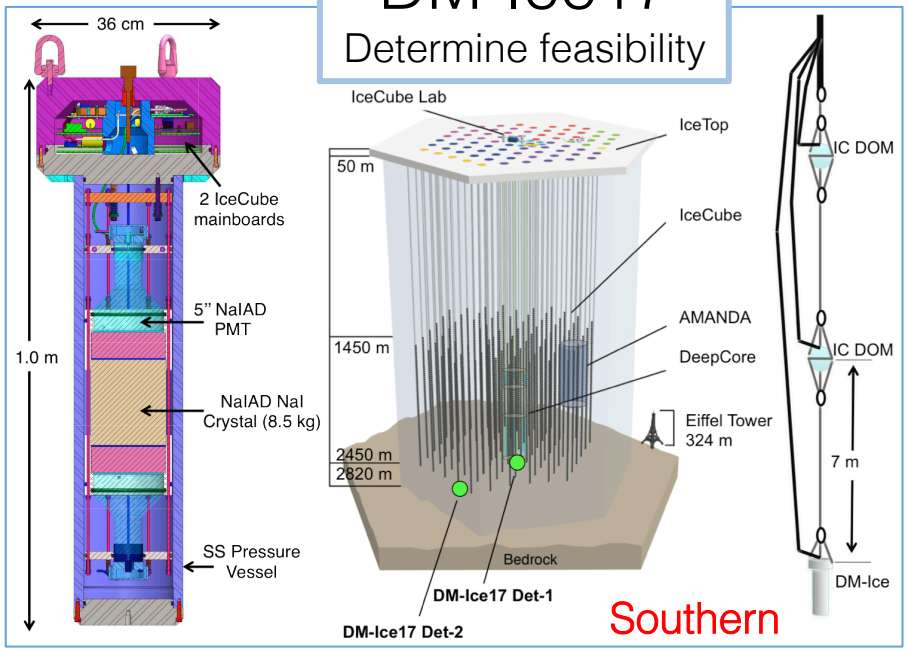
Wright Laboratory

Muon-Induced Backgrounds in DM-Ice17

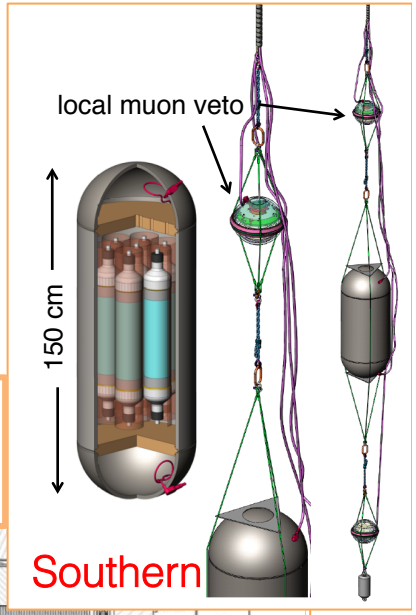
Antonia Hubbard
for the DM-Ice collaboration
University of Wisconsin - Madison

DM-Ice

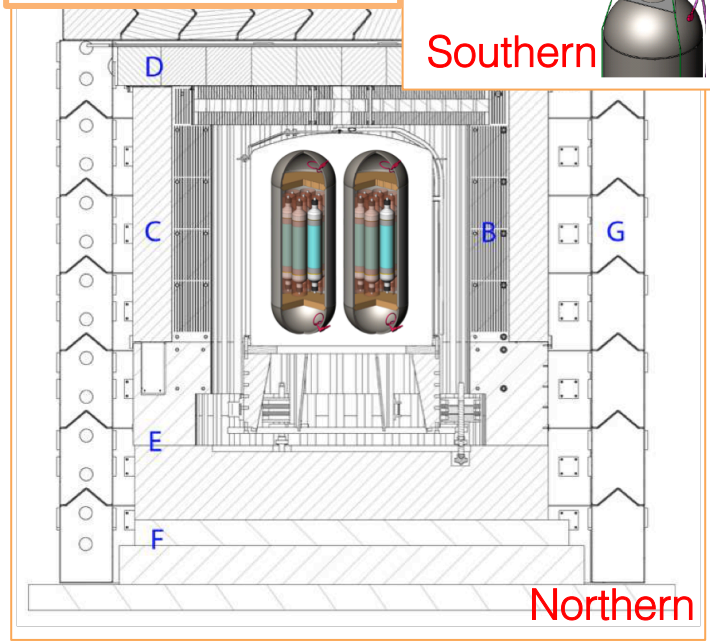
DM-Ice17
Determine feasibility



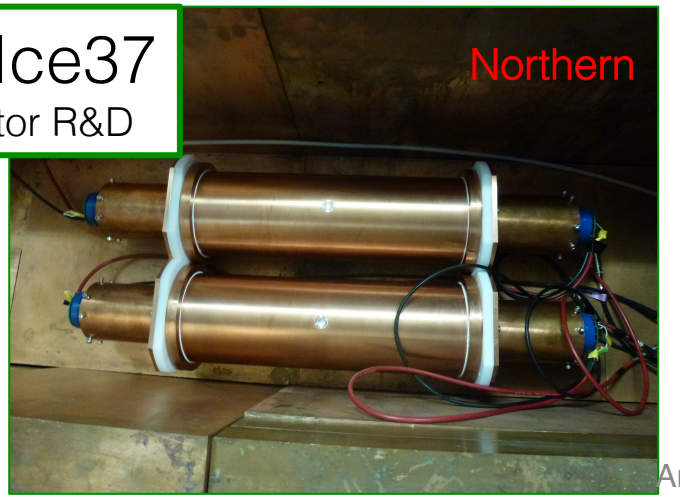
DM-Ice is a phased program that will run in <u>both hemispheres</u> to test the dark matter interpretation of the DAMA modulation



DM-Ice250
Set limits



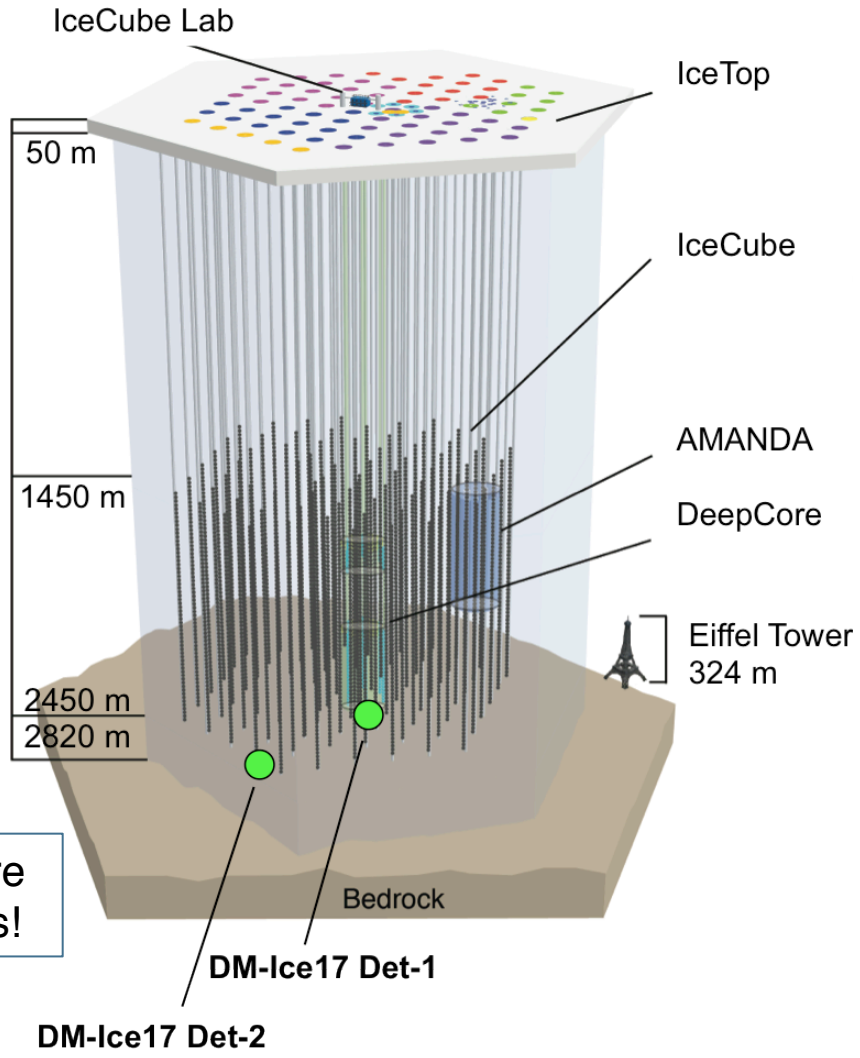
DM-Ice37
Detector R&D



DM-Ice17 and IceCube

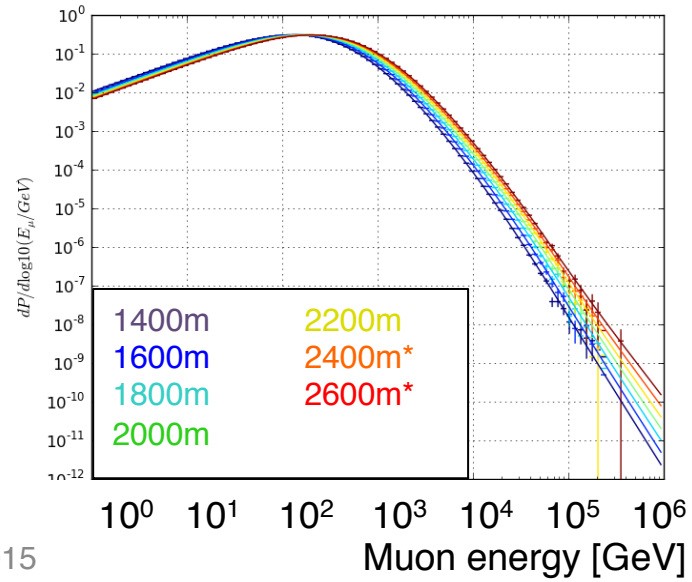
- DM-Ice17
  - Deployed December 2010
  - Located in IceCube volume
  - 2450 m deep
  - 2 detectors
    - 5'' dia. x 6'' NaI(Tl) crystals
    - Optically isolated from ice
    - 2 PMTs/crystal
- IceCube
  - 5160 PMTs in 1km^3
  - 1500 – 2500 m deep
  - Neutrinos: up-going
  - Atm. muons: down-going

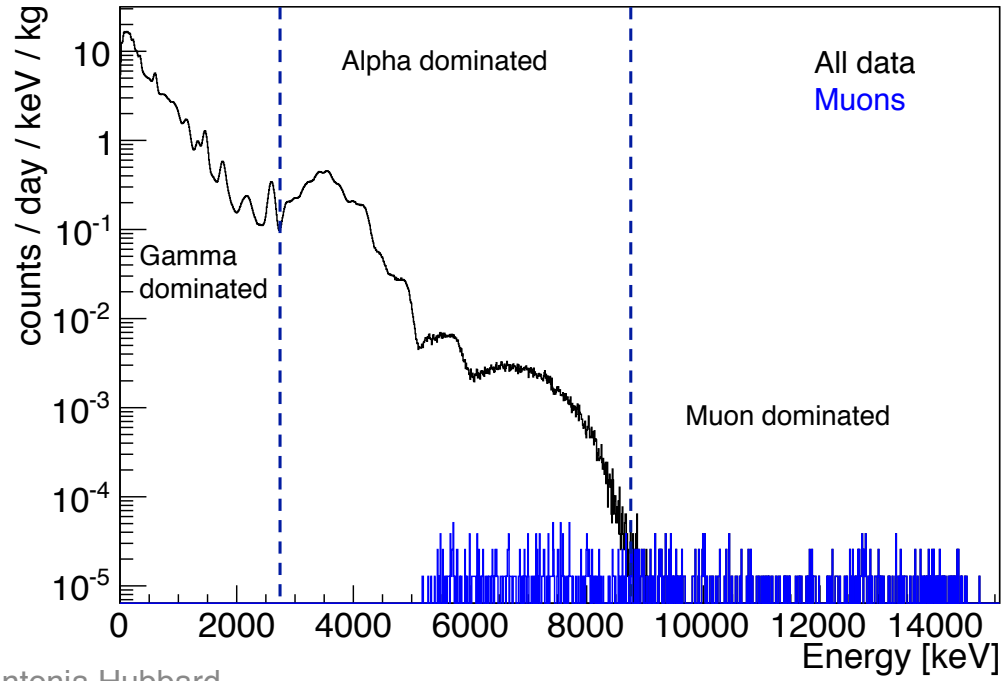
Neutrinos are 1/10^6 events!



Muon Background

- Backgrounds: internal and atmospheric muons
- ~2-3 muons/crystal/day
  - 5'' crystals, optically isolated from the ice
- MIP energy deposition (~80 MeV)
  - 100-10^4 GeV muons
  - Highly quenched

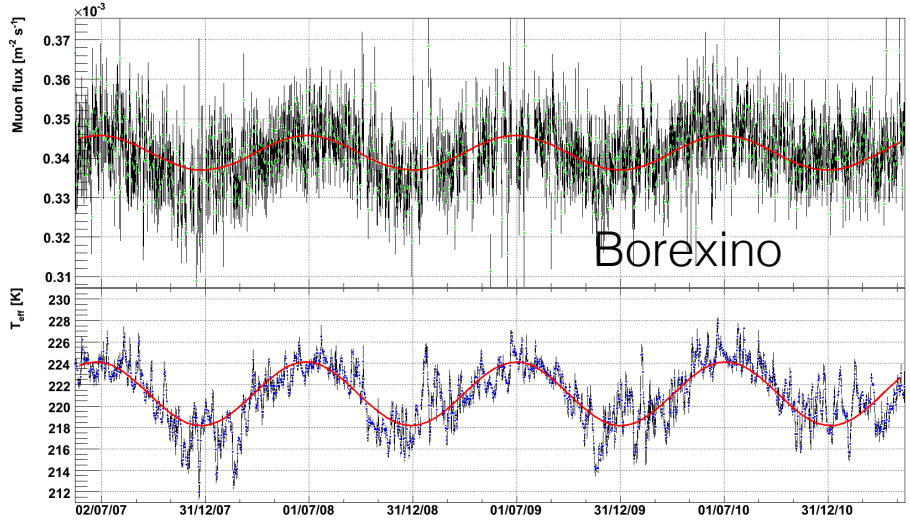


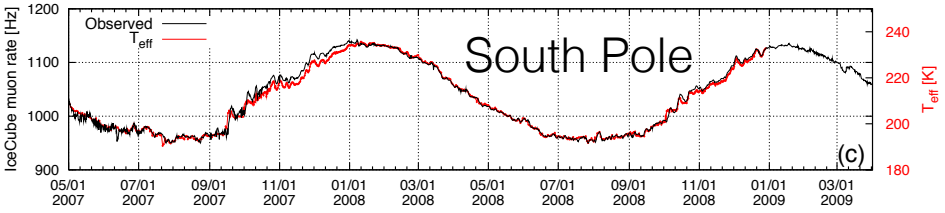


Muon Modulation

- Muon production follows atmospheric temp.
  - Opposite phase in each hemisphere
- Imperfect sine creates phase uncertainty
  - Uneven rise and fall; yearly variations
  - Introduces over 10 days of uncertainty
  - Borexino phase: 5 days from temperature phase

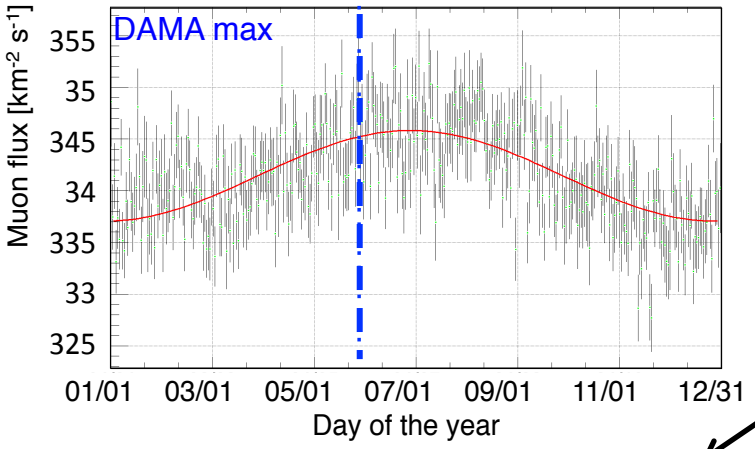
Borexino 2012





Desiati- ICRC 2009

DAMA Controversy: Muons



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

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

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

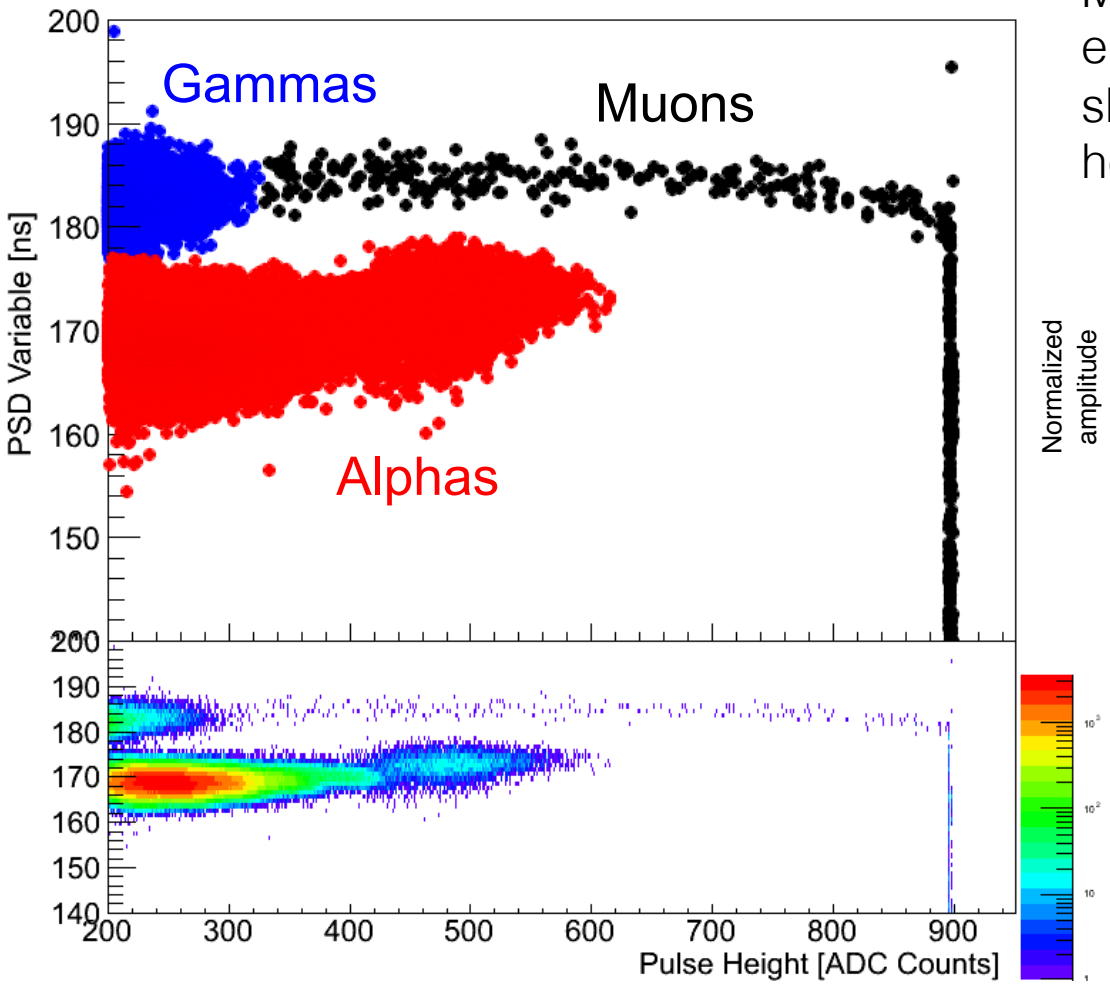
Counter: No second modulation has been shown to produce this. *Bernabei 1409.3516*, *Klinger 1503.07225*

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

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

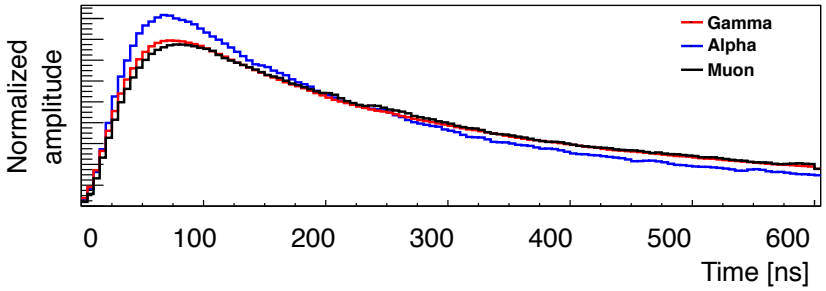
New annual modulation experiments must understand their muon backgrounds!

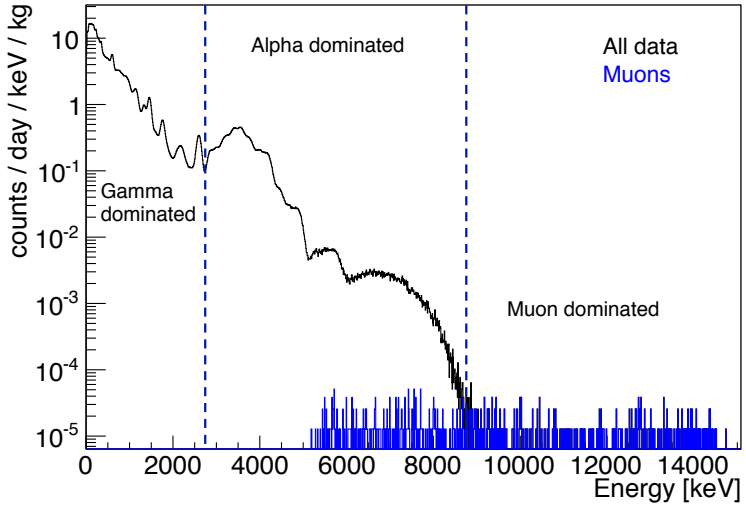
Muon Identification



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

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

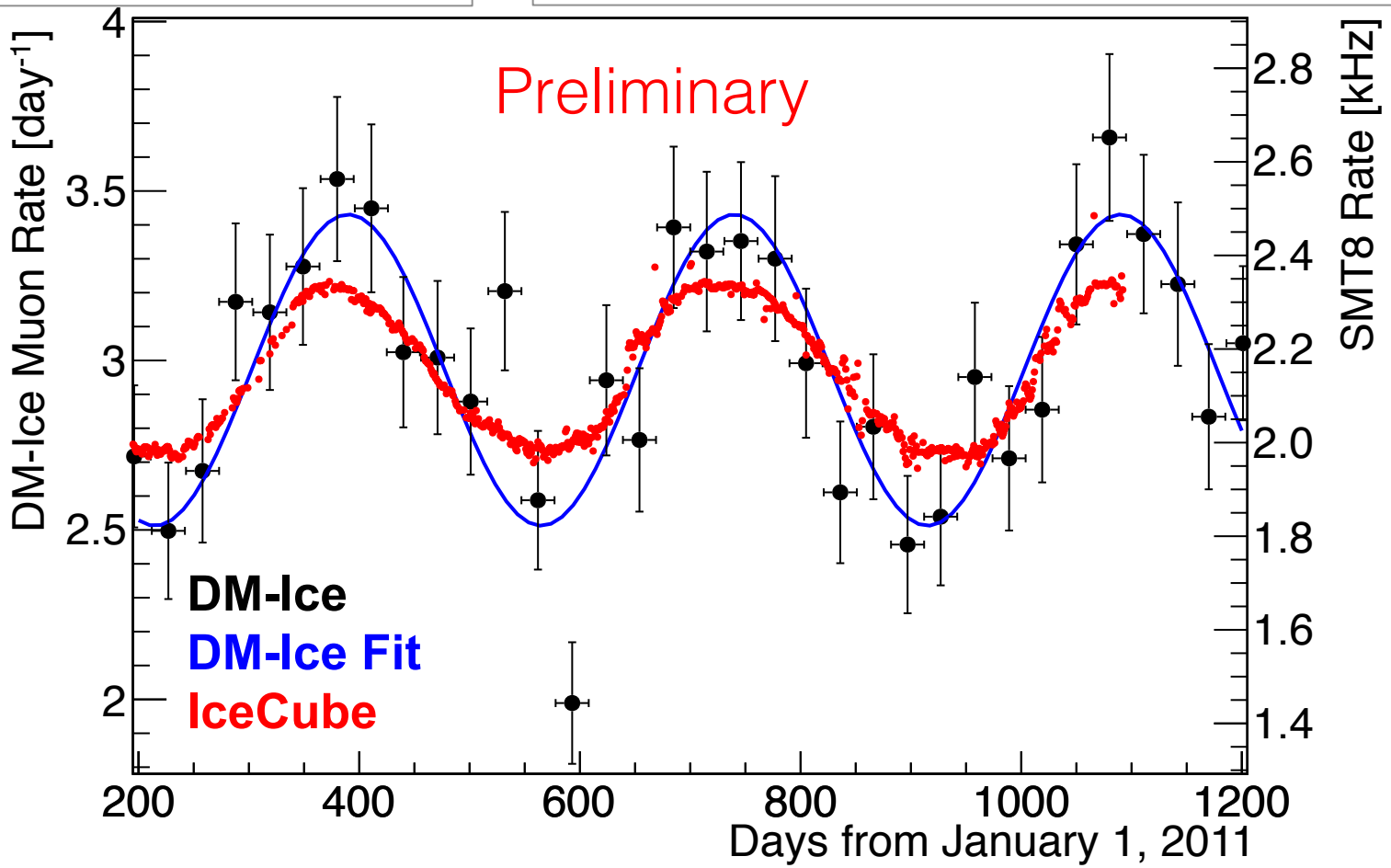




Muon Modulation

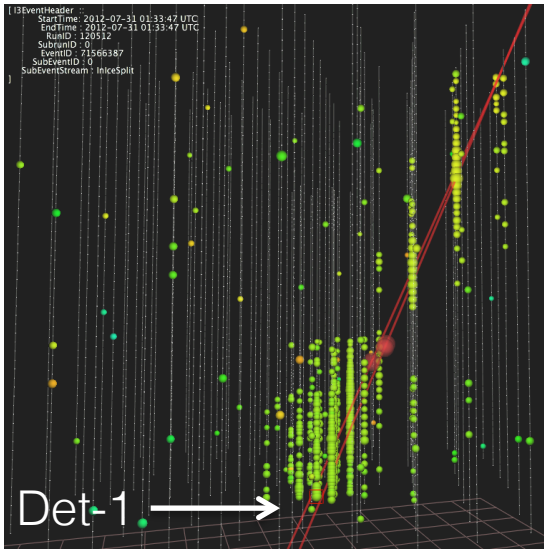
DM-Ice17: 15% modulation
IceCube: 8% modulation
LNGS: 2% modulation

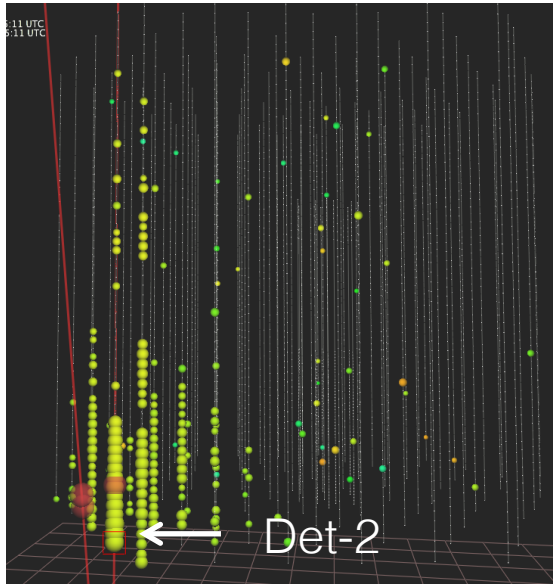
DM-Ice17, at the bottom of IceCube, sees a higher energy muon sample, leading to a higher fractional modulation amplitude



Strength of IceCube Coincidence

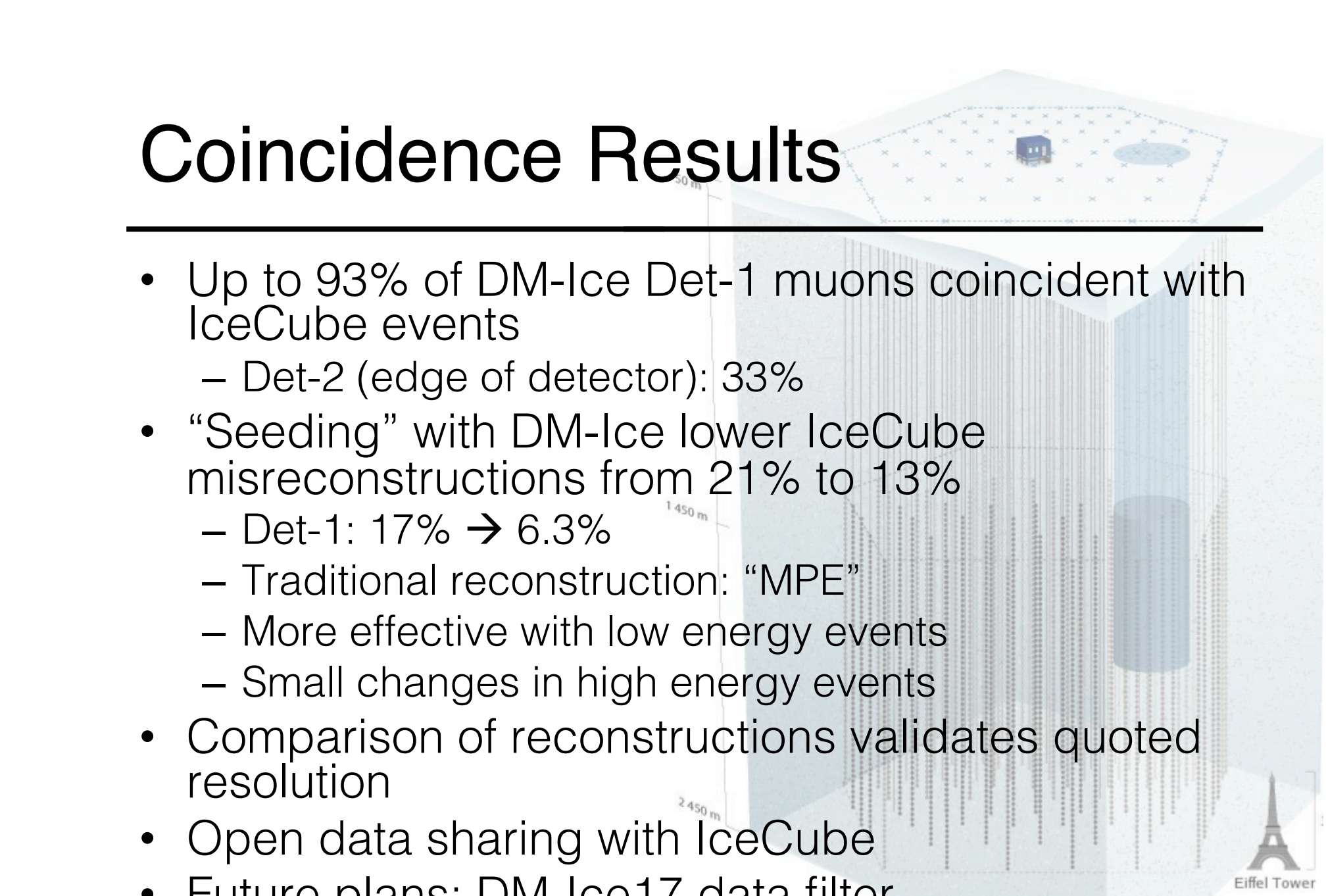
- Validates DM-Ice17 muon tag and provides new muon information
  - Verify identification
  - Energy, direction
- Provides IceCube with a novel calibration tool
  - Known ~5''x6'' volume in which to restrict the track
  - Confirms reconstruction resolution





Coincidence Results

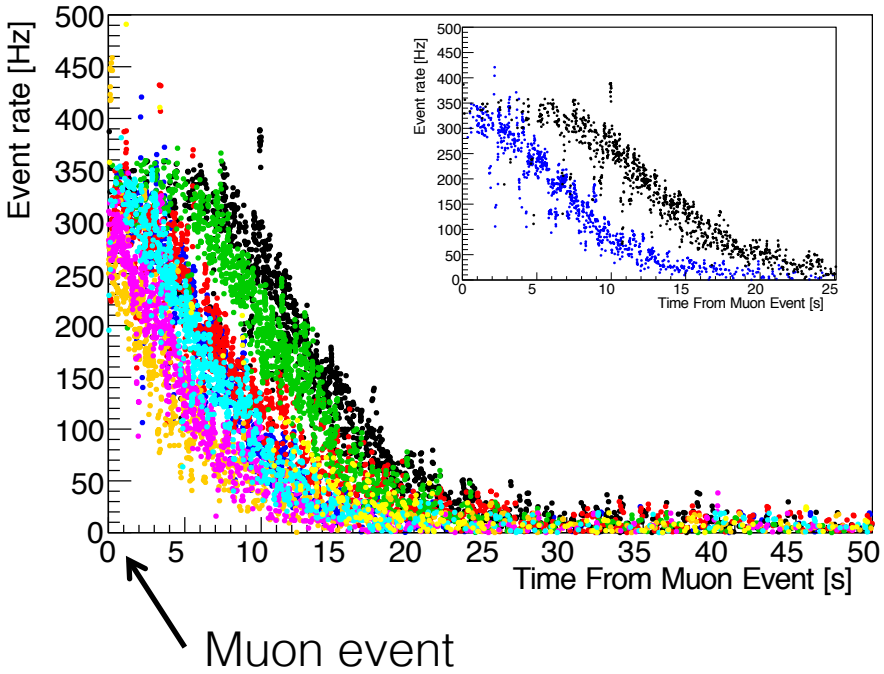
- Up to 93% of DM-Ice Det-1 muons coincident with IceCube events
  - Det-2 (edge of detector): 33%
- "Seeding" with DM-Ice lower IceCube misreconstructions from 21% to 13%
  - Det-1: 17% → 6.3%
  - Traditional reconstruction: "MPE"
  - More effective with low energy events
  - Small changes in high energy events
- Comparison of reconstructions validates quoted resolution
- Open data sharing with IceCube
- Future plans: DM-Ice17 data filter



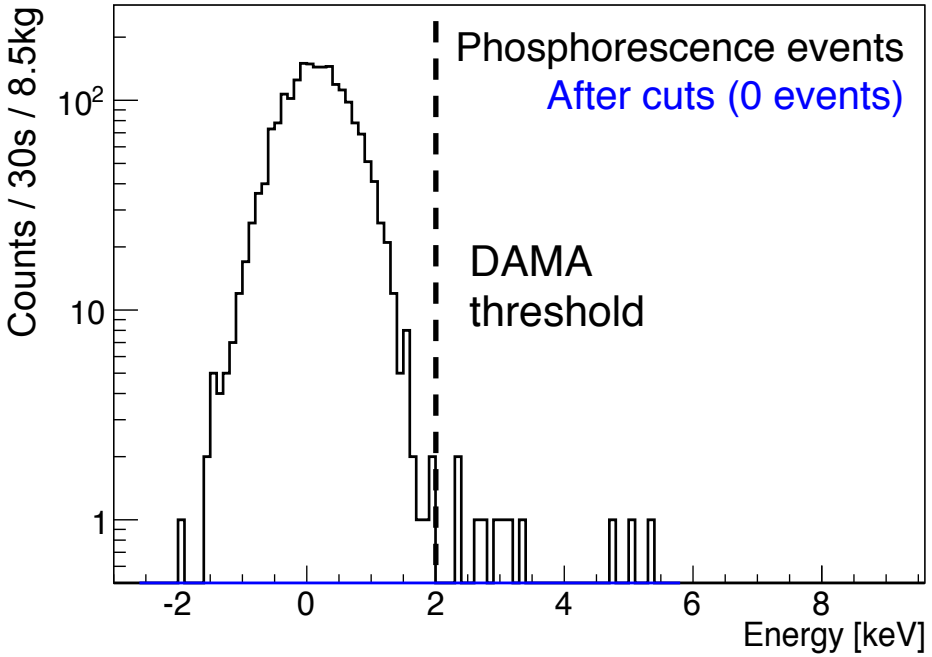
Muon-Induced Phosphorescence

The 2% highest energy muons each induce 100s of low energy events following the muon event

Timing characteristics: 9±2s decay
Normal rate: 2.5 Hz
DAQ saturation visible ~300 Hz



Energy characteristics: no events pass noise cuts (EMI and peak finding); predominantly <2 keV

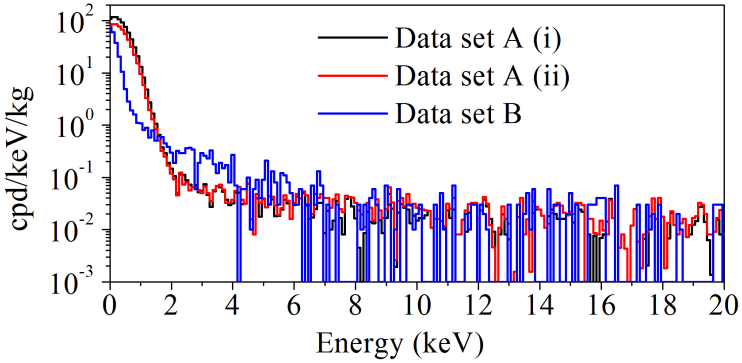


Phosphorescence and Dark Matter

- Concern about phosphorescence inducing a low energy modulation in phase with muons
  - David Nygren proposed this could be the DAMA modulation
  - This could amplify the effect of a muon modulation *arXiv:1108.0815*
- DM-Ice17: phosphorescence looks like noise and is removed
- DAMA: 500 μs deadtime after all events
- Phosphorescence often discussed in NaI(Tl) literature
  - Previous experiments have observed decays from μs – 45 days

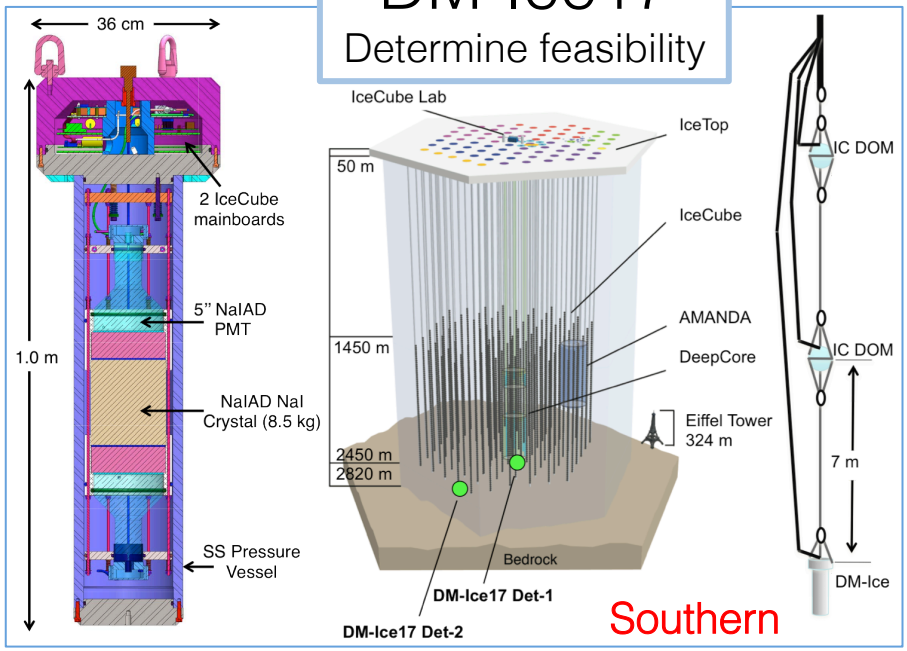
Experiment	Phos. decay time	Phos. energies
DM-Ice17	9 s	< 2 keV
ANAIS	70-100 ms	< 20 keV
St. Gobain	Minutes – hours	6-10 keV
DAMA	N/A	N/A

ANAIS 2014

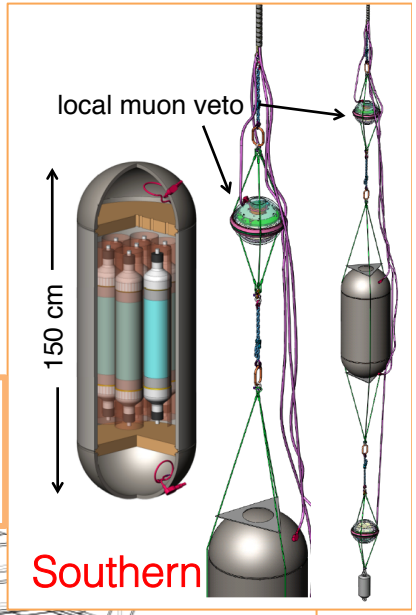


DM-Ice

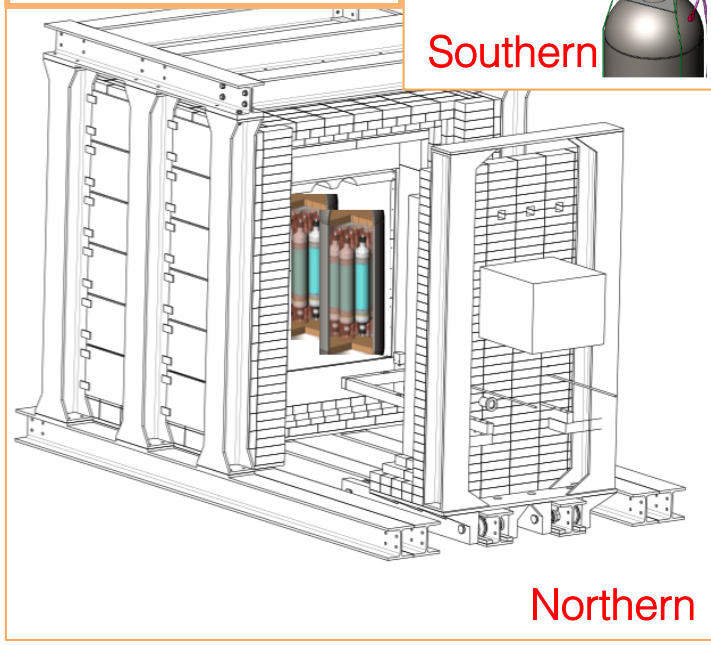
DM-Ice17
Determine feasibility



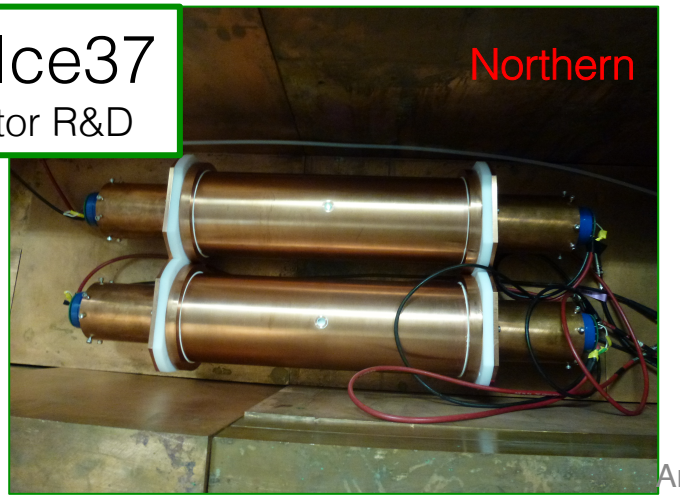
DM-Ice is a phased program that will run in <u>both hemispheres</u> to test the dark matter interpretation of the DAMA modulation



DM-Ice250
Set limits

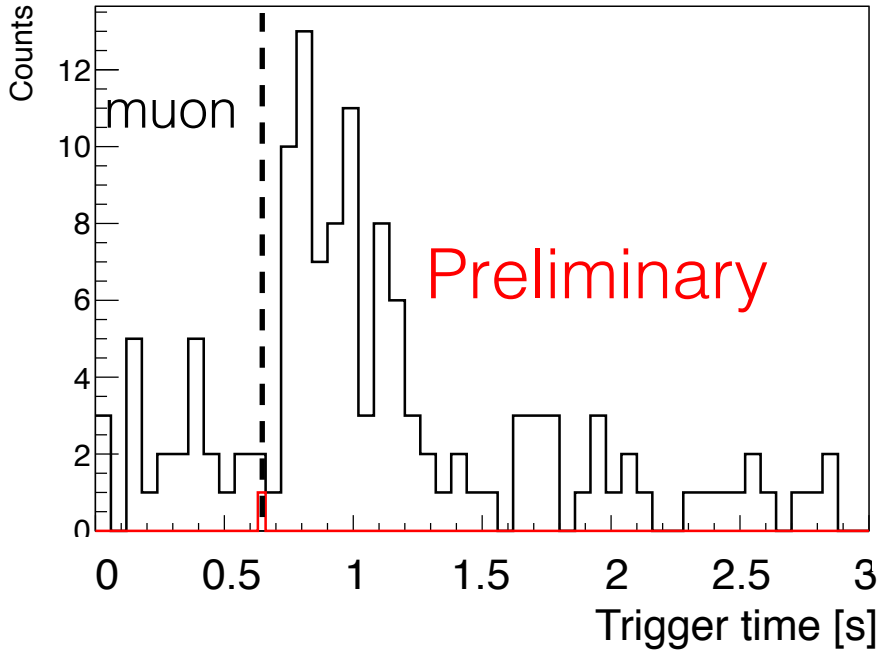


DM-Ice37
Detector R&D



DM-Ice37 Phosphorescence

- 2-18.3 kg crystal running at Boulby
- 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



Conclusions

- DM-Ice17
  - Muons can be identified in the crystal
  - IceCube coincidence has been successful
  - Phosphorescence must be monitored
- Phosphorescence and dark matter
  - Uncertainty in muon phase, amplitude
- Boulby R&D is progressing swiftly
  - Significant background reduction
  - Phosphorescence observed with significantly shorter lifetime


Questions?

Global NaI(Tl) Effort

DM-Ice
- Successful 17 kg detector
- Currently in R&D with 37 kg
- Only Southern Hemisphere detector
- Location: South Pole (2450 mwe), Boulby (2850 mwe)

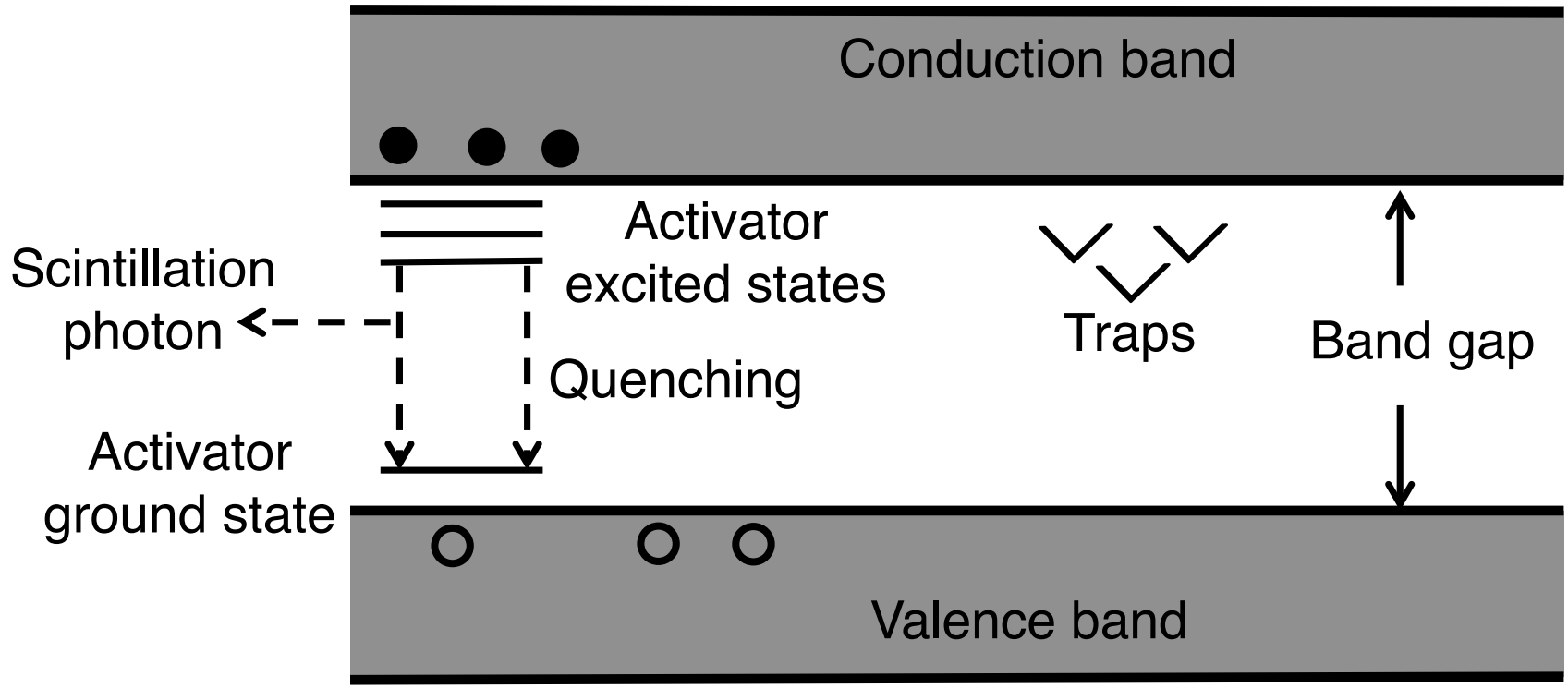
SABRE
- Currently in R&D
- Only detector with liquid scintillator veto planned
- Location: LNGS (3450 mwe)

KIMS
- CsI(Tl) experts
- Successful 17 kg detector
- Location: Y2K (700 mwe)

ANAIS
- Successful 10 and 25 kg detectors
- Currently in R&D with 37 kg
- Location: Canfranc (2450 mwe)

DM-Ice, KIMS, ANAIS: collective R&D effort with Alpha Spectra
All experiments: cooperative effort to prove/confirm DAMA, including data comparison

Scintillation Mechanism

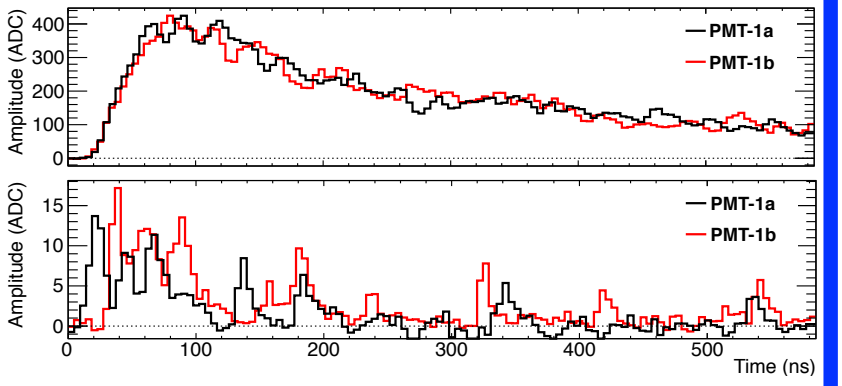


Event Types

Scintillation events

High energy: characteristic NaI(Tl) rise and fall time

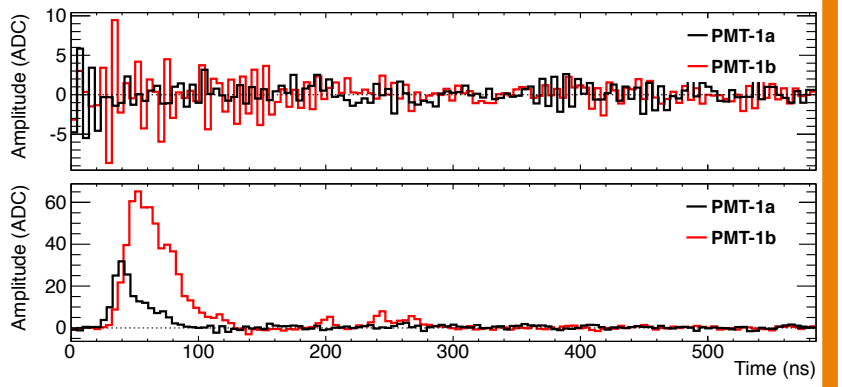
Low energy: series of single photoelectrons



Noise cuts

EMI cut: PSD removes EM interference (EMI)

Number of peaks cut: require 5 peaks from each PMT, removing anomalously fast pulses



IceCube Neutrino Observatory

- 5160 PMTs in 1km^3
  - 1500 – 2500 m deep
  - Neutrinos: up-going
  - Atm. muons: down-going
- Cherenkov light
  - Like a sonic boom of light

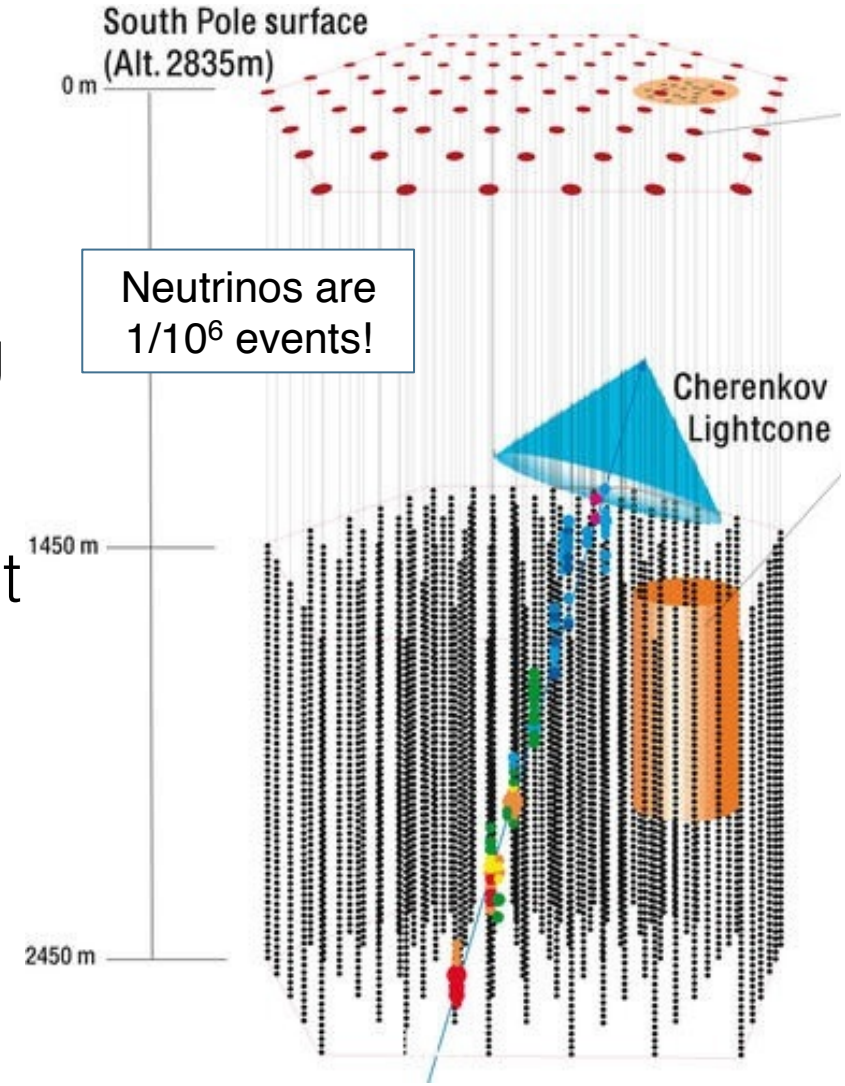
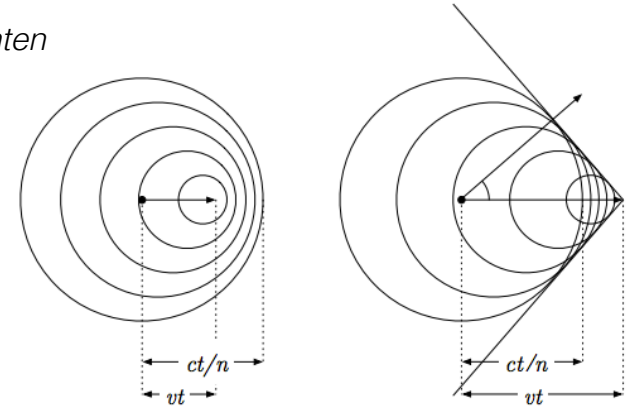
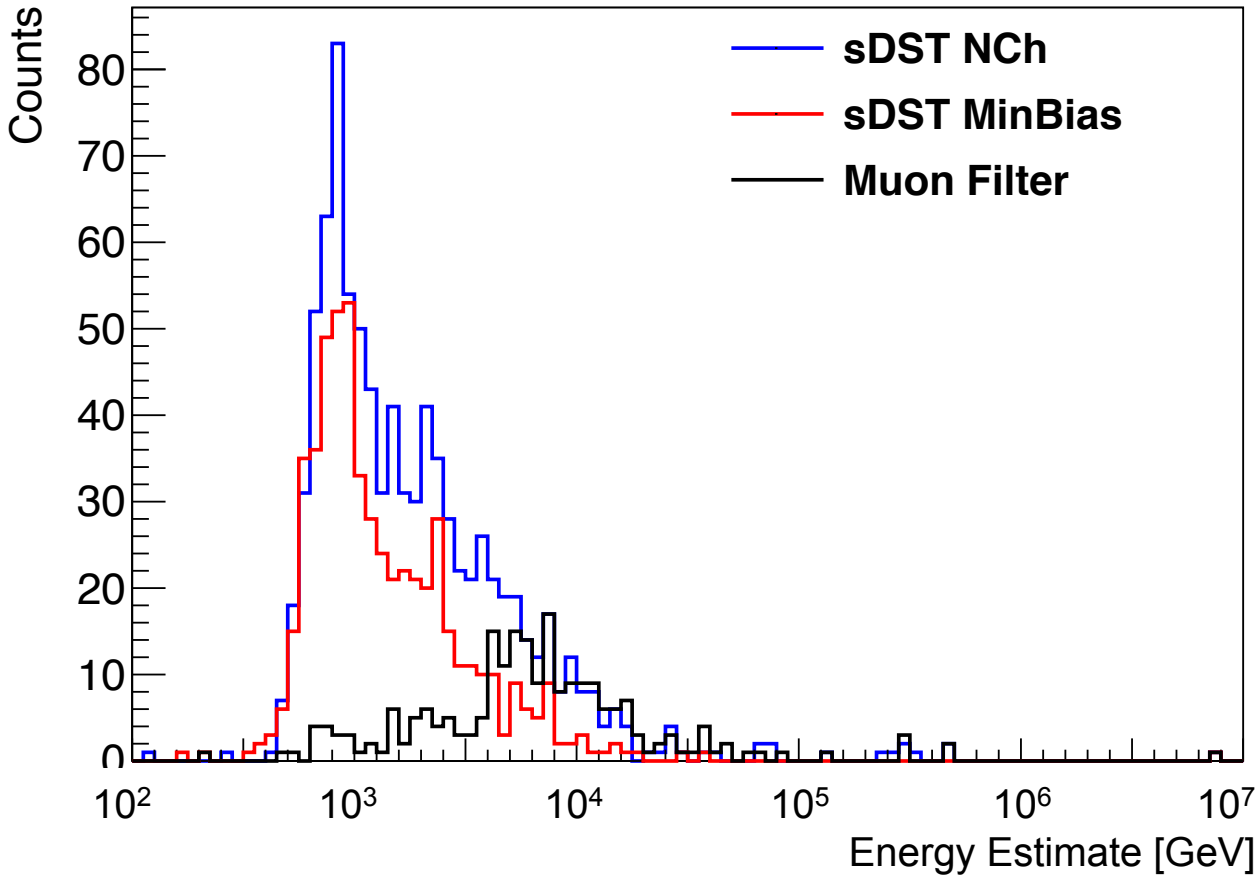


Image: van Santen

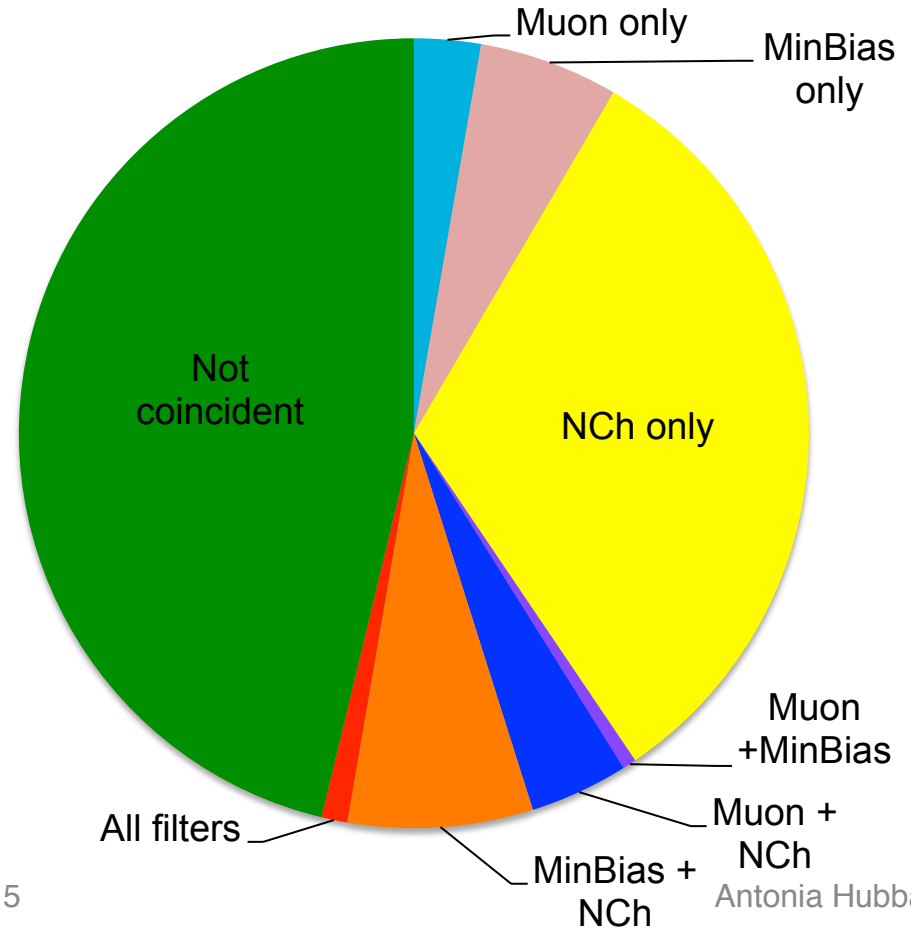


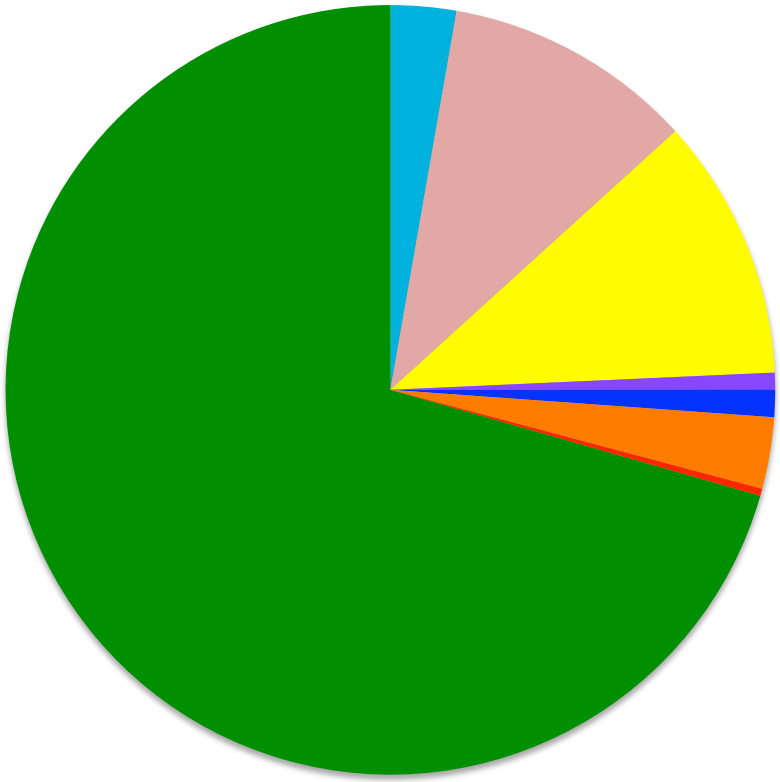
Filter Energies



Coincidence Results: 2012-13

- DM-Ice17: 1666 coincident/3978 muons
  - Det-1: 1072/1981, Det-2: 594/1997

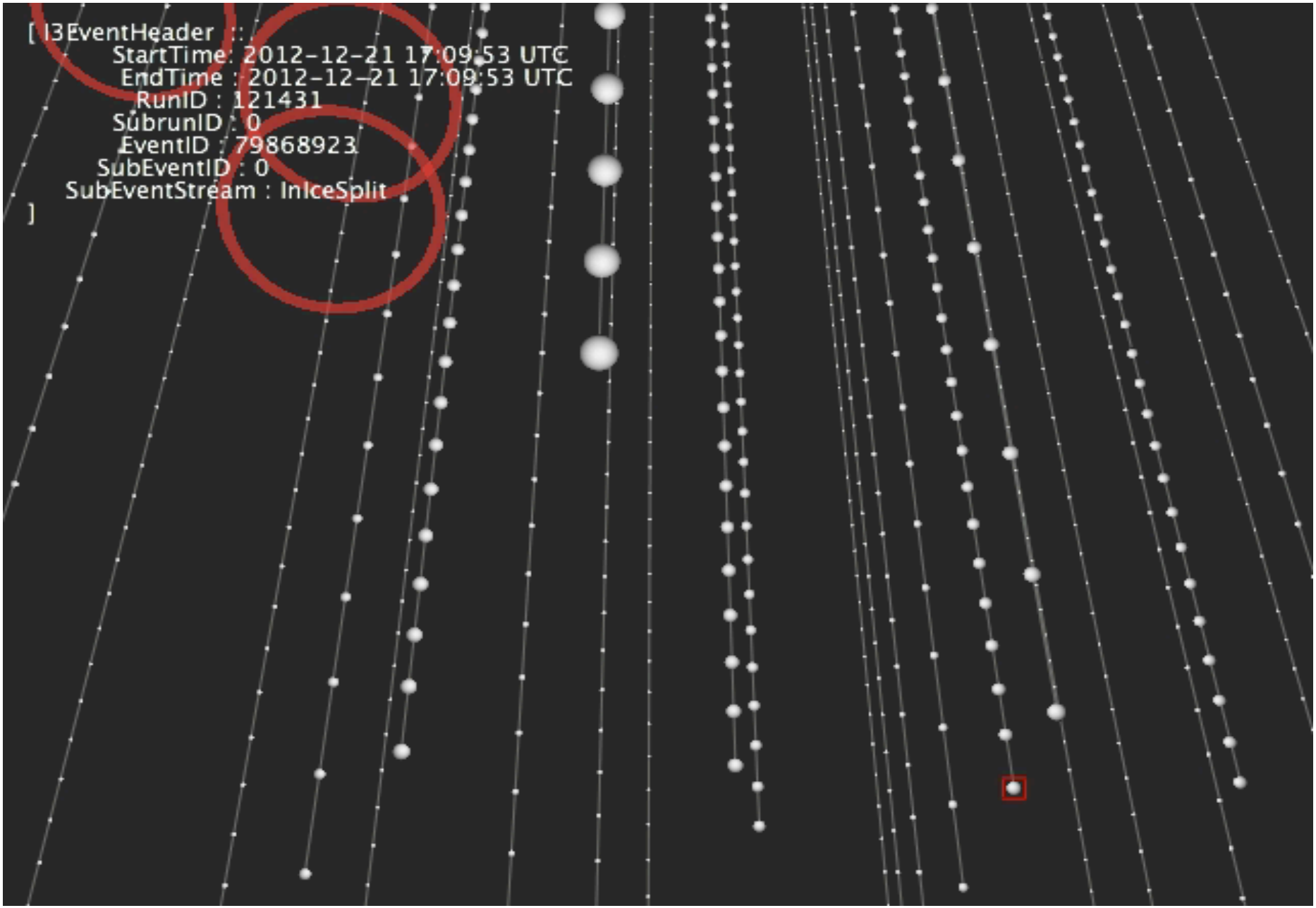




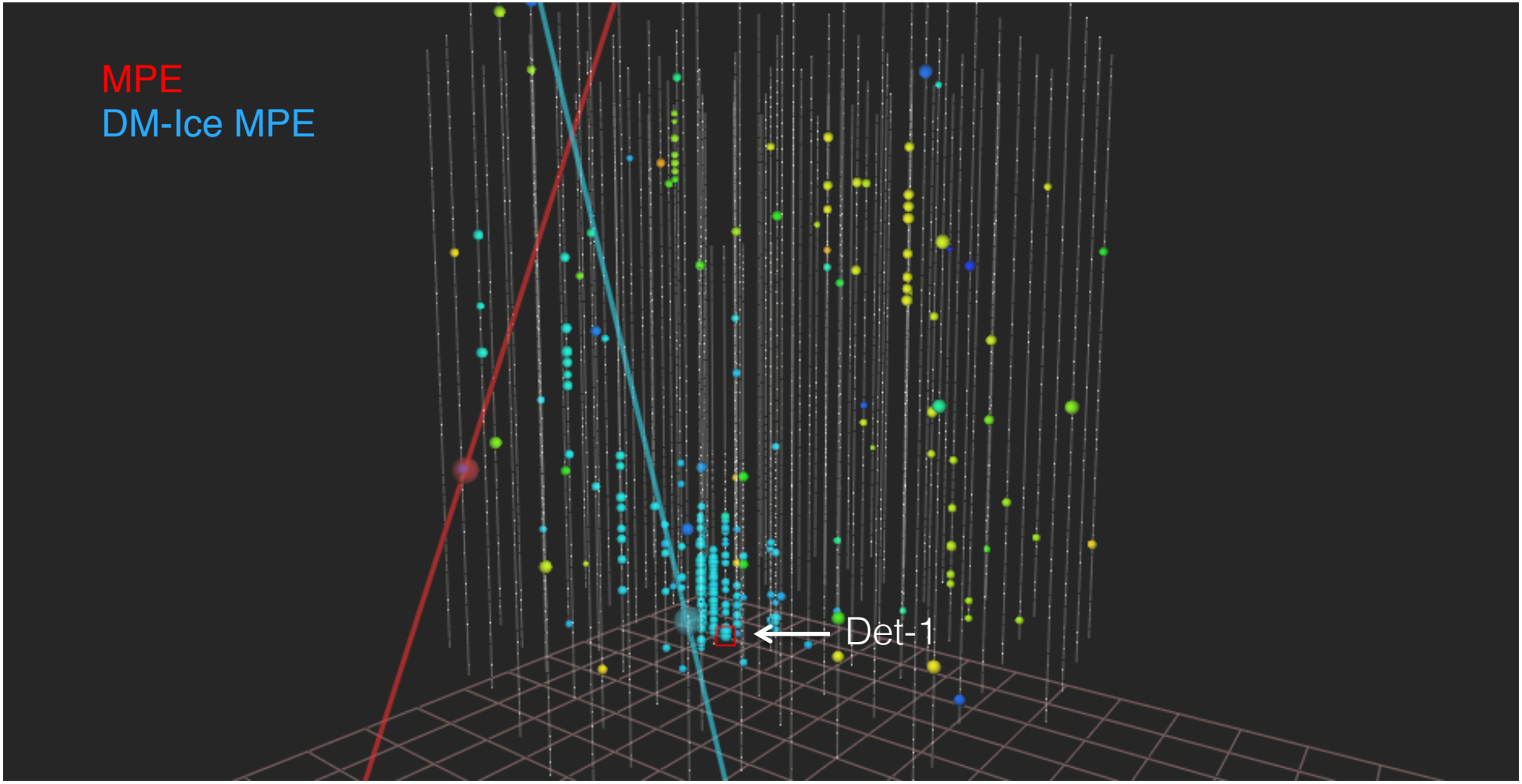
*NCh in 2012

IceCube Data

- Muon Filter: 34 Hz
  - High energy events; expect ~5% coincidence
- sDST MinBias: 454 Hz
  - Every 5th event; expect ~20% coincidence
- sDST NCh: 432 Hz
  - Events with NCh> 25; expect ~90% coincidence
  - 2012 only
  - NCh saw 93(33)% coincidence with Det-1(2)

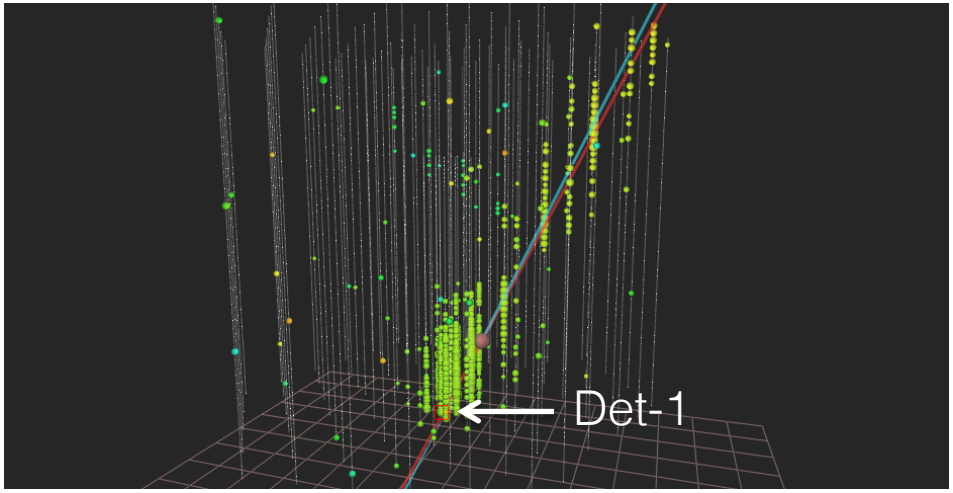

[I3EventHeader ::
StartTime : 2012-12-21 17:09:53 UTC
EndTime : 2012-12-21 17:09:53 UTC
RunID : 121431
SubrunID : 0
EventID : 79868923
SubEventID : 0
SubEventStream : InIceSplit
]

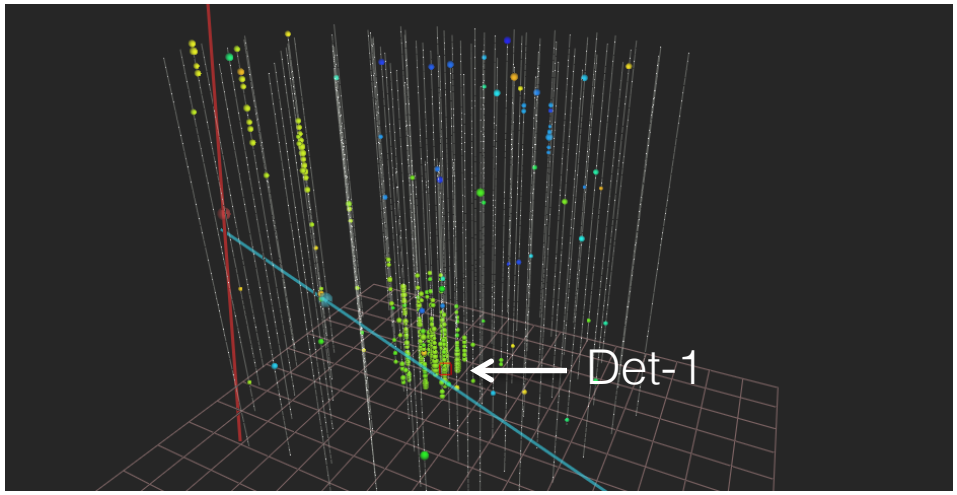
Fail MPE/Pass DM-Ice



Pass DM-Ice/Pass MPE

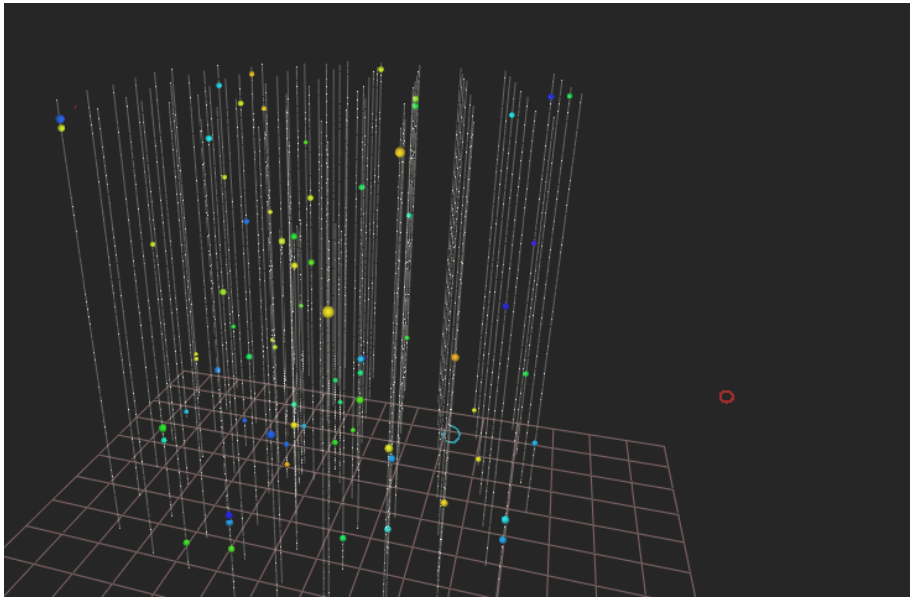
MPE
DM-Ice MPE



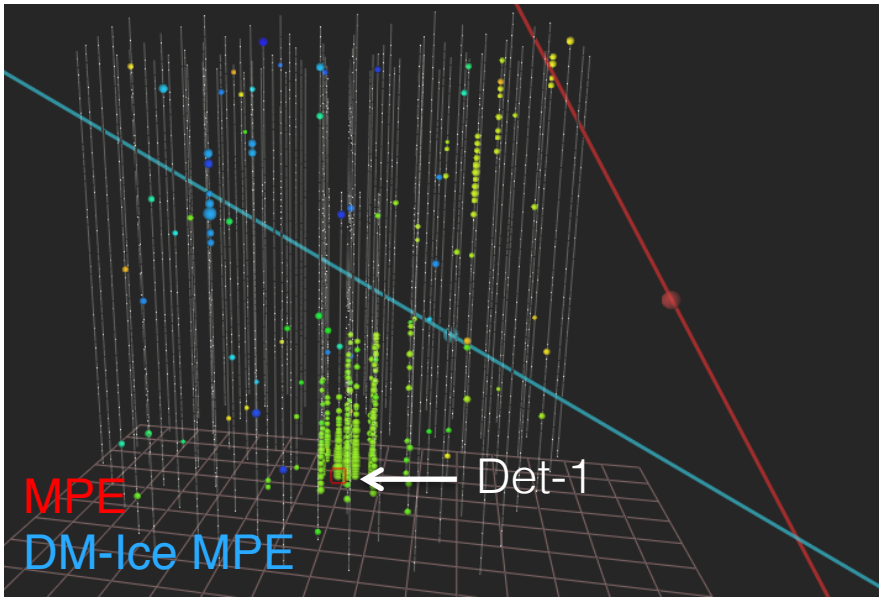


Fail MPE/Fail DM-Ice

Noise



Event-like



Summary 2012 + 2013

	# DM μ	# w/ IC (deadtime)	coincident	# Muon Filter	# sDST NChannel	# sDST MinBias
Det-1	1981	1952 (1.5%)	1072 (55%)	166 (8.5%)	887*(93%)	295 (15%)
Det-2	1997	1956 (2.1%)	594 (30%)	98 (5.0%)	309* (33%)	290 (15%)
Total	**3978**	**3908 (1.8%)**	**1666 (43%)**	**264 (6.8%)**	**1196* (63%)**	**585 (15%)**

*based on 2012 only (955 / 934 / 1889 events)

- **Muon Filter:** 34 Hz; high energy events
- **sDST MinBias:** 454 Hz; every 5th event
- **sDST NCh:** 432 Hz; all events with NCh>25

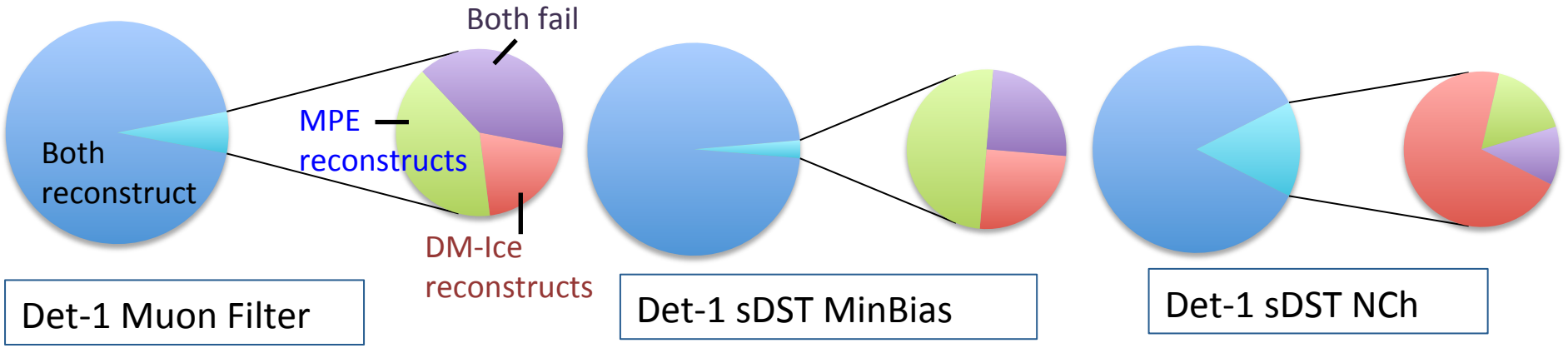
Misreconstructions

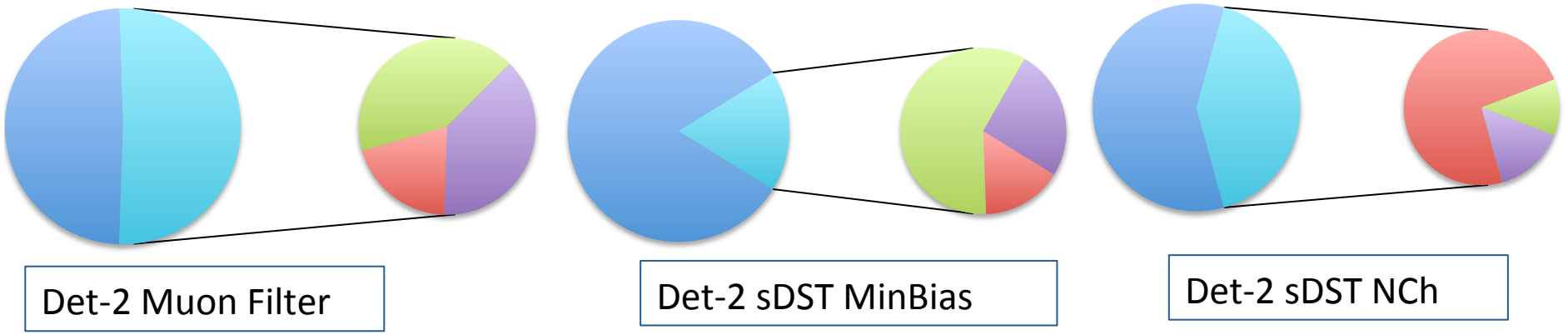
Improvement from NCh only

Detector	Zenith > 90°	Energy < 100GeV	Distance > 20m	Nan Reco
Det-1 Traditional	115 (10.7%)	62 (6.5%)	141 (15.8%)	5 (0.6%)
Det-1 DM-Ice seed	44 (4.1%)	23 (2.2%)	166 (16.5%)	0
Det-2 Traditional	145	23	94	1
Det-2 DM-Ice seed	100	22	111	0
Total Traditional	260	85	235	6
Total DM-Ice seed	144	45	277	0

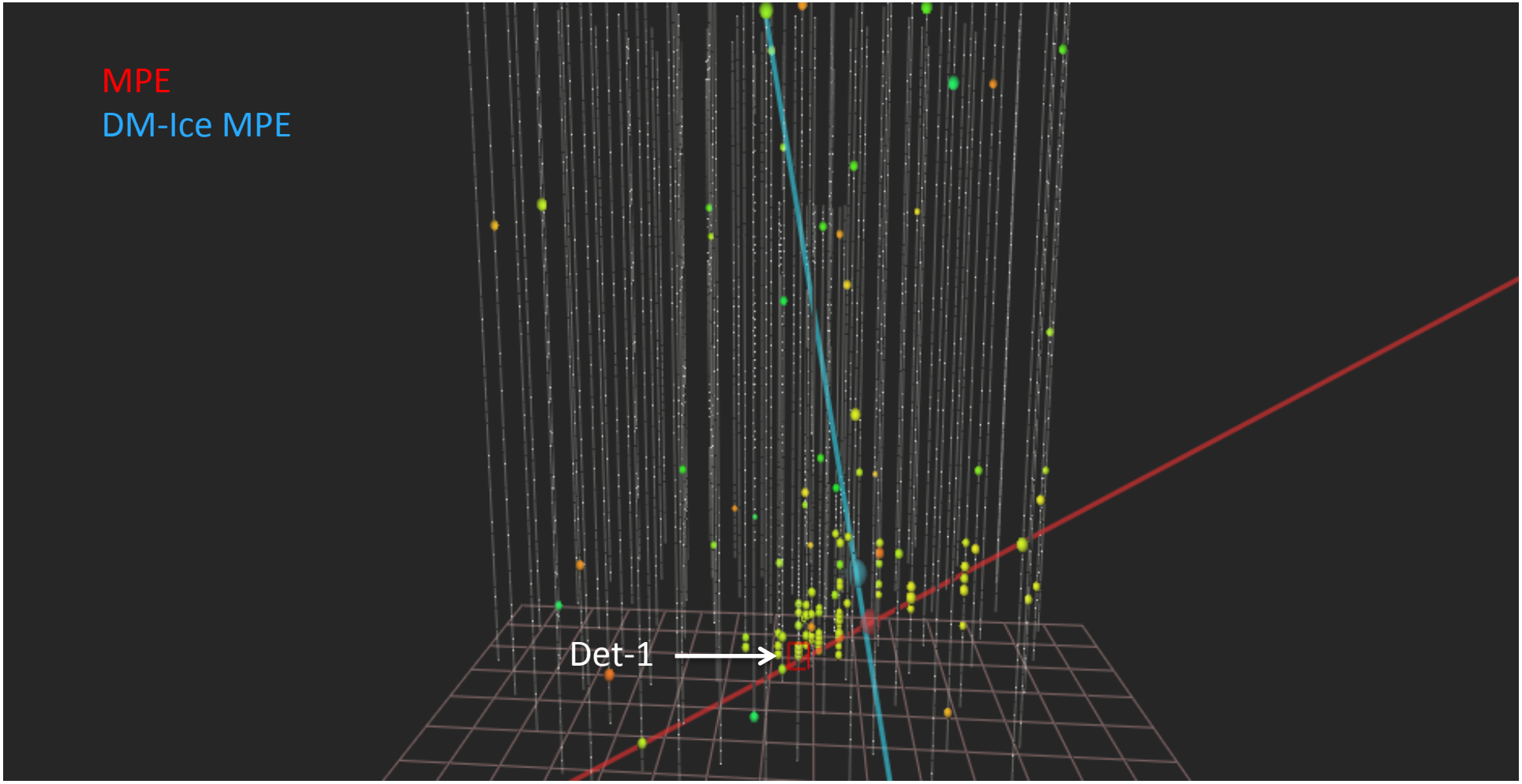
Total number coincident: 1666 (43% coincident)
Expected accidental coincidence/crystal ~ 20

Misreconstructions: Zenith





Fail DM-Ice/Pass MPE



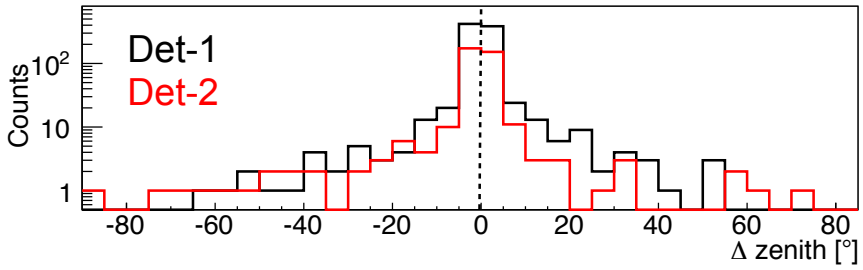
Misreconstruction conclusions

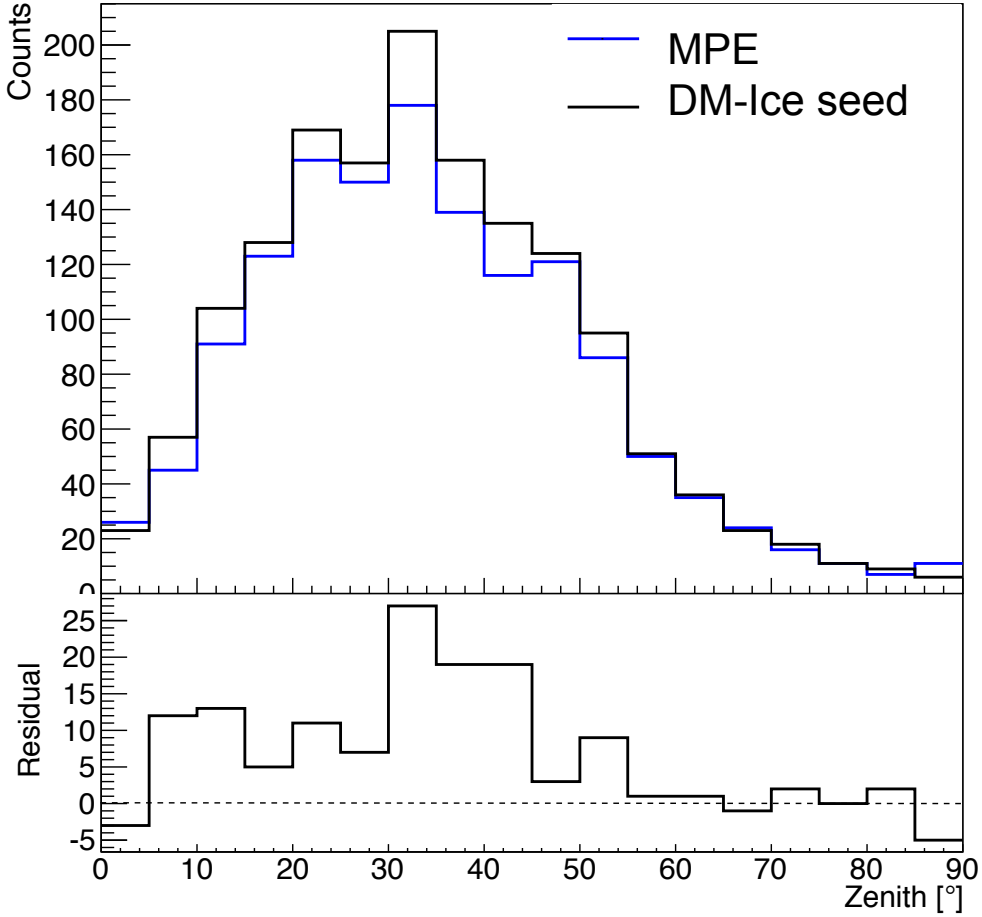
- DM-Ice seed helps low energy events
  - Less relevant for high energy
- Full likelihood may be required for improvement
  - Penalty for distance from DM-Ice

- *How does the DM-Ice seed change passing reconstructions?*

Reconstruction Comparisons

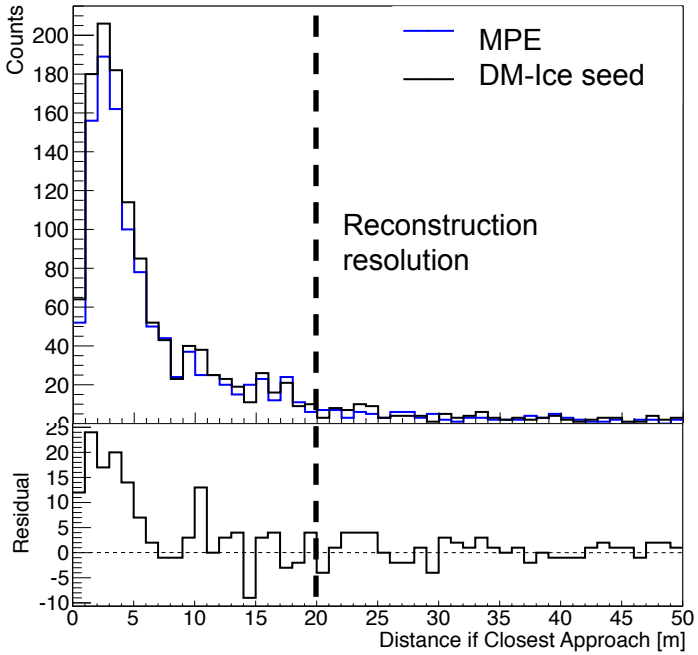
- Agreement between both seeds indicates both are reconstructing well

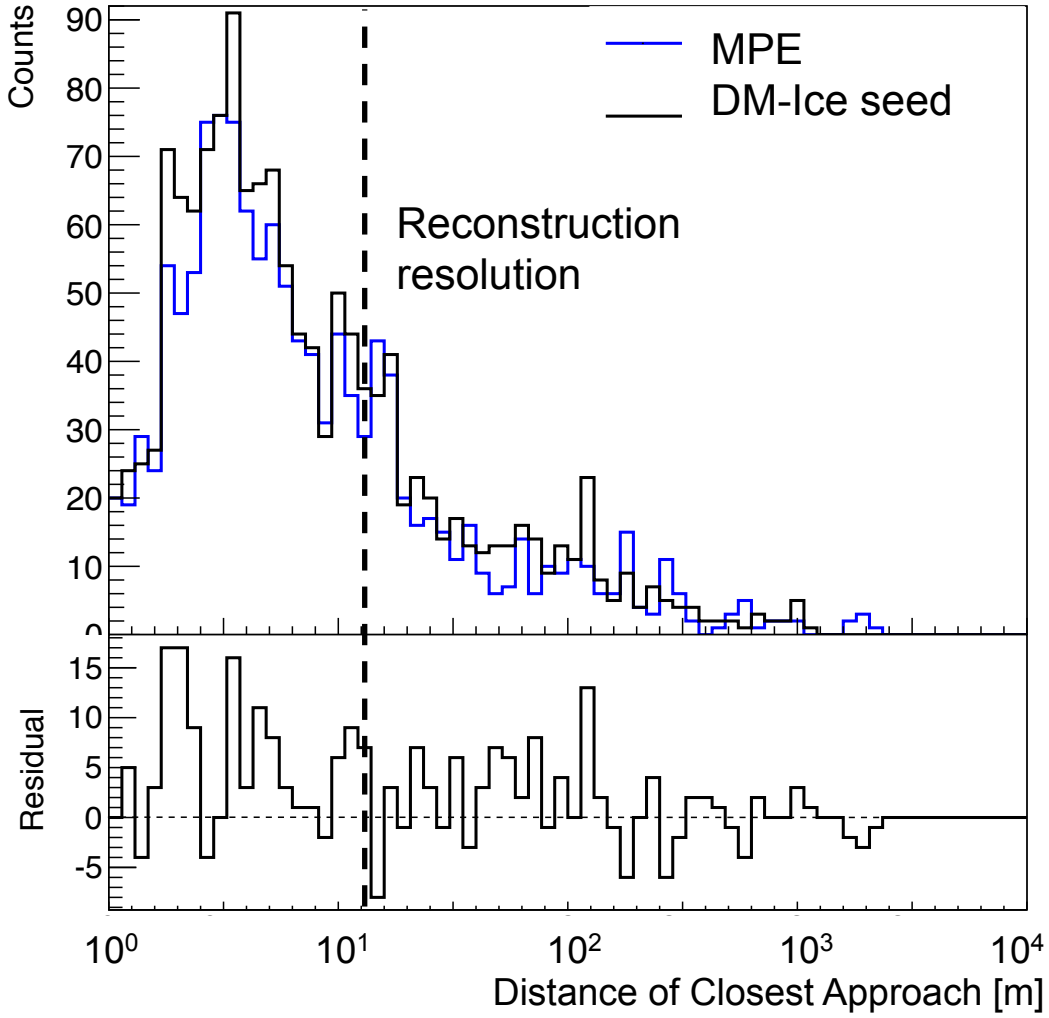




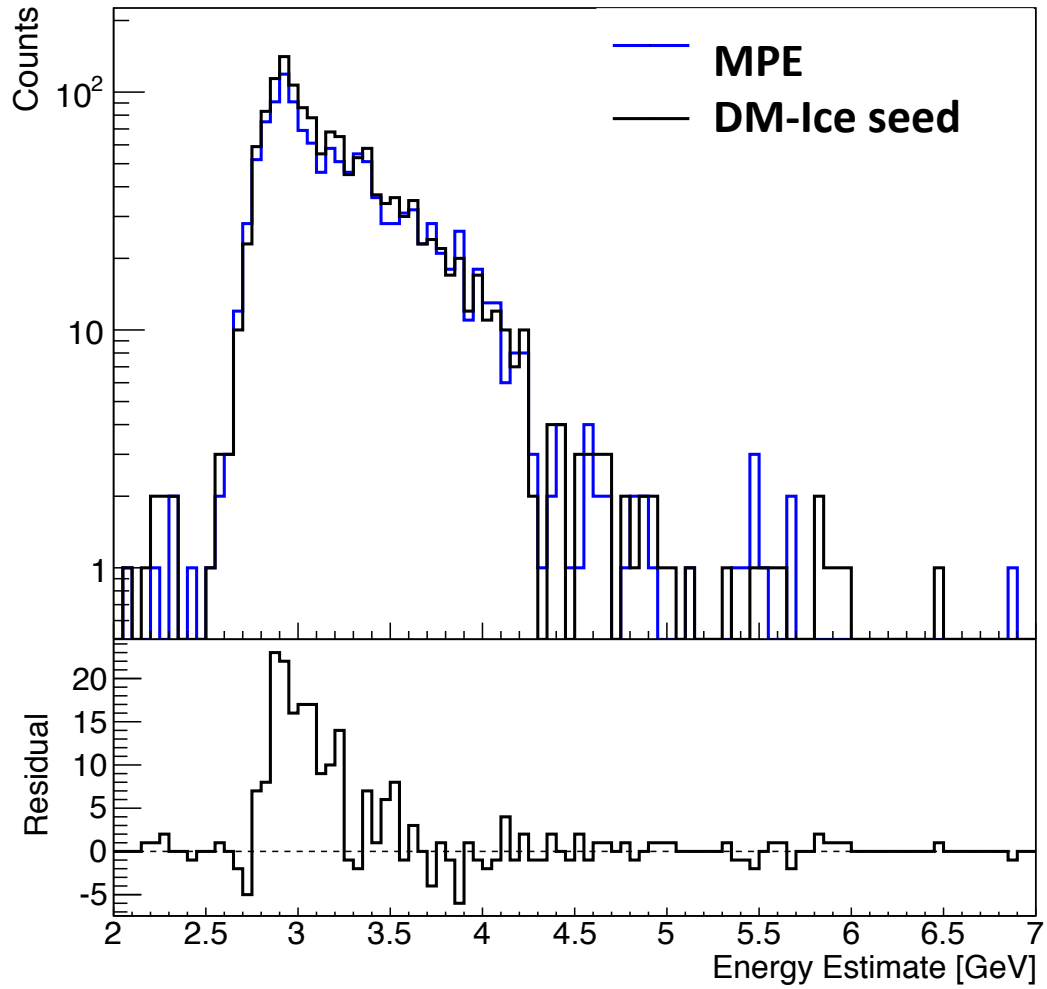
Reconstruction Comparisons

- Distance of closest approach indicates room for improvement

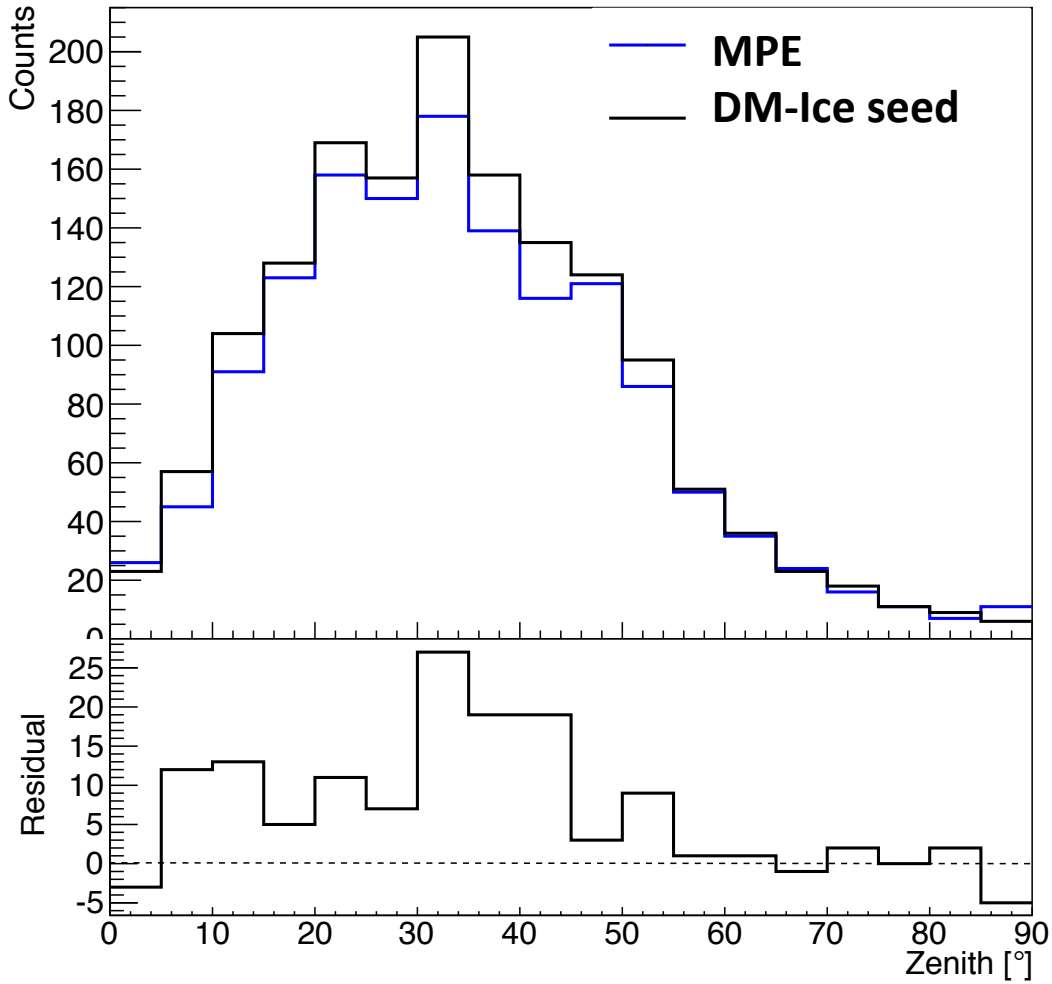




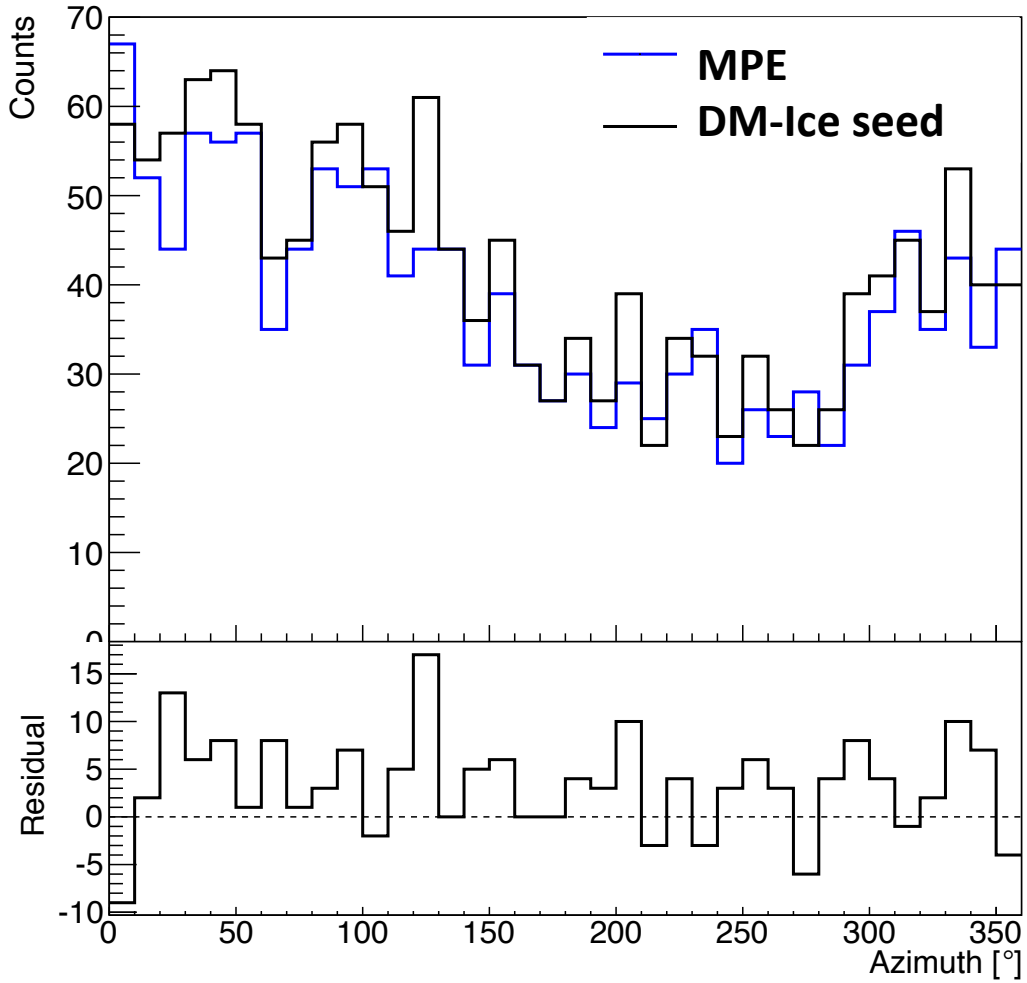
Energy Spectrum



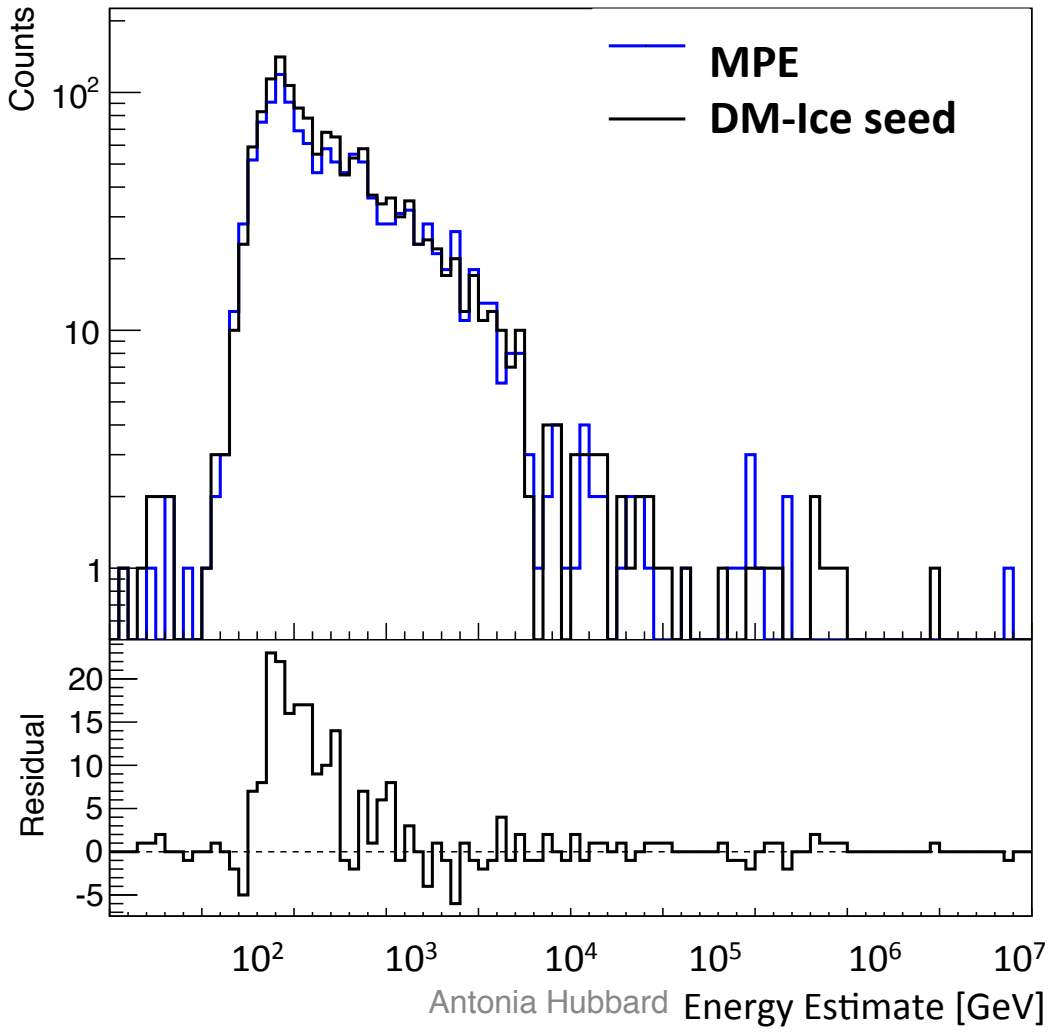
Zenith



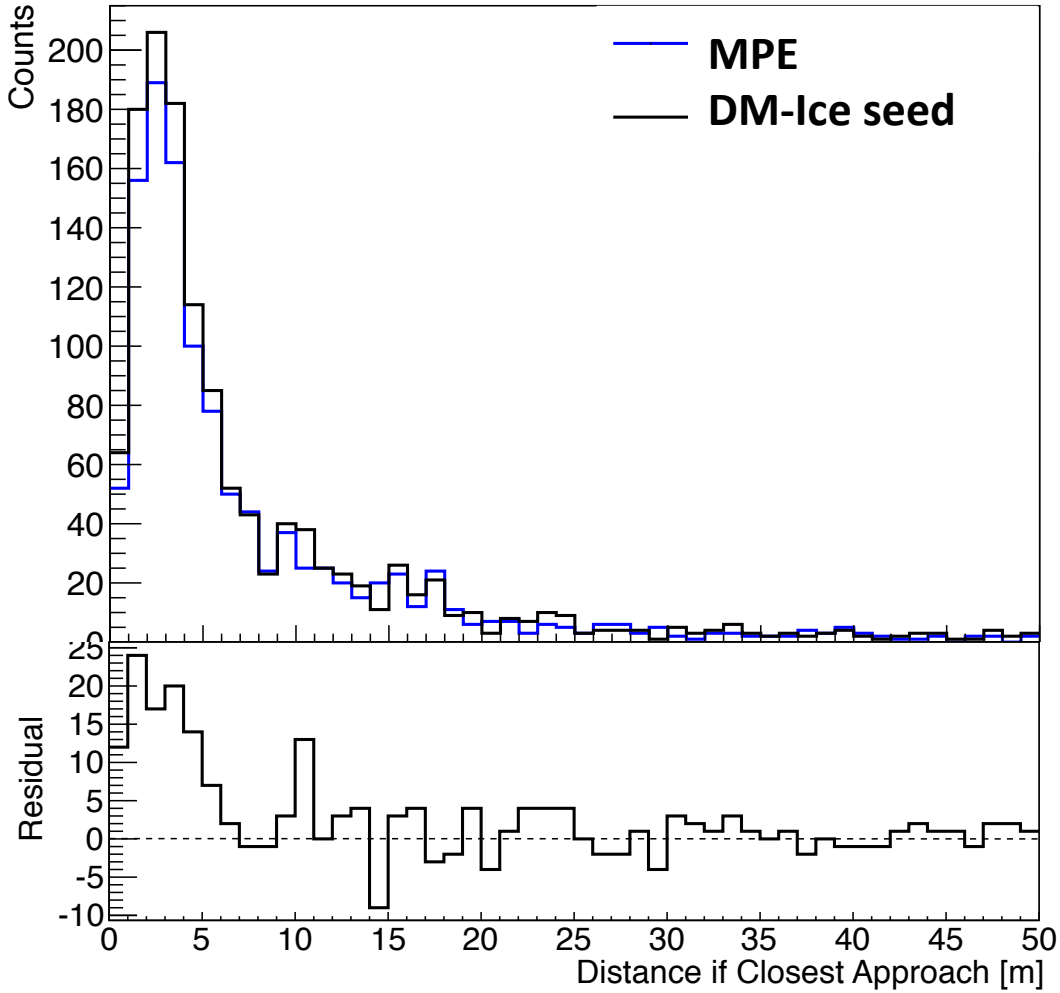
Azimuth



Energy



Distance


Counts
MPE
DM-Ice seed
Residual
Distance if Closest Approach [m]

DM-Ice37

- **Current R&D**: 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

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
  - 3 mBq/kg ^{40}K, ^{210}Pb reduction in R&D

Significant improvements in location and PMTs