Results of DM-Ice17 and the Status of COSINE-100

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on behalf of DM-Ice and COSINE-100 Collaboration

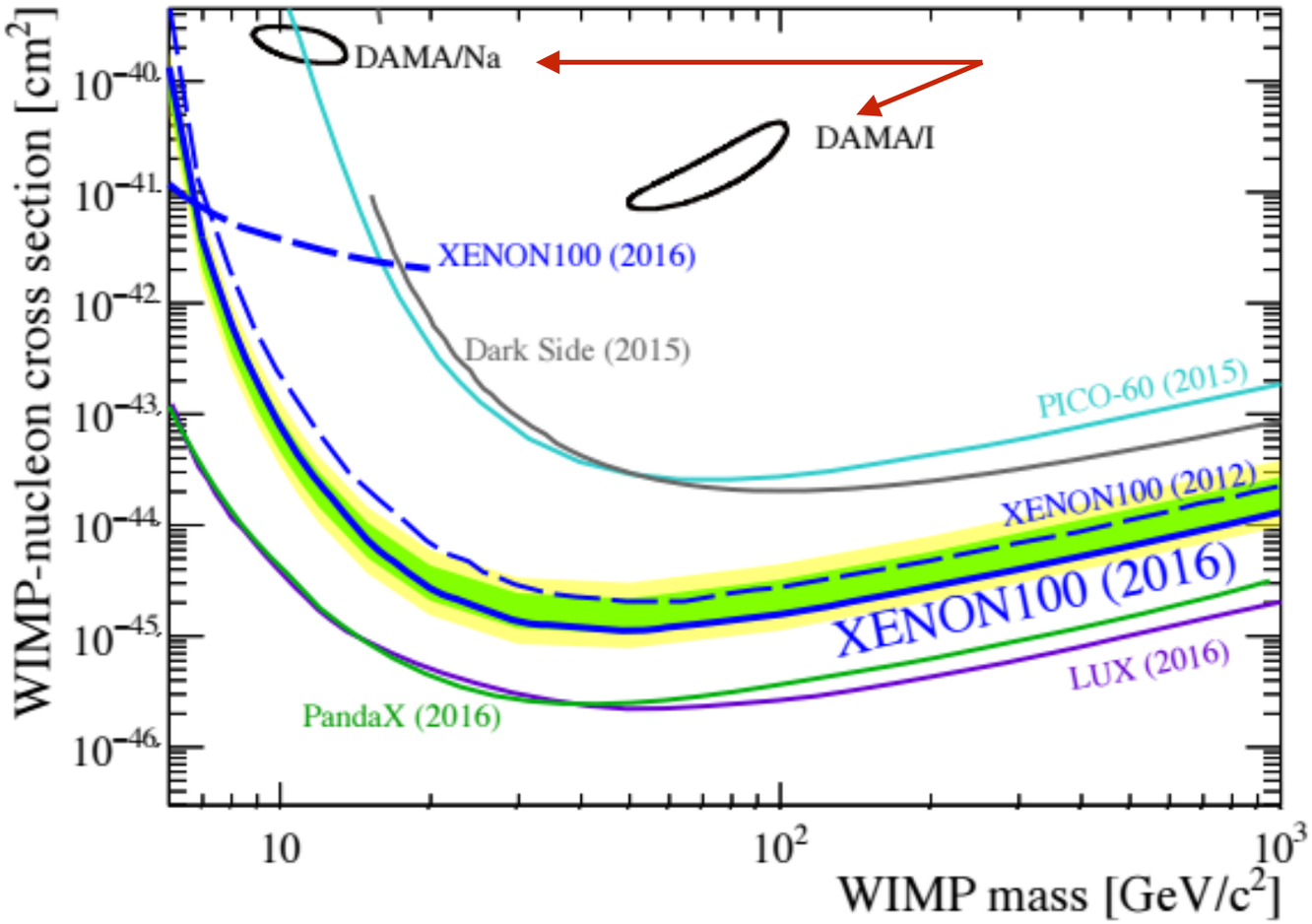
Yale University

IPA 2017
May 8, 2016

Yale

Wright Laboratory

Current Dark Matter Field

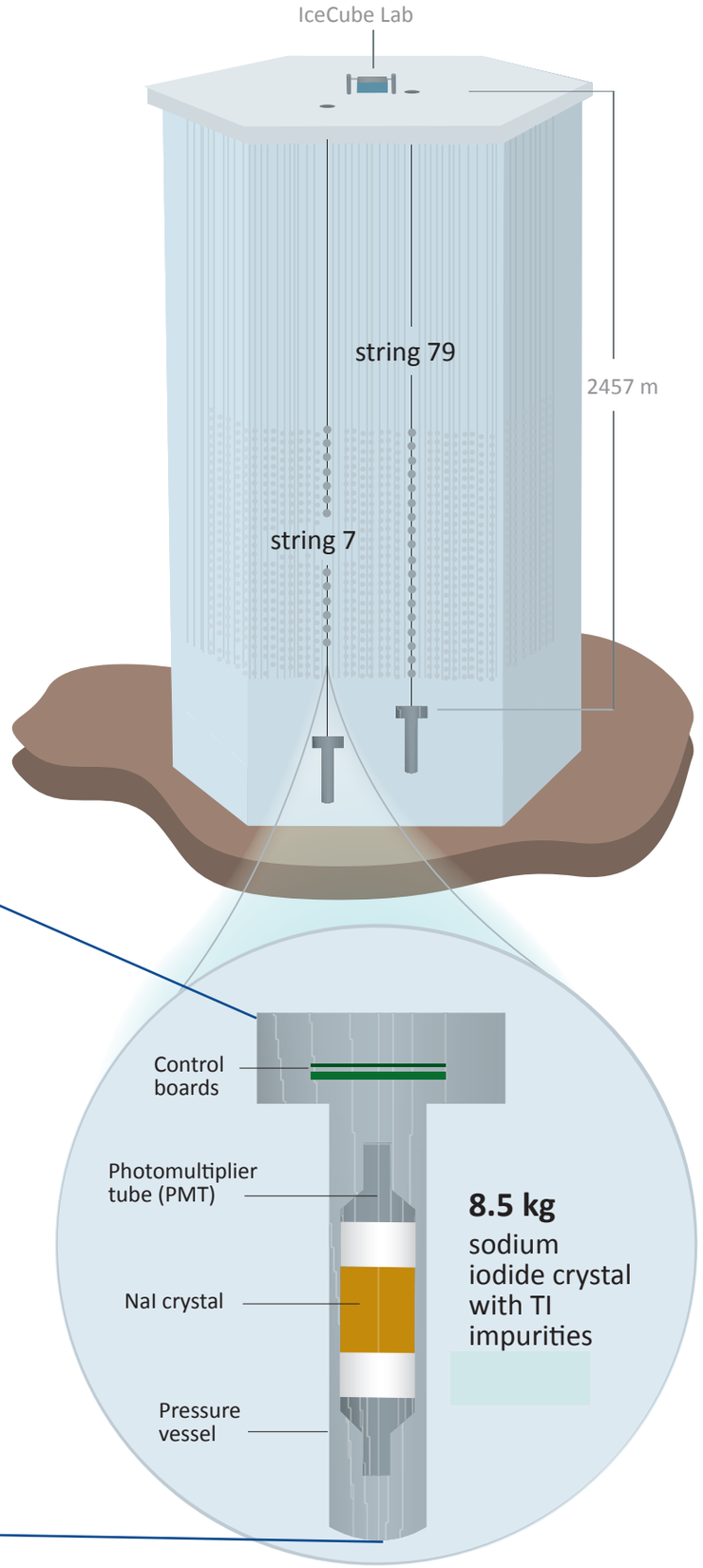


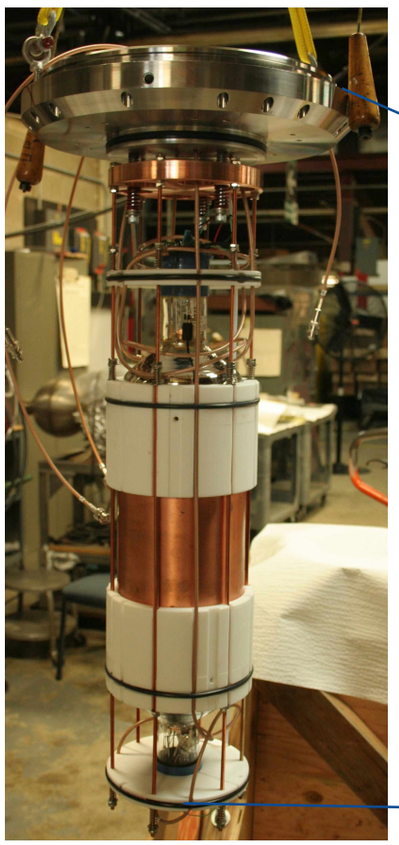
arXiv: 1609.06154

- 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

DM-Ice17 Experiment

- Located at South Pole
- Two 8.5 Kg NaI(Tl) crystals
- Installed: Dec. 2010, Physics run: Jun. 2011 - Jan. 2015
- Goals
  - Demonstrate the feasibility of deploying and operating NaI(Tl) detectors in the Antarctic ice for a dark matter search
  - *In situ* measurement of the radiopurity of the Antarctic ice at 2450 m depth
  - Study environmental stability
  - First search for annual modulation with NaI(Tl) in the Southern Hemisphere





Why the South Pole?

- If found, the same dark matter signal in both hemispheres

- Seasonal variation reversed in phase
  - Opposite muon rate, tagging of muons verified by IceCube/DeepCore

- Overburden from 2450 m ice (2200 m.w.e.)
  - Negligible environmental radioactivity: ppt $^{238}U/^{232}Th$, ppb ^{40}K
  - Stable temperature under ice

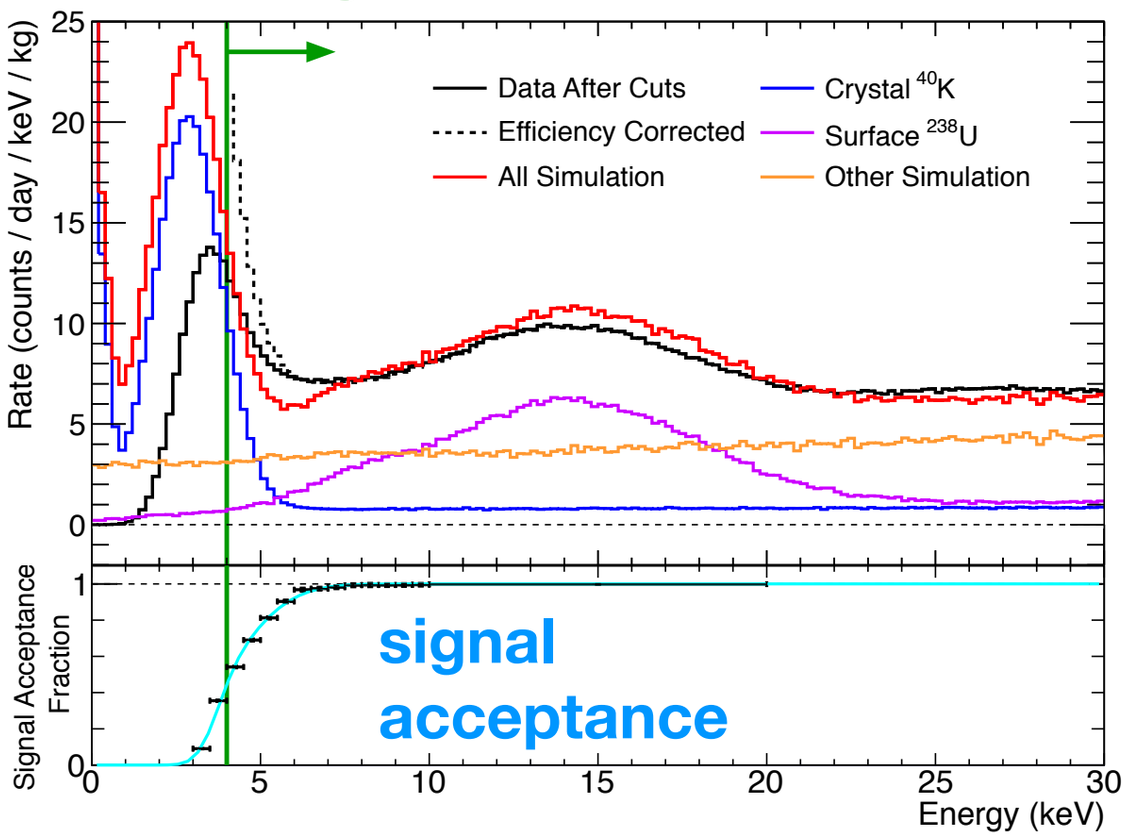
- Support infrastructure of Amundsen-Scott South Pole Station

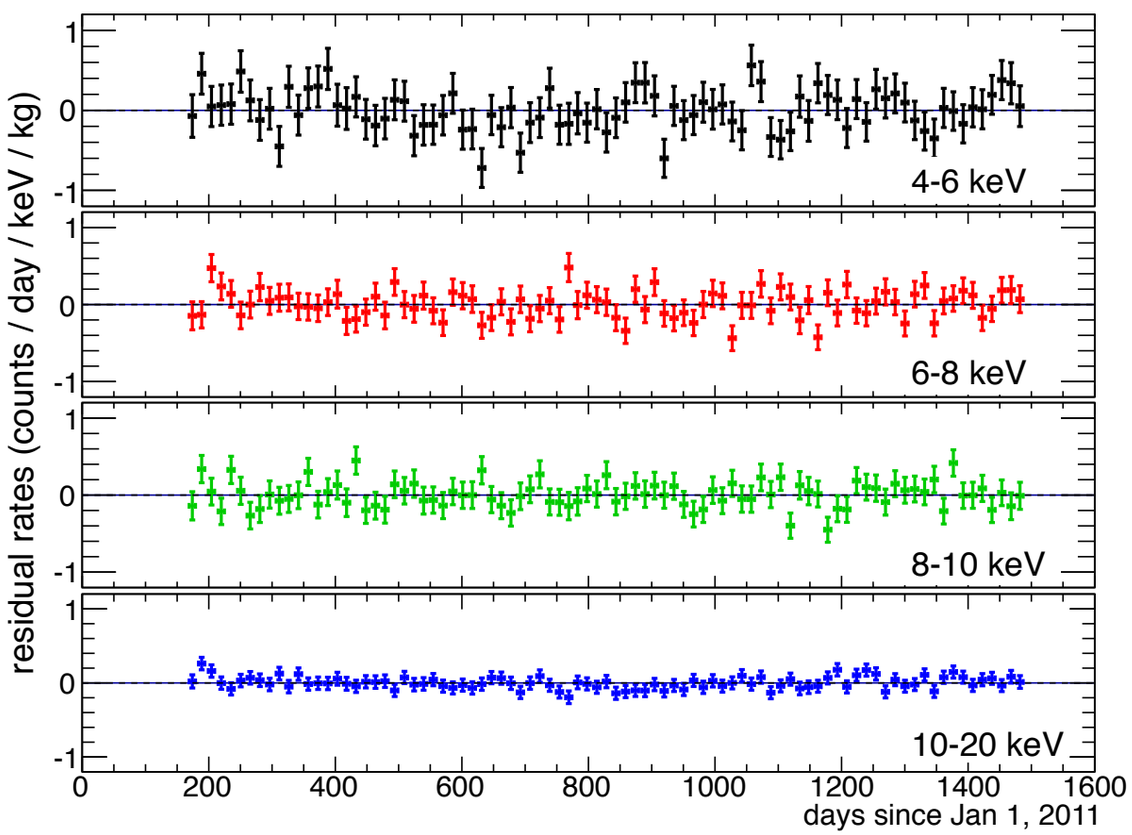
Low Energy Event Rates

- Analysis threshold at 4 keV
- 3 keV peak from ^{40}K contamination in the crystals, ~15 keV feature from surface ^{238}U contamination on the copper encapsulation
- The data are consistent with the null hypothesis in each energy bin

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

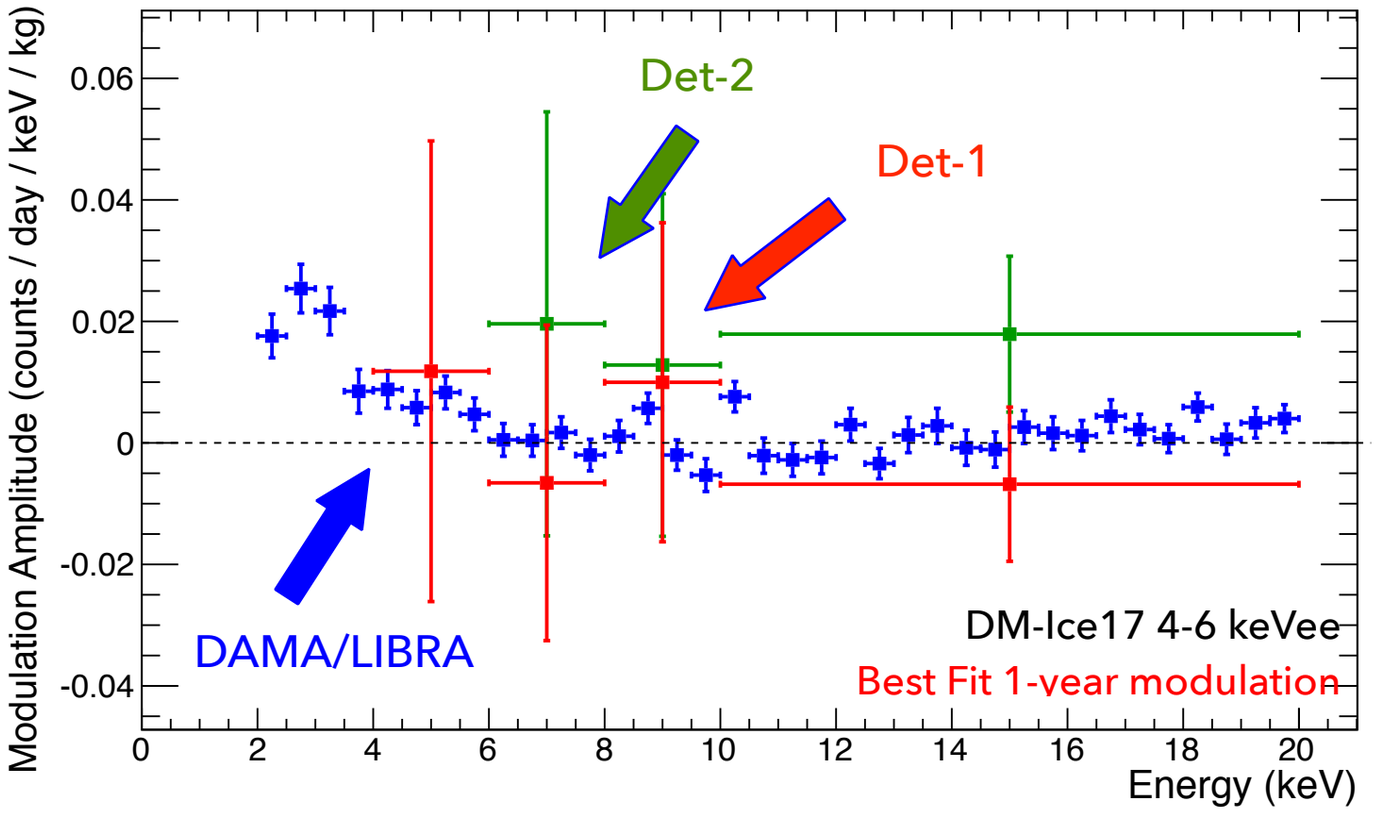
Analysis threshold



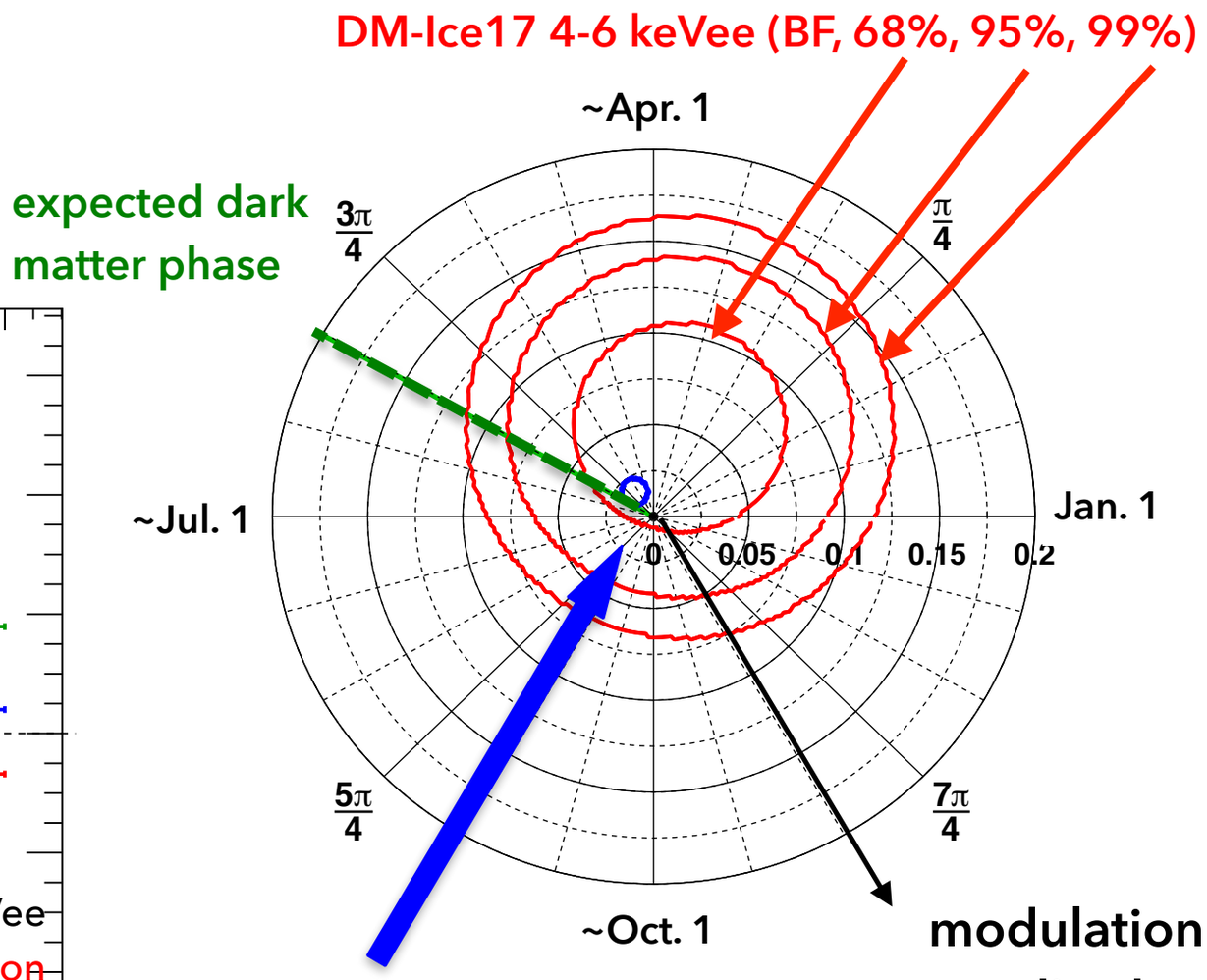


Annual Modulation Allowed Region

- Comparing sinusoidal modulation to background subtracted event rates
- Maximum likelihood fits for DAMA and DM-Ice17
- Period/phase fixed with 1 year/June 2
- Dark matter modulation amplitudes are consistent at all energies with both **no modulation** and the DAMA signal



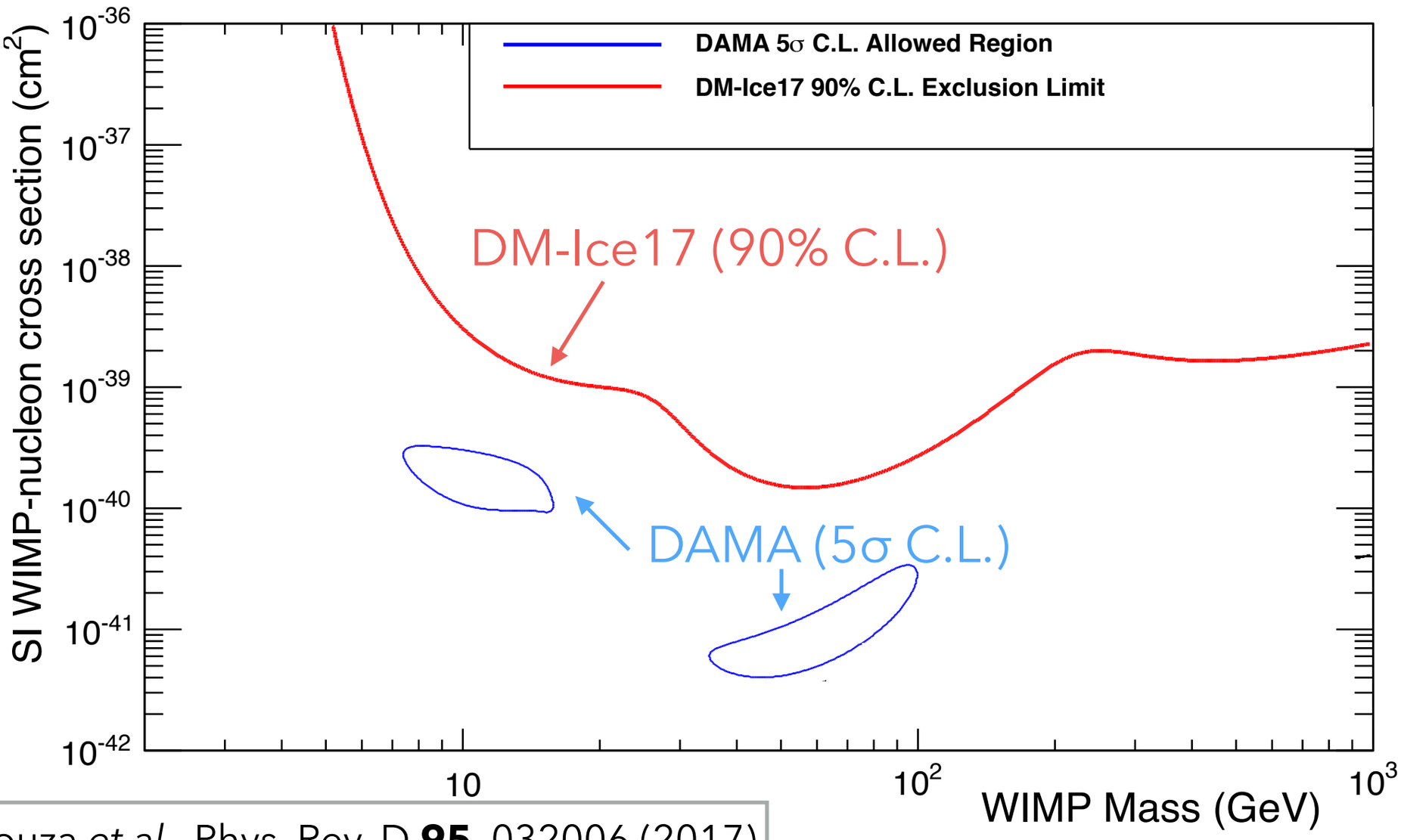
Barbosa de Souza *et al.*, Phys. Rev. D **95**, 032006 (2017)



DM-Ice17 Exclusion Limit

- The strongest exclusion limit in the Southern Hemisphere

- To test DAMA result, more mass, lower background, and lower analysis threshold are required



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

COSINE-100

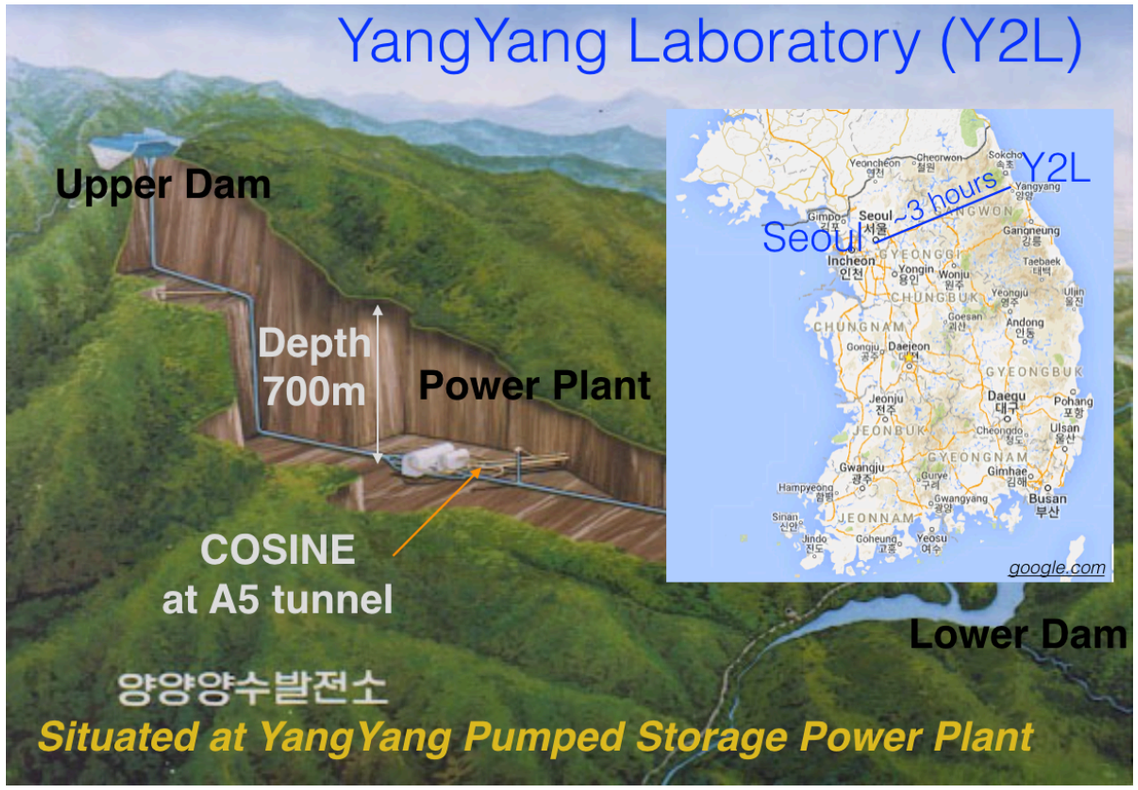
- A joint effort between DM-Ice and KIMS collaboration

- 8 crystals with 106 kg in total

DM-ICE + KIMS Korea Invisible Mass Search Experiment

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

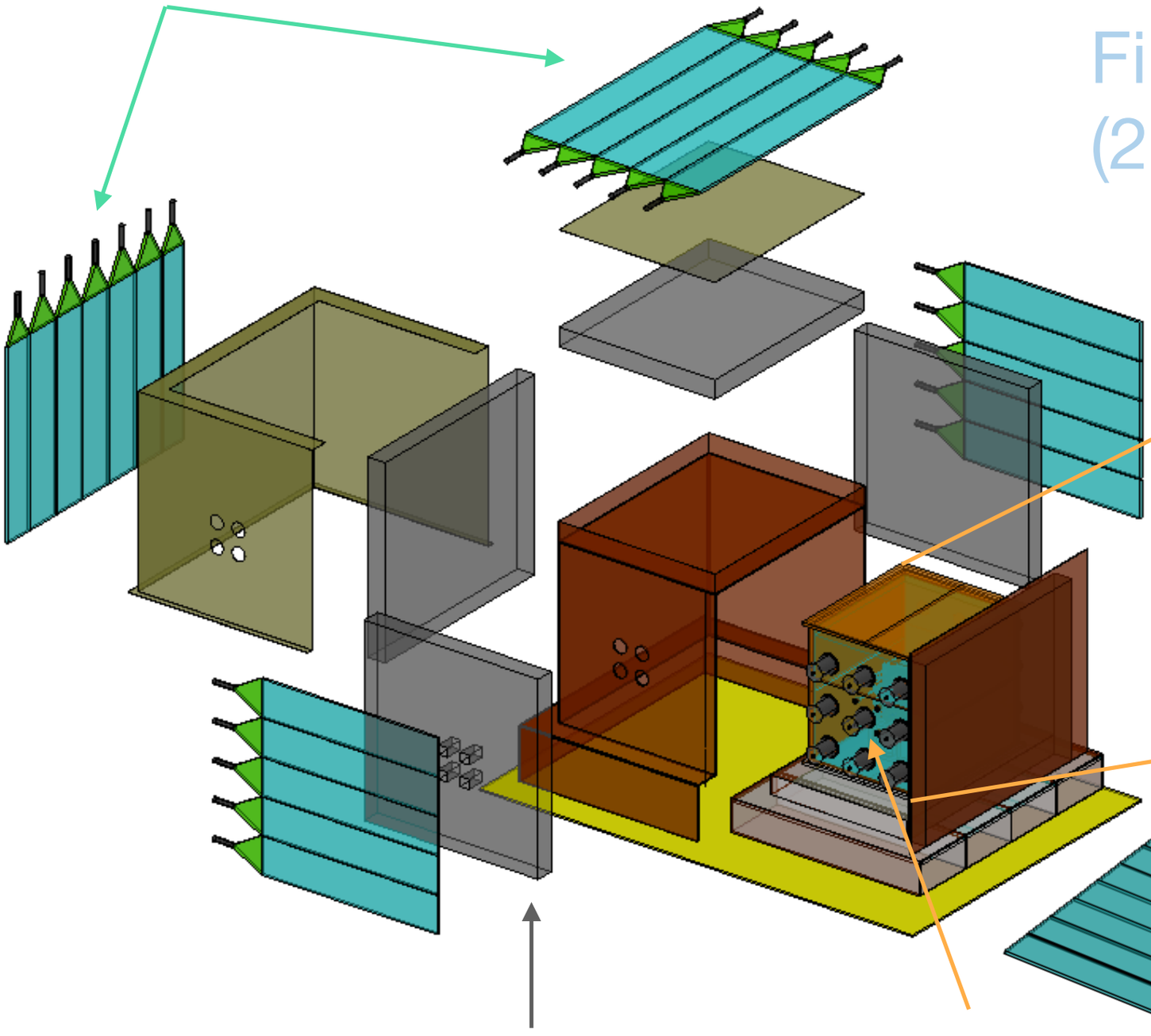
- Physics run started September 2016

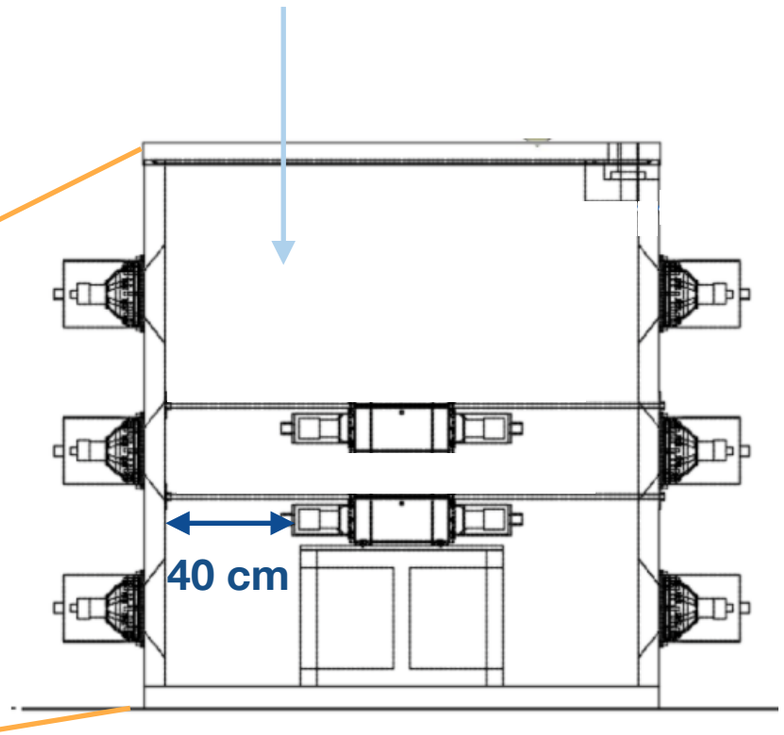


COSINE-100 Shielding Structure

Plastic Scintillators

Filled with Liquid Scintillator (2L)





NaI(Tl) Crystals (106 kg)

Lead Shielding (20 cm)

Cu Box (3 cm)

Crystal Installation

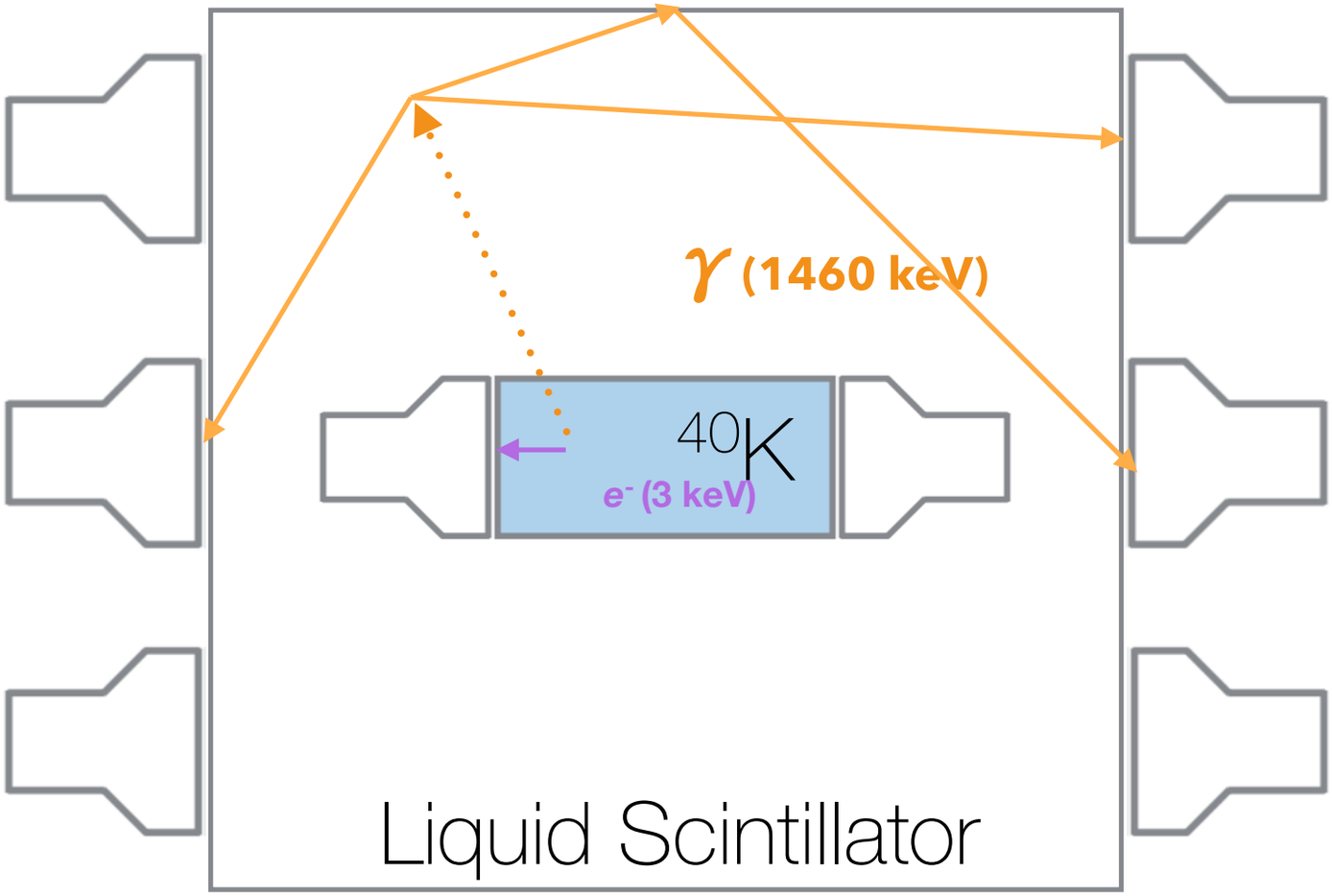
COSINE-100 NaI(Tl) Crystals

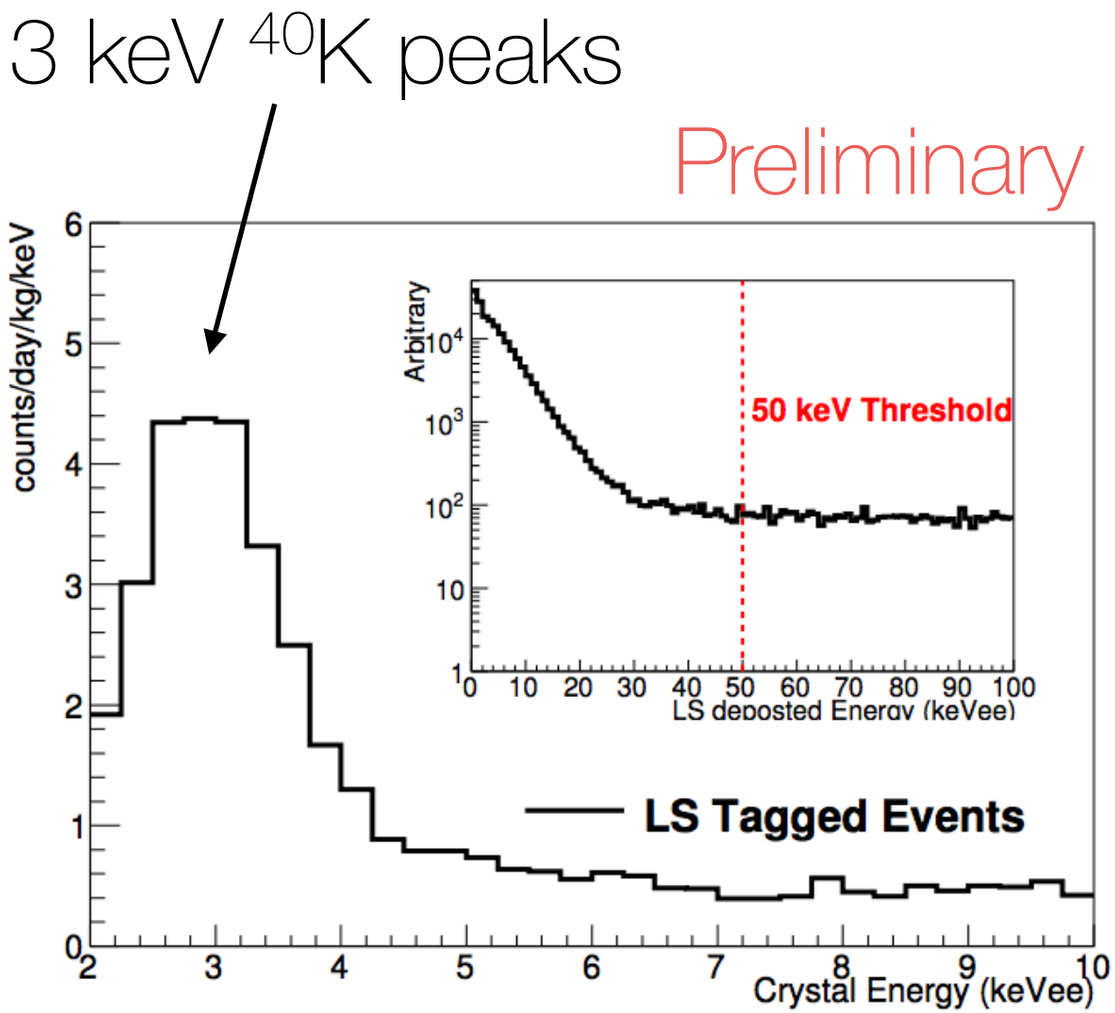
Preliminary

Crystal	Mass (kg)	Powder	Alpha Rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light Yield (PEs/keV)
Crystal-1	8.3	AS-B	3.20 ± 0.08	43.4 ± 13.7	<0.02	1.3 ± 0.4	14.9 ± 1.5
Crystal-2	9.2	AS-C	2.06 ± 0.06	82.7 ± 12.7	<0.12	<0.6	14.6 ± 1.5
Crystal-3	9.2	AS-WSII	0.76 ± 0.02	41.1 ± 6.8	<0.04	0.4 ± 0.2	15.5 ± 1.6
Crystal-4	18.0	AS-WSII	0.74 ± 0.02	39.5 ± 8.3		<0.3	14.9 ± 1.5
Crystal-5	18.3	AS-C	2.06 ± 0.05	86.8 ± 10.8		2.4 ± 0.3	7.3 ± 0.7
Crystal-6	12.5	AS-WSIII	1.52 ± 0.04	12.2 ± 4.5	<0.02	0.6 ± 0.2	14.6 ± 1.5
Crystal-7	12.5	AS-WSIII	1.54 ± 0.04	18.8 ± 5.3		<0.6	14.0 ± 1.4
Crystal-8	18.3	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

- 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



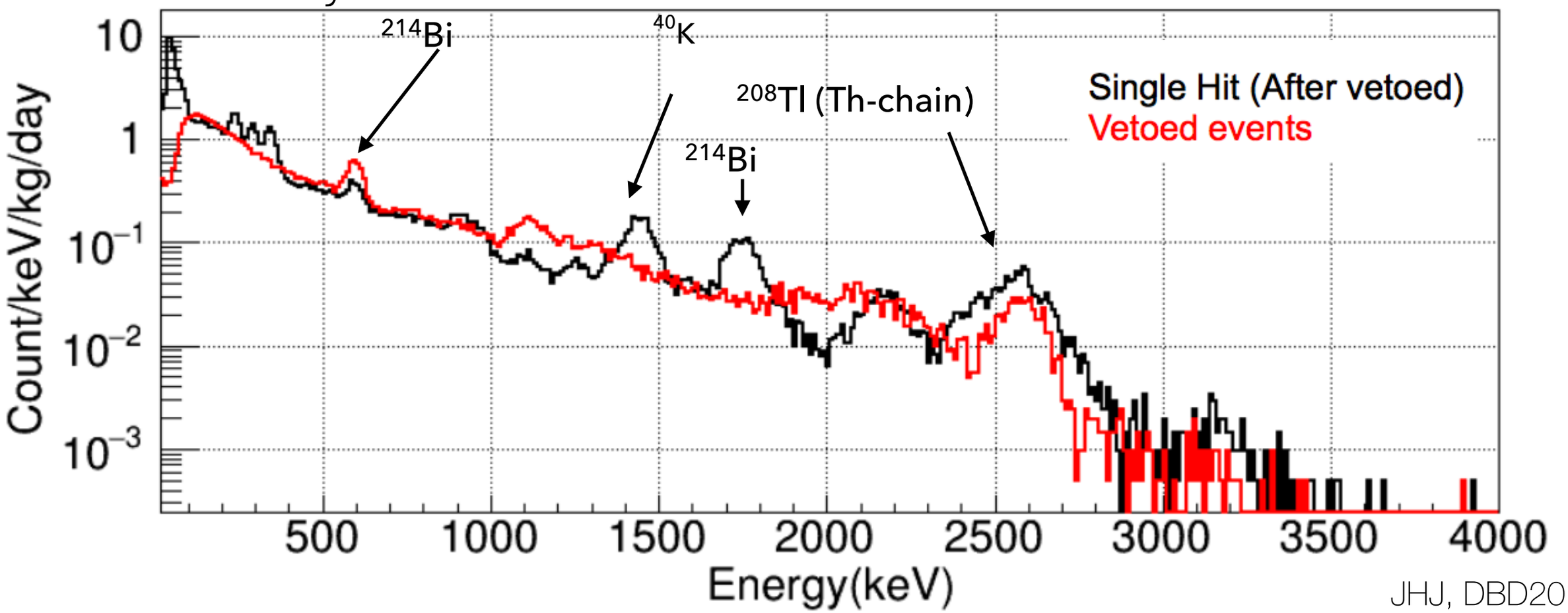


- ^{40}K emits 1460 keV gamma with 3 keV Auger electron energy deposition in NaI crystal

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

COSINE-100 High Energy Spectrum

Preliminary

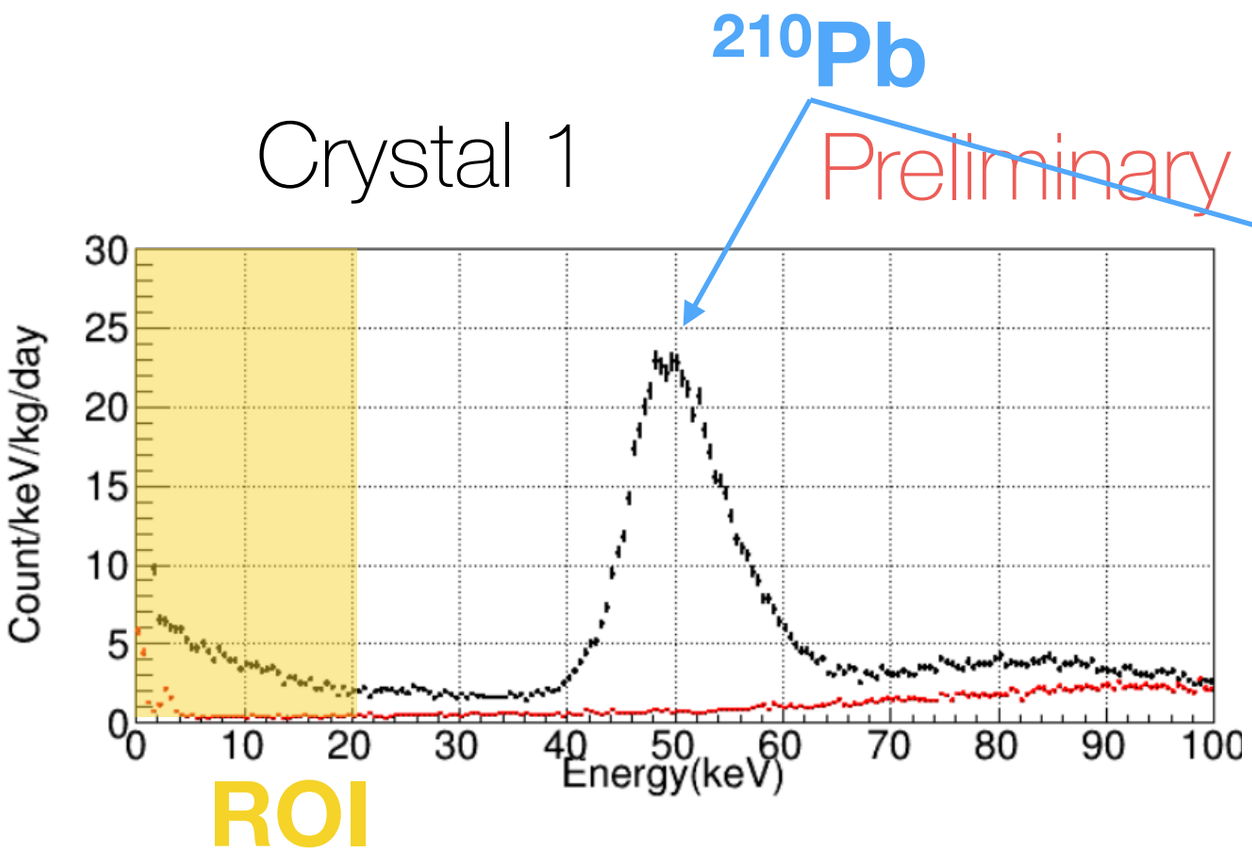


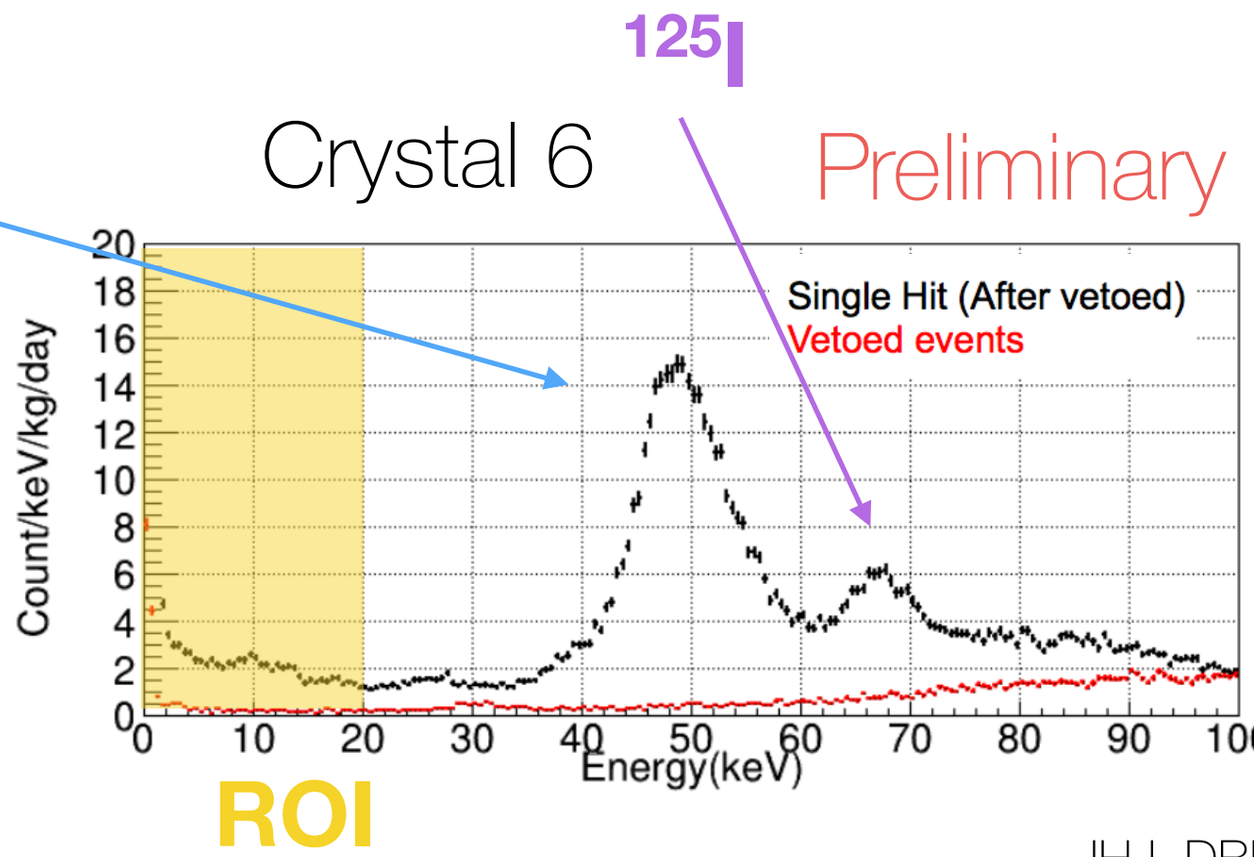
JHJ, DBD2016

- 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

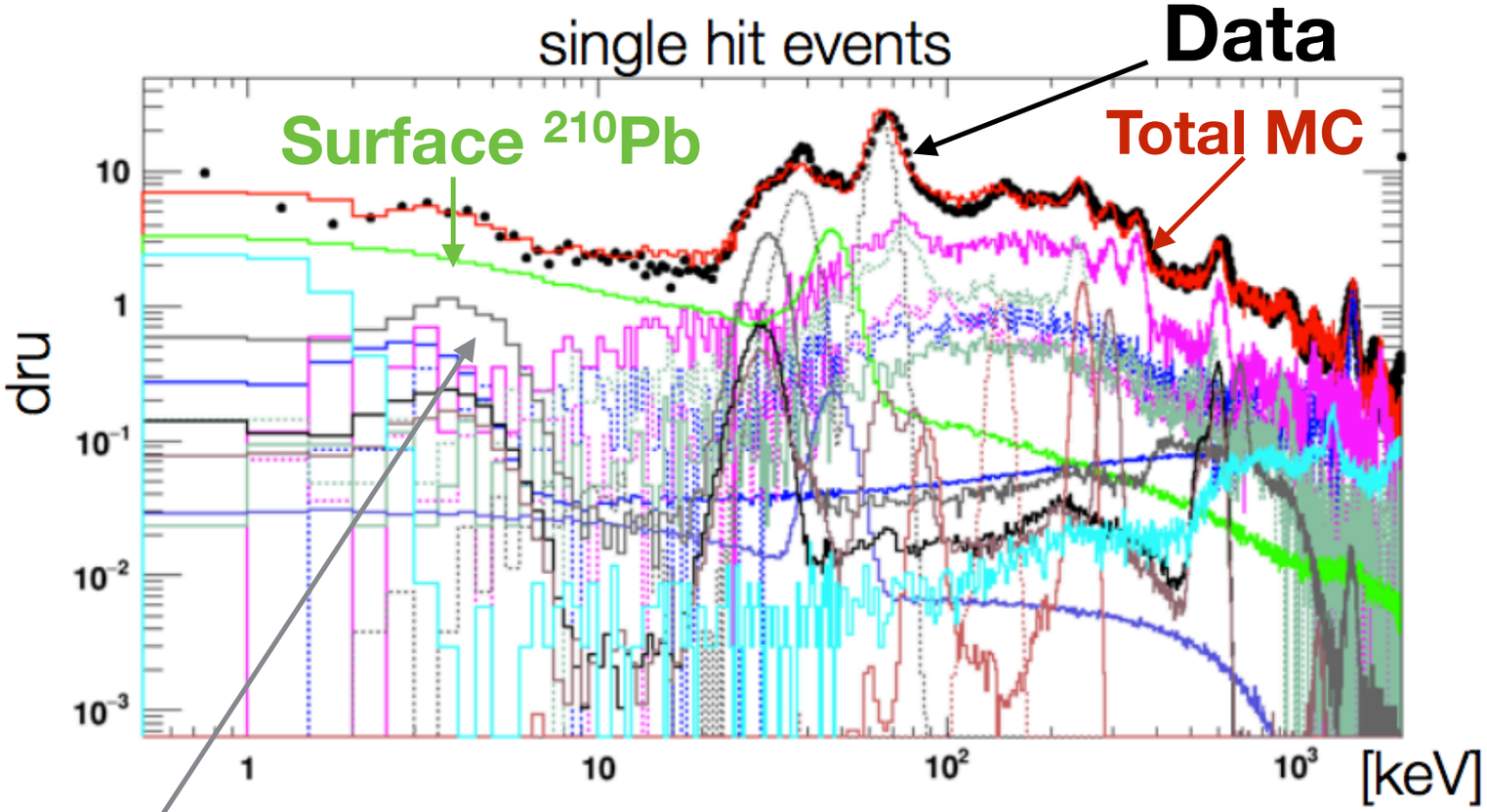




JHJ, DBD2

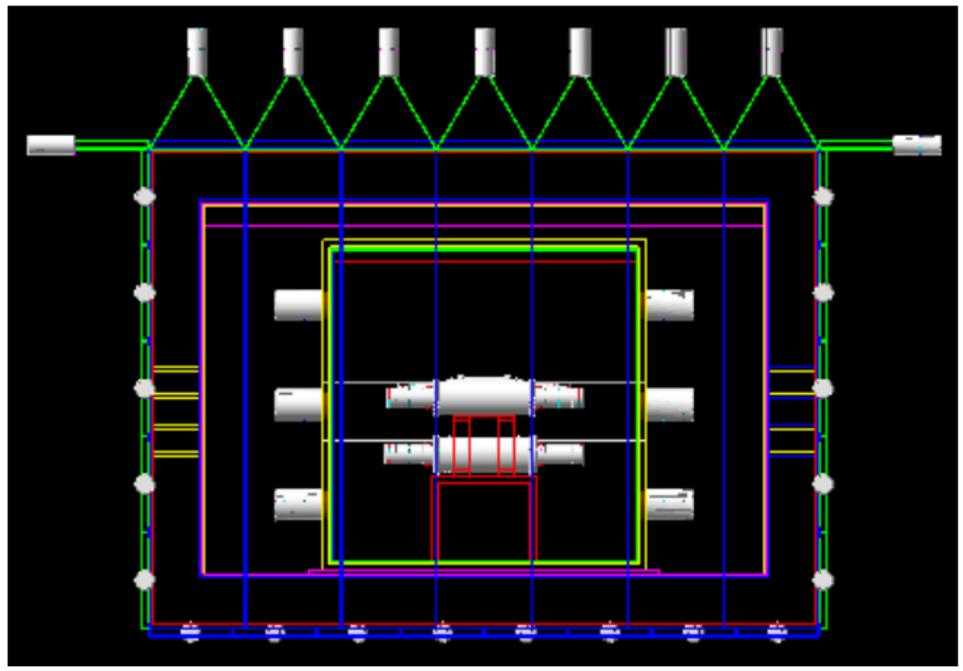
- 10 days of data, current set of event selection applied (not final!)
- Depending on crystal, background level ~3 dru at the region of interest
- Cosmogenic peaks remain in certain crystals
- There are still room for improvements

COSINE-100 NaI Crystal Simulation



Simulation within R&D array (C3)

Preliminary

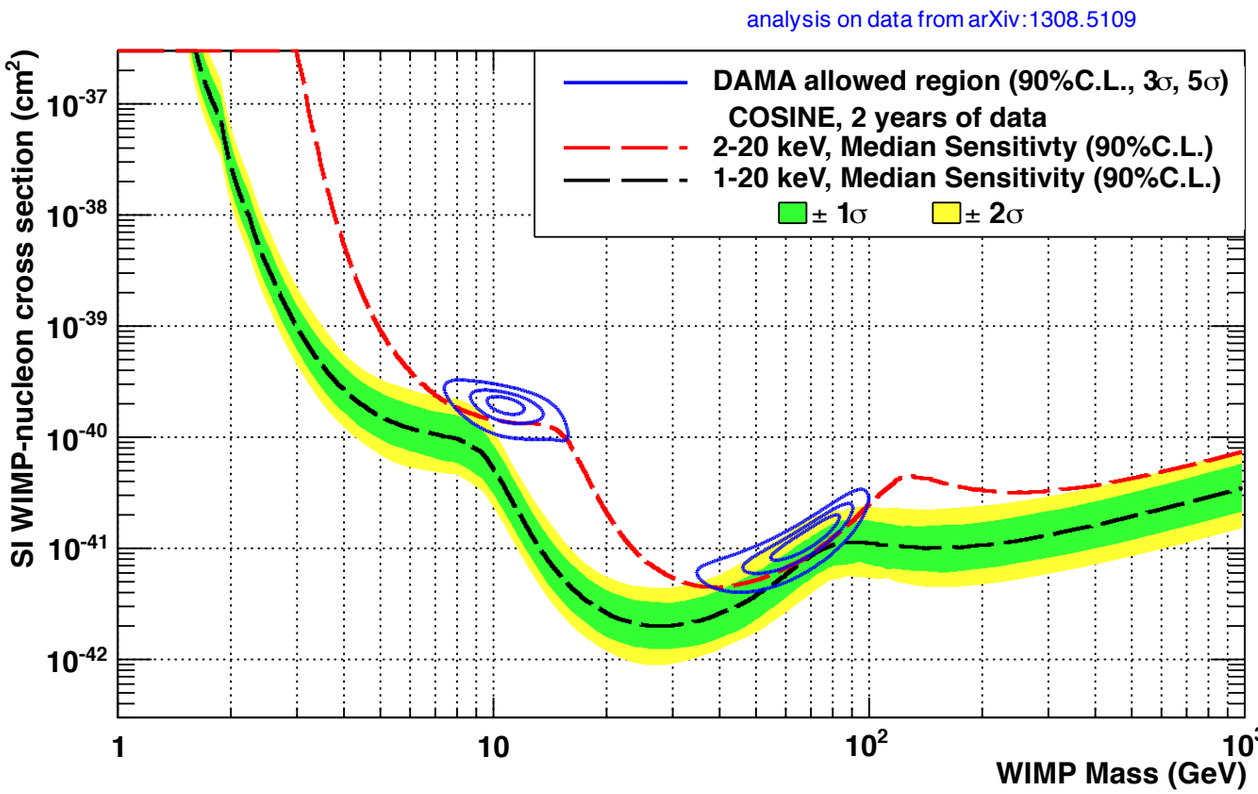


Detector Geometry at COSINE-100

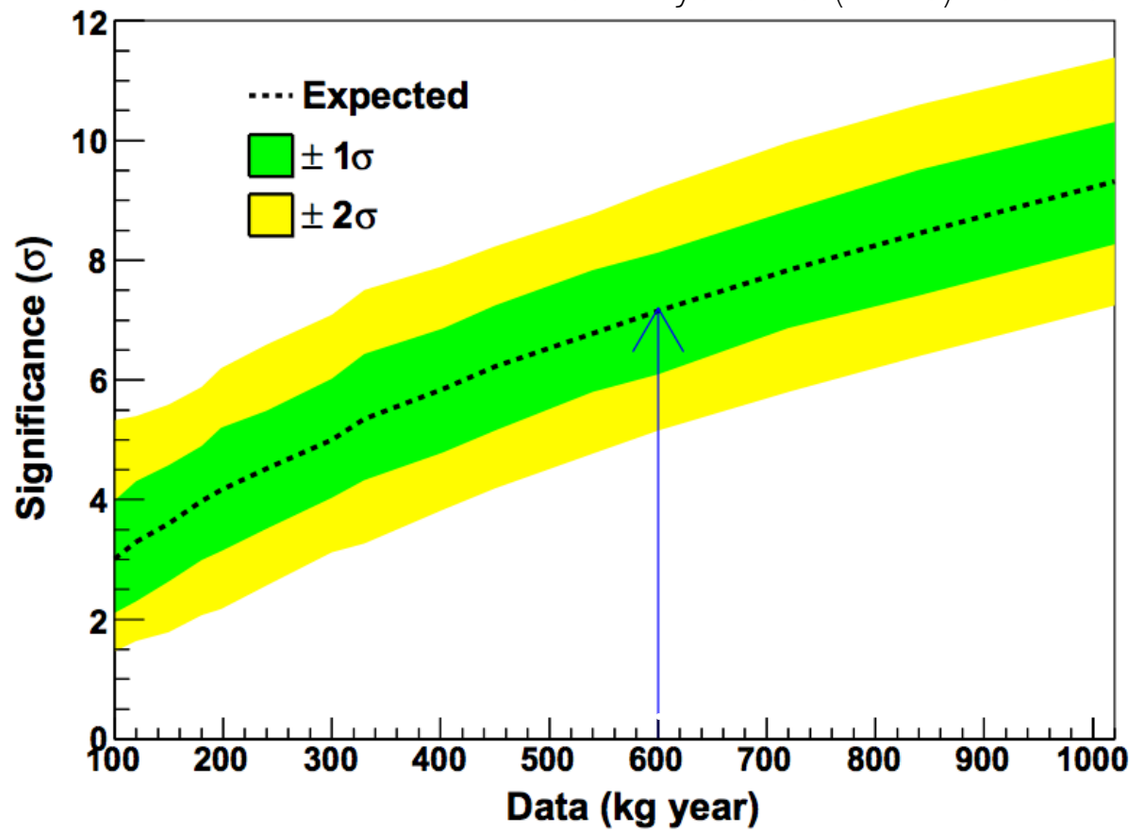
- Work in progress, Geant4 framework
- Using NaI energy spectrum in R&D setup for the first step
- Surface ^{210}Pb is suspected to be the dominant background, followed by ^{40}K internal to crystal

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)

Conclusion

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

- DM-Ice17

  - DM-Ice17 demonstrates South Pole as viable underground location for dark matter experiments

  - DM-Ice17 set the strongest Southern Hemisphere dark matter exclusion limit

- COSINE-100

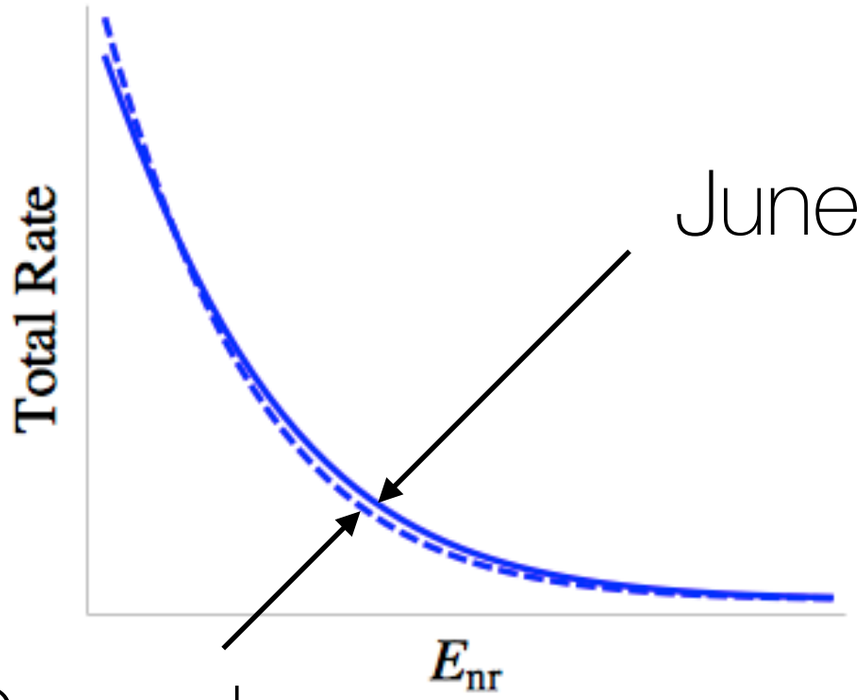
  - COSINE-100 is running with 108 kg of NaI(Tl) crystals, with lower backgrounds and better technology

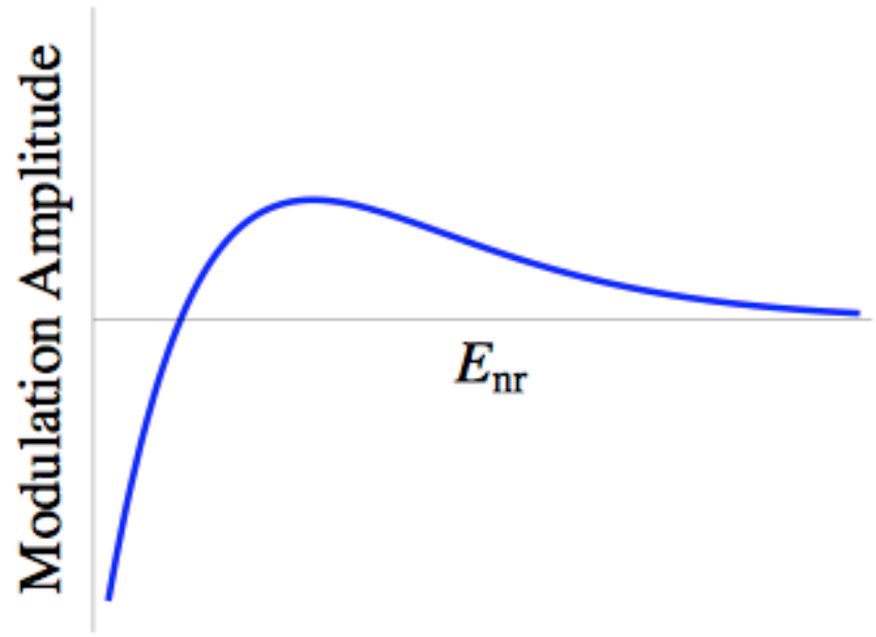
  - Initial performances of COSINE-100 are promising, expecting to have DAMA-comparable sensitivity in ~2 years

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

Backups

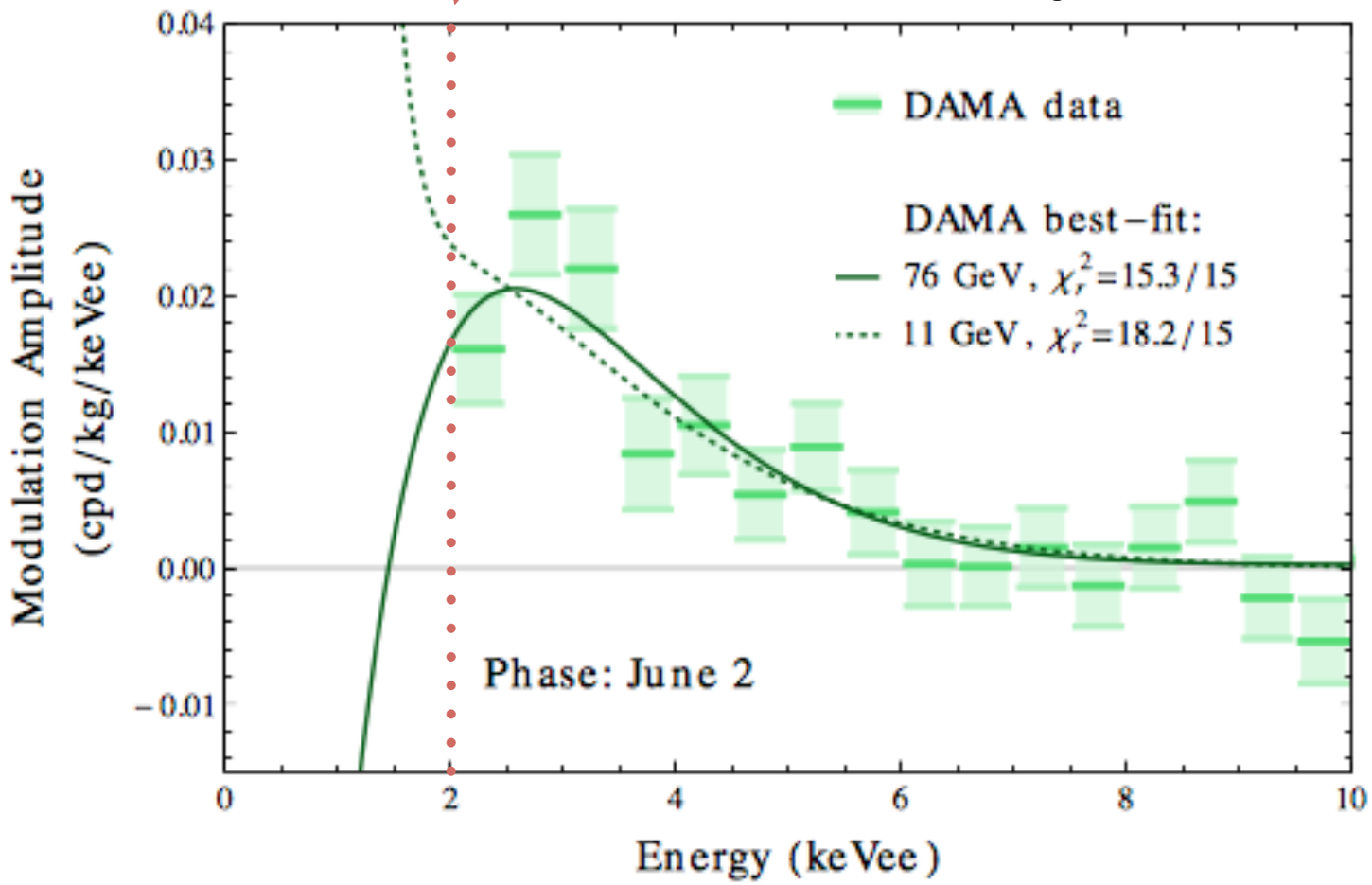
Interpretation of the DAMA Result





DAMA energy threshold

Savage et al. arxiv:0808:3607



DM-Ice17 Detector Component/Crystal Contamination

Detector Component

Material	^{40}K	^{232}Th	^{238}U (^{234}Th)	^{238}U (^{226}Ra)	^{235}U	^{60}Co
Quartz Light Guides	0.50 ± 0.03	< 4.9	12		...	...
ETL 9390B PMT	9300	1000	2400		...	...
Steel Pressure Vessel *	13.77 ± 6.38	6.49 ± 0.96	118.31 ± 60.11	2.28 ± 0.72	8.79 ± 1.68	7.19 ± 0.82
Drill Ice *	3.71 ± 1.36	0.55 ± 0.17	6.69 ± 3.02	0.39 ± 0.14	0.38 ± 0.21	0.12 ± 0.05
Silicone Optical Gel * †	39.50 ± 18.60	< 0.12	2.08 ± 1.10	38.50 ± 61.00	0.96 ± 1.30	0.32 ± 0.42
PTFE Supports * †	0.34 ± 5.09	0.52 ± 0.44	< 0.41	24.46 ± 21.37	1.92 ± 0.72	< 0.089
Copper Plate * †	< 5.13	< 1.22	0.17 ± 0.92	< 0.67	3.56 ± 1.79	< 0.12
Glacial Ice †	$\sim 3 \times 10^{-4}$	$\sim 4 \times 10^{-4}$	$\sim 10^{-4}$		...	...

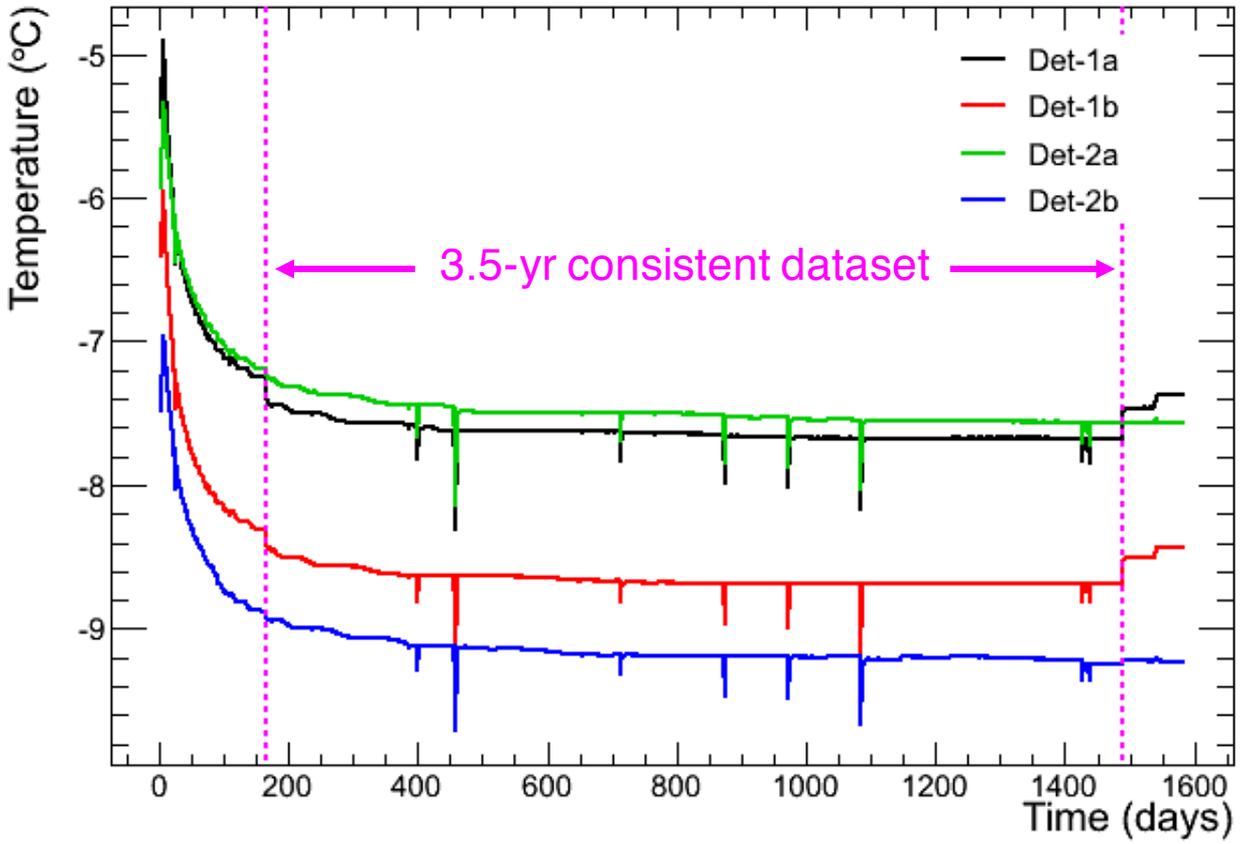
Crystal

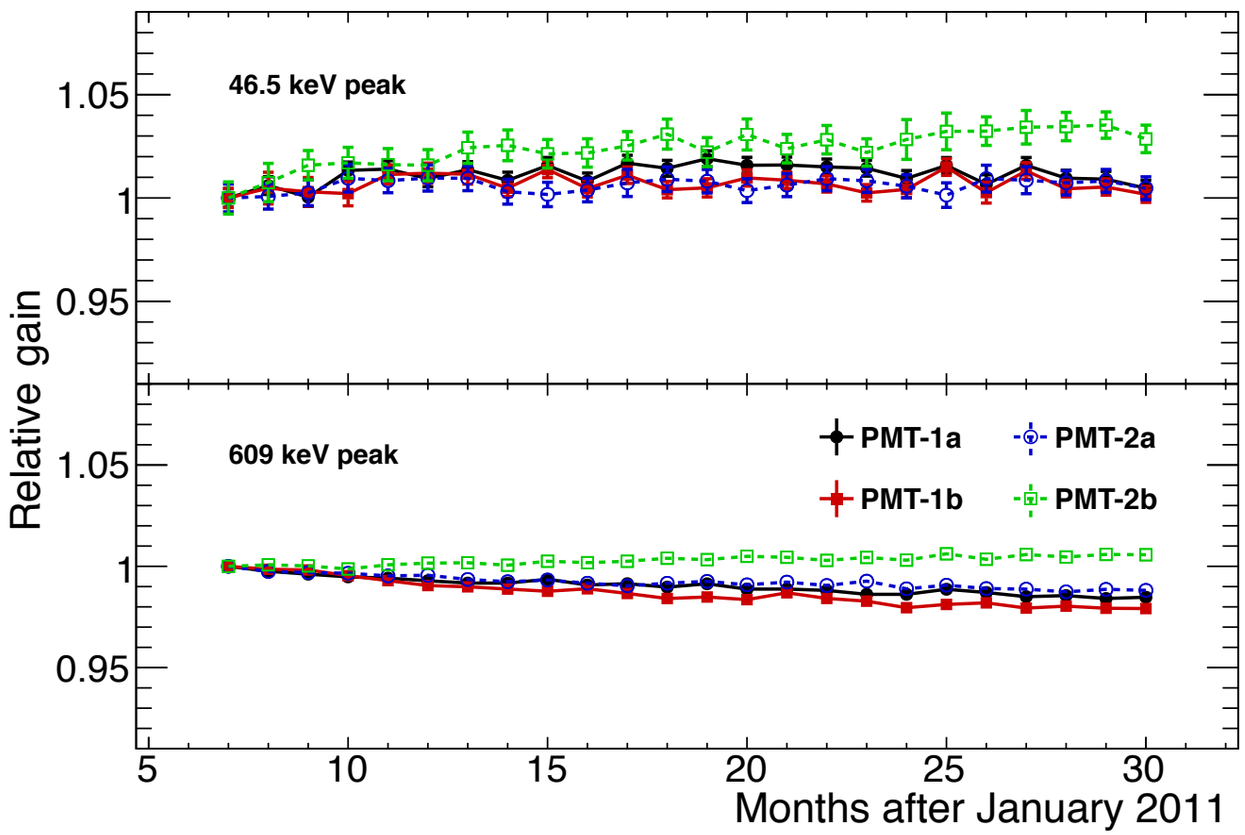
Isotope	Subchain	Activity (mBq/kg)
^{40}K		17
^{129}I		1
^{232}Th	^{232}Th	0.01
	^{228}Ra – ^{208}Tl	0.16
^{238}U	^{238}U – ^{234}Pa	0.017
	^{234}U – ^{230}Th	0.14
	^{226}Ra – ^{214}Po	0.90
	^{210}Pb – ^{210}Po	1.5

DM-Ice17 Temperature Stability

- Ice environment provides stable temperature
  - Fast decrease during freeze-in
  - Slower decrease over a few months after freeze-in
  - < 0.025˚C daily RMS
- PMT gain stability: <2% in 2 years, smaller than energy resolution

Cherwinka *et al*., Phys. Rev. D **90** (2014) 092005



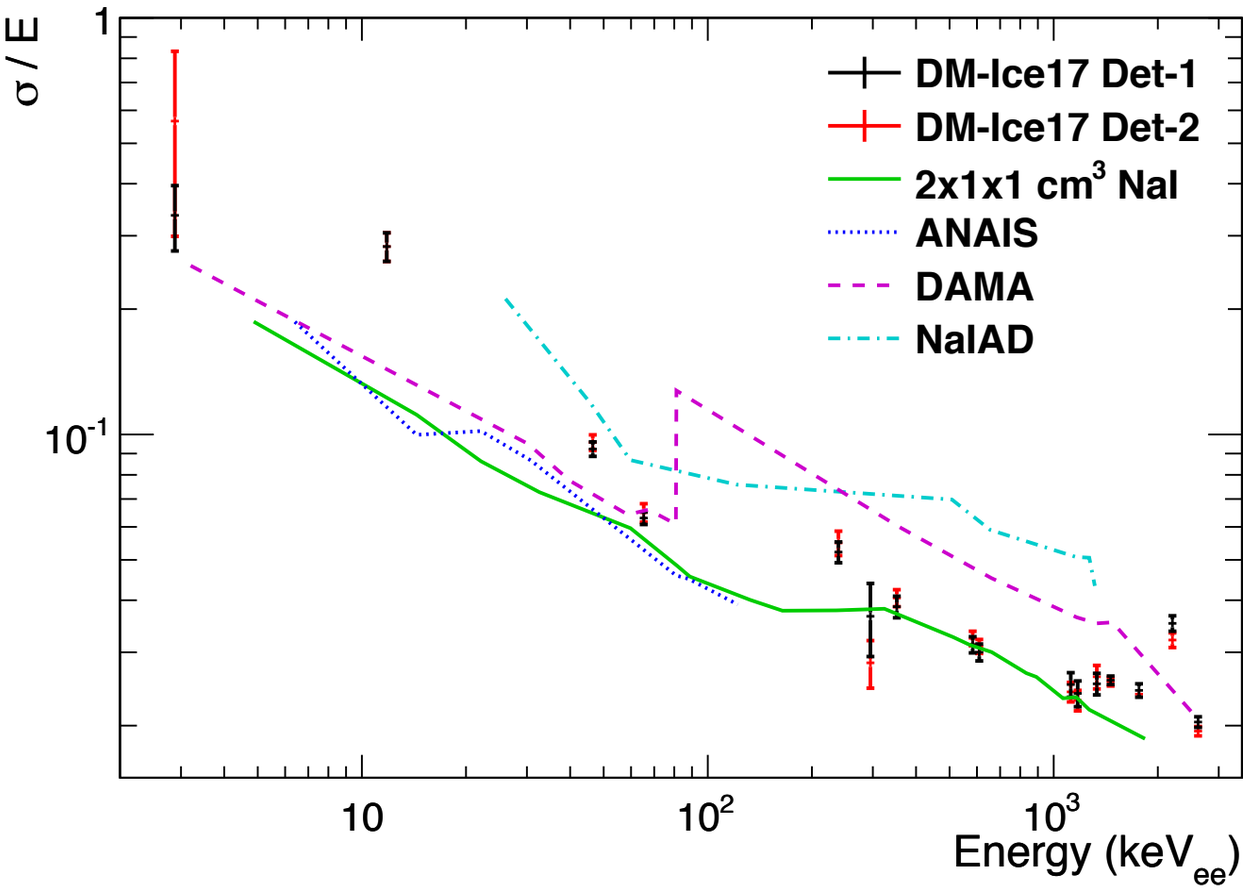


DM-Ice17 Energy Resolution

Cherwinka *et al.*, Phys. Rev. D **90** (2014) 092005

- Resolution assessed from same background peaks giving calibration

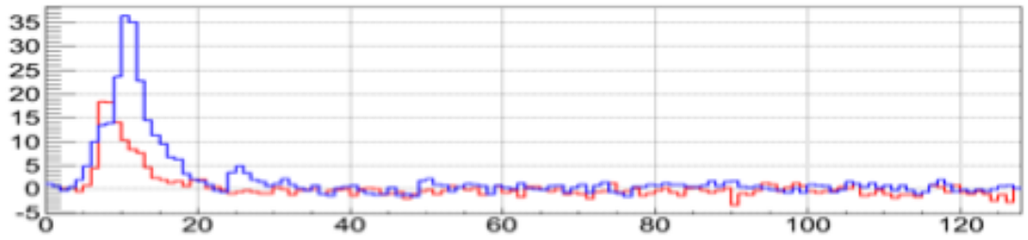
- Comparable resolution to other similarly sized NaI experiments



Event Types

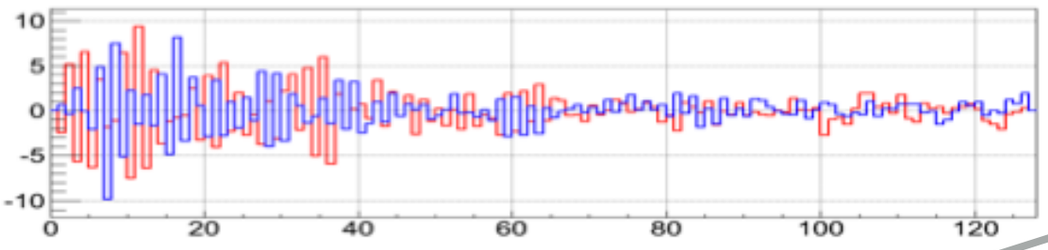
Noise: "Thin pulse"

- Asymmetric deposition, fast decay tail

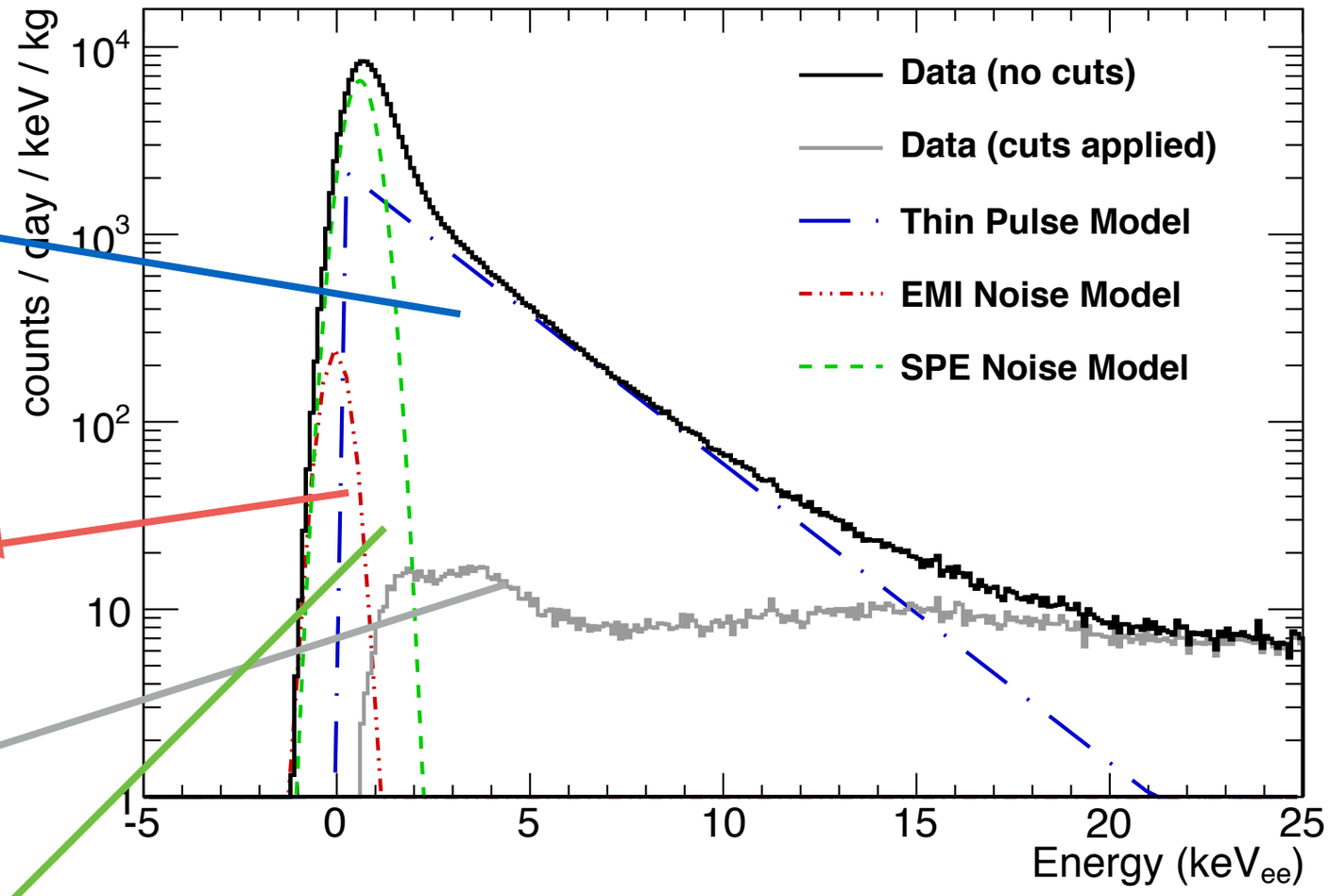


Noise: "EMI"

- Oscillatory waveform

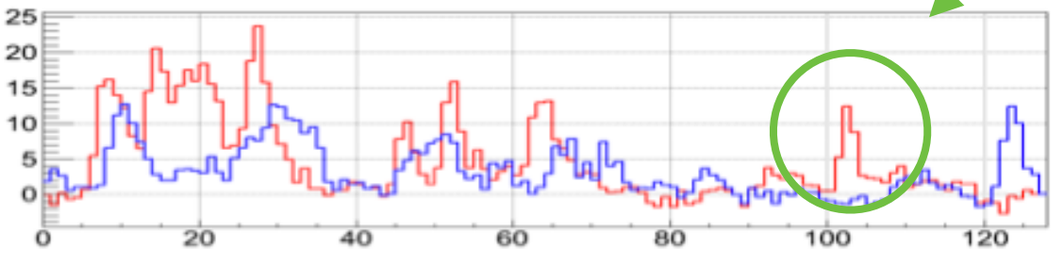


Cherwinka *et al.*, Phys. Rev. D **90** (2014) 092005



Signal: < 100 keV

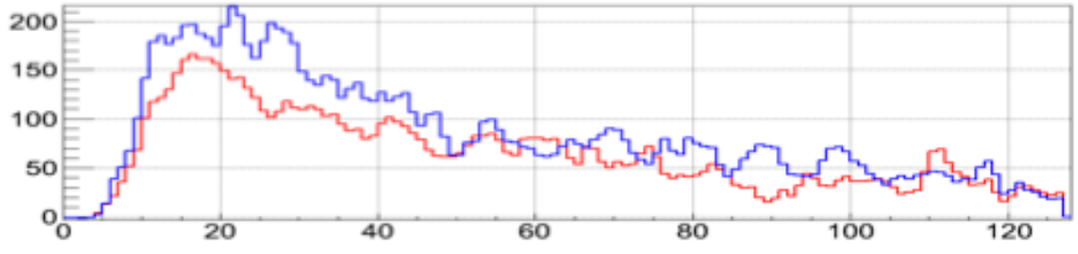
- Sequence of SPEs



SPE

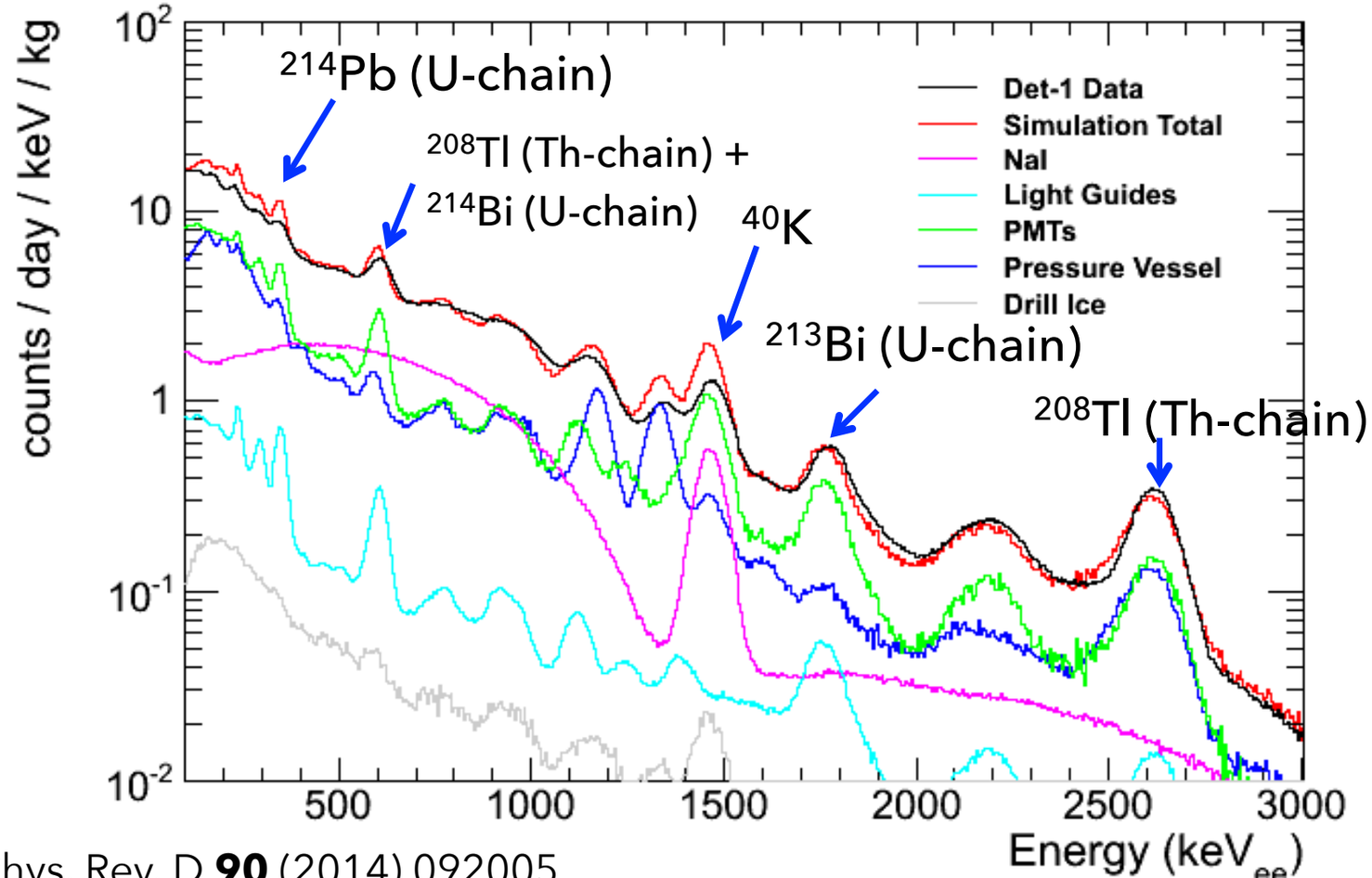
Signal: > 100 keV

- SPE structure suppressed



DM-Ice17 Background Model

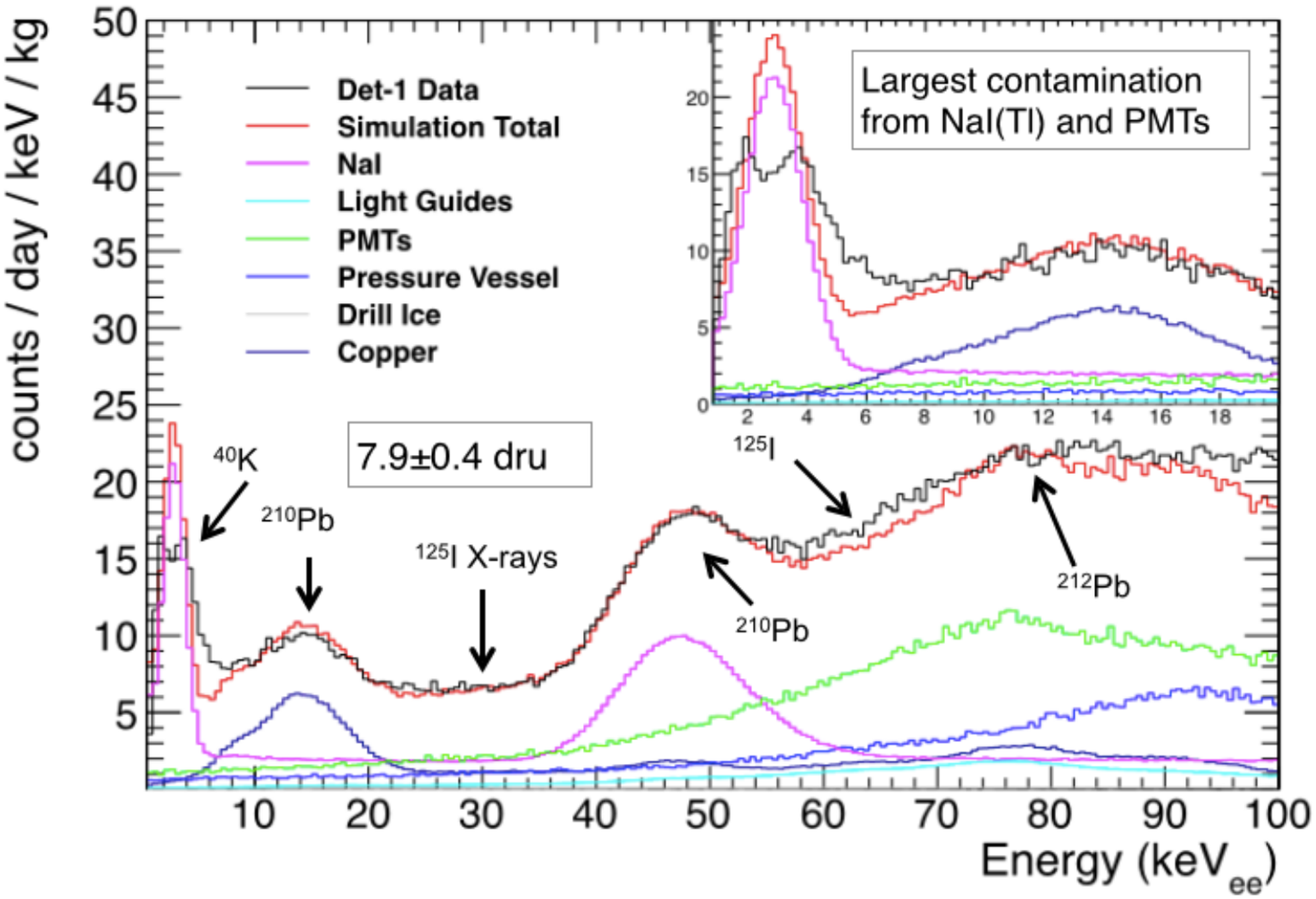
- β/γ separated from alpha with PSD
- Well matched by background model
- Largest contamination from crystals and PMTs at <100 keV due to U/Th/K
- Negligible contribution from the ice



Cherwinka *et al.*, Phys. Rev. D **90** (2014) 092005

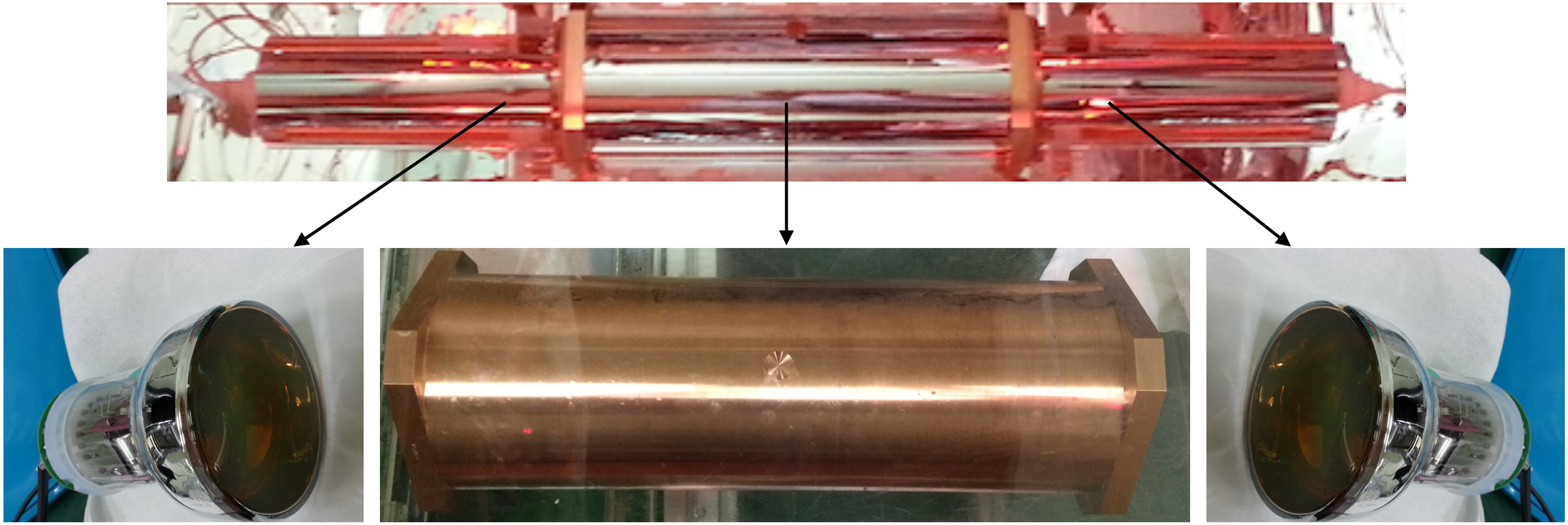
DM-Ice17 Background Model: Low Energy Region

- Below 5 keV, background is dominated by
  - ^{40}K and ^{210}Pb in NaI(Tl)
  - PMTs
  - Surface ^{210}Pb and Light guides
- 7.9±0.4 dru observed between 6.5-8 keV



Cherwinka *et al.*, Phys. Rev. D **90** (2014) 092005

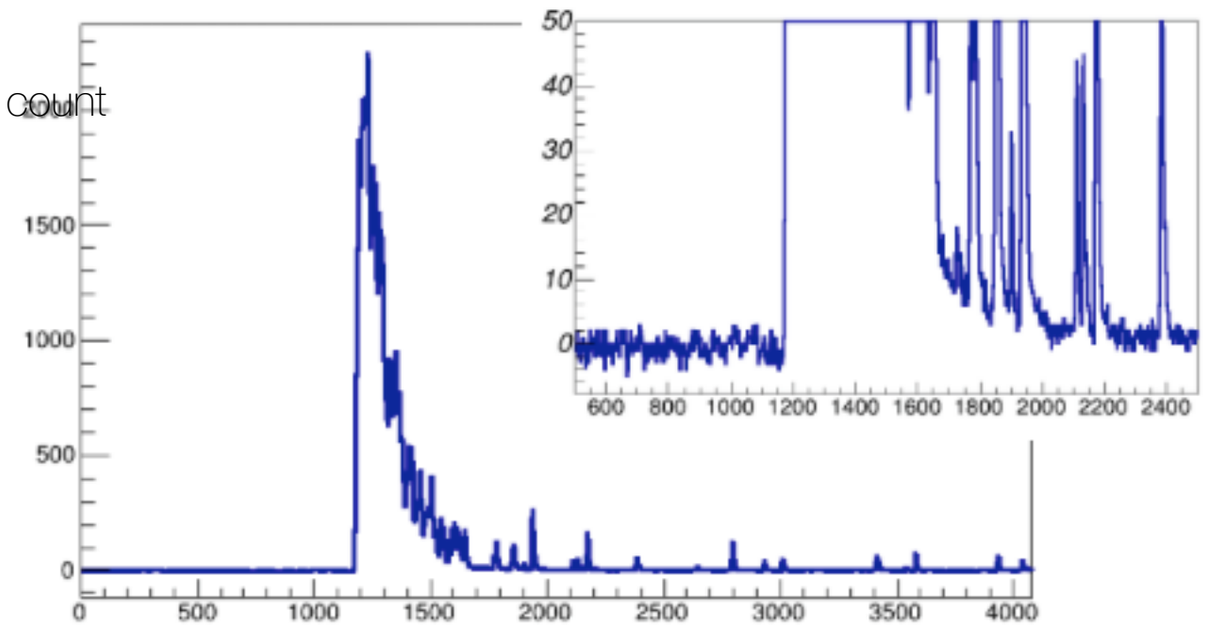
COSINE-100 Crystal-PMT Assembly



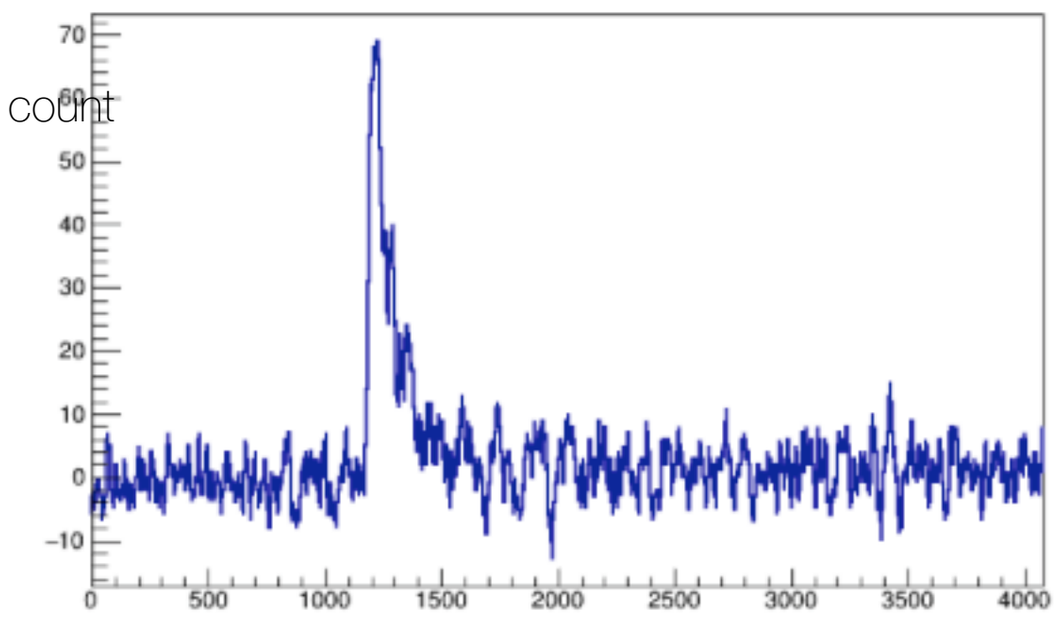
- OFE Cu-encapsulated NaI crystal is attached with two 3-inch PMTs
- PMT: R12669 from Hamamatsu, 35% Quantum Efficiency at 420 nm
- Outer surface of crystal and PMT cap is wrapped with Vikuiti reflective films

Crystal PMT Waveforms

Anode Waveform (0-120 keV)



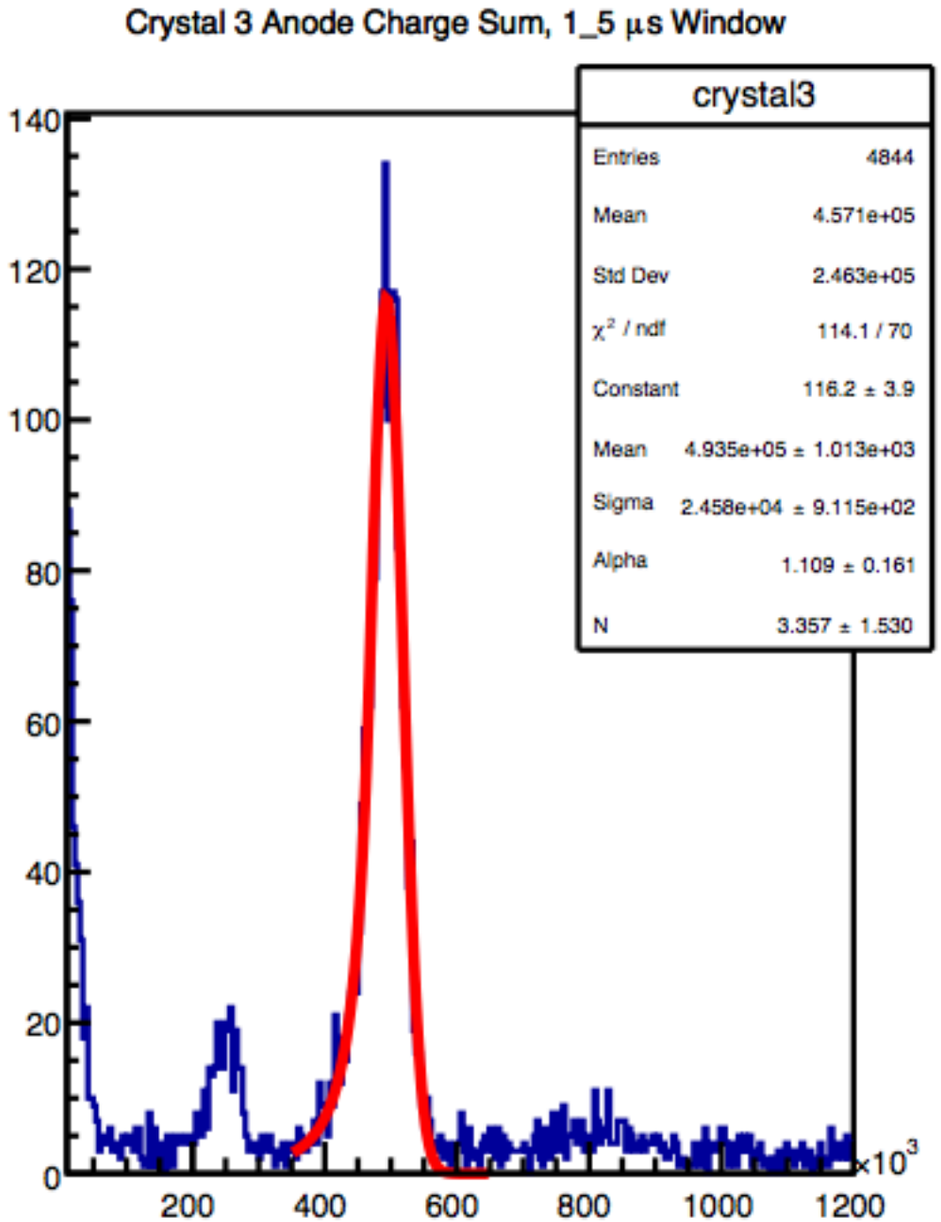
Dynode Waveform (50-10,000 keV)



- 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

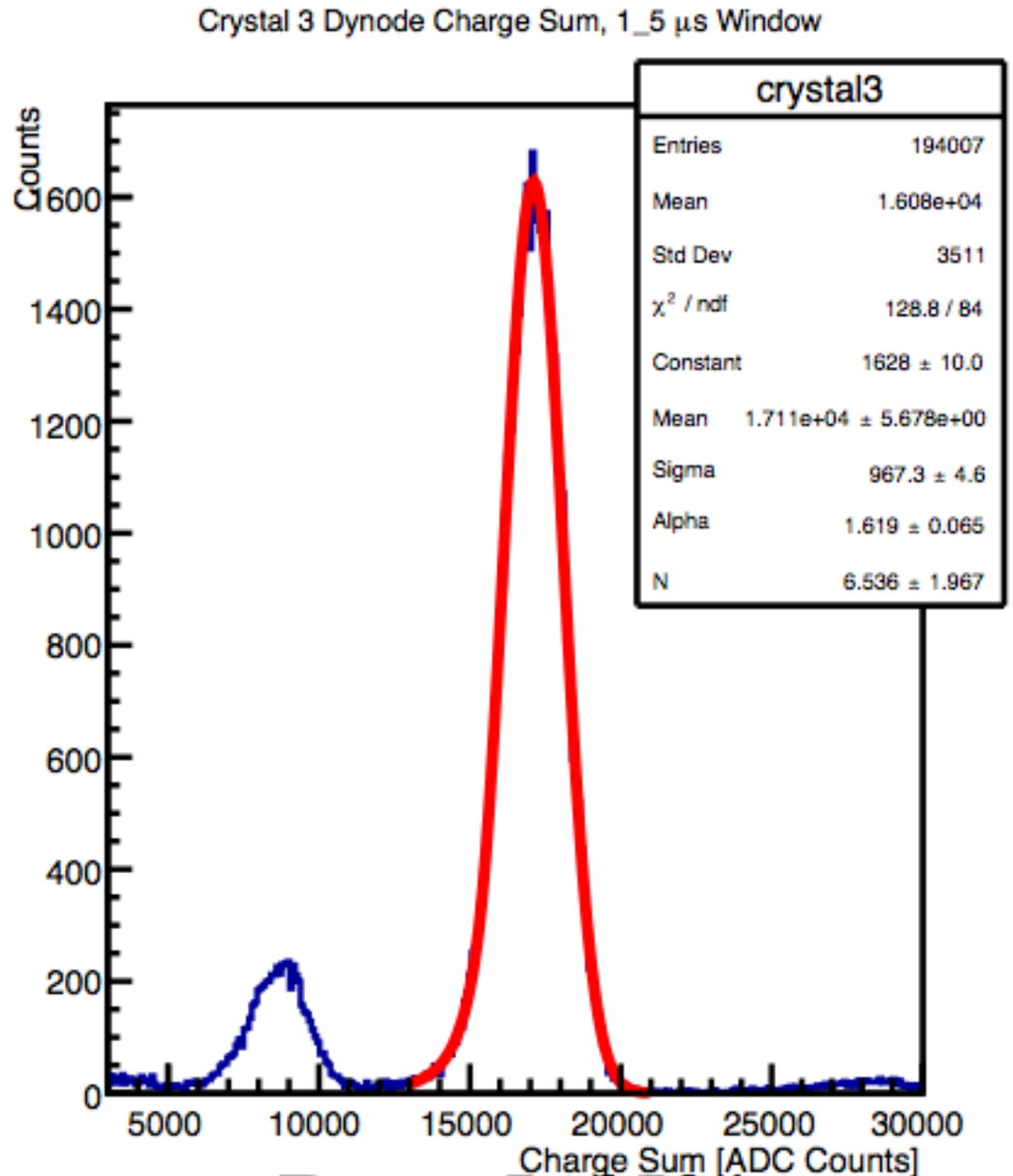
Resolution @ 60 keV

Am-241 ADC sum (Anode)



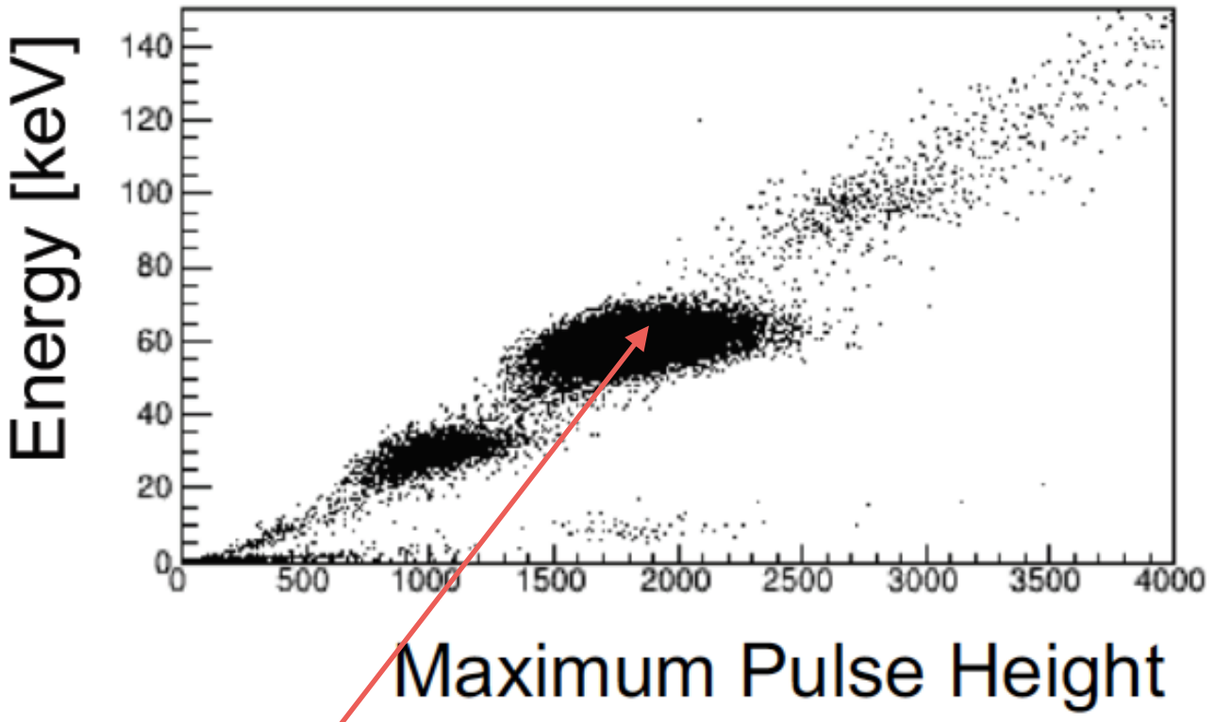
Res: 4.98%

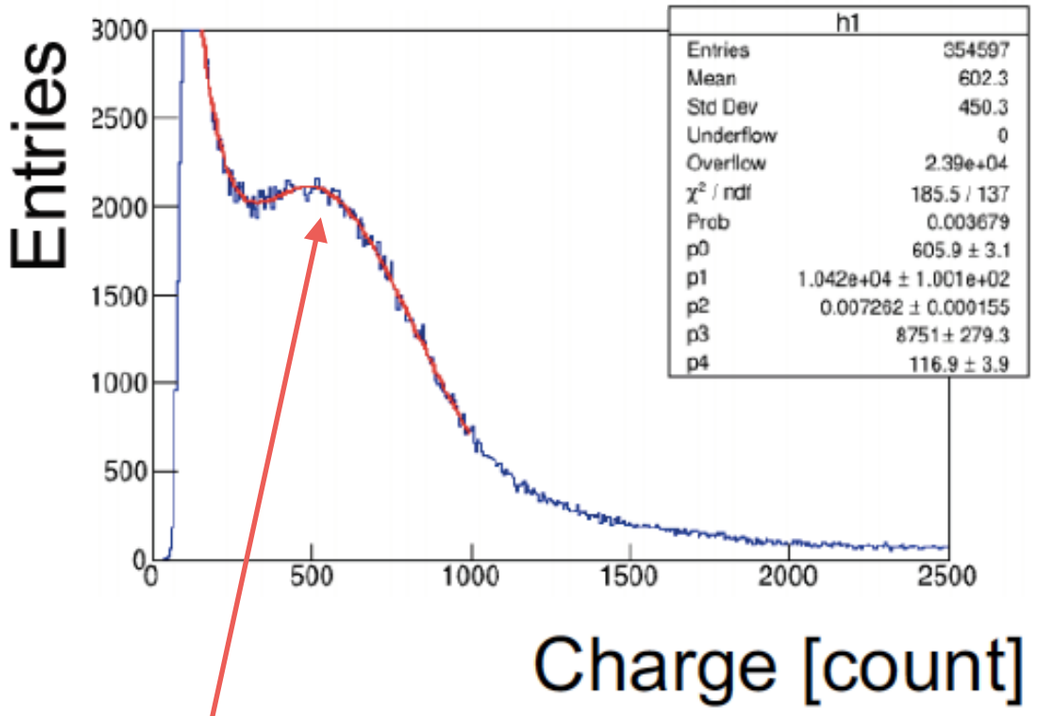
Am-241 ADC sum (Dynode)



Res: 5.65%

Calibration/Light yield calculation



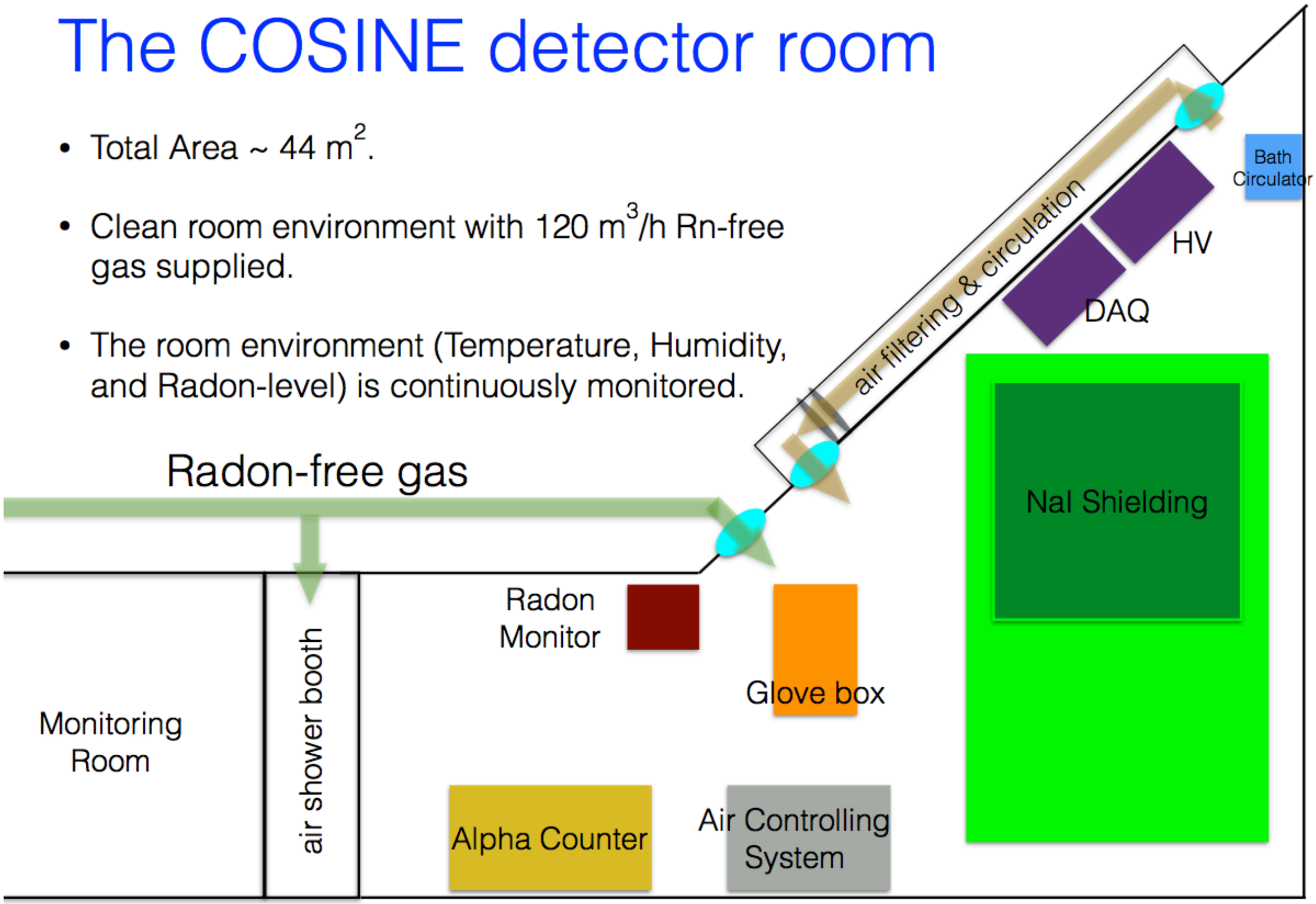


60 KeV gamma SPE

- ^{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

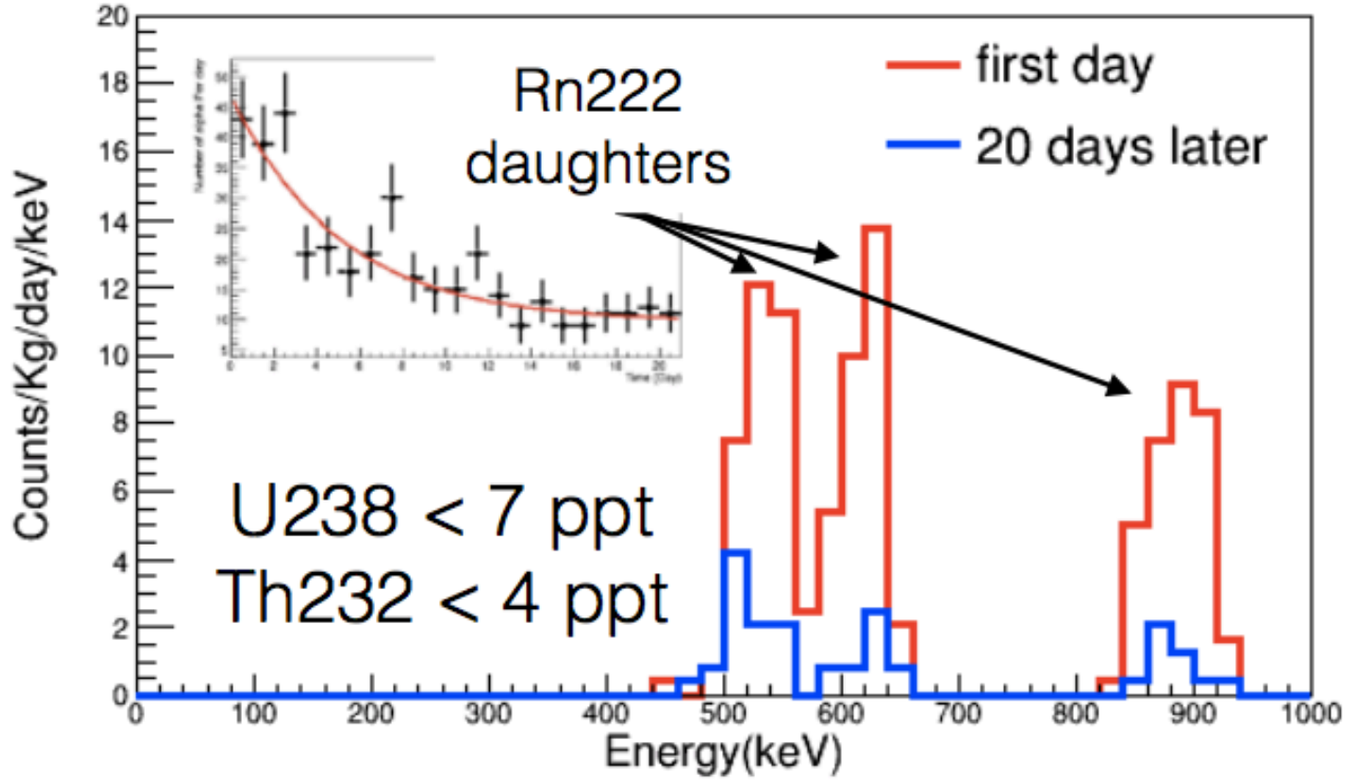
The COSINE detector room

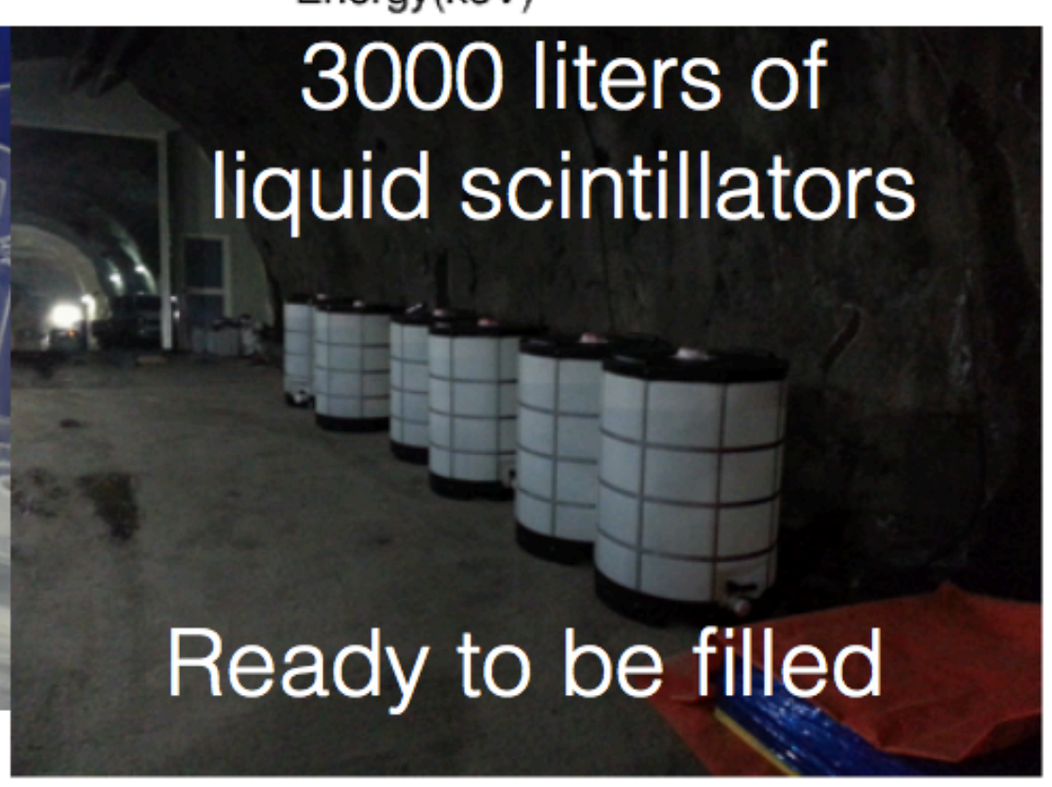
- Total Area ~ 44 m^2.
- Clean room environment with 120 m^3/h Rn-free gas supplied.
- The room environment (Temperature, Humidity, and Radon-level) is continuously monitored.



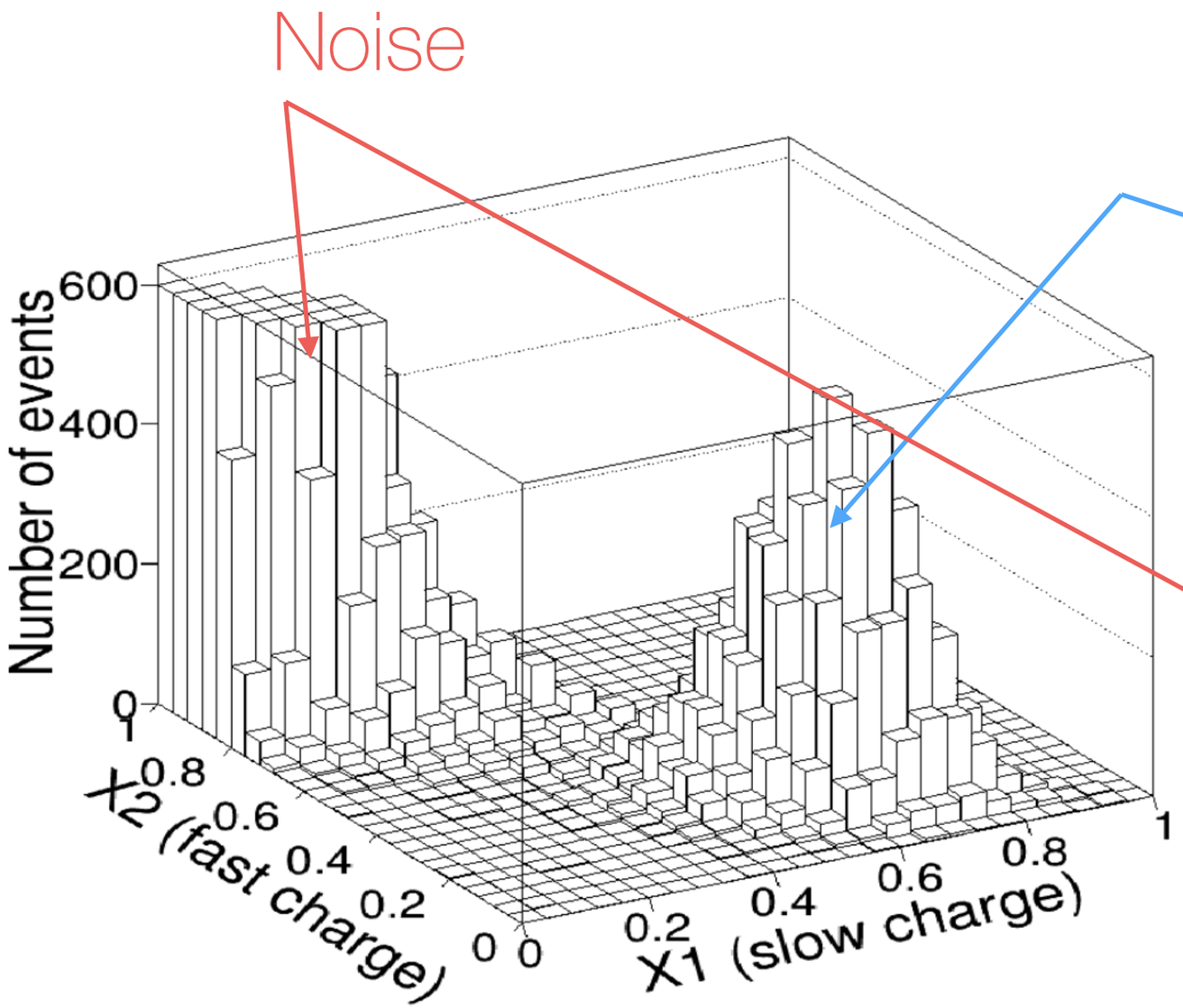
LS for COSINE-100

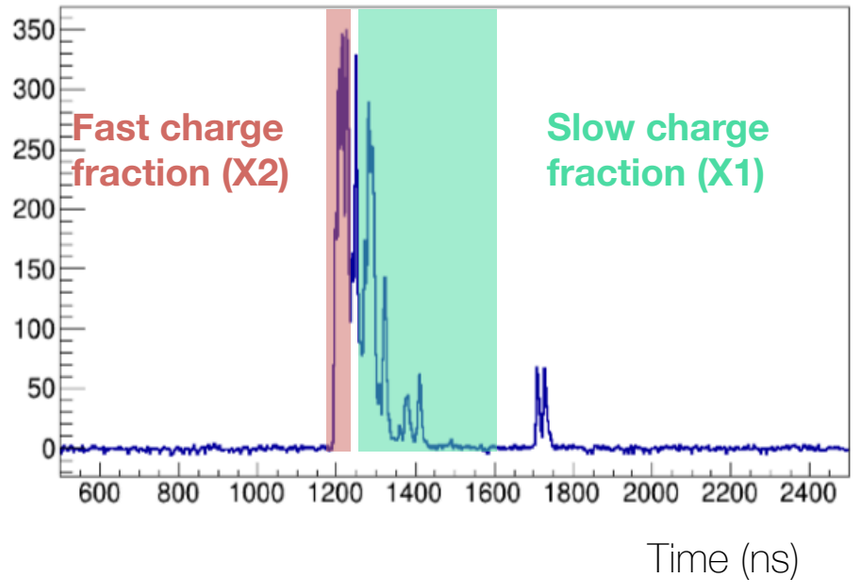
Linear alkylbenzene (LAB) :
Good optical/radioactive properties
2,5-Diphenyloxazole (PPO) :
fluor, scintillator/wavelength shifter
p-bis-(o-methylstyryl)-benzene (bis-MSB) : wavelength shifter

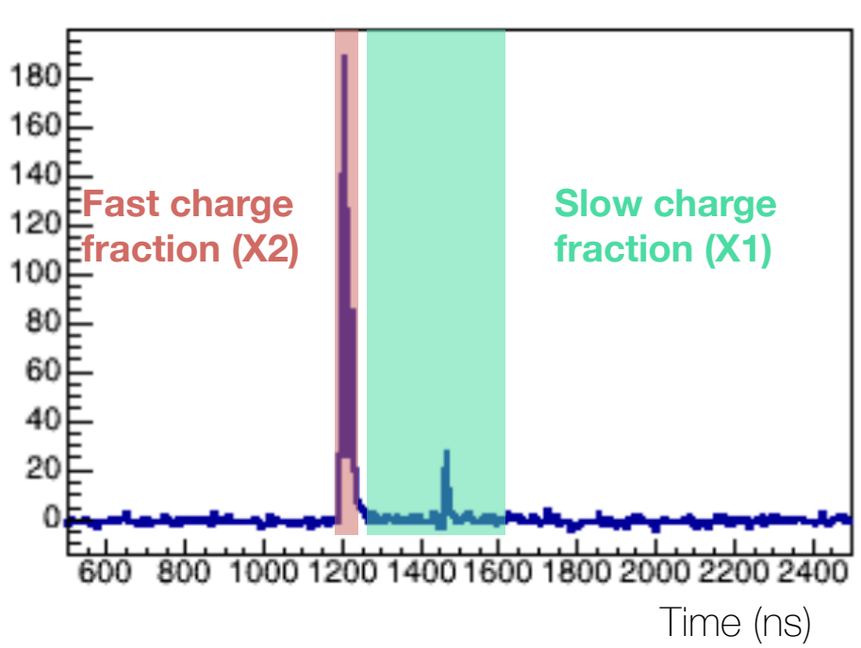




COSINE-100 Event Selection

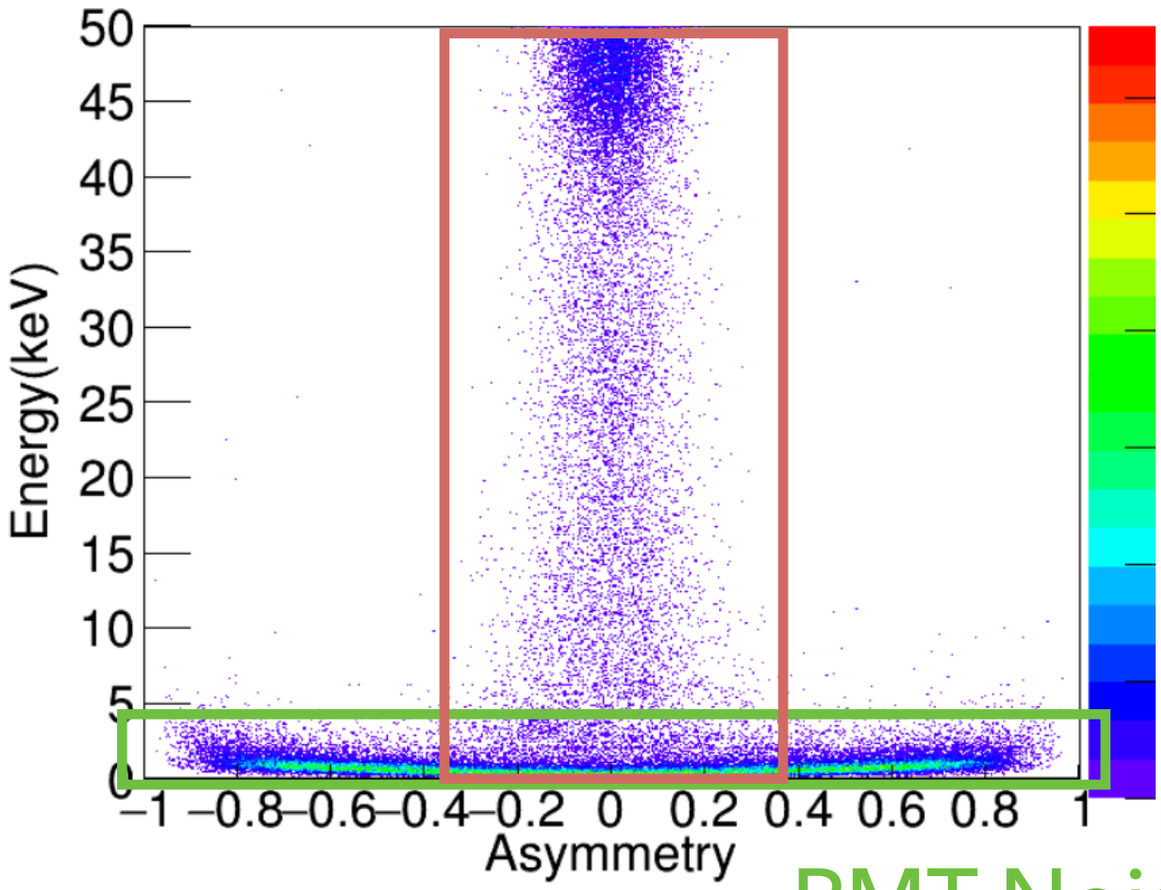


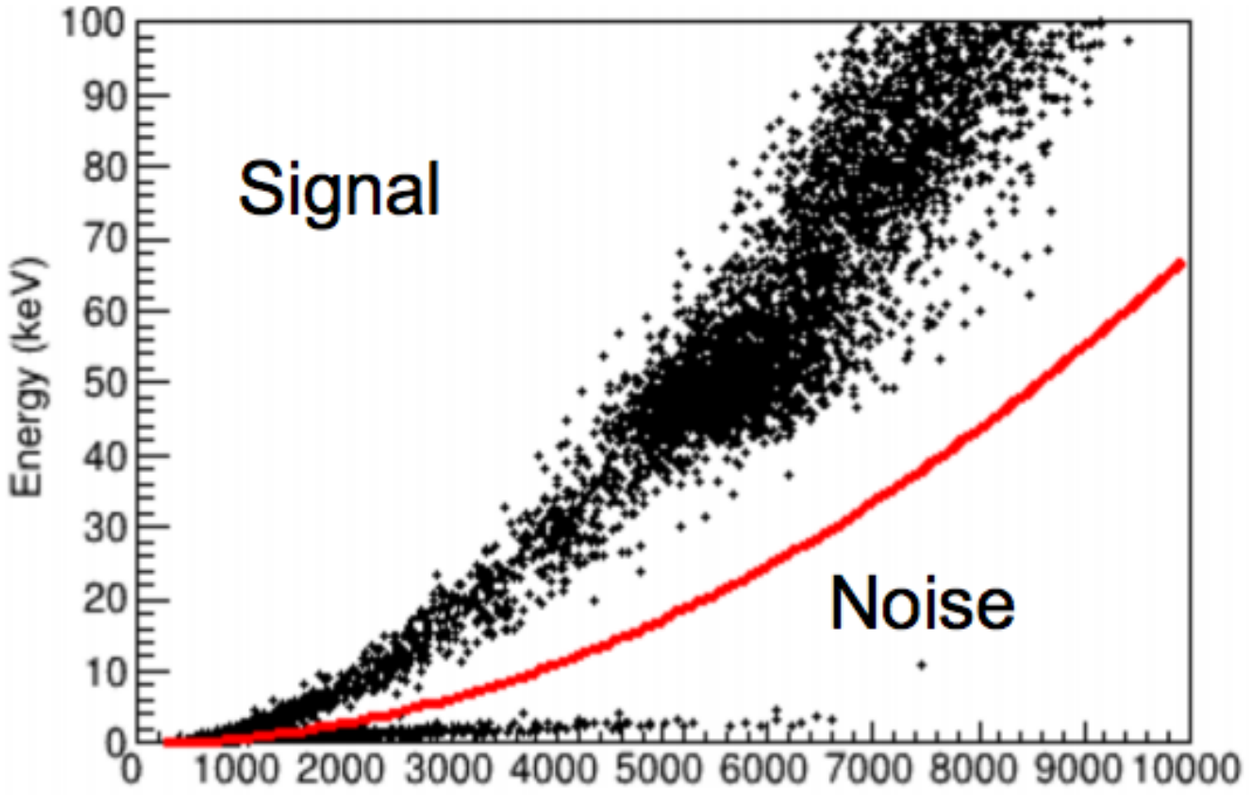




- Looking at charge ratio between rising edge and falling edge of a pulse gives good noise separation power

COSINE-100 Event Selection

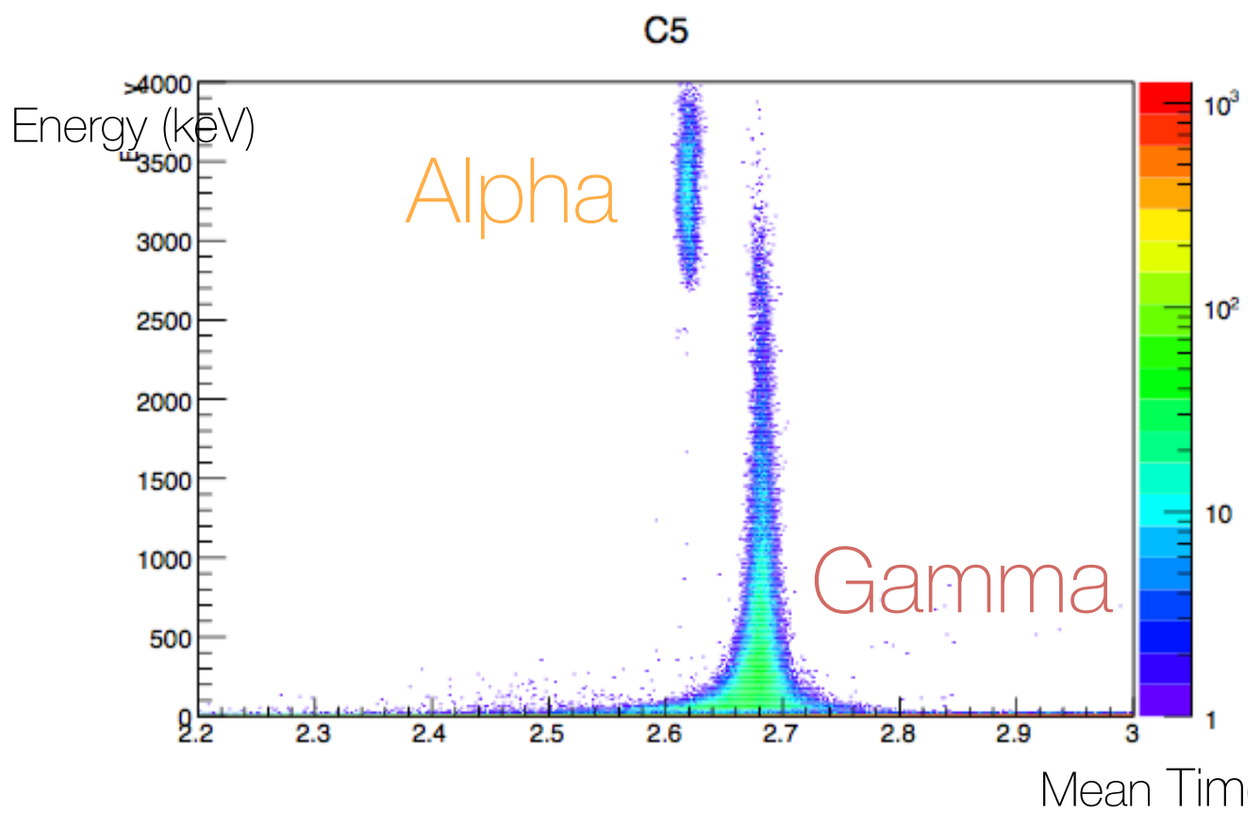




- Additional noise reduction cuts have been developed:
  - Charge asymmetry between 2 PMTs in each crystal
  - Charge/peak: Average charge per SPE

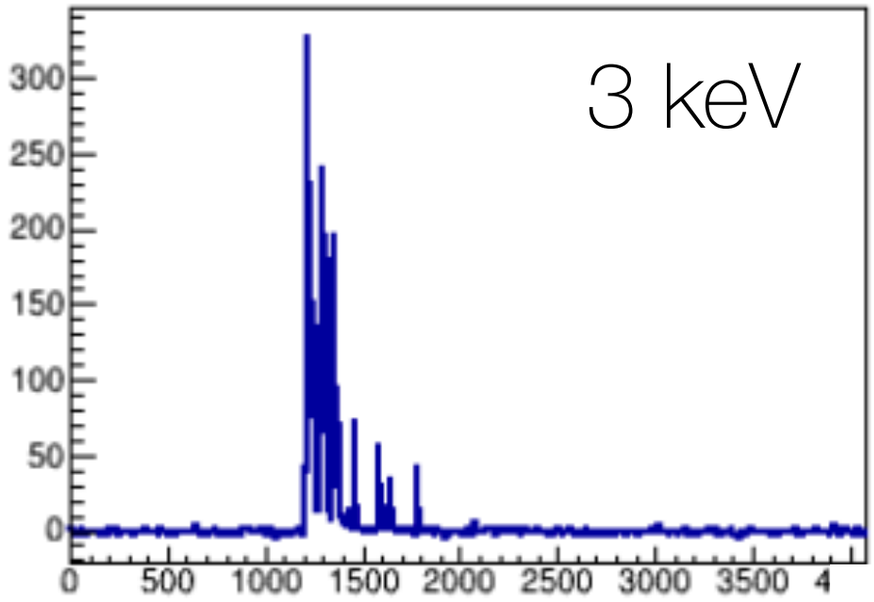
Pulse Shape Discrimination for Alpha

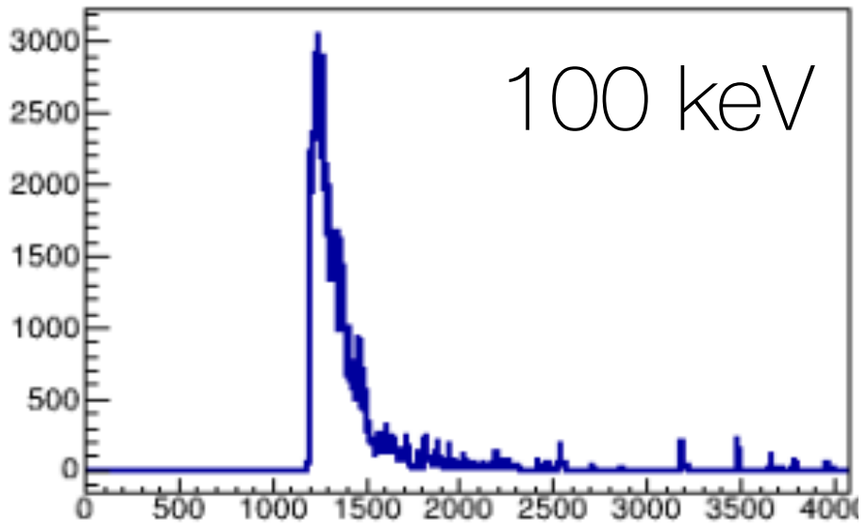
Preliminary

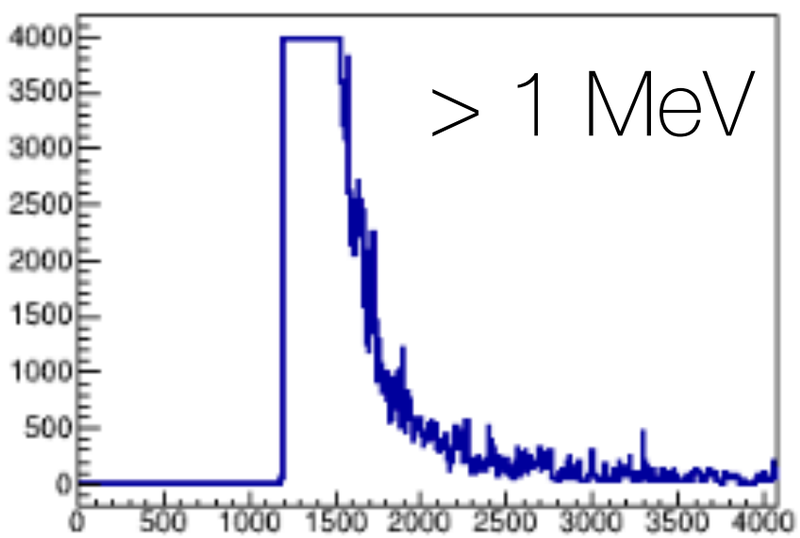


- Pulse Shape Discrimination technique works well for alpha separation
- Using charge-weighted mean time
- With separated alpha events, estimation of ^{210}Po background can be performed
  - 0.5~3 mBq/kg for COSINE-100 crystals

Examples of Signal Events (Anode Channel)





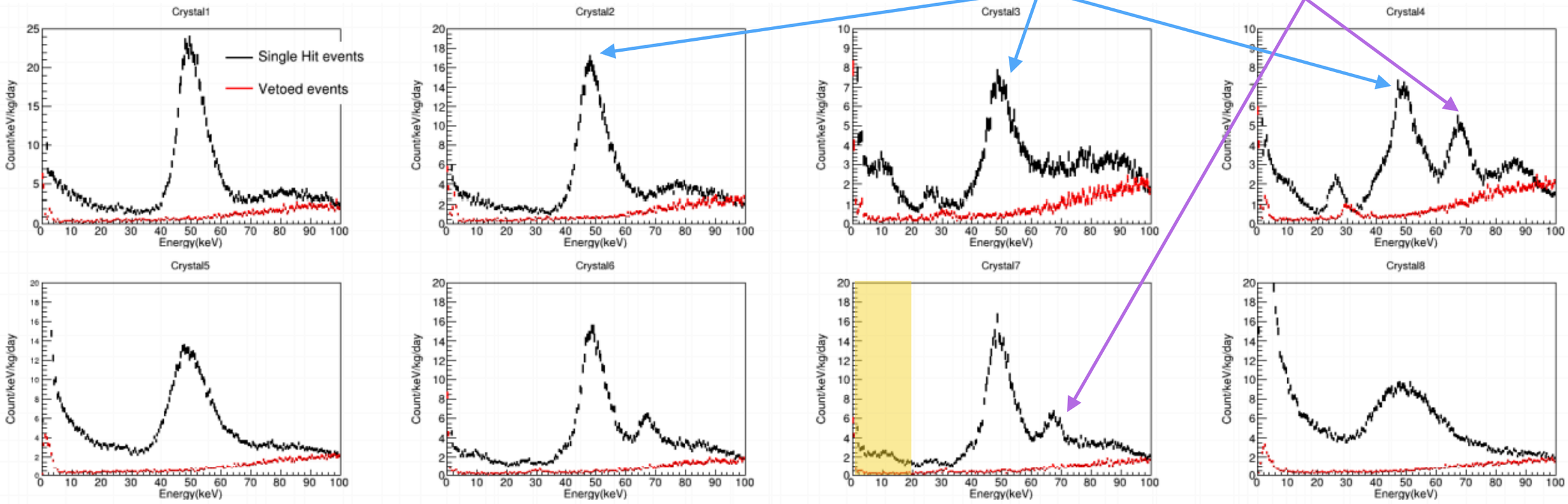


Low Energy Spectrum

Preliminary

^{210}Pb

^{125}I



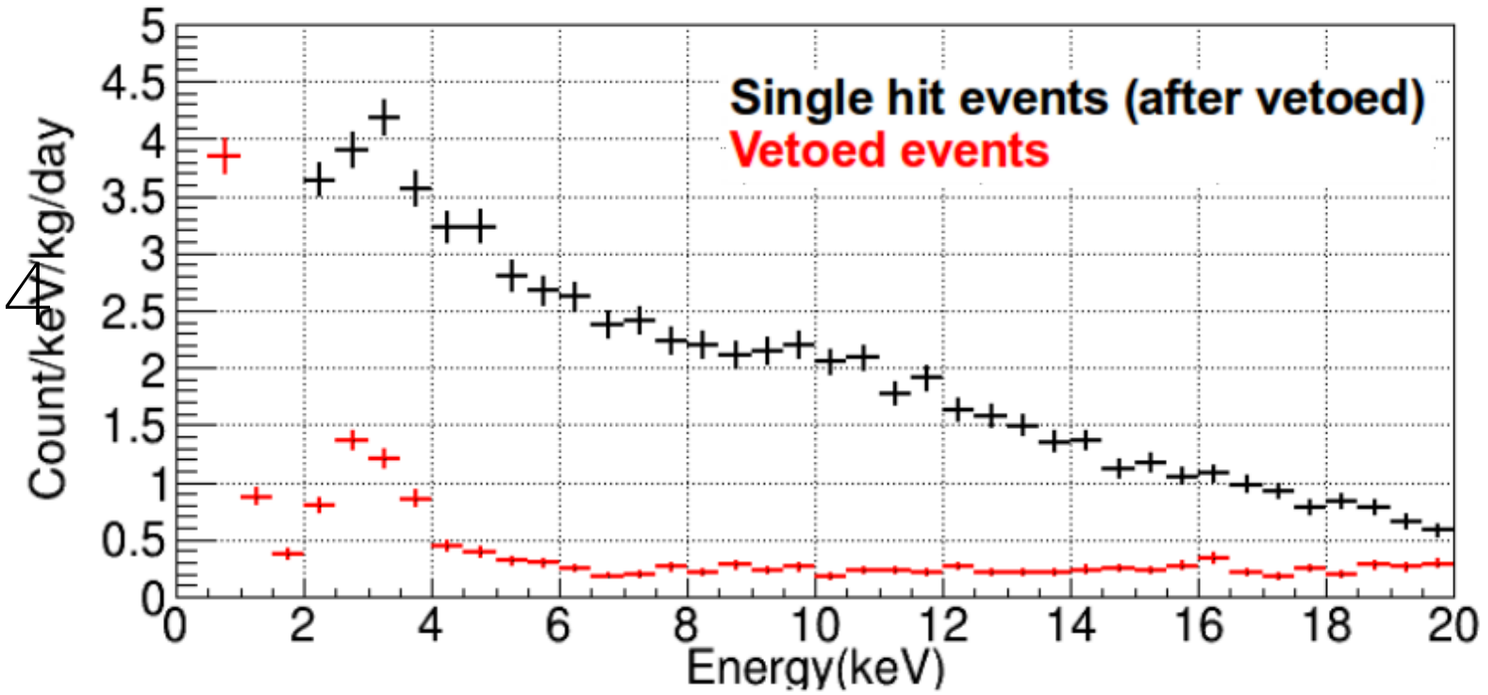
ROI

- 10 days of data, 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

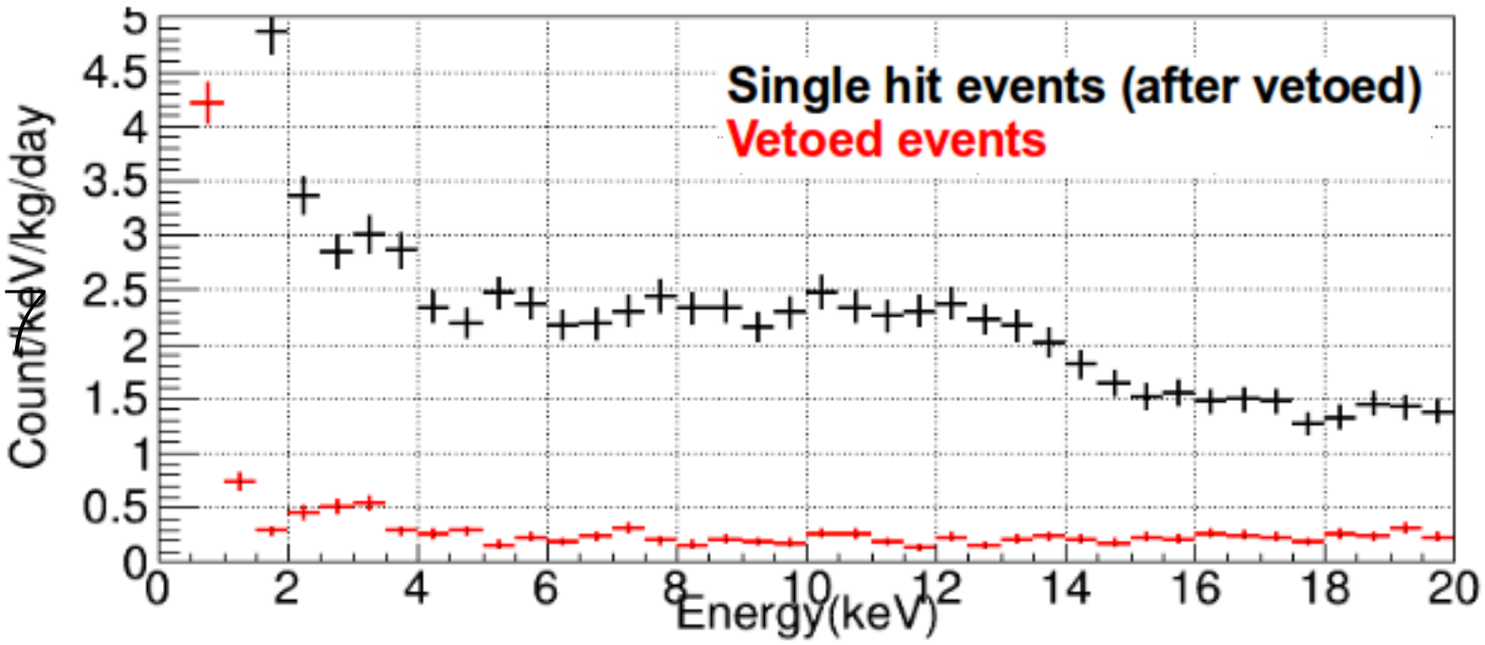
COSINE-100 Low Energy Spectrum (< 20 keV)

Preliminary

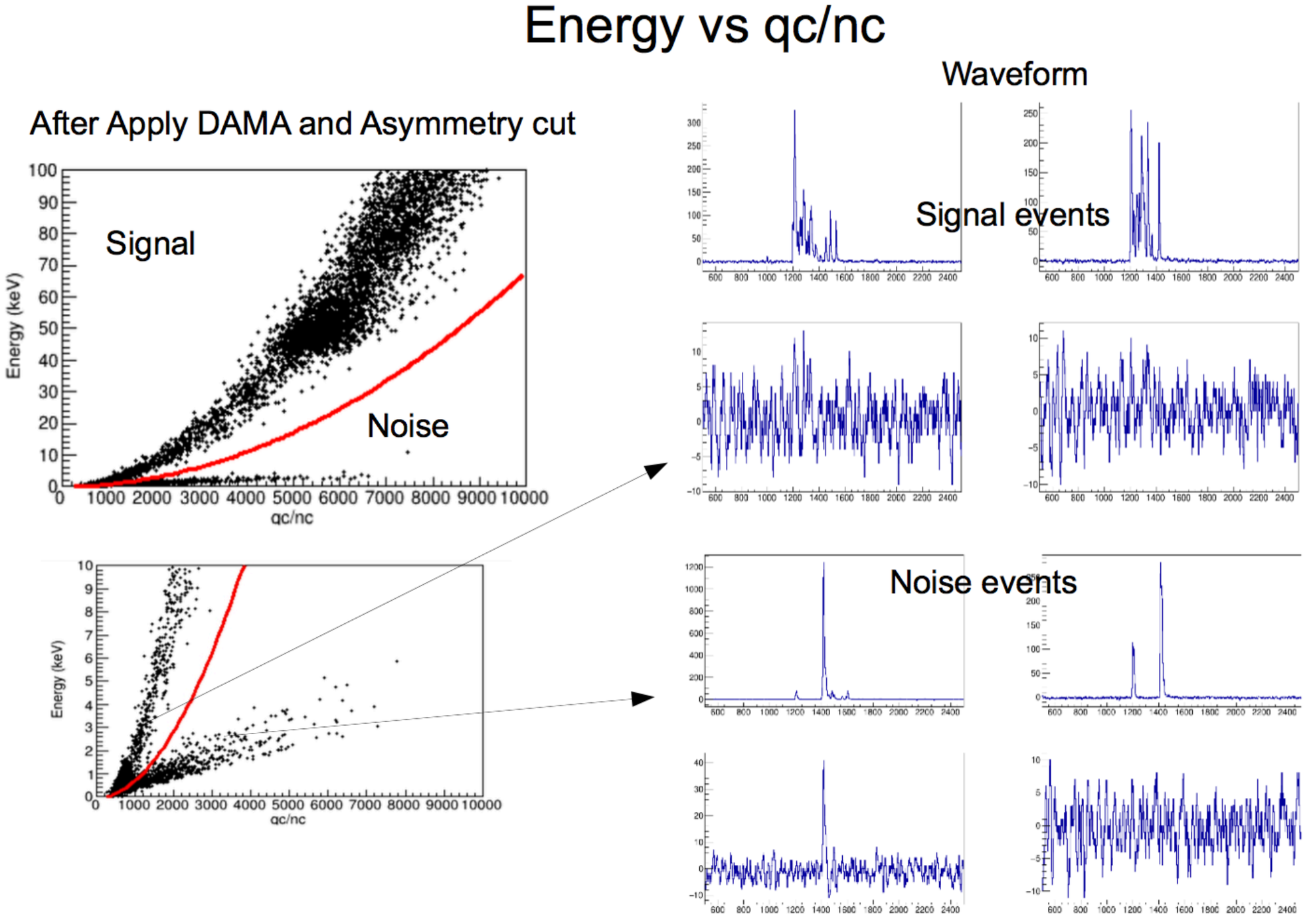
Crystal 4



Crystal 7



Average charge/SPE cut



Crystal growing in Korea

Under development

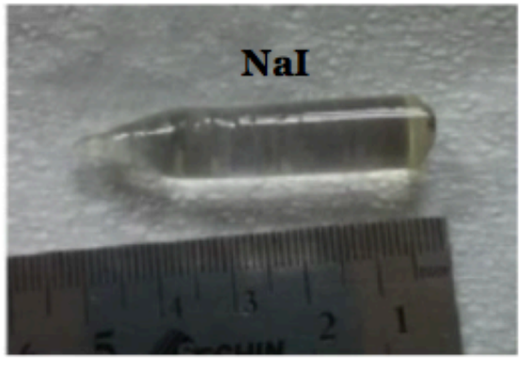
Czochralski Furnace

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

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