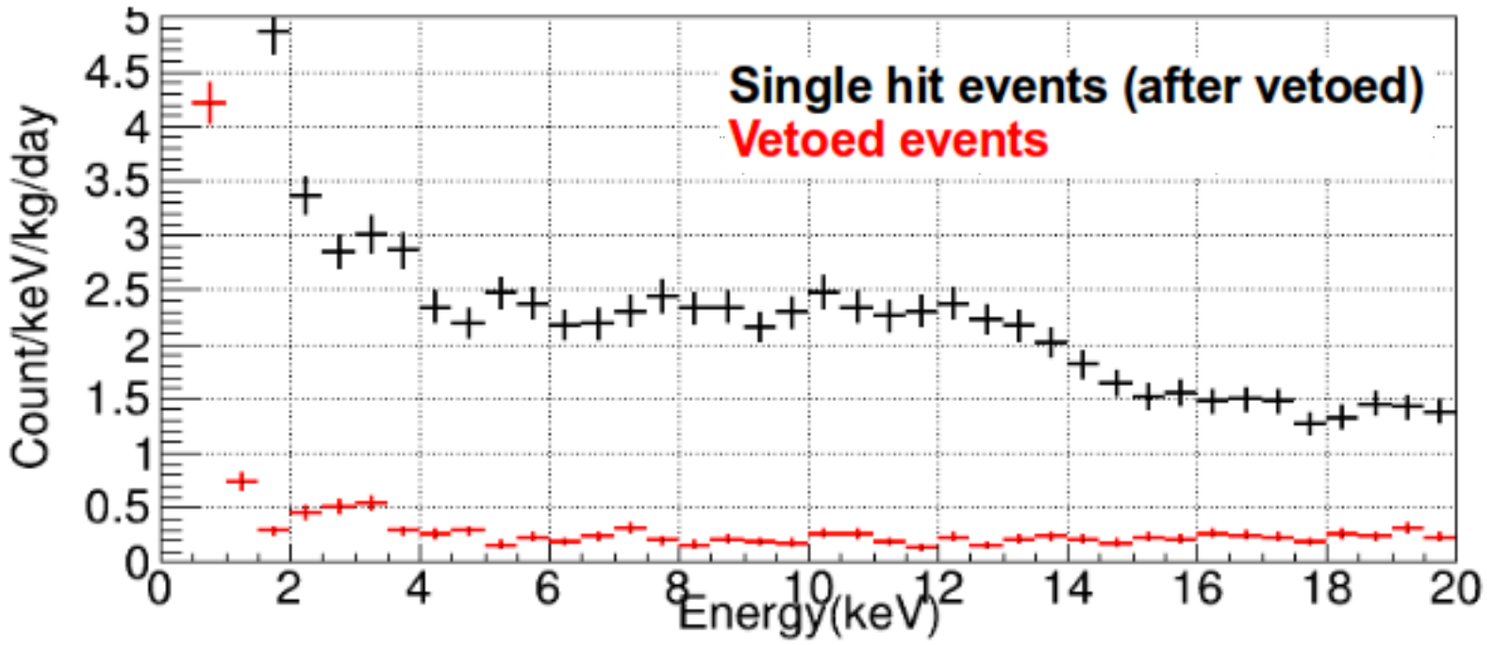
COSINE-100 Low Energy Spectrum (ROI)

Preliminary

Crystal 4

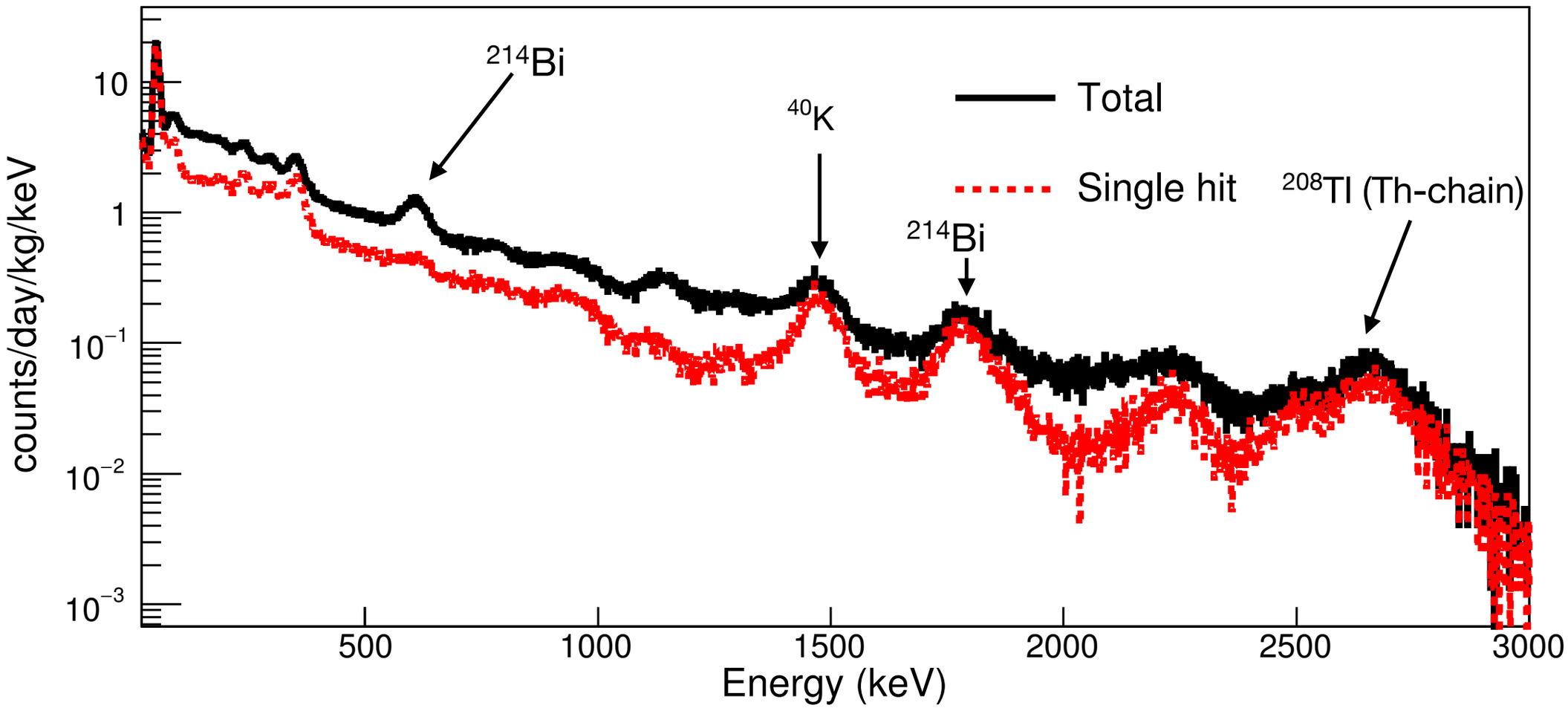


Crystal 7



COSINE-100 High Energy Spectrum

Preliminary

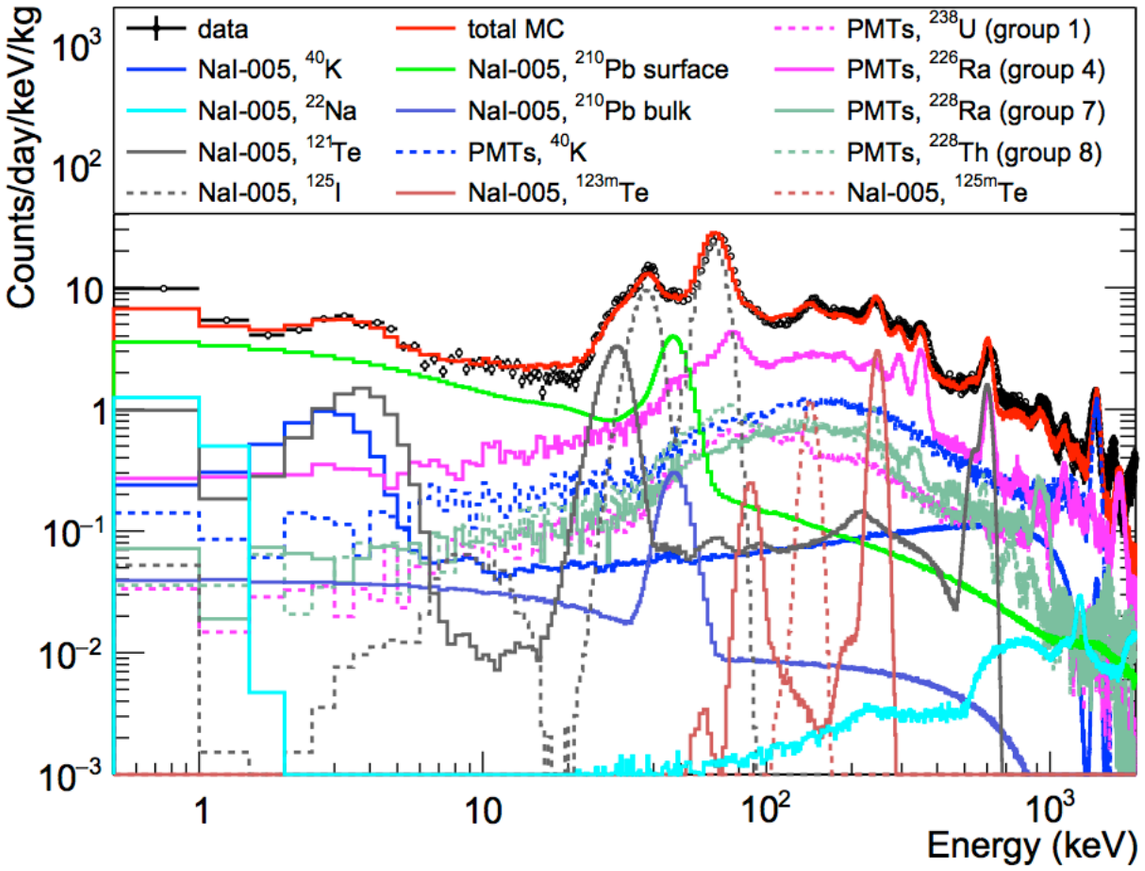


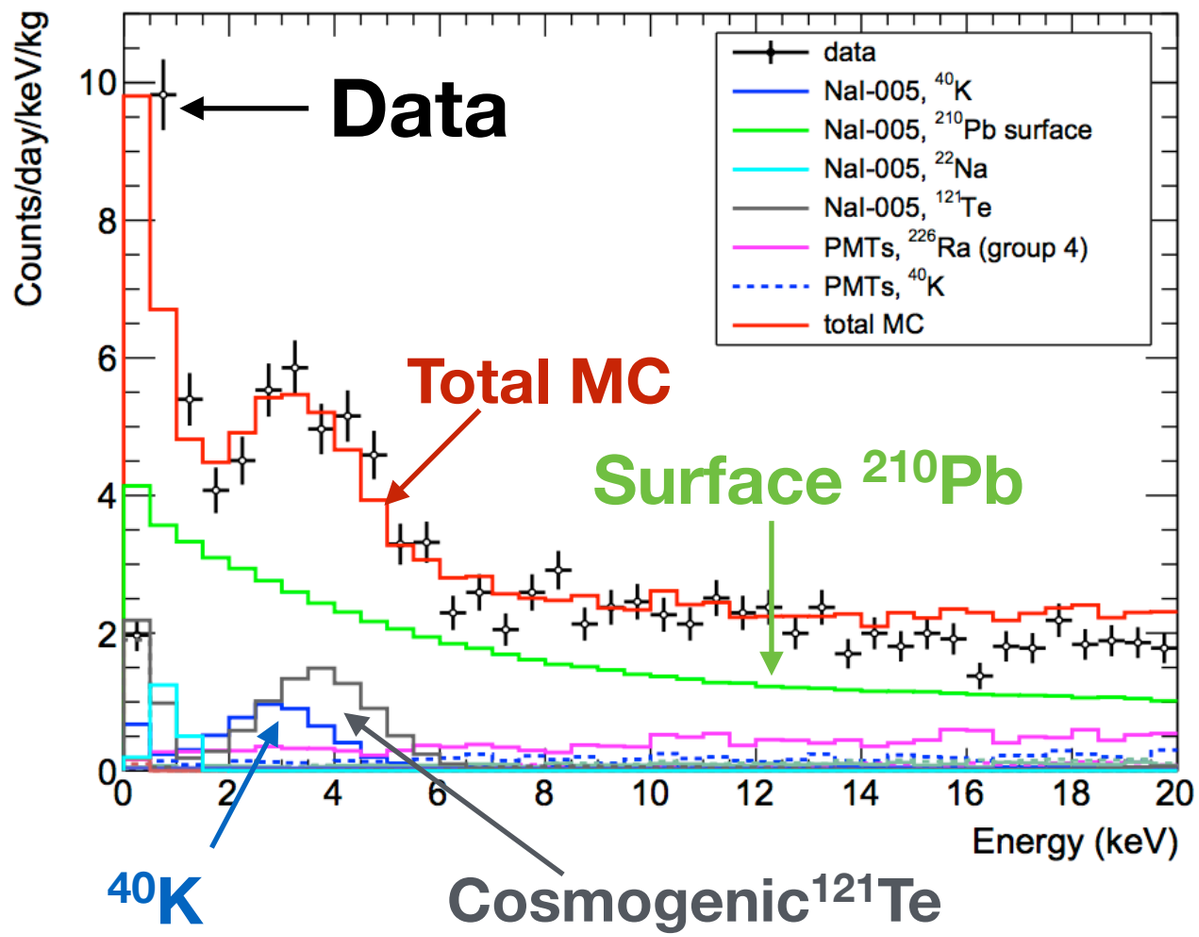
- Gamma spectrum shows pronounce background peaks including 1460 keV from ^{40}K

- Dynamic range for high energy signals is > 5 MeV

COSINE-100 NaI Crystal Simulation @ R&D Setup

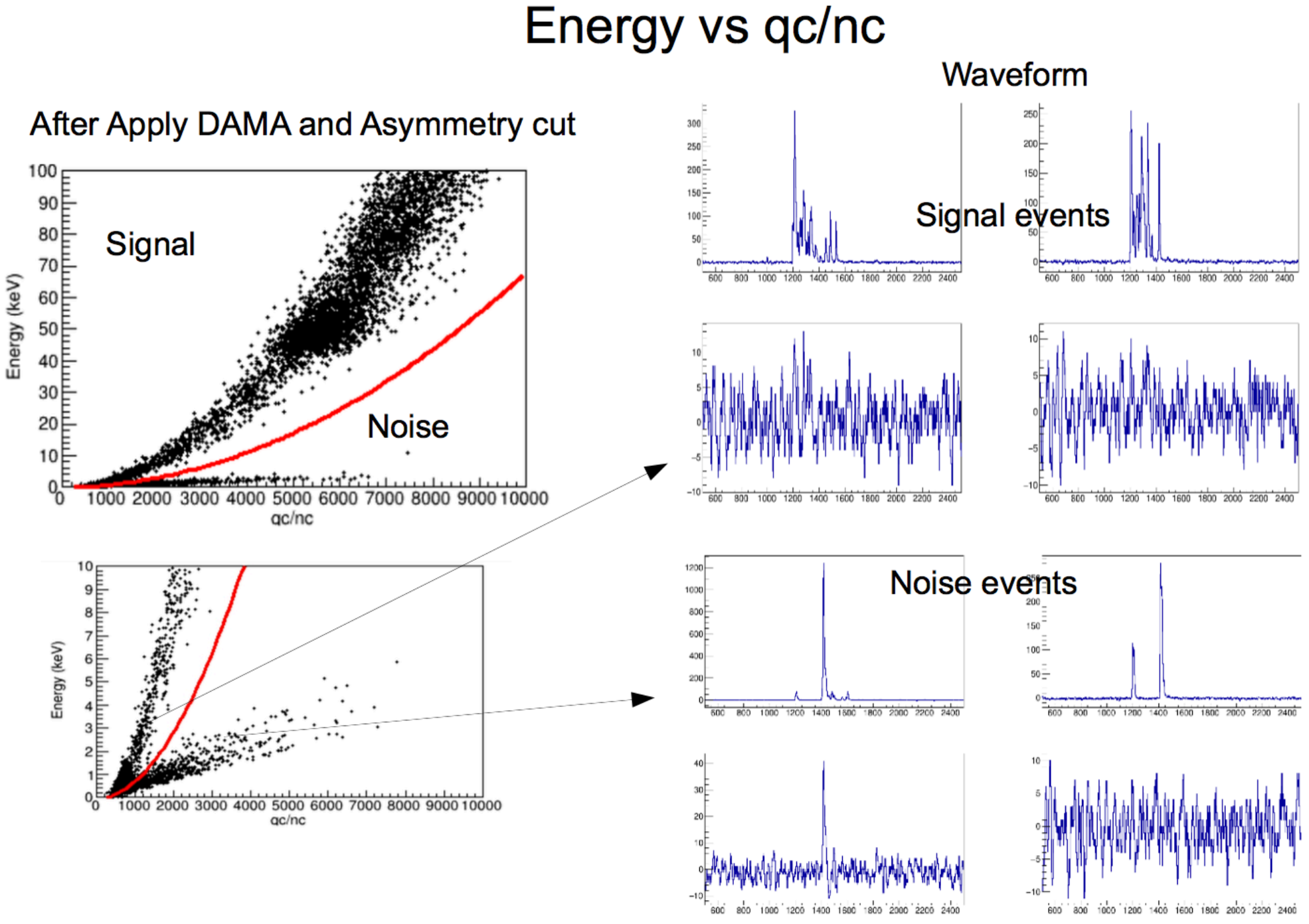
Adhikari et al., arxiv:1703.01982





- 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 in the ROI, followed by ^{40}K within crystal

Average charge/SPE cut



Crystal growing in Korea

Under development

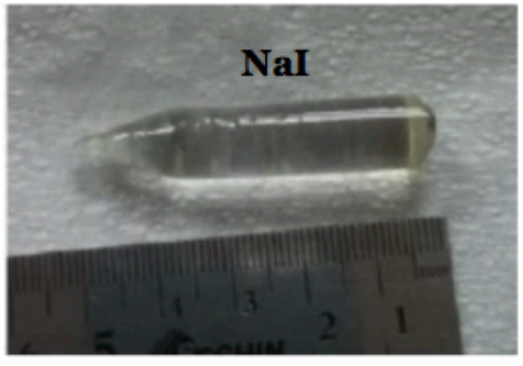
Czochralski Furnace

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

ANAIS

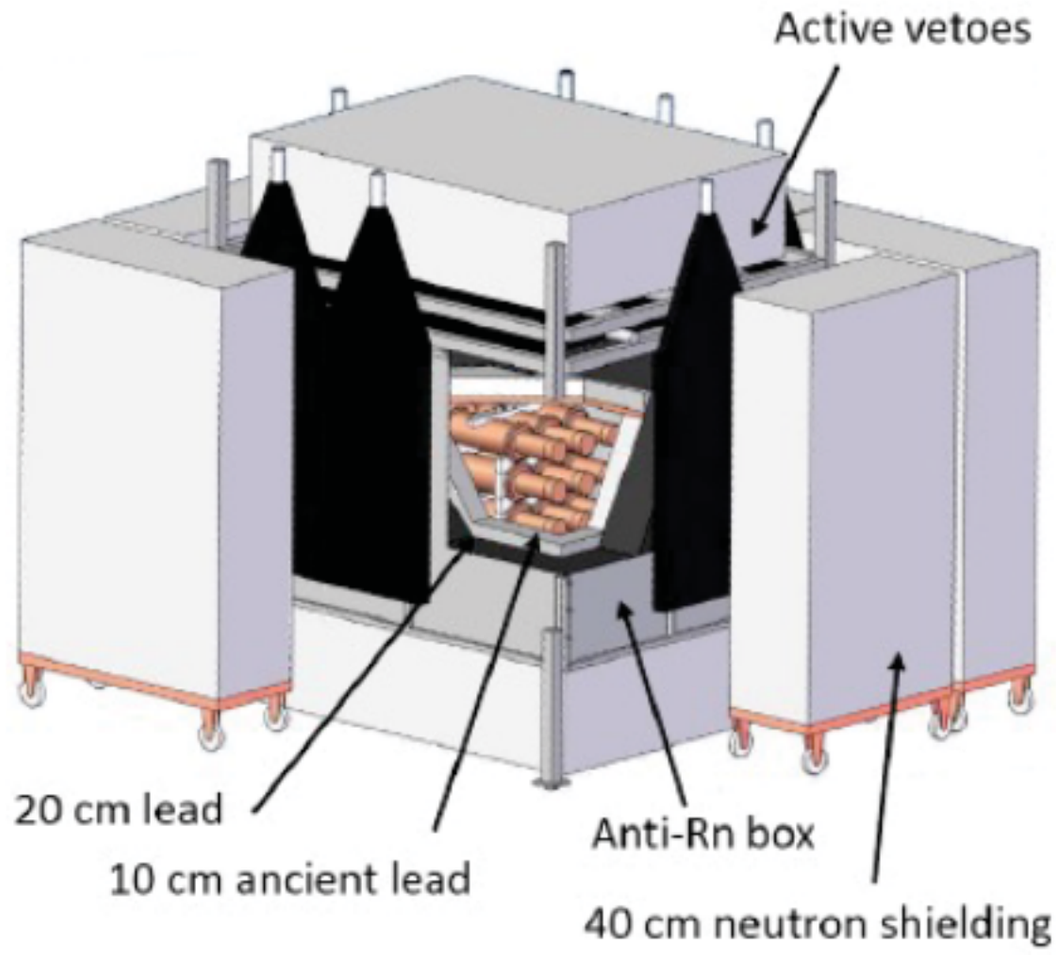
- 112.5 Kg in a 3 x 3 array configuration

  - 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

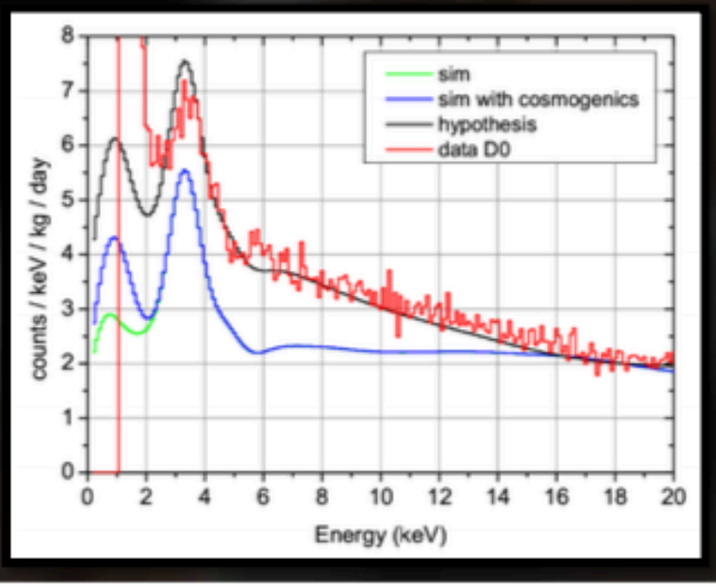


ANAIS: Background

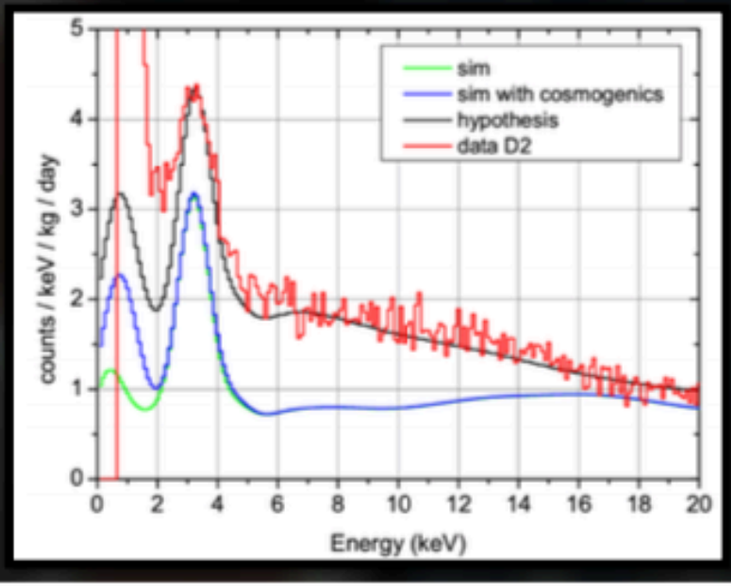
P. Vilar, RENATA 2016

	^{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)

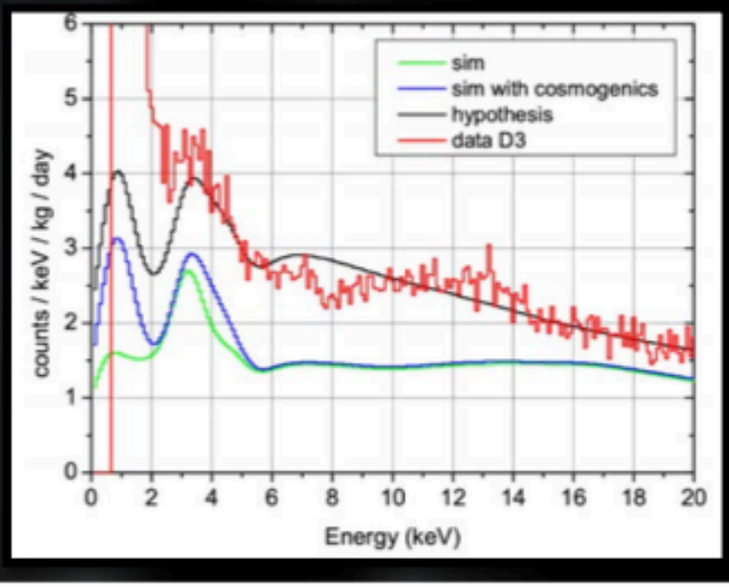
D0 Detector



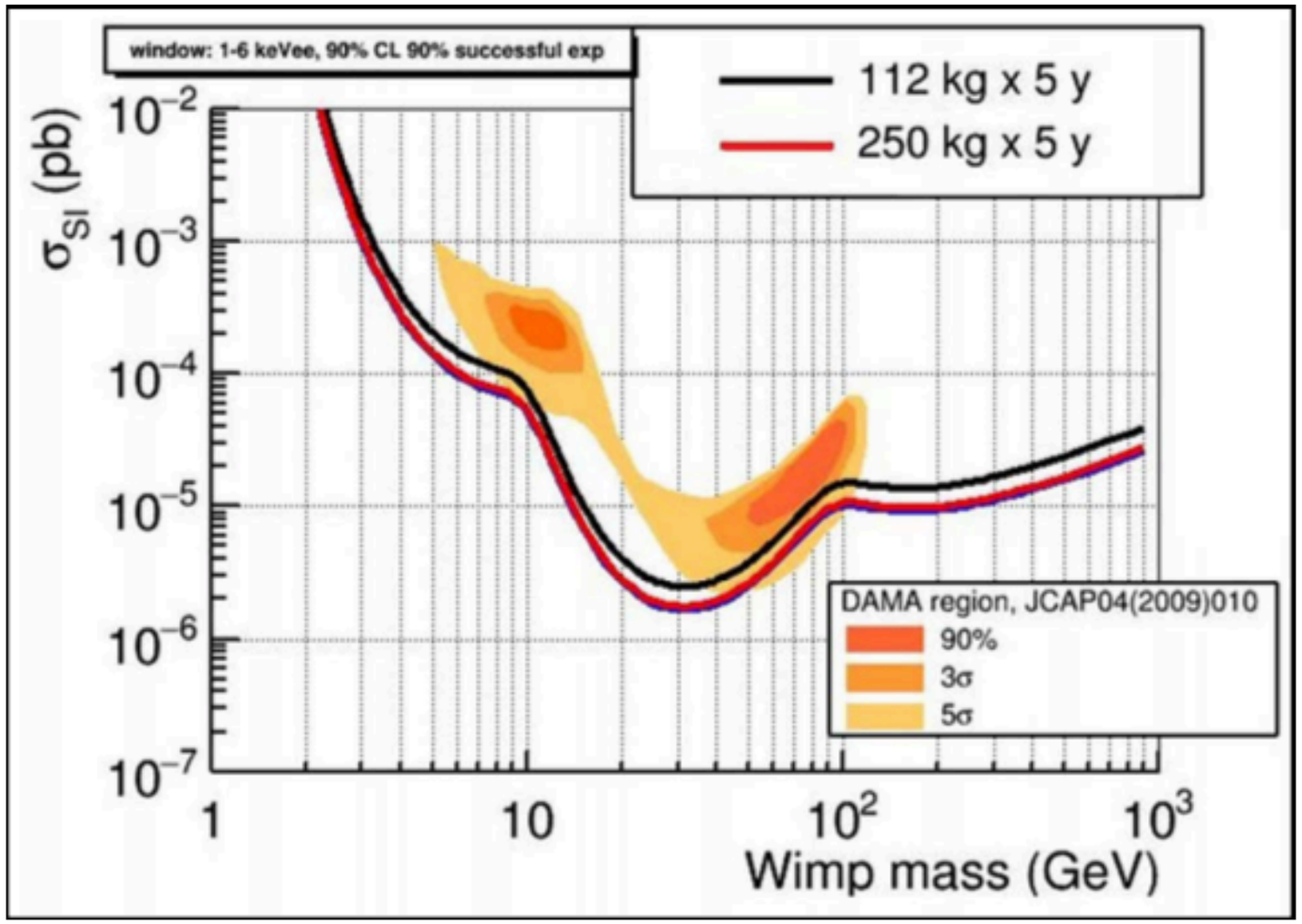
D2 Detector



D3 Detector

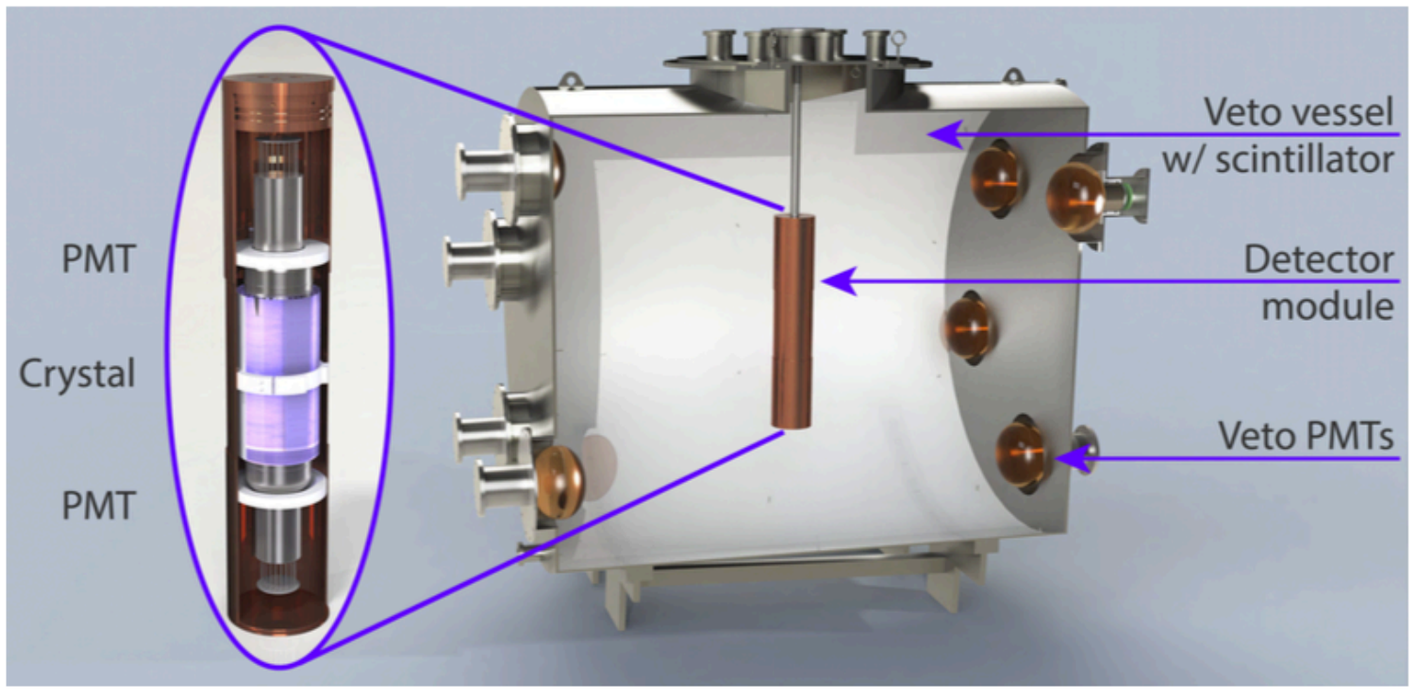


ANAIS: Plan and Sensitivity



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



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

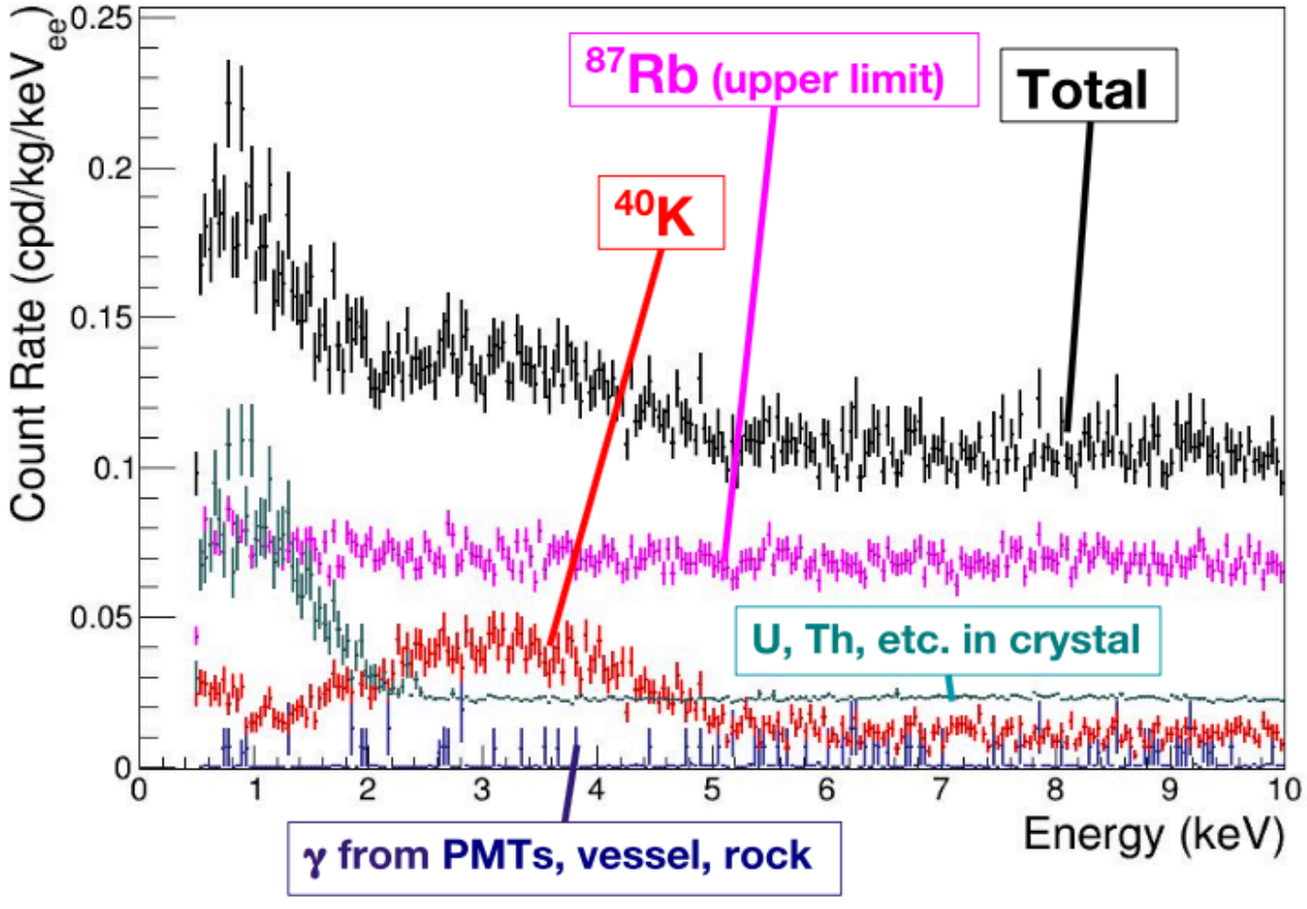
- With new NaI power purification, < 10 ppb was achieved

  - 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

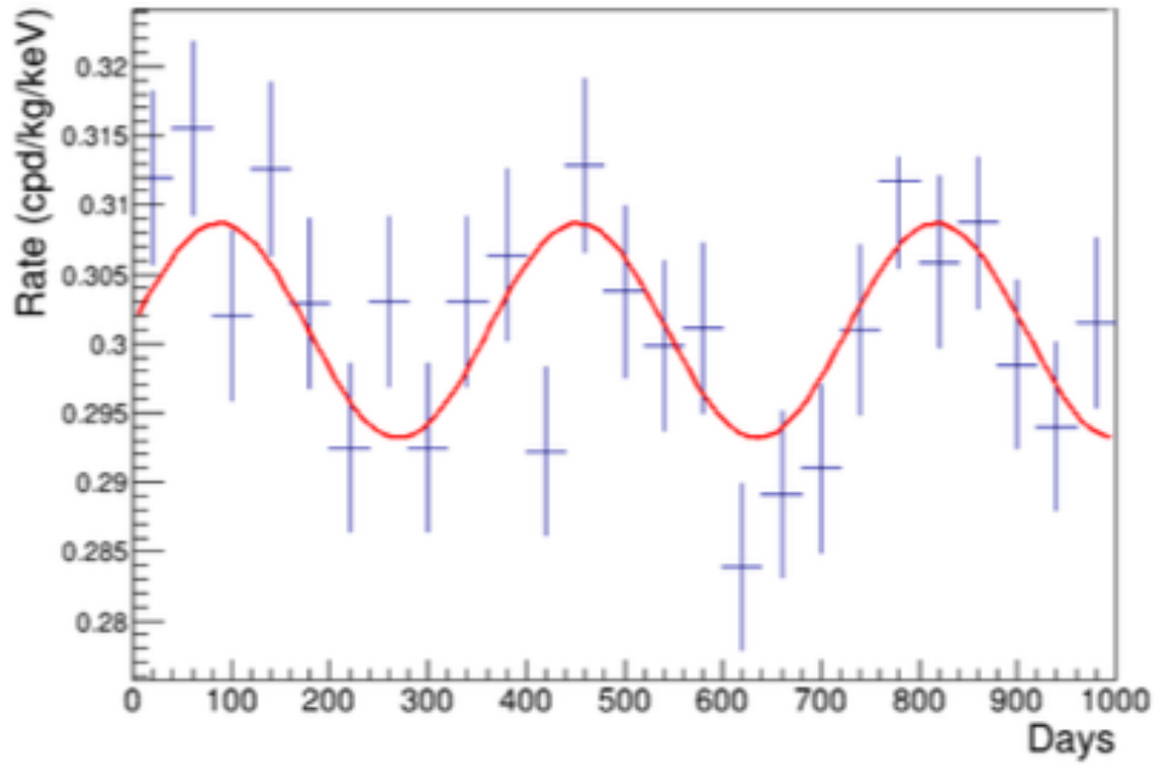
- Full detectors construction at LNGS and SUPL start in 2017

- 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