Walter C. Pettus
Yale University
25 January 2015



The DM-Ice Dark Matter Experiment

Outline

- Dark Matter Introduction
- DM-ICE17 Experiment
- COSINE and DM-ICE250

Understanding the Universe

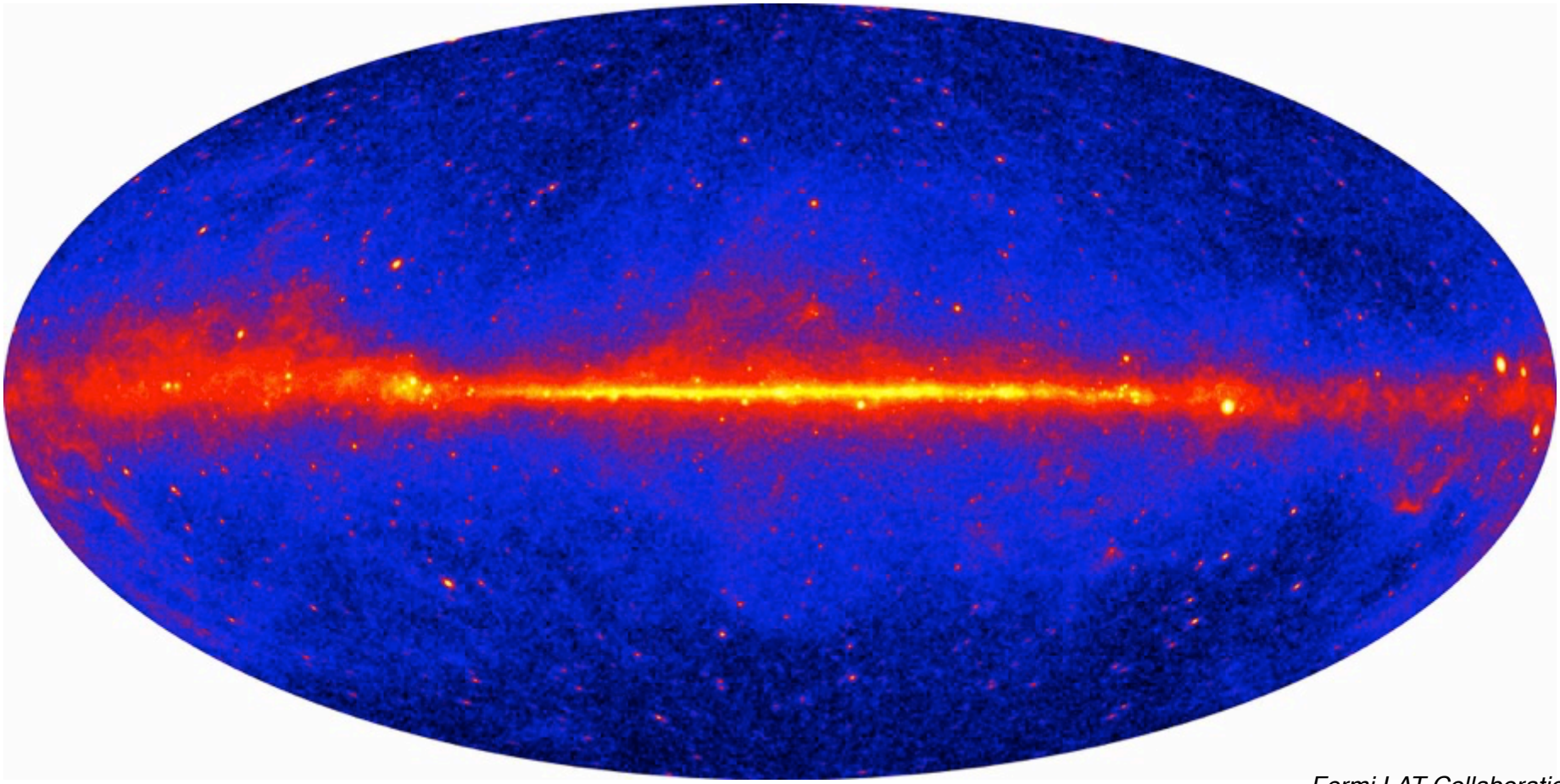
Visible Sky



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

Understanding the Universe

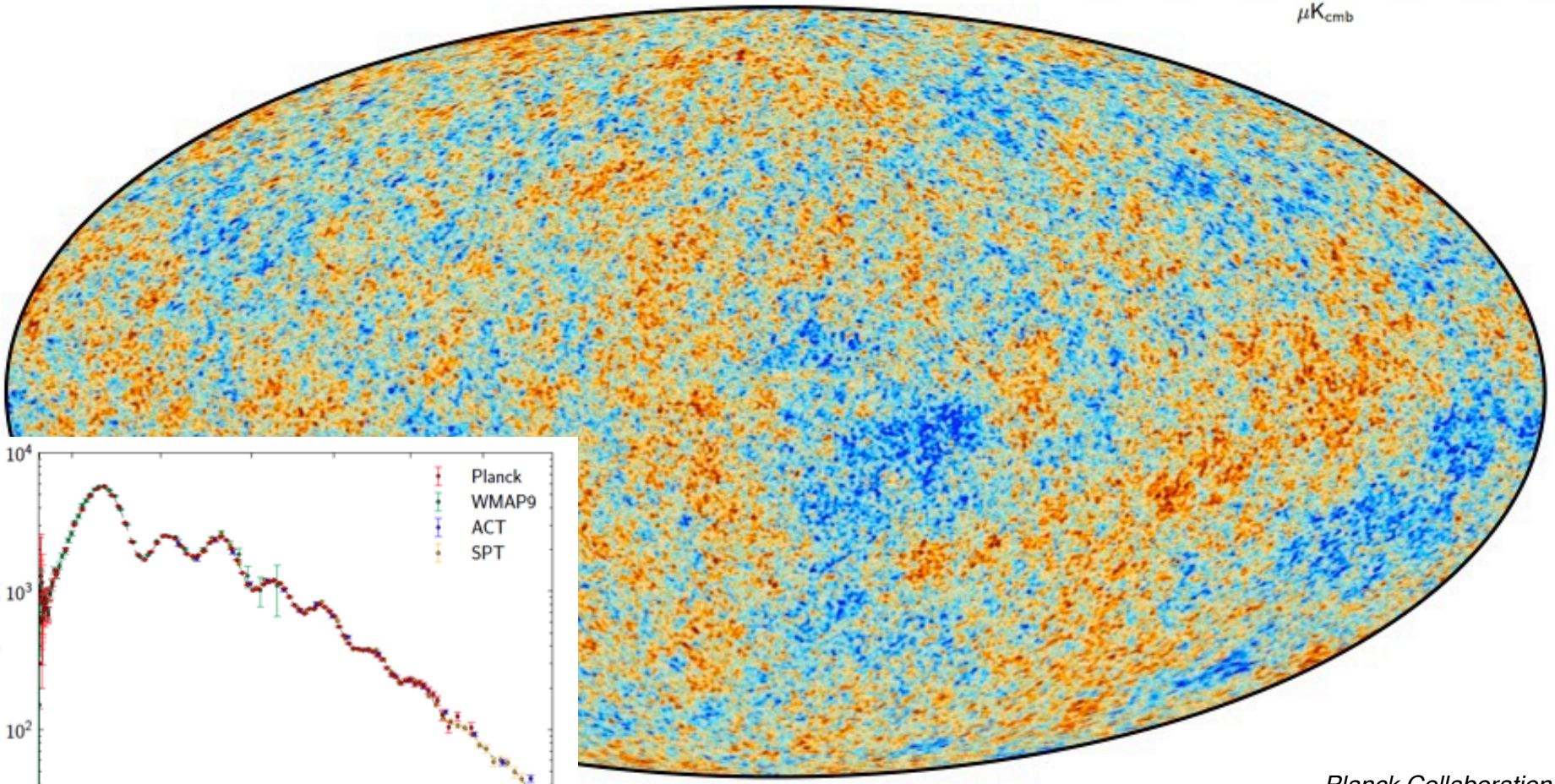
Gamma Ray Sky



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

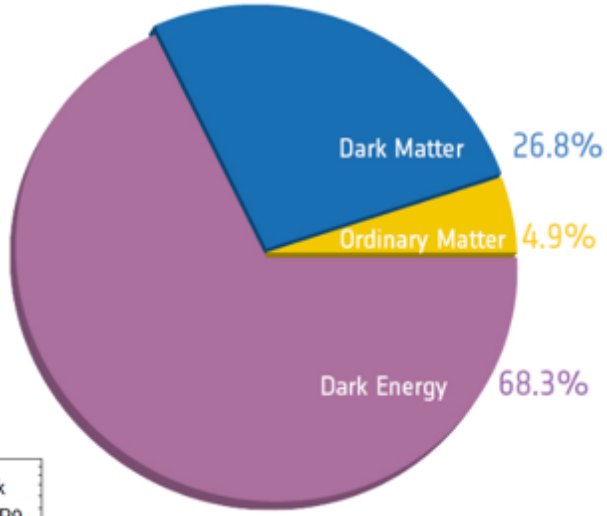
Understanding the Universe

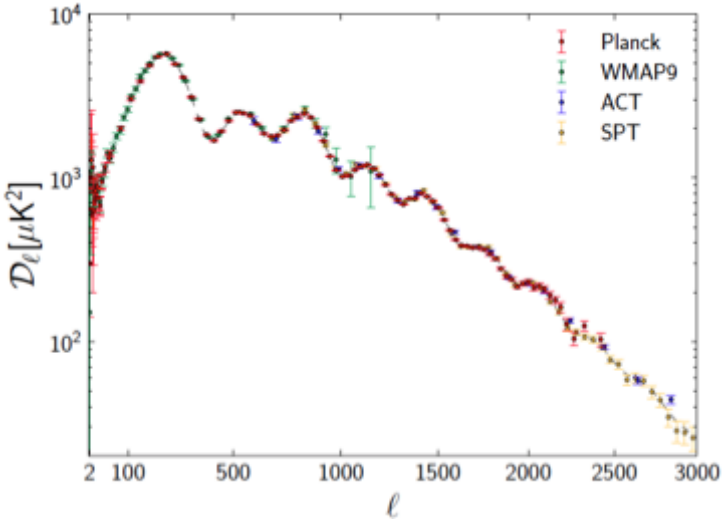
Microwave Sky

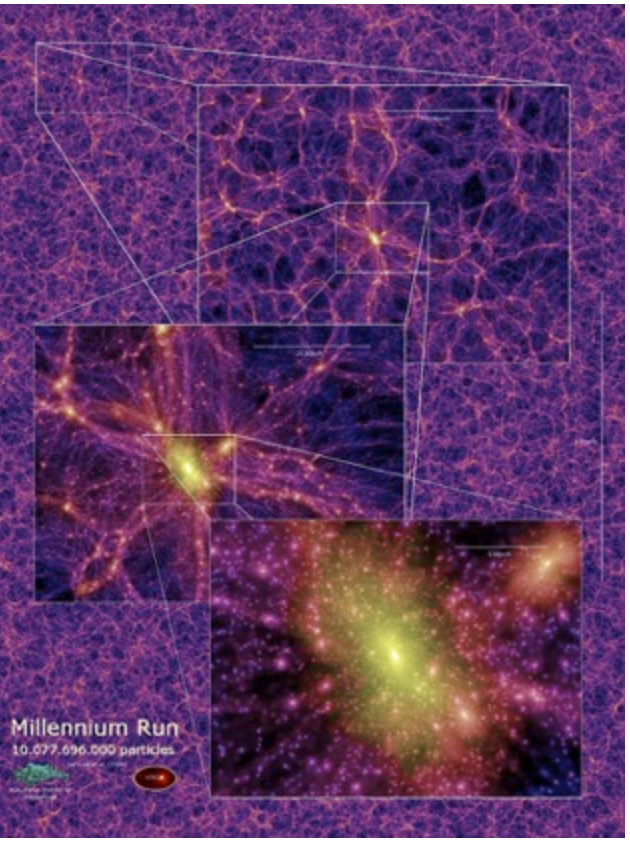


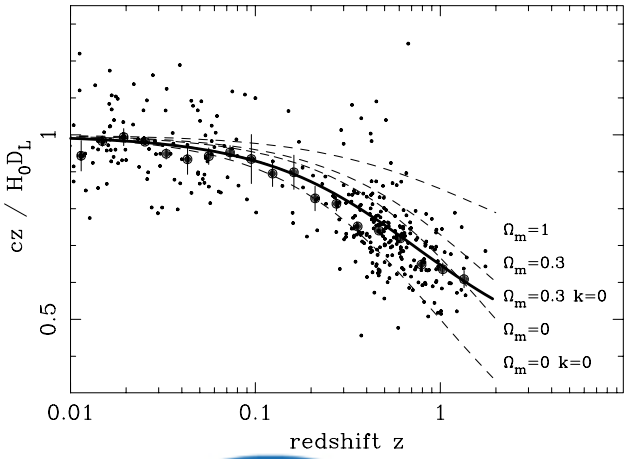
Planck Collaboration, [arXiv:1502.01582]

A Dark Universe

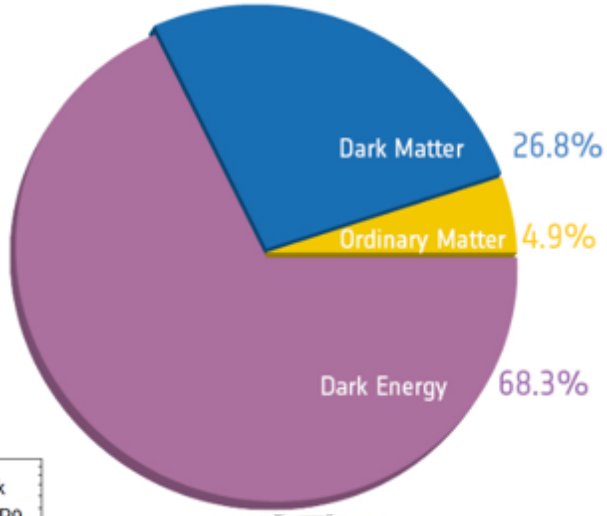


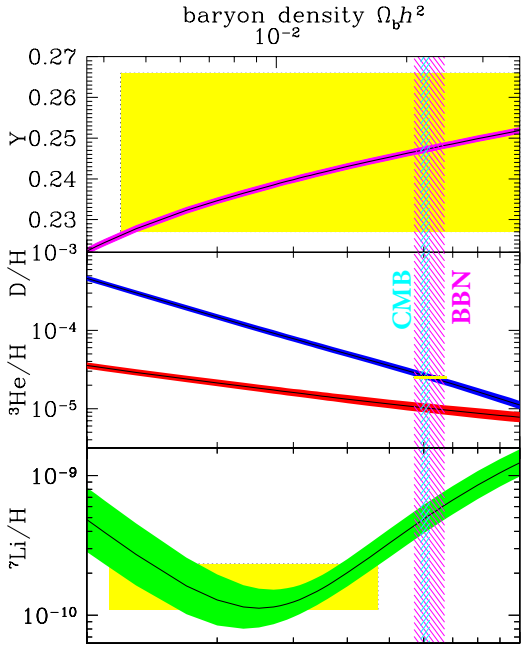


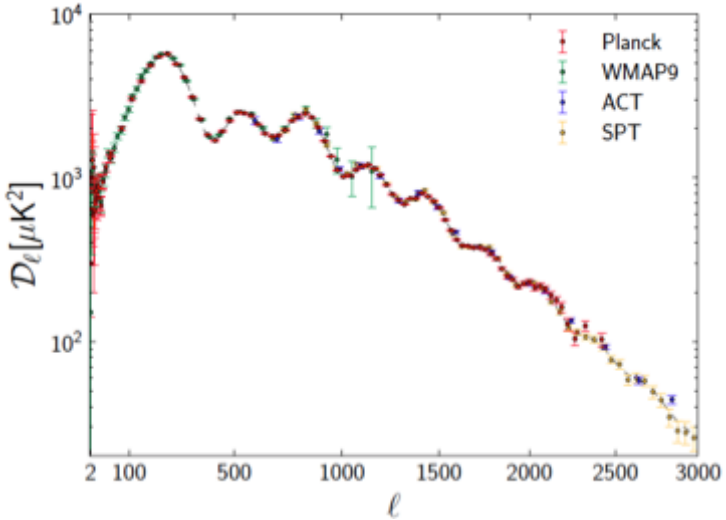

Millennium Run
10,077,696,000 particles

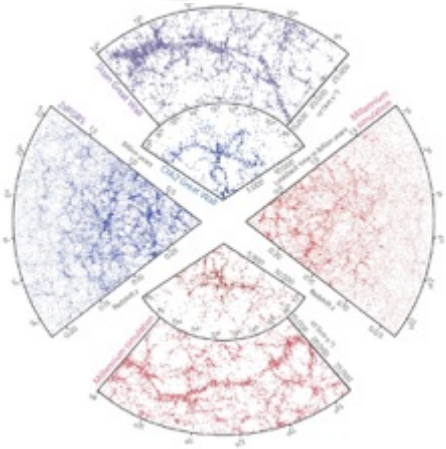

cz / H0DL
redshift z
0.01
0.1
1
0.5
1
Ωm=1
Ωm=0.3
Ωm=0.3 k=0
Ωm=0
Ωm=0 k=0

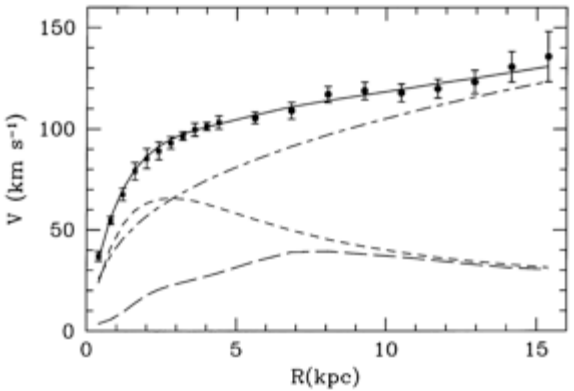



Dark Matter
26.8%
Ordinary Matter
4.9%
Dark Energy
68.3%


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
Dℓ[μK2]
ℓ
2
100
500
1000
1500
2000
2500
3000



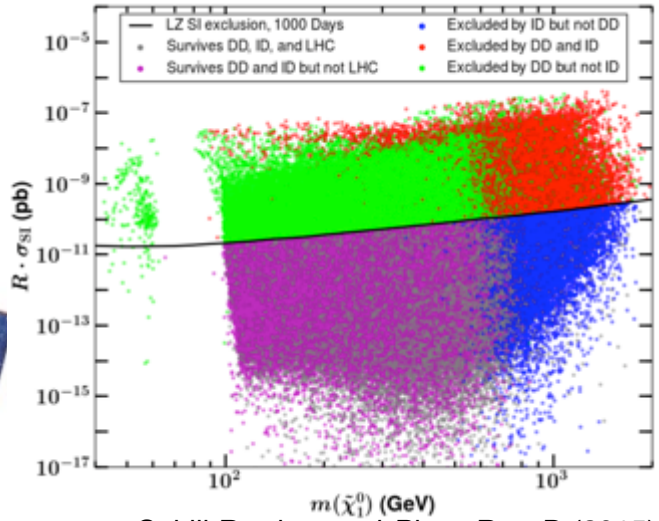

V (km s-1)
R(kpc)
0
50
100
150
0
5
10
15

Detecting Dark Matter

Indirect Searches

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





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

Collider Searches

- Identify production signatures of dark matter in collision



Direct Searches

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



Event Rates and Cross Section

Event rate dependence:

- velocity distribution
- local WIMP density
- scattering cross section

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

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

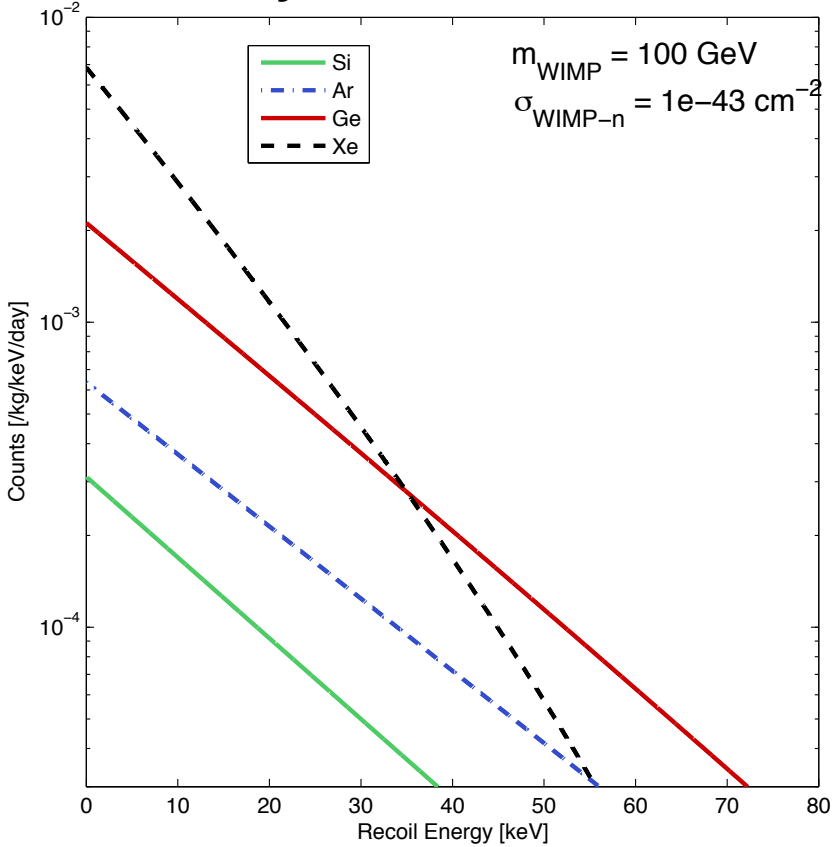
Astrophysics:
$\rho_0 \approx 0.3$ GeV/cm^3
$v_{rms} \approx 270$ km/s
$v_{max} \approx 650$ km/s

Particle physics:
$\sigma_{SI} \sim \sigma_0 A^2 |F(q)|^2$

$m_\chi \sim 100$ GeV
$\sigma_\chi \sim 10^{-45}$ cm^2

Exponential signal

- very low rates



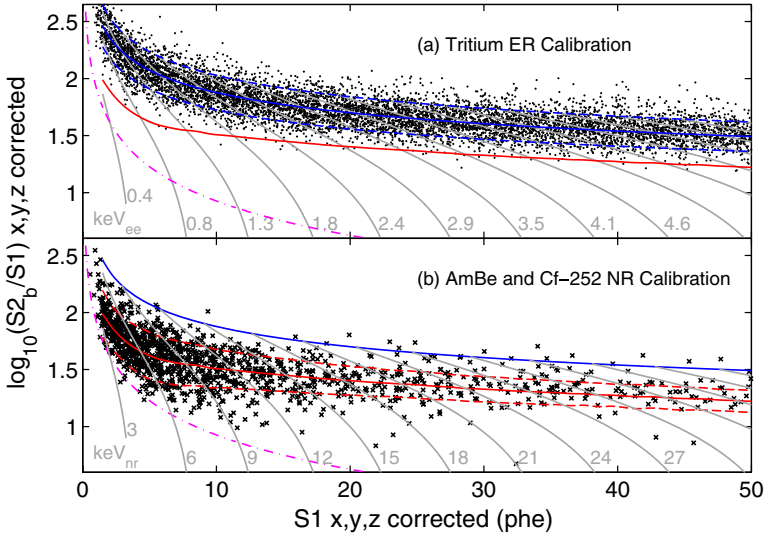
Baudis, SUSY07, (2007)

Background Reduction

Identify signatures of dark matter recoil signal to discriminate background

Recoil-Type ID:

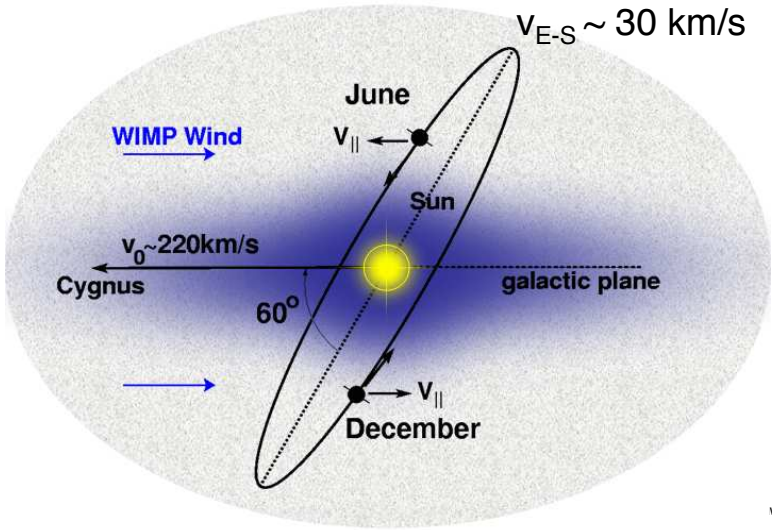
- WIMP signal from nuclear recoils
- Most backgrounds (radioactive decays) from electron recoils



LUX Collaboration, Phys. Rev. Lett., (2014)

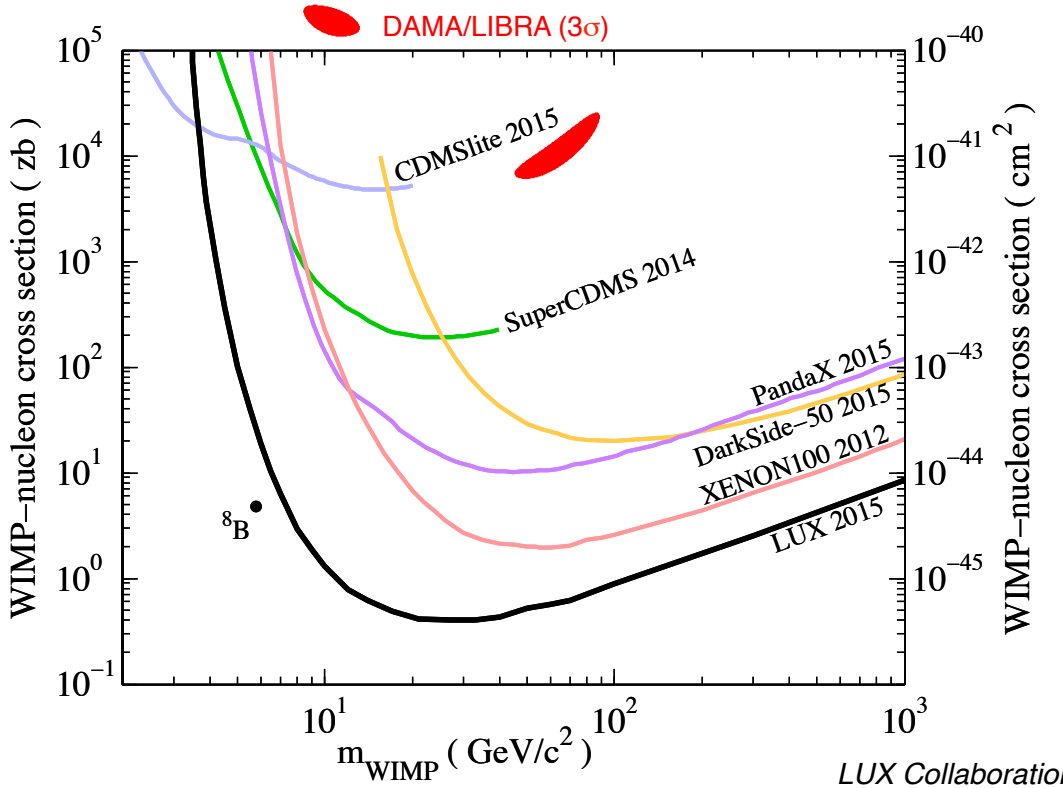
Annual Modulation:

- From Earth's motion around the Sun
- ± 7% effect
- Peak signal phase: June 2



Current Field Status

- Monolithic dual-phase liquid xenon detectors provide world-leading sensitivity to spin-independent WIMP scattering
- Signal excesses (from dark matter?) in other experiments in tension under standard interaction models



LUX Collaboration, [arXiv:1512.03506]

DAMA Detectors

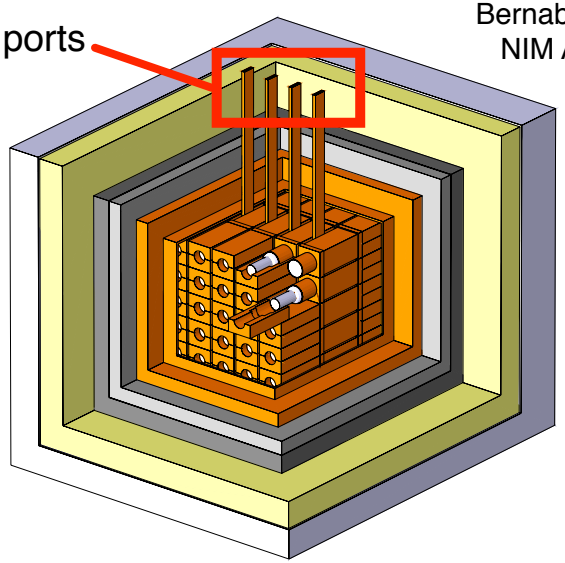
- 25 x 9.70 kg NaI(Tl) detectors
  - Grown by Saint-Gobain
    - Individually copper encapsulated
    - 0.85 – 1.3 cpd/kg/keV total bg rate
- 2 PMTs/crystal (Hamamatsu R6233MOD)
  - High QE, ~38.5% (average)
    - 5.5-7.5 pe/keV
  - Low dark rate, <500 Hz
  - Low background, 10 cm qtz lightguides







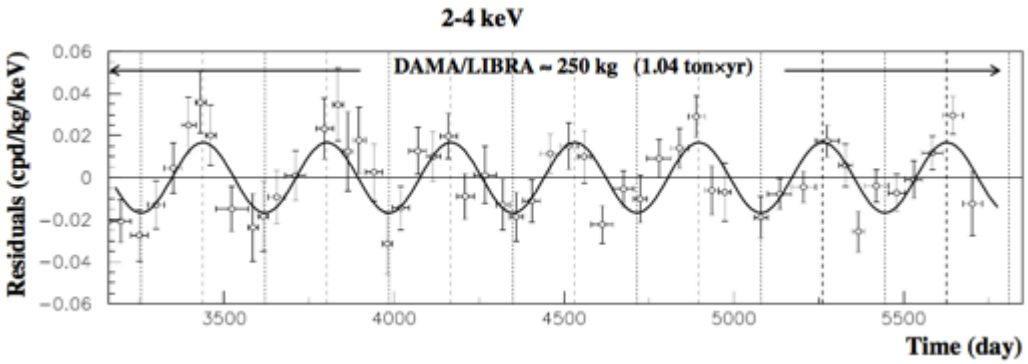
Bernabei *et al.*, JINST, (2012)



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

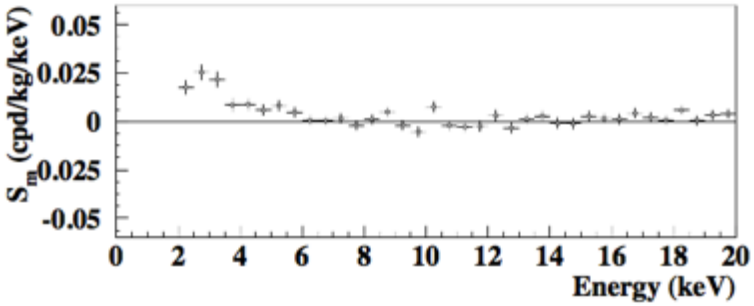
DAMA Result

Performed annual modulation experiment
- Observe non-zero amplitude at ***9.3-sigma***



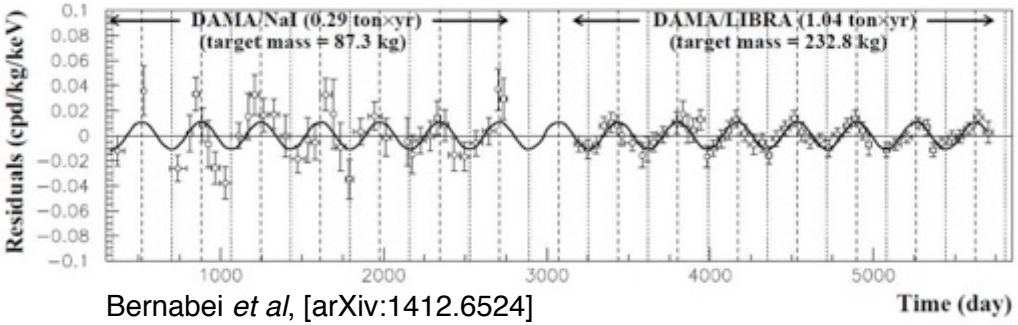
Bernabei *et al*, Eur. Phys. J. C (2013)

Modulation only observed at low-energy:



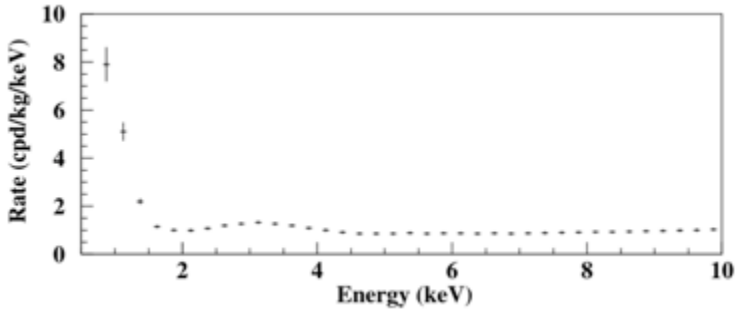
Bernabei *et al*, Eur. Phys. J. C (2013)

Consistent modulation signal spanning 14 measured cycles



Bernabei *et al*, [arXiv:1412.6524]

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



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

Is this astrophysics? nuclear/particle physics? instrumental effect? background?

DM-Ice Collaboration

Yale University

Reina Maruyama, Karsten Heeger, Walter Pettus, Antonia Hubbard, Kyungeun Lim, Estella de Souza, William Thompson, Brooke Russell, Field Rogers

University of Wisconsin – Madison

Francis Halzen, Michael DuVernois, Albrecht Karle, Matt Kauer, Zachary Pierpoint, Bethany Reilly, Ben Broerman

University of Sheffield

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

Fermilab

Lauren Hsu, Raymond Co

Boulby Underground Science Facility

Sean Paling, Chris Toth

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

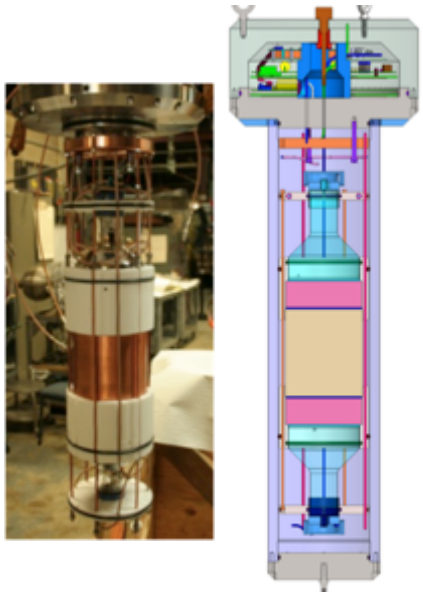
SNOLAB

Bruce Cleveland

DM-Ice Experimental Program

DM-Ice17

(*January 2011 – present*)

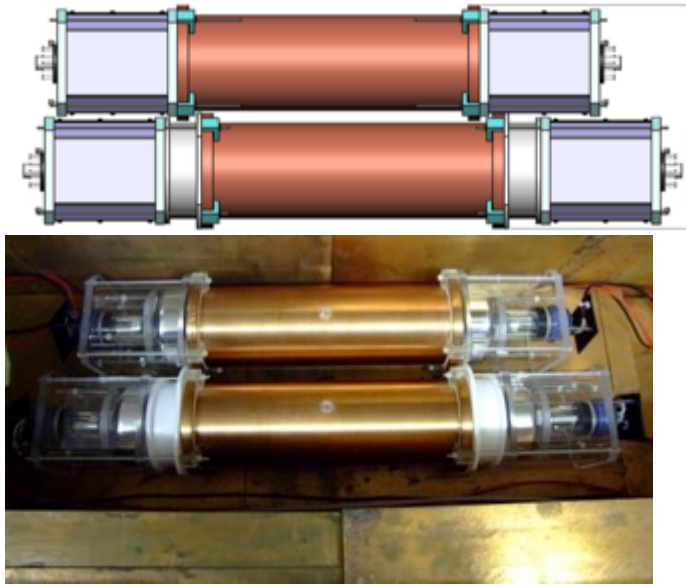


First dark matter experiment in South Pole ice

- Demonstrated viability and advantages of environment

DM-Ice37

(*April 2014 – present*)

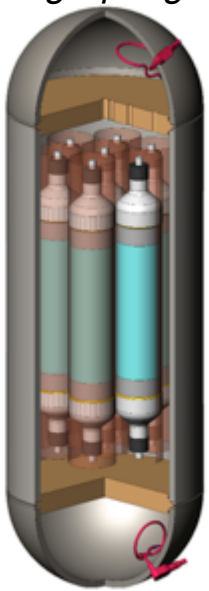


R&D testbed for NaI detectors

- Crystal background
- Light collection
- Background levels

COSINE / DM-Ice250

(*starting Spring 2016*)

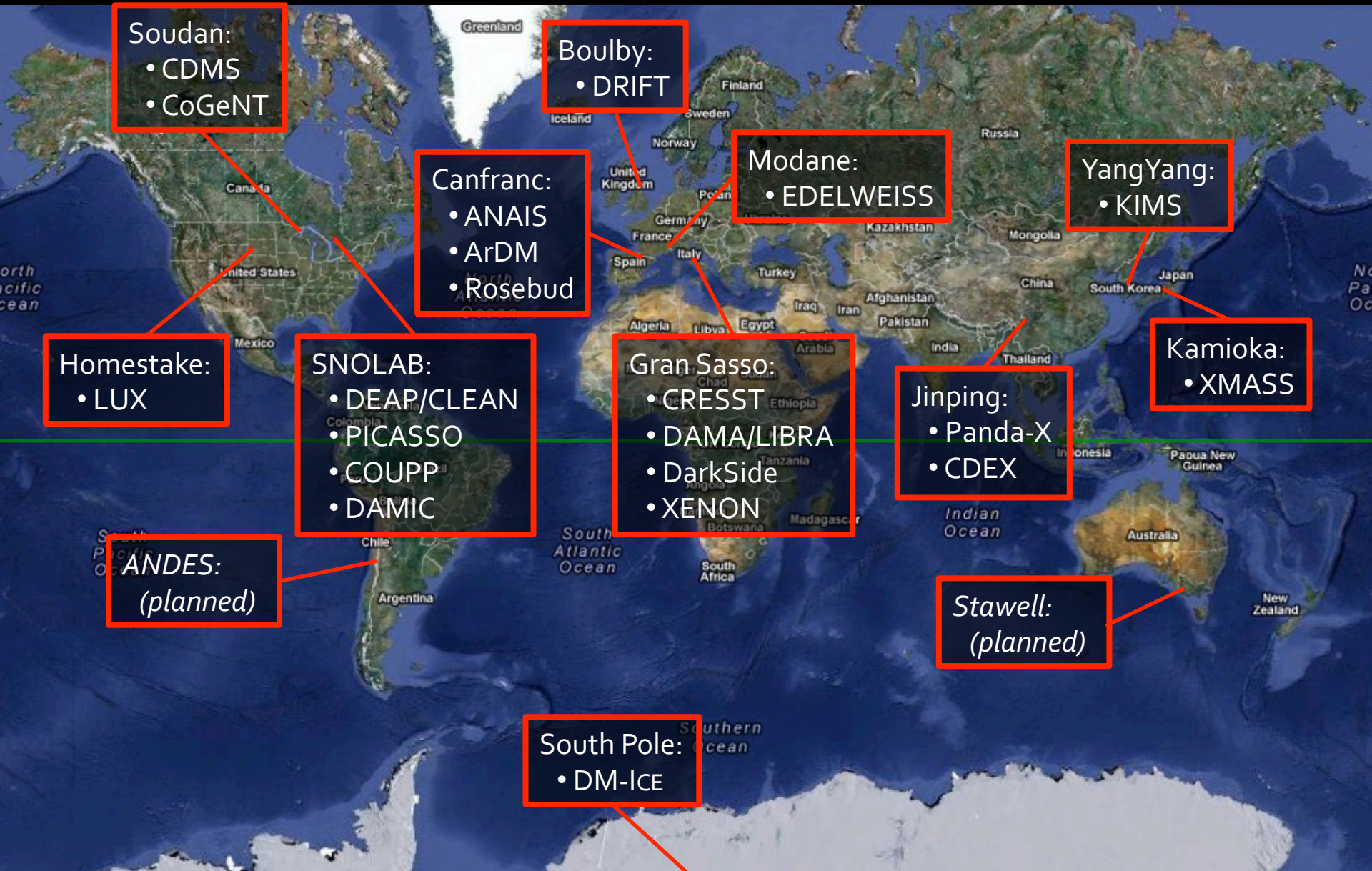


Science result

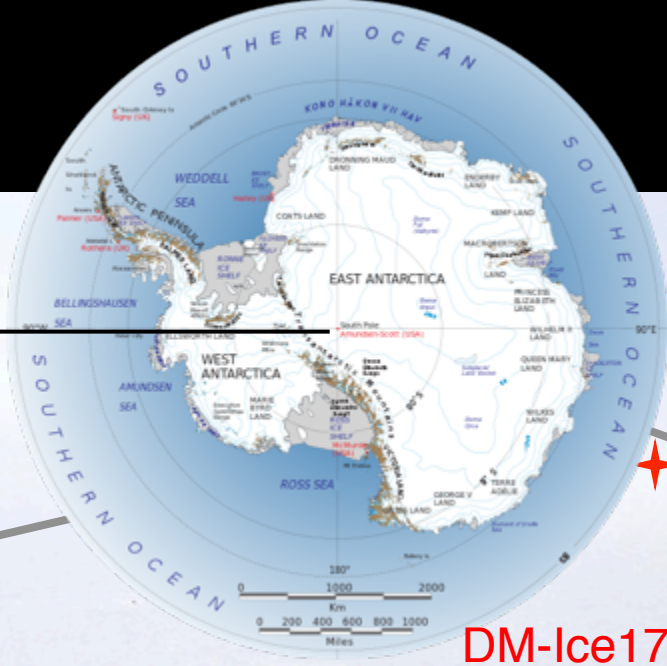
- Definitive test of DAMA dark matter claim

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

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

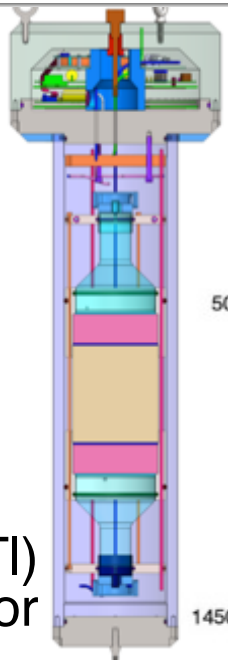
Advantages of South Pole

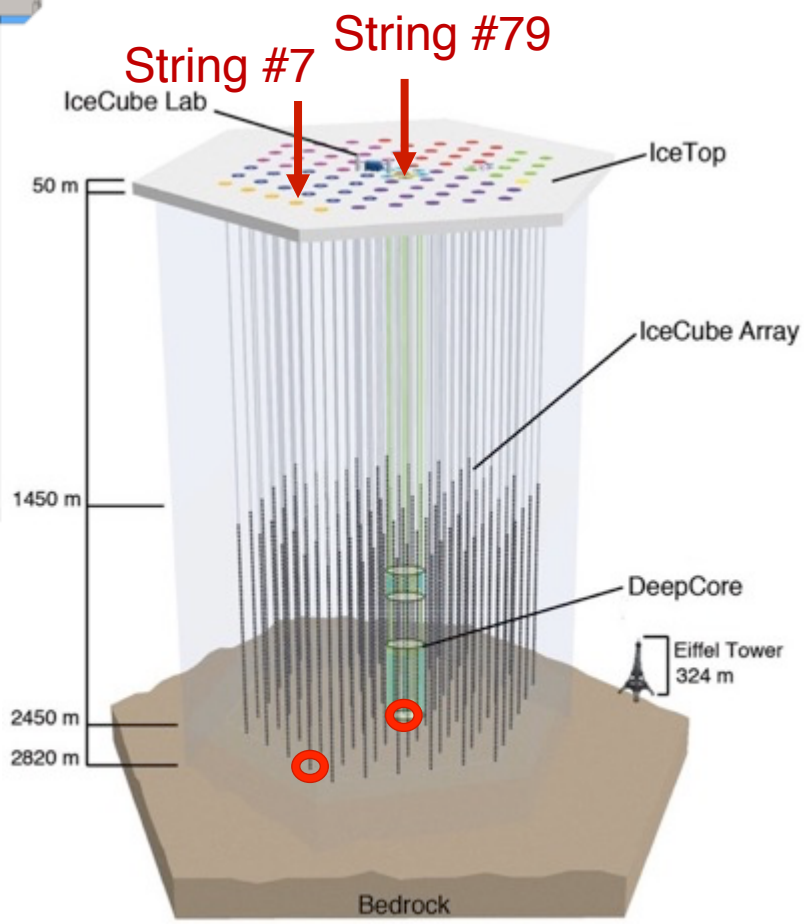
- Same dark matter signal in both hemispheres
- Opposite muon rate
  - Tagging of muons by IceCube/DeepCore
  - Spallation neutrons moderated by ice
- Overburden from 2450 m ice (2200 m.w.e.)
  - Drilling established by IceCube
  - Negligible environmental radioactivity
    - ppt $^{238}U/^{232}Th$,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

DM-Ice17 Experiment

(2x) 8.5-kg NaI(Tl) modules
- Installed Dec 2010
- Physics run:
  - June 2011 - Jan. 2015

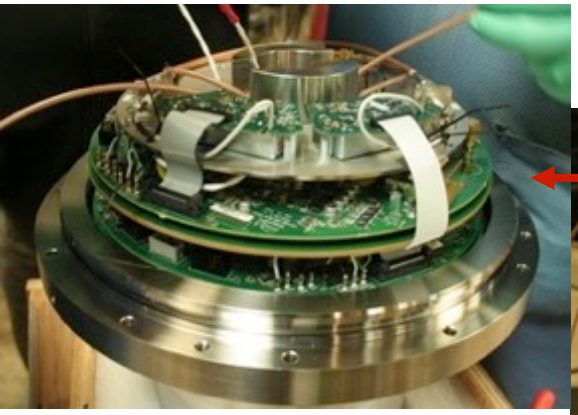
Goals:
- Demonstrate the feasibility of deploying and operating NaI(Tl) detectors in the Antarctic Ice for a dark matter search
- *In situ* measurement of the radiopurity of the Antarctic ice / hole ice at 2450 m depth
- Study environmental stability
- Study the capability of IceCube to veto muons

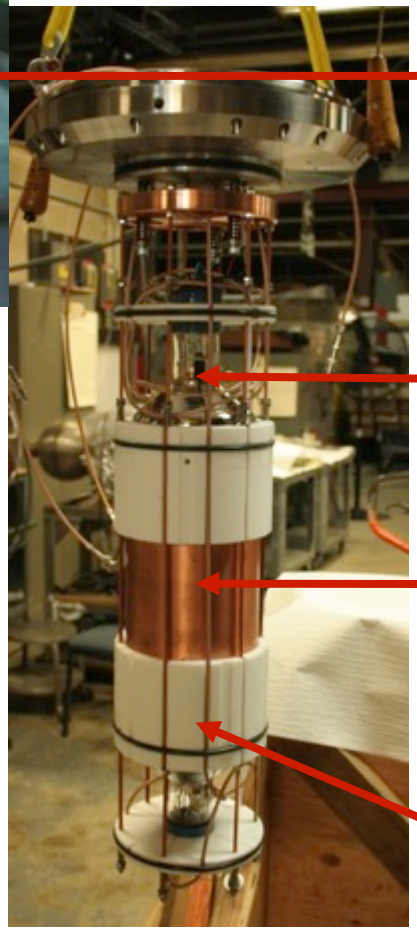




see also Cherwinka *et al.*
Phys. Rev. D **90** (2014) 092005

DM-Ice17 Detectors





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

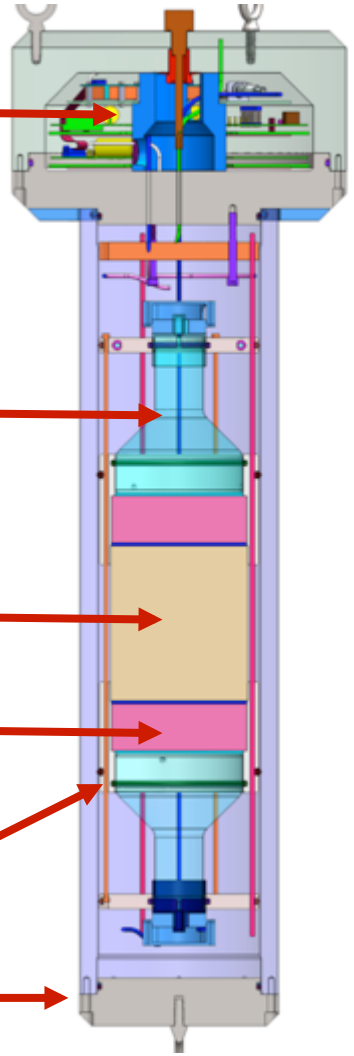
ETL 5” PMTs (x2) (NaIAD)

Encapsulated NaI crystal (NaIAD)

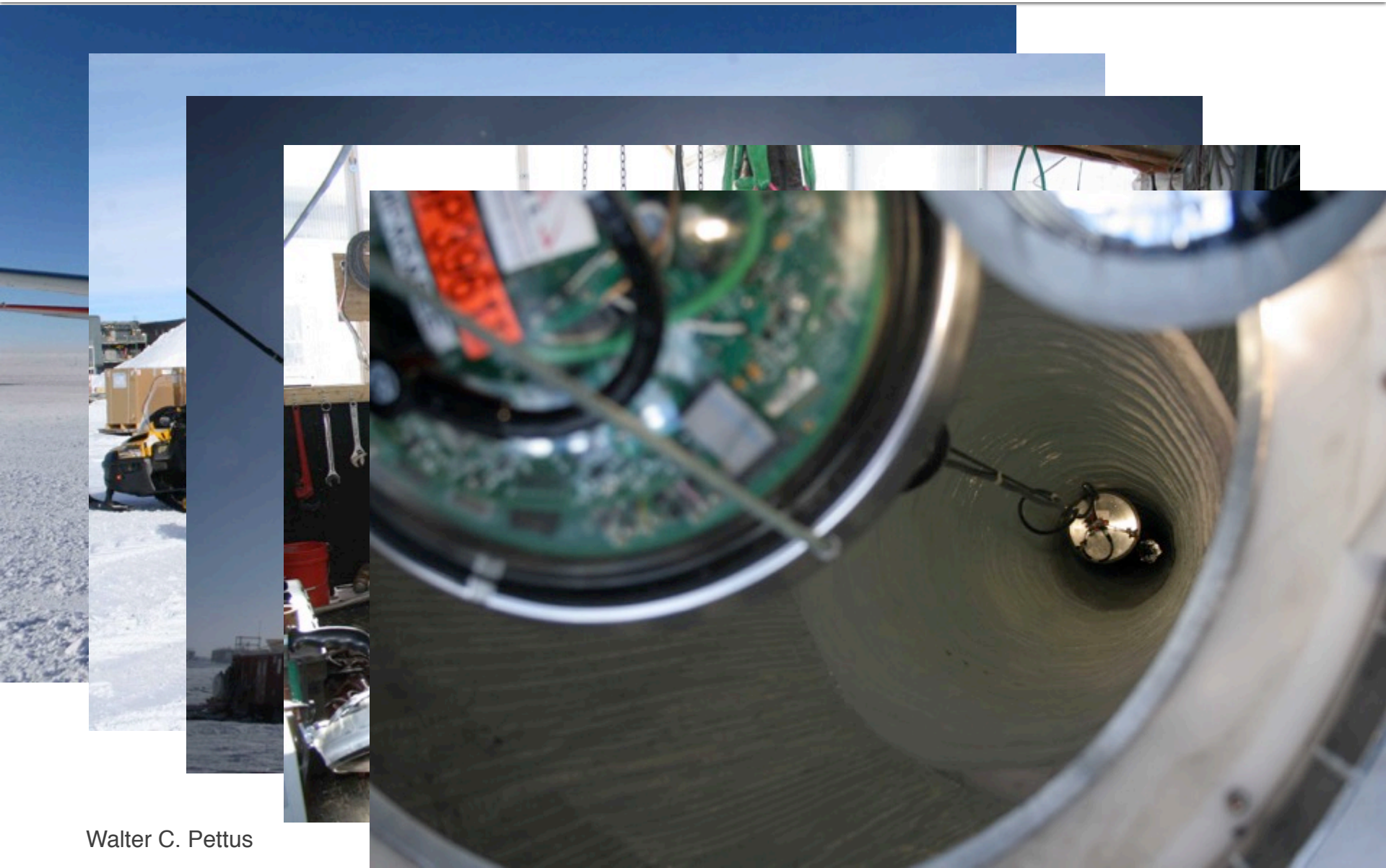
Quartz Lightguides (x2) (NaIAD)

PTFE light reflector (x2)

Steel pressure vessel



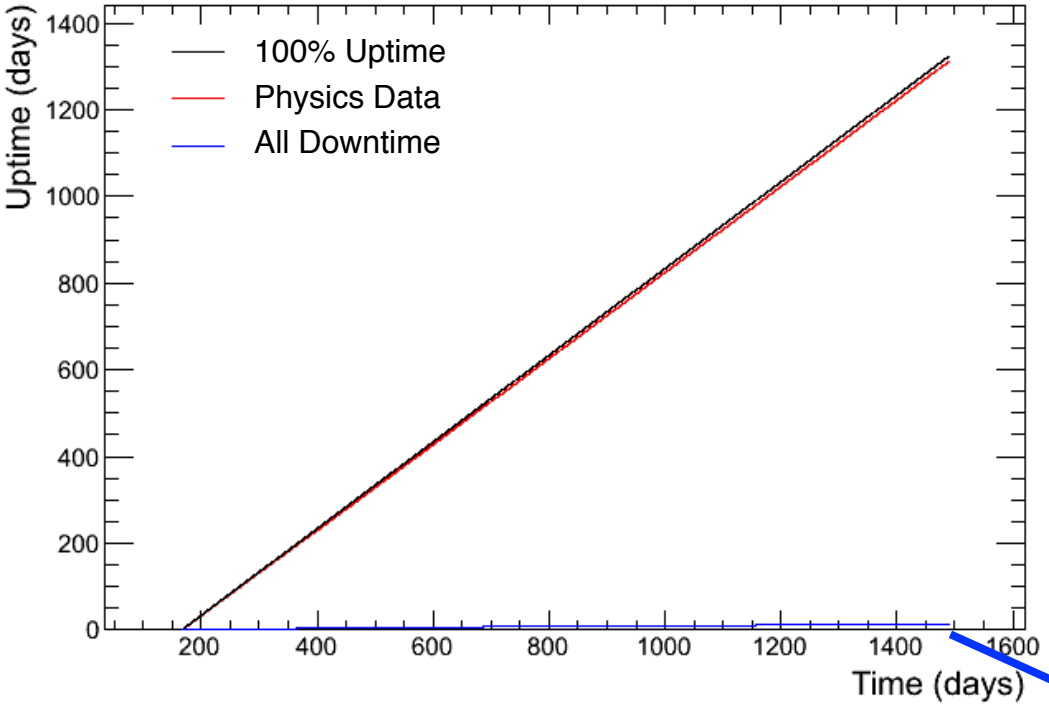
South Pole Logistics



Walter C. Pettus

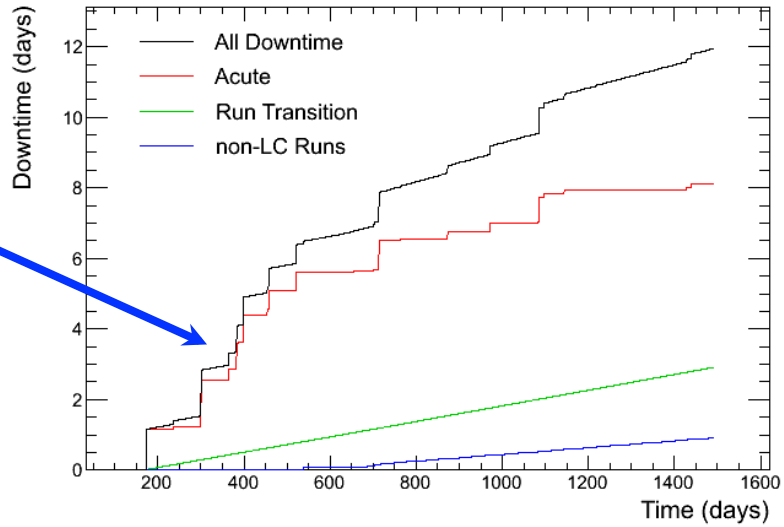
DM-Ice17 Uptime

> 99% uptime



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

- Uptime has improved over physics data run



60.8 kg*yr exposure for physics analysis

- Largest dataset from any dark matter experiment after DAMA

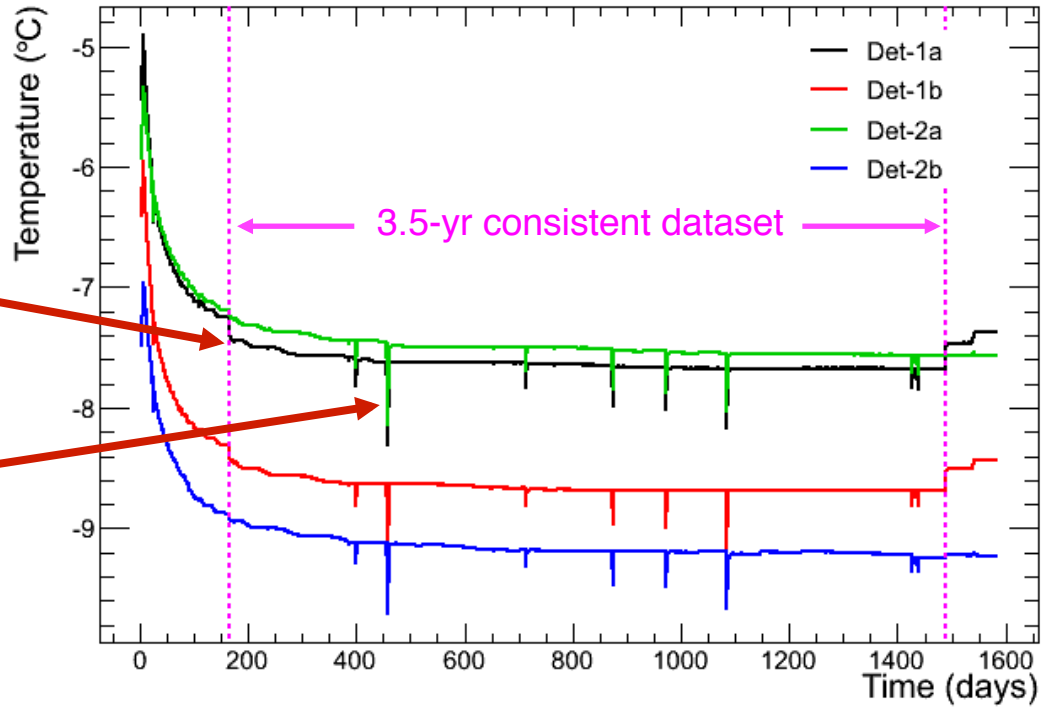
[arXiv:1510.00378]

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

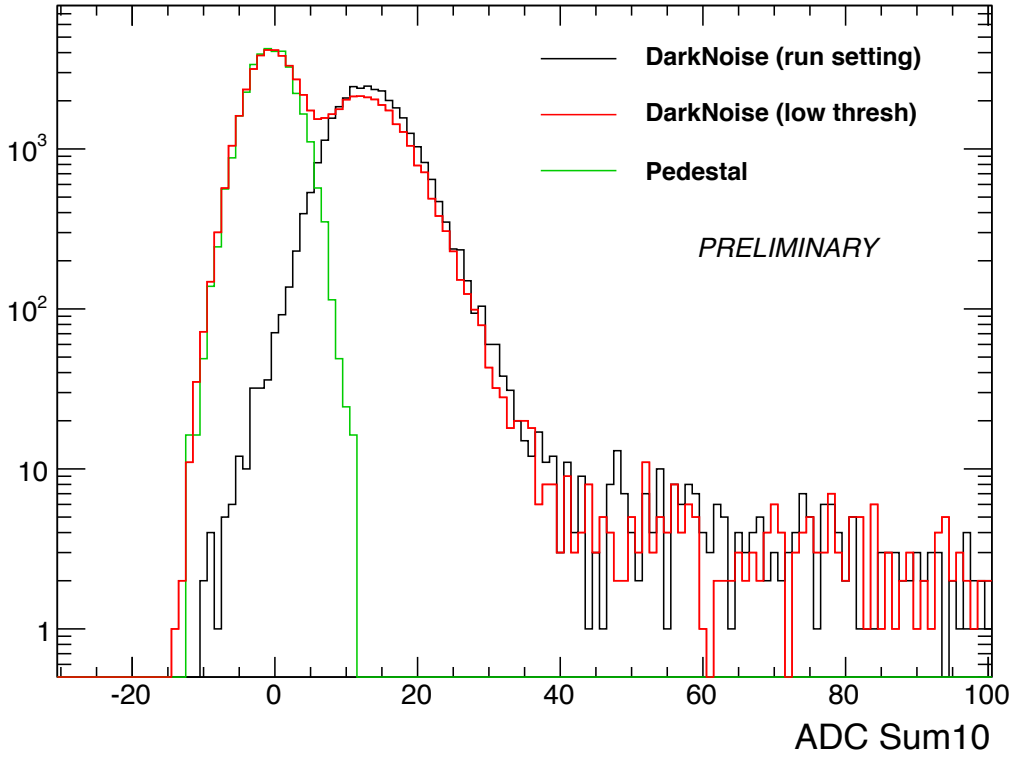
Power outages affect MB temp, not crystal temp



[arXiv:1510.00378]

SPE Response

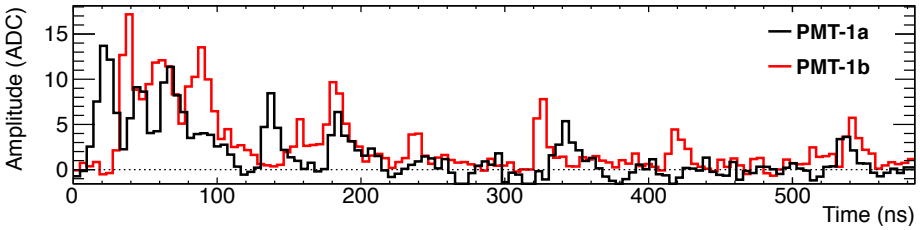
- Only *in situ* calibration is `DarkNoise' to assess single photoelectron response and `Pedestal' to assess digitizer noise



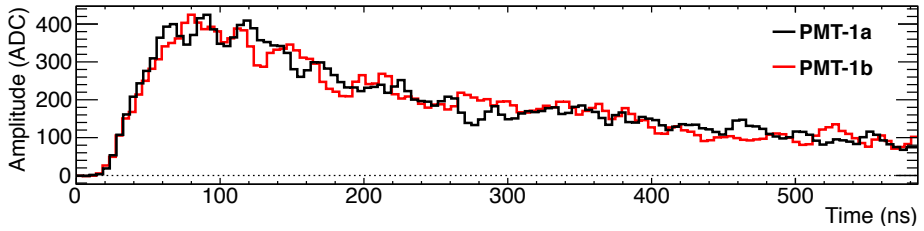
* No evidence of changing SPE over dataset

Event Types

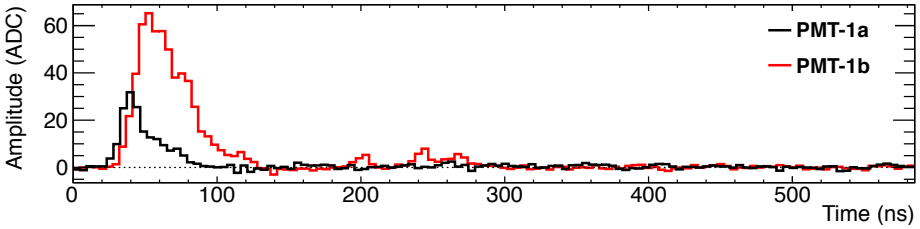
- Low-Energy Scintillation
  - Sequence of SPEs:



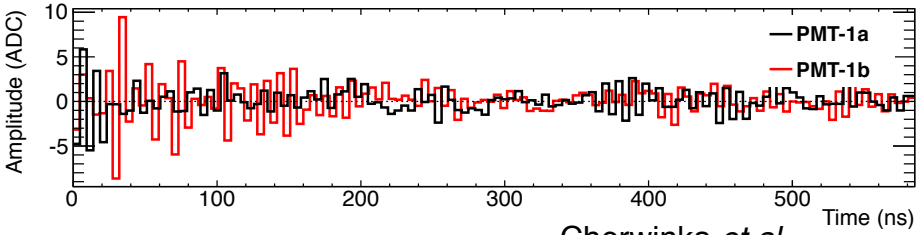
- High-Energy Scintillation
  - SPE structure suppressed
  - Statistics generate exponential decay tail



- Thin Pulse Noise
  - Asymmetric deposition
  - Fast decay tail



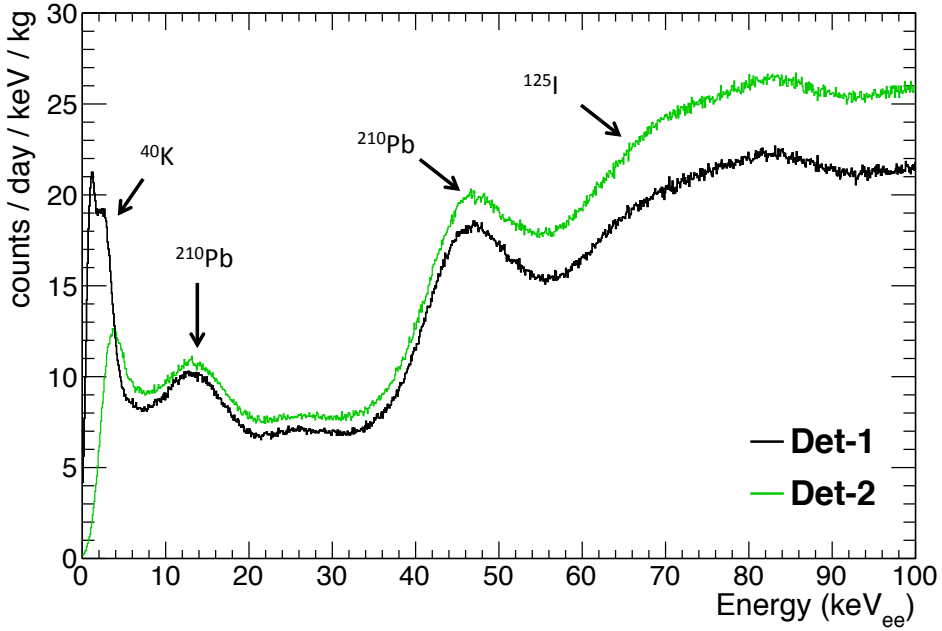
- EMI Noise
  - Oscillatory waveform
  - Zero integrated charge

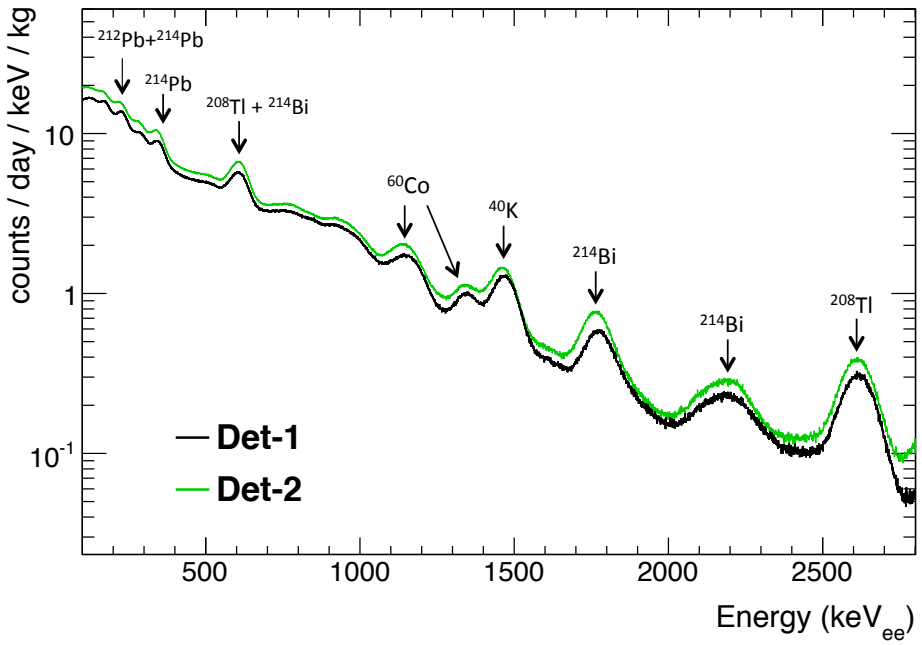


Cherwinka *et al.*
Phys. Rev. D **90** (2014) 092005

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





Cherwinka *et al.*
Phys. Rev. D **90** (2014) 092005

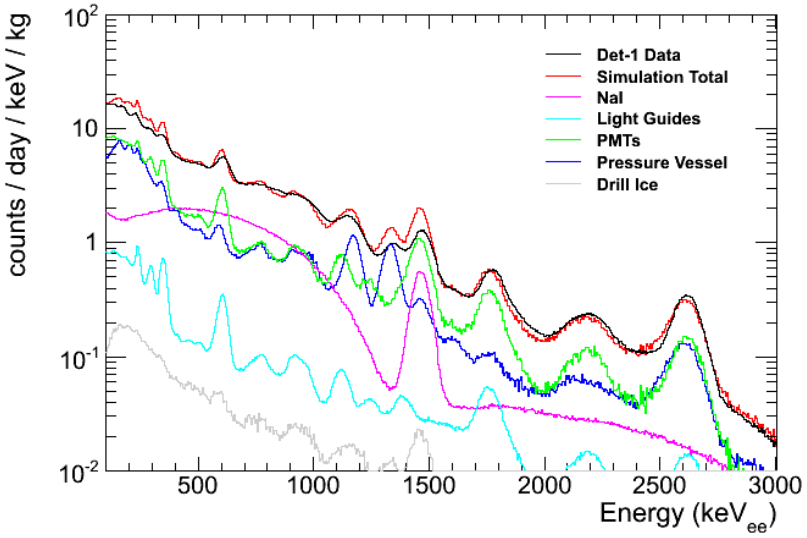
DM-Ice17 Background

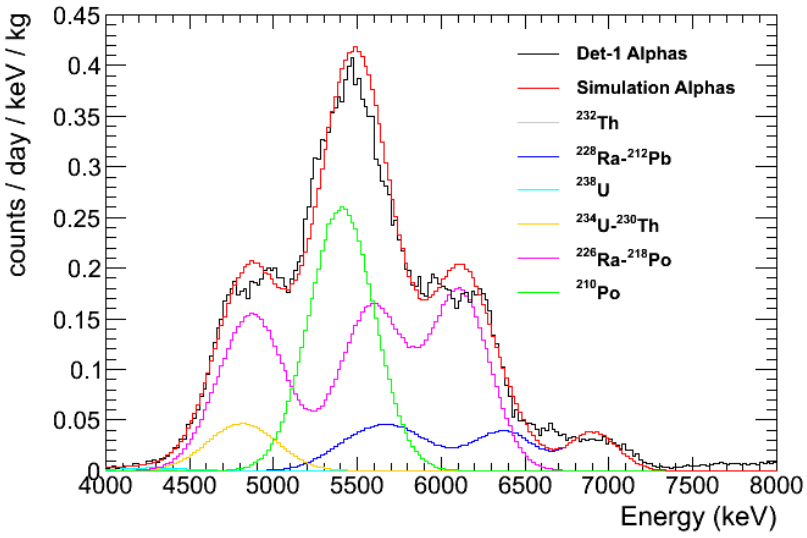
Betas & Gammas:

- 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





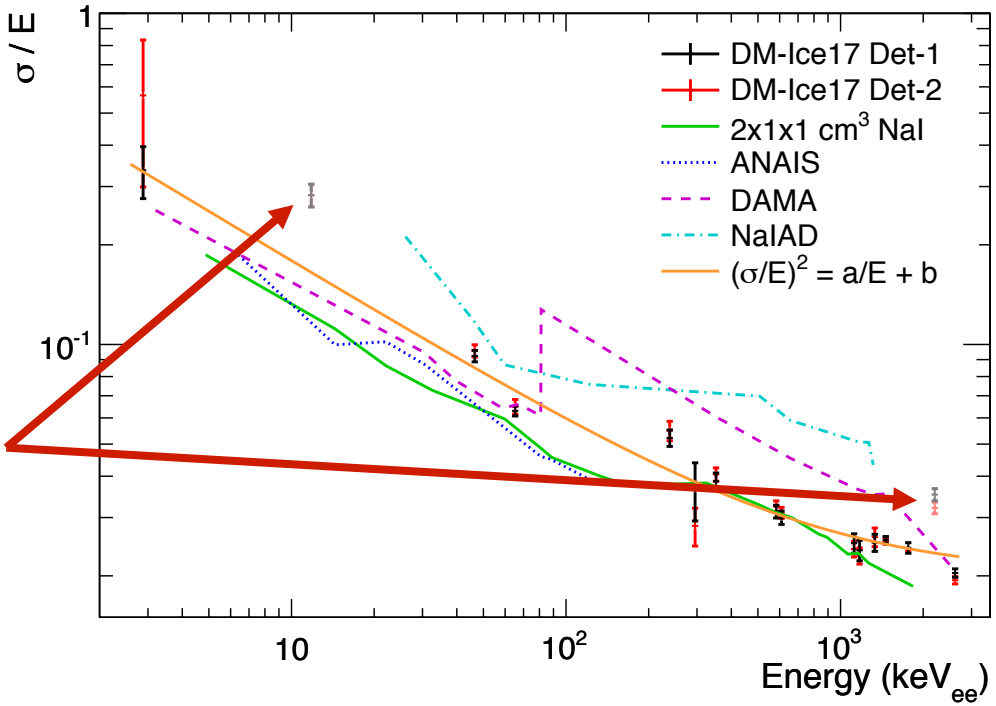
Detector backgrounds dominate at all energies;
Negligible contributions from environmental background

Cherwinka *et al.*
Phys. Rev. D **90** (2014) 092005

Energy Resolution

- Resolution assessed from same background peaks giving calibration
  - Comparable resolution to other NaI experiments

But you must understand the underlying spectral features!



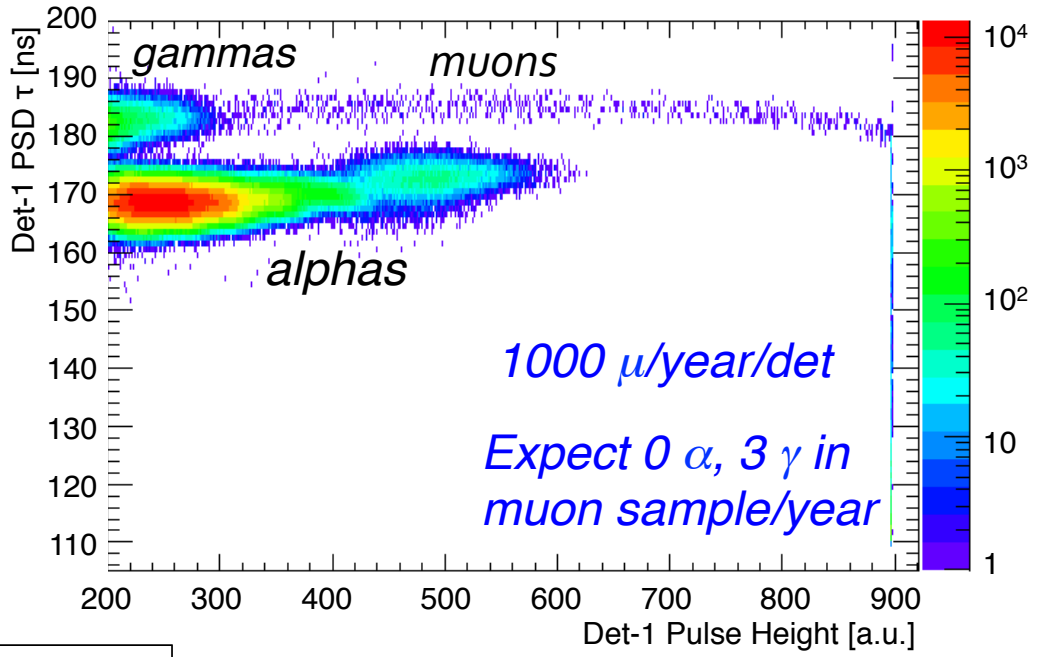
Cherwinka *et al.*
Phys. Rev. D **90** (2014) 092005

Muon Identification

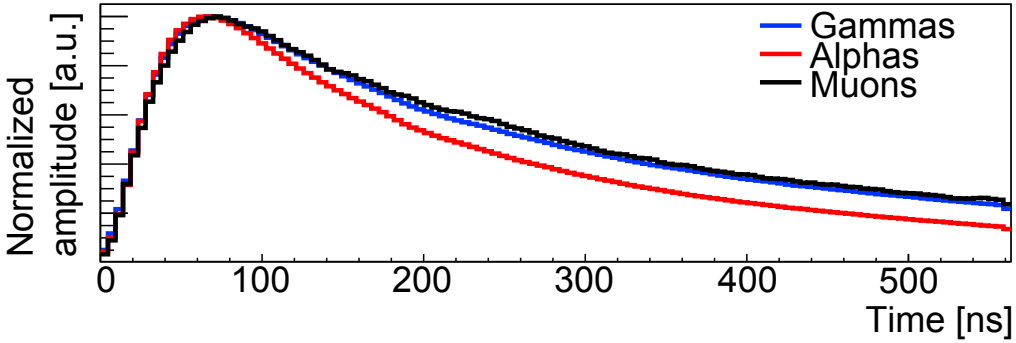
Muons are identified by their large energy deposition and "gamma-like" pulse shape

Pulse-shape discrimination (PSD) variable uses the pulse height (h_i) at time (t_i):

$$PSD = \frac{\sum h_i t_i}{\sum h_i}$$



Longer decay tail for gammas and muons than "alpha-like" events:

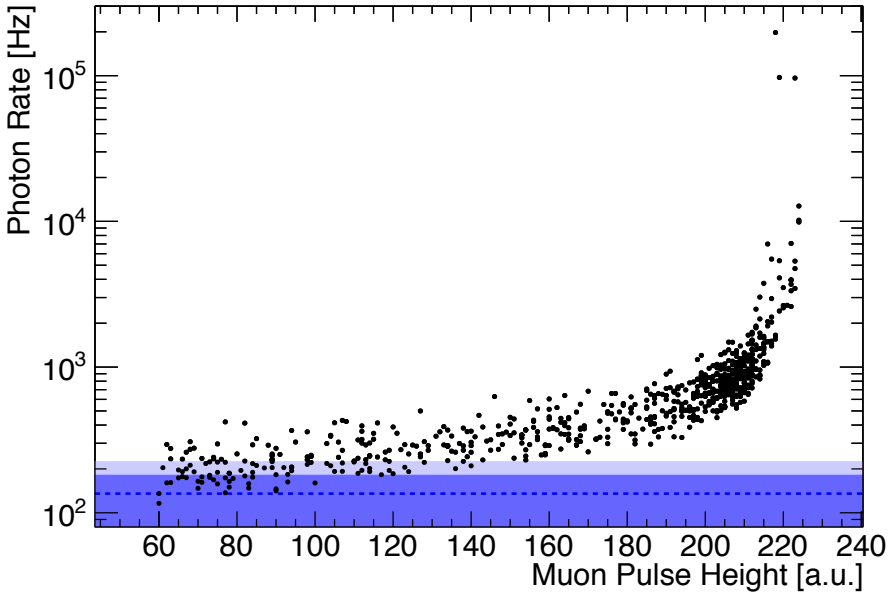


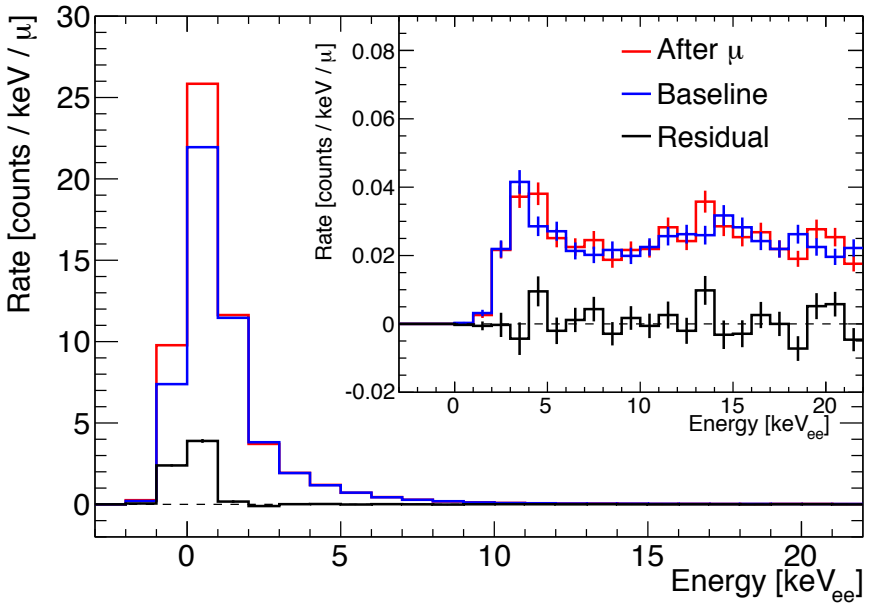
see also Cherwinka *et al.*, accepted in Phys. Rev. D [arXiv:1509.02486]

Muon-Induced Phosphorescence

Muons induce long-lived (~6 sec decay) crystal excitations which result in delayed single photon emission

- Delayed phosphorescence proportional to muon deposited energy
  - Up to ~10^8 photons in largest event observed
- No viable mechanism for these to produce DAMA signal

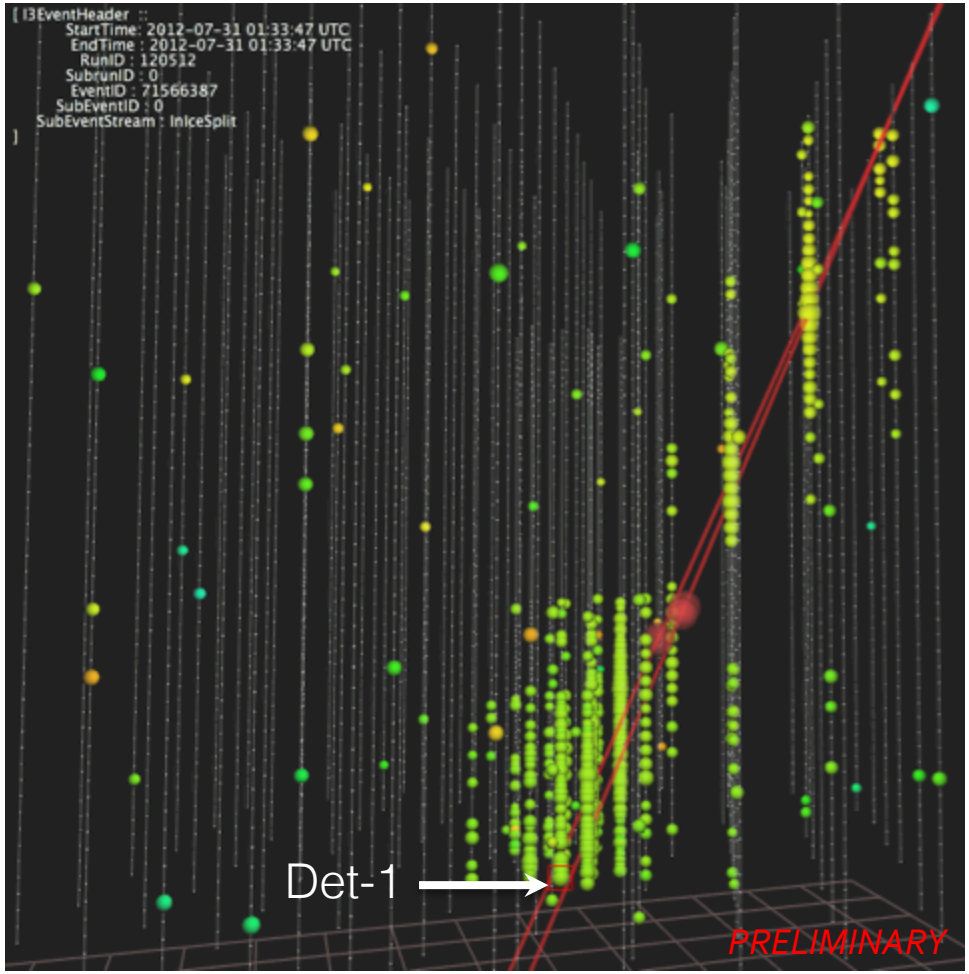




Muon Coincidence in IceCube

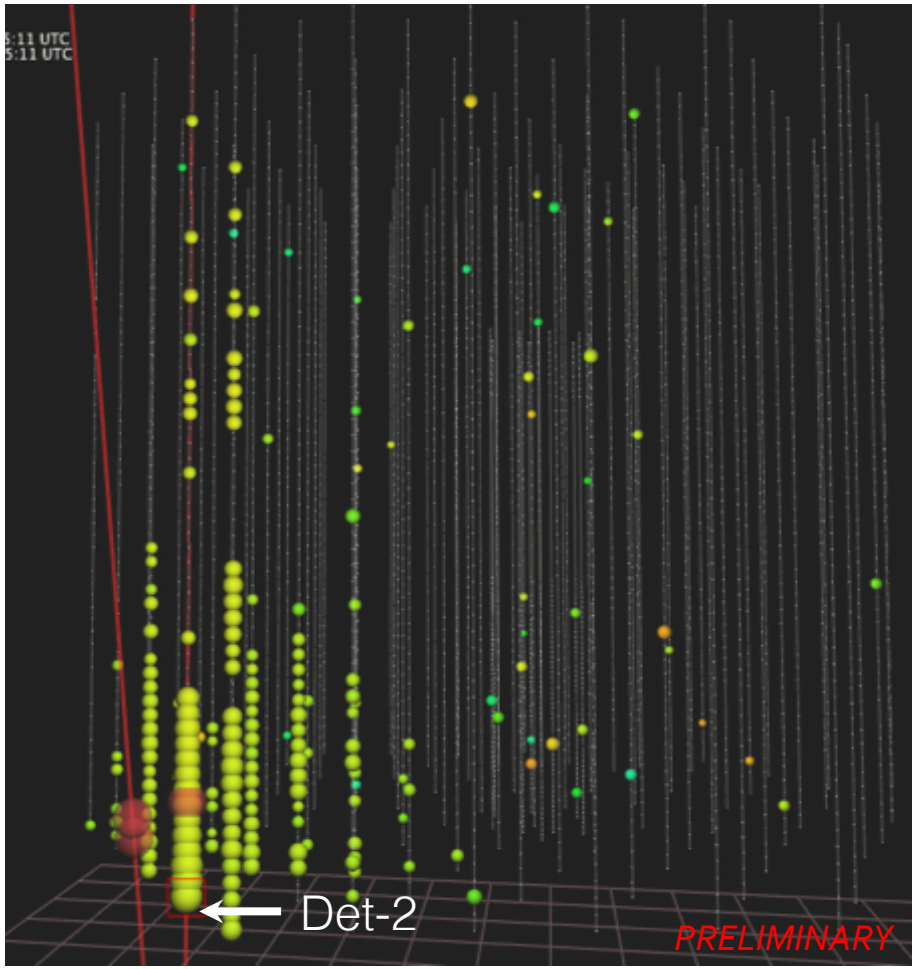
DM-IceCube17 Det-1

93% coincidence



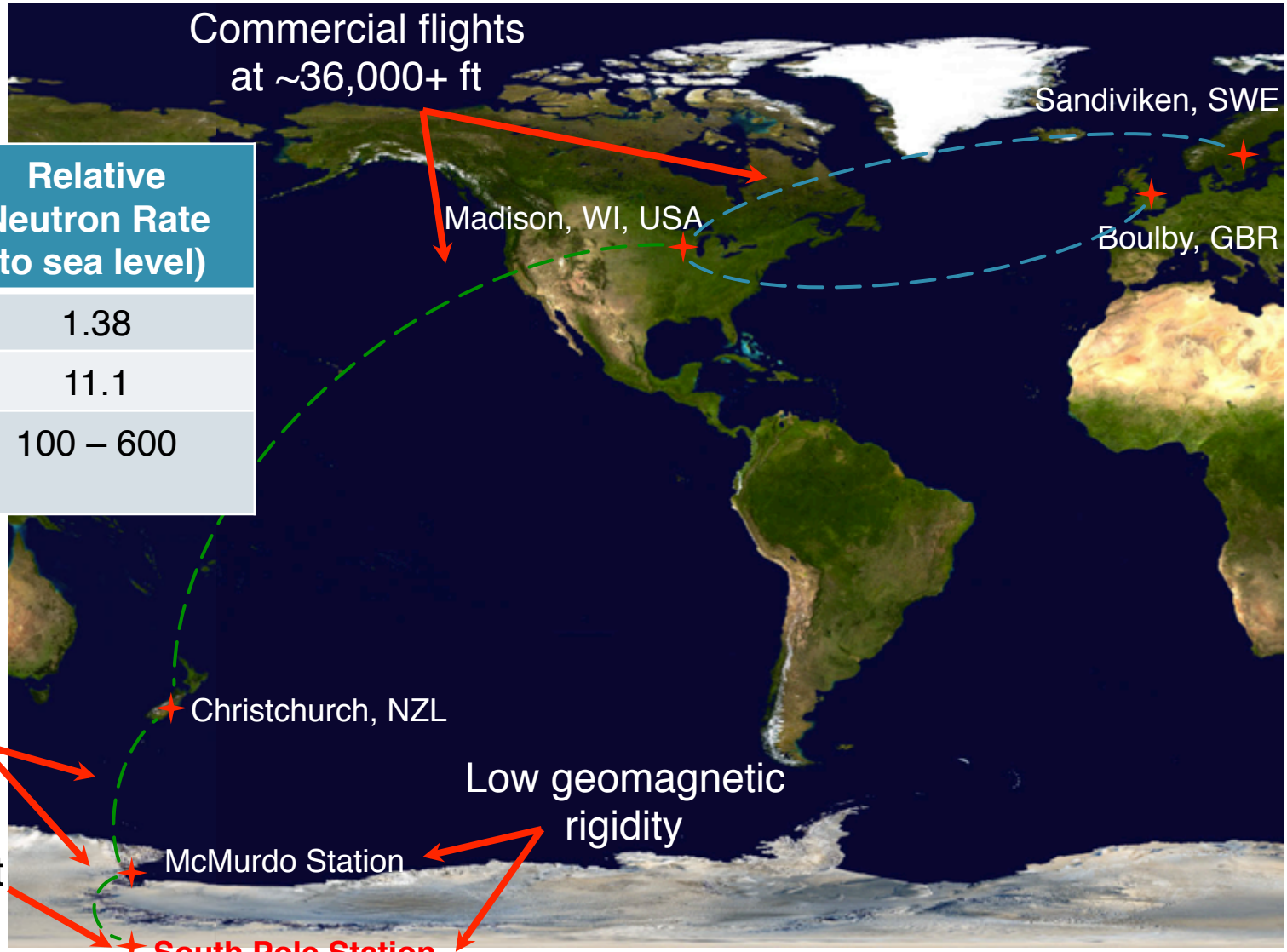
DM-IceCube17 Det-2

33% coincidence



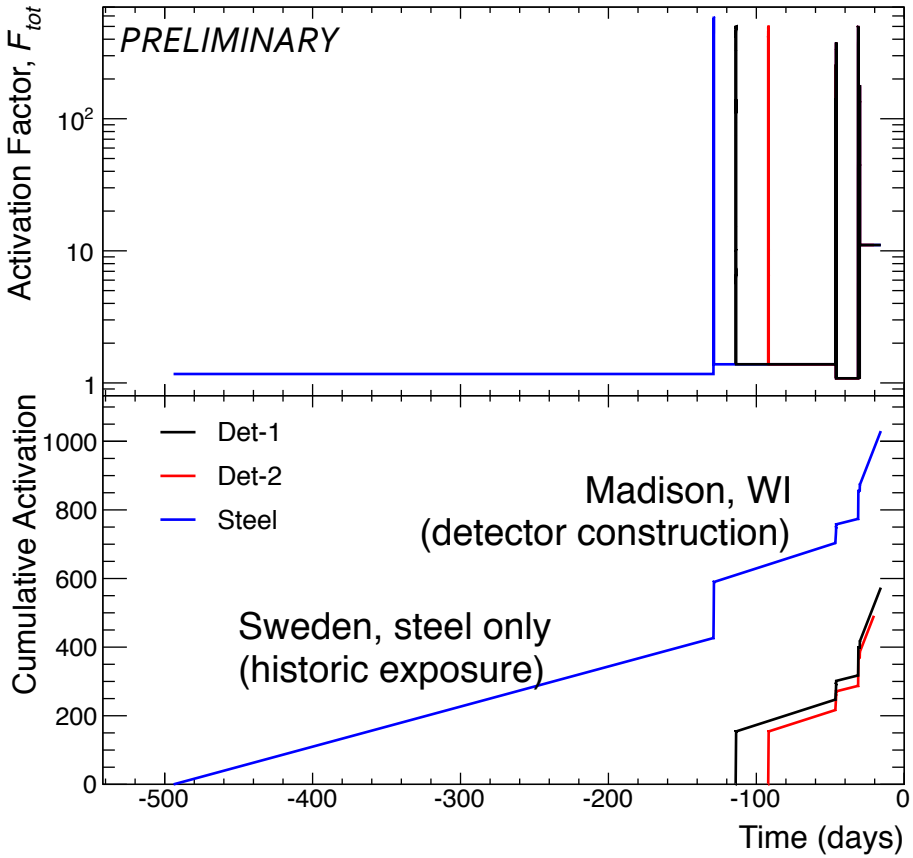
Cosmogenic Activation Hazards

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)

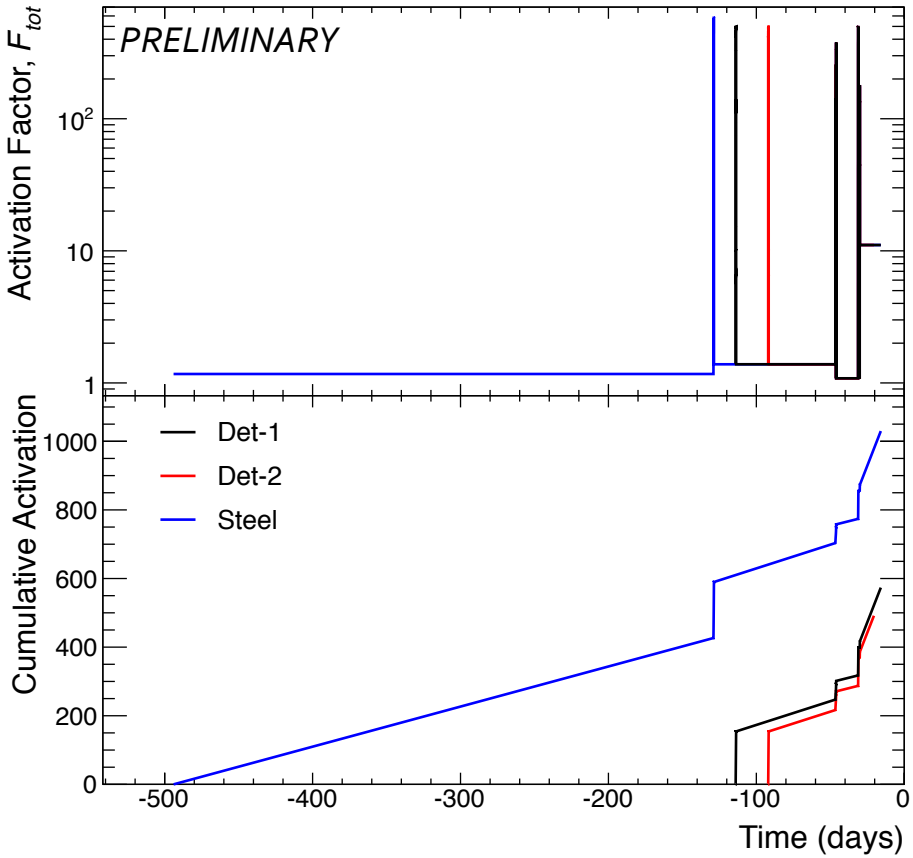
- Long periods of low-level exposure during storage and construction
- Punctuated exposure from flight shipment

"Cumulative Activation" – Time-integrated neutron flux scaling

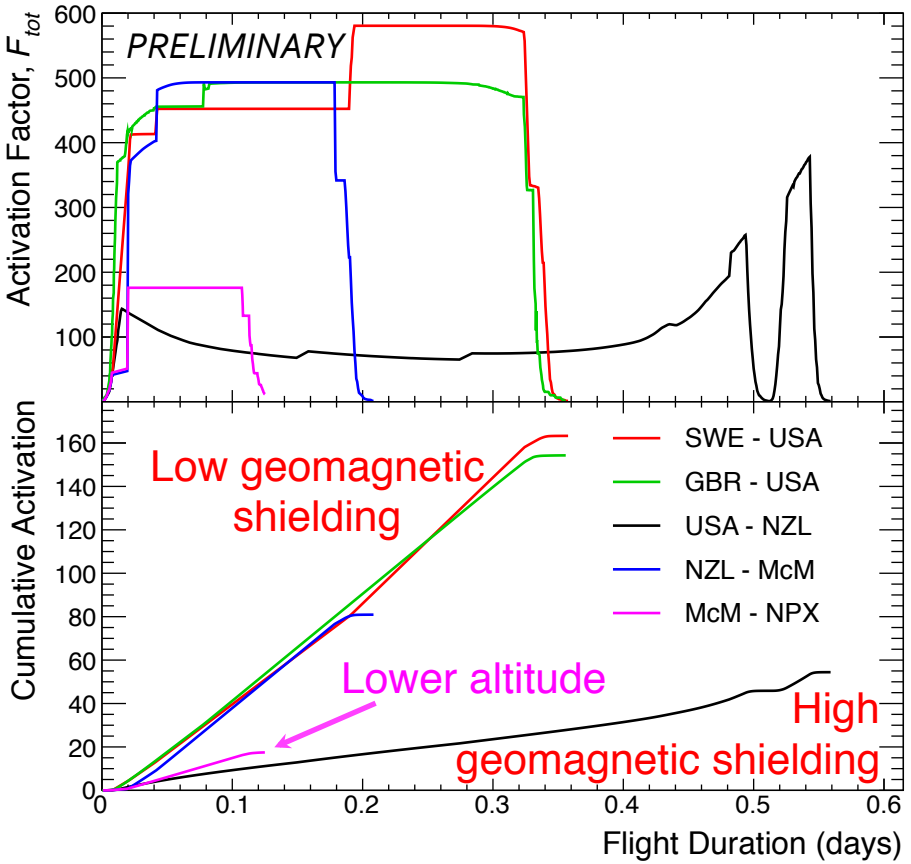
- Different detector components have different exposure histories
- Two DM-Ice17 detectors have different deployment times

Cosmic Ray Exposure Timeline

Full Detector Component History



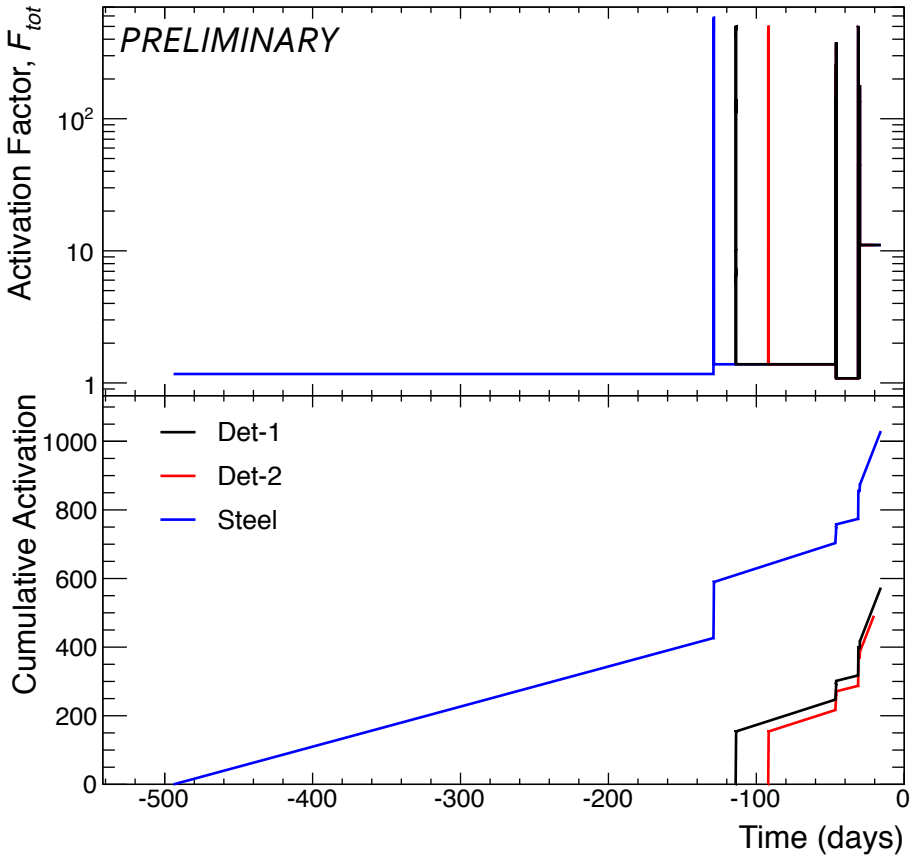
Flight Segments



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

Cosmic Ray Exposure Timeline

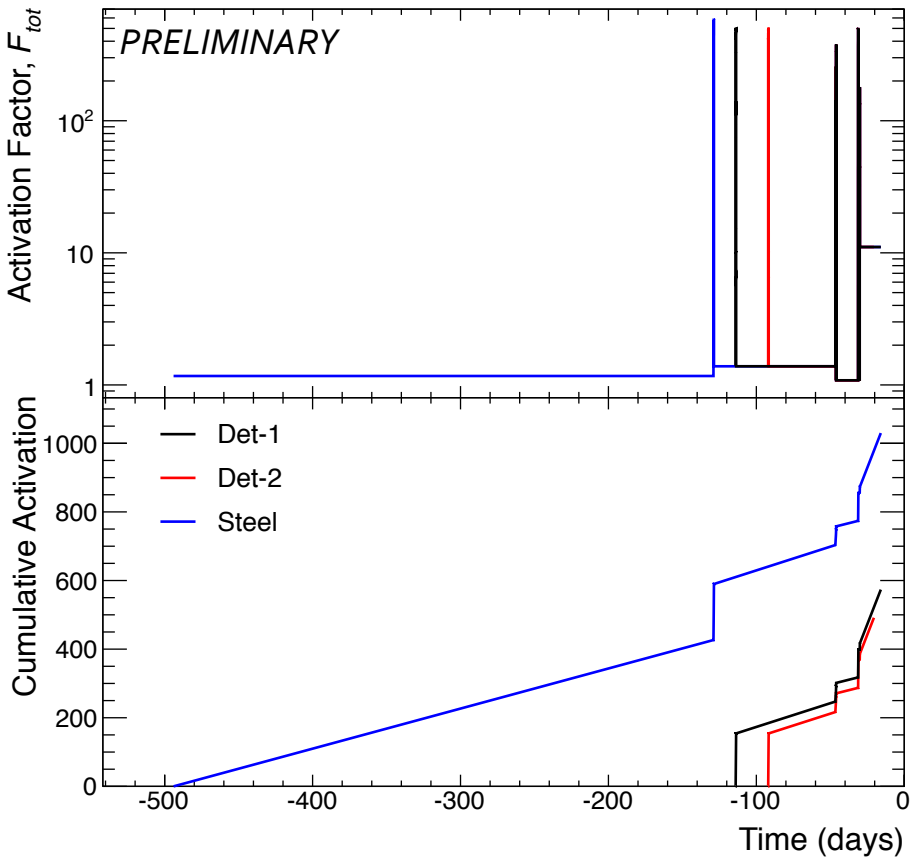
Full Detector Component History



~50% of activation relevant to low-energy background occurs at South Pole or Antarctica flights

Cosmic Ray Exposure Timeline

Full Detector Component History



Flights to South Pole are lowest-activation transport option

High altitude (C-17):

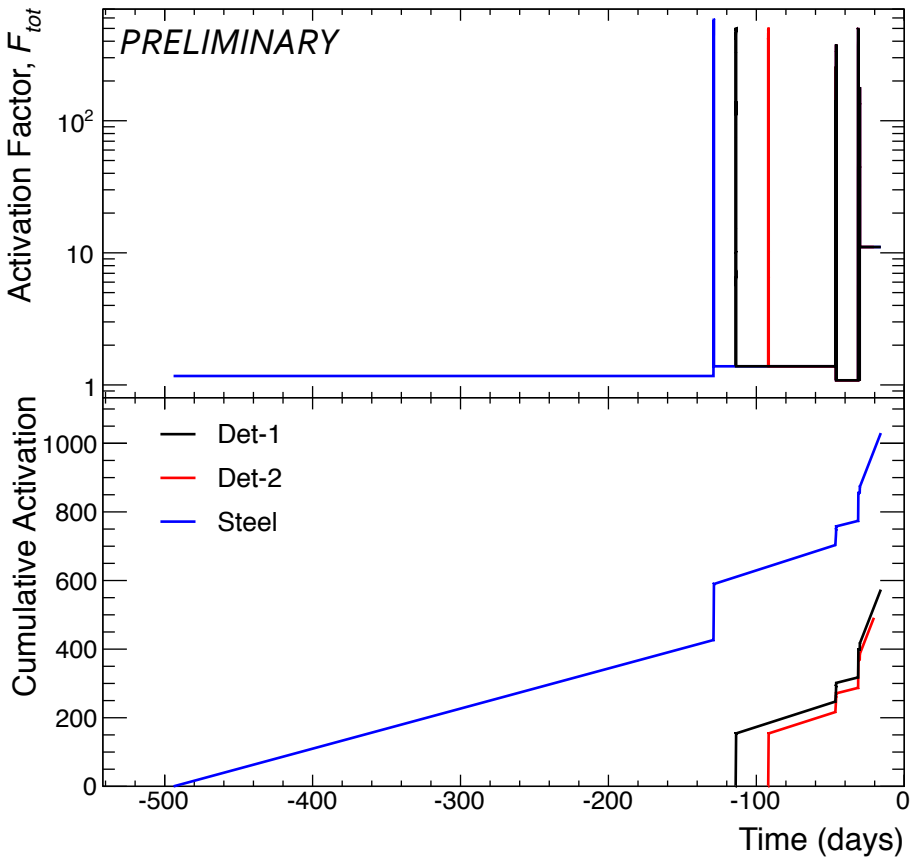


Low altitude (LC-130):



Cosmic Ray Exposure Timeline

Full Detector Component History



Storage in tunnel can reduce South Pole surface activation by factor of 10

Surface Overburden Availability:

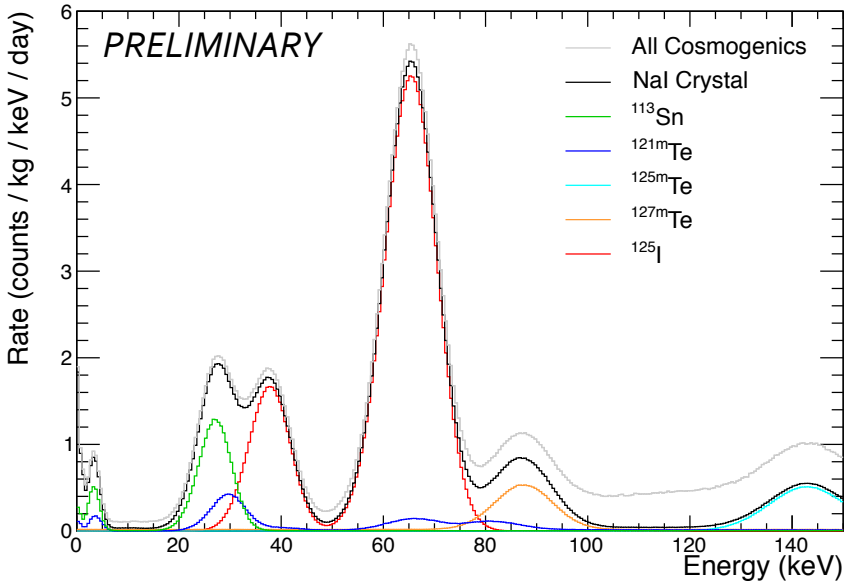


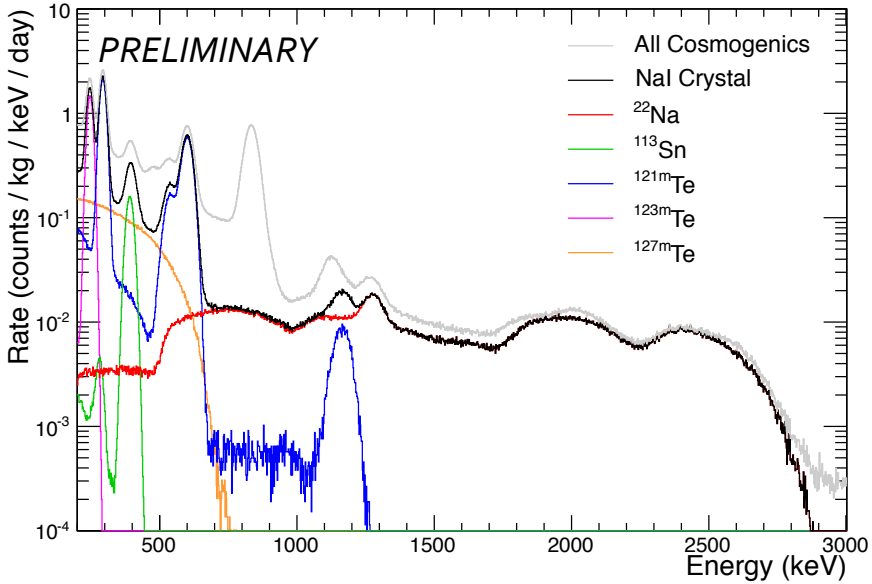
Tunnel Storage Option:



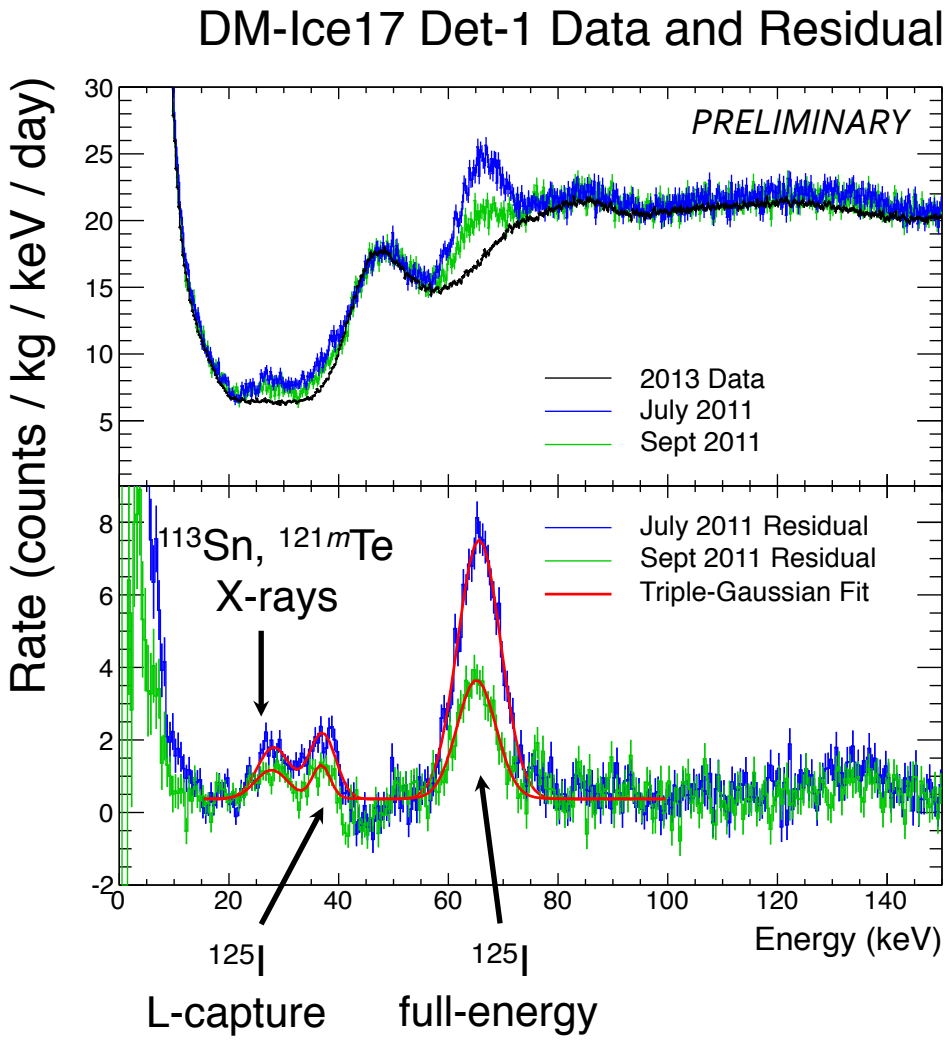
Cosmogenic Prediction

- 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



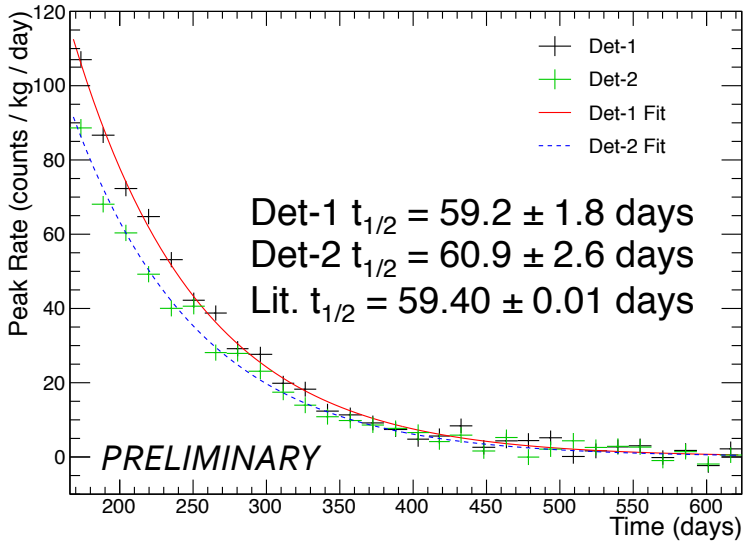


Cosmogenic Decay Peaks

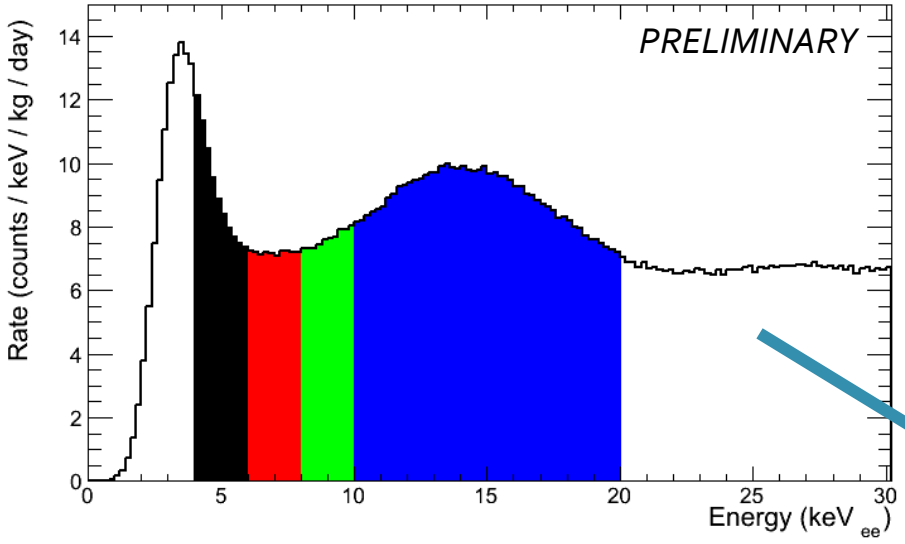


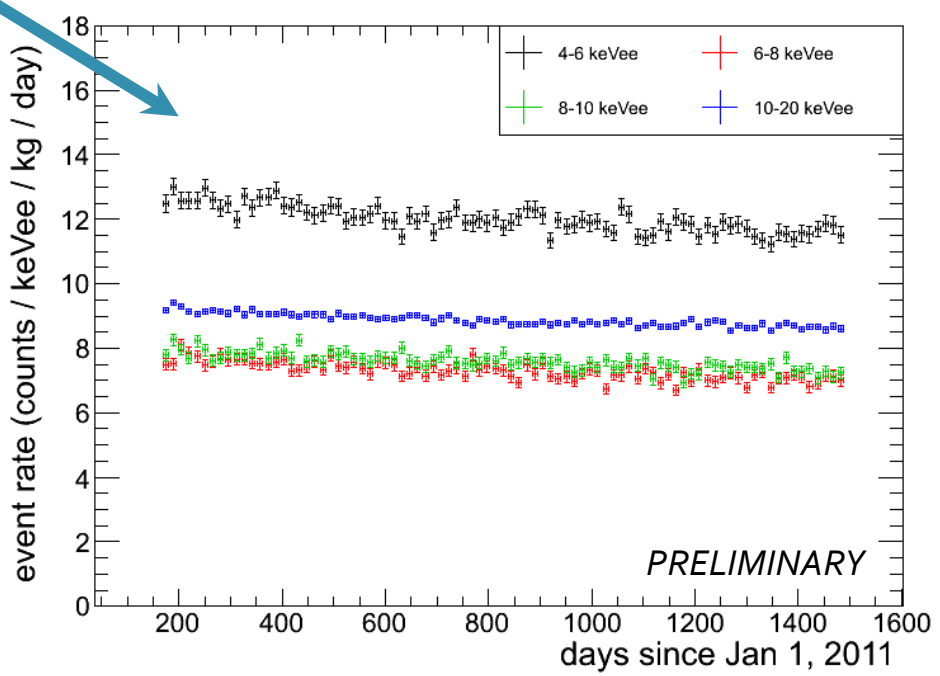
Confirm identity of cosmogenic peaks:

- 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



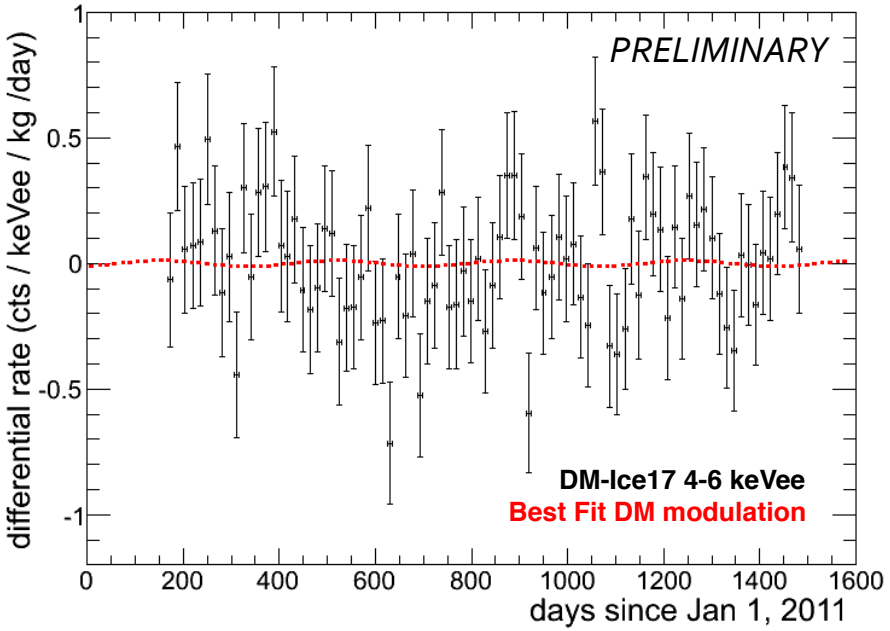
Low-Energy Rates



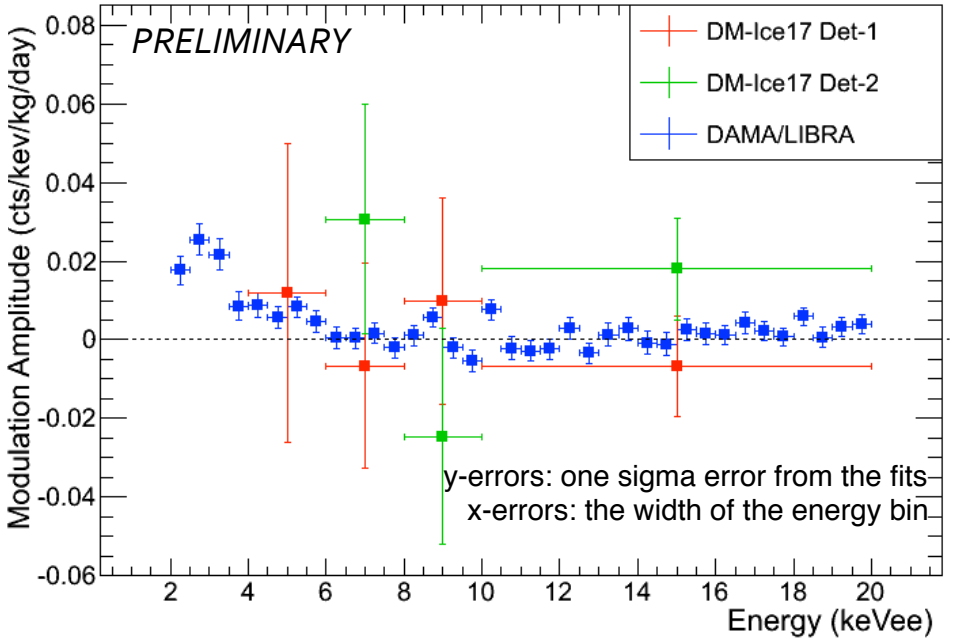


- Rates decrease for all energy ranges by ~10% over 3.5 years
- No statistically significant modulation component

Dark Matter Modulation Fits



maximum likelihood fits
with fixed period (1 year)
and fixed phase (June 2)



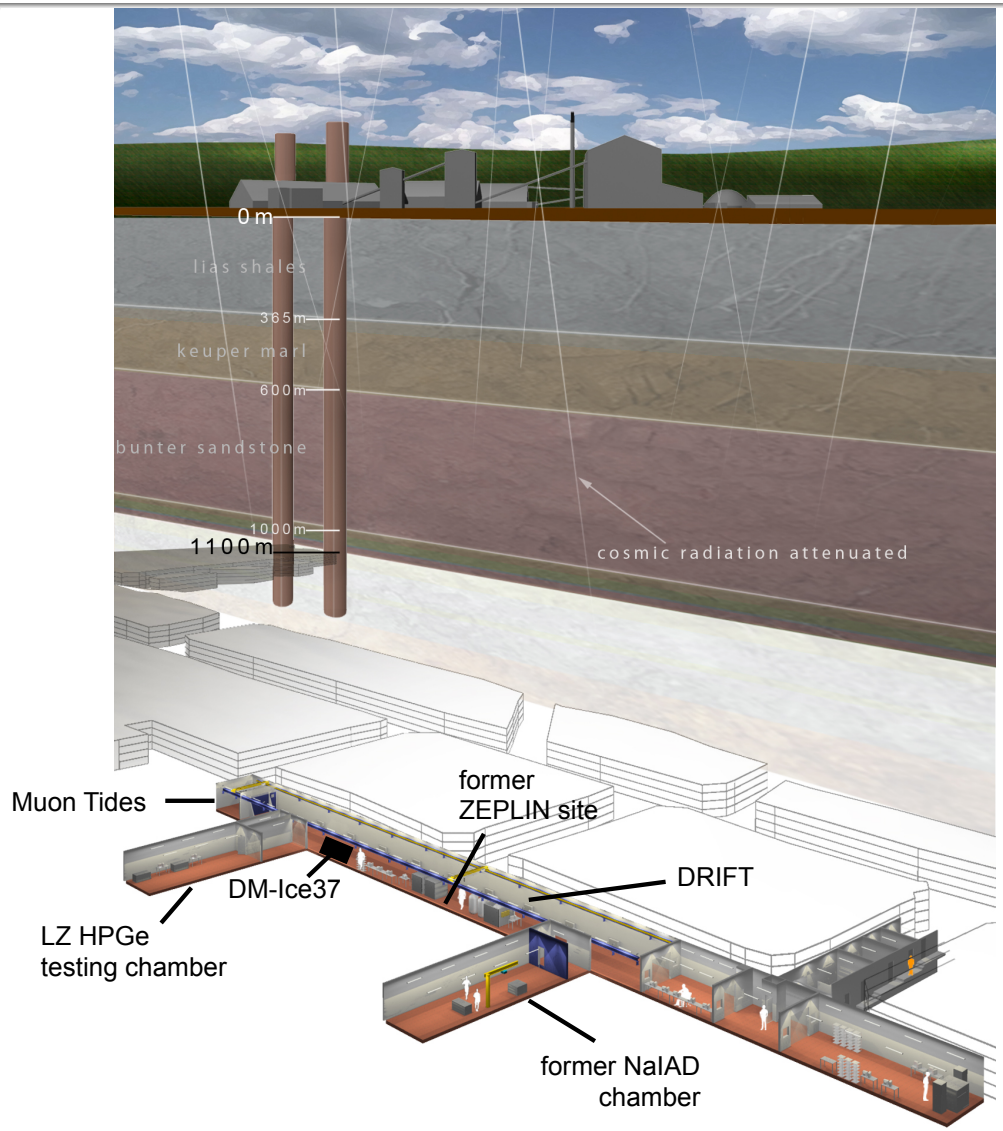
Dark matter modulation (phase = June 2) amplitudes are consistent at all energies with both *no modulation* and the *DAMA/LIBRA signal*.

DM-Ice37 : R&D Work

Operating newly-grown NaI crystals at Boulby Lab (UK)

- 2850 m.w.e. overburden
- Low radon environment
- Copper-lined lead castle

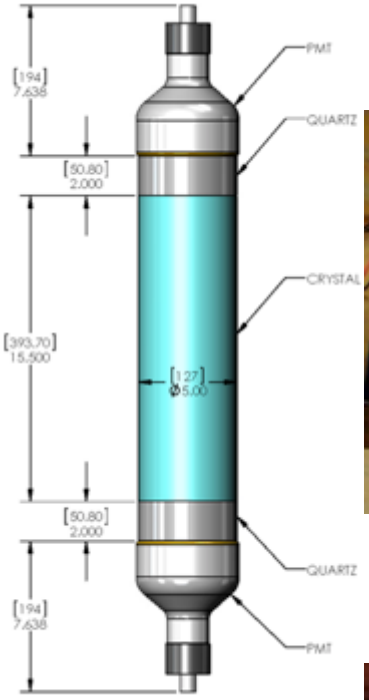




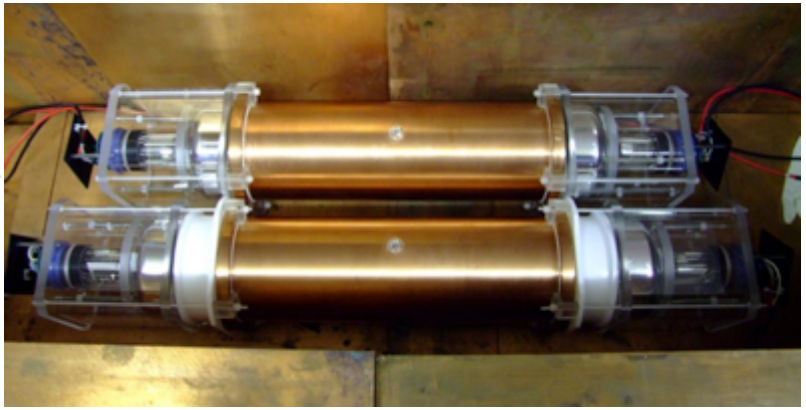
DM-Ice37 Objectives

Open Questions:

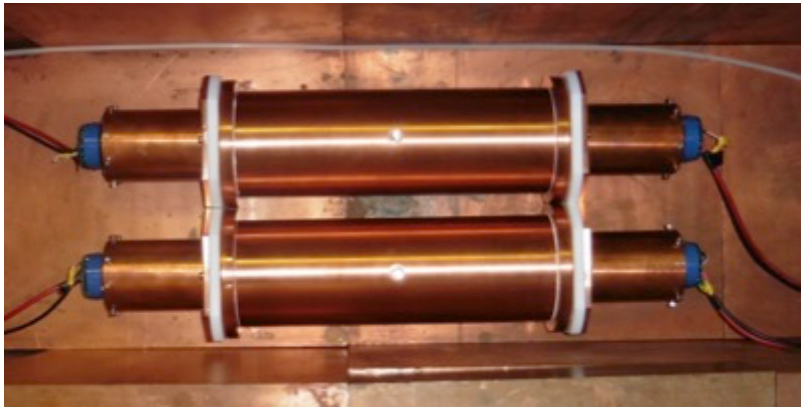
- Crystal purity
- Light yield
  - Energy resolution
- PMT background
  - *Lightguides?*
- Photon collection
  - Photocathode coverage
  - *Lightguides?*



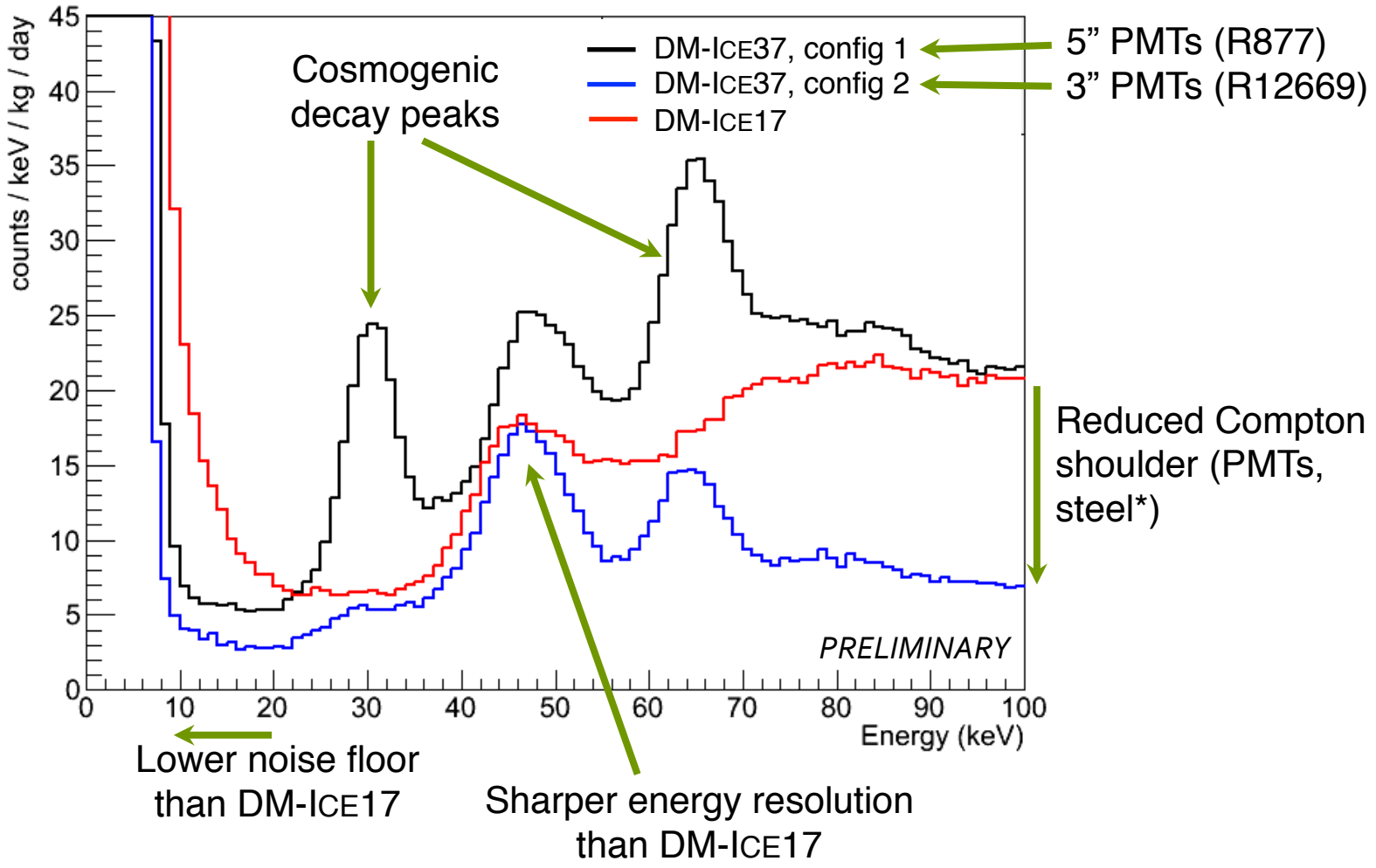
Configuration 1:
- 5” PMTs, lightguide test



Configuration 2:
- 3” PMTs, reflector test



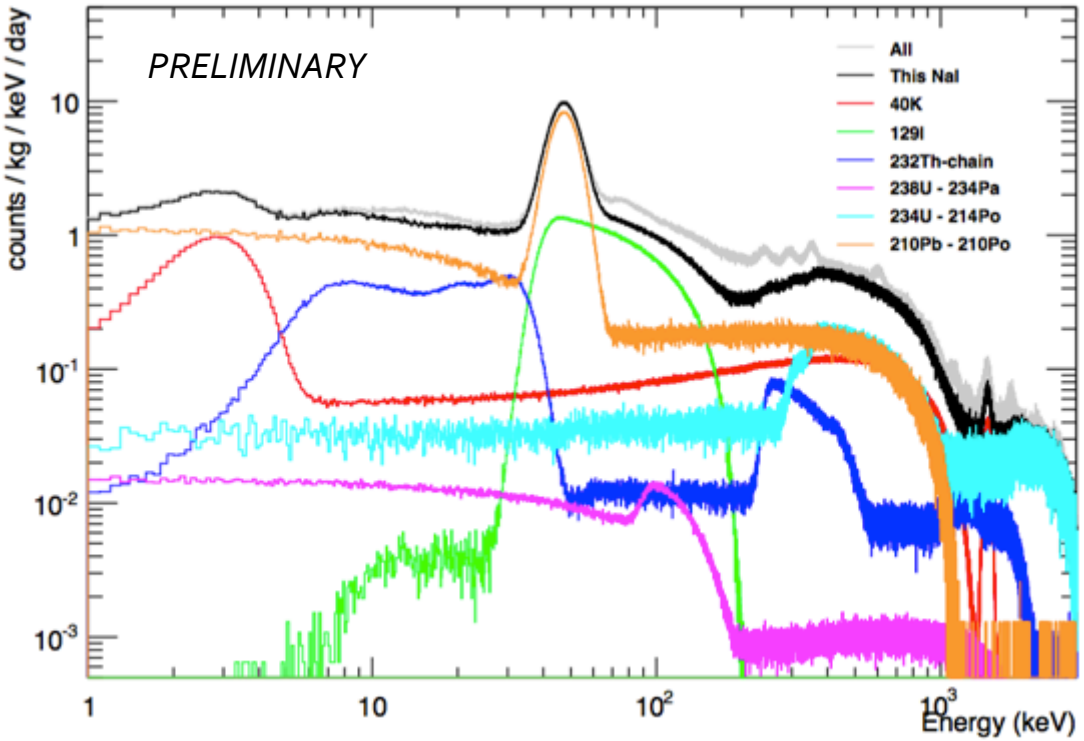
DM-ICE37 Spectrum



NaI Background Simulation

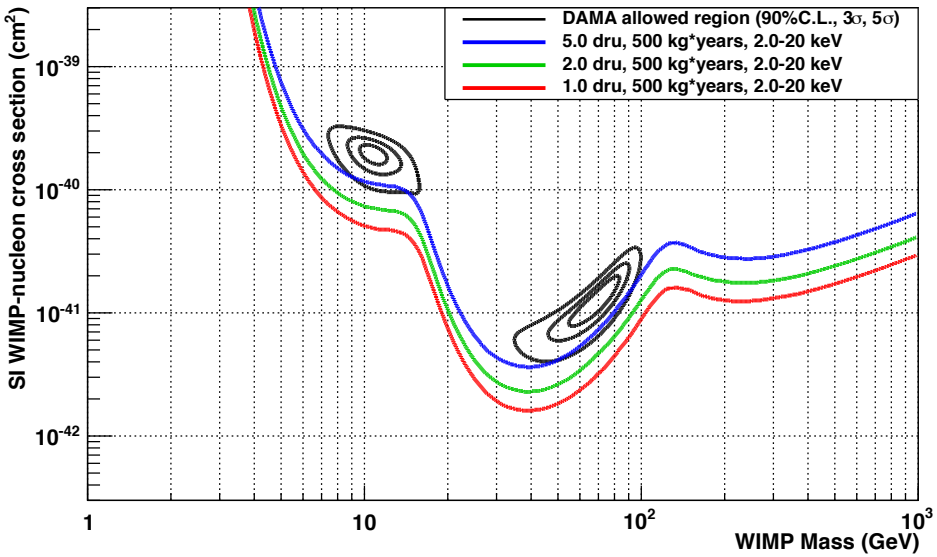
- Low-energy crystal background from both ^{40}K and ^{210}Pb (^{238}U-chain)
  - Further crystal R&D necessary to validate NaI background model

Outer crystal, vetoed NaI background only

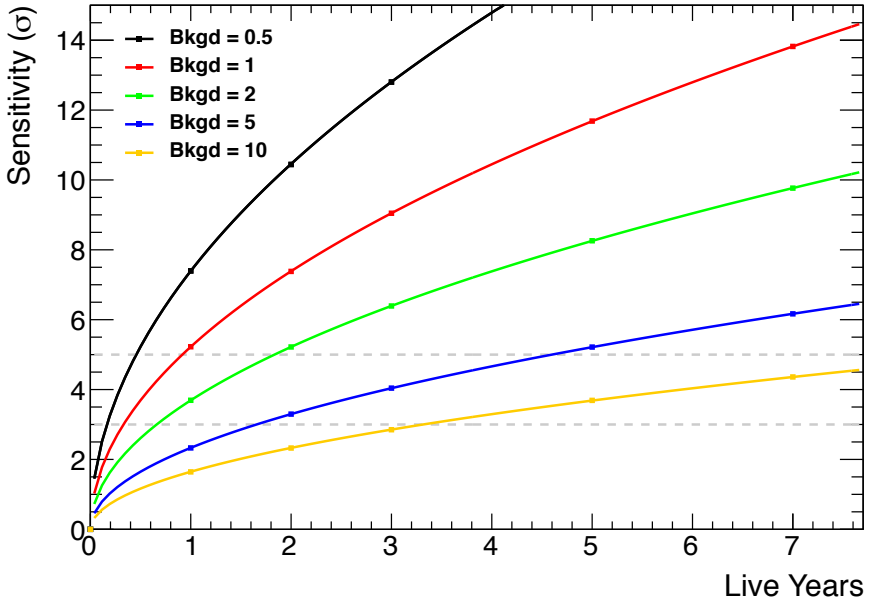


Sensitivity Projection

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

COSINE

An International Consortium of Sodium Iodide Experiments

ANAIS   **DM-Ice**   **KIMS**

Boulby

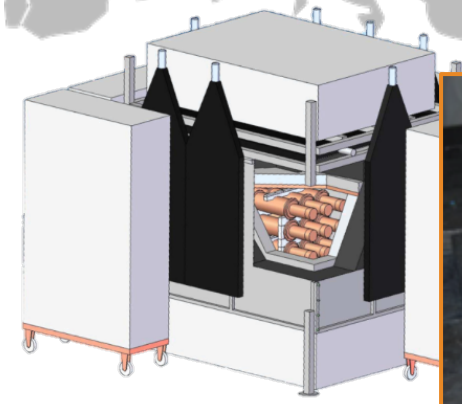
Canfranc

Yangyang

ANAIS
113 kg array
External muon veto

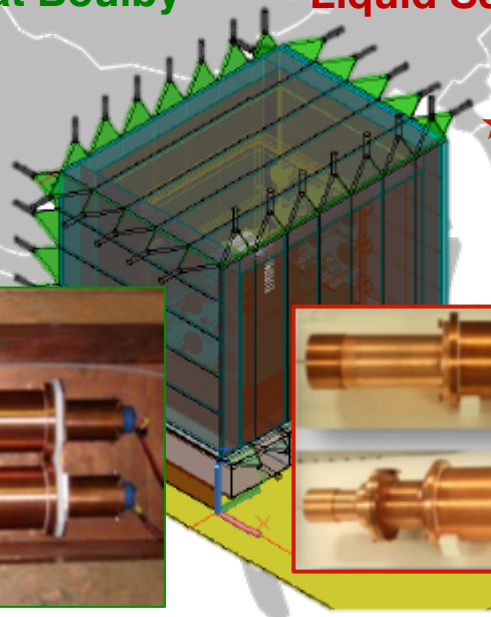
DM-Ice
55 kg in Yangyang array
Crystal R&D at Boulby

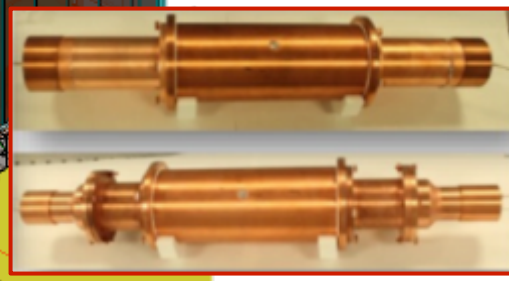
KIMS
52 kg in Yangyang array
Liquid Scintillator veto







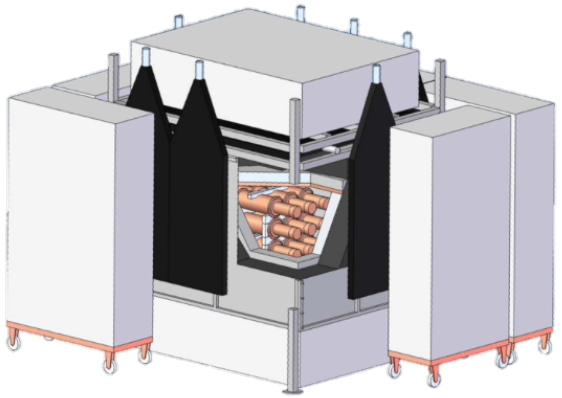


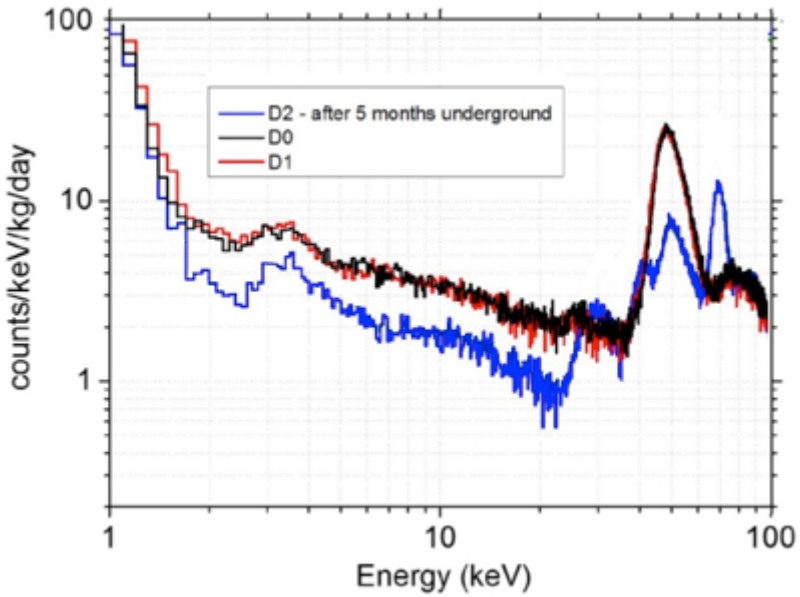


- Cross-collaboration data analysis and hardware coordination effort
- 220 kg combined sensitive mass
- Start data taking by summer 2016, target exposure summer 2018

ANAIS

- Deployment at Canfranc, Spain
- 3x3 tight-packed array
  - Initial results of D0, D1, D2 released
  - Remaining six crystals arrive in 2016
- Commissioning summer 2016



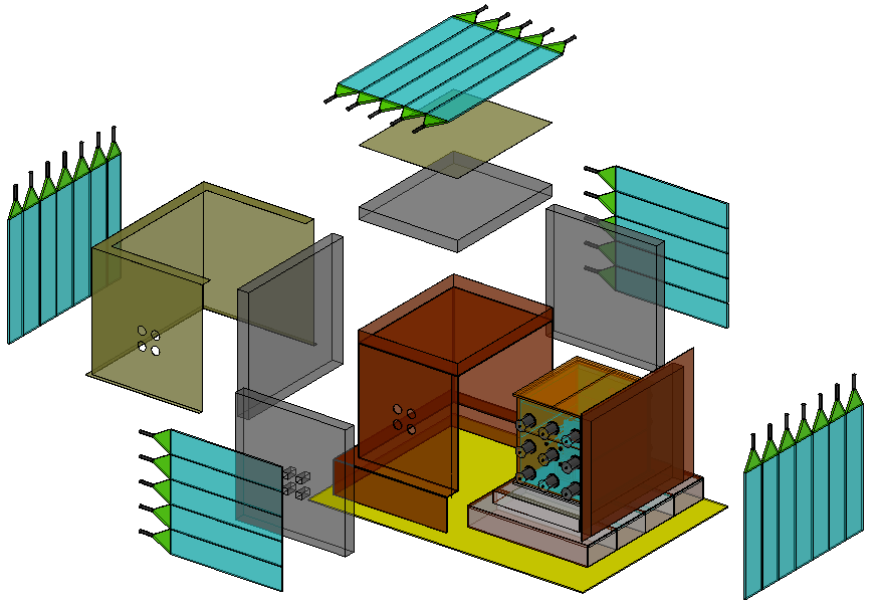


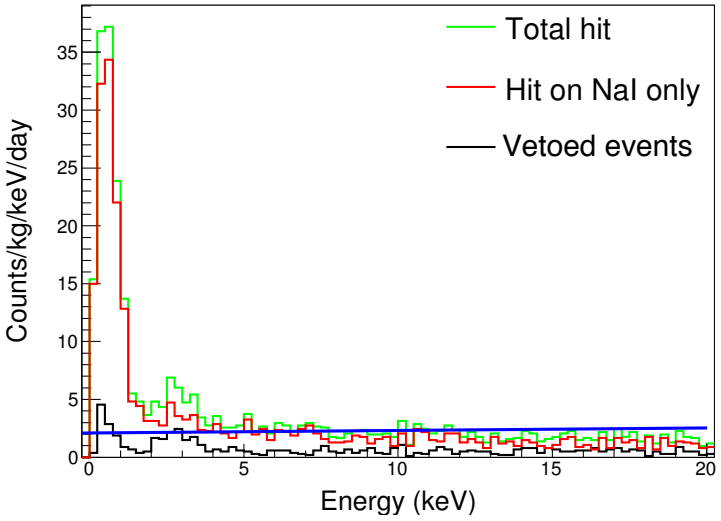
- 15 pe/keV light yield demonstrated
  - 1 keV analysis threshold achieved
- Crystal backgrounds significantly improved
  - 1.1 mBq/kg ^{40}K (3 keV peak)
  - 0.7 mBq/kg ^{210}Pb (flat background)
  - Within factor of two of DAMA levels

ANAIS Collaboration, [arXiv:1601.01184]

KIMS + DM-Ice

- Deployment at Yangyang, Korea
- Shielding designed for 200 kg of crystal mass
  - Crystals in tight-packed array
    - Different geometry for DM-Ice and KIMS crystals
  - Immersed in LS veto
    - 10 keV veto threshold
- Commissioning Spring 2016





- 2 dru background demonstrated with LS veto
- Same light yield as ANAIS
- Even lower background in some test crystals
  - 0.8 mBq/kg ^{40}K (alternate powder)
  - 0.5 mBq/kg ^{210}Pb (better radon control)

NaI Crystal Background

Worldwide effort of NaI dark matter experiments (ANAIS, DM-Ice, KIMS) working with crystal grower (Alpha Spectra) to produce low-background crystals

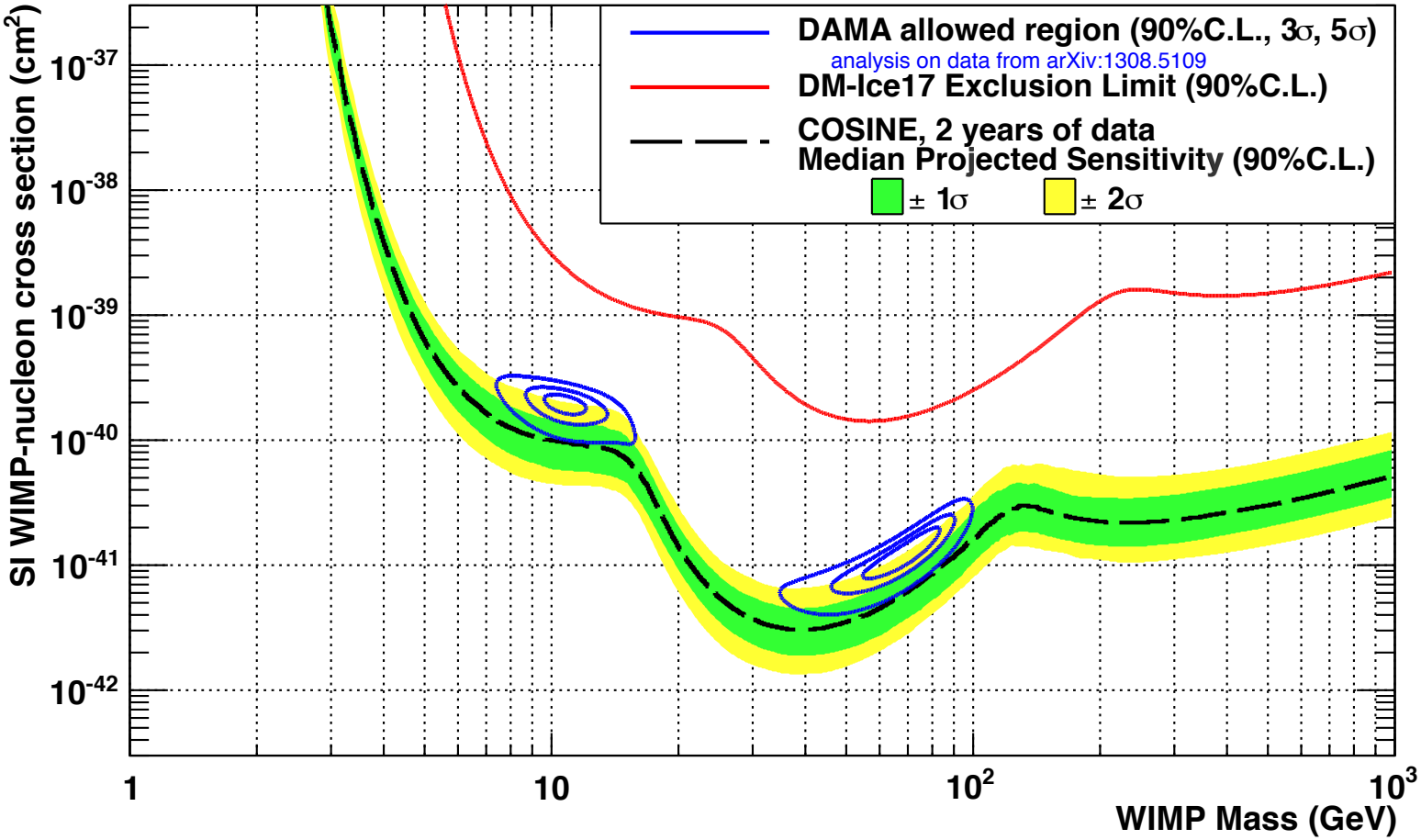
- Powder purity controls ^{40}K
- Radon abatement during growth controls ^{210}Pb

(all rates in μBq/kg)

Decay	DM-Ice17[A]	ANAIS-0[B]	DAMA[C]	ANAIS-25[D] (KIMS-001)	KIMS-002[E] (DM-Ice37)	KIMS R&D[F]	PICO-LON R&D[F]
^{40}K	17000	12700	600	1250	1490	780*	<3000
^{232}Th	10	13		2	2		
^{228}Ra – ^{208}Tl	160	35	2-30	2	2		1.5
^{238}U	17	75	4.4	10	<12		
^{234}U	140	75	15.8				
^{226}Ra – ^{214}Po	900	98	21.7	10	<1.5		58
^{210}Po	1500	188	24.2 (500*)	3150	1760	470*	29

A – Cherwinka *et al.*, Phys. Rev. D **90** (2014)
B – Cebrián *et al.*, Astropart. Phys. **37** (2012)
C – Bernabei *et al.* NIM A **592** (2008)
D – Amaré *et al.* NIM A **742** (2014)
E – Kim *et al.* Astropart. Phys. **62** (2014)
F – *(TAUP2015)*

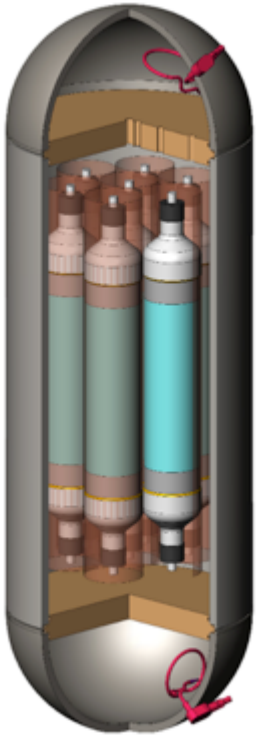
COSINE Sensitivity



Two years of data sufficient to exclude DAMA (null hypothesis)
> Late 2018 <

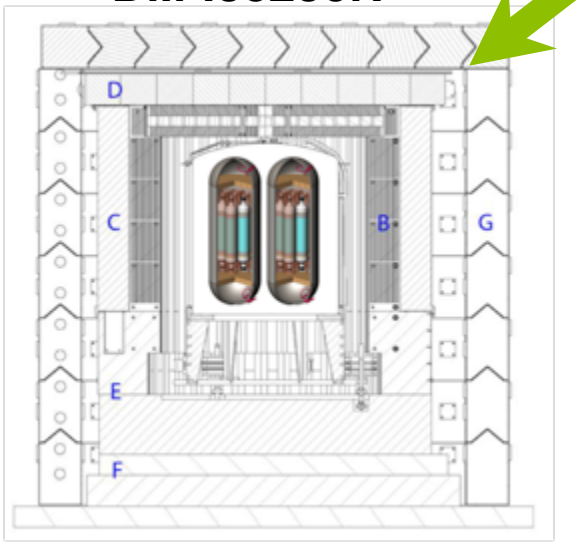
Deployment Possibilities

Definitive *confirmation* of DAMA modulation would require a Southern Hemisphere measurement



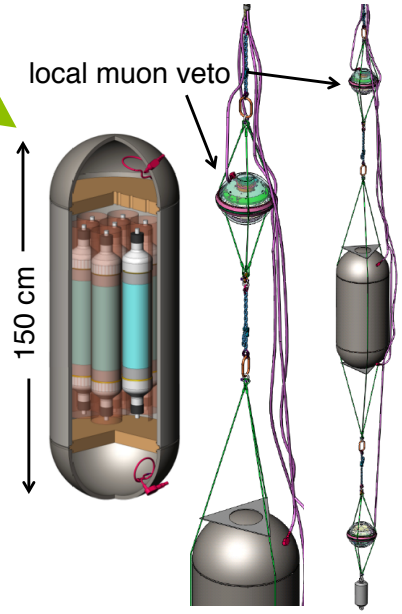
Modular detector design supports deployment in both hemispheres

DM-Ice250N



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

DM-Ice250S



Conclusions

- DM-Ice17 has completed its 3.5-yr science run with 99% uptime and excellent stability
  - Serves as trailblazer for future rare event searches in South Pole ice
  - Completed important measurements of NaI crystal response for future low-background experiments
- COSINE and DM-Ice250 present path forward to testing DAMA modulation signal
  - Late 2018 for first COSINE results
  - Further R&D and preparation ongoing for Southern Hemisphere deployment


Geographic South Pole