DM-Ice

A search for dark matter with NaI

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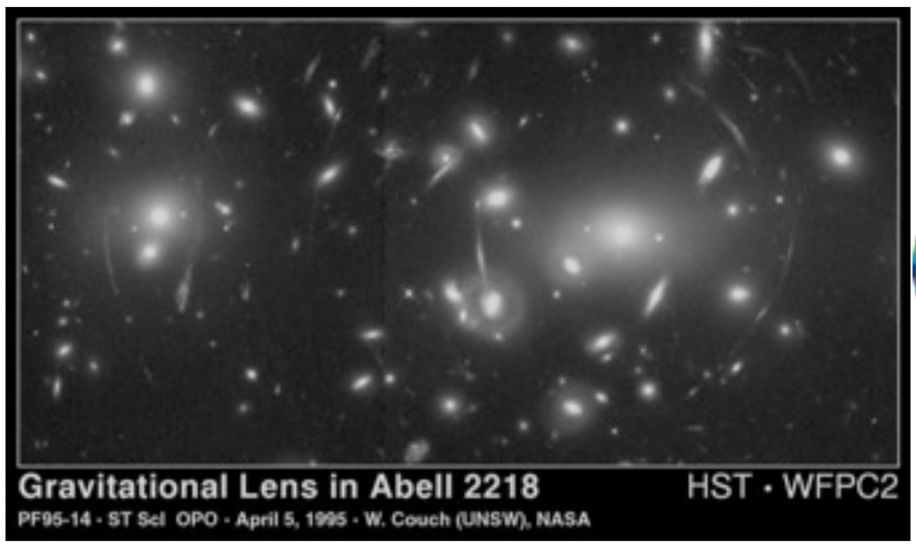
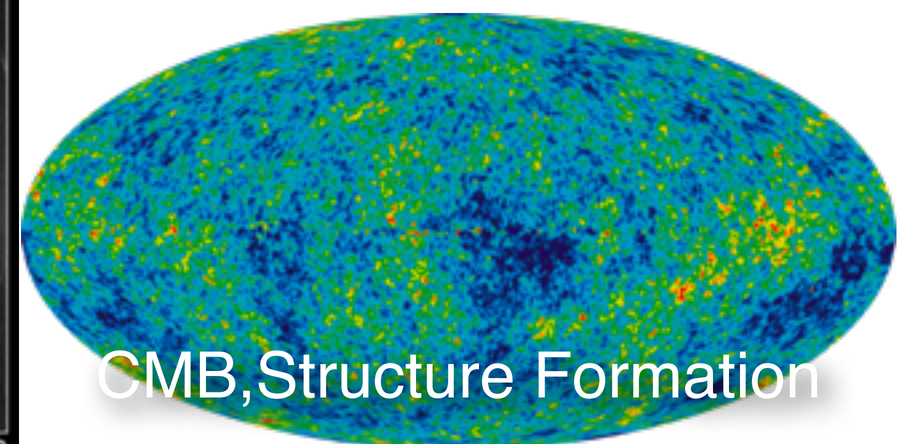
University of Wisconsin - Madison

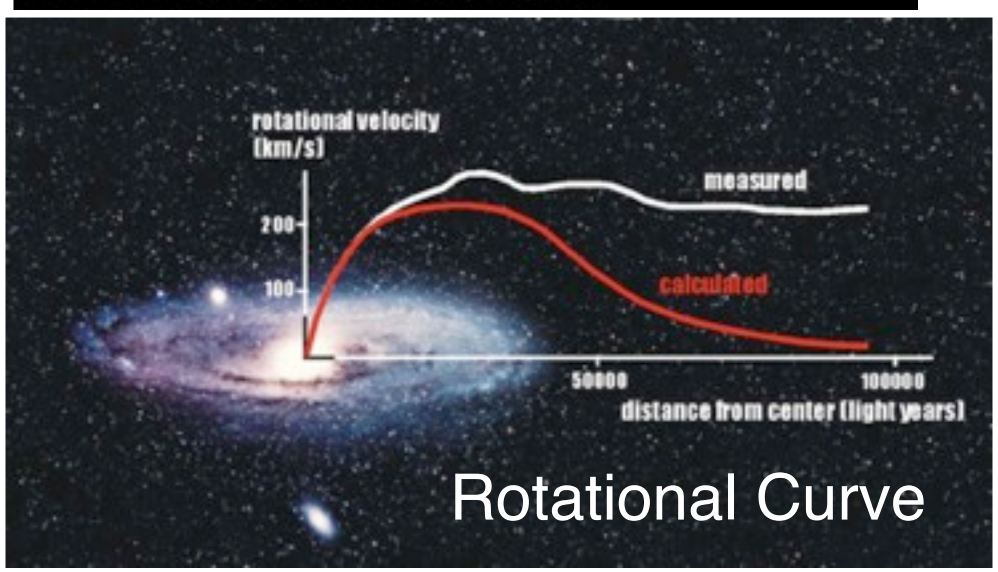
NDM 2012
Nara, Japan
June 11 - 15, 2012

Evidence for Dark Matter

- Many gravitational evidence for dark matter







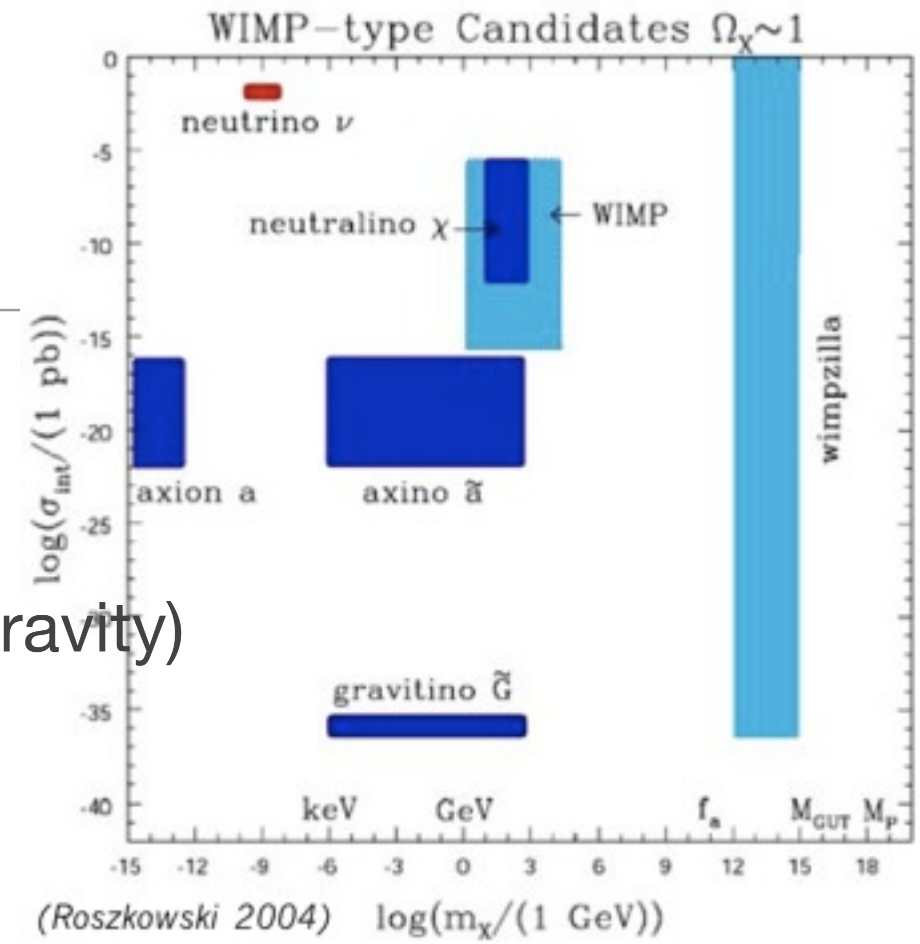
All consistent with 23% dark matter content.

But... what is it? ... and where is it?

Dark Matter Candidates

Observational evidence indicate:

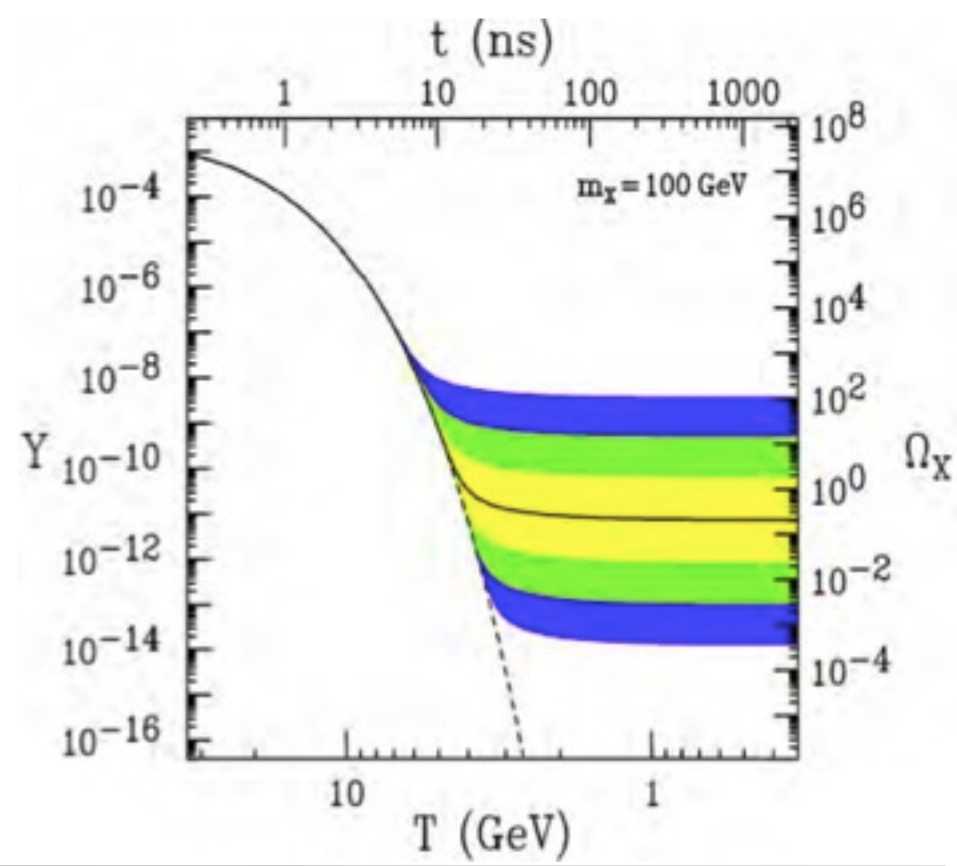
- Non-baryonic
- Cold and massive (non-relativistic and exerts gravity)
- Interact little with ordinary matter
- Stable and long-lived



Leading Candidates: WIMPs & Axions

WIMPs: Weakly Interacting Massive Particles

- mass of 1 GeV – 10 TeV
- Lightest supersymmetric particles
- "WIMP miracle" ... abundance is just right for weak scale cross sections



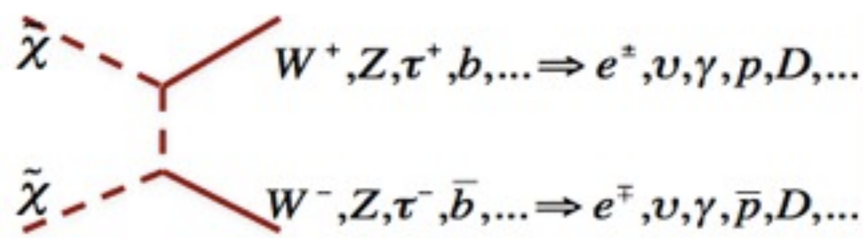
$\sigma \approx 10^{-39}$ - 10^{-46} cm^2

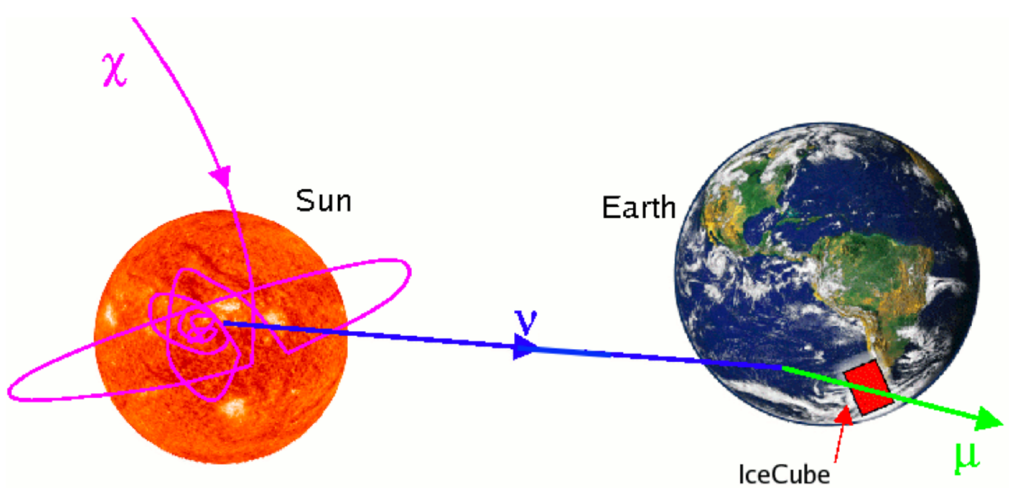
$<\sigma_A v> \approx 10^{-26}$ cm^3/s $\qquad m_\chi \approx 100$ GeV

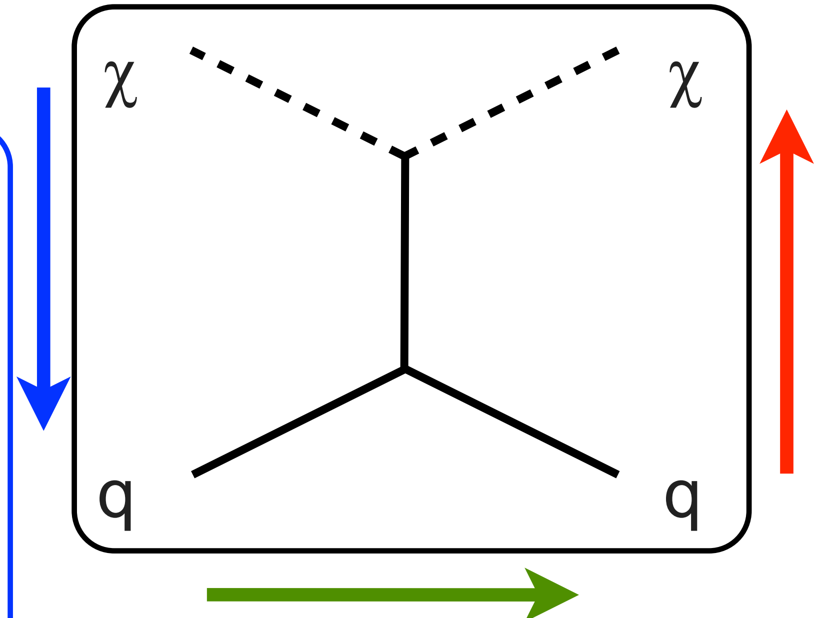
Detecting WIMPs

Indirect Searches

Search for annihilation products from massive objects
(gamma rays, e^-/e^+, neutrinos...)

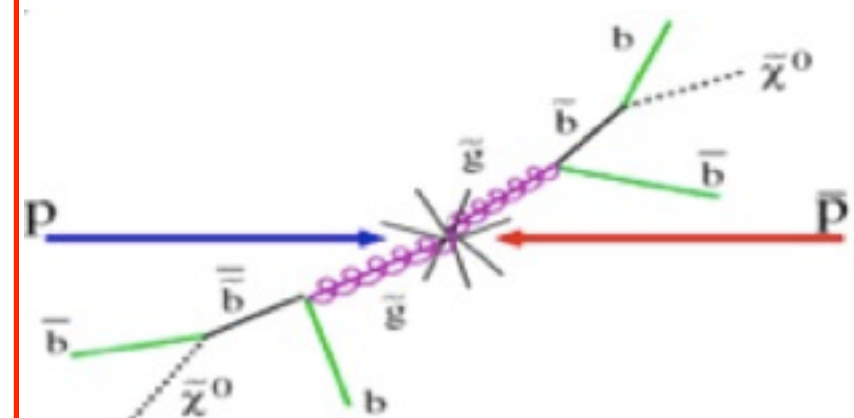


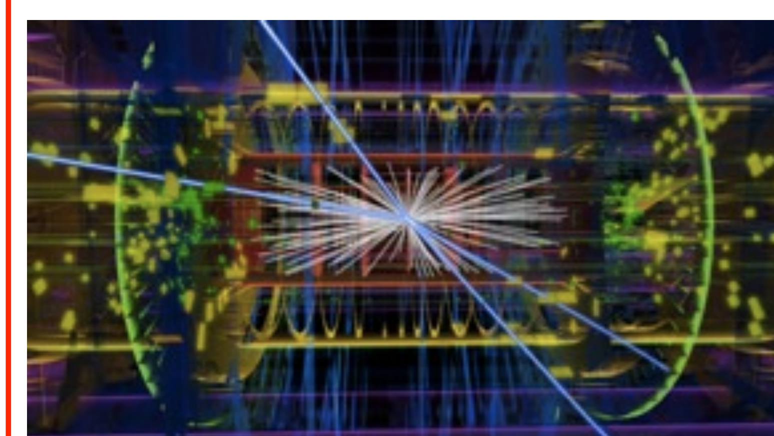




Production

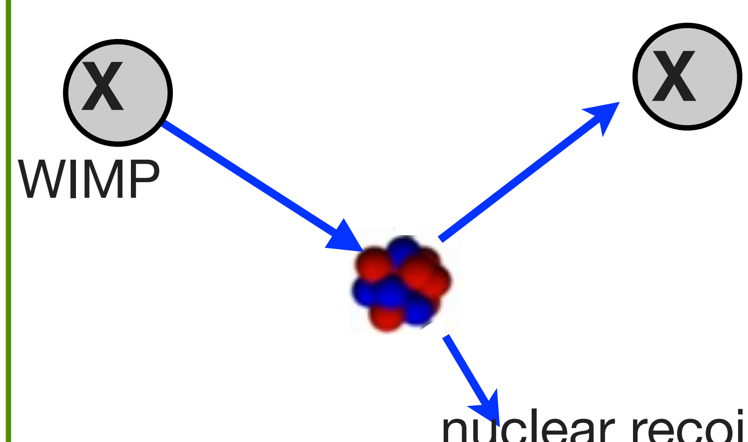
Colliders
Look for the missing energy





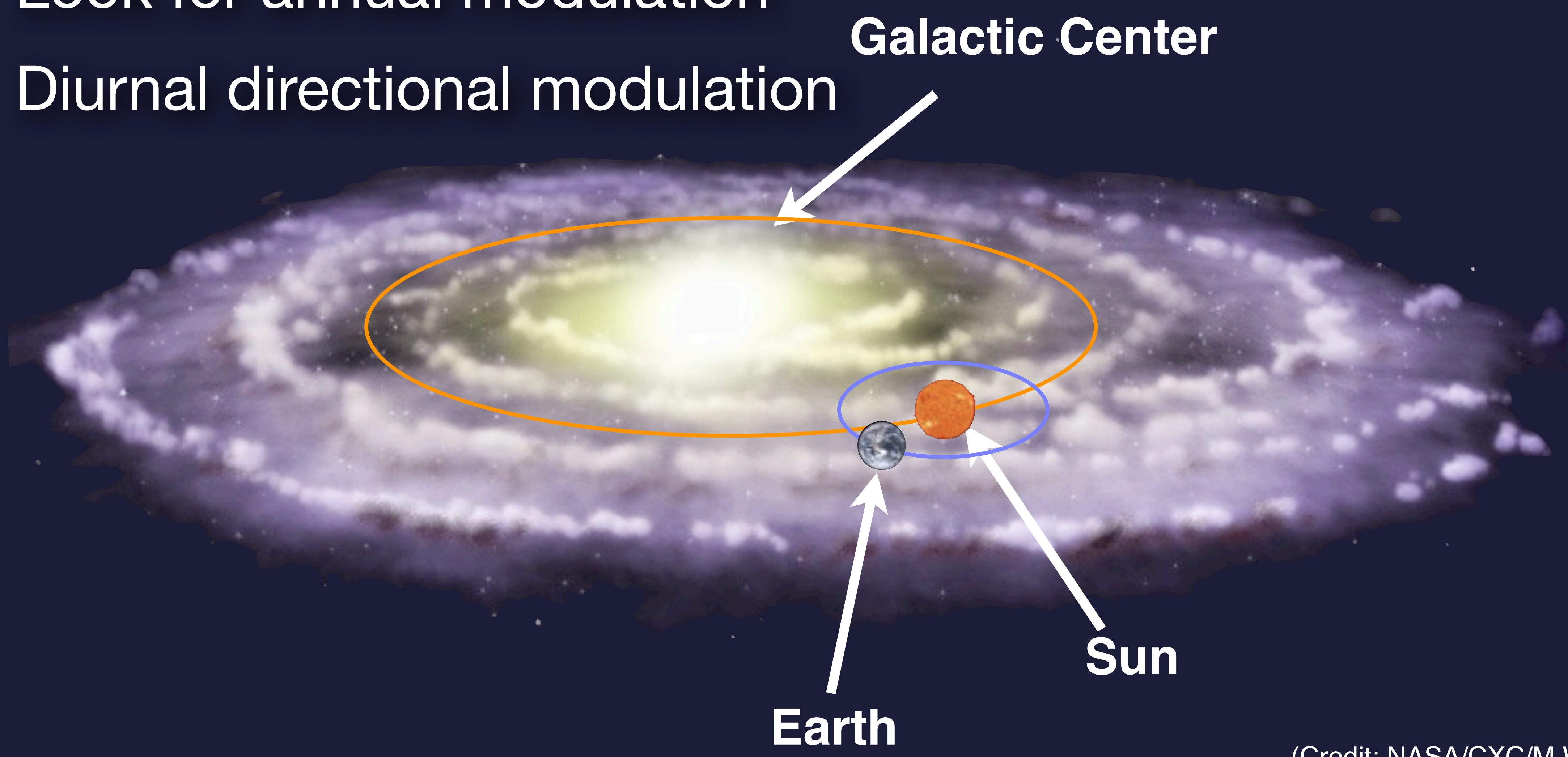
Direct Searches

WIMP-nucleon scattering
Look for nuclear recoil



Direct Detection Search Strategies

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



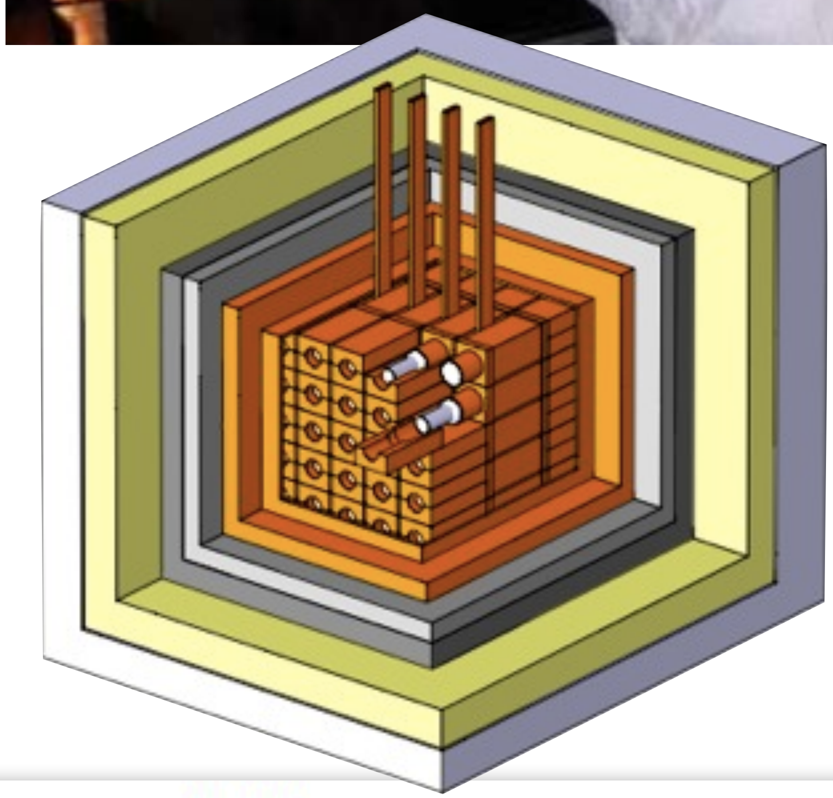
(Credit: NASA/CXC/M.Weiss)

The world wide dark matter search

Laura Baudis
Neutrino 2012

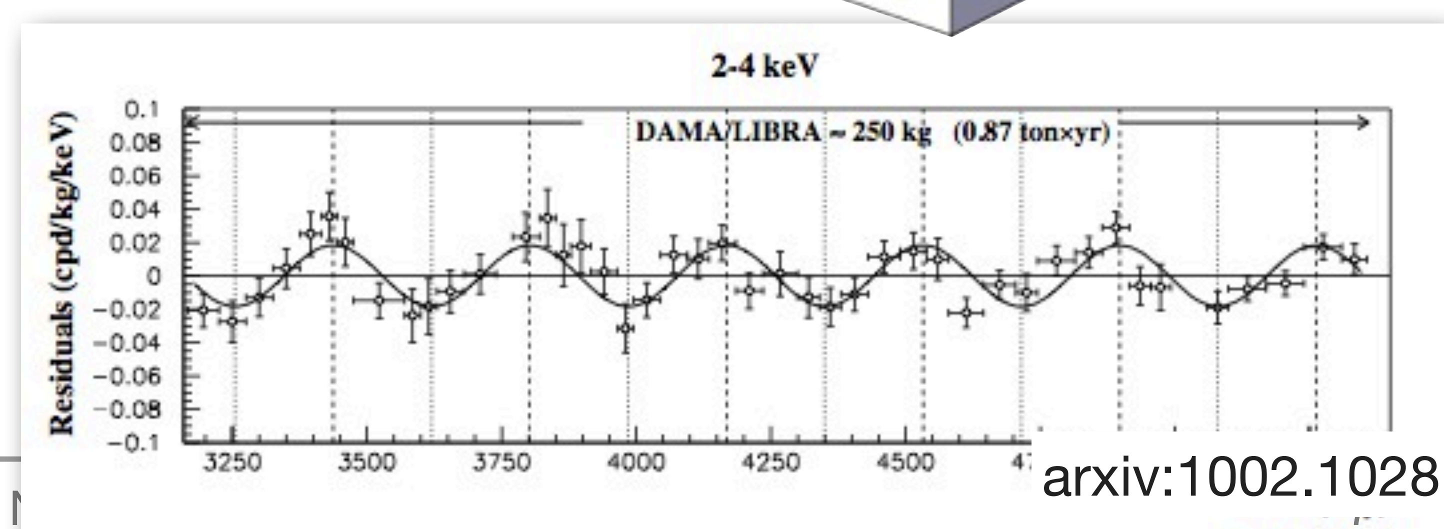
Modulation Observed by DAMA

- DAMA/NaI: 100 kg (1996 - 2003)
- DAMA/LIBRA: 250 kg (2003 - present)
- 1.17 ton-yr over 13 annual cycles
- Modulation consistent with dark matter:
  - Background: ~ 1 cnts/keV/kg/day
  - Amplitude: 0.01 cnts/keV/kg/day
  - phase: 146 ± 7 days (peak on June 2)
  - period: 0.999 ± 0.002 yr



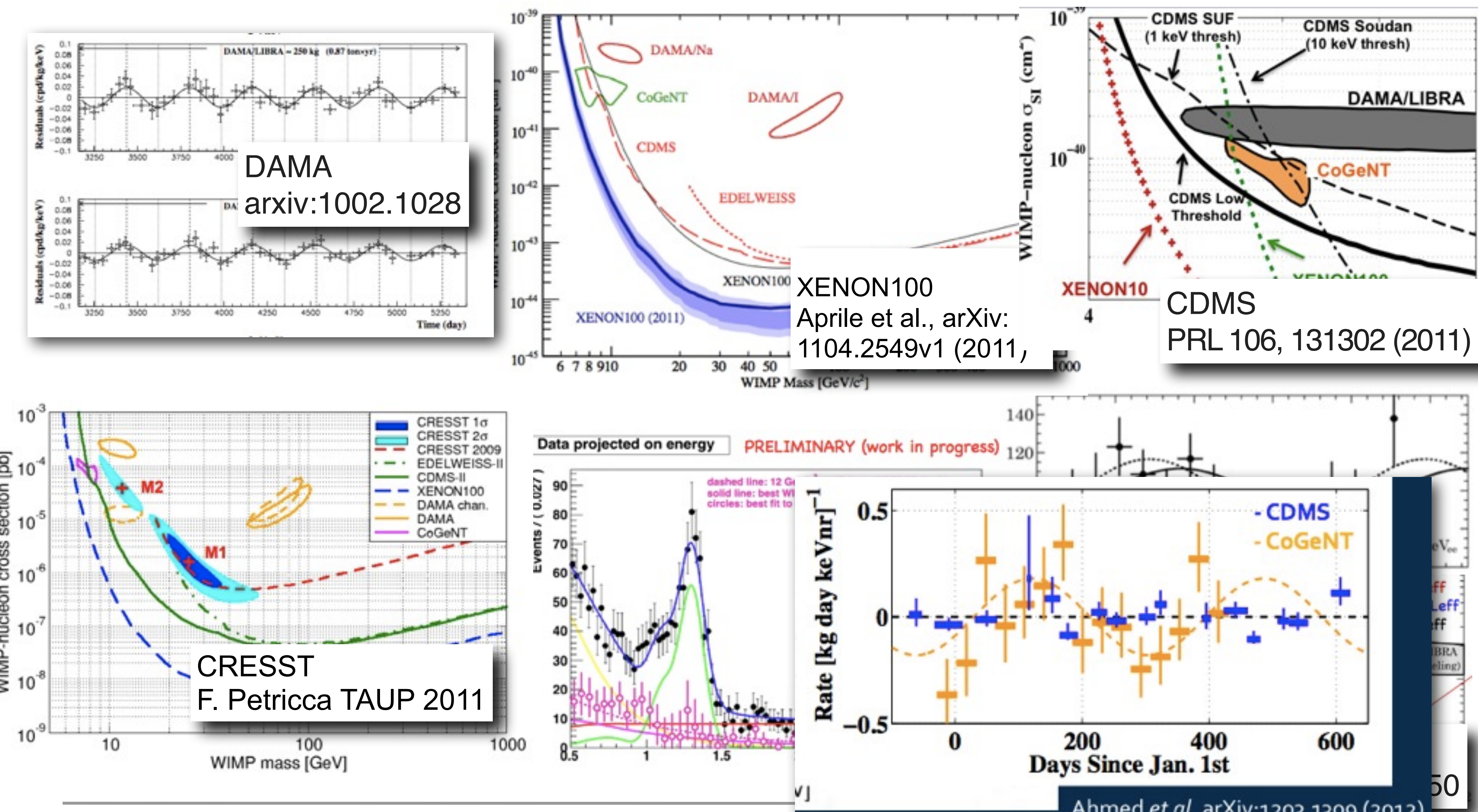
8.9σ modulation observed

but is it dark matter?



arxiv:1002.1028

Current Status of Bounds on Dark Matter from spin-independent direct detection experiments



Are we seeing Dark Matter?

- Many things modulate annually:
  - Ambient temperature variation
  - Muon flux depend on temperature in the upper atmosphere
  - Spallation neutrons from muons in rock
  - Radon diffusion from rocks may be varying with time
  - Scintillator phosphorescence

Fernandez-Martinez and Mahbubani arXiv:1204.5180

~~or not. see e.g.Blum arXiv:1110.0857~~

DAMA rules these out.
See e.g. arXiv:1202.4179

take them out! Fox, Liu & Weiner Phys.Rev. D83 (2011) 103514

- Detector Effects?
  - Quenching & channeling
  - Target nucleus
  - Threshold effects?

- Astrophysical Uncertainties?
  - f(v)? v_{esc}? v_0? co-rotating? streams?
- Which Dark Matter?
  - *insert your favorite model here*

Testing DAMA's Dark Matter Claim

Use NaI(Tl)

- Eliminate uncertainties due to astrophysics, detector effects, and dark matter models

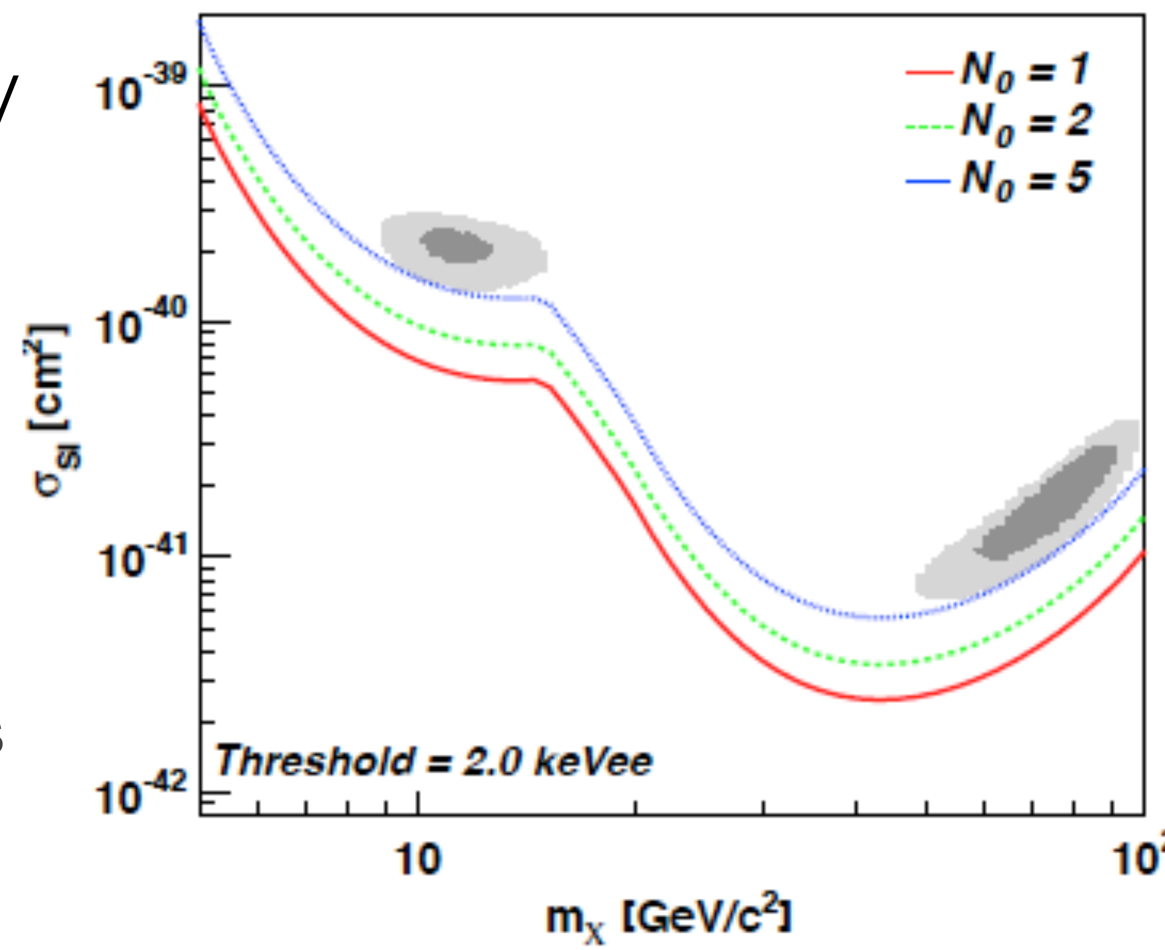
Definitive (5σ) detection or exclusion w/

- 500 kg-yr NaI(Tl) (DAMA x 2 yrs)
- threshold < 2 keV_{ee}
- background < 5 cnts/keV/kg/day (DAMA x 5)

Change the environment / background

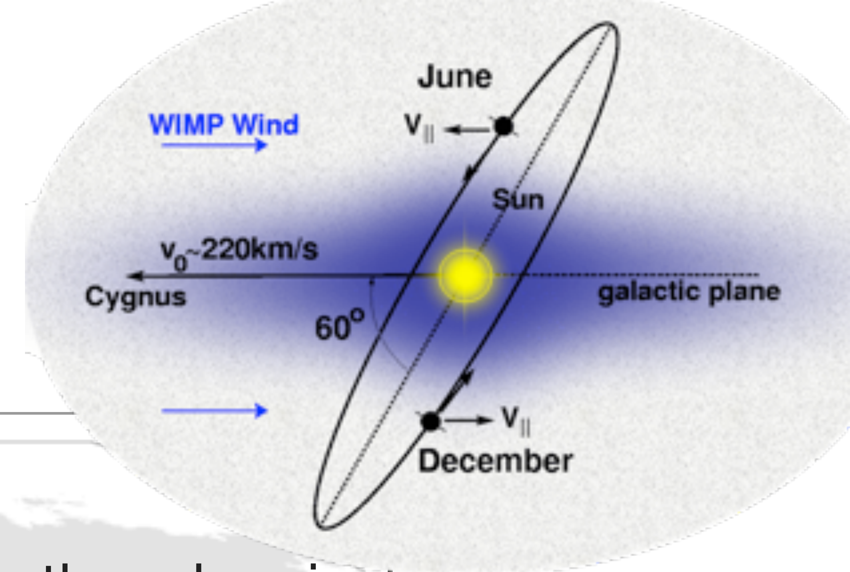
- Control or eliminate possible sources of background & annual modulation
- Go deeper, tag*, or go to the southern hemisphere

500 kg·year NaI detector sensitivity
(2 - 4 keV) with bgd of 1, 2, and 5 cnts/keV/kg/day.



Cherwinka et al.
arXiv:1106.1156

Annual Modulation Dark Matter Searches with NaI Detectors



DM-induced annual modulation signal the same in northern and southern hemispheres.

northern hemisphere definitive only if there is no signal	Gran Sasso DAMA/Libra 250kg running	Gran Sasso Princeton-NaI R&D	Canfranc ANAIS ~100kg starting in 2014?	PICO-LON KIMS etc...	
southern hemisphere limited underground access	South Pole DM-Ice DM-Ice-17 running R&D for 500kg	ANDES (proposed, LOI) NaI DM search proposed for new lab			

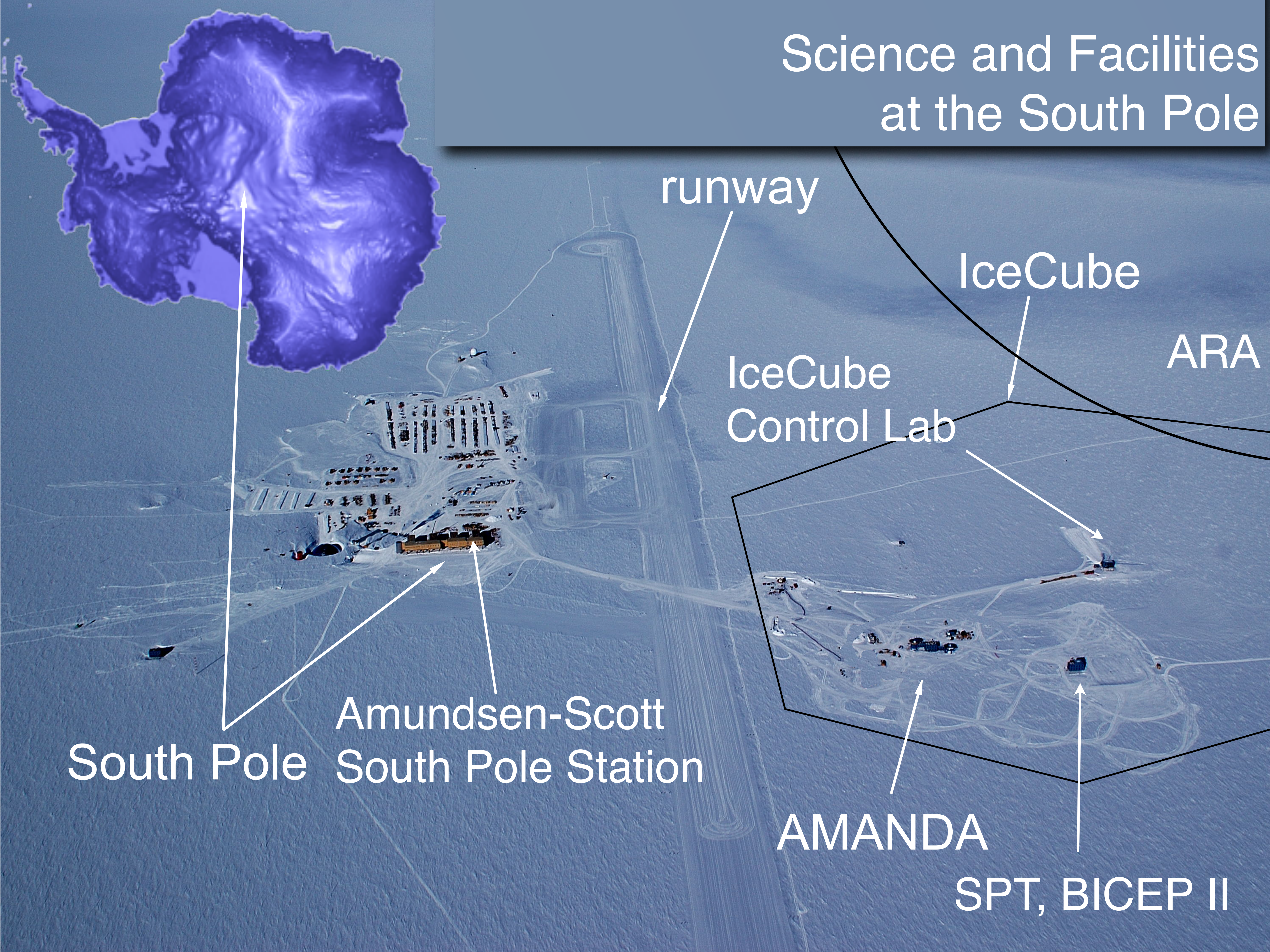
See talk by K. Fushimi

ice	rock

DM discovery would require

- consistent phase of annual modulation signal in multiple experiments
- different ambient environments to exclude unknown background signal
- unambiguous separation of seasonal variations of backgrounds and DM-induced annual modulation signal

Science and Facilities at the South Pole



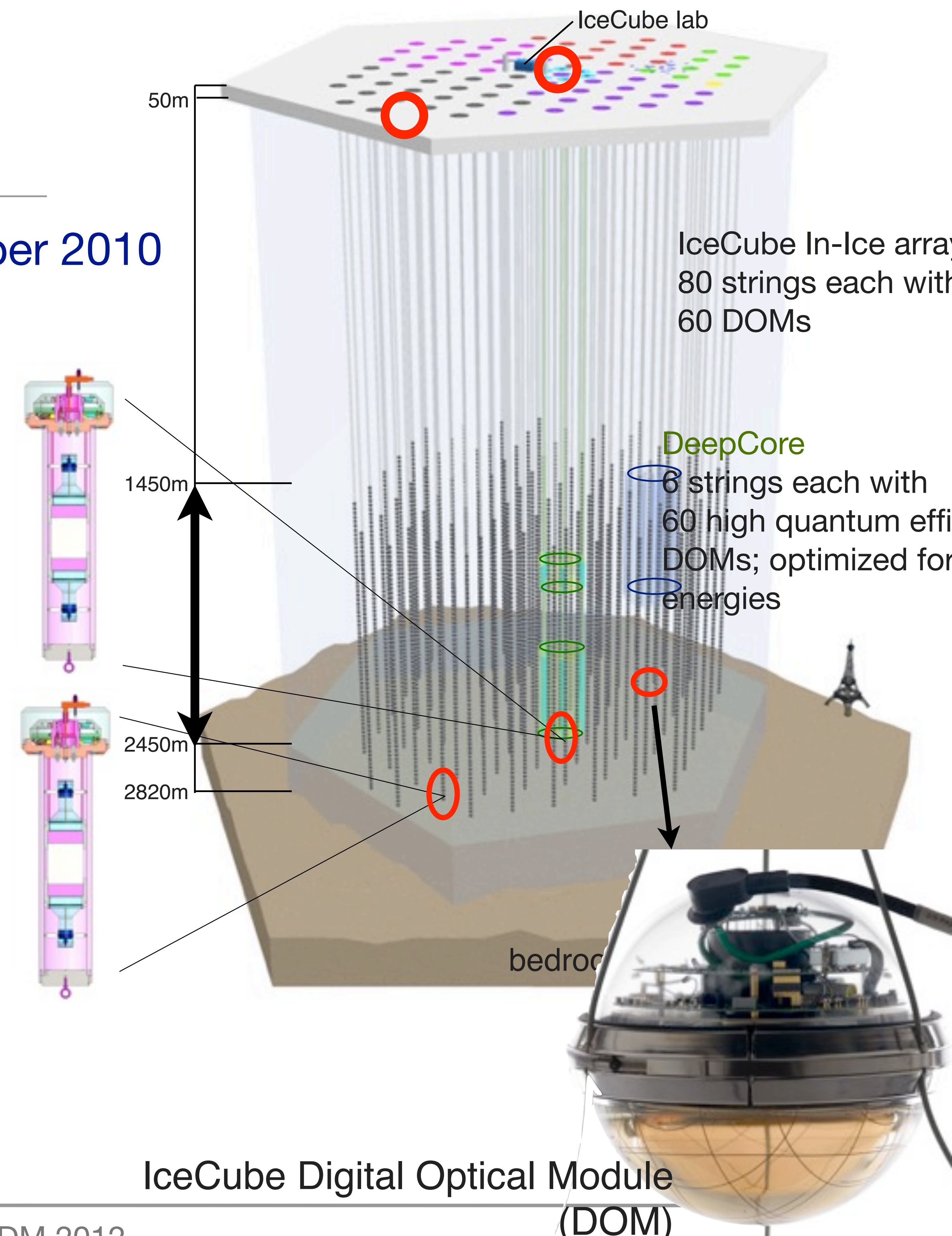
Prototype: DM-Ice-17

Co-Deployed with IceCube in December 2010

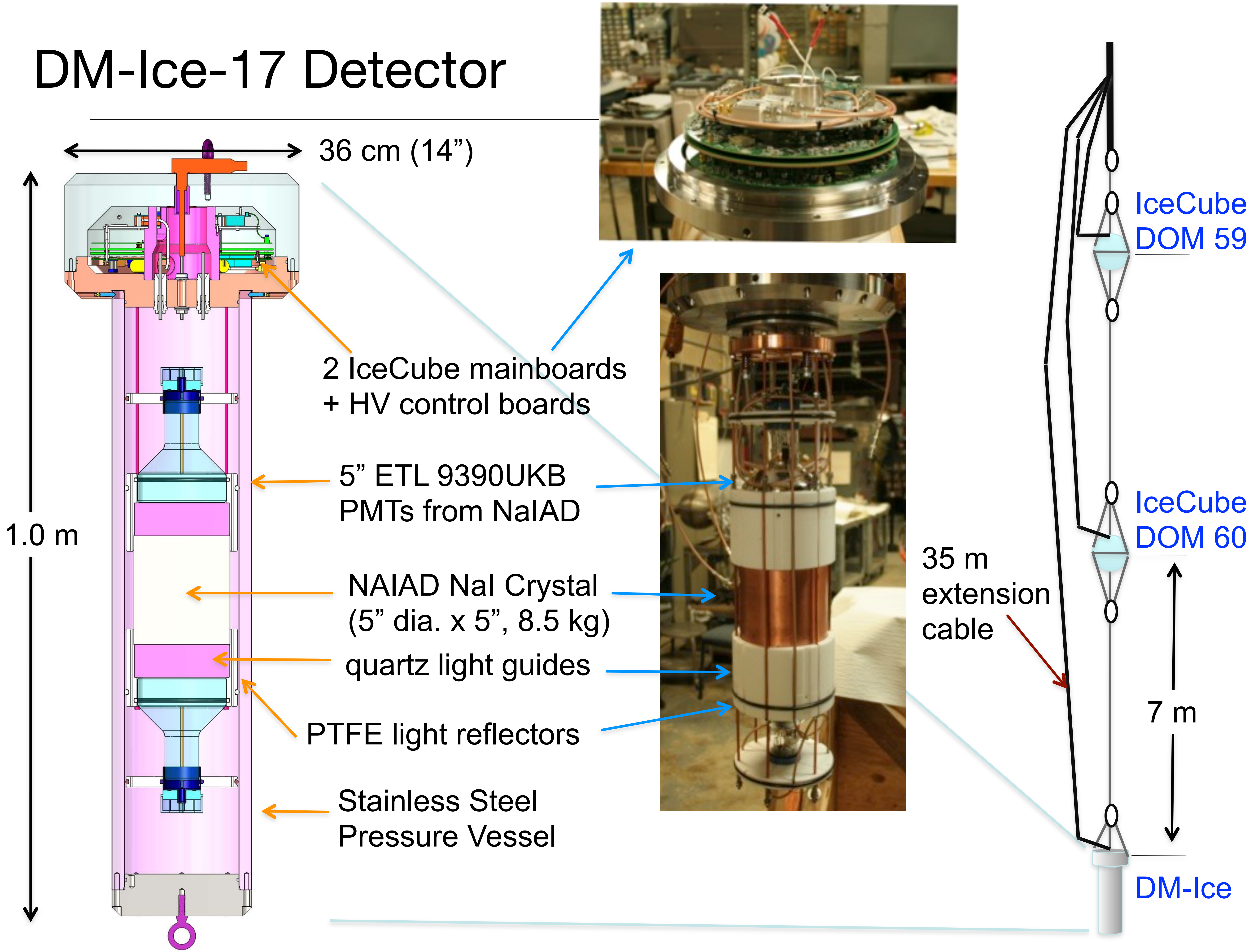
- A 17 kg detector
- designed and built in 10 mo.
- Stable operation since Feb. 2011
- Data sent over satellite

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



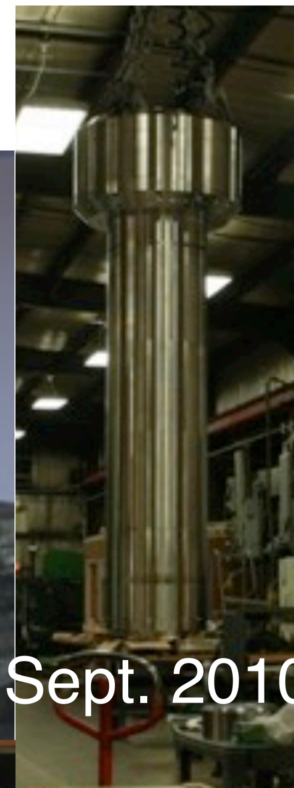
DM-Ice-17 Detector

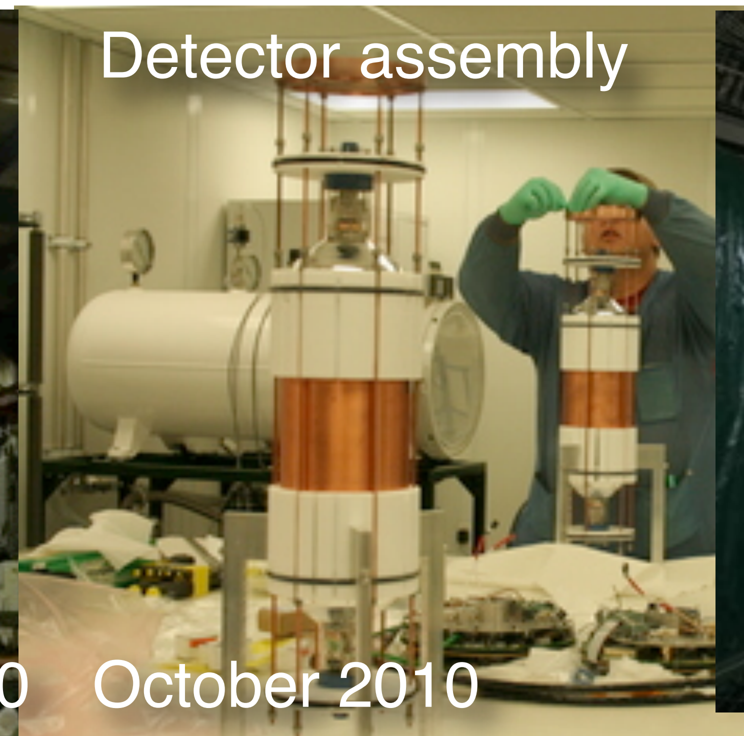


DM-Ice-17 Construction & Deployment

Design begin Feb. 2010


Revive NAIAD xtals
July 2010


Sept. 2010


Detector assembly
October 2010

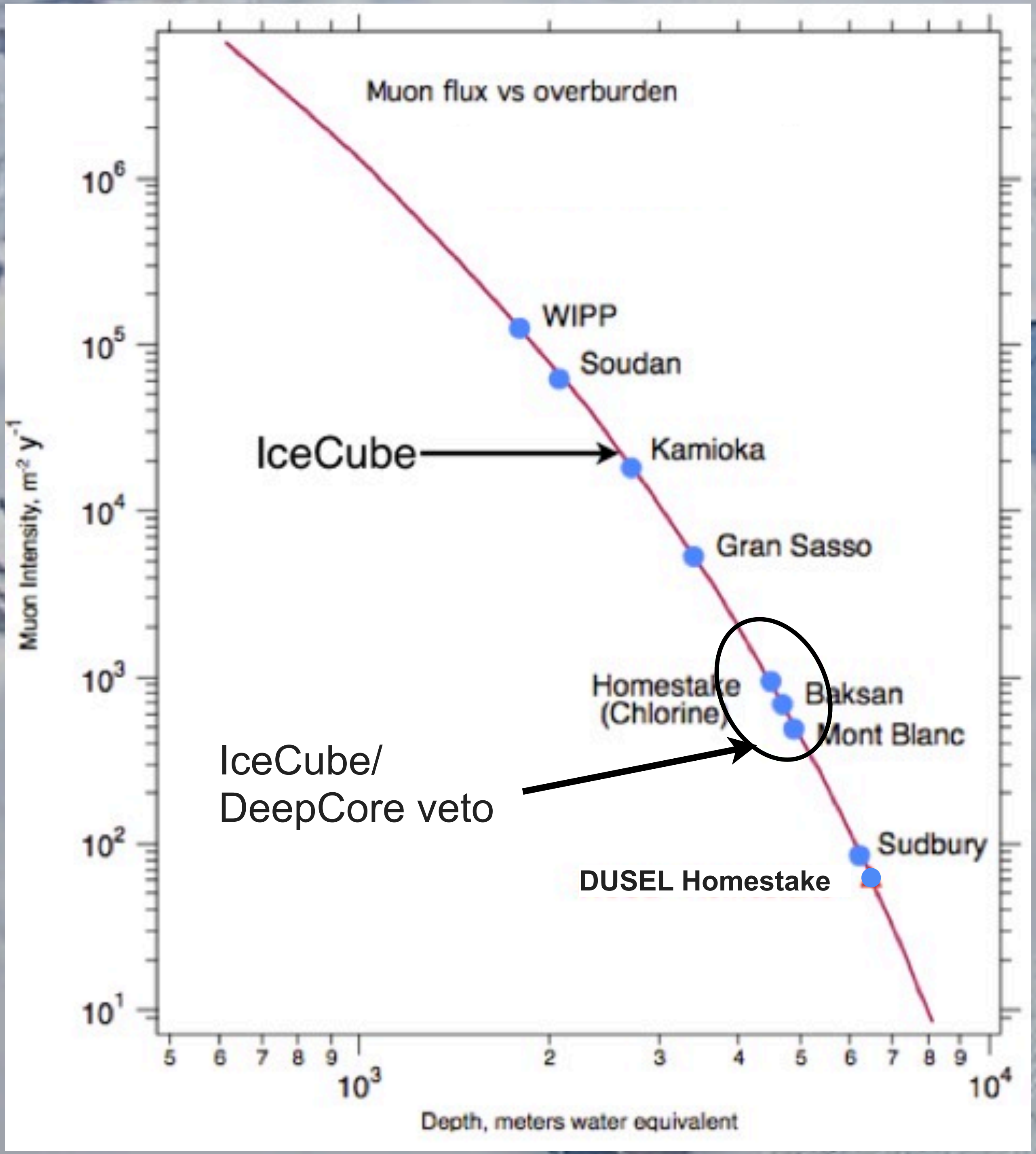

Flying to Antarctica
Dec. 1, 2010


Transport
across the Ice

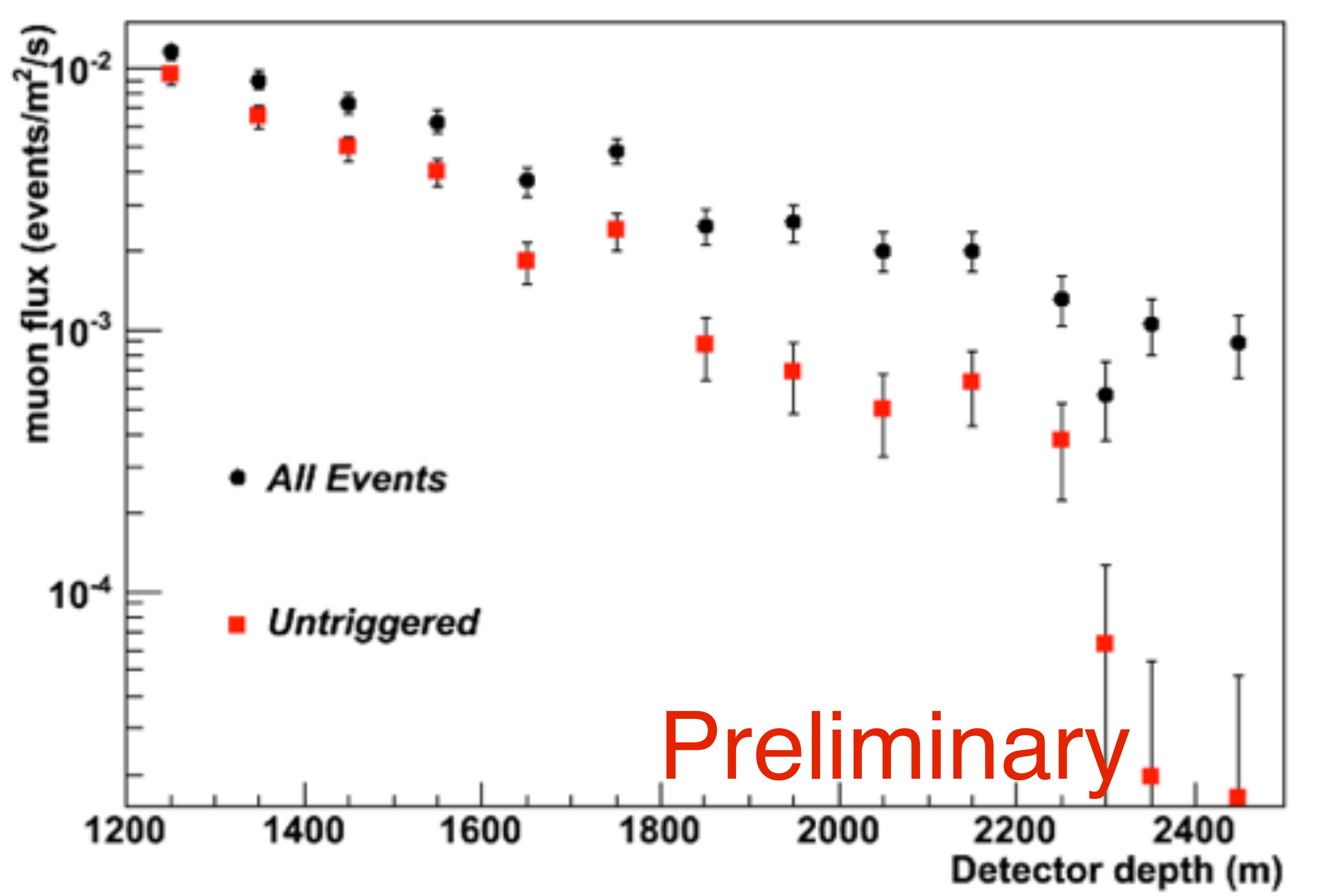

Deployment
Dec. 11, 2010


Detector in the hole

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

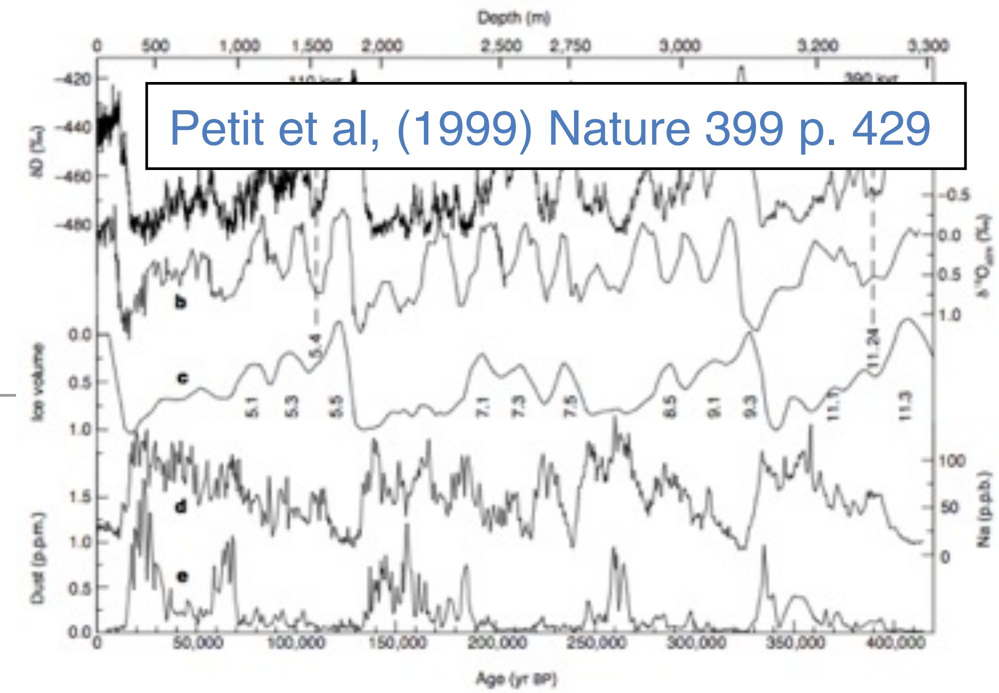


- ~85 muons/m^2/day at bottom of IceCube
- IceCube/DeepCore veto reduces rate by ~1-2 orders of magnitude.



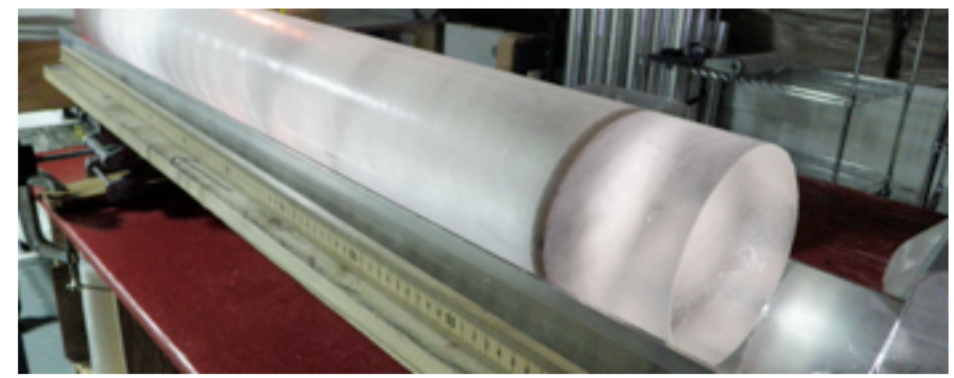
Muon flux vs. depth in the ice, total and those untriggered by IceCube/DeepCore.

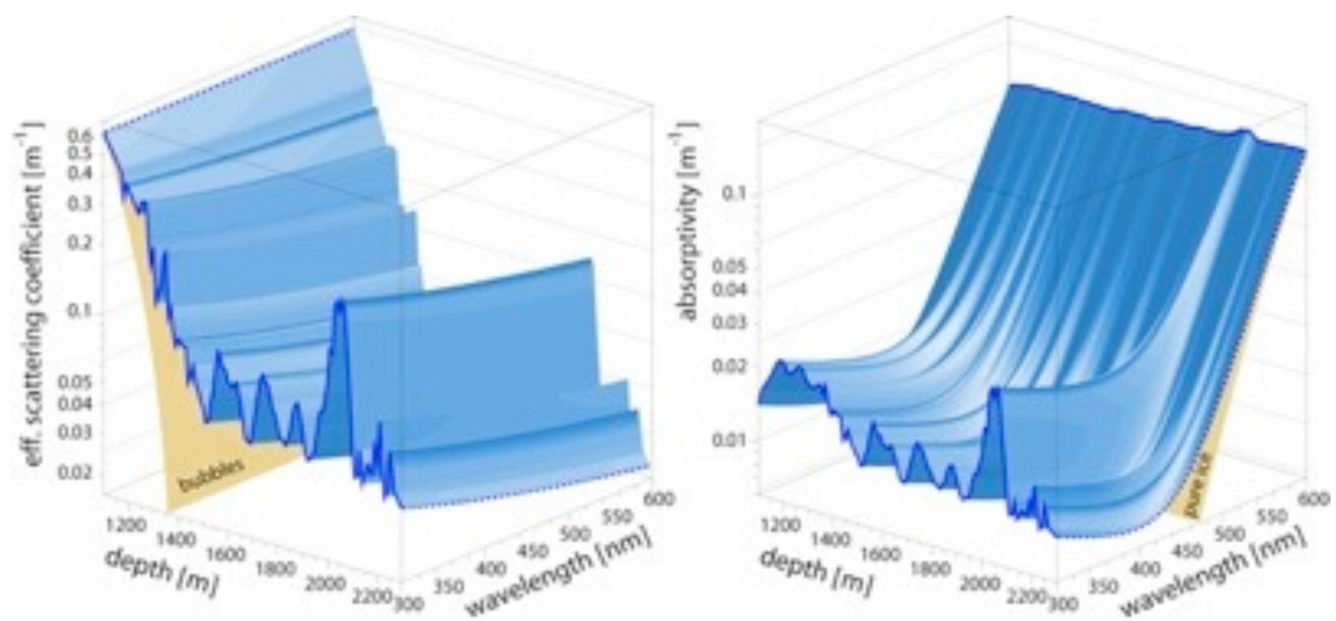
Antarctic Ice: Radiopurity



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

- 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



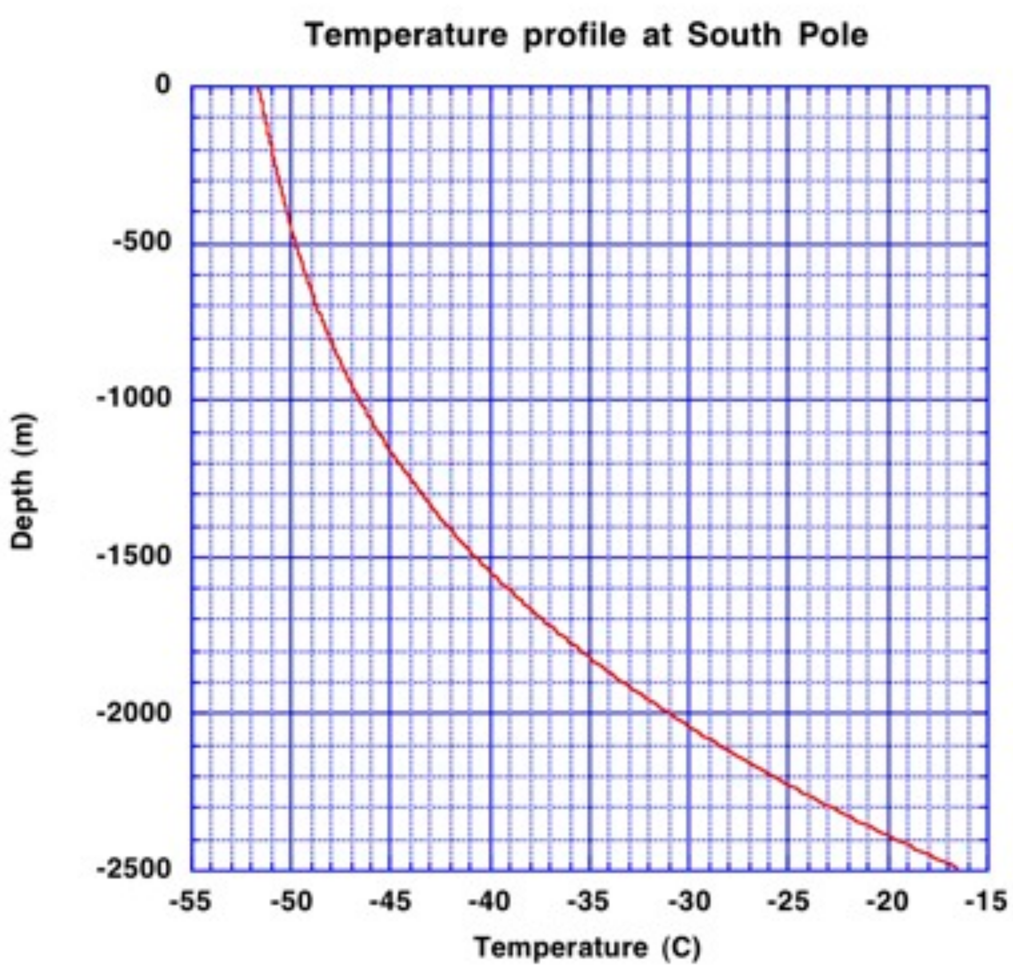


No shielding required!

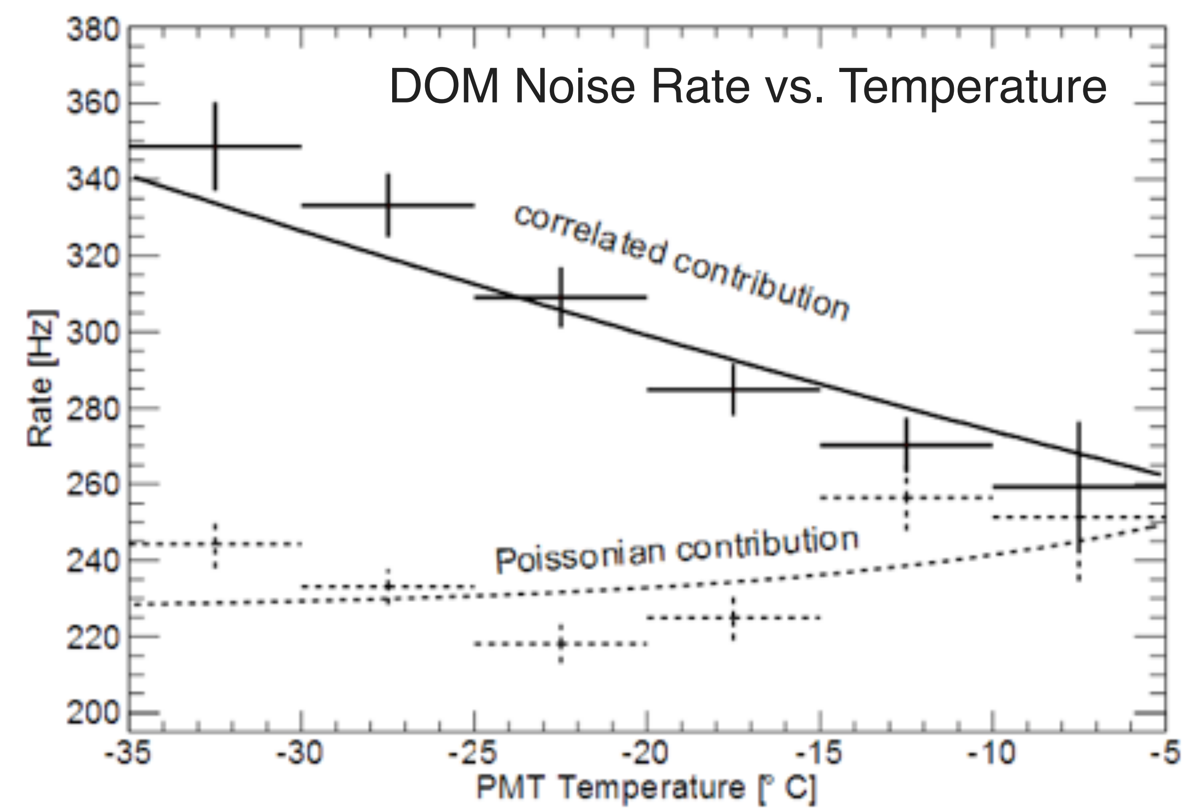
J. Geophys. Res., 111, D13203 (2006)

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



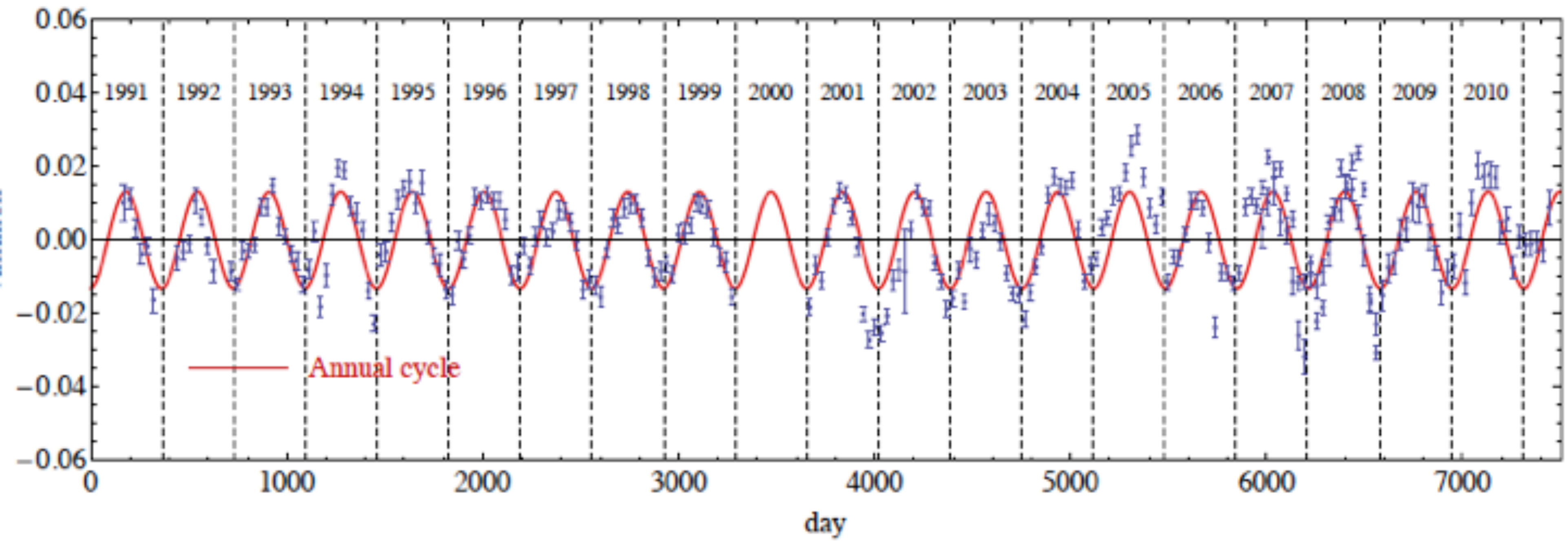
Kurt Woschnagg (IceCube)



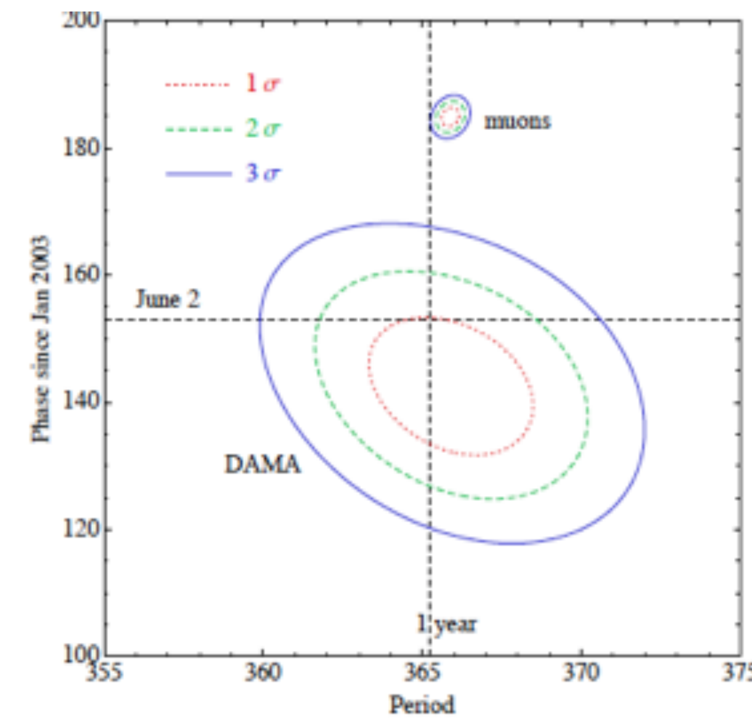
IceCube Collaboration, arXiv:1108.0171, A&A 535, A109 (2011)

Is DAMA modulation compatible with muon rate?

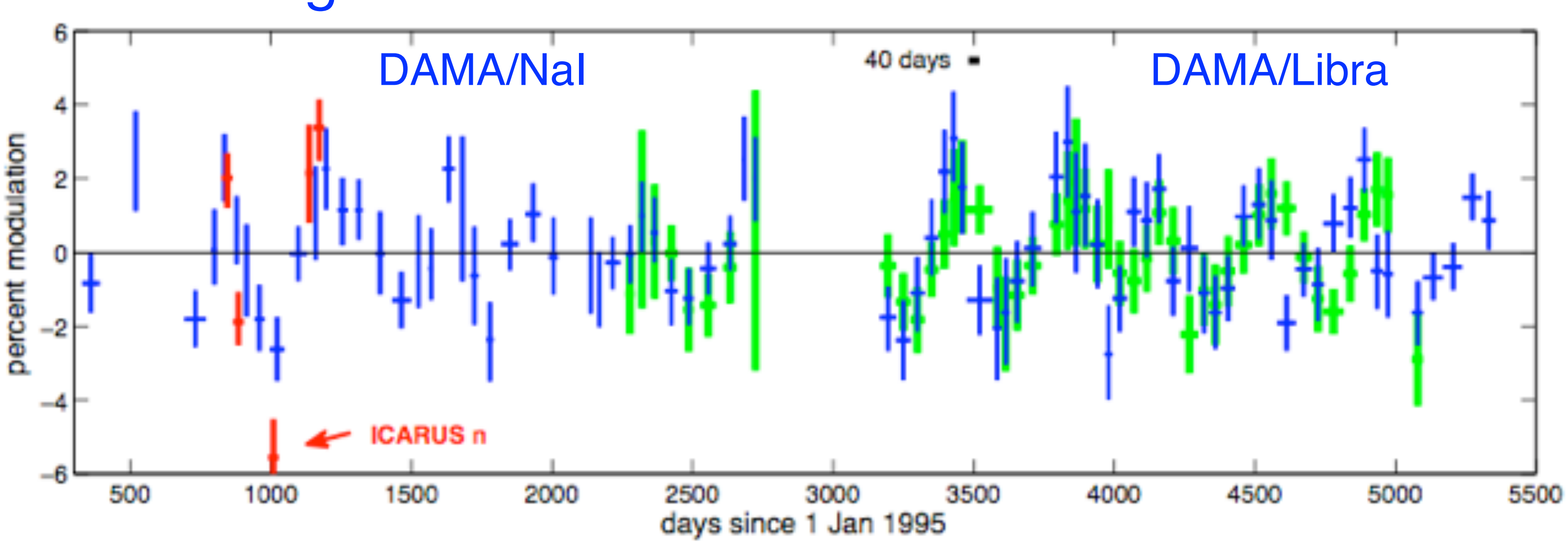
arXiv: 1204.5180 analyzes 20 years of muon measurements at Gran Sasso (MACRO, LVD, Borexino)



arXiv: 1204.5180 finds muon phase incompatible with DAMA at 5.2σ



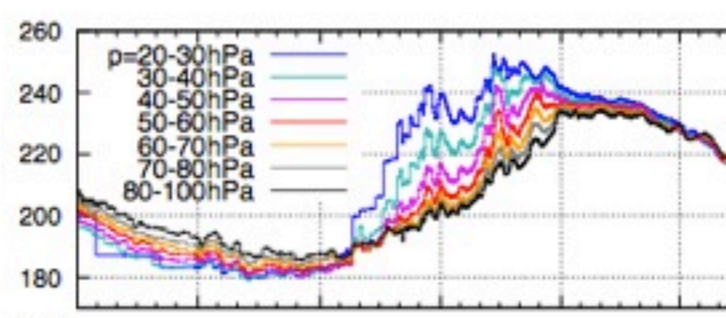
arXiv: 1110.0857 establishes "tight correlation" between DAMA signal and muon flux



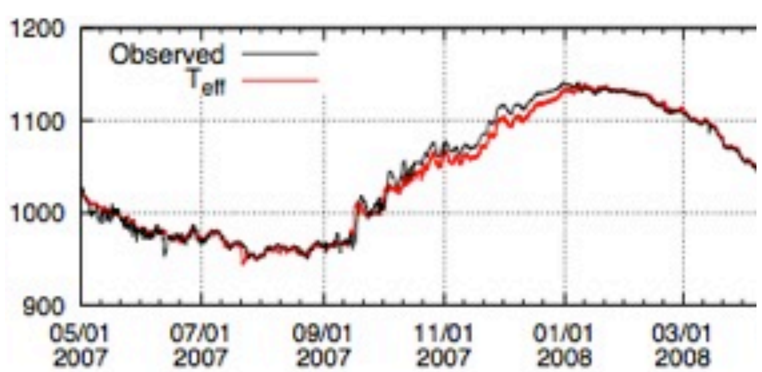
Seasonal Muon Rate Modulation with IceCube

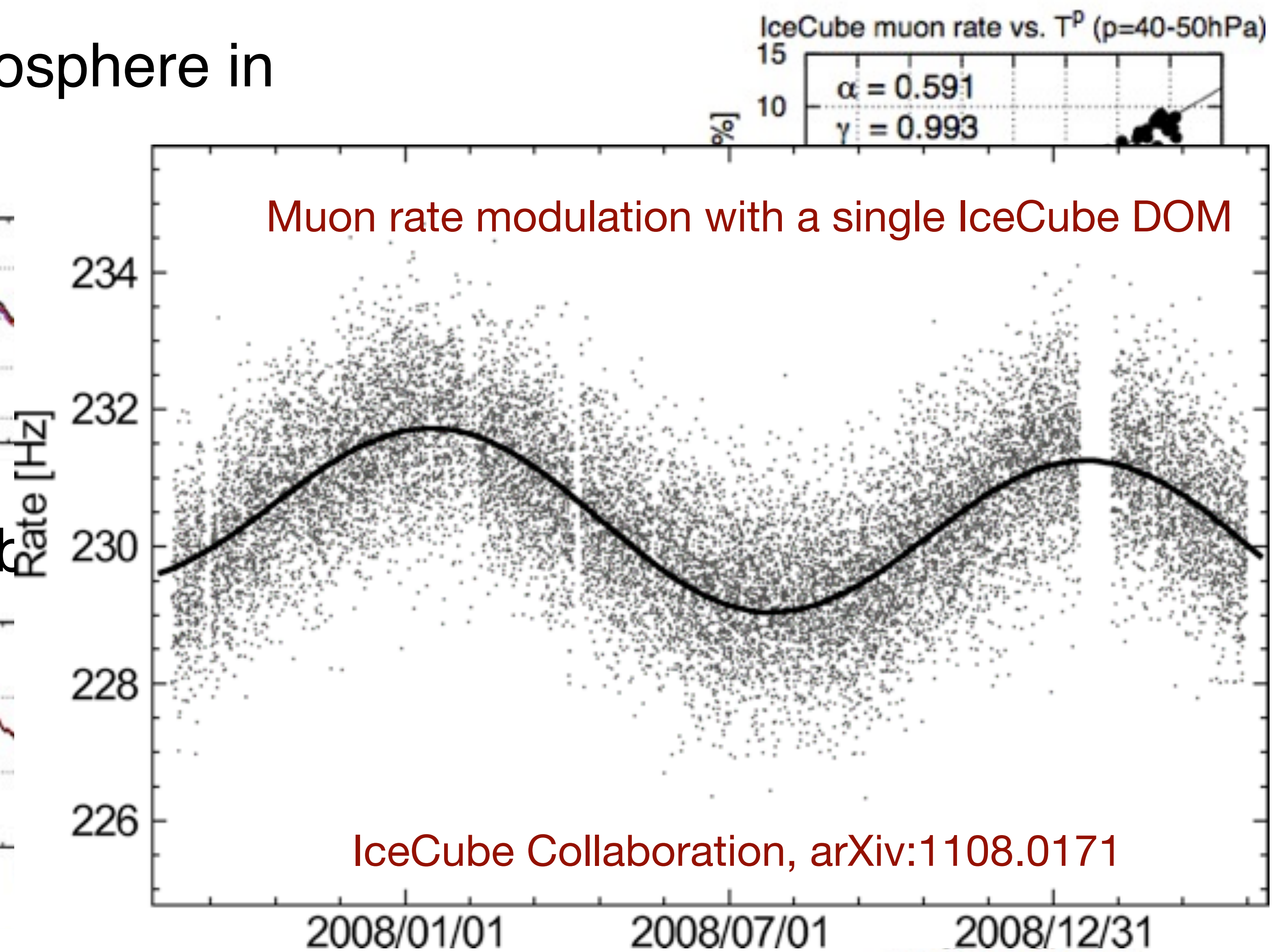
The muon rate at the South Pole well measured by IceCube

Temperature of the stratosphere in pressure layers, T^P [K]



IceCube muon rate [Hz] (b





Tilav et al, arXiv:astro-ph/1001.0776

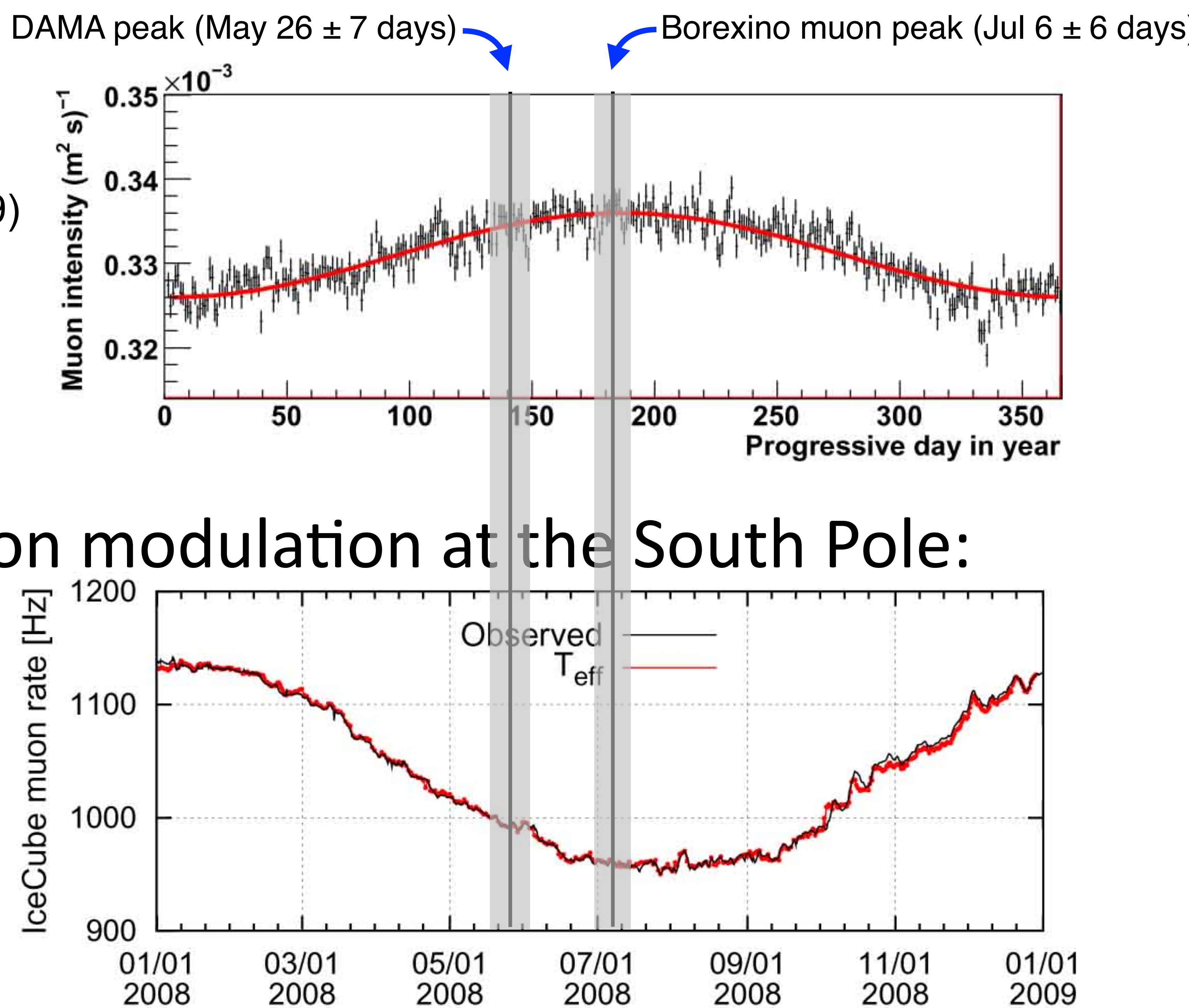
Muon Rate at Gran Sasso vs. South Pole

- LVD:

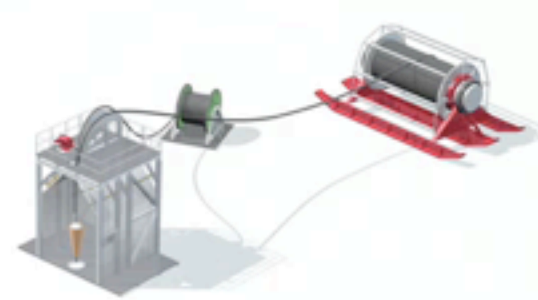
Selvi, Proc. 31st ICRC. (2009)

- Opposite Muon modulation at the South Pole:

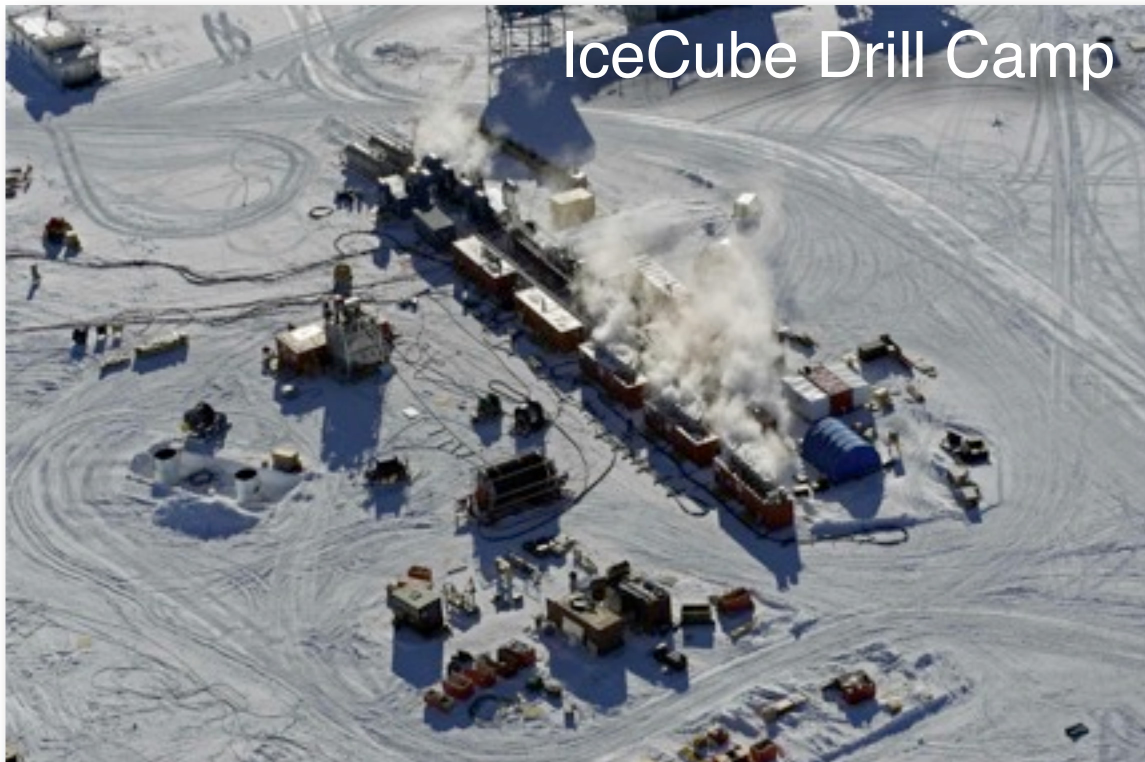
Tilav, Proc. 31st ICRC. (2009)

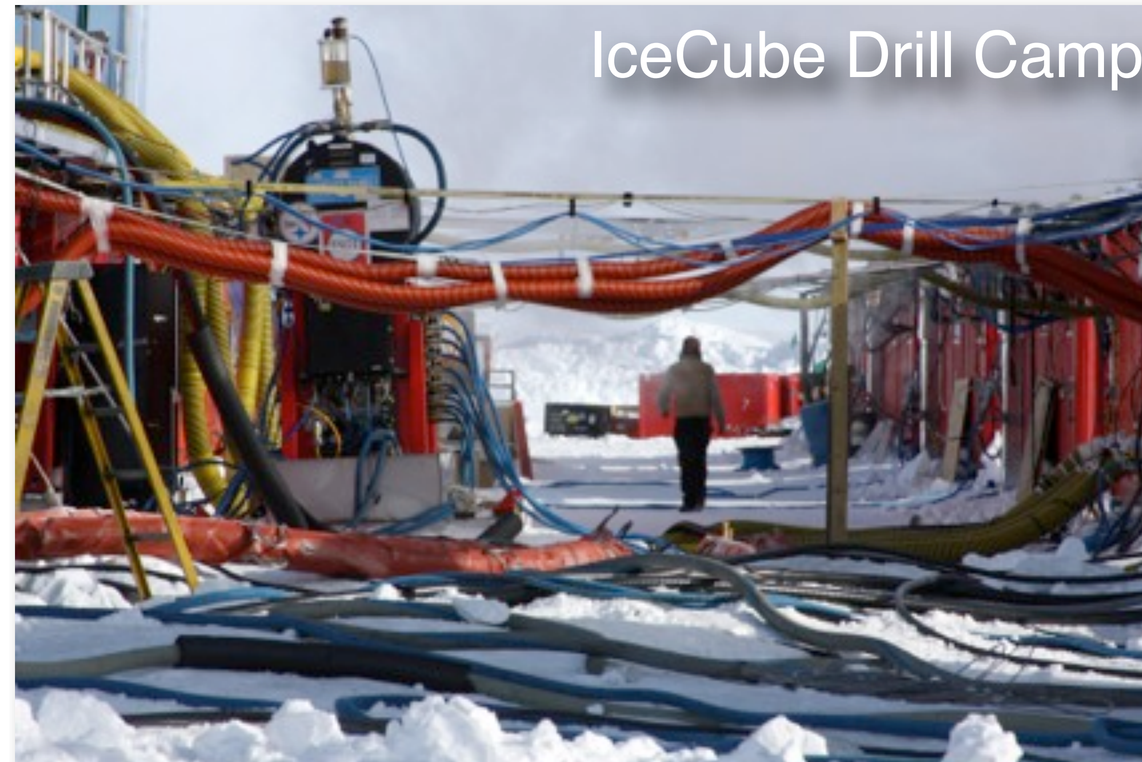


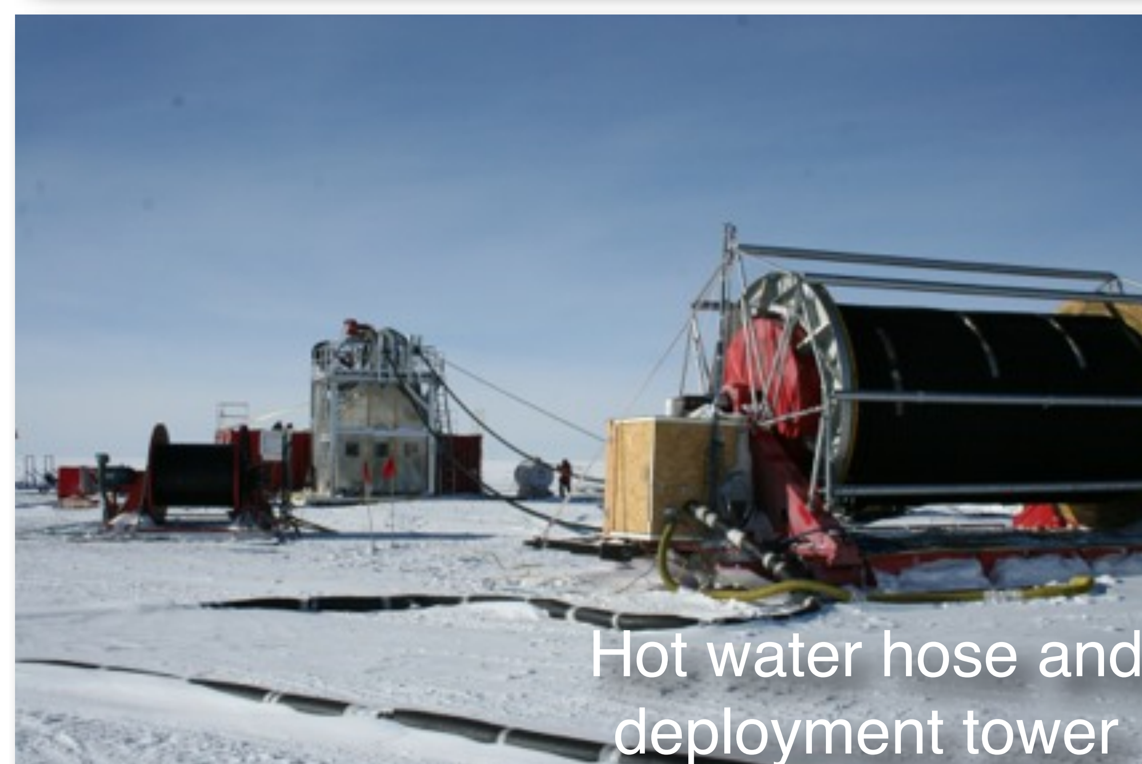
Drilling 2500 m into the South Pole Ice



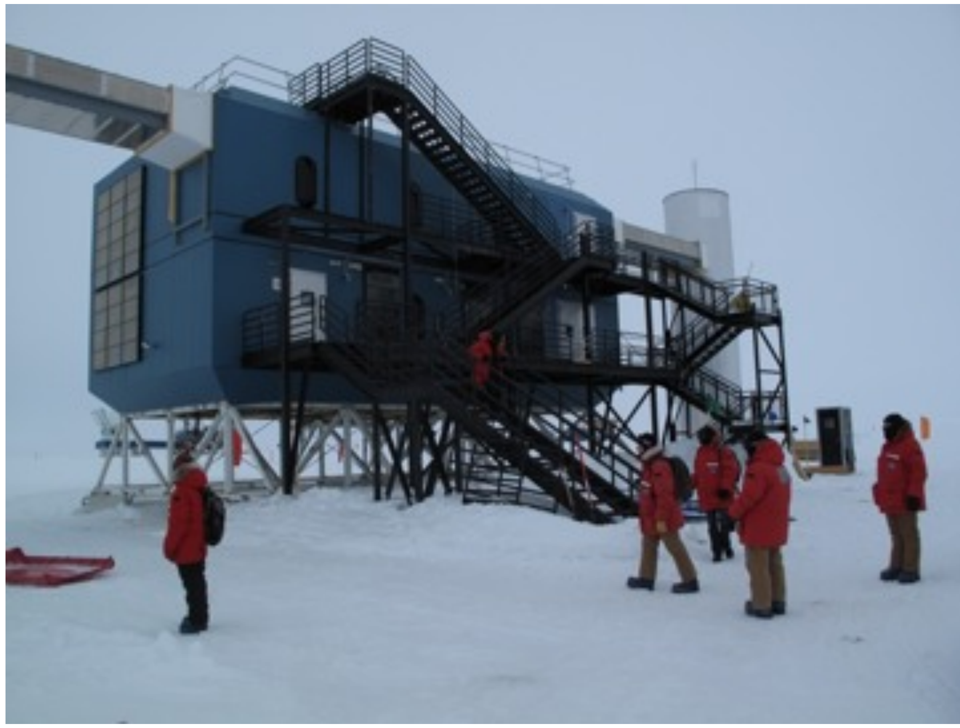
Drilling to -2500 m in the Antarctic Ice





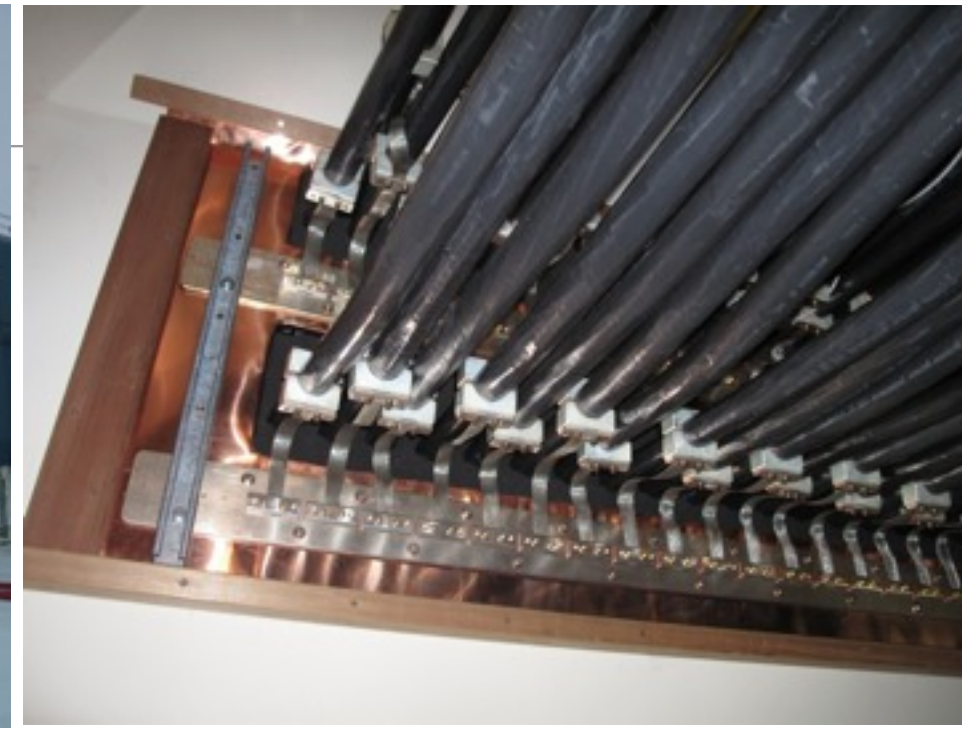


DM-Ice17 Electronics in IceCube Counting Lab



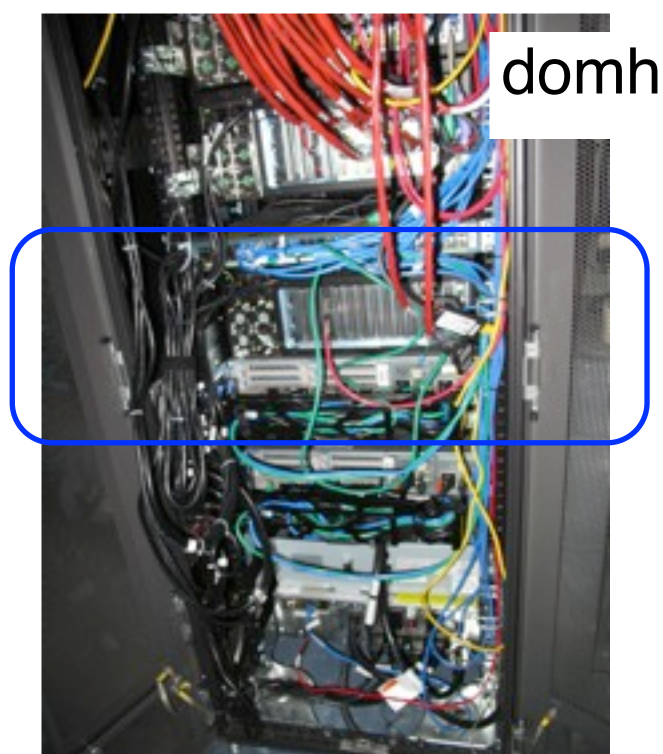
ICL

“beer can” with string cables



string cable penetrations into ICL

patch panels



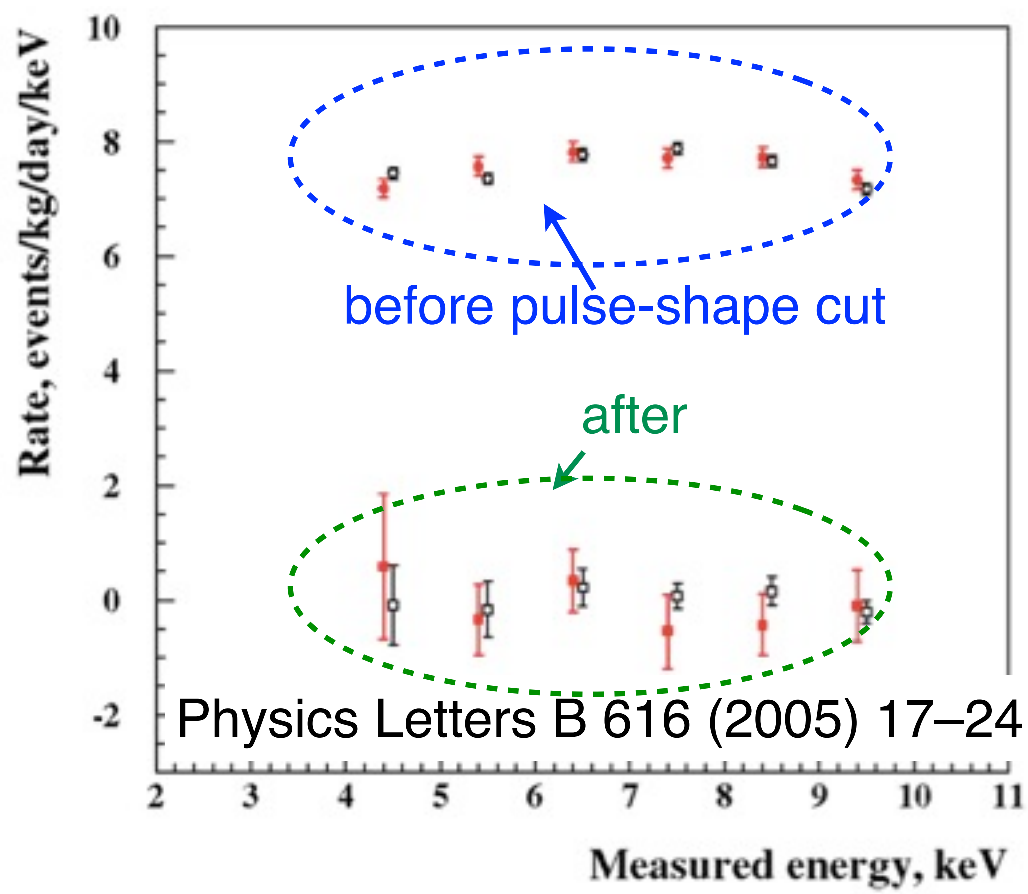
domhubs

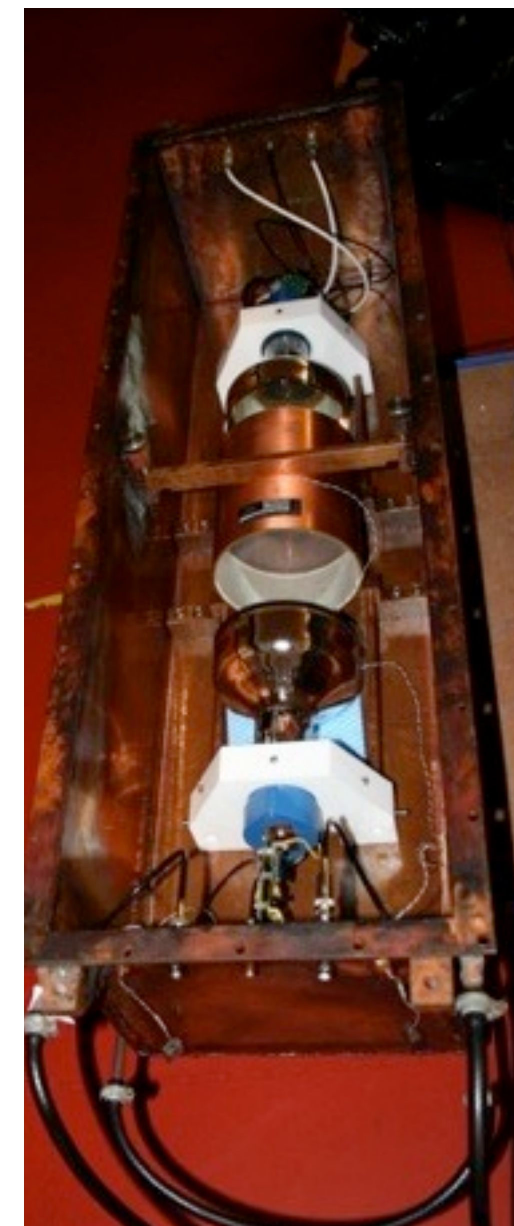
event building

DM-Ice17 / NaIAD Crystals

- DM-Ice 17 uses 2 crystals (17 kg) from the NaIAD experiment
- NaIAD intrinsic background was 5 – 10 times the reported DAMA background, 4 keV threshold for pulse-shape discrimination
- Ran at Boulby Underground Laboratory (1100 m deep) (2000 - 2003)

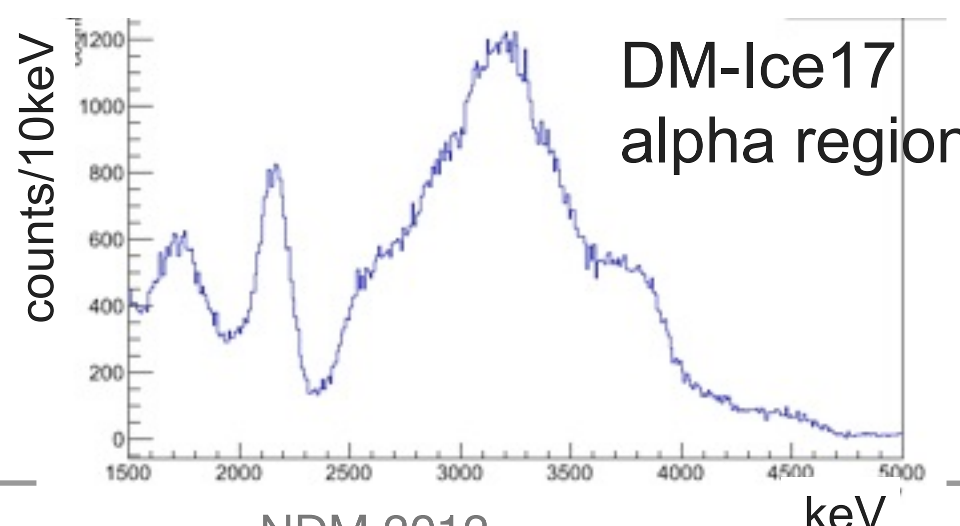
NaIAD Backgrounds

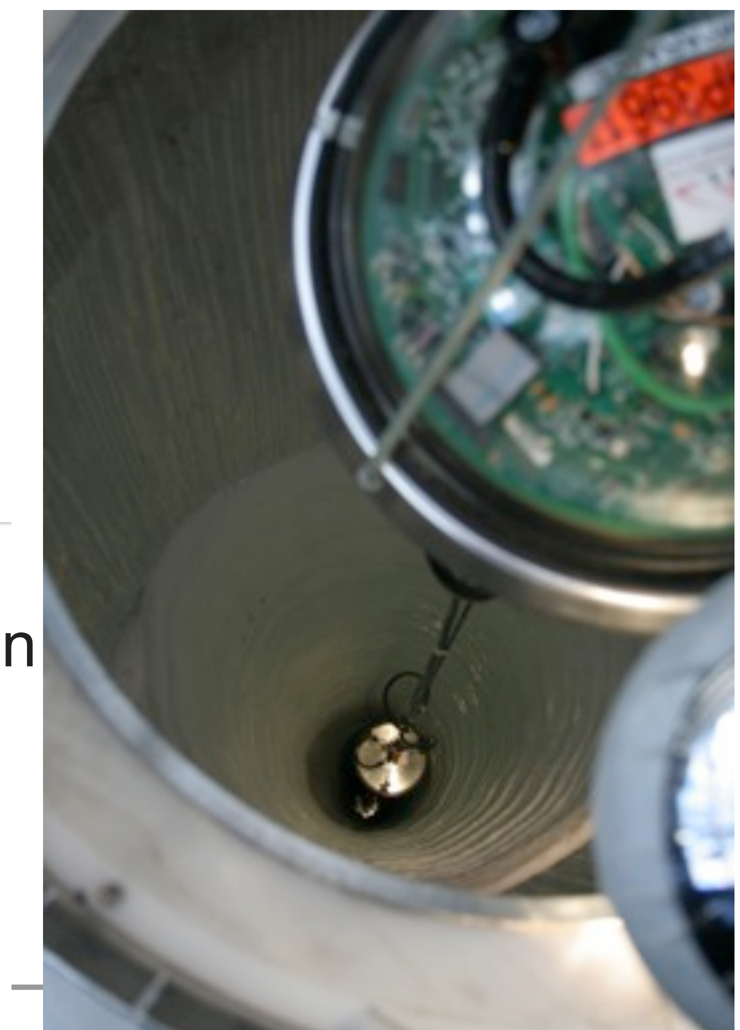




DM-Ice-17 / NaIAD Crystals

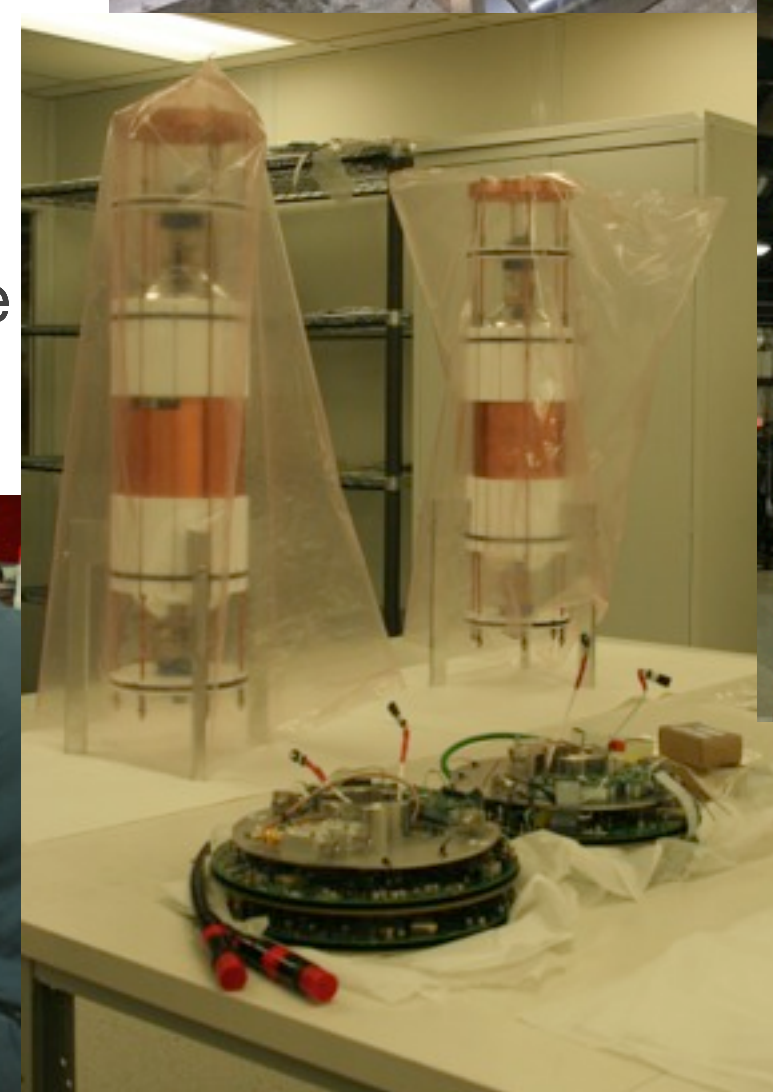
- 2 NAIAD crystals (Bicron) revived and tested at Boulby with 5-inch ETL PMTs.
- Low energy background and threshold still under investigation
- U/Th contamination assessed from alphas (2-5 MeV)
    - U/Th: ~150 uBq.kg
        - (DAMA: 5 - 25 uBq.kg)
- Nominally consistent with NaIAD





Pressure vessel, support structures, etc

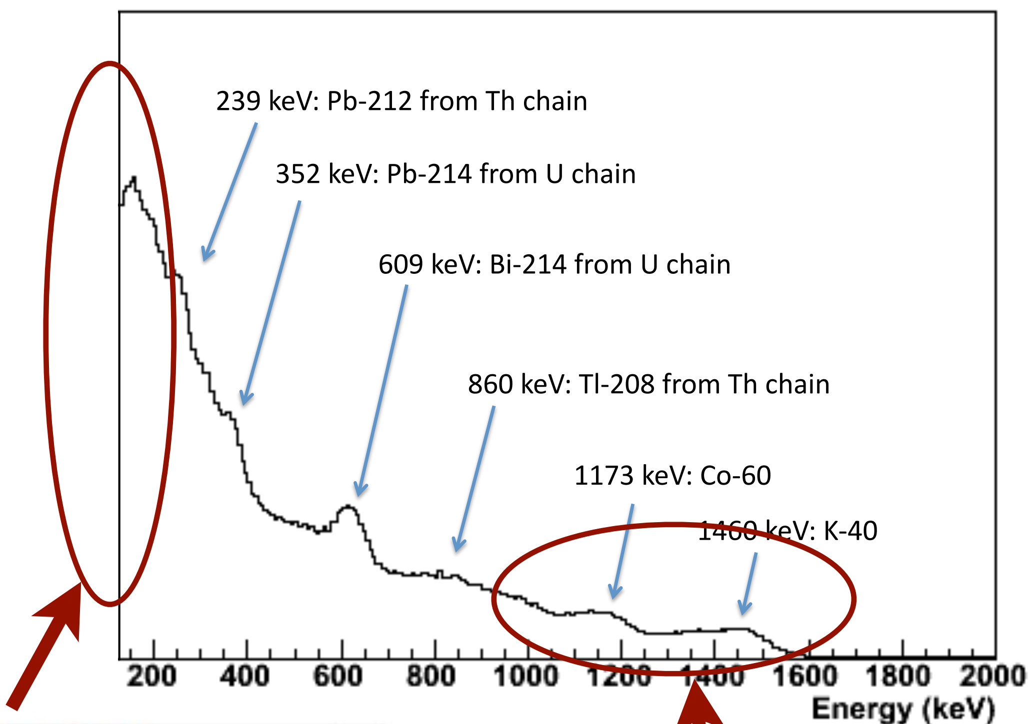
- Stainless, Teflon, etc. selected from vendors known to produce clean material.
  - Scraps radio-assayed post-deployment at SNOLAB.
- Pressure vessel tested to 6200 psi
  - static pressure of water ~ 3500 psi
  - 6000+ psi during ice refreeze in the hole
  - U/Th: 1 - 10 ppb, K-nat: 400 ppb

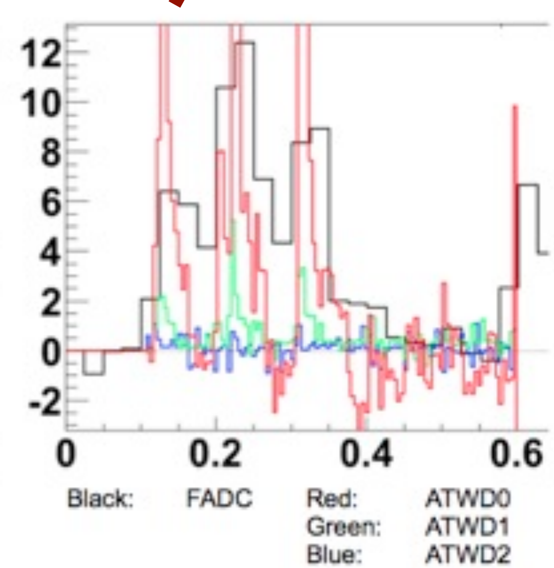


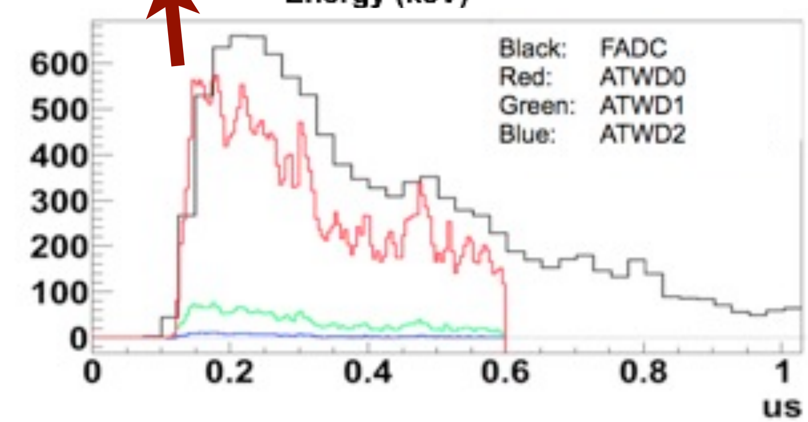
DM-Ice-17 Status

DM-Ice-17

- taking data, continuous operation since Jan. 2011
- Materials counting complete
- Ongoing studies:
    - Optimizing low energy analysis
    - Pulse shape discrimination
    - temperature dependence
    - Temperature stability
    - Energy calibration stability
    - threshold stability
    - IceCube muon veto studies







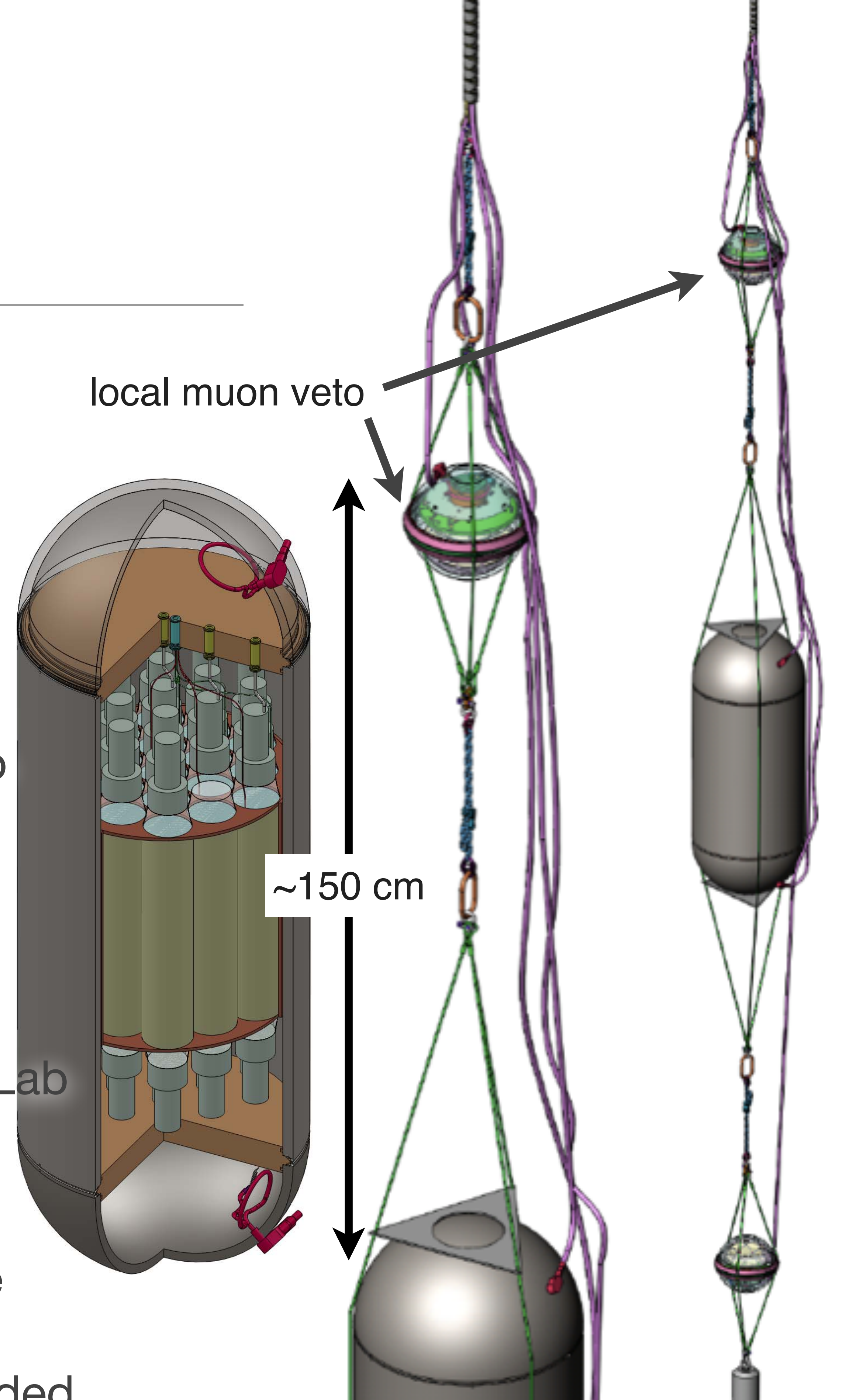
DM-Ice: Full Scale

Detector
- 250–500 kg NaI(Tl)
- Closely-packed inside pressure vessel for coincidence veto
- Two PMTs/Crystal

Location
- South Pole, ~ 2500 m deep in the ice
- Near the center of IceCube for additional veto

Electronics
- Compact, low power to accommodate all channels
- Pulse digitization inside the vessel
- Power from SP Station or IceCube Counting Lab
- Remotely controllable

Pressure vessel
- Withstand > 7000 psi of freeze-back pressure
- Low-background stainless steel
- Low background copper shielding where needed



In-ice strings for DM-Ice deployment

Background, background, background...

- Goal: < 1 counts/day/kg/keV in ROI
  - Select/produce material that are low in naturally occurring radioactive isotopes (e.g. ^{238}U, ^{232}Th, & ^{40}K)

	^{238}U	^{232}Th	^{nat}K
DAMA Crystals	0.7 - 10 ppt	0.5 - 7.5 ppt	< 20 ppb
DAMA Copper Housing	< 0.5 ppb	< 1 ppb	< 0.6 ppm
Antarctic Ice	0.1 - 1 ppt	0.1 - 1 ppt	0.1 - 1 ppb
Drill Water	0.05 - 1 ppb (out of equilibrium ^{226}Ra to ^{234}Th)	0.15 ppb	150 ppb
Pressure Vessel S.S. in DM-Ice17*	10 ppb**	1 ppb	400 ppb

*better material available from same vendor

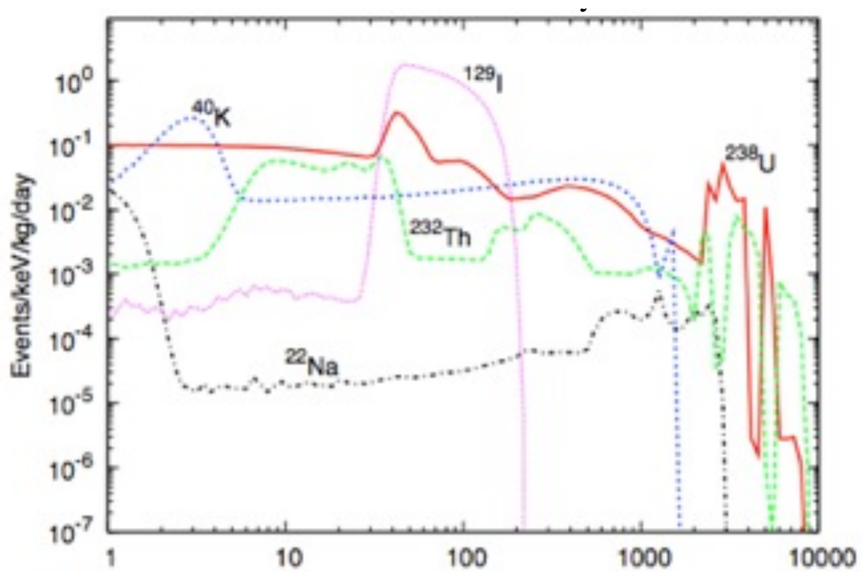
*Other materials counted: Stainless steel for pressure vessel, Teflon, Copper, optical gel, NaI powder

NaI(Tl) Detector

The first 32 inch diameter NaI(Tl) crystal. Pictured from left to right are Dr. Swinehart, Ed Jablon, Joe Knaus and Marko Stilgoi.

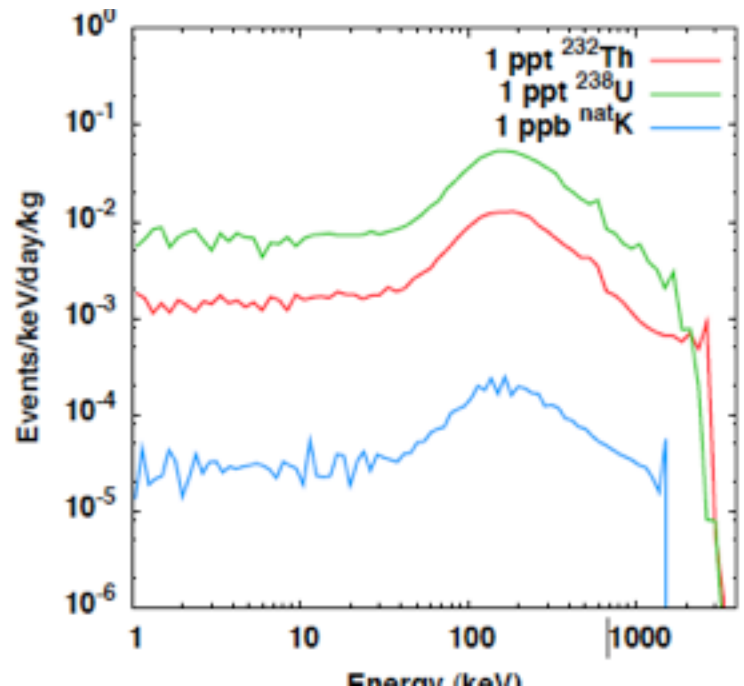
- Likely to be limited by intrinsic backgrounds in NaI crystals
- Growing NaI(Tl) crystals:
  - U/Th seems under control, but K requires extra chemistry.
- DAMA's crystal: ^{238}U: 5 ppt, ^{232}Th: 5 ppt, ^{nat}K: 20 ppb (NIMA 592 (2008) 297– 315)
- NAIAD crystal: 5 - 10x DAMA bgd in ROI (PLB 616 (2005) 17–24)
- Several possible crystal vendors
- Powder source to within a factor of 5 of DAMA's published powder contamination identified (U: 0.04 ppb, Th: 0.09 ppb, K: 0.4 ppm)

simulated backgrounds from
intrinsic contamination in DAMA crystals



TAUP2009 Kudryatsev et al.

simulated activity in NaI crystals **from radioactivity in ice**



arXiv:1106.1156

Water Purity Analysis

- Drill water may introduce impurities in the water
- Water samples from 3 holes taken during 2009 - 2010 season for IeCube
- Additional analysis from 2010/11 holes
- Samples taken from return from the inlet in to “Tank-1” as water is pumped out from the hole
- Samples counted at SNOLAB
  - < ppb of U/Th
  - 150 ppb K-40
- IceCube drill engineers investigating ways to minimize contamination and volume near detector

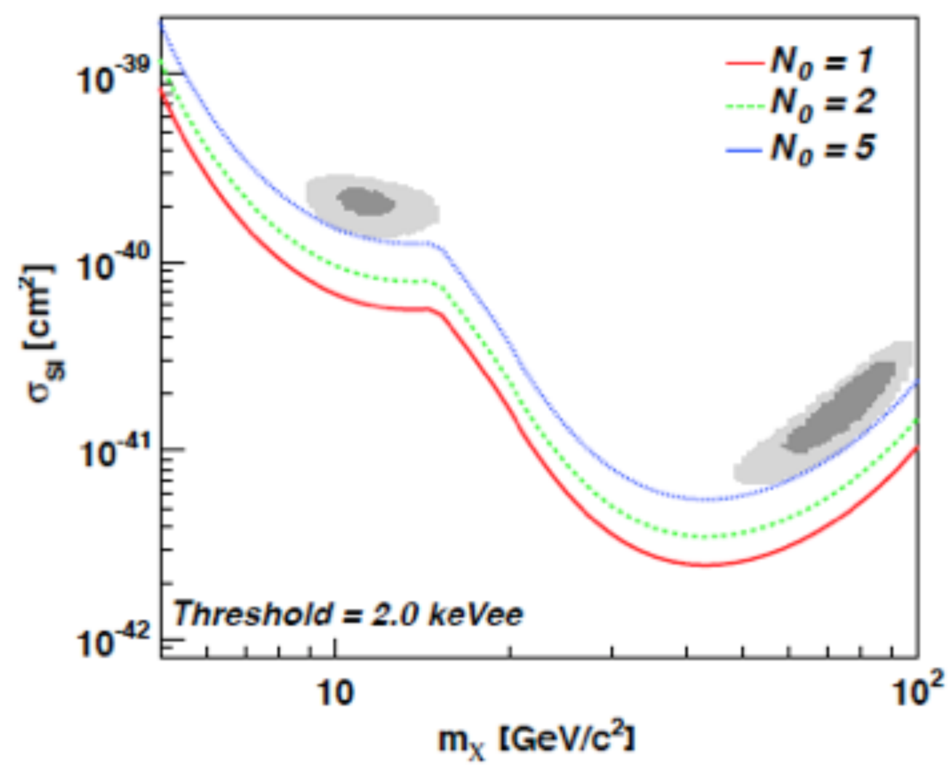
Jonas Kalin, Jan. 2010

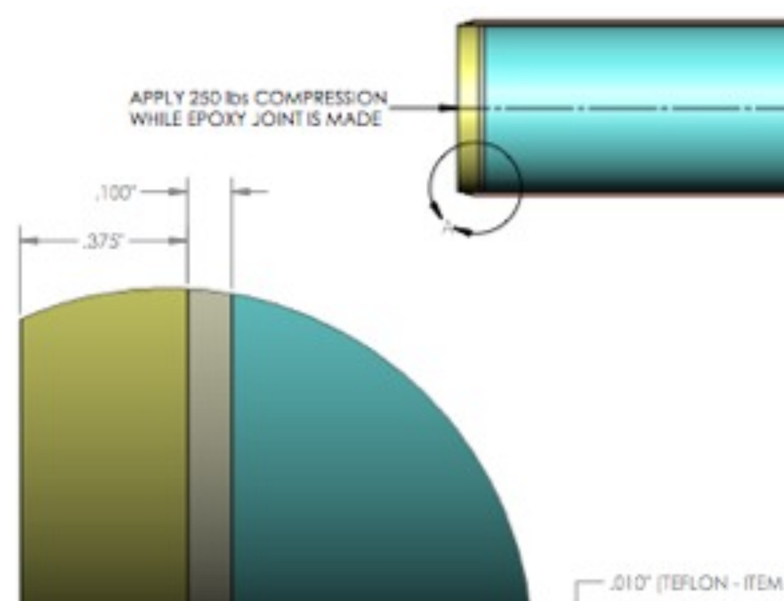
Threshold & Calibration

DAMA's modulation signal is 8.9σ.

- 2 keVee threshold required
  - optimize light collection via
    - High QE PMTs
    - Crystal geometry
    - Light guide thickness
    - Crystal surface
- Remotely deployable calibration
  - Frequency will be based on stability of DM-Ice17

500 kg·year NaI detector sensitivity
(2 - 4 keV) with 1, 2, and 5 dru bgd.

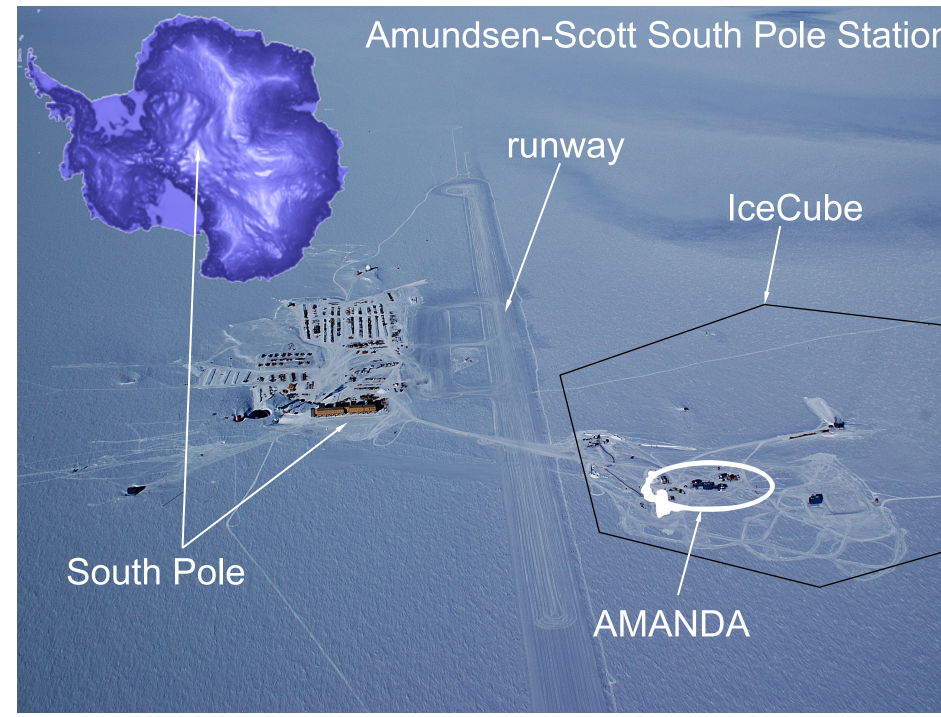


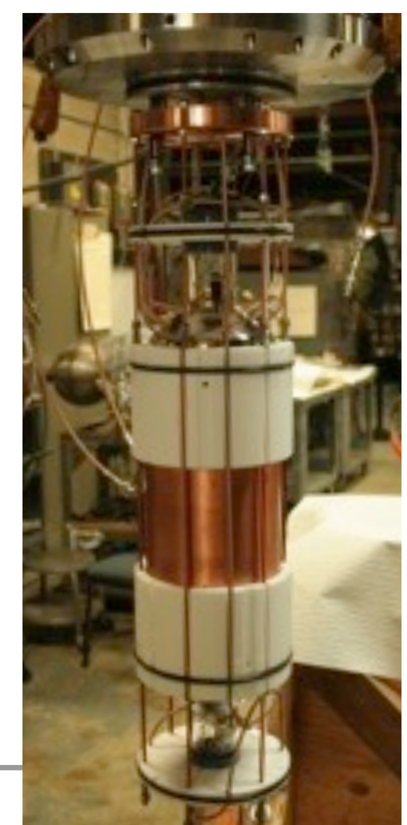


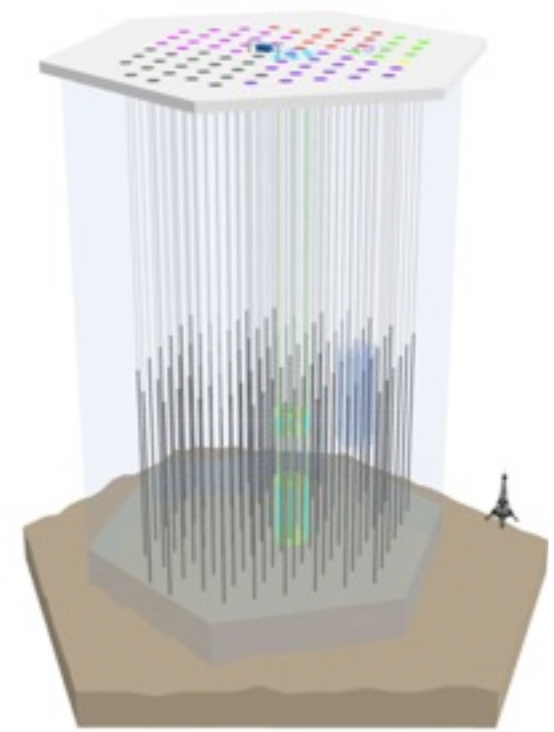
DM-Ice: A Dark Matter Experiment at the Pole

Summary & Conclusions

- DAMA modulation needs confirmation or an explanation
- Overburden with Antarctic ice offers backgrounds and systematics very different from any other underground location.
- Two prototype NaI(Tl) detectors (17kg) installed and operating in the South Pole ice since Dec 2010.
- Design and R&D studies towards a full-scale experiment currently under way.







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