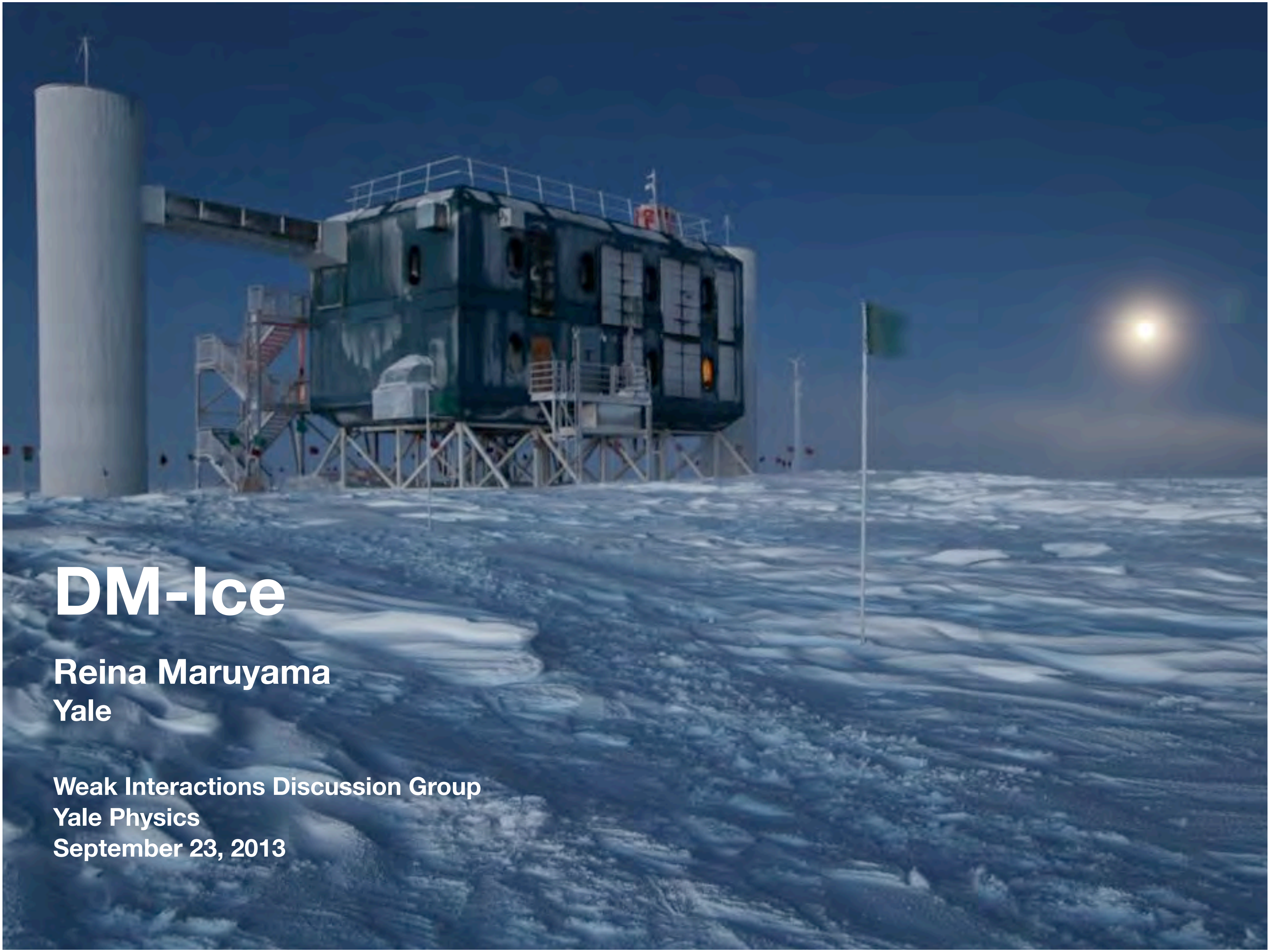


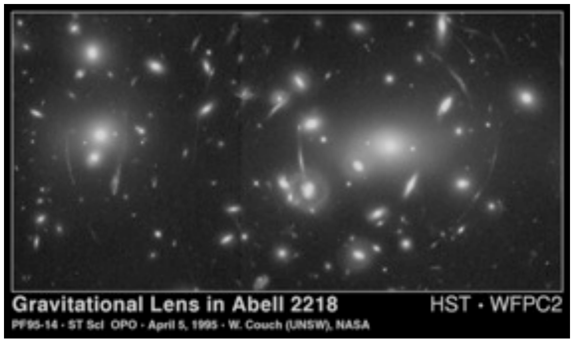
DM-Ice

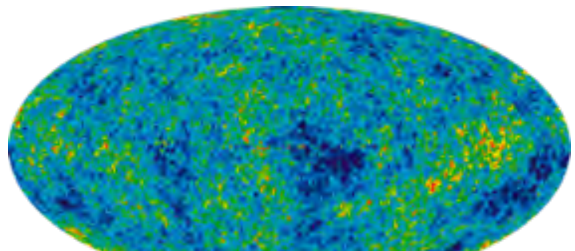
Reina Maruyama
Yale

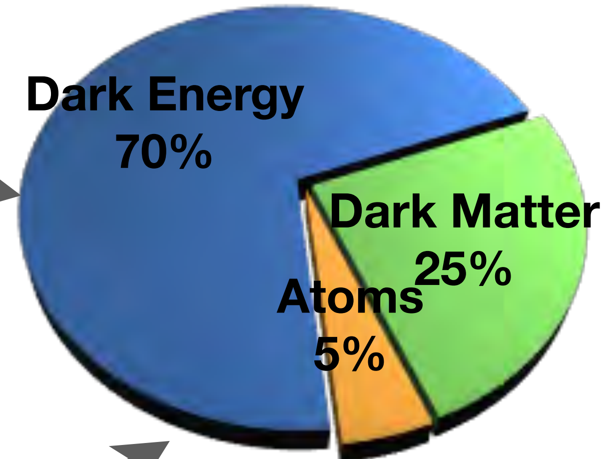
Weak Interactions Discussion Group
Yale Physics
September 23, 2013

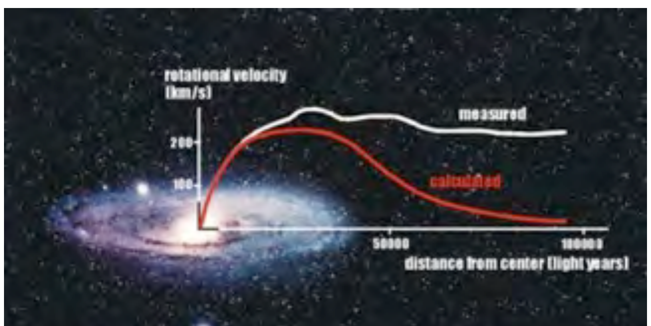
Evidence for Dark Matter

- Many gravitational evidence for dark matter

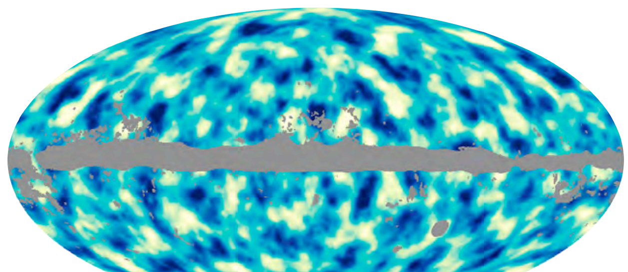


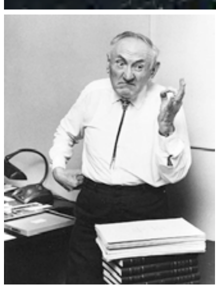

WMAP

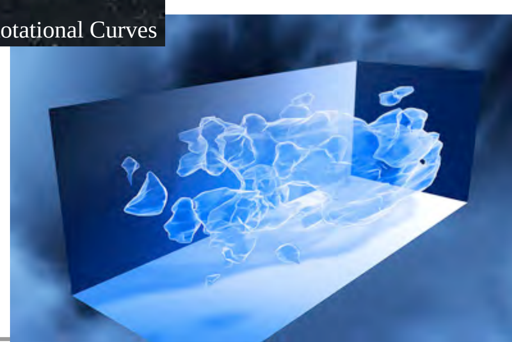




Rotational Curves


ESA Planck




COSMOS 3D

All consistent with ~25% dark matter (give or take).

But... what is it?

What is Dark Matter?

Observational evidence indicates:

- Non-baryonic
- Cold(ish) and massive (non-relativistic and exerts gravity)
- Interact little with ordinary matter
- Stable and long-lived

Leading Candidates:

Axions

- mass ~10^{-3} – 10^{-6} eV
- Arises in the Peccei-Quinn solution to the strong-CP problem

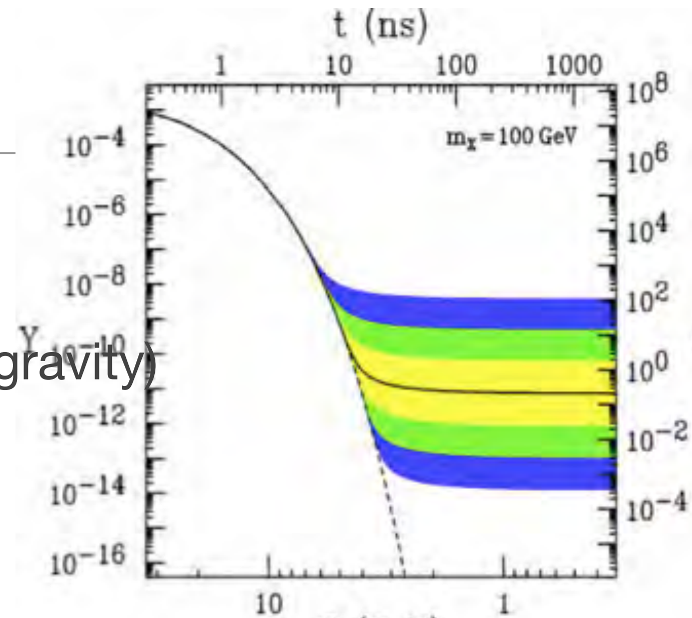
WIMPs: Weakly Interacting Massive Particles

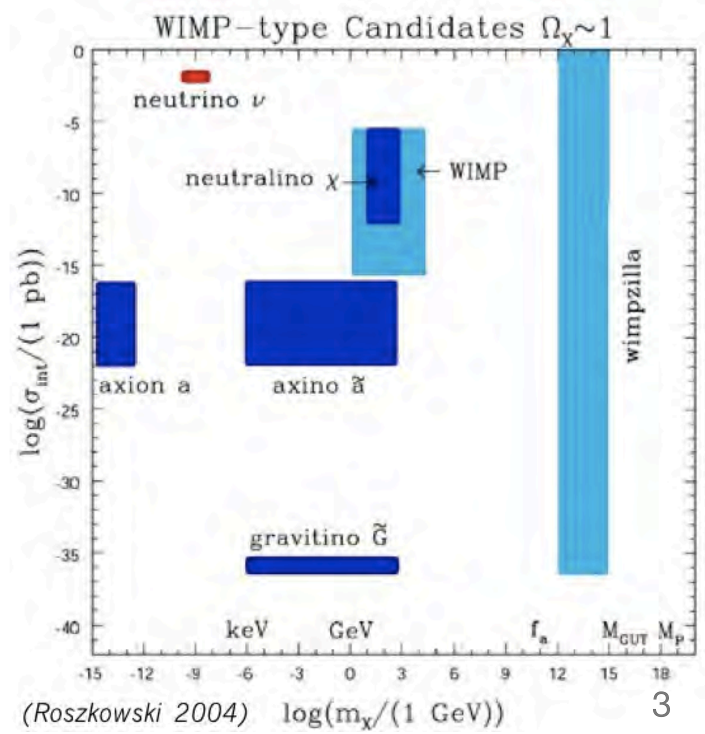
- mass of 1 GeV – 10 TeV
- weak scale cross sections results in observed abundance

$$\sigma \approx 10^{-39} - 10^{-46}\ \mathrm{cm}^2$$

$$\langle \sigma_A v \rangle \approx 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

$$m_\chi \approx 100\ \mathrm{GeV}$$





(Roszkowski 2004)

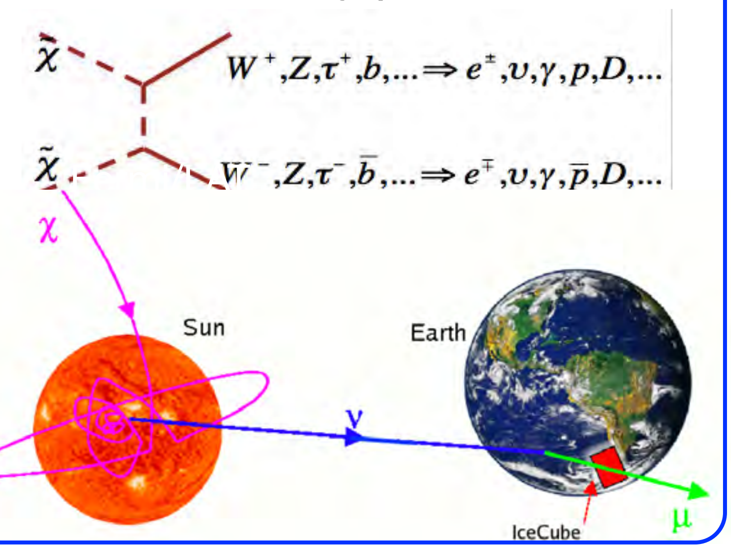
Detecting WIMPs

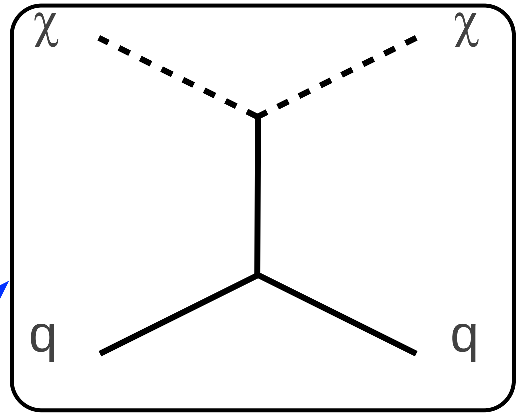
annihilation

“Indirect Detection”

Collect dark matter in Stars and Galaxies, then let them annihilate among themselves.

Detect the decay particles



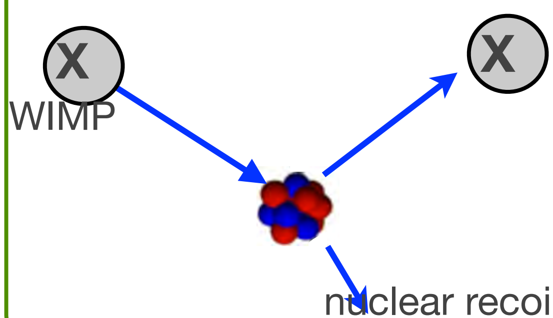


scattering

“Direct Detection”

Let dark matter recoil off of nuclei

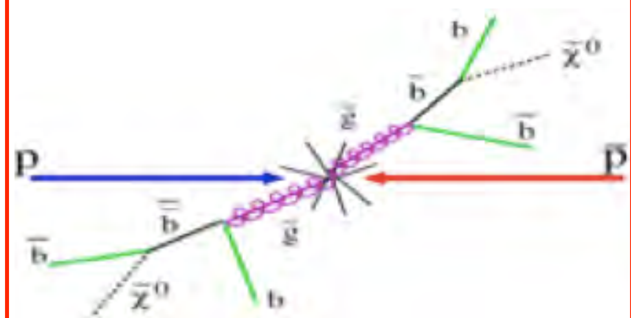
Look for nuclear recoil

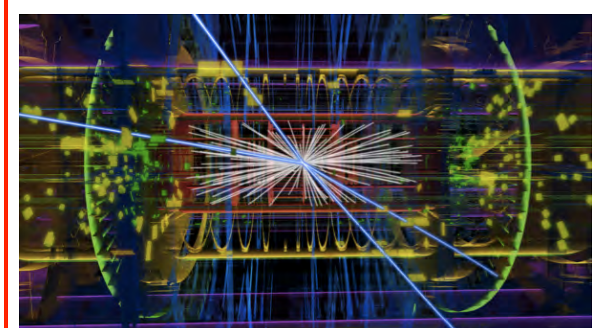


production

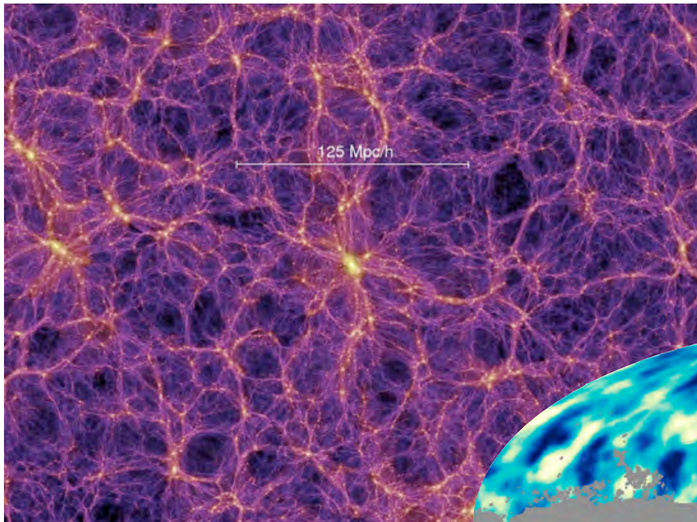
Colliders

Look for the missing energy

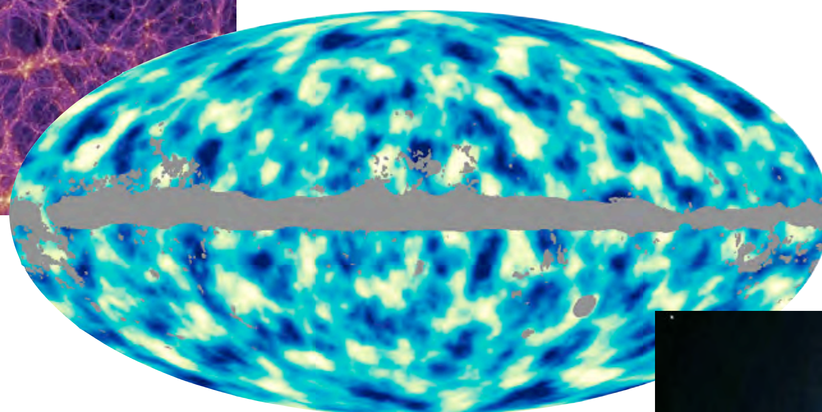




Dark Matter Distribution



Large scale dark matter distribution
Millenium Simulation
http://www.mpa-garching.mpg.de/galform/virgo/millennium/

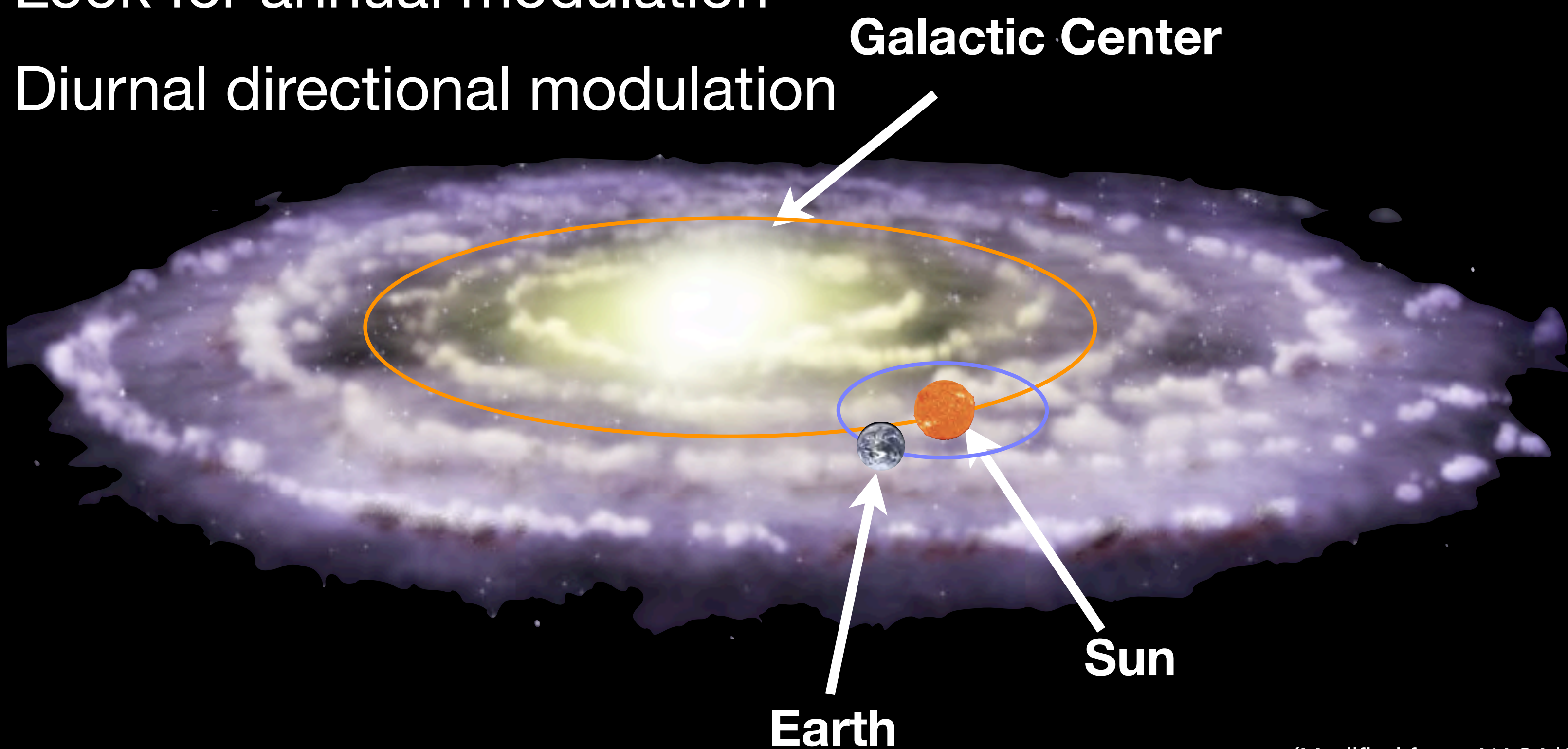


Planck all-sky image of the distribution of dark matter via distortions on CMB by gravitational lensing (April 2013)

Artist's impression of the Milky Way galaxy. The blue halo of material surrounding the galaxy indicates the expected distribution of dark matter. (ESO/Calçada)

Direct Detection Search Strategies

1. Count individual nuclear recoils
2. Look for annual modulation
3. Diurnal directional modulation



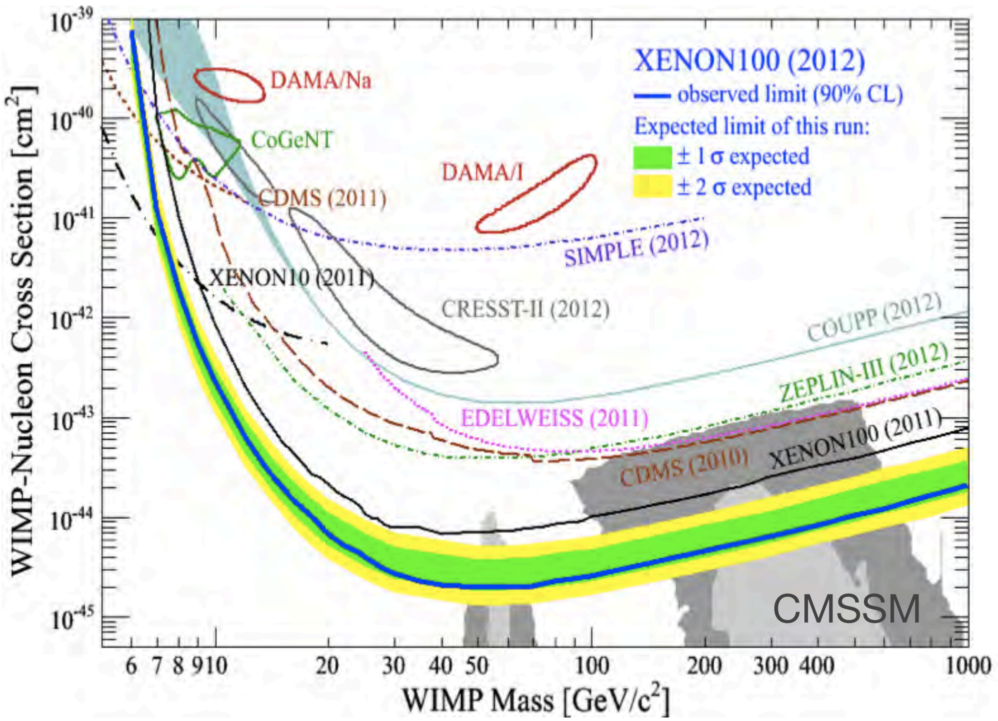
(Modified from: NASA/CXC/M.Weiss)

Direct Detection Experiments

Laura Baudis, University of Zurich   Neutrino 2012, Kyoto

7

“Tension” in Direct Detection Experiments



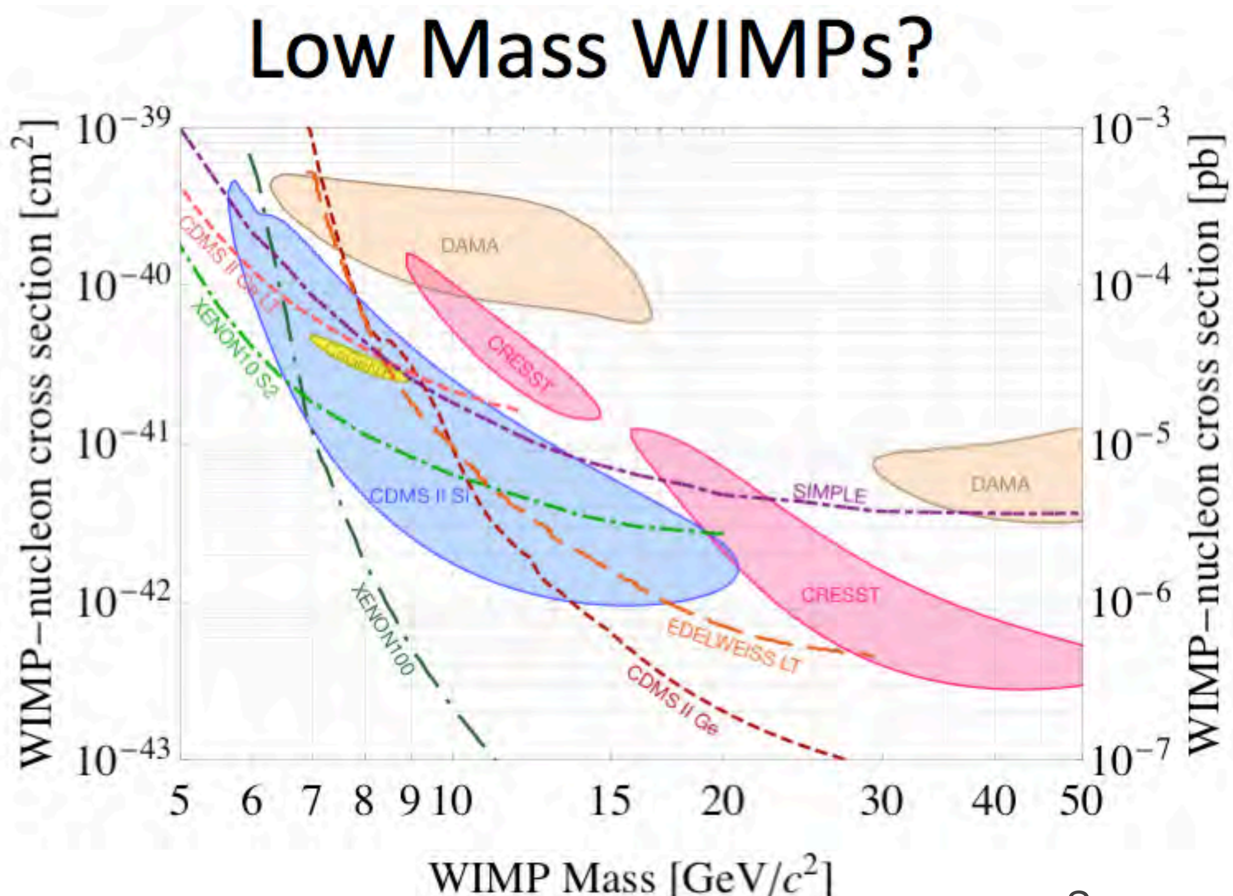
arXiv:1207.5988, PRL 109, 181301 (2012)

- Exclusion from CDMS, SIMPLE & XENON100
- Hints in CoGeNT and CRESST-II
- Claim for 9.3 σ signal from DAMA

Assumptions for this plot:

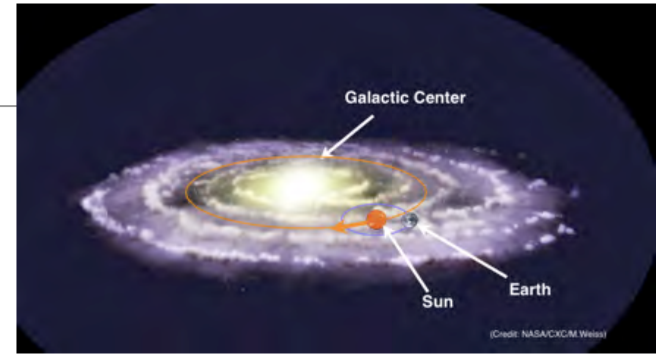
- Dark matter is made of WIMPs
- scattering is spin-independent
- elastic scattering off of nuclei
- WIMPs are distributed in an isothermal halo with:
  - v_0 = 220 km/s
  - v_{esc} = 544 km/s
  - ρ_X = 0.3 GeV/cm^3

Hints and Claims for Direct Detection of DM



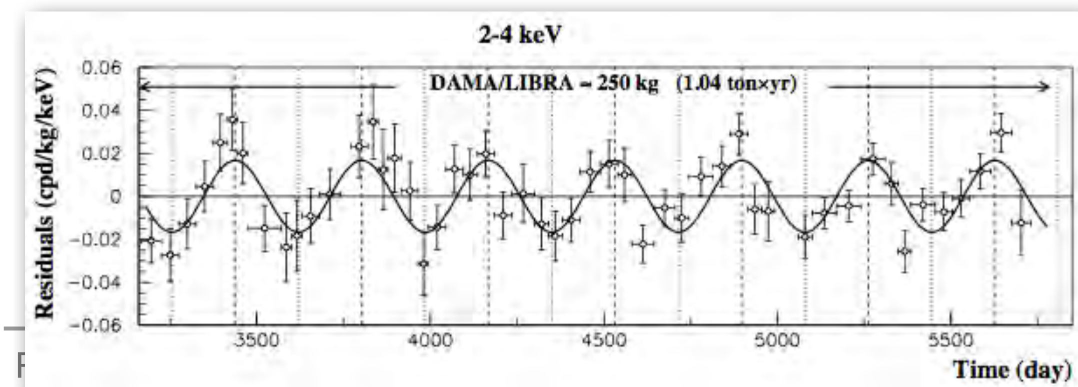
Snowmass 2013

Modulation Observed by DAMA



9.3 σ modulation observed

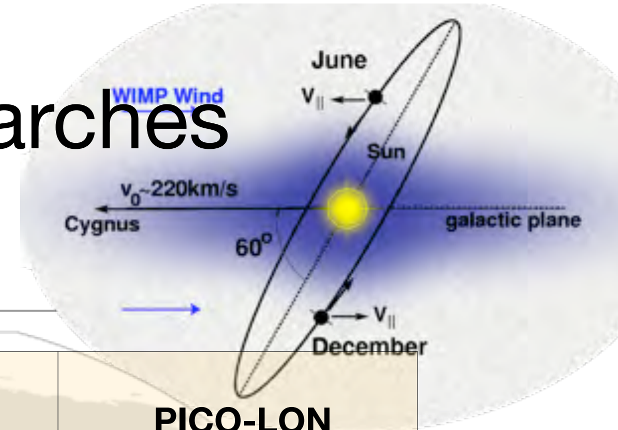
- Modulation consistent with dark matter:
  - **Phase:** 144 ± 7 days (peak on May 24)
  - **Period:** 0.998 ± 0.002 yr
  - **Background:** ~ 1 cnts/keV/kg/day
  - **Amplitude:** 0.0112 ± 0.0012 cnts/keV/kg/day
- Two generations:
  - DAMA/NaI: 100 kg (1996 - 2003)
  - DAMA/LIBRA-phase1: 250 kg (2003 - 2010)
- 1.33 ton-yr over 14 annual cycles



but is it dark matter?

arxiv:1308.5109

Annual Modulation Dark Matter Searches with NaI Detectors



Northern Hemisphere	Gran Sasso **DAMA/Libra** 250kg running	Gran Sasso **Princeton-NaI** R&D	Canfranc **ANAIS** 250 kg starting in 2014?	**PICO-LON KIMS** etc...
Southern Hemisphere	South Pole **DM-Ice** 17 kg running R&D for 250 kg	**ANDES** Lab (proposed) expected start ~~2018~~ 2017		

ice rock
under development

Several Groups conducting ultra-pure crystal with several vendors to go to the full scale

DM-Ice:

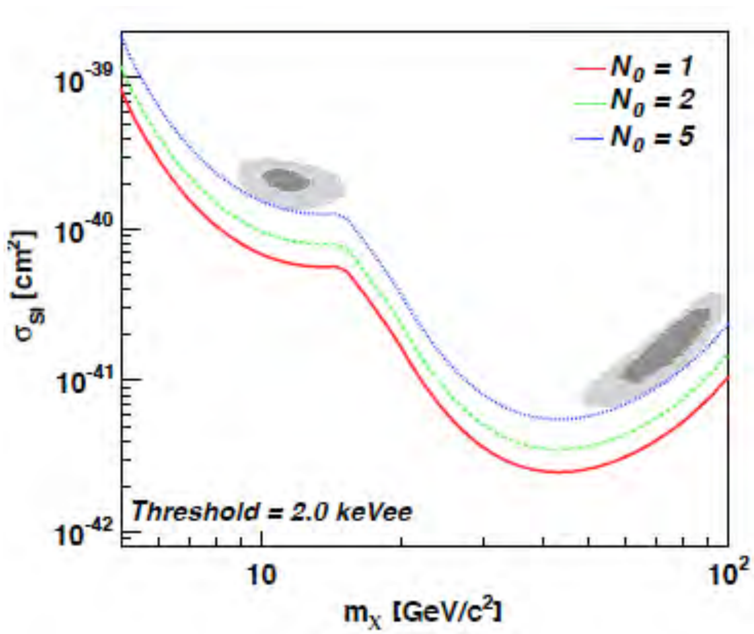
- NaI dark matter search in an entirely different environment
- South Pole offers:
  - Ultra-clean and ultra-stable environment
  - Seasonal variation unambiguously different from dark matter modulation
  - IceCube offers muon monitoring and veto as well as experience
  - NSF-run South Pole Station for logistical support

Testing DAMA's Dark Matter Claim

Definitive (5σ) detection or exclusion with

arXiv:1106.1156

- 500 kg-yr NaI(Tl) (DAMA x 2 yrs)
- same or lower threshold (< 2 keV_{ee})
- background < (DAMA x 5)



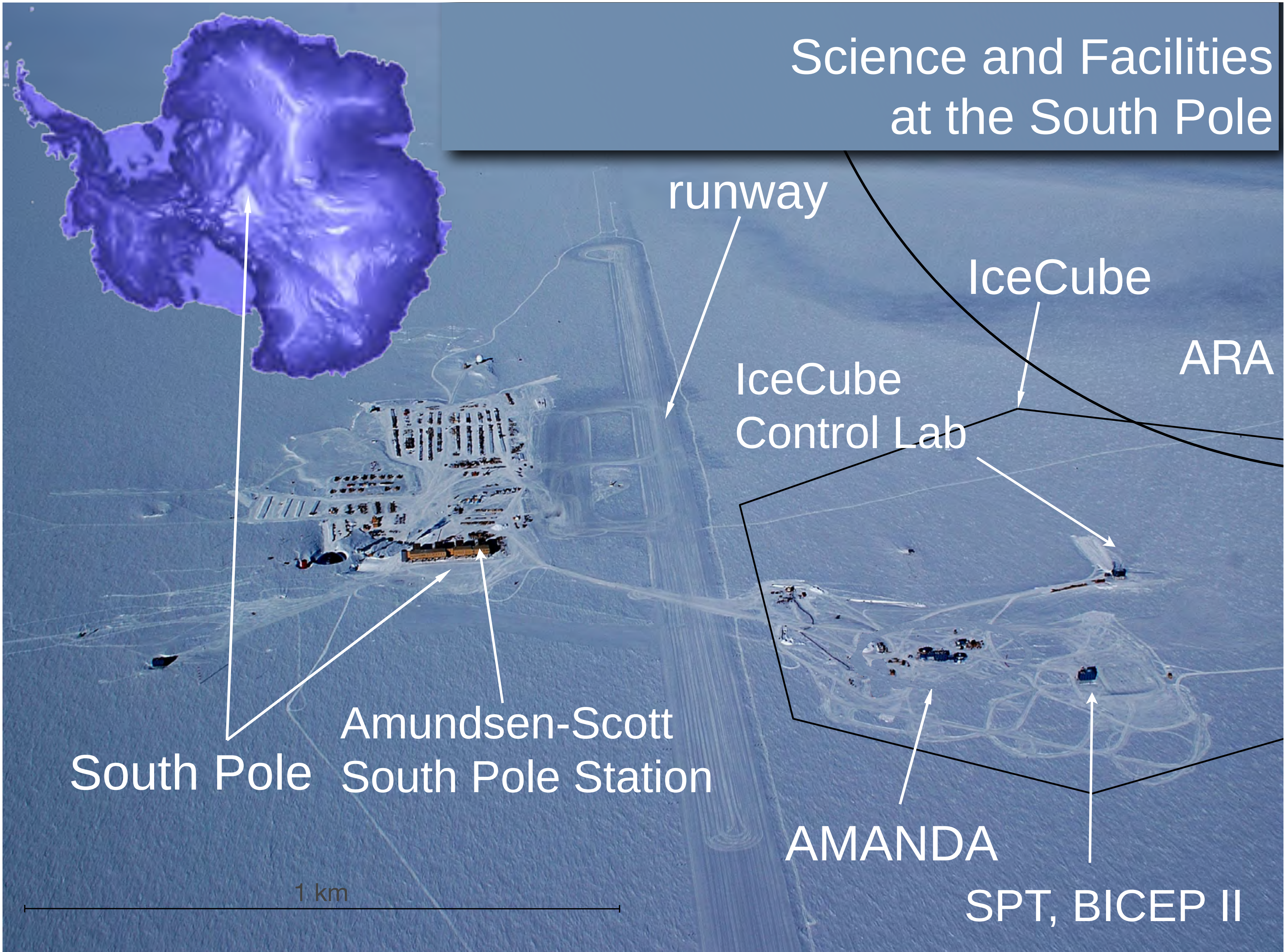
500 kg•year NaI detector sensitivity

(2 - 4 keV) with bgd of 1, 2, and 5 cnts/keV/kg/day.

		[illegible]	NAIAD size	DAMA size
	Years	17.0 kg	44.5 kg	250 kg
x8 DAMA background	1	0.45	0.72	1.71
	3	0.77	1.25	2.96
	5	1.00	1.61	3.82
	7	1.18	1.91	4.52
x4 DAMA background	1	0.63	1.02	2.42
	3	1.09	1.77	4.18
	5	1.41	2.28	5.40
	7	1.67	2.70	6.39
Double DAMA background	1	0.85	1.37	3.26
	3	1.47	2.38	5.64
	5	1.90	3.07	7.29
	7	2.25	3.64	8.62
DAMA background	1	1.20	1.94	4.61
	3	2.08	3.37	7.98
	5	2.69	4.35	10.31
	7	3.18	5.14	12.19
1/10 DAMA background	1	3.80	6.15	14.57
	3	6.58	10.65	25.24
	5	8.50	13.75	32.59
	7	10.06	16.27	38.56

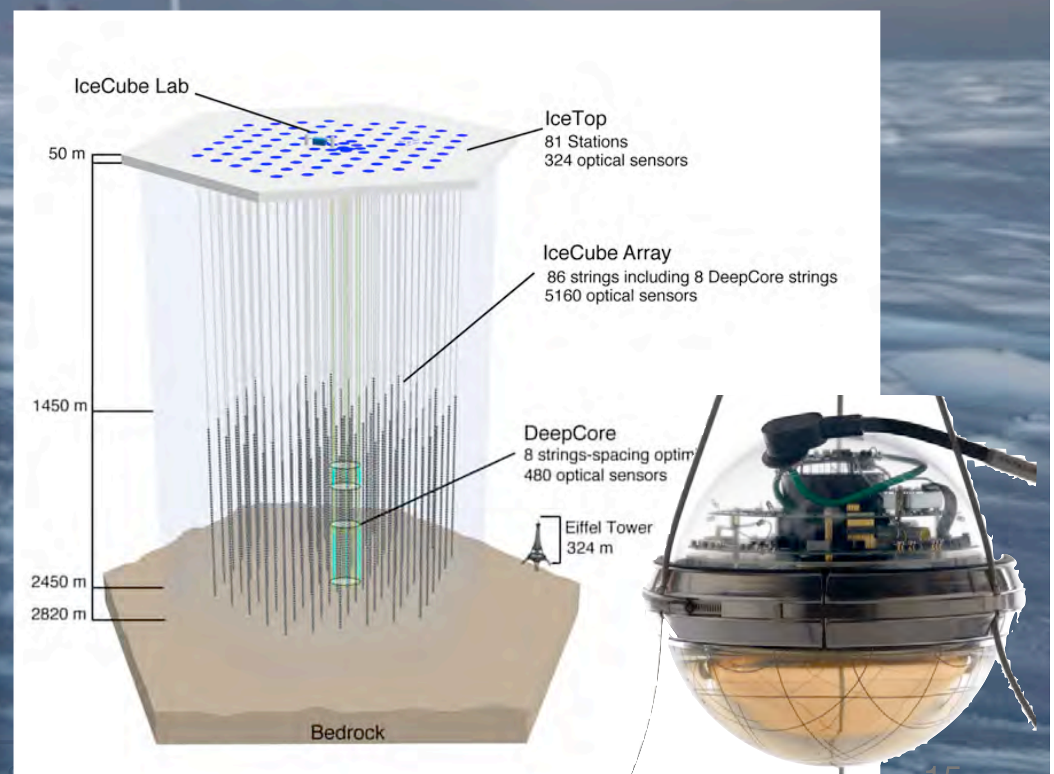

DM-Ice
13

Science and Facilities at the South Pole



The IceCube Neutrino Observatory

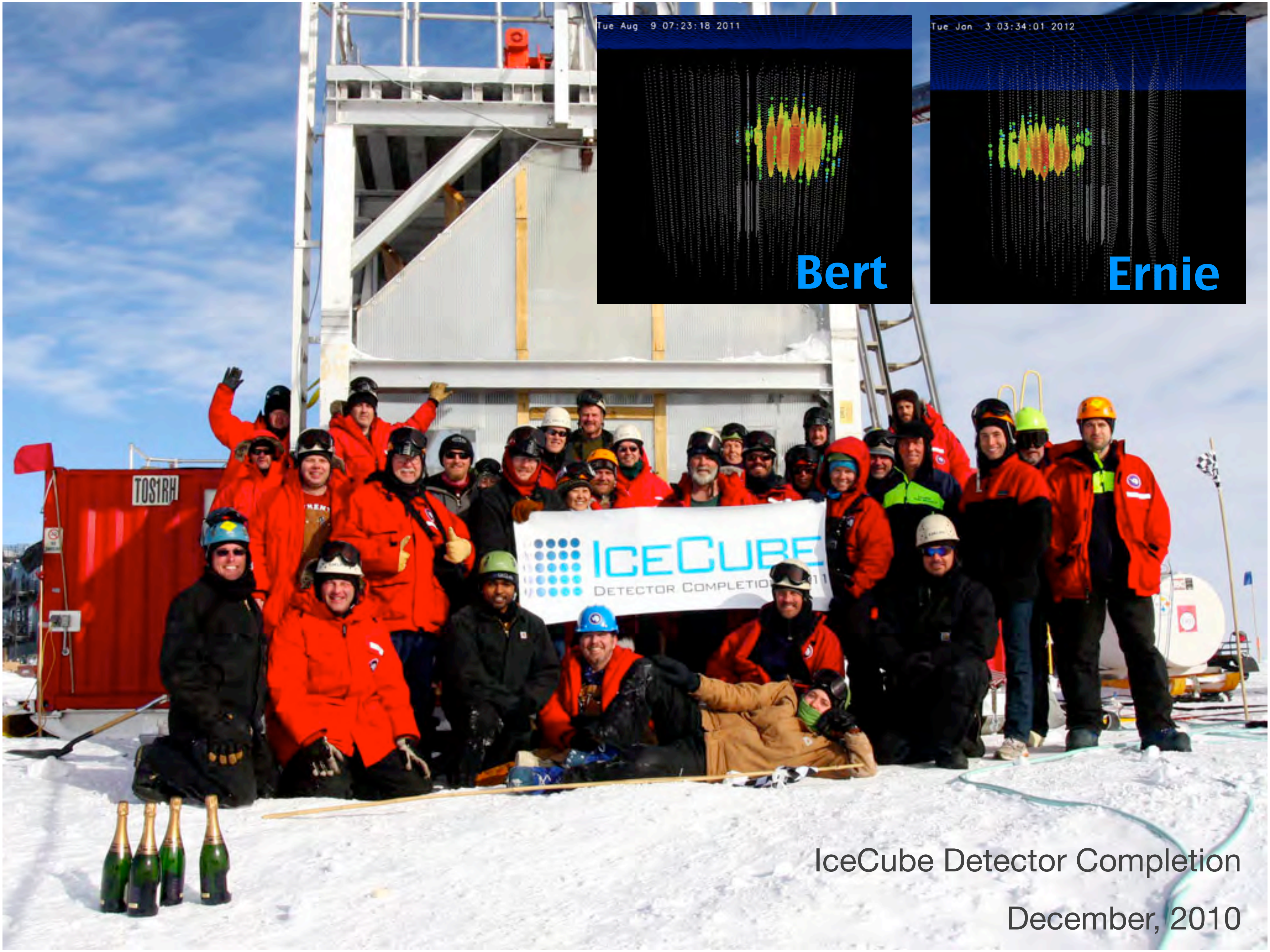
- Completed in 2011, South Pole
  - Partial detector in operation since 2005
- Search for **astrophysical neutrinos**, dark matter, nu oscillations, cosmic ray, atmospheric neutrinos, glaciology...



The IceCube Collaboration

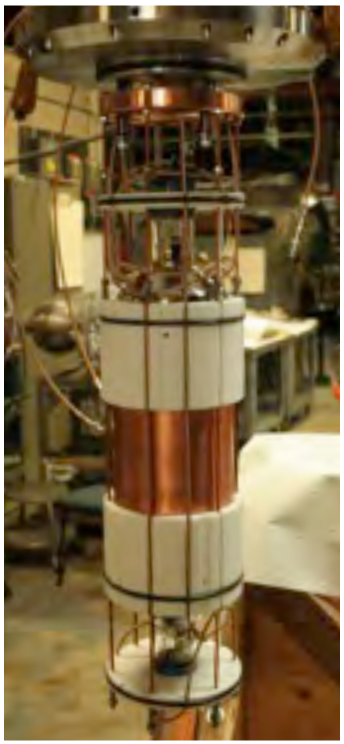
International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)


Tue Aug 9 07:23:18 2011
Bert
Tue Jan 3 03:34:01 2012
Ernie
TOS1RH
ICECUBE
DETECTOR COMPLETIO
IceCube Detector Completion
December, 2010

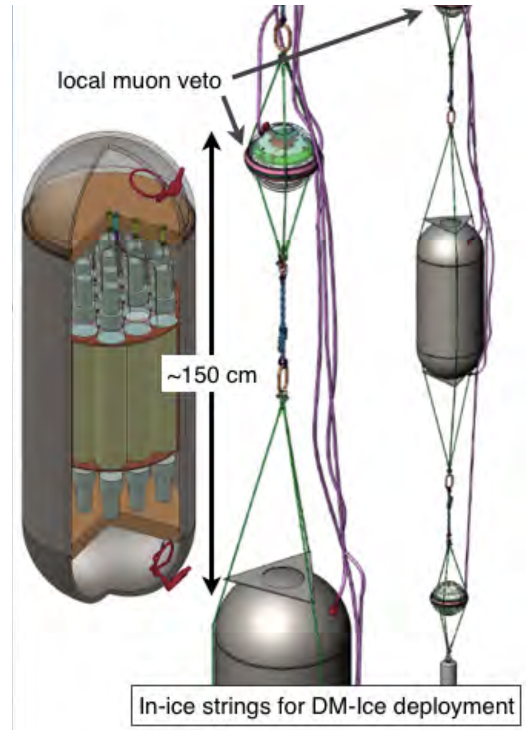
DM-Ice-17, DM-Ice

Currently in Operation: DM-Ice17



17 kg of NaI(Tl), operation since 2011
Funding: NSF-Polar Programs &
NSF-CAREER for R&D
First results expected in Spring

Proposed Full-Scale: DM-Ice



250 kg of ultra-pure NaI(Tl)
Proposed deployment: Dec. 2015

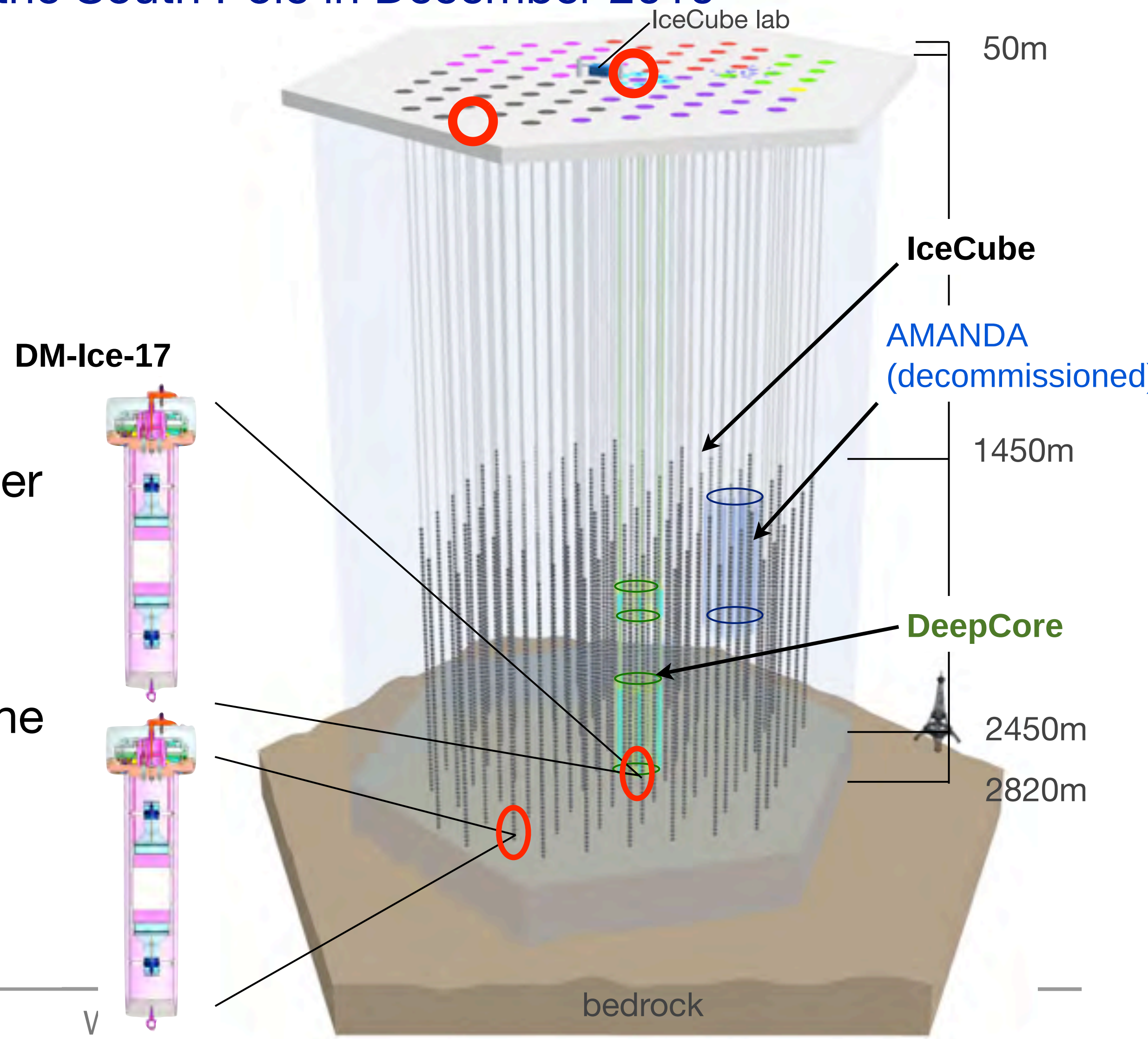
Prototype: DM-Ice-17

Co-Deployed with IceCube at the South Pole in December 2010

- A 17 kg NaI detector
- Operation since Feb. 2011
- Data run from June 2011
- Data sent over satellite

Goals:

- Feasibility of deploying a remotely-operable dark matter detector in the Antarctic Ice
- Assess the environmental stability
- Establish the radiopurity of the antarctic ice / hole ice
- Explore the capability of IceCube to veto muons
- Look for modulations



DM-Ice-17 Construction & Deployment

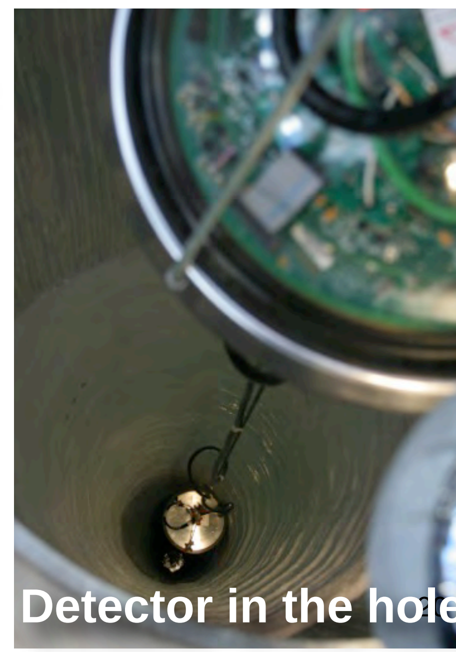
Design begin Feb. 2010


Revive NAIAD xtals
July 2010

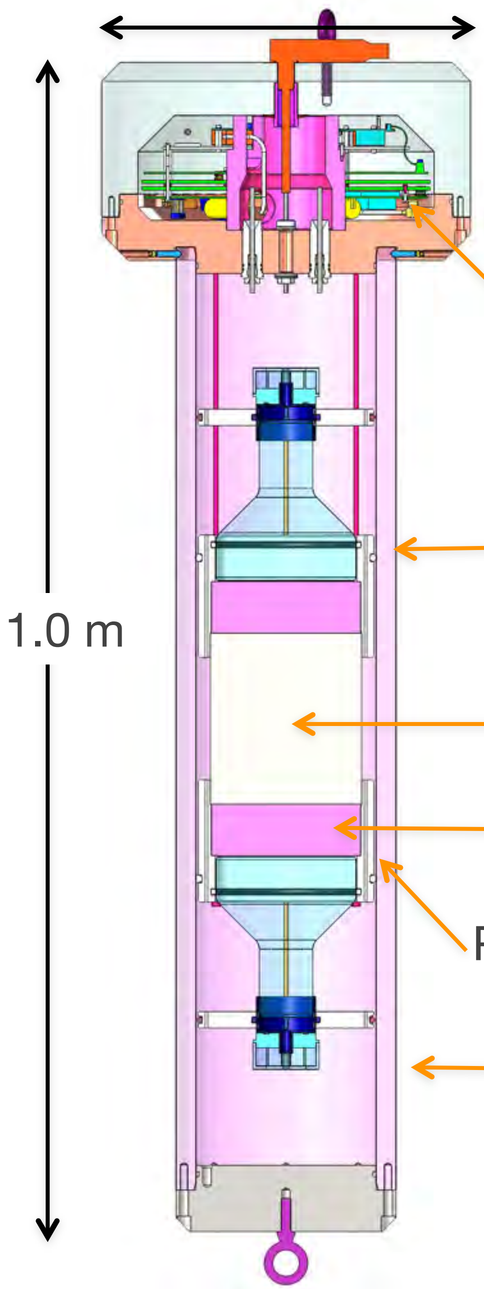

Detector assembly
Sep - Oct. 2010

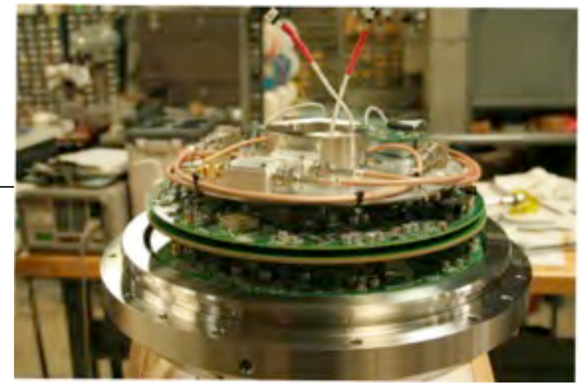

Shipment to Antarctica
Dec. 1, 2010

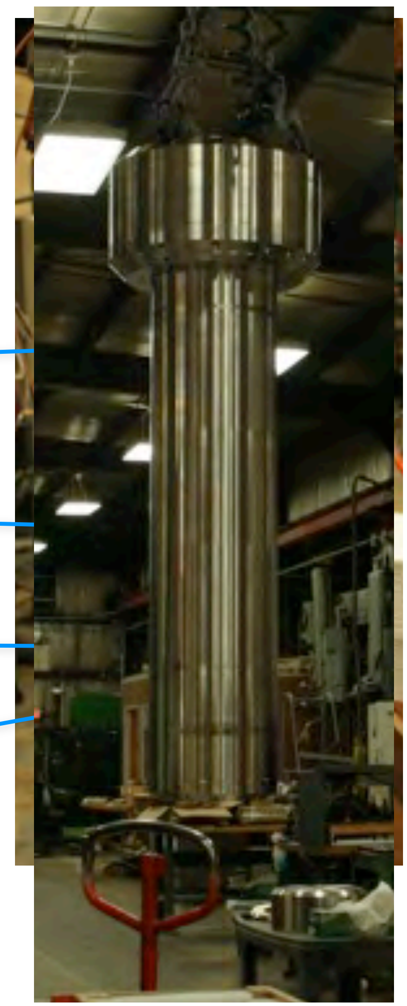

Deployment
Dec. 11, 2010

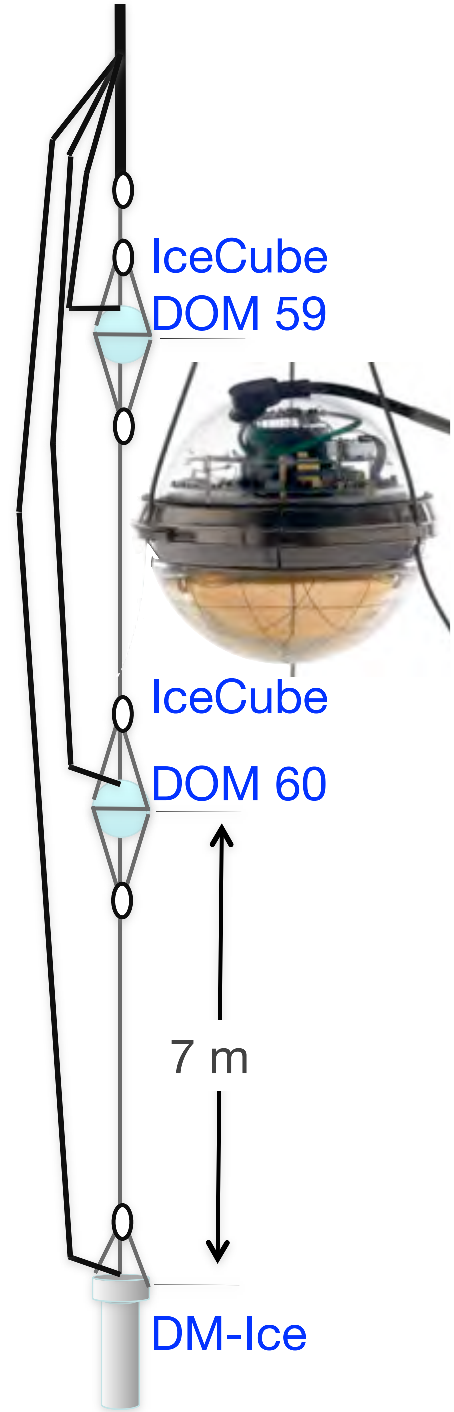

Detector in the hole

DM-Ice-17 Detector

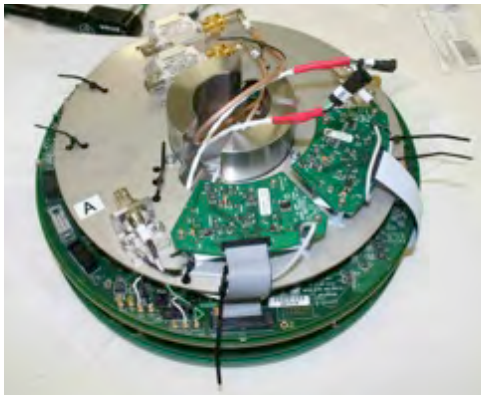


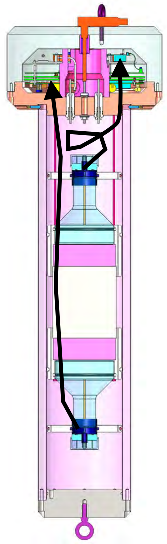


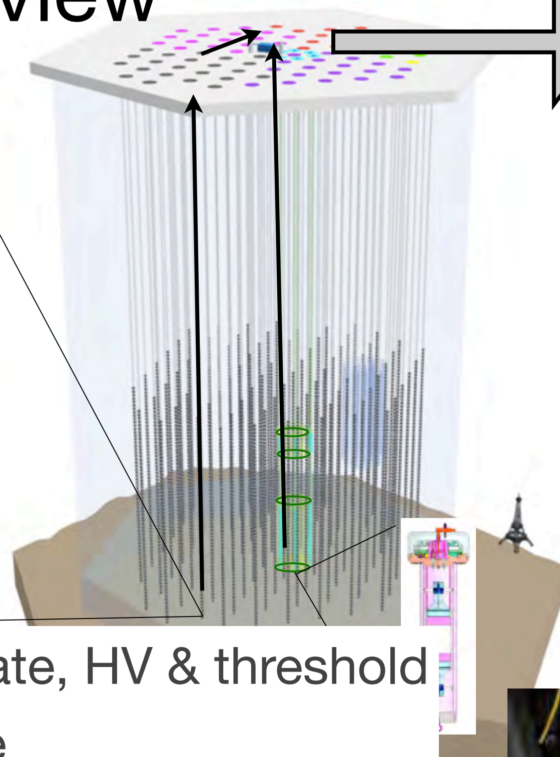


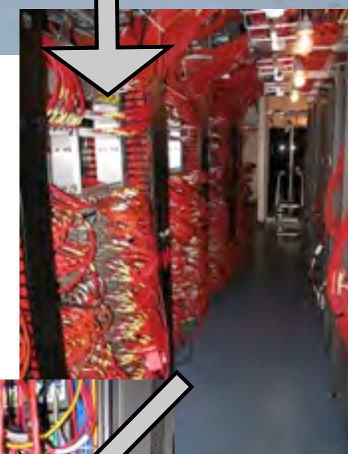


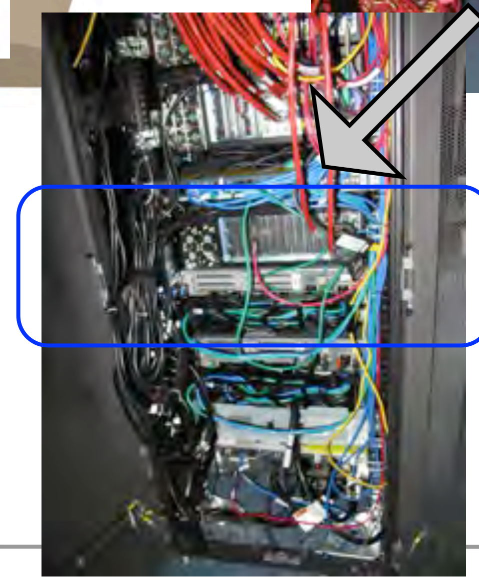
DM-Ice17 DAQ Overview





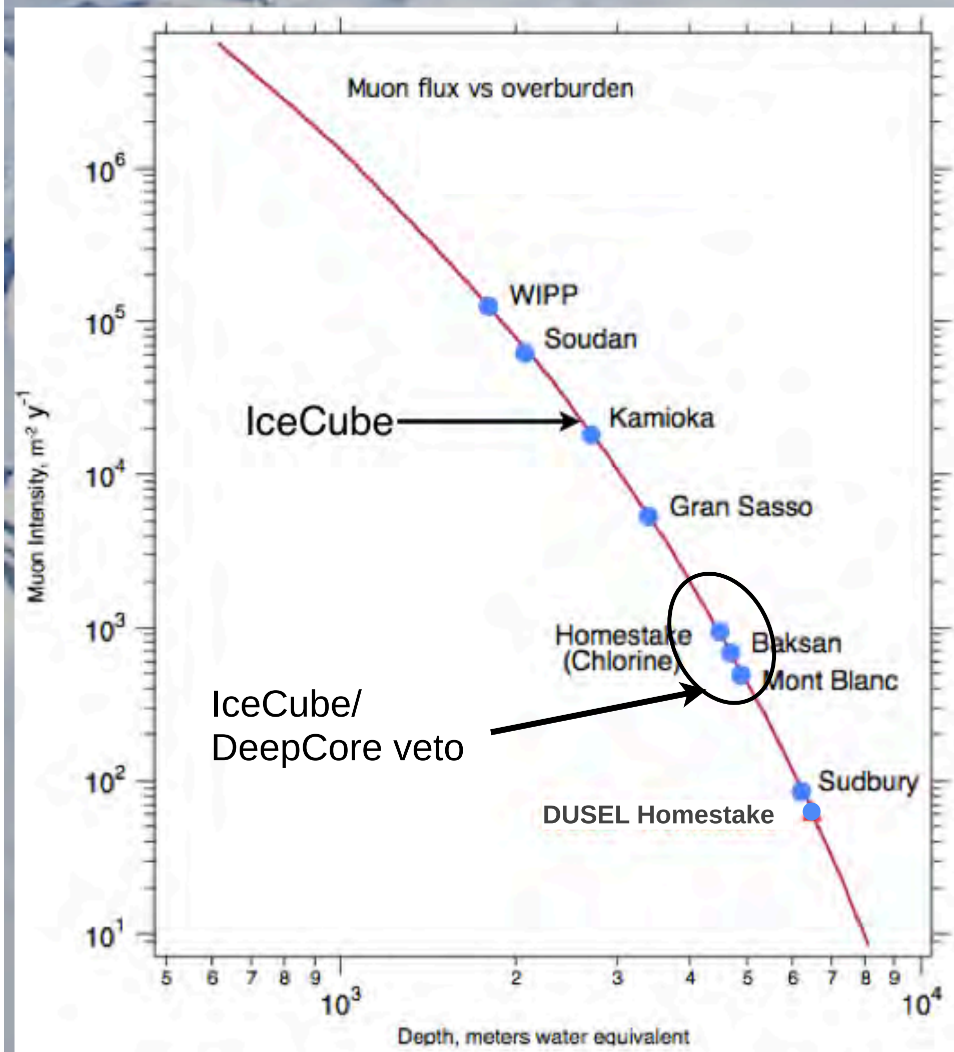




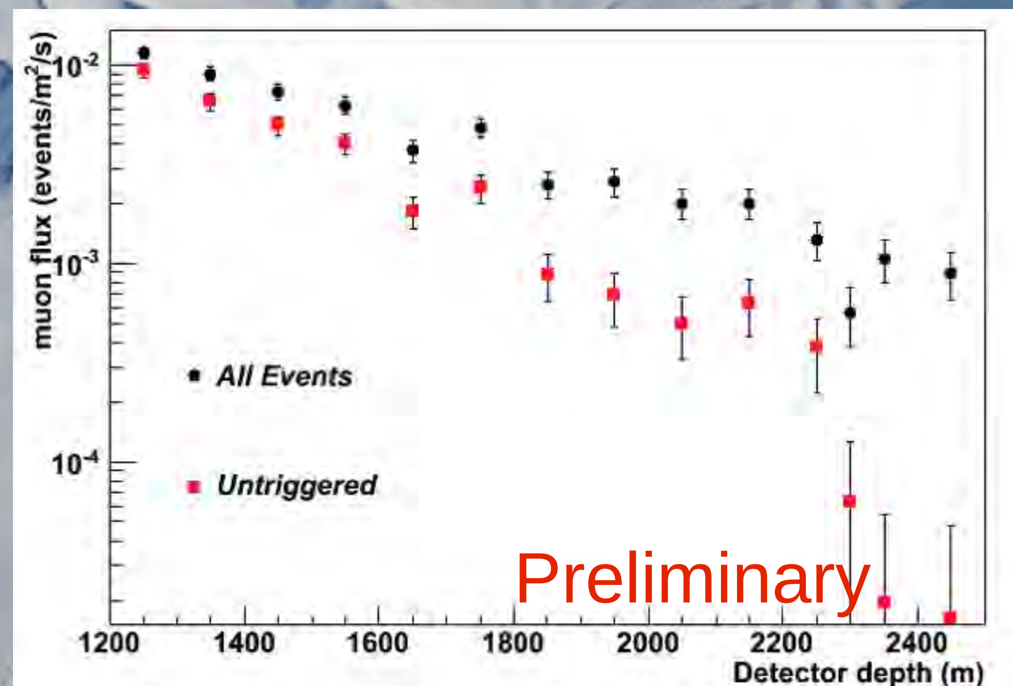


- Remotely programable sample rate, HV & threshold
- Each PMT set to trigger ~0.2 spe
- Waveform recorded only when coincidence between both PMTs w/in 800 ns on a single crystal
- Waveform from each PMT digitized separately in the ice by IceCube mainboards and sent to hub
- Time stamp synchronized to IceCube GPS and calibrated for transit time
- Data sent over satellite to Madison, WI

Antarctic Ice: Overburden at -2500 m (2200 m.w.e.)



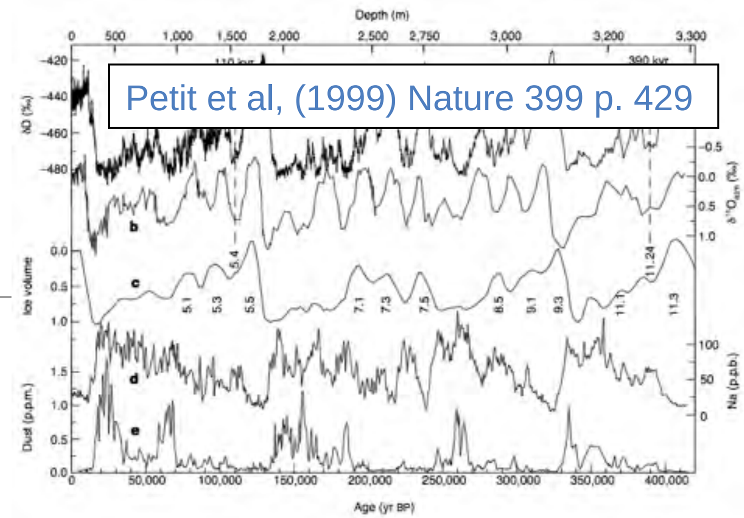
- ~85 muons/m^2/day at bottom of IceCube
- IceCube/DeepCore veto reduces rate by ~1-2 orders of magnitude.



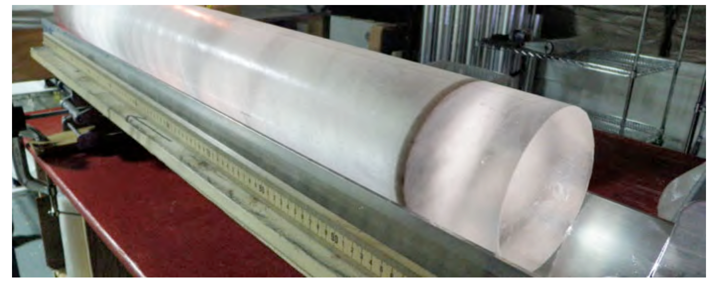
Muon flux vs. depth in the ice, total and those untriggered by IceCube/DeepCore.

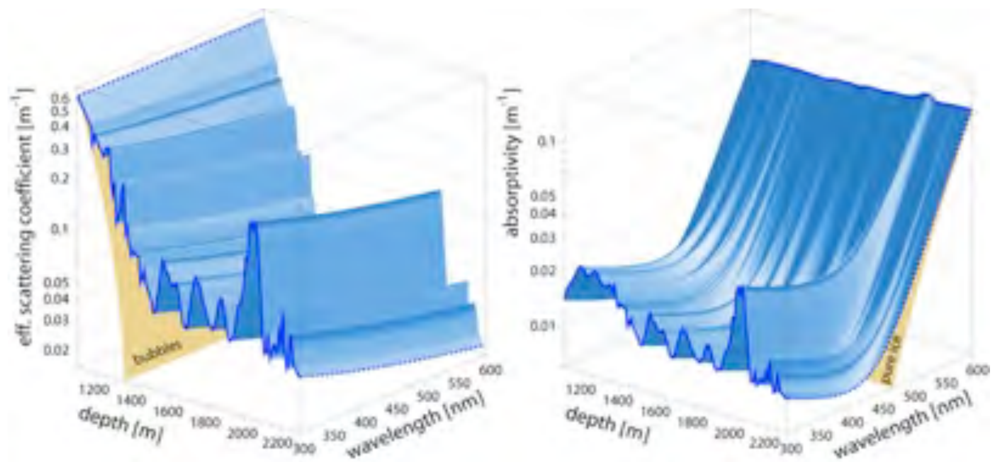
Antarctic Ice: Radiopurity

- Measurements from ice cores at Vostok.
- Absorption and scattering lengths measured by AMANDA/ IceCube
- -2500 m at South Pole is ~100,000 years old
- Most of the impurities come from volcanic ash, < 0.1 ppm
- Radioactive contaminants in ice:
  - U ~ 0.1 - 1 ppt
  - Th ~ 0.1 - 1 ppt
  - K ~ 0.1 - 1 ppb



Petit et al, (1999) Nature 399 p. 429

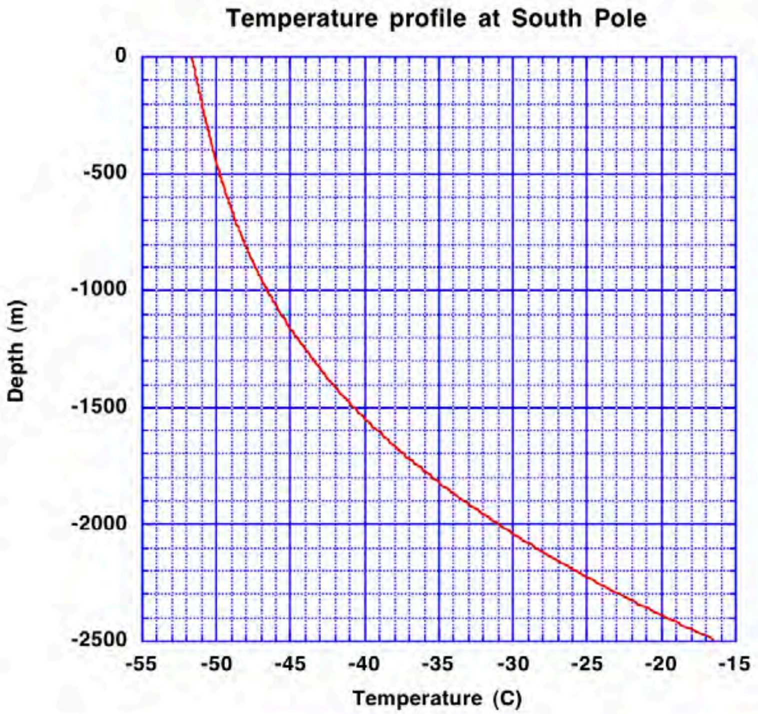




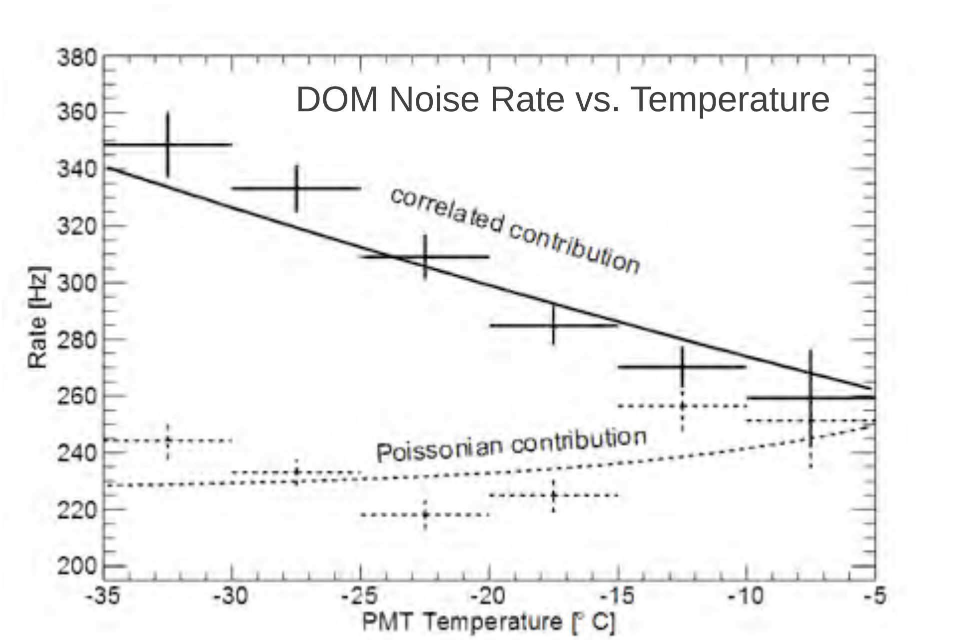
J. Geophys. Res., 111, D13203 (2006)

Antarctic Ice: Stability & Temperature

- Temperature measured by each IceCube DOM & additional sensors on the cables
- At -2500 m, the ice is -20 °C
- Temperature is stable throughout the year



Kurt Woschnagg (IceCube)

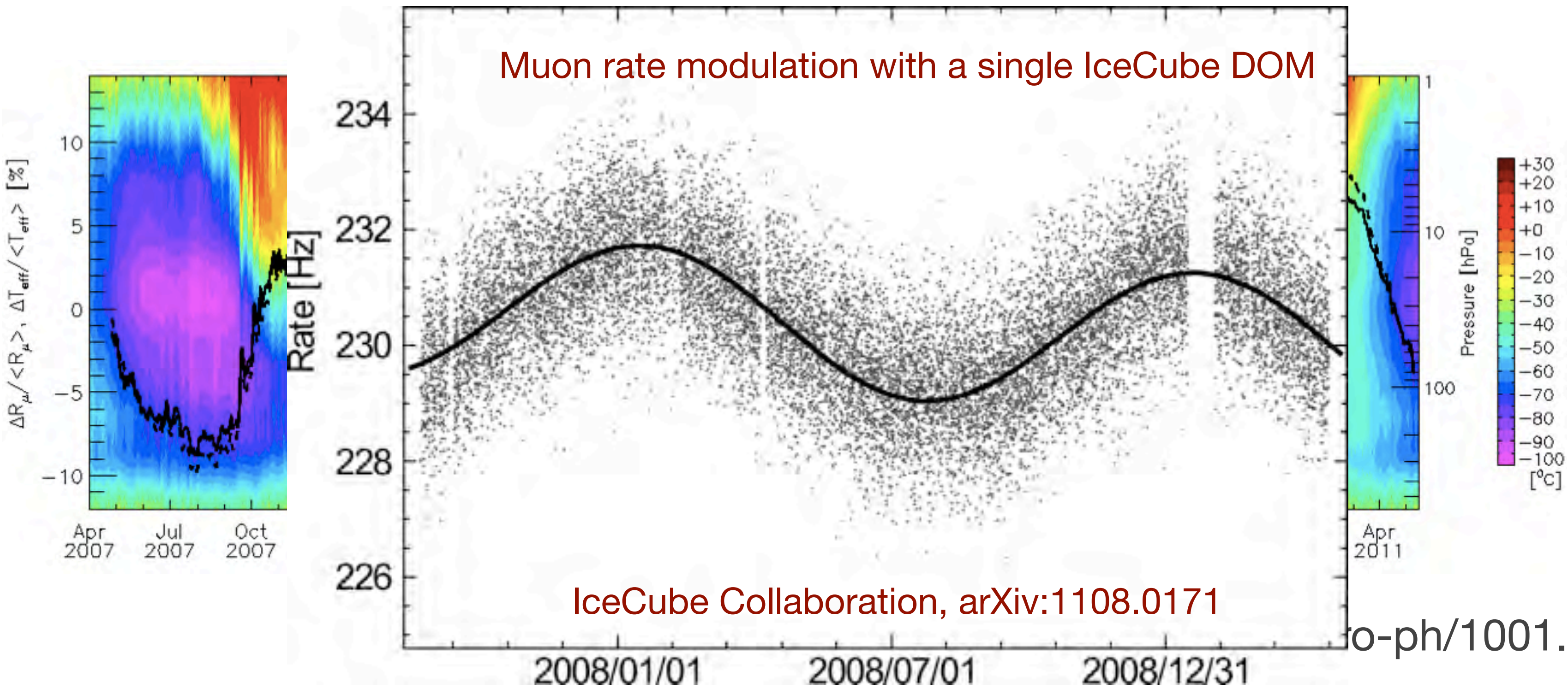


IceCube Collaboration, arXiv:1108.0171, A&A 535, A109 (2011)

IceCube as a Muon Detector

The muon rate at the South Pole well measured by IceCube

IceCube muon rate variation (solid) & T_{eff} (dotted)

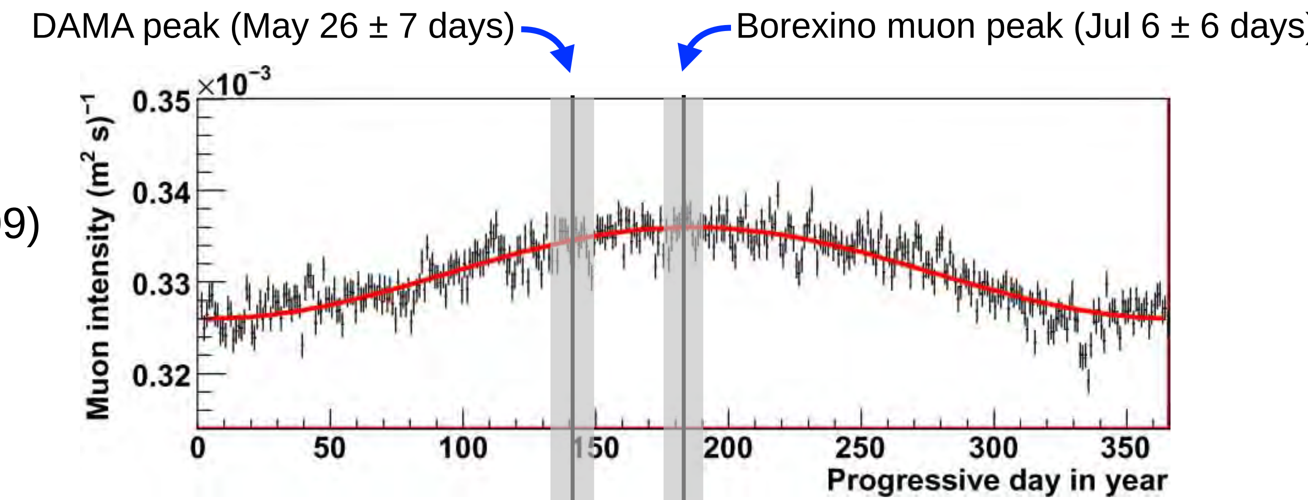


o-ph/1001.0776

Muon Rate at Gran Sasso vs. South Pole

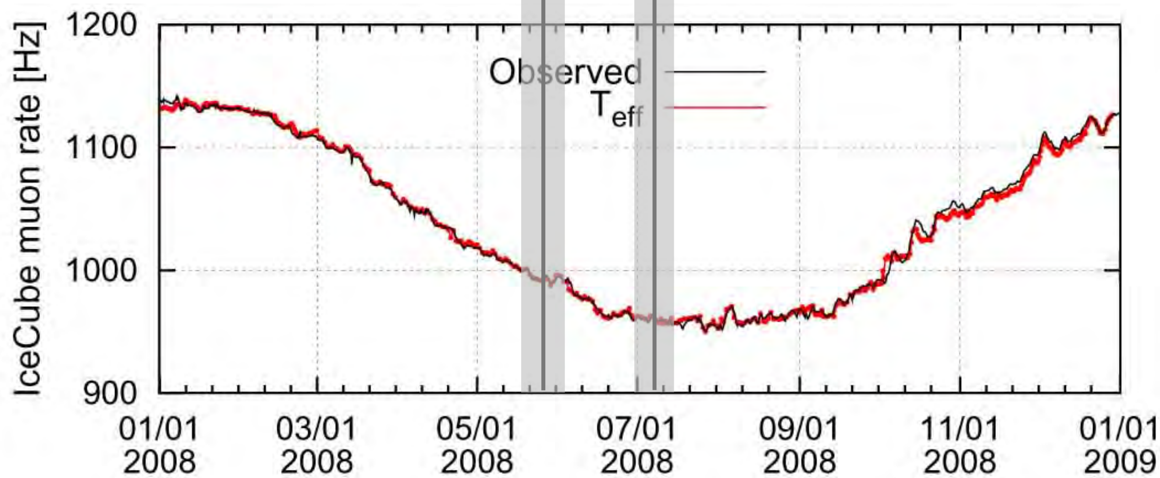
- LVD:

Selvi, Proc. 31st ICRC. (2009)



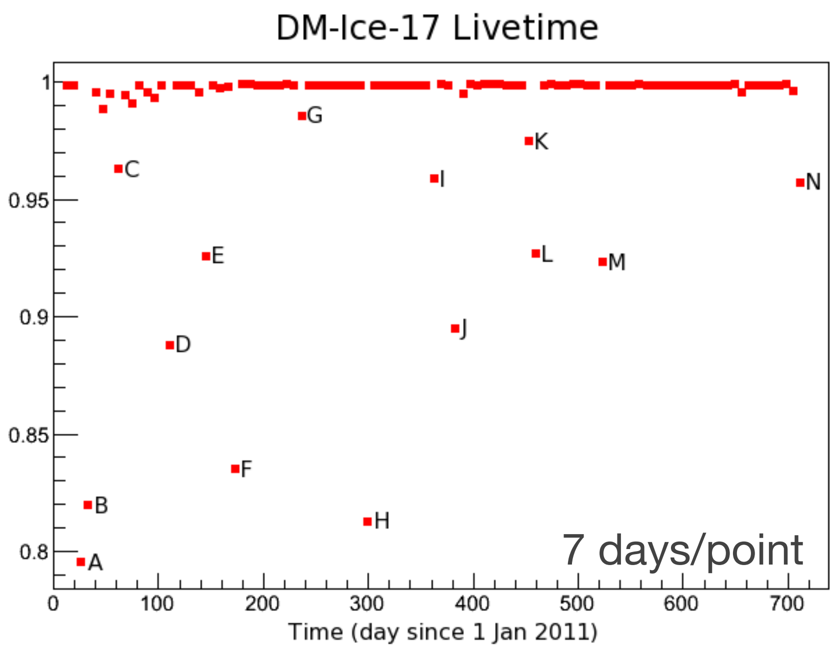
- Opposite Muon modulation at the South Pole:

Tilav, Proc. 31st ICRC. (2009)

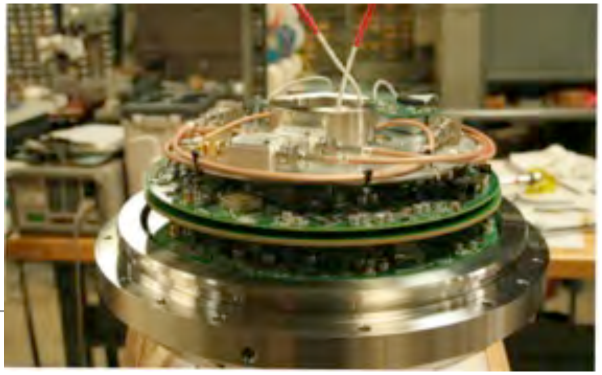


Detector Uptime

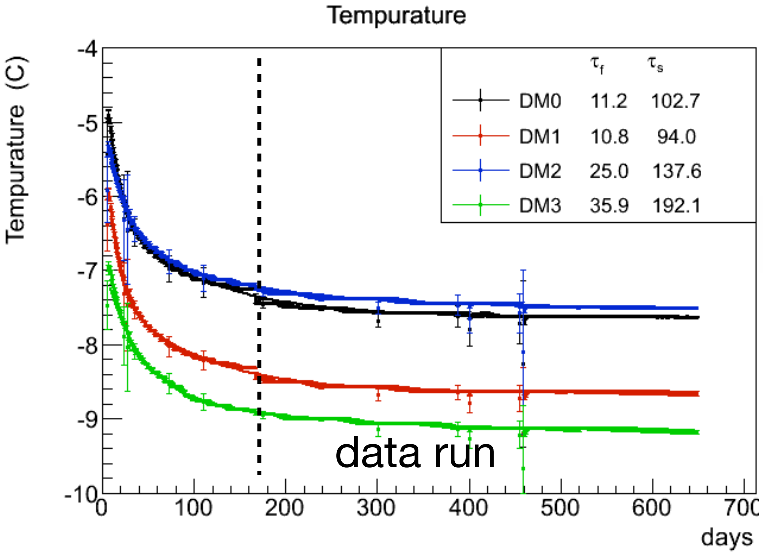
- Commissioning and optimization from Feb - June 2011
- Data run since June 2011
- 99.8% uptime for most weeks with well defined down time for occasional power cycling + pedestal and dark noise runs

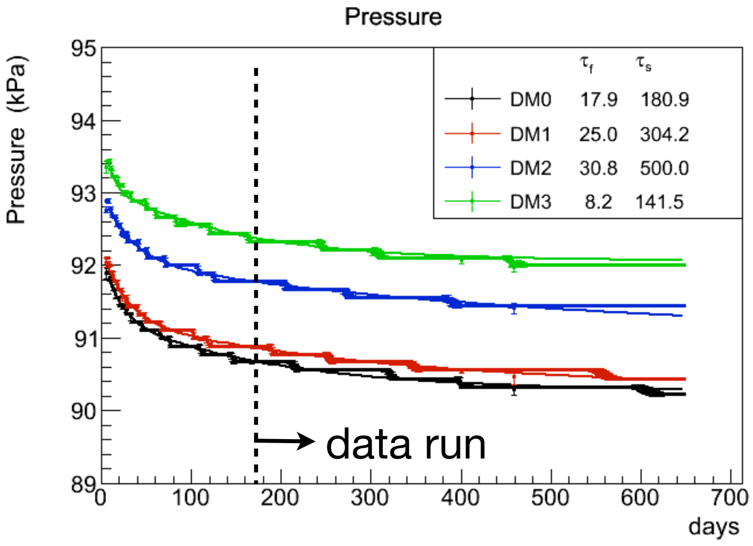


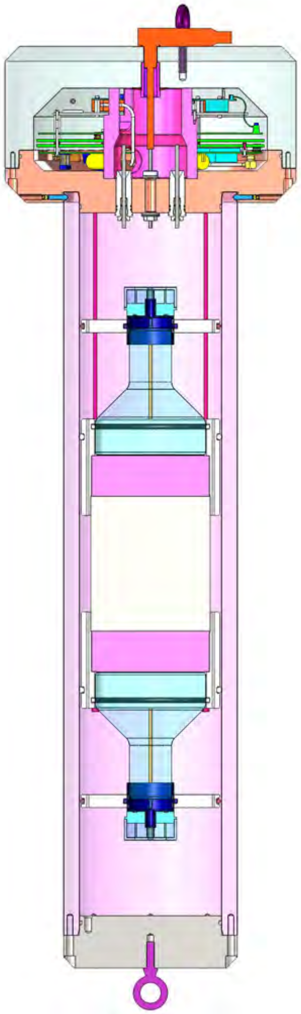
Detector Monitoring



- Monitored quantities:
  - 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
  - Pressure follows similar trend as temperature (ADC resolution limited)
- Values recorded every 2 sec. before April 2012. Every 60 sec. since April 2012.

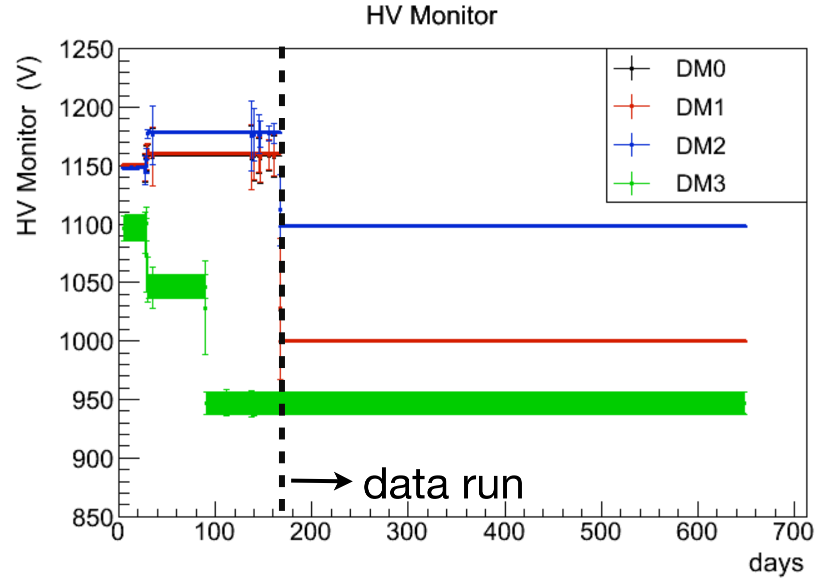




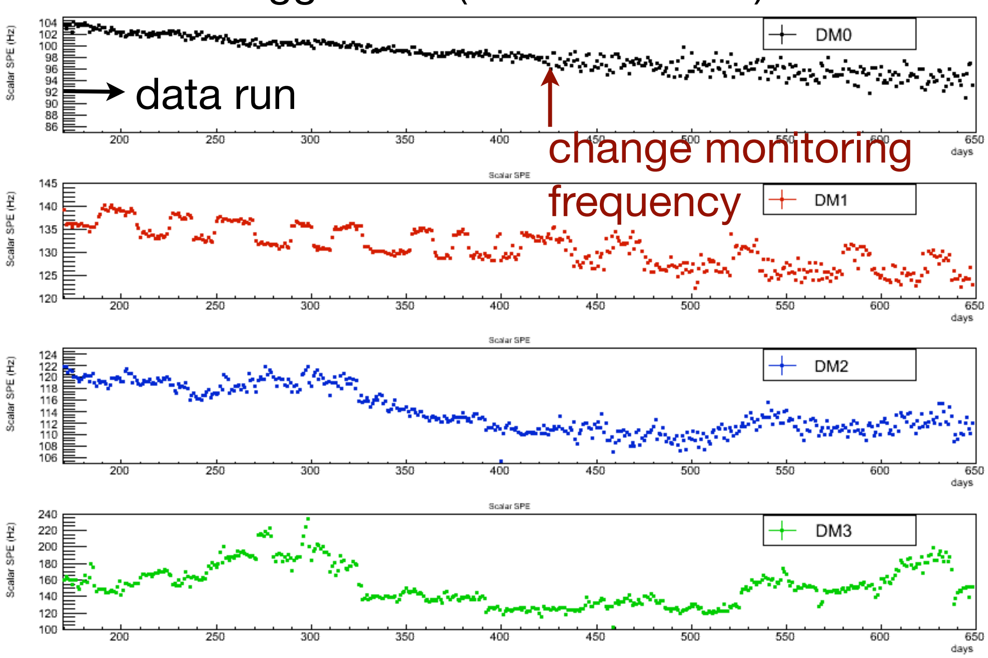


Detector Monitoring

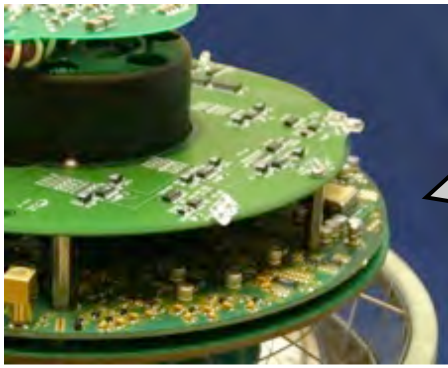
- High voltage of each PMT
  - commissioning until day 167
- Single PMT total trigger rate
  - General decay over time
  - single trigger rate variation seems mostly in the noise (not observed in coincidence data after cuts)

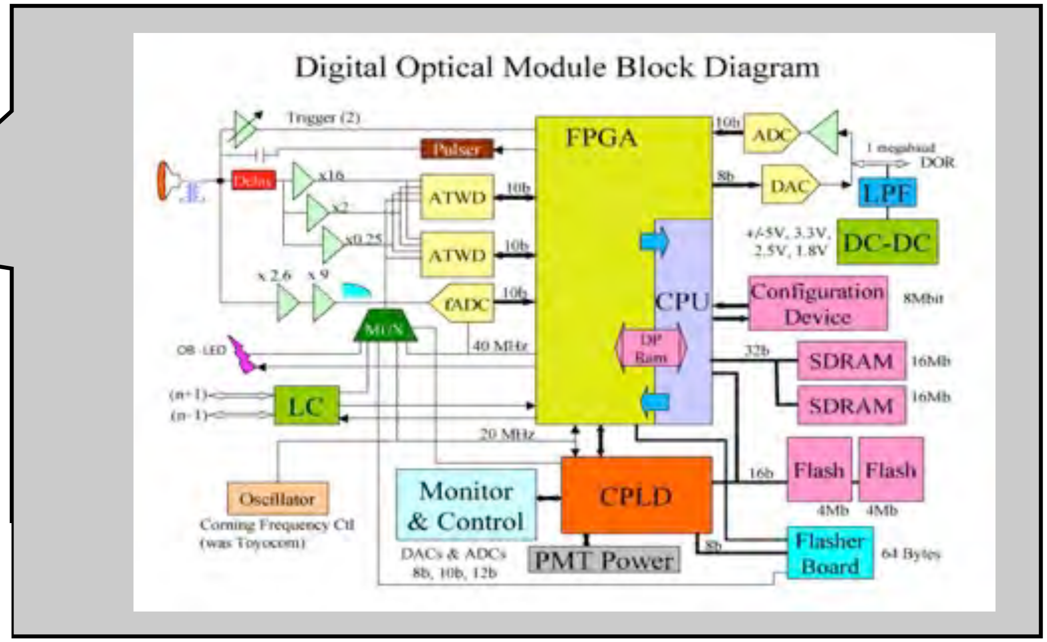


Trigger rate (individual PMT)

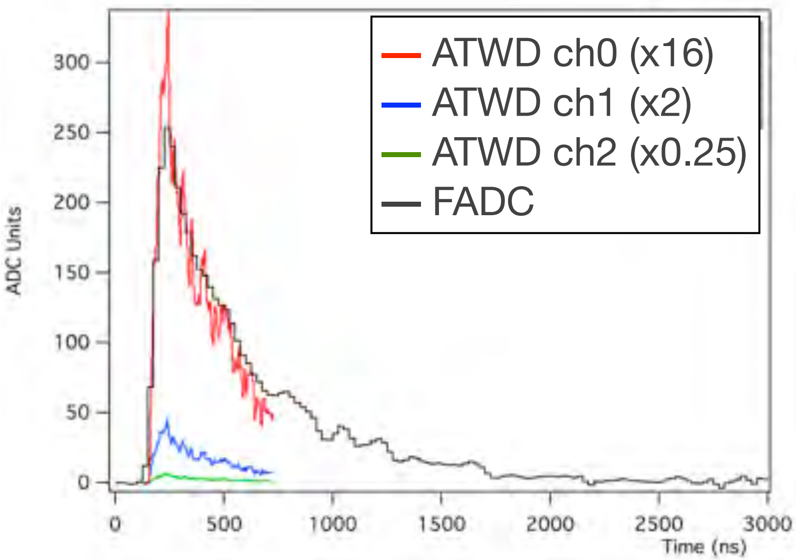


Capturing Waveforms with IceCube Mainboards





Example waveform from all channels



ATWD:

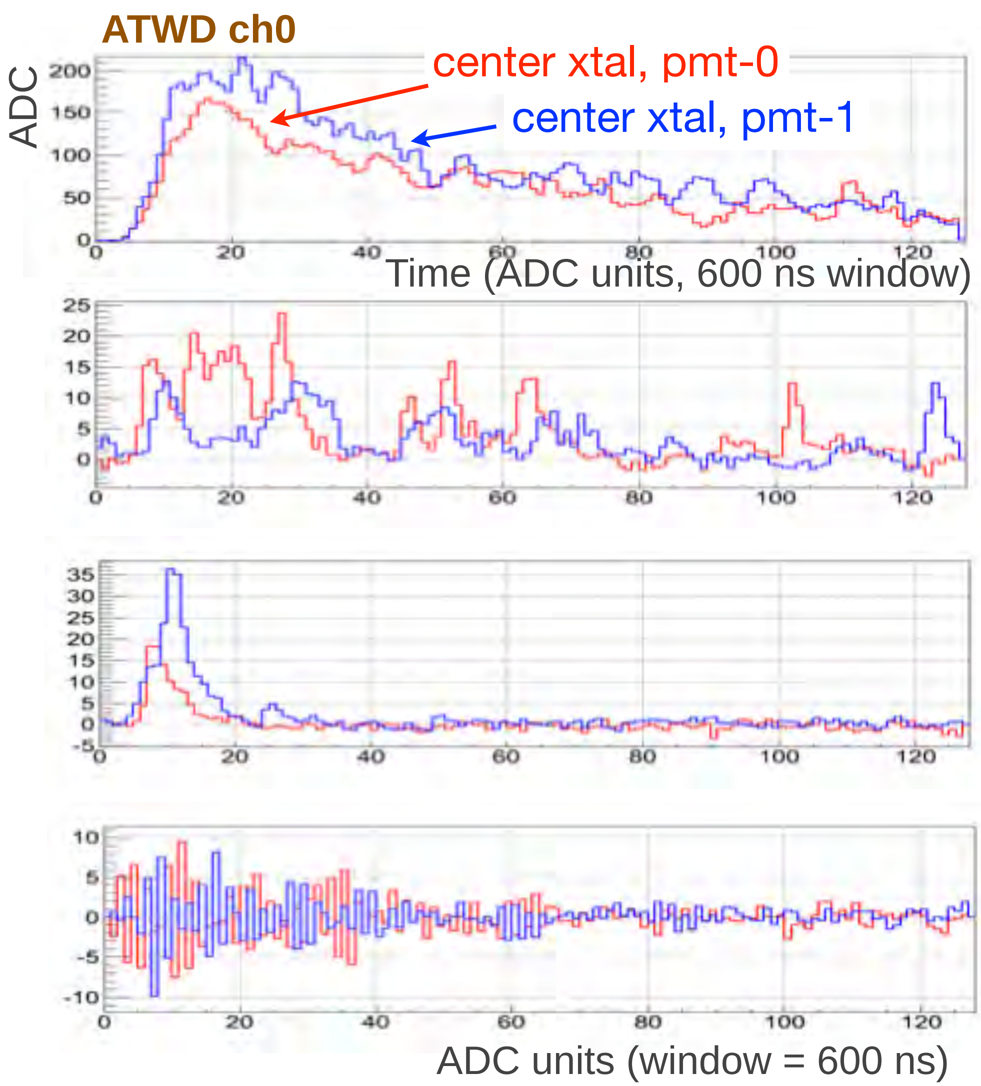
- 213 MS/sec x 128 samples = 600 ns window
- 3 gains:
  - channel-0: high gain
  - channels-1 & 2: useful for > 1500 keV where ch-0 is saturated

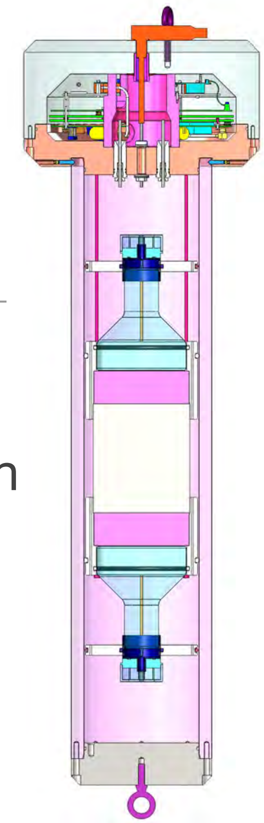
FADC: slower sampling rate, wide time window

- 40 MS/sec x 256 samples = 6.4 μsec time window (3 μs shown)

Reina Maruyama

Waveform Examples





high energy events (>100 keV)

Typical scintillation pulses with decay time ~350 ns

low energy events (<100 keV)

single photo-electrons visible

“thin” pulses

Fast pulses with large amplitudes

cut via waveform

“EMI” events

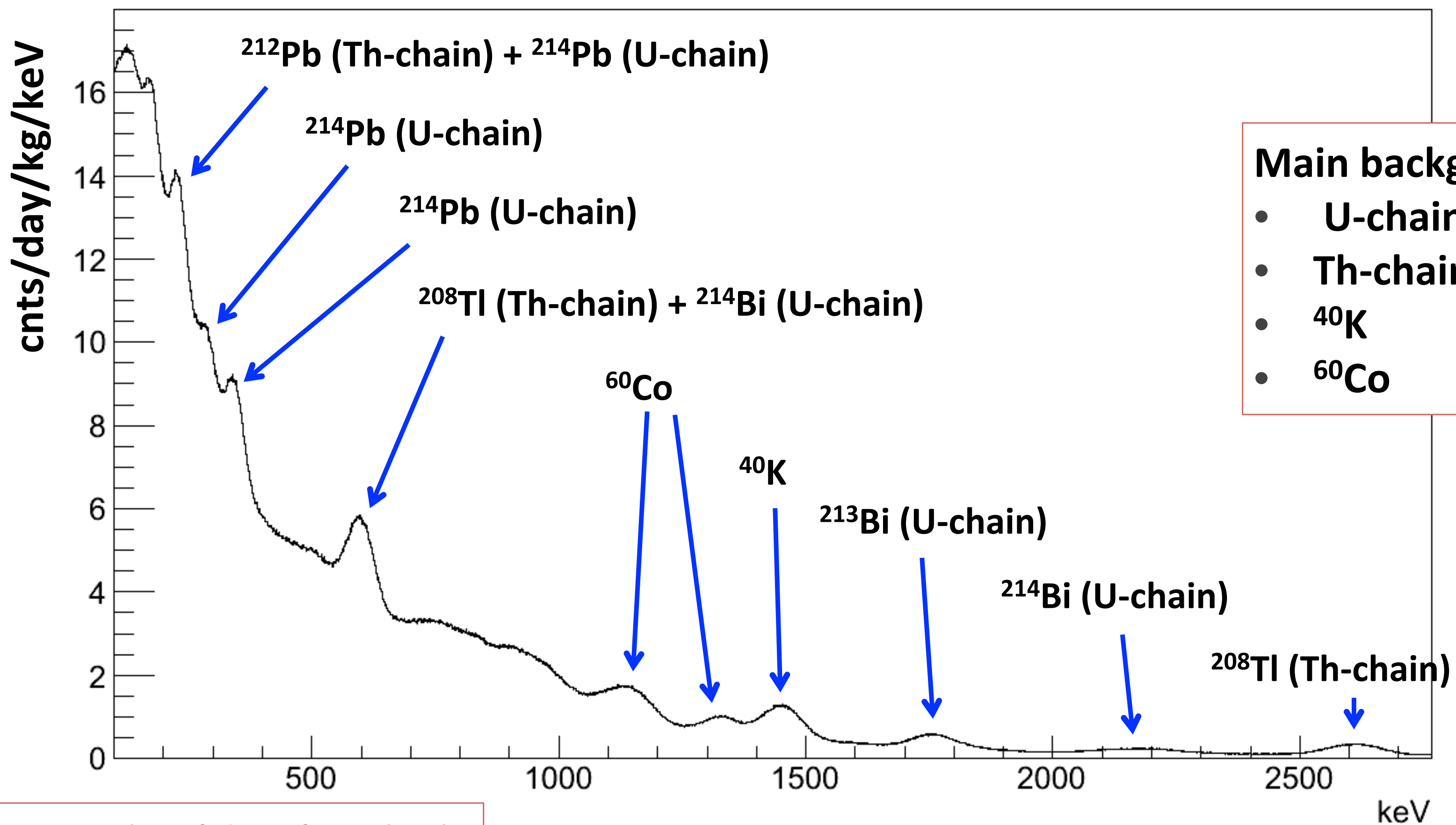
Interference with detector monitoring.

Well characterized by timing and shape.

(no interference with IceCube or ARA seen)

DM-Ice17 Spectrum

DM-Ice17 Prototype1 Spectrum



Main backgrounds:

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

18 months of data from both PMTs on a single crystal

Internal contamination lines used for calibration

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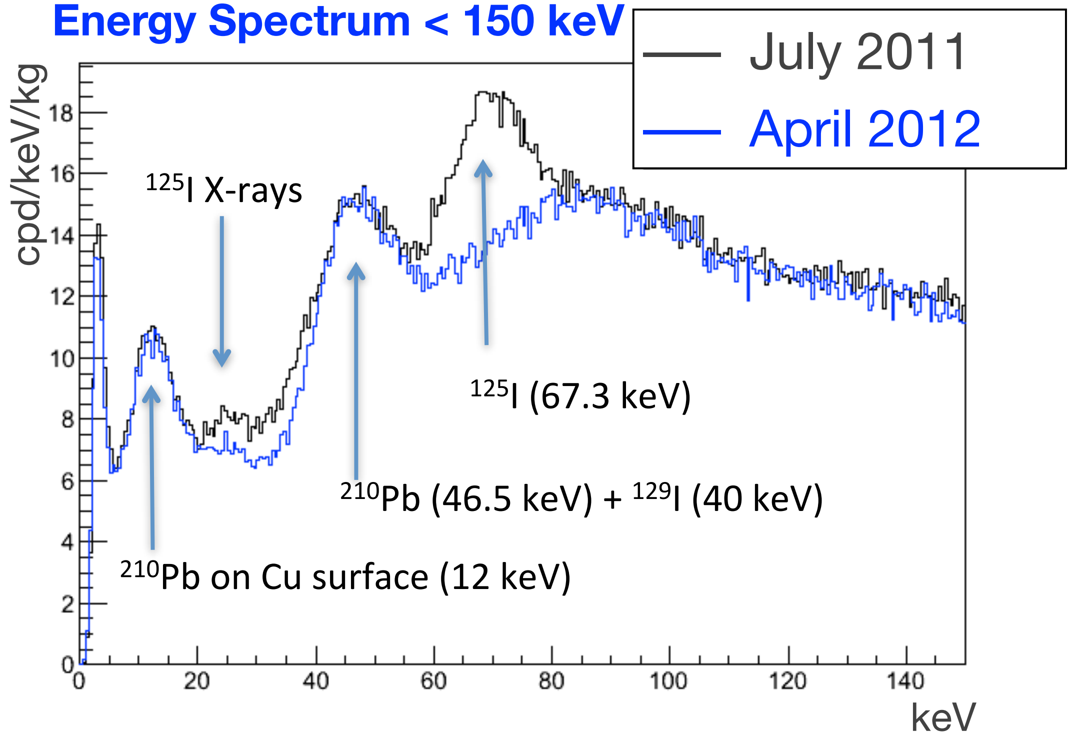
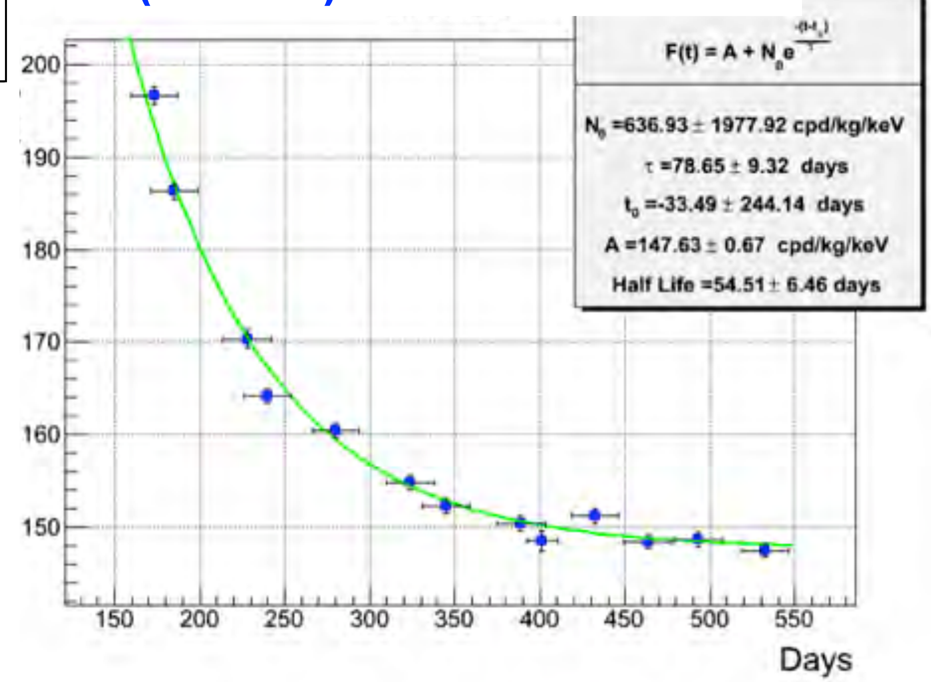
Low Energy Background Spectrum

Energy Spectrum < 150 keV

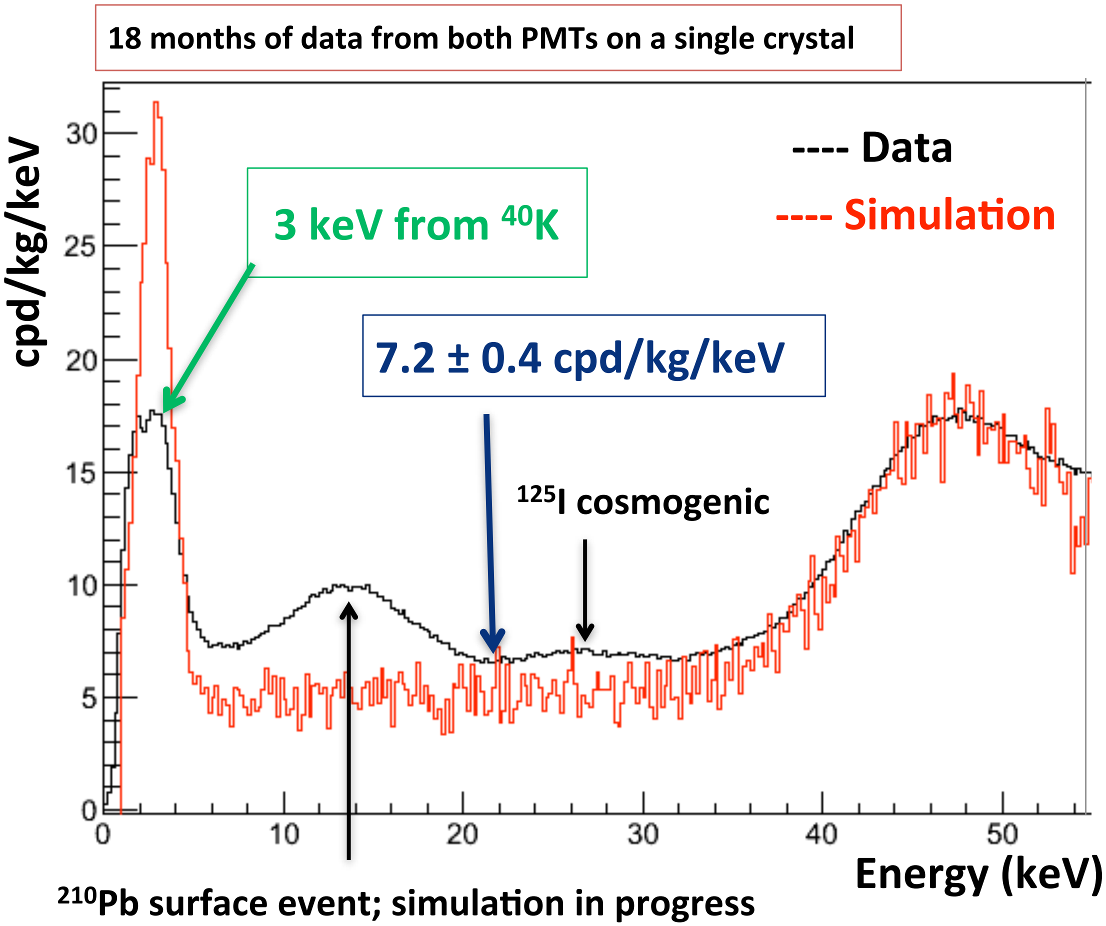


^{125}I (67.3 keV) Peak counts v. time



- 7 - 10 cpd/keV$_{ee}$/kg between 8 - 30 keV$_{ee}$.
- Low energy region calibrated with internal lines from Pb-210, I-125, & I-129
- Cosmogenic activation of ^{125}I observed with $T_{1/2}$ = 59.4 days
- K-40 line at 3.2 keV also visible.

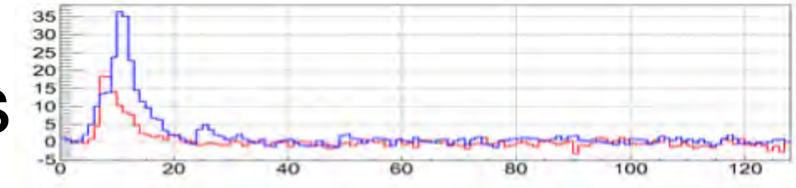
Region of Interest



- **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**

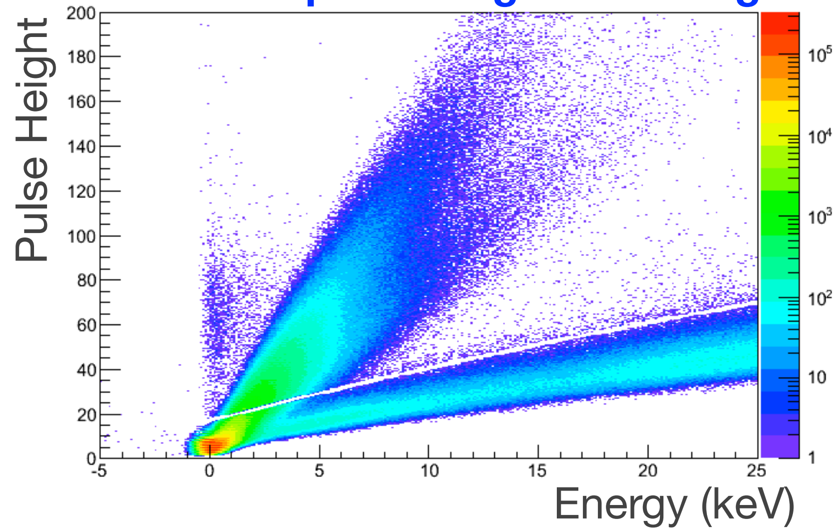
Looking ahead:
- **Backgrounds in ROI 5x higher than simulated for full scale DM-Ice**
- **Multi-crystal veto will suppress 3 keV events**

Event Selection: “Thin” pulses

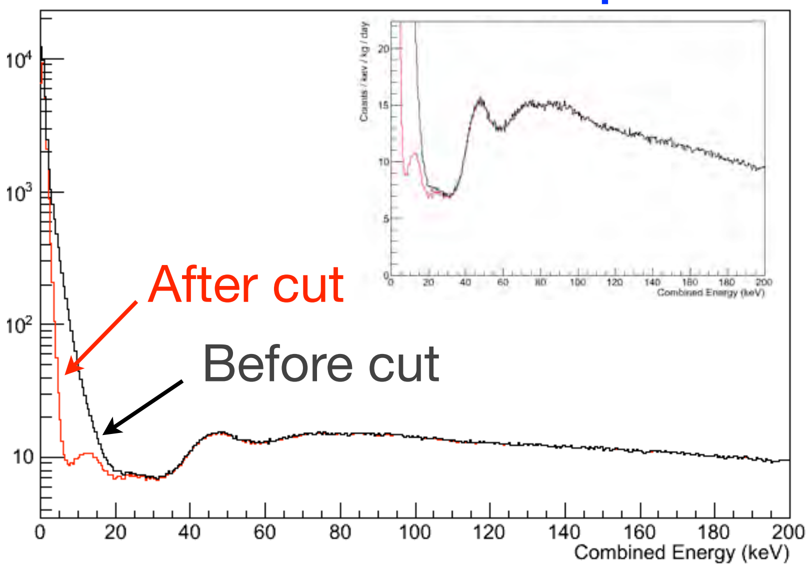


- Characteristics:
  - high pulse-height relative to charge
  - asymmetric between two PMTs
- 90% of events between 5-10 keV are “thin”
- Current cut effective above 7 keV

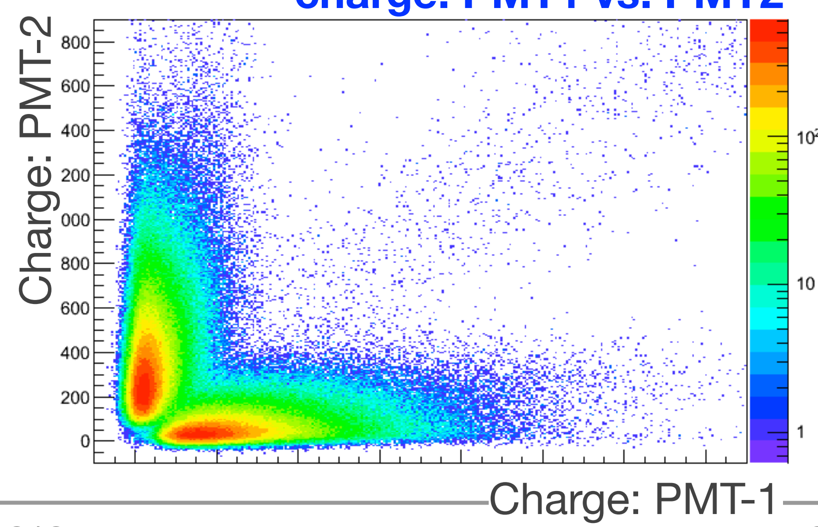
pulse height vs. charge



energy spectrum:
before & after thin pulse cut

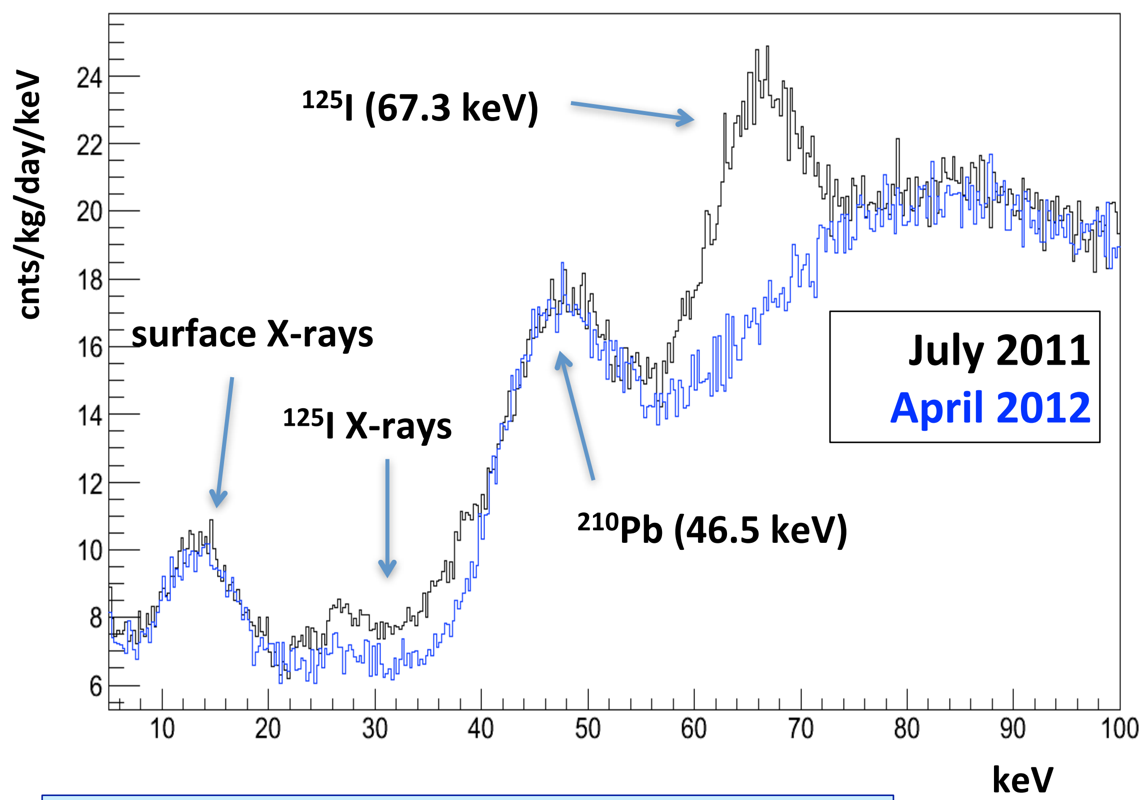


charge: PMT1 vs. PMT2

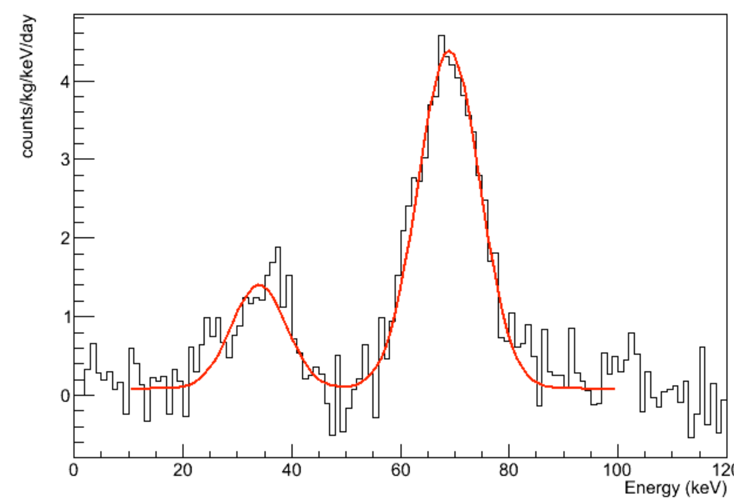


Cosmogenic ^{125}I (in the NaI crystal)

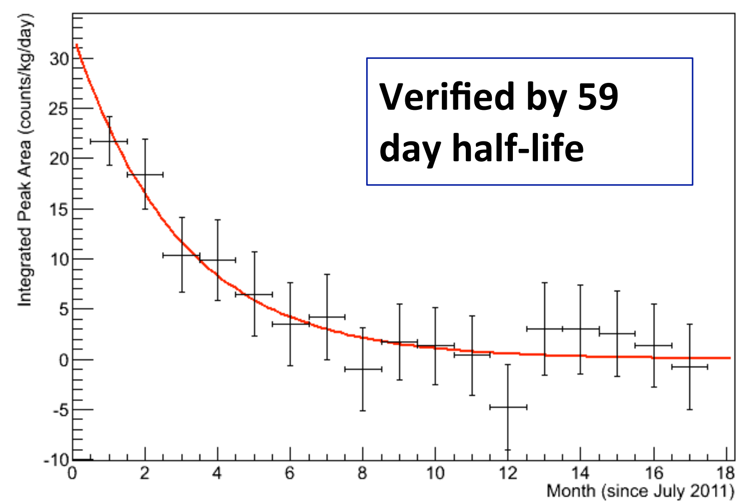
Decay of ^{125}I



July – April Residual



^{125}I Peak Decay



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

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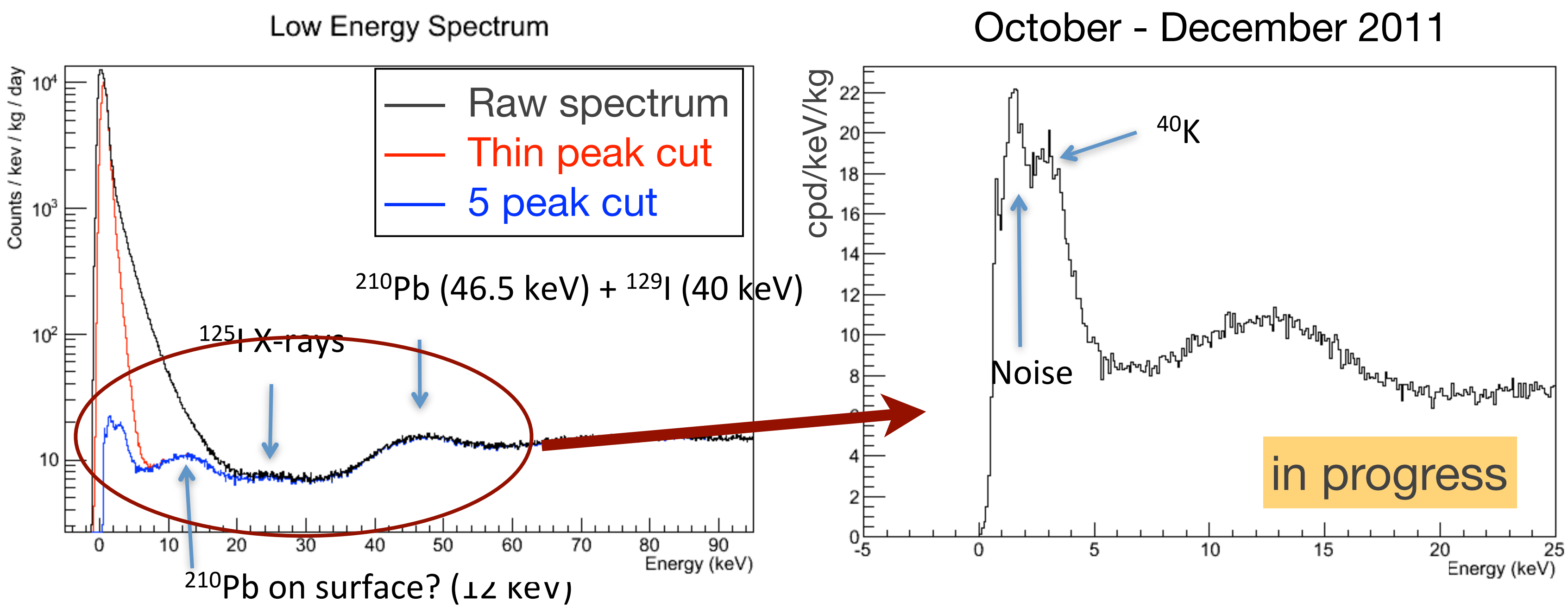
Pushing down the threshold: work in progress

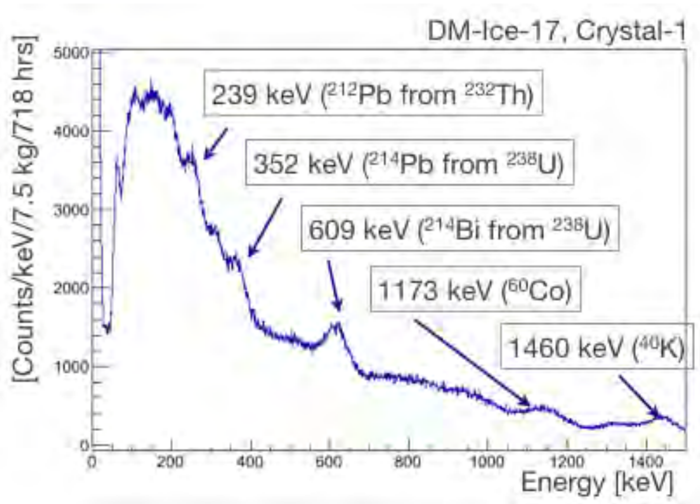


- Since our crystals are separated by 500 m, not possible to look for ^{40}K coincidence between 1460 keV and 3 keV
- Cut noise further by requiring there be multiple photo-electrons in both PMT. ("5 peak" cut shown here)
- 3 keV peak is visible above noise, we still don't understand efficiency etc. still in progress...

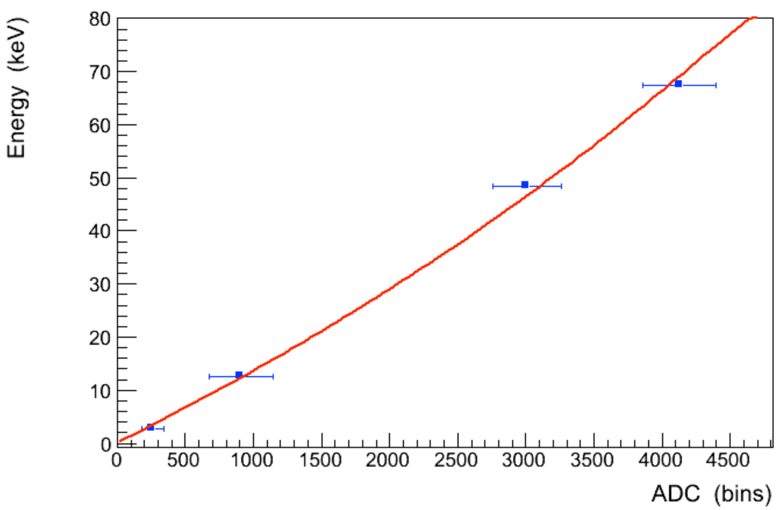
Energy Calibration

- power law < 100 keV
- linear >100 keV

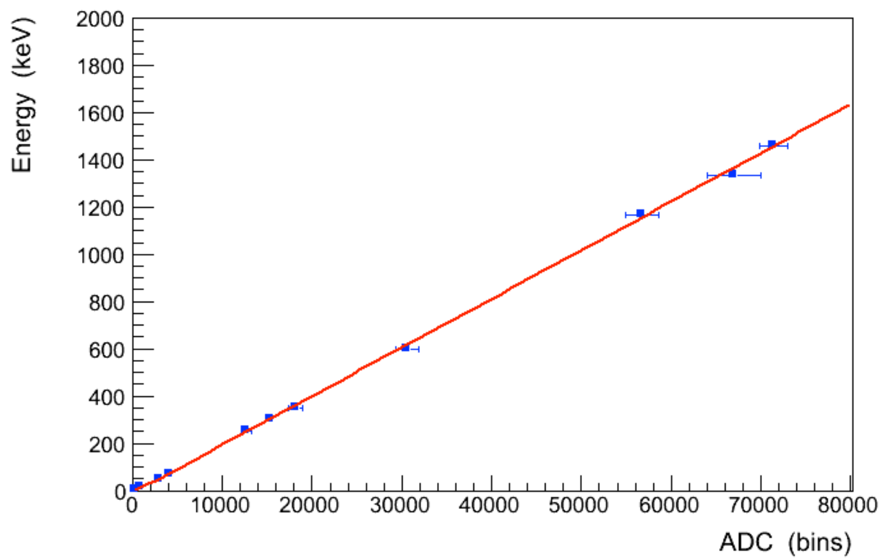
Energy (keV)	source
3.2	K-40
12.5	Pb-210
46.5	Pb-210
67.3	I-125
252	Pb-212, Pb-214
301	Pb-212
352	Pb-214
599	Tl-208, Bi-214
1166	Bi-214, Co60
1333	Co-60
1460	K-40



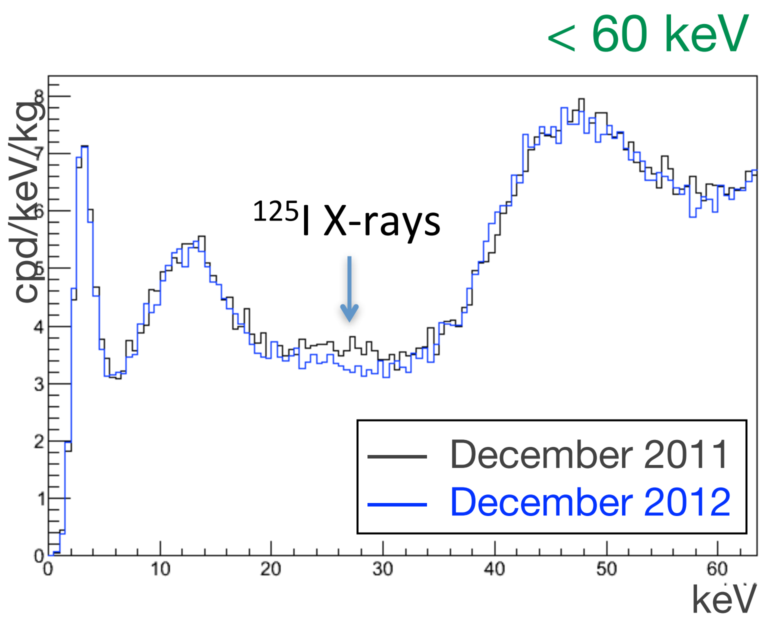
0 - 80 keV

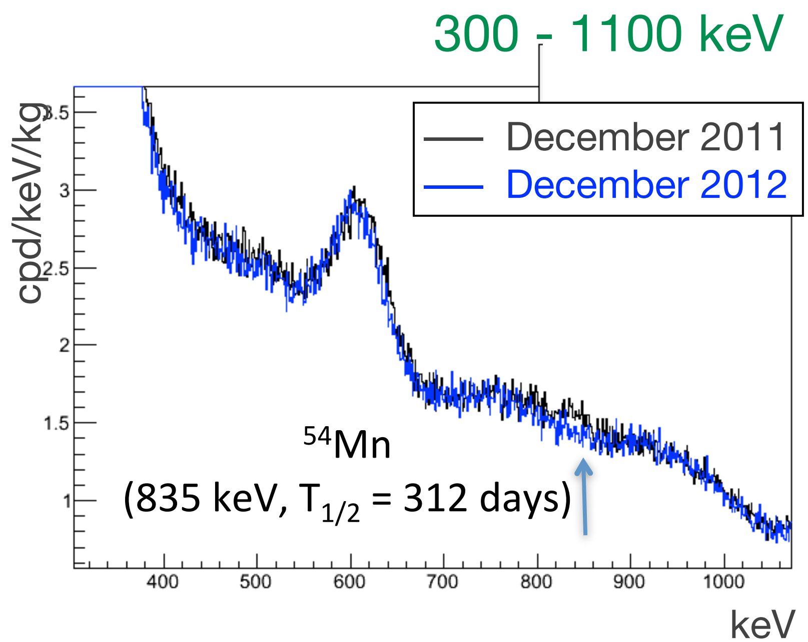


0 - 2000 keV



Detector Stability

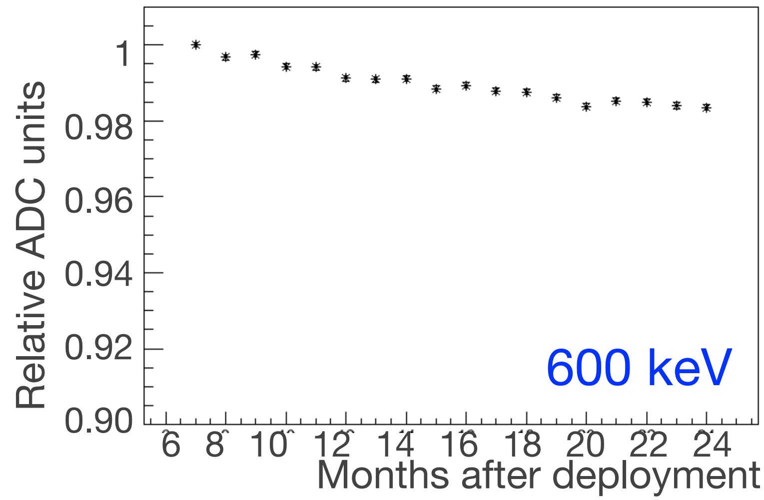


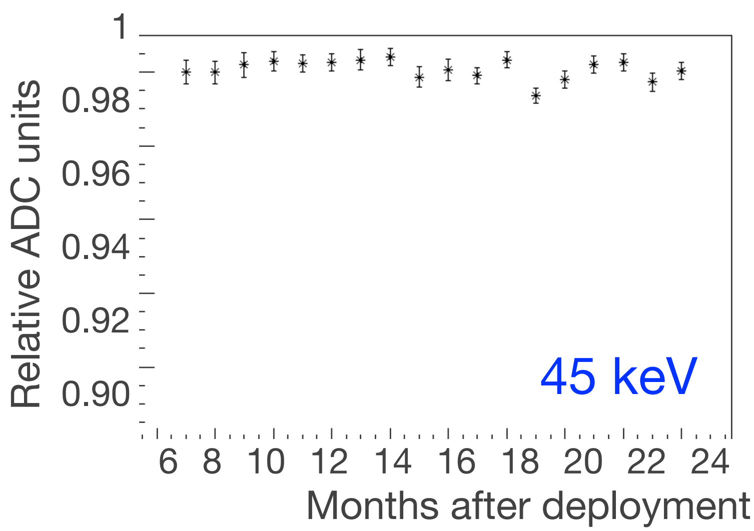


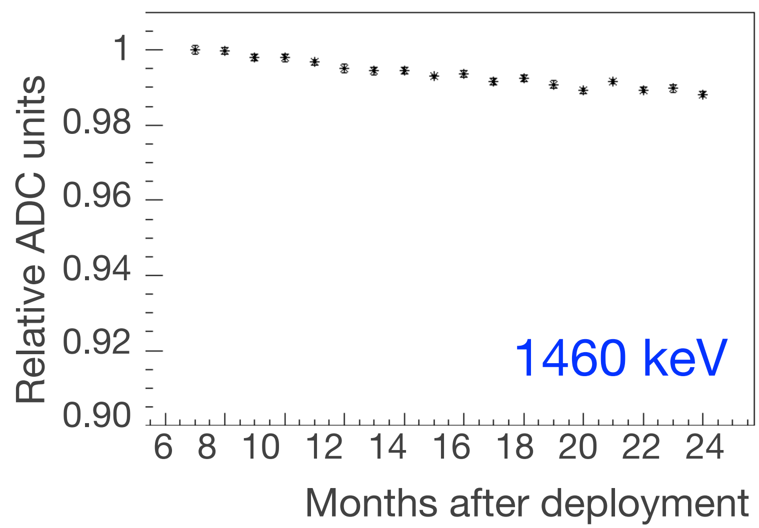
- Spectra are nearly identical over the course of one year
- Longer half-life cosmogenic lines also visible (^{54}Mn, ^{125}I x-rays)

Gain Stability

- Detector calibration is stable to 1% over 18 months.
- 1% decrease over 18 months in light collection (peak position) observed at 600 and 1460 keV
- No observable change in calibration at 45 keV

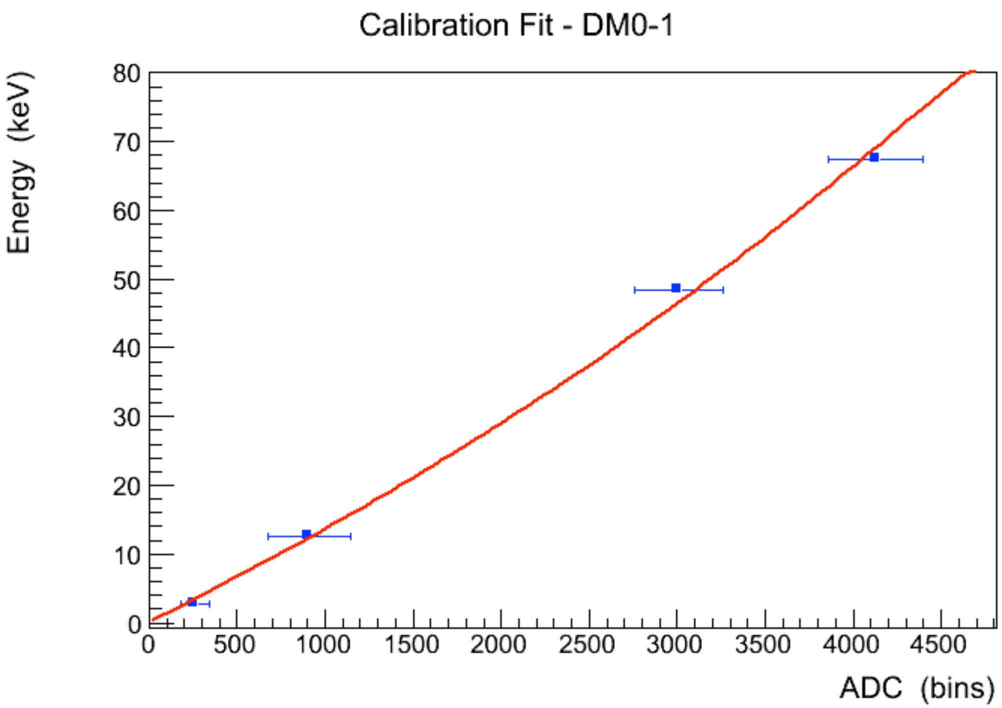


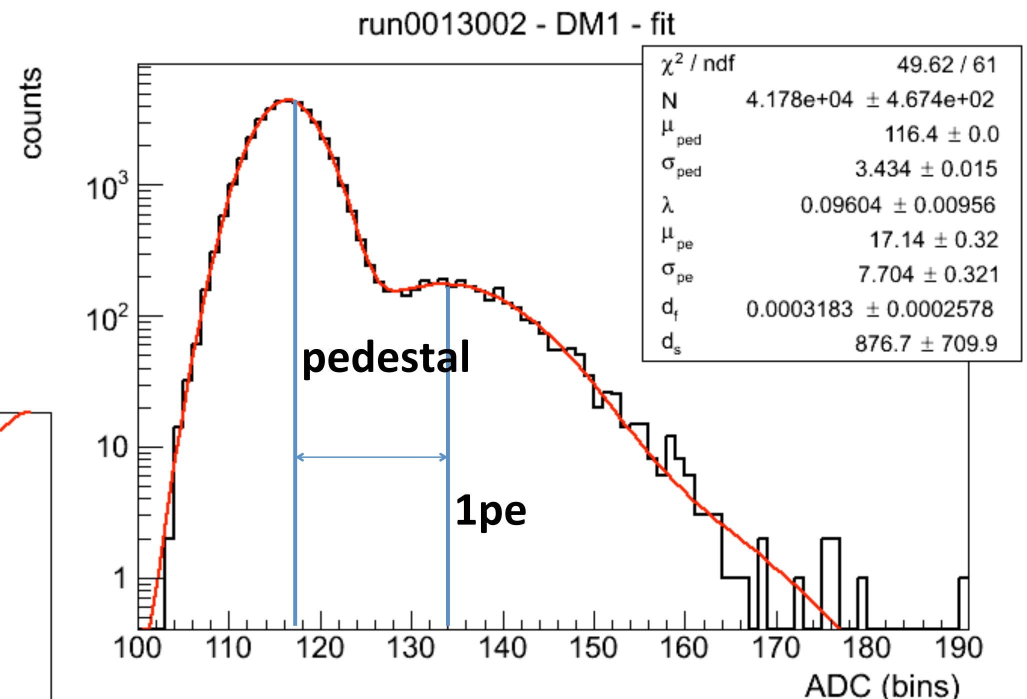




Number of Photoelectrons / keV

Obtain 1p.e.-ped separation from dark noise runs (ie no coincidence requirement)





Normalize the energy to keV using the energy calibration

xtal-1 = 6.1 pe/keV

xtal-2 = 4.7 pe/keV

Backgrounds

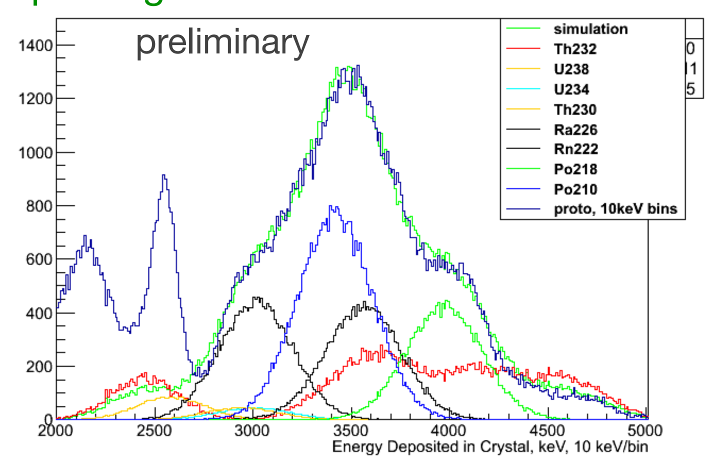
Going from DM-Ice17 to DM-Ice

- Background goal: < 1 cpd/keV$_{ee}$/kg in 2 - 10 keV$_{ee}$ (factor of 10 reduction)
- Contamination levels in DM-Ice17 estimated from in-ice data and radio-assay, verified by simulation
  - Dominant background in DM-Ice17: ^{40}K & ^{210}Pb in the crystals
  - Surrounding ice is extremely clean, drill ice is clean enough
  - Ultra-clean crystals are under development (see F. Calaprice's talk)
  - Cleaner PMT, Pressure Vessel, & Quartz are available
  - Direct muon interaction contribute O(10^{-5}) below other backgrounds
    - Muon monitor & tag with IceCube

Crystal contamination in DM-Ice17 & DAMA

	DM-Ice17	DAMA
^{nat}K	500 ppb	< 20 ppb
^{232}Th	50 ppt	0.5 - 7.5 ppt
^{238}U (upper part of chain)	7.5 ppt	0.7 - 10 ppt
^{238}U (below Pb-210)	2 mBq/kg	5 - 30 μBq/kg

Alpha region in DM-Ice17 vs. Simulation



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 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
Bicron/Saint Gobain	Crystal	NaIAD/DM-Ice	20*	20*	650*
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

*preliminary

- **Also working with SICCAS (Shanghi)**

Technical challenge == a method to measure K < 100 ppb level
- **ICPMS → < 10 ppb ?**

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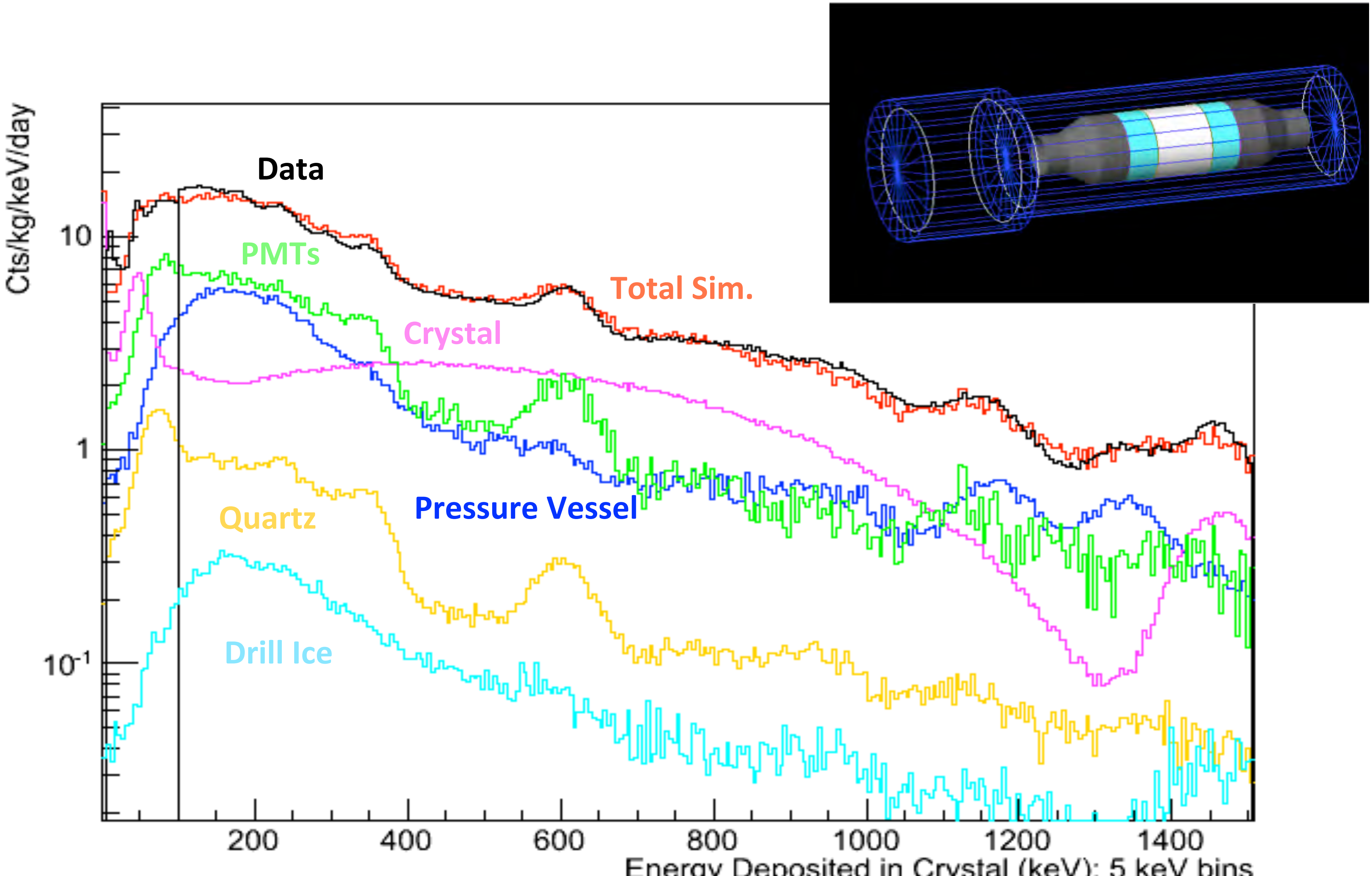
Background Model for DM-Ice17



Additional reduction from crystal-crystal coincidence expected

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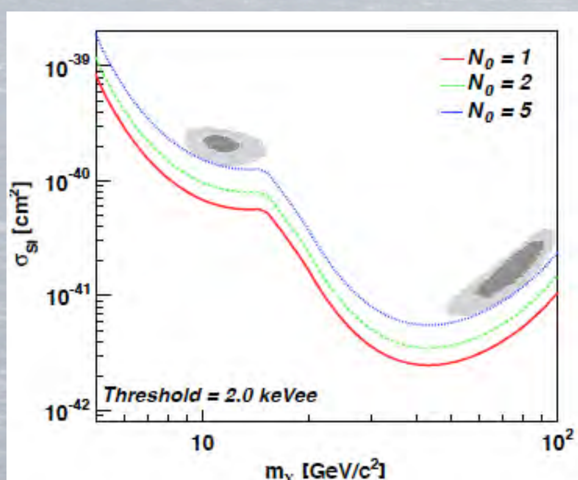
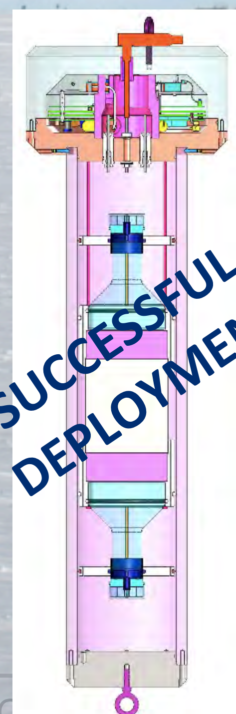
Conclusions

- Success installation of DM-Ice17 along with IceCube and running stably
- Background level nominally as expected and in agreement with simulations
- Making good progress on cleaner NaI
- R&D and design for the full-scale experiment underway

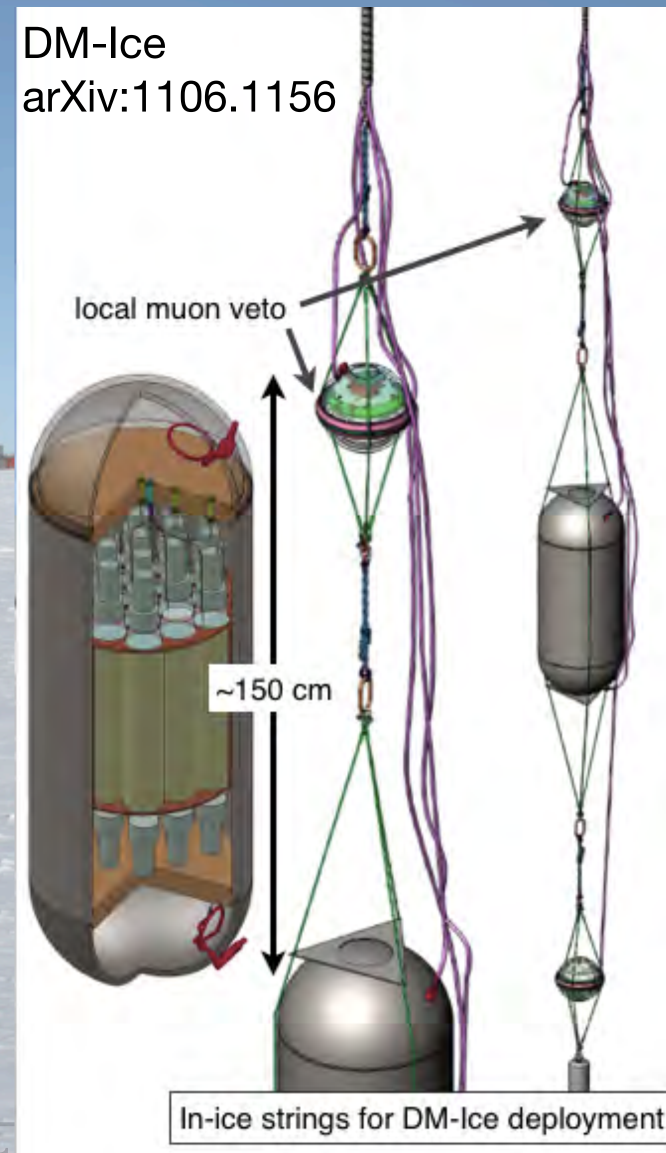


500 kg·year NaI detector sensitivity

(2 - 4 keV) with 1, 2, and 5 dru bgd.



SUCCESSFUL DEPLOYMENT



DM-Ice Collaboration

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University of Sheffield
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Penn State
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NIST-Gaithersburg
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University of Stockholm
Chad Finley, Per Olof Hulth, Klas Hultqvist, Christian Walach

DigiPen
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Boulby Underground Science Facility
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SNOLAB
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