

Cosmogenic Activation in NaI Detectors for Dark Matter Searches

Walter C. Pettus
UW – Madison: Physics

Thesis Defense
7 May 2015

STEWARDSHIP SCIENCE GRADUATE FELLOWSHIP

WIPAC
WISCONSIN ICECUBE PARTICLE ASTROPHYSICS CENTER

THE UNIVERSITY of WISCONSIN MADISON

DM-Ice Collaboration

Yale University

Reina Maruyama, Karsten Heeger, Kyungeun Lim, Estella de Souza, Brooke Russell, Field Rogers

University of Wisconsin – Madison

Francis Halzen, Michael DuVernois, Albrecht Karle, Matt Kauer, Antonia Hubbard, Walter Pettus, Zachary Pierpoint, Bethany Reilly, Ben Broerman

University of Sheffield

Neil Spooner, Vitaly Kudryavtsev, Anthony Ezeribe, Calum Macdonald, Christopher Oates, Frederic Mouton, Matt Robinson, Sam Telfer, Lee Thompson, Dan Walker

Fermilab

Lauren Hsu, Raymond Co

Boulby Underground Science Facility

Sean Paling

University of Illinois at Urbana-Champaign

Liang Yang

University of Alberta

Darren Grant

Pennsylvania State University

Doug Cowen, Ken Clark

NIST-Gaithersburg

Pieter Mumm

University of Stockholm

Chad Finley, Per Olof Hulth, Klas Hultqvist, Chistian Walck

SNOLAB

Bruce Cleveland

STEWARDSHIP SCIENCE GRADUATE FELLOWSHIP

PSL

STFC Boulby

NSF

LUX ET VERITAS

WARF

WISCONSIN ICECUBE PARTICLE ASTROPHYSICS CENTER

ALFRED P. SLOAN FOUNDATION 1934

Individual Contributions

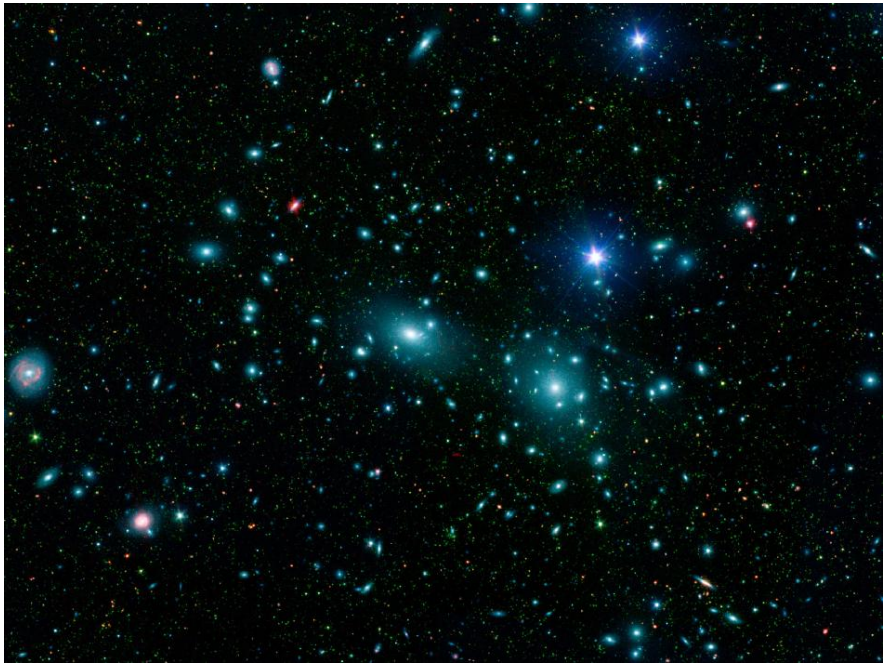
- Walter
  - Component testing
  - Assembly and design review
  - Detector operations for 4 years
  - Detector commissioning and run settings
  - Construction and operation of muon detector
  - Stability and Monitoring
  - Simulation production
  - Cosmogenic activation analysis
  - Fermilab test stand assembly/operation
  - Boulby detector installation
  - R&D DAQ testing
- Antonia
  - Data processing framework
  - Detector calibration
  - Muon identification
  - Phosphorescence analysis
  - IceCube coincidence
  - IceCube event reconstruction
  - Boulby detector installation
- Zack
  - Waveform correction
  - Noise cuts/removal
  - Pulse shape identification
  - Modulation analysis
  - Fermilab test stand assembly/operation
  - Boulby detector installation

Outline

- Dark Matter Physics & Detection
- DM-ICE17 Experiment
- Cosmogenic Activation
- DM-ICE250 Experiment

Dark Matter – History I

- First successfully postulated by Fritz Zwicky in 1933
  - Based on observations of Coma Cluster
  - System could not be virialized with visible mass alone

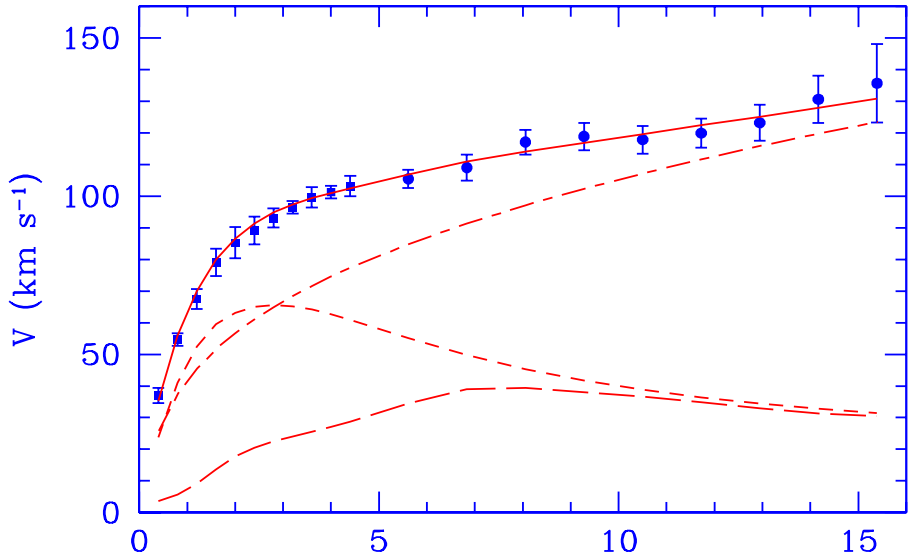


Spitzer Space Telescope (2007)

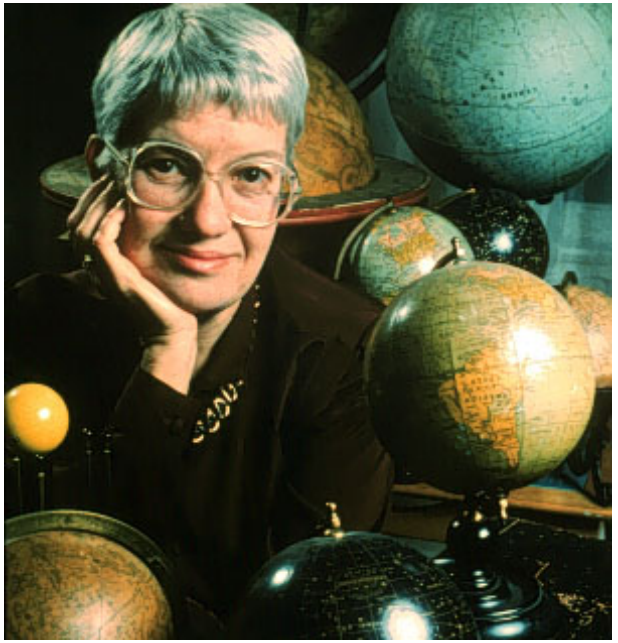


Dark Matter – History II

- Vera Rubin measured rotation curve of M31 (Andromeda galaxy)
  - Observed rotational velocity flattening at large R
  - Inconsistent with Newtonian gravity (~1/R)

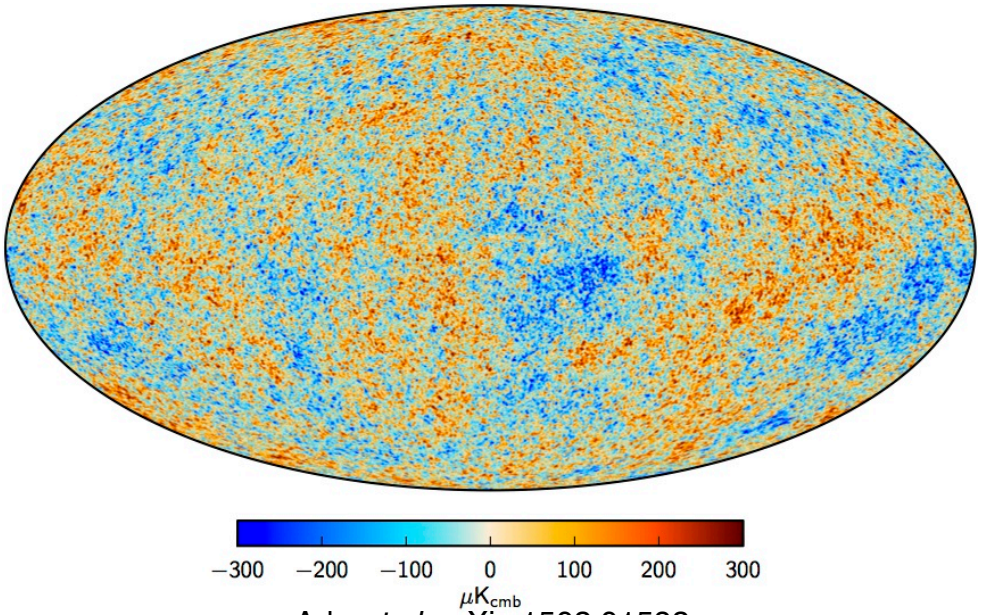


Corbelli and Salucci, MNRAS, (2000)

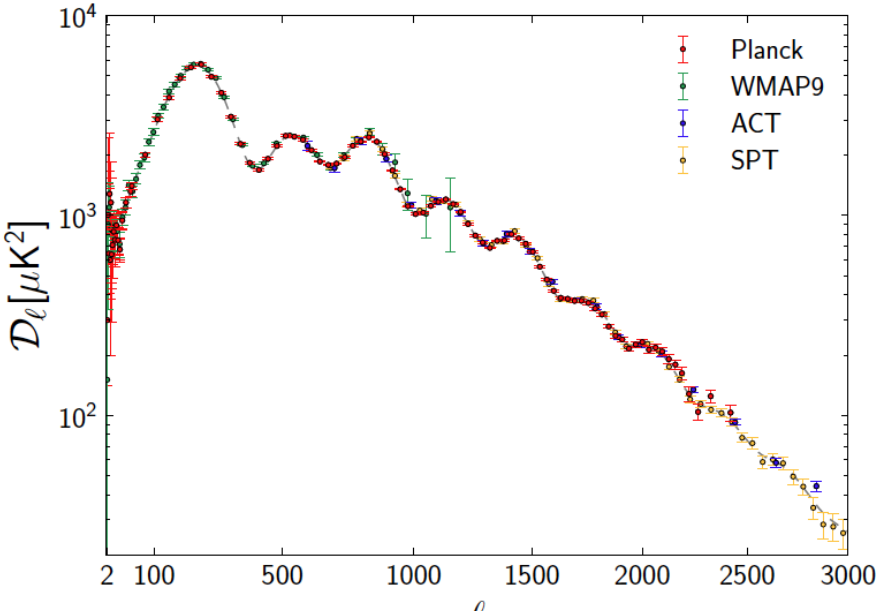


Cosmic Microwave Background

- Photons of cosmic microwave background (CMB) carry imprint of young universe
- Rich diagnostic of cosmology impacting evolution of universe

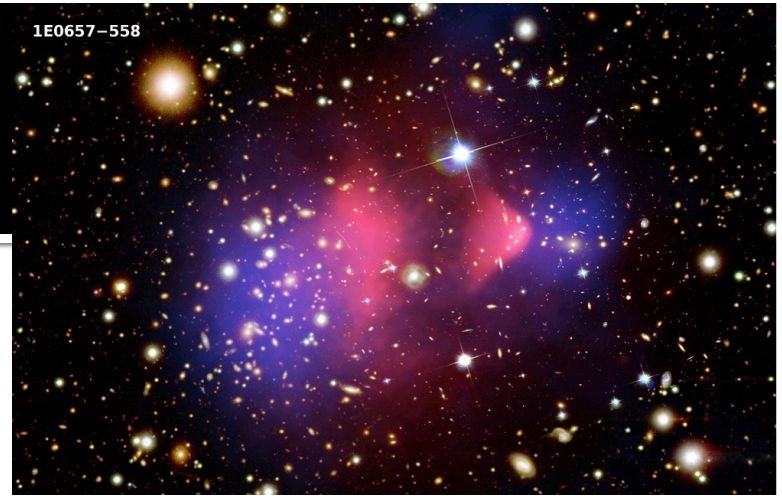


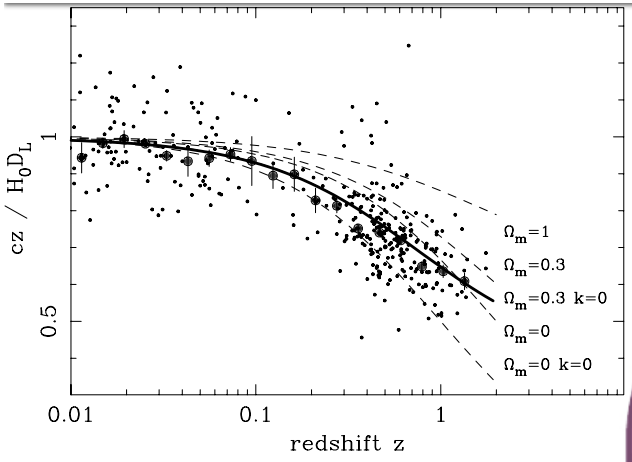
Ade *et al*, arXiv:1502.01582

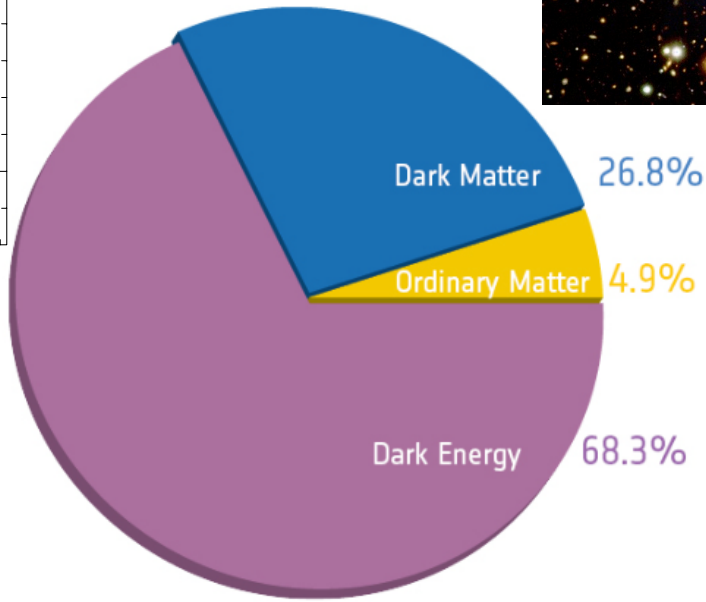


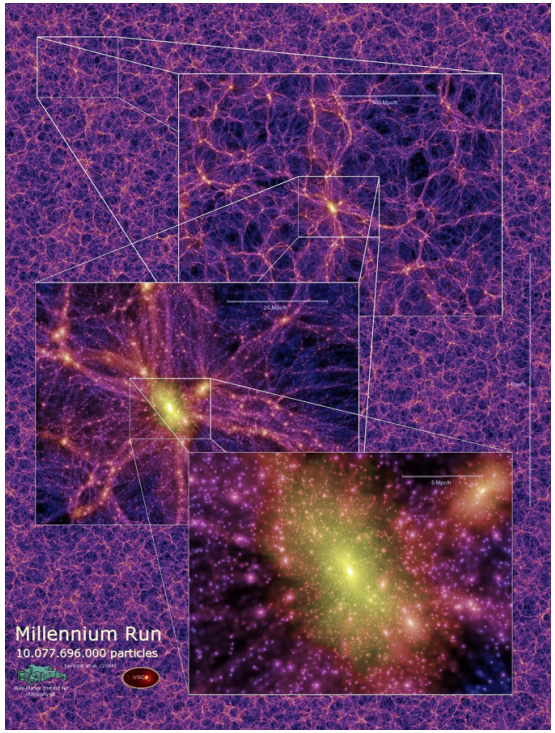
Ade *et al*, A&A (2014)

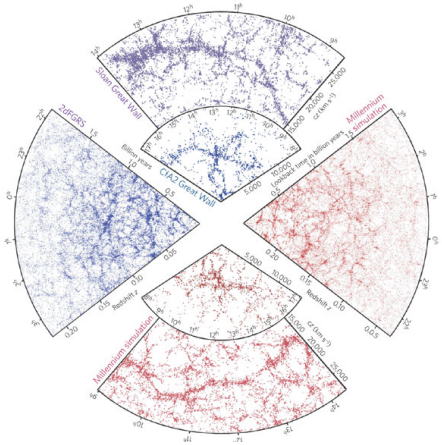
ΛCDM Universe

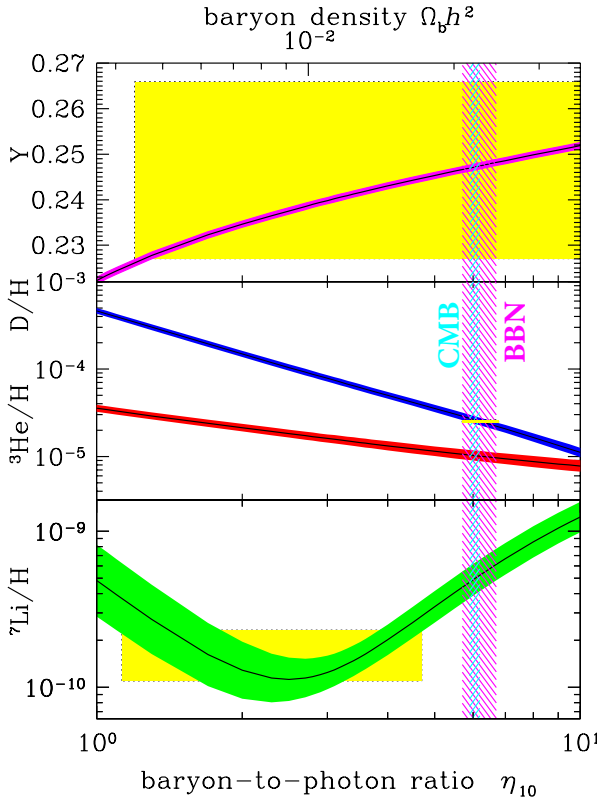












Detecting Dark Matter

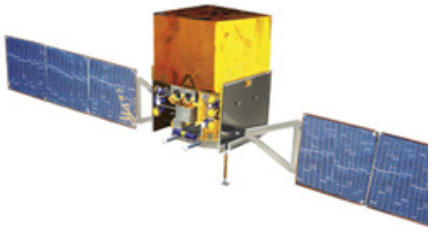
Direct Searches

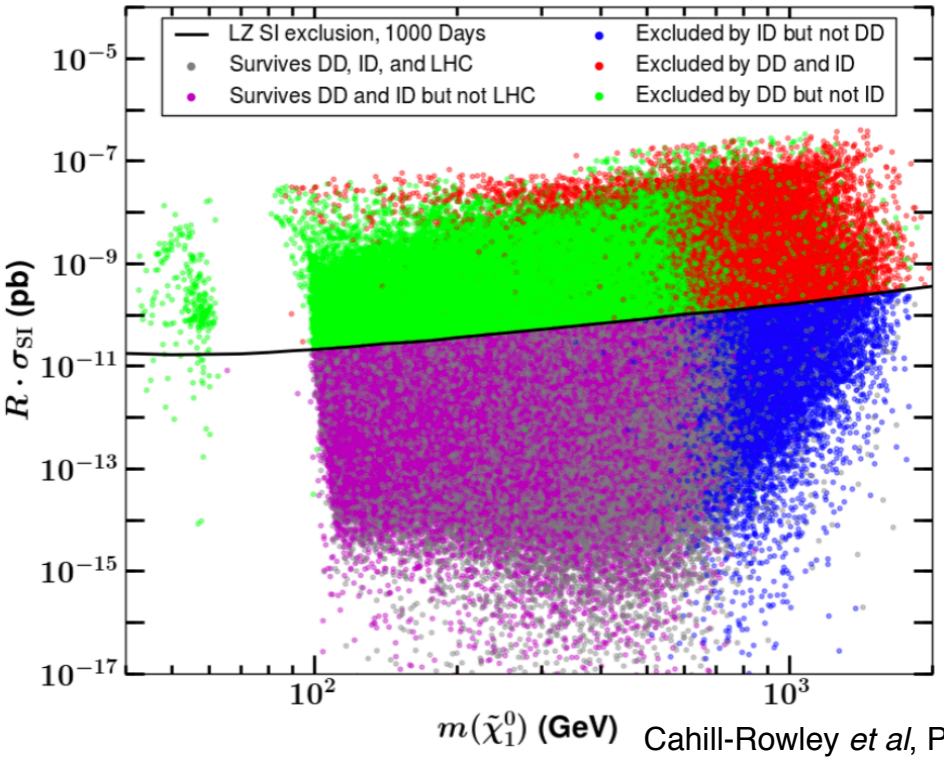
- Identify energy deposition from dark matter interaction in a terrestrial detector



Indirect Searches

- Identify annihilati
  decay products of
  matter from
  extraterrestrial so





Collider Searches

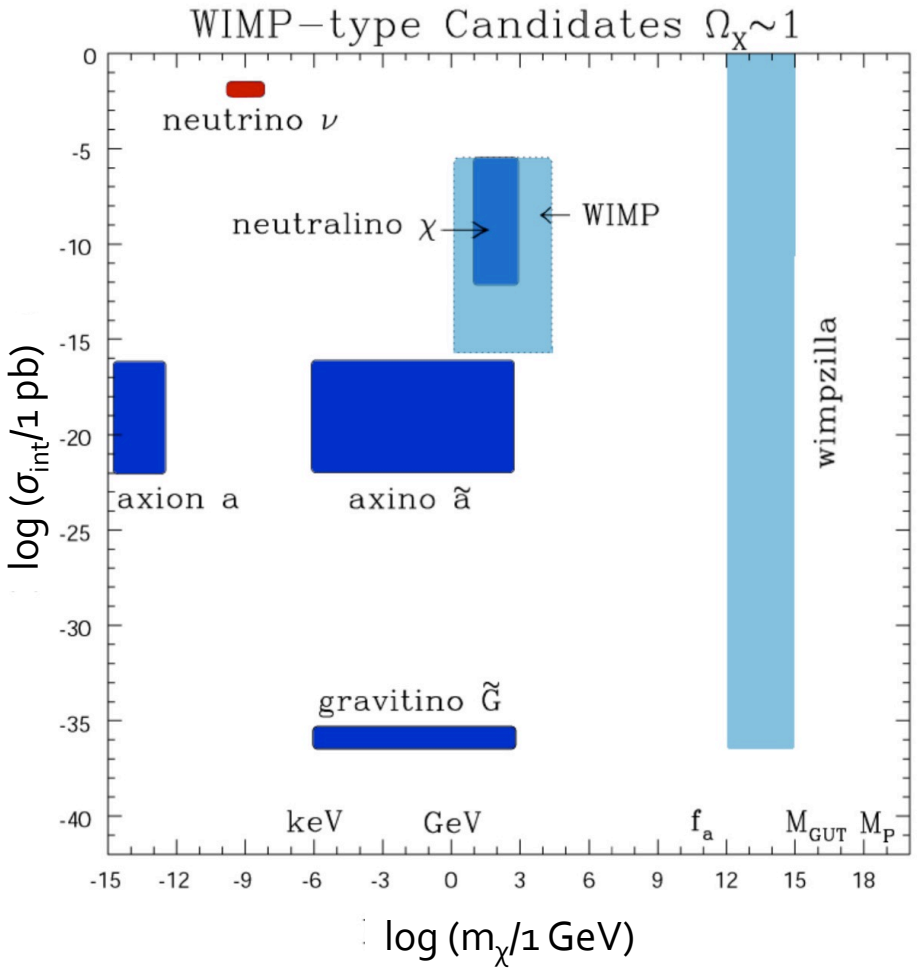
- Identify production signatures of dark matter in collision



Cahill-Rowley *et al*, Phys Rev D (2015)

Oh Dark Matter, Where Art Thou?

- Variety of theoretically-motivated candidates
- Dark matter properties constrain what kind of detector you build



Roszkowski, Pramana, (2004)

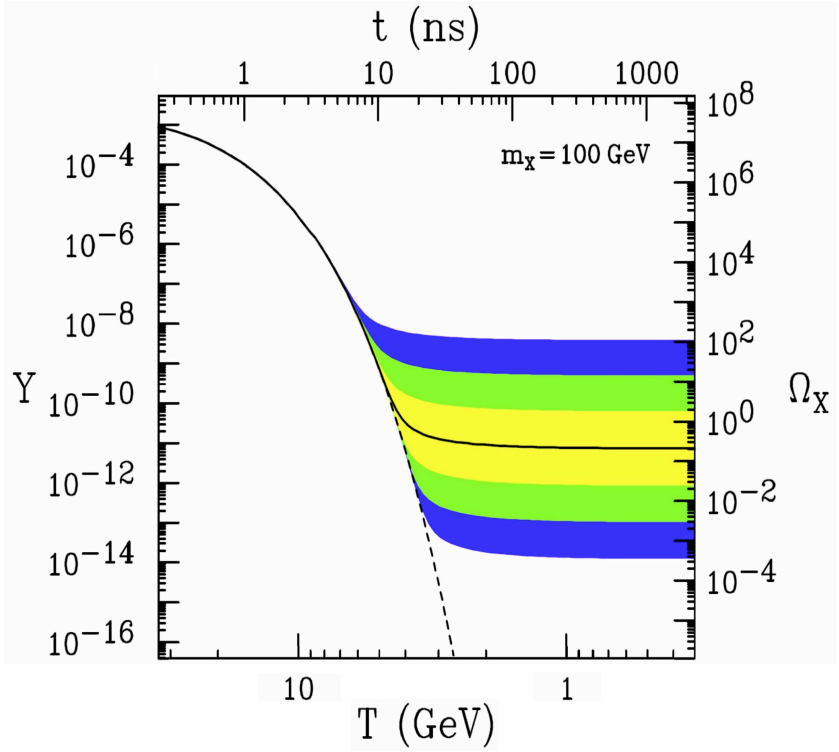
Thermal Relic – Freeze Out

- Thermal relic number density must satisfy Boltzmann Equation:

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle\sigma_A v\rangle\left(n_\chi^2 - \left(n_\chi^{\mathrm{eq}}\right)^2\right)$$

$$\Omega_\chi \sim \frac{x_f T_0^3}{\rho_c M_{Pl}}\langle\sigma_A v\rangle^{-1}$$

$\langle\sigma_A v\rangle \approx 10^{-26}$ cm^3/s
for m_χ = 100 GeV



Feng, Ann Rev Astronomy & Astrophysics, (2010)

Event Rates and Cross Section

Event rate dependence:

- velocity distribution
- local WIMP density
- scattering cross section

$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \int_{v_{\min}}^{v_{\max}} dv\, f(v)\, v \frac{d\sigma}{dE_R}$$

$$R \sim N_T \frac{\rho_0}{m_\chi} \sigma_\chi f(v)$$

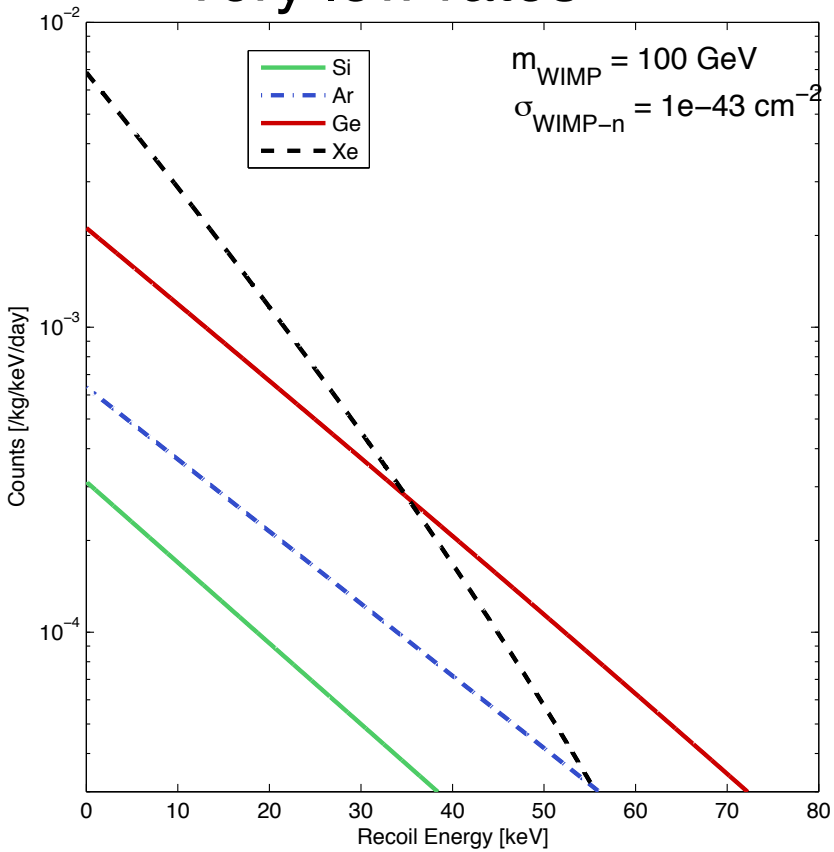
Astrophysics:
ρ_0 = 0.3 GeV/cm^3
$v_{rms} \approx 270$ km/s
$v_{max} \approx 650$ km/s

Particle physics:
$\sigma_{SI} \propto \sigma_o A^2 |F(q)|^2$

$m_\chi \sim 100$ GeV
$\sigma_\chi \sim 10^{-44}$ cm^2

Exponential signal

- very low rates



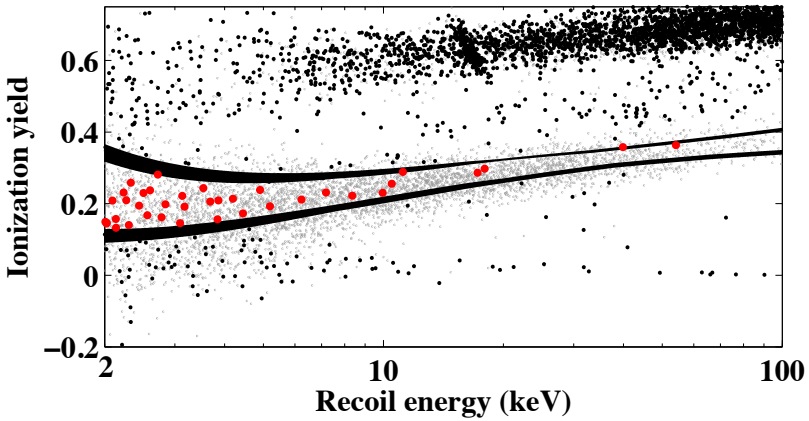
Baudis, SUSY07, (2007)

Background Reduction

Identify signatures of dark matter recoil signal to discriminate background

Recoil-Type ID:

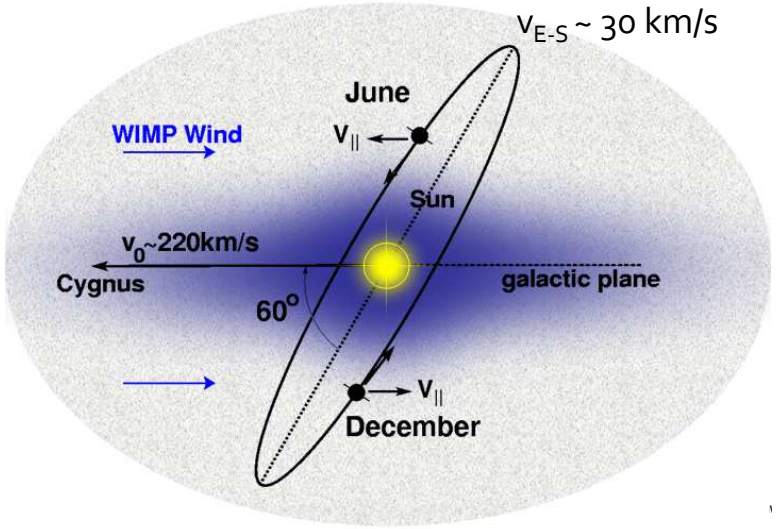
- WIMP signal from nuclear recoils
- Most backgrounds (radioactive decays) from electron recoils



Ahmed *et al.* Phys Rev Lett, (2011)

Annual Modulation:

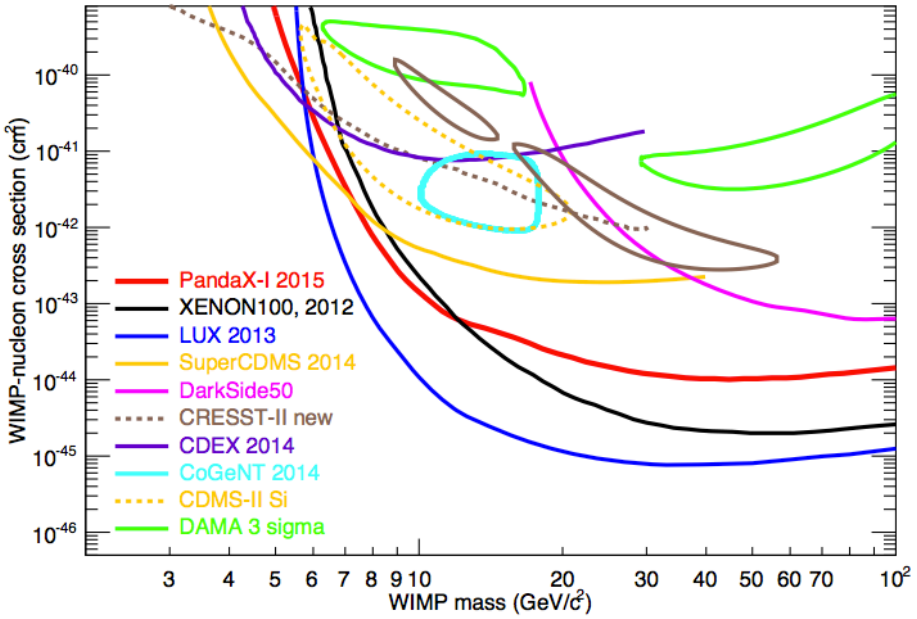
- From Earth's motion around the Sun
- ± 7 % effect
- Phase (peak signal): 156.5 days (June 2nd)



Current Field Status

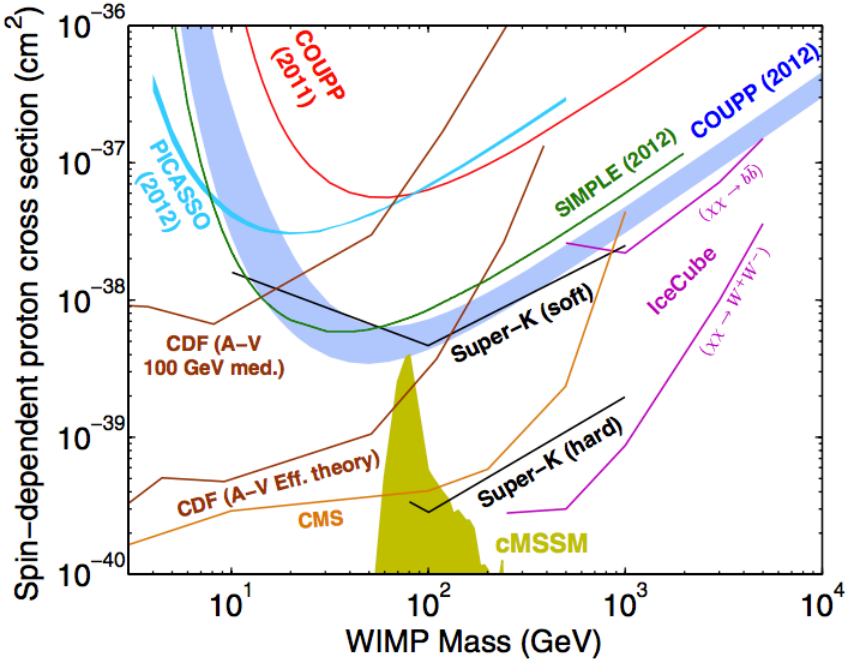
Different WIMP-nucleon scattering models examined:

Spin-Independent
Coherent scattering off entire nucleus



Xiao *et al.* arXiv:1505.00771

Spin-Dependent
Scattering off unpaired nucleons



Behnke *et al.* Phys Rev D 86 (2012)

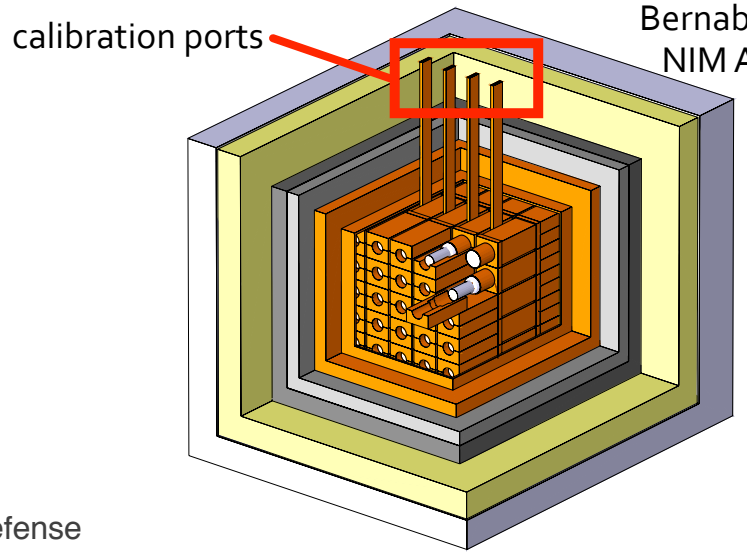
DAMA Detectors

- 25 x 9.70 kg NaI(Tl) detectors
  - Grown by Saint-Gobain
    - Individually encapsulated
    - 0.85 – 1.3 cpd/kg/keV rate
- 2 PMTs per crystal
  - Hamamatsu R6233MOD
    - Low background, high QE





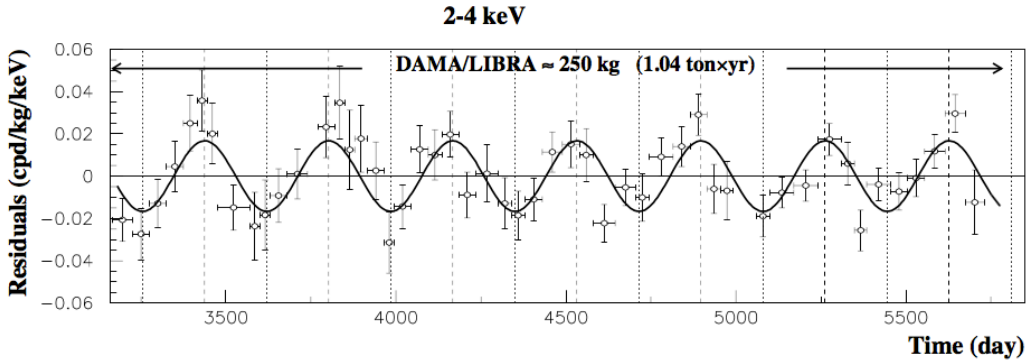




DAMA Result

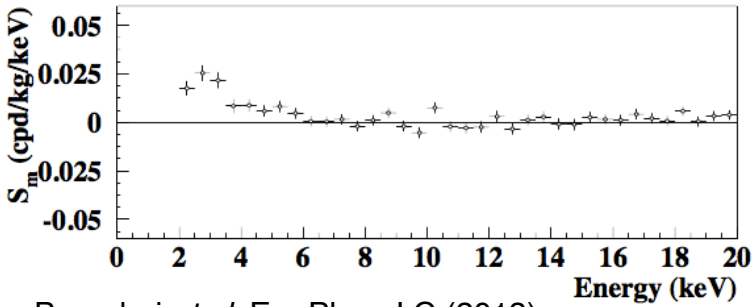
Performed annual modulation experiment

- Observe non-zero amplitude at ***9.3-sigma***



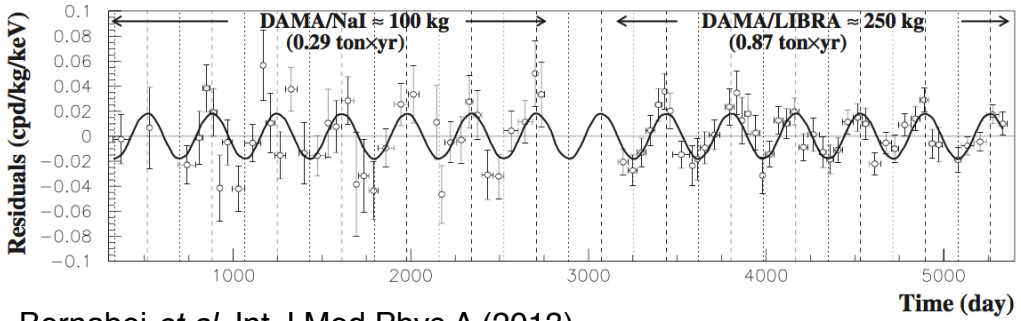
Bernabei *et al*, Eur Phys J C (2013)

Modulation only observed at low-energy:



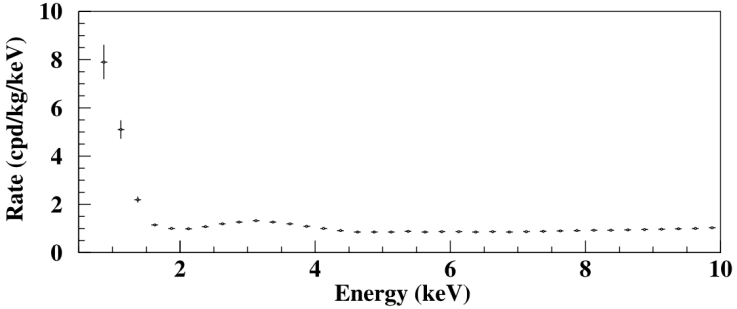
Bernabei *et al*, Eur Phys J C (2013)

Consistent modulation signal spanning 14 measured cycles



Bernabei *et al*, Int J Mod Phys A (2013)

Relative amplitude is <3% of singles (background) rate



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

Outline

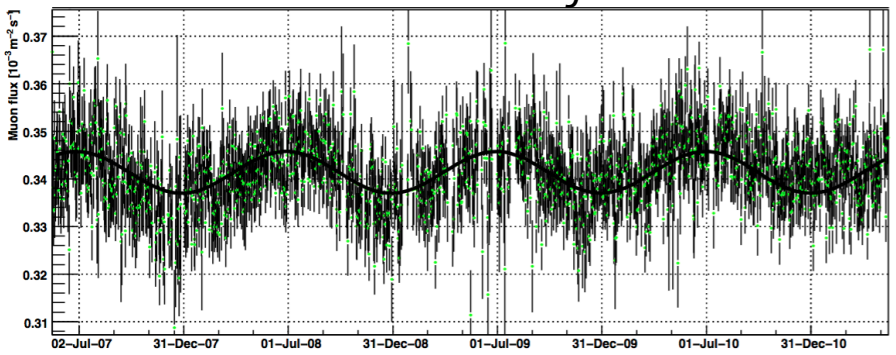
- Dark Matter Physics & Detection
- DM-ICE17 Experiment
- Cosmogenic Activation
- DM-ICE250 Experiment

Goal of DM-Ice Experiments

- Investigate the DAMA modulation signal
  - Eliminate or alter possible systematics

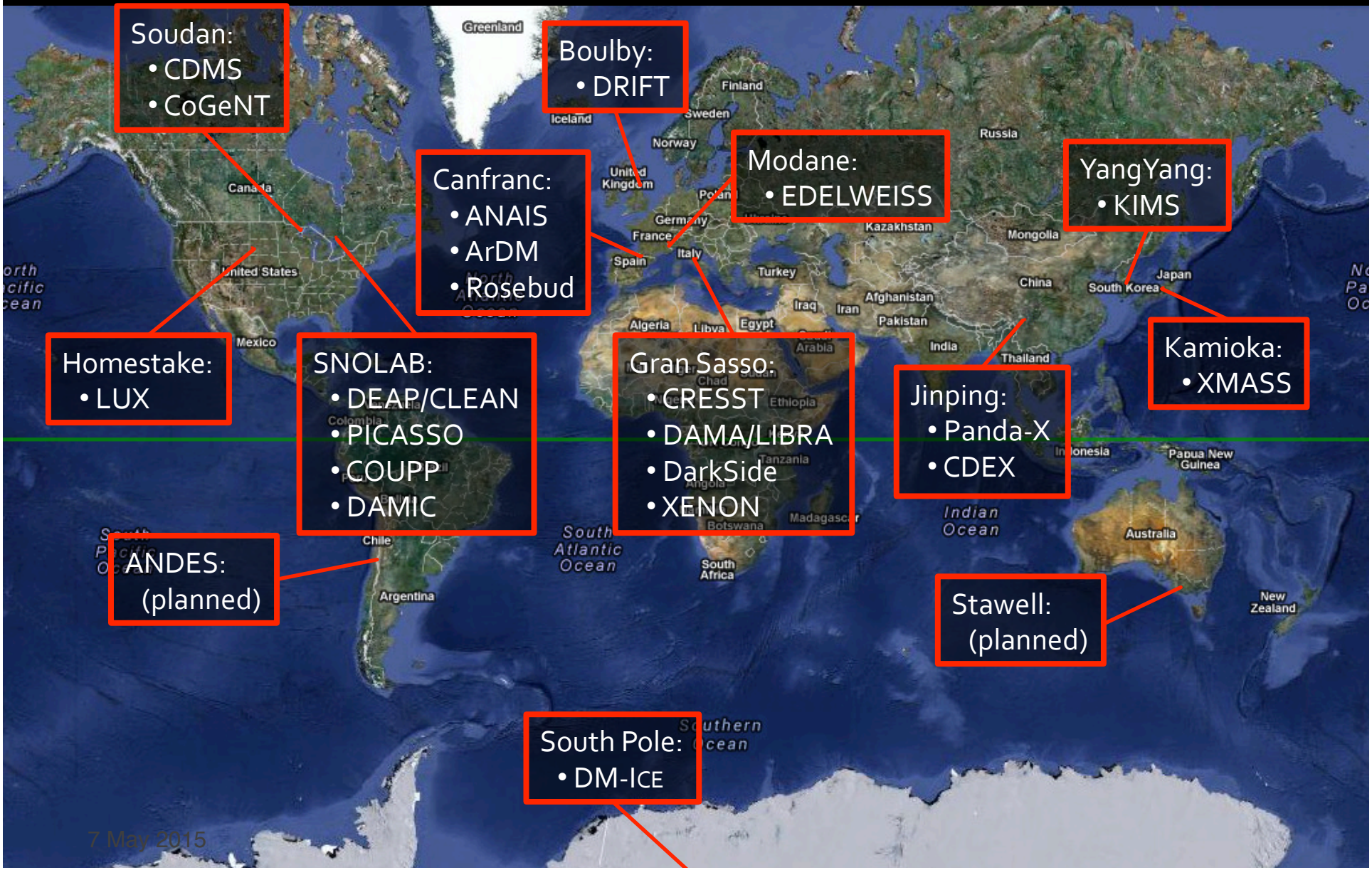
- What can modulate seasonally?
  - Muons
  - Spallation Neutrons
  - Lab temperature
  - Environmental radon

LNGS muon flux:

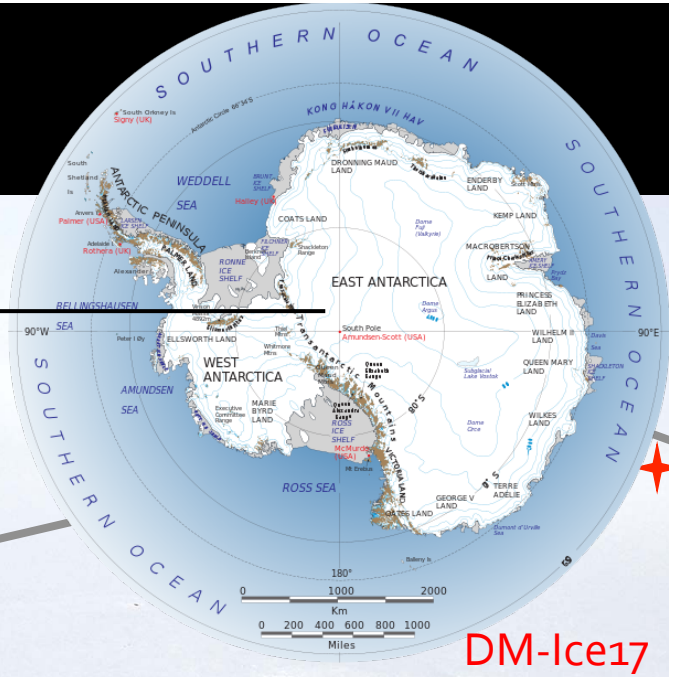


D'Angelo *et al*, ICRC (2011)

A World of Dark Matter Searches



South Pole Science



Geographic South Pole



Amundsen-Scott South Pole Station

Skiway

DM-Ice17

IceCube
IceTop



Keck Array



BICEP3, SPT

Advantages of South Pole

- Same dark matter signal in both hemispheres
- Opposite muon rate
  - Tagging of muons by IceCube/DeepCore
  - Spallation neutrons moderated by ice
- Overburden from 2450 m ice (2200 m.w.e.)
  - Drilling established by IceCube
  - Negligible environmental radioactivity
    - ppt $^{238}U/^{232}Th$, ppb ^{40}K
  - No radon fluctuation for sealed detectors
- No temperature fluctuation
- Support infrastructure of Amundsen-Scott South Pole Station

see also Cherwinka *et al.*
Astroparticle Physics **35** (2012) 749

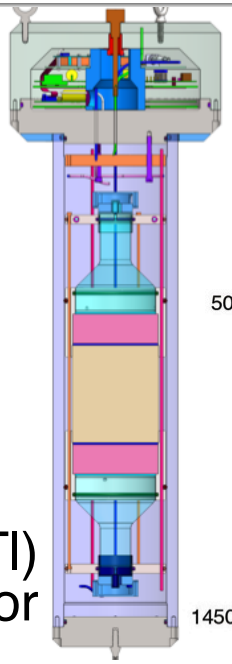
DM-Ice17 Experiment

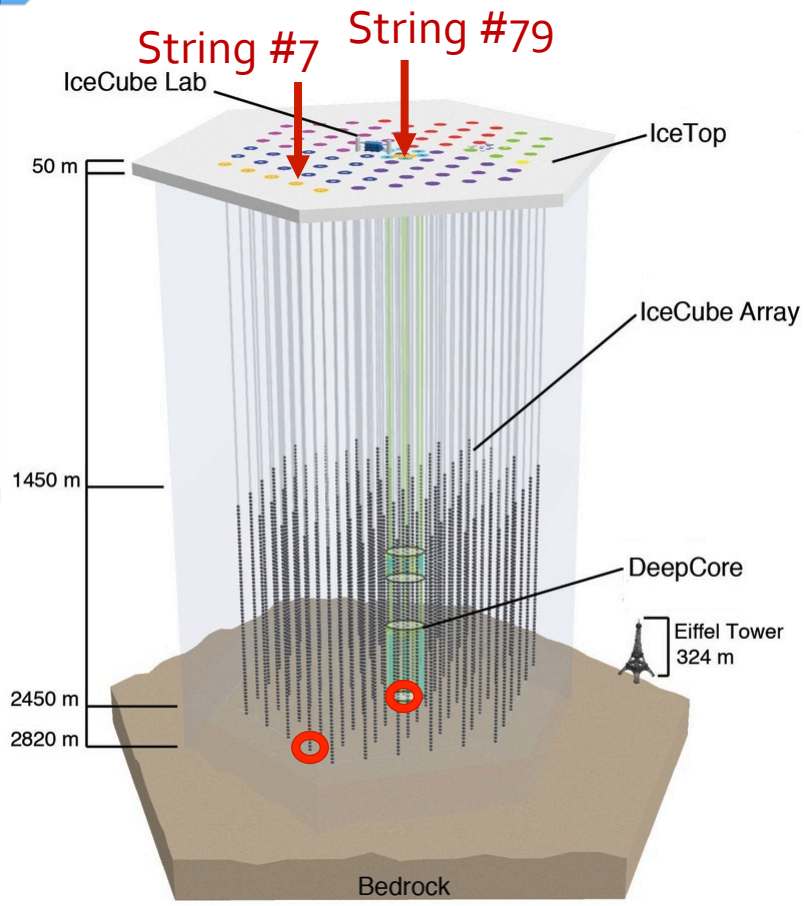
(2x) 8.5-kg NaI(Tl) modules

- Installed Dec 2010
- Data run began June 2011
- Data set closed Jan. 2015

Goals:

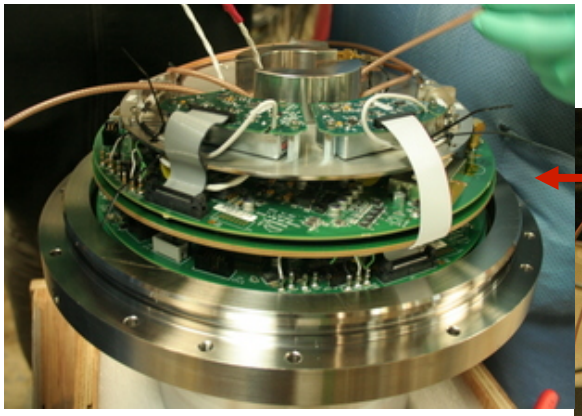
- Demonstrate the feasibility of deploying and operating NaI(Tl) detectors in the Antarctic Ice for a dark matter search
- *In situ* measurement of the radiopurity of the Antarctic ice / hole ice at 2450 m depth
- Study environmental stability
- Study the capability of IceCube to veto muons

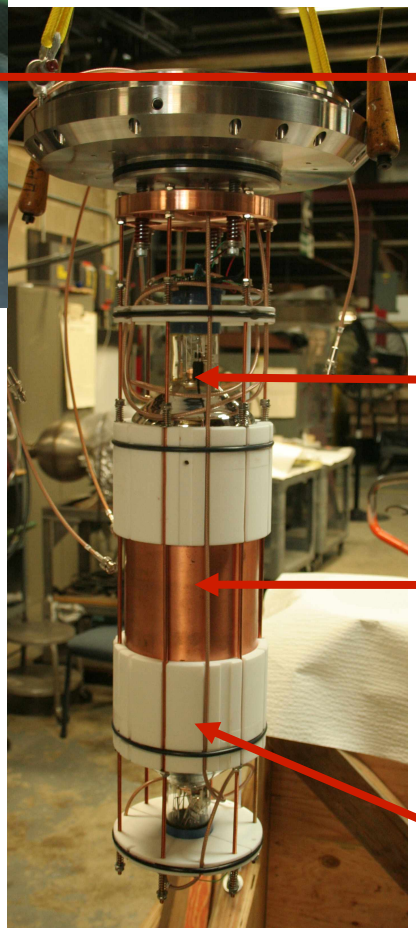




see also Cherwinka *et al.*
Phys Rev **D90** (2014) 092005

DM-Ice17 Detectors





Digitizing/control mainboards + HV control (x2) (IceCube)

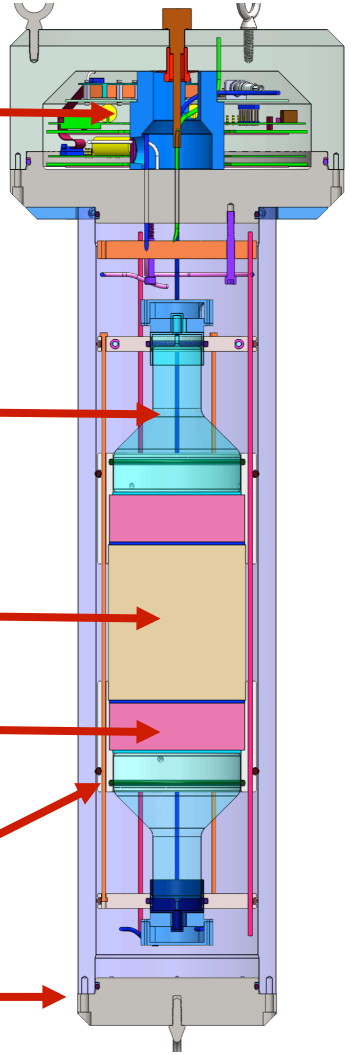
ETL 5" PMTs (x2) (NaIAD)

Encapsulated NaI crystal (NaIAD)

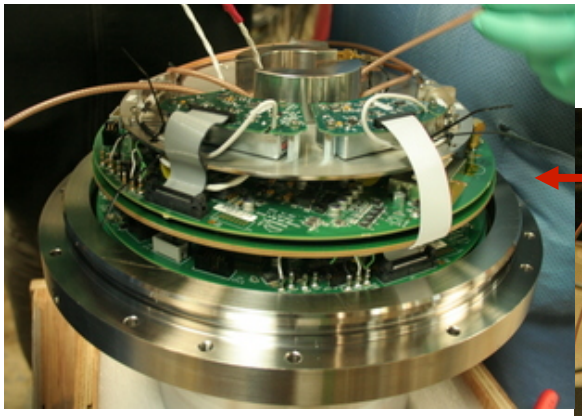
Quartz Lightguides (x2) (NaIAD)

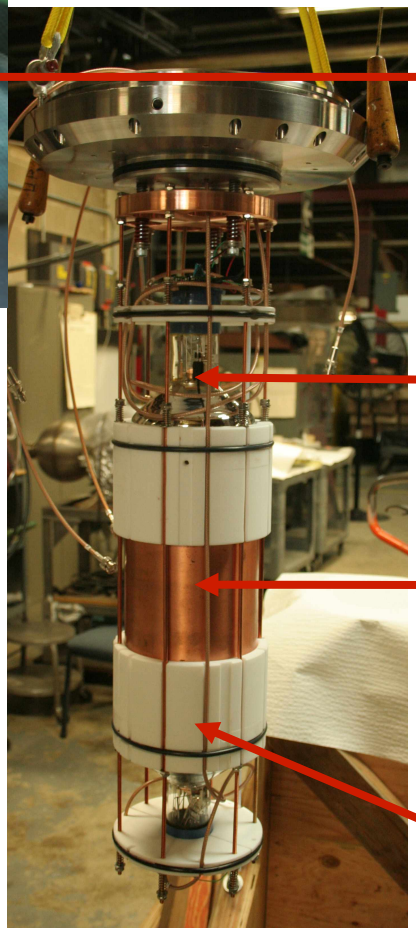
PTFE light reflector (x2)

Steel pressure vessel



DM-Ice17 Detectors





indicates tested component

Digitizing/control mainboards + HV control (x2) (IceCube)

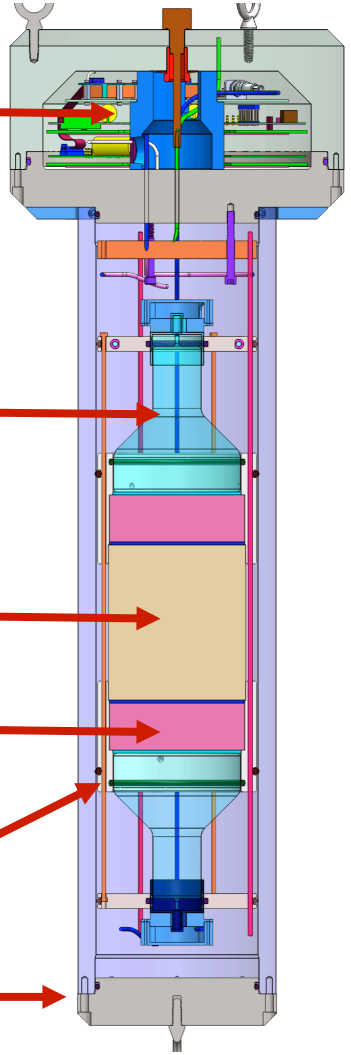
ETL 5" PMTs (x2) (NaIAD)

Encapsulated NaI crystal (NaIAD)

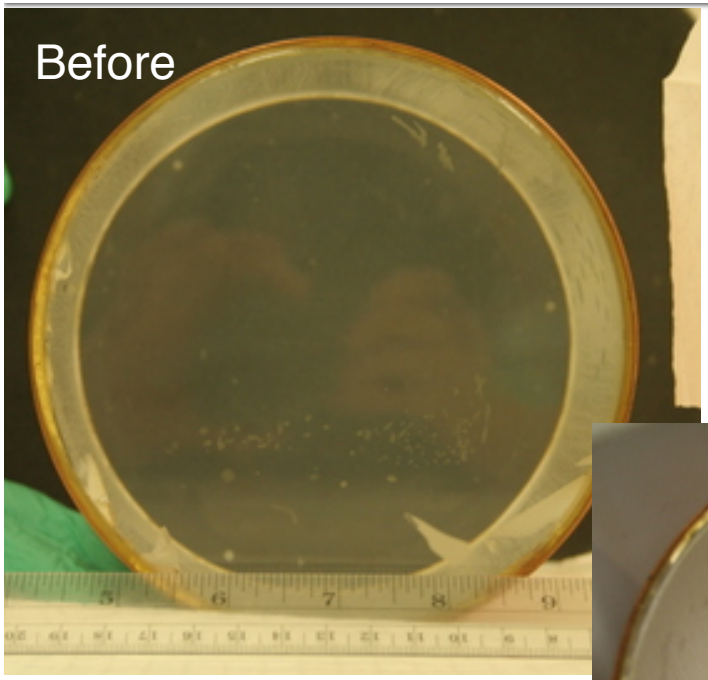
Quartz Lightguides (x2) (NaIAD)

PTFE light reflector (x2)

Steel pressure vessel



Temperature Cycling Tests



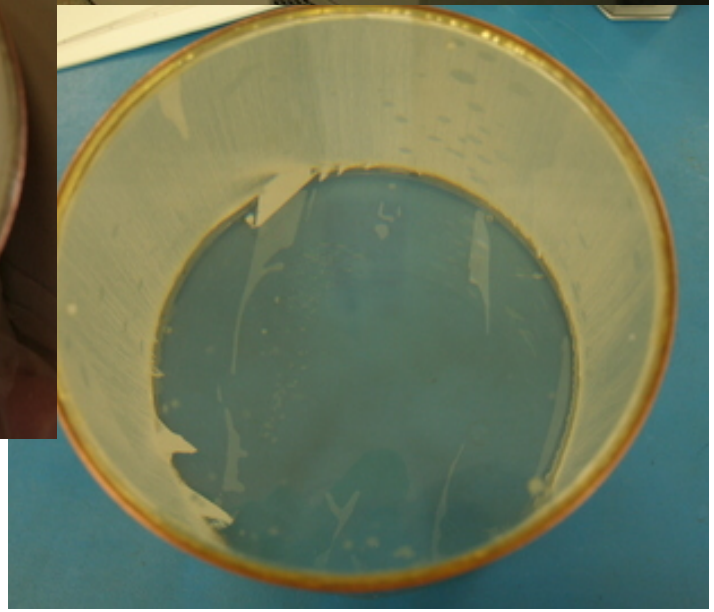


Cycle to
0° C



Decoupling of NaI-quartz interface and crystal cracking investigated

Cycle to
-25° C



Pressure Vessel Testing



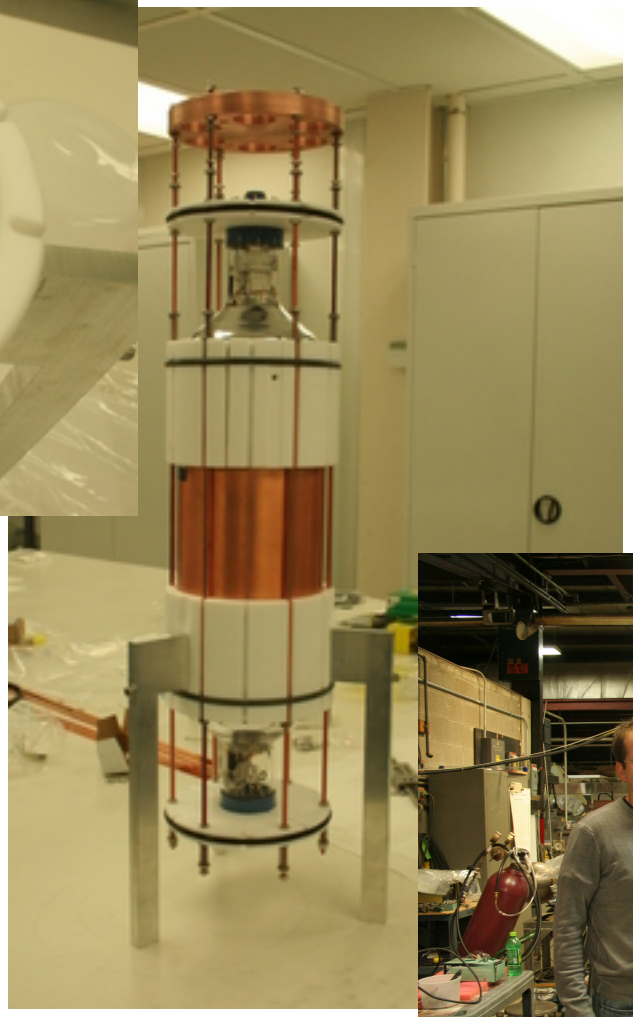


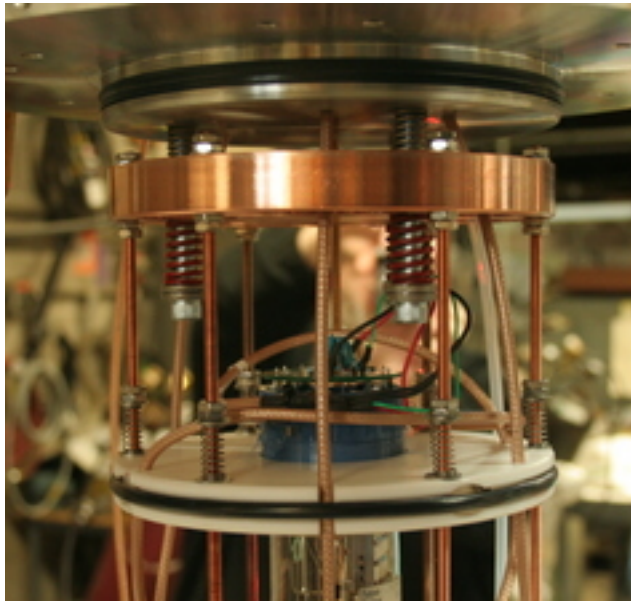
Integrity of steel pressure vessel tested against >7000 psi (freeze-in test)

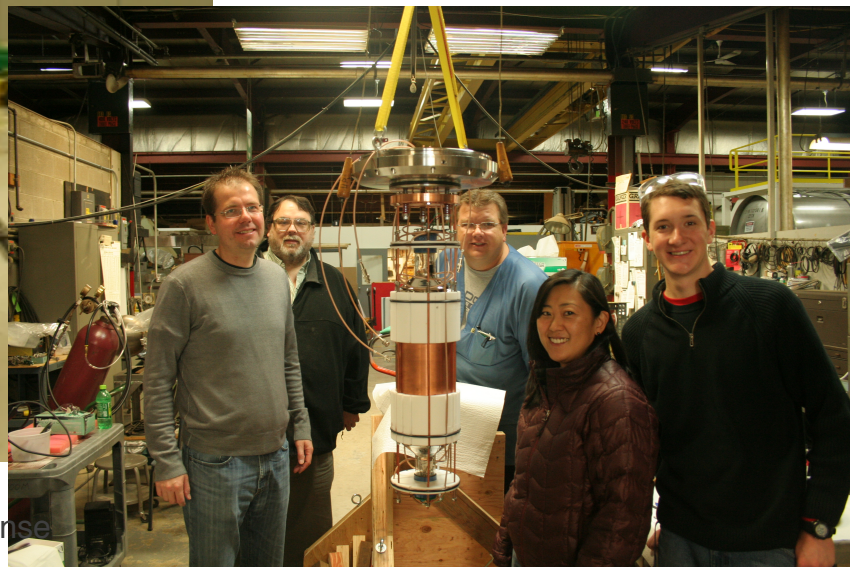


DM-Ice17 Assembly





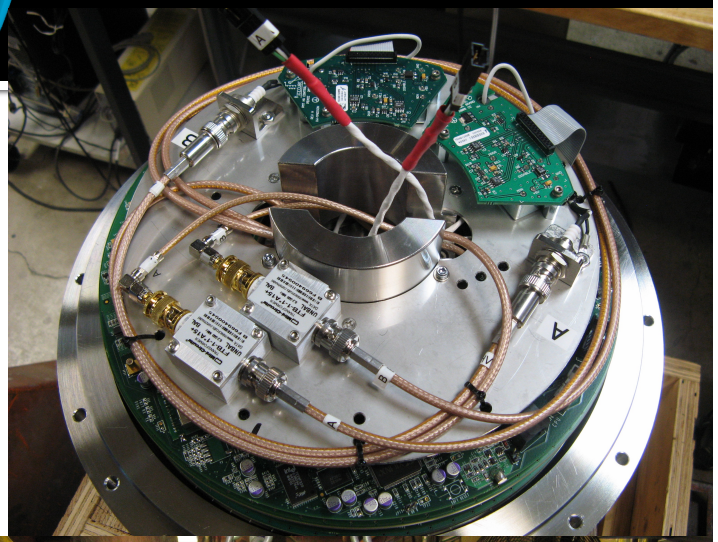




Optical coupling of PMT, quartz, NaI established with optical grease and gel. Mechanical shock mitigation from spring and O-ring assembly.

DM-Ice17 Assembly







Final assembly and wiring.
Lower volume purged with nitrogen and sealed from electronics.

Shipping DM-Ice17



packing insulation



Sensor for mechanical and temperature shock study



The final journey



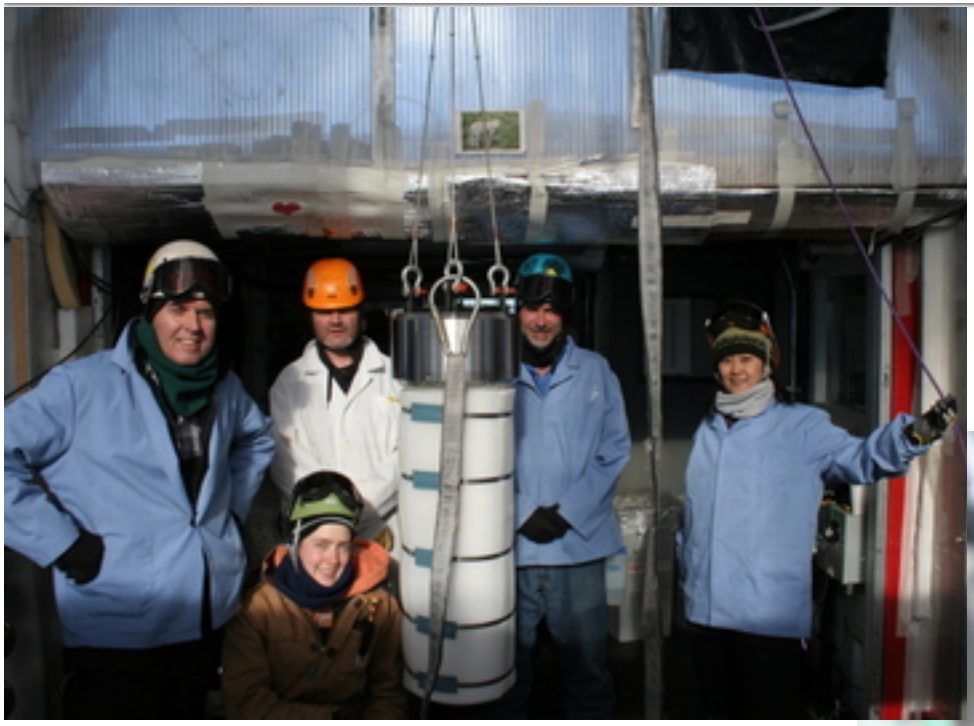
Transport to deployment tower



Staging for Deployment



The End Is Only the Beginning

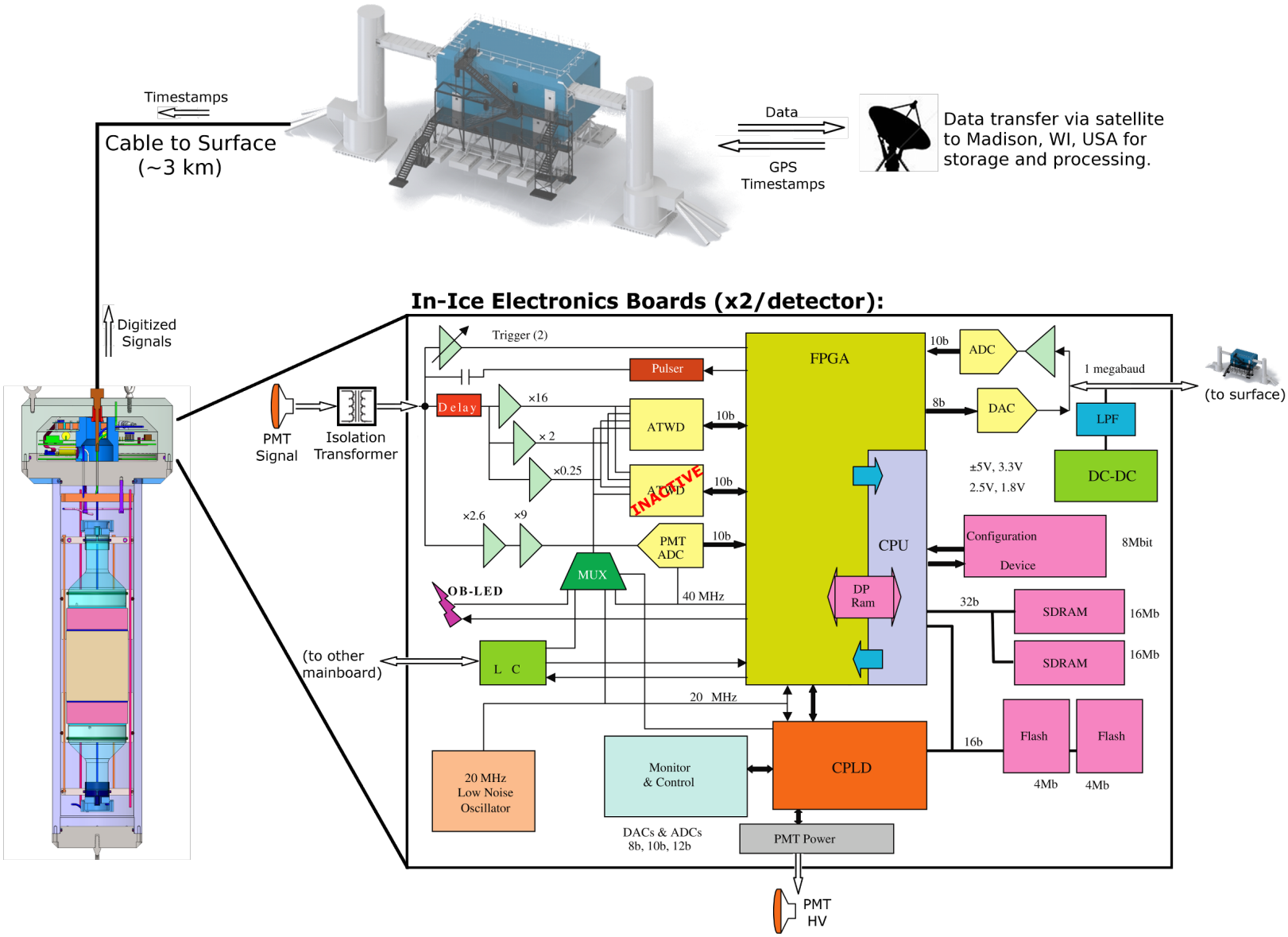


Det-1 deployment team

Det-1 below DOM60 on String 79

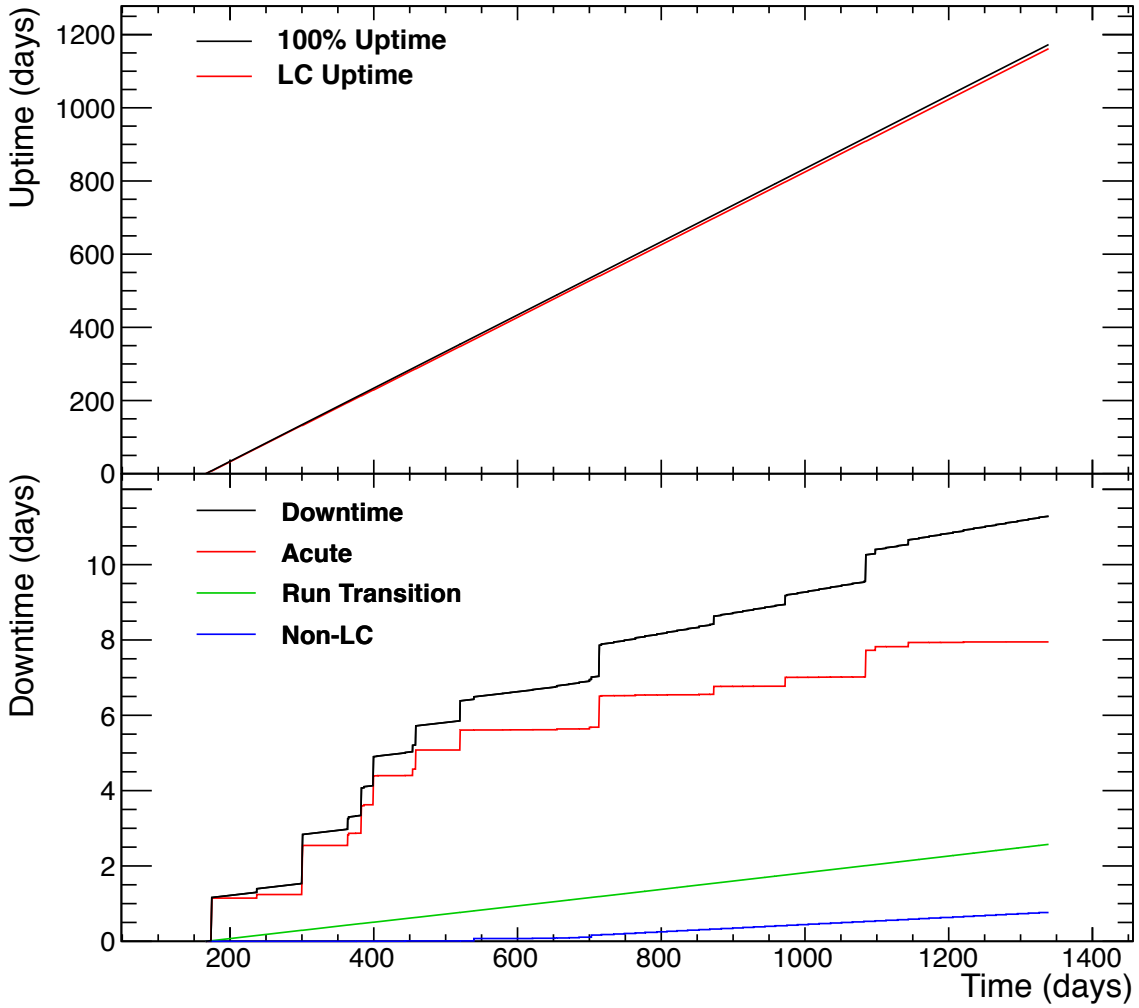


DM-Ice17 Electronics



DM-Ice17 Uptime

- > 99% uptime
- Sources of downtime understood
  - Uptime has improved over physics data run

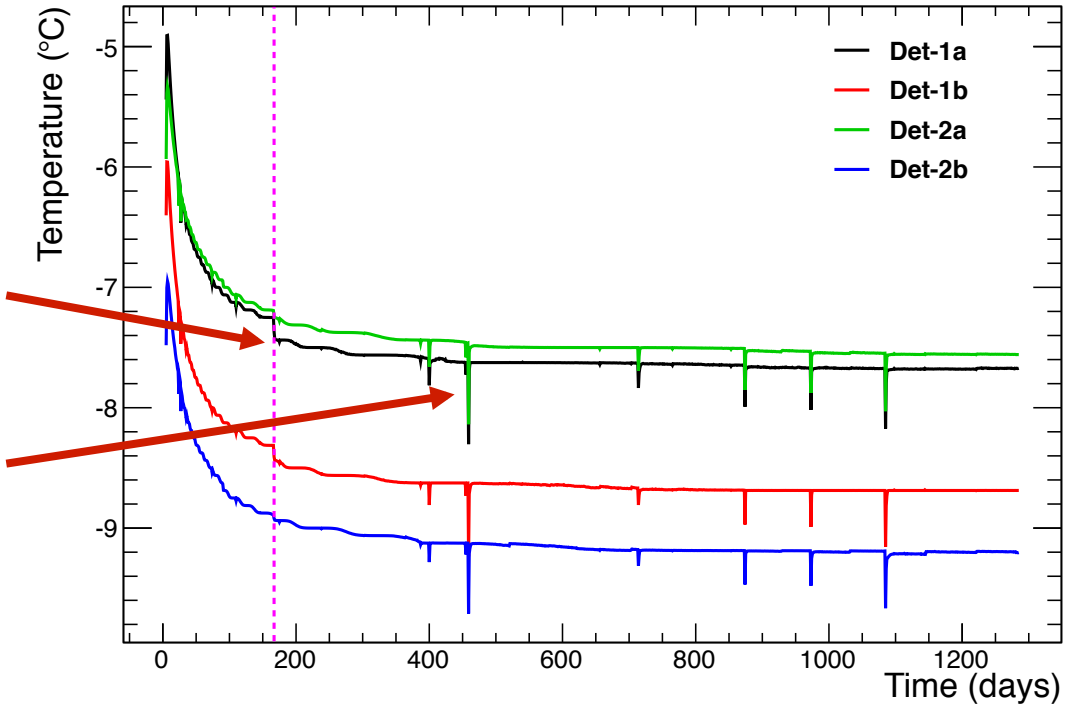


Temperature Stability

- Temperature is very stable
  - < 0.025°C daily RMS
  - 0.25°C cooling over 3.5 years

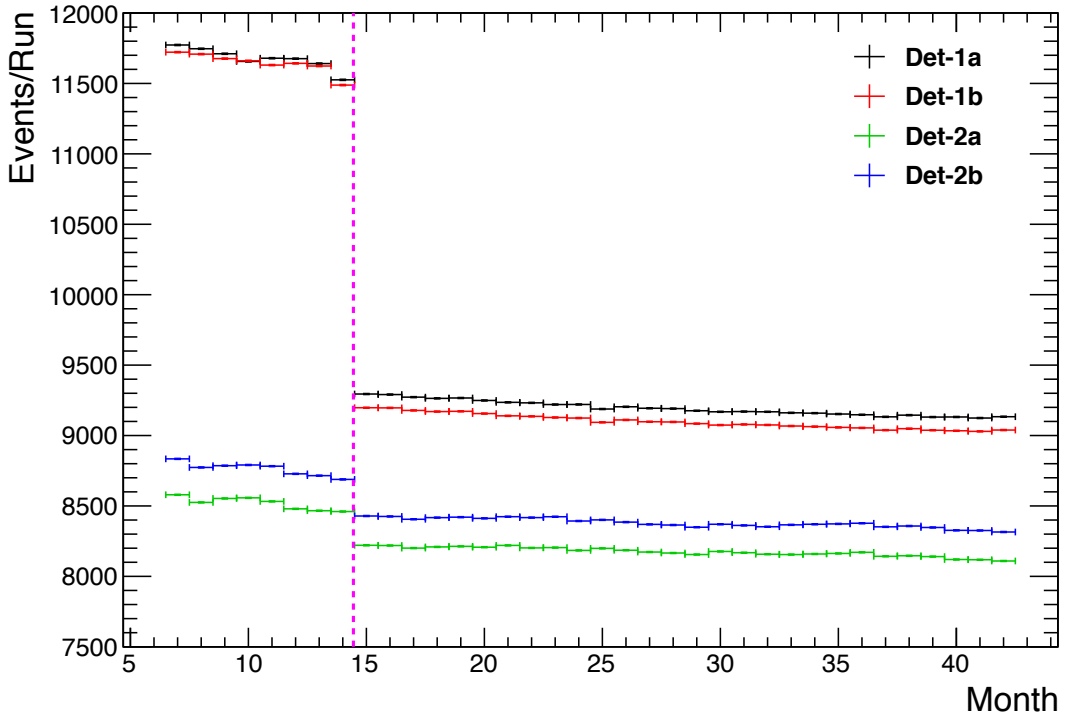
Changing HV setting affects MB temperature

Power outages affect MB temp, not crystal temp



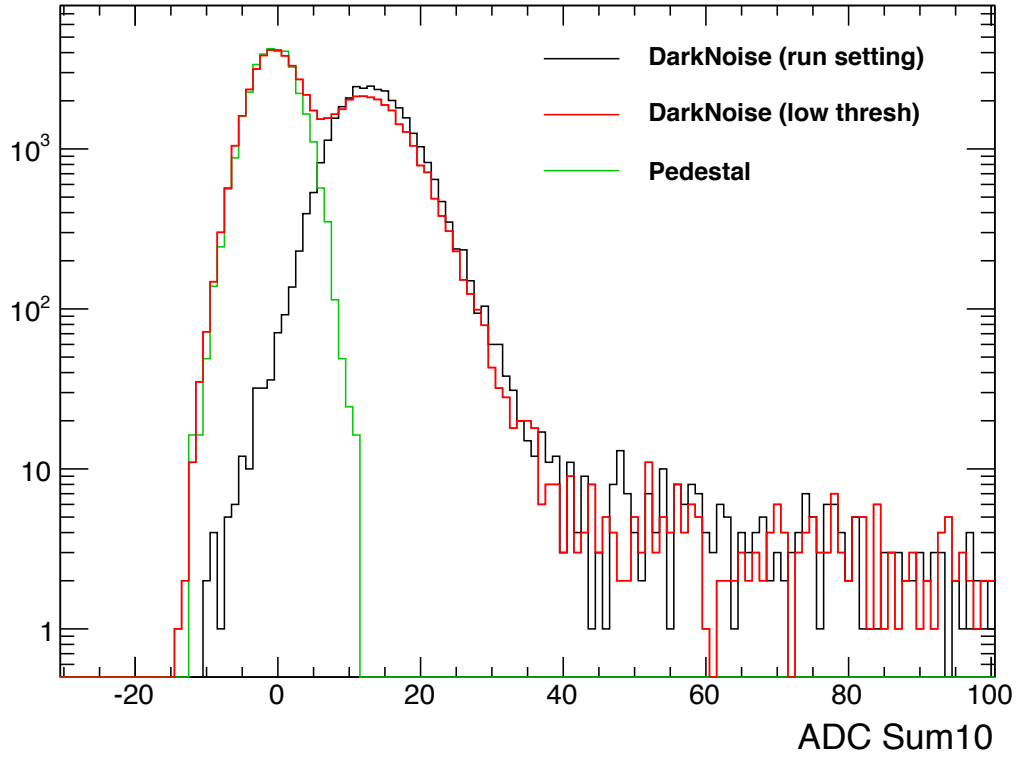
Event Rate

- Small decrease in event rate due to quieting noise
- Abrupt change due to EMI noise



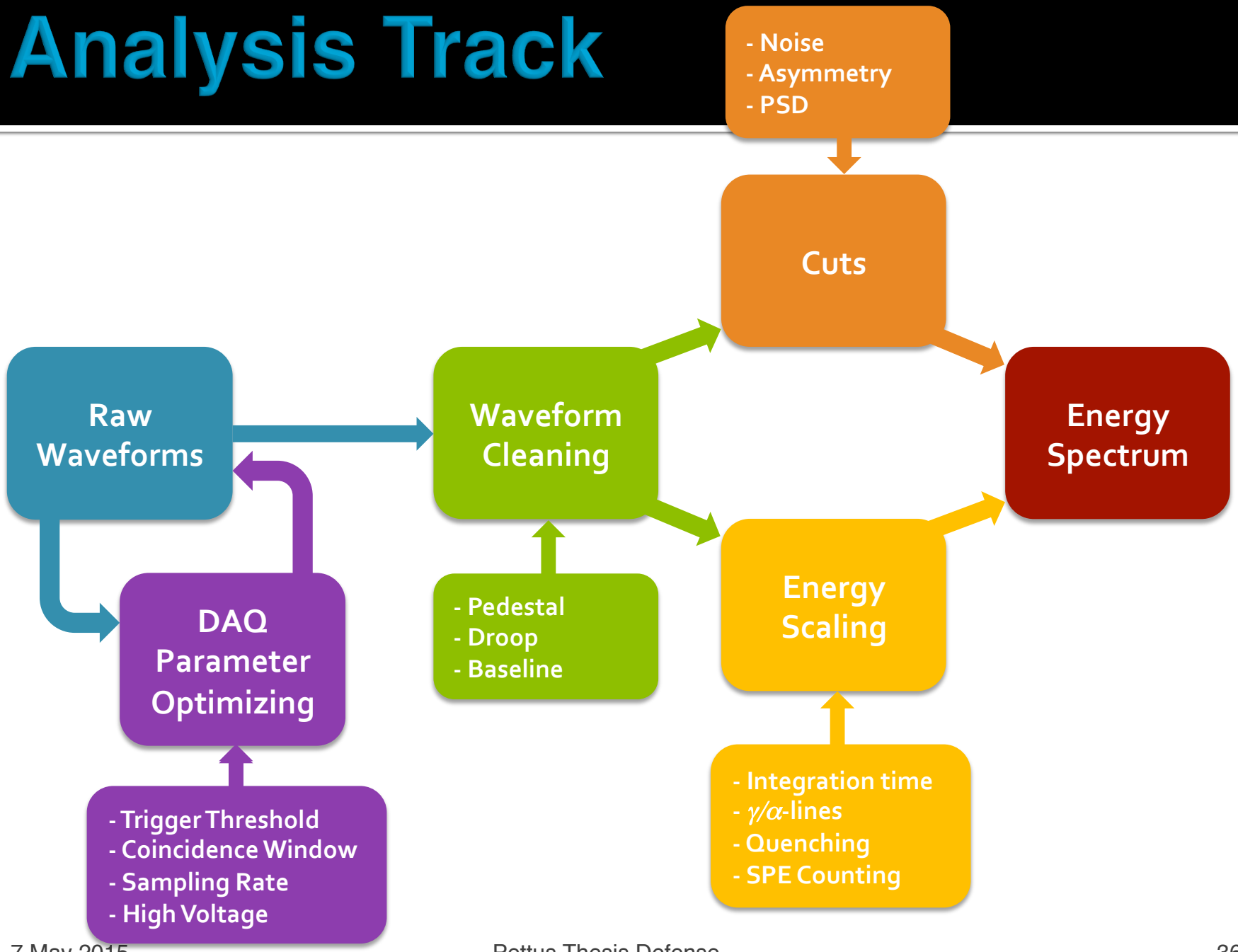
SPE Response

- Only *in situ* calibration is `DarkNoise' to assess single photoelectron response and `Pedestal' to assess digitizer noise



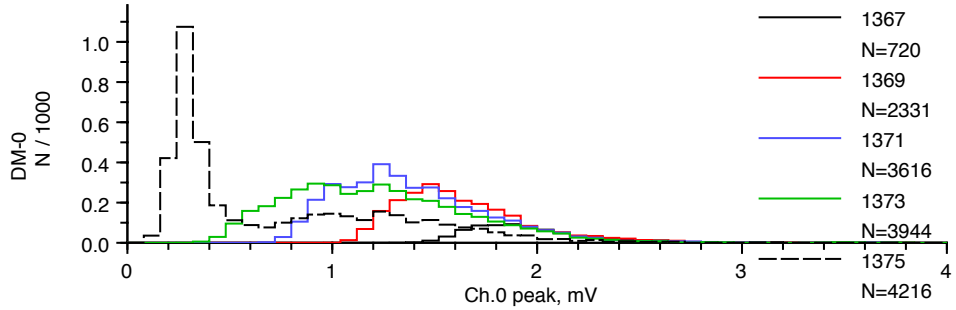
* No evidence of changing SPE over dataset

Analysis Track



Detector Settings

Trigger Threshold:



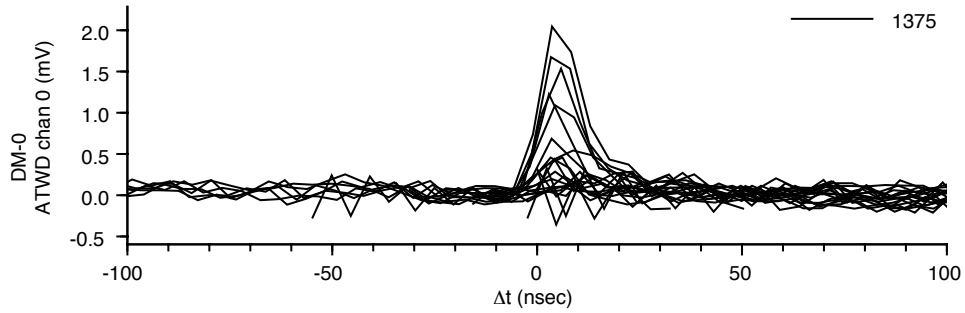
DAC=580
DAC=570
DAC=560
DAC=550
DAC=540

DM-0

	1367	1369	1371	1373	1375	1377	
Mon. records	29	29	29	30	29	29	
MB Temp avg	-6.8	-6.8	-6.8	-6.8	-6.8	-6.8	°C
Pressure avg	91.2	91.2	91.2	91.2	91.2	91.2	kPa
SPE Rate avg	23	72	108	125	271	27	Hz
PMT HV avg	1160	1160	1160	1160	1159	1160	volts

Settings adjusted to optimize low-energy response

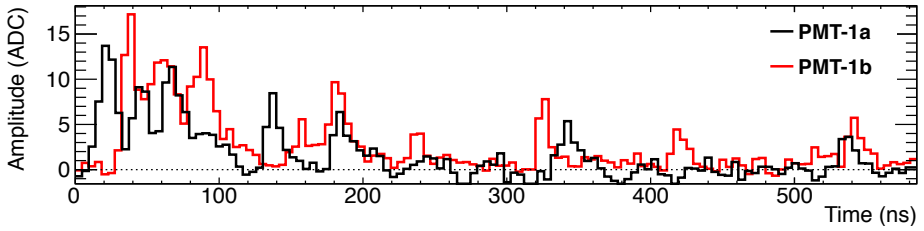
- Threshold at noise-SPE valley
- Dark rates of ~100 Hz



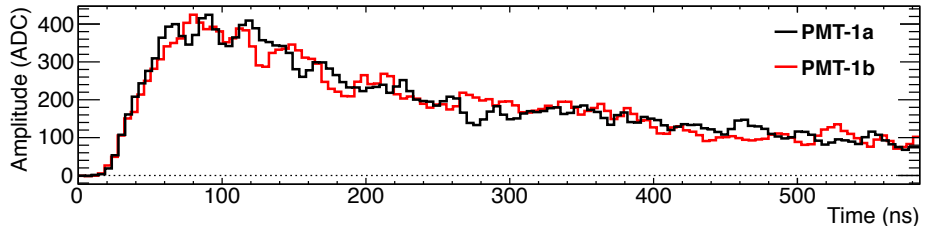
DAC=540

Event Types

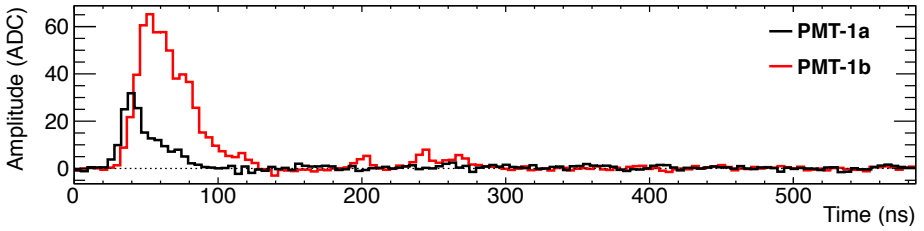
- Low-Energy Scintillation
  - Sequence of SPEs:



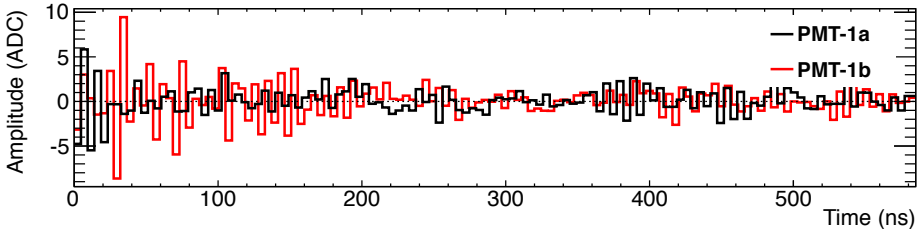
- High-Energy Scintillation
  - SPE structure suppressed
  - Statistics generate exponential decay tail



- Thin Pulse Noise
  - Asymmetric deposition
  - Fast decay tail

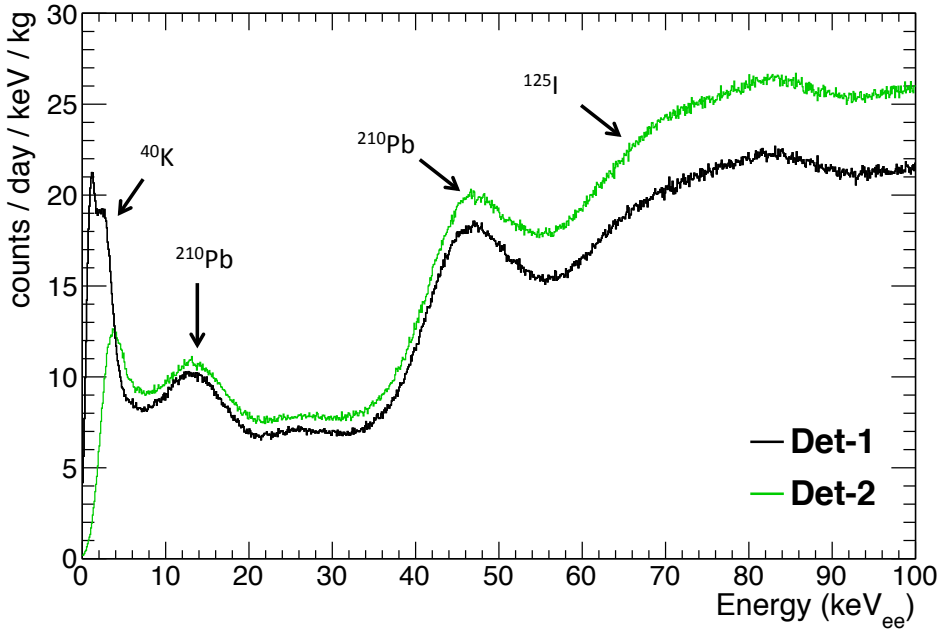


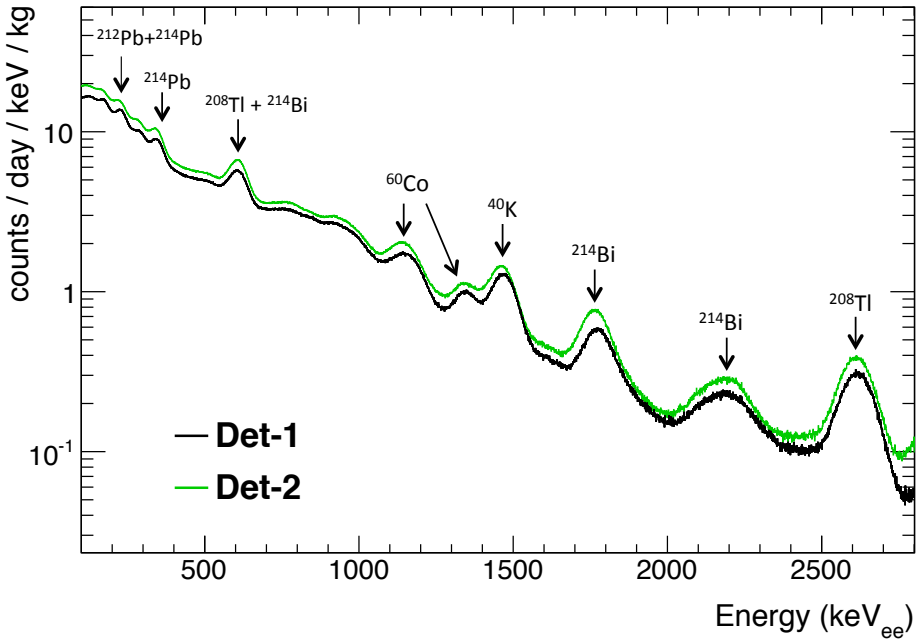
- EMI Noise
  - Oscillatory waveform
  - Zero integrated charge



Energy Spectrum

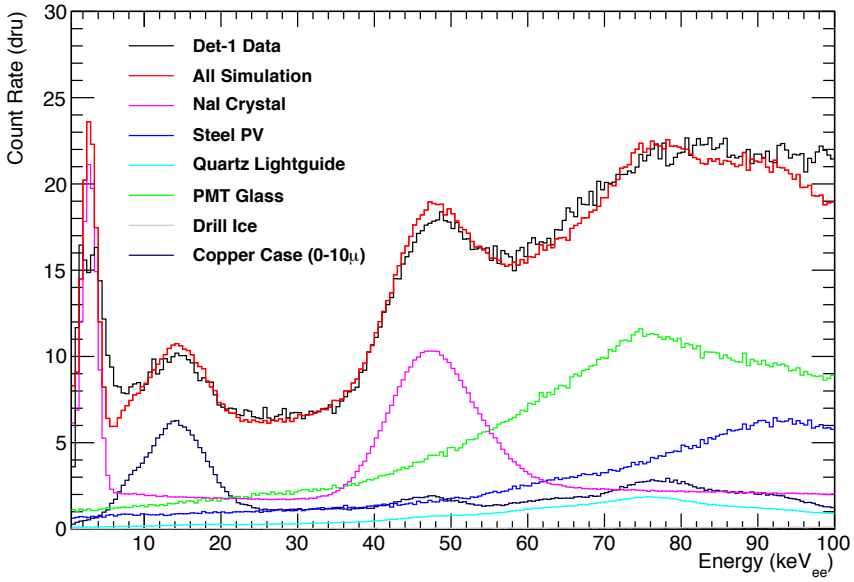
- Separate low (<100 keV) and high energy calibrations
  - Necessitated by non-linear NaI light-response
- Intrinsic and cosmogenic background lines used to calibrate

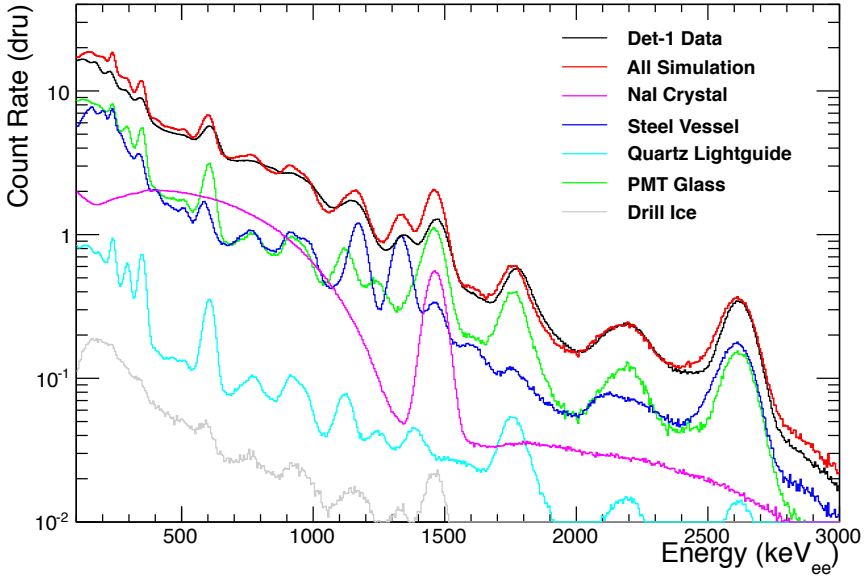




Background Simulation

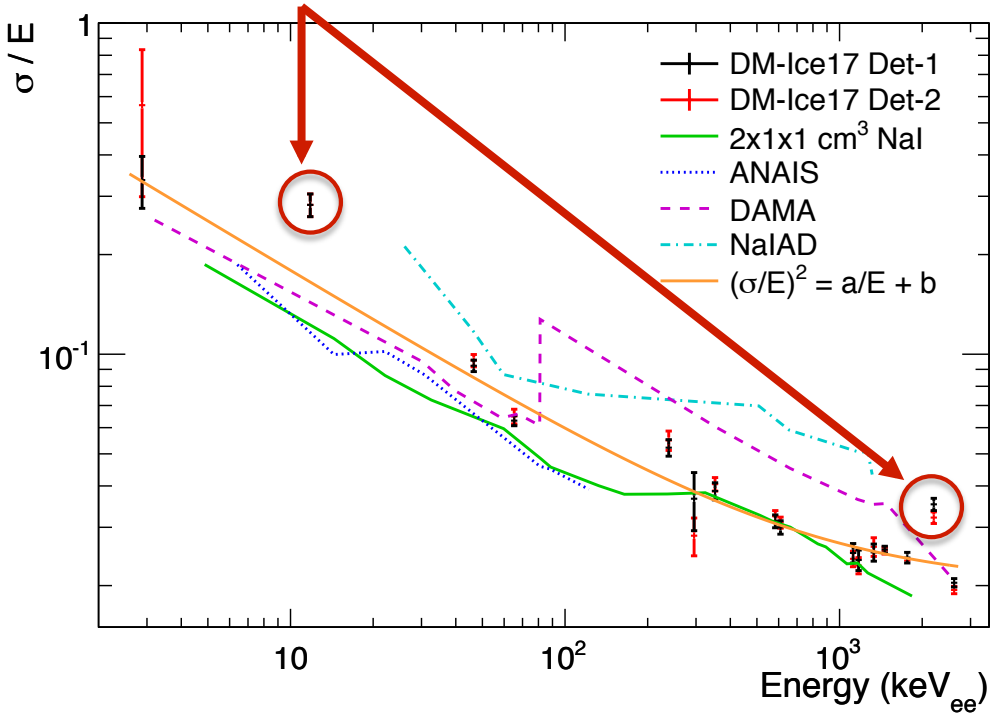
- Intrinsic background model built from:
  - SNOLAB radioassay results (steel, ice, copper, teflon)
  - Literature values (PMT, quartz)
  - Data match (NaI, copper surface)





Energy Resolution

- Resolution assessed from same background peaks giving calibration
  - Comparable resolution to other NaI experiments
  - Subject to broadening from overlapping features



Outline

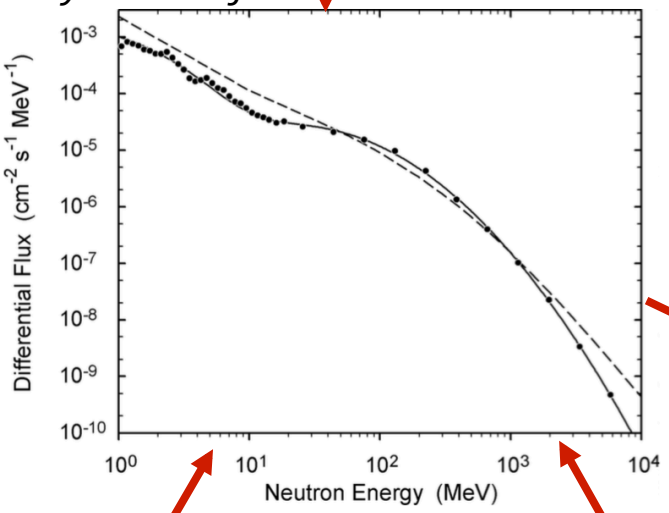
- Dark Matter Physics & Detection
- DM-ICE17 Experiment
- Cosmogenic Activation
- DM-ICE250 Experiment

publication in preparation

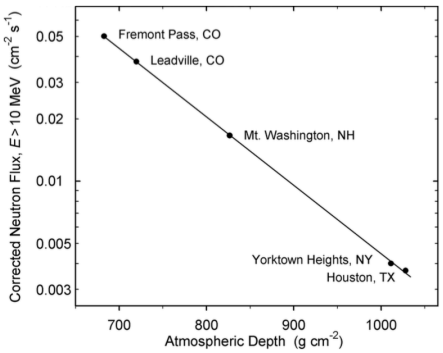
Cosmogenic Activation

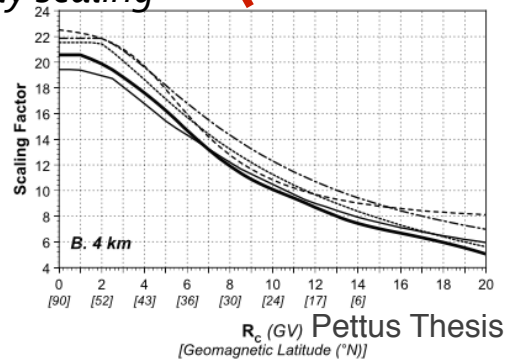
$$R \propto \int \phi_n(E) \cdot \sigma(E) \cdot dE$$

cosmic ray neutron flux:



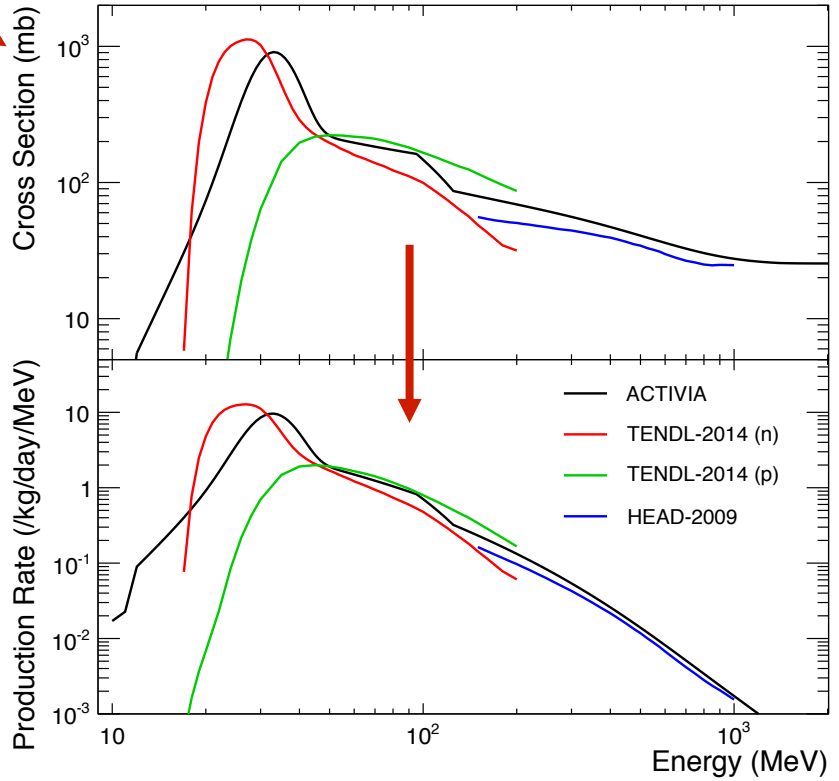
cosmic ray scaling





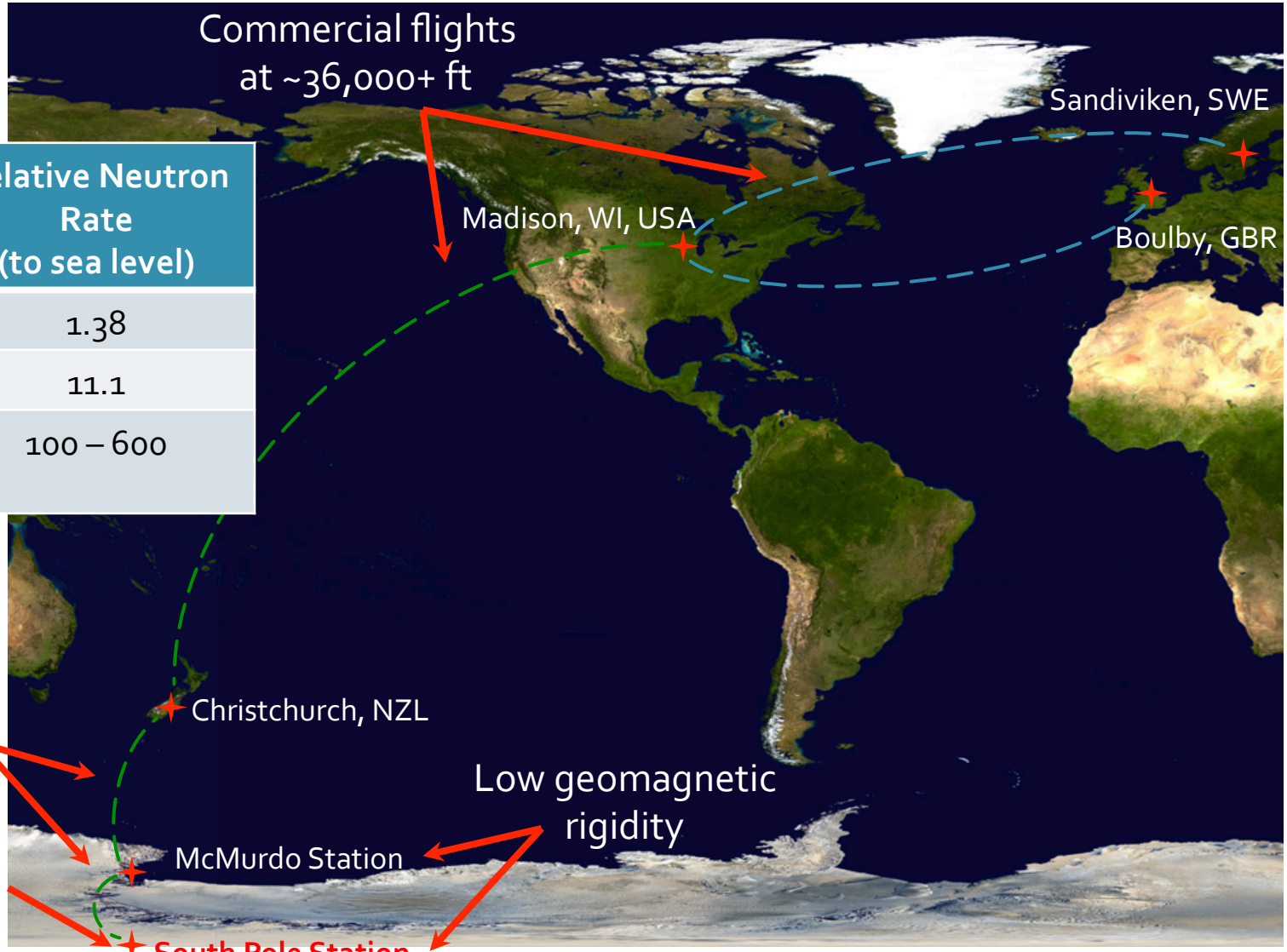
Isotopes of interest identified from ACTIVIA activation code

- Cross section validated from evaluated libraries



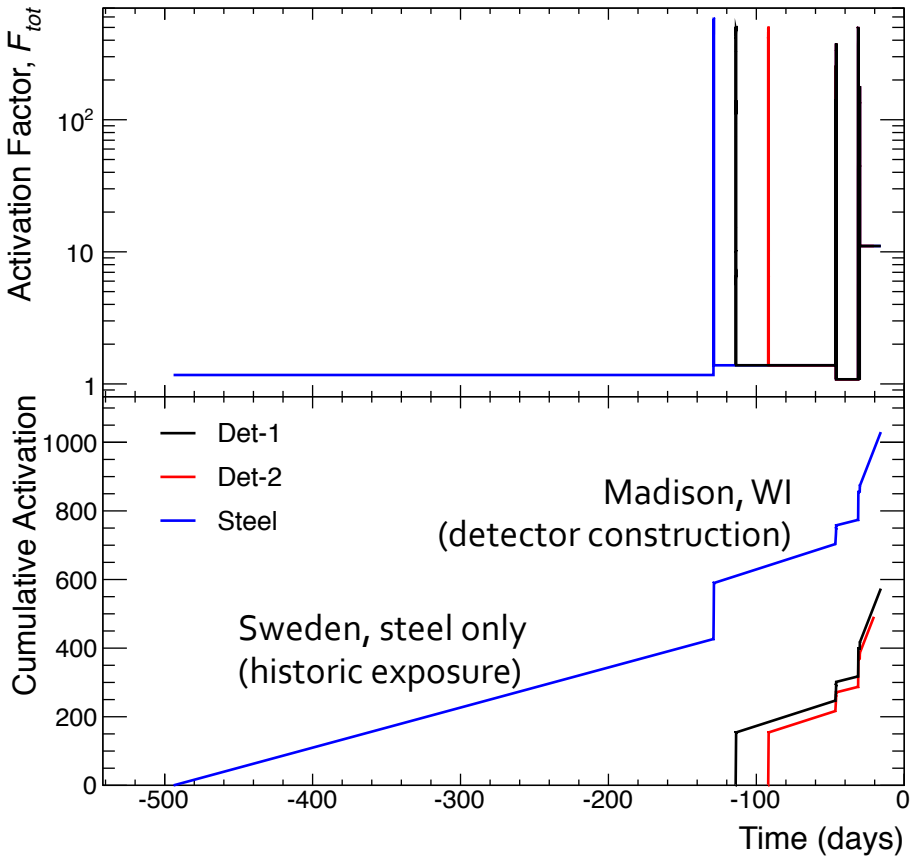
Cosmogenic Activation Hazards

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



Cosmic Ray Exposure Timeline

Full Detector Component History



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

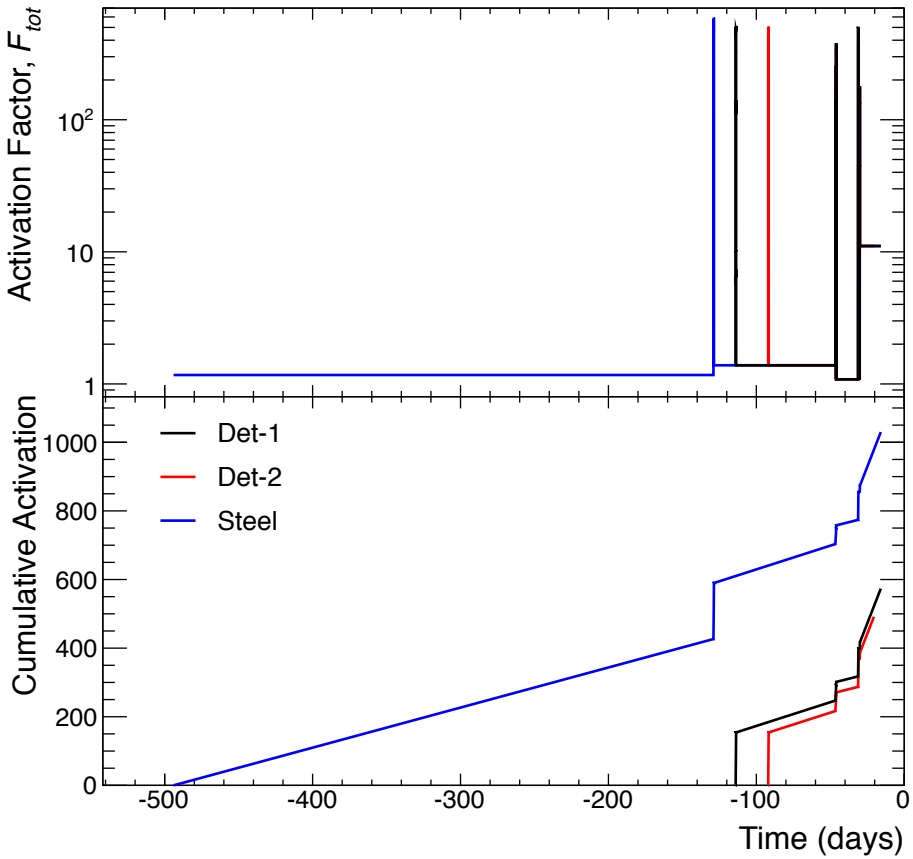
- Long periods of low-level exposure during storage and construction
- Punctuated exposure from flight shipment

"Cumulative Activation" – Time-integrated neutron flux scaling

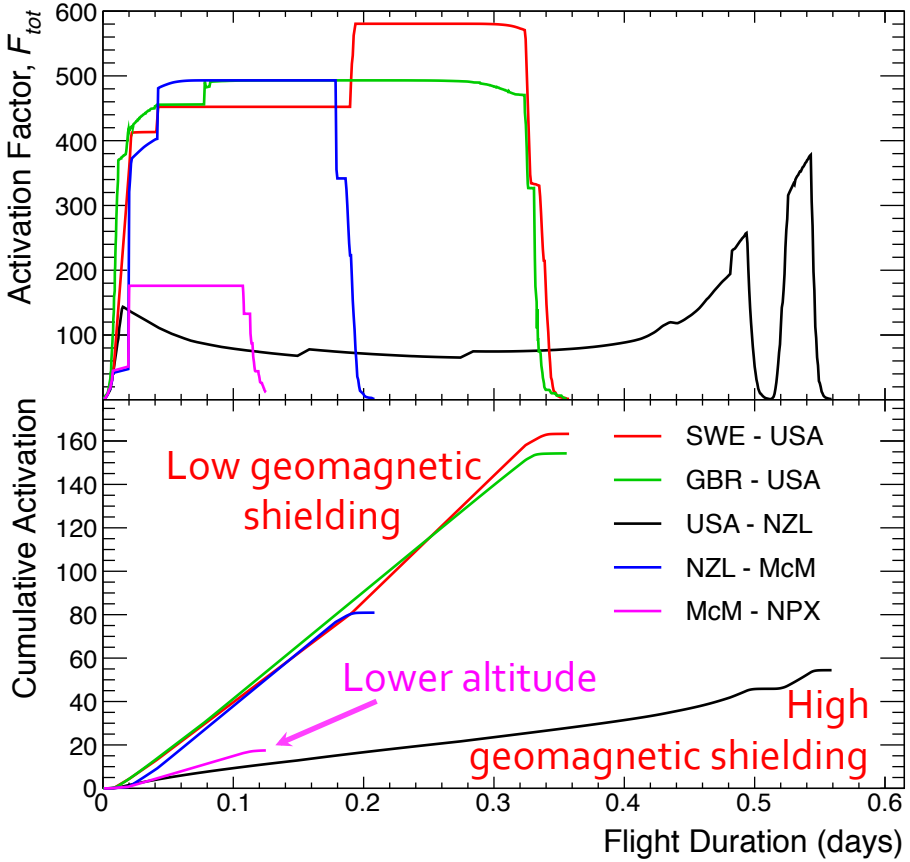
- Different detector components have different exposure histories
- Two DM-Ice17 detectors have different deployment times

Cosmic Ray Exposure Timeline

Full Detector Component History



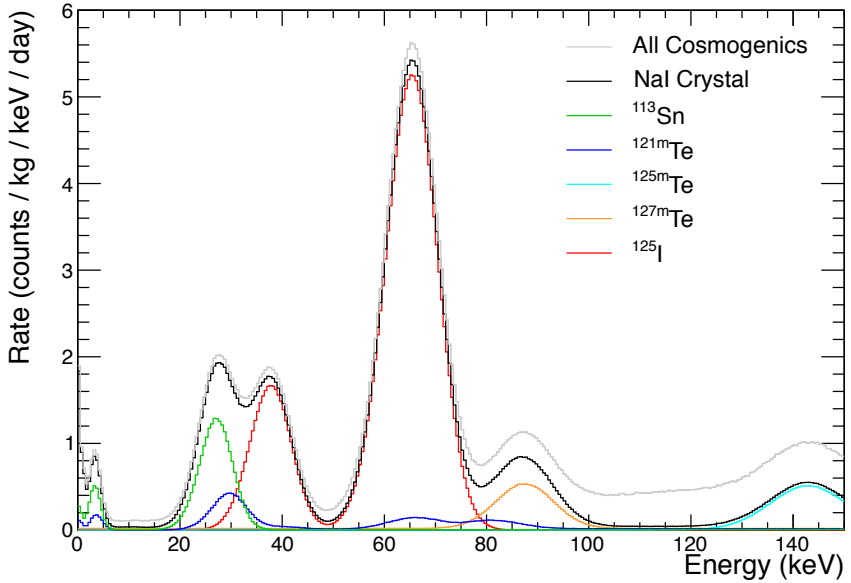
Flight Segments

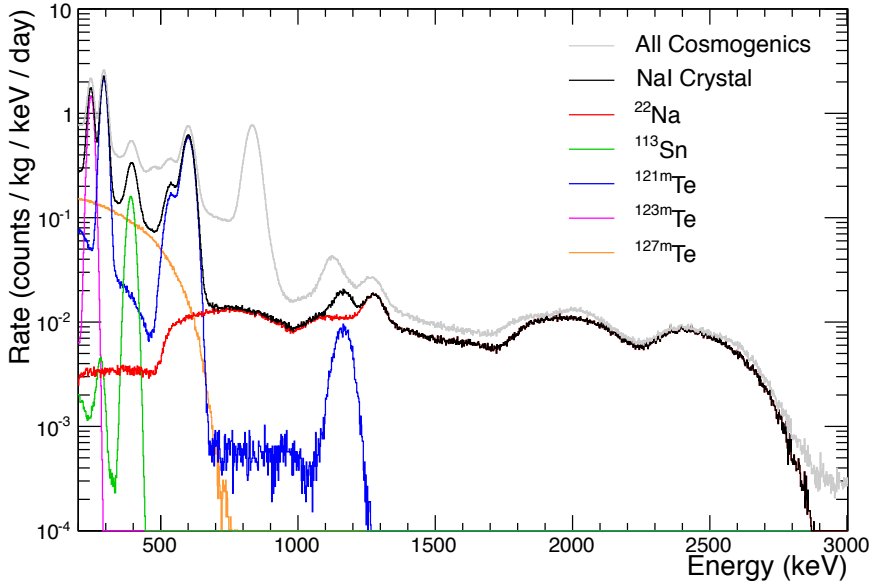


But decay not included: $\lambda N = R \cdot \left(1 - e^{-\lambda t}\right)$

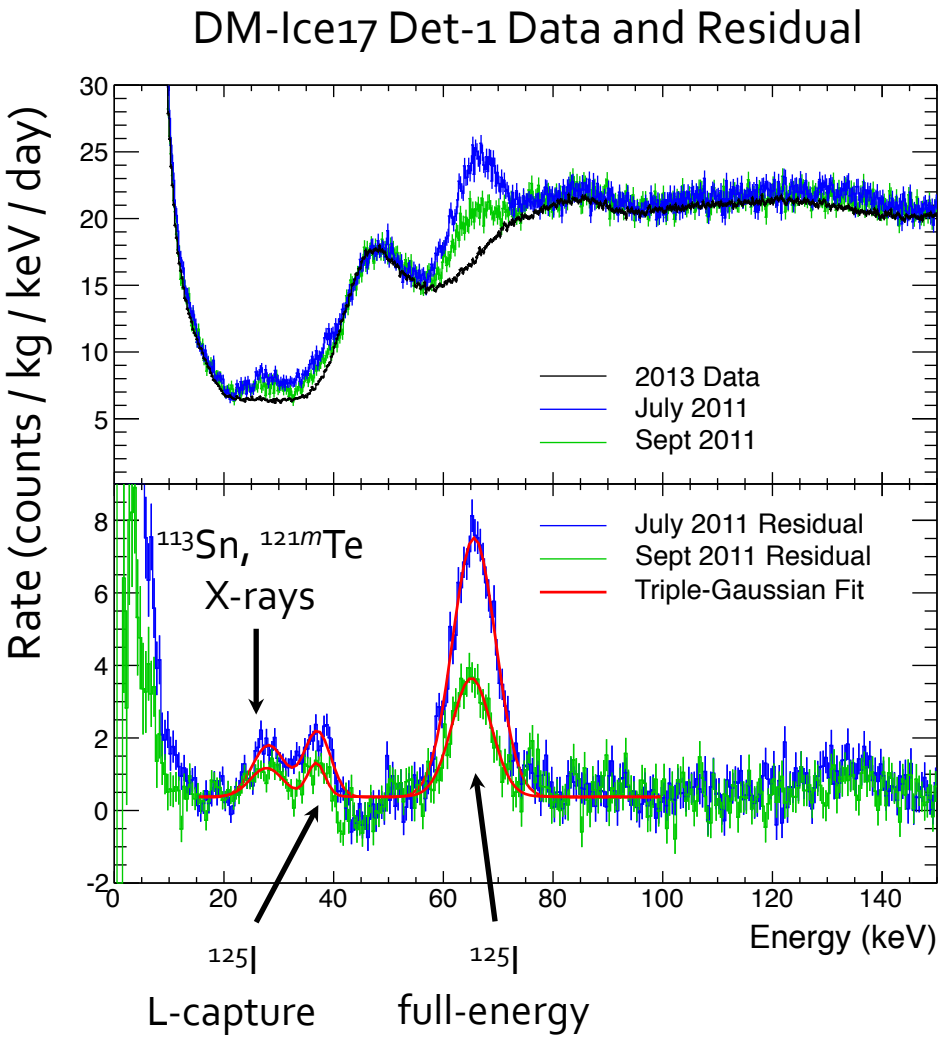
Cosmogenic Prediction

- 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



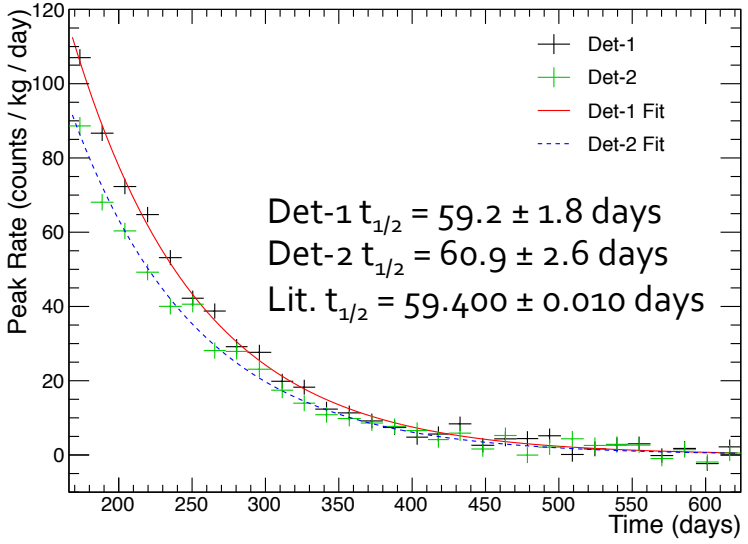


Cosmogenic Decay Peaks



Confirm identity of cosmogenic peaks:

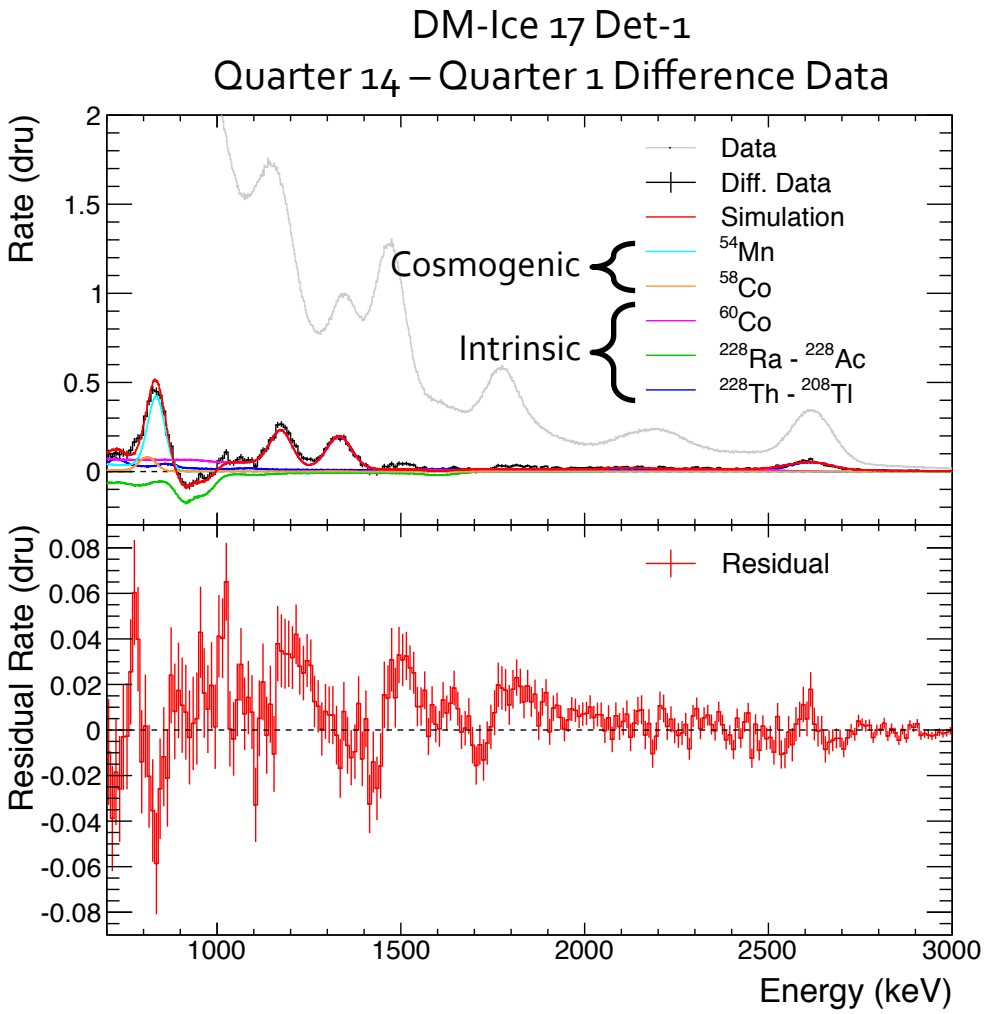
- Match simulated spectral features
  - Expect 65.3 keV full-energy and 37.6 keV L-shell capture peaks for ^{125}I
- Measuring decay time
  - Expect 59.4 day half-life for ^{125}I



High-Energy Spectrum

Examining changing spectrum at high-energy

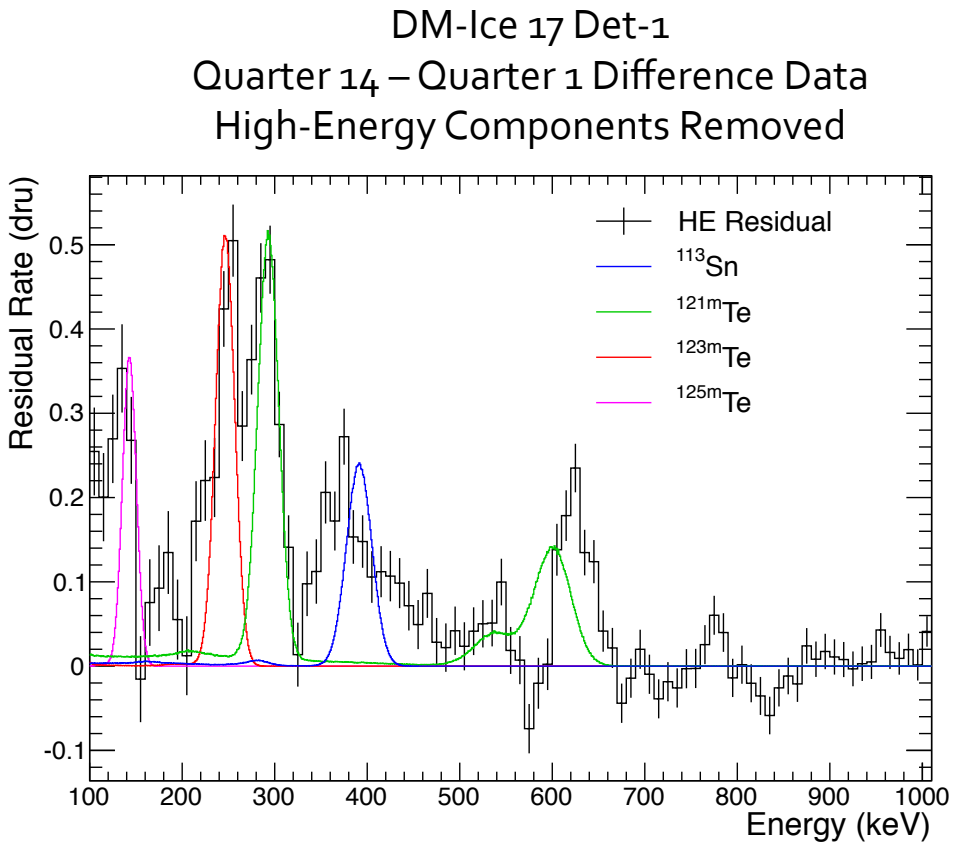
- Demonstrates presence of cosmogenic decays
  - ^{54}Mn ($t_{1/2}$ = 312 days) and ^{58}Co ($t_{1/2}$ = 71 days)
- Reveals decay of intrinsic contaminants
  - ^{60}Co ($t_{1/2}$ = 5.3 yr) in steel pressure vessel
  - Maximally broken ^{232}Th-chain in steel



Medium-Energy Spectrum

100–700 keV spectrum

- Dominated by NaI cosmogenics
  - ^{113}Sn ($t_{1/2}$ = 115 days), ^{121m}Te ($t_{1/2}$ = 164 days), ^{123m}Te ($t_{1/2}$ = 119 days), and ^{125m}Te ($t_{1/2}$ = 57.4 days)
- Calibration uncertainty prevents quantitative analysis



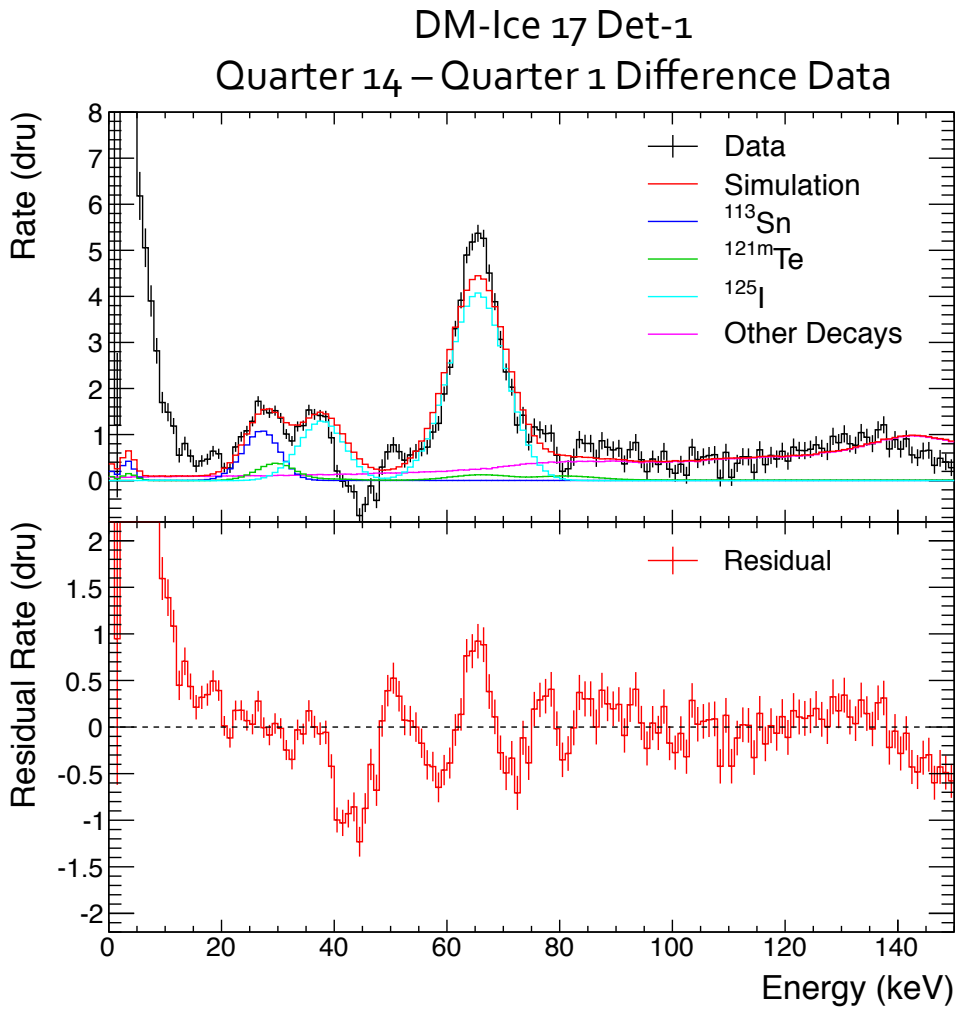
Low-Energy Spectrum

Low-energy spectrum has fewer features, but all cosmogenic:

- ^{125}I ($t_{1/2}$ = 59 days)
  - only low-energy features
- ^{113}Sn ($t_{1/2}$ = 115 days) and ^{121m}Te ($t_{1/2}$ = 164 days)
  - Constrained by peaks at 200 – 700 keV

Provides feedback to energy resolution for simulation

- Significant overestimate for both ^{125}I peaks

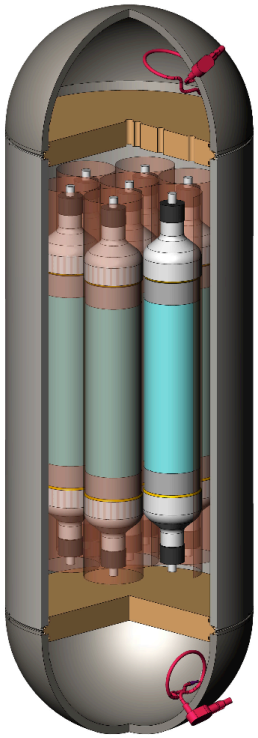


Outline

- Dark Matter Physics & Detection
- DM-ICE17 Experiment
- Cosmogenic Activation
- DM-ICE250 Experiment

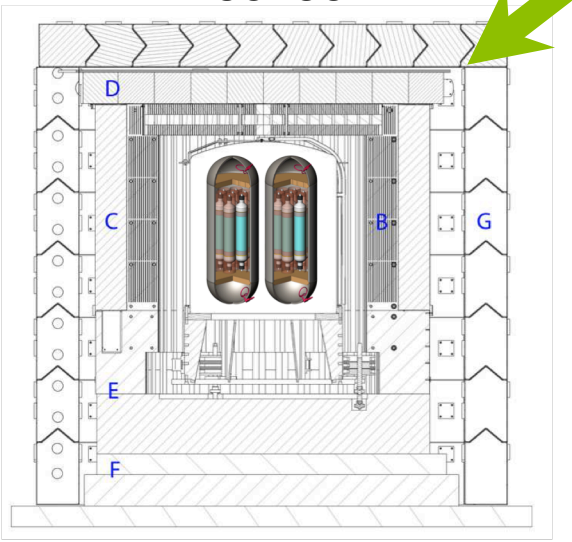
DM-Ice250 Experimental Program

Modular detector supporting deployment in both hemispheres

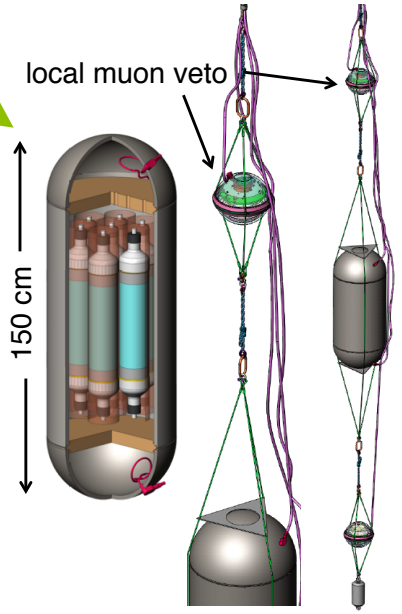


- 125 kg NaI(Tl) / module
- 7-crystal array
  - Coincidence between PMTs
  - Anti-coincidence between crystals

DM-Ice250N

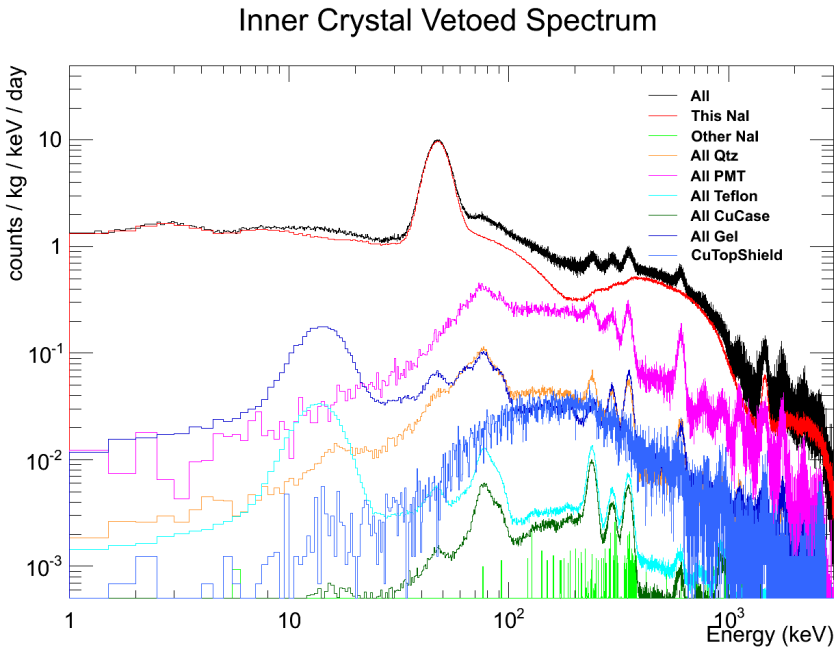


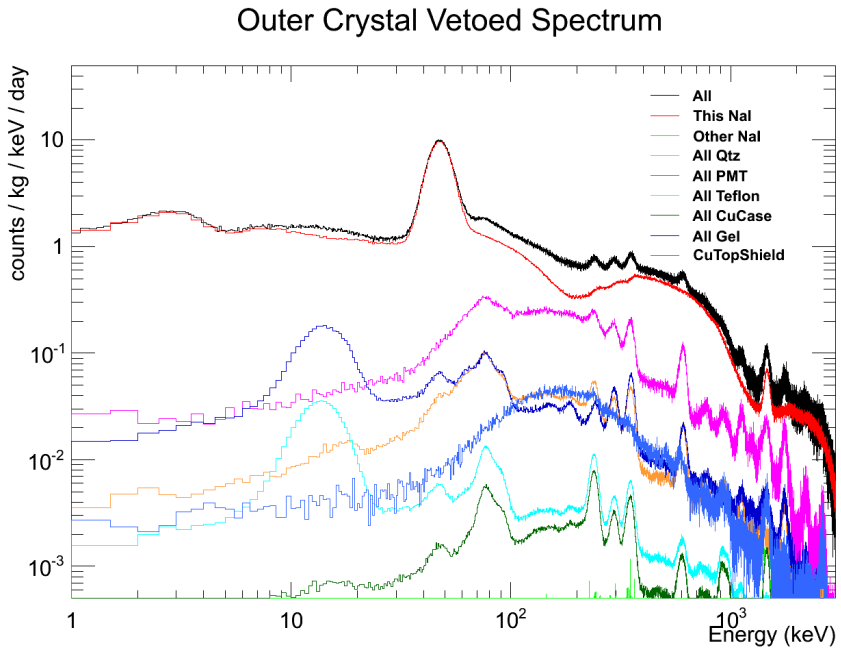
DM-Ice250S



Background Simulation

- Inner and outer crystals simulated separately
  - More efficient anti-coincidence veto for inner crystal removes more low-energy background
  - Crystal backgrounds dominate at all energies

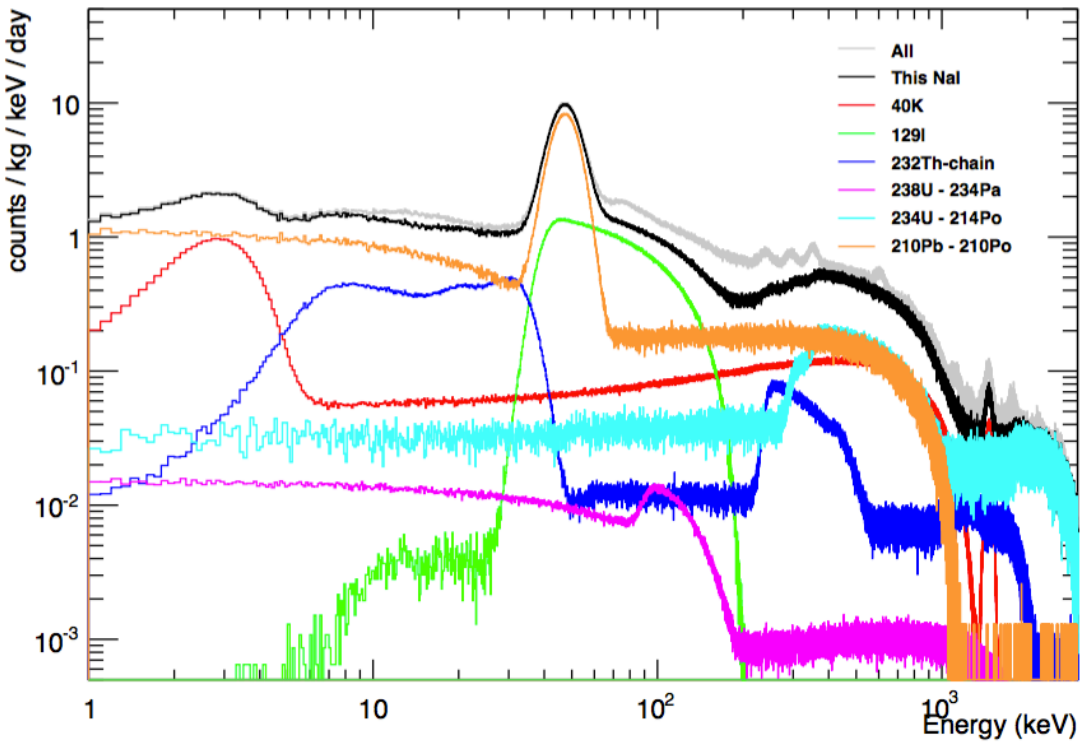




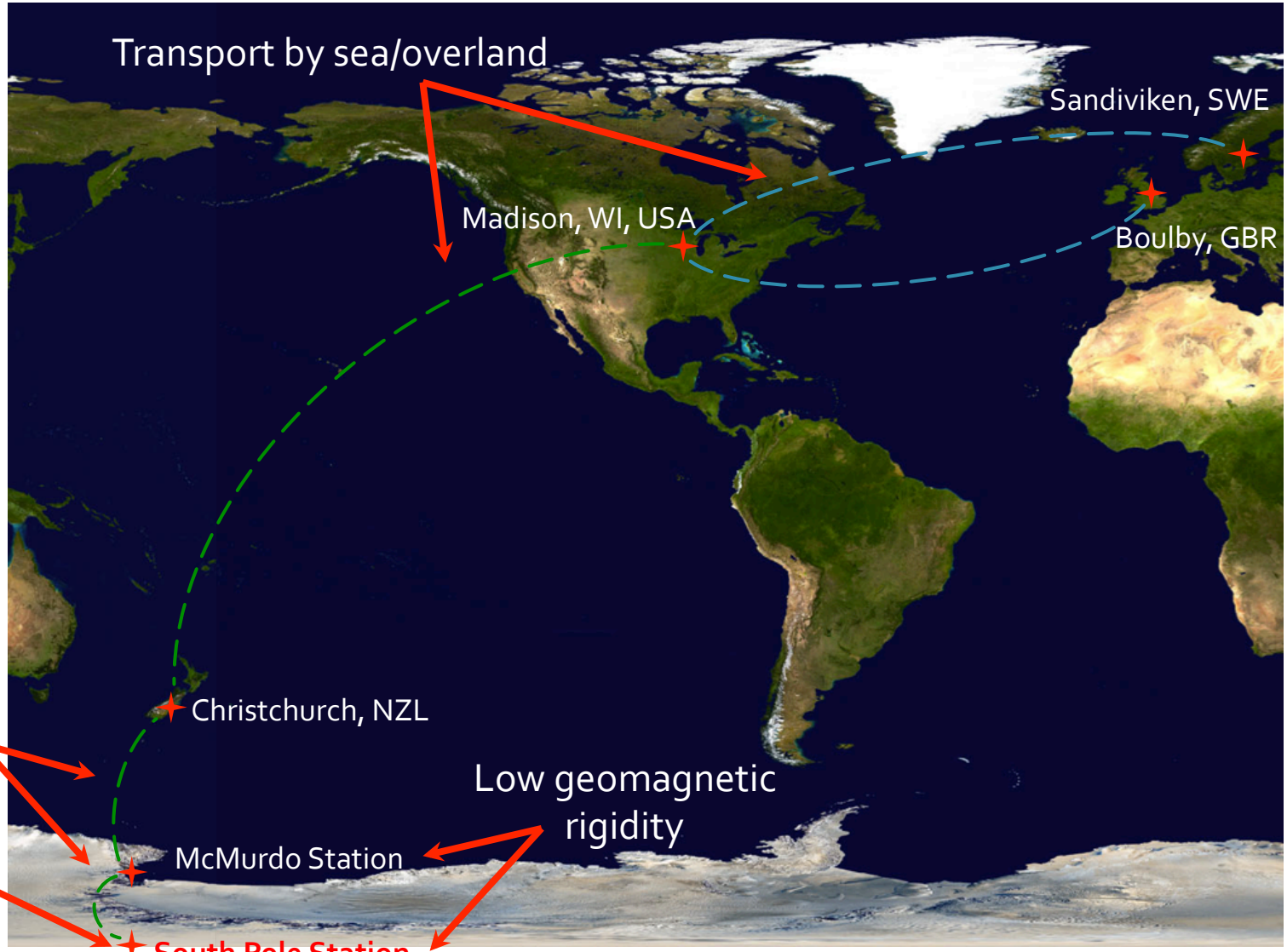
NaI Background Simulation

- Low-energy crystal background from both ^{40}K and ^{210}Pb (^{238}U-chain)
  - Further crystal R&D necessary to validate NaI background model

Outer Crystal, Vetoed NaI background only



DM-Ice250S Activation



Polar program flights remain

Reduce storage time at 9,301 ft

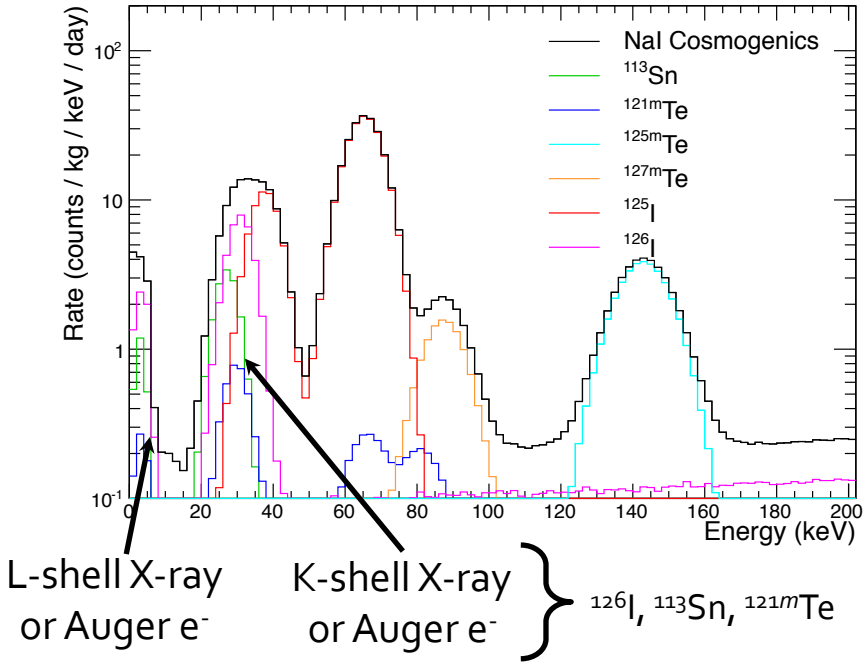
DM-Ice250S Cosmogenics

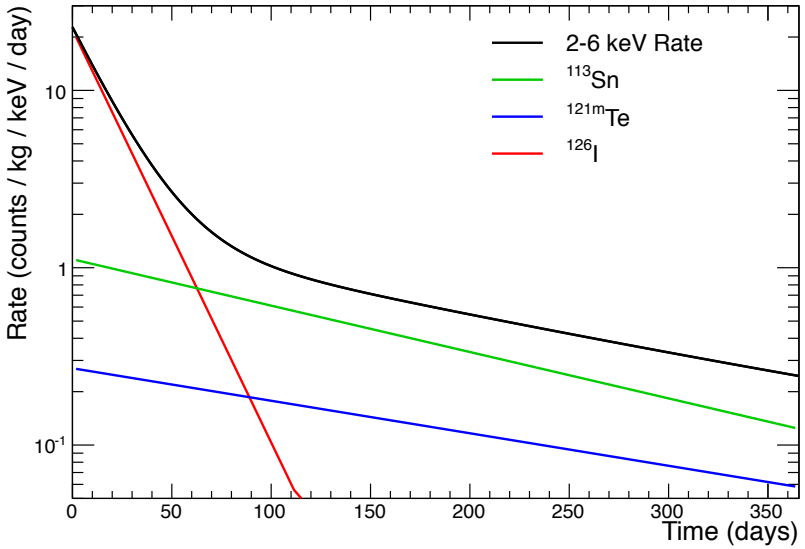
Event rate one month after deployment

- 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

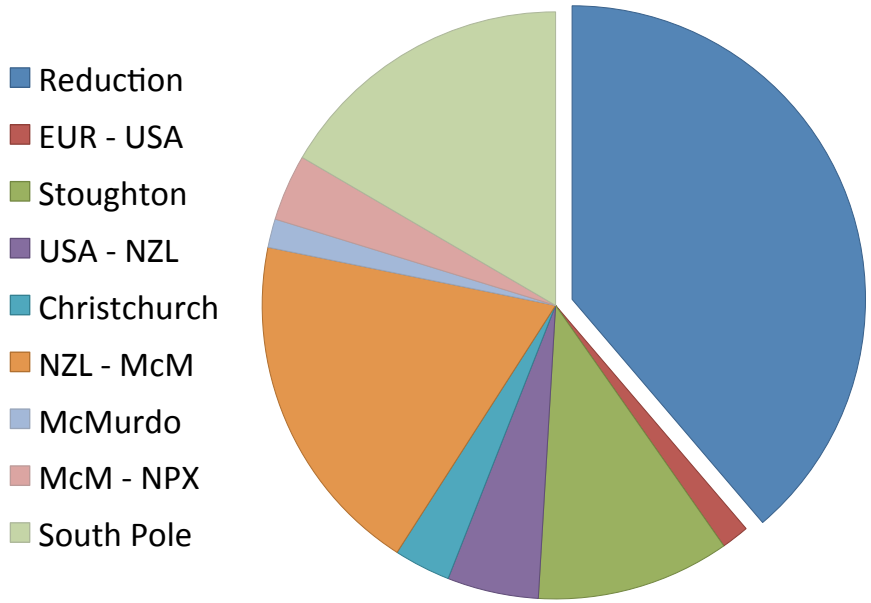




Cosmogenic Mitigation

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

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



Further reductions:

- 50% reduction in low-altitude NZL-McM flight (10% of total)

Low altitude (LC-130):

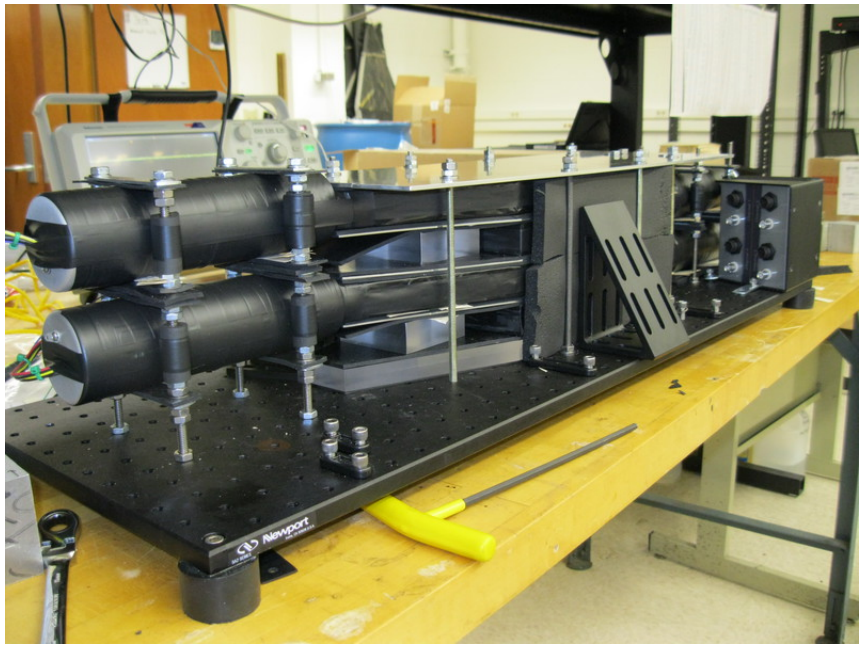


High altitude (C-17):



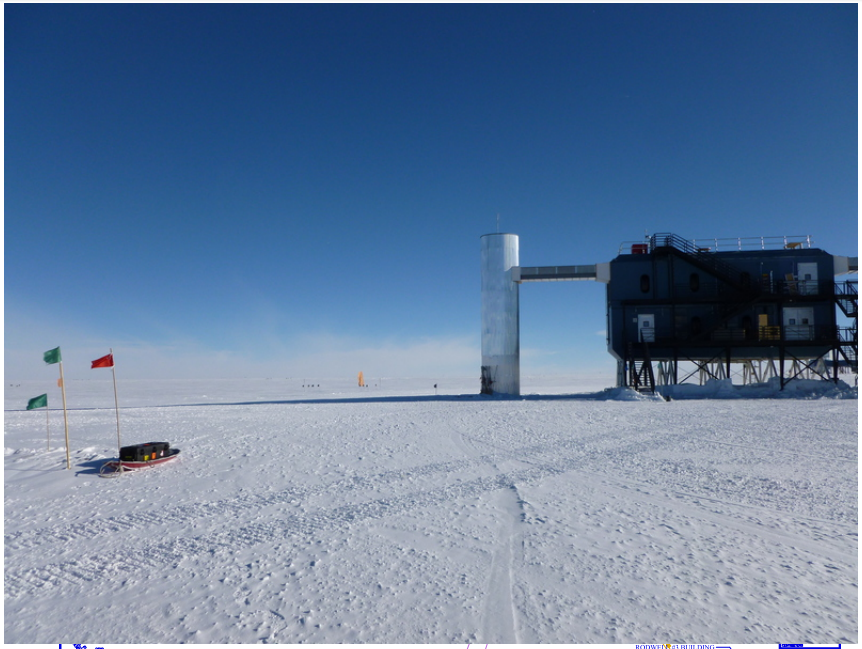
Measuring Overburden

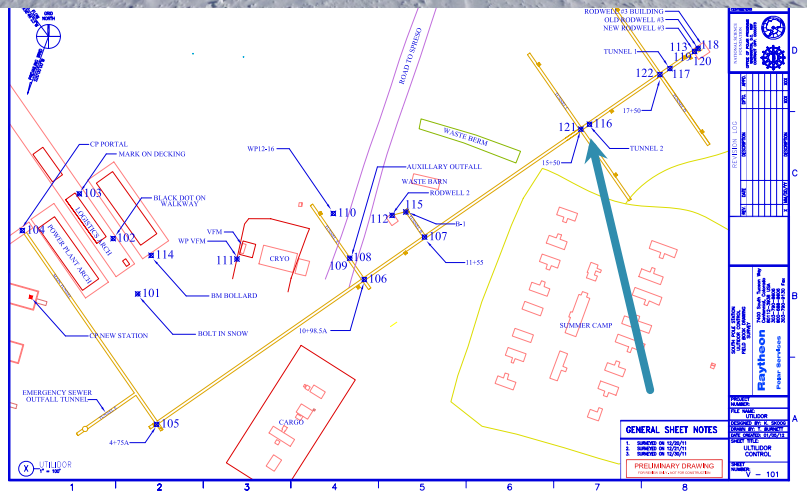
- Muon detector built for measuring flux at potential Polar storage locations
  - Plastic scintillator (EJ200) sensitive volume
    - 25 mm thickness for larger signal
  - Coincidence capability between four paddles





South Pole Storage





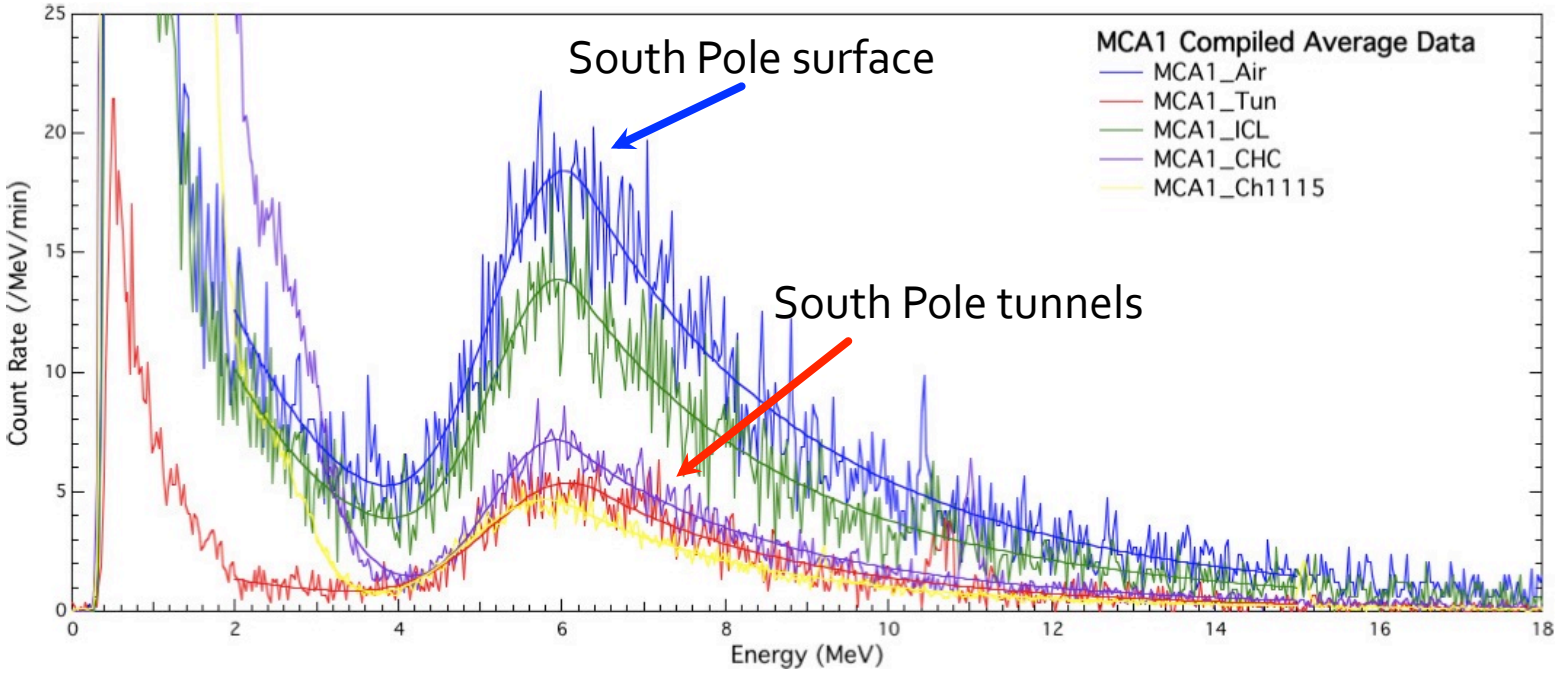
Limited overburden options

- Best choice is tunnels
  - 40-50 ft of firn
  - ~7 m.w.e.



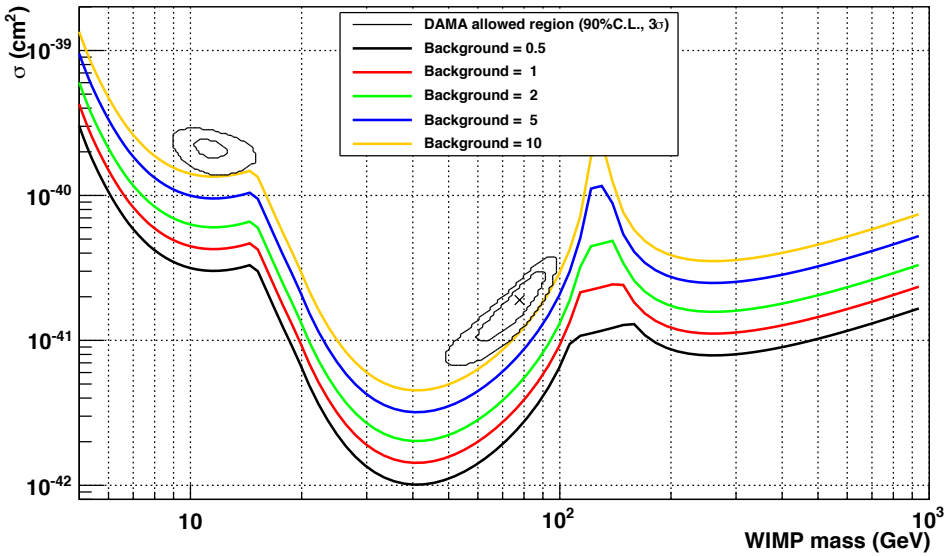
Muon flux reduction

- Muon spectra comparison of South Pole sites with Christchurch and Madison data
  - Tunnel storage provides reduction in cosmic ray flux to sea level (factor of 10 reduction for neutrons)

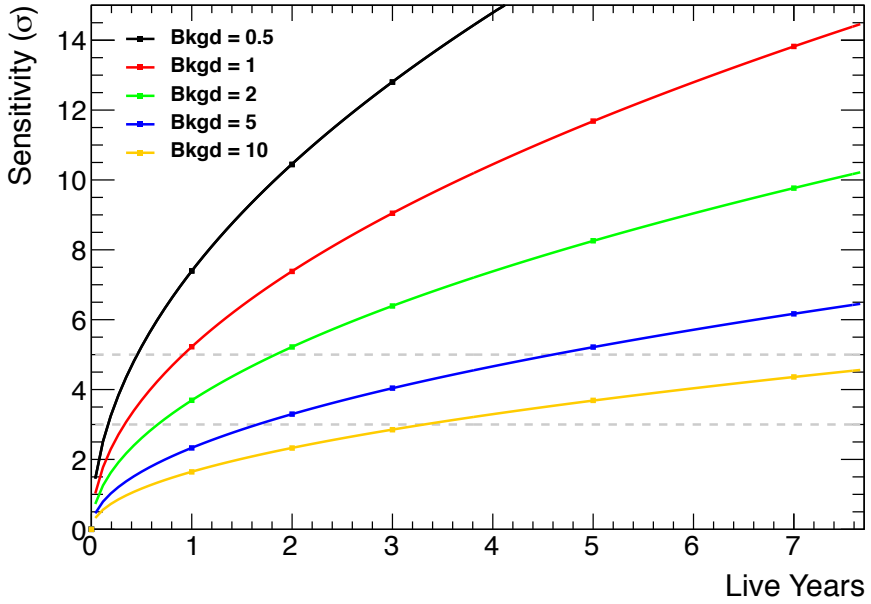


Sensitivity Projection

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



Null 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

Conclusions

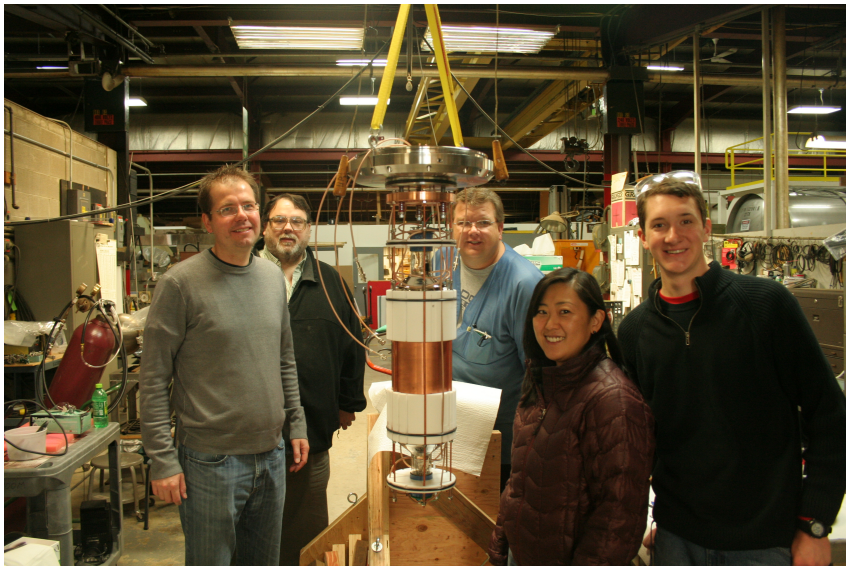
- DM-Ice17 has completed its 3.5-yr science run with 99% uptime and excellent stability
  - Trailblazer for future rare event searches in South Pole ice
- Cosmogenic isotopes have been identified contributing to the detector background
  - Activation model is verified by the rates of these radionuclides
  - An additional isotope, ^{113}Sn, was identified with dominant contribution to ROI over experimental run
- Simulation work demonstrates capability to test DAMA dark matter claim with DM-Ice250
  - Intrinsic backgrounds dominated by crystal purity, but < 2 dru
  - Cosmogenic activation from South Pole deployment can be mitigated to not affect science potential

Acknowledgements

Advisors:
Karsten Heeger, Reina Maruyama, & Francis Halzen

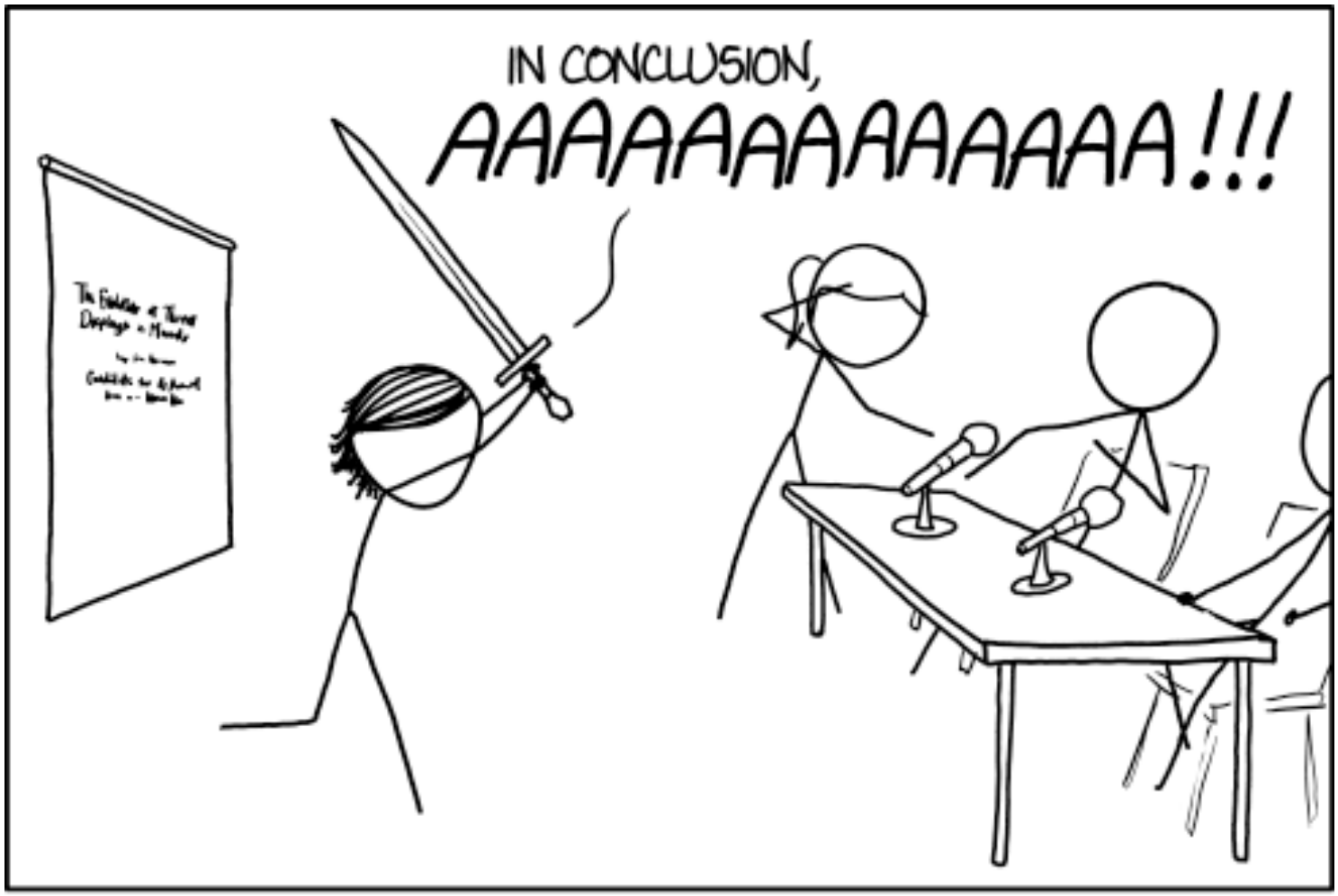
Colleagues:
Matt Kauer, Antonia Hubbard, & Zack Pierpoint

Krell Institute, WIPAC, Wright Lab





Questions


IN CONCLUSION,
AAAAAAAAAAAAAA!!!
THE BEST THESIS DEFENSE IS A GOOD THESIS OFFENSE.