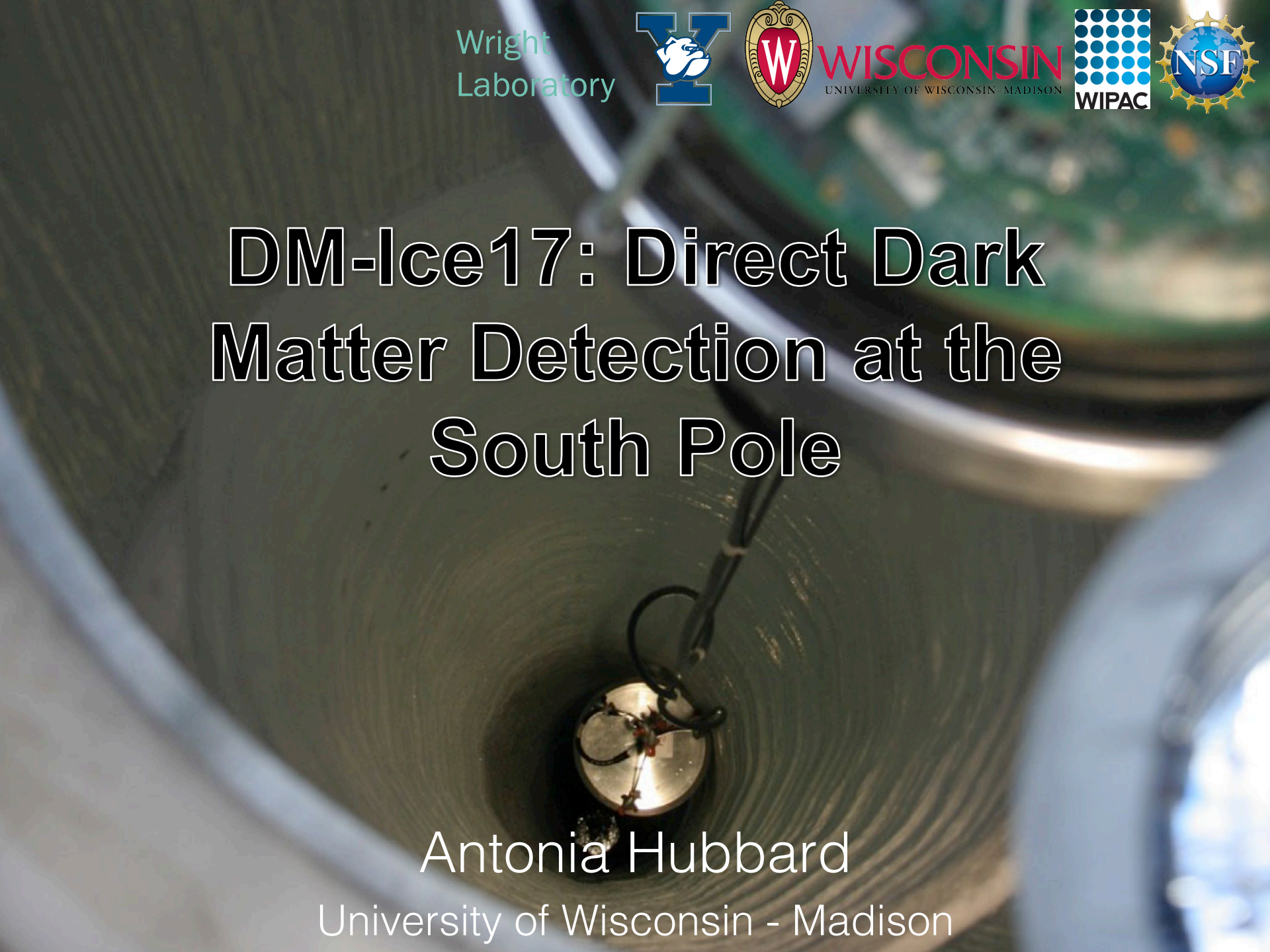


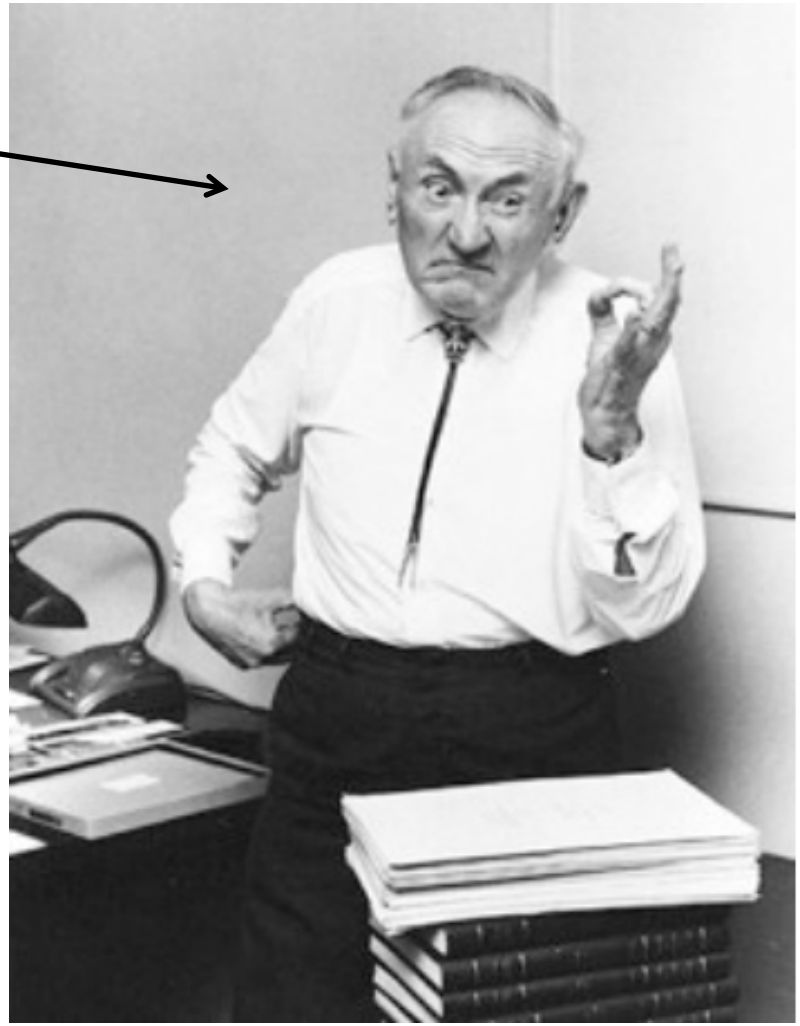
Wright Laboratory

DM-Ice17: Direct Dark Matter Detection at the South Pole

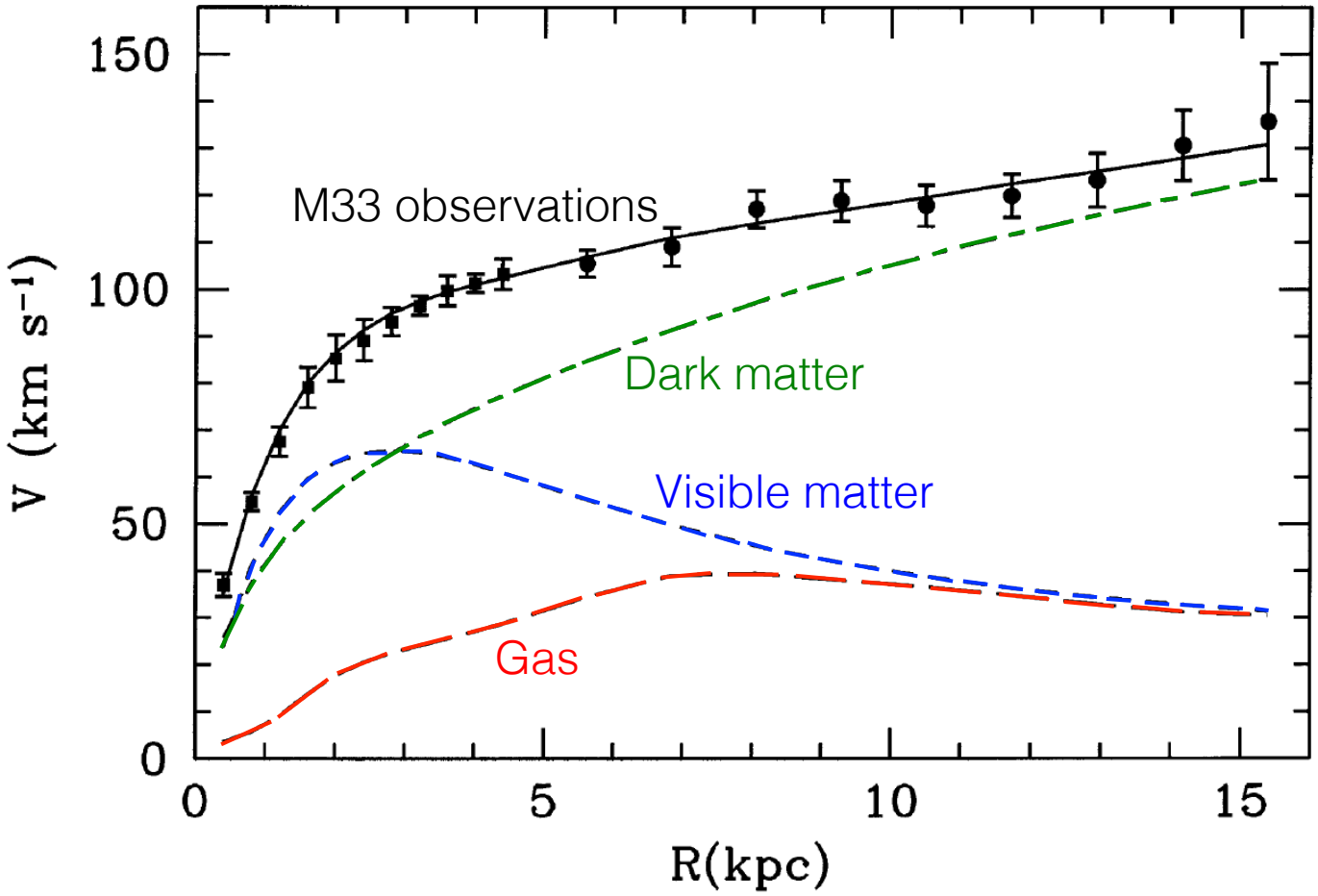
Antonia Hubbard
University of Wisconsin - Madison

First Evidence of Dark Matter

- 1933: Fritz Zwicky analyzes the Coma cluster and sees a large discrepancy
  - Galaxies are moving too fast!
- Infers that unseen "dark" matter is dominating the gravitational movement



Evidence: Rotation Curves

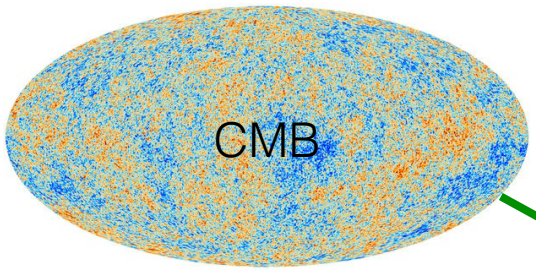


$$g = \frac{v_{rot}^2}{r} = \frac{GM}{r^2}$$

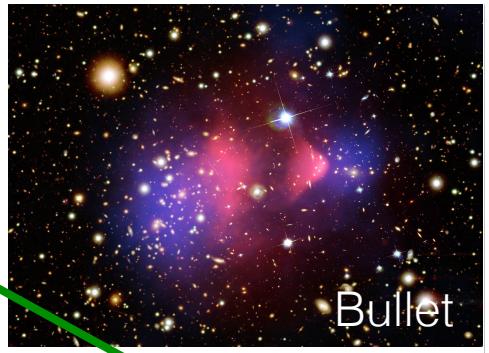
$$v_{rot} = \sqrt{\frac{GM}{r}}$$

Corbelli and Salucci (2000)

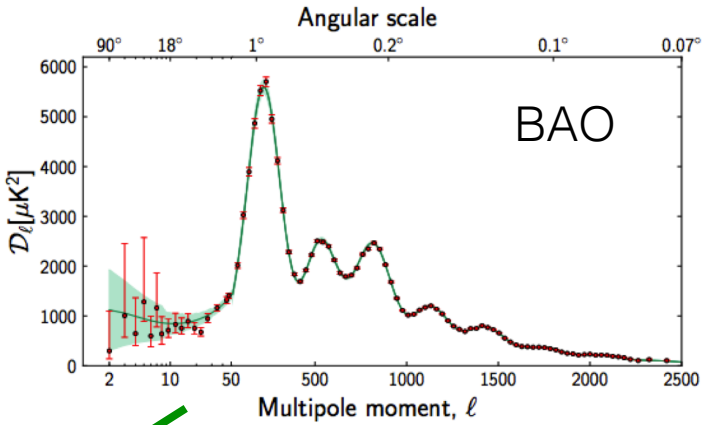
Evidence for Dark Matter



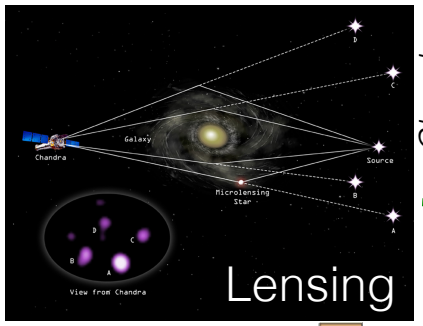
arXiv: 1303.5075



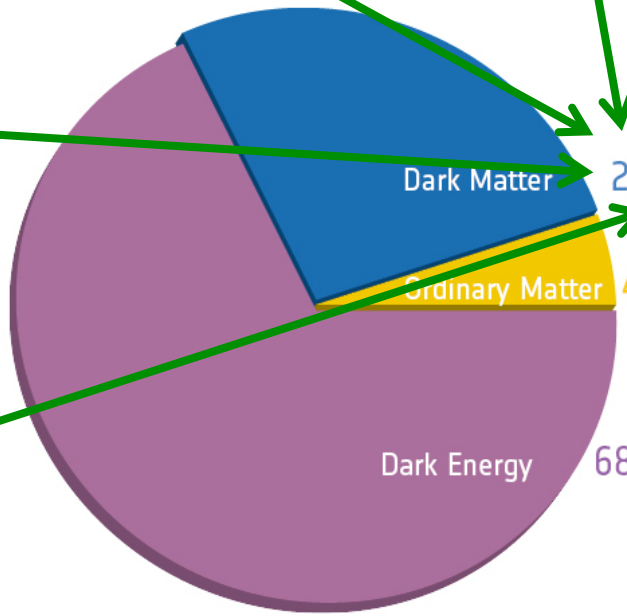
NASA



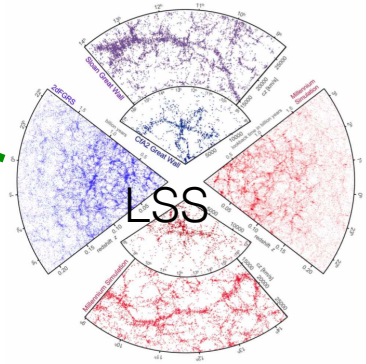
ESA/Planck Collaboration



Chandra

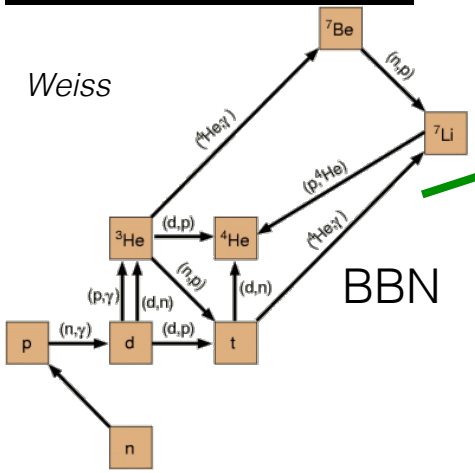


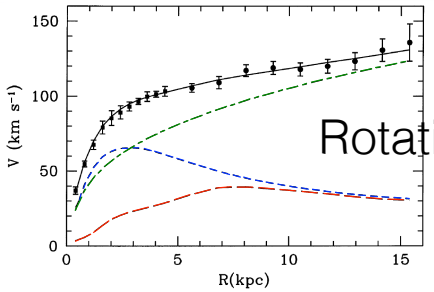
ESA/Planck Collaboration



doi: 10.1038/nature04805

Weiss



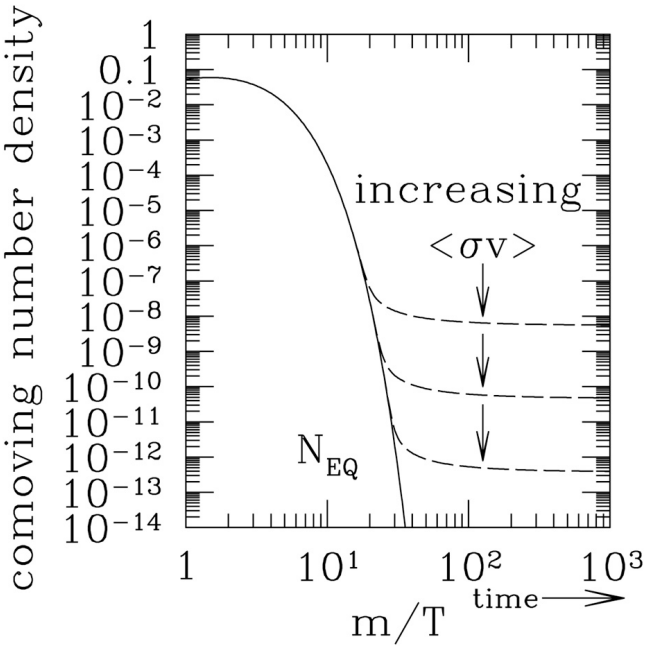


Corbelli and Salucci (2000)

What is Dark Matter?

- Requirements
  - Stable, massive, non-baryonic, neutral
- WIMPs: Weakly-Interacting Massive Particles
  - "WIMP Miracle": weak cross-section matches predictions
  - GeV - TeV mass

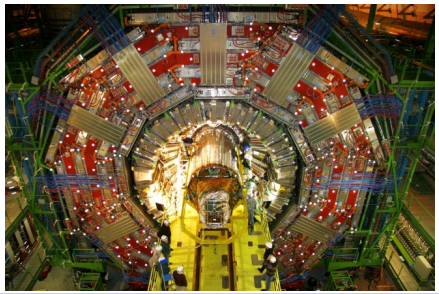
Beyond the Standard Model



Dark Matter Detection

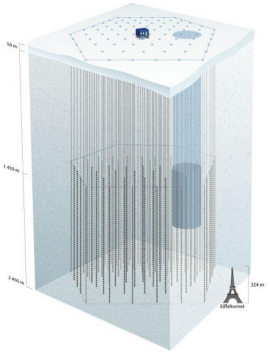
Collider Production

Produce WIMPs and detect them as missing energy



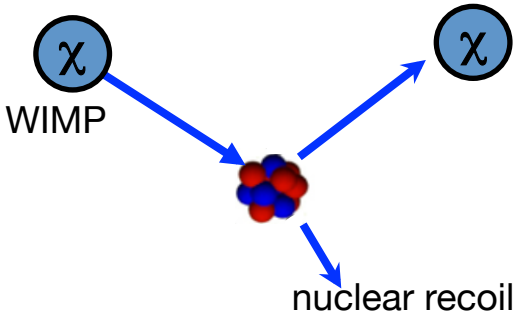
Indirect Detection

Search for excess of annihilation products (solar core, GC…)



Direct Detection

Detect nuclear recoil from WIMP-nucleon scattering



$$\frac{dR}{dE_r} = \frac{\rho_0}{M_\chi M_A} \int_{v_{min}}^{v_{max}} v f(v) \frac{d\sigma_{\chi A}}{dE_R}(v, E_R) dv$$

Astrophysics

ρ_0 = 0.3 GeV/cm^3

v: WIMP wind ~220 km/s

Particle physics

SI elastic:

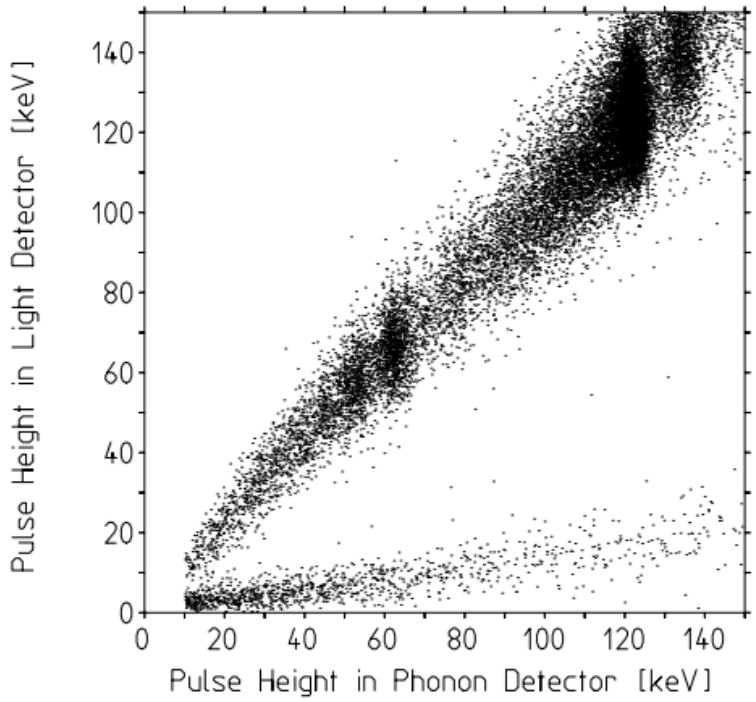
$\sigma \sim 10^{-44}$ -10^{-47}cm^2

Direct Detection Techniques

To identify signal over background:

Separate electronic and nuclear recoils

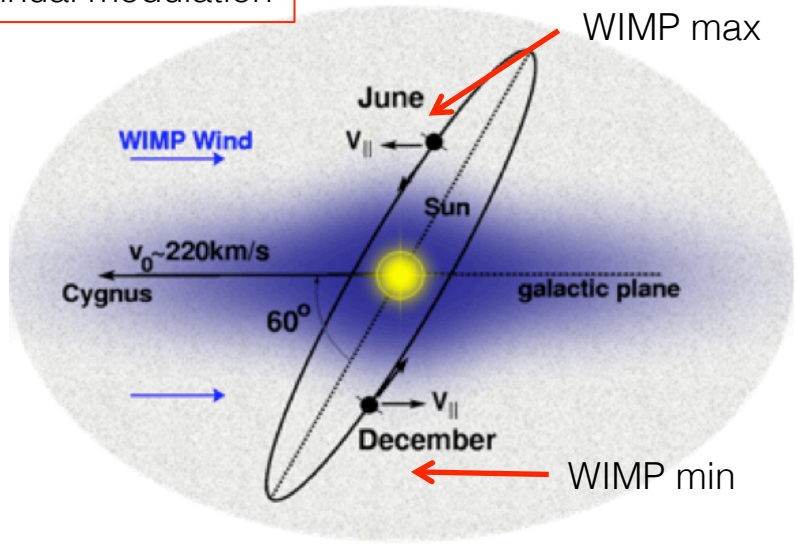
CRESST 2001



Observe modulation: annual or diurnal

$$v_e(t) = 232 + 15cos\left(2\pi\frac{t-152.5}{365.25}\right)$$

7% WIMP flux annual modulation

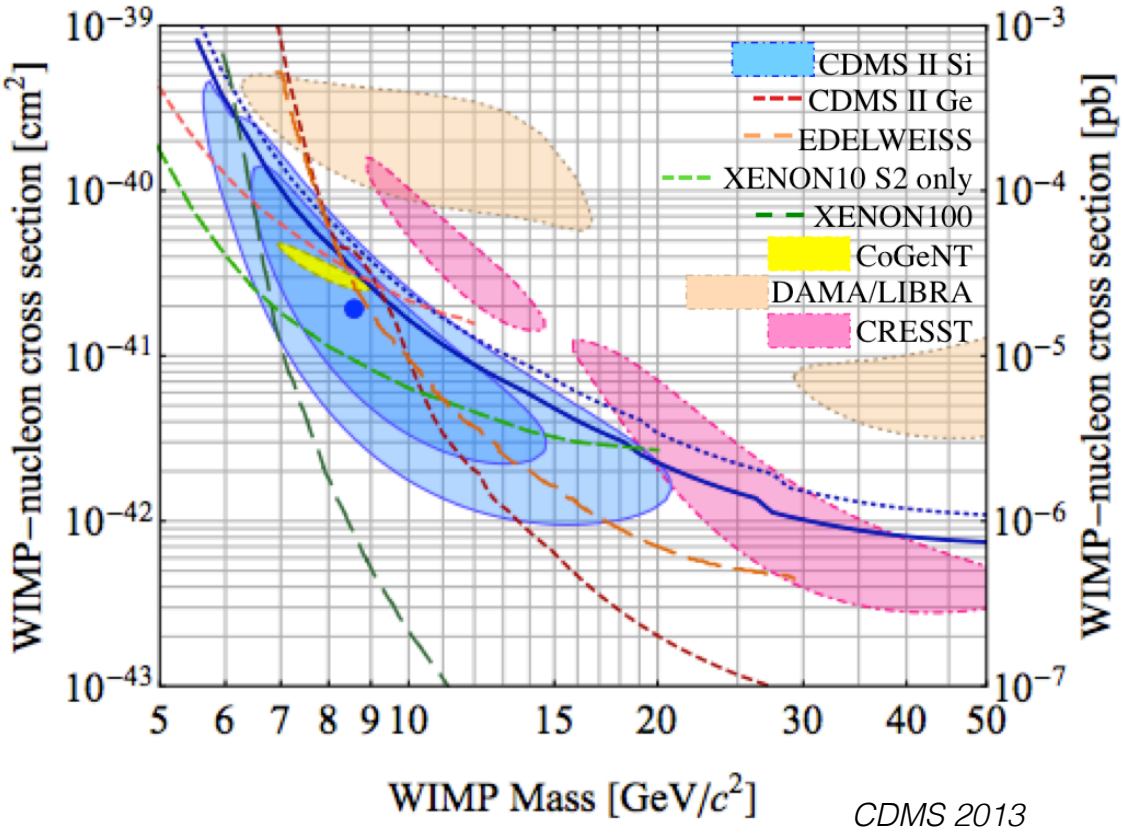


Positive Hints of Detection

CDMS Si (2013)
- 3σ excess
- Excluded by CDMS Ge

CoGeNT (2011)
- 2.8σ annual modulation
- Postulated to be surface events

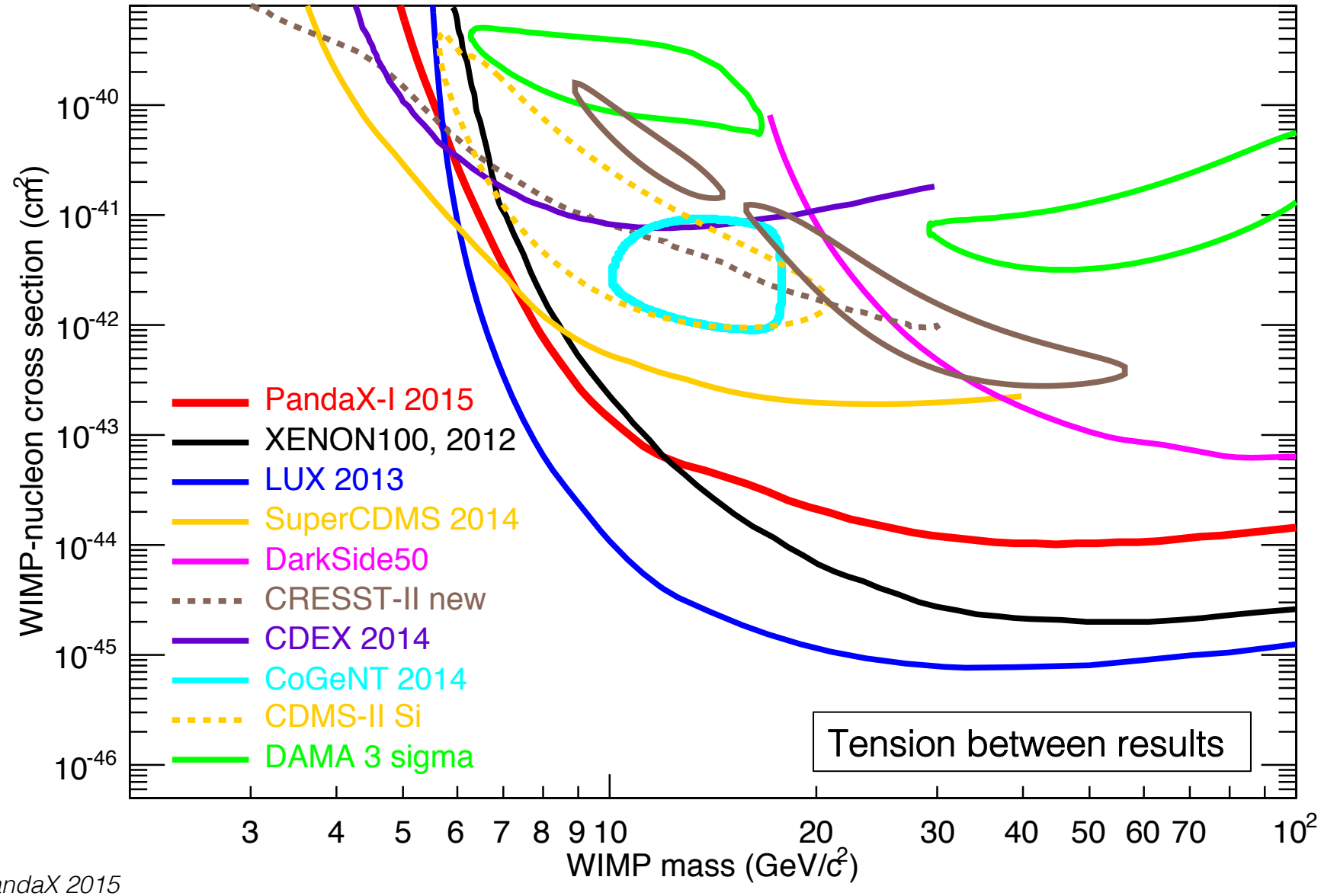
CRESST (2011)
- 4σ excess
- Signal excluded after detector upgrades and background reduction



CDMS 2013

DAMA: only result not excluded by same target medium/collaboration, although KIMS (using CsI(Tl)) has ruled out Iodine recoils

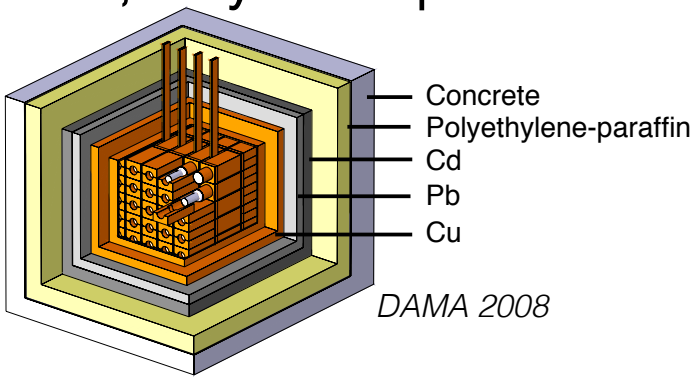
DAMA (2013)
- Scintillation
- 14 annual modulations
- 9.5σ


WIMP-nucleon cross section (cm^2)
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
PandaX-I 2015
XENON100, 2012
LUX 2013
SuperCDMS 2014
DarkSide50
CRESST-II new
CDEX 2014
CoGeNT 2014
CDMS-II Si
DAMA 3 sigma
Tension between results
3 4 5 6 7 8 9 10 20 30 40 50 60 70 10^2
WIMP mass (GeV/c^2)

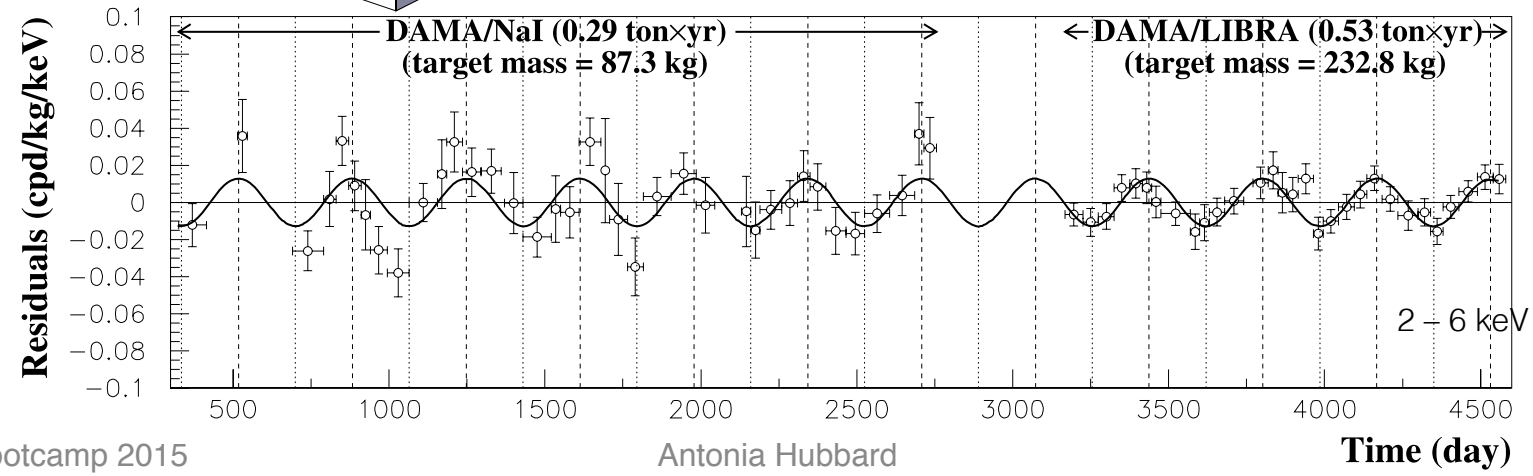
PandaX 2015

DArkMAtter (DAMA)

- Largest signal at 9.5σ annual modulation over 14 years
  - NaI(Tl) scintillation detectors
  - 1% modulation on 1 dru background
  - 1 yr period; May 24±7 phase

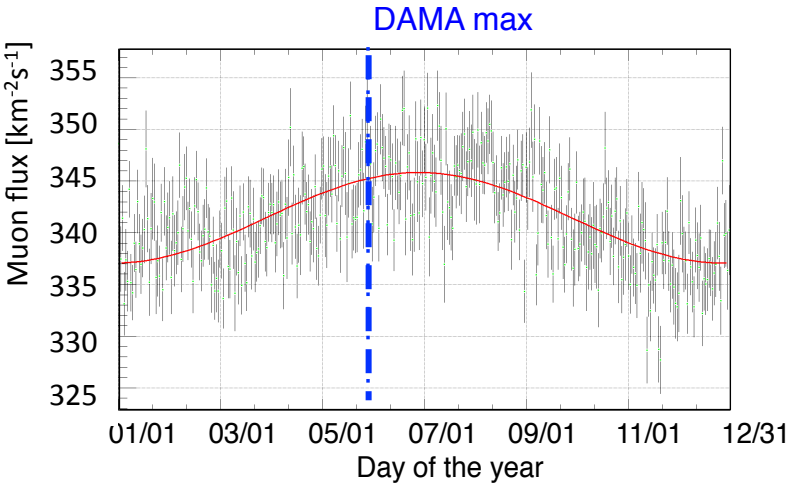


DAMA 2008



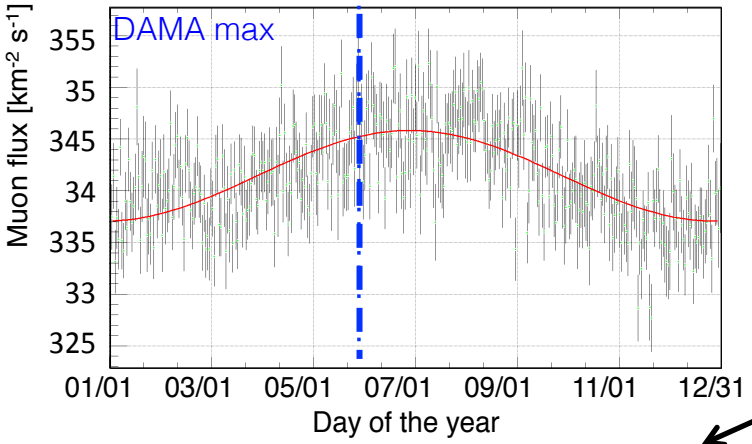
DAMA Result Controversy

- Signal excluded by other experiments
- Could something else be modulating?
  - 100s of papers suggesting environmental backgrounds, internal backgrounds, experiment systematics…
    - Is the threshold moving? Temperature change in electronics? Radon? Muons?
  - No background explanation can successfully explain the signal



Borexino 2012

DAMA Controversy: Muons



Argument: The DAMA signal may be muons or muon-induced neutrons. *Blum 1110.0857*

No. The muon rate is not high enough, and it is out of phase with the modulation. *Bernabei 1202.4179, Fernandez-Martinez 1204.5180*

A second modulation could combine with muons to be in phase with DAMA. *Davis 1407.1052*

No second modulation has been shown to produce this. *Bernabei 1409.3516*, *Klinger 1503.07225*

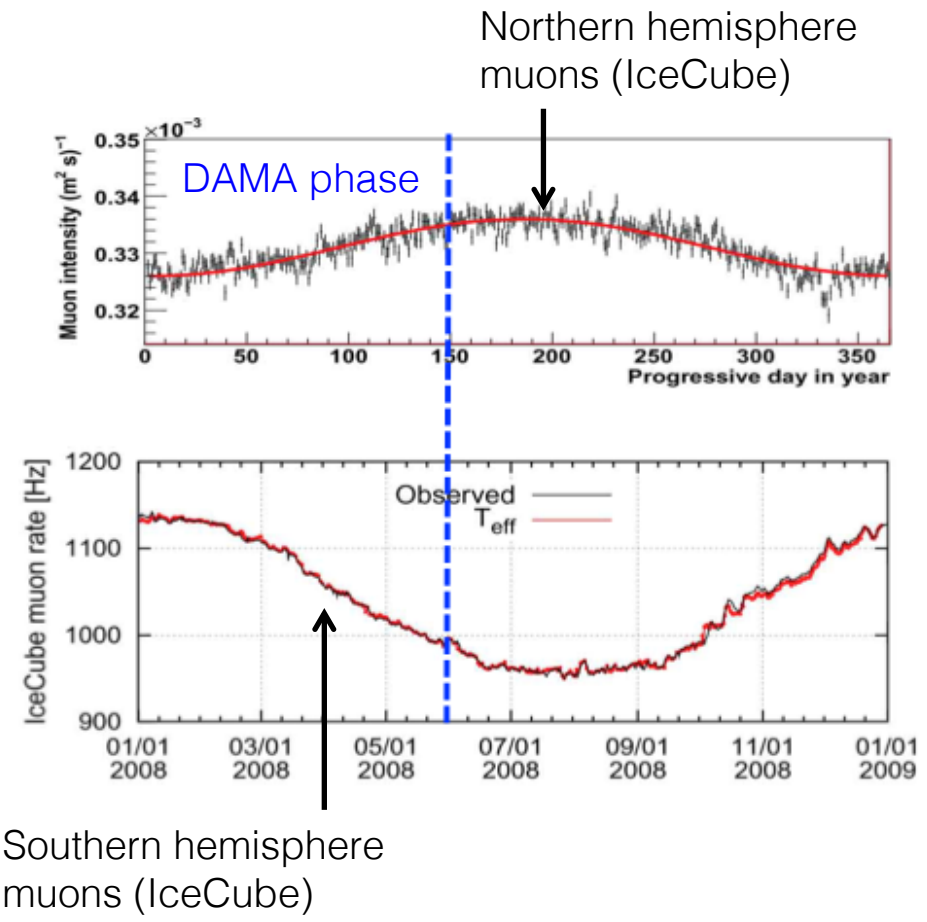
The muon signal may be amplified by cascades of events following muons. *Nygren 1102.0815*

This has not been observed in DAMA. *Bernabei 1202.4179*

New annual modulation experiments must understand their muon backgrounds and provide new information!

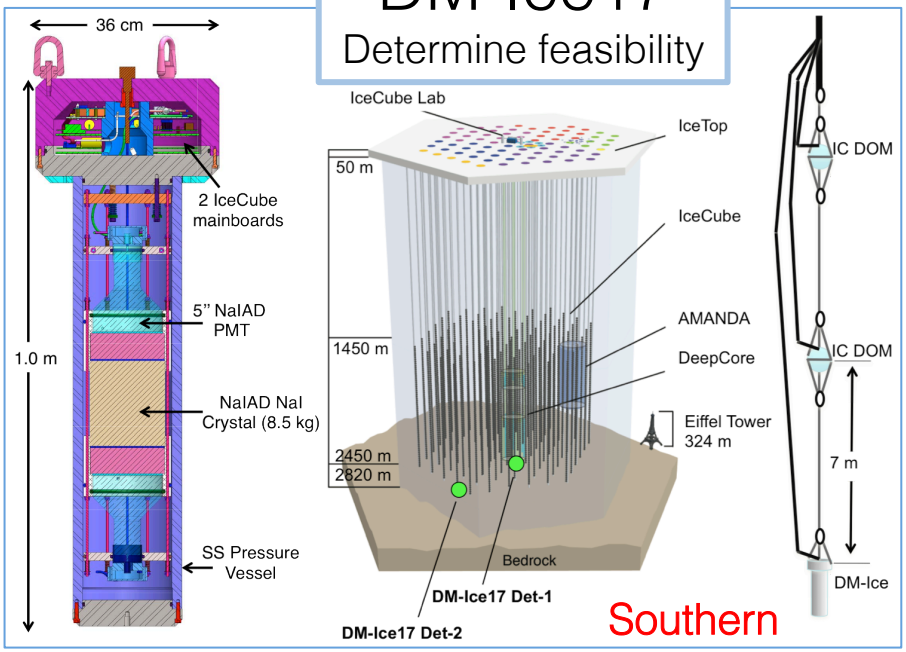
The DM-Ice Concept

- Complement DAMA and study modulation
  - NaI(Tl) detector of similar size and threshold
- Minimize potential modulating background
  - Constant temperature
    - Constant -20° C
  - Understand muon background
    - IceCube coincidence
  - Neutron moderation
    - Water ice
  - Clean environment
    - 2500m overburden
    - U, Th ~ 0.1 – 1 ppt
    - K ~ 0.1- 1 ppb

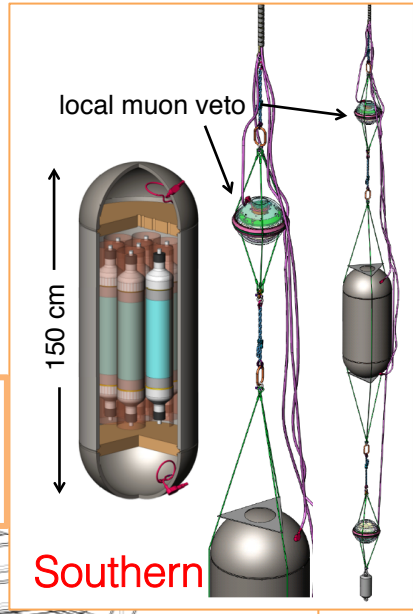


DM-Ice

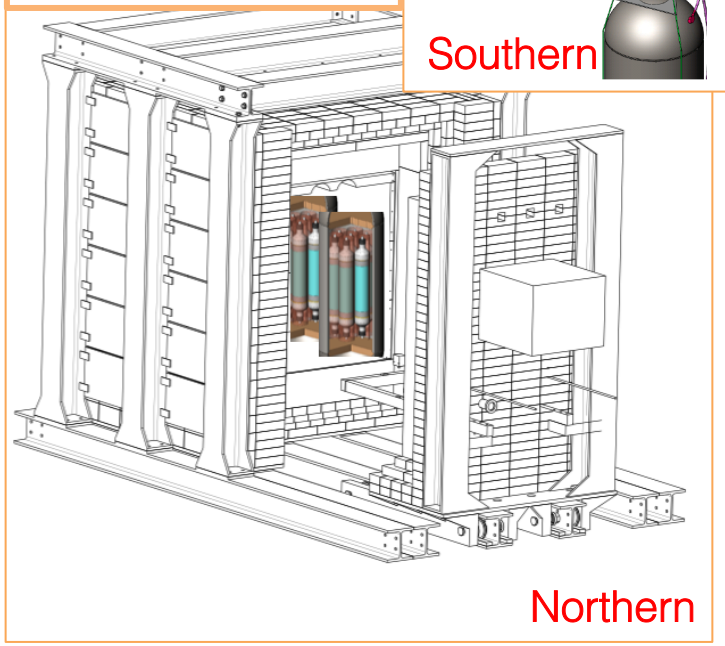
DM-Ice17
Determine feasibility



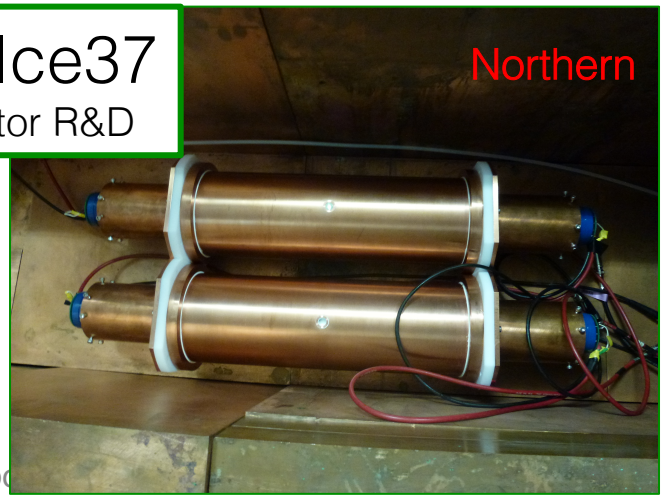
DM-Ice is a phased program that will run in <u>both hemispheres</u> to test the dark matter interpretation of the DAMA modulation



DM-Ice250
Set limits

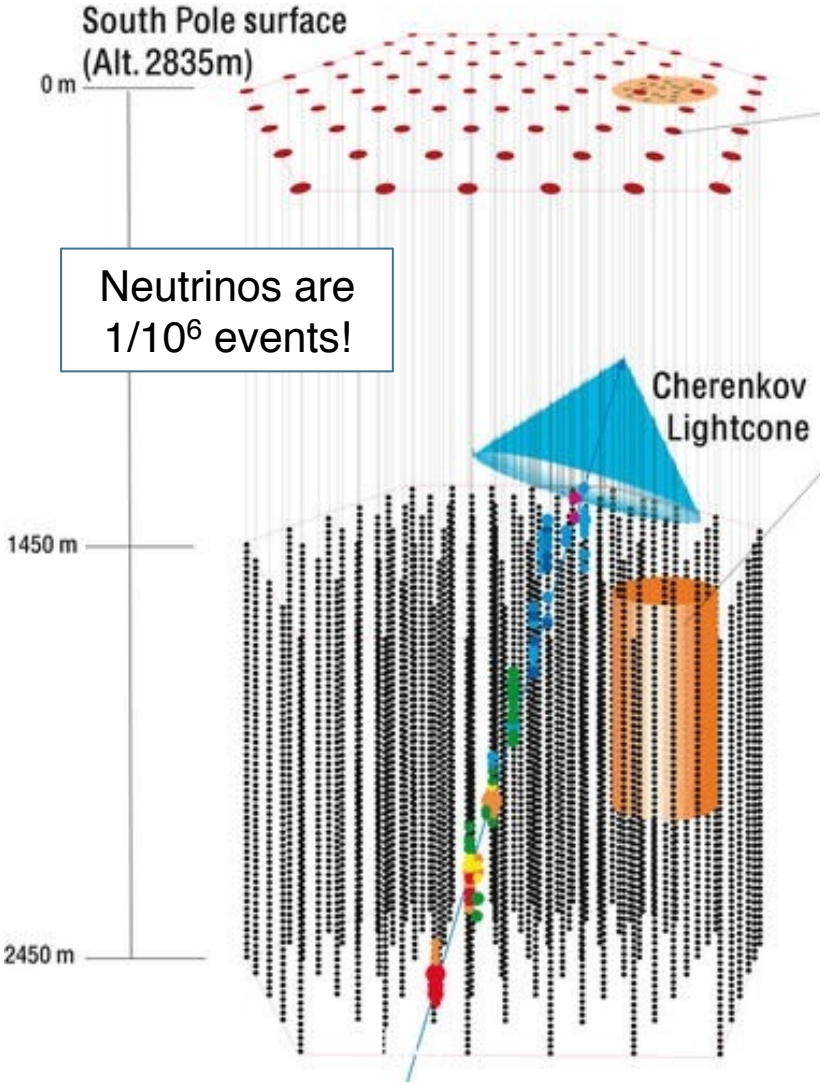


DM-Ice37
Detector R&D



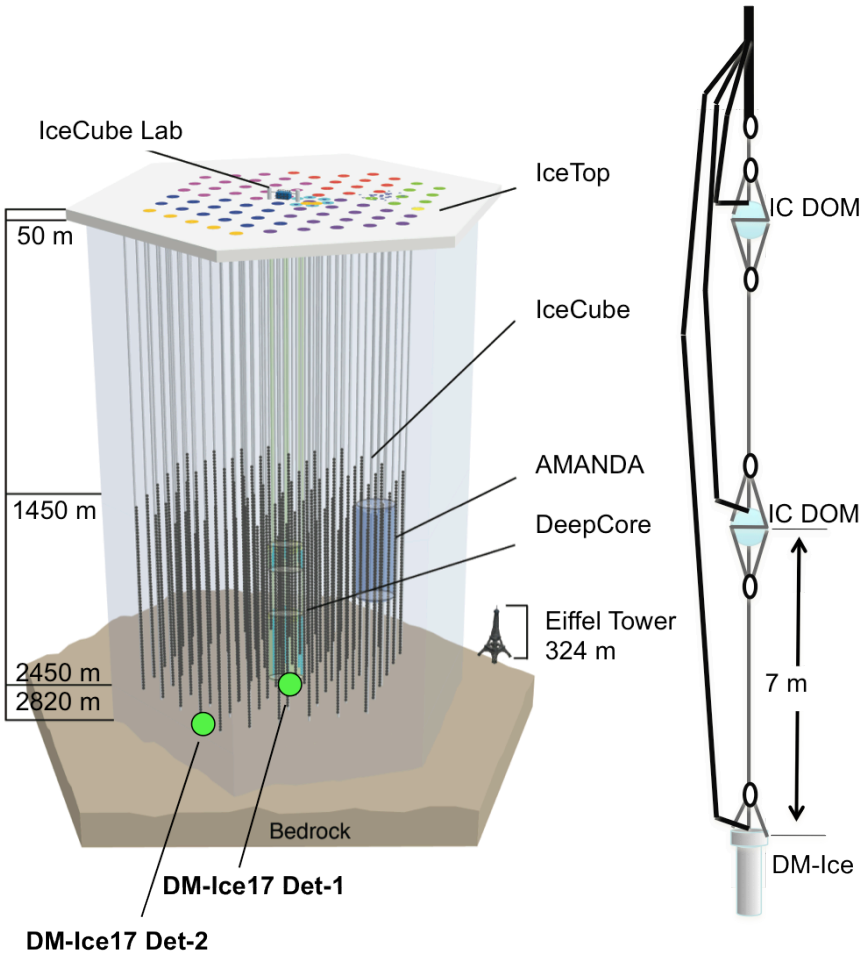
IceCube Neutrino Observatory

- 5160 PMTs in 1km^3
  - 1500 – 2500 m deep
  - Neutrinos: up-going
  - Atm. muons: down-going

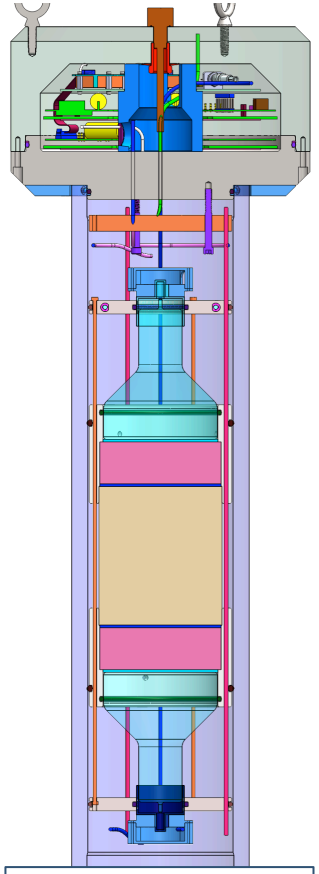


DM-Ice17 Goals

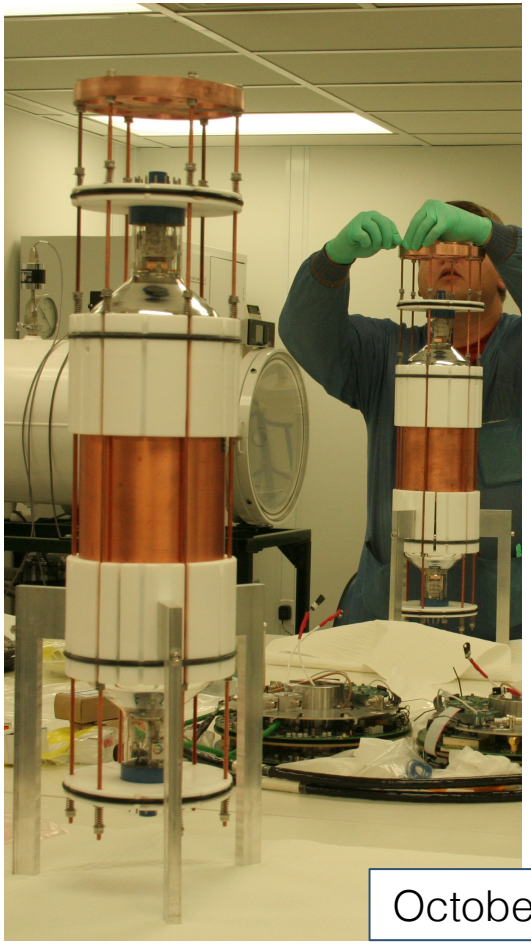
- Illustrate feasibility of NaI(Tl) detector in South Pole ice
- Environmental studies
  - Backgrounds, stability
- IceCube muon coincidence



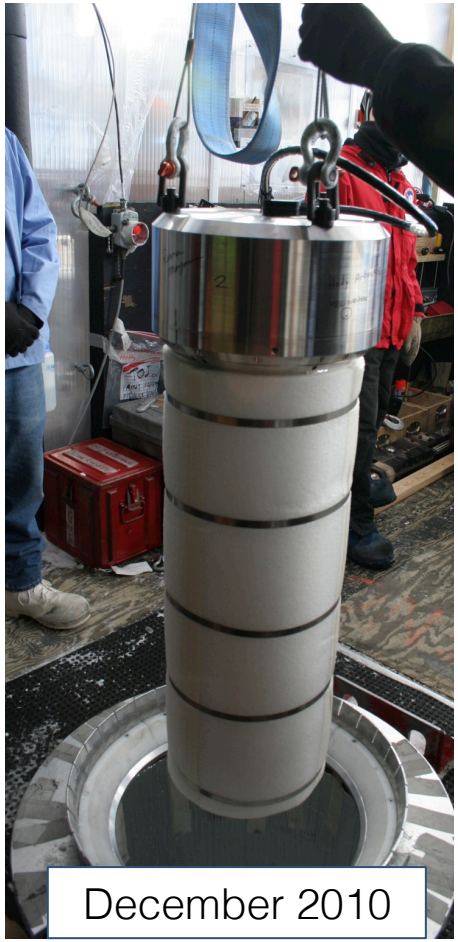
DM-Ice17



Summer 2010



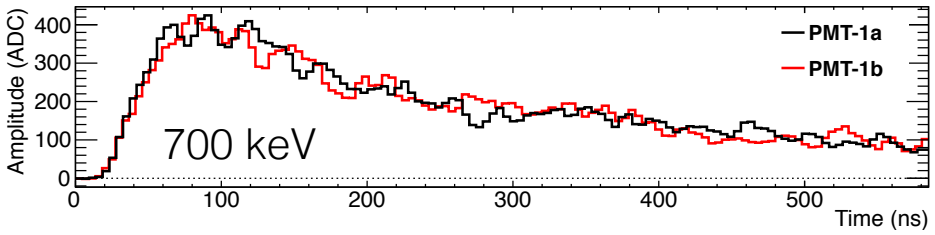
October 2010

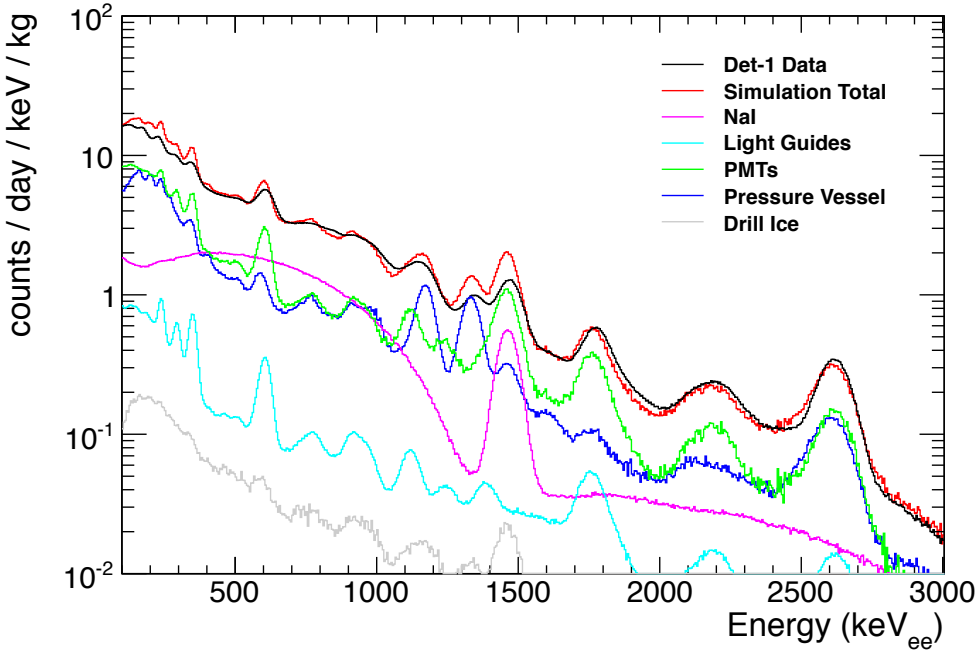


December 2010

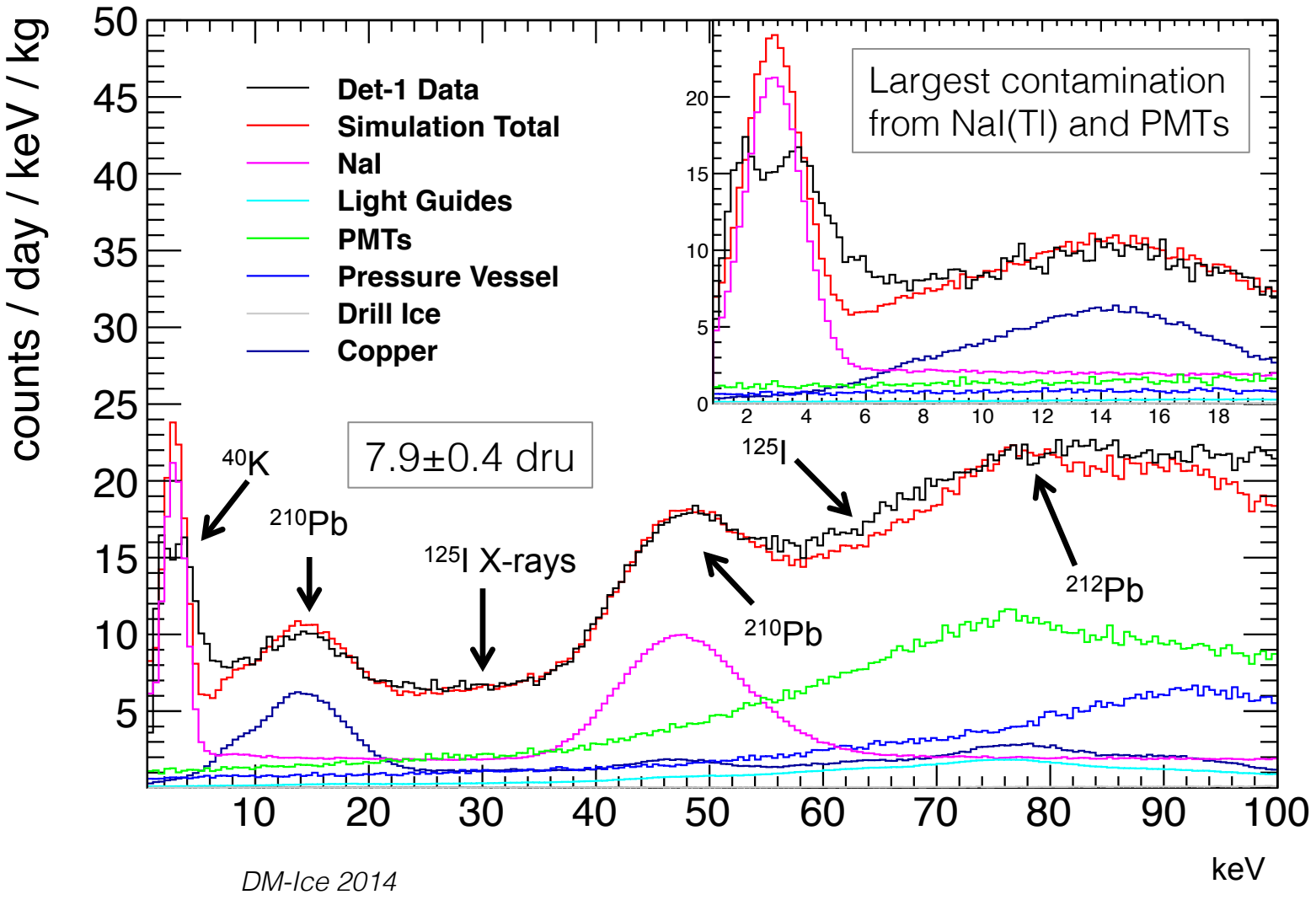
DM-Ice17 Data

- Stable data taking since January 2011
  - 99% uptime
- Calibrated using internal contamination
  - Source runs taken before deployment



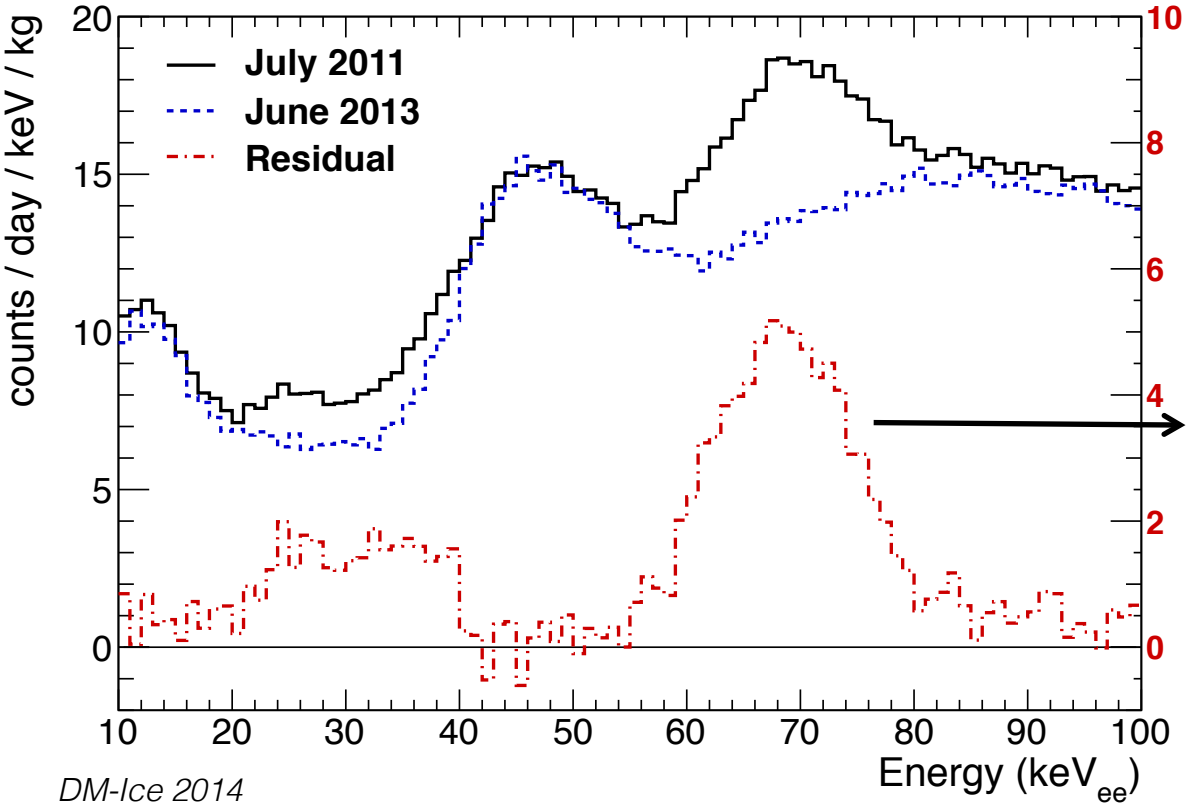


Low Energy Background Model

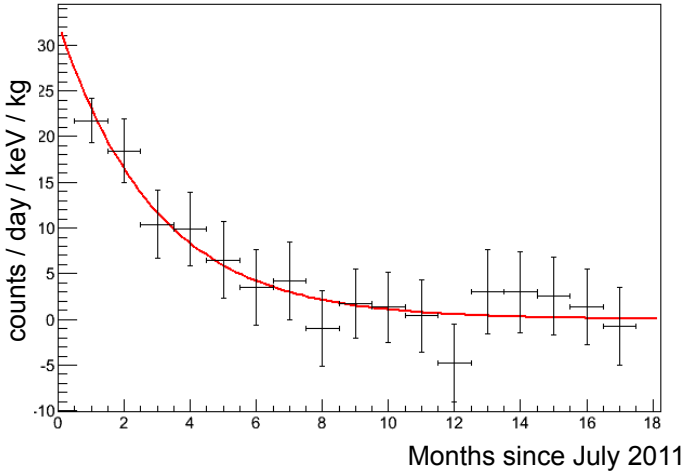


Cosmogenic Activation

Short-lived isotopes verify the energy calibration

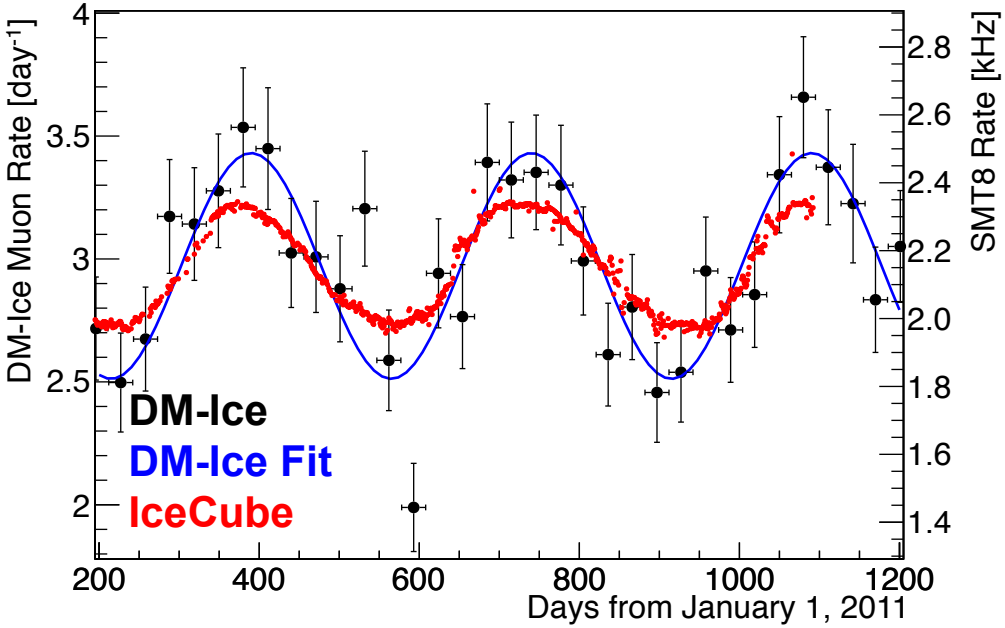


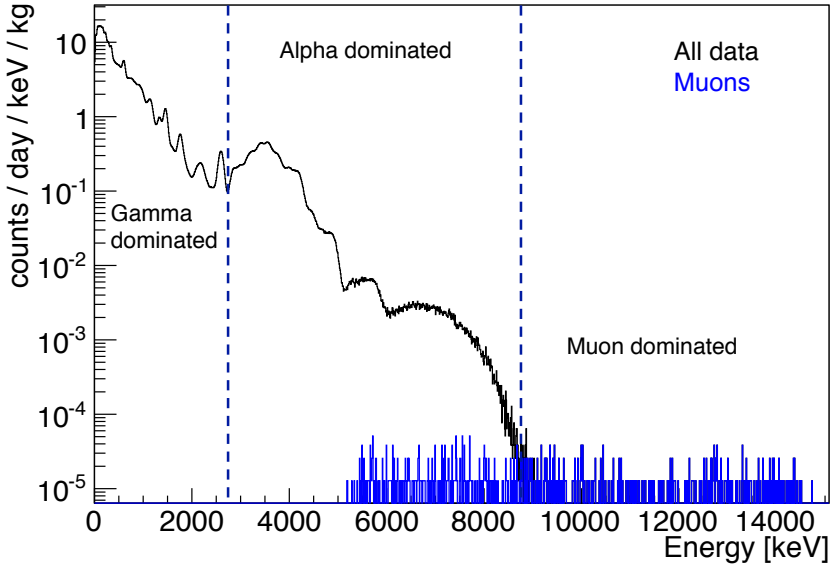
^{125}I verification through half-life, measured to be 59.4±2.7 days, consistent with the quoted value of 59.40±0.01 days



Muon Background

- ~3 muons/crystal/day
- Identified through energy and pulse shape
- Modulation agrees with IceCube observations

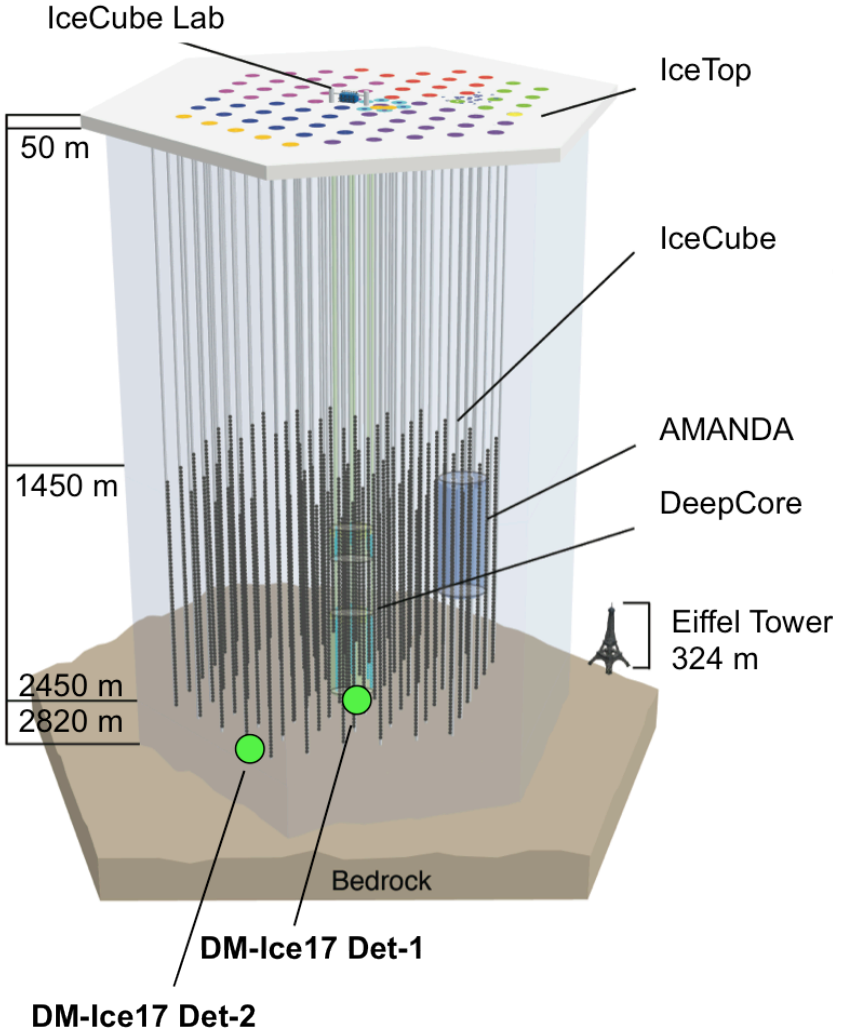


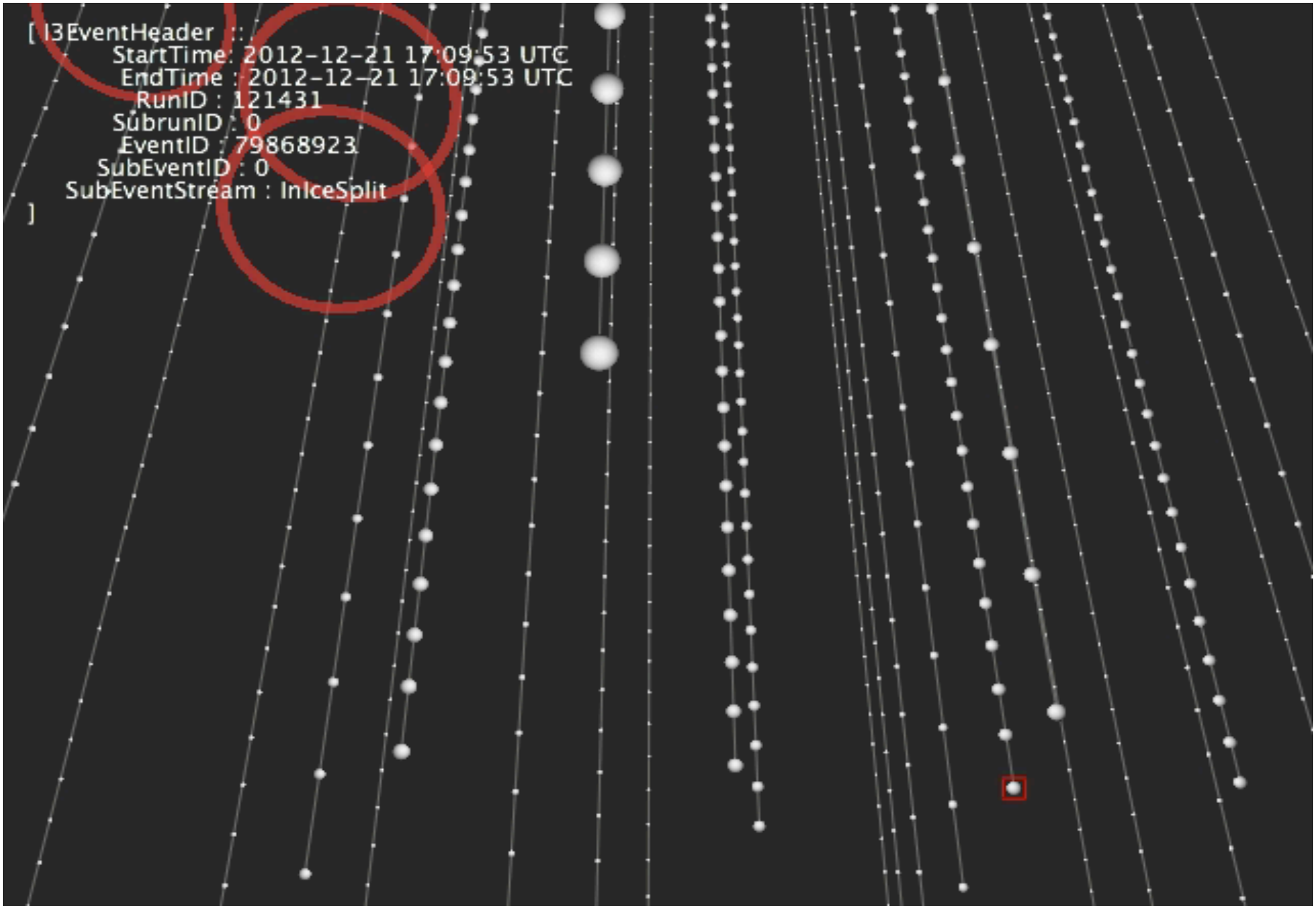


IceCube Coincidence

DM-Ice goals: verify muon identification; provide energy, direction

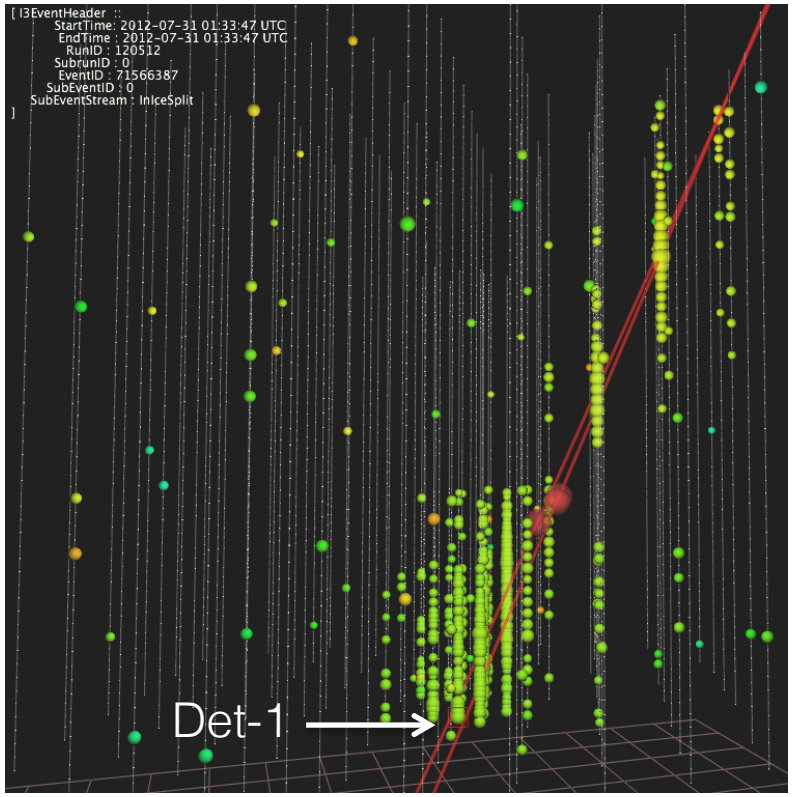
IceCube goals: improve reconstructions with known location along track

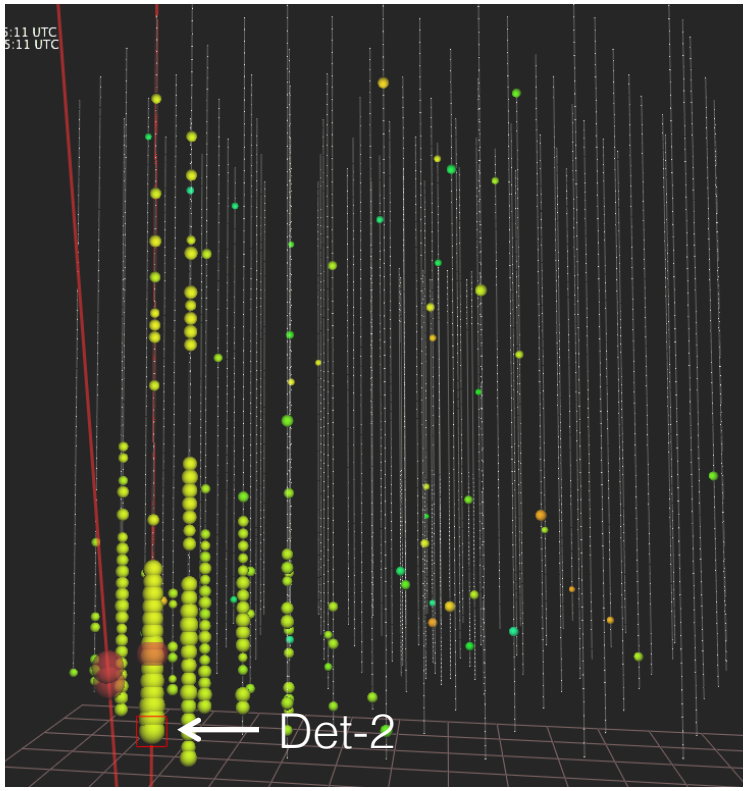



[I3EventHeader ::
StartTime: 2012-12-21 17:09:53 UTC
EndTime : 2012-12-21 17:09:53 UTC
RunID : 121431
SubrunID : 0
EventID : 79868923
SubEventID : 0
SubEventStream : InIceSplit
]

Coincidence Results

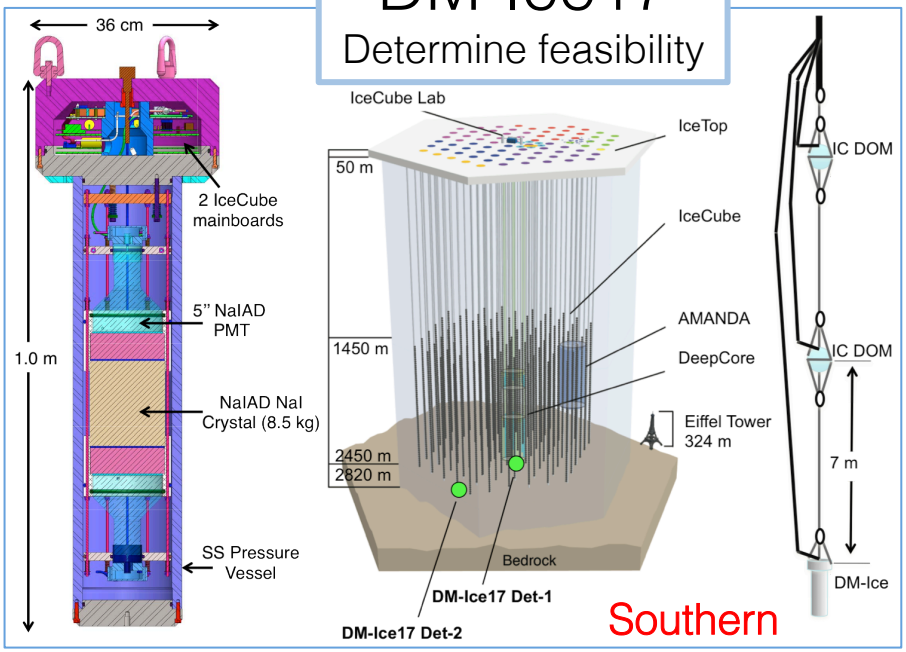
- Up to 93% (33%) of Det-1 (2) muons are coincident
- Including DM-Ice's location lowers the reconstruction fail rate and verifies precision
  - Fewer misreconstructions particularly for low energy



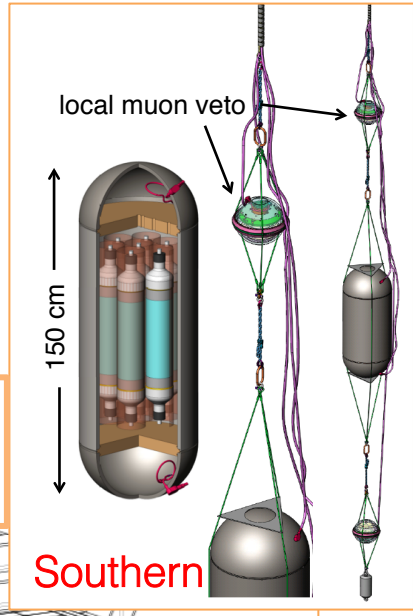


DM-Ice

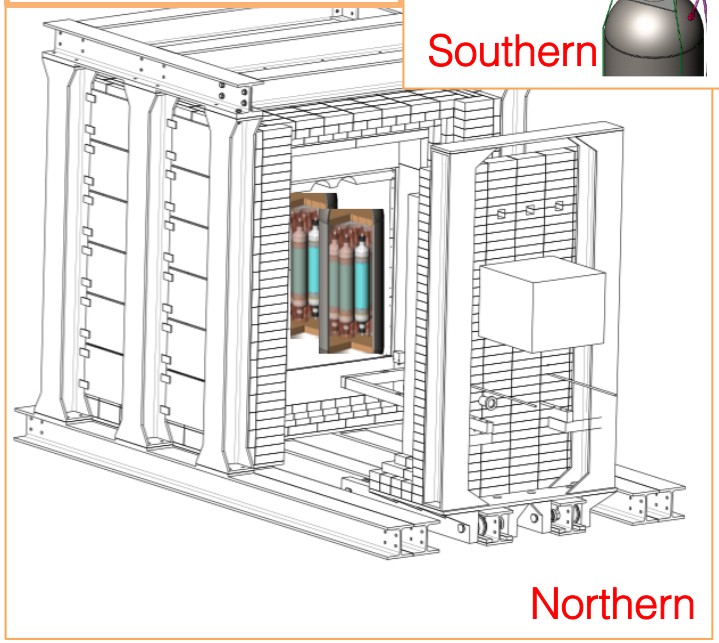
DM-Ice17
Determine feasibility



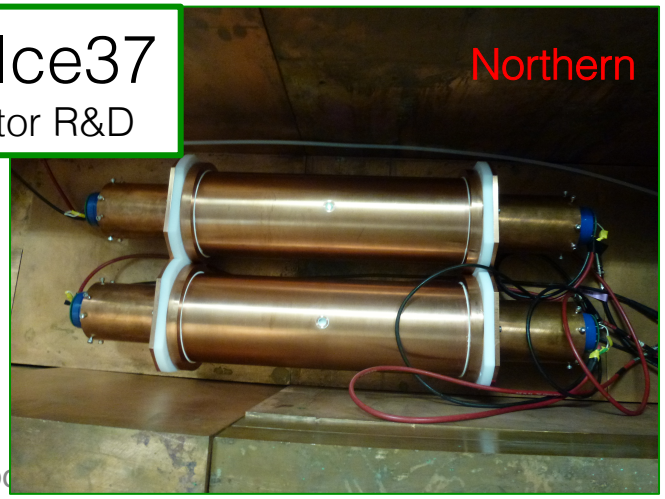
DM-Ice is a phased program that will run in <u>both hemispheres</u> to test the dark matter interpretation of the DAMA modulation



DM-Ice250
Set limits



DM-Ice37
Detector R&D



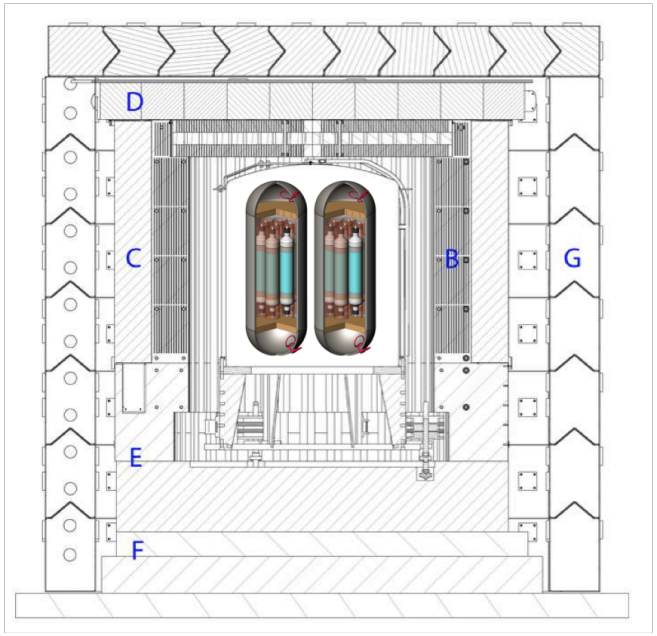
DM-Ice37

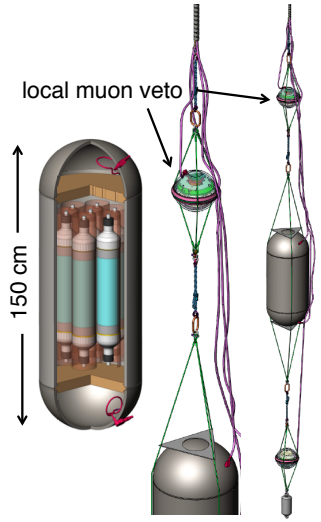
- 2-18.3 kg crystals running at Boulby
- Background reduction from DM-Ice/ANAIS/ KIMS effort

Crystals	^{40}K [mBq/kg]	^{210}Pb [μBq/kg]	^{228}Ra-^{208}Tl
DM-Ice17	17	1500	160
DAMA	0.6	24.2	8.5
In progress	1.5	188	2

Future of DM-Ice

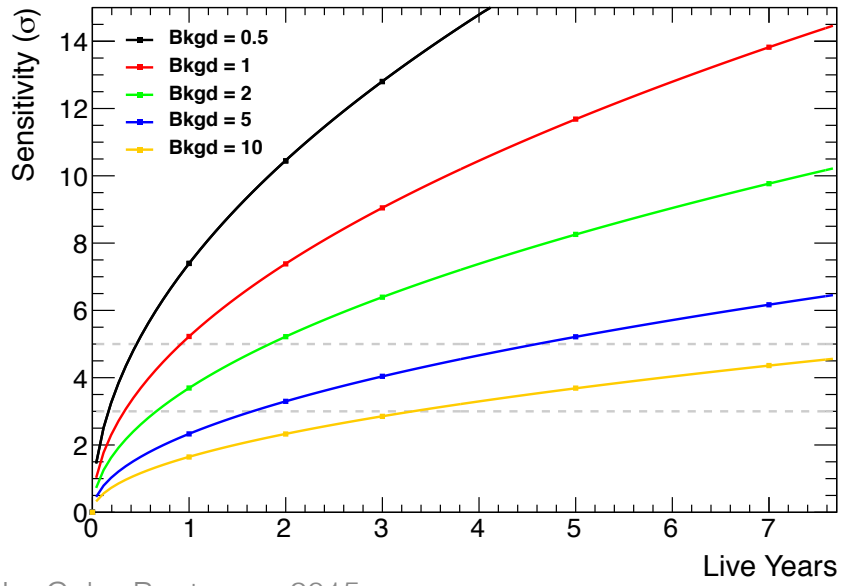
- DM-Ice37
  - Reached 3 dru background
  - R&D to get cleaner
    - Goal < 1 dru
    - DM-Ice17: 7.9 dru
- DM-Ice250 North
  - Boulby: clean, well modeled environment
    - ZEPLIN shielding available
- DM-Ice250 South
  - Co-deployment with PINGU will be mutually-beneficial

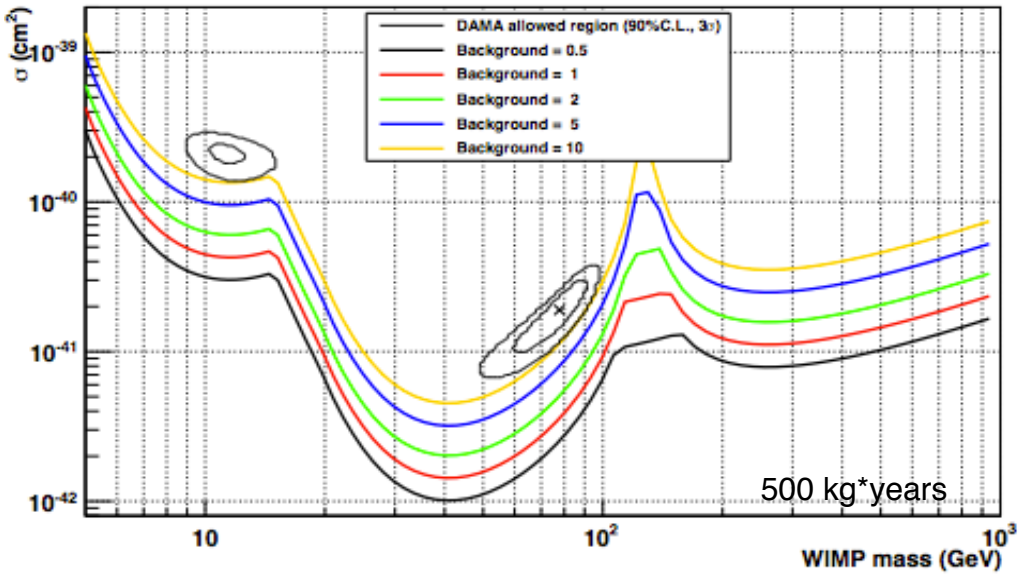




Conclusions

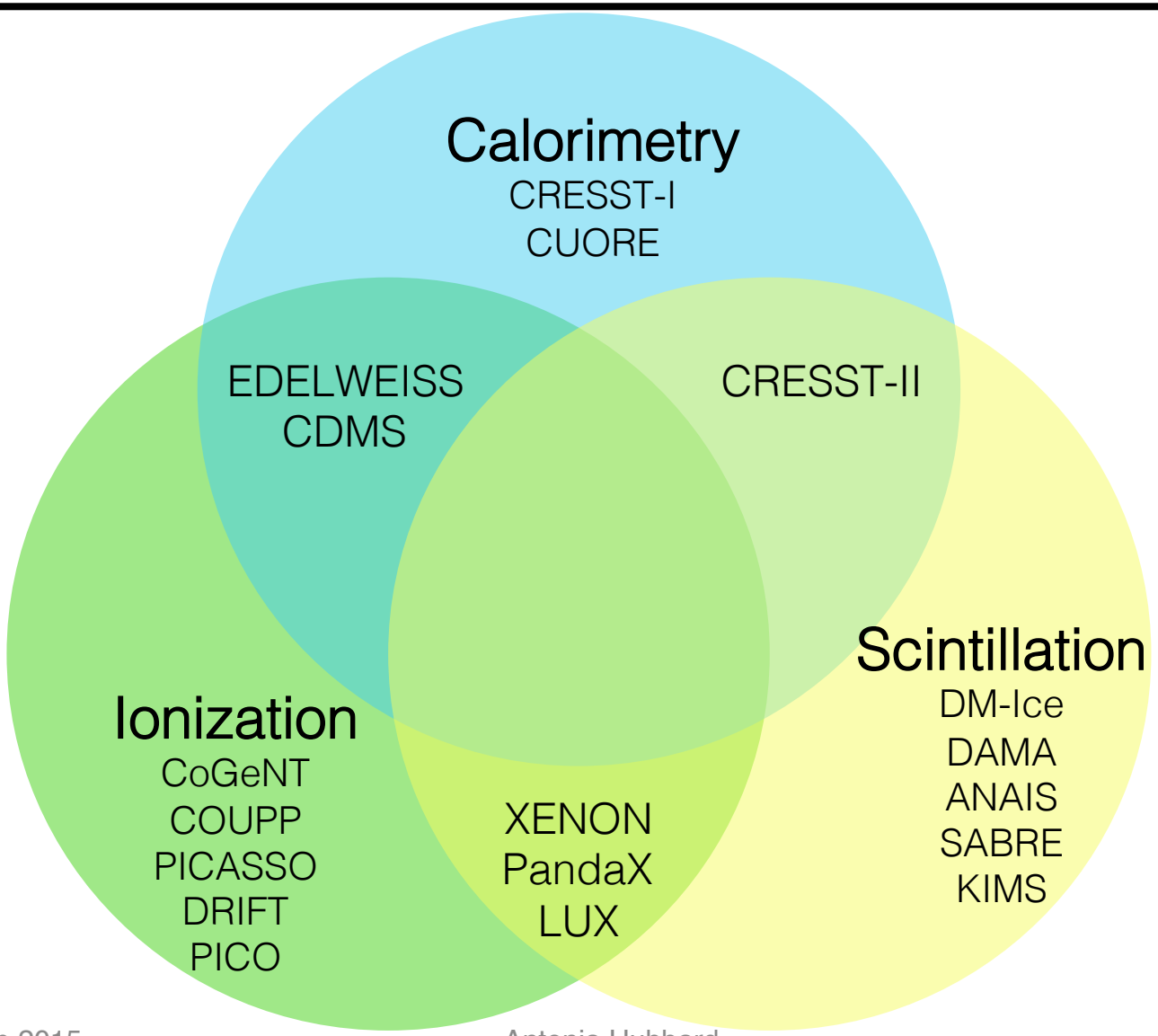
- This is an exciting time for dark matter!
- DM-Ice17: successful operation in the ice
  - Mutually beneficial analysis with IceCube
- R&D progressing swiftly
- DM-Ice250: unique position to definitively test DAMA by running in both hemispheres



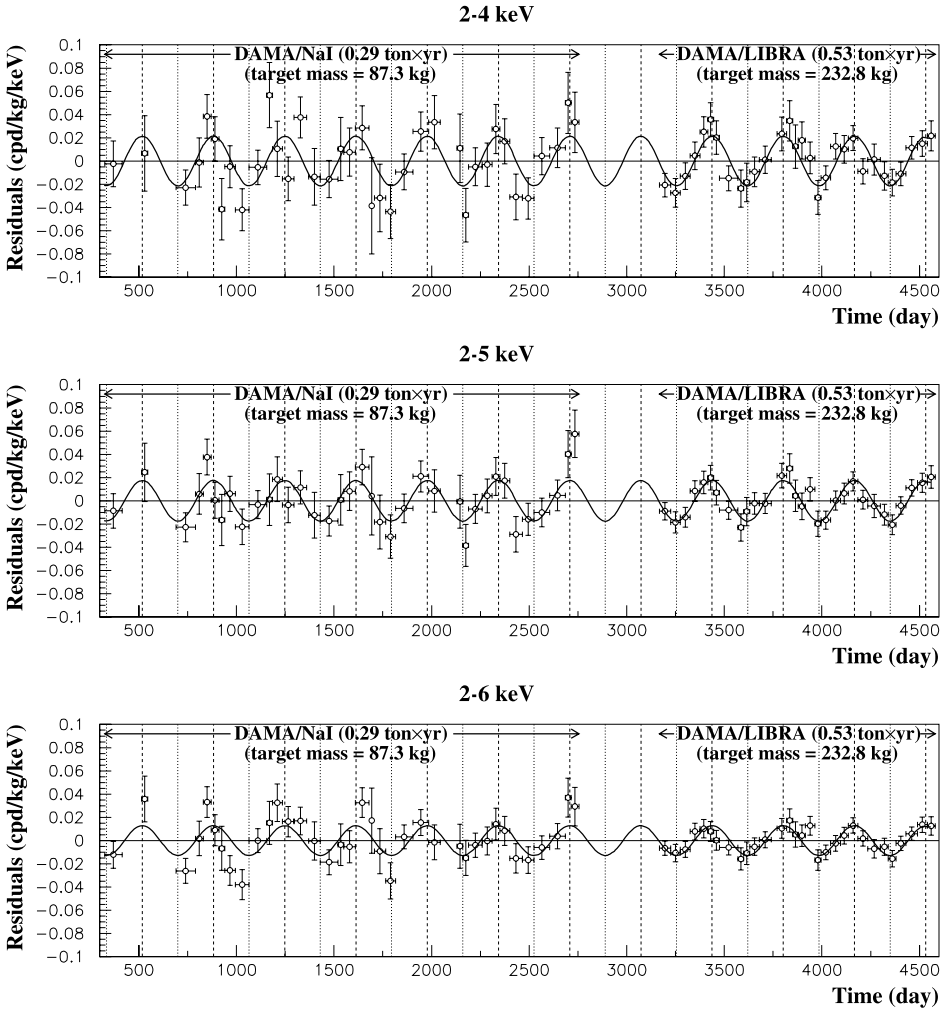


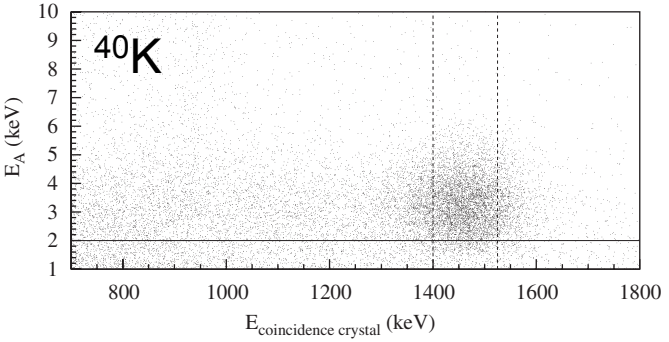

Questions?

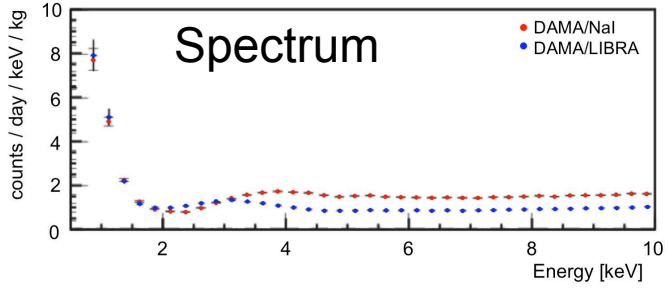
Direct Detection Experiments

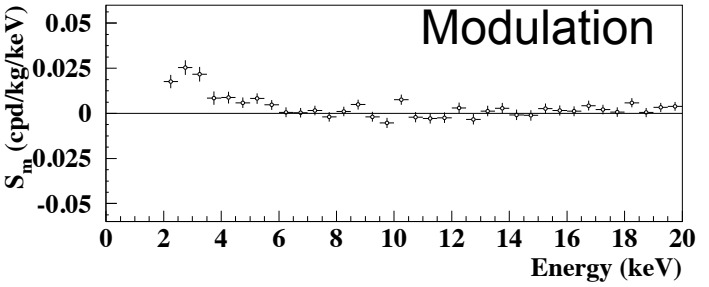


DAMA Data

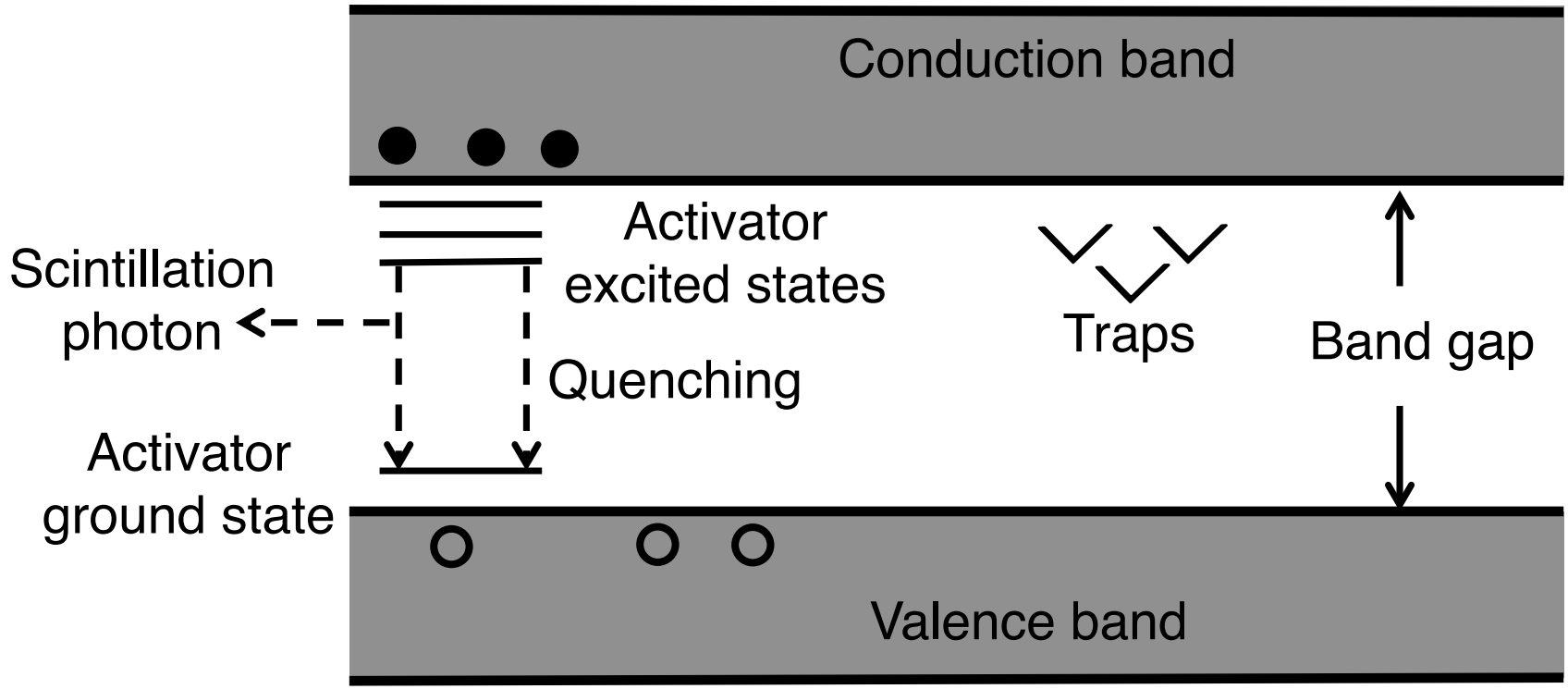

2-4 keV
2-5 keV
2-6 keV
DAMA/NaI (0.29 ton×yr)
(target mass = 87.3 kg)
DAMA/LIBRA (0.53 ton×yr)
(target mass = 232.8 kg)
Residuals (cpd/kg/keV)
Time (day)


^{40}K
E_A (keV)
$E_{coincidence\ crystal}$ (keV)

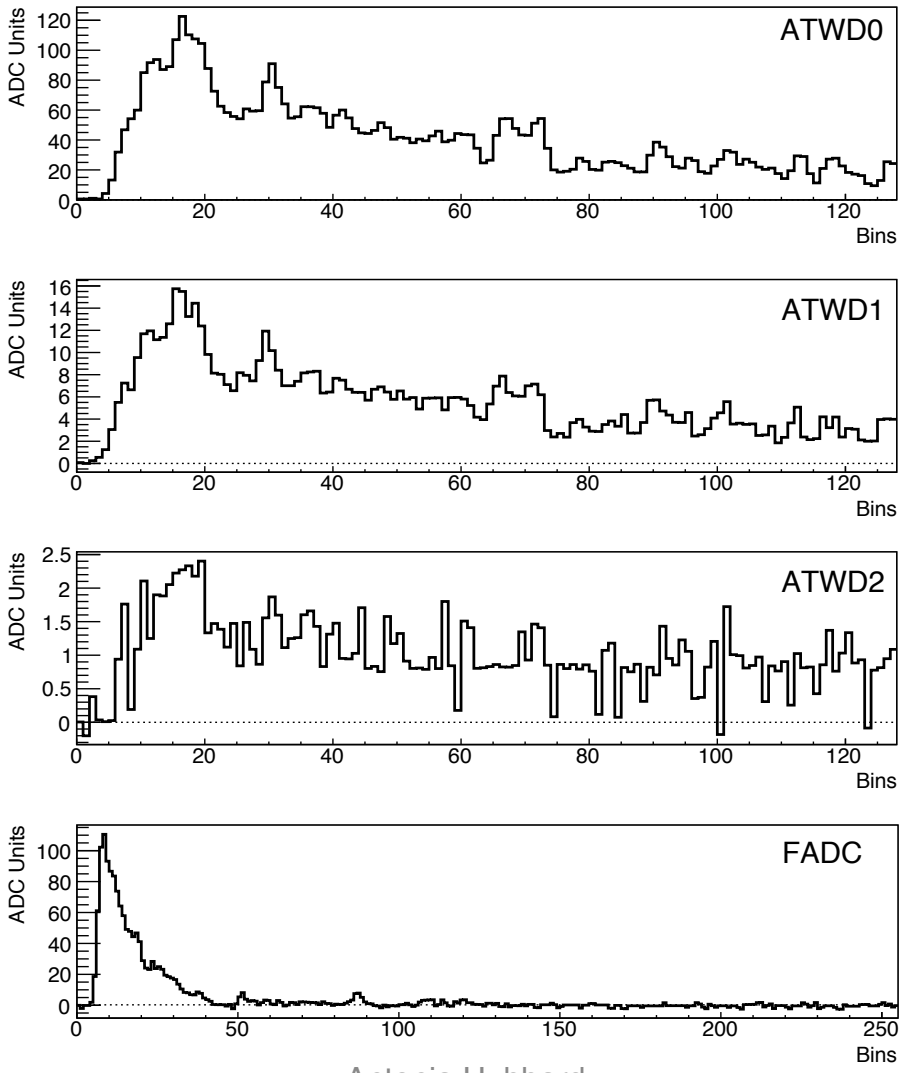

Spectrum
DAMA/NaI
DAMA/LIBRA
counts / day / keV / kg
Energy [keV]


Modulation
S_m (cpd/kg/keV)
Energy (keV)

Scintillation Mechanism

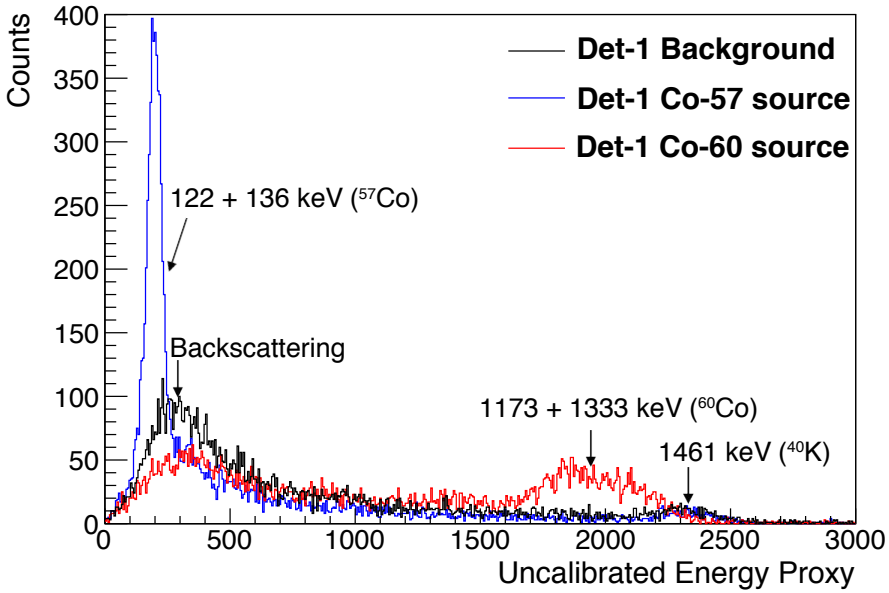


DM-Ice17 Data

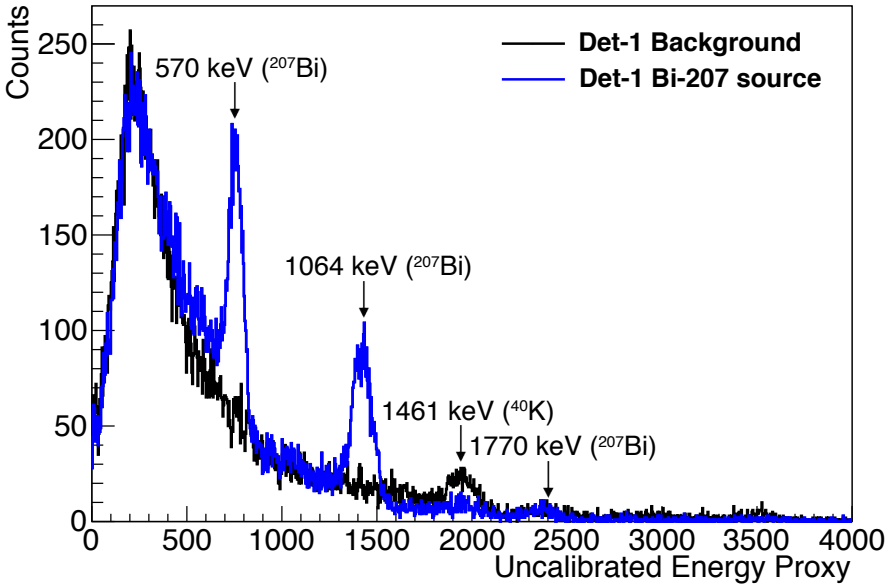


Pre-Deployment Source Runs

Boulby, UK
^{57}Co, ^{60}Co

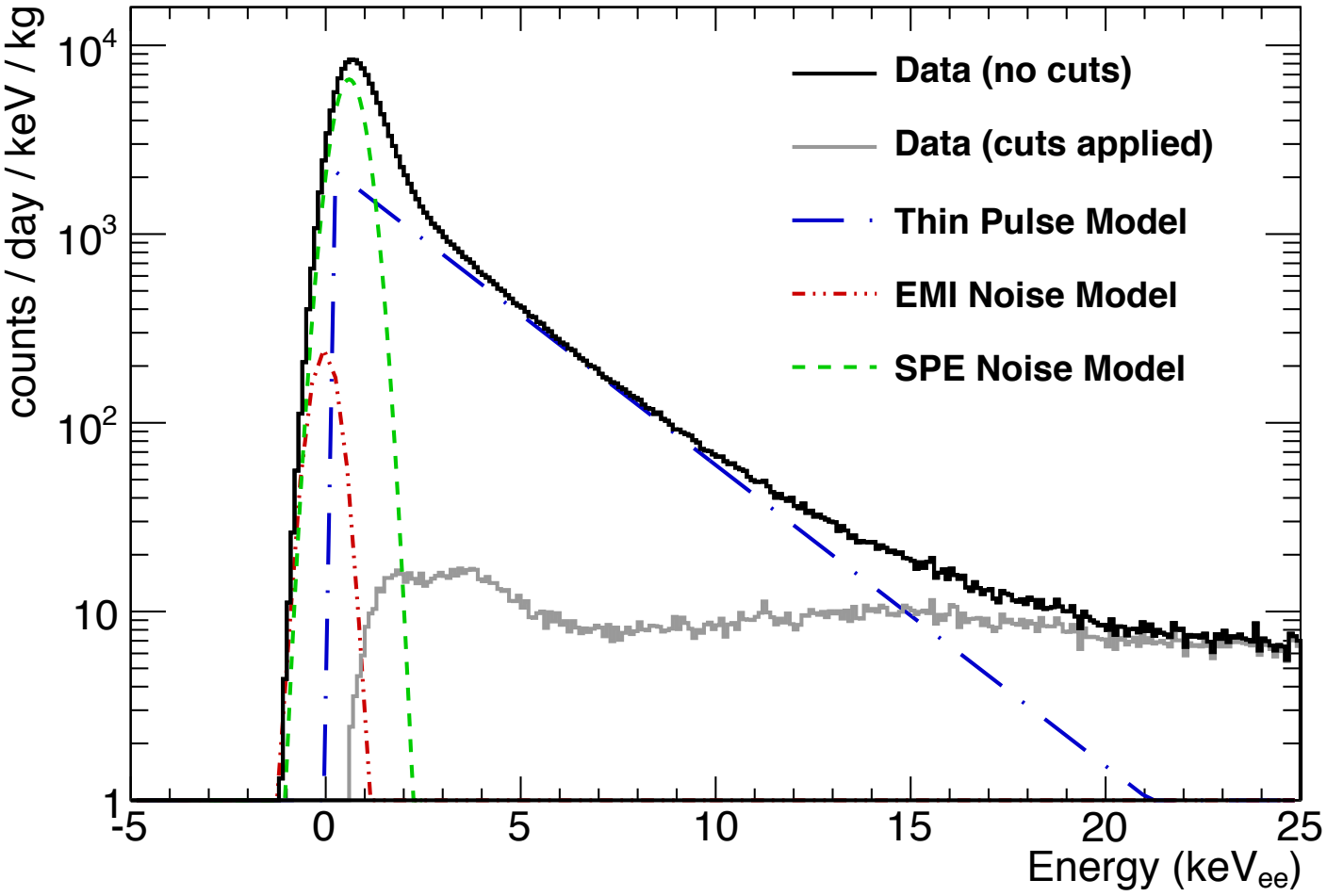


PSL, WI
^{207}Bi

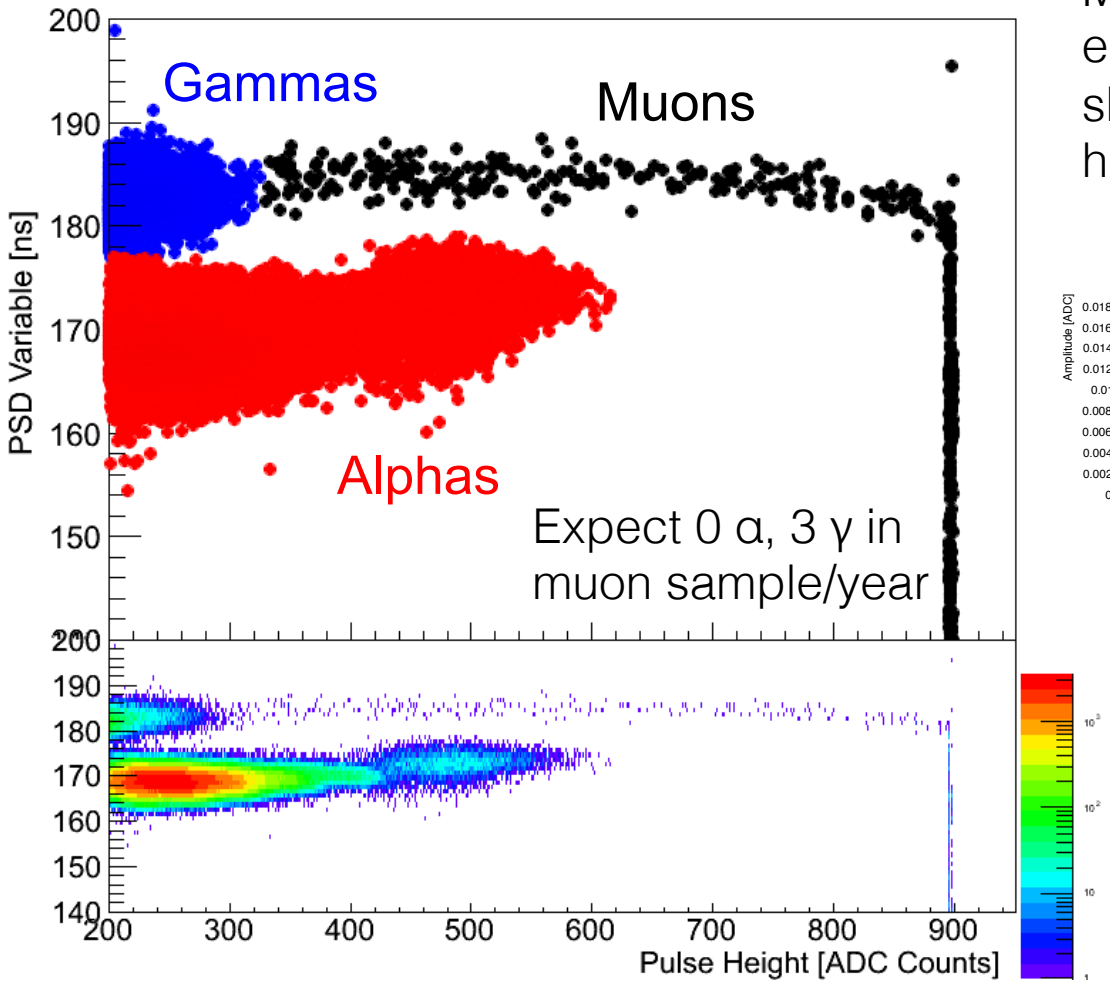


Calibration estimate

Noise Removal

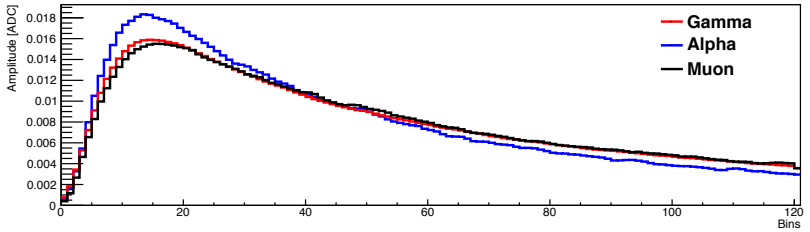


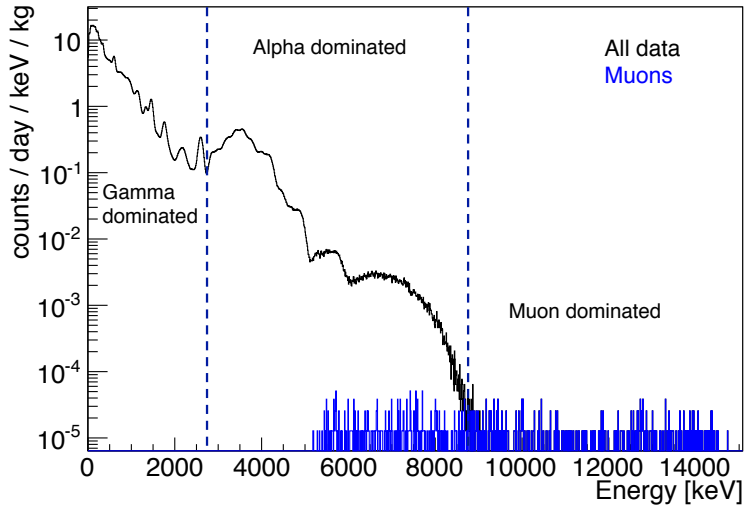
Muon Identification



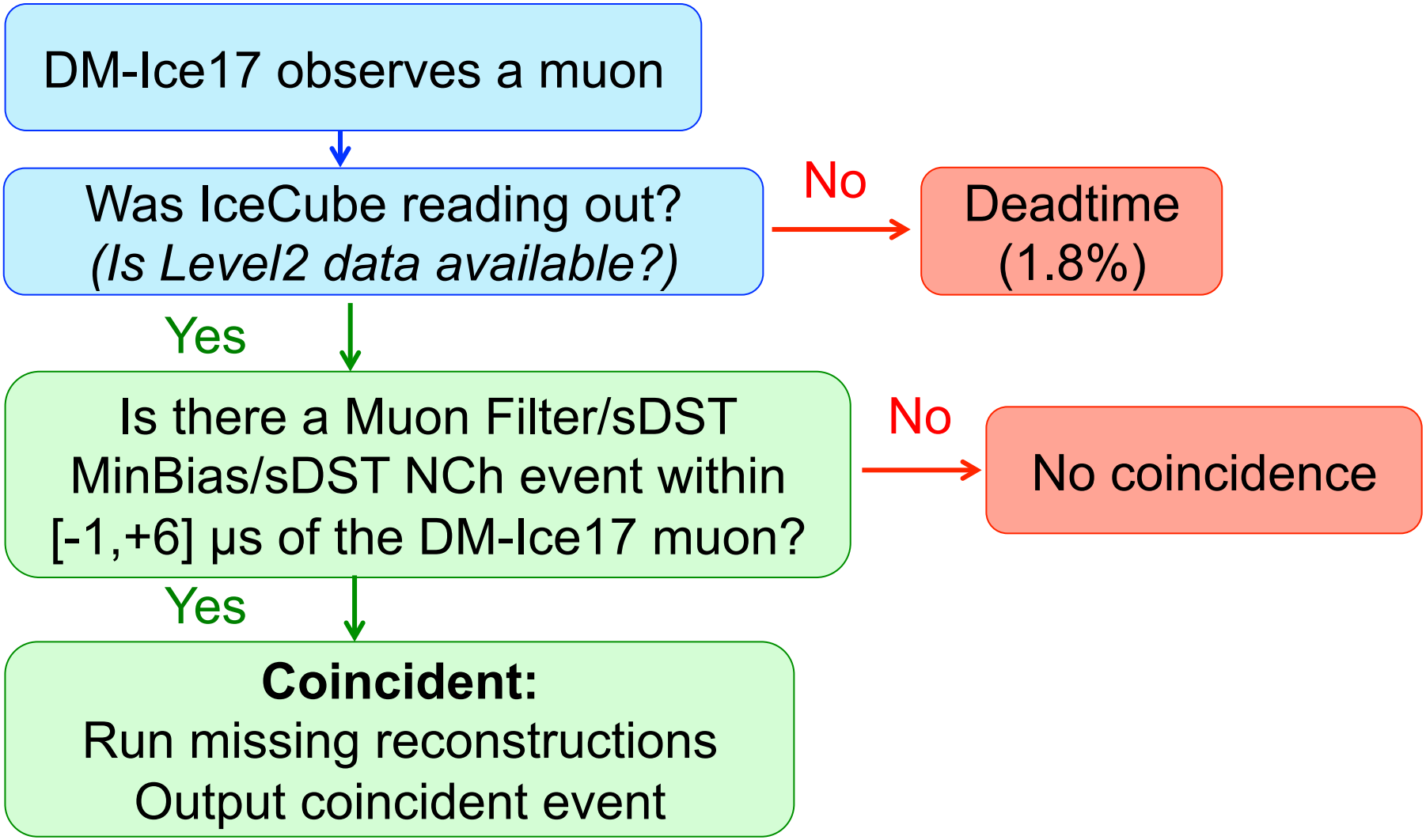
Muons are identified with their high energy depositions and pulse shape variable using the pulse height (h_i) at time (t_i):

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





Coincidence Processing



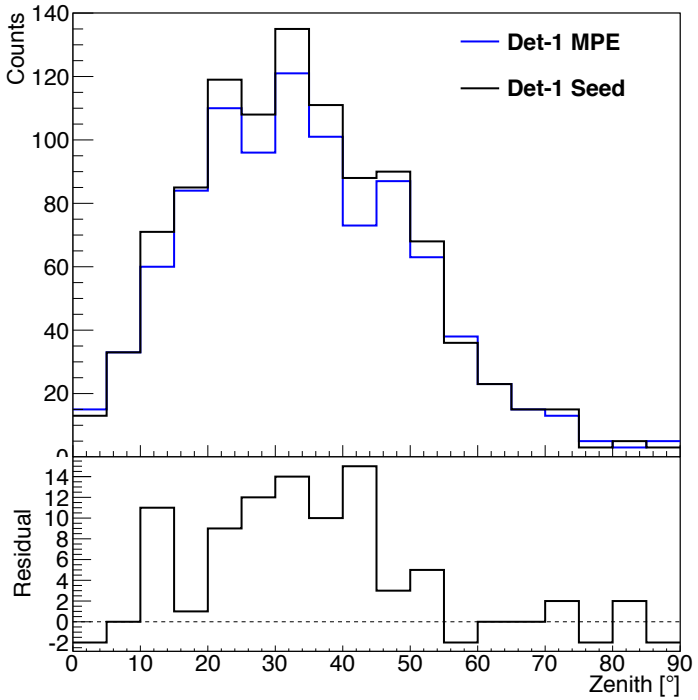
Effect on Misreconstructions

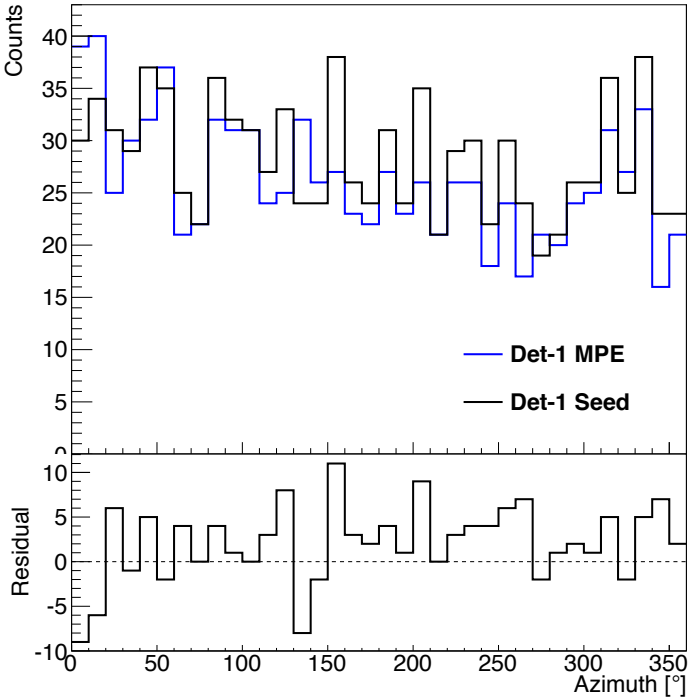
- Total number coincident: 1666 (43% coincident)
- Expected accidental coincidence/crystal ~ 20
- Misreconstruction rate reduced in Det-1 from 17% to 6.3%
- Improvement from NCh only

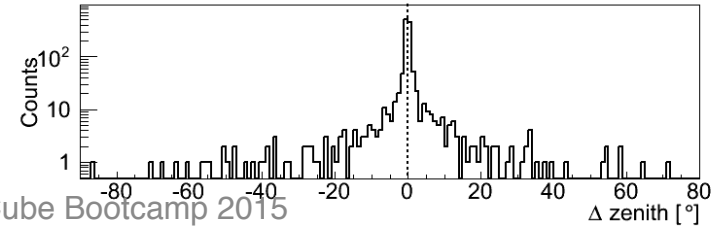
Detector	Total	Zenith > 90°	Energy < 100GeV	Distance > 20m	Nan Reco
Det-1 Traditional	*1072*	*115*	*62*	*141*	*5*
Det-1 DM-Ice seed	1072	44	23	166	0
Det-2 Traditional	*594*	*145*	*23*	*94*	*1*
Det-2 DM-Ice seed	594	100	22	111	0

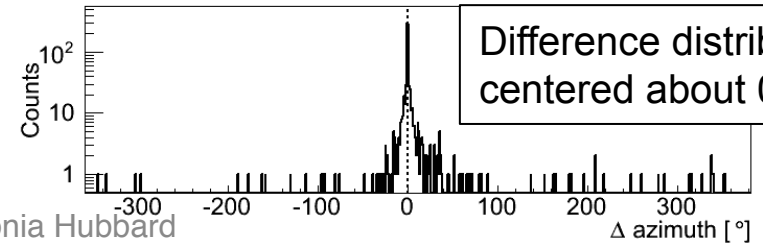
Reconstruction: Zenith & Azimuth

- Comparison of reconstruction parameters with/ without DM-Ice seeds confirms IceCube resolution





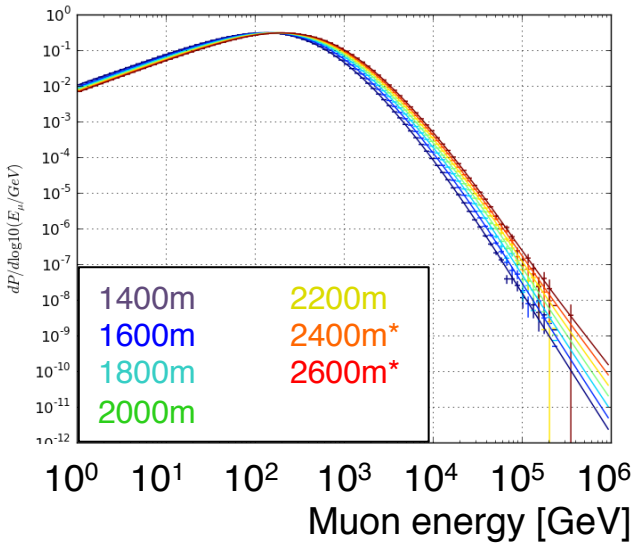


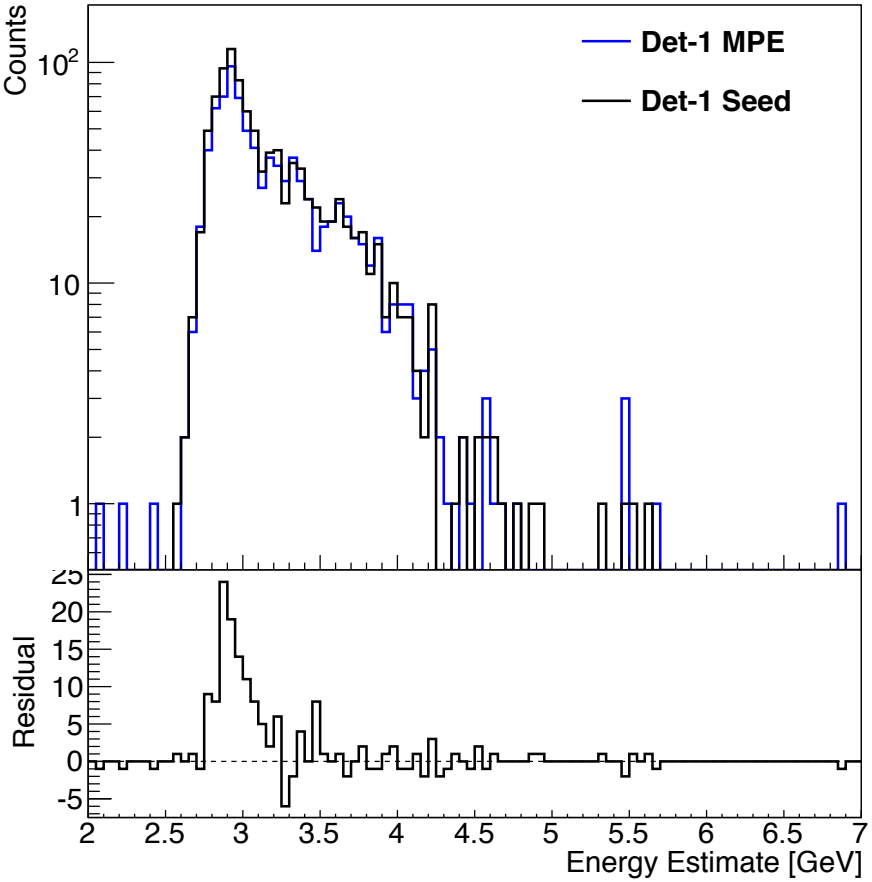


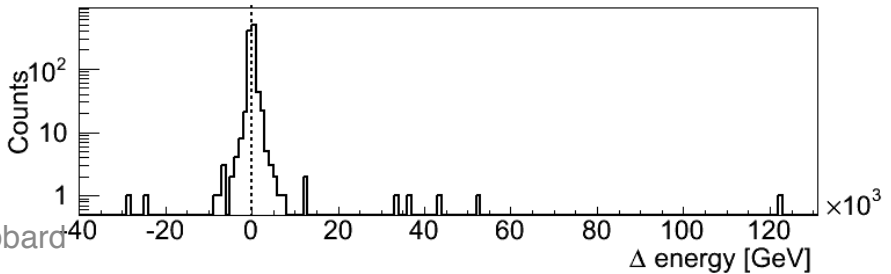
Difference distributions centered about 0 ± 0.7°

Energy

- DM-Ice17 slightly prefers a higher energy reconstruction
  - Through-going events
  - Difference centered about 84 ± 600 GeV

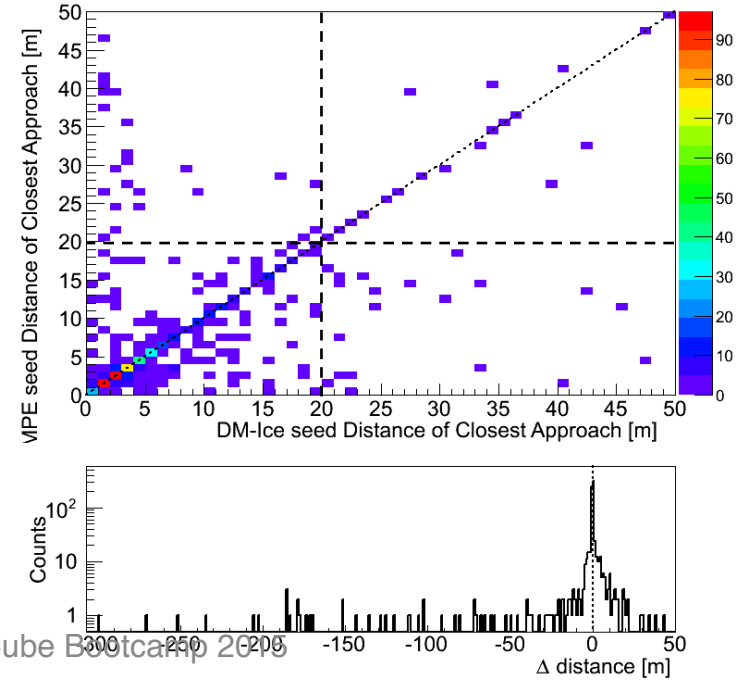


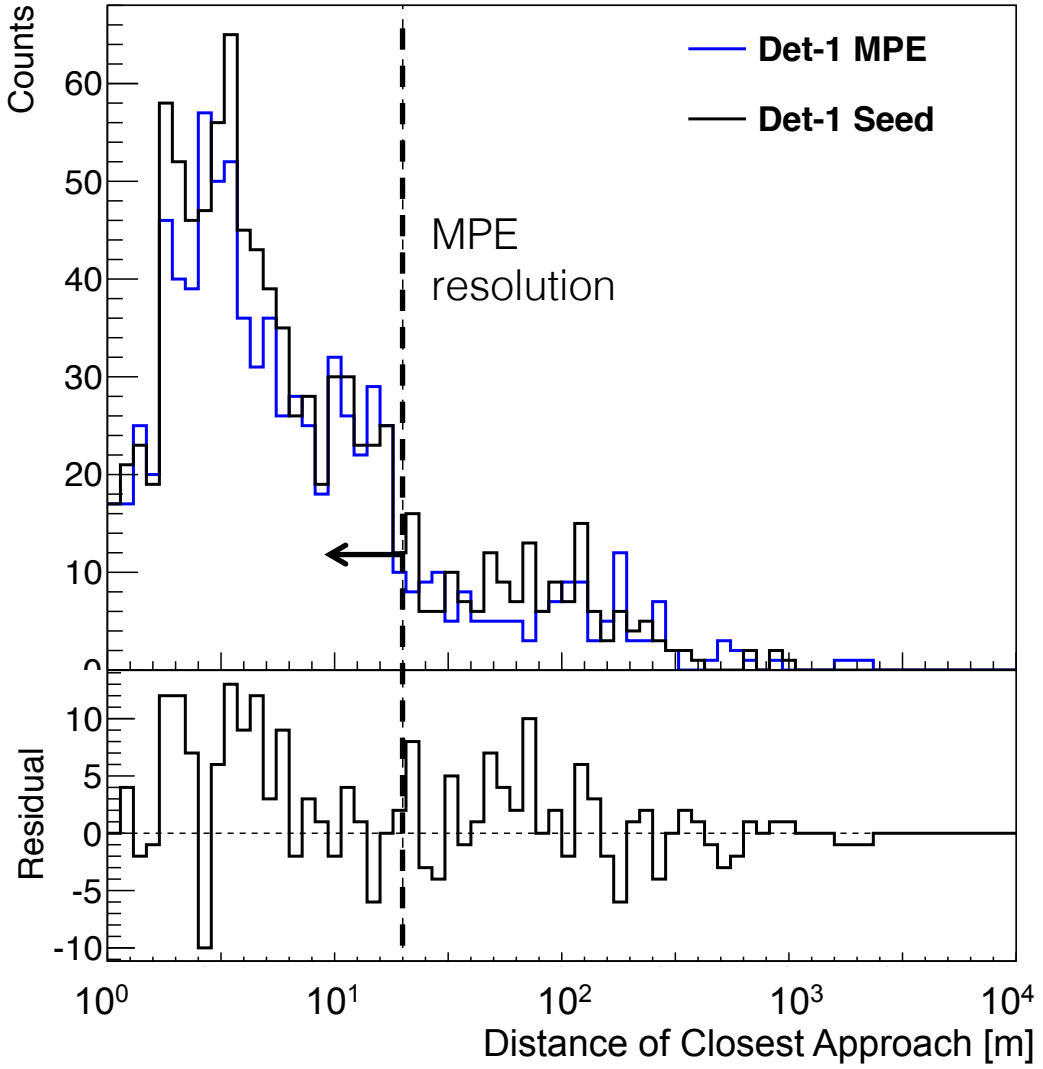




Reconstruction Comparisons

- Distance of closest approach indicates room for improvement
- 53% of events reconstruct closer with DM-Ice seed





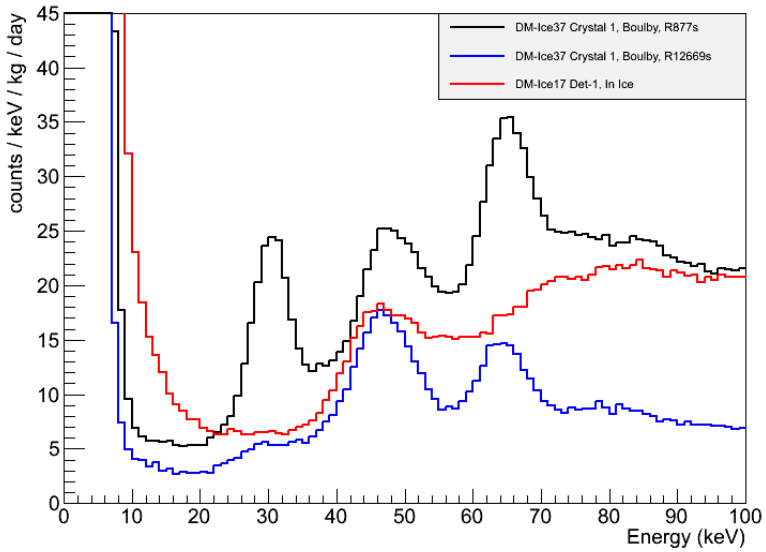
Conclusions: DM-Ice17/IceCube

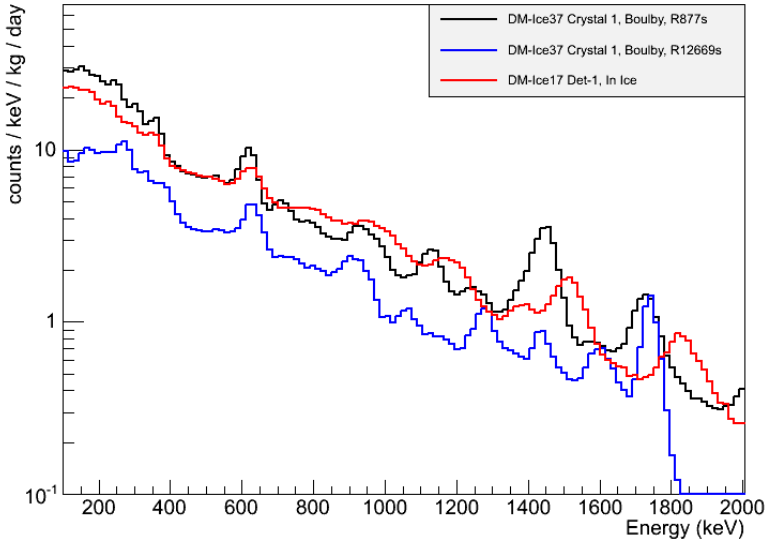
- Successful coincidence identification
- IceCube verifies DM-Ice muon tag
  - Energy and direction information
- DM-Ice17 offers a calibration tool for IceCube
  - Particularly for low energy
- Interest from low energy, calibration, and reconstruction working groups
- Future: optimization of reconstruction use, integration of IceTop, PINGU development

DM-Ice37 Contamination

- Collective NaI(Tl) effort (DM-Ice, ANAIS, KIMS)
  - Goal set by DAMA: 1 dru in ROI
  - Currently: 3 dru above noise energies
    - Noise removal in progress
    - DM-Ice17: 8 dru
  - 3 mBq/kg ^{40}K, ^{210}Pb reduction in R&D

Significant improvements in location and PMTs





DM-Ice37 Phosphorescence

- Phosphorescence observed with R&D crystals
- ~300 ms decay
  - Longer time in ice likely from older crystals
  - Exposure to radiation can produce crystal defects and traps