DM-Ice

A Direct Dark Matter Search at the South Pole

see arXiv:1106.1156

Neil Spooner

University of Sheffield

on behalf of the DM-Ice Collaboration

(special thanks to Karsten Heeger and DM-Ice for slides)

TeVPA2011

DM-Ice Collaboration

UW-Madison
Francis Halzen*, Karsten Heeger, Albrecht Karle*, Reina Maruyama*, Walter Pettus, Antonia Hubbard*, Bethany Reilly

University of Sheffield
Neil Spooner, Vitaly Kudryavtsev, Dan Walker, Sean Paling, Matt Robinson

University of Alberta
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Doug Cowen*

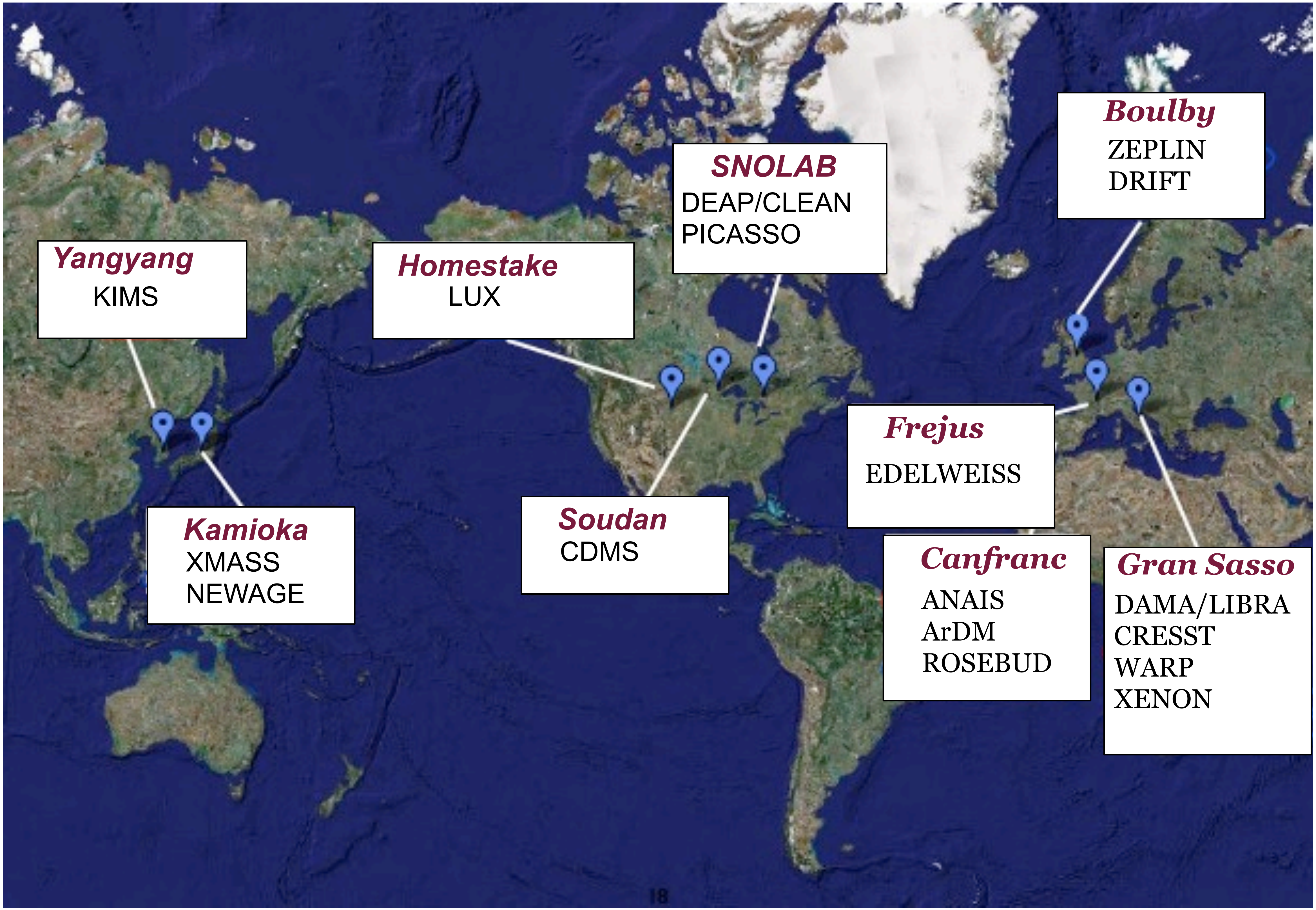
Fermilab
Lauren Hsu

University of Stockholm
Seon-Hee Seo*

* IceCube collaboration members

we are working closely with the IceCube collaboration

Main WIMP Experiments



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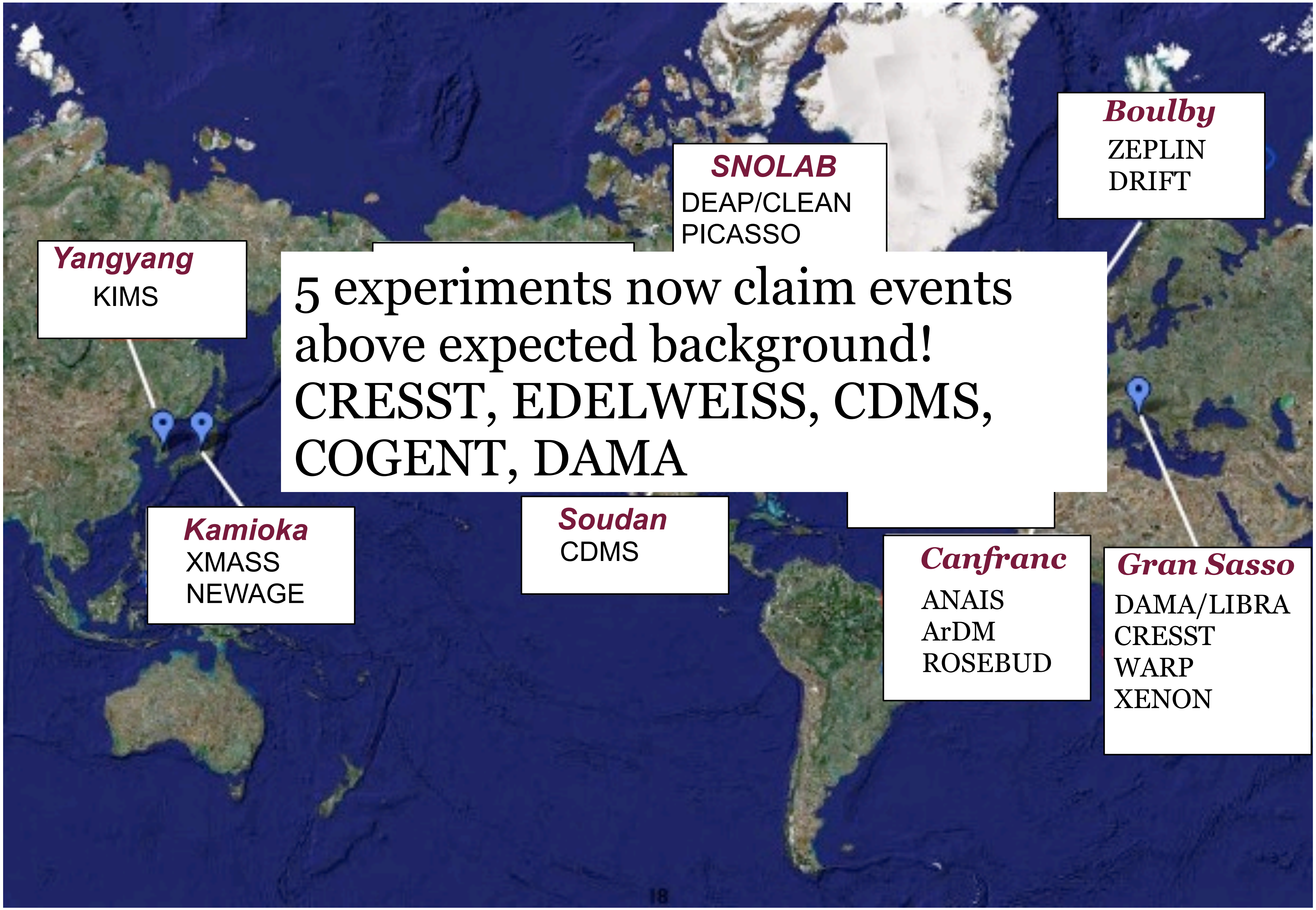
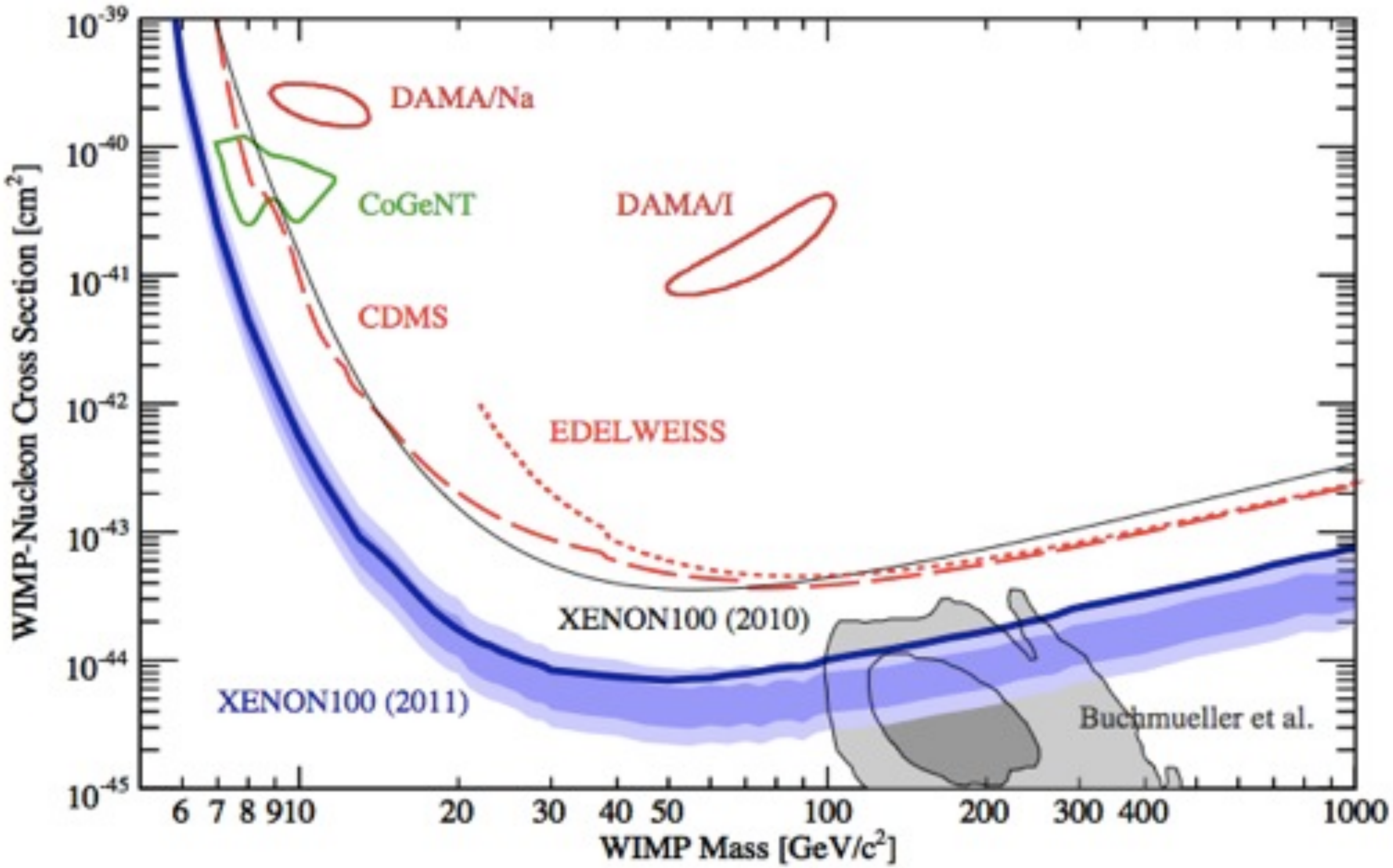


Direct Detection Experiment Bounds...

Spin-Independent



Aprile et al., arXiv:1104.2549v1 (2011)

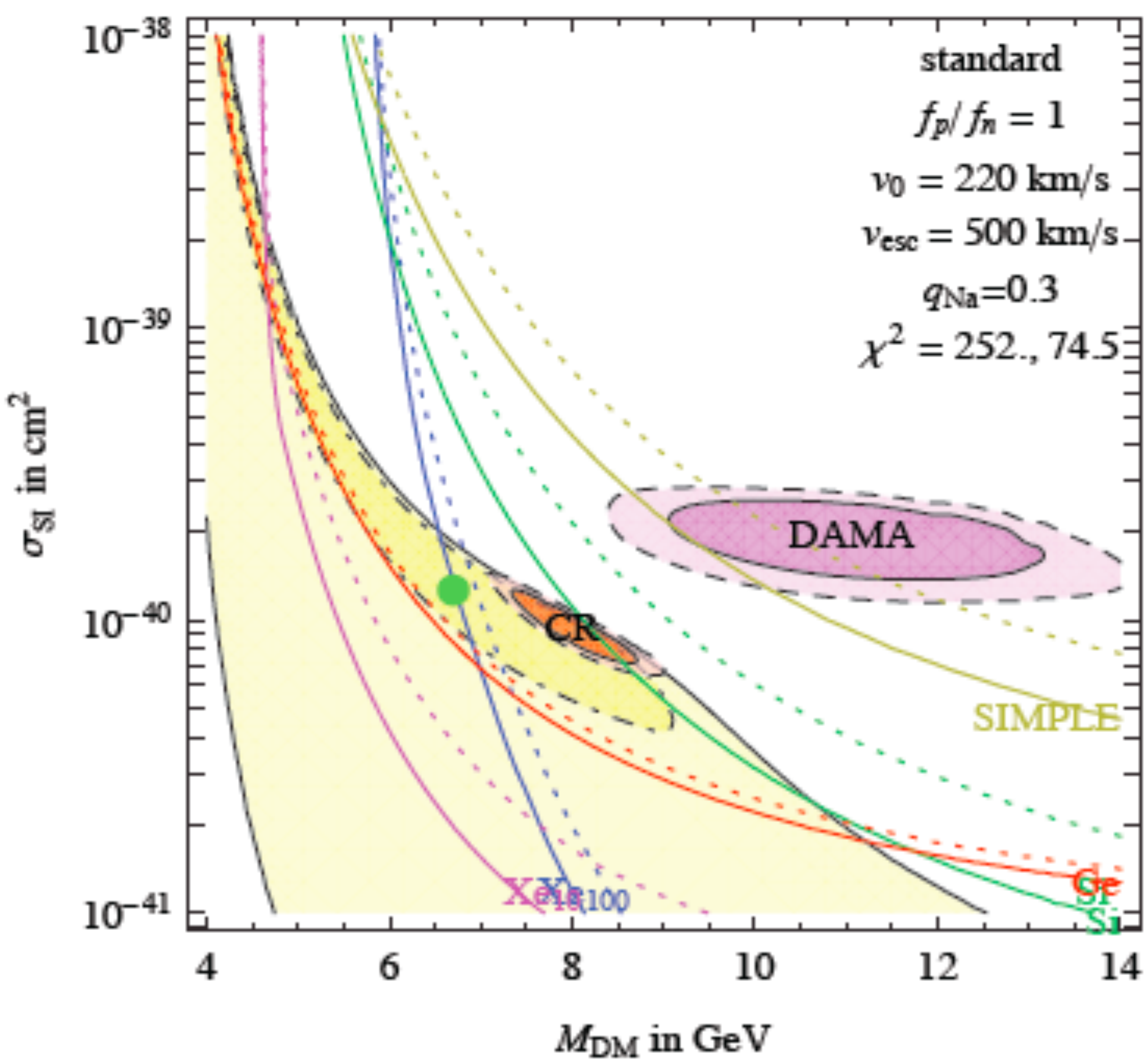
One, maybe two signals.

One claim for discovery: DAMA

DAMA vs. CoGeNT Are recent results compatible?

- For standard fit DAMA and CoGeNT do not overlap and are excluded by other experiments
- But there are several means by which greater compatibility can be obtained by different assumptions, e.g.: quenching factors, DM velocity distribution, isospin violation model, inelastic DM model, channeling etc.
- Much caution is needed on all these plots, particularly at low energy/mass

standard



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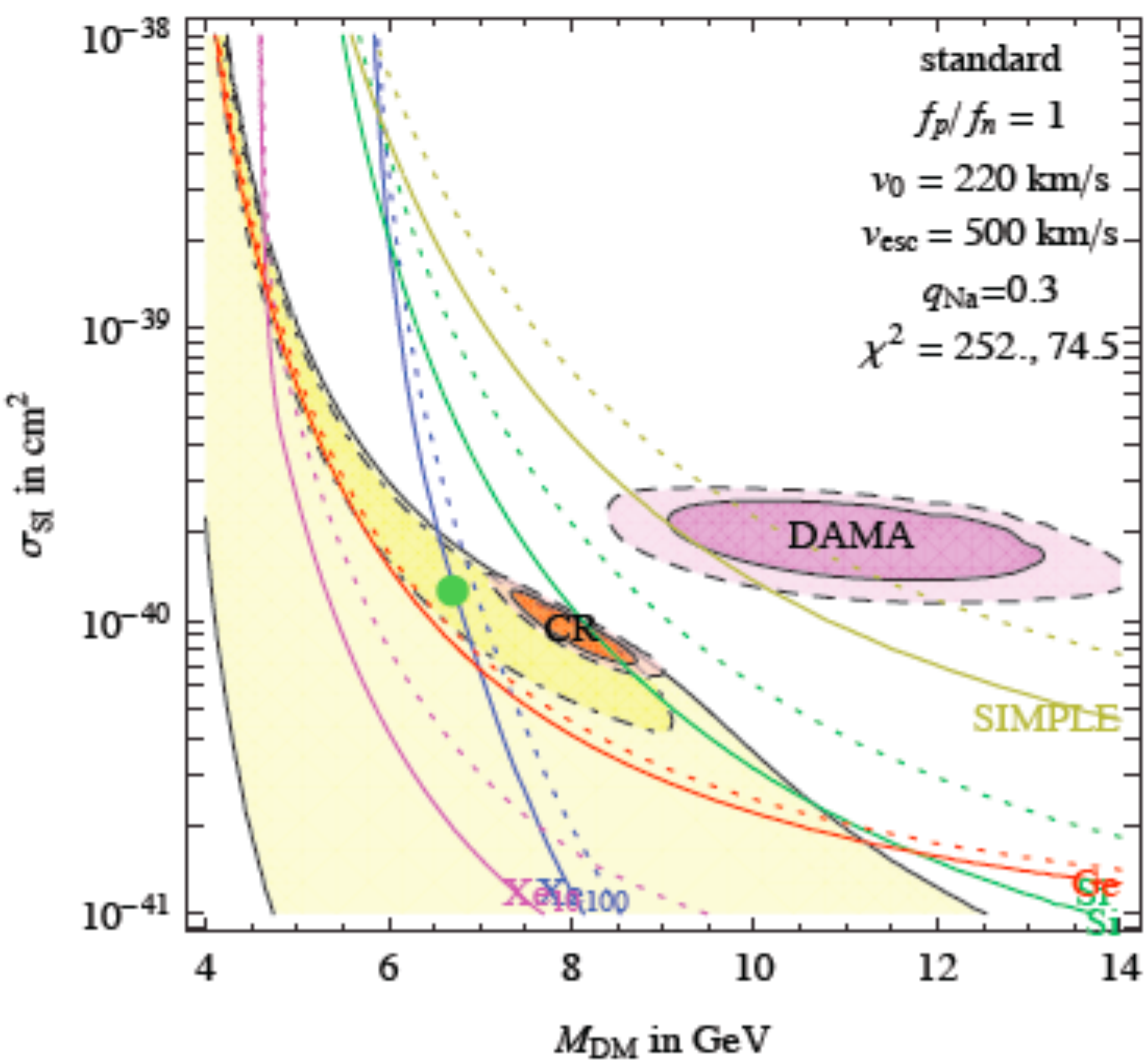
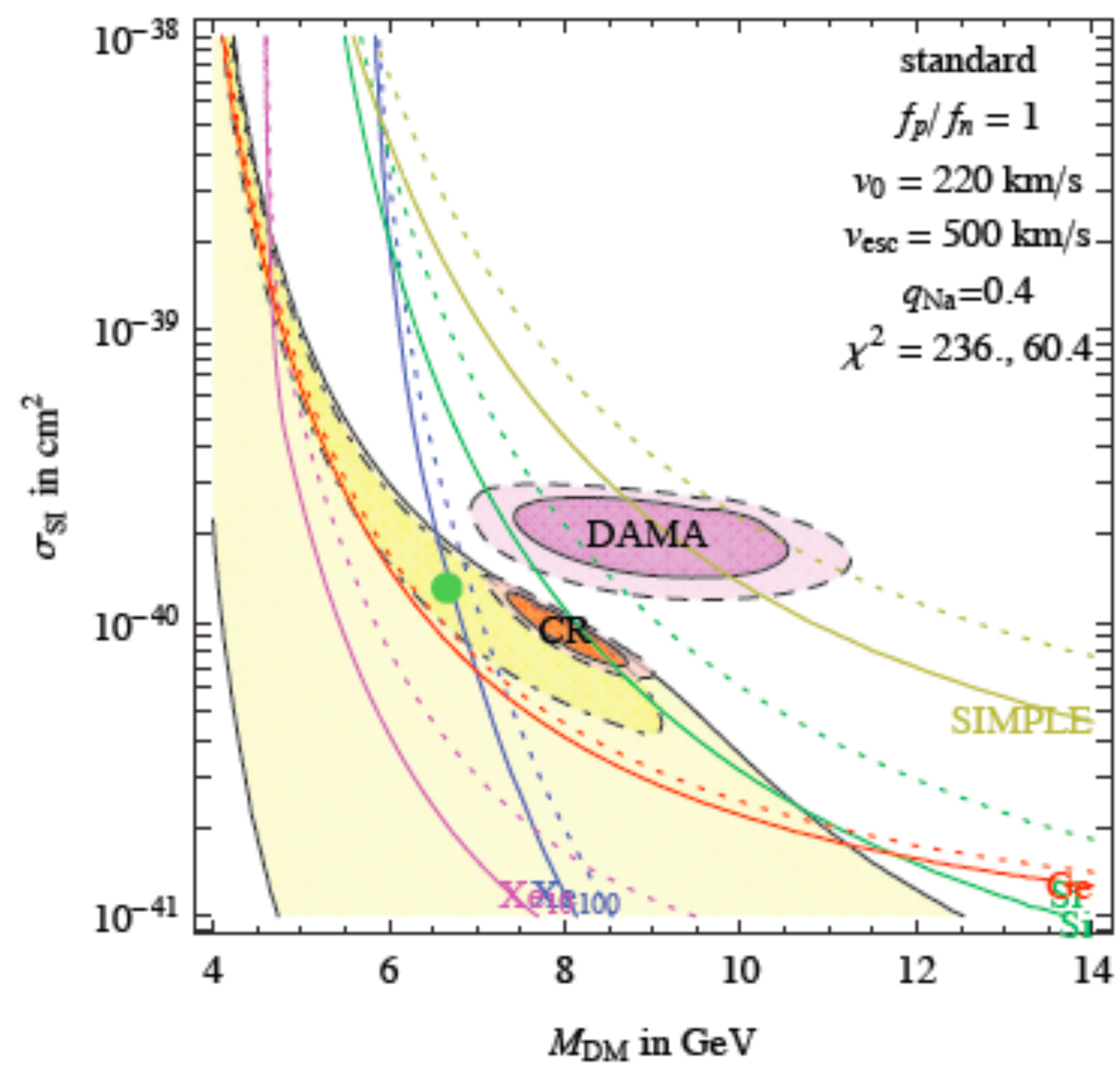
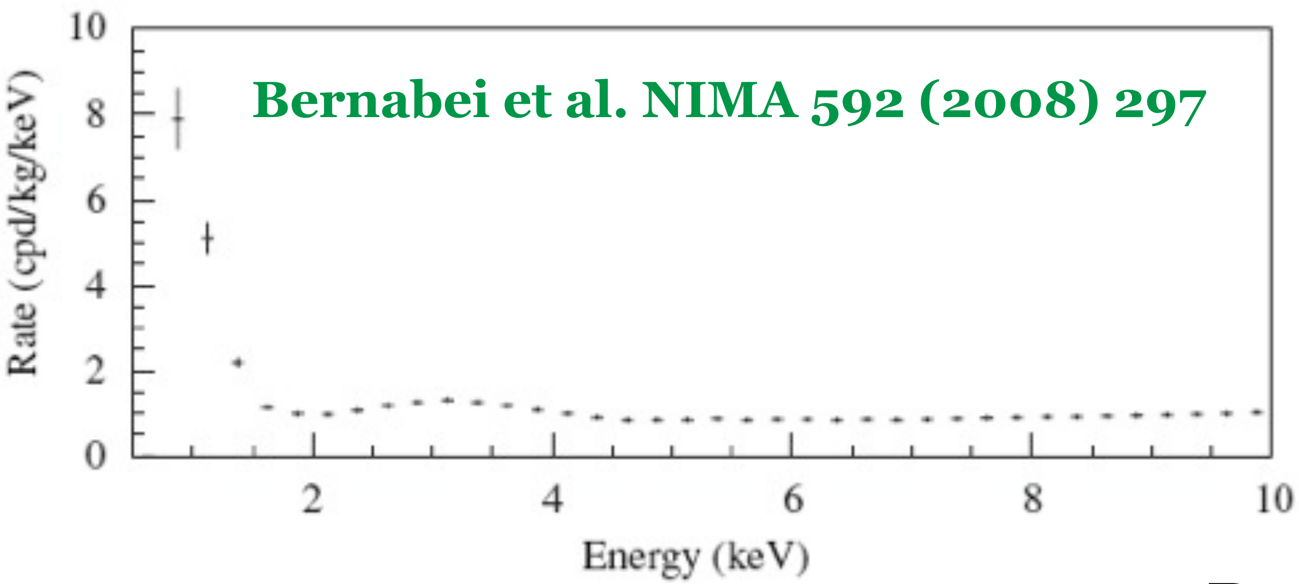


higher quenching factor q_{Na}



Unphysical Background in DAMA?

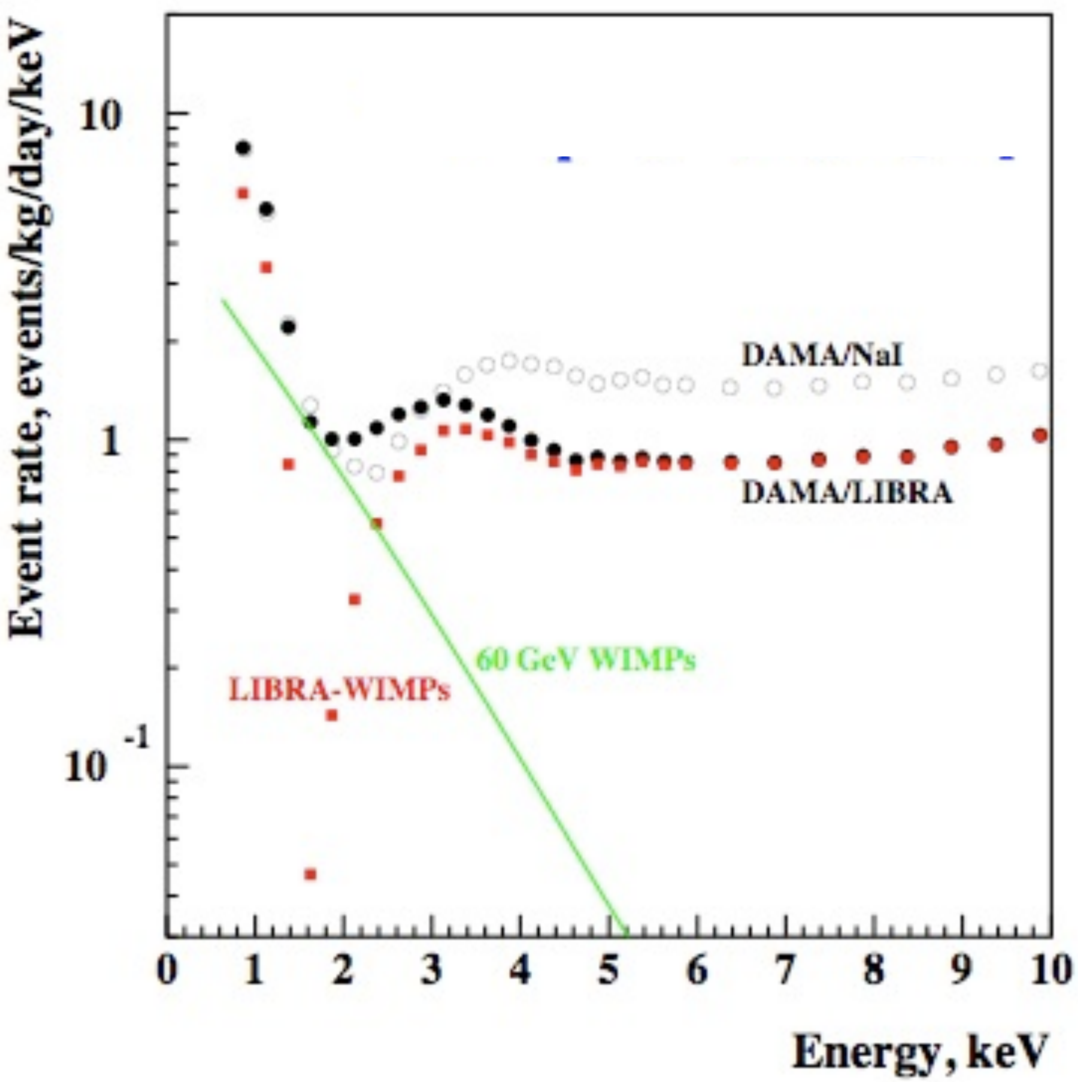


Raw integrated spectrum as published should comprise:

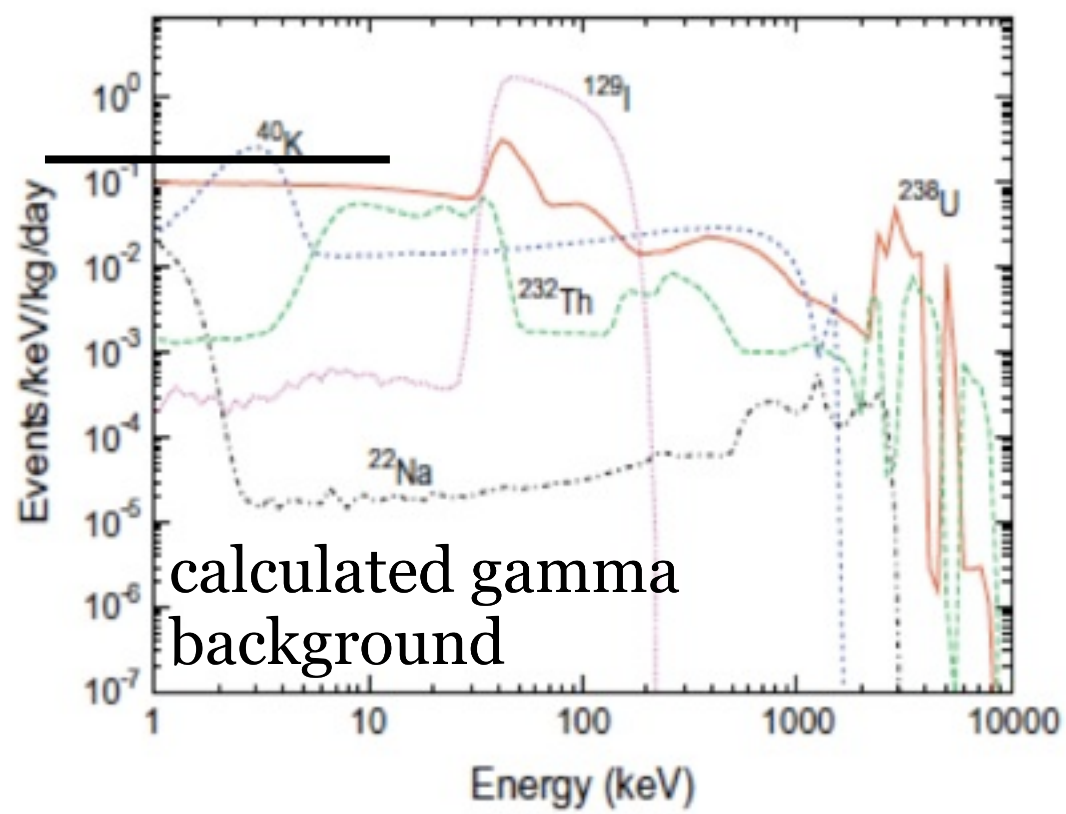
We predict ~flat DAMA background spectrum <10 keV

V. Kudryavtsev, N. Spooner, M. Robinson
Astroparticle Physics 33 (2010) 91

Now subtract predicted (exponential) WIMP spectrum



Background in DAMA independently simulated with GEANT 4 using published radio-purity of ^{238}U, ^{232}Th, ^{40}K, ^{129}I and ^{22}Na



So subtraction of $S_0(E)$ in DAMA must mean background drops sharply below 3-4 keV

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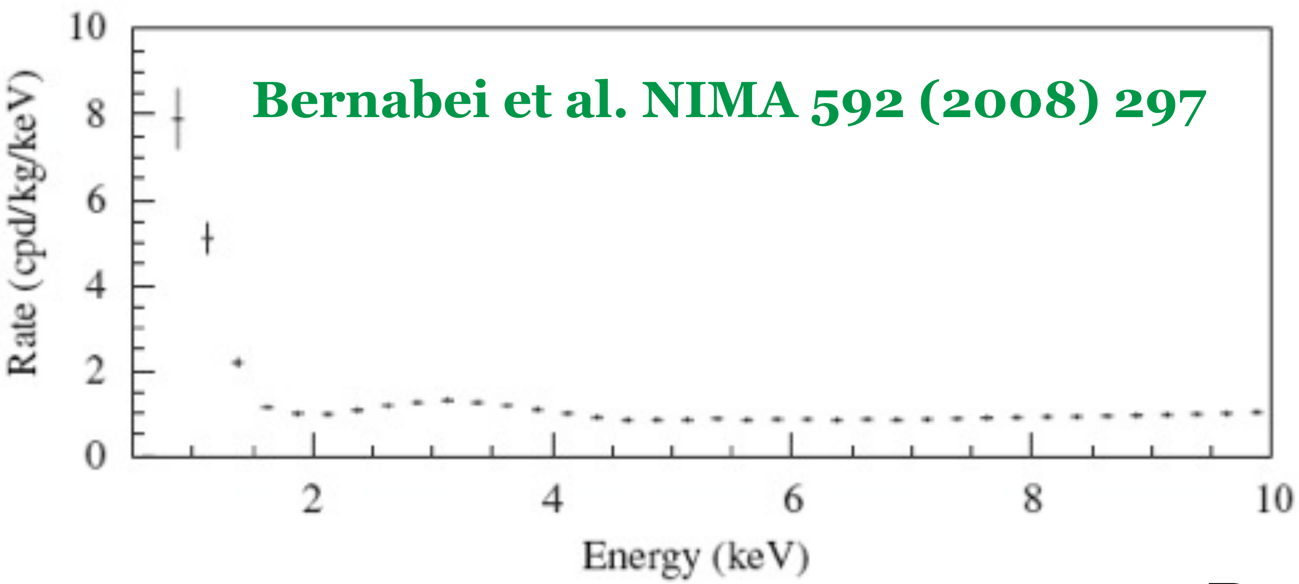

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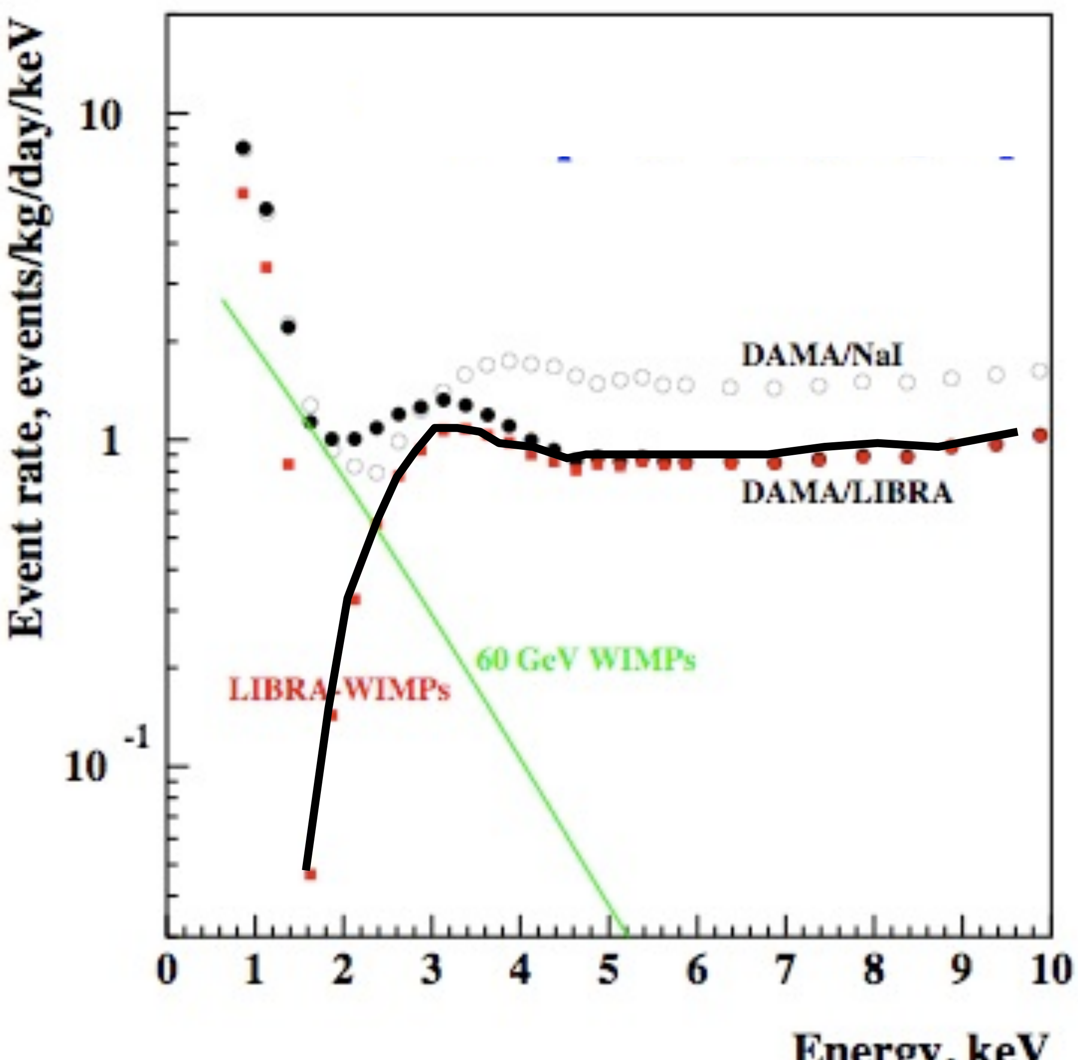

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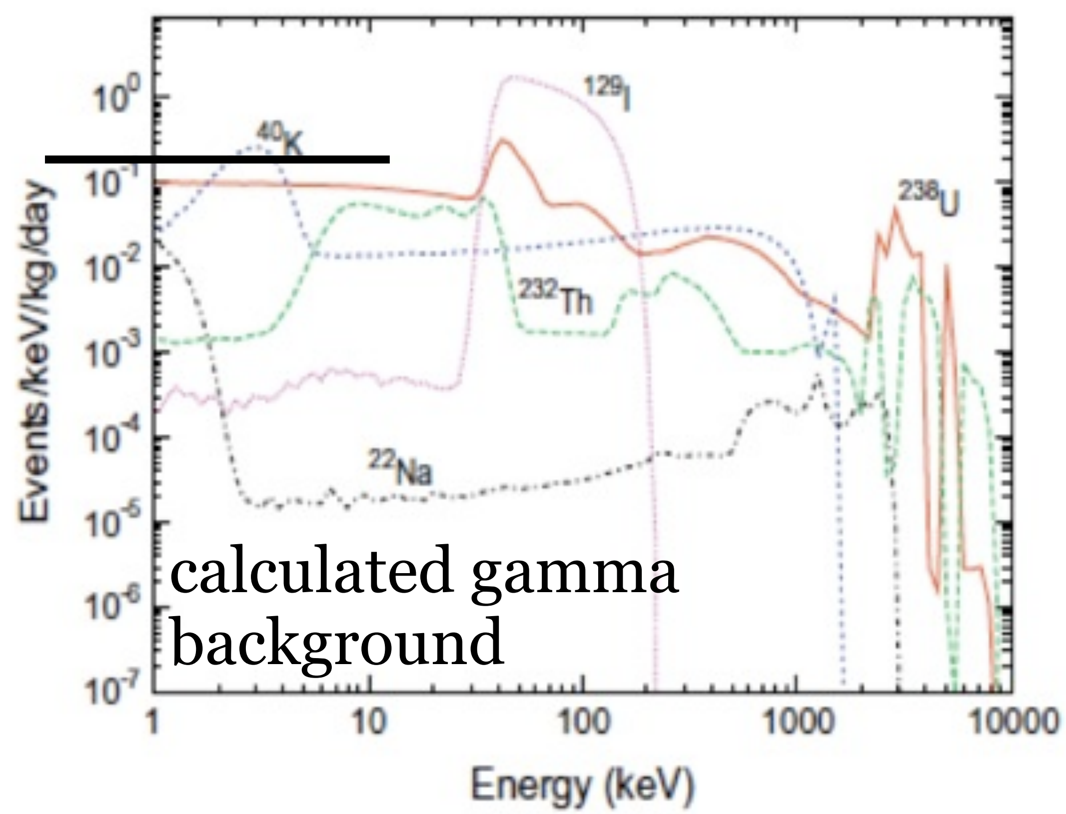

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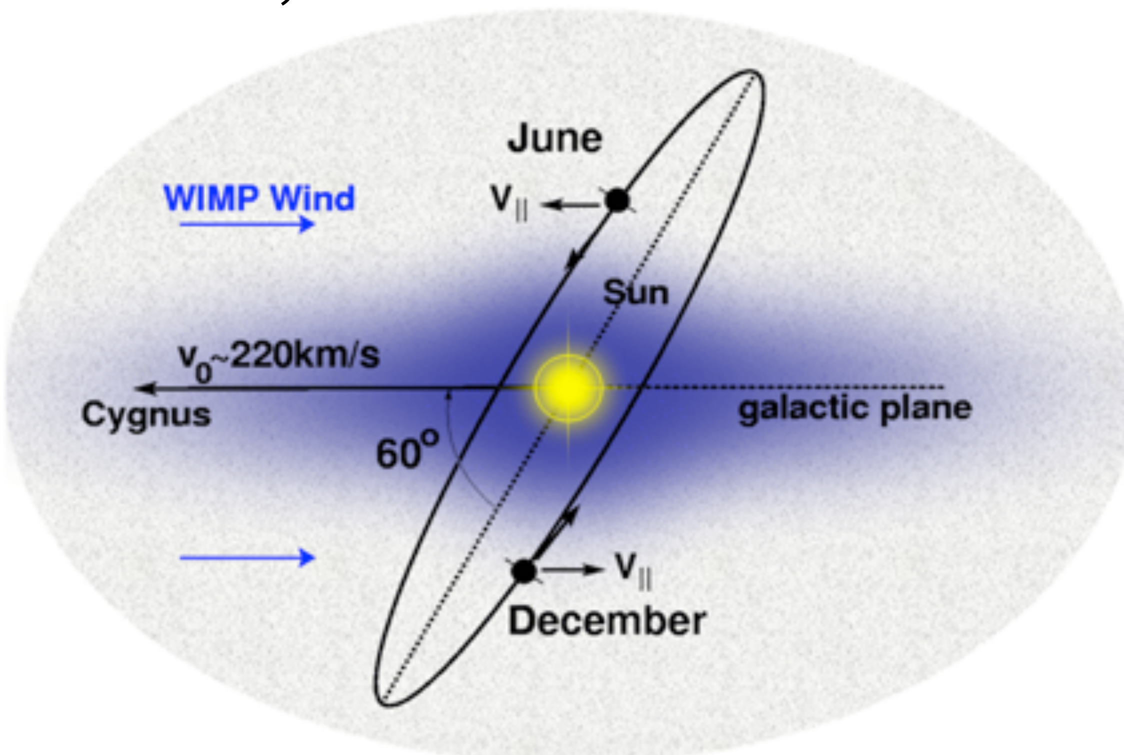
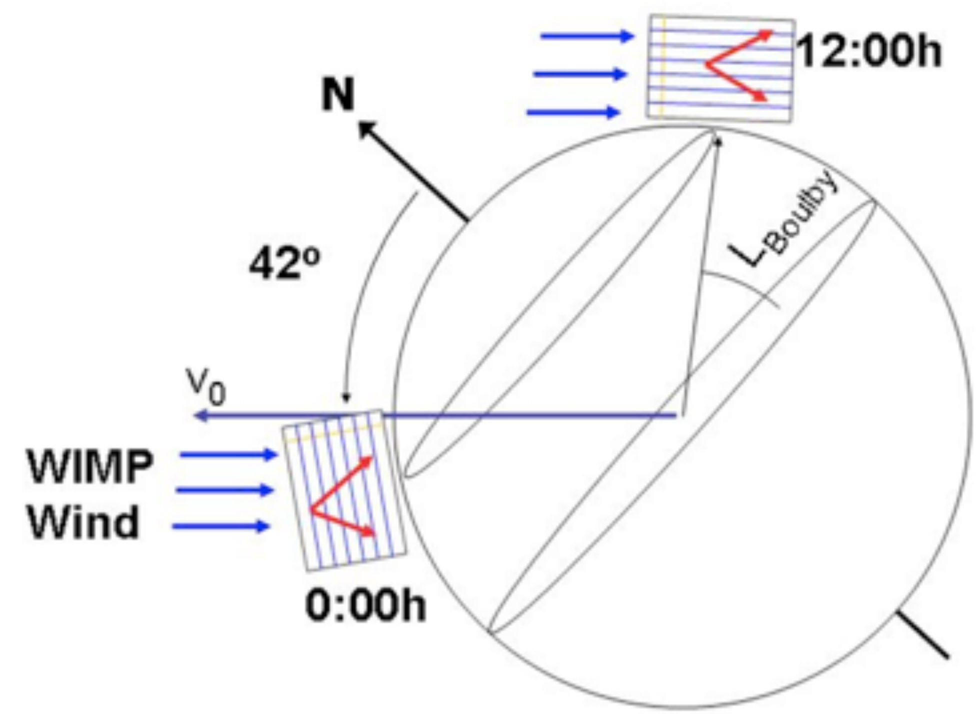
Two Dark Matter Galactic Signatures

- Earth's motion in static WIMP 'halo' -> Earth is subject to a 'wind' of WIMPs
- Average speed ~220kms^{-1} roughly from the direction of Cygnus constellation.
- Earth's rotation relative to the WIMP wind -> daily modulation in recoil directions, annual modulation in flux and spectrum





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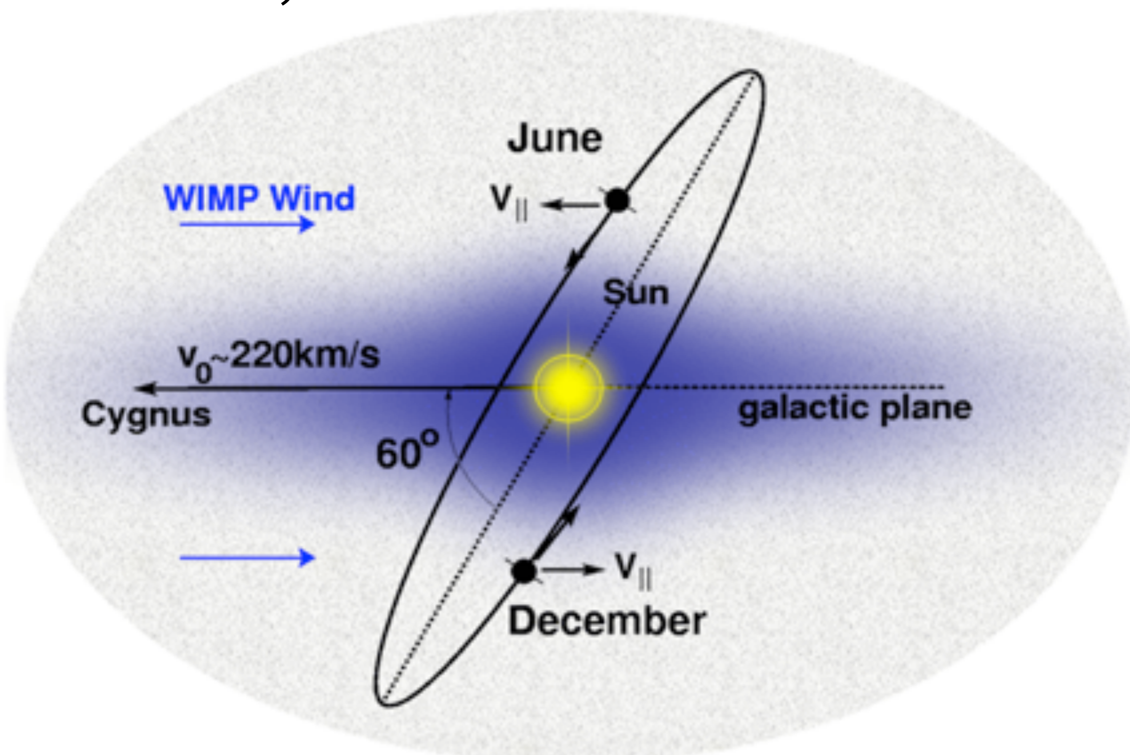
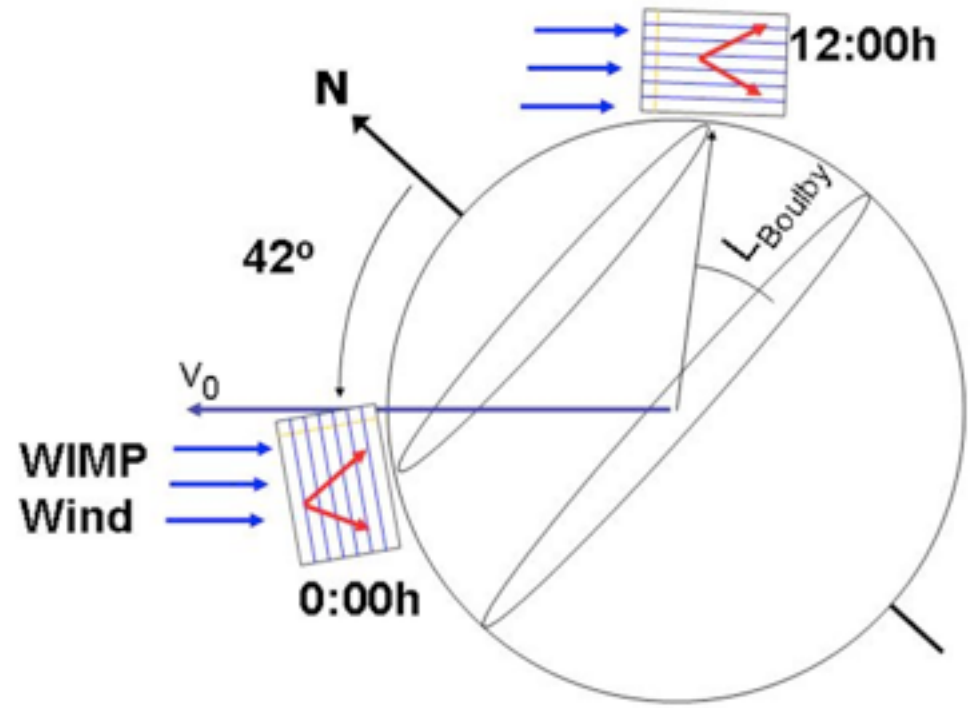
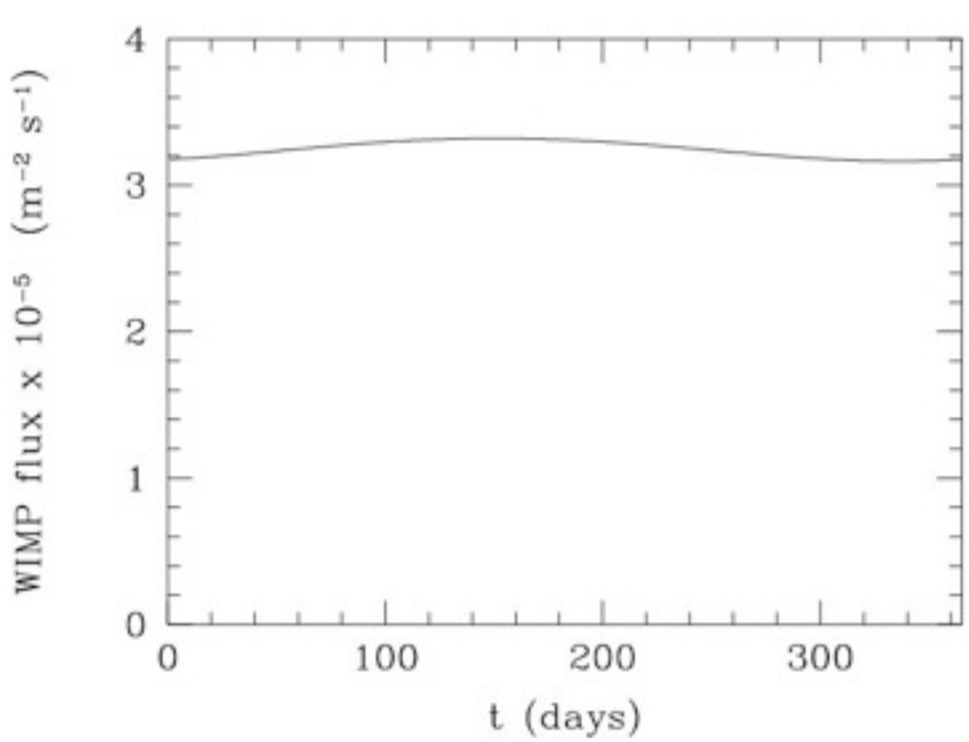
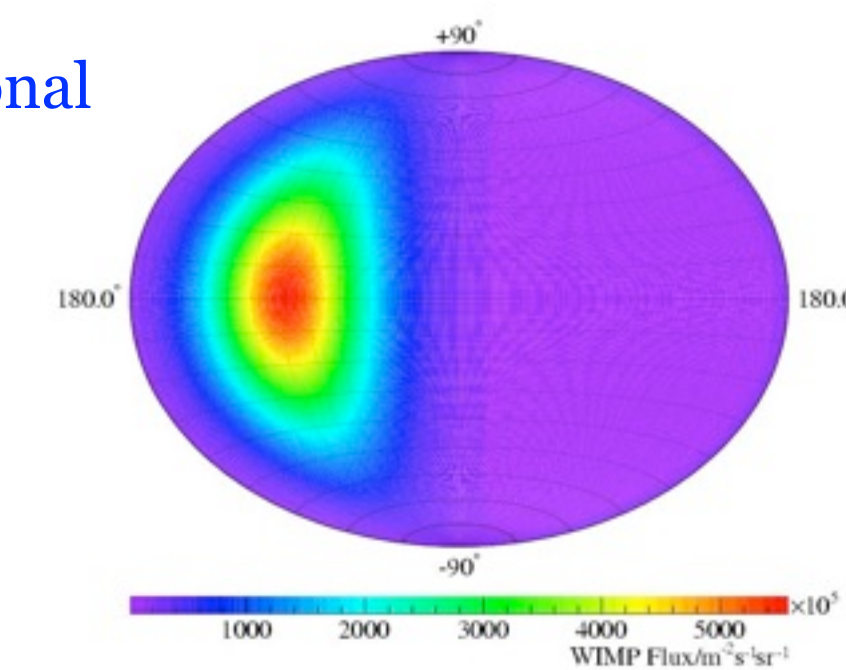




Annual modulation signal



Directional signal



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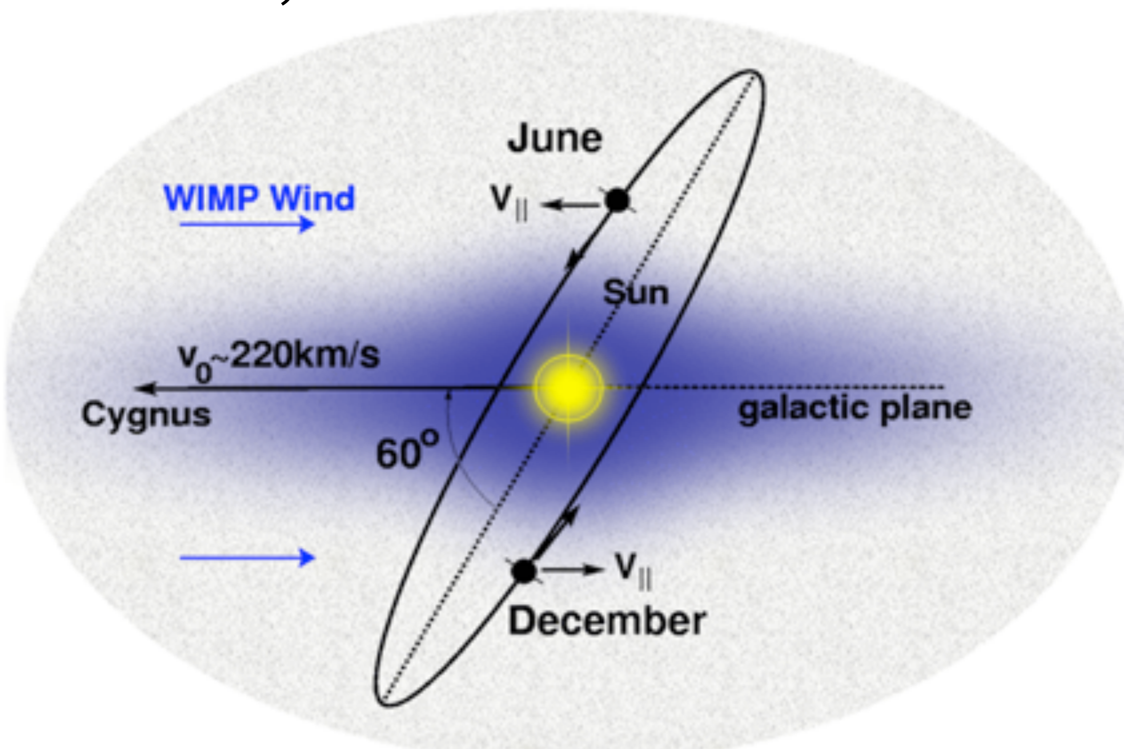

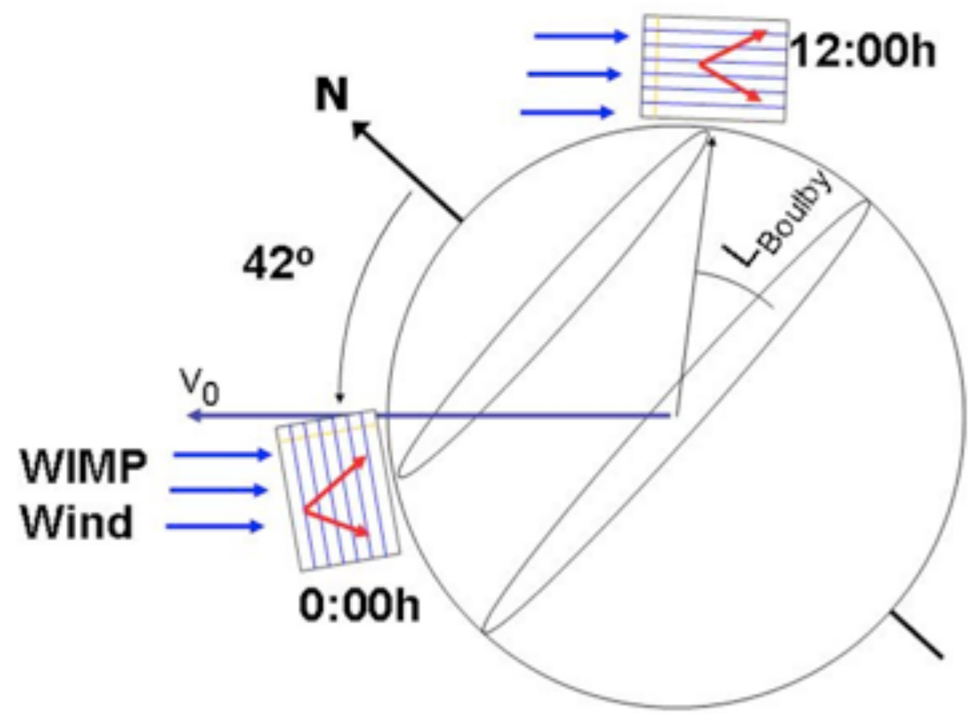

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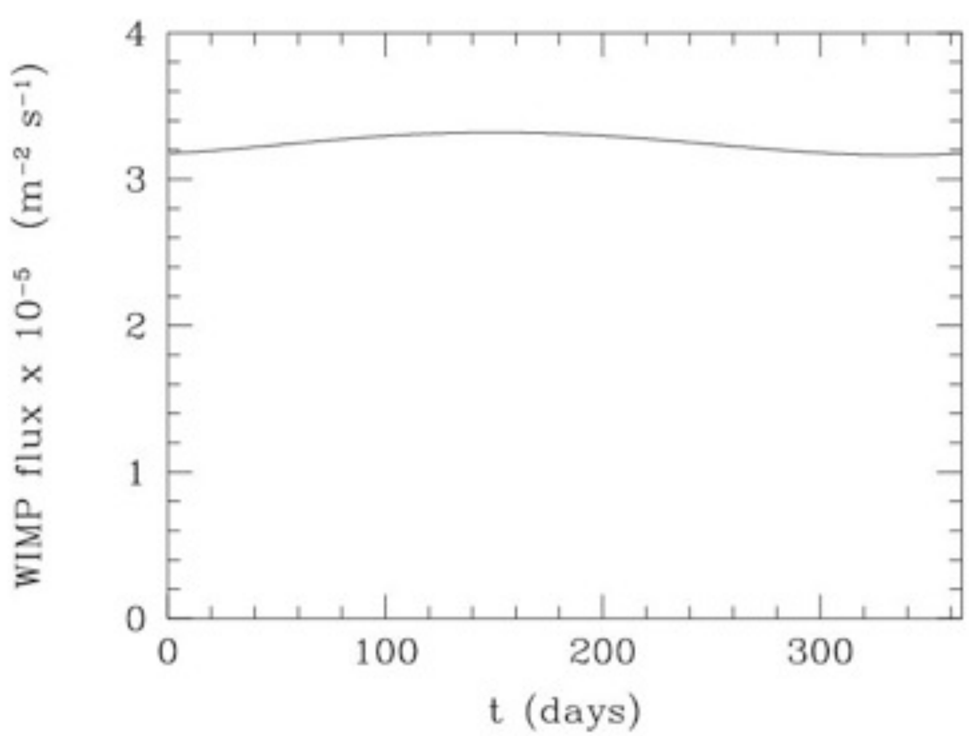
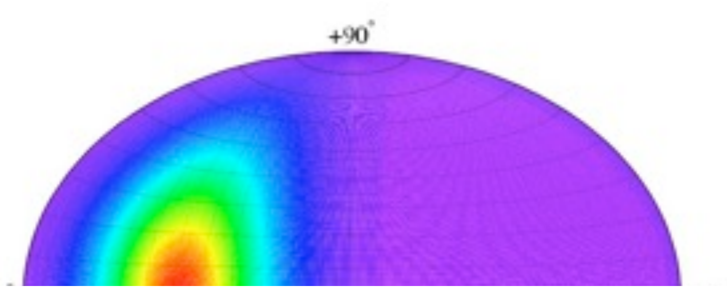


Directional signal



5 directional experiments now: DRIFT, MIMAC, NEWAGE, DM-TPC, D3

Challenge of Annual Modulation

- Environmental Effects/Backgrounds
  - Ambient temperature variation
  - Muon flux depend on temperature/pressure in the upper atmosphere
  - Spallation neutrons from muon interaction in rock
  - Radon diffusion from rocks may be varying with time
  - detector and lab maintenance timing
- NaI Detector Effects
  - Quenching factor
  - Channeling
  - “Nygren effect”

Many of these factors tend to have periodicity of 1 year

- Astrophysical Uncertainties?
  - f(v)? v_{esc}? v_O? co-rotating?
- Dark Matter Physics
  - Inelastic scattering
  - Iso-spin violation
  - Spin-dependent

Conclusion on Annual Modulation

- Inherently good to do because it seeks a real GALACTIC SIGNATURE
- Hard to do because you must well CONTROL SYSTEMATICS
- Topical to do now because DAMA/CoGeNT have MODULATION “SIGNALS”

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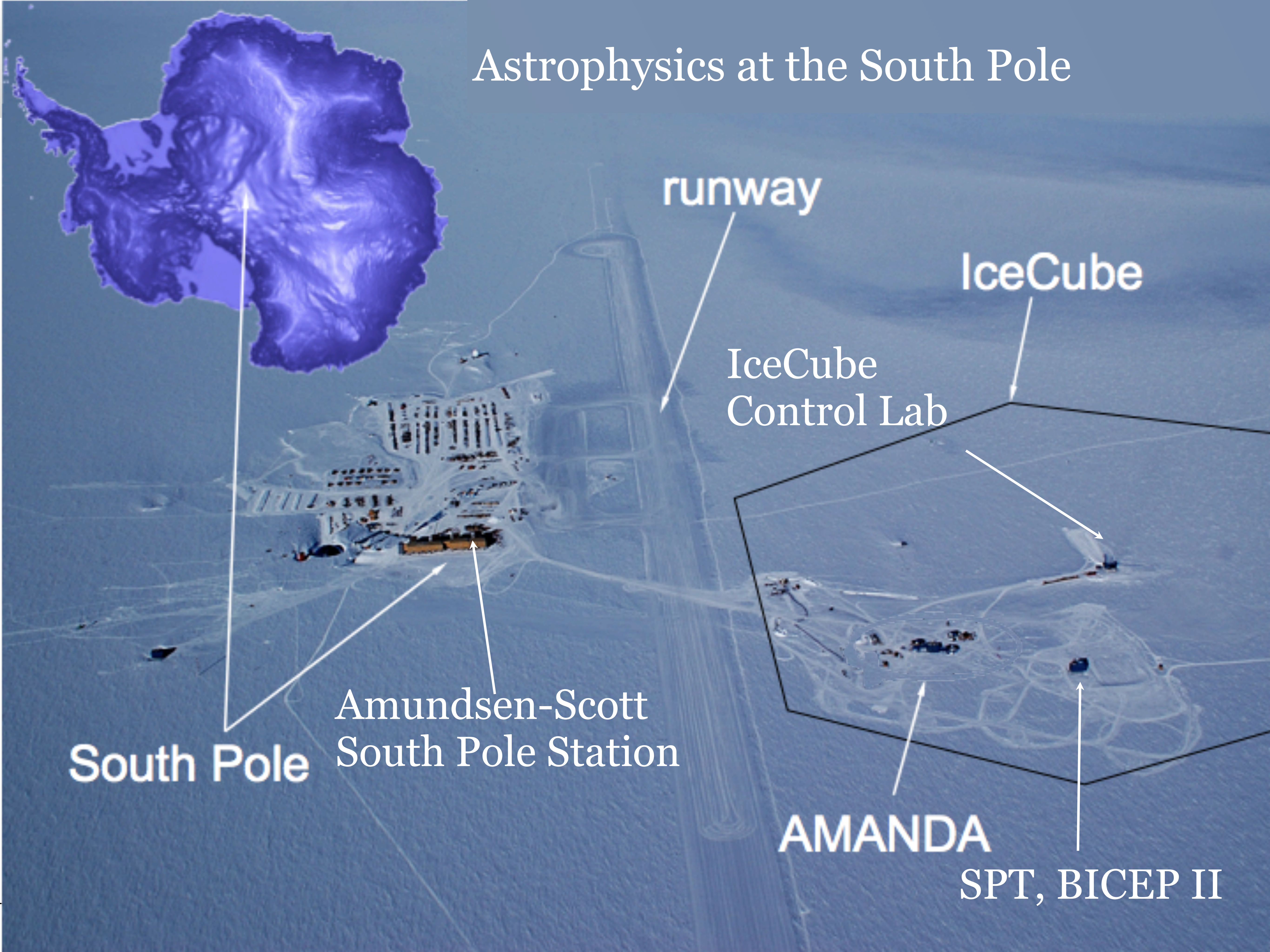
DM-ICE

- Aim to do the best possible annual modulation experiment
- Aim to prove or refute DAMA

New Annual Modulation Test - Requirements

- Environment/location with different systematics
  - Site with different systematics and backgrounds than what might mimic the observed annual modulation signal
  - Southern Hemisphere?
- Low background rates (< 1 event/kg/keV/day)
  - Use clean detectors and surrounding materials. Limited by intrinsic NaI(Tl) background.
  - Deep underground site with muon shielding
- > 250kg of NaI(Tl) detectors
  - Same or larger size than DAMA to collect sufficient statistics
- Long-term stability in operation (> 2 years)
  - Would like to see at least 2 annual modulations if signal is seen

Astrophysics at the South Pole



Advantages of South Pole for AM

Annual Modulation Signal

- Phase of the dark matter modulation is the same.
- Opposite seasonal modulation, e.g. muon rate (max in December).

Overburden with clean, radiopure ice (> 2500 m.w.e.)

- Many sources of backgrounds either non-existent or different from other underground sites.
- Clean ice → Very little uranium/thorium. No radon.
- Ice is a great neutron moderator.
- Ice as an insulator → No temperature modulation.

Existing infrastructure

- NSF-run Amundsen-Scott South Pole Station
- Ice drilling down to 2500 m developed by IceCube
- Muon rates well understood by IceCube/DeepCore
- Infrastructure for construction, signal readout, and remote operation

Challenges

- Extreme environment; Detector will be inaccessible once deployed

Muons and Seasonal Modulation

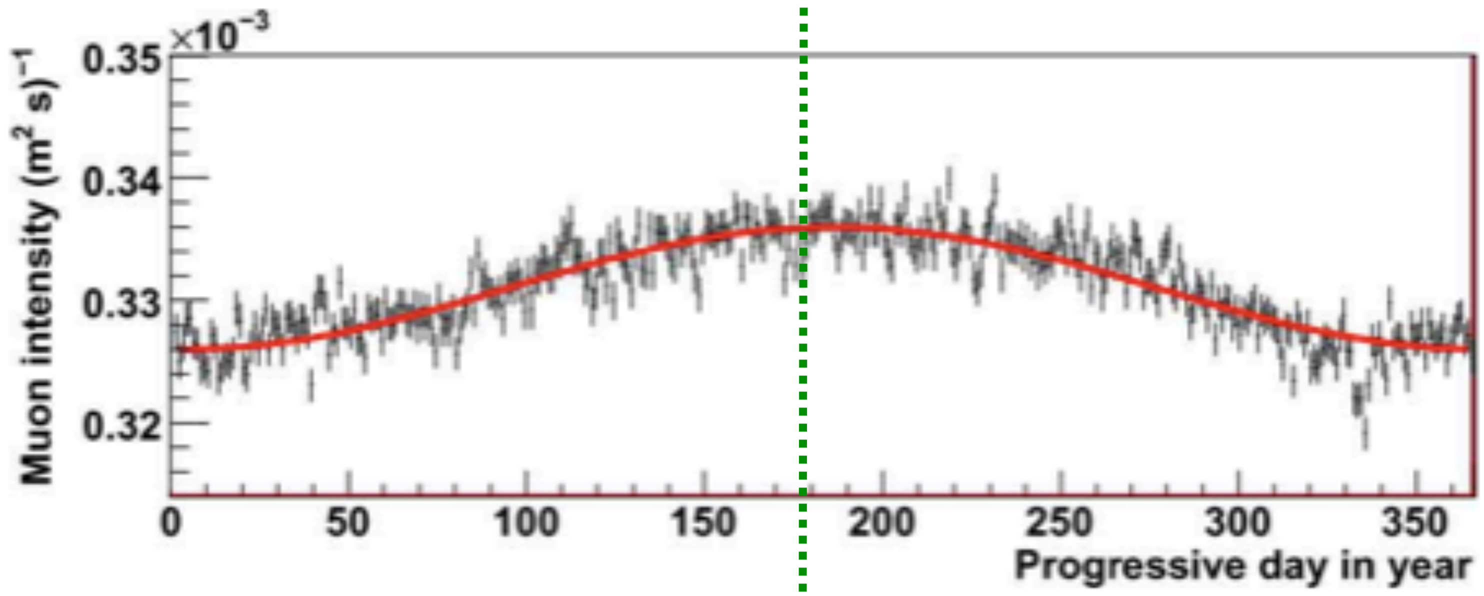
- Overburden 2500 m depth (2200 m.w.e.)
- ~85 muons/m²/day at bottom of IceCube, IceCube/DeepCore veto reduces rate by ~1-2 orders of magnitude, Ice is a good neutron moderator

Gran Sasso

- LVD:

Selvi, Proc. 31st ICRC. (2009)

summer



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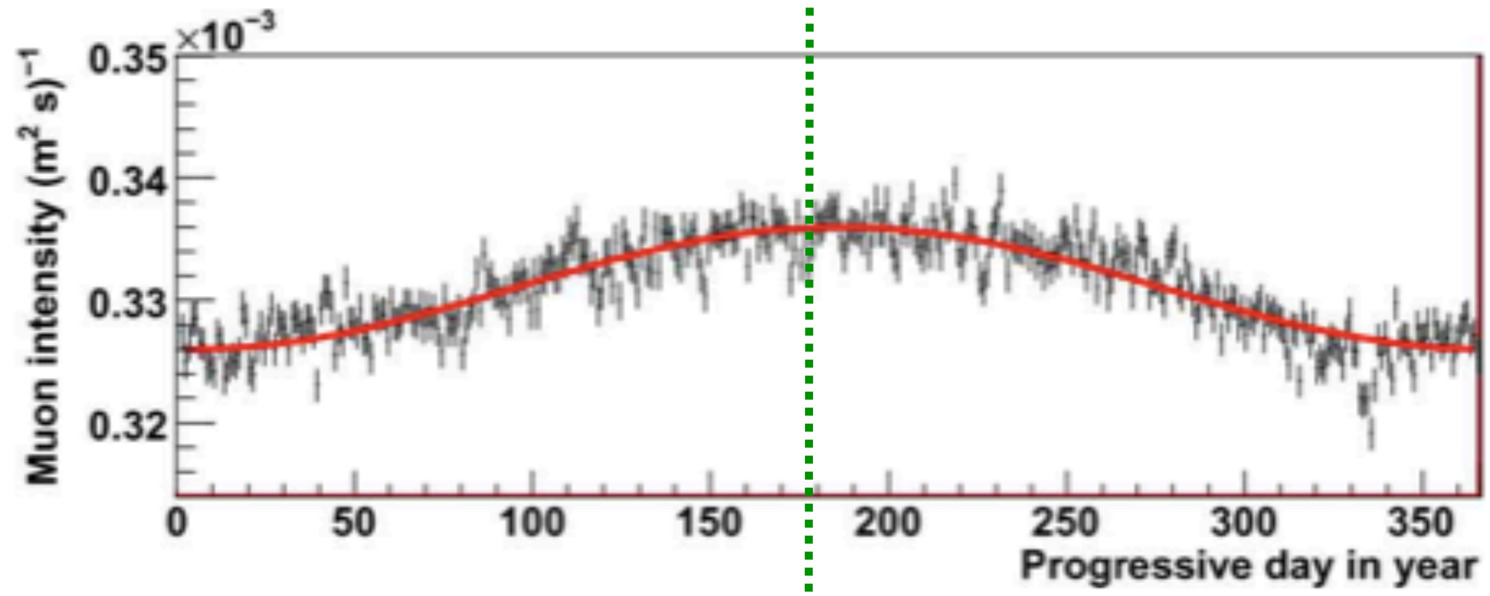
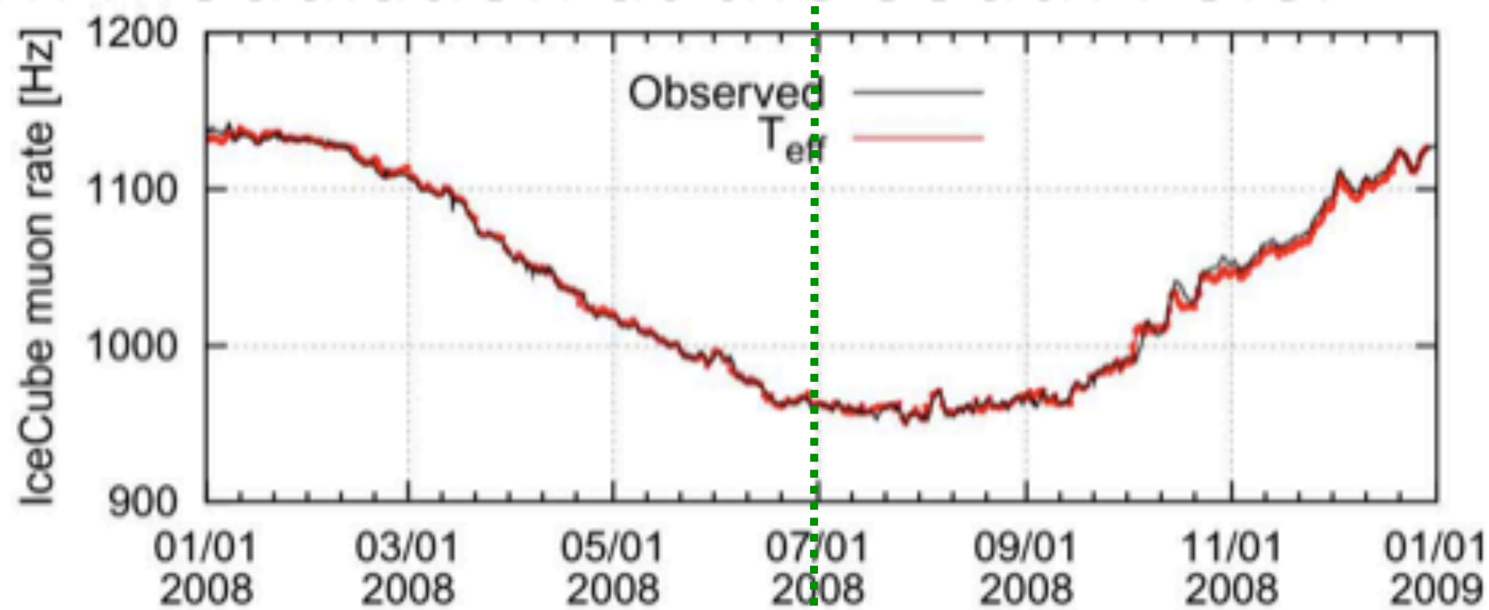


South Pole

- Opposite Muon modulation at the South Pole:

Tilav, Proc. 31st ICRC. (2009)



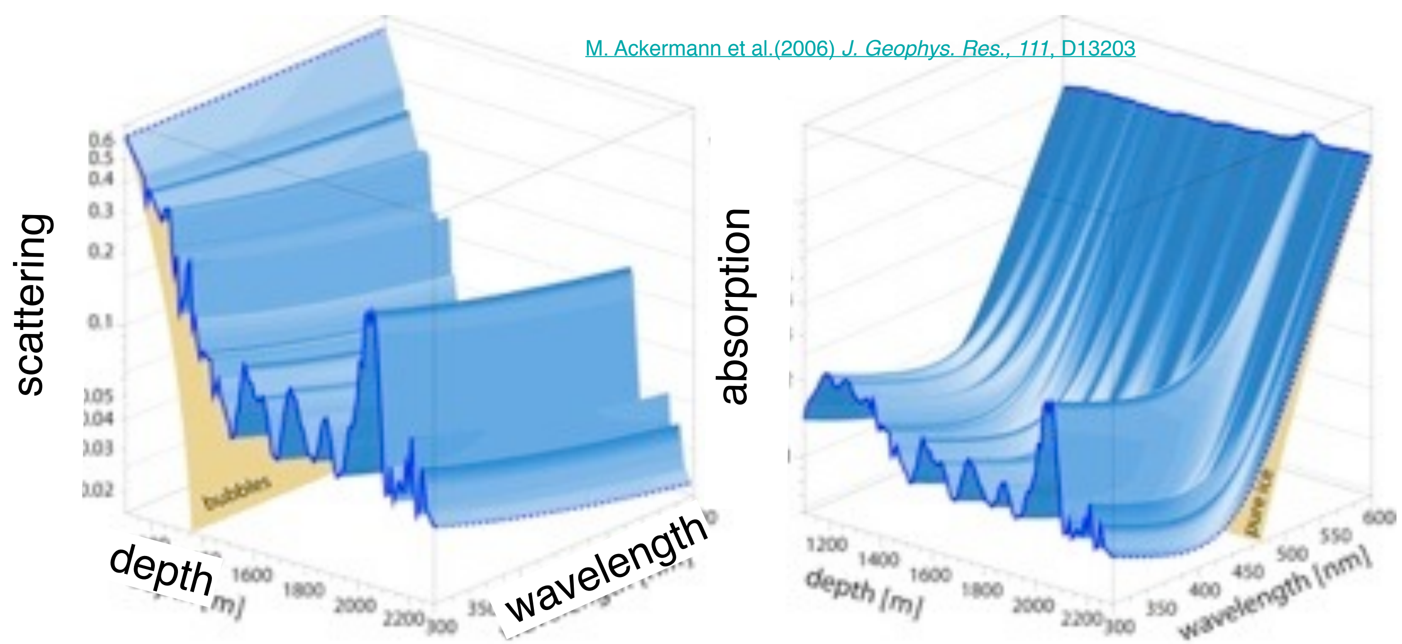
Antarctic Ice Gamma Background

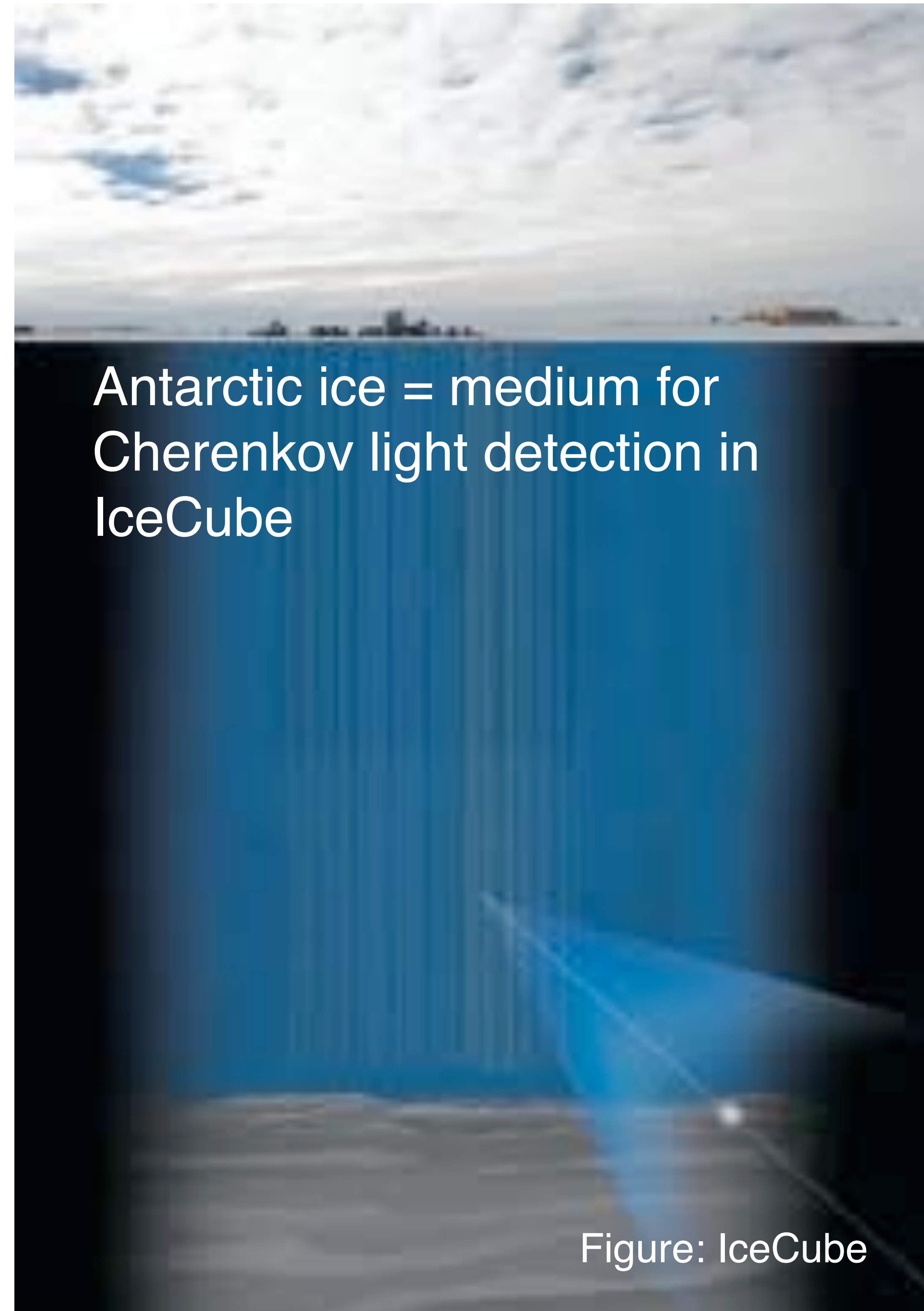
Radio-purity

- -2500 m at South Pole is ~100,000 years old
- Ice is nearly as clean as materials used for ultra-low background experiments.
- U ~ 0.1ppt, Th ~ 0.1ppt, K ~ 100 ppt
- Most of the impurities come from volcanic ash, < 0.1 ppm

Scattering/absorption studies in ice

M. Ackermann et al.(2006) *J. Geophys. Res., 111*, D13203





The 17 kg DM-ICE Prototype

First step: development of 17 kg prototype and deployment at the Pole

Window of opportunity: last ICECUBE deployment - Dec 2010

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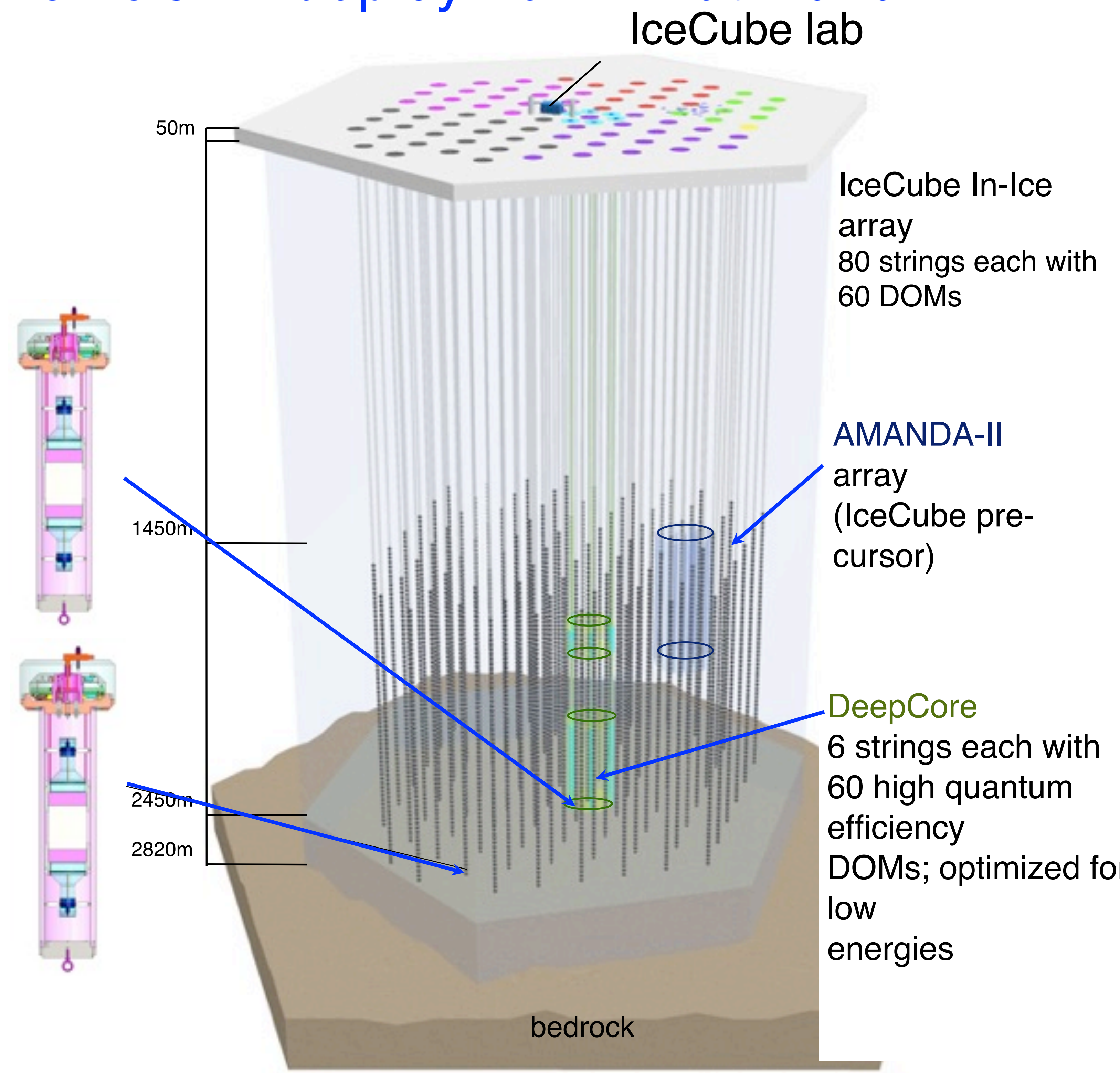
Goals

- Assess the feasibility of deploying NaI(Tl) crystals in the Antarctic Ice for a dark matter detector. Establish the radiopurity of the antarctic ice / hole ice
- Explore the capability of IceCube to veto muons

Detectors

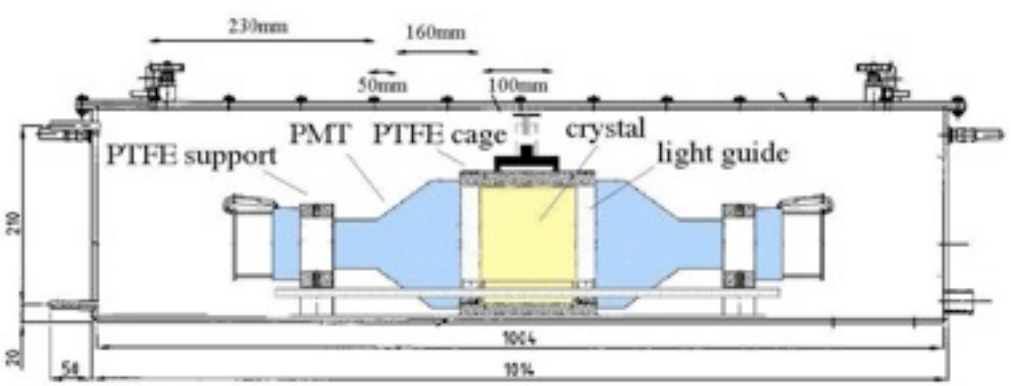
- Two 8.5 kg NaI detectors recycled from the original NAIAD experiment at Boulby.....



The Original NAIAD Crystals at Boulby

- NAIAD was an array of encapsulated and unencapsulated NaI(Tl) with high light yield used for early dark matter searches from ~1998-2004
- NAIAD was used to set upper limits on the WIMP-nucleon spin-independent and WIMP-proton spin-dependent cross-sections
- Pulse shape analysis used to discriminate between nuclear recoils, as may be caused by WIMP interactions, and electron recoils due to gamma background

Boulby mine old
NAIAD Laboratories



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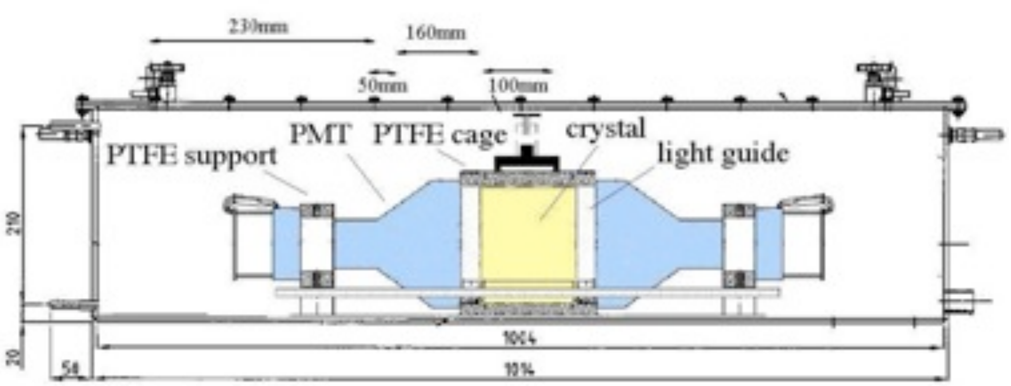
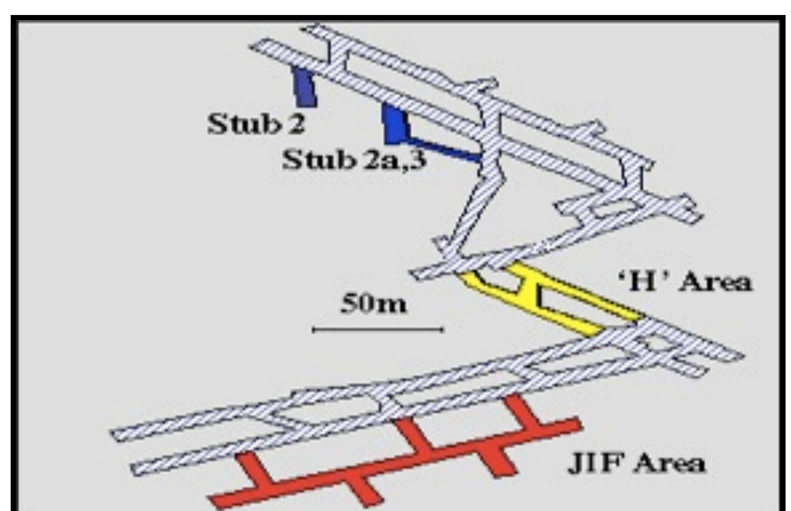
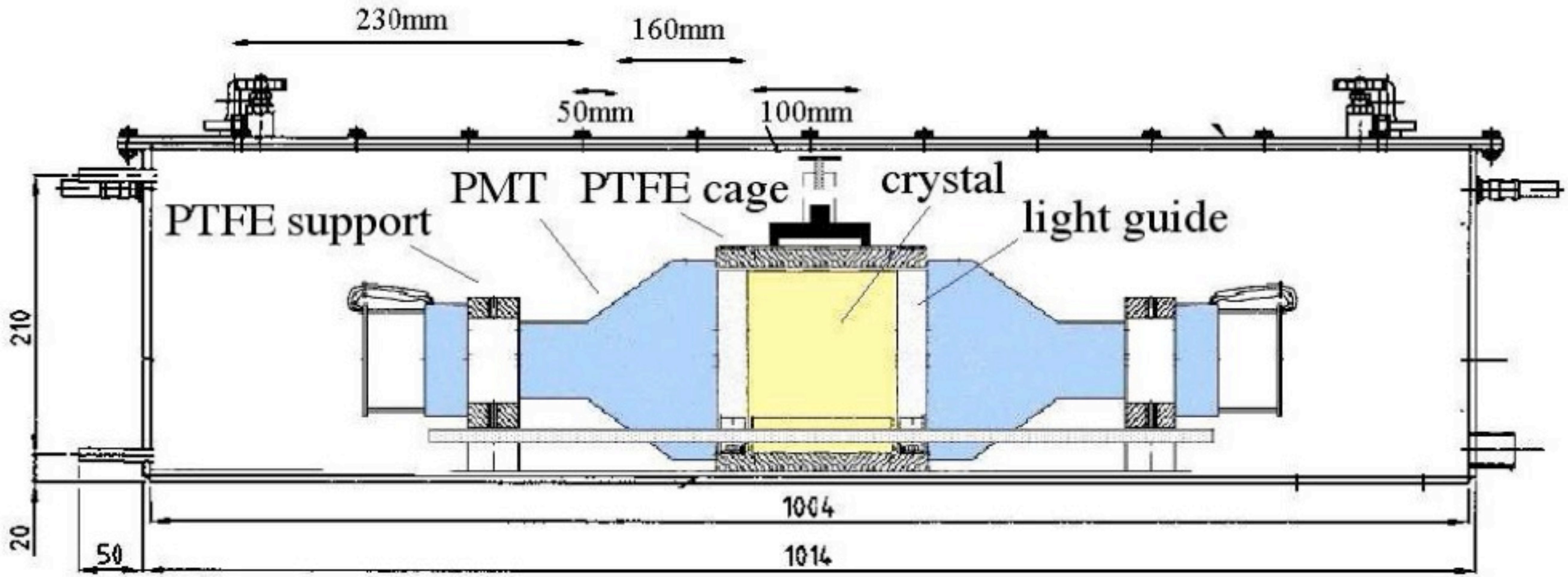




Old NAIAD Design

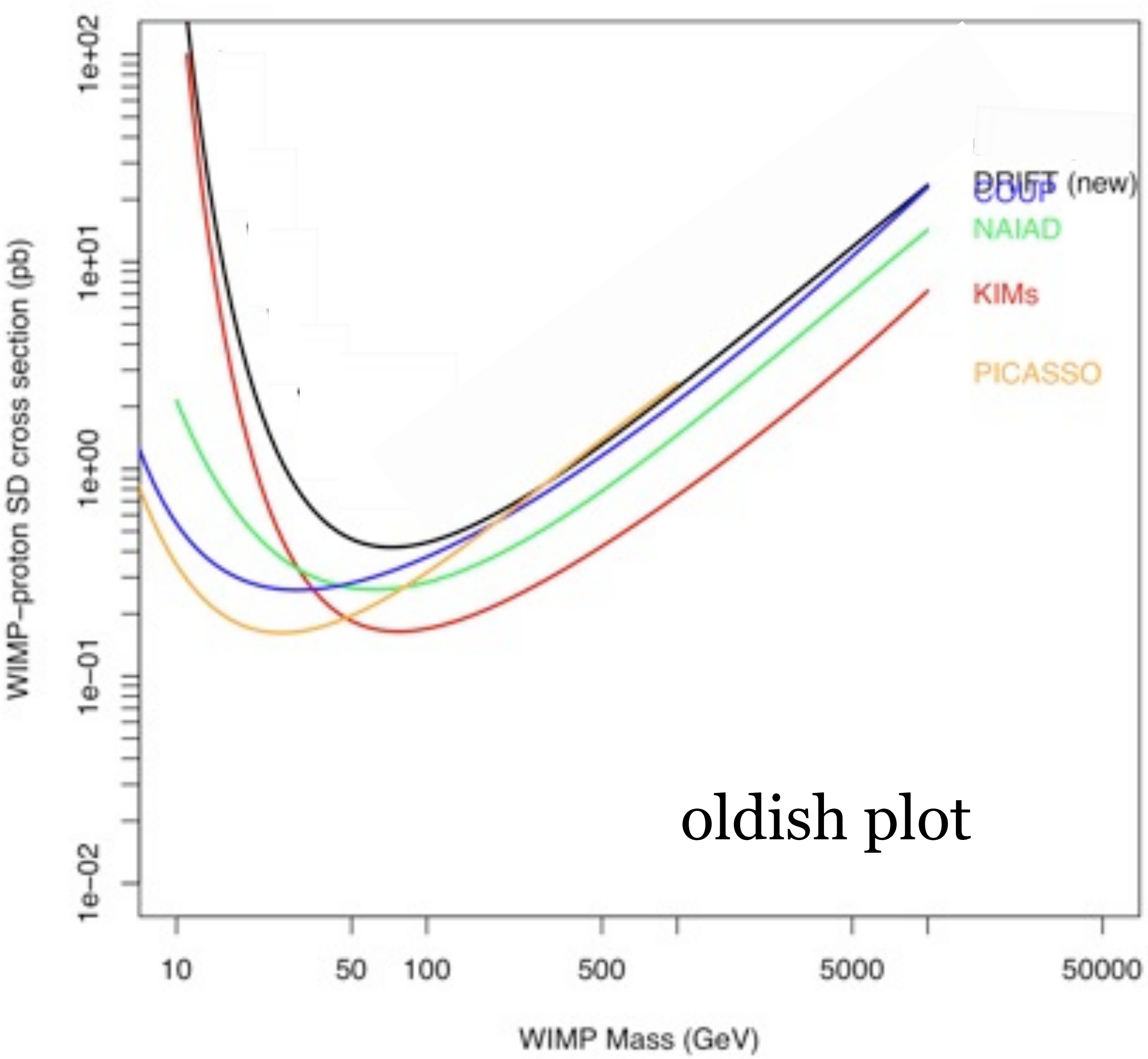


- Crystals sealed in copper boxes and cooled to 5^{o}C
- Only selected low background materials used in the detector design including oxygen-free high-conductivity copper and PTFE
- PMTs integrated using a buffer circuit, PMTs is set to give about 2.5 mV per photoelectron
- Light yield from 4.6 up to 9 pe/keV

NAIAD Still Competitive for SD WIMP-p

Crystal	Mass, kg	Light yield, pe/keV	Time, days	Exposure, kg×days
DM70-Saclay	10.0	5.1 ± 0.4	157.2	1571.7
DM74	8.40	8.4 ± 0.4	298.3	2505.4
DM76	8.32	4.6 ± 0.3	131.0	1089.6
DM77	8.41	6.1 ± 0.3	221.9	1866.2
DM80	8.47	8.0 ± 0.5	312.0	2642.7
DM81	8.47	6.6 ± 0.4	336.2	2847.2
Total exposure				12523

Statistics for NAIAD detectors running in 2002-2003



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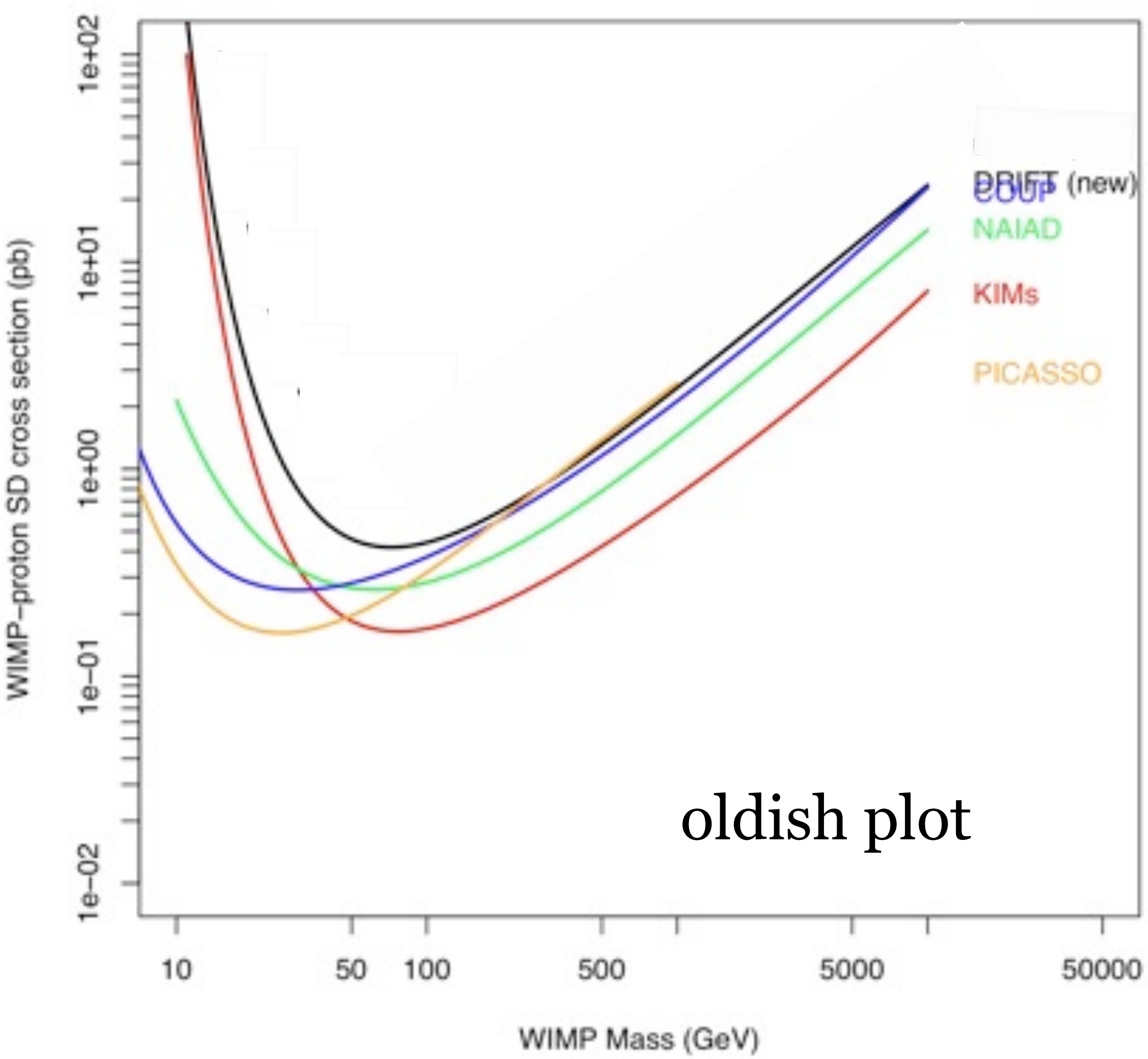
Statistics for NAIAD detectors running in 2002-2003

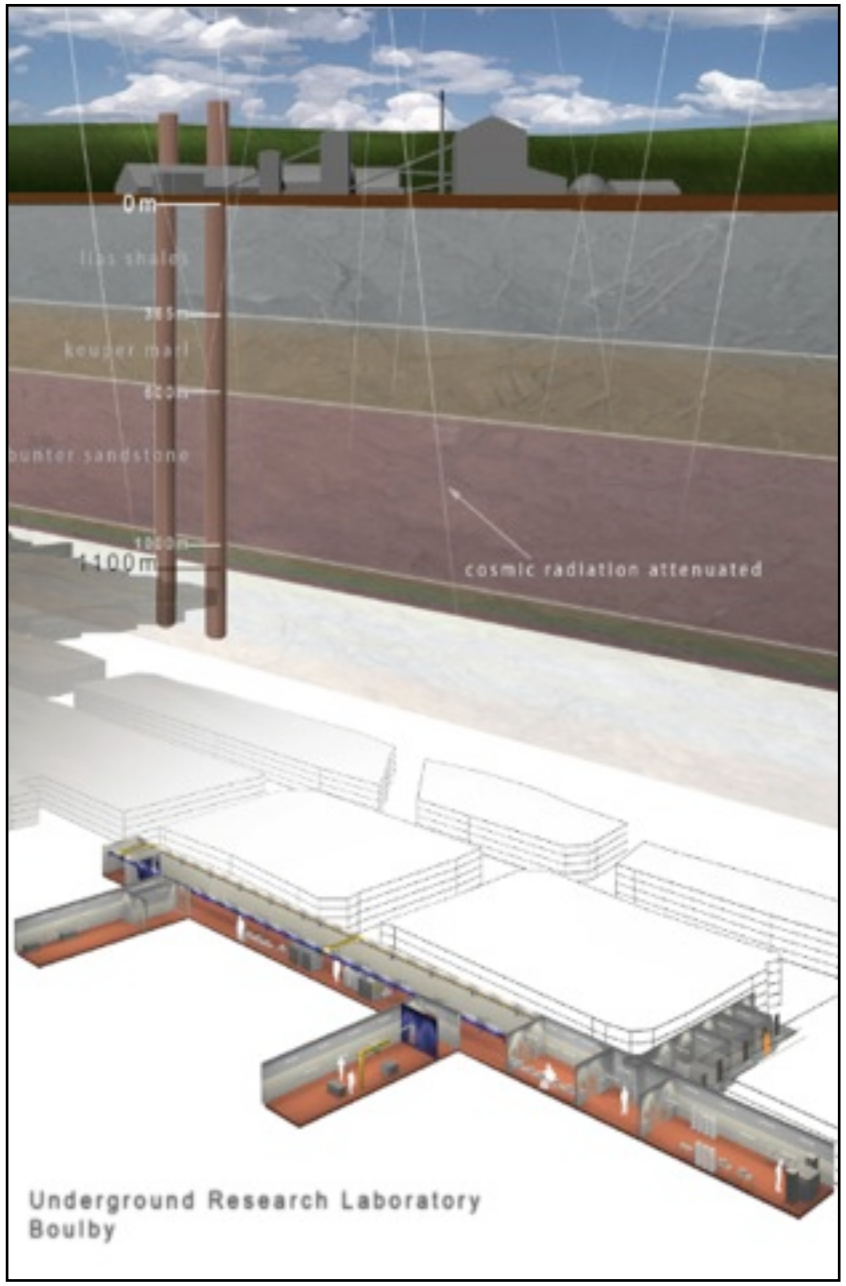
- Selected two best NAIAD crystals (17 kg) for DM-ICE
- Intrinsic backgrounds ~5-7 times DAMA reported
- Assembly with silica lightguides and 5in. ELT PMTs

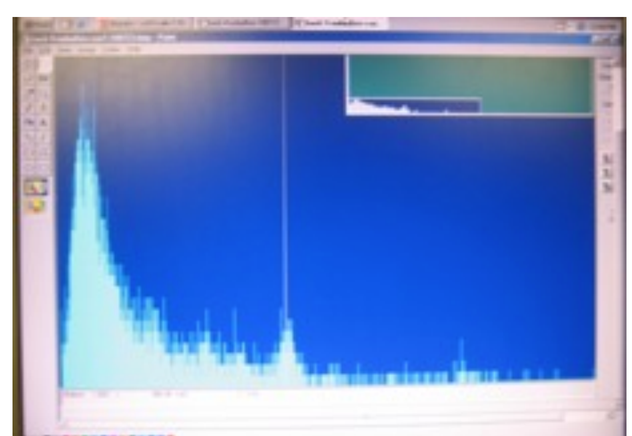


- Recovered in April 2010 and transferred to the new Palmer Laboratory at Boulby.....

DM-ICE Prototype Assessment at Boulby

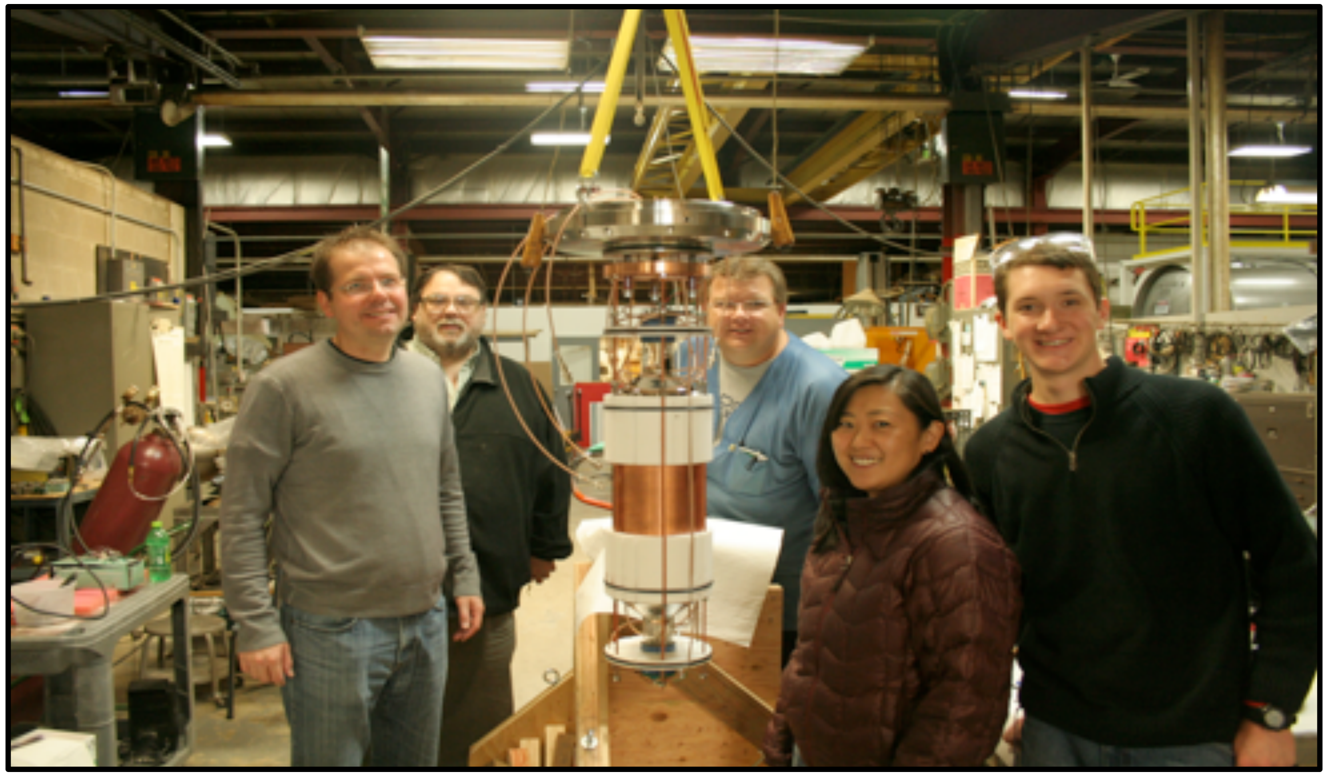
- Boulby Palmer Lab tests at 1.1km depth

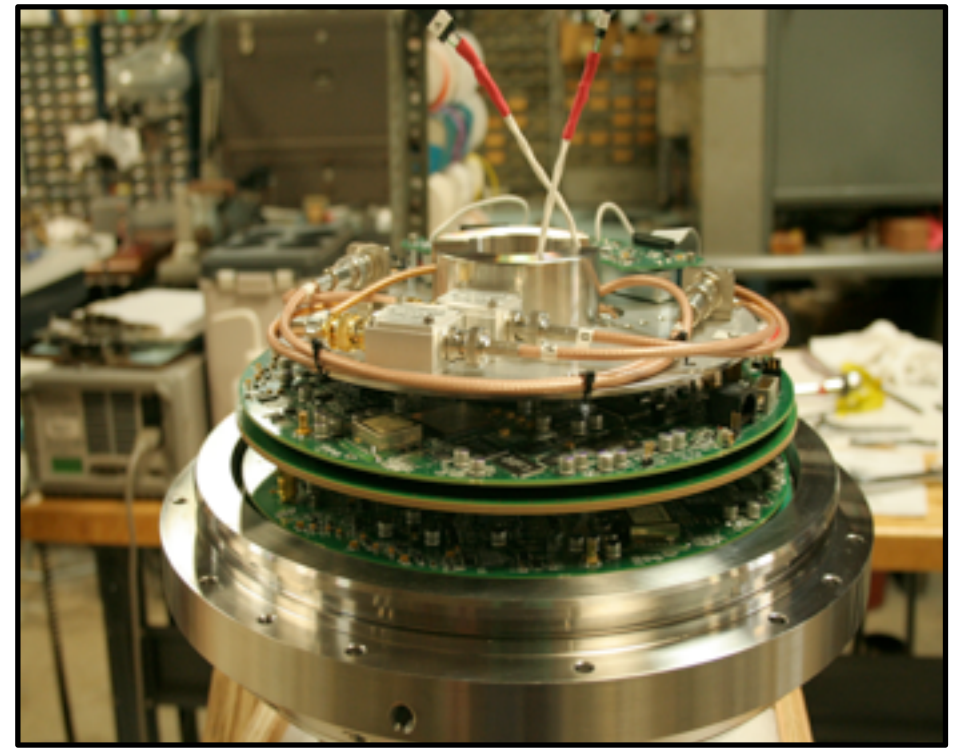




- Both crystals and PMTs tested and found to be in excellent condition
- Packed and shipped to Madison....

Construction and Assembly at Madison

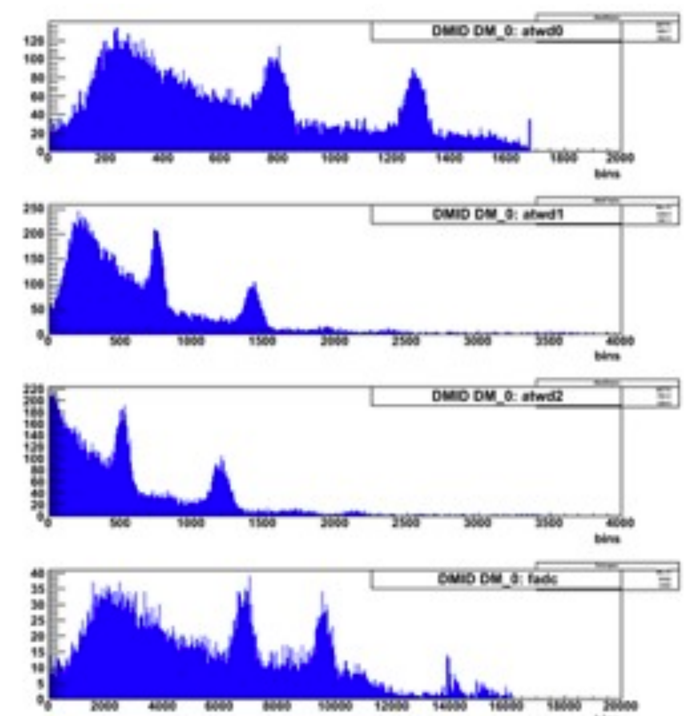




DM-Ice Pressure Vessel

- Stainless, Teflon, etc. selected from vendors known to produce clean material - activity measurements at LBNL, SNOLAB & Boulby
- Pressure vessel tested to 6200 psi - static pressure of water ~ 3500 psi, 6000+ psi during ice refreeze in the hole

Calibrations in Madison

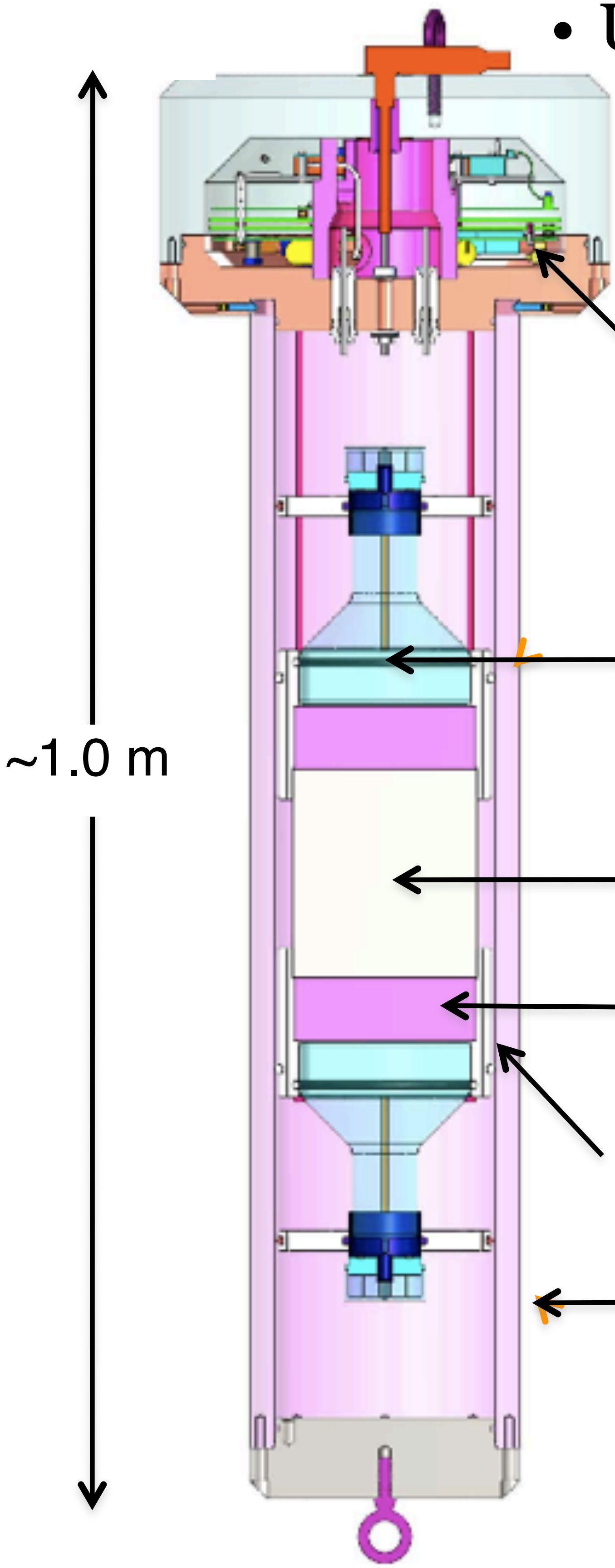


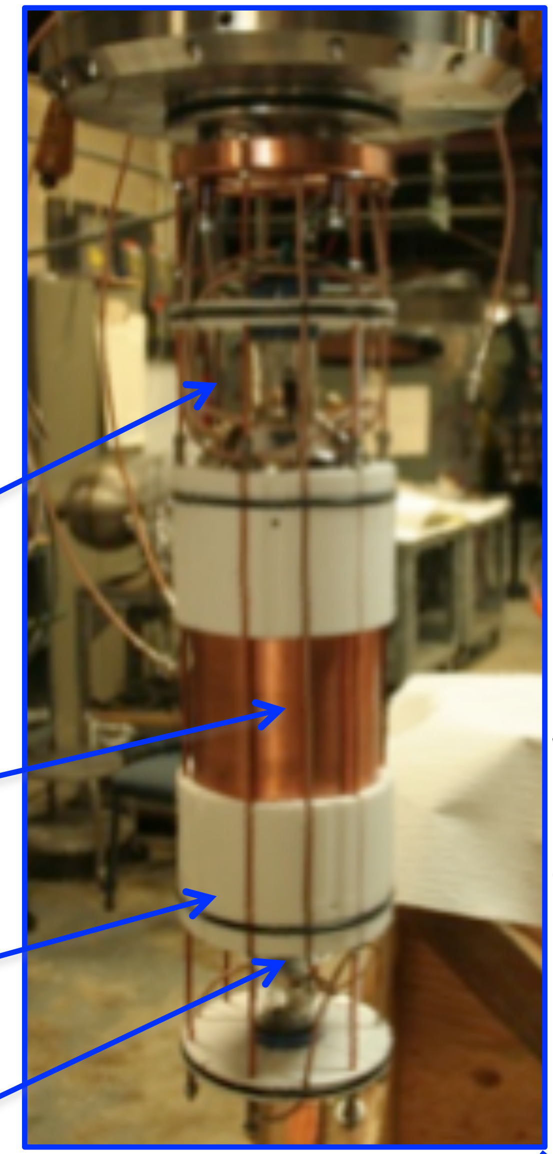
IceCube DOM Mainboards

- 14-bits, coincidence trigger, separate HV board, programmable from surface, established reliable technology

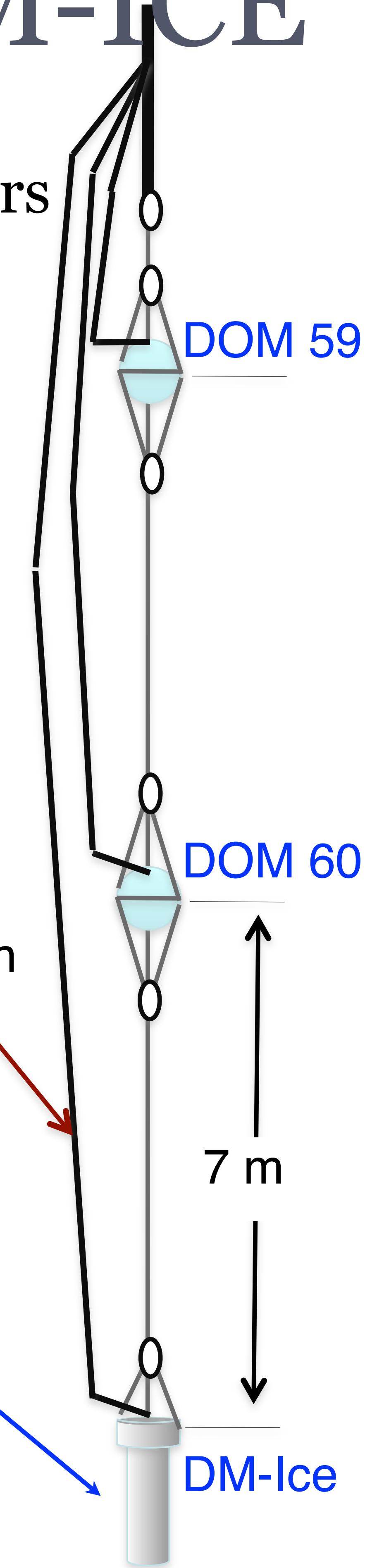
Detector Internals Design for DM-ICE

- New support structure and housing at Madison
  - Used original lightguides, PMTs, PTFE reflectors

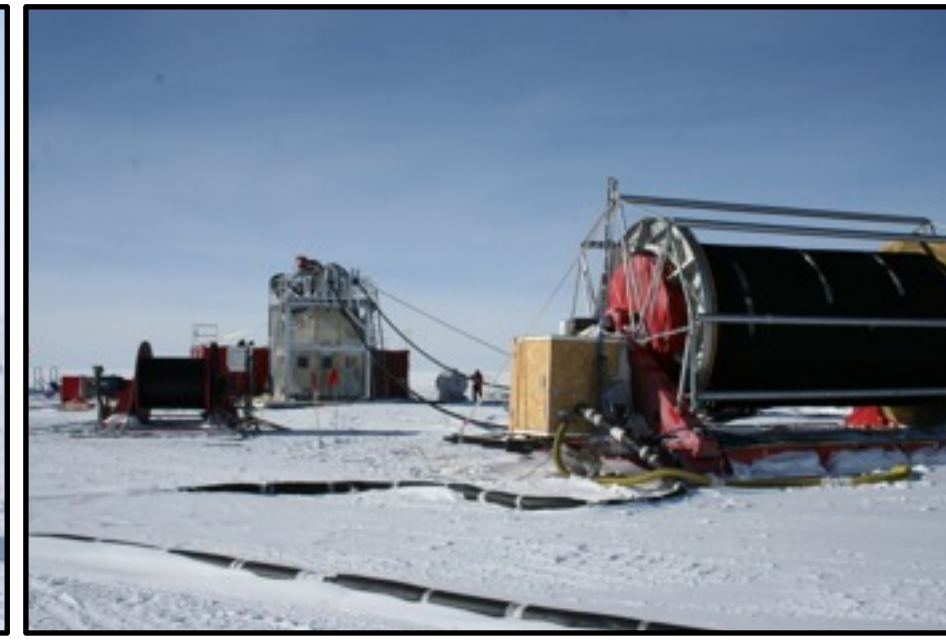




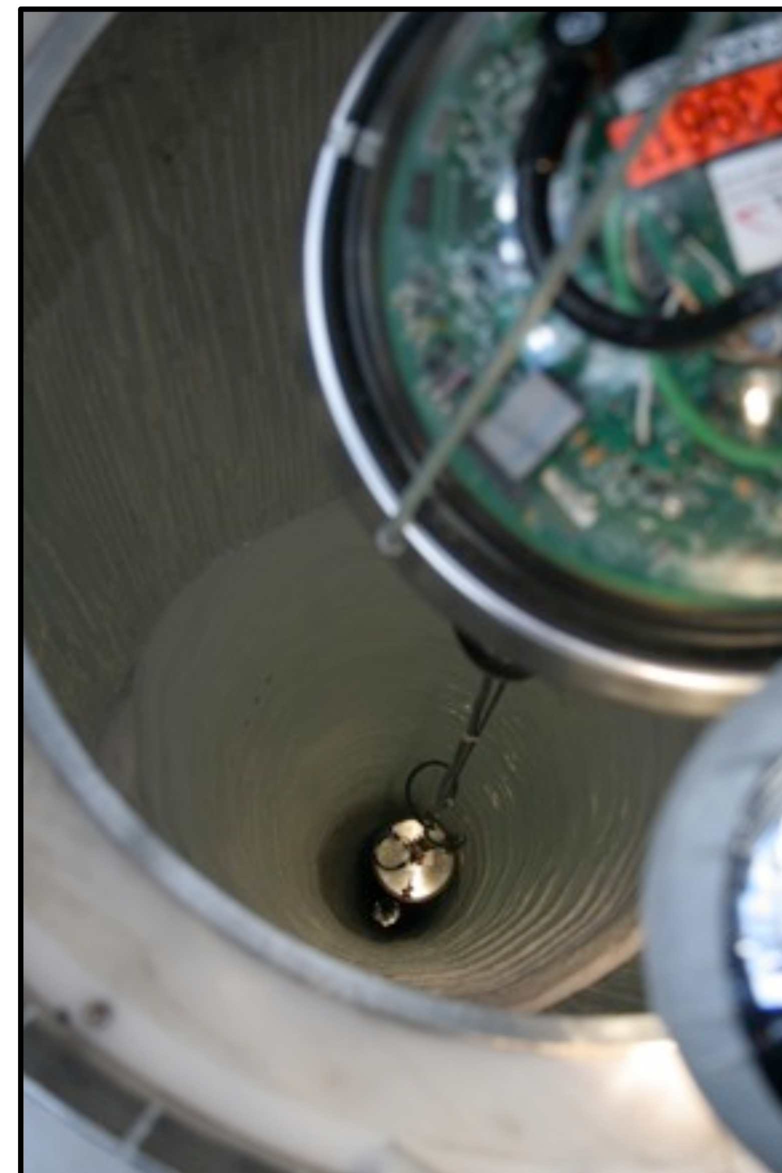
attached to end of IceCube strings



Transfer to South Pole and Installation



- Transfer by plane to South Pole in Dec 2010
- Installed below last ICECUBE strings
- ***~9 months from idea to deployment in the ice!!!***

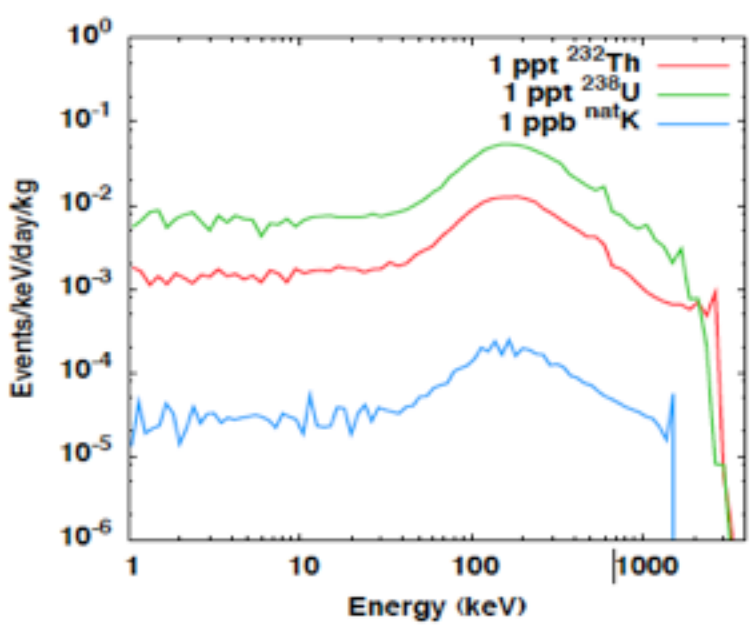


Background Assessments

- Aim for prototype to match NAIAD, i.e. dominated by NaI background ~5 DRU

Material	^{238}U	^{232}Th	^{nat}K
drill ice [27]	0.076±0.046	0.47±0.14	<262
Antarctic ice	10^{-4}	10^{-4}	0.1
PMT [26]	30	30	60000
steel PV [27]	0.2	1.6	442
NaI	0.005	0.005	10

Material	event rate in NaI ($cpd/kg/keV_{ee}$)
drill ice	0.8
Antarctic ice	< 0.001
photomultiplier tubes	0.01-0.02
steel PV	0.2-0.6
NaI crystal	~0.3



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

Background Assessments

- Aim for prototype to match NAIAD, i.e. dominated by NaI background ~5 DRU

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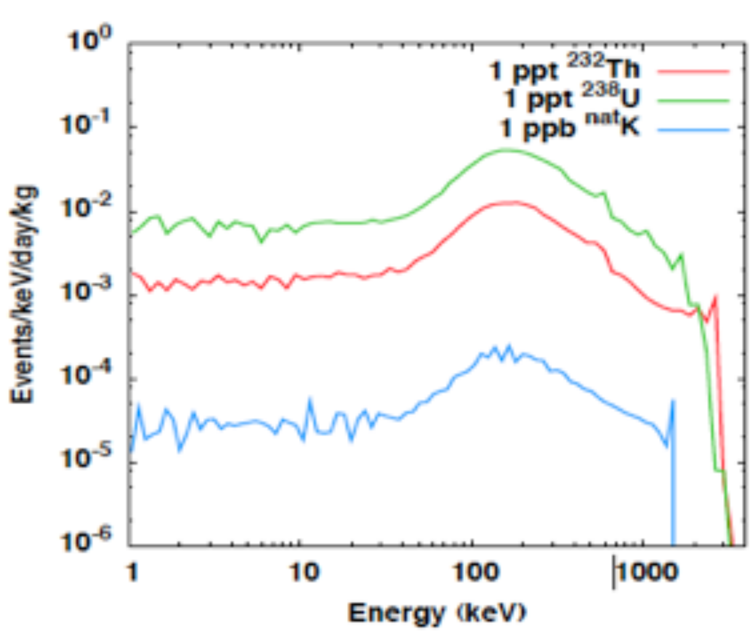

simulated activity in NaI crystals **from radioactivity in ice**

Later Goals: < 1 cpd/kg/keV
Reducing the backgrounds:

drill water/ice
- won't reuse, circulate water
- minimise volume of drill ice around

detector
steel pressure vessel (PV)
- can use better material, custom steel
- may be able to use Cu or Ti for full detector

NaI crystal
- purify raw materials

- Likely to be limited by intrinsic backgrounds in NaI crystals
- Growing NaI(Tl) crystals: know how to remove U/Th, but K is difficult.

Prototype Status and Preliminary Results

DM-ICE Prototype Successful Operations in the Ice

- Taking data, continuous operation since Dec 2010
- Data transmitted over satellite

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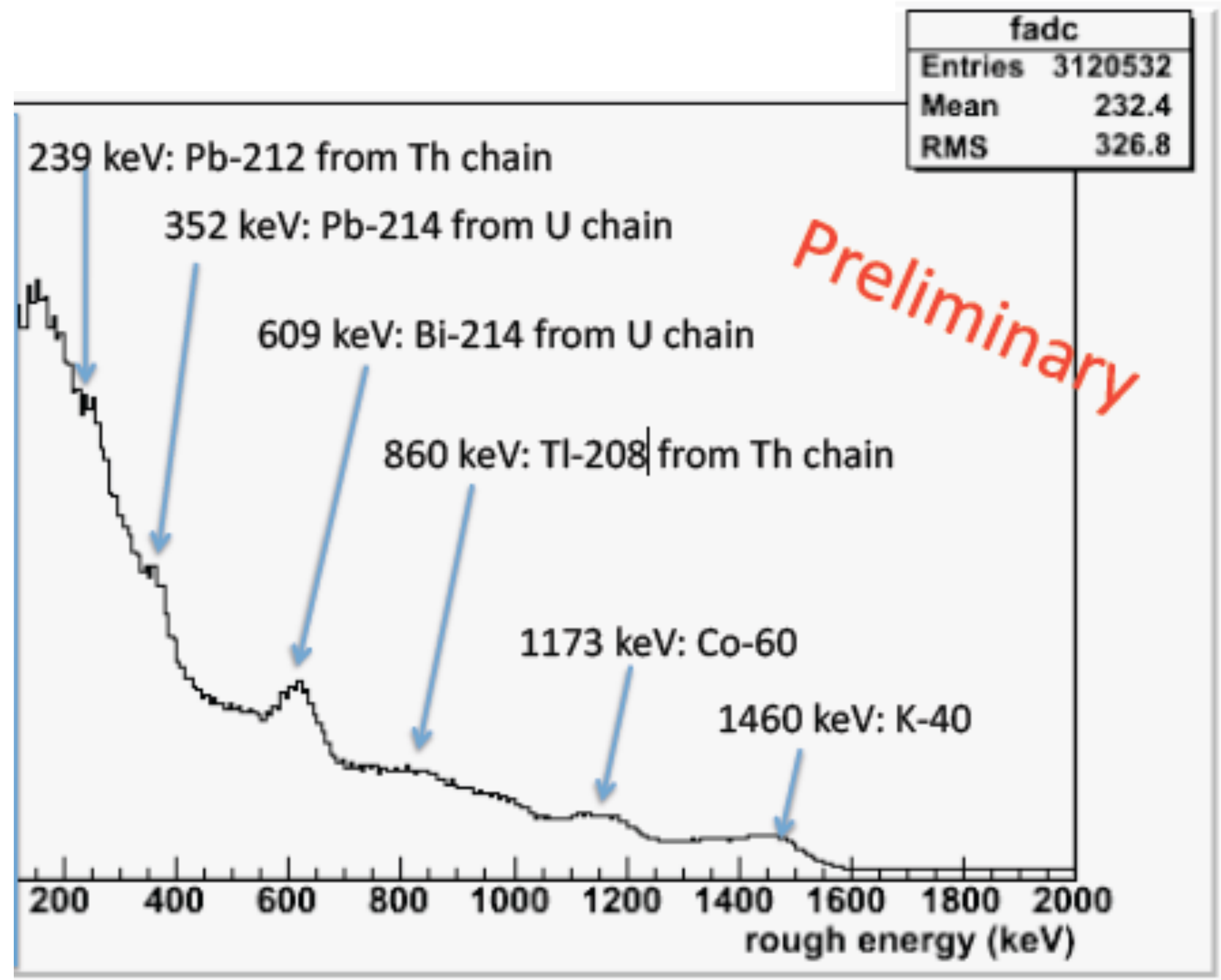
Data

- Correct spectra seen from both crystals
- Similar background seen as in NAIAD at Boulby
- NaI background dominates



Prototype Goals Achieved

- Installation and operation of low background NaI crystals is feasible in the South Pole deep ice

Current prototype work and aims

- Optimise low energy cuts for minimum background in dark matter region
- Aim for 1 year annual modulation analysis data release

Development of Noise Cuts Underway

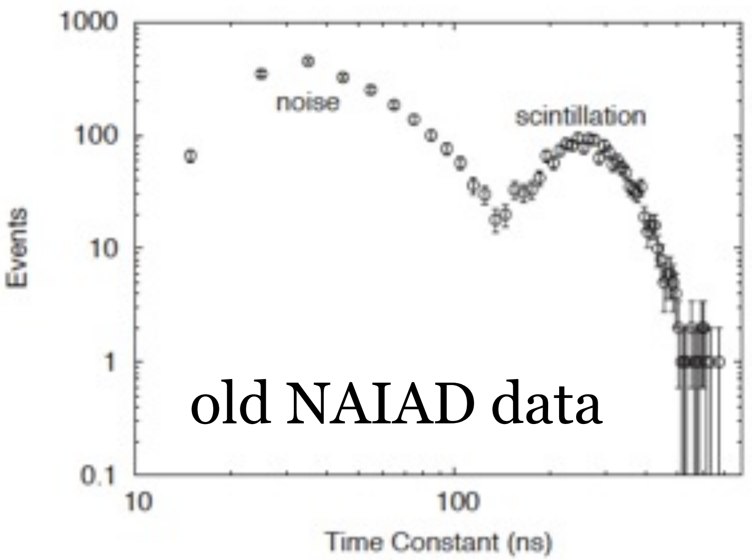
Noise cuts based on NAIAD experience in addition to normal coincident cuts, e.g.:

Pulse Shape Analysis Cuts

- To reduce PMT noise and, particularly, events where a spark (flash) in the dynode structure of one PMT is seen by both PMTs, so-called “asymmetry cuts” are applied. These cuts are based on Poisson statistics and used the **asymmetry in amplitude, time constant and start time of noise** (non-scintillation) pulses from the two PMTs to remove them

Asymmetry Cuts

- Typical NAIAD time constant distribution for the energy range 4–6 keV showing the encroachment of the noise into the scintillation region in data selected by asymmetry cuts.



Steppiness Cuts

- A means to quantify the tendency of the digitised PMT coincident noise pulse to be made up of multiphotoelectron steps.

- See M. Robinson et al. NIM A 545 (2005) 225

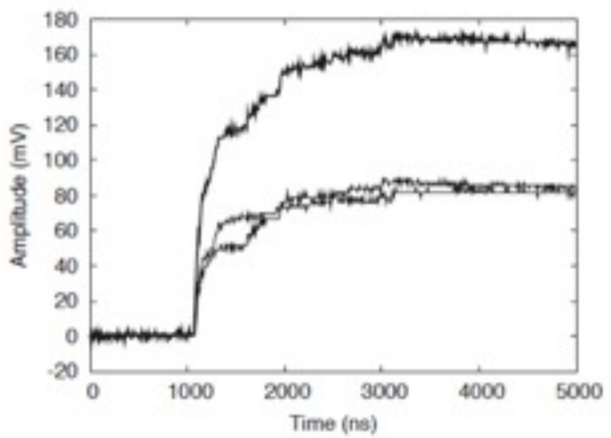
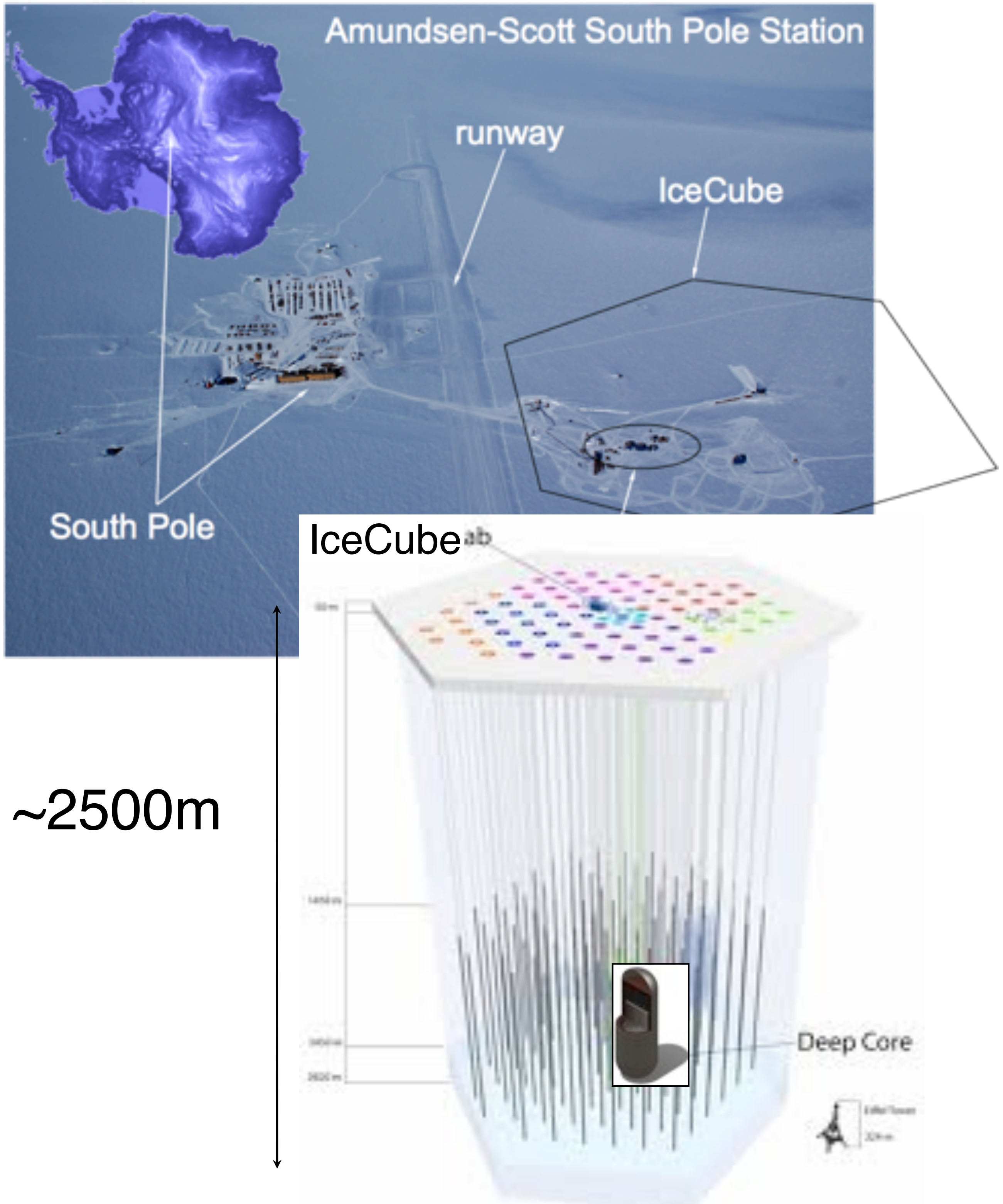


Fig. 4. Event collected in noise measurement experiment mimicking scintillation. As in Fig. 3, the two lower curves show the integrated signals from the individual PMTs. The upper curve shows the sum of these signals.

DM-ICE 250 kg Concept

250kg NaI Detector Array Deep in the Ice



arXiv:1106.1156

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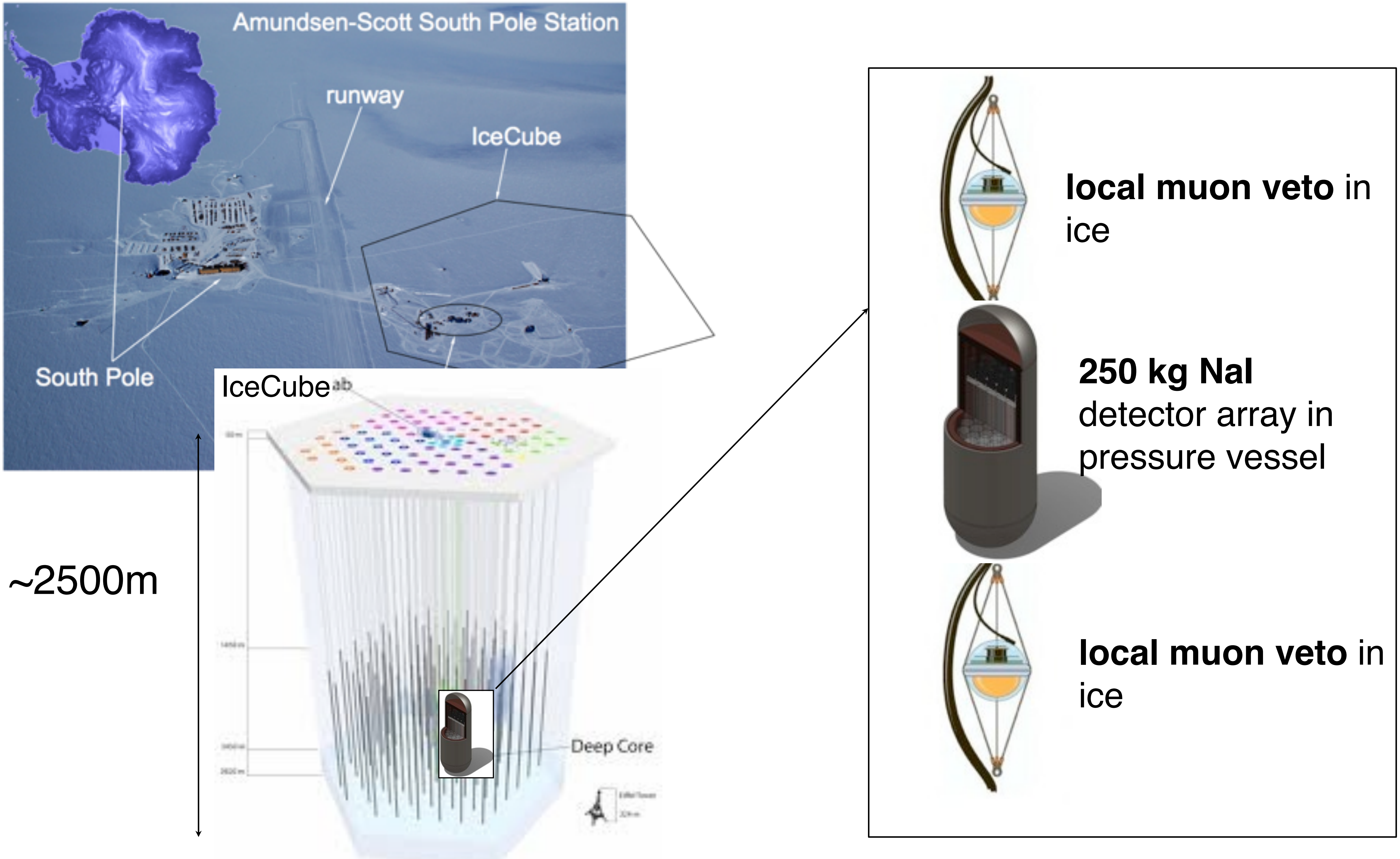

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DM-ICE 250 kg Concept

- Large pressure vessel
- 2 detectors to mitigate deployment risk
- portable detector, hermetically sealed for in-ice (water?) deployment
- 1500 kg total including pressure vessel
- segmented crystals with ~250 kg mass (e.g. 38@6.5kg)

Electronics Space at each end
Electronics and Feedthrus not modelled

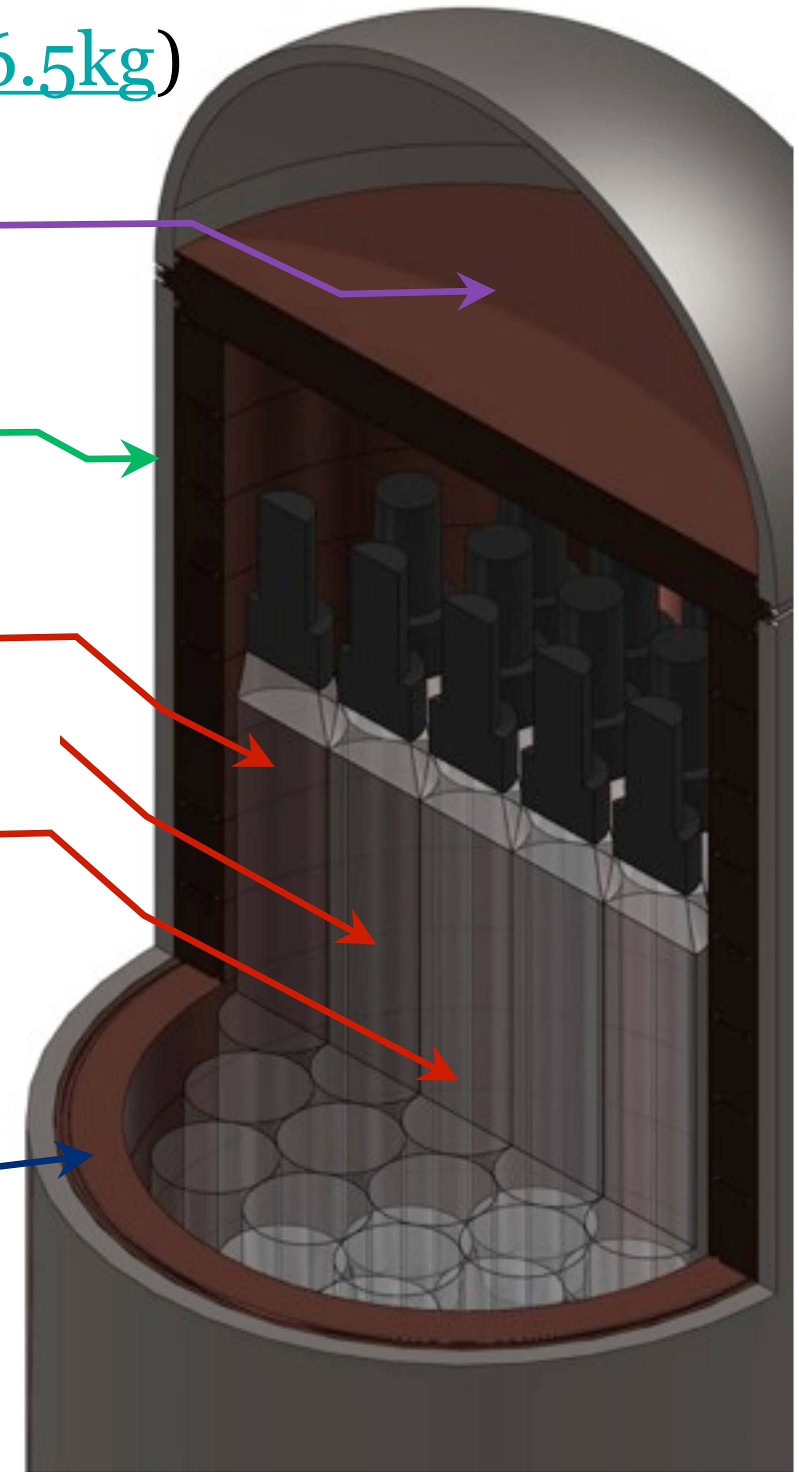
Pressure Vessel Cylinder & Hemisphere
Needs to be high strength to survive
7200 psi freeze pressure
Could be copper if 3500 psi maximum pressure

Thirteen Crystal Outer Zone

Six Crystal Middle Zone

One Crystal Inner Zone

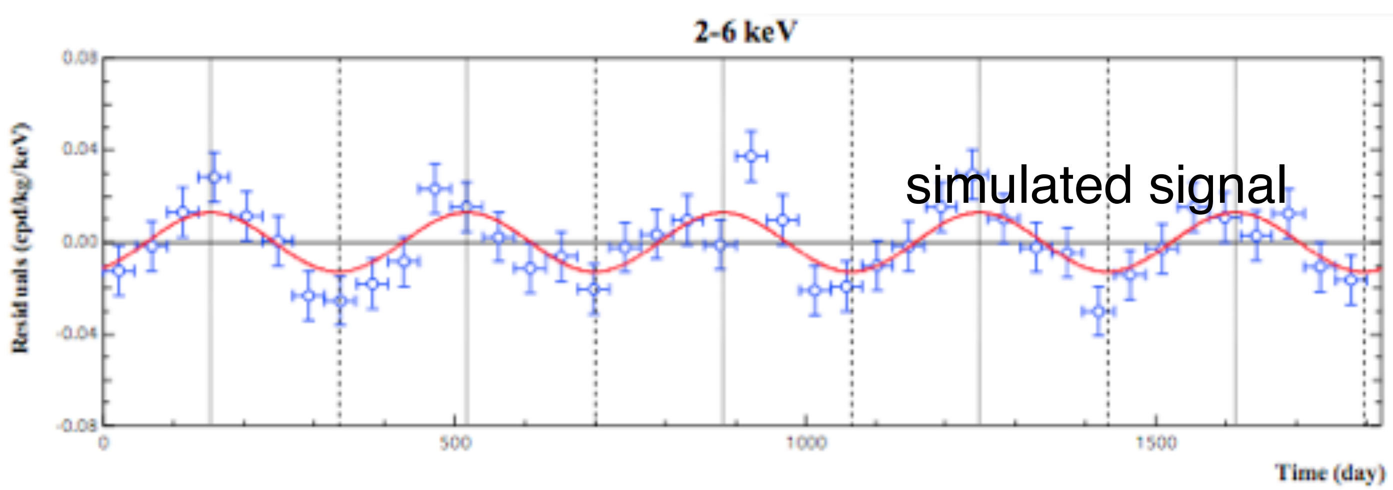
Stacked 75 mm thick shielding rings
Can be sealed together with O-rings to form leak tight cylinder
Can carry structural pressure load is freeze pressure is limited



x2

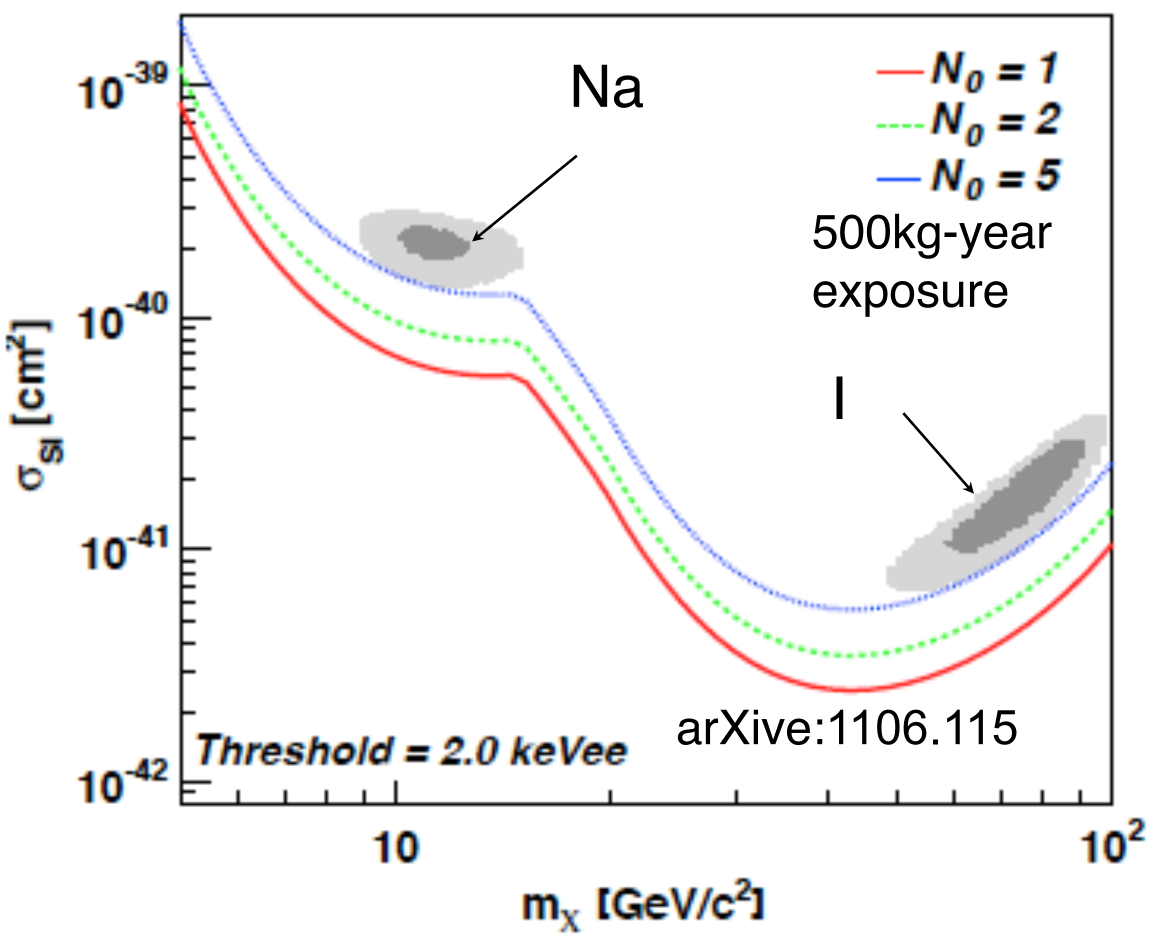
DM-ICE Sensitivities

Model-Independent: Assume DAMA-like signal, statistics



	Years	2 NAIAD 17.0 kg	NAIAD size 44.5 kg	DAMA size 250 kg
NAIAD 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
50% NAIAD 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

Spin-Independent



- 5-σ detection of DAMA-like signal with a 250-kg / 2-year running time (2 - 4 keV) and comparable backgrounds to DAMA

Conclusions

Conclusions

DM-Ice: A Dark Matter Experiment at the Pole

- We have an opportunity for a unique annual modulation experiment in Southern Hemisphere.
- 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 - backgrounds as expected (**fastest ever dark matter experiment??**)
- Full-scale (250kg) experiment currently under design
- An unambiguous discovery of DM requires signal in multiple experiments with different targets **and a galactic signature**