First Data and Prospects for DM-Ice

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

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

UW Madison, Bootcamp
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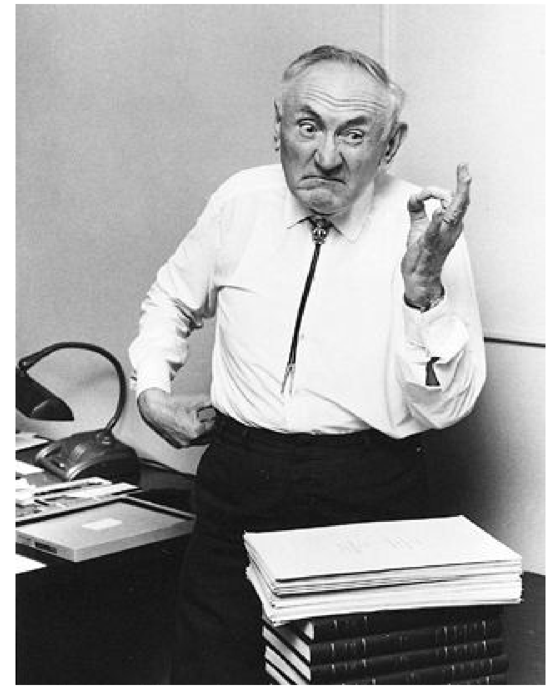
WISCONSIN ICECUBE PARTICLE ASTROPHYSICS CENTER
University of Wisconsin - Madison

Outline:

- Introduction
- Motivation for SP
- DM-Ice17 @ SP
- DM-Ice37 @ FNAL
- Conclusions

First Evidence for Dark Matter

Fritz Zwicky



1933

Coma galaxy cluster

Compare mass calculated from:

Luminosity $\propto M^4$ & $M = v^2R/G$

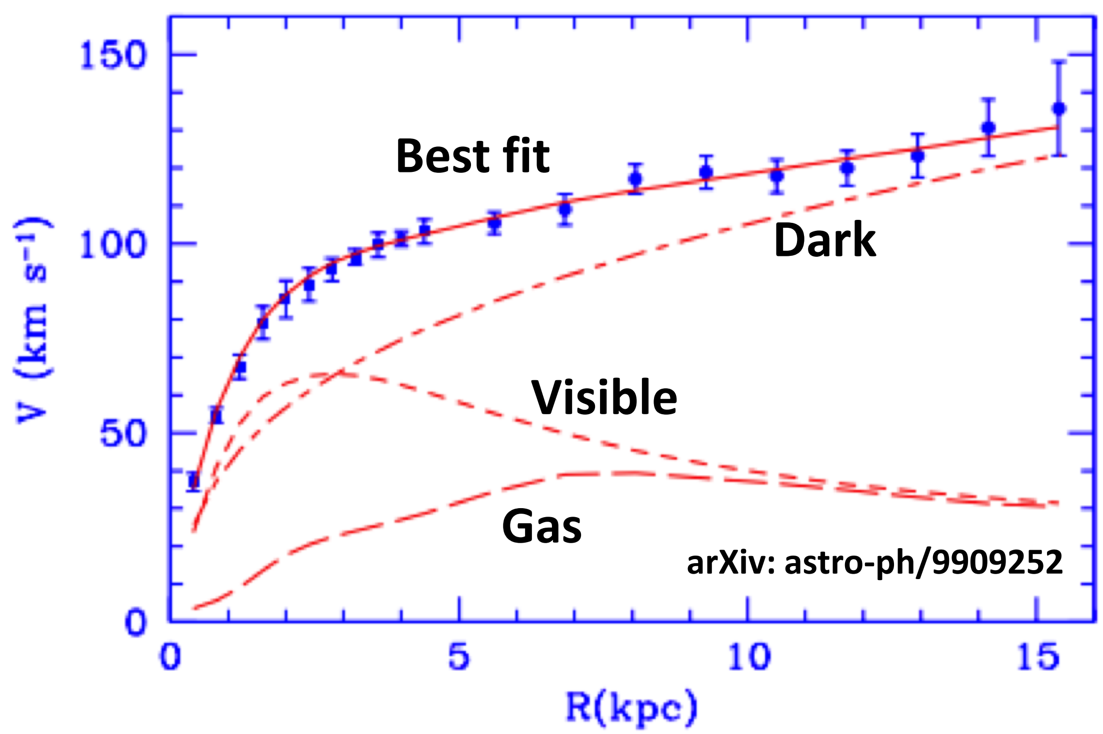
Only 10% of kinematically-required mass was visible

Vera Rubin

1960's

"What you see in a spiral galaxy ... is not what you get."

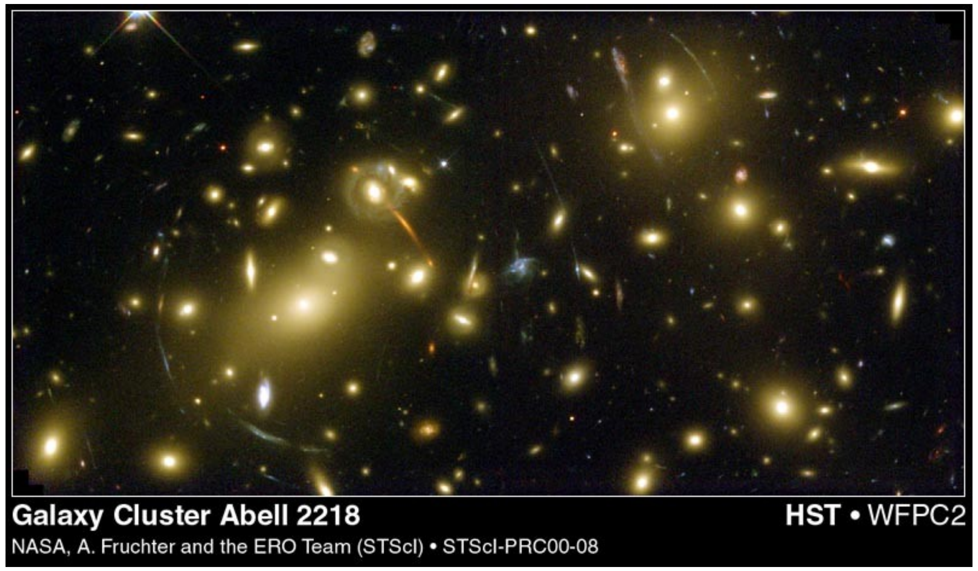
M33 Observations

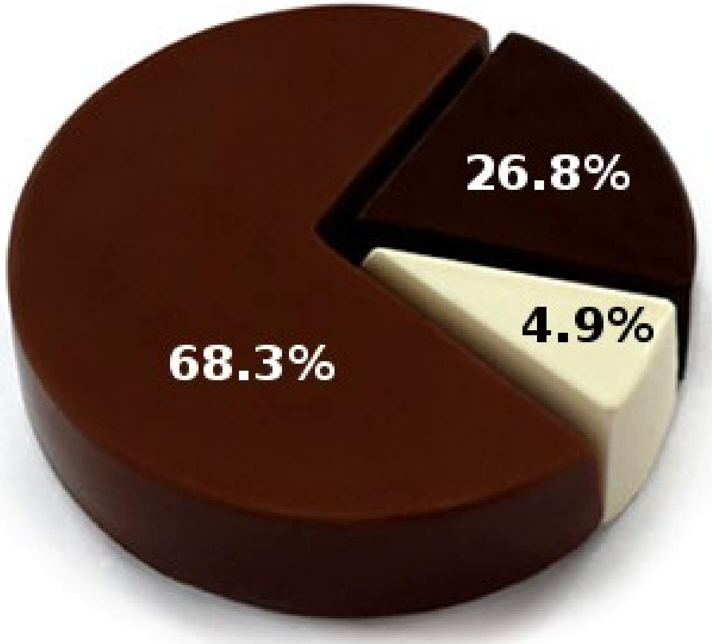


Much More Evidence…

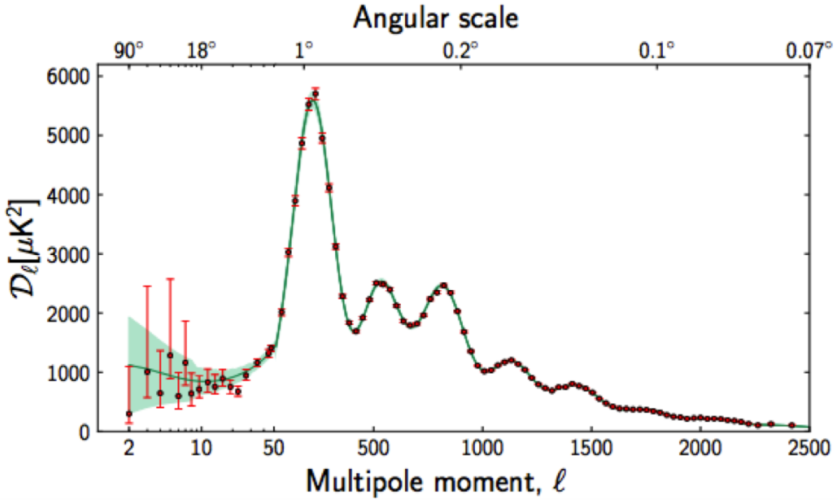
Galaxy cluster interactions

Gravitational lensing

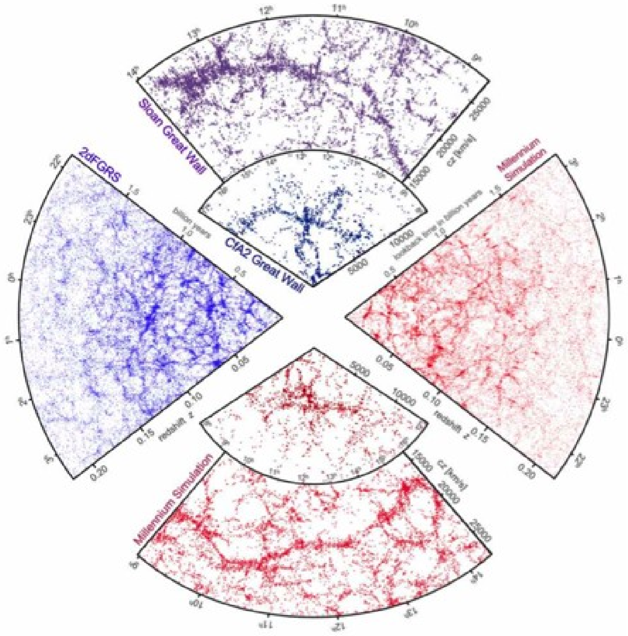




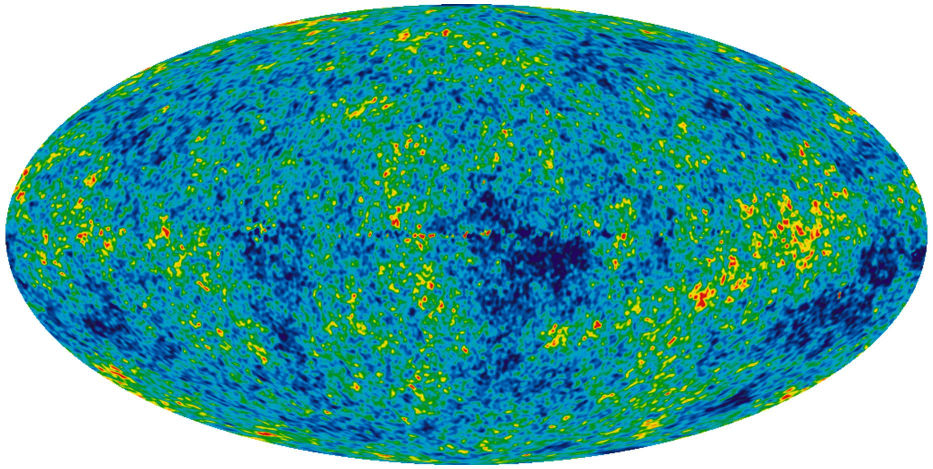
Baryon Acoustic Oscillations



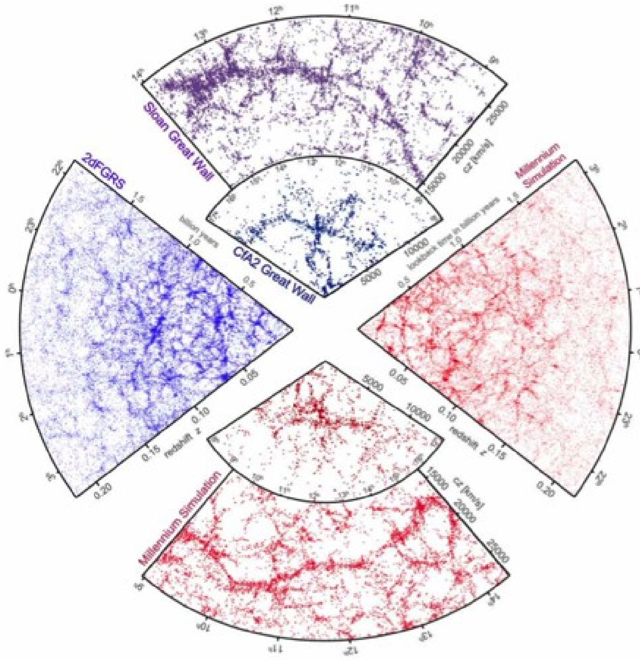
Large structure formation

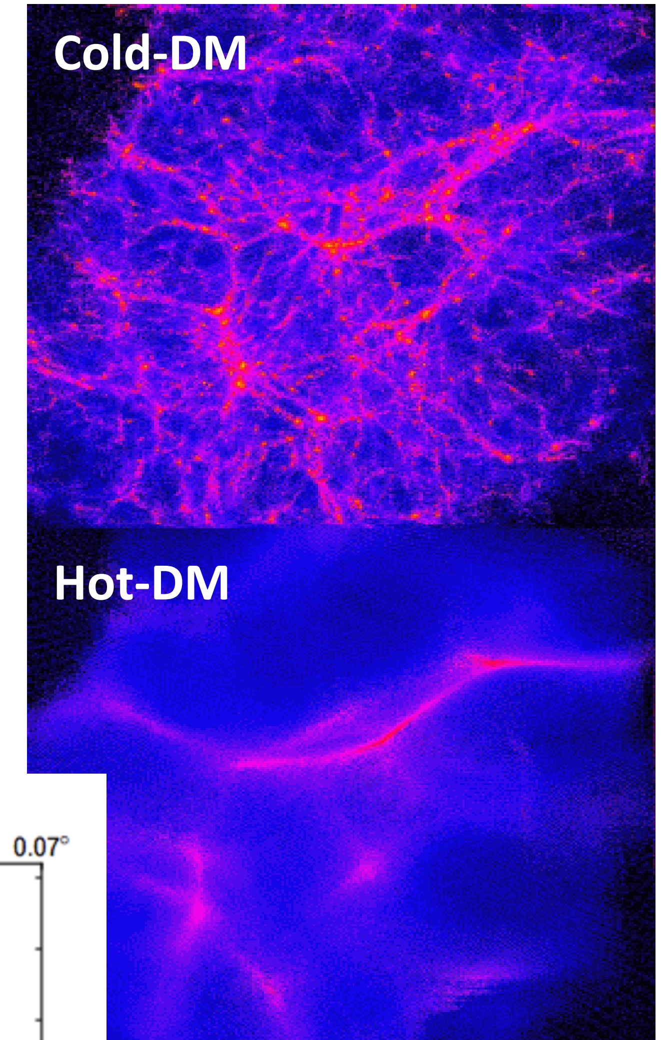


Cosmic Microwave Background



What is Dark Matter?



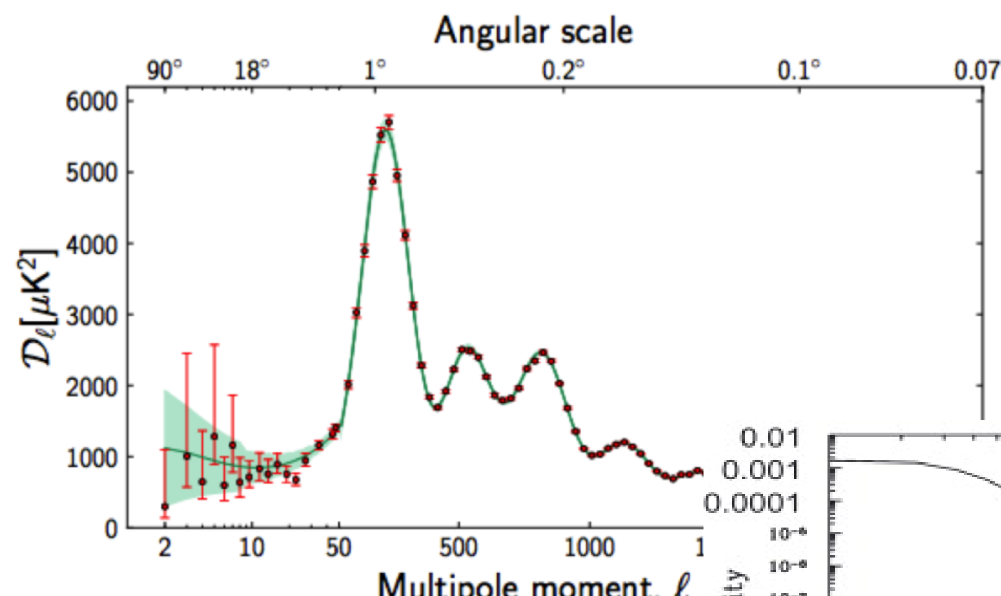


Cold

- Bottom-up structure formation
- Formation of Large-Scale Structure

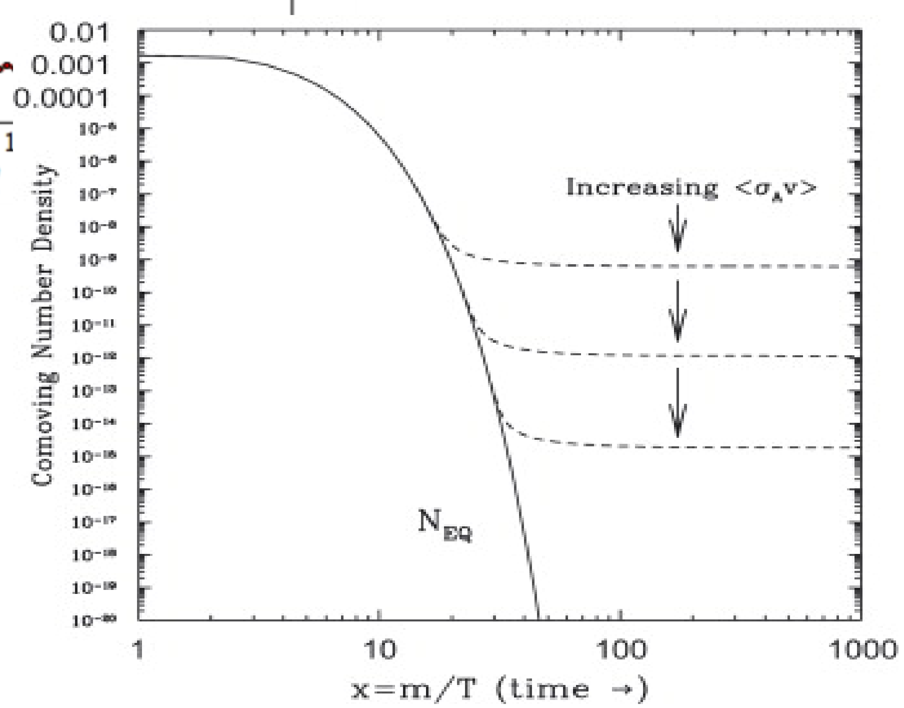
Non-baryonic

- Baryon fraction is measured
- Light elements from BBN
- BAO peaks

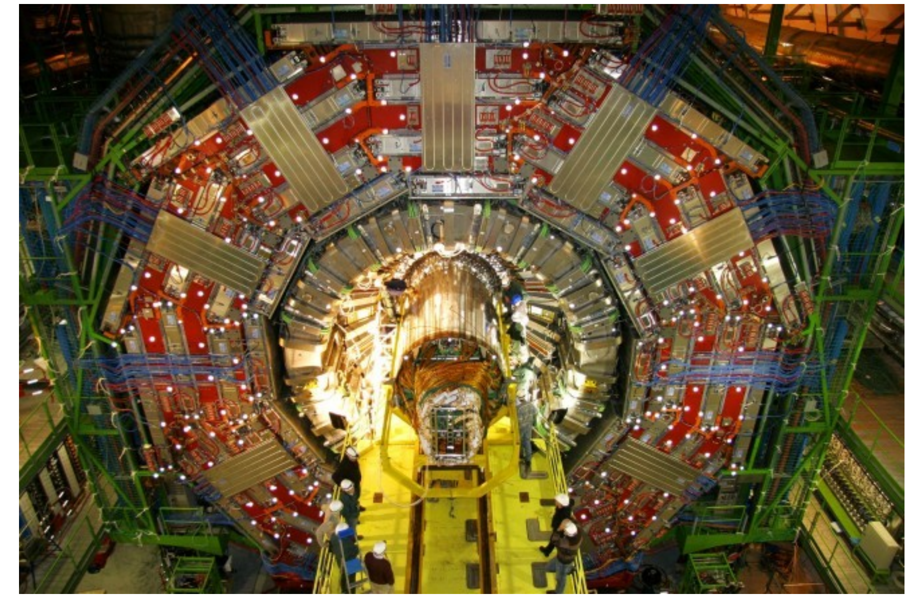


"WIMP Miracle"

- Weak annihilation cross-section predicts proper relic density

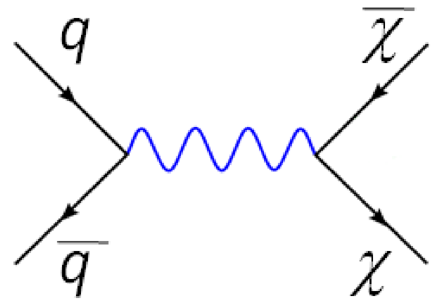


Looking for Dark Matter



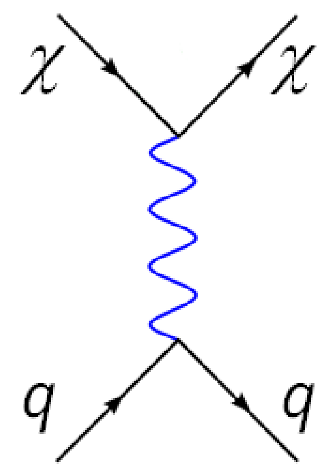
Collider Production

- **Produce WIMPs and detect them as missing energy**



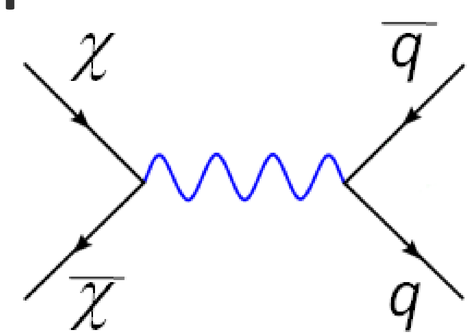
Direct Detection

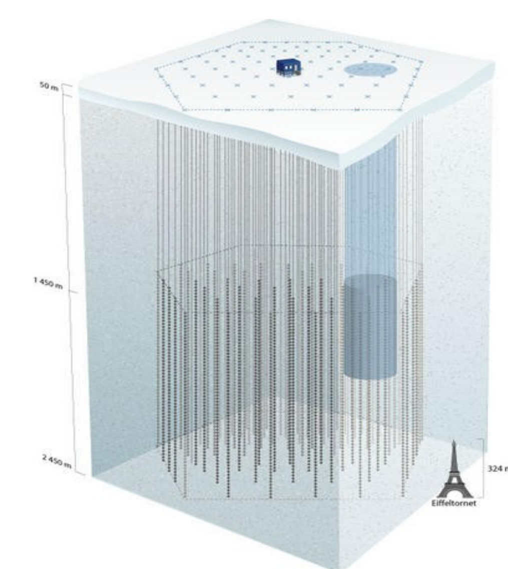
- **Detect nuclear recoil from WIMP-nucleon scattering**



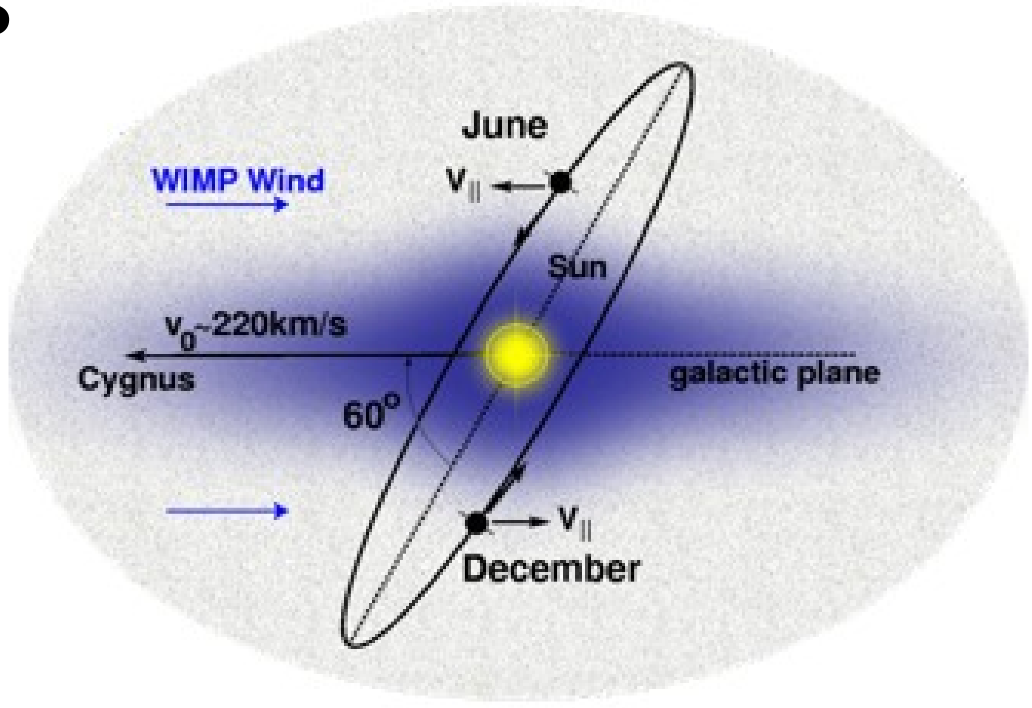
Indirect Detection

- **Search for excess of annihilation products**
- **Galactic Center, Solar core, Earth core**





Dark Matter Direct Detection Priors



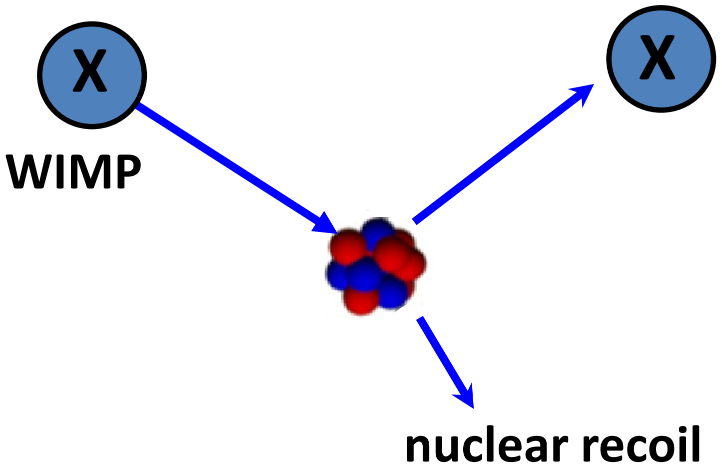
Assumptions:

- Dark matter is made of WIMPs
- scattering is spin-independent
- elastic scattering off of nuclei
- WIMPs are distributed in an isothermal halo with:
  - v_0 = 220 km/s
  - v_{esc} = 544 km/s
  - ρ_X = 0.3 GeV/cm^3
  - Flux = $10^8 - 10^{10}$ wimps/m^2 s

Direct Searches

WIMP-nucleon scattering

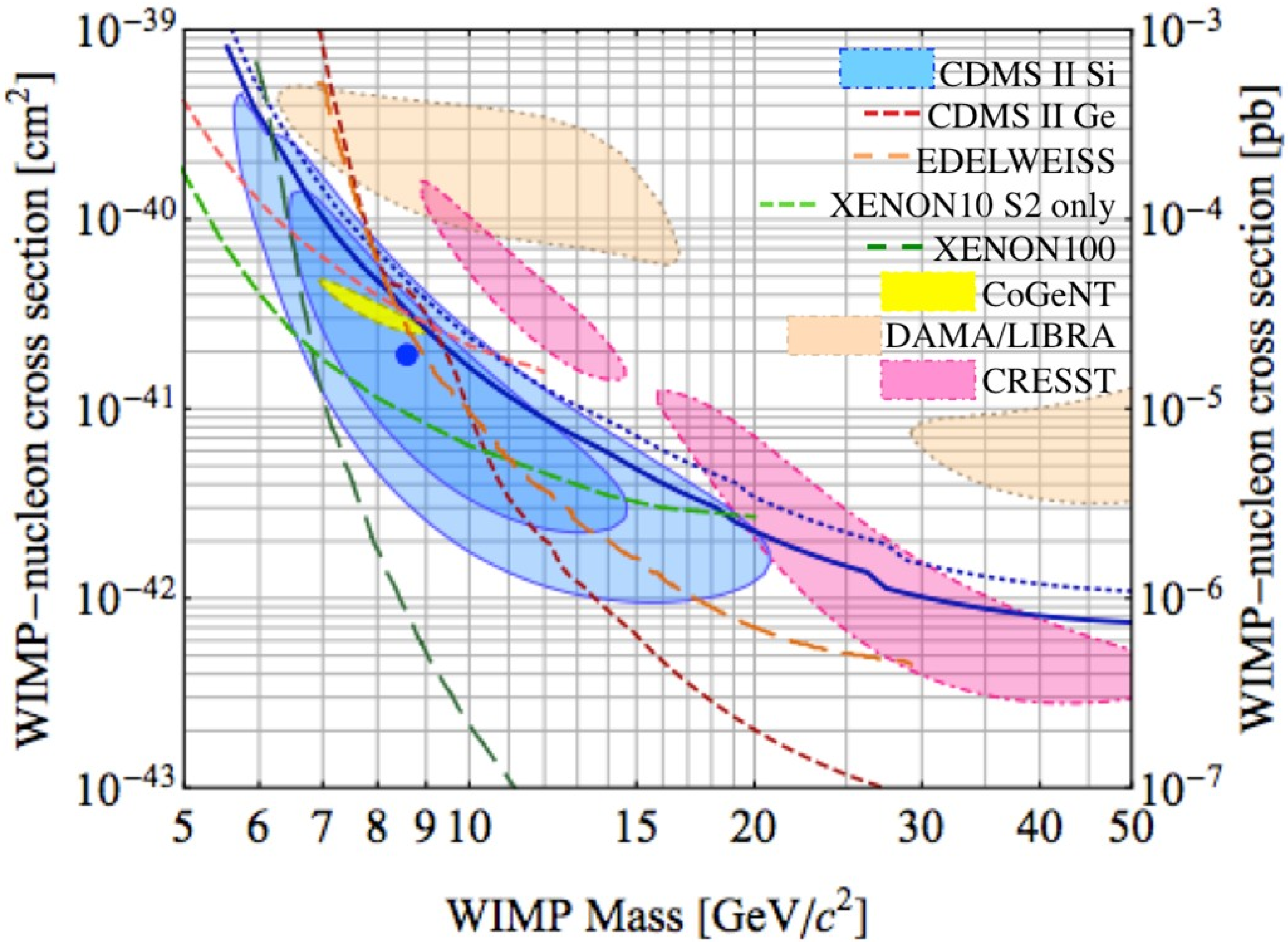
Look for nuclear recoil



Hints of Direct Detection

DAMA (2008)
- Scintillation
- 13 annual modulations
- 8.9σ

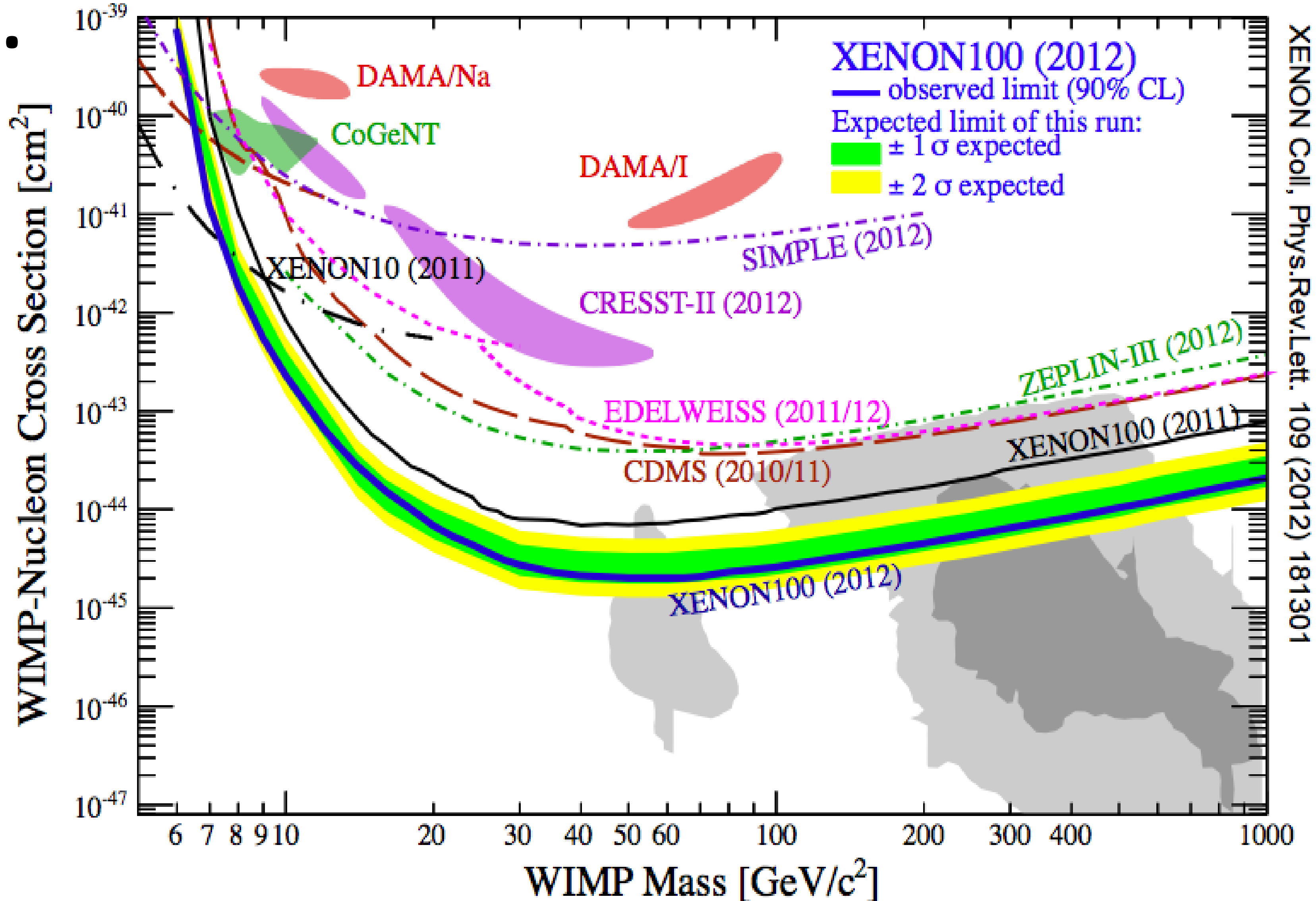
CoGeNT (2011)
- Ionization
- 1.25 annual modulations
- 2.8σ

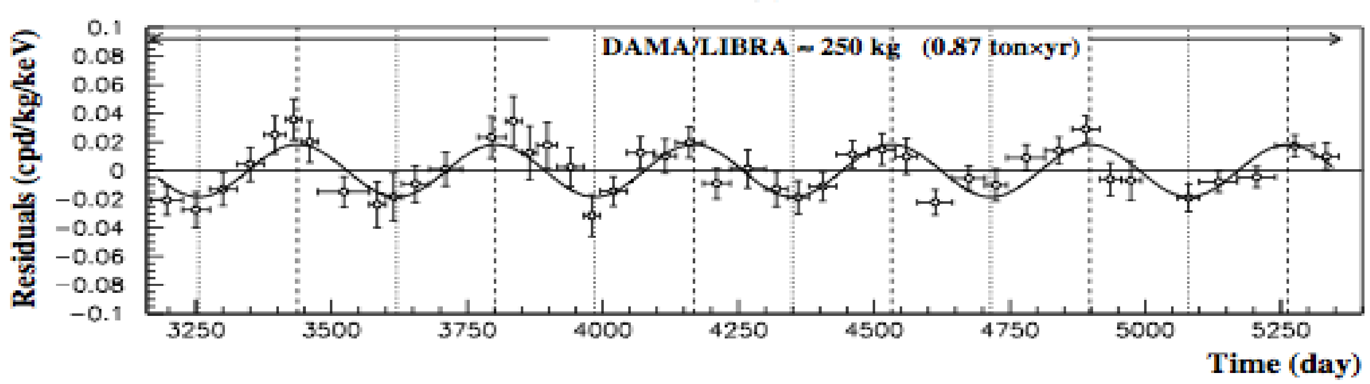


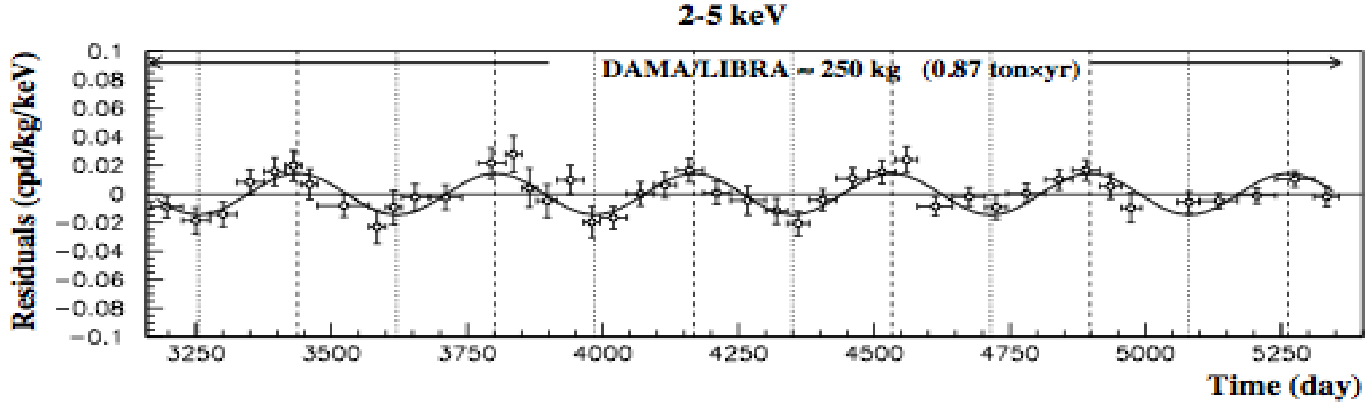
CDMS Si (2013)
- Ionization + phonons
- 4σ excess

CRESST (2011)
- Scintillation + phonons
- 4σ excess

"Tension" in the field …







Expected DM max = June 2nd

DAMA 8.9σ Modulation:

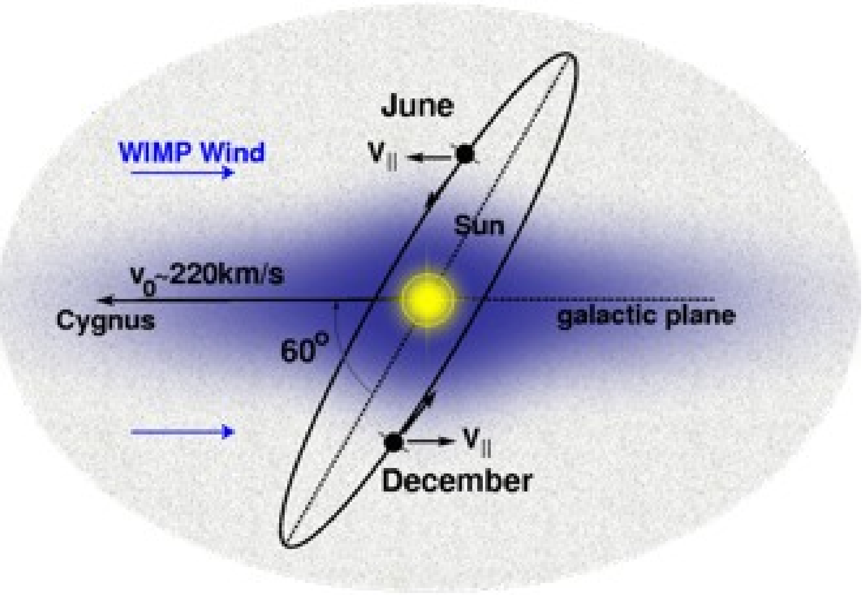
Phase: May 26th ± 7 days

Period: 0.999 ± 0.002 yr

Background: ~ 1 cpd/kg/keV

Amplitude: 0.01 cpd/kg/keV

Annual Modulation Dark Matter Searches with NaI Detectors



Northern Hemisphere	Gran Sasso **DAMA/Libra** 250kg running	Gran Sasso **Princeton-NaI** R&D	Canfranc **ANAIS** ~100kg starting in 2014?	**PICO-LON** **KIMS** etc...
Southern Hemisphere	South Pole **DM-Ice** 17 kg running R&D for 250 kg			**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.

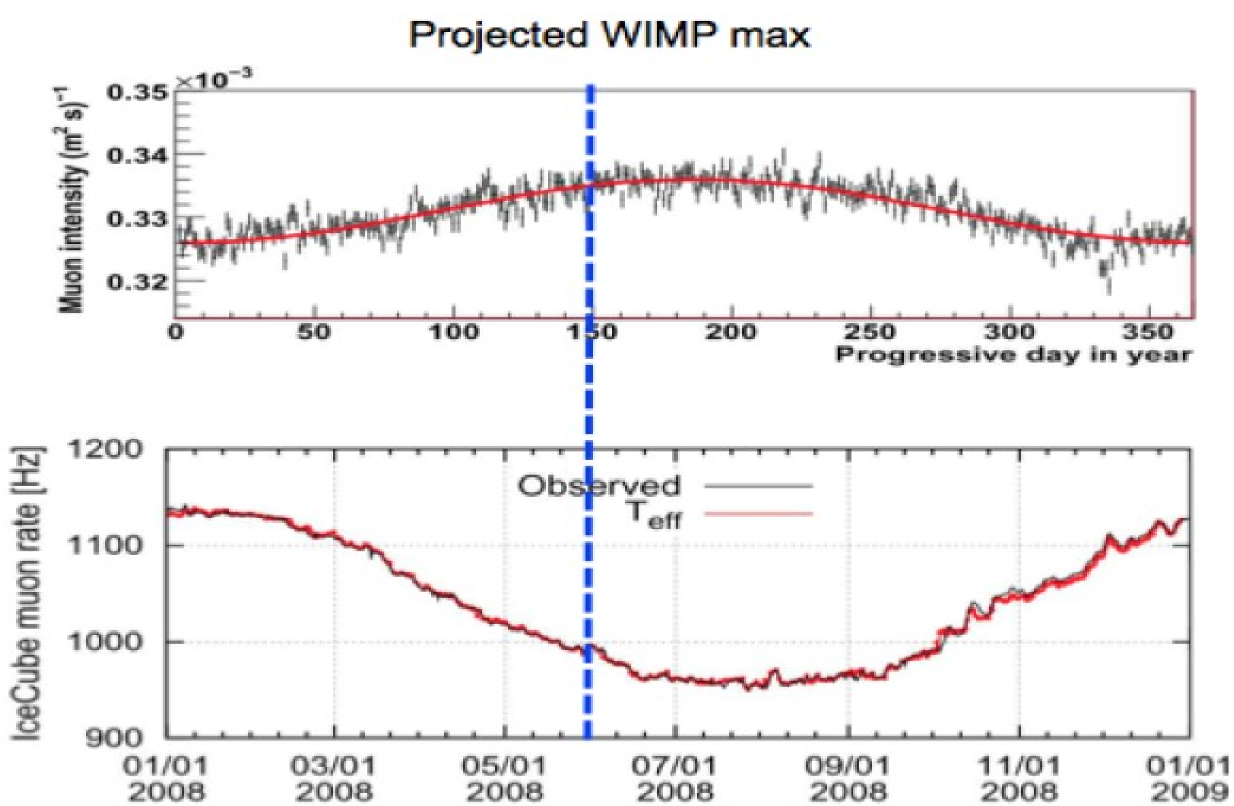
Why put NaI in the Ice?

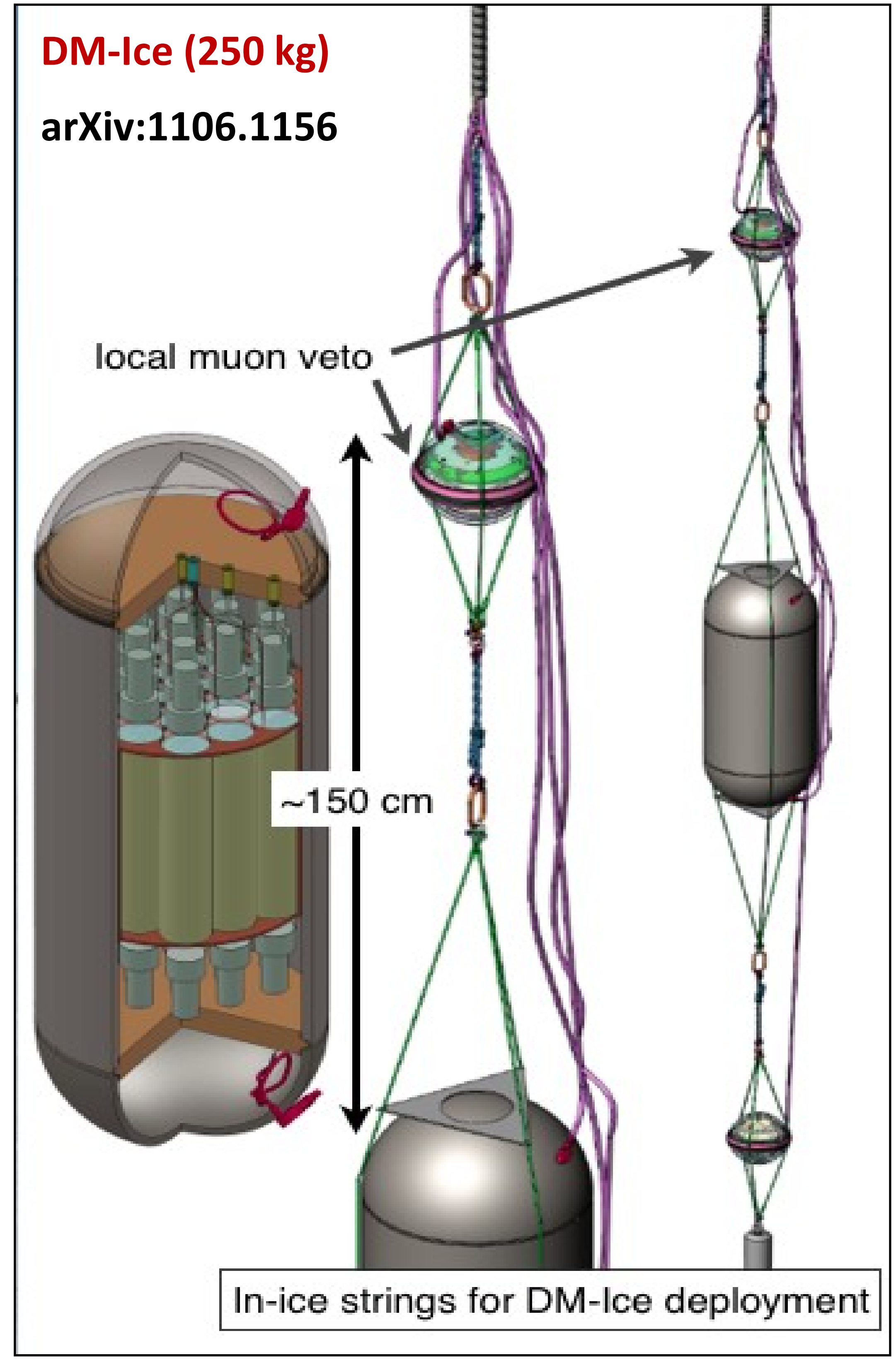
Use NaI(Tl)

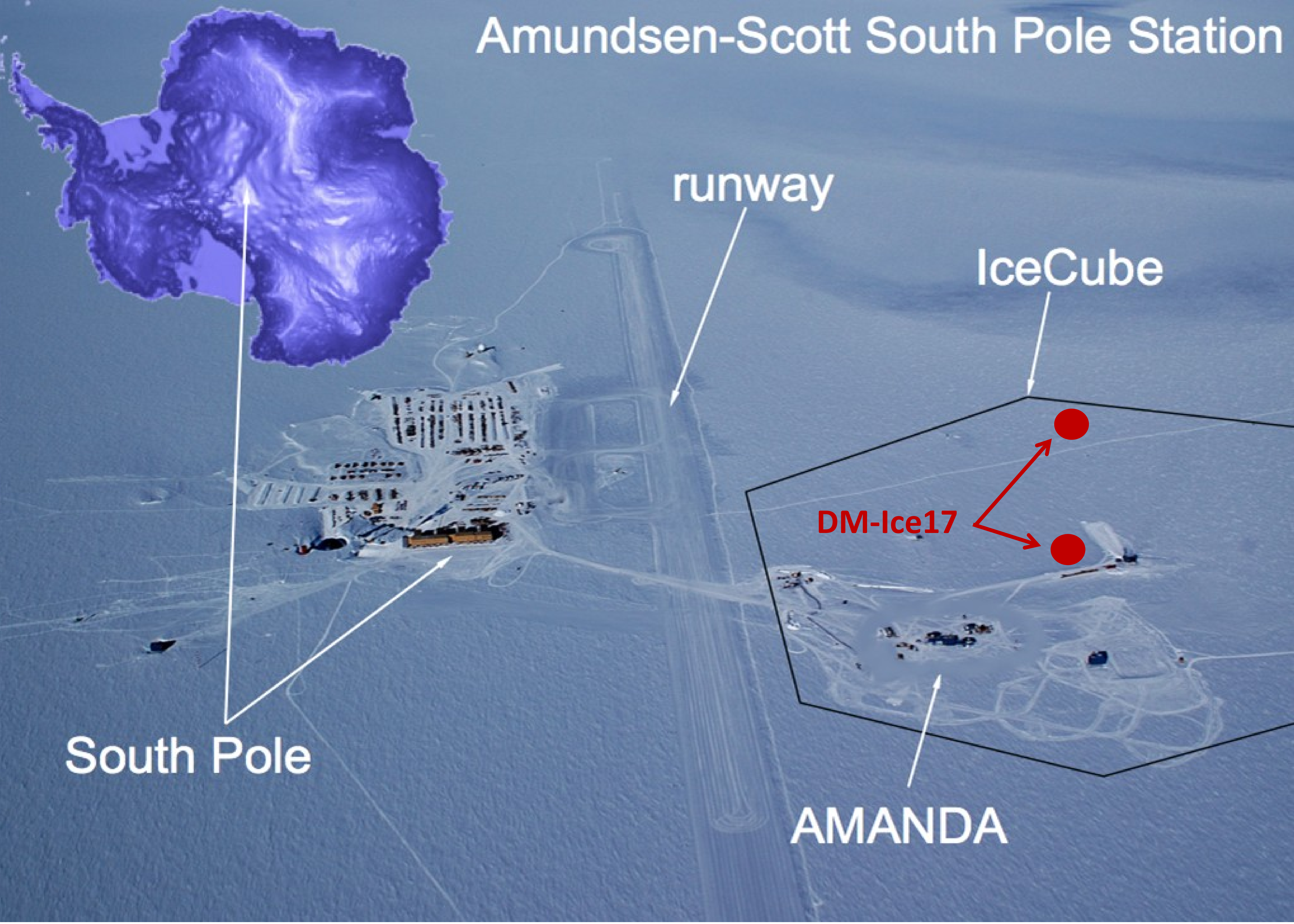
- Eliminate uncertainties due to detector effects, thresholds, recoil energies, etc
- Crystal Array for sophisticated event tagging

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






Amundsen-Scott South Pole Station
runway
IceCube
DM-Ice17
South Pole
AMANDA

DM-Ice17 Deployment

Feb 2010

- a great idea!

10 months

Dec 2010

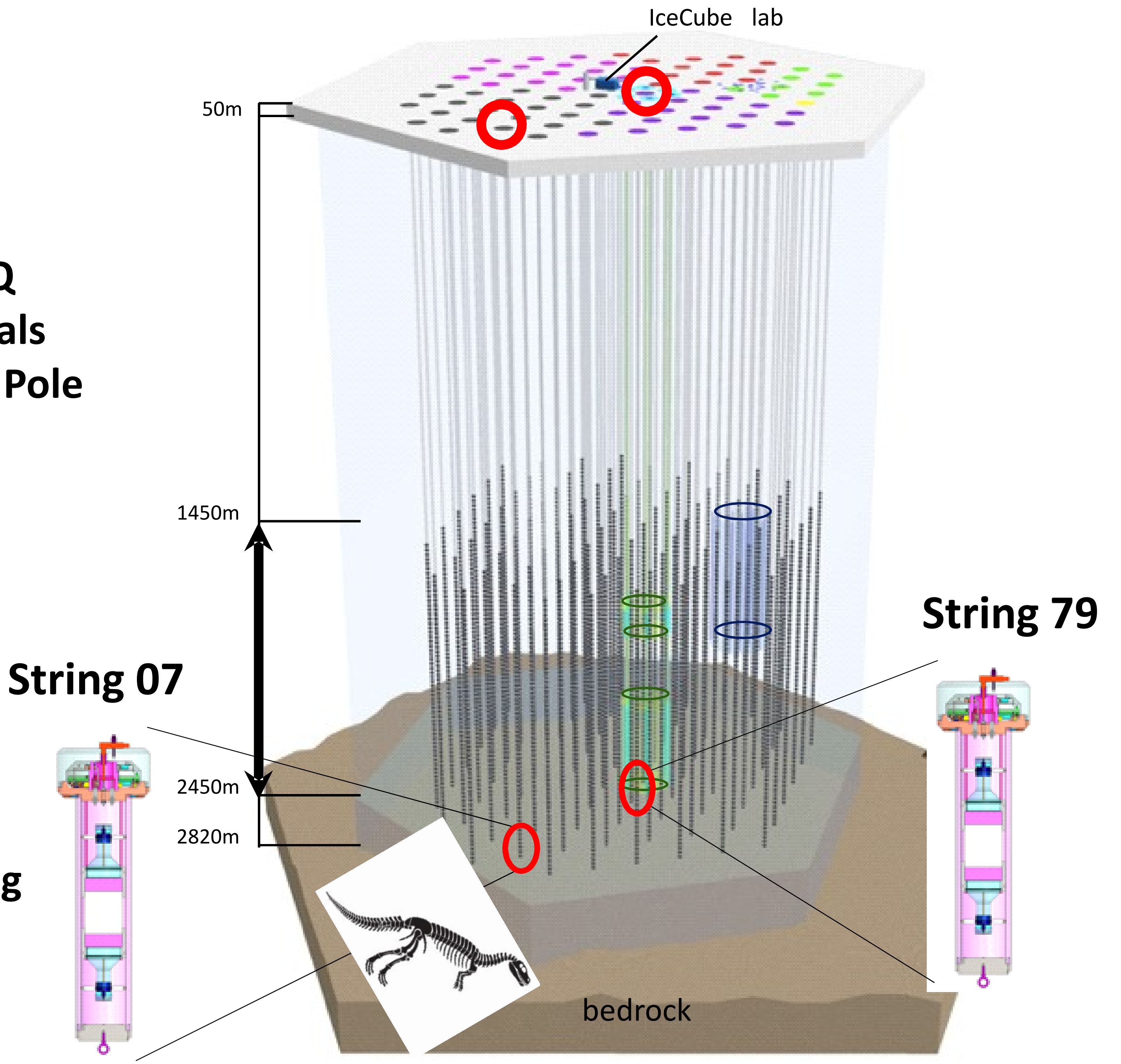
- IceCube DAQ
- NAIAD crystals
- deployed at Pole

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

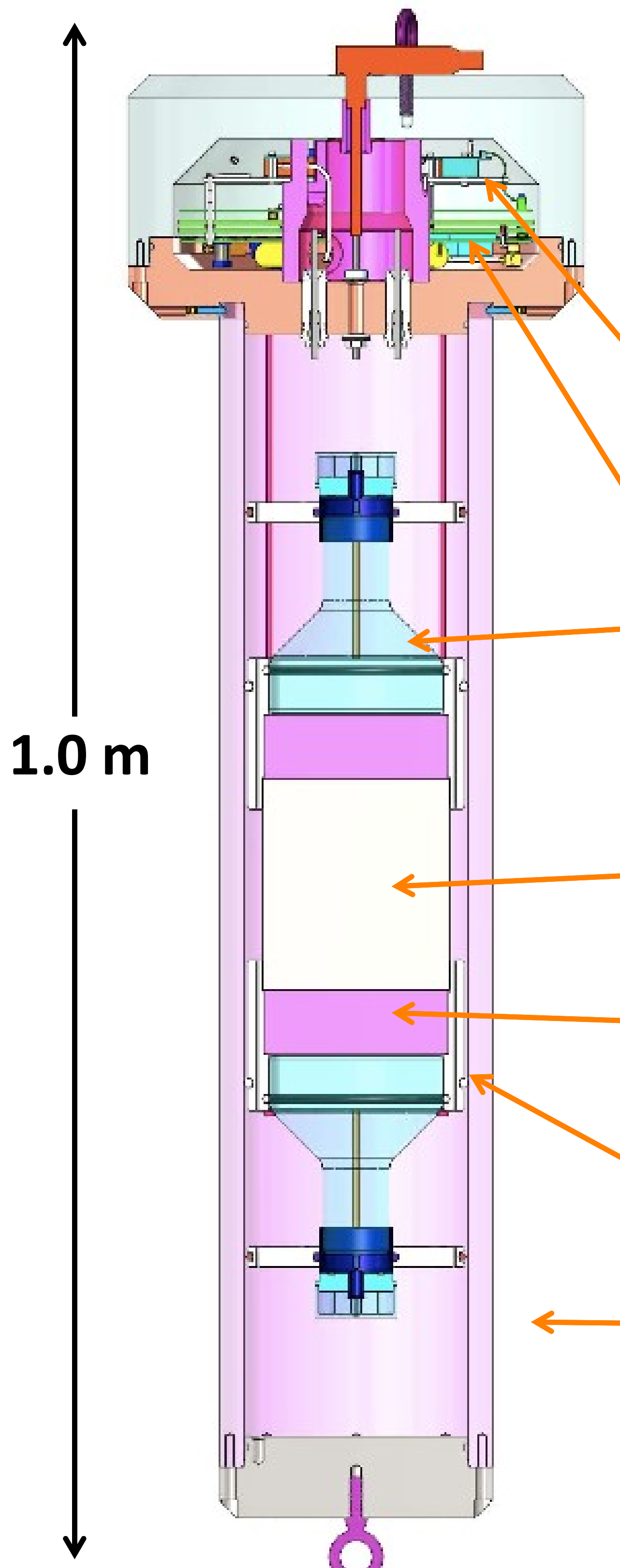


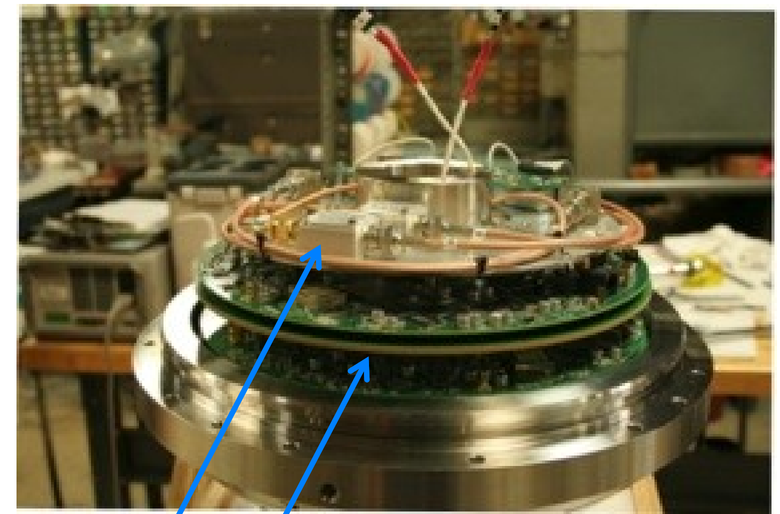
- 2200 M.W.E. overburden
- ~85 muons/m^2/day

DM-Ice17 Detectors

36 cm (14”)

1.0 m





Prototype x2

2 HV control boards

2 IceCube mainboards

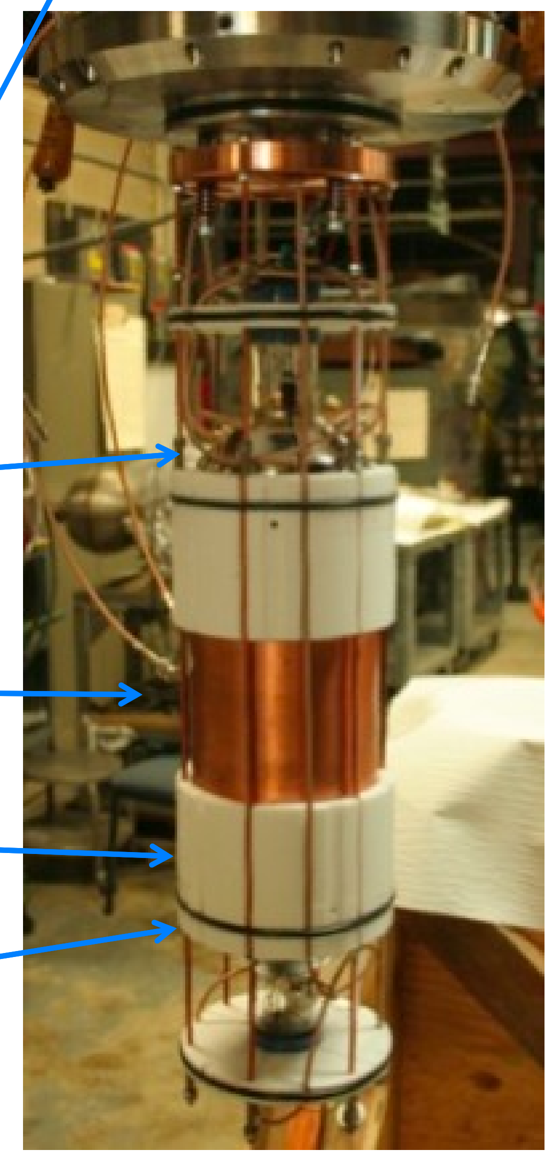
PMTs:
5” ETL 9390-UKB

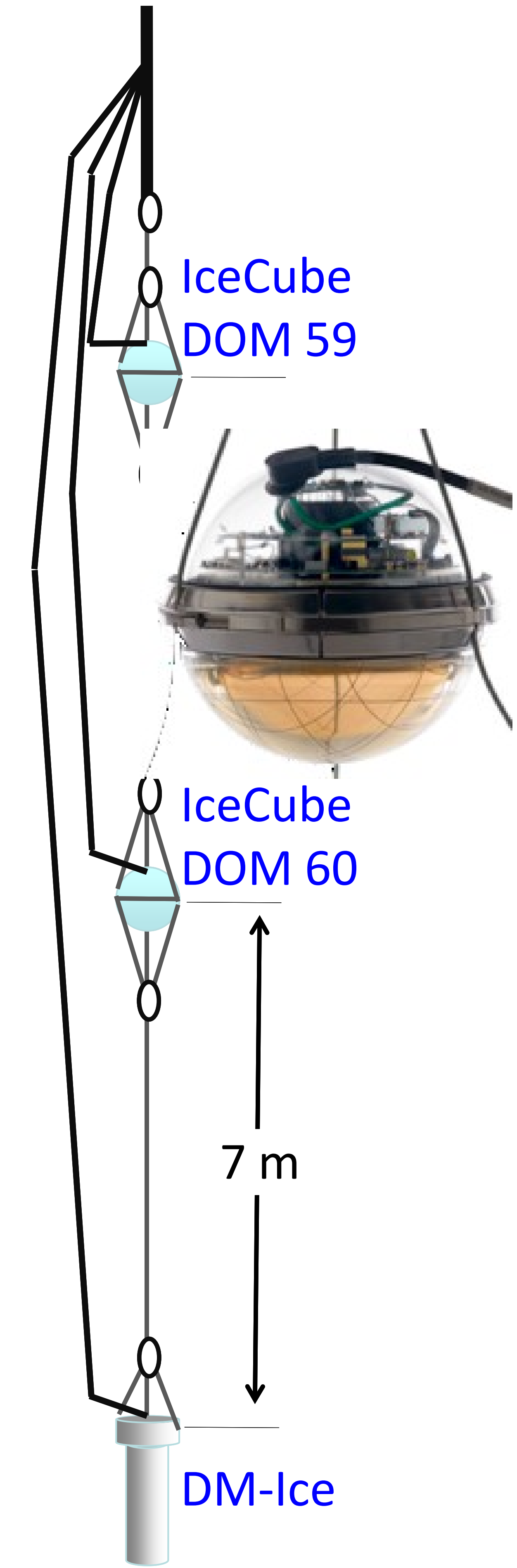
NAIAD NaI Crystal
(Ø 5.5” x 6”, 8.5 kg)

5 cm quartz lightguides
(Suprasil B)

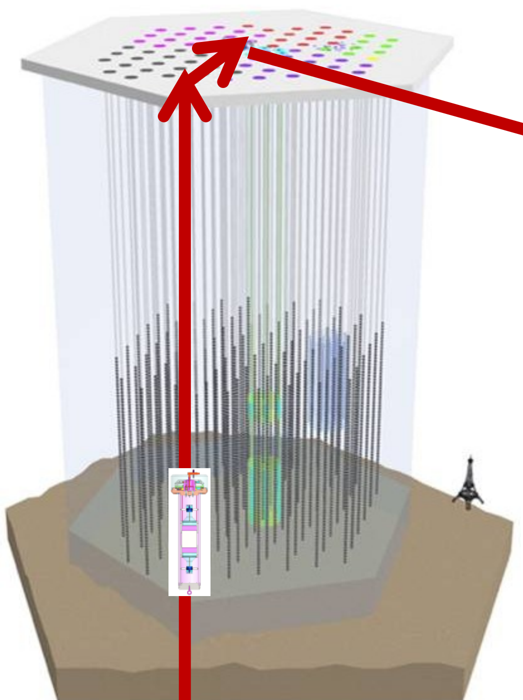
PTFE light reflectors

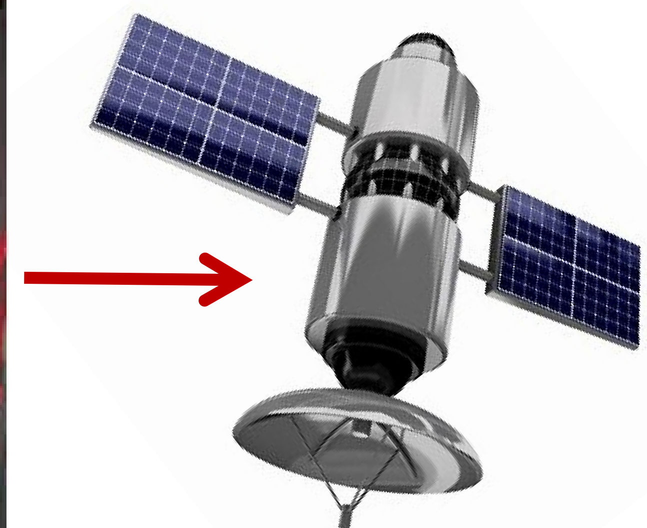
Stainless Steel
Pressure Vessel



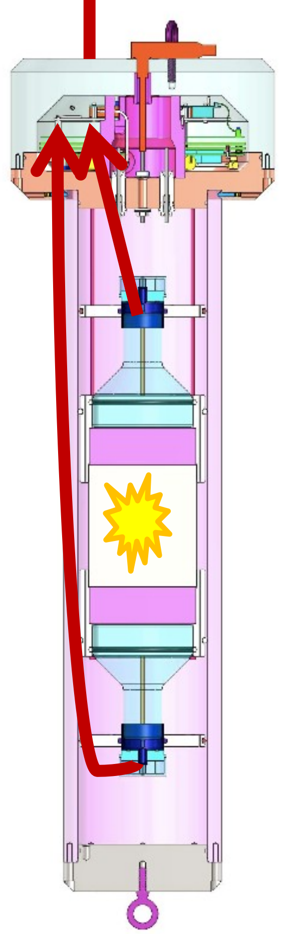


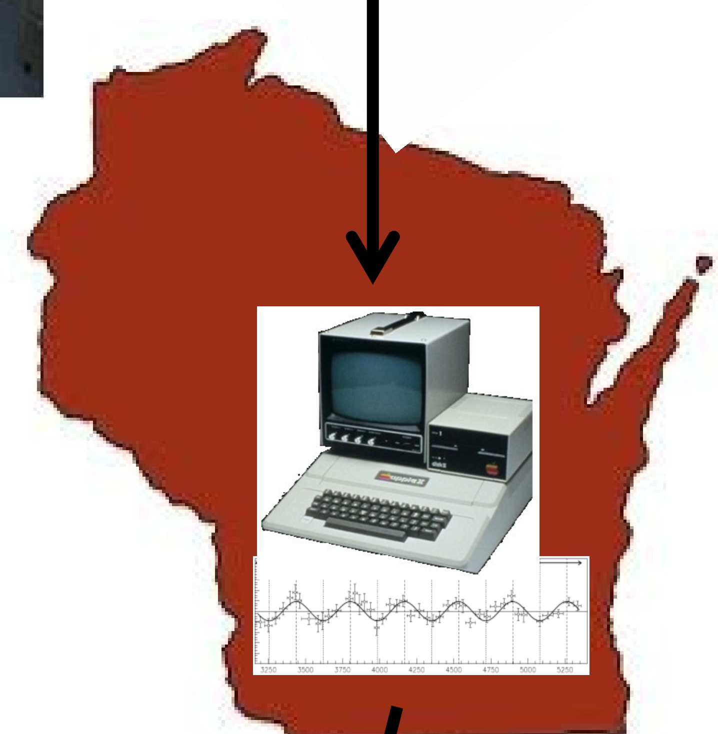
Data Transfer





- 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



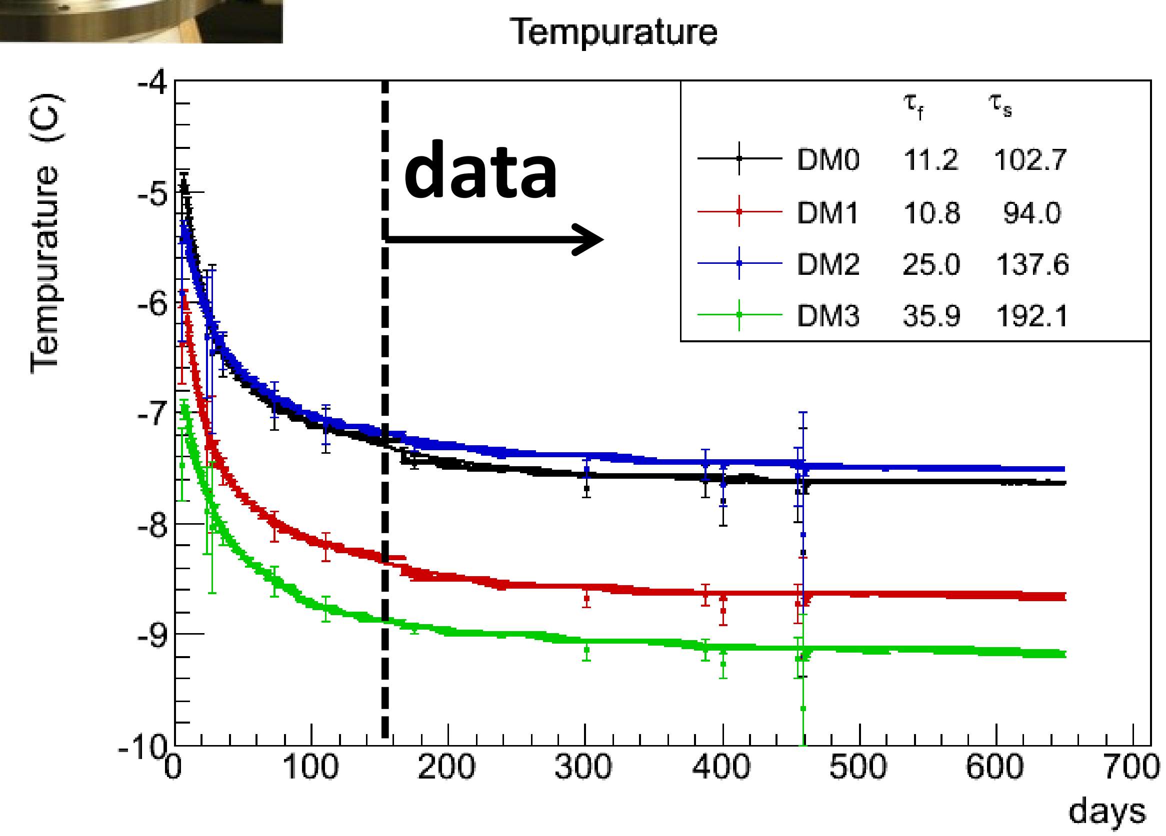


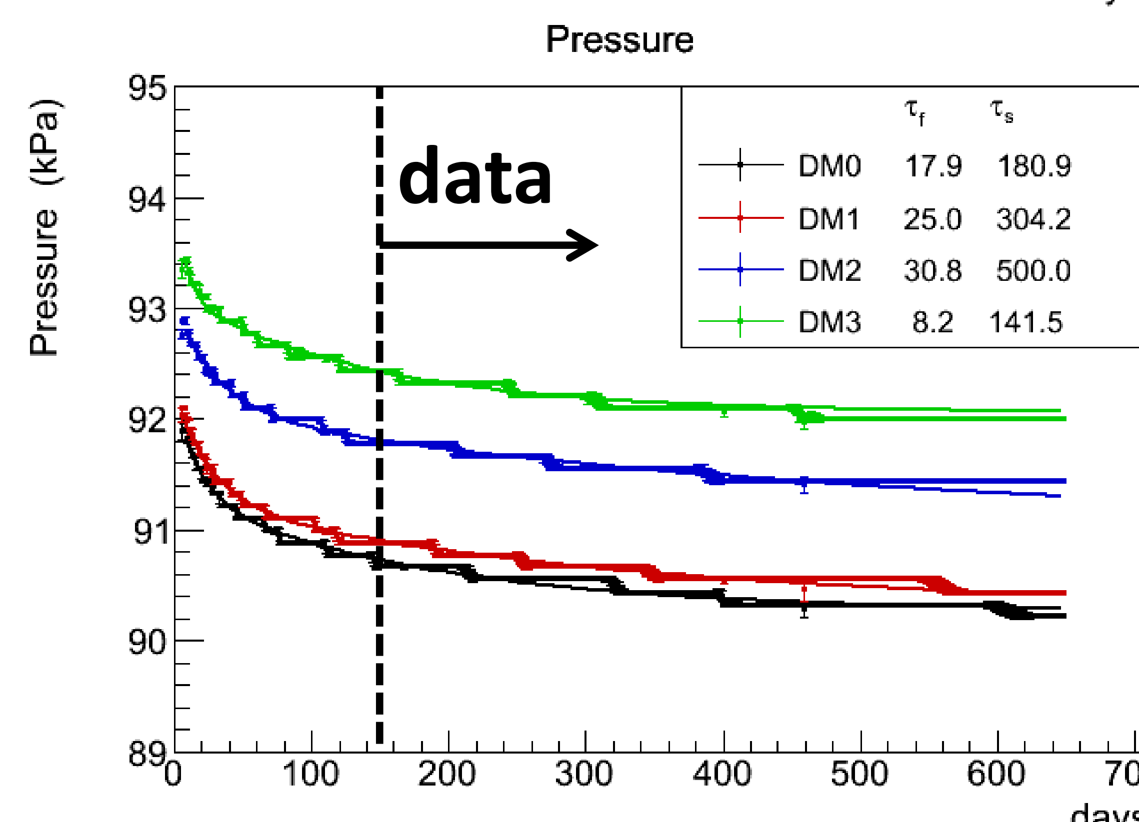
Detector Monitoring

Temp and pressure sensors mounted on the mainboards

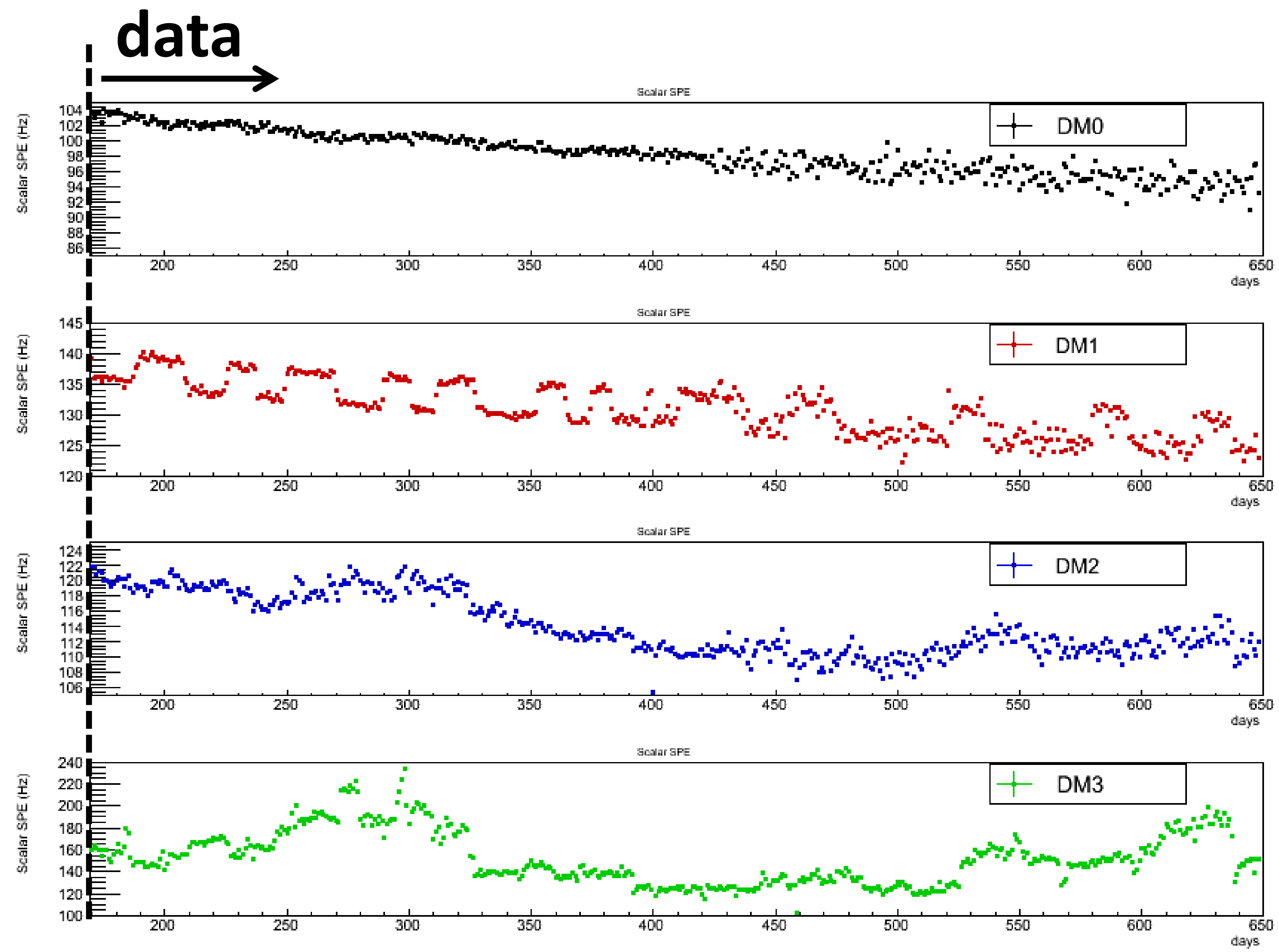
1. Temperature of the boards
   - ~10°C above surrounding ice
   - Fast (2-3 weeks) decrease during freeze-in
   - Slower decrease over a few months after freeze-in
2. Pressure follows similar trend as temperature (ADC resolution limited)
3. High Voltage on the PMTs

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



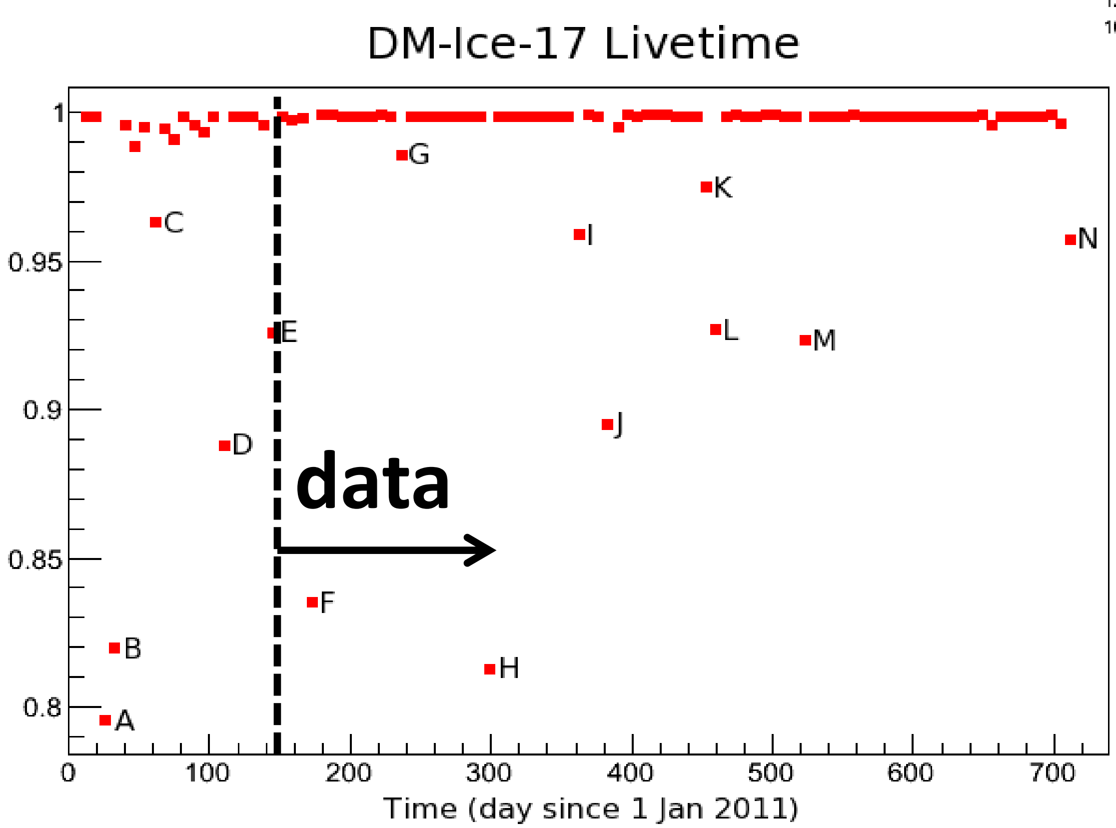


Detector Monitoring



PMT Trigger Rates

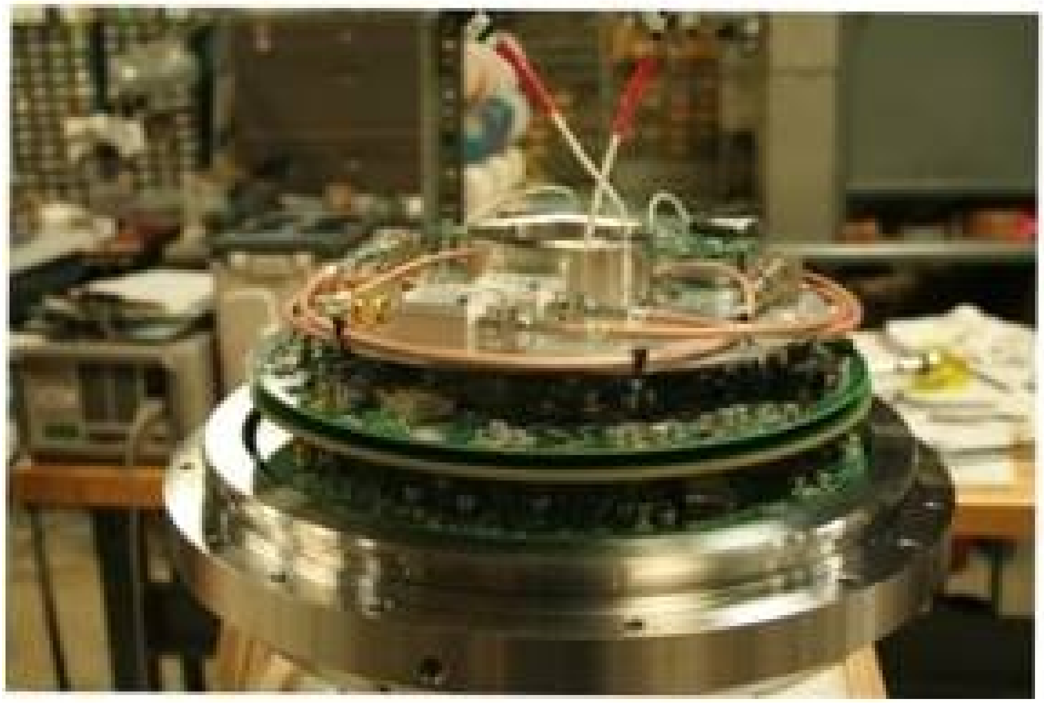
- Single PMT trigger rates
- General decay over time
- Single trigger rate variation seems mostly in the noise (not observed in coincident data)



DM-Ice17 Livetime

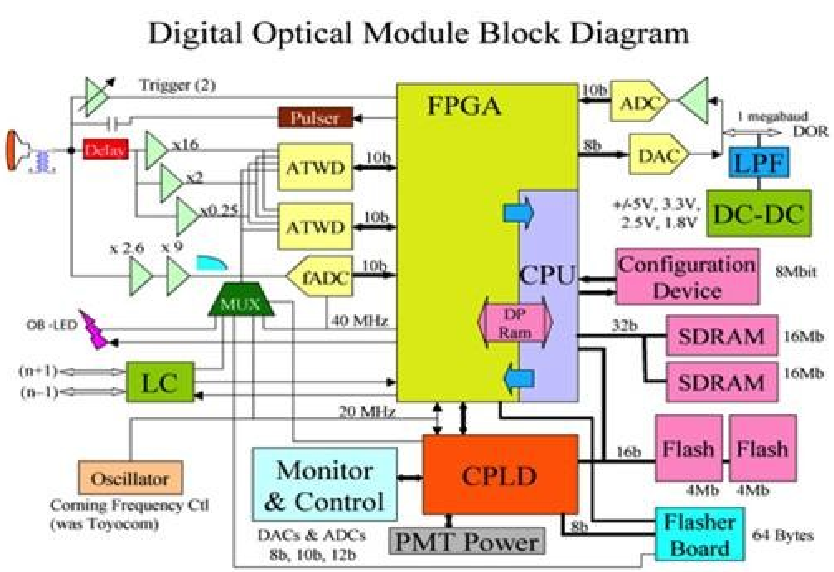
- Data run since June 2011
- 99.75% uptime
- well known down times (power cycling, pedestal and dark noise runs)

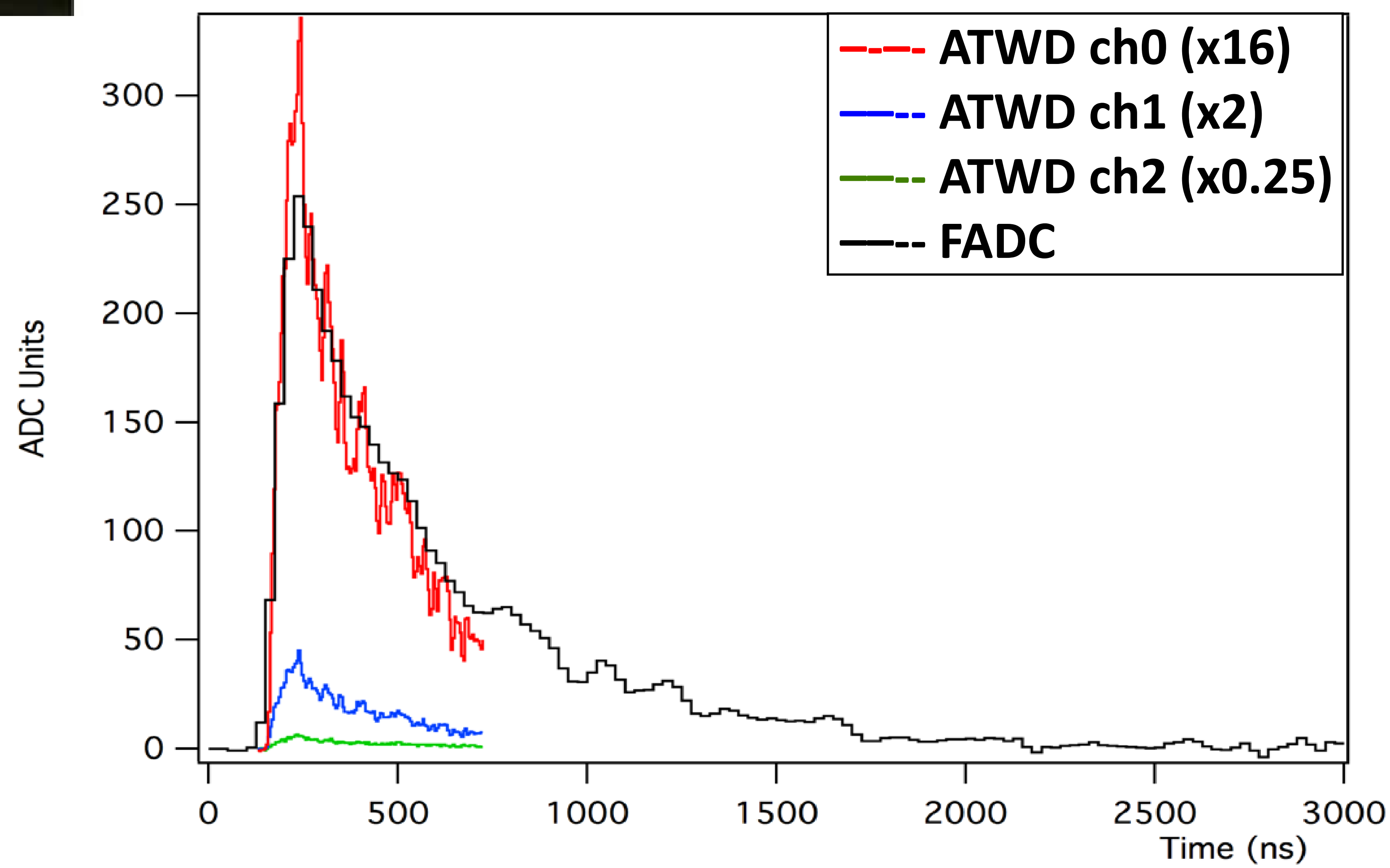
Data Acquisition and Digitizing



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	~ 3 Hz

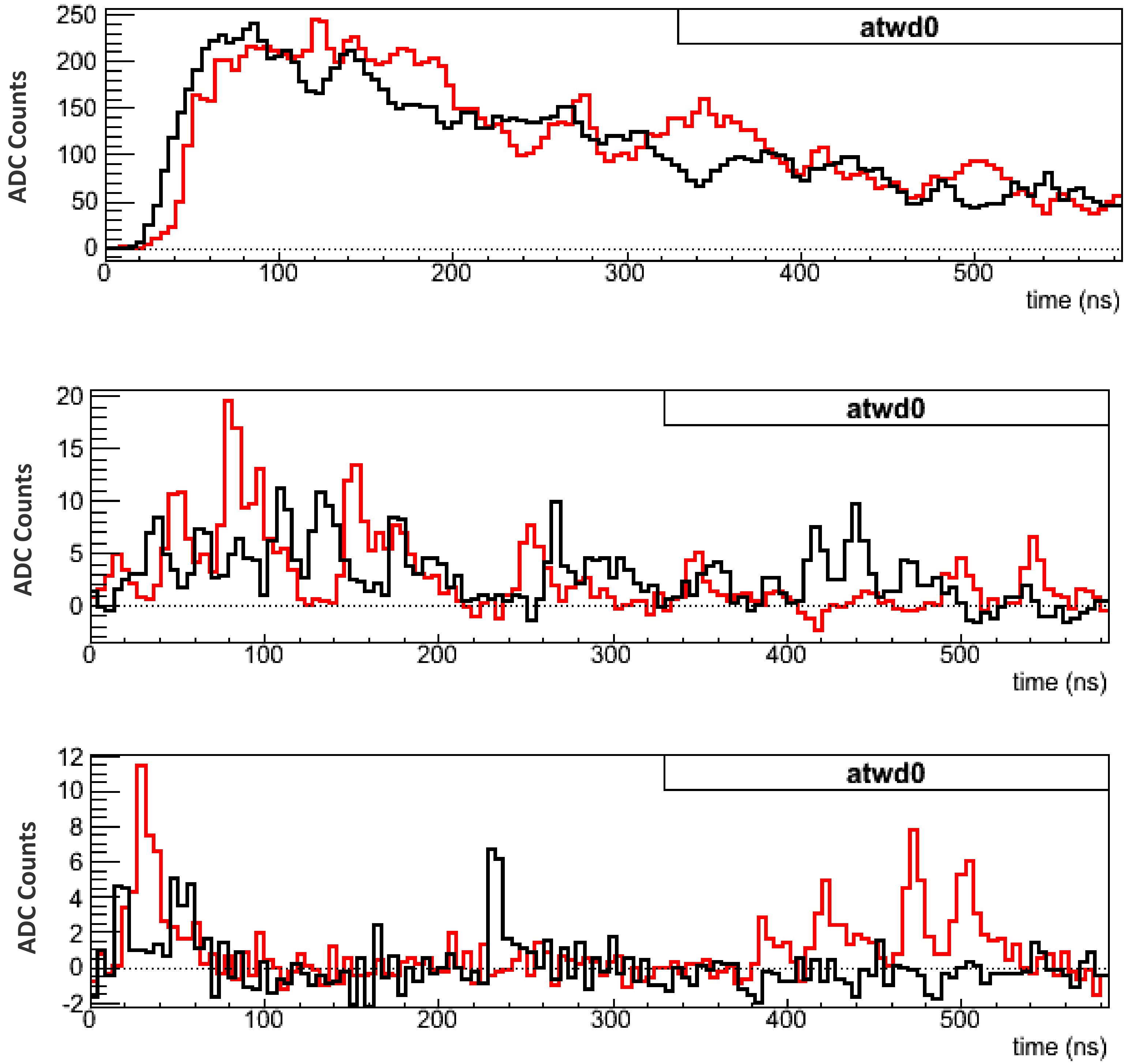
- IceCube mainboards
- Thoroughly engineered and tested
- Slightly modified for DM-Ice



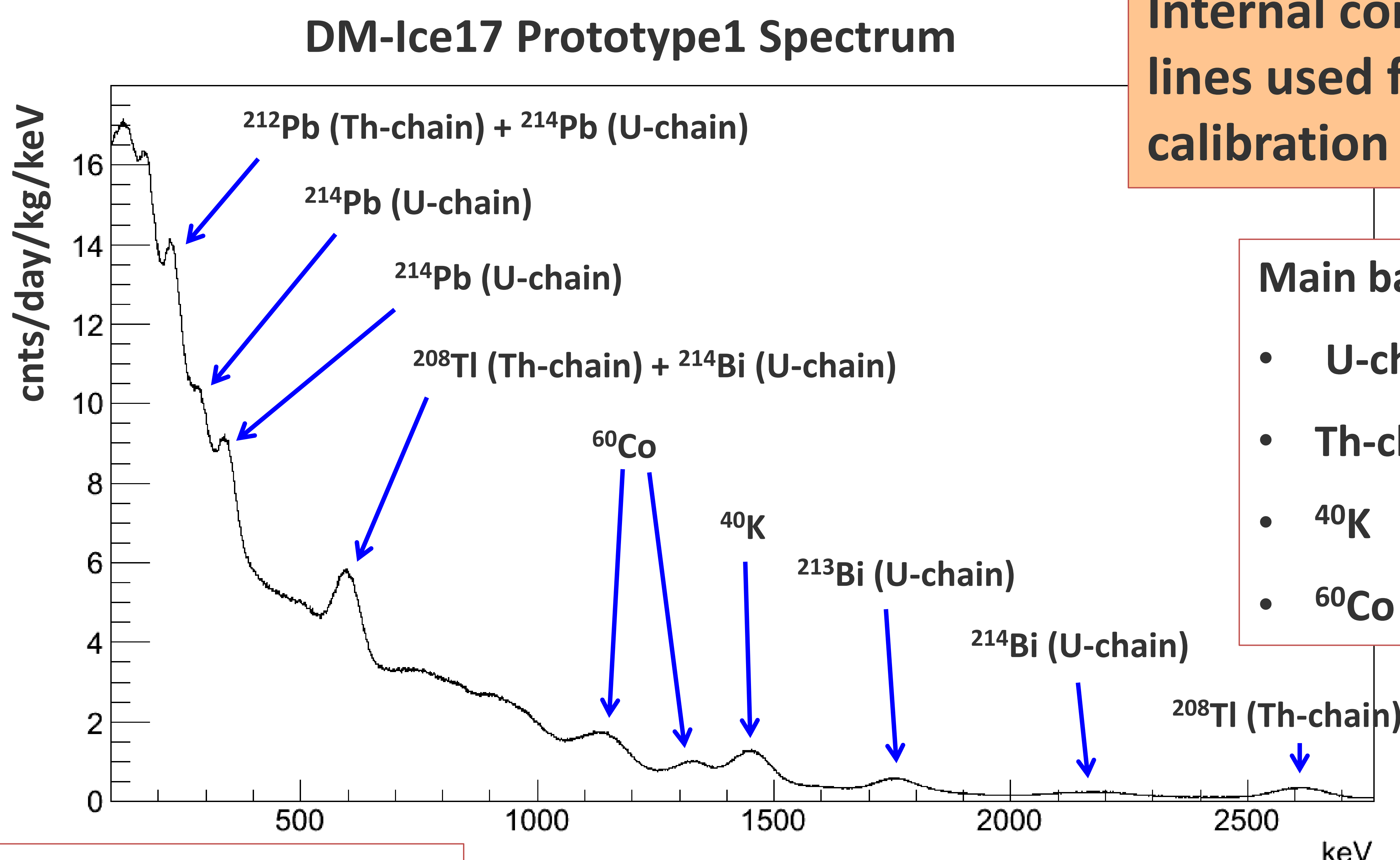


Scintillation Events

- 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, events become a series of single photo-electrons.



Energy Spectrum: Gammas



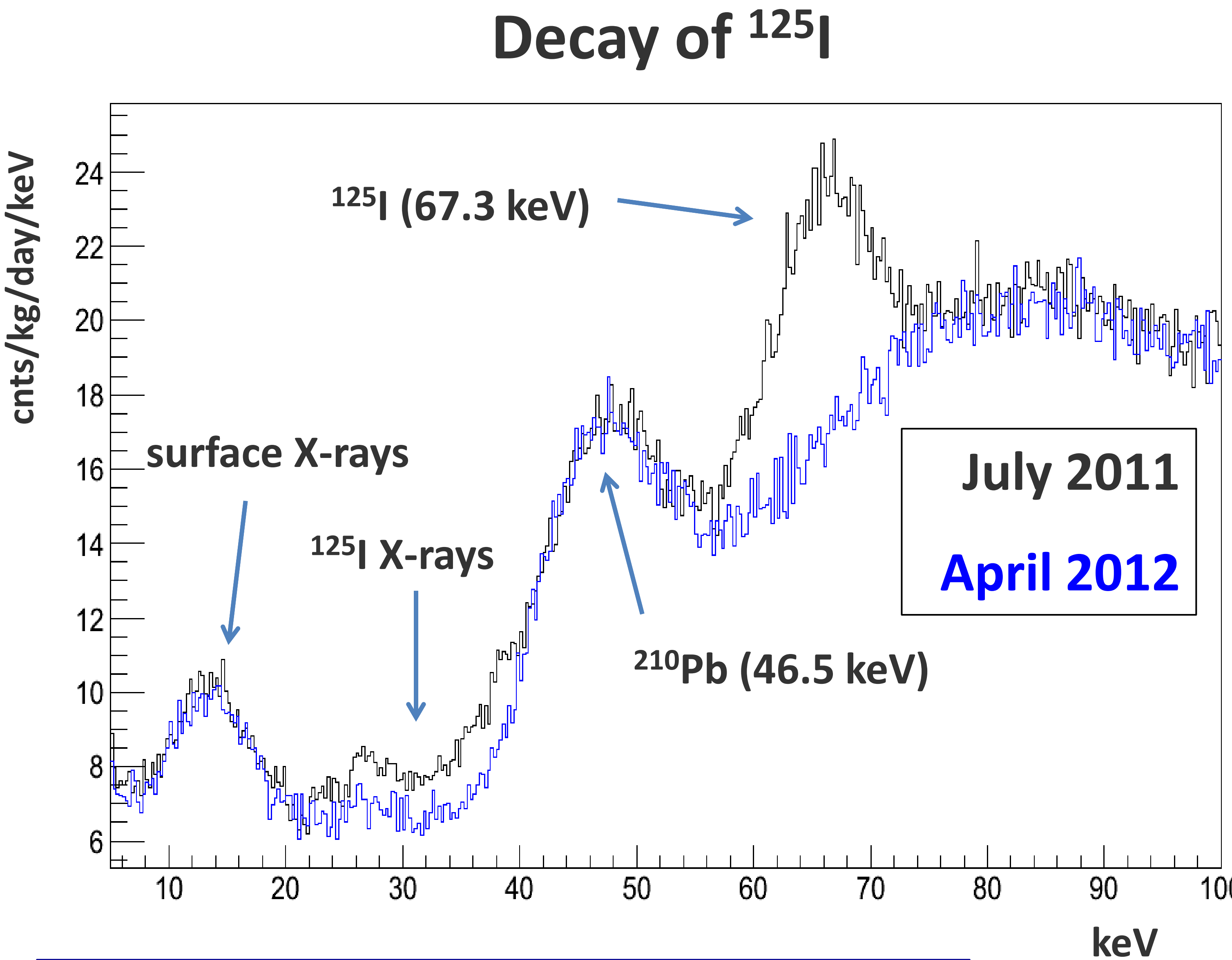
Internal contamination lines used for calibration

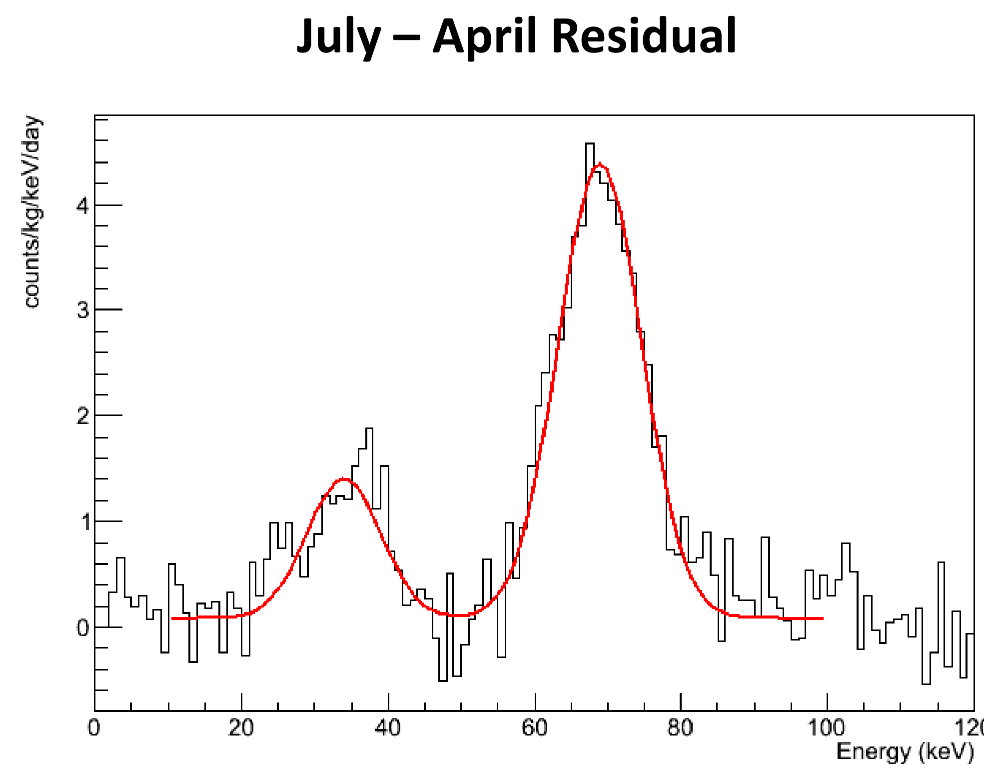
Main backgrounds:

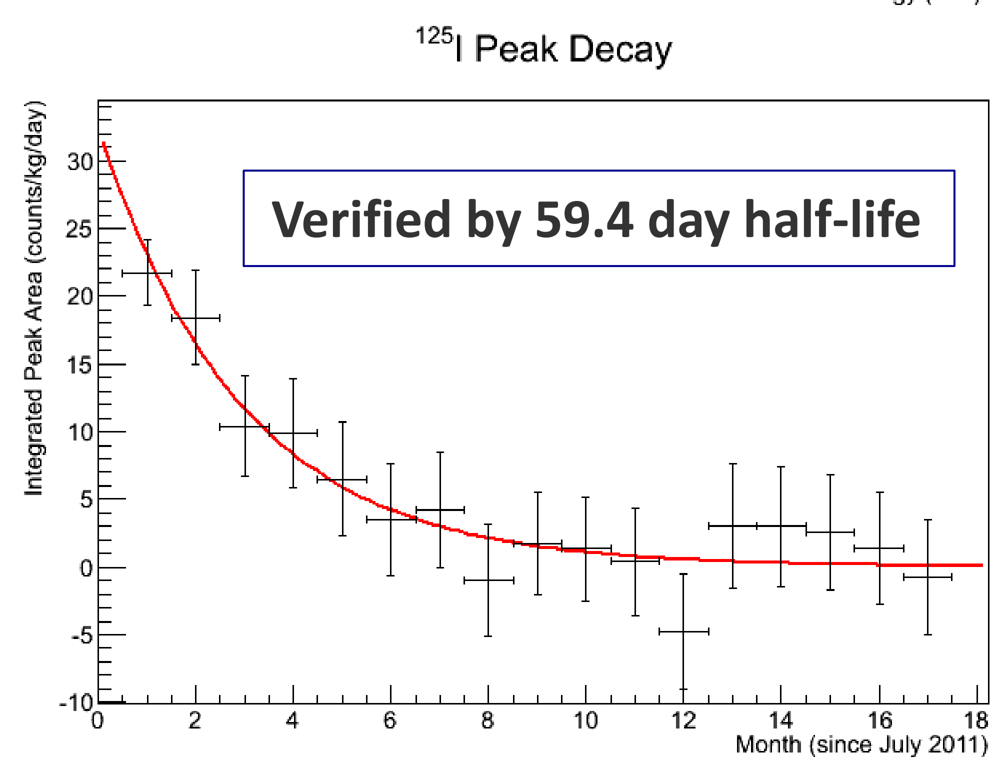
- U-chain
- Th-chain
- ^{40}K
- ^{60}Co

18 months of data from both PMTs on a single crystal

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



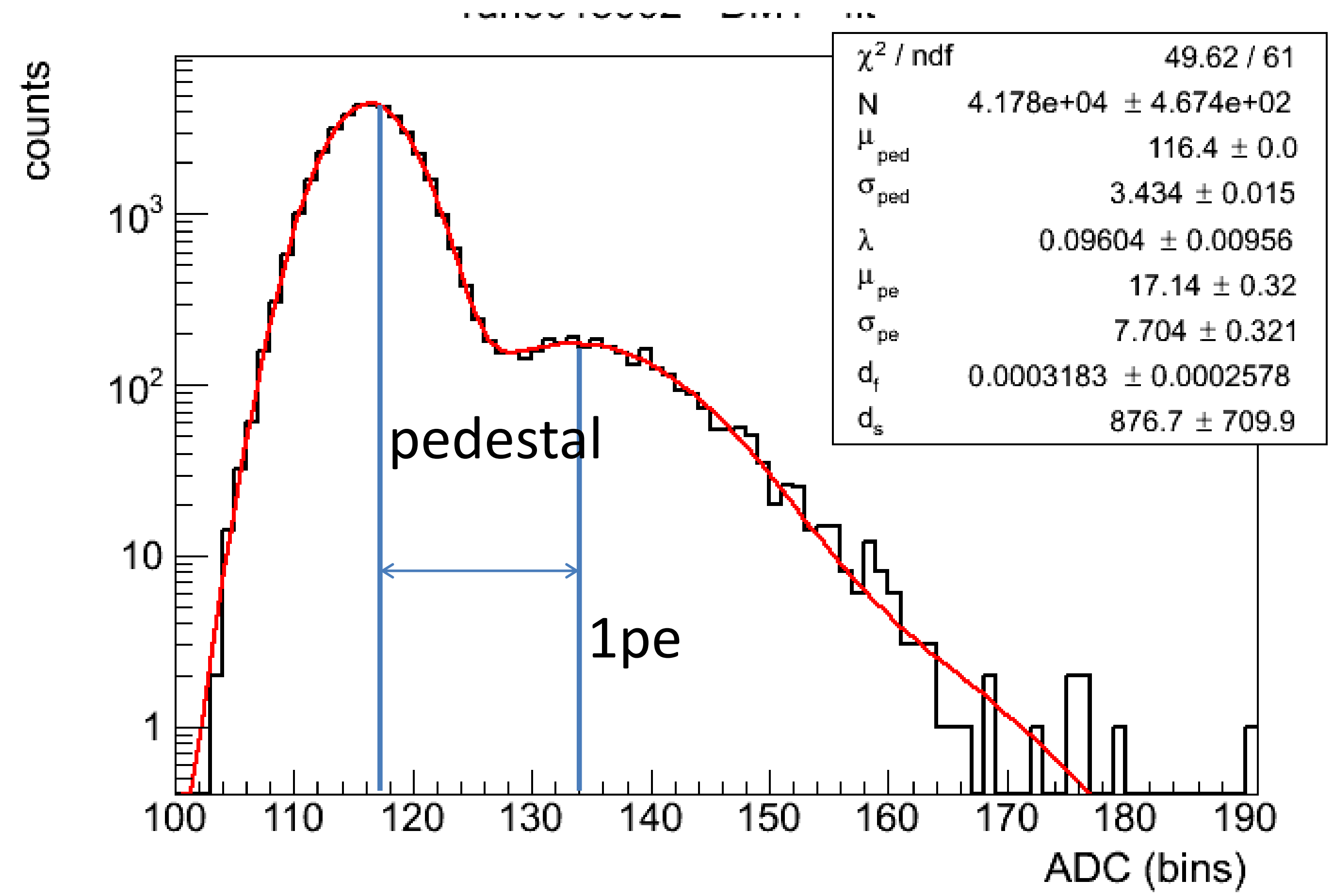




Cosmogenic lines verify our energy calibration; this is particularly useful for the prototype since we do not have an in-ice source.

NaI Light Yield

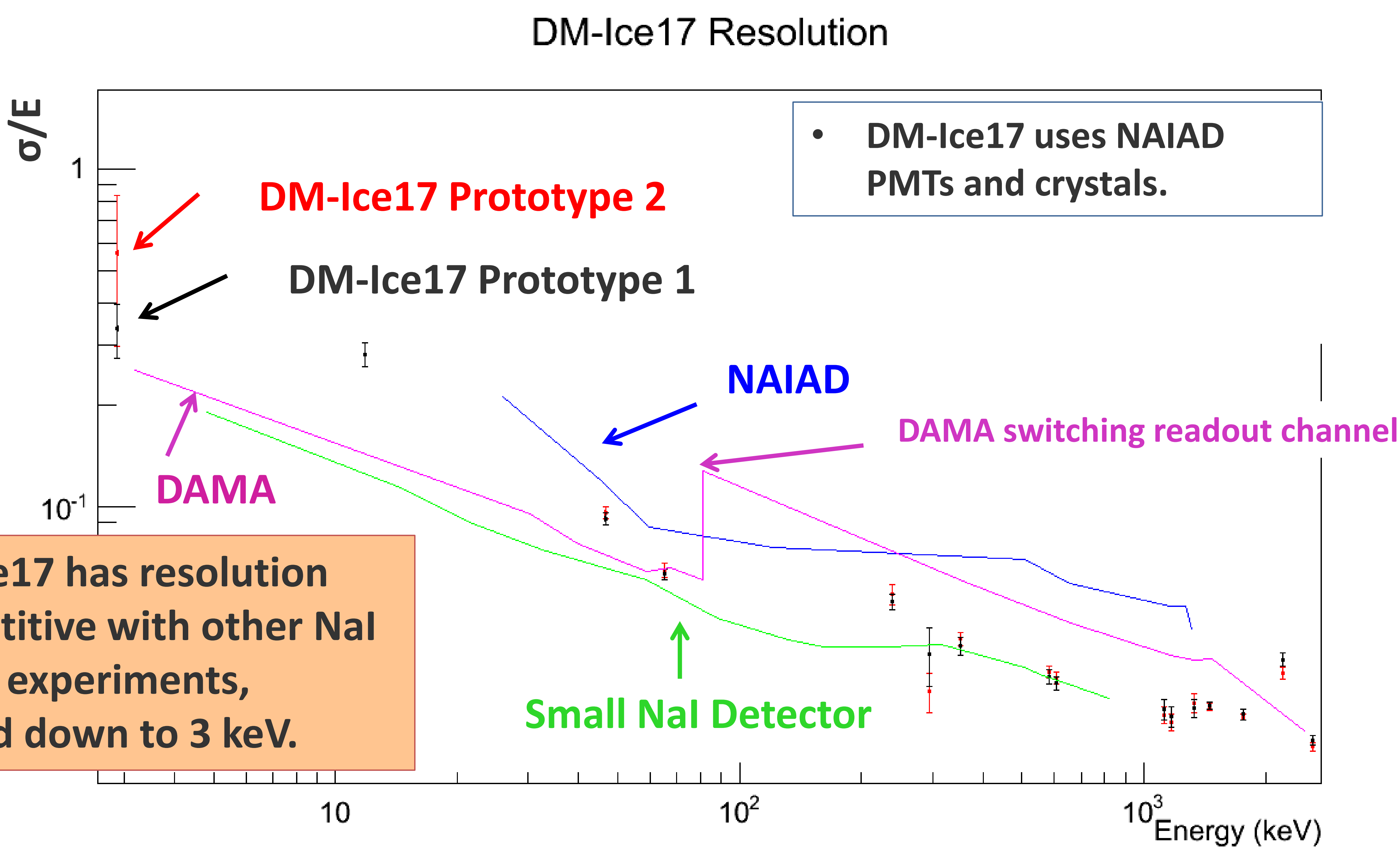
- **Obtain 1pe-ped separation from dark noise runs (ie no coincidence requirement)**
- **Normalize the energy to keV using the energy calibration**



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**

Energy Resolution



- 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.

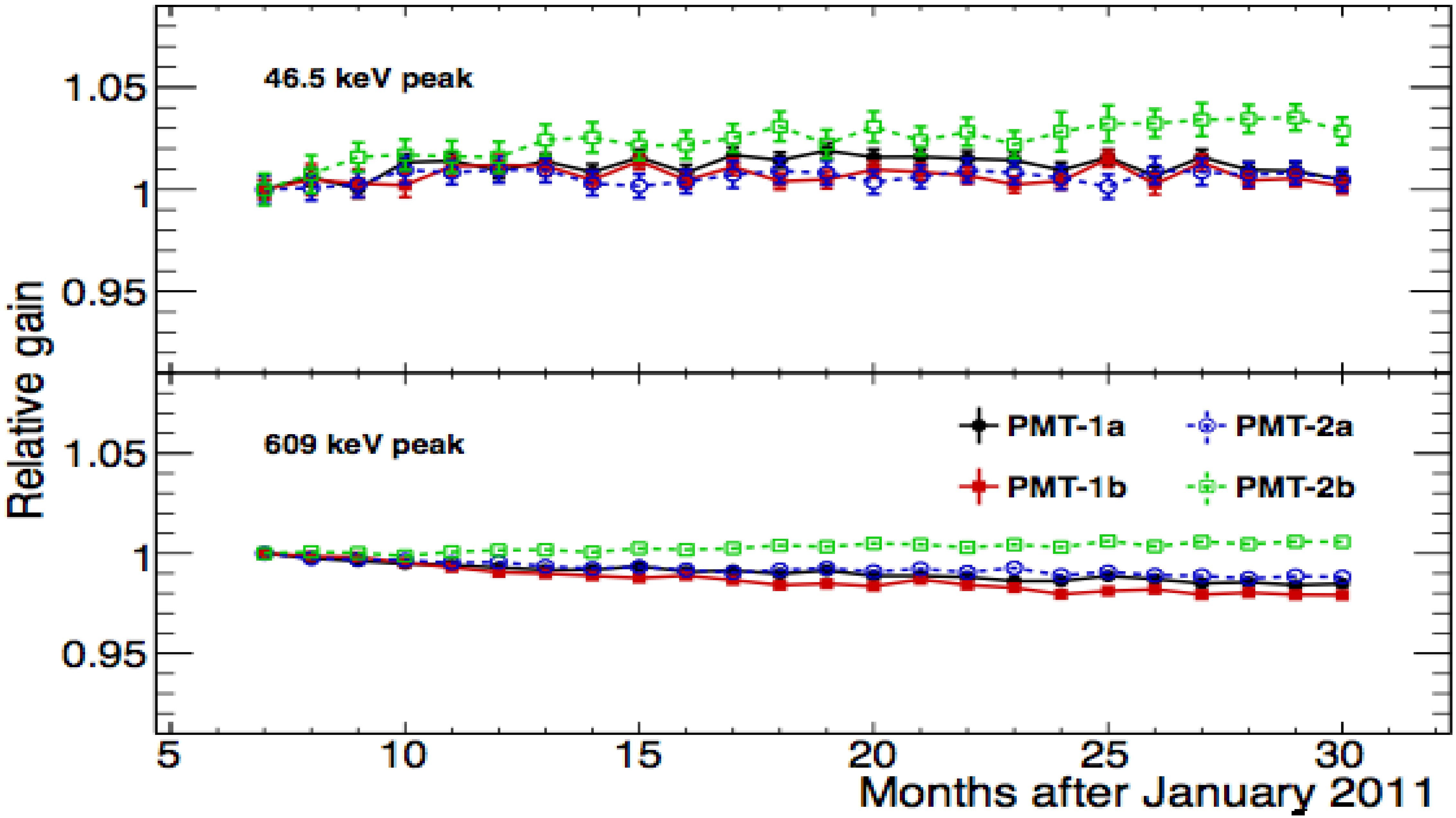
Small NaI: E. Sakai, IEEE Transactions on Nuclear Science NS-34 (1987) 418.

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.

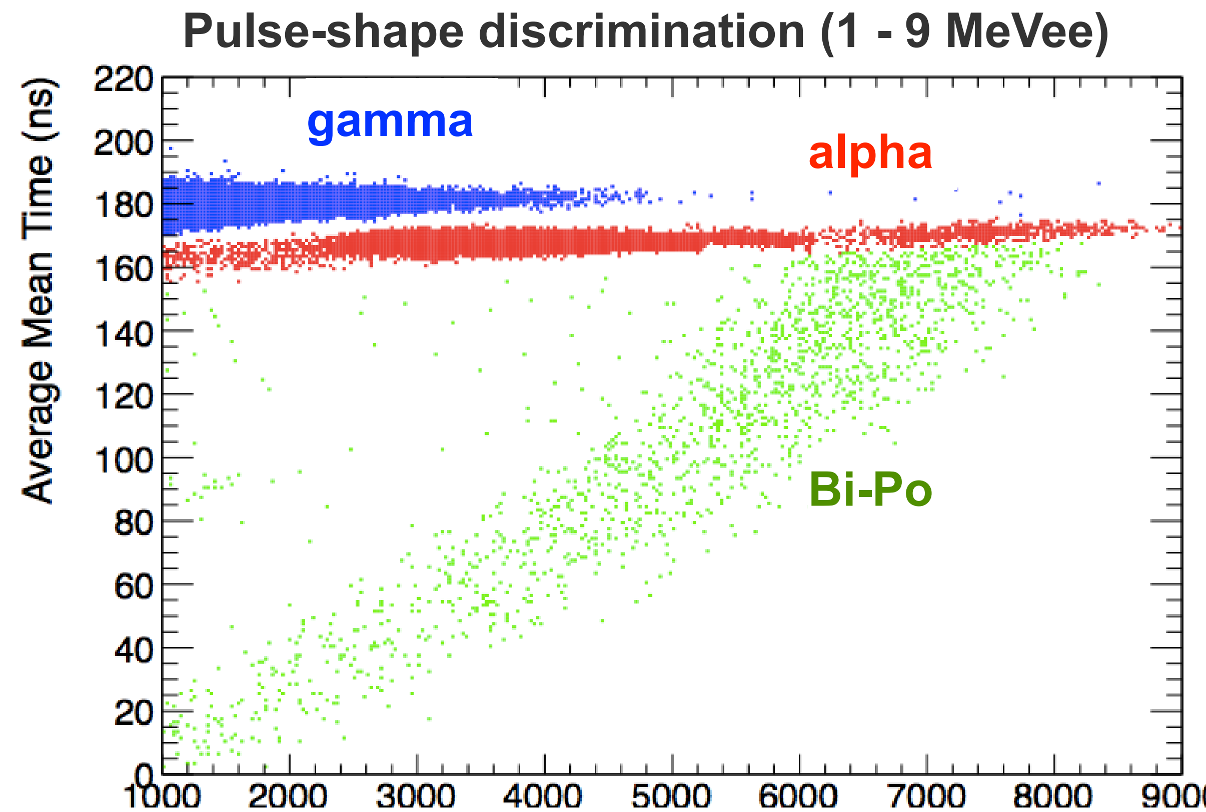
Detector Stability

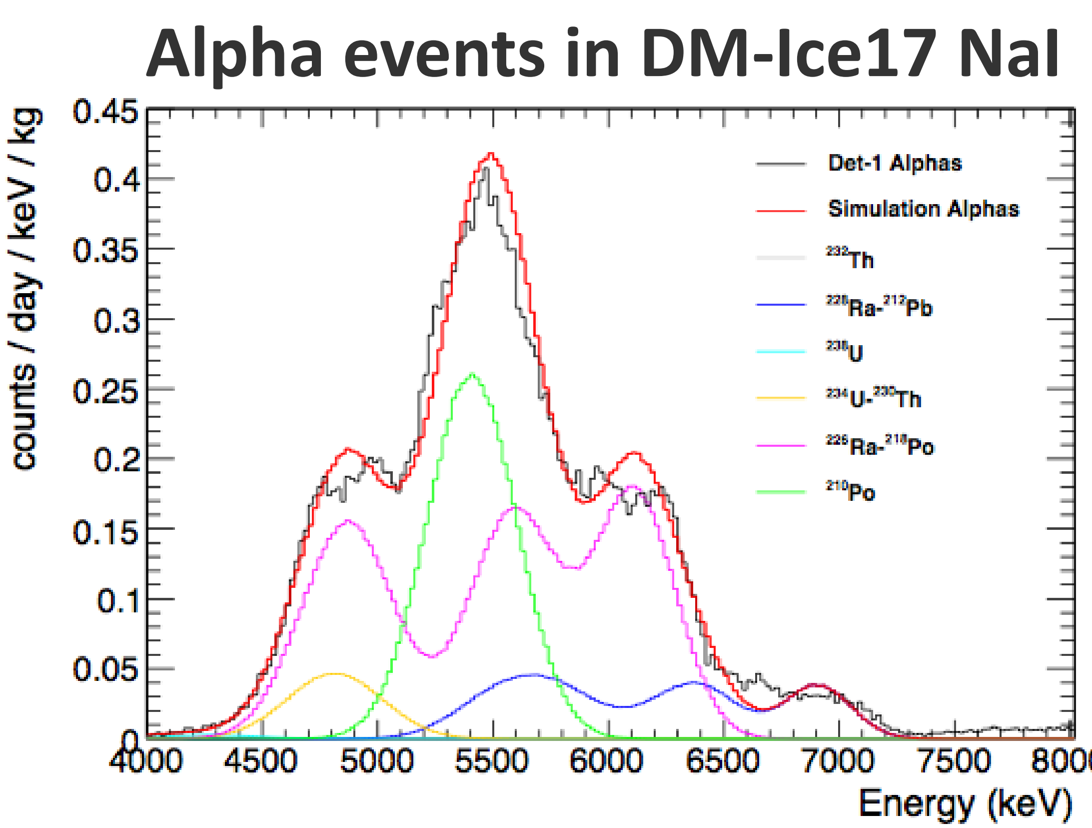
- Energy calibration is stable to 1.3% over 18 months.
  - 1.3% decrease over 18 months in light collection (peak position) observed at 600 and 1460 keV
  - No significant change in calibration at 45 keV

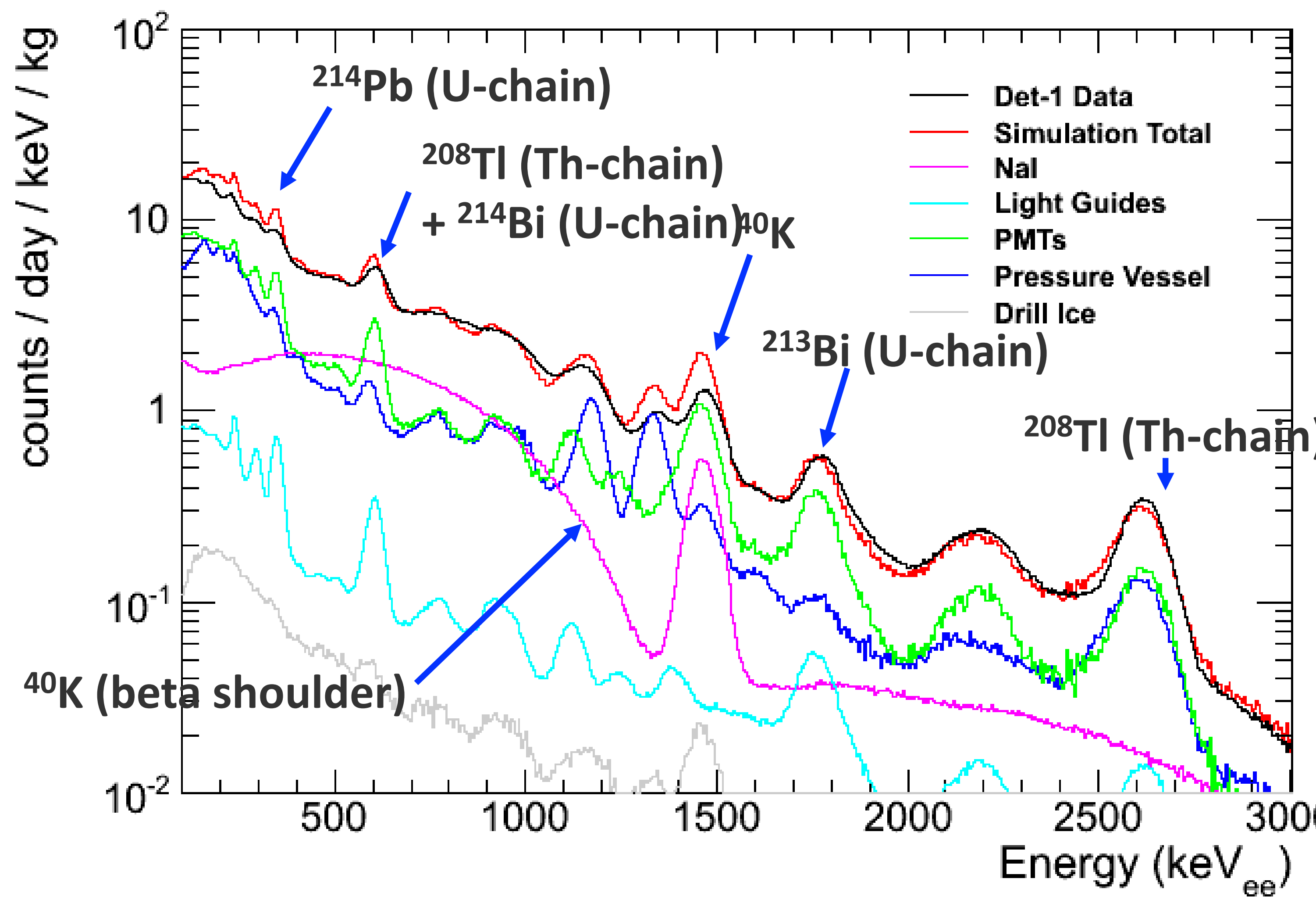


Spectrum vs. Simulation

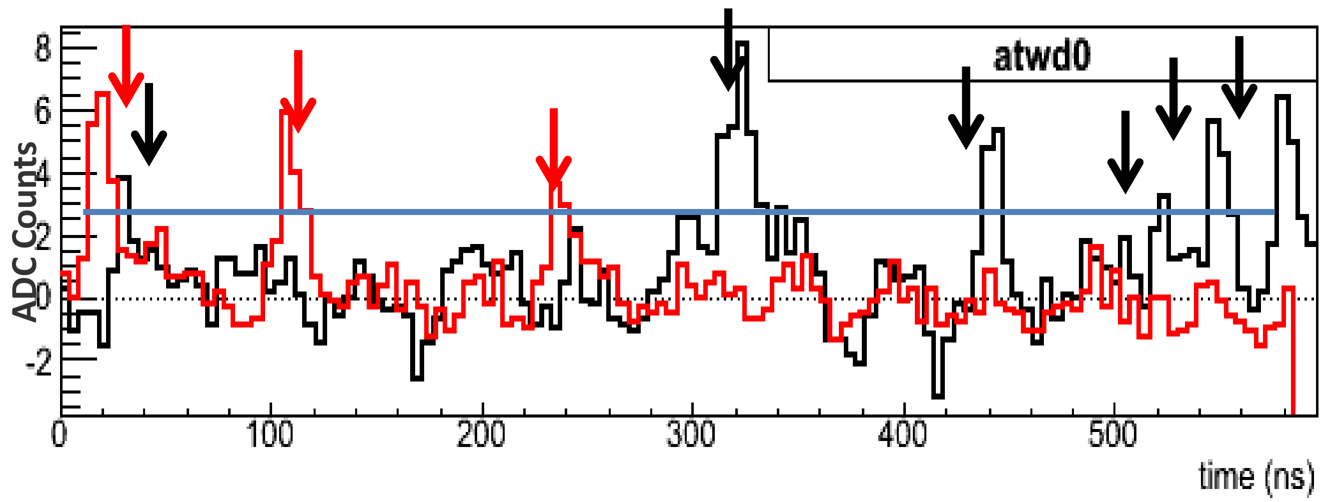
- Good agreement with simulation
- Simulation based on:
  - NaI from alphas and K from data
  - HPGe measurement of spare parts





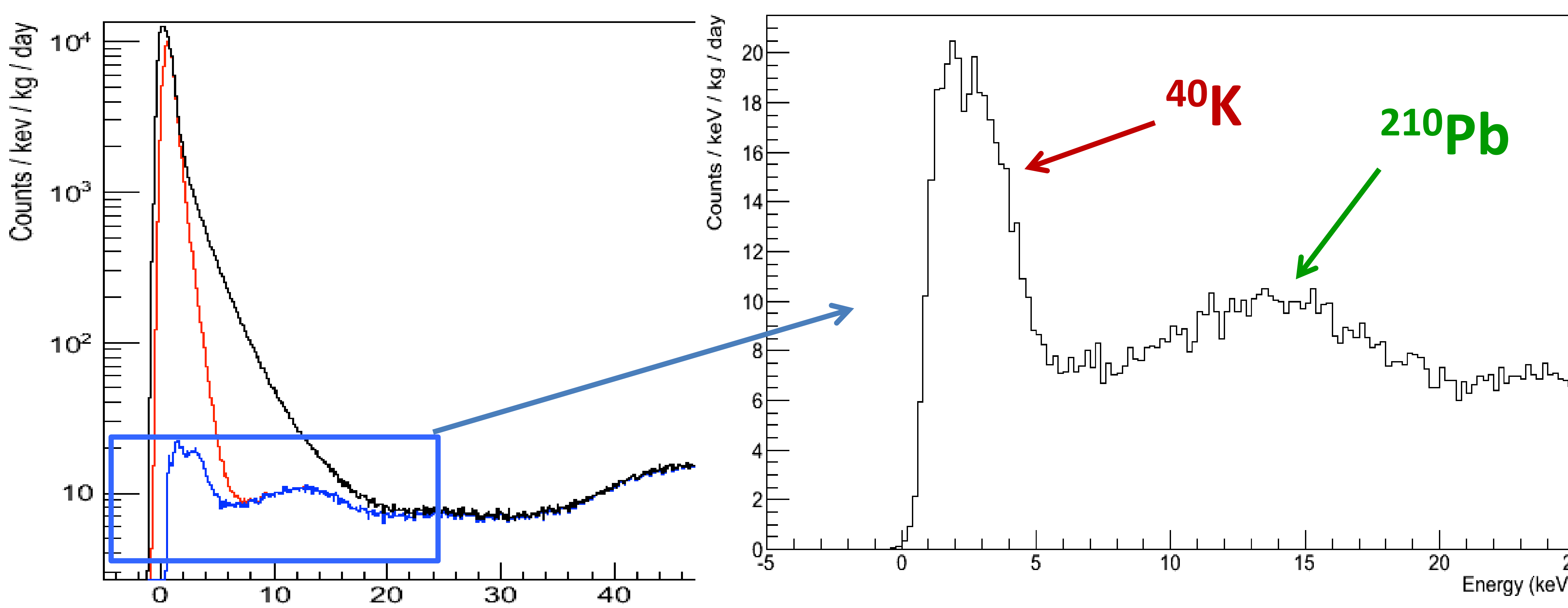


“Peak Finding” Cut

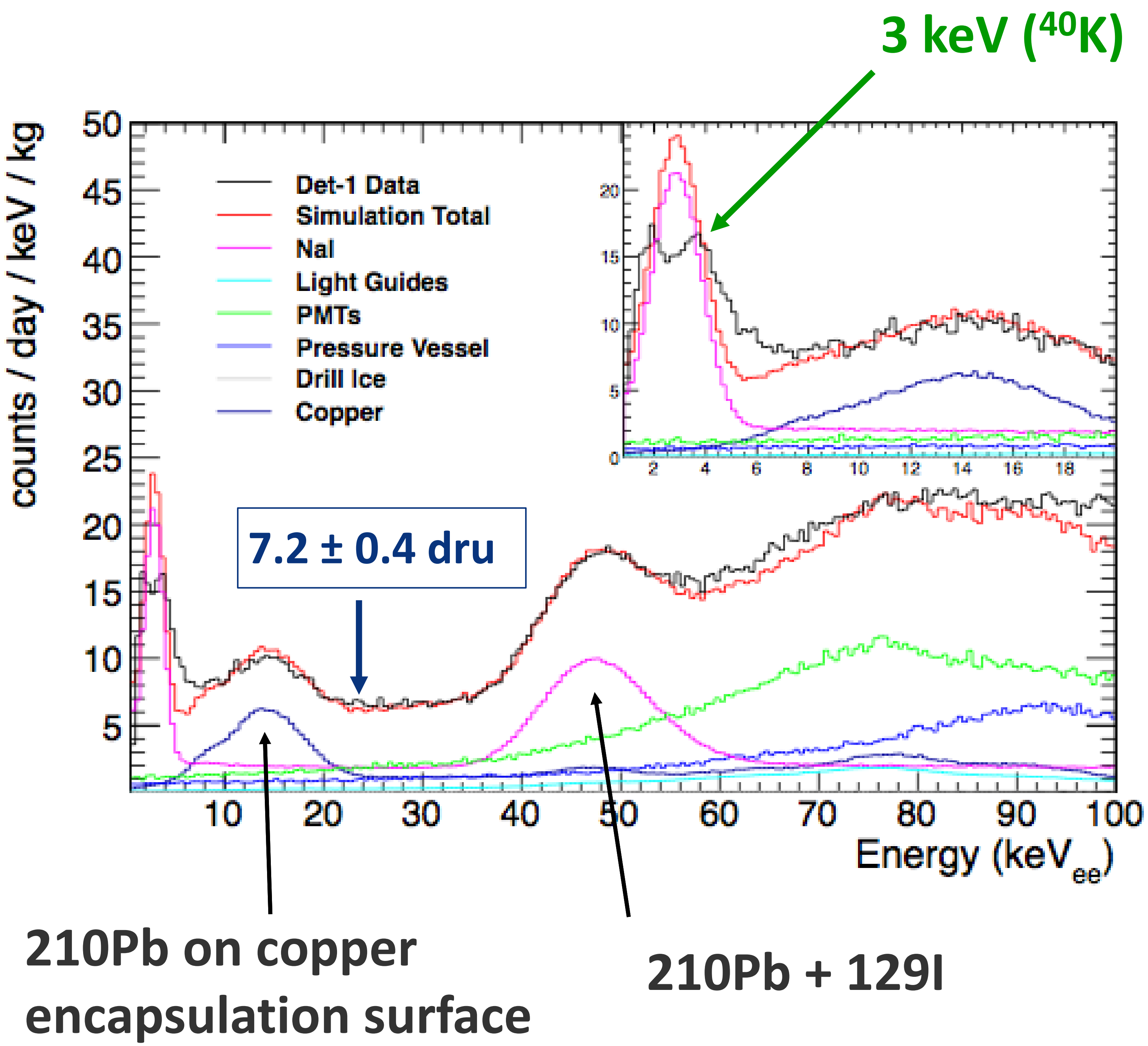


- **Beat down non-scintillation sources of noise**

Energy Spectrum after Peak Finding Cut



Region of Interest



- Good agreement with simulation above 8 keV
- We understand our detector to 4 keV
- Understanding cut efficiencies <8 keV in progress

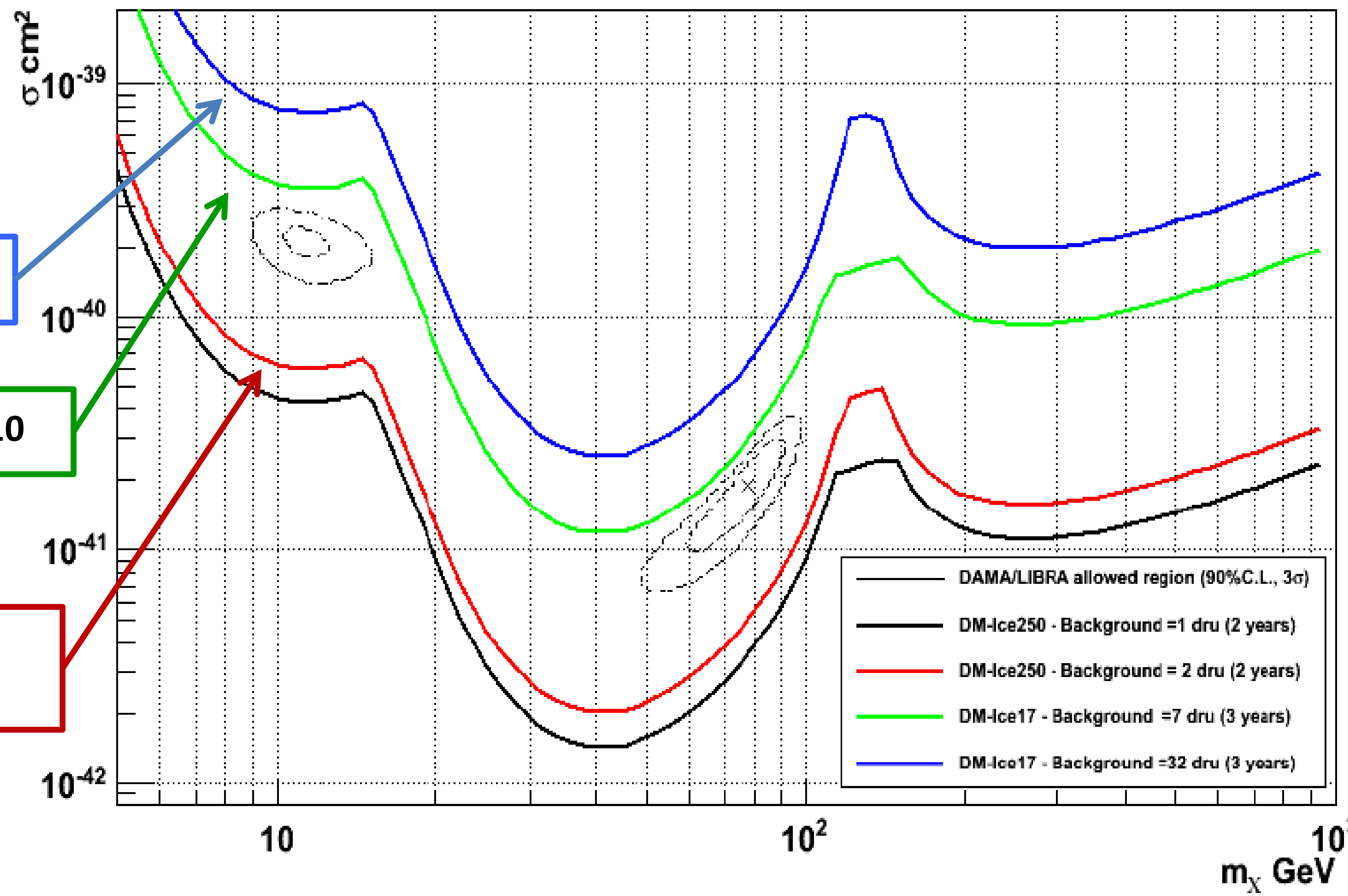
Where does that put us now…

- DM-Ice17 sensitivity is limited by internal K40 and surface Pb210
  - We knew this would be the case using NaI with ~10x higher internals
  - DM-Ice17 was a technical proof of principle for South Pole deployment
- Next phase is for NaI R&D to push those internal backgrounds down

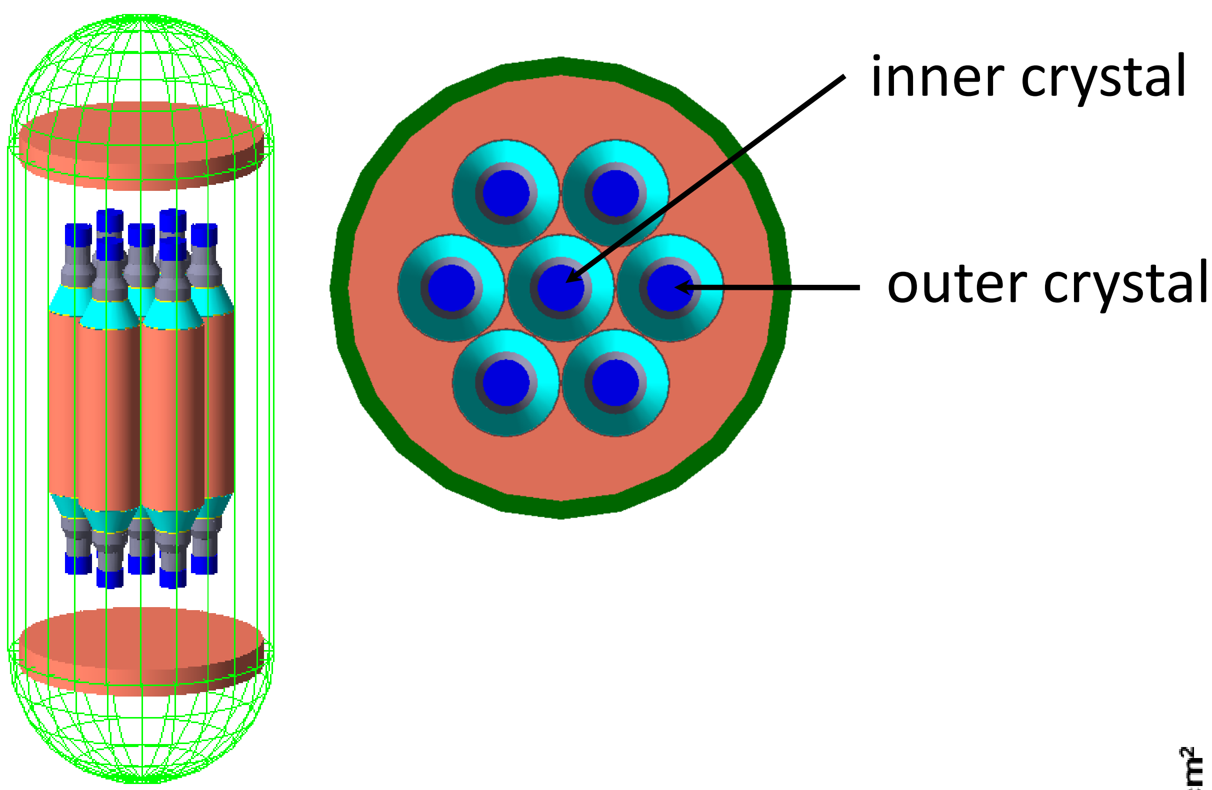
2-4 keV region dominated by K40

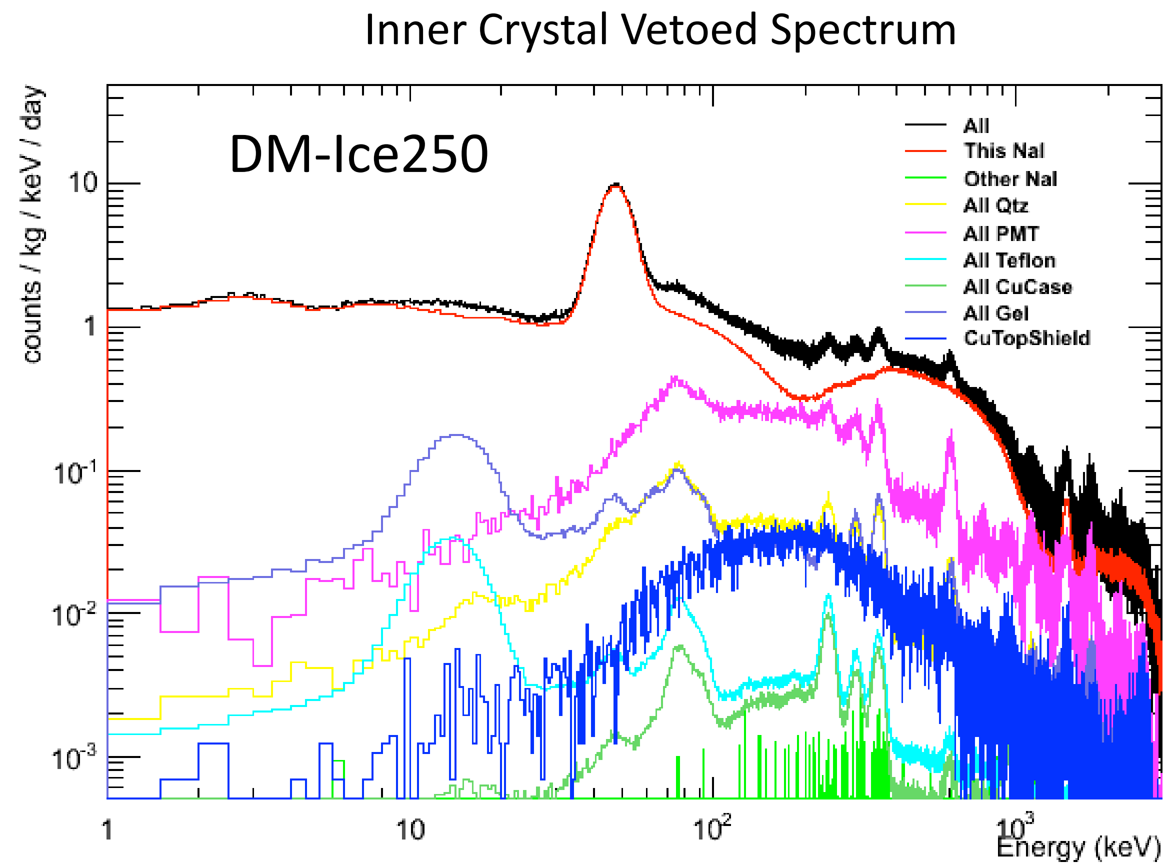
4-8 keV region dominated by Pb210

With cleaner NaI, we'll be able to make significant claims



DM-Ice250 Simulations

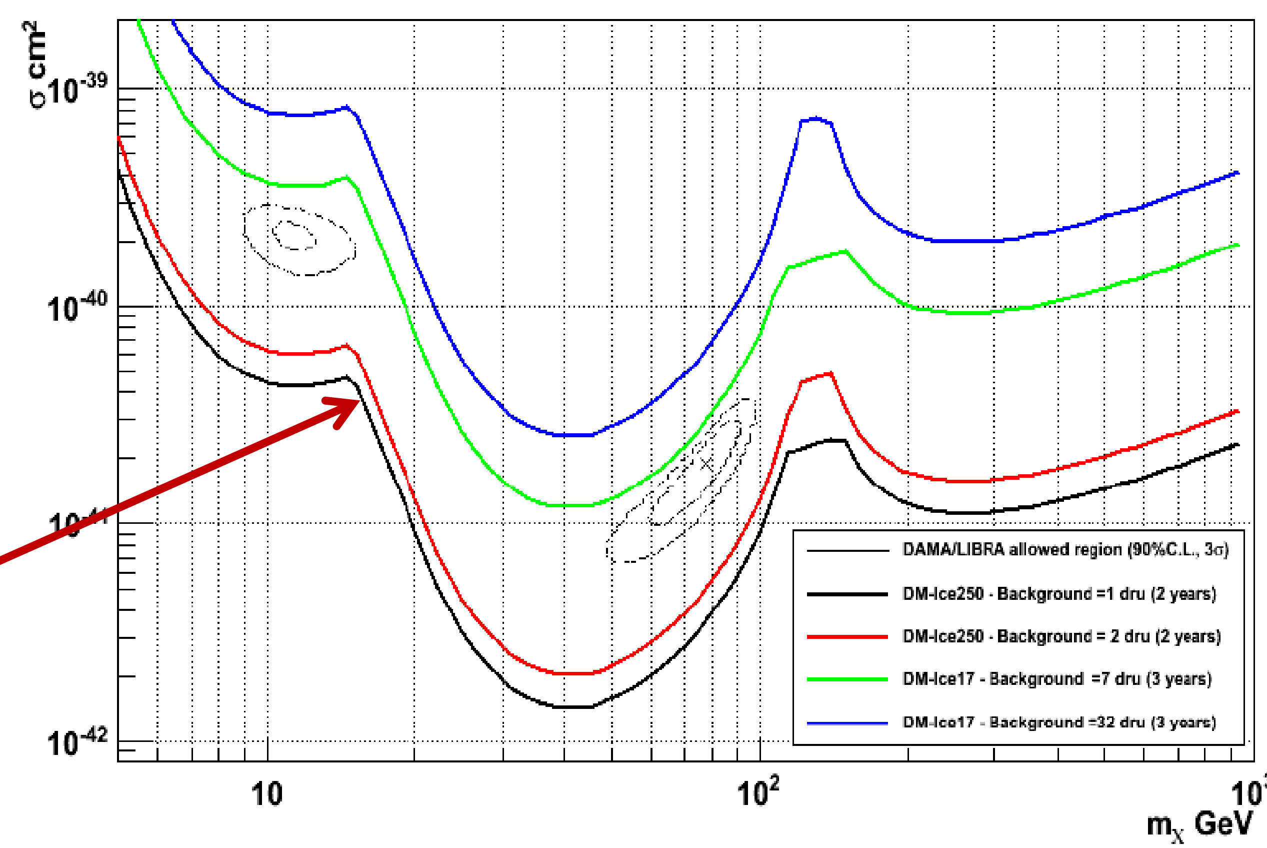




Simulations with conservative bkgs show:

2-6 keV region: 1.75 dru average

Puts us in the "Champagne" region



Moving forward…

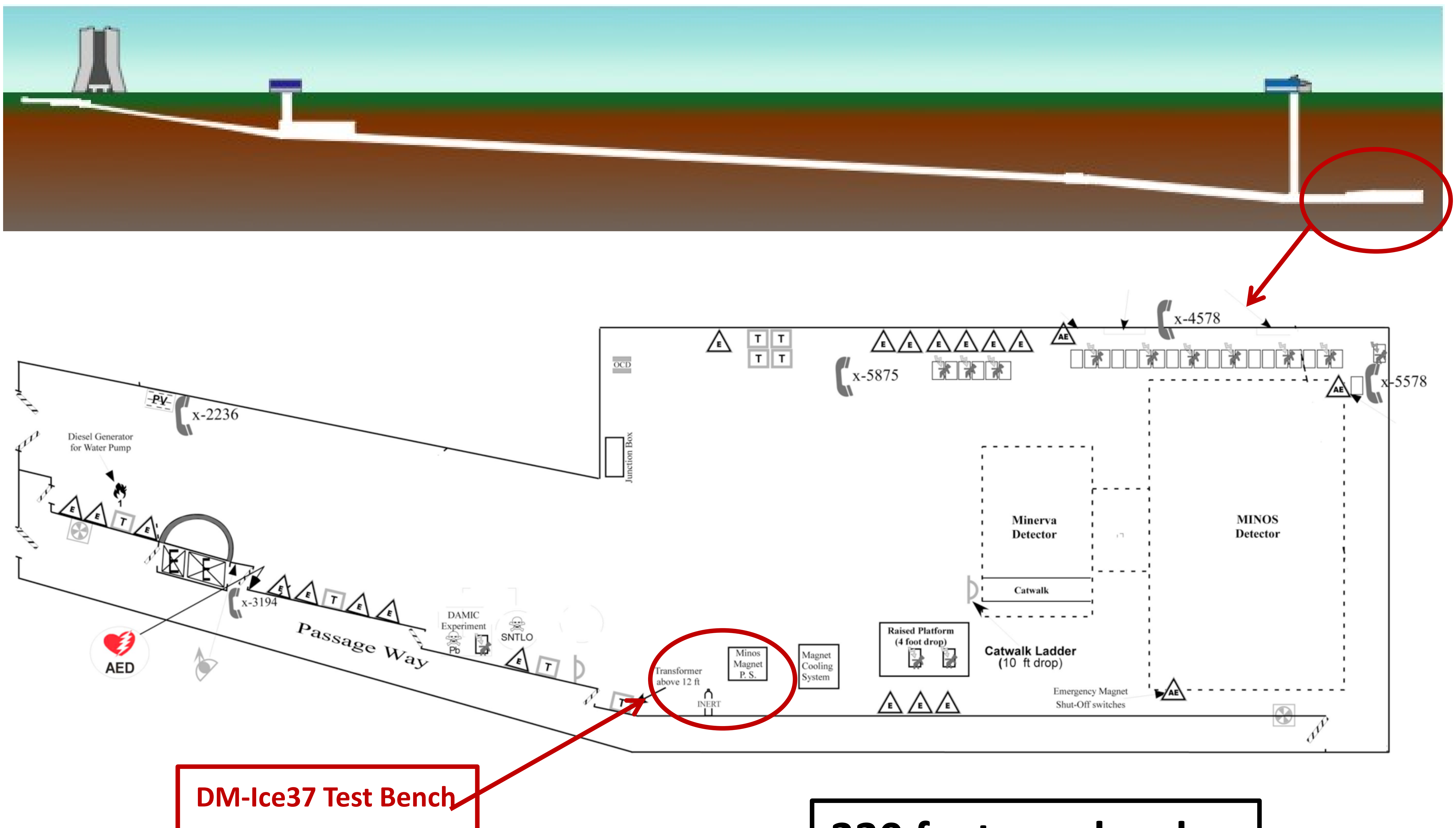
- Internal backgrounds dominate, particularly 3 keV ^{40}K
- DAMA's crystals (NIMA 592 (2008) 297– 315) :
  - ^{238}U : 1 - 10 ppt
  - ^{232}Th : 1 - 10 ppt
  - ^{nat}K : < 20 ppb
- NAIAD (DM-Ice17) crystals : 5 - 10x DAMA bkg

  (PLB 616 (2005) 17–24)

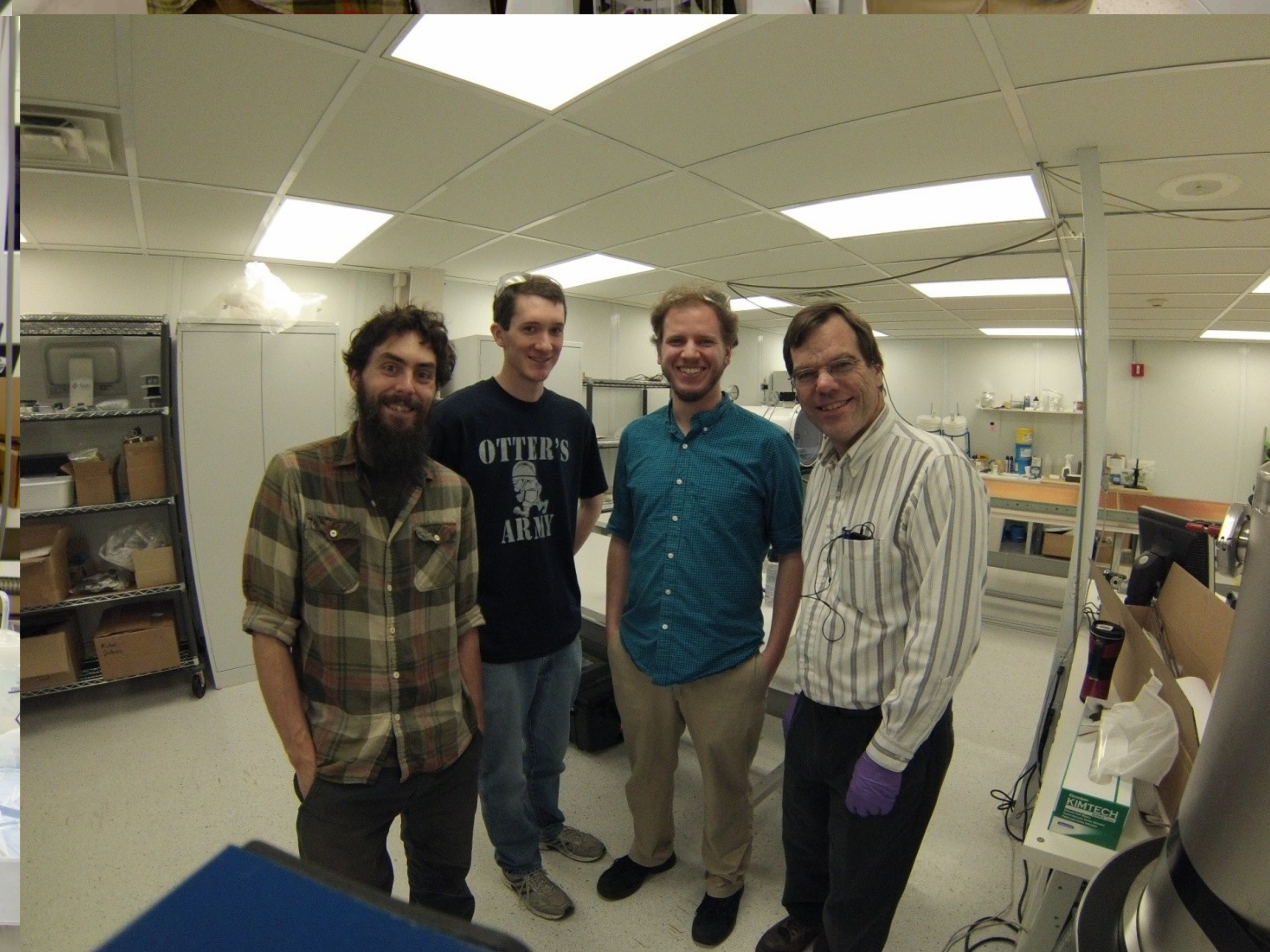
Manufacturer	Form	Measurement	^{238}U (ppt)	^{232}Th (ppt)	^{nat}K (ppb)
Saint Gobain	Powder	DAMA (HPGe)	< 20	< 20	< 100
Saint Gobain	Crystal	DAMA/LIBRA	0.7 - 10	0.5 - 7.5	< 20
Saint Gobain	Crystal	ANAIS-0	6.1	3.2	410
Saint Gobain	Crystal	DM-Ice (FNAL)			
Sigma-Aldrich	Powder (standard grade)	DM-Ice (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

DM-Ice37 at FNAL

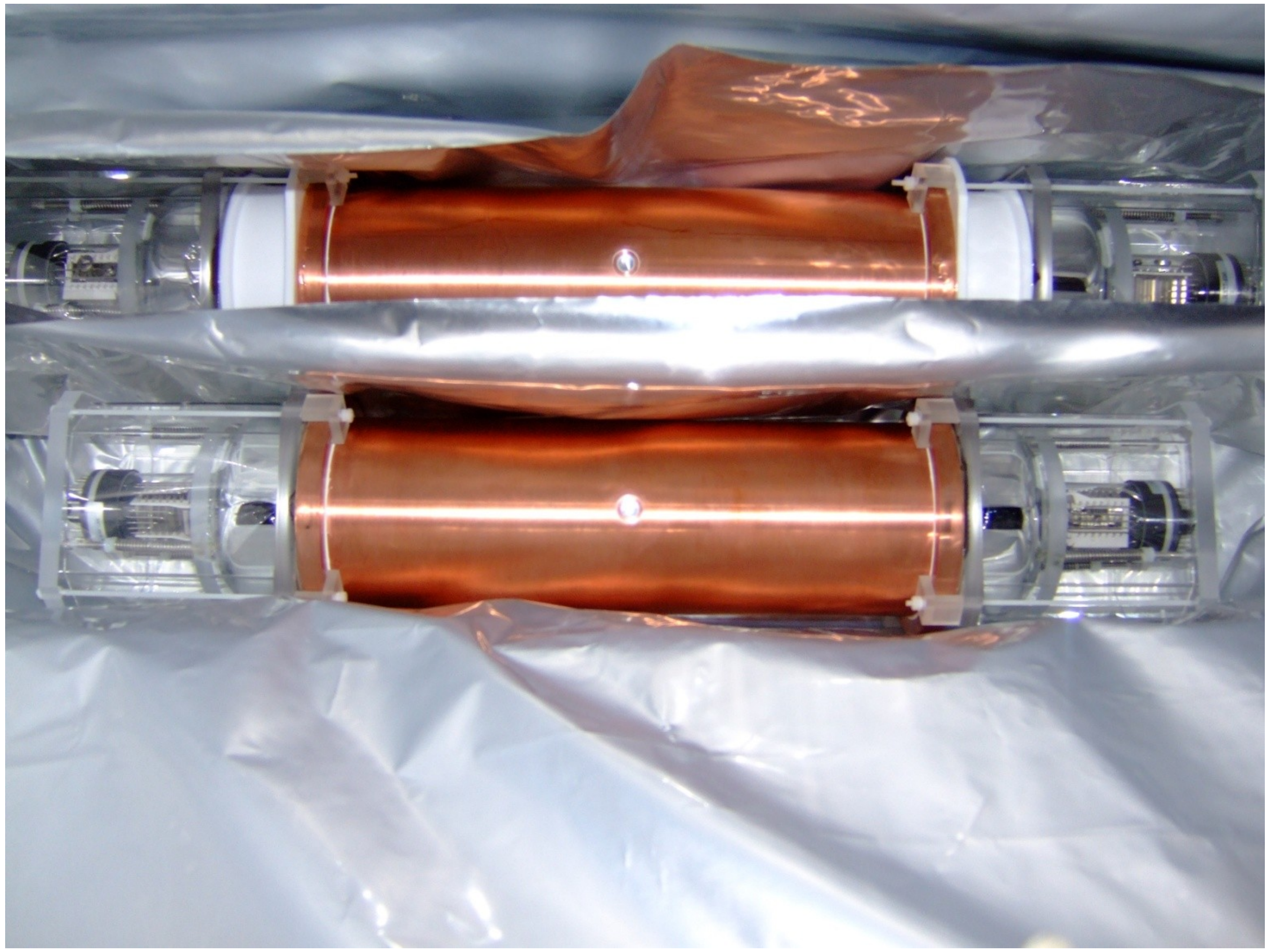
- Crystal R&D
- NaI Purity Measurements
- Multi-crystal K40 veto



330 feet overburden


OTTER'S
ARMY

DM-Ice37 Preliminary Results



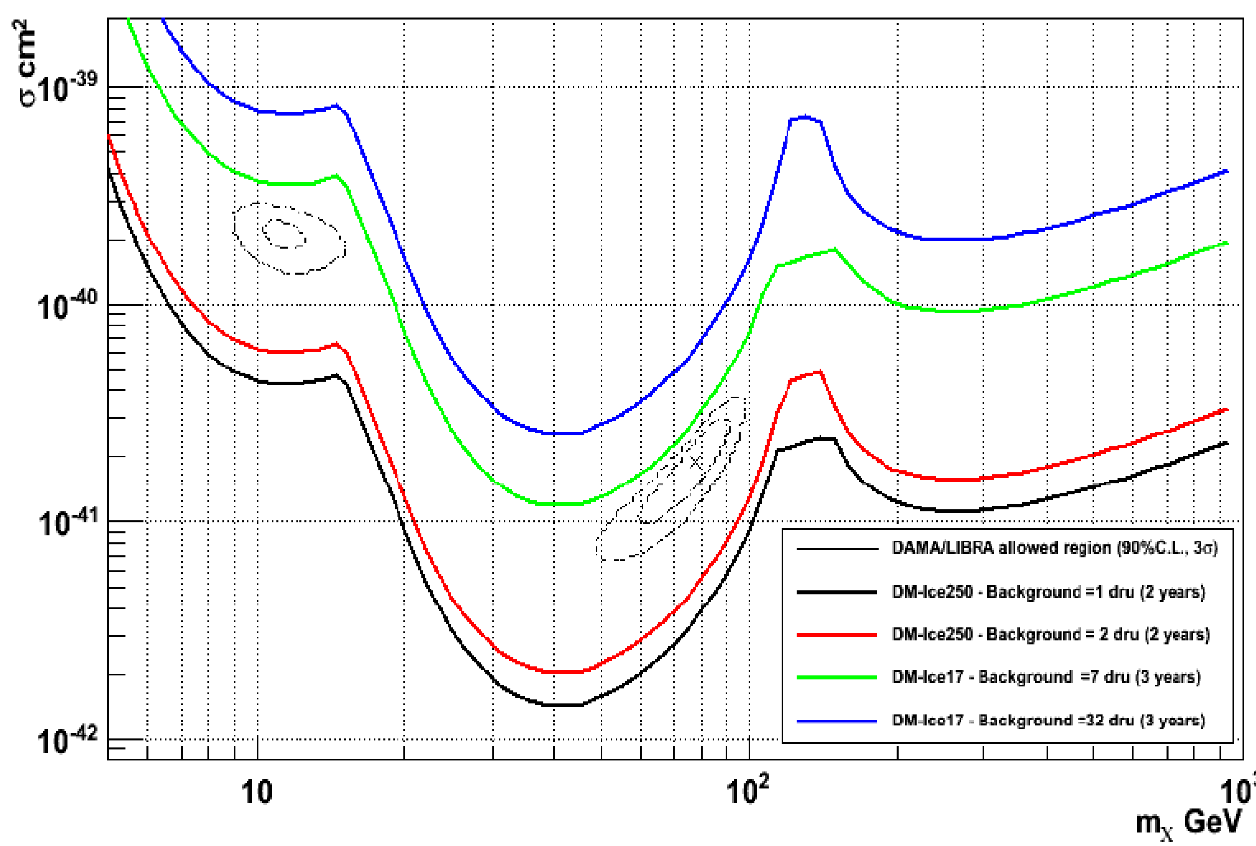
- Backgrounds < 2 dru
- Sufficient to test the DAMA > 5σ with 3 years of data
- Alpha-Spectra can have 250kg ready in 12 months

Conclusions

- **DM-Ice17** is performing better than expected
  - Confirmed the feasibility for South Pole deployment
  - Environmental stability is much better than underground locations
  - Seasonal effects have opposite phase (ideal for Dark Matter detection)

- **DM-Ice37** is meeting expectations
  - Backgrounds < 2 dru
  - Crystal growth can meet our 12 month goal
  - In 3 years with 250kg we can make a 5 sigma statement about the DAMA result

- **DM-Ice250** is going to happen
  - Everyone wants to see a significant Southern Hemisphere result
  - An in-ice detector mitigates effects of Radon, spallation neutrons, external backgrounds, ect.
  - It can make a very strong statement about dark matter



University of Wisconsin – Madison

Reina Maruyama, Francis Halzen, Karsten Heeger, Albrecht Karle, Carlos Pobes, Walter Pettus, Zachary Pierpoint, Antonia Hubbard, Bethany Reilly, Matthew Kauer

University of Sheffield

Neil Spooner, Vitaly Kudryavtsev, Dan Walker, Matt Robinson, L. Thompson, Sam Telfer, Calum McDonald

University of Alberta

Darren Grant

Shanghai Jiao Tang University

Xiangdong Ji, Changbo Fu

Penn State

Doug Cowen, Ken Clark

NIST-Gaithersburg

Pieter Mumm

University of Stockholm

Chad Finley, Per Olof Hulth, Klas Hultqvist, Christian Walach

University of Illinois at Urbana-Champaign

Liang Yang

Fermilab

Lauren Hsu

DigiPen

Charles Duba, Eric Mohrmann

Boulby Underground Science Facility

Sean Paling

SNOLAB

Bruce Cleveland

Physical Sciences Laboratory
University of Wisconsin-Madison

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