Walter C. Pettus
Yale University
(formerly UW–Madison)

SSGF Annual Program Review
29 June – 2 July 2015

Background Characterization and Detector Sensitivity in DM-Ice

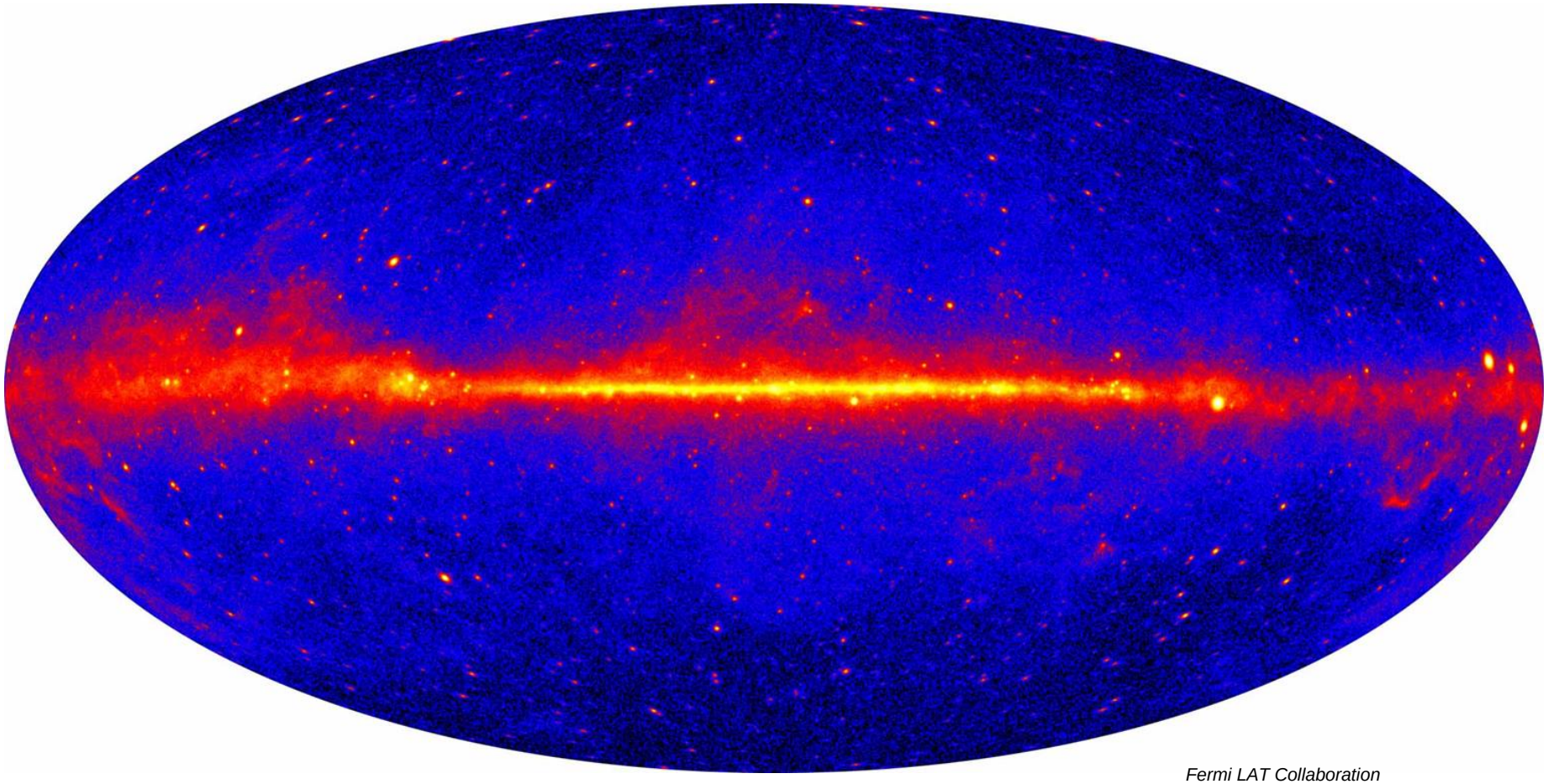
Understanding the Universe

Visible Sky

Axel Mellinger
http://apod.nasa.gov/apod/ap010202.html

Understanding the Universe

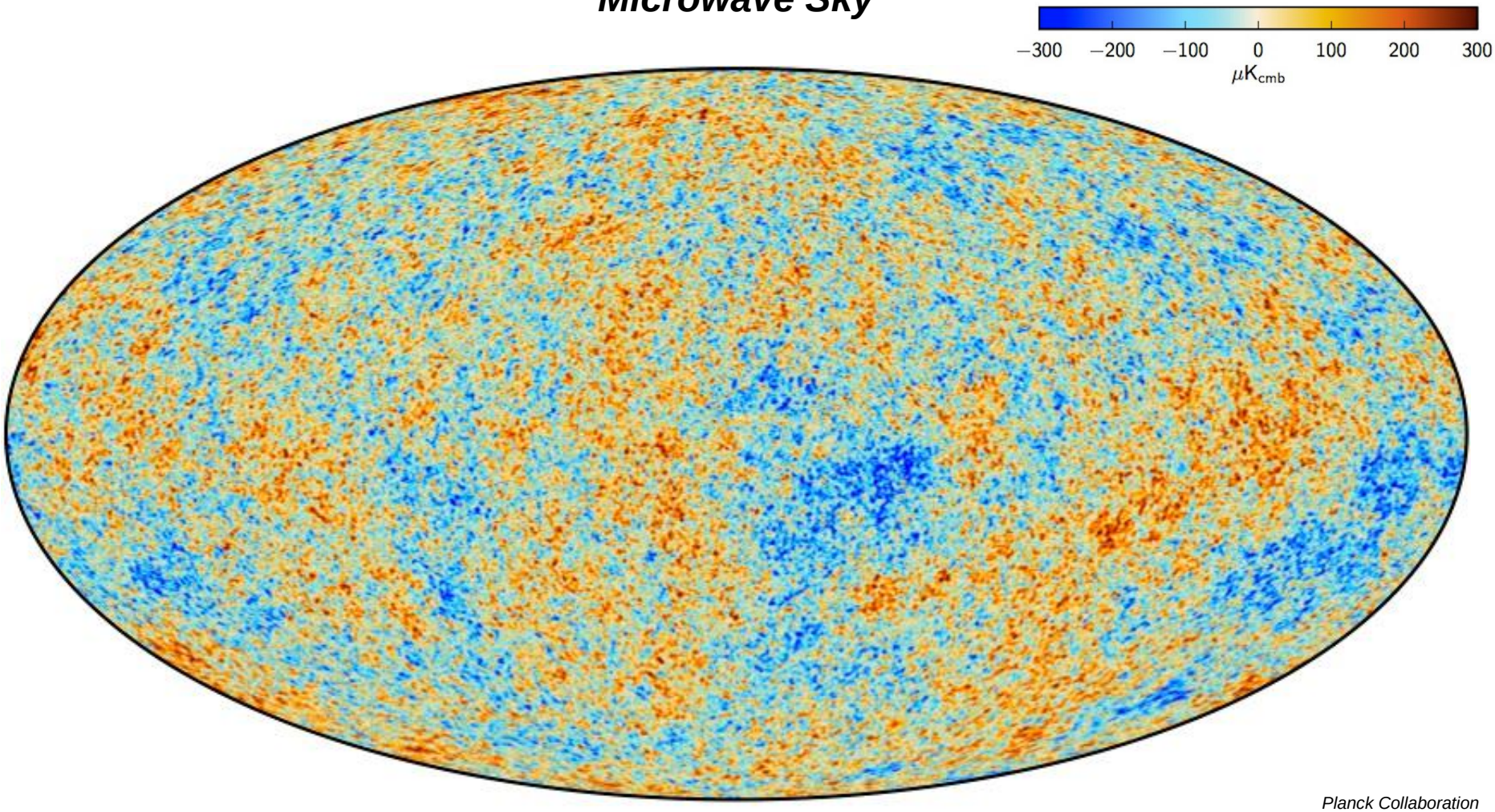
Gamma Ray Sky



Fermi LAT Collaboration
http://fermi.gsfc.nasa.gov/ssc/Fermi_5_year.jpg

Understanding the Universe

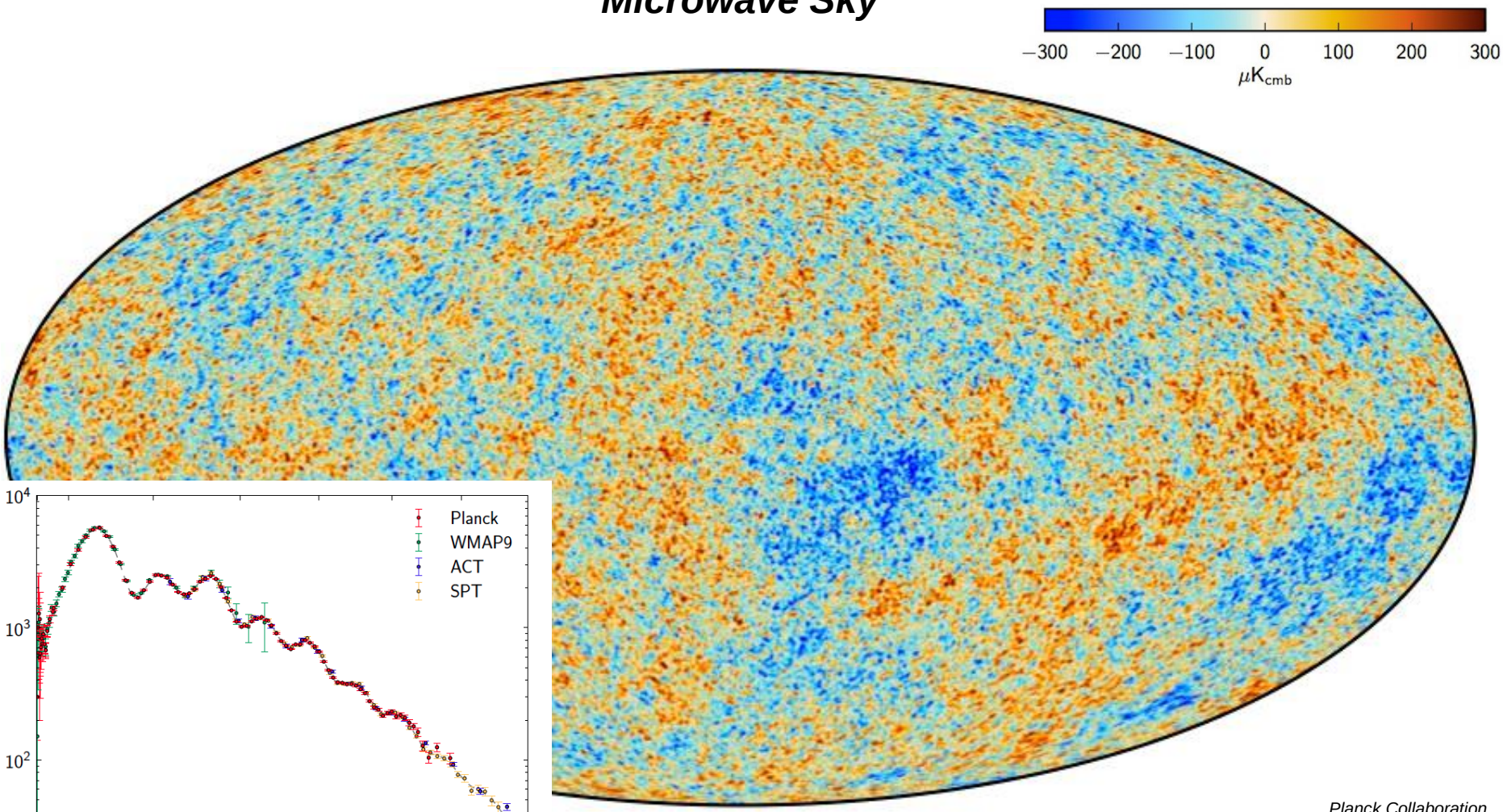
Microwave Sky

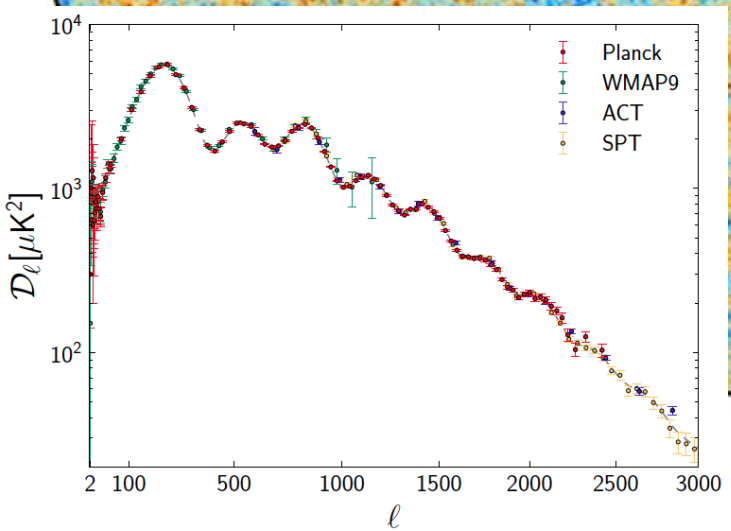


Planck Collaboration
arXiv:1502.01582

Understanding the Universe

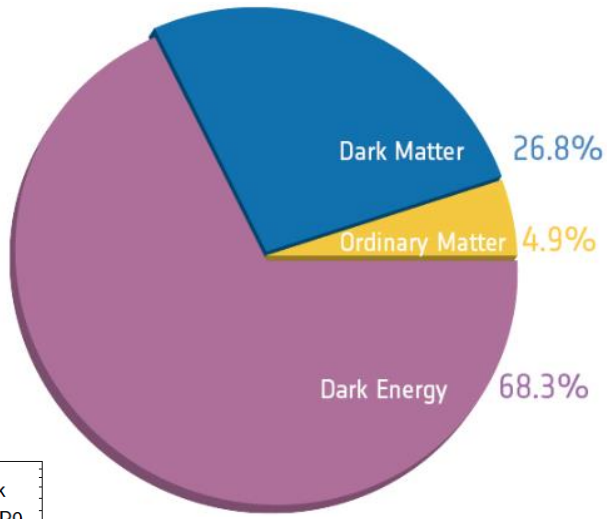
Microwave Sky

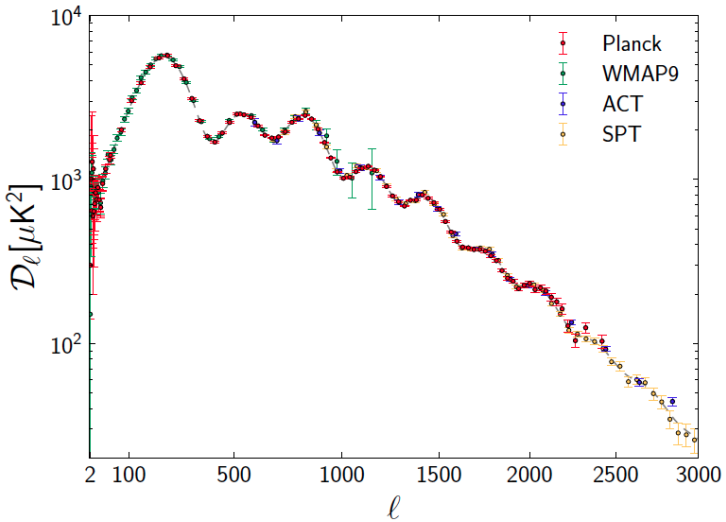


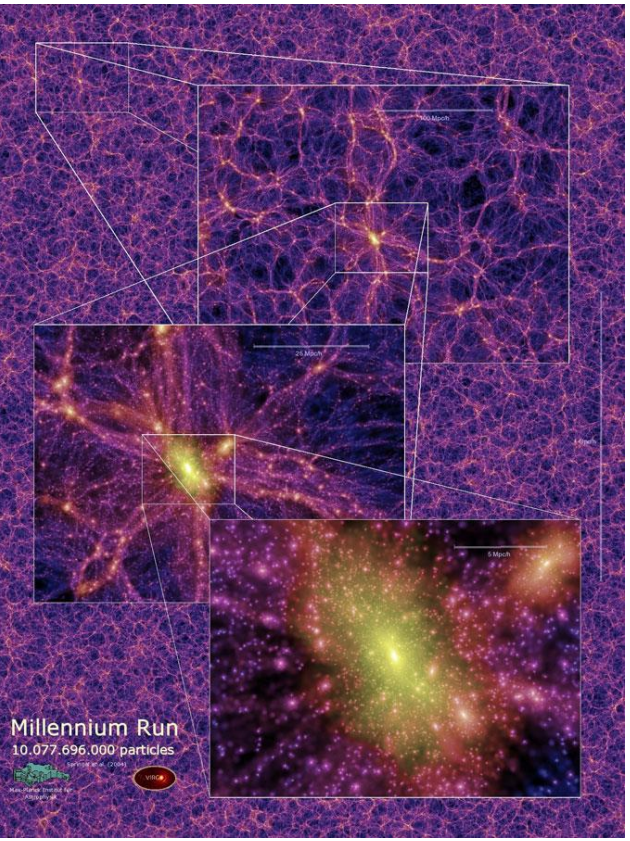


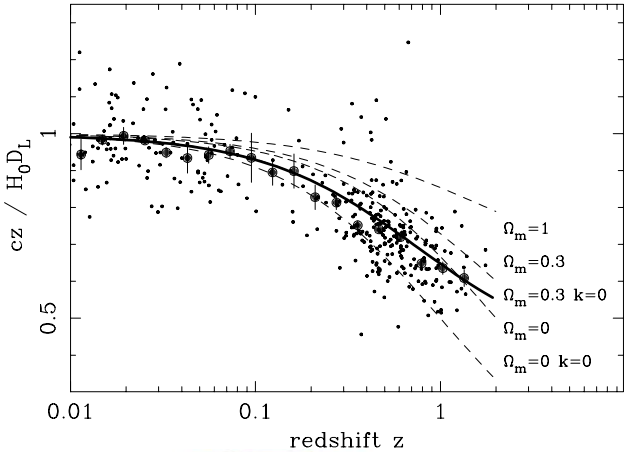
Planck Collaboration
arXiv:1502.01582

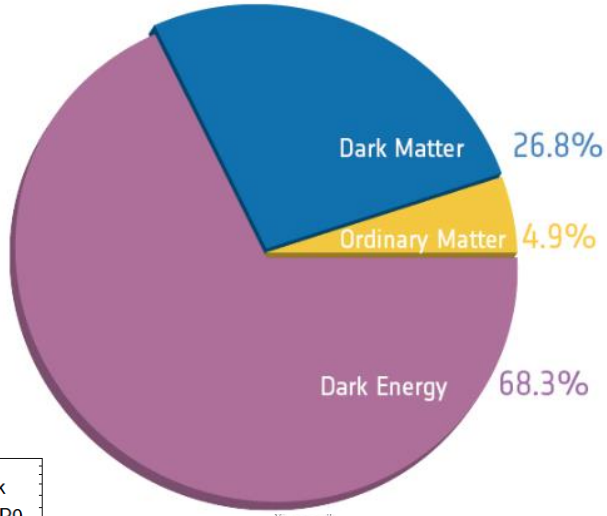
ΛCDM Universe

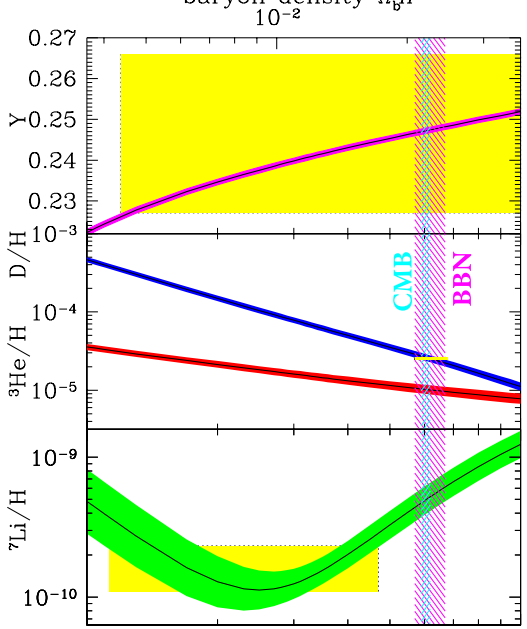


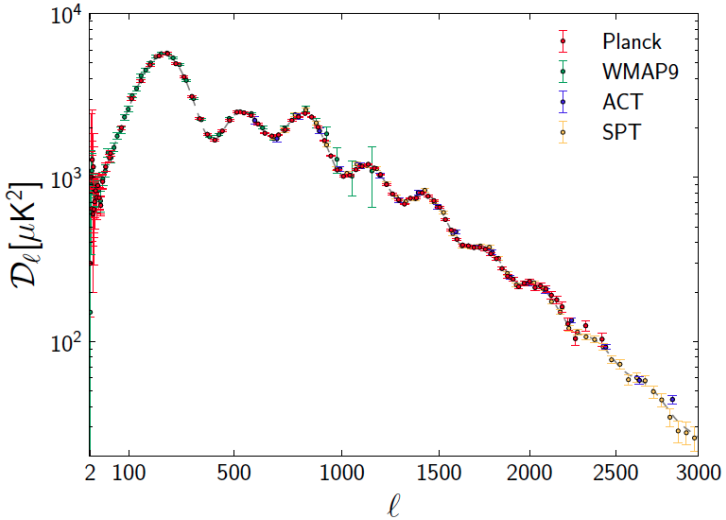


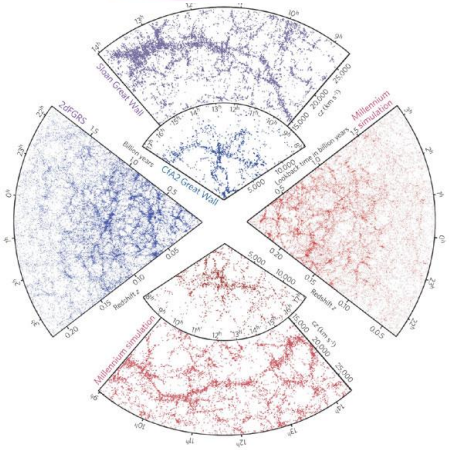

Millennium Run
10.077.696.000 particles

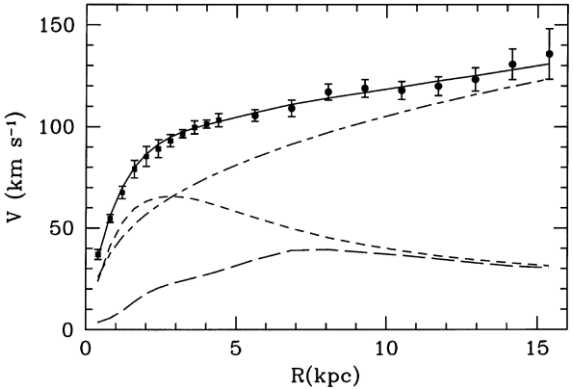

cz / H0DL
1
0.5
0.01
0.1
1
redshift z
Ωm=1
Ωm=0.3
Ωm=0.3 k=0
Ωm=0
Ωm=0 k=0


Dark Matter
26.8%
Ordinary Matter
4.9%
Dark Energy
68.3%


baryon density Ωbh²
10⁻²
Y
0.27
0.26
0.25
0.24
0.23
D/H
10⁻³
³He/H
10⁻⁴
10⁻⁵
⁷Li/H
10⁻⁹
10⁻¹⁰
CMB
BBN


Planck
WMAP9
ACT
SPT
$\mathcal{D}_\ell[\mu K^2]$
10⁴
10³
10²
2
100
500
1000
1500
2000
2500
3000
ℓ

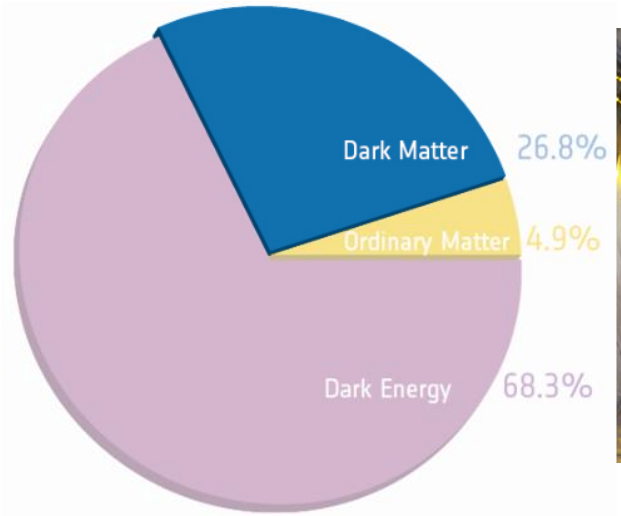



V (km s⁻¹)
150
100
50
0
0
5
10
15
R(kpc)

Detecting Dark Matter

Indirect Searches

- Identify annihilation/decay products of dark matter from extraterrestrial sources



Collider Searches

- Identify production signatures of dark matter in collision

Direct Searches

- Identify energy deposition from dark matter interaction in a terrestrial detector

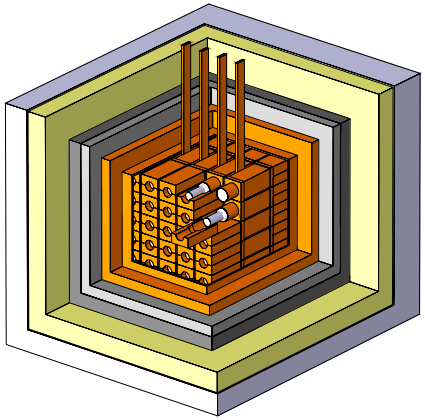
Experiment Design – DAMA

Monolithic detectors
(up to ton-scale)

Component radiopurity
(control of radioactive backgrounds)

Environmental stability and control
(temperature, radon, …)

Performed search for dark matter annual modulation with NaI(Tl) crystal array



Bernabei *et al.*, NIM A, (2008)

Experiment Design – DAMA

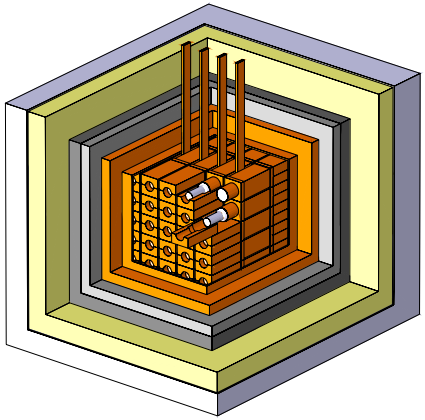
Monolithic detectors
(up to ton-scale)

Component radiopurity
(control of radioactive backgrounds)

Environmental stability and control
(temperature, radon, …)

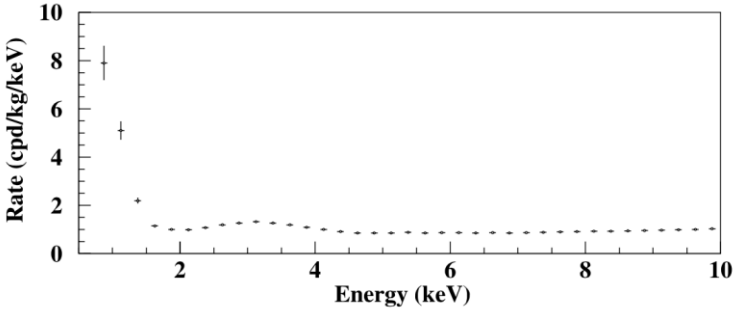
Low-energy (~1 keV) thresholds necessary for dark matter sensitivity
(characterization and removal of noise)

Performed search for dark matter annual modulation with NaI(Tl) crystal array



Bernabei *et al.*, NIM A, (2008)

Demonstrated excellent background reduction:

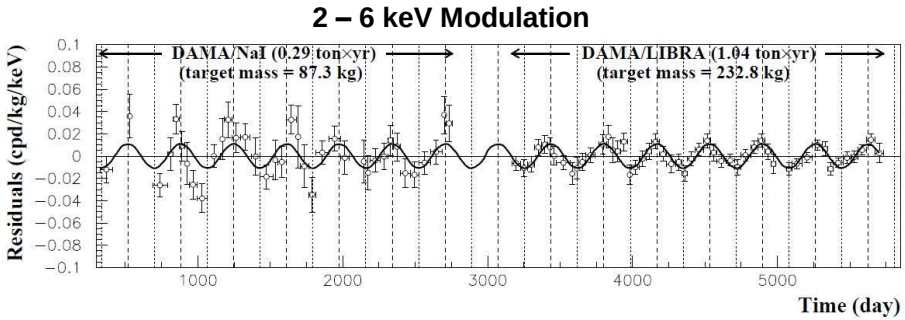


Bernabei *et al*, Eur Phys J C (2008)

DAMA/LIBRA – Detection?

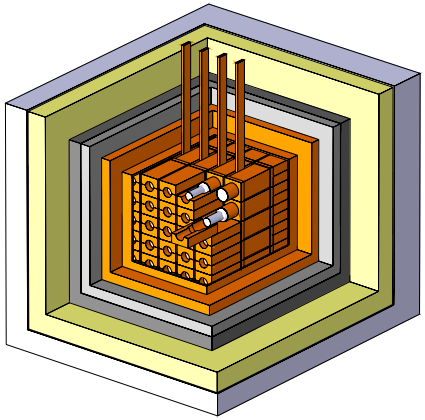
A Solitary (and Persistent) Signal

- Observed modulating signal with ***9.3-sigma*** significance
- Matches dark matter expectation

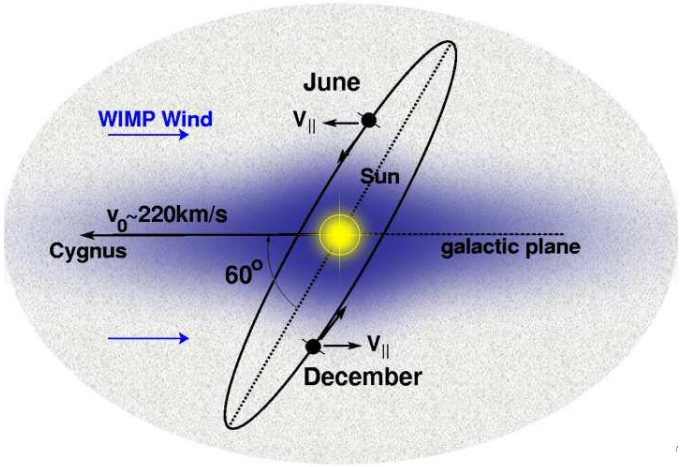


Bernabei *et al*, arXiv:1412.6524

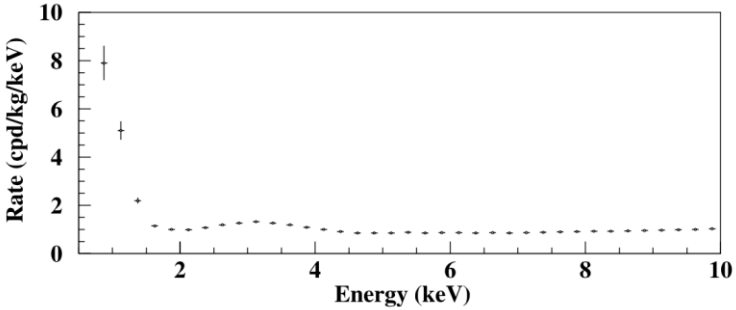
Performed search for dark matter annual modulation with NaI(Tl) crystal array



Bernabei *et al*., NIM A, (2008)



Demonstrated excellent background reduction:

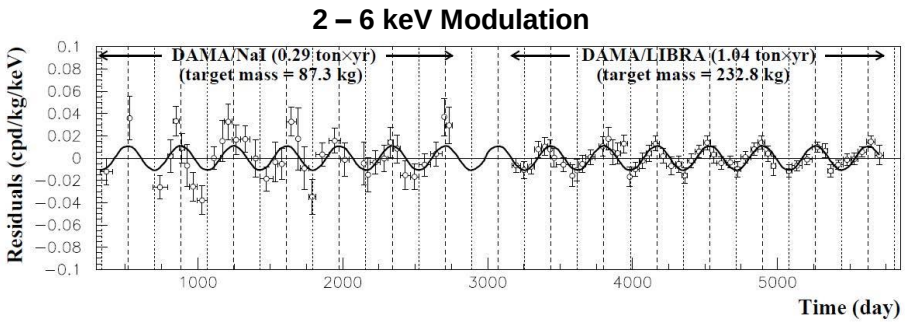


Bernabei *et al*, Eur Phys J C (2008)

Tension of Experimental Results

A Solitary (and Persistent) Signal

- Observed modulating signal with ***9.3-sigma*** significance
- Matches dark matter expectation

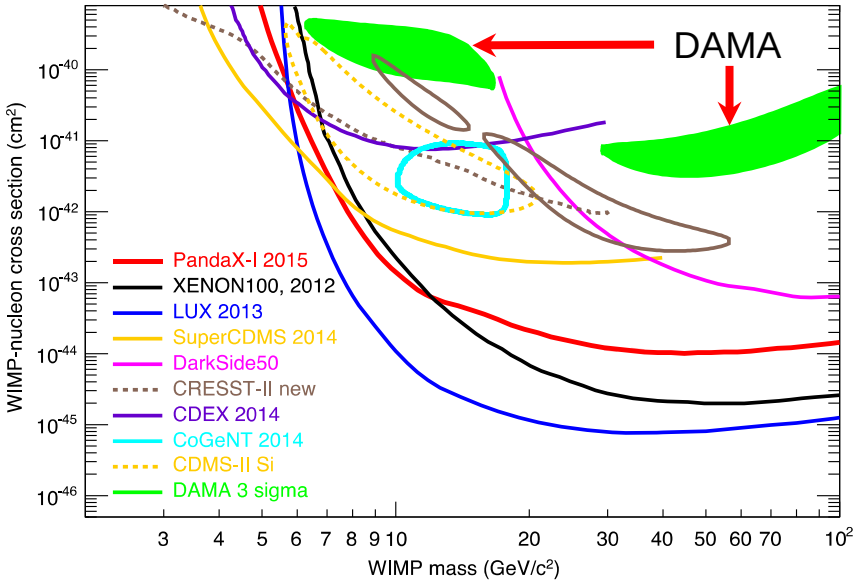


Bernabei *et al*, arXiv:1412.6524

Resolution hidden in
Astrophysics?
Particle Physics?
Instrumental Effects?
Uncharacterized Background?

Conflict with Null Results

- DAMA remains the only experiment to claim dark matter detection
- Strongly excluded by numerous other experiments

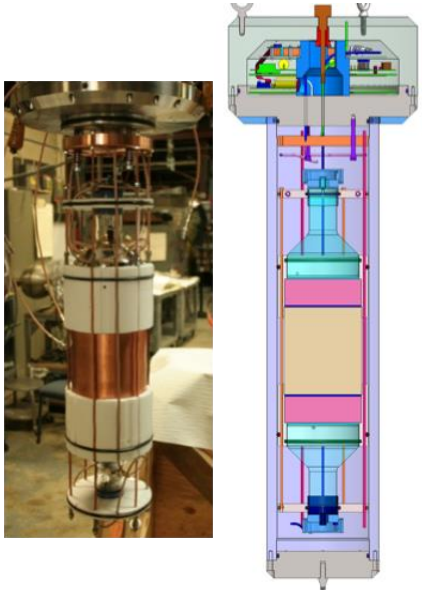


PandaX Collaboration, arXiv:1505.00771

DM-Ice Experiments

DM-Ice17

(*January 2011 – present*)

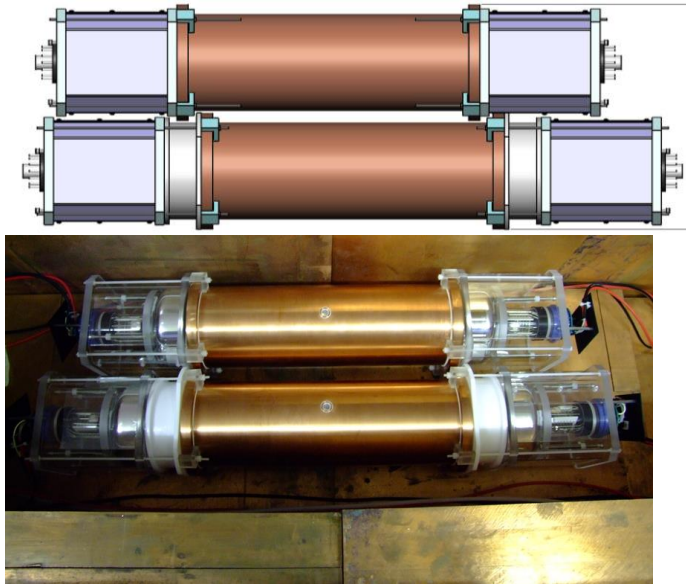


First dark matter experiment in South Pole ice

- Demonstrated viability and advantage of environment

DM-Ice37

(*April 2014 – present*)

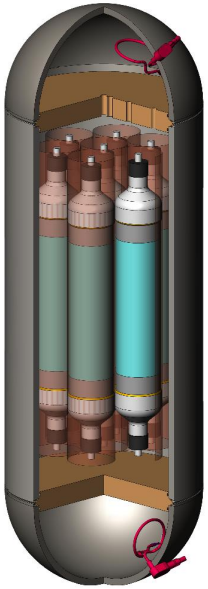


R&D testbed for NaI detectors

- Crystal background
- Light yield
- PMT/lightguide configurations

DM-Ice250

(*future*)

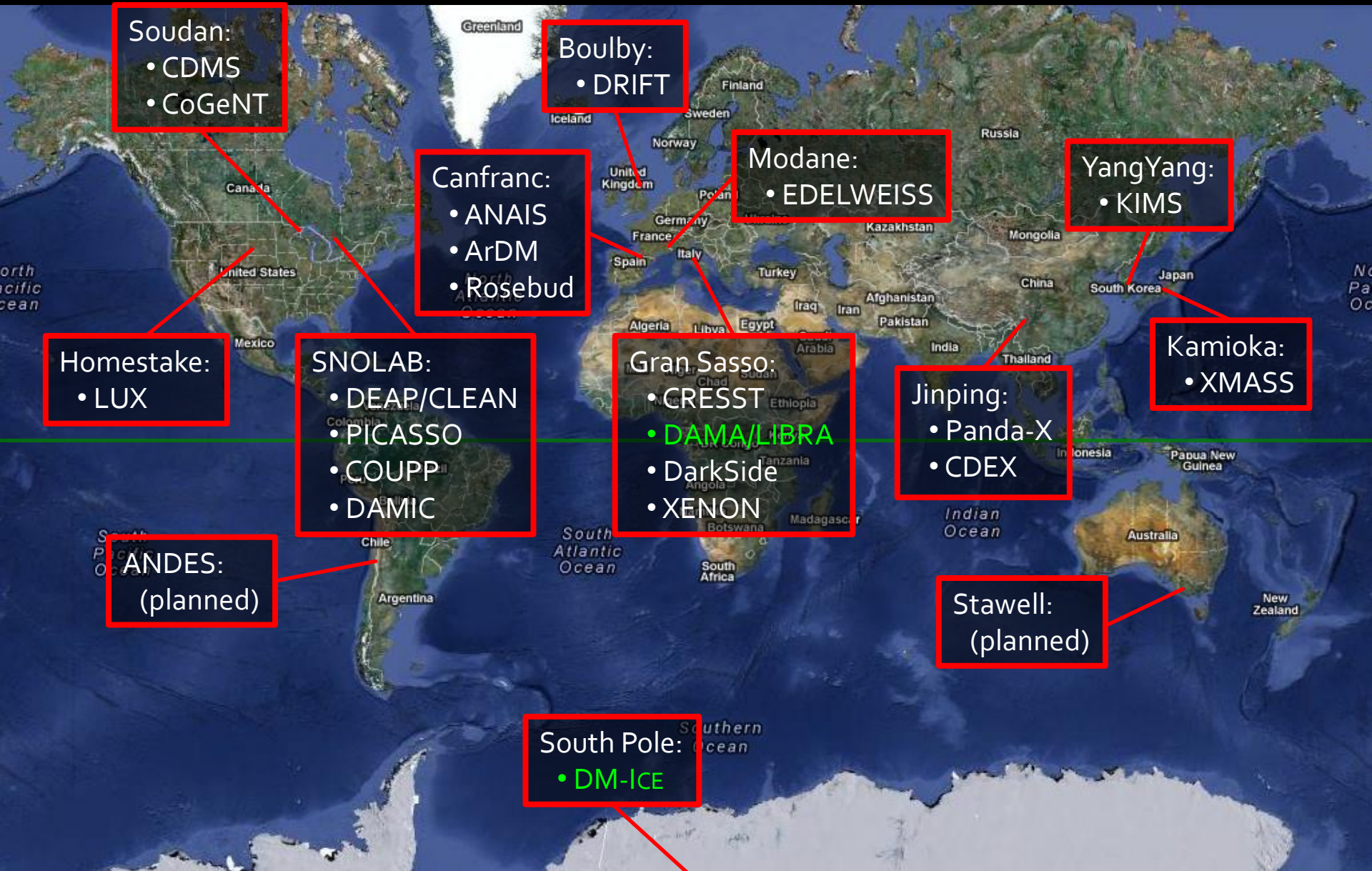


Science result

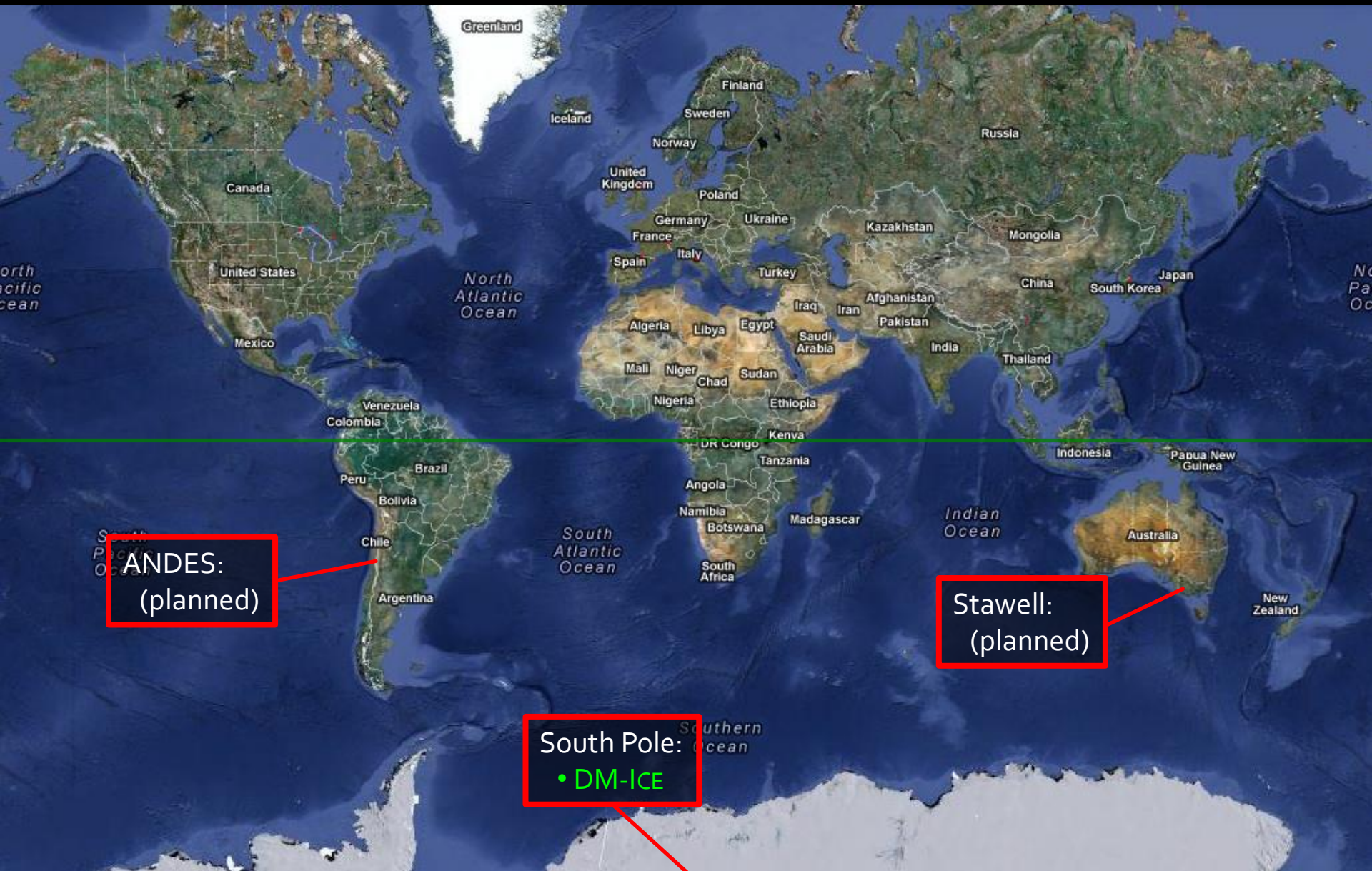
- Definitive test of DAMA dark matter claim

See also: Cherwinka *et al*., Astropart. Phys **35** (2012)

A World of Dark Matter Searches



A World of Dark Matter Searches



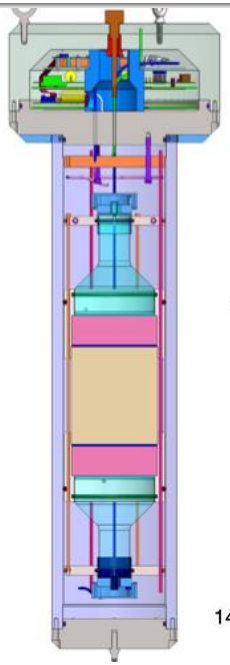
DM-ICE17 Experiment

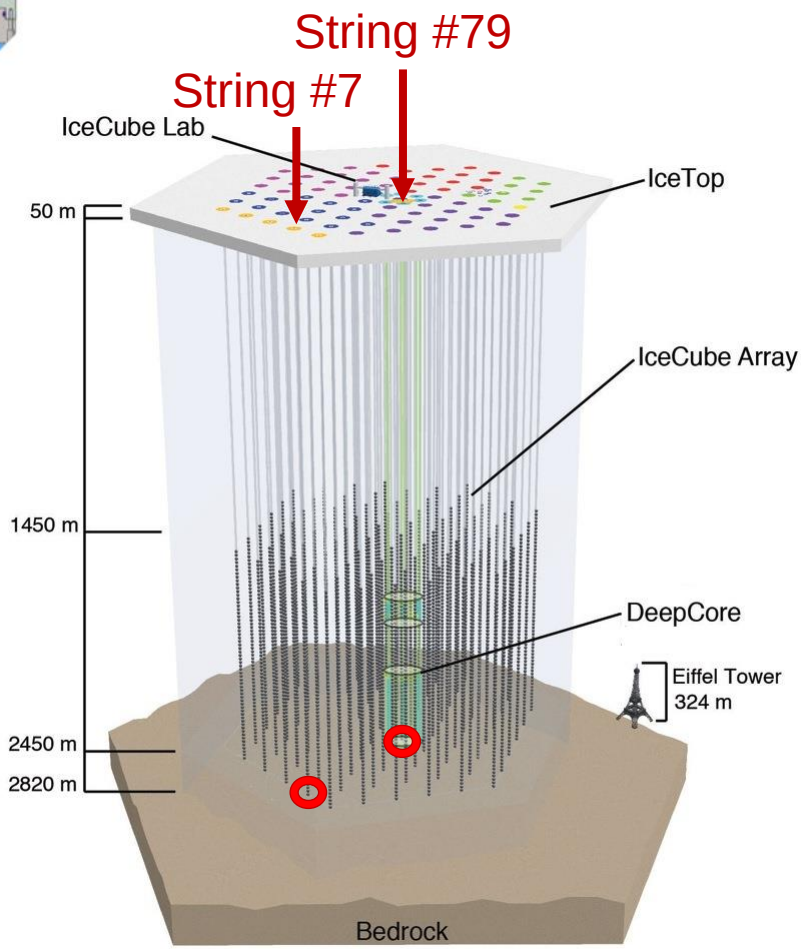
(2x) 8.5-kg NaI(Tl) modules

- Installed Dec 2010
- Data run from June 2011 to January 2015

Goals:

- Demonstrate the feasibility of deploying and operating NaI(Tl) detectors in the Antarctic Ice for a dark matter search
- Study environmental stability
- *In situ* measurement of the radiopurity of the Antarctic ice / hole ice at 2450 m depth
- Study the capability of IceCube to veto muons

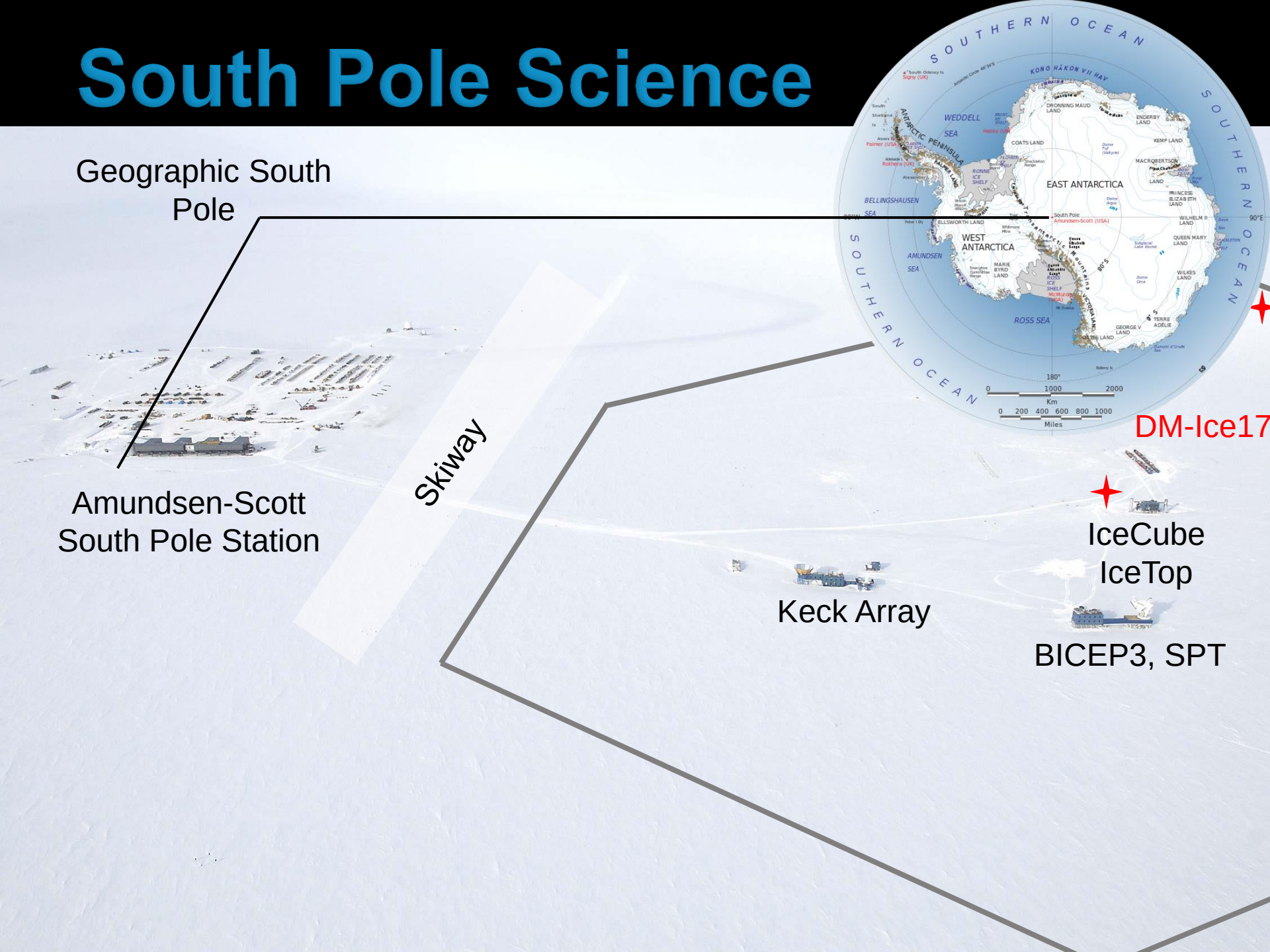




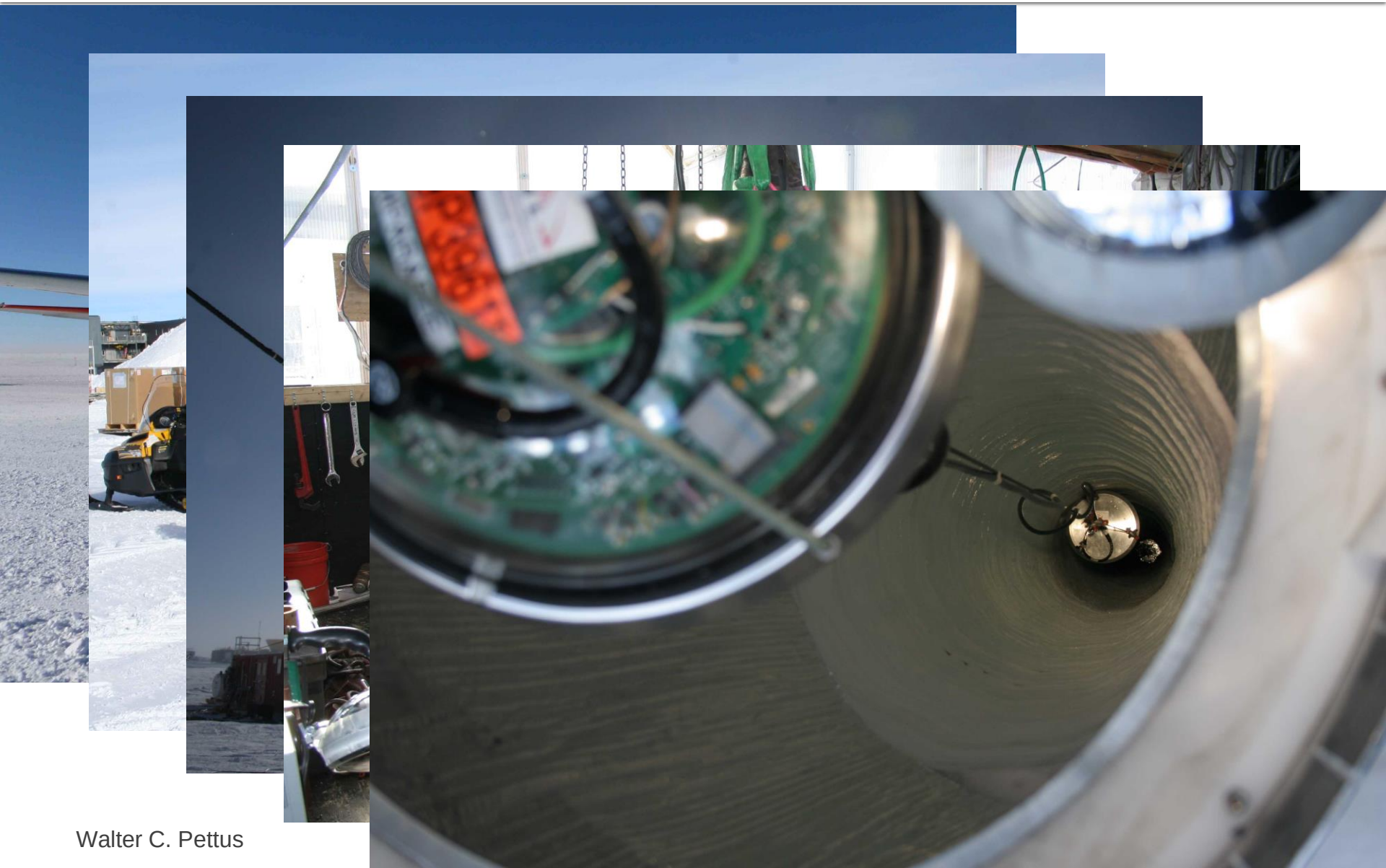
First results published:

Cherwinka *et al*., Phys. Rev. D **90** (2014)

South Pole Science



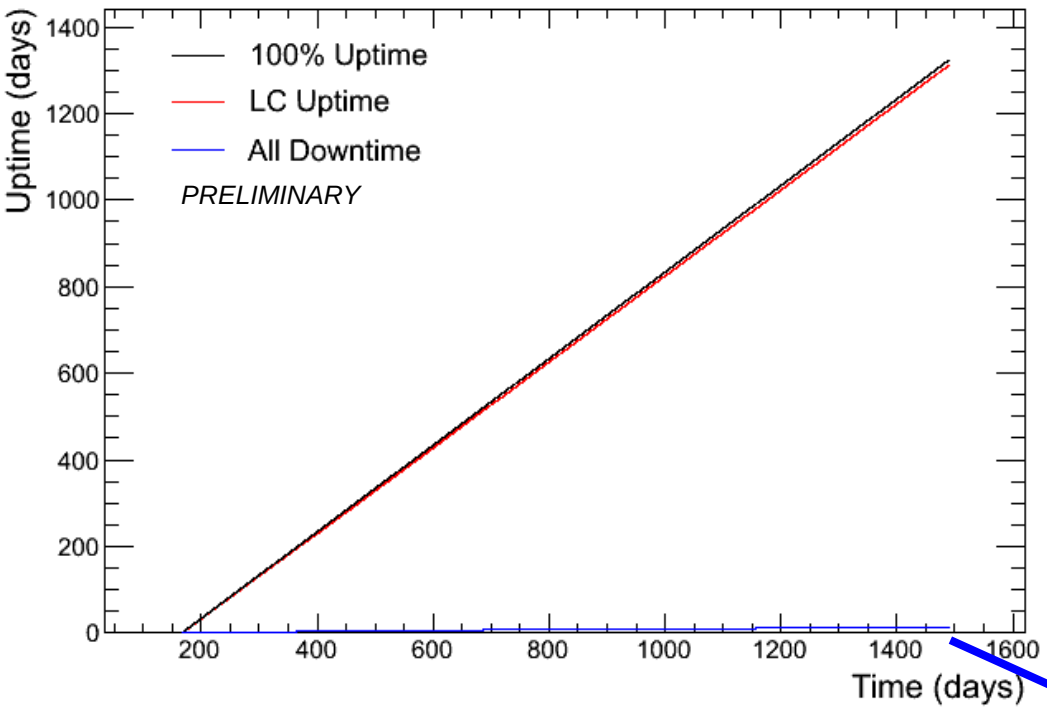
South Pole Logistics



Walter C. Pettus

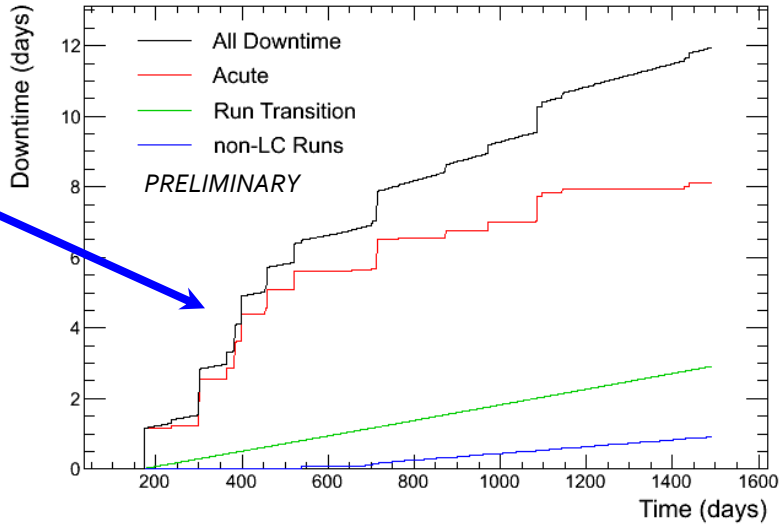
DM-Ice17 Uptime

> 99% uptime



Sources of downtime understood (DAQ, characterization data, satellite issues)

- Uptime has improved over physics data run

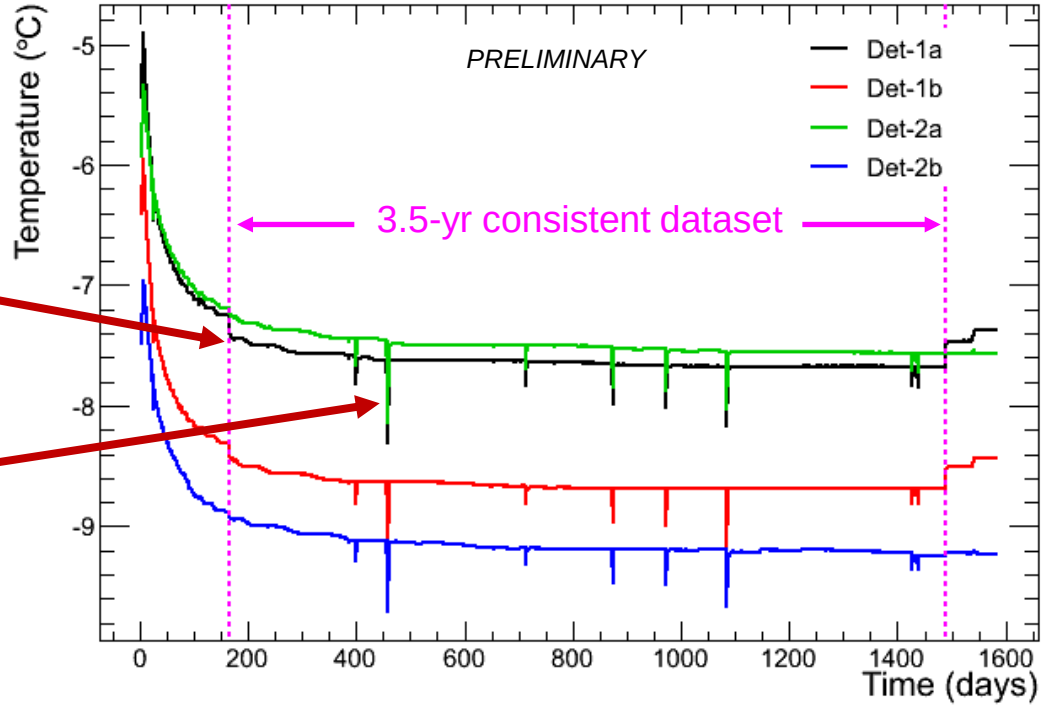


Temperature Stability

- Ice environment provides stable temperature
  - 0.3°C cooling over 3.5 years measured at mainboard
  - < 0.025°C daily RMS

Changing PMT HV setting affects MB temperature

Power outages affect MB temp, not crystal temp



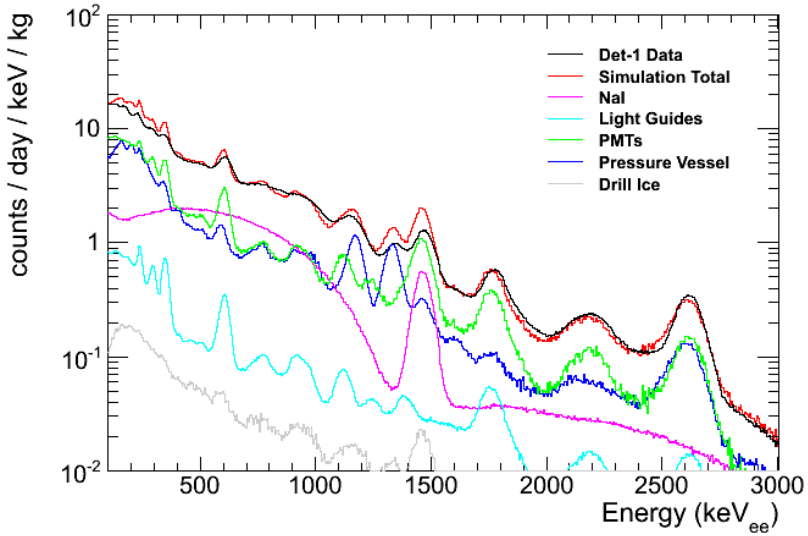
DM-Ice17 Background

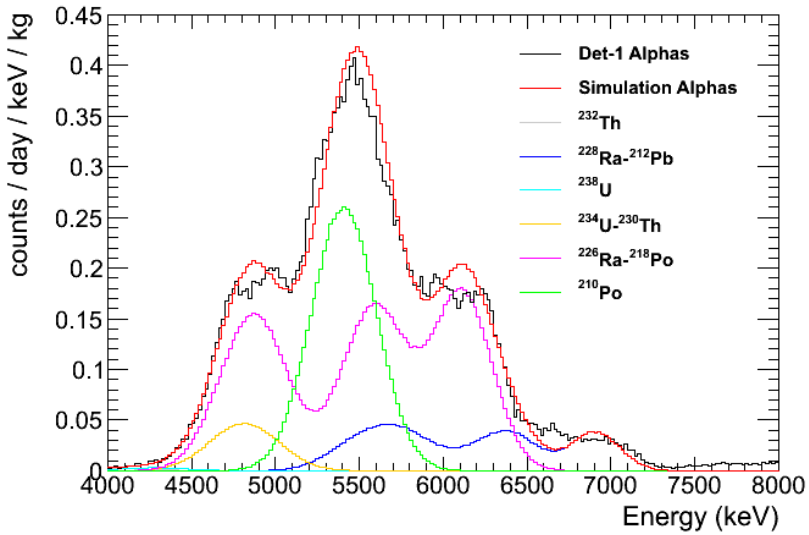
Betas & Gammas:

- Internal contamination lines allow calibration
- Well matched by *a priori* background model
  - Only crystal background unconstrained

Alphas

- Crystal contaminants only
- Constrains ^{232}Th-, ^{235}U-, ^{238}U- and chain levels

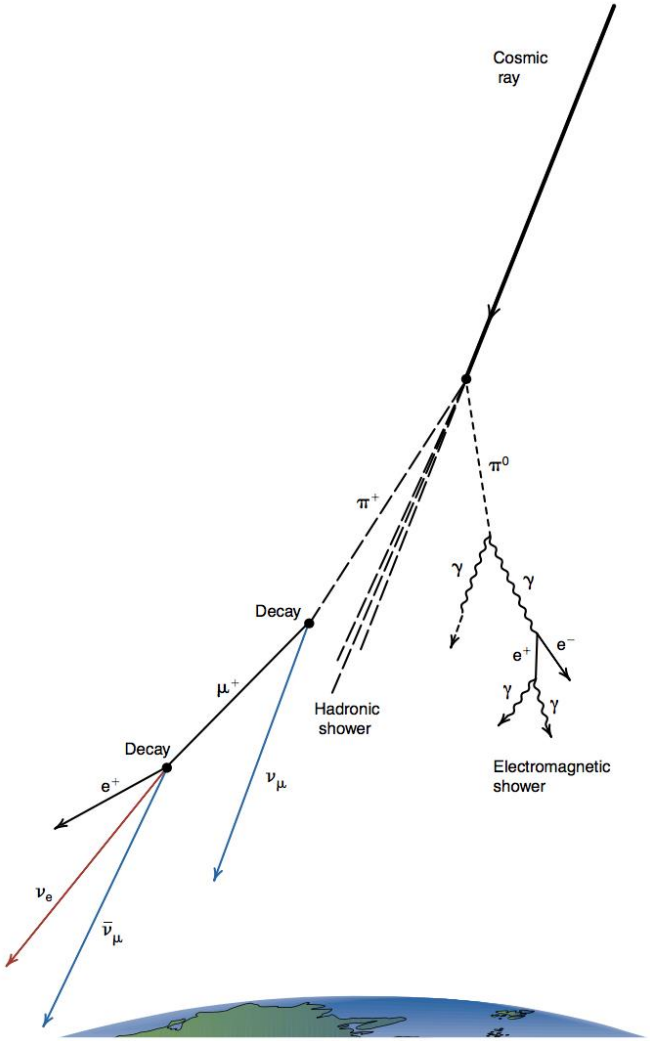




Detector backgrounds dominate at all energies;
Negligible contributions from environmental background

Cherwinka *et al*., Phys. Rev. D **90** (2014)

Cosmic Ray Air Showers

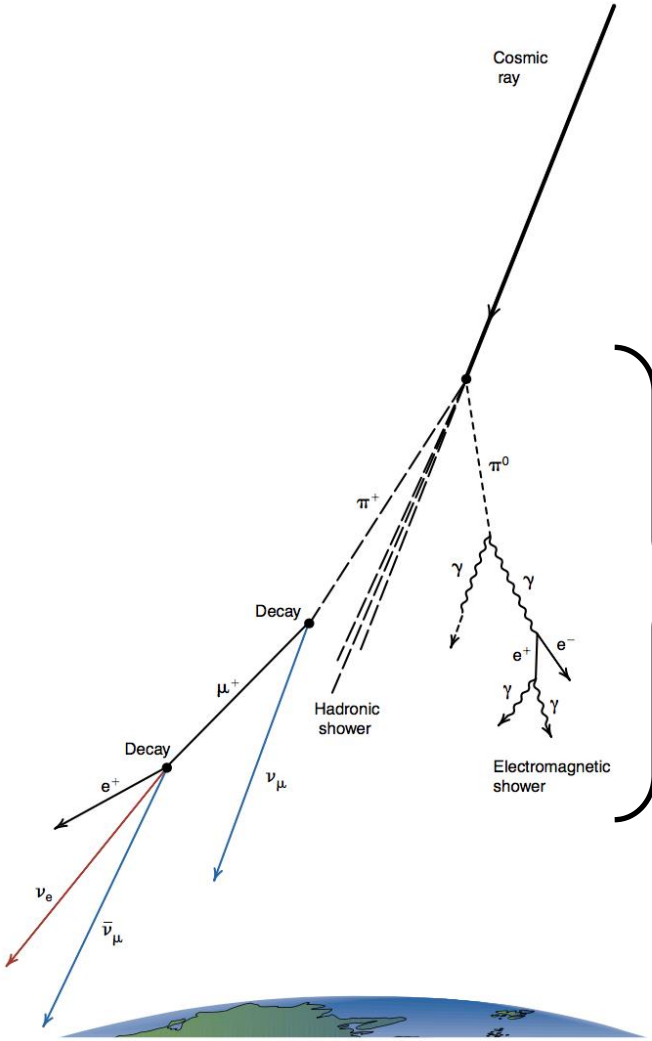


Louis *et al.*, Los Alamos Science (1997)

High energy particles, ‘cosmic rays’ penetrating through Earth’s atmosphere produce cascades of secondary particles following interaction

- cosmic ray intensity varies with position on Earth
- shower intensity varies with altitude
- secondary particles are a source of both prompt and delayed background

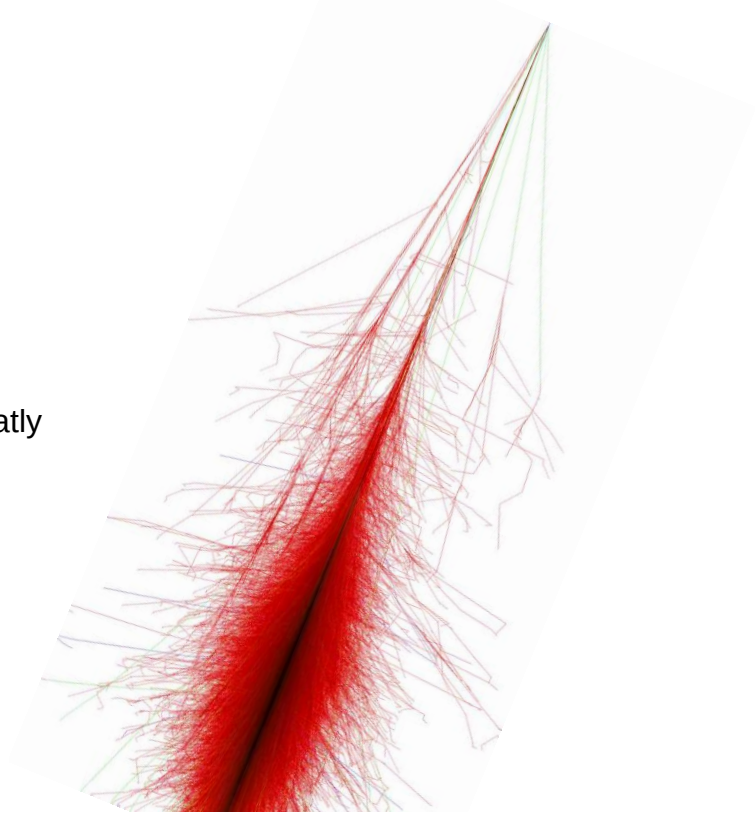
Cosmic Ray Air Showers



* shower greatly simplified

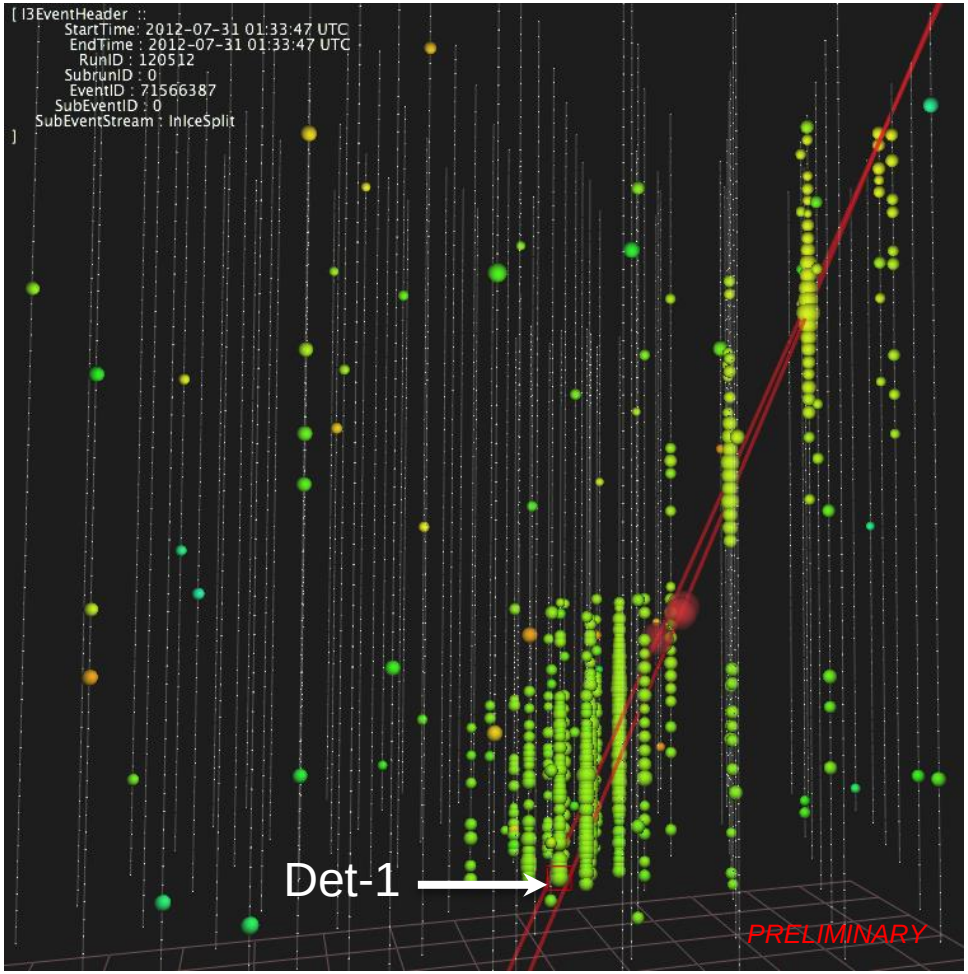
10 TeV Proton Shower
(millions of secondaries)

CORSIKA Simulation, https://www.ikp.kit.edu/corsika/



Louis *et al.*, Los Alamos Science (1997)

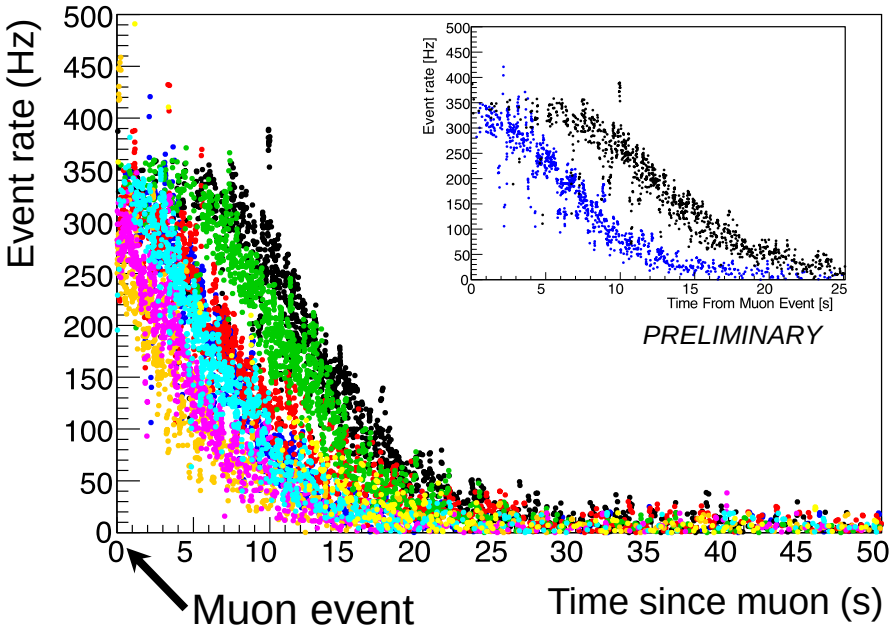
Prompt Cosmic Background



In preparation, under collaboration review

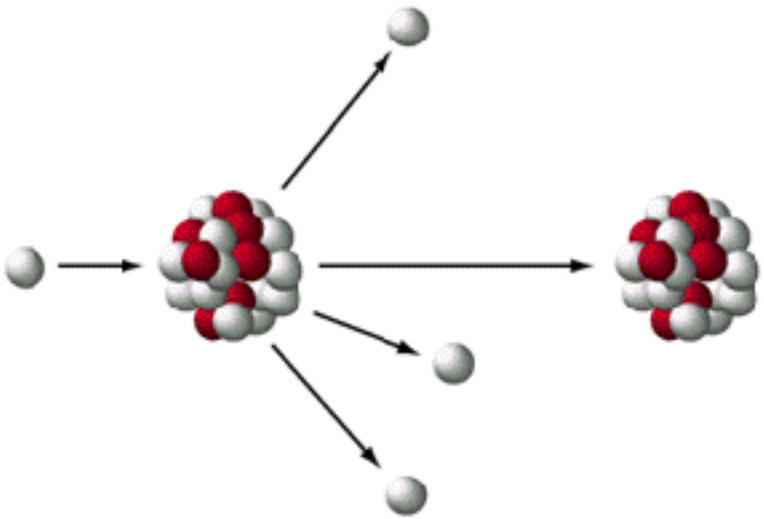
Cosmic ray muons passing directly through DM-Ice detectors

- Highest energy signals measured
  - Unambiguous identification of muons with IceCube detector demonstrated
- Induces seconds-long afterpulsing



Delayed Cosmic Background

^{127}I (n,3n) ^{125}I

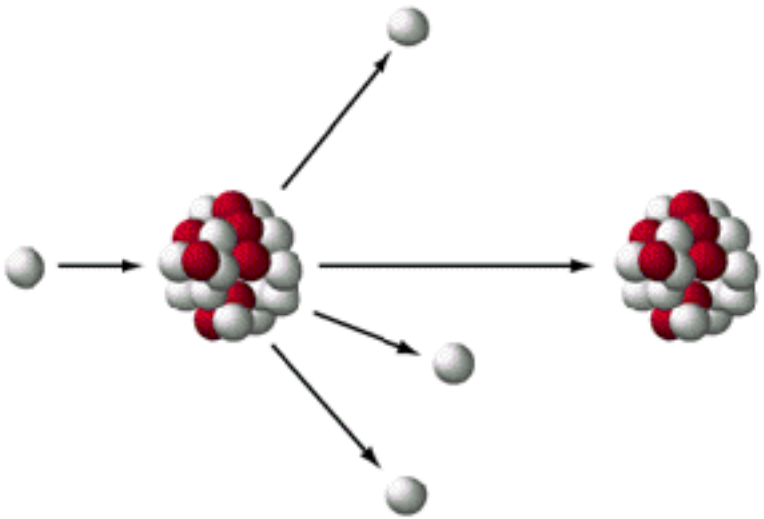


Cosmic ray hadrons interact with nuclei in detector components

- Transmutation of nucleus to radioisotope via spallation or capture processes
- Decay over days or years governed by radioactive half-life

Delayed Cosmic Background

^{127}I (n,3n) ^{125}I

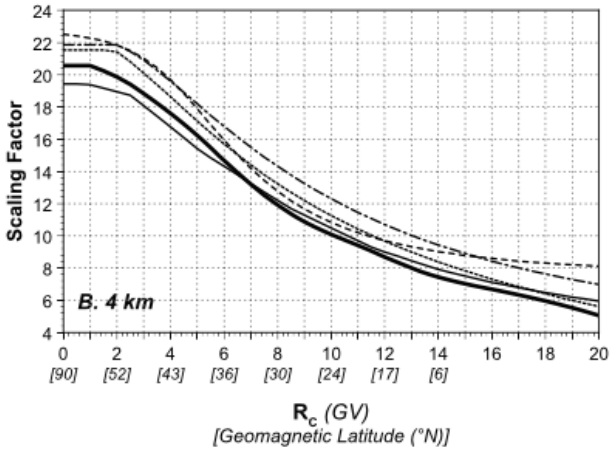


Cosmic ray hadrons interact with nuclei in detector components

- Transmutation of nucleus to radioisotope via spallation or capture processes
- Decay over days or years governed by radioactive half-life

- Neutrons dominate cosmogenic activation rates
- Activation cross section peaked for 10 – 100 MeV neutrons
- Activation rates scale with cosmic ray rate
  - Dependence on altitude, position, …

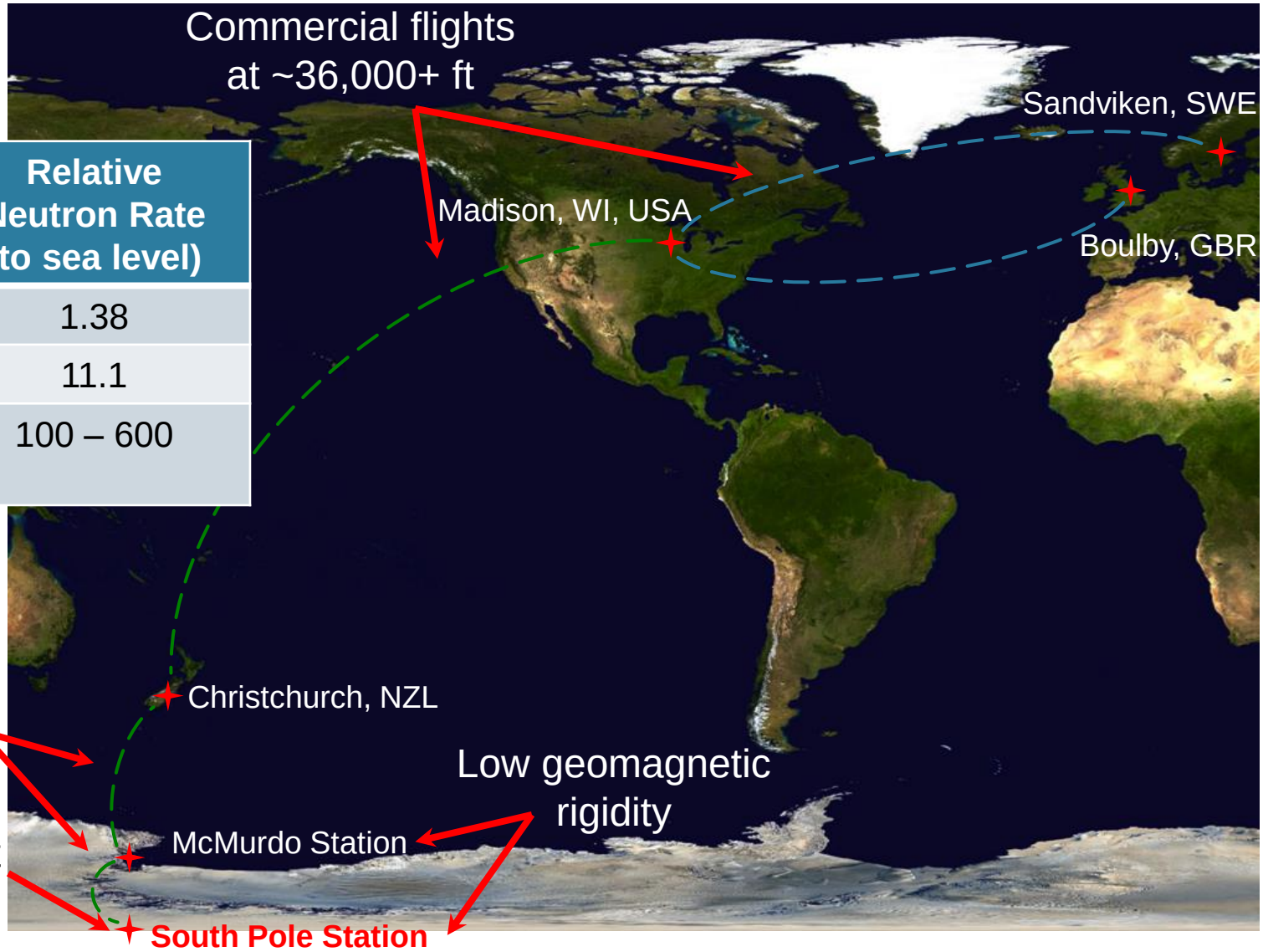
Position Scaling



Lifton *et al.*, Earth and Plan. Sci Lett. (2014)

Cosmogenic Activation Hazards

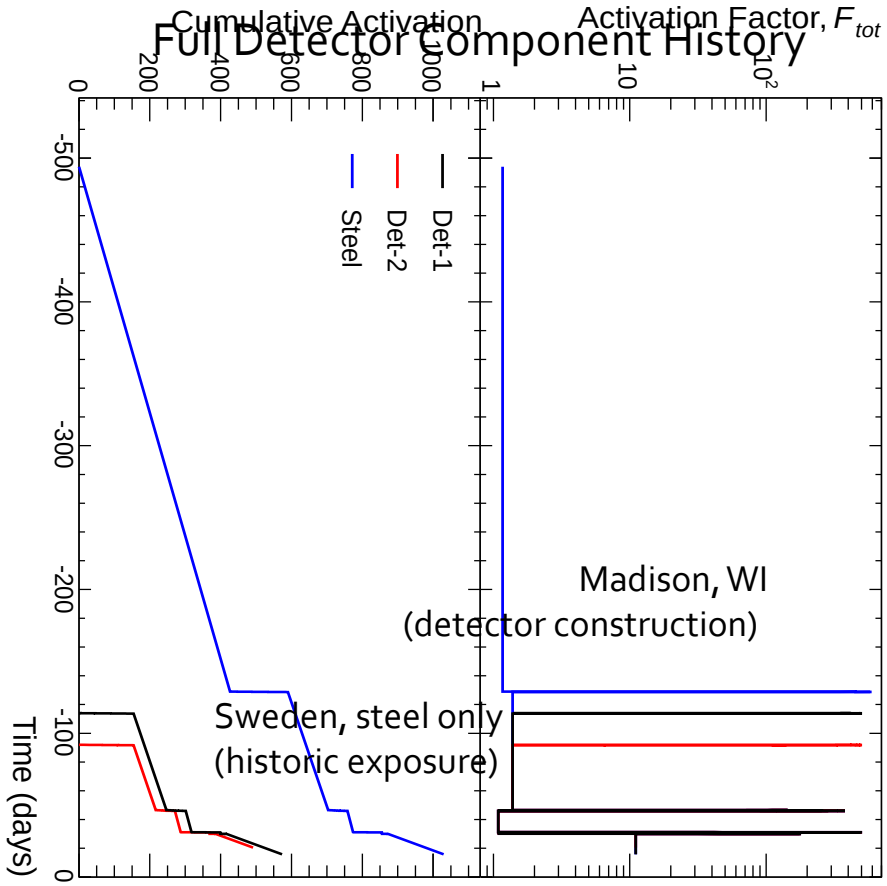
Location	Relative Neutron Rate (to sea level)
Madison, WI	1.38
South Pole	11.1
Commercial Flight	100 – 600



Polar program flights

Storage at 9,301 ft

Cosmic Ray Exposure Timeline



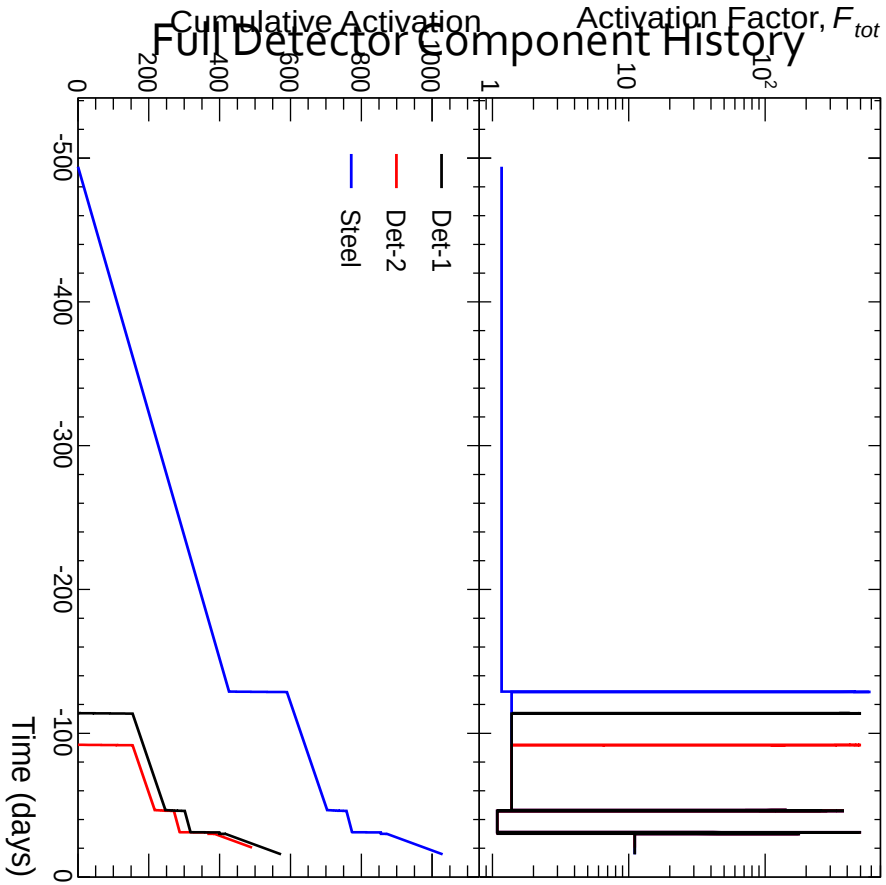
F_{tot} – Relative cosmic ray neutron flux (scaling from sea level)

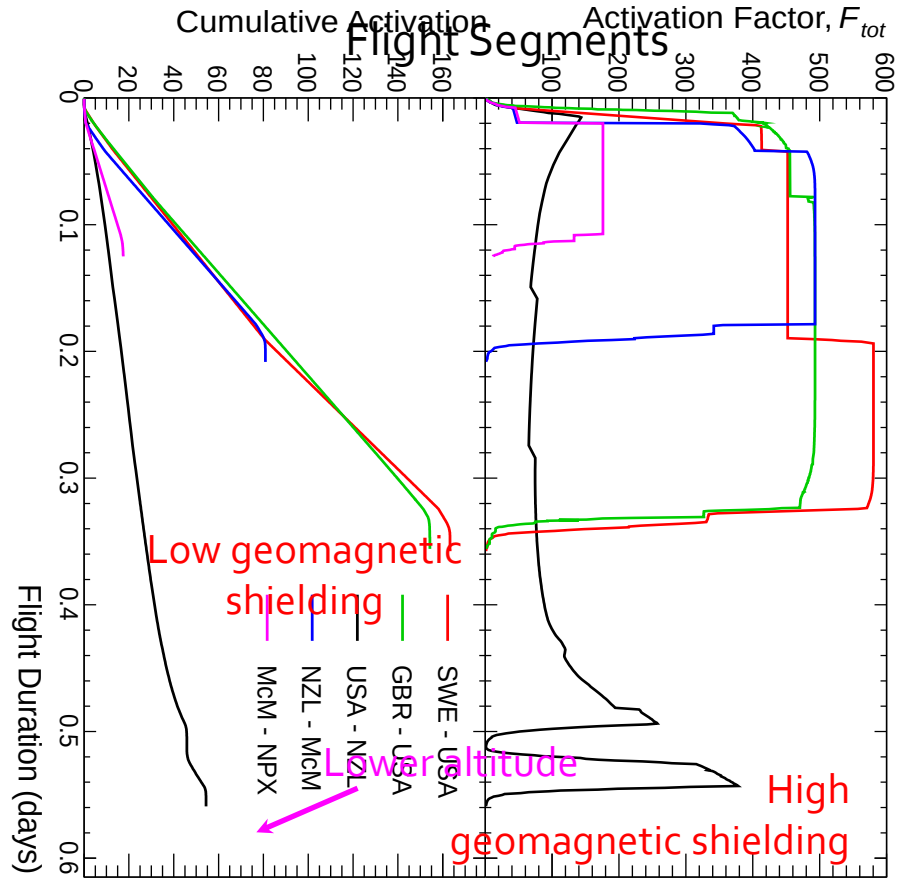
- Long periods of low-level exposure during storage and construction
- Punctuated exposure from flight shipment

"Cumulative Activation" – Time-integrated neutron flux scaling

- Different detector components have different exposure histories
- Two DM-Ice17 detectors have different deployment times

Cosmic Ray Exposure Timeline

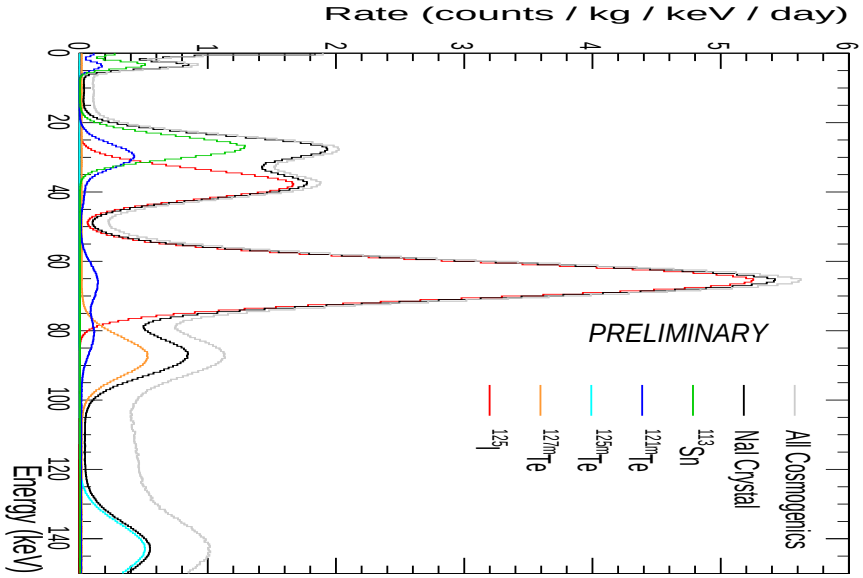


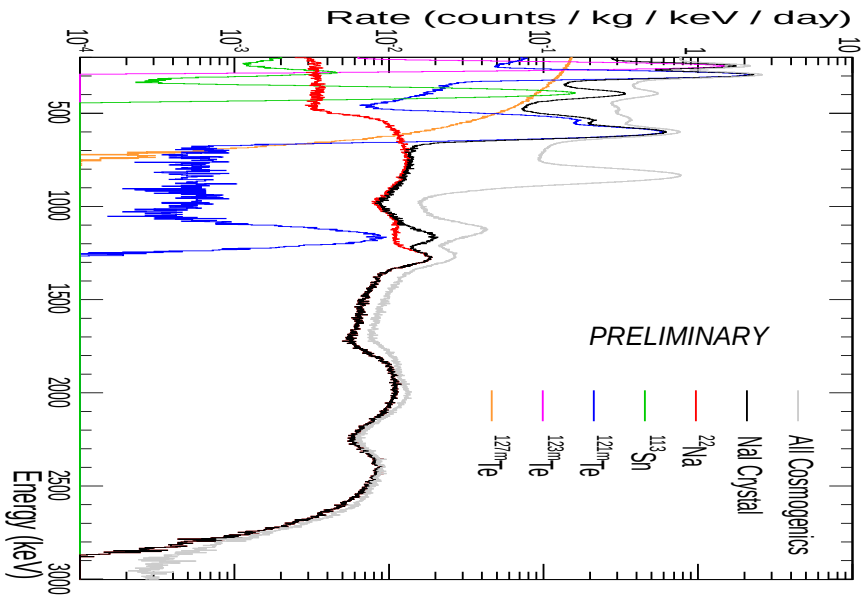


But decay not included: $I/N = R \times \left(1 - e^{-t/\tau}\right)$

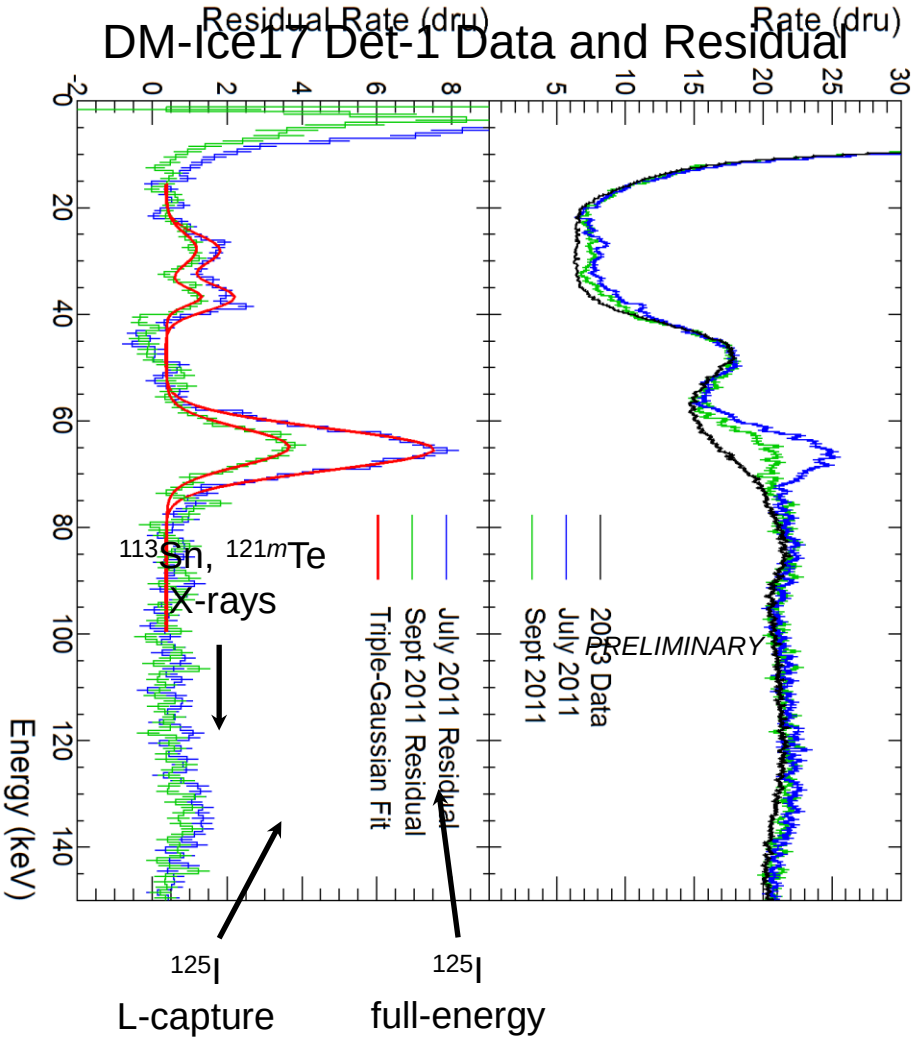
Cosmogenic Prediction

- Most cosmogenic features arise from NaI activation
  - Rates simulated for start of dataset (6 months of decay)
  - Five peaks (four isotopes) with > 1 dru rate
    - All of which have been identified in data



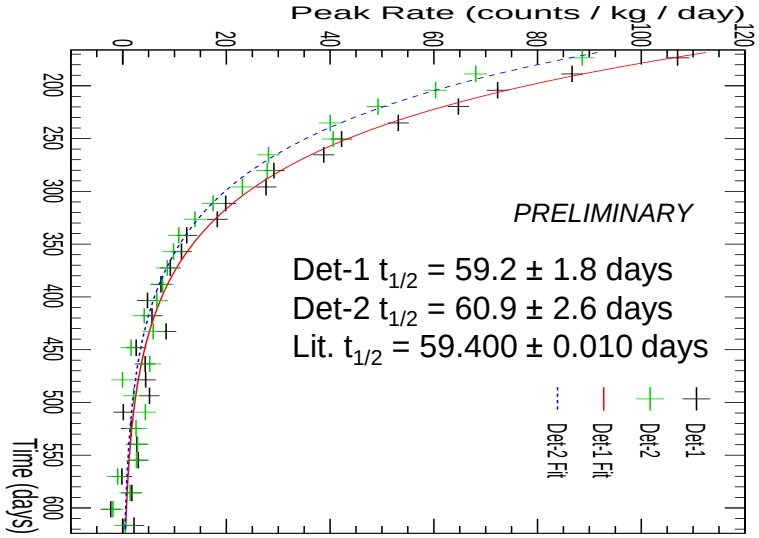


Cosmogenic Decay Peaks



Confirm identity of cosmogenic peaks:

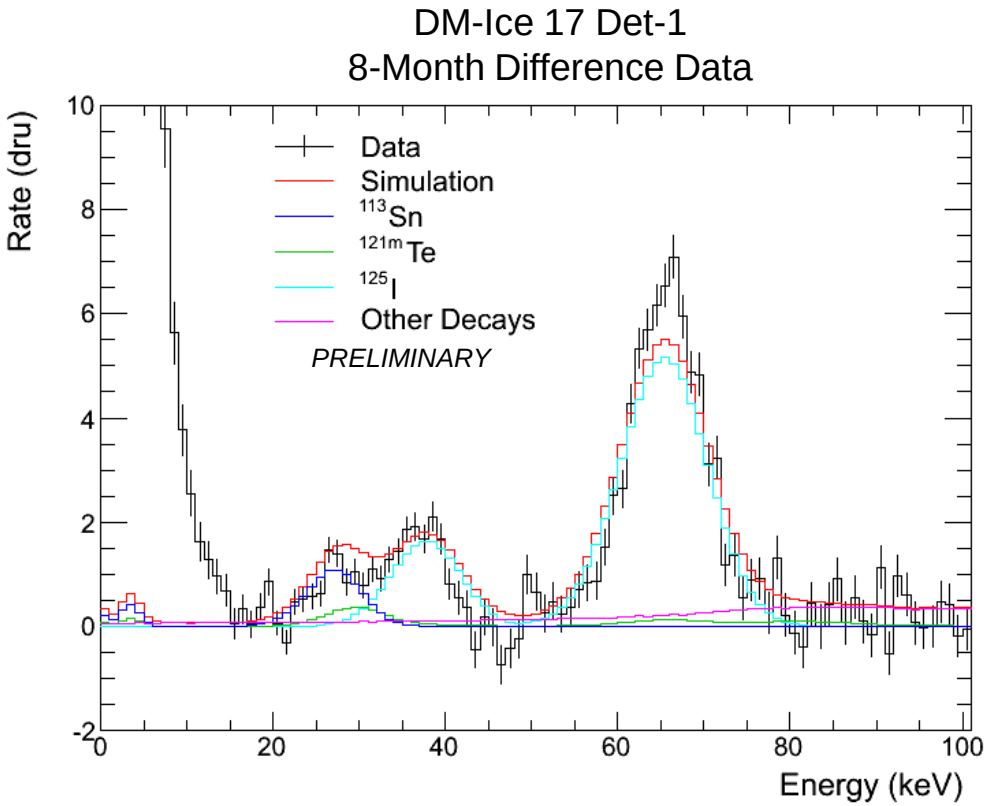
- Match simulated spectral features
  - Expect 65.3 keV full-energy and 37.6 keV L-shell capture peaks
- Measuring decay time
  - Expect 59.4 day half-life



Low-Energy Spectrum

Simulation can reproduce changing spectral features

- Requires 6 cosmogenic isotopes
- Improved total background model via broken chains (^{232}Th in pressure vessel)
- Independent measurement of ^{60}Co ($t_{1/2}$ = 5.3 yr)
- Improvement in energy resolution modeling
  - Mismatch of 65 keV peak width
- Region of interest rates constrained indirectly
  - All 3 keV cosmogenic components have higher-energy peaks



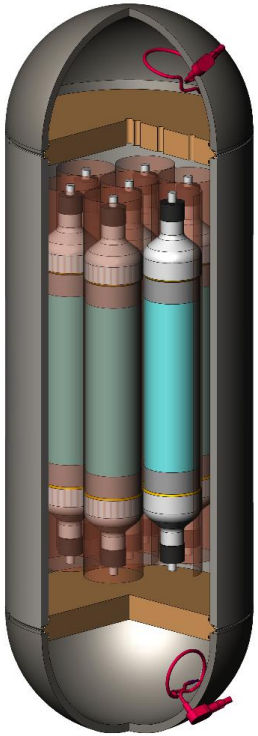
DM-Ice17 Cosmogenics

- Good agreement with other NaI activation measurements
  - Validation of scaling model
- Identification of one new activated radioisotope (^{113}Sn)
  - Implications for low-energy region of interest

	Isotope	$t_{1/2}$ (days)	DM-Ice17 (#/kg/day)	Literature (#/kg/day)
requires multi-crystal →	^{22}Na	951	-	45.1 ± 1.9
	^{113}Sn	115.1	16	-
short half-life →	^{121}Te	19.2	-	9.9 ± 3.7
	^{121m}Te	164.2	25	23.5 ± 0.8
discrepant →	^{123m}Te	119.2	21	31.6 ± 1.1
	^{125m}Te	57.4	27	28.2 ± 1.3
	^{127m}Te	106.1	< 9	10.2 ± 0.4
	^{125}I	59.4	230	220 ± 10
short half-life →	^{126}I	12.9	-	283 ± 36

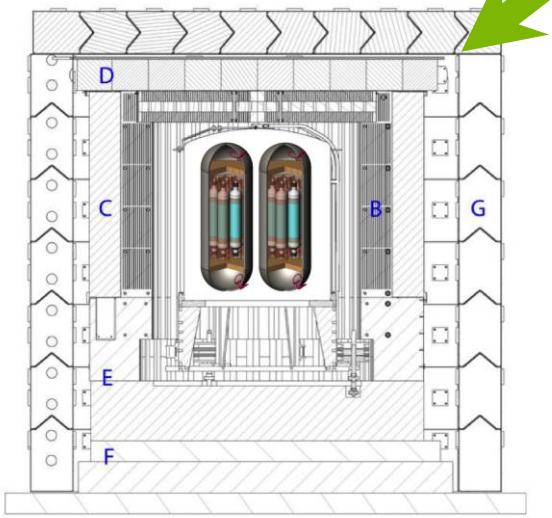
DM-Ice250 Experimental Program

Modular detector supporting deployment in both hemispheres

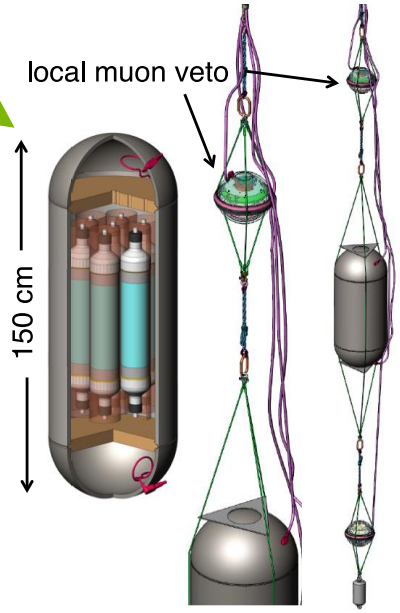


- 125 kg NaI(Tl) / module
- 7-crystal array
  - Coincidence between PMTs
  - Anti-coincidence between crystals

DM-Ice250N



DM-Ice250S

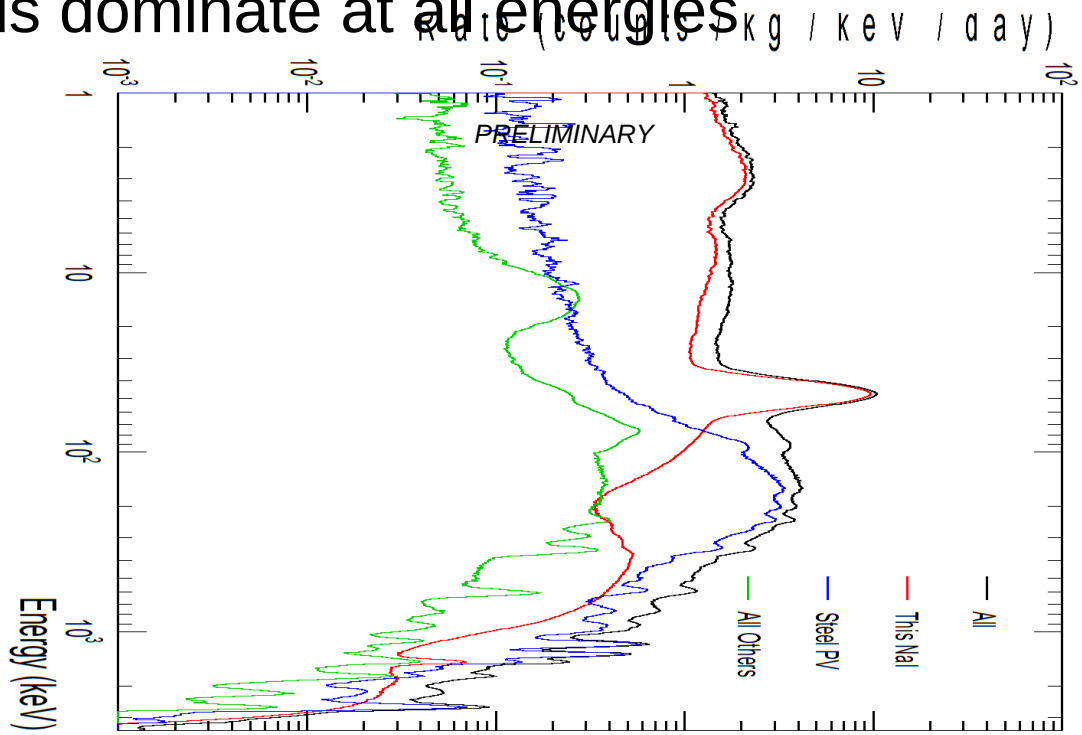


Background Simulation

- Crystal array geometry allows for coincidence studies
  - Reduction in total background rate via anti-coincidence
  - Stronger constraint on background model via MC comparison
- Crystal backgrounds dominate at all energies

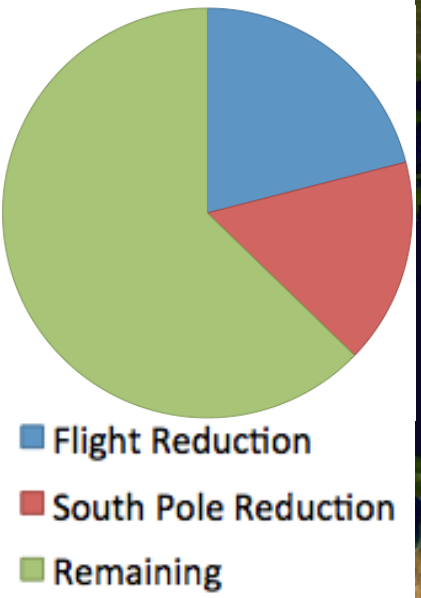
Outer Crystal Spectrum
(*after veto*)

- ^{40}K 3 keV peak complicates ROI
  - Veto reduction of 37-67%
- ^{210}Pb flat background is remaining low-energy background
  - Minimal improvement with veto
- High light yield imperative for resolution and noise reduction
  - 15 pe/keV demonstrated in alternate geometry



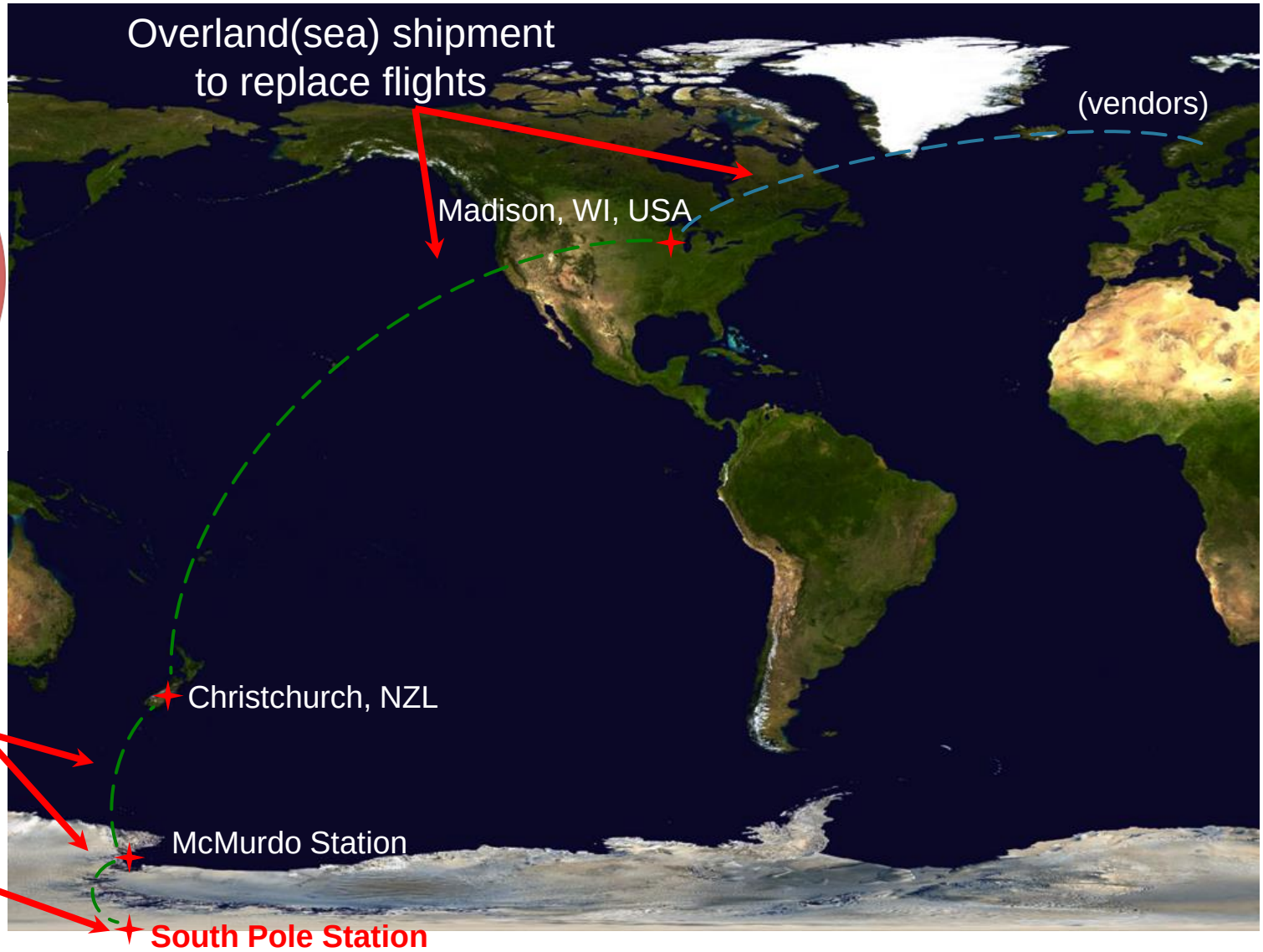
DM-ICE250S Activation

relative to DM-ICE17:



Maintain polar program flights

Minimize storage time



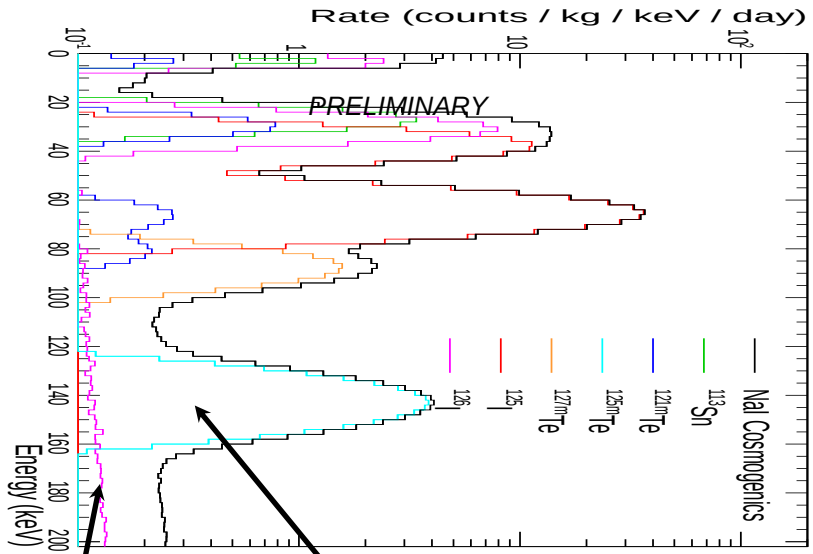
DM-ICE250S Cosmogenics

Event rate one month after deployment

- Multiple strong cosmogenic calibration lines
- Significant contributions to 2 – 6 keV region of interest

Cosmogenic contribution to ROI:

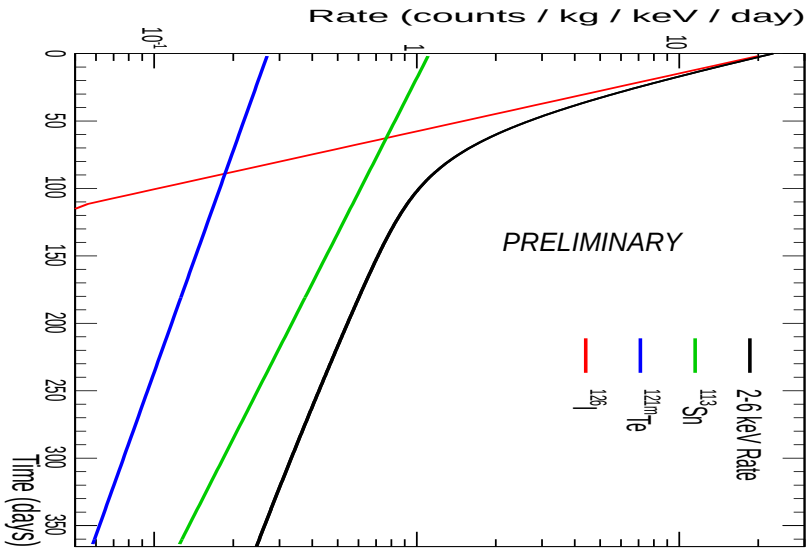
- ^{126}I ($t_{1/2}$ = 13 days)
  - lead contribution at deployment
- ^{113}Sn ($t_{1/2}$ = 115 days)
  - dominates rate over physics run



L-shell X-ray or Auger e$^-$

K-shell X-ray or Auger e$^-$

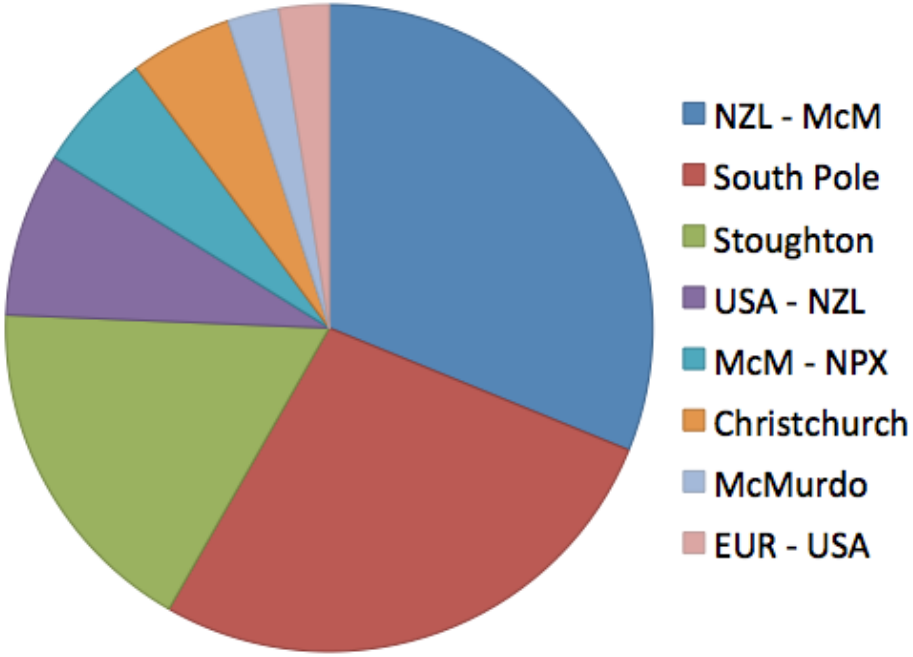
^{126}I, ^{113}Sn, ^{121m}Te



Cosmogenic Mitigation

"Exposure budget" for ^{113}Sn in DM-Ice250S:

- After "easy" 40% reduction
- Major contributions remain from NZL-McM flight and South Pole



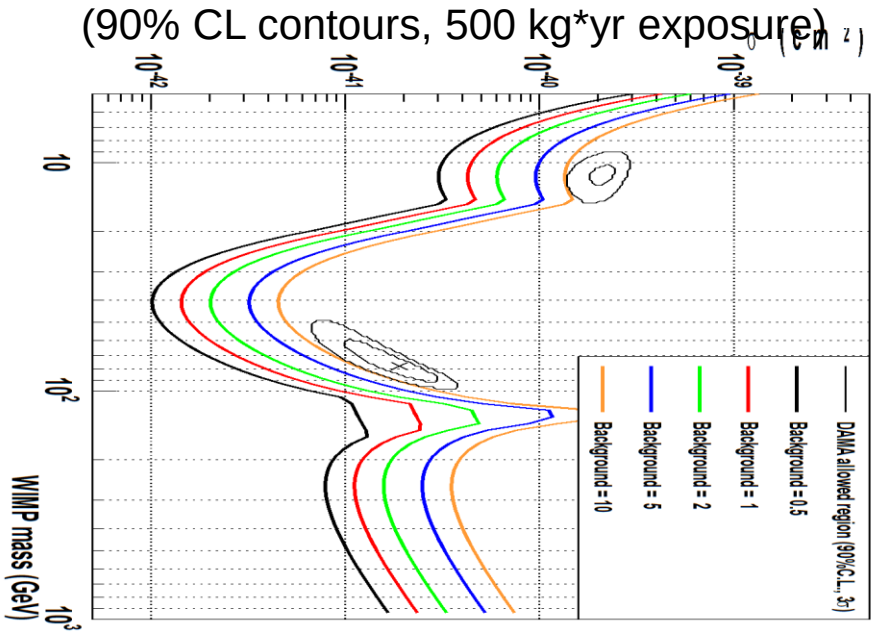
Further reductions:

- 50% reduction in low-altitude NZL-McM cargo flight (15% of total)

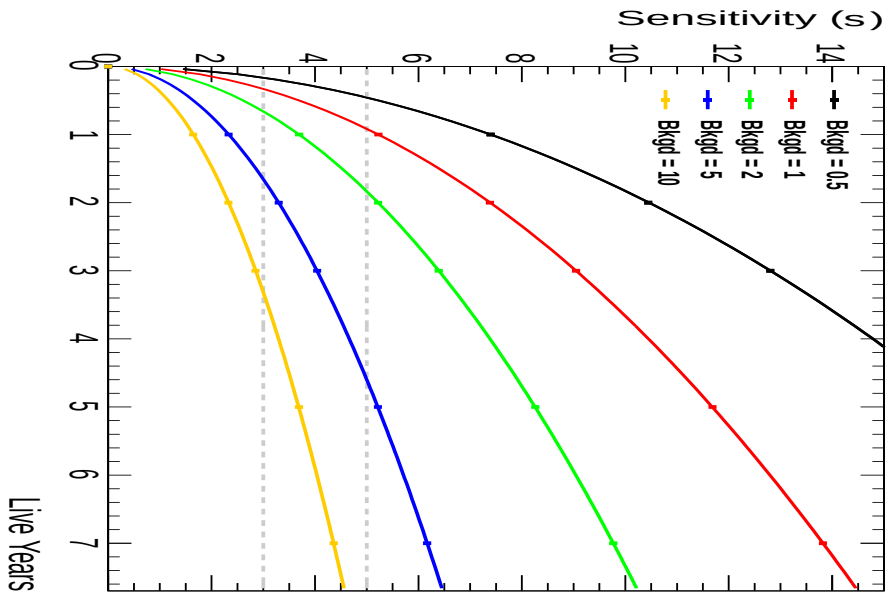
- 90% reduction in South Pole activation from under-ice storage

Sensitivity Projection

Null Hypothesis:
(90% CL contours, 500 kg*yr exposure)



Signal Hypothesis:
(250 kg detector)



DAMA dark matter claim can be definitively tested with 500 kg*yr exposure

- 5-sigma test possible with background of 2 dru
  - *cf.* DAMA background of ~1 dru

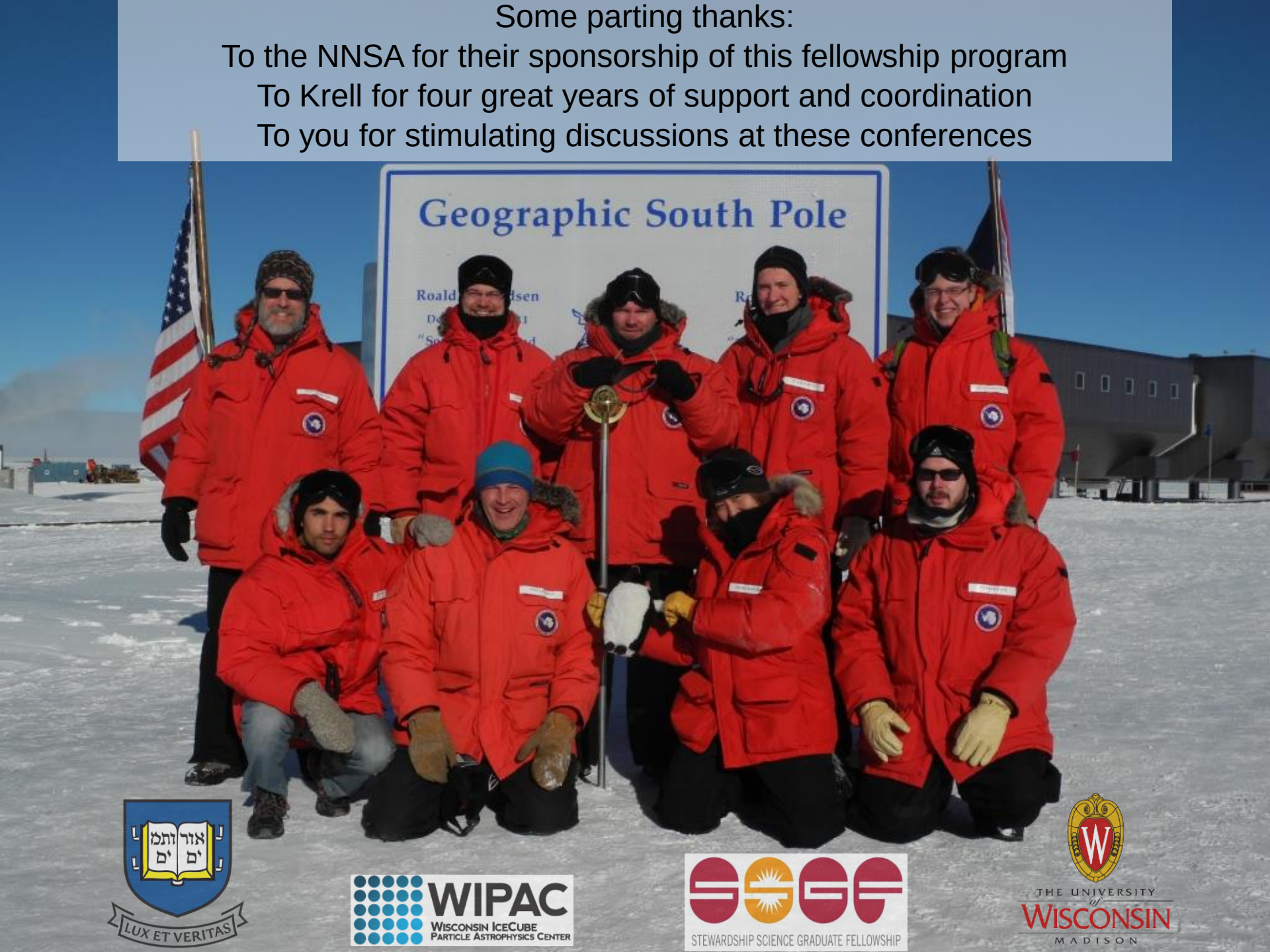
- DM-ICE17 has completed a successful 3.5-yr data run
  - 1 concept paper and 1 results paper published
  - +4 more papers by year end
- NaI(Tl) continues to have a promising future as a detector for dark matter searches
  - Verification or refutation of DAMA within few years
  - Still learning about activation products, phosphorescence,…
  - DM-ICE250 uniquely poised as planned Southern Hemisphere experiment
- Four detector built and operated
  - 3 NaI(Tl) and 1 plastic scintillator
    - (last R&D detector has been deconstructed and rebuilt 2 more times)
  - Uncountably many tons of lead moved

Some parting thanks:

To the NNSA for their sponsorship of this fellowship program

To Krell for four great years of support and coordination

To you for stimulating discussions at these conferences



LUX ET VERITAS

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