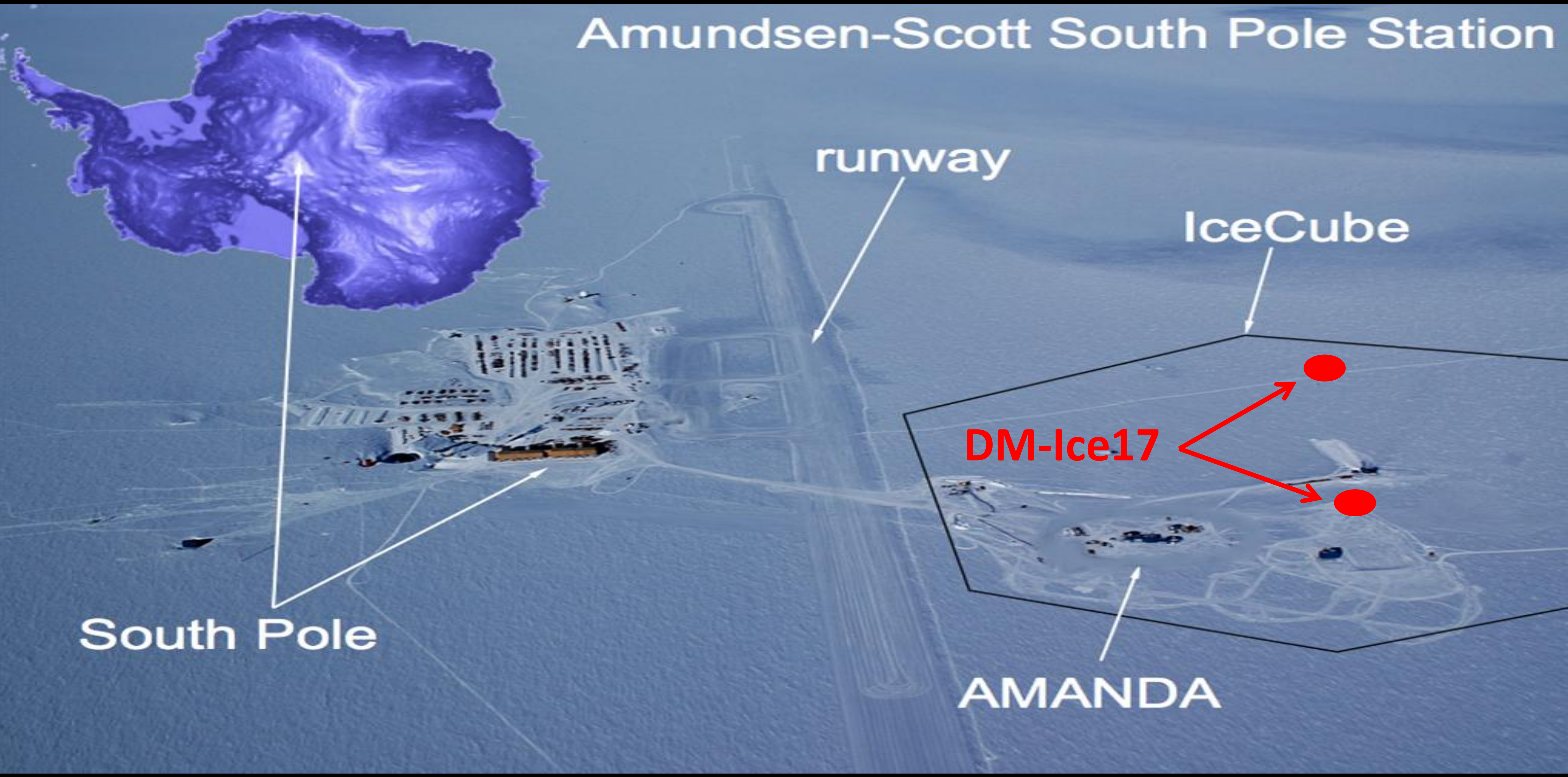
Operation and First Data of DM-Ice17 at the South Pole



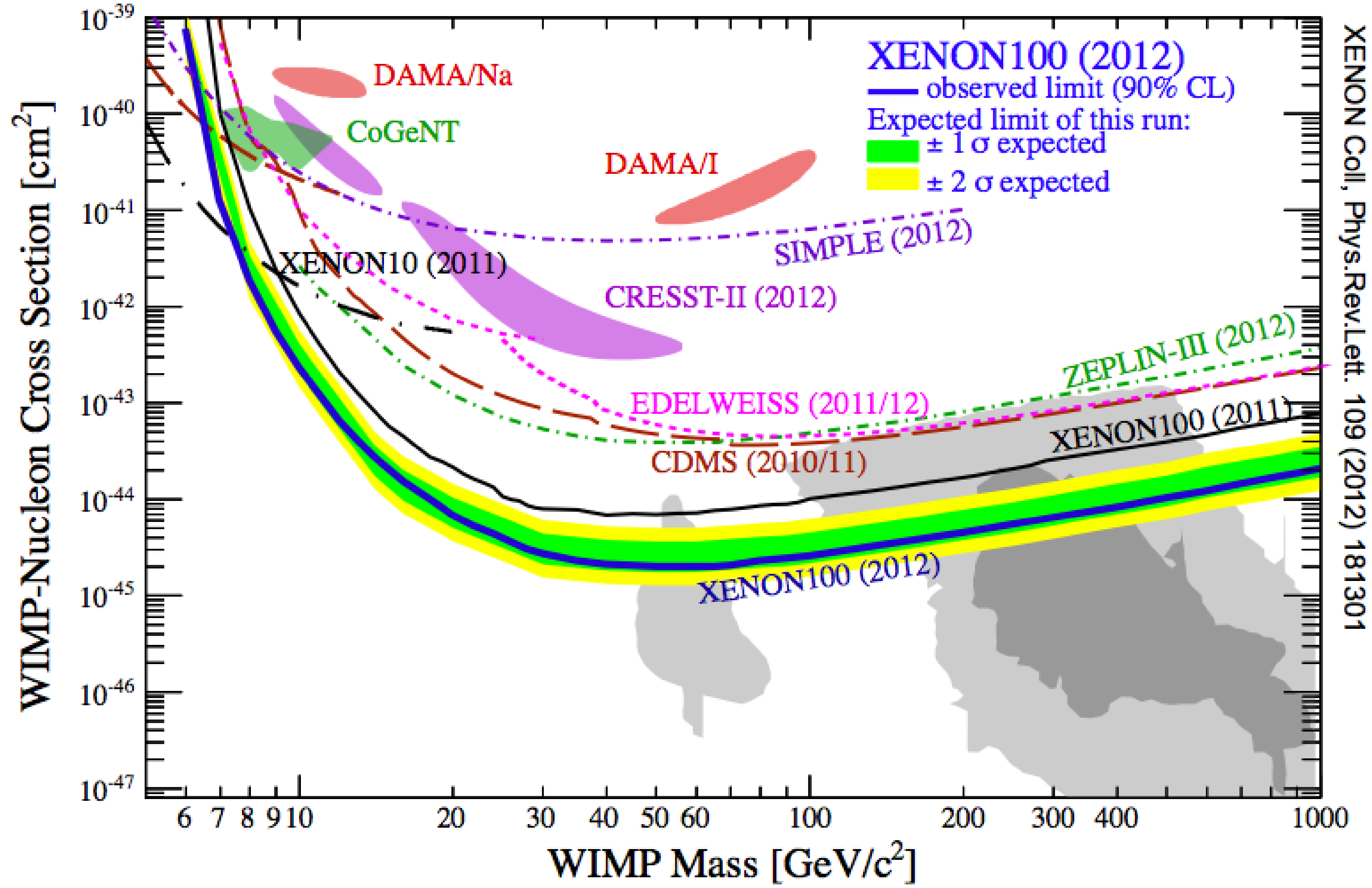
DM-Ice
A Dark Matter detector in the South Pole Ice

Matthew Kauer
(on behalf of the DM-Ice collaboration)

IPA 2013
Madison, WI
May 13

WISCONSIN ICECUBE PARTICLE ASTROPHYSICS CENTER
University of Wisconsin - Madison

“Tension” in the field



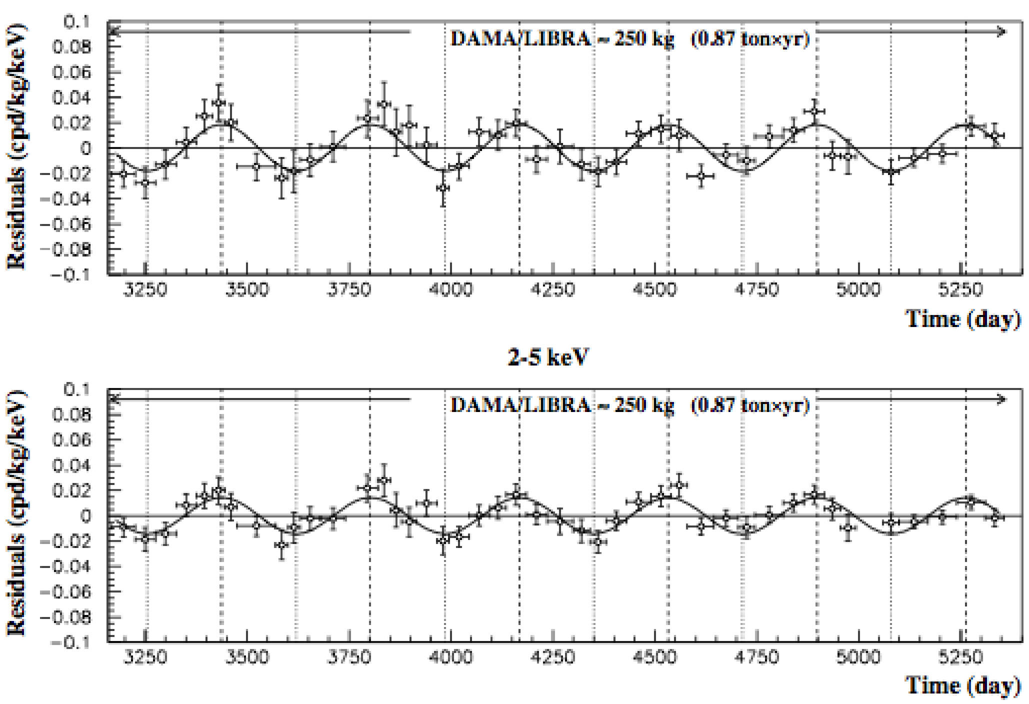
DAMA 8.9σ Modulation:

Phase: 146 ± 7 days

Period: 0.999 ± 0.002 yr

Background: ~ 1 cpd/kg/keV

Amplitude: 0.01 cpd/kg/keV



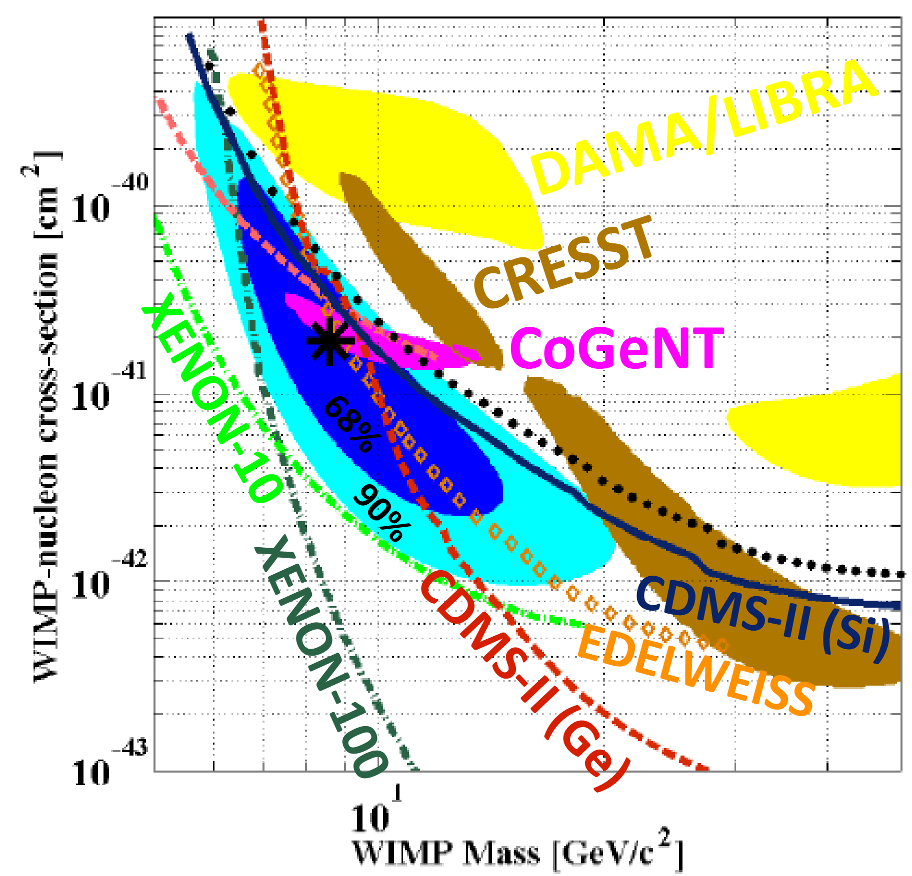
CDMS II

Silicon Analysis

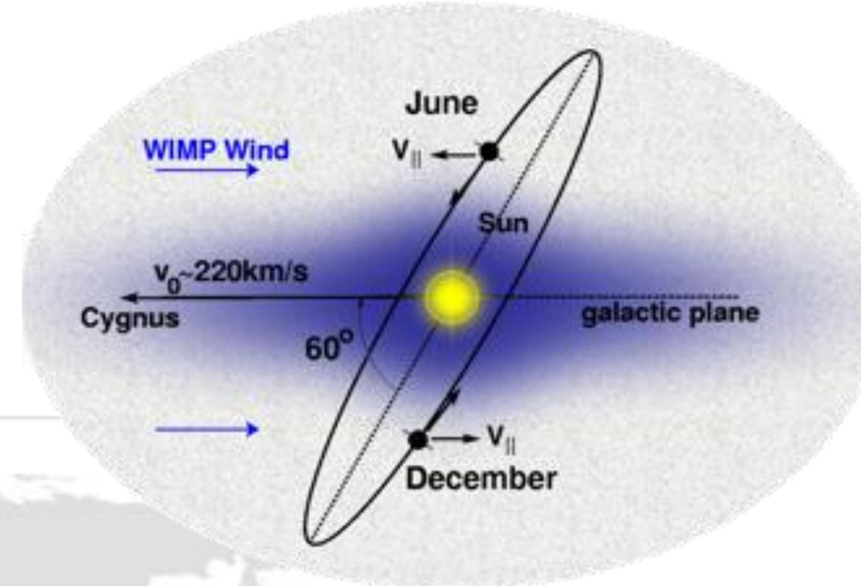
140 kg.days

3 events 5-7σ

arXiv: 1304.4279



Annual Modulation Dark Matter Searches with NaI Detectors



Northern Hemisphere	Gran Sasso **DAMA/Libra** 250kg running	Gran Sasso **SABRE** (Princeton) R&D	Canfranc **ANAIS** ~100kg starting in 2014?	(Japan) **PICO-LON** (Korea) **KIMS**
Southern Hemisphere	South Pole **DM-Ice** 17 kg running R&D for 250 kg	**ANDES** Lab (proposed) expected start 2018		**ice** **rock**

Several groups conducting ultra-pure crystal R&D with several vendors to go to the full scale

Only experiments in the Southern Hemisphere can definitively confirm DAMA.

DM-Ice (250 kg NaI)

Use NaI(Tl)

- Eliminate uncertainties due to detector effects and dark matter models
- Crystal Array for sophisticated event tagging

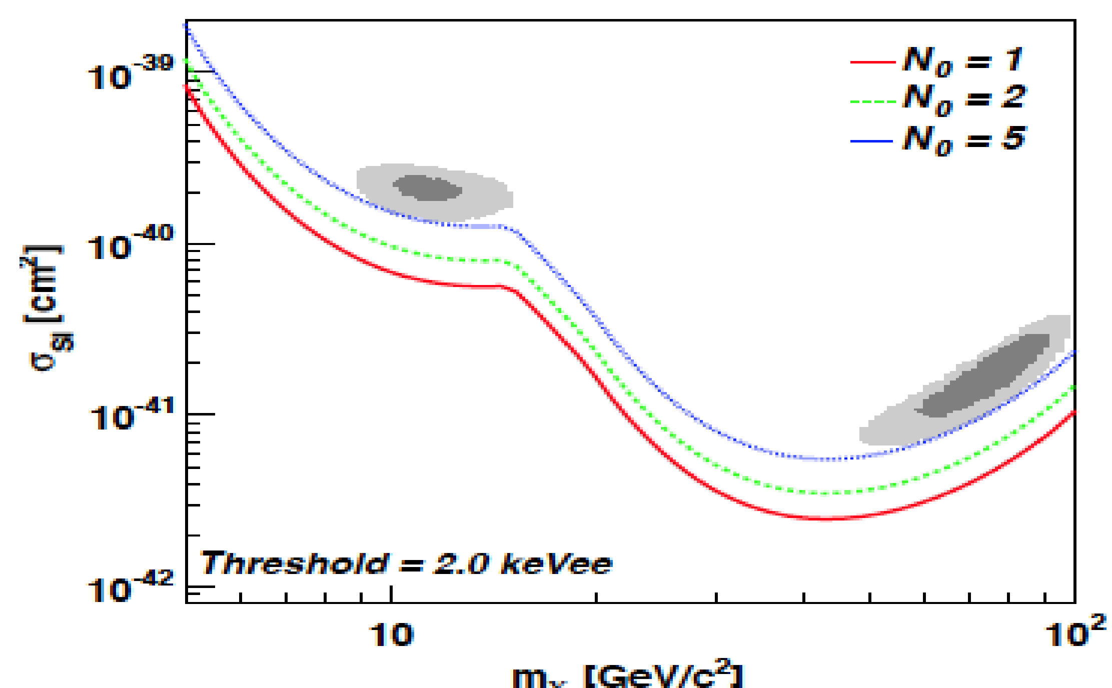
Detection (5σ) or exclusion

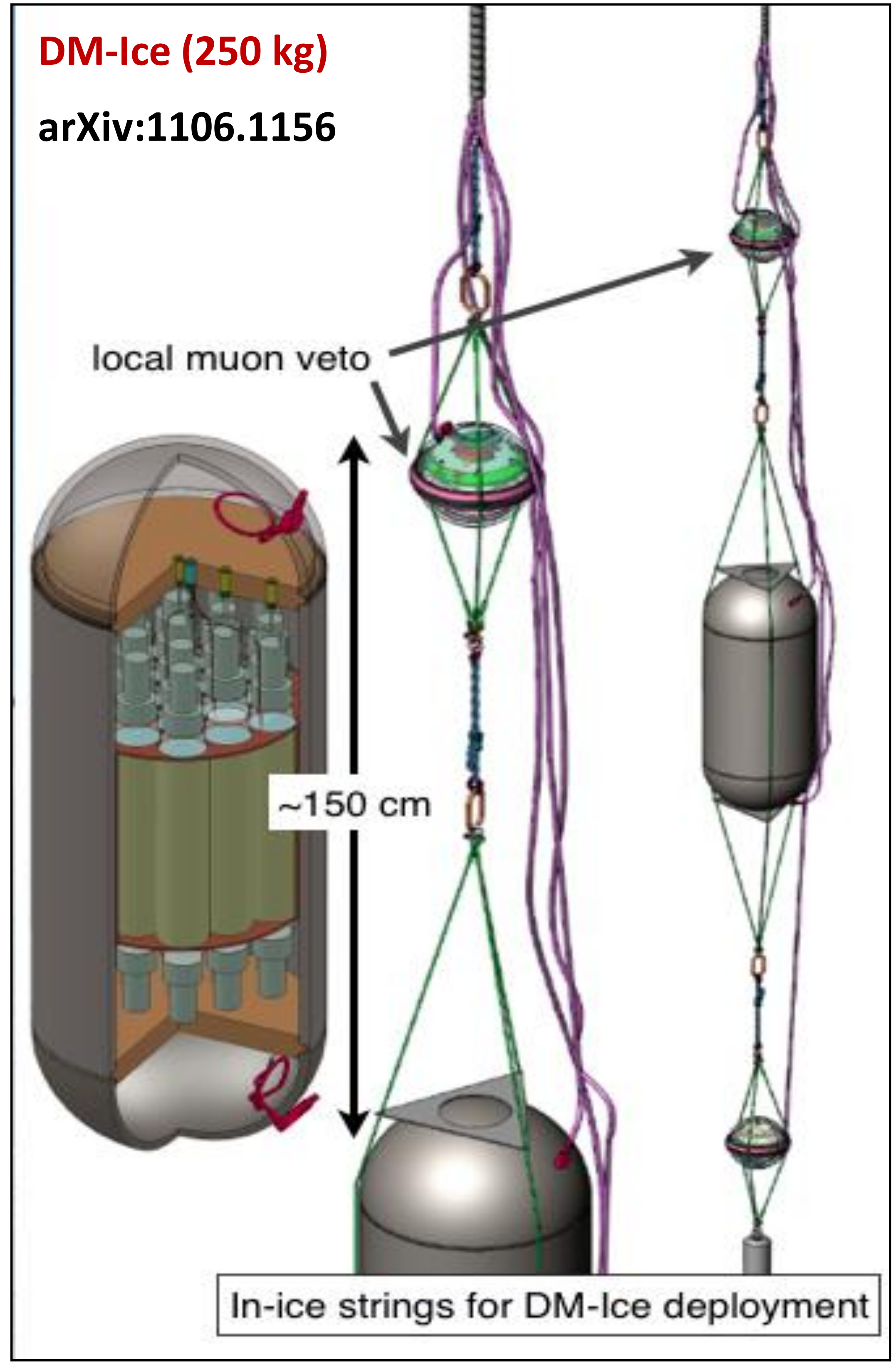
- 500 kg*yr NaI (same scale as DAMA)
- Threshold < 2 keV_{ee}
- Background < 5 cpd/kg/keV

Go to the South Pole

- Seasonal effects have opposite phase
- 2200 mwe overburden
- Ice < 1 ppt U/Th (radon ~0)
- Ice < 1 ppb K
- Ice == great neutron moderator

DM-Ice Sensitivity
500 kg•yr NaI
(2 - 4 keV) with 1, 2, and 5 dru bkg





Global NaI Powder R&D

- From simulation, internal backgrounds dominate, particularly 3 keV ^{40}K
- DAMA's crystals (NIMA 592 (2008) 297– 315) :
  - ^{238}U : 1 - 10 ppt
  - ^{232}Th : 1 - 10 ppt
  - ^{nat}K : < 20 ppb
- NAIAD crystals : 5 - 10x DAMA bkg (PLB 616 (2005) 17–24)

DM-Ice17 now has 2 NAIAD crystals

32" diameter NaI Crystal

Manufacturer	Form	Measurement	^{238}U (ppt)	^{232}Th (ppt)	^{nat}K (ppb)
Saint Gobain	Powder	DAMA (HPGe)	< 20	< 20	< 100
Saint Gobain	Crystal	DAMA/LIBRA	0.7 - 10	0.5 - 7.5	< 20
Saint Gobain	Crystal	ANAIS-0	6.1	3.2	410
Saint Gobain	Crystal	DM-Ice (FNAL)			
Sigma-Aldrich	Powder (standard grade)	DM-Ice (HPGe)	40	89	440
Sigma-Aldrich	Powder (astro grade)	DM-Ice (HPGe)	63	< 95	< 126
Sigma-Aldrich	Powder (astro grade)	A-S (ICPMS)	-	-	~ 4
Alpha-Spectra	Powder	DM-Ice (HPGe)	< 100	< 200	< 120
Alpha-Spectra	Powder	ANAIS-25 (HPGe)	< 55	< 130	< 90

- Also working with SICCAS (Shanghi)

Technical challenge == a method to measure K < 100 ppb level
- ICPMS is promising → < 10 ppb
- Samples have been sent…

DM-Ice17 Deployment

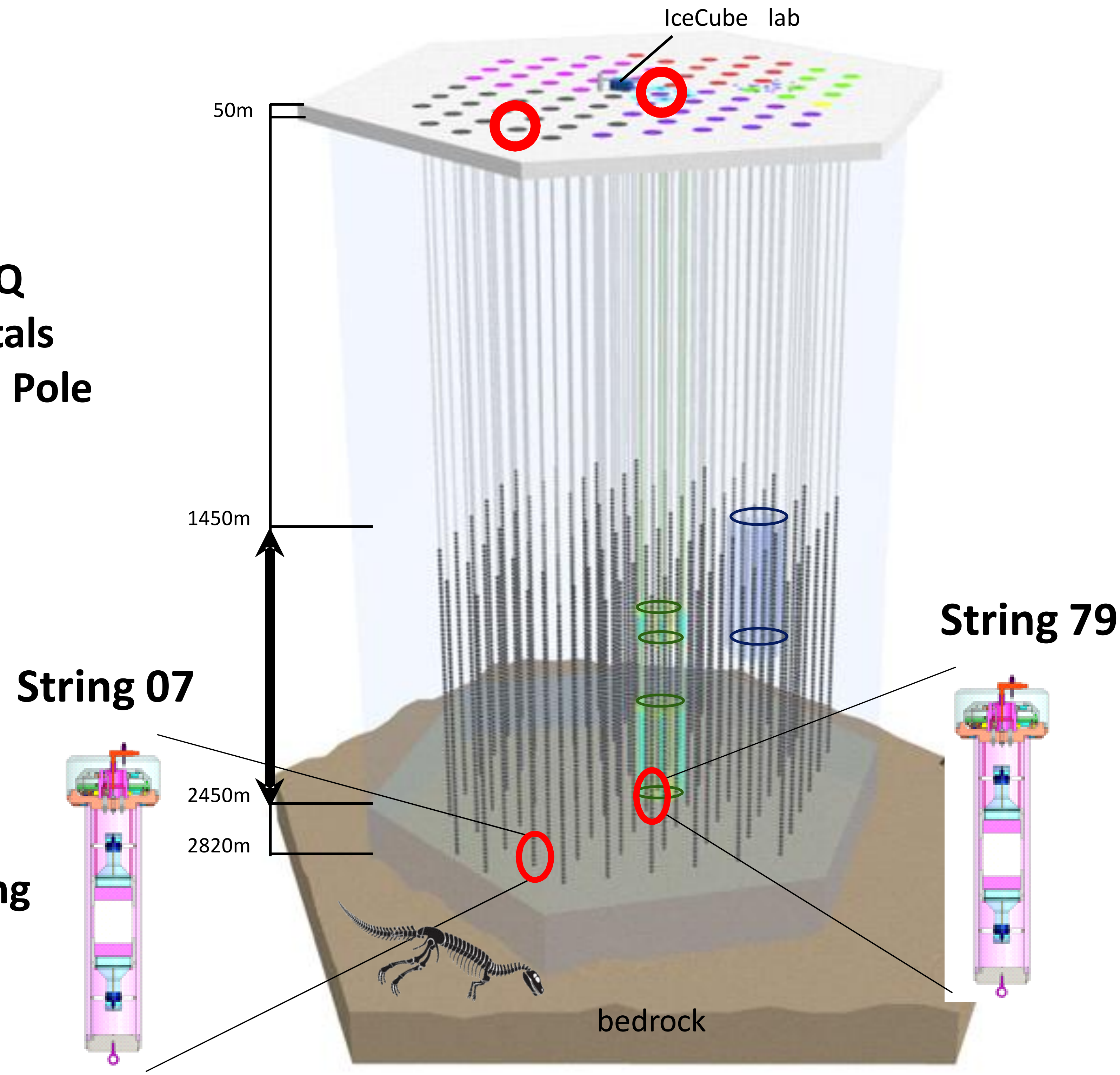
Feb 2010
- a great idea!

10 months →

Dec 2010
- IceCube DAQ
- NAIAD crystals
- deployed at Pole

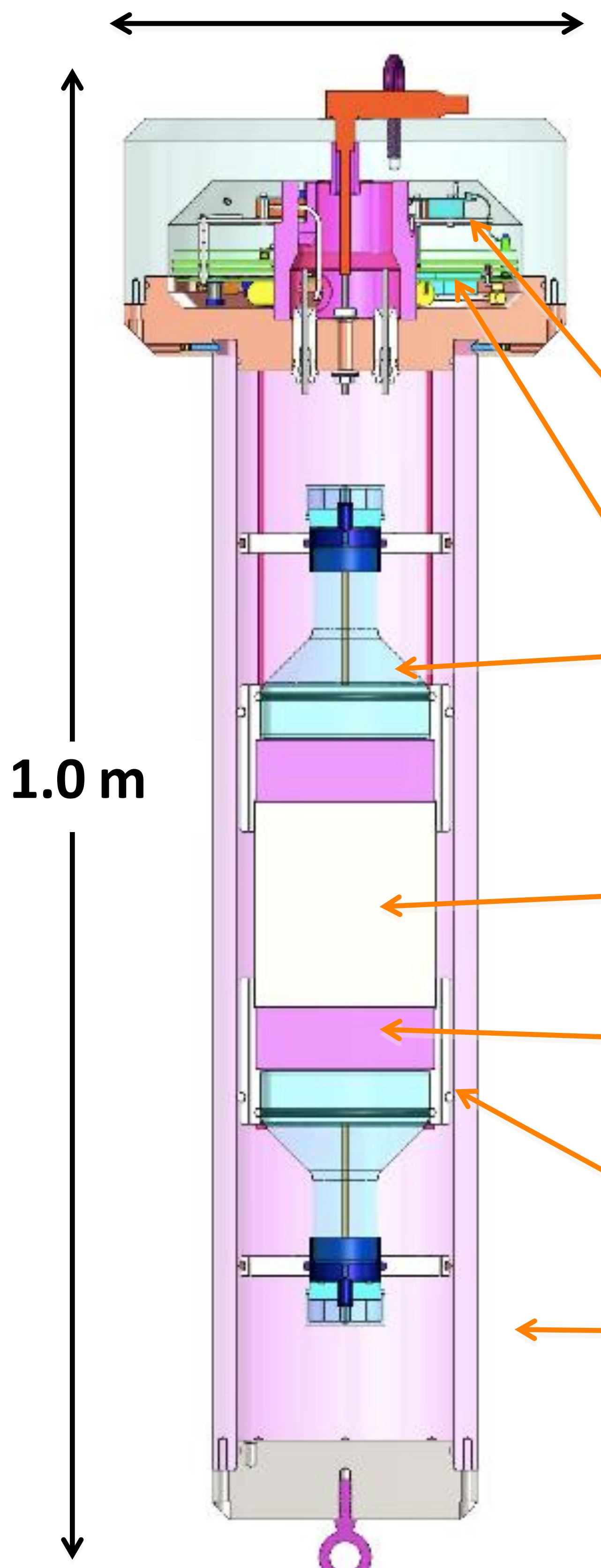
Co-Deployed with IceCube at the South Pole in December 2010
- A 17 kg NaI detector
- Operation since Jan. 2011
- Data run from June 2011

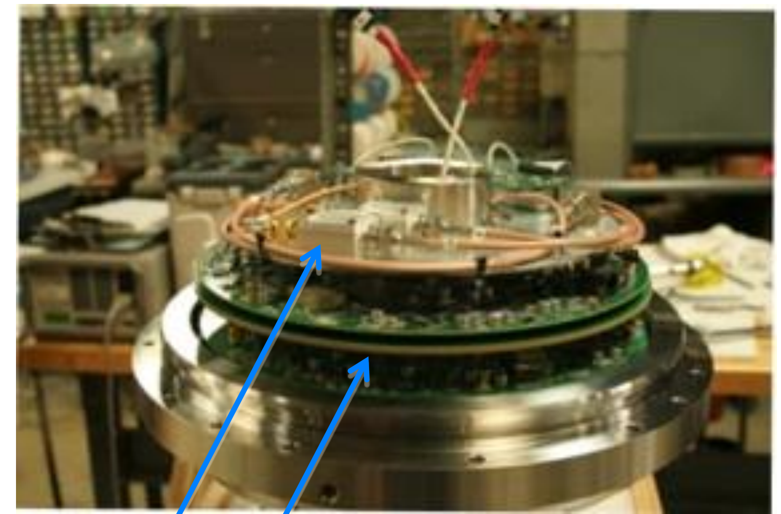
Goals…
- determine the feasibility of deploying a remotely-operable detector in the Antarctic Ice
- Assess the environmental stability
- Establish the radiopurity of the Antarctic ice / drill ice
- Explore the capability of IceCube to veto muons
- Look for modulations

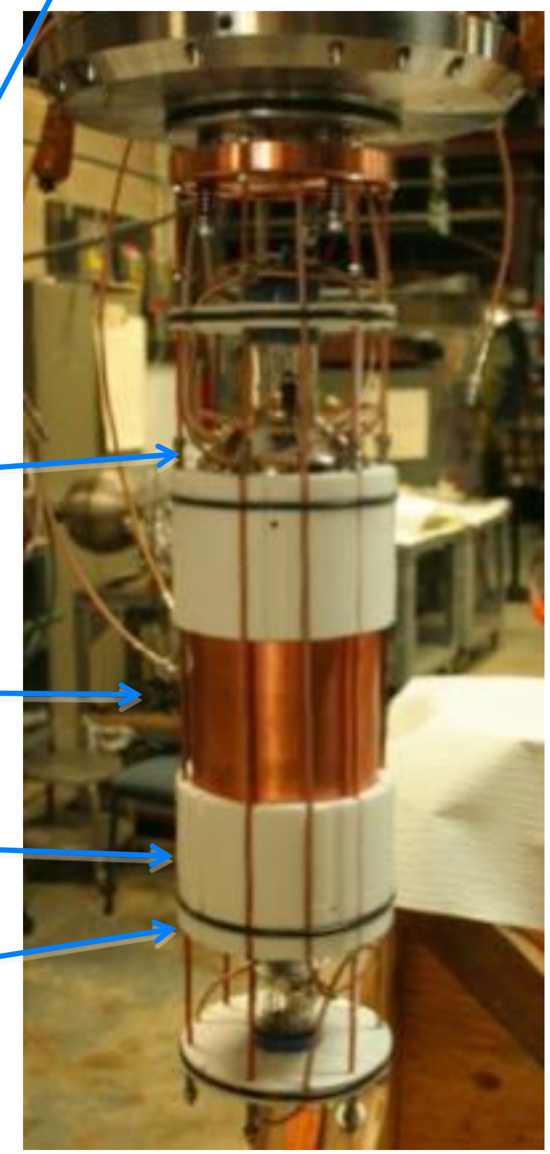


- 2200 M.W.E. overburden
- ~85 muons/m^2/day

DM-Ice17 (prototypes)

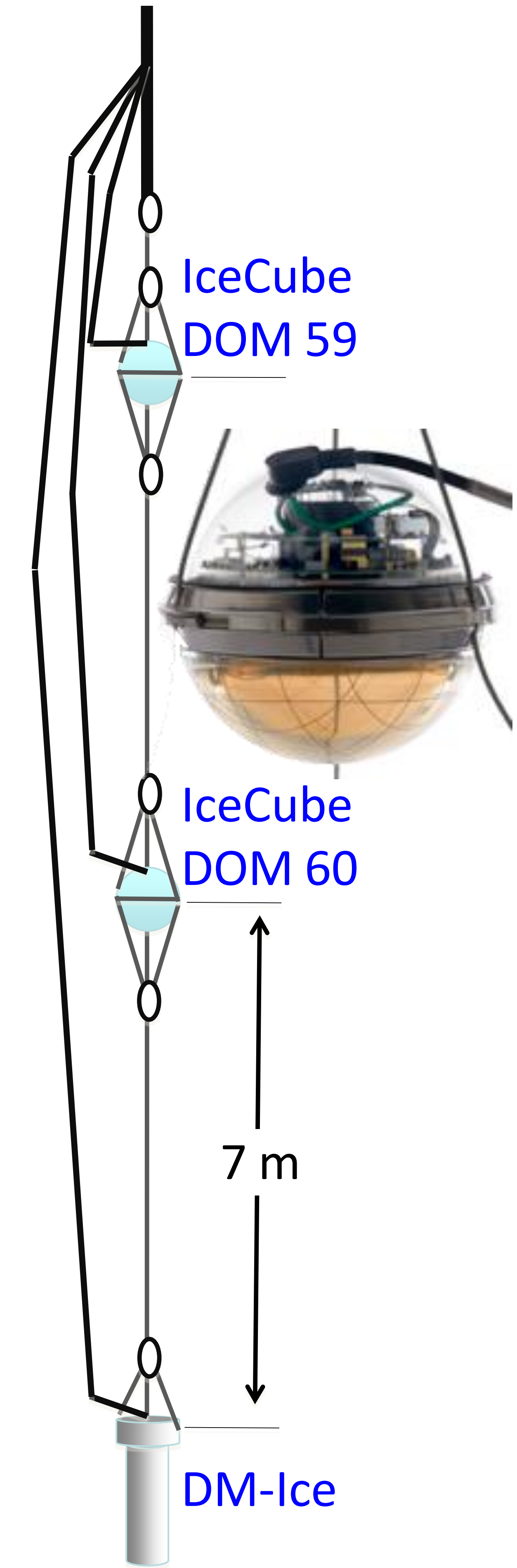




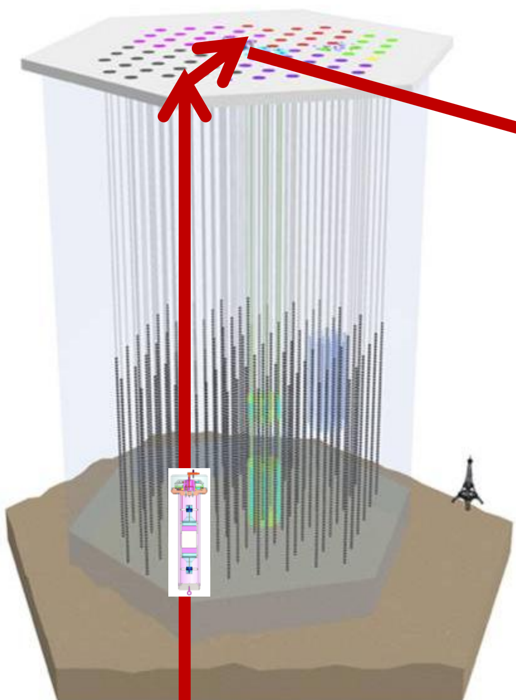


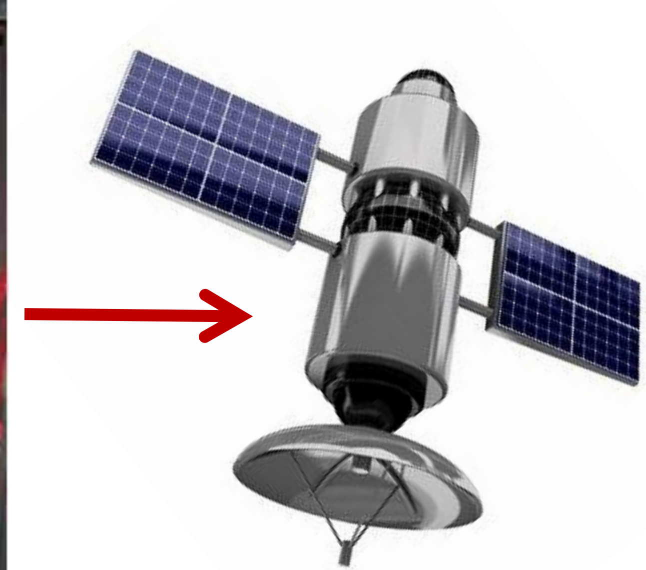
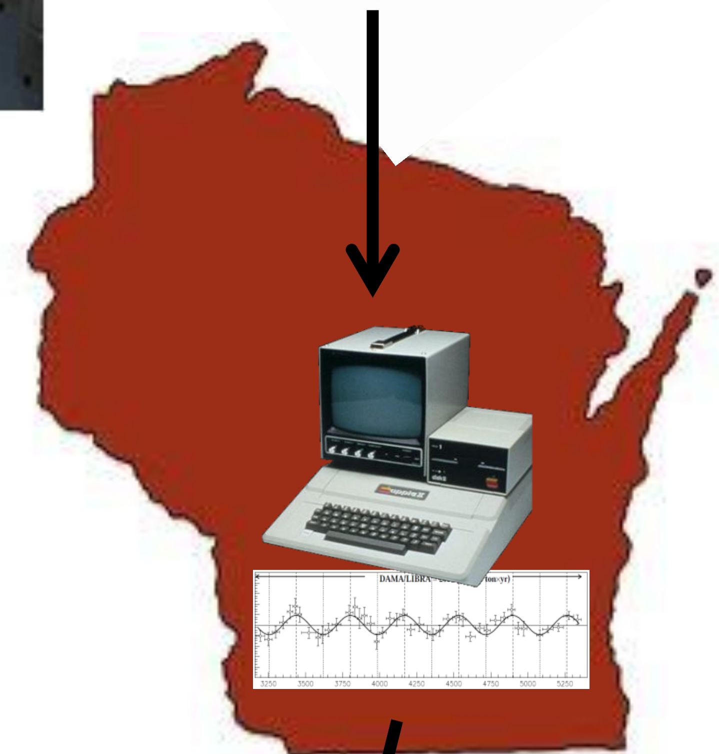
Prototype x2

- 2 HV control boards
- 2 IceCube mainboards
- PMTs:
  5" ETL 9390-UKB
- NAIAD NaI Crystal
  (Ø 5.5" x 6", 8.5 kg)
- 5 cm quartz lightguides
  (Suprasil B)
- PTFE light reflectors
- Stainless Steel
  Pressure Vessel

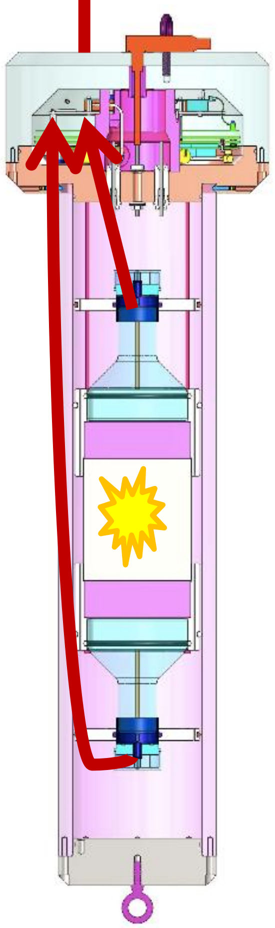


Data Transfer



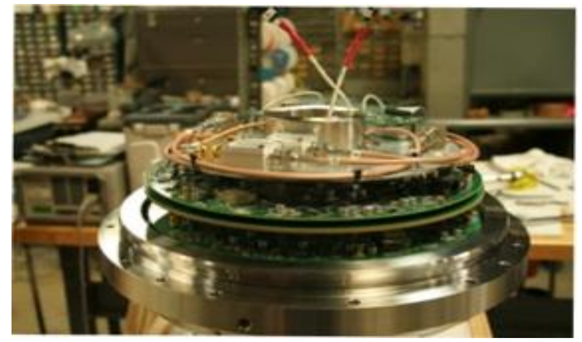
- **Remotely programmable sample rate, HV & threshold**
- **Each PMT set to trigger ~ 0.3 spe**
- **Waveform recorded only when coincidence between both PMTs w/in 800 ns on a single crystal**
- **Waveform from each PMT digitized separately in the ice by IceCube mainboards and sent to hub**
- **Time stamp synchronized to IceCube GPS and calibrated for transit time**
- **Data sent over satellite to Madison, WI**



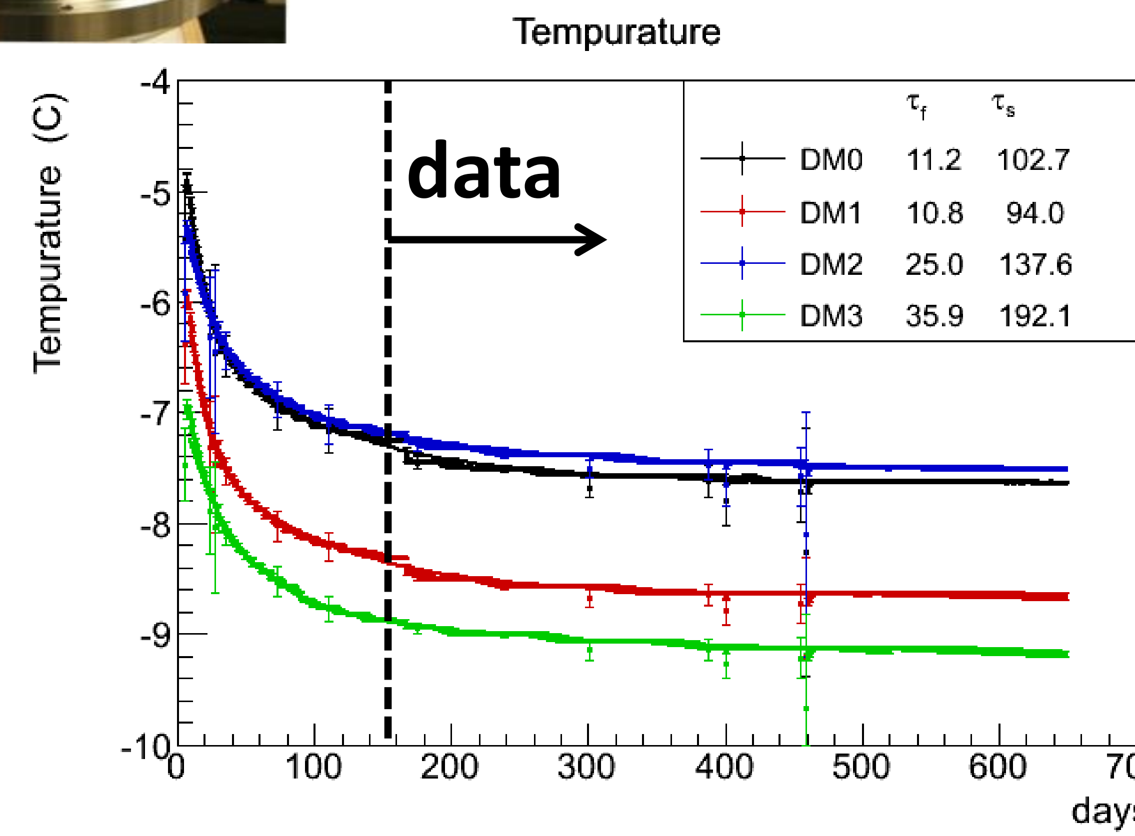

Detector Monitoring

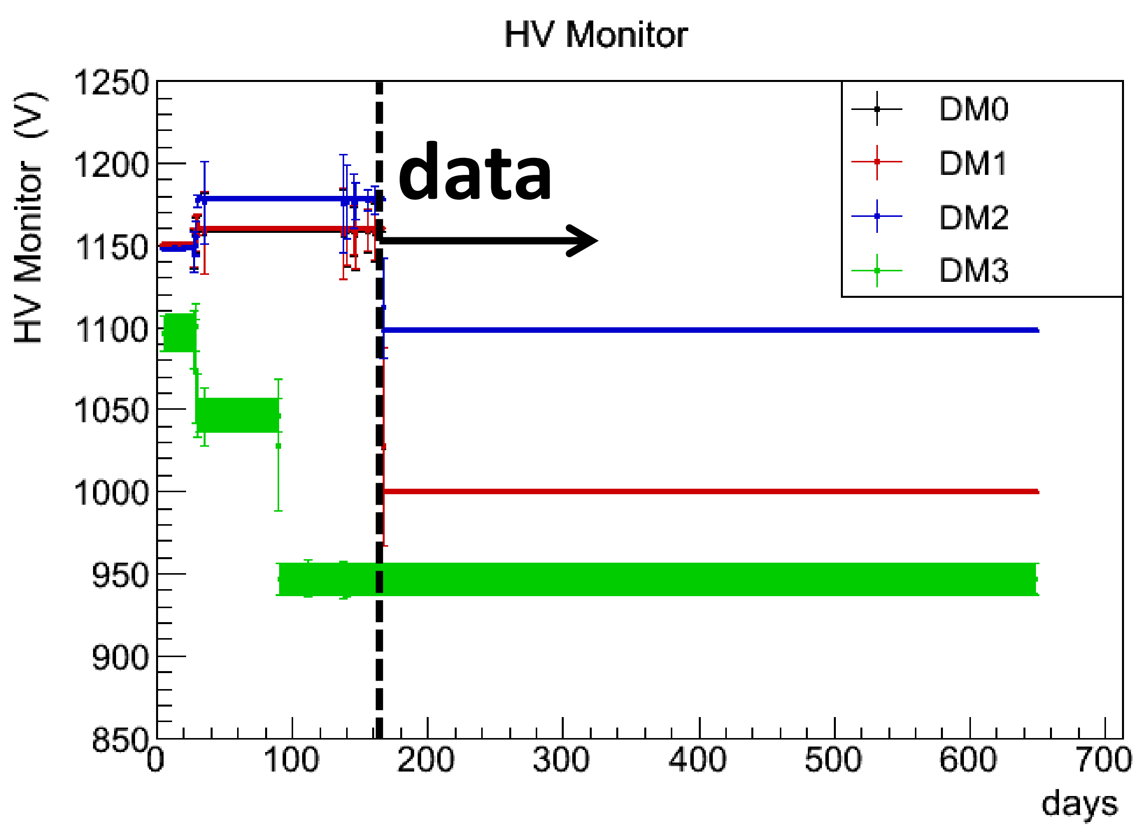
1. Temperature of the boards
   - ~10°C above surrounding ice
   - Fast (2-3 weeks) decrease during freeze-in
   - Slower decrease over a few months after freeze-in
2. Pressure follows similar trend as temperature (ADC resolution limited)
3. High Voltage on the PMTs

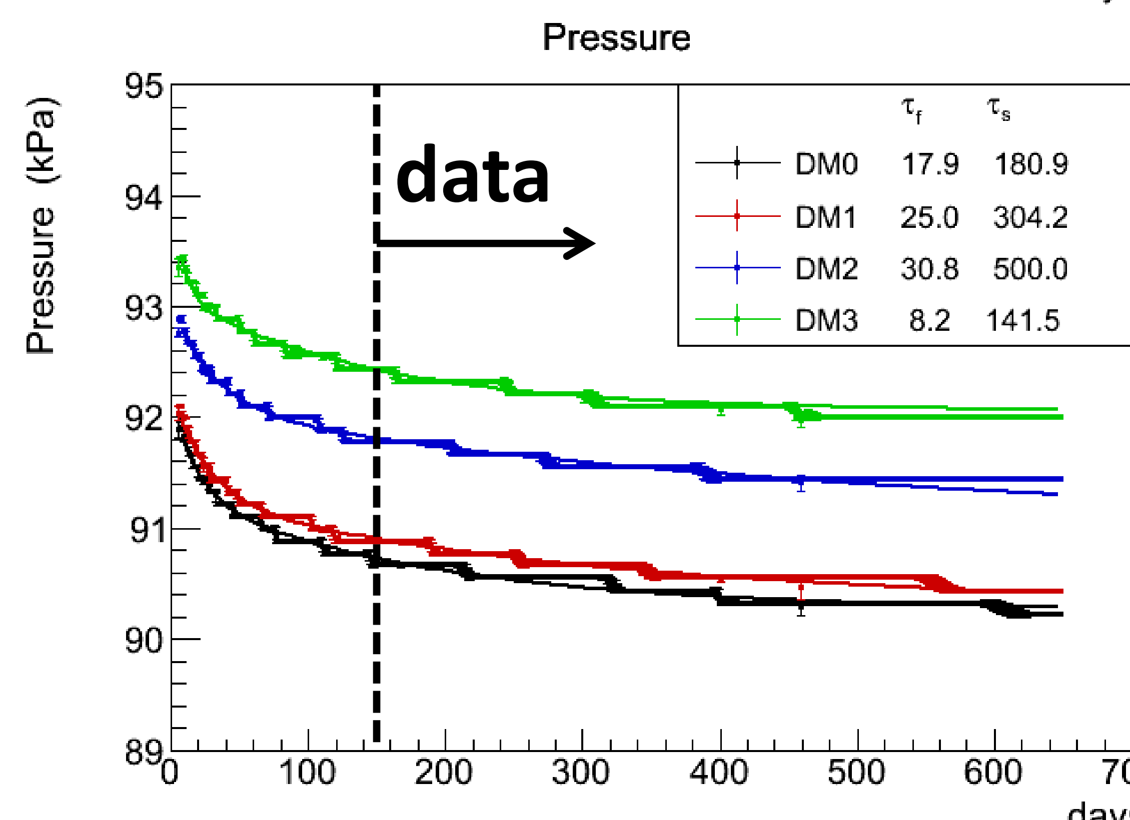
Values recorded every 2 sec. before April 2012. Every 60 sec. since April 2012.



Temp and pressure sensors mounted on the mainboards



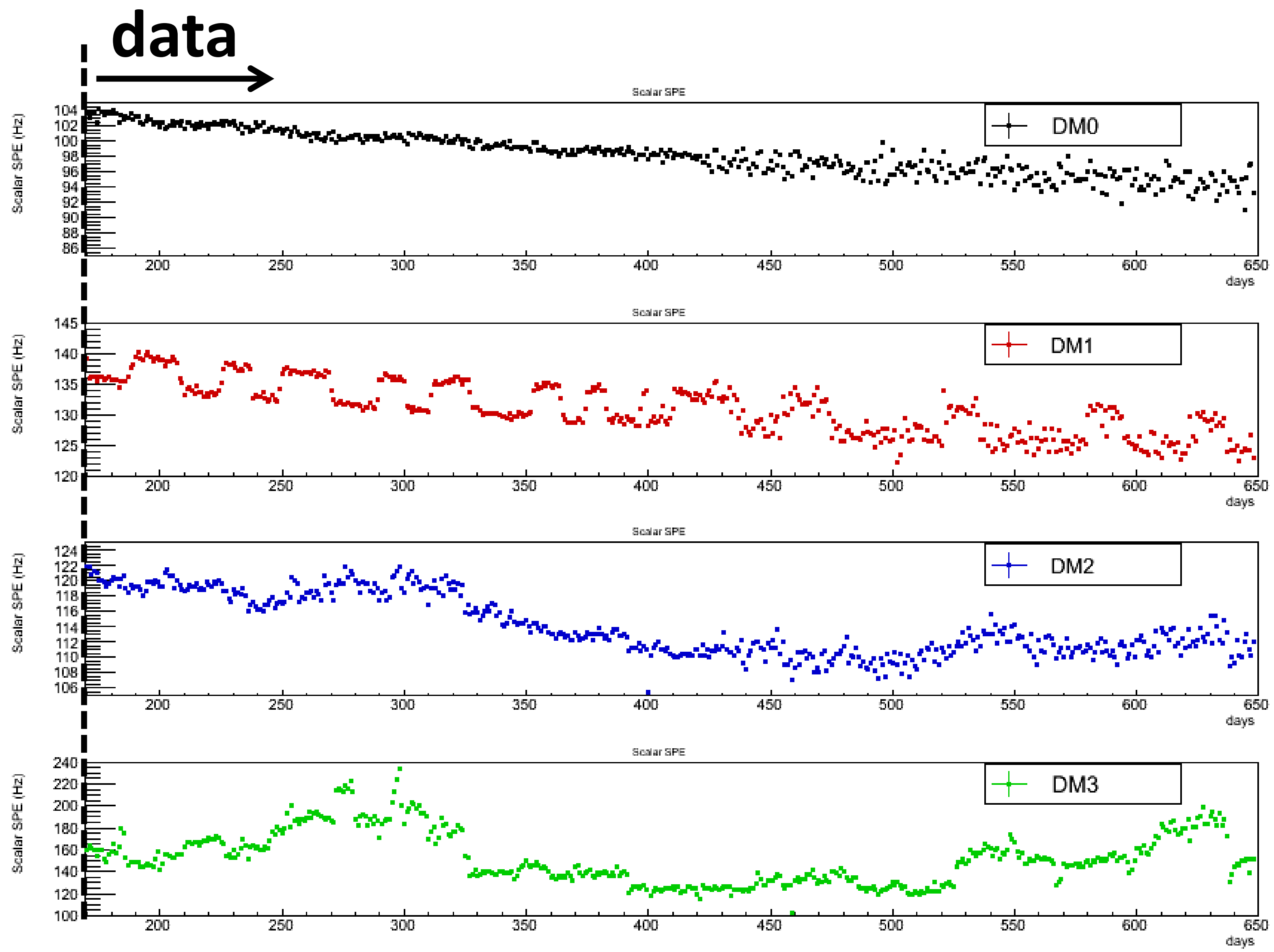


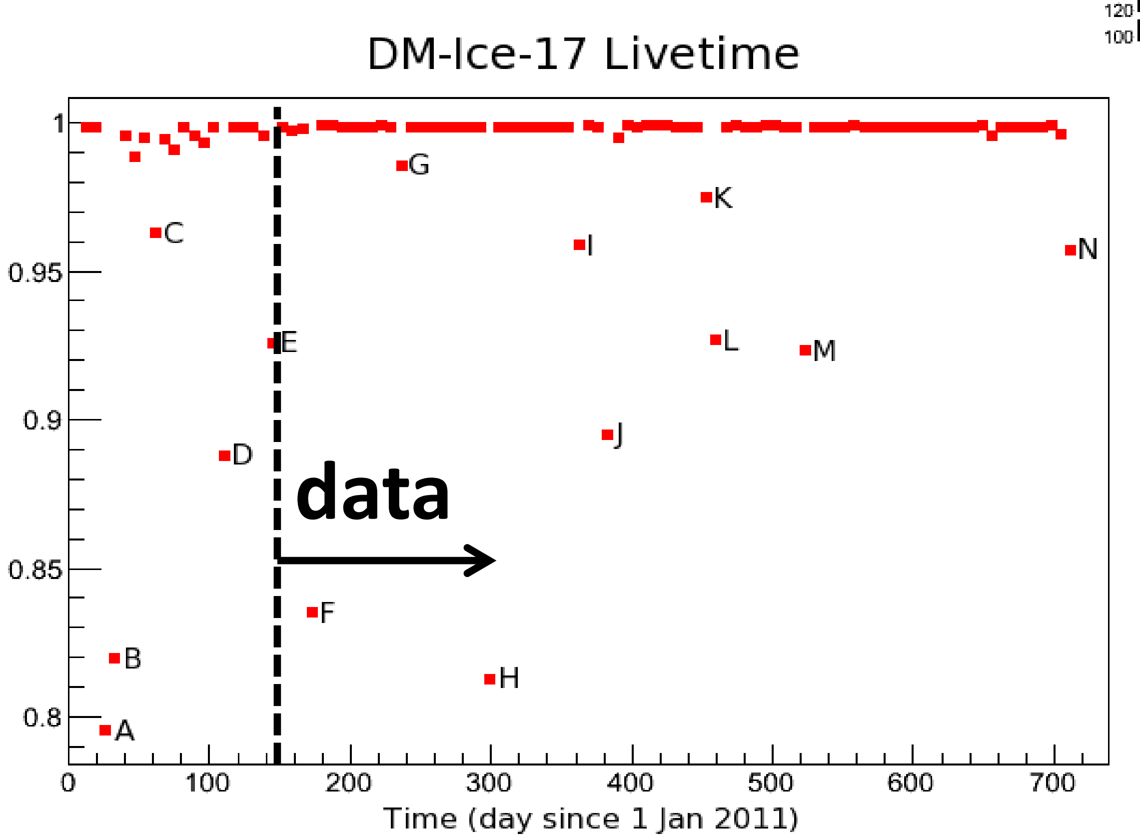


Detector Monitoring

PMT Trigger Rates

- Single PMT trigger rates
- General decay over time
- Single trigger rate variation seems mostly in the noise (not observed in coincident data)

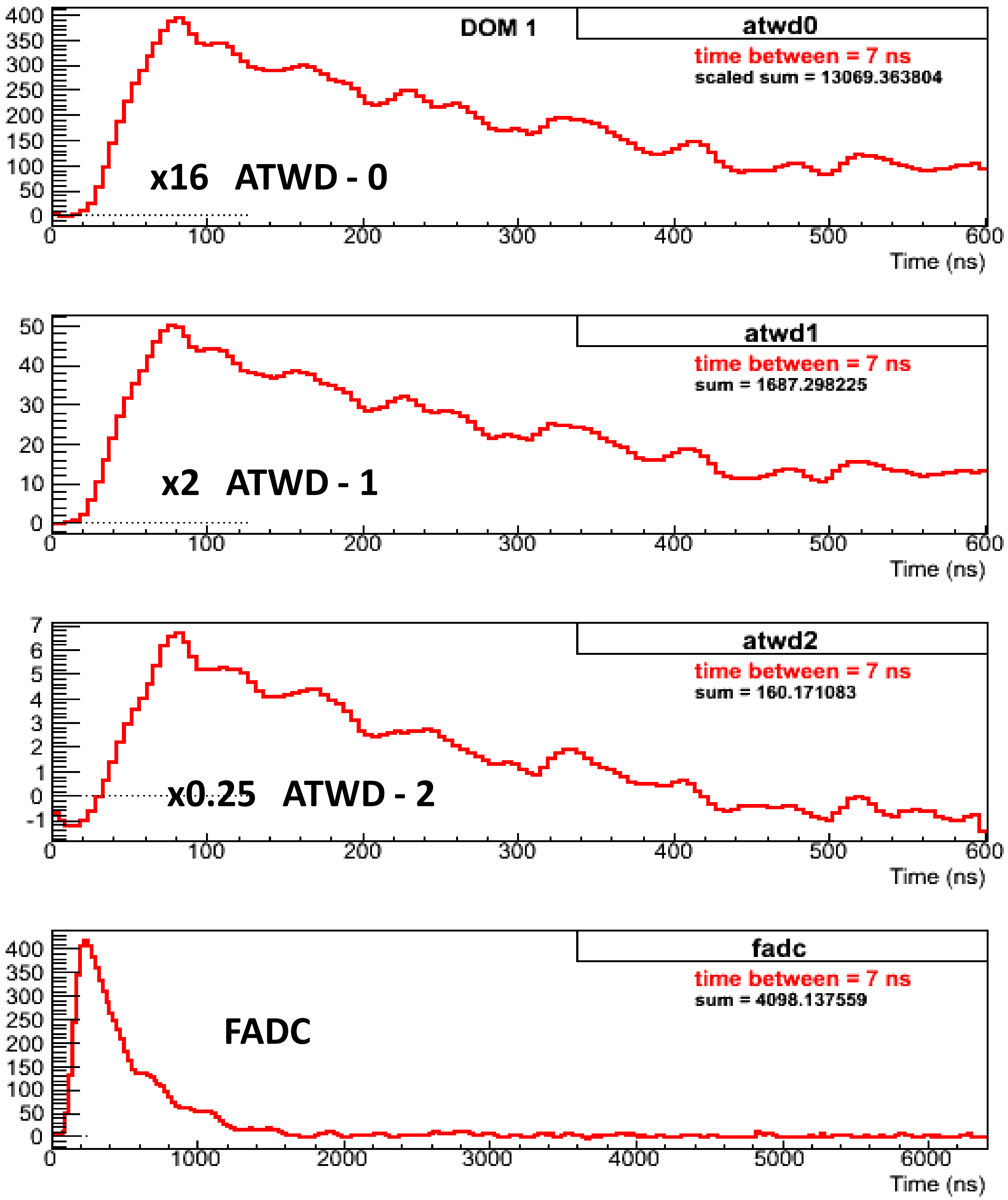




DM-Ice17 Livetime

- Data run since June 2011
- 99.75% uptime
- well known down times (power cycling, pedestal and dark noise runs)

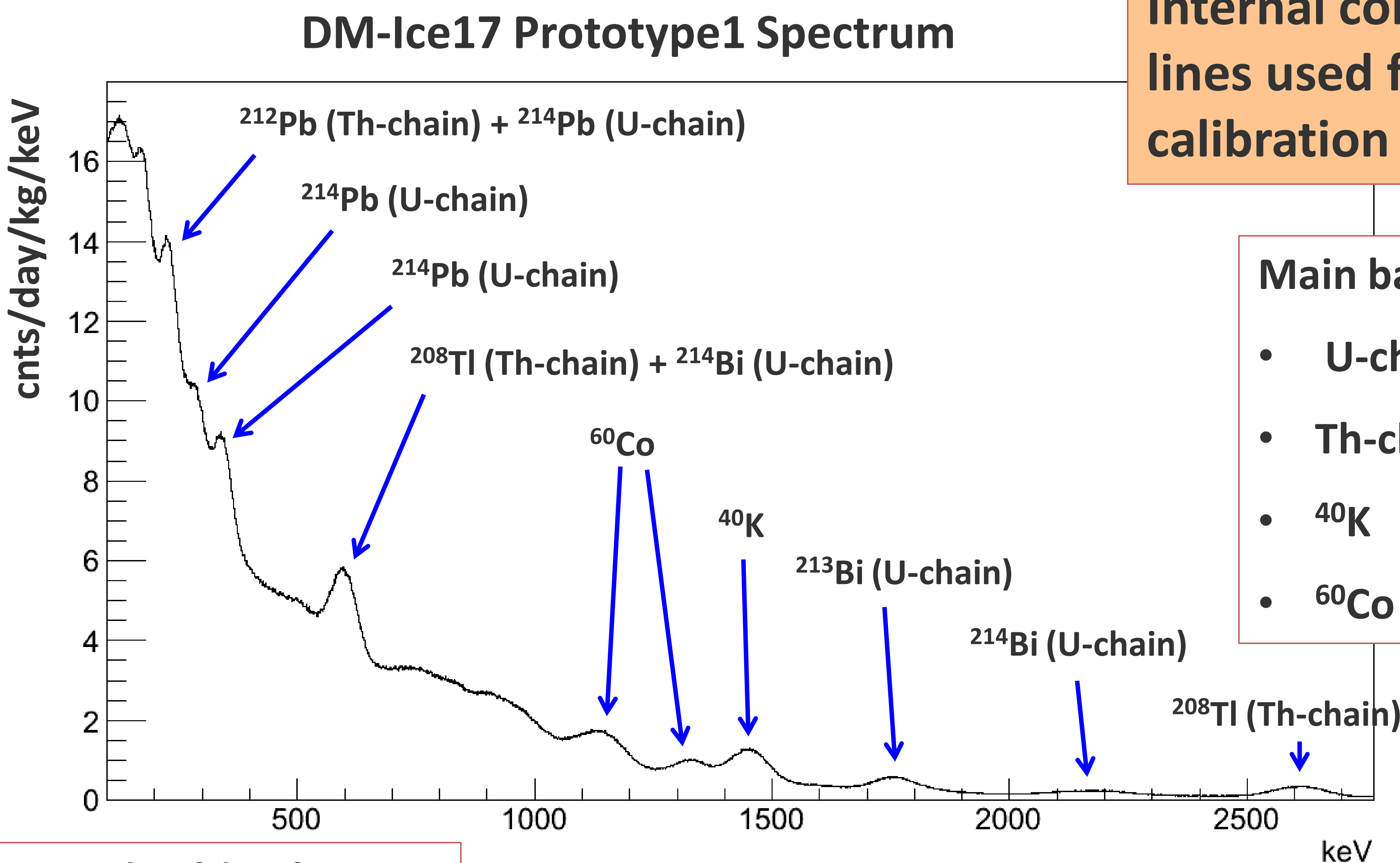
Signal Channels



- **4-channel output**
  - **Record each event passing coincidence between PMTs**
  - **ATWD = 14bits dynamic range**
- **Energy = sum over entire ATWD waveform**
  - **5-6 photoelectrons/keV**
  - **Sum over 600 ns**
  - **FADC currently does not resolve as well**
- **Stable data taking since June 2011**
  - **29.6 kg.yr of stable data to date**
  - **99.75% livetime**

Energy Spectrum: Gammas

Internal contamination lines used for calibration

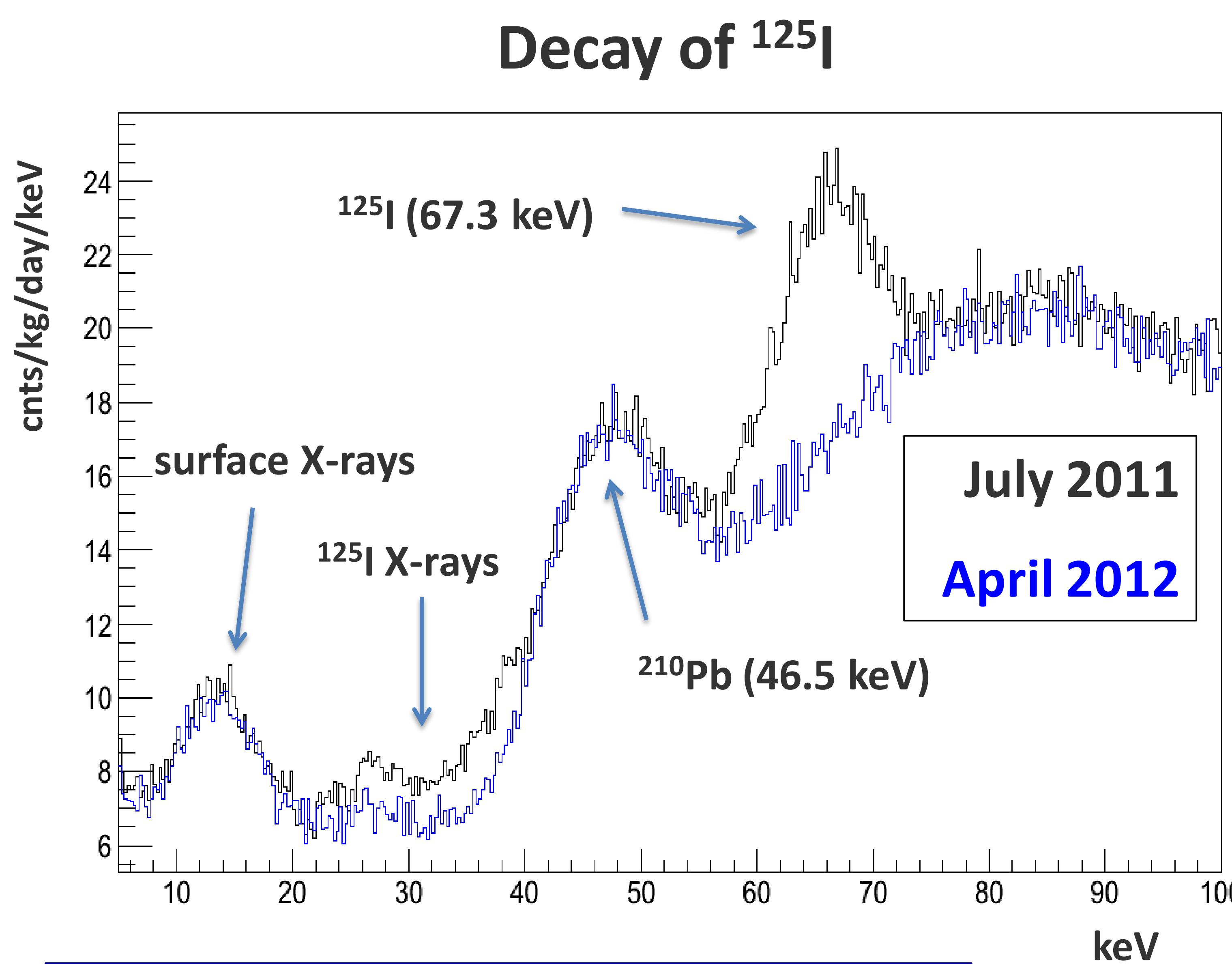


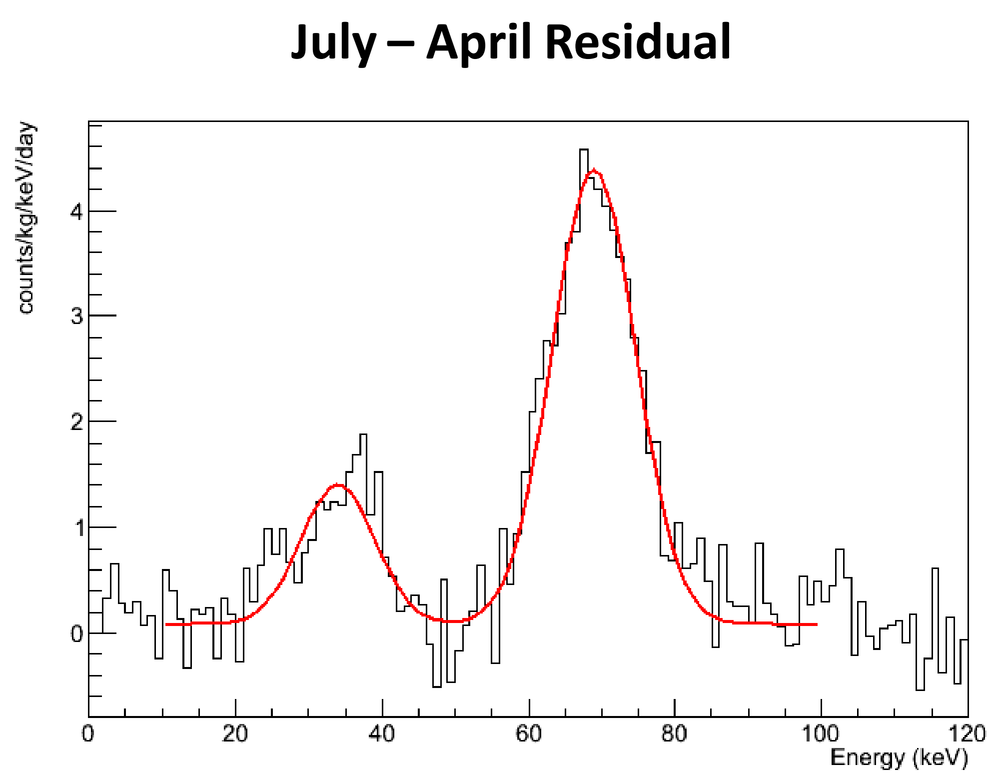
Main backgrounds:

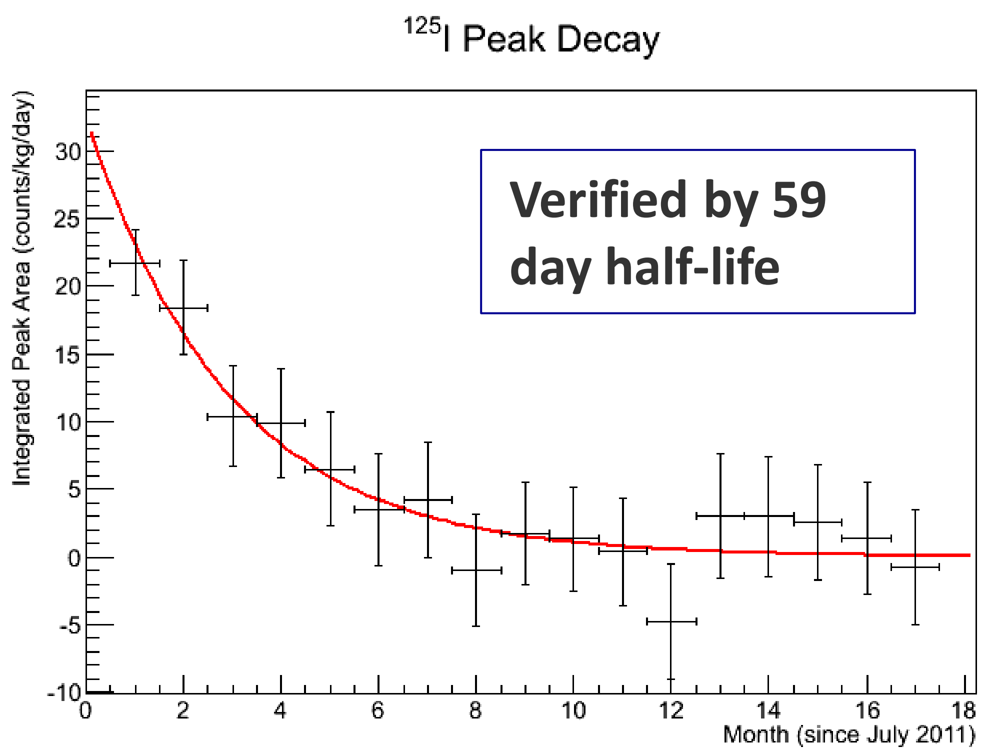
- U-chain
- Th-chain
- ^{40}K
- ^{60}Co

18 months of data from both PMTs on a single crystal

Cosmogenic ^{125}I (in the NaI crystal)

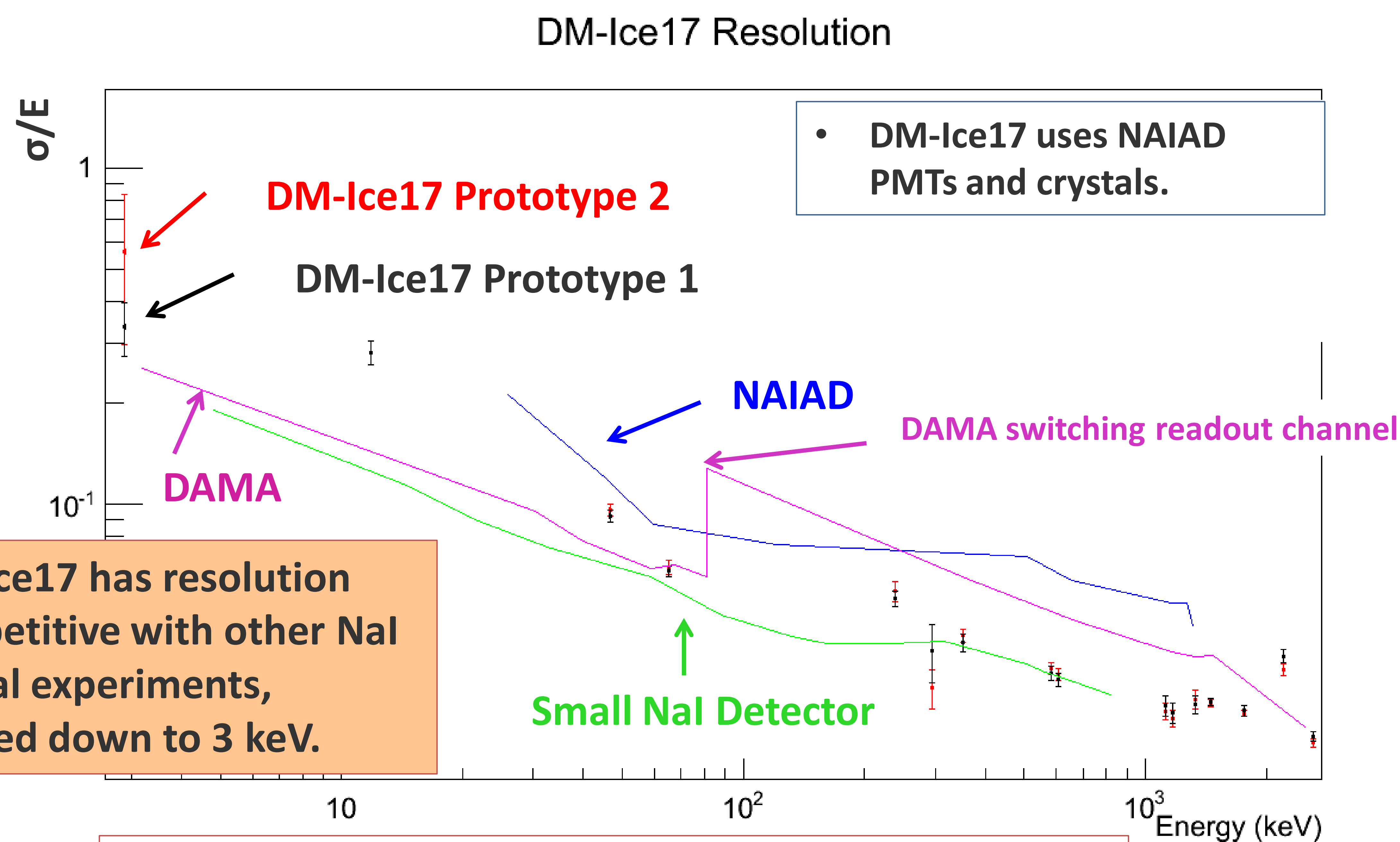






Cosmogenic lines verify our energy calibration; this is particularly useful for the prototype since we do not have an in-ice source.

Resolution of DM-Ice17



- DM-Ice17 uses NAIAD PMTs and crystals.

DM-Ice17 has resolution competitive with other NaI crystal experiments, studied down to 3 keV.

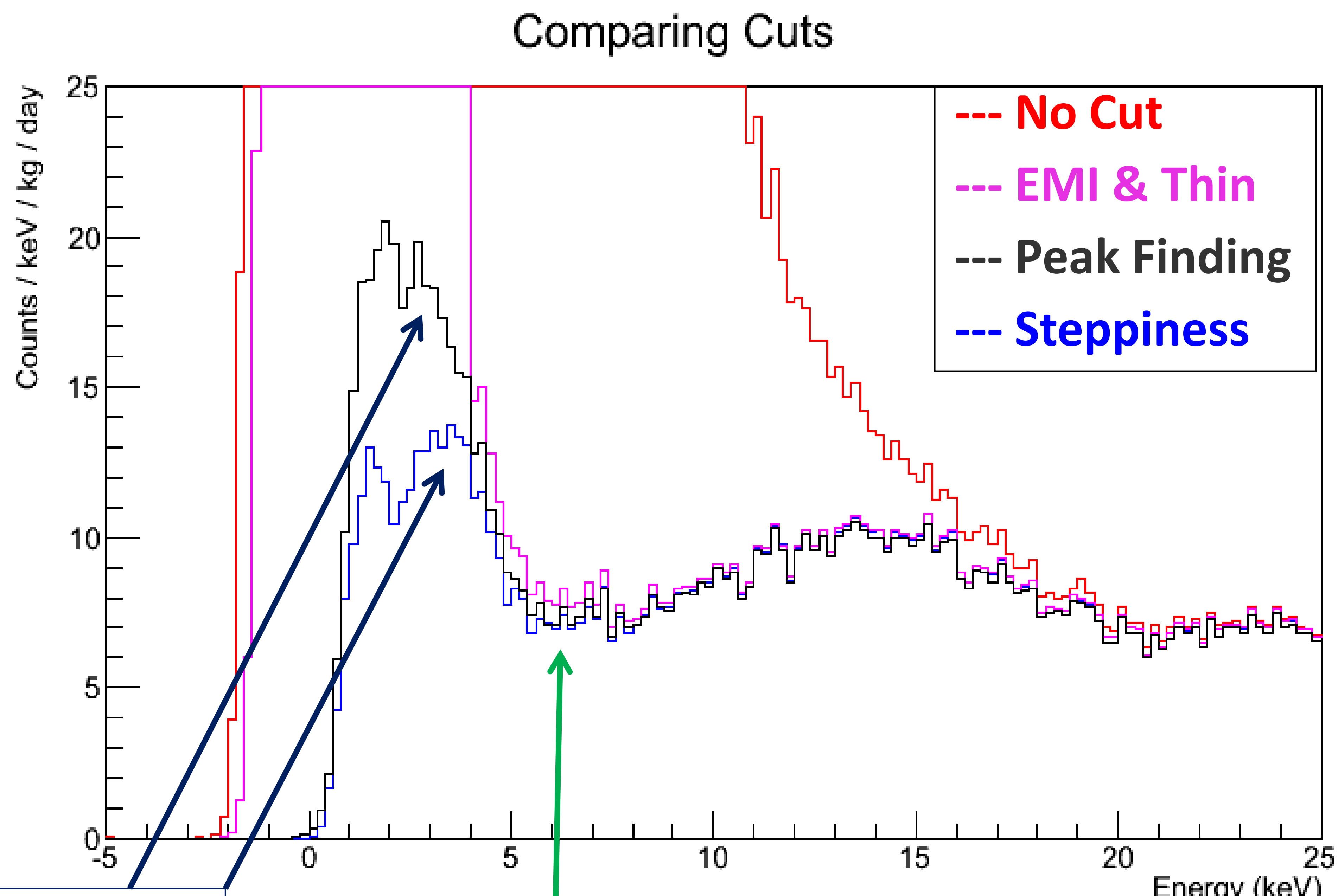
DM-Ice17: 1 month of data from both PMTs for each crystal.

Small NaI: E. Sakai, IEEE Transactions on Nuclear Science NS-34 (1987) 418.

NAIAD: The NAIAD experiment B. Ahmed et al, Astropart. Phys. 19 (2003) 691.

DAMA: R. Bernabei et al., Nucl. Instrum. Methods A 592 (2008) 297.

3 keV ^{40}K Peak



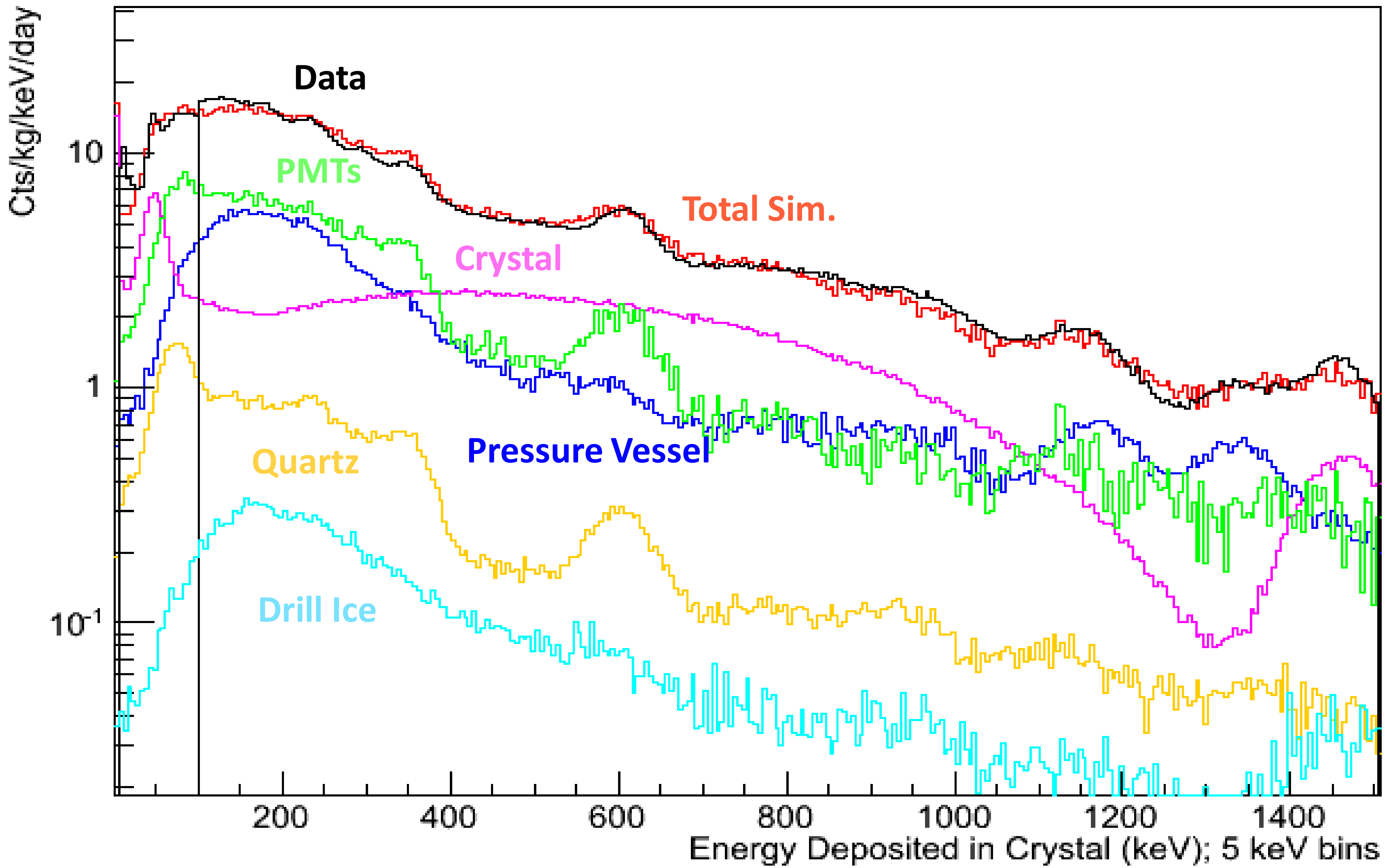
We understand our spectrum well down to 4 keV.

Below 4 keV, we are capable of revealing the ^{40}K peak despite the difficulties of single crystal analysis.

At 6 keV we see 7.2 ± 0.4 cpd/kg/keV. Simulations for the full scale DM-Ice give 1-2 cpd/kg/keV @ 5 keV (not including multi-crystal "hit" rejection)

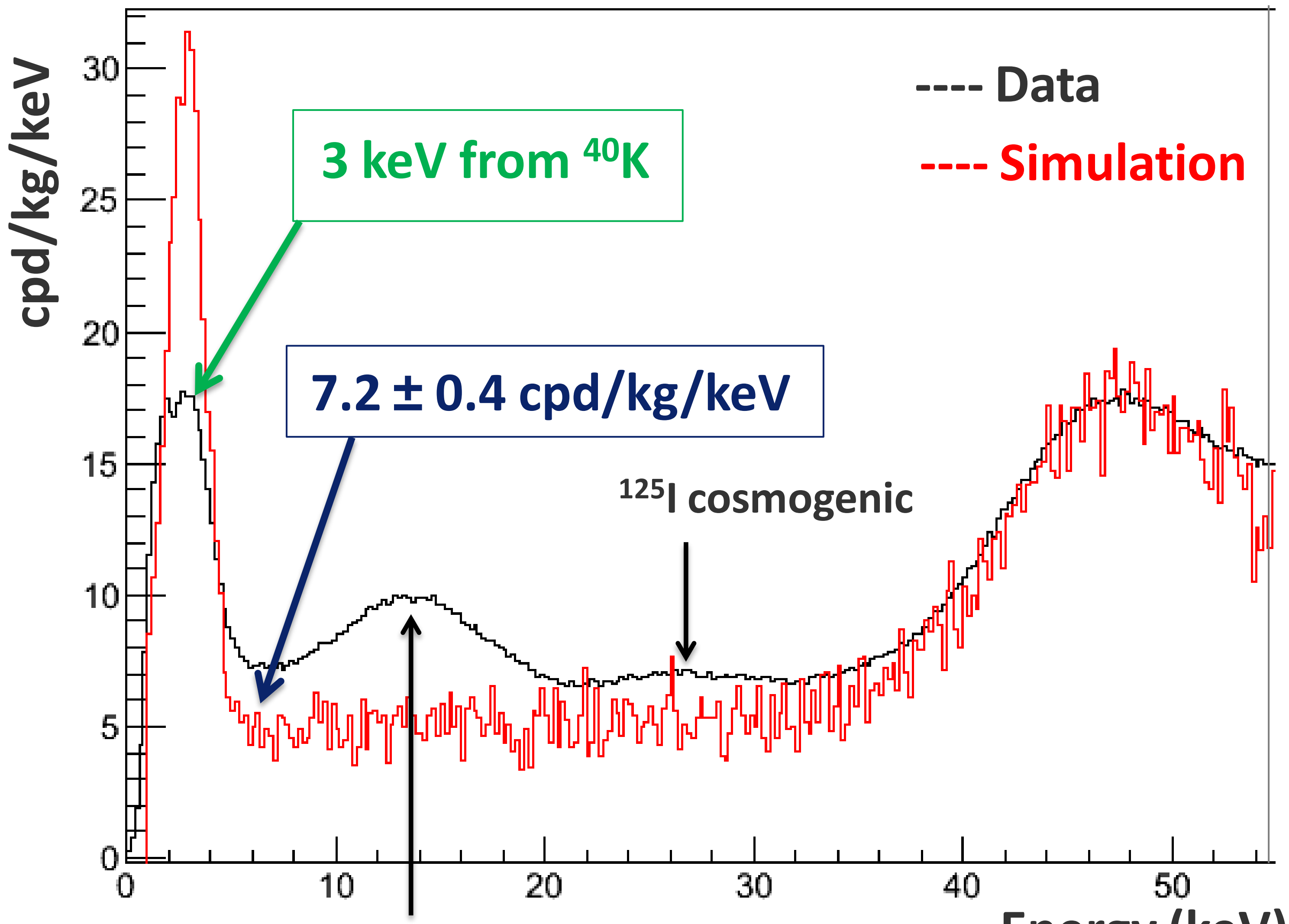
Background Model

All components measured/estimated and simulated



Region of Interest

18 months of data from both PMTs on a single crystal



^{210}Pb surface event; simulation in progress

- Good agreement with simulation above 20 keV
  - Surface event simulation at 12 keV in progress
- We understand our detector to 4 keV
  - NAIAD published to 4 keV; we are pushing lower
- We model our 3 keV peak to within a factor of 2 of simulation
  - Understanding efficiencies <3 keV in progress

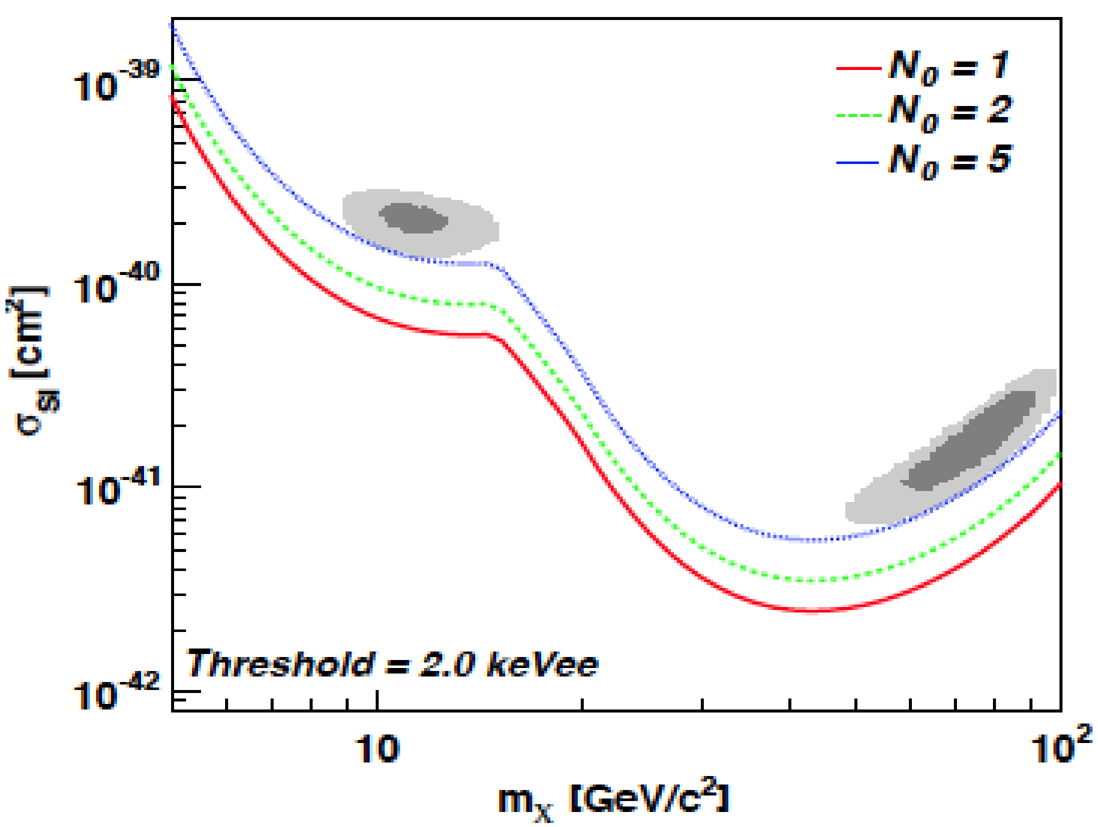
Looking ahead:

- **Backgrounds in ROI 5x higher than simulated for full scale DM-Ice**
- **Multi-crystal veto will suppress 3 keV events**

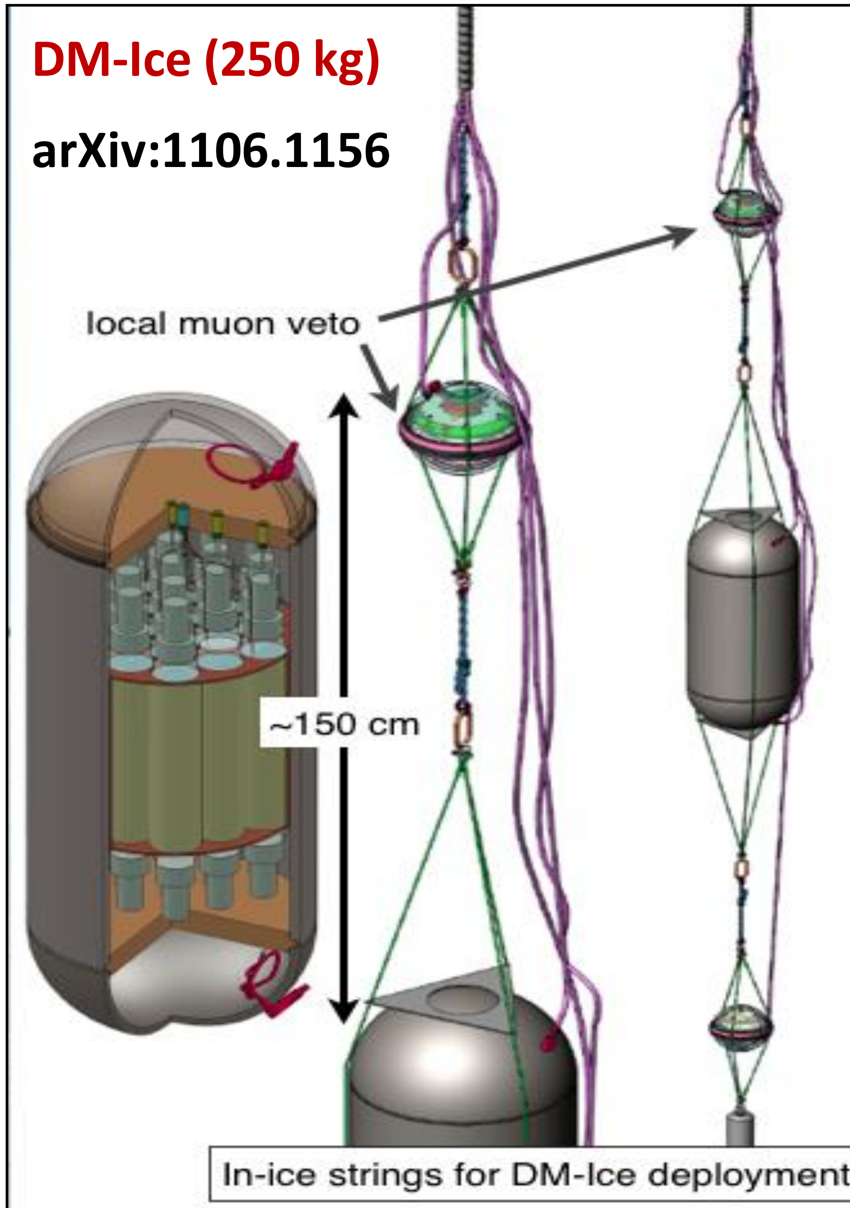
Conclusions:

- successfully deployed two detectors 2450 meters in the ice
- incredibly stable environment
- calibration from internal/external backgrounds (no calib sources)
- Geant4 background model in agreement with data
- good understanding down to 4 keV (~ 7 cpd/kg/keV)
- pushing our energy threshold < 2 keV

DM-Ice Sensitivity
500 kg•yr NaI
(2 - 4 keV) with 1, 2, and 5 dru bkg



DM-Ice (250 kg)
arXiv:1106.1156



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Lauren Hsu

DigiPen

Charles Duba, Eric Mohrmann

Boulby Underground Science Facility

Sean Paling

SNOLAB

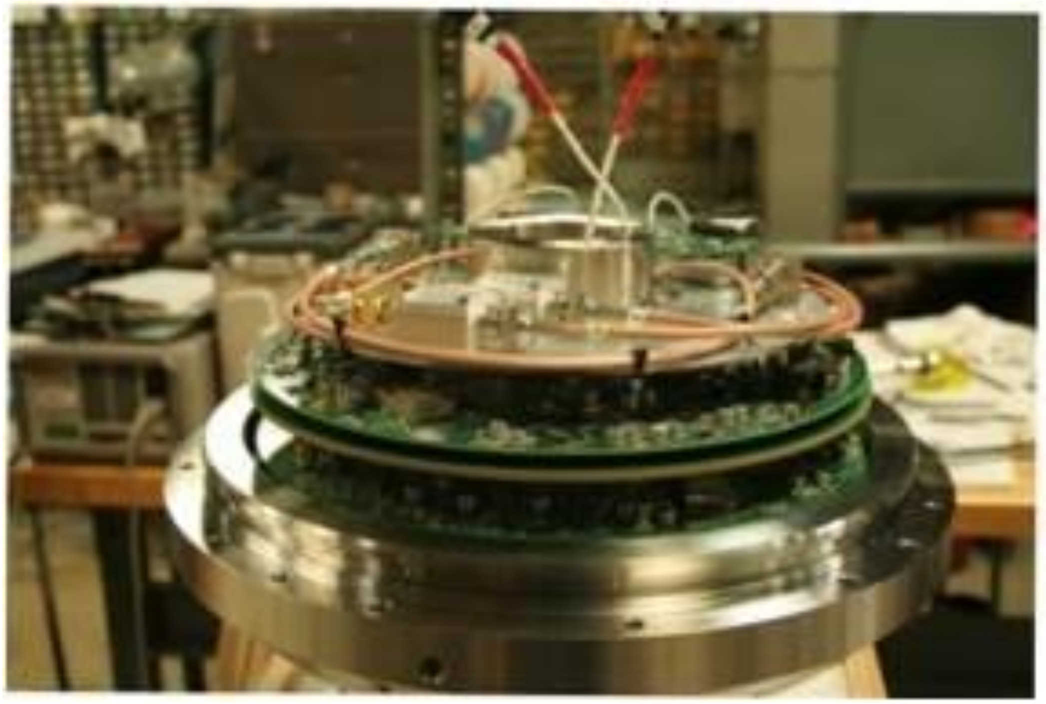
Bruce Cleveland

NSF ANT-1046816

PHY-1151795

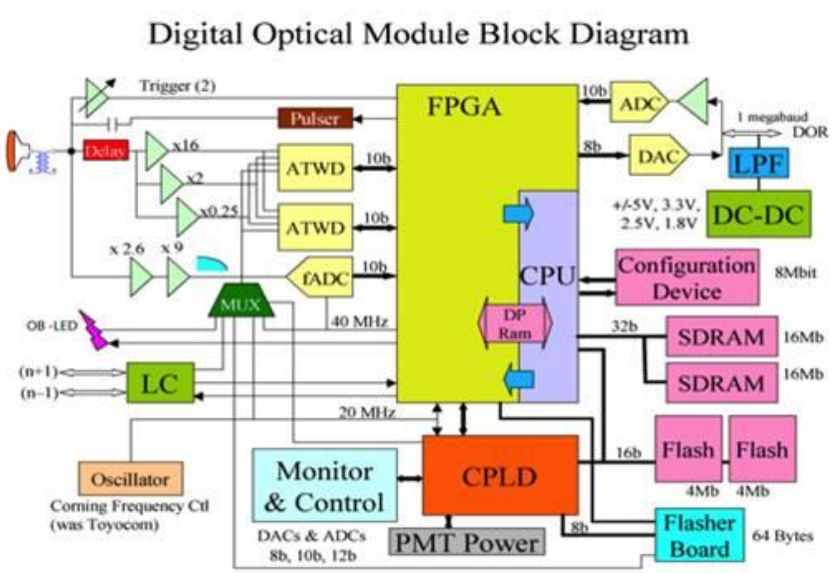
BACKUP SLIDES

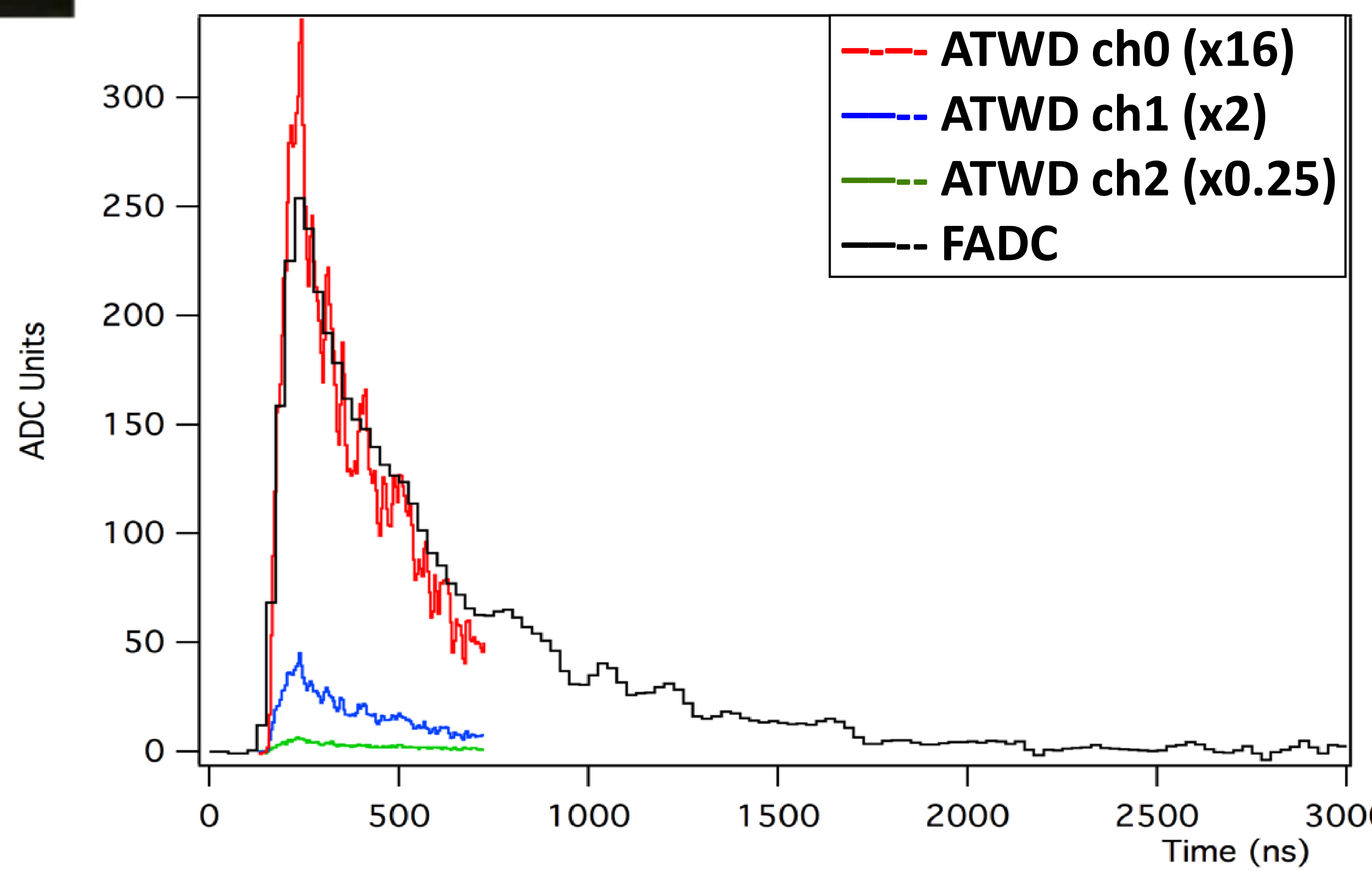
Data Acquisition and Digitizing



PMT thresholds	~ 0.3 PE
Coincidence requirement	< 800 ns
FADC (@ 40 MHz)	255 bins = 6.375 us
ATWD (@ 200 MHz)	128 bins = 600 ns
PMT Trigger Rate	100-150 Hz
Coincidence Trigger Rate	~ 4 Hz

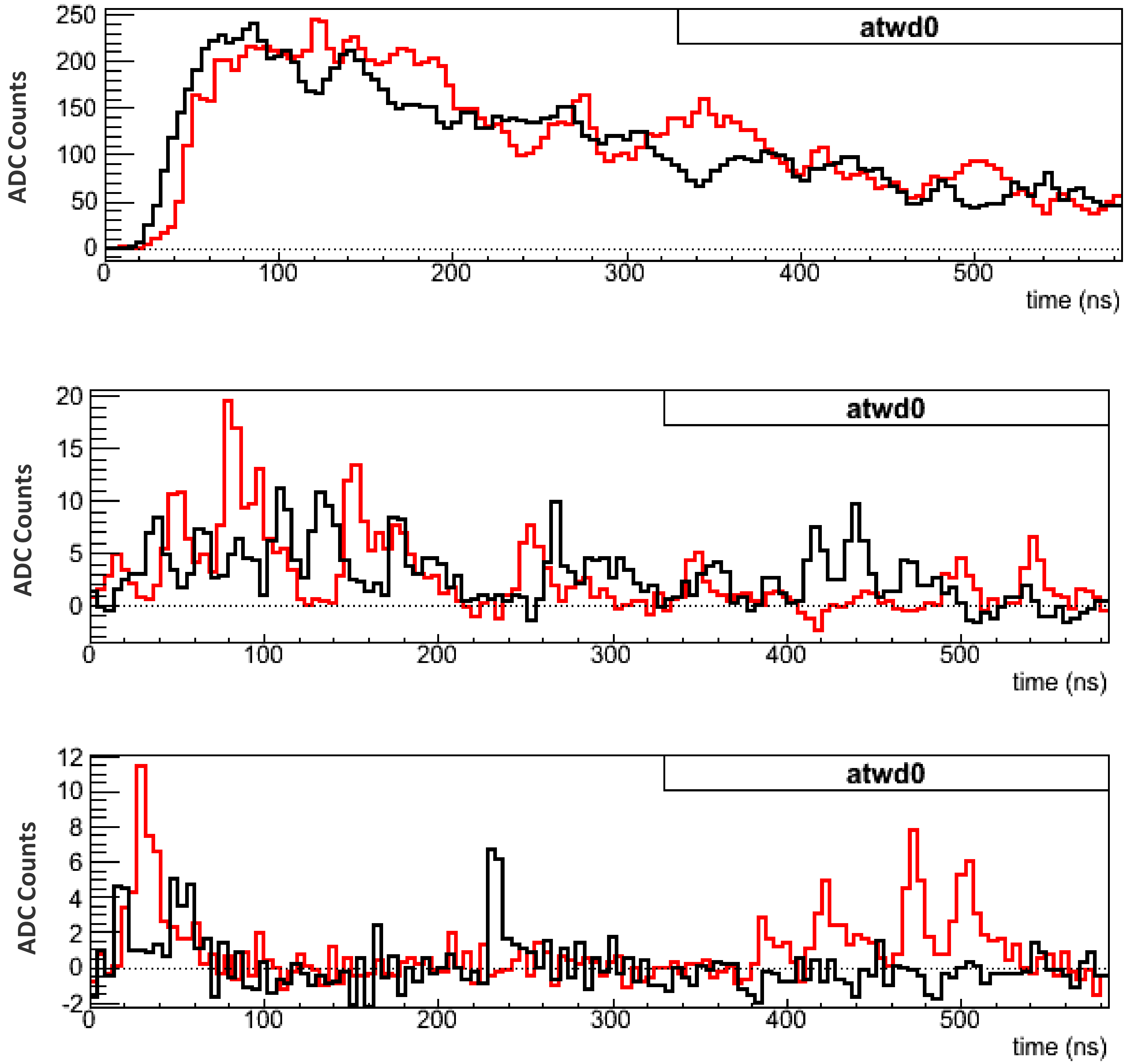
- IceCube mainboards
- Thoroughly engineered and tested
- Slightly modified for DM-Ice



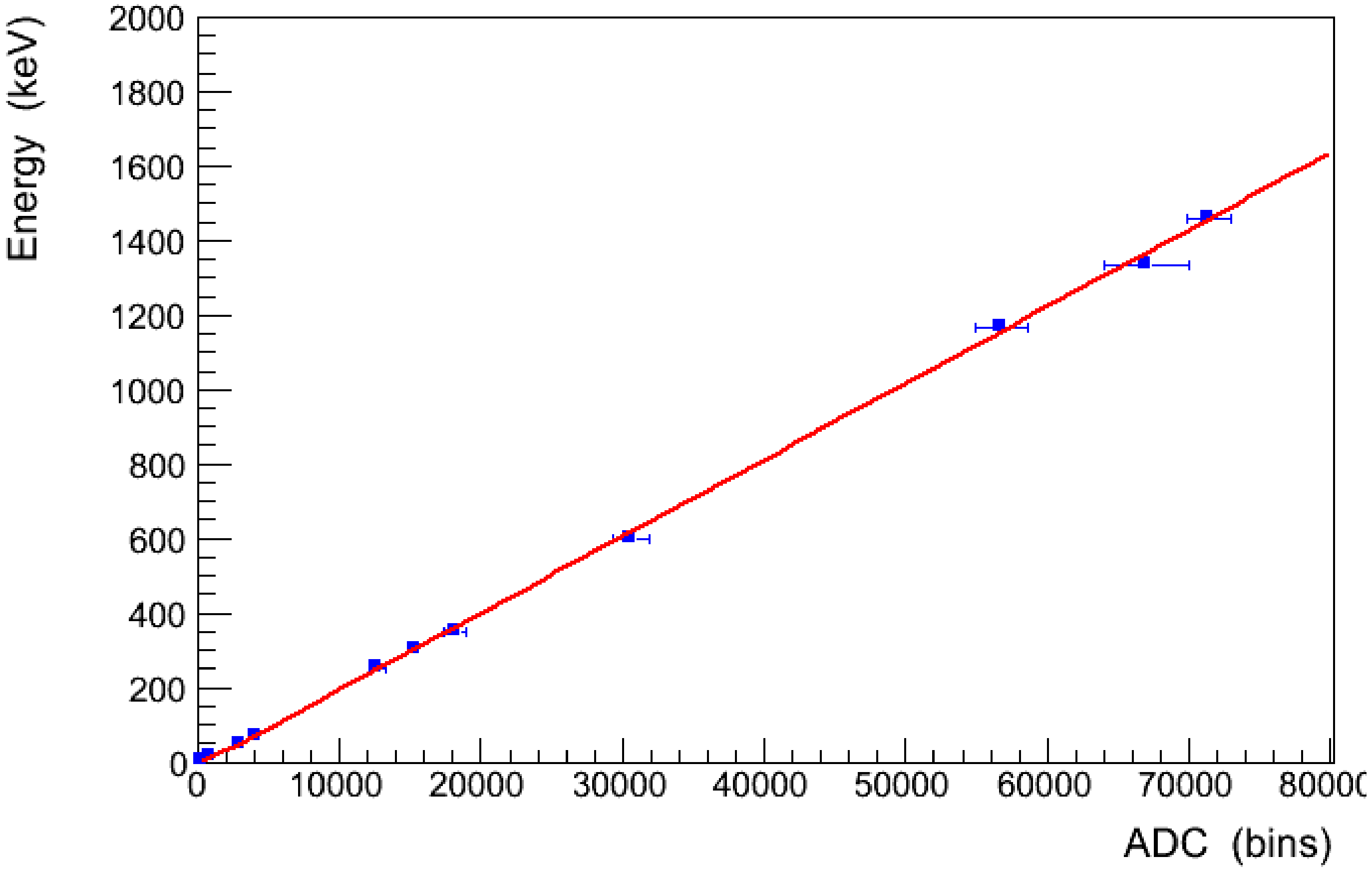


Scintillation Events

- Signal comes from scintillation in the crystal.
- Coincidence required between the two attached PMTs (800 ns).
- At high energies, signal has the characteristic scintillation pulse shape.
- At low energies, increasingly events are just a series of single photo-electrons.

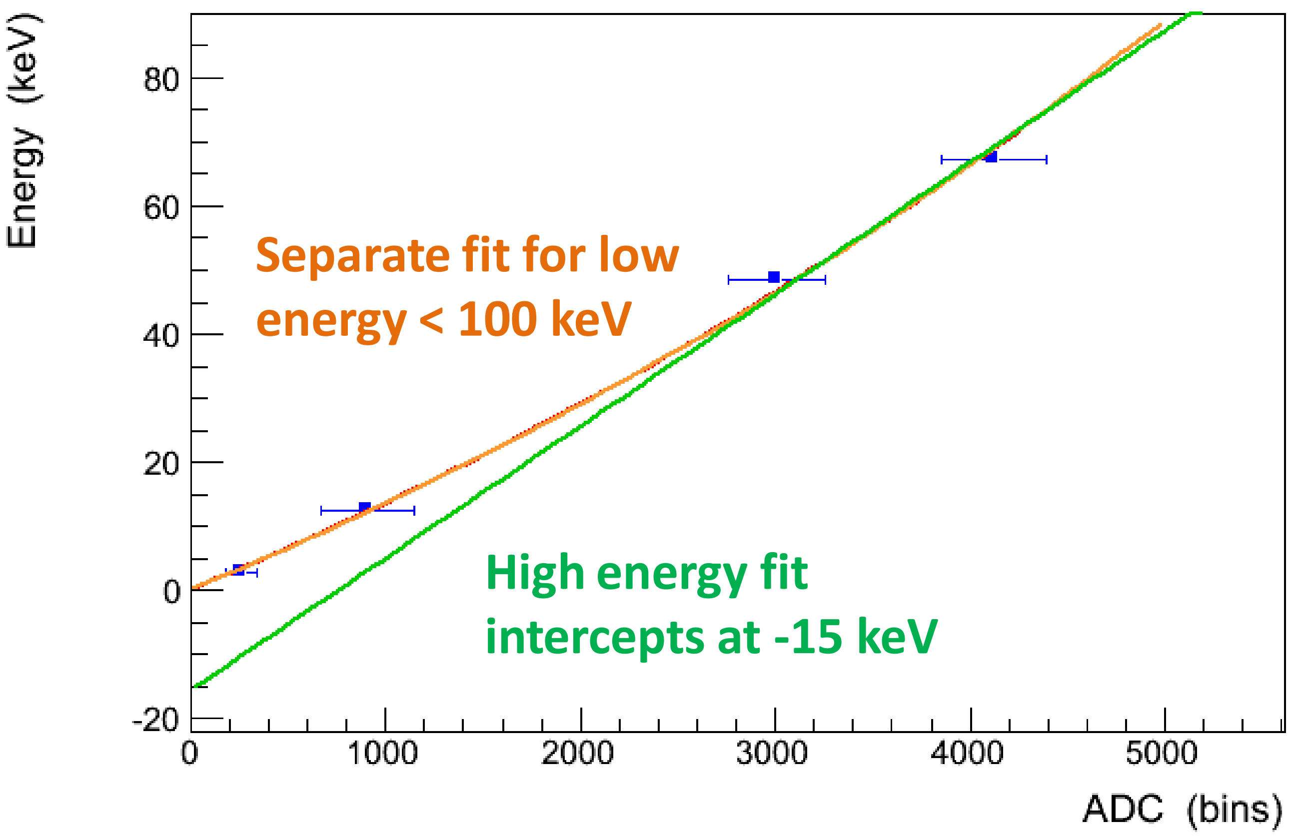


Energy Calibration



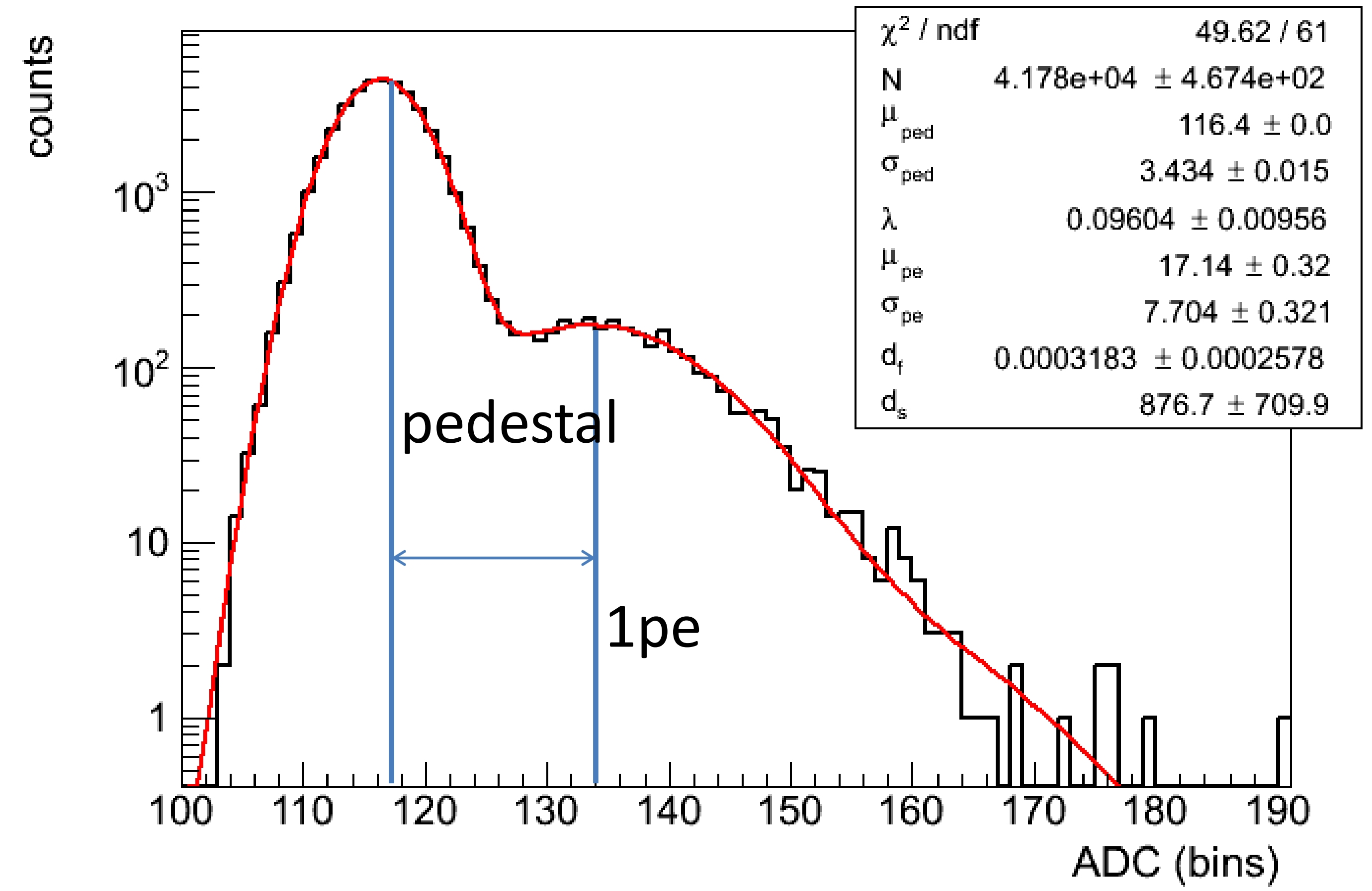
- **High energy fit (> 100 keV) is linear**
- **Low energy fit (< 100 keV) deviates from linearity**

As observed in other literature:
- **Rev.Sci.Inst. 27, 589 (1956)**
- **Nuc.Inst.Meth. 15, 55-58 (1962)**
- **J.Appl.Phys. 107, 113513 (2010)**



NaI Light Yield

- Obtain 1pe-ped separation from dark noise runs (ie no coincidence requirement)
- Normalize the energy to keV using the energy calibration

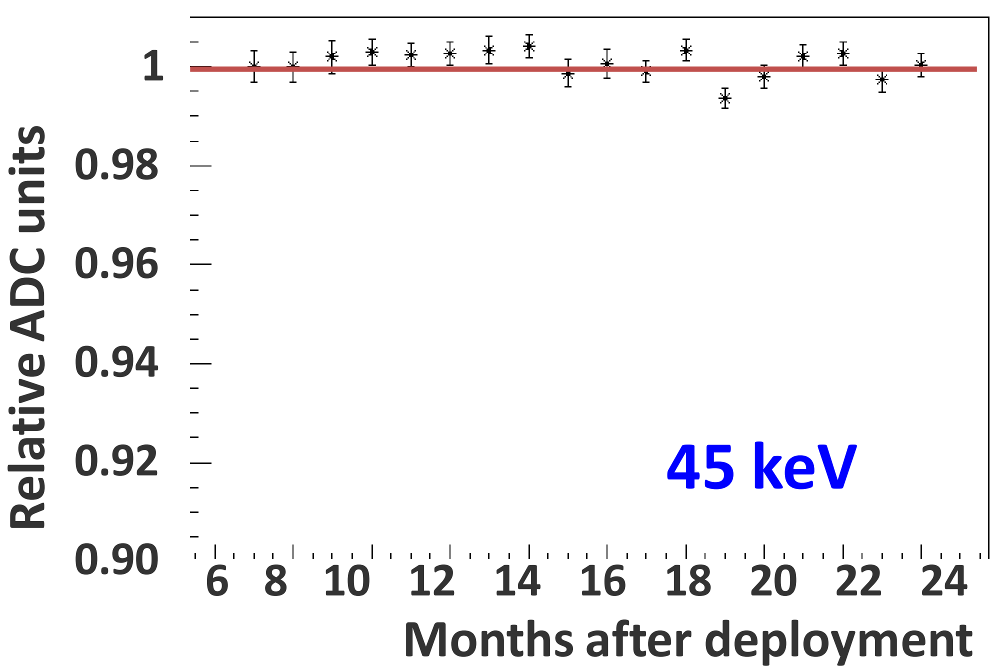


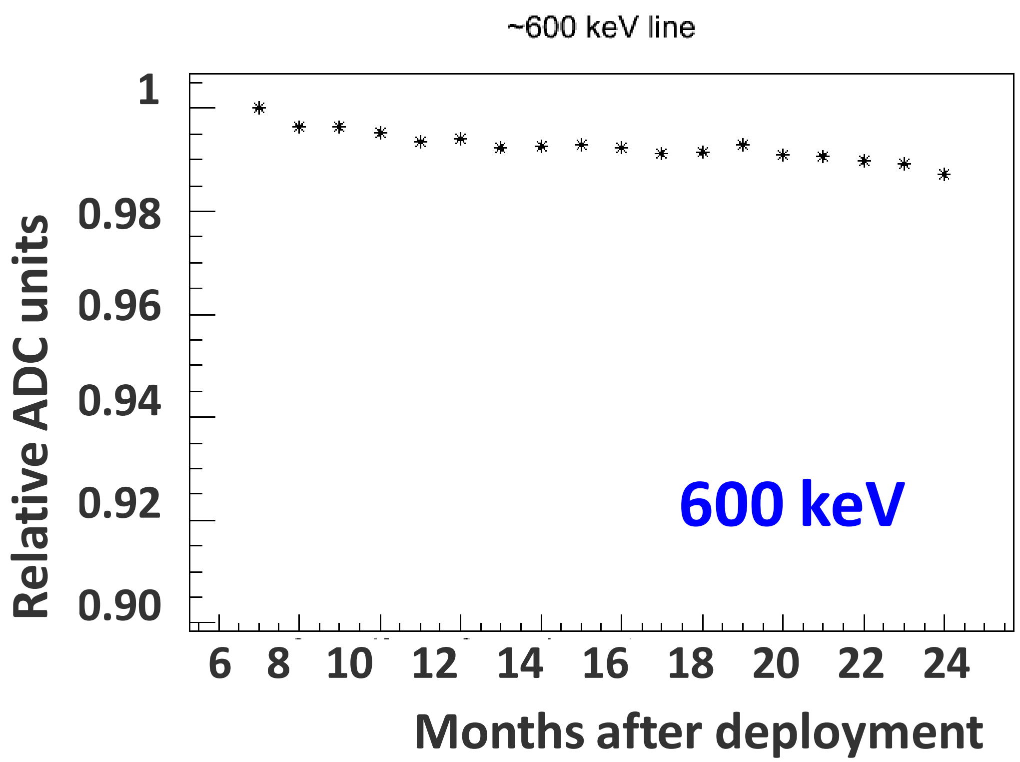
xtal-1 = 6.1 +/- 0.07 pe/keV
xtal-2 = 4.9 +/- 0.05 pe/keV

Consistent with:
- **DAMA = 5.5 – 7.5 pe/keV**
- **NaiAD = 5 – 8 pe/keV**

Detector Stability

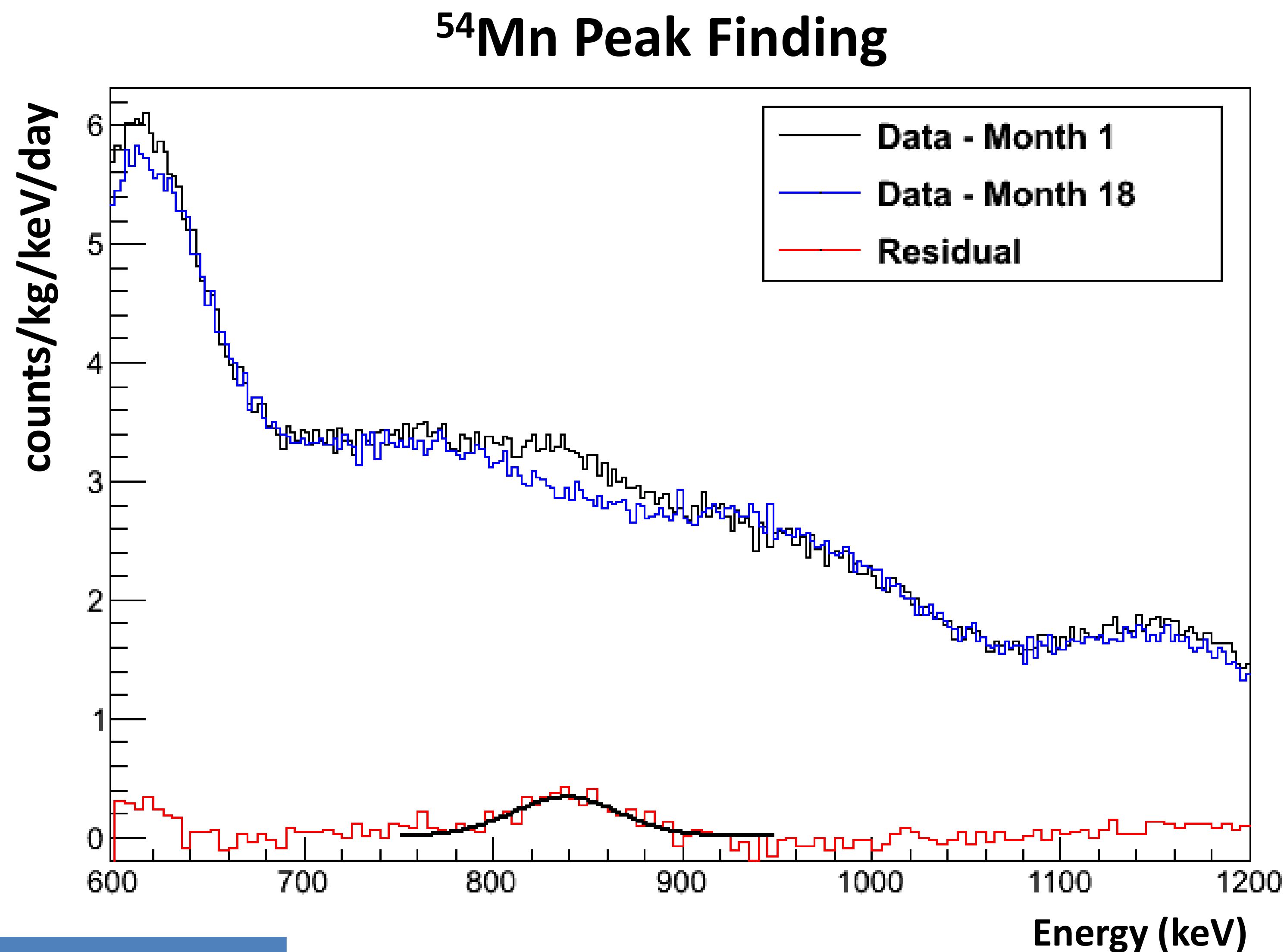
- Detector calibration is stable to 1.3% over 18 months.
  - 1.3% decrease over 18 months in light collection (peak position) observed at 600 and 1460 keV
  - No observable change in calibration at 45 keV
  - We have not had to change our calibration with time
    - Any changes at higher energies are smaller than our resolution





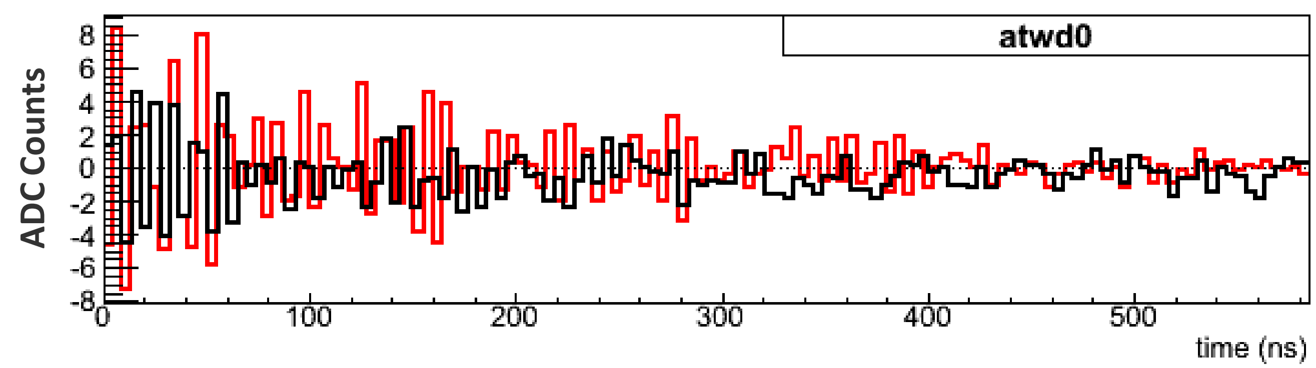
Cosmogenic ^{54}Mn (in the steel)

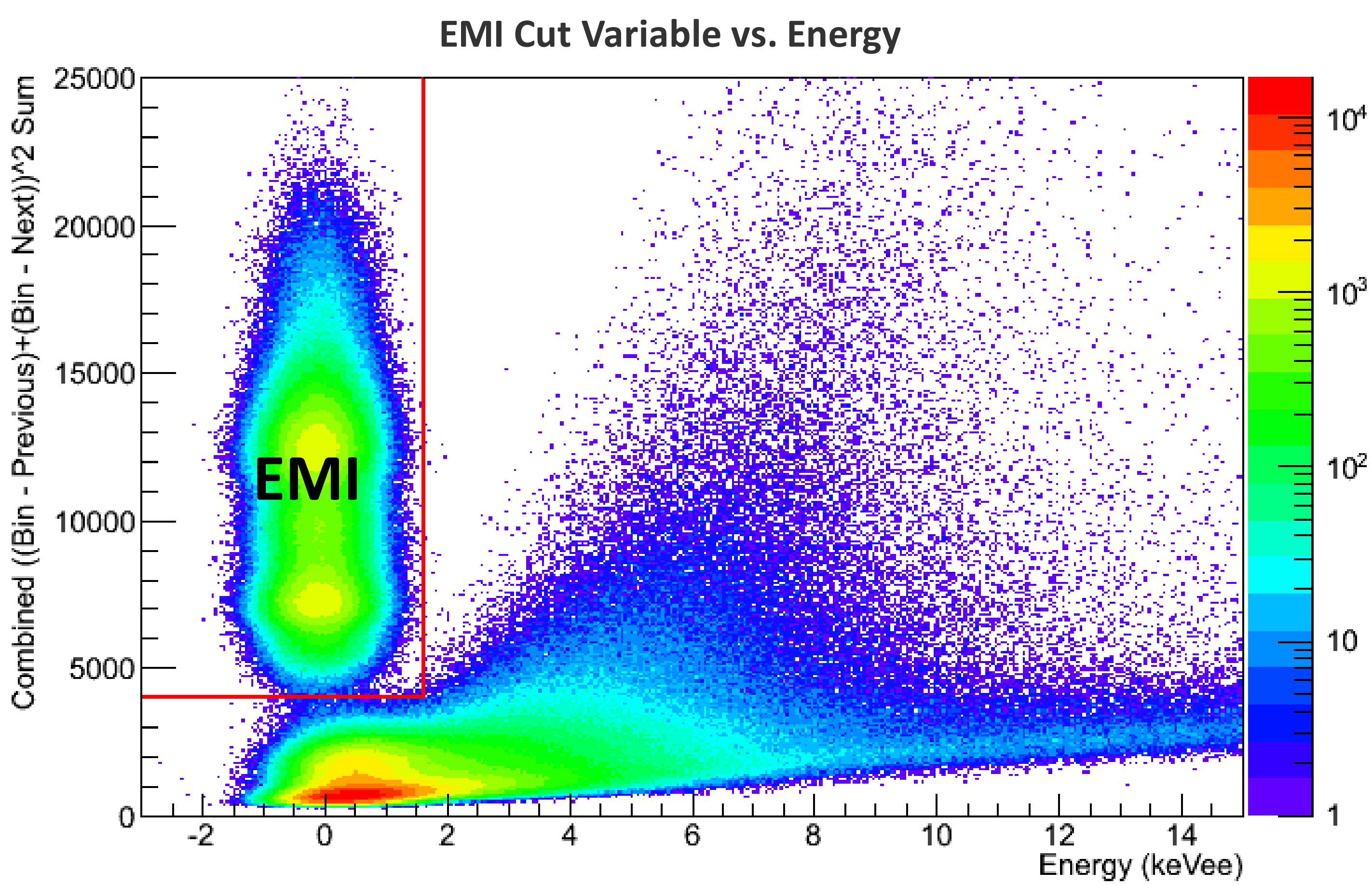
- gamma expected from ^{54}Mn
  - E_γ = 835 keV
  - $t_{1/2}$ = 312.03 days



	Fit	Expectation
Energy (keV)	836.1 ± 3.0	834.8
Sigma (keV)	36.9 ± 3.7	23.3
Deploy Rate (decays/day)	51,700 ± 6,500	135,800

EM Interference (EMI) Events

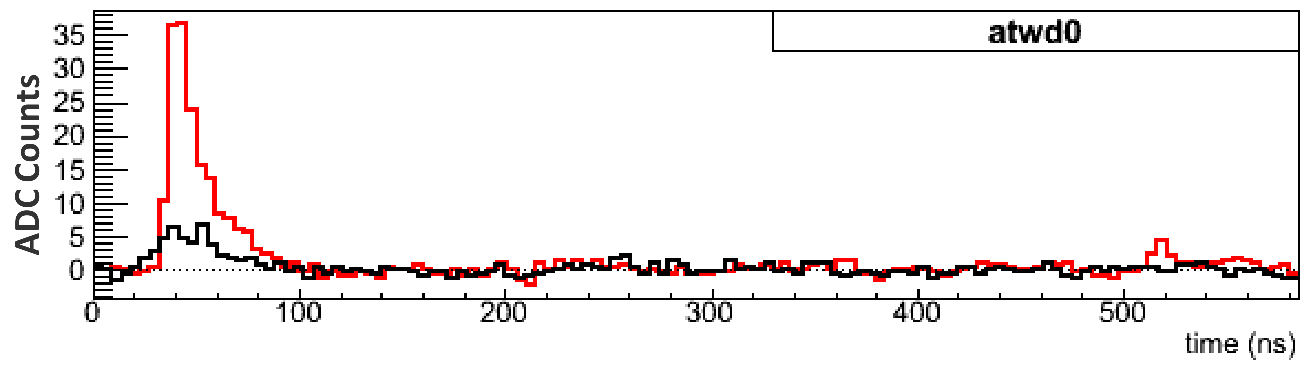


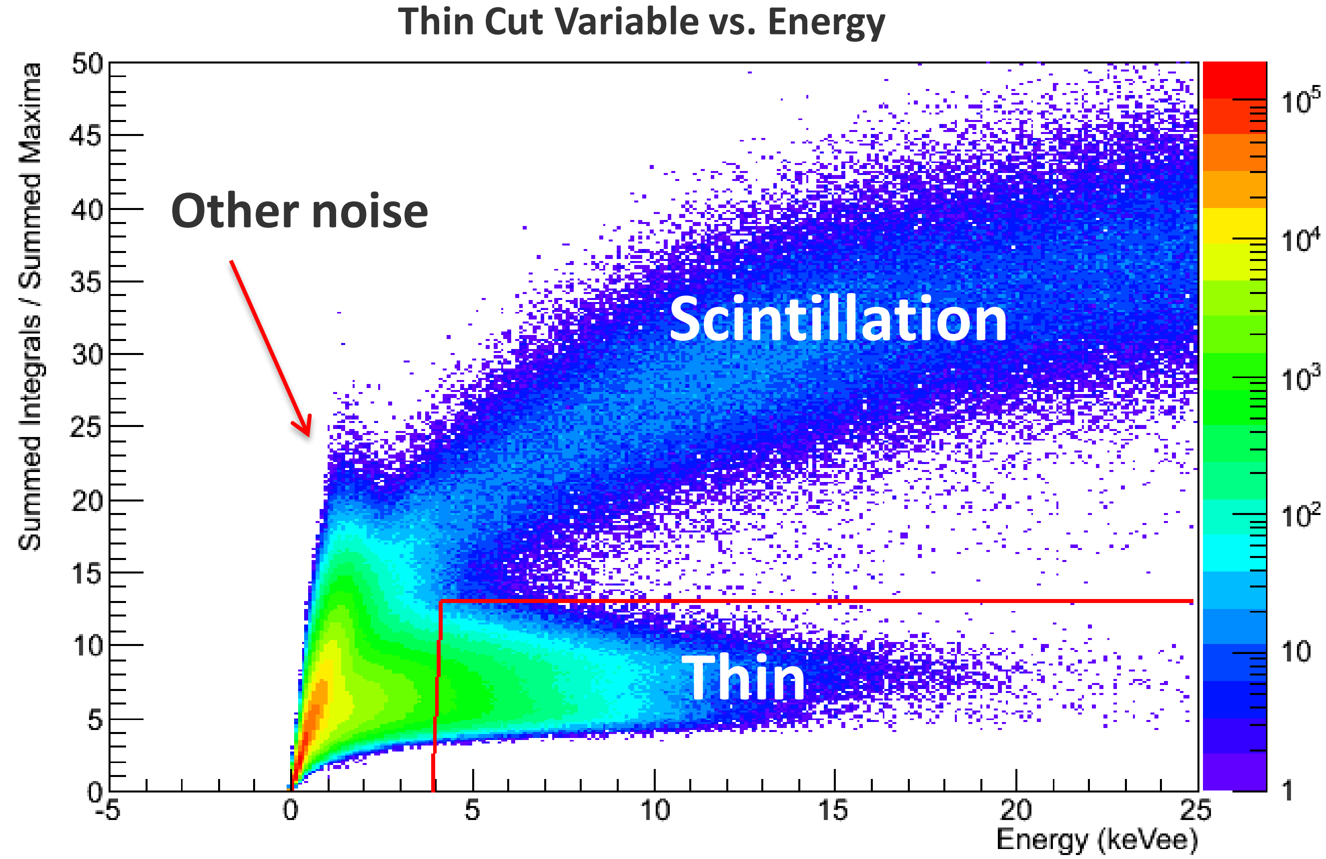


- **Electromagnetic interference caused by the hardware monitoring can trigger the detector.**
- **Monitoring reduced from every ~2 seconds to every ~60 seconds in March 2013 to reduce this event rate.**
- **This change reduced EMI events from 21% of all events to 0.9% of all events in prototype 1.**
- **Current cut variable relies on 'spikiness' of waveform :**
  - **Sum(((next – bin) – (bin – previous)) ^2)**

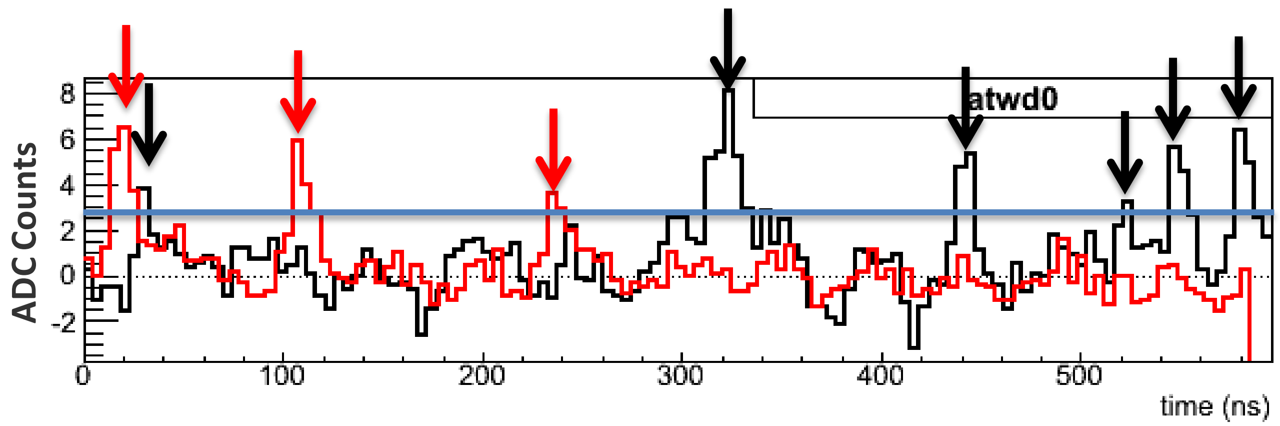
“Thin Pulse” Events

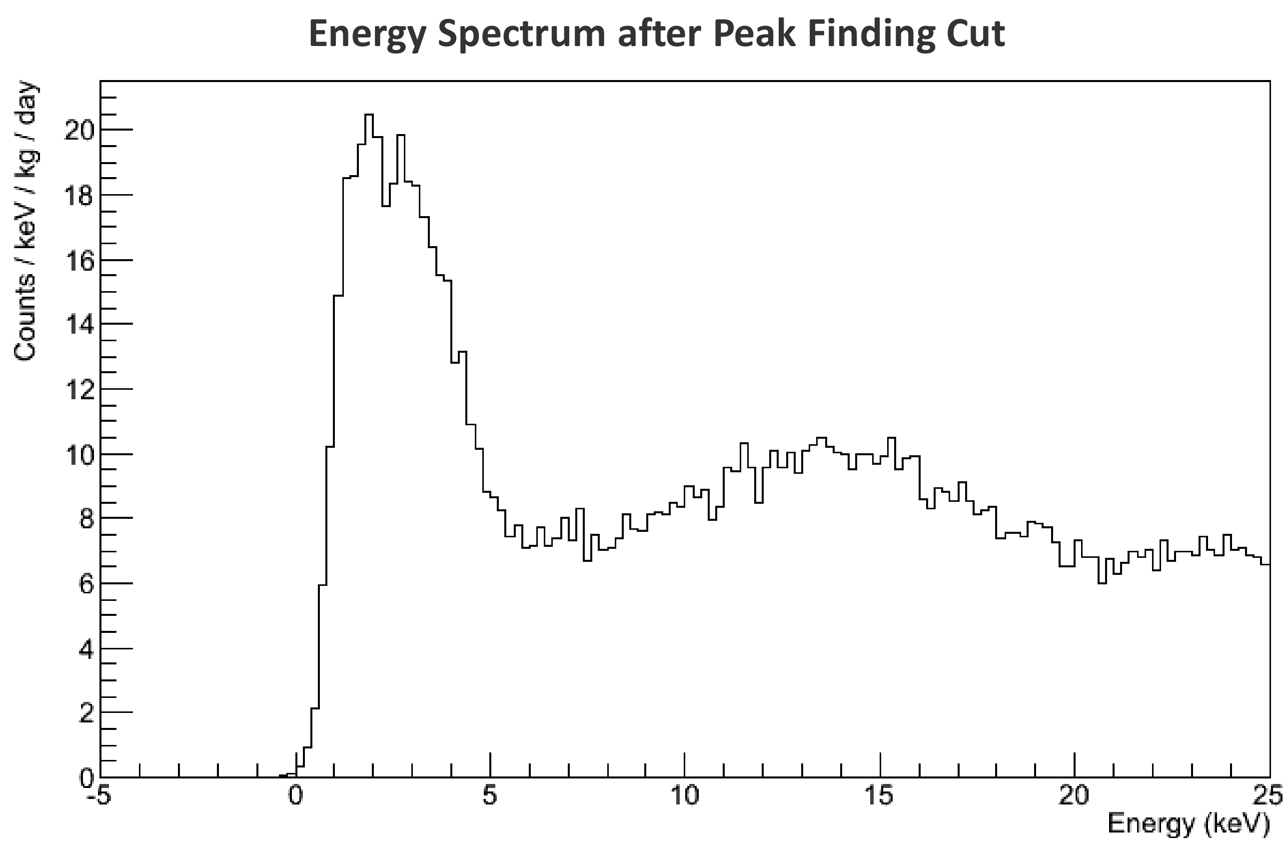
- **Interactions within the light guides and/or PMTs can also trigger the detector.**
- **These events are referred to as thin events due to their characteristic pulse shape.**
- **Current cut variable :**
  - **Pulse Integral / Pulse Maximum**
- **Current cut value chosen to preserve 75% of signal with a signal to noise ratio > 10 in cut region.**
- **Current Energy Threshold : 4 keV**





Peak Finding Cut (Dm-Ice Madison)

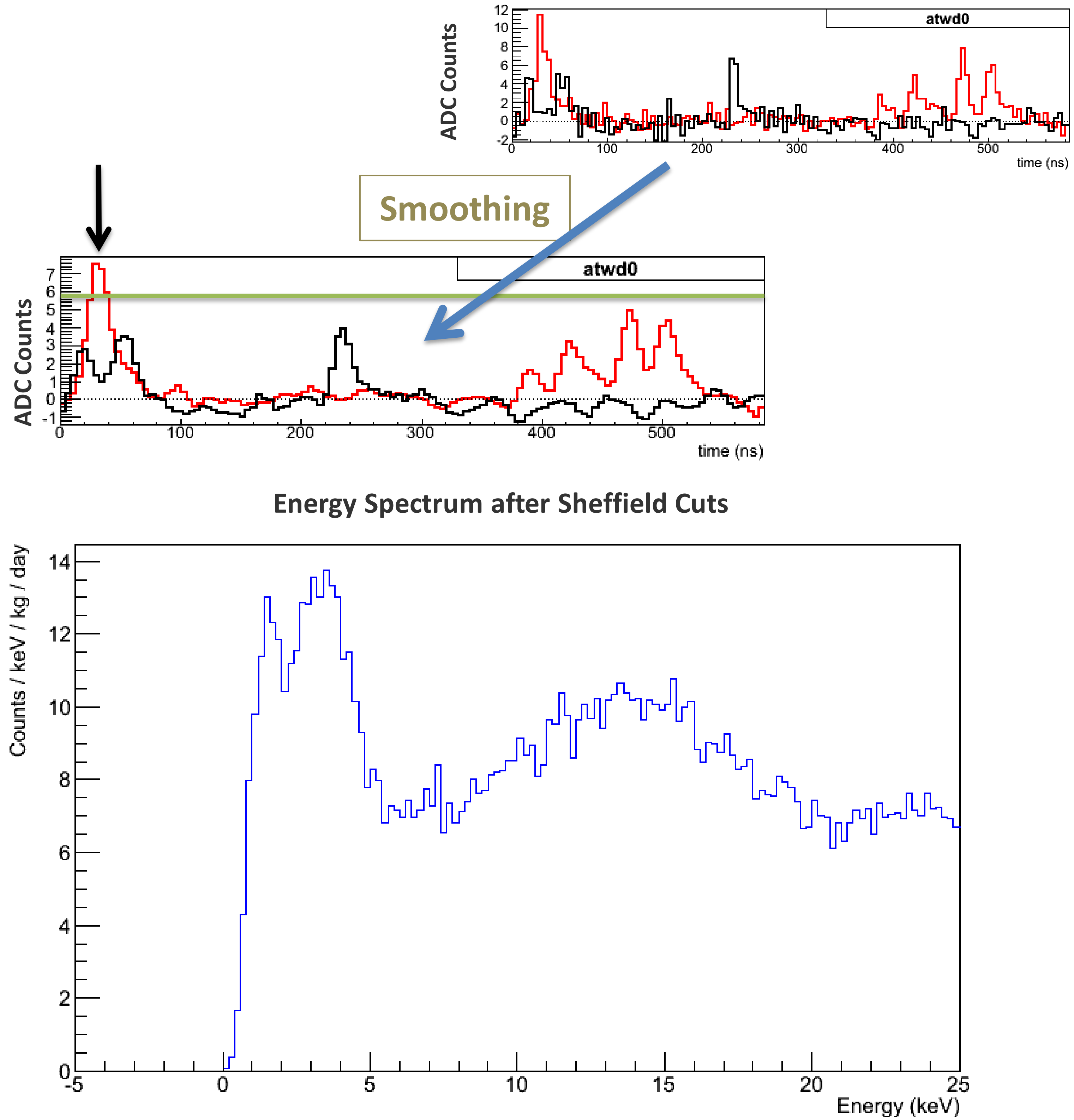




- **"Peak Finding" in theory counts the number of photoelectrons in each PMT.**
- **In practice, a simple peak finding algorithm is used to count local maxima above a threshold.**
- **Cut Requirement : Each PMT sees >4 peaks**

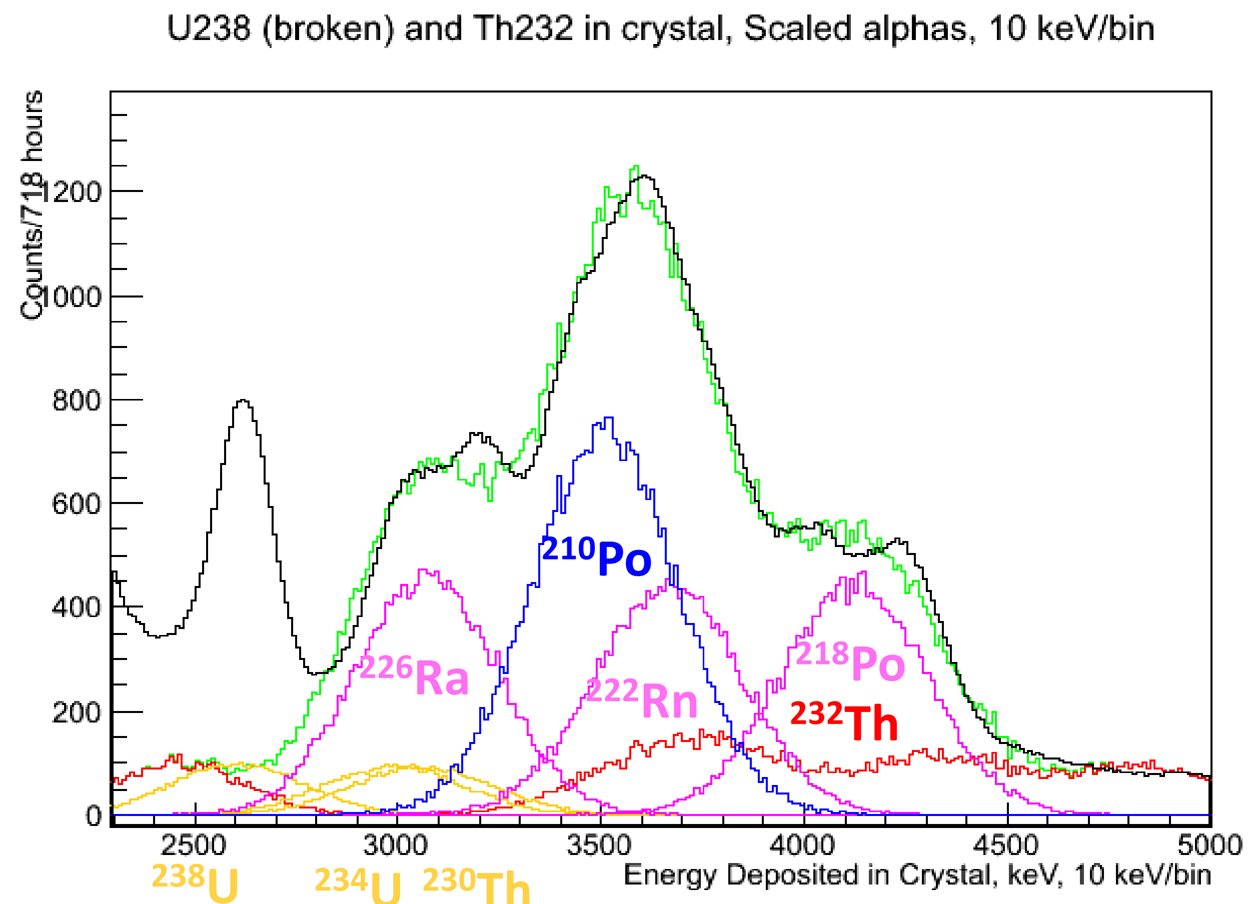
Steppiness Cut (DM-Ice Sheffield, UK)

- Steppiness in essence requires multiple SPEs to occur in quick succession in at least one PMT.
- This is achieved by requiring a smoothed waveform to break a threshold.
- Steppiness is not a good cut of thin pulses so a series of cuts is required to remove them.
  - Energy symmetry between the two PMTs
  - Mean time symmetry between the two PMTs
  - Mean time
  - Tail energy fraction



Internal Crystal Contamination

- Internal ^{238}U and ^{232}Th contamination in our crystal is estimated by looking at the alpha region
- Matching simulation to data yields this estimate
- ^{238}U chain is out of equilibrium
- Alpha quenching is similar to that seen by DAMA



Alpha Quenching

DM-Ice17: $\alpha/\gamma = 0.50 + 0.0245 * E_\alpha(\text{MeV})$

DAMA: $\alpha/\gamma = 0.47 + 0.0257 * E_\alpha(\text{MeV})$

	DM-Ice17 (uBq/kg)	DAMA (uBq/kg)	DM-Ice17 to DAMA ratio
U238	No info	2	-
U234	93	12	7.8
Th230	93	12	7.8
Ra226-Pb210	933	18	52
Bi210-Pb206	1680	33	51
Th232	214	6	36

^{40}K in the Crystal

- ^{40}K in the crystal is estimated from the beta shoulder
- Matching simulation to data yields about 650 ppb ^{40}K