Astrophysical Neutrinos and Alerts from IceCube

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Astro-COLIBRI Multi-Messenger Astrophysics Workshop
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Photo credit: J. Werthebach IceCube/NSF

IceCube Astrophysical neutrinos

- In 2013, IceCube announced the discovery of astrophysical high-energy neutrinos.

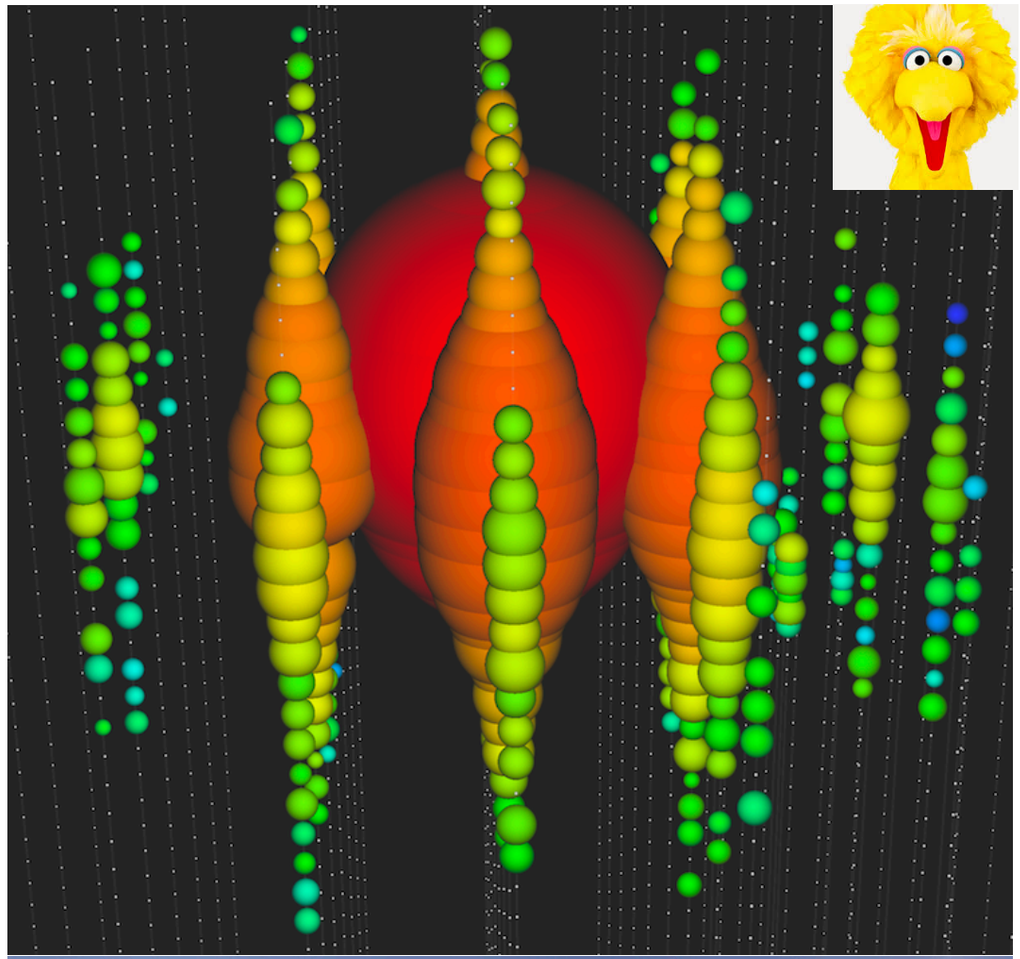
- Today I'll cover:

  - What is IceCube and how does it work?

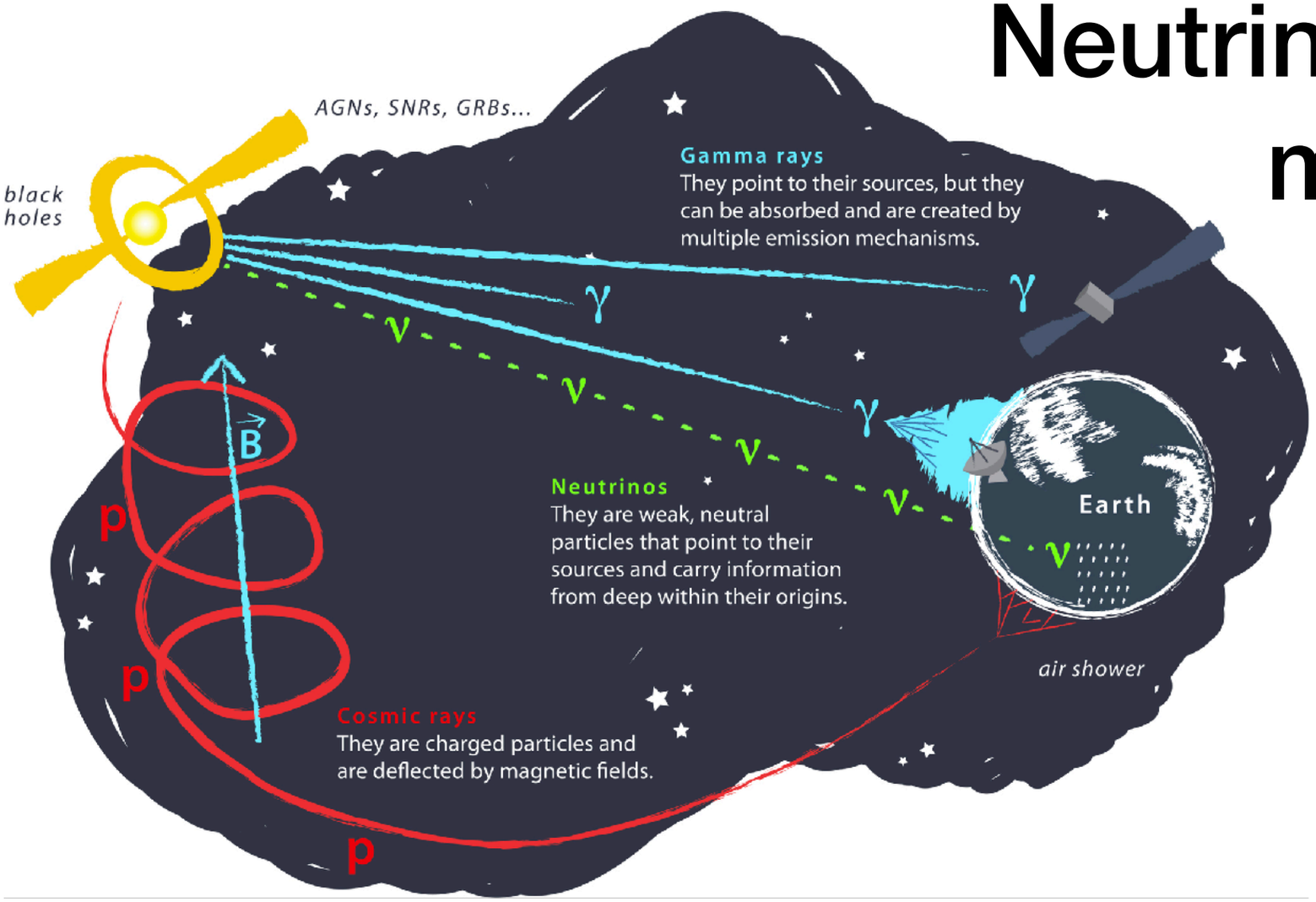
  - IceCube's measurement of astrophysical neutrinos

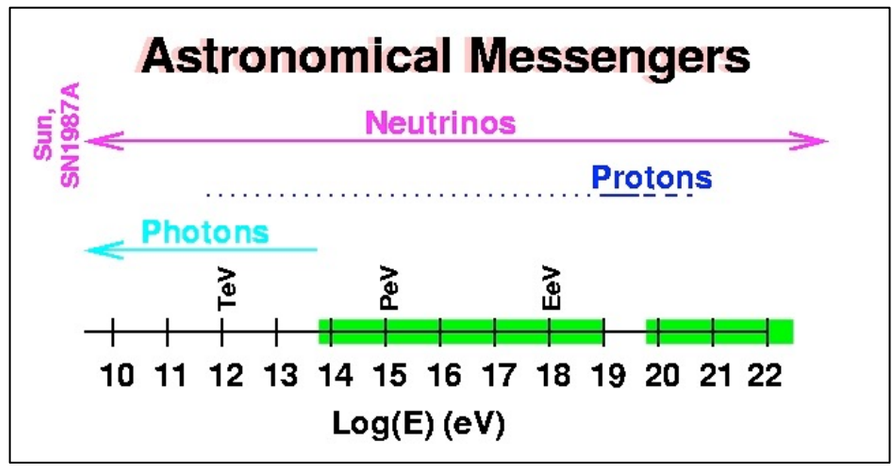
  - Realtime alerts, TOO neutrino searches

  - What happens next?



Neutrinos: Astronomical messengers





- Neutrinos can be created by hadronic interactions within or near cosmic accelerators
- At the highest energies, neutrinos are an astronomical messenger with several advantages:
  - Neutral
  - Freely propagate from source regions

Cable for power, communication and support

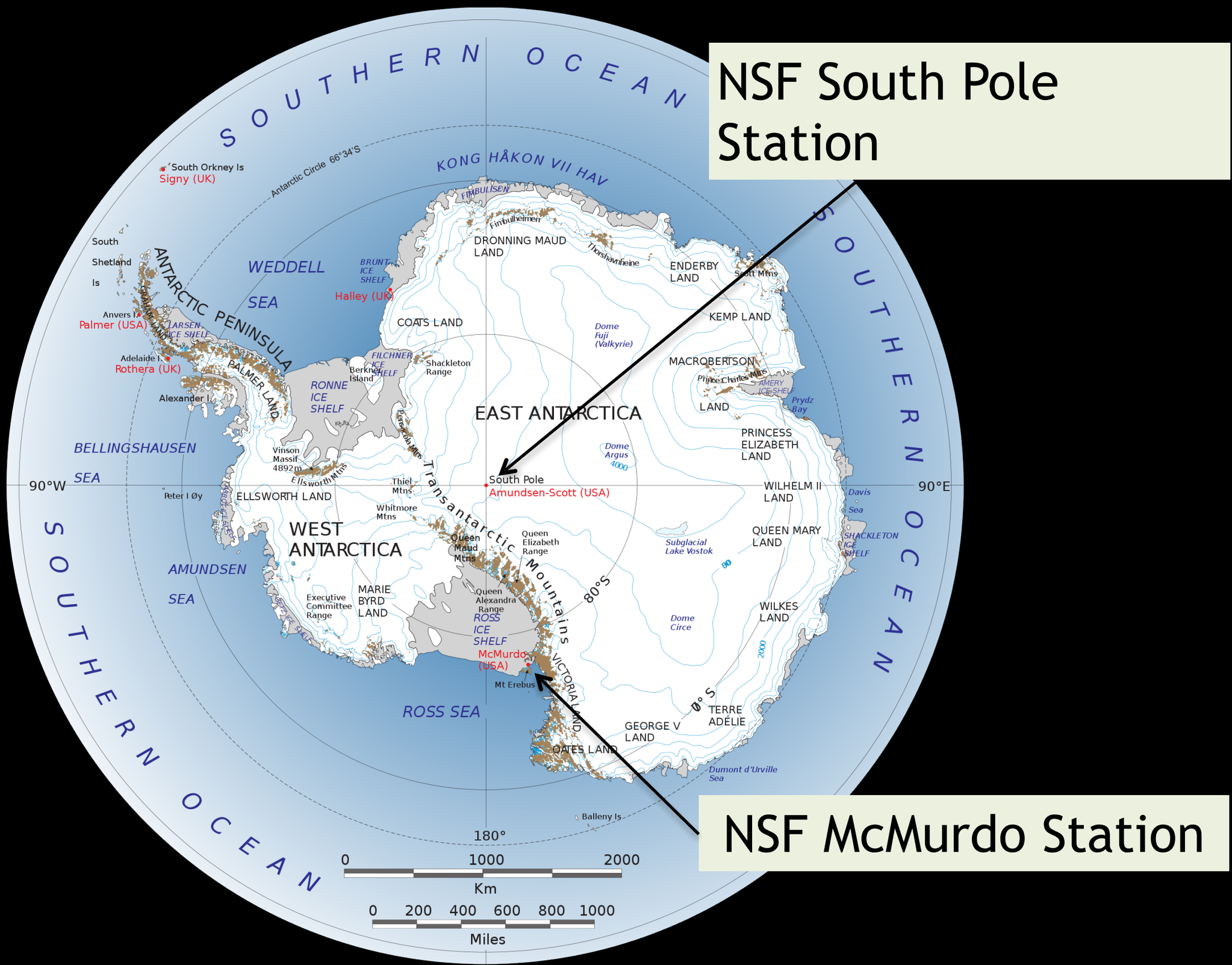
Digital optical modules (phototubes and data acquisition)

Clear ice serves as both a target medium and a Cherenkov radiator

μ

ν_μ

1 km³ of natural clear ice
→ The South Pole glacial icecap



IceCube

South Pole Neutrino Observatory

IceCube Laboratory

Data is collected here and sent by satellite to the data warehouse at UW–Madison

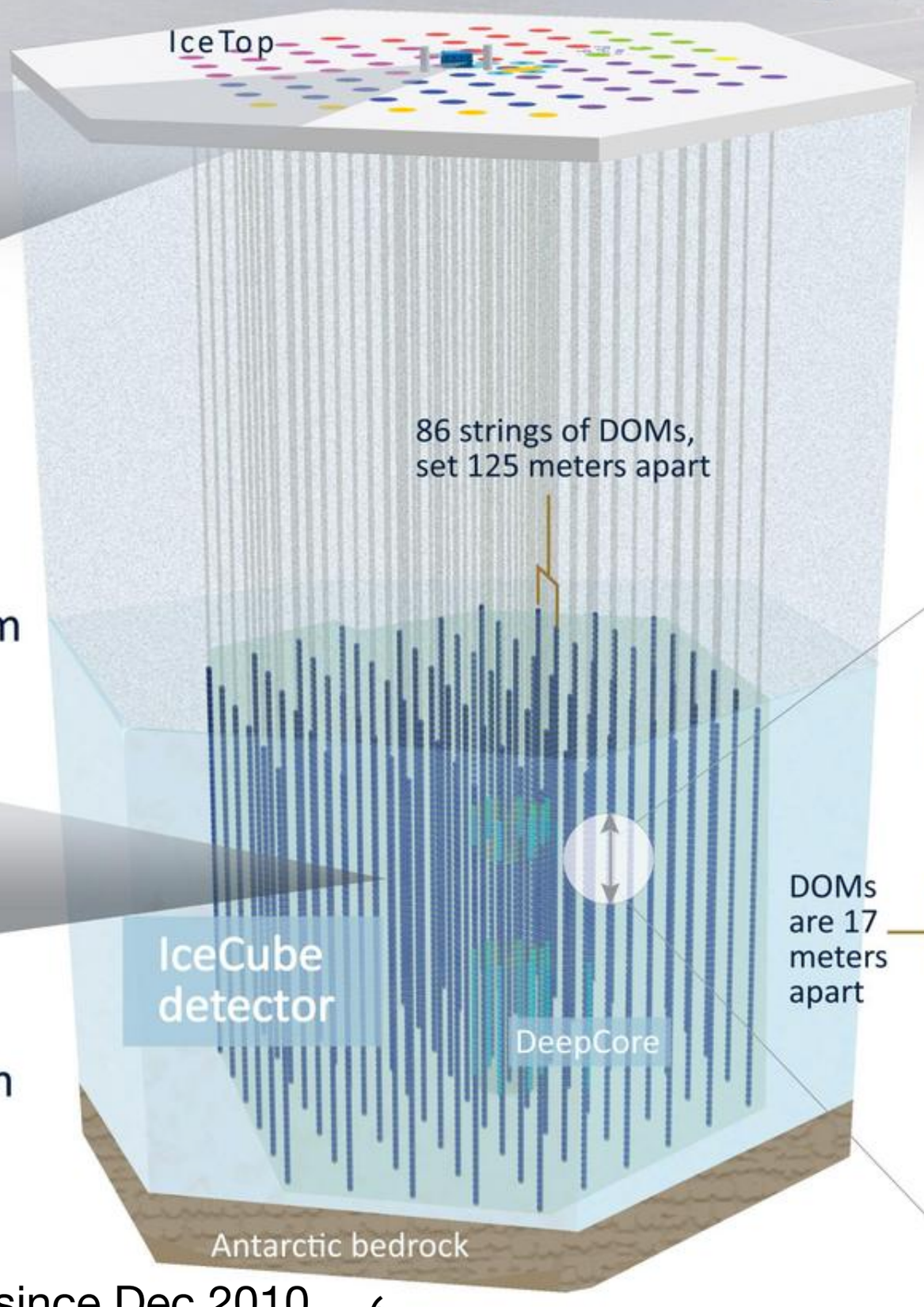
50 m

1450 m

Digital Optical Module (DOM)

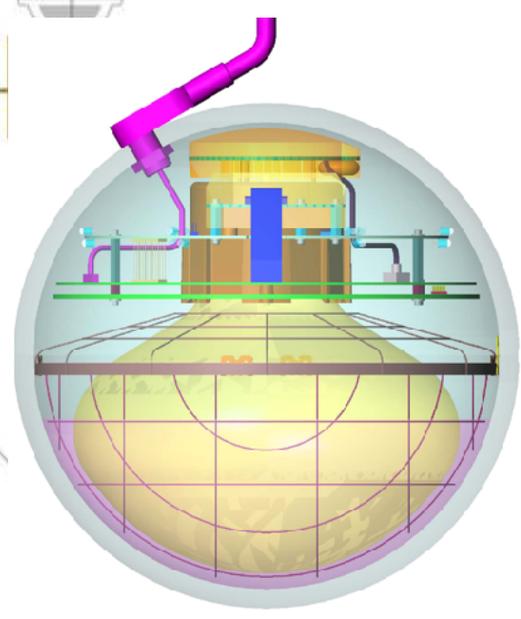
5,160 DOMs deployed in the ice

2450 m

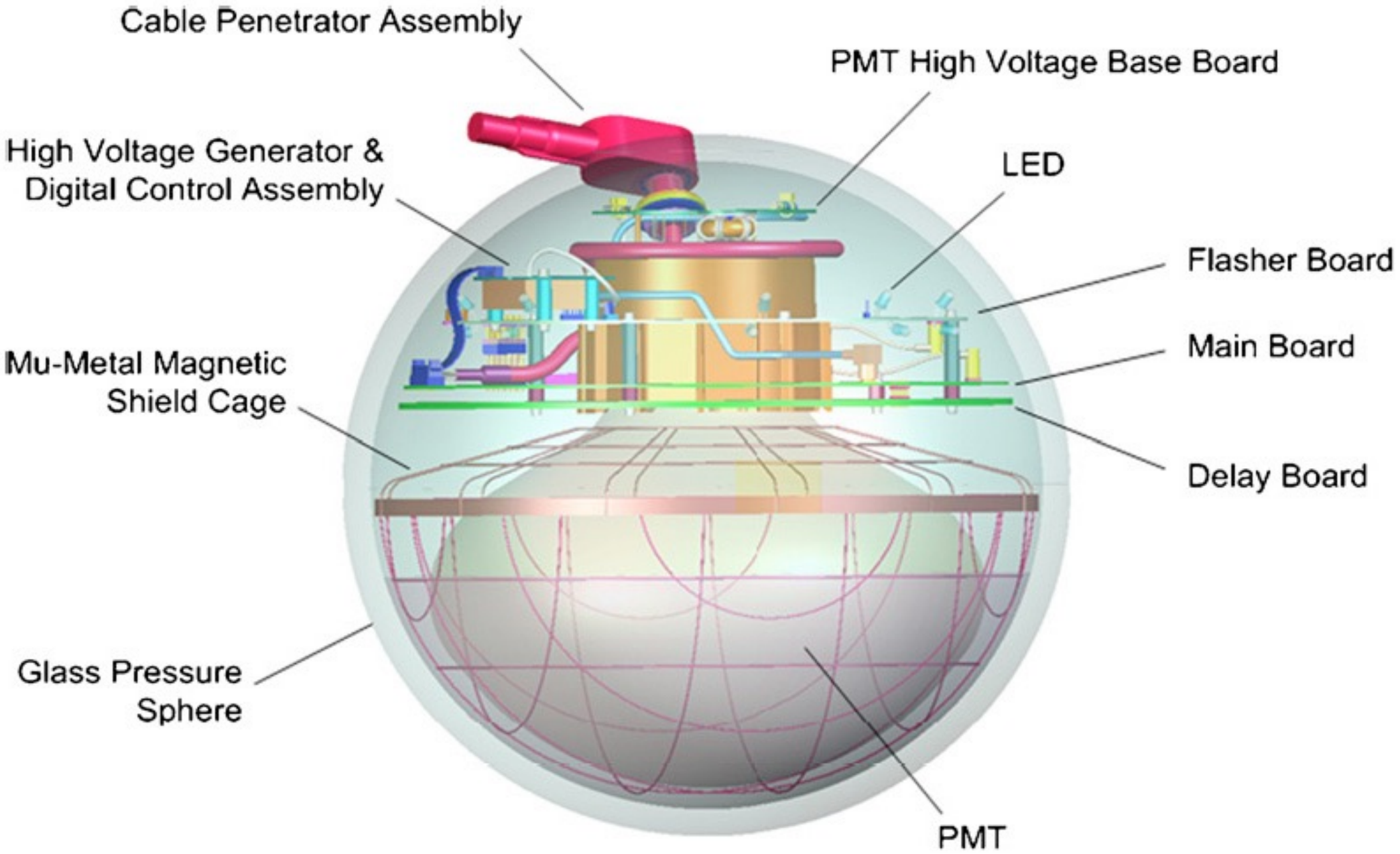


Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility



Completed and taking data since Dec 2010



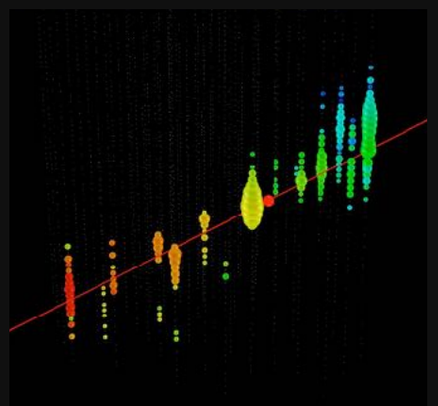
The IceCube Digital Optical Module (DOM)

~98% of DOMs still returning high quality data in 2022

~98% of DOMs still retur
high quality data in 20

IceCube sensitive to ALL ν flavors

CC Muon Neutrino

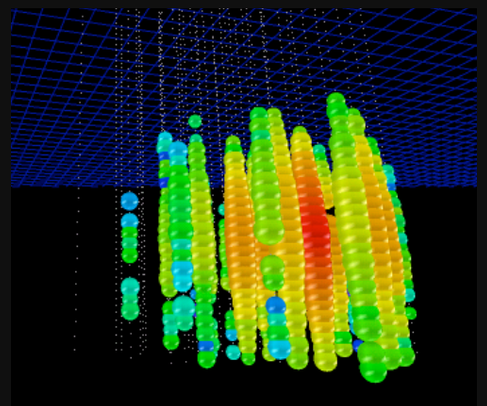


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

Neutral Current / CC Electron Neutrino



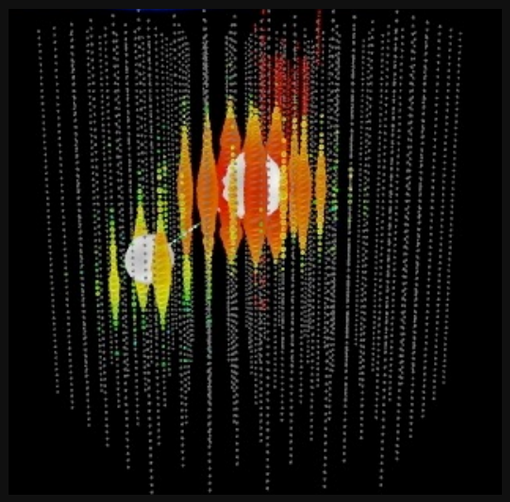
$$\nu_{\mathrm{e}} + N \rightarrow \mathrm{e} \ + X$$

$$\nu_{\mathrm{x}} + N \rightarrow \nu_{\mathrm{x}} + X$$

shower (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100TeV)

CC Tau Neutrino

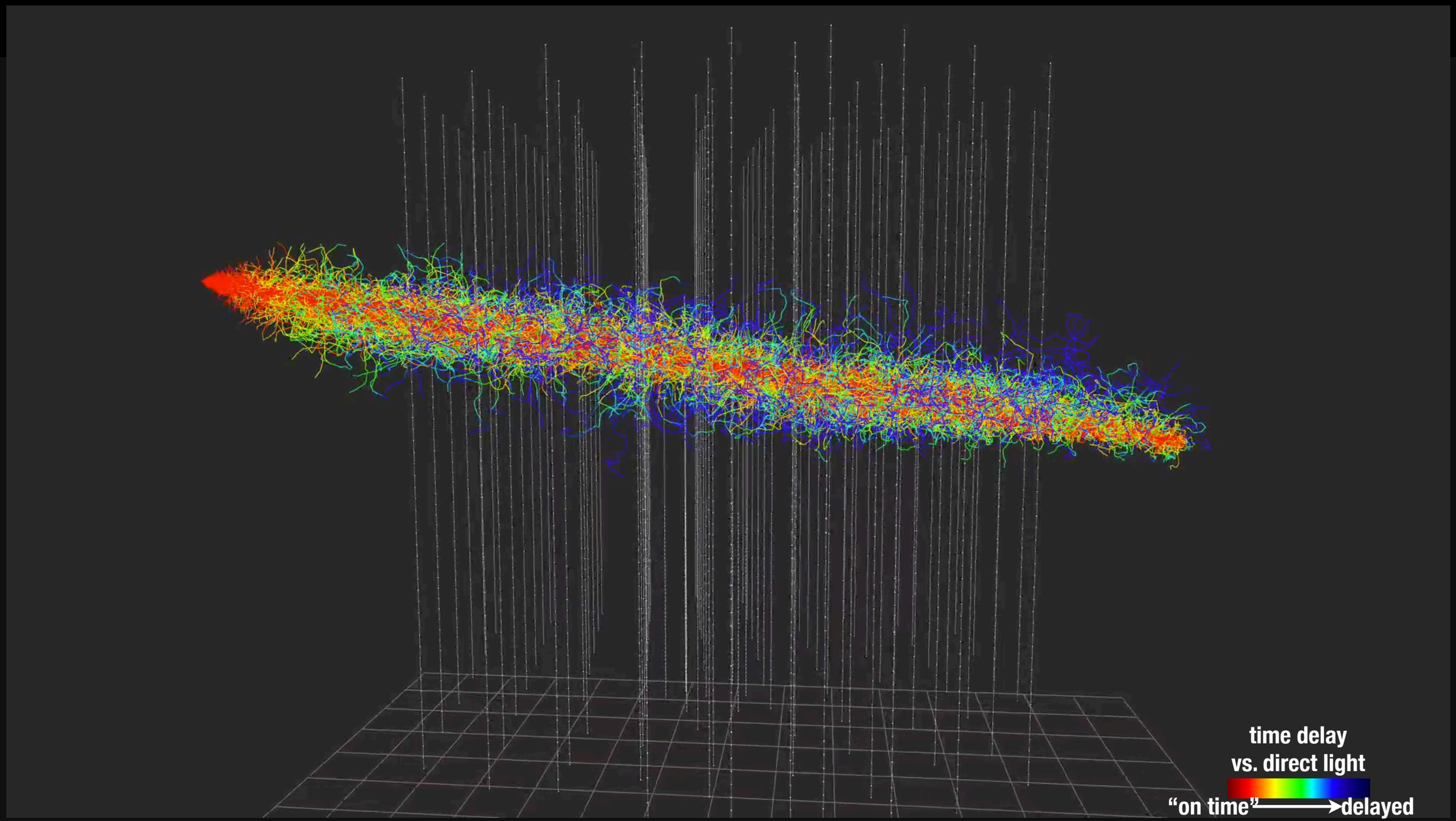


$$\nu_\tau + N \rightarrow \tau + X$$

“double-bang” and other signatures (simulation)

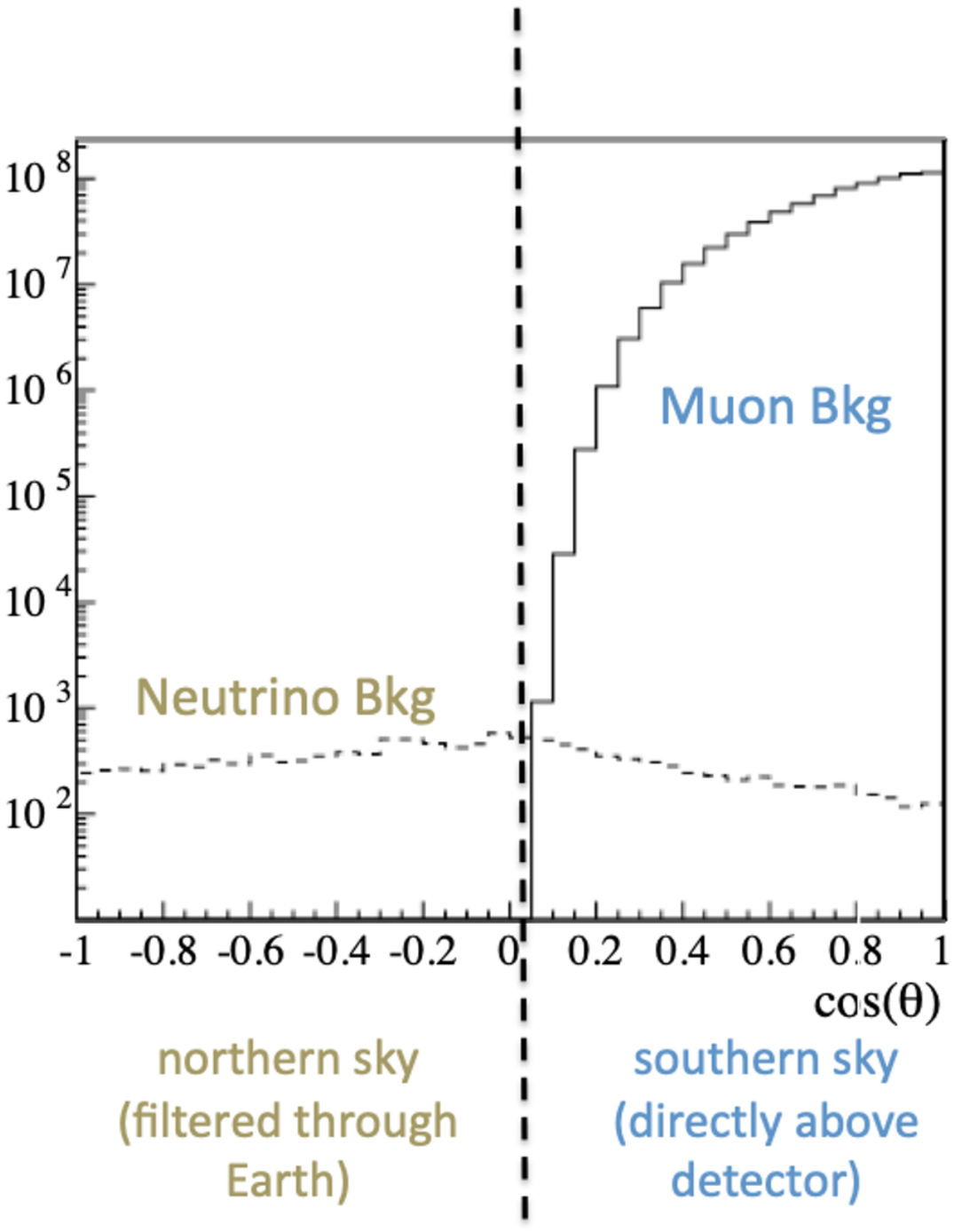
(not observed yet)

Observing charged particles in Ice.

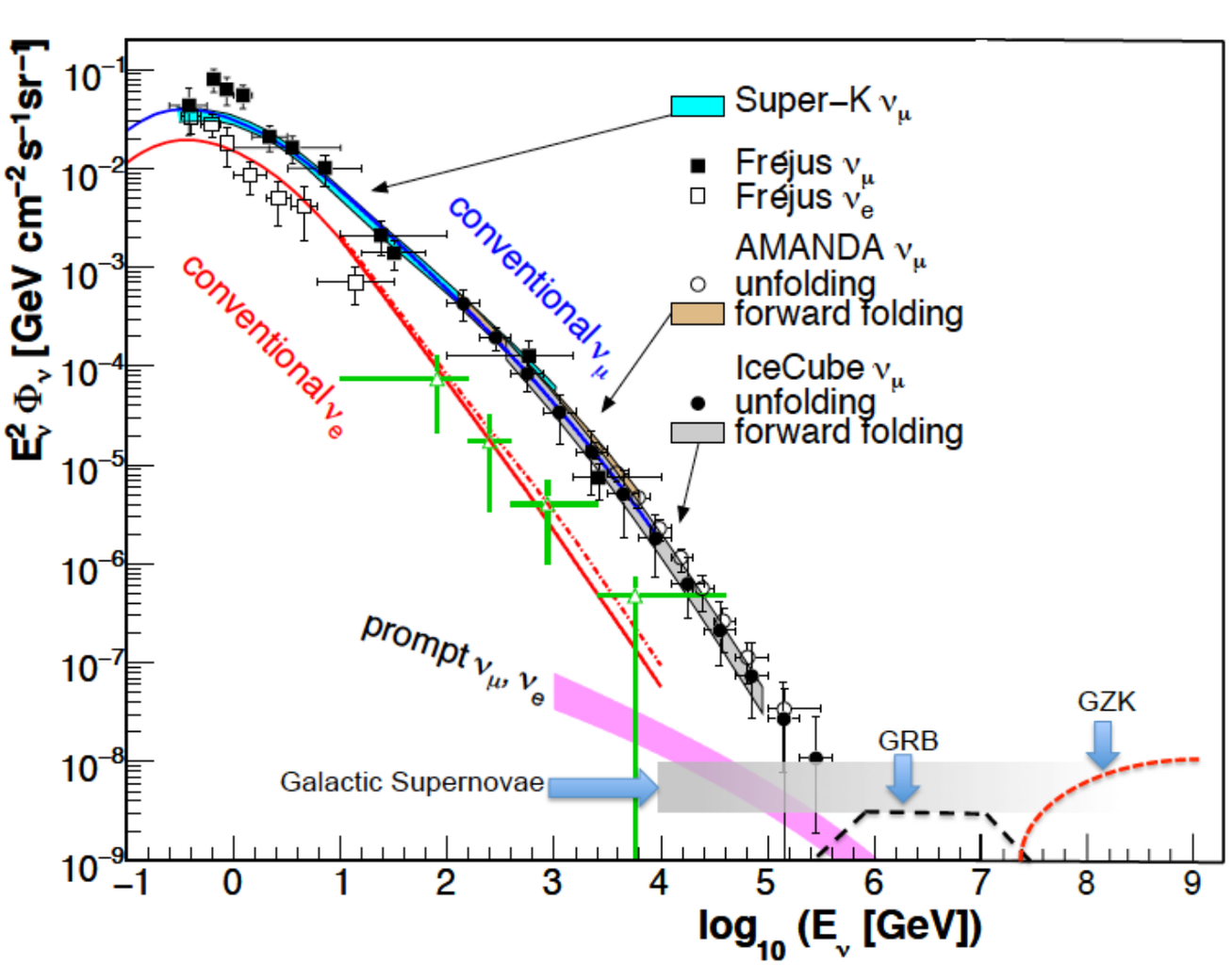


0.01% of all Cherenkov photons generated by a 100 TeV muon in ice.

Identifying Astrophysical Neutrinos

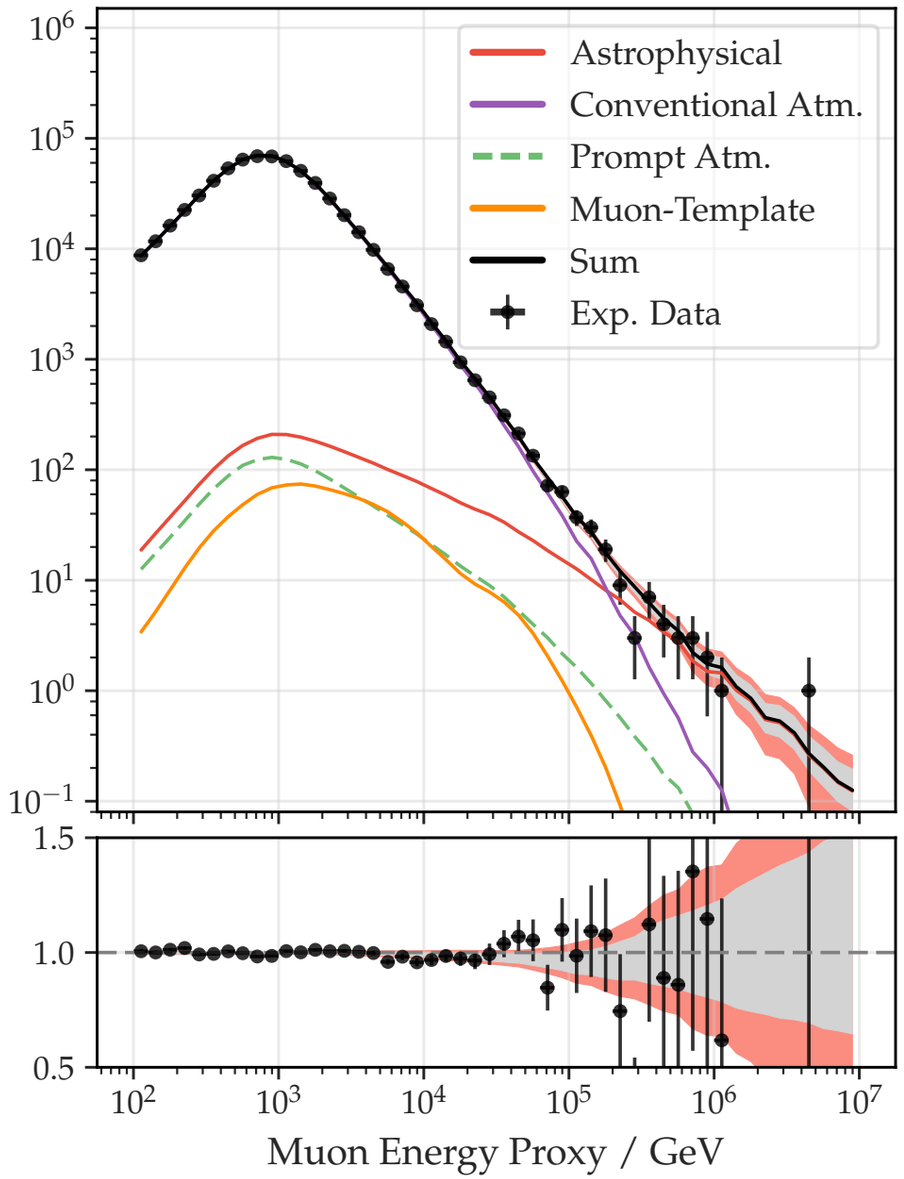


- At lower energies, backgrounds dominate detection
  - Atmospheric muons (Southern hemisphere)
  - Atmospheric neutrinos (Northern hemisphere)
- Prefer high energy events
  - Through-going tracks
  - High-Energy Starting Events



An established diffuse astrophysical neutrino flux

9.5 yr Up-going tracks

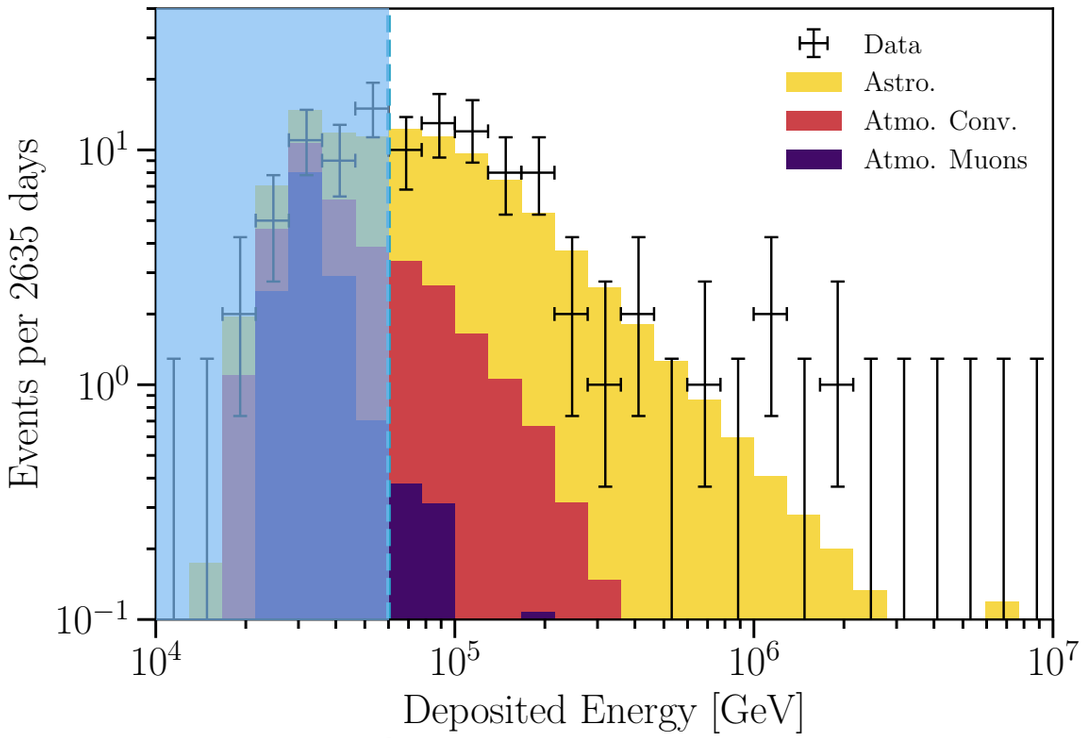


Spectral index: 2.37
Atm-only hypothesis rejected at 5.6σ

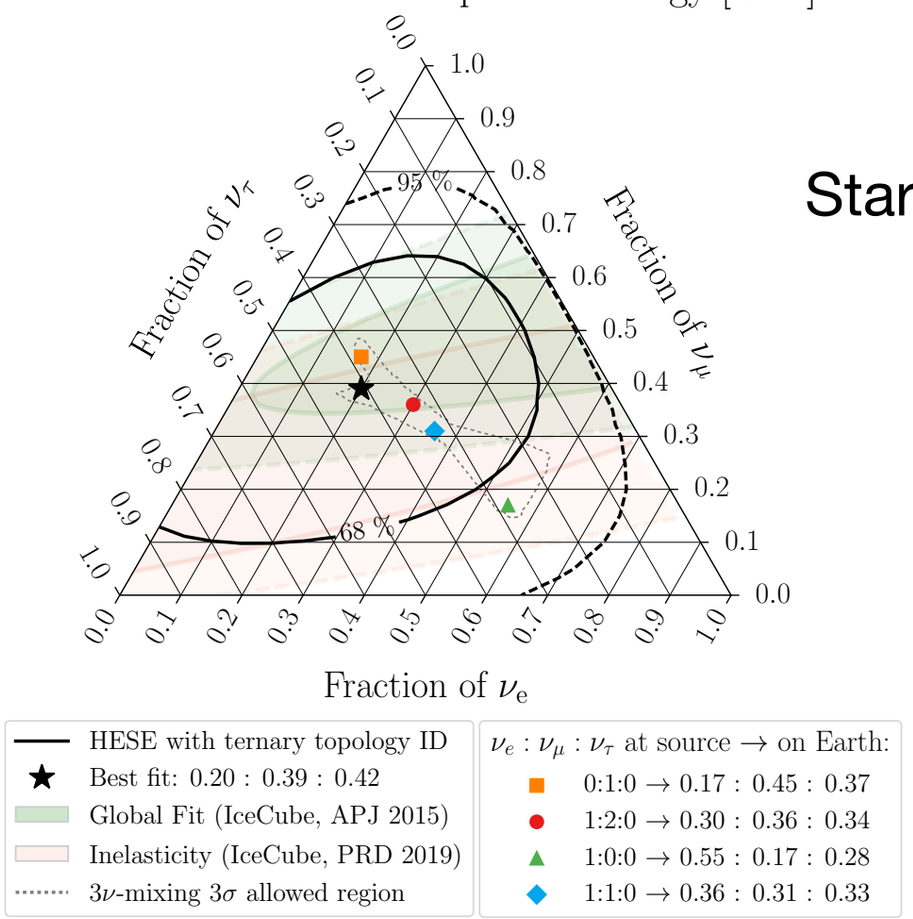
IceCube, Astrophys. J. 928 (2022) 50

7.5 yr Starting tracks

IceCube, Phys. Rev. D 104, 022002 (2021)



Spectral index:
2.87
Atm-only
hypothesis
rejected at >5σ



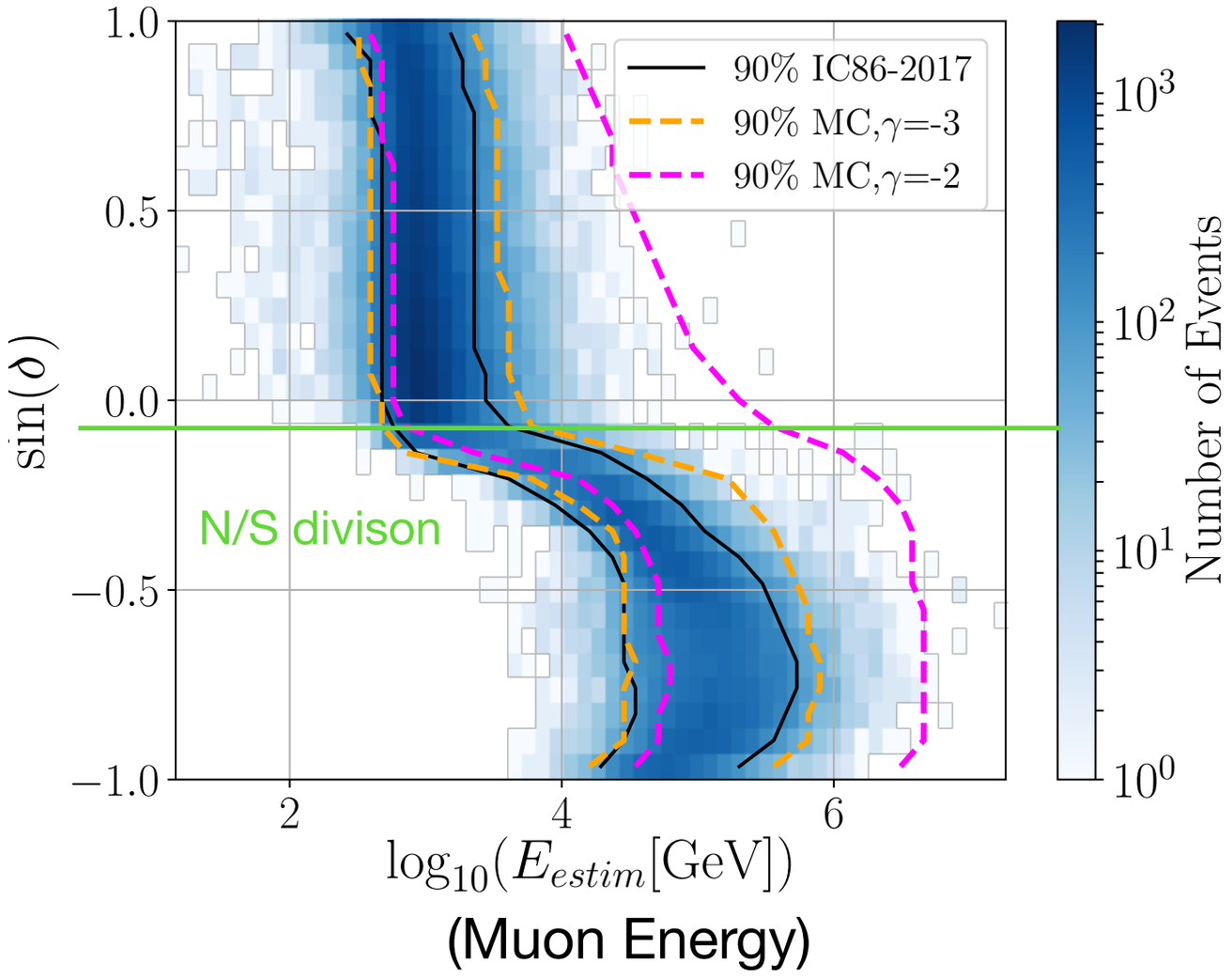
Starting track Taus

Reject no-Tau
hypothesis at 2.8σ

arXiv:2011.03561

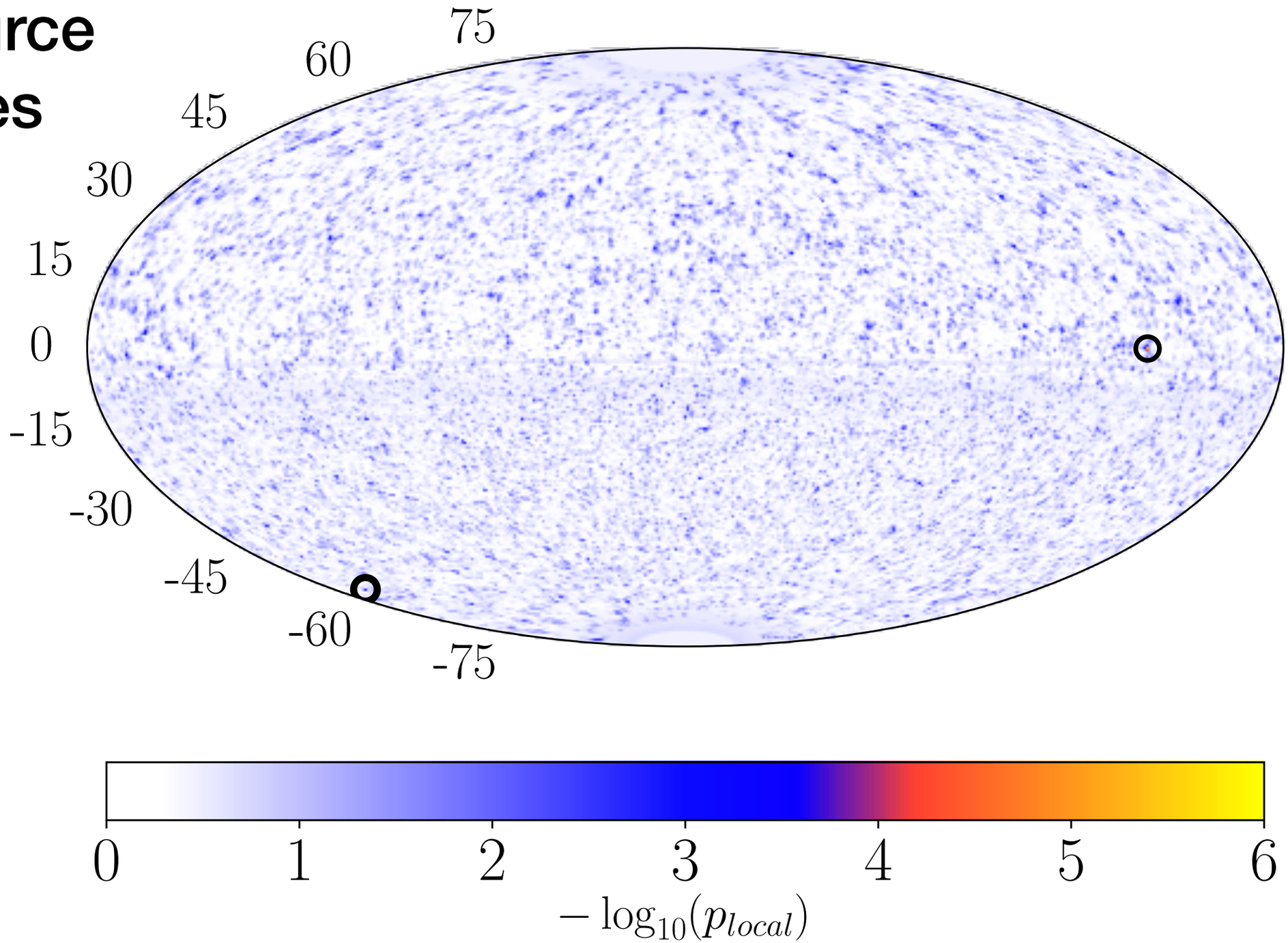
Neutrino events - Tracks

- Through-going muon tracks give preferred for astronomy
  - Best angular resolution and largest effective volumes
- All-sky sensitivity.
  - Different backgrounds in Northern/ Southern skies.
  - Sensitivity to different energies
- South Pole location:
  - Stable operations - 99% uptime
  - Uniform sensitivity at a given declination
  - Efficient: ~100,000 track candidates per year. (~4 mHz)
- Available in ***realtime*** for TOO searches



10 Years of IceCube Point Source data sample

Point Source Searches



Most recent data periods:
~80k northern hemisphere evt/yr (atm ν)
~35k southern hemisphere evt/yr (atm μ)

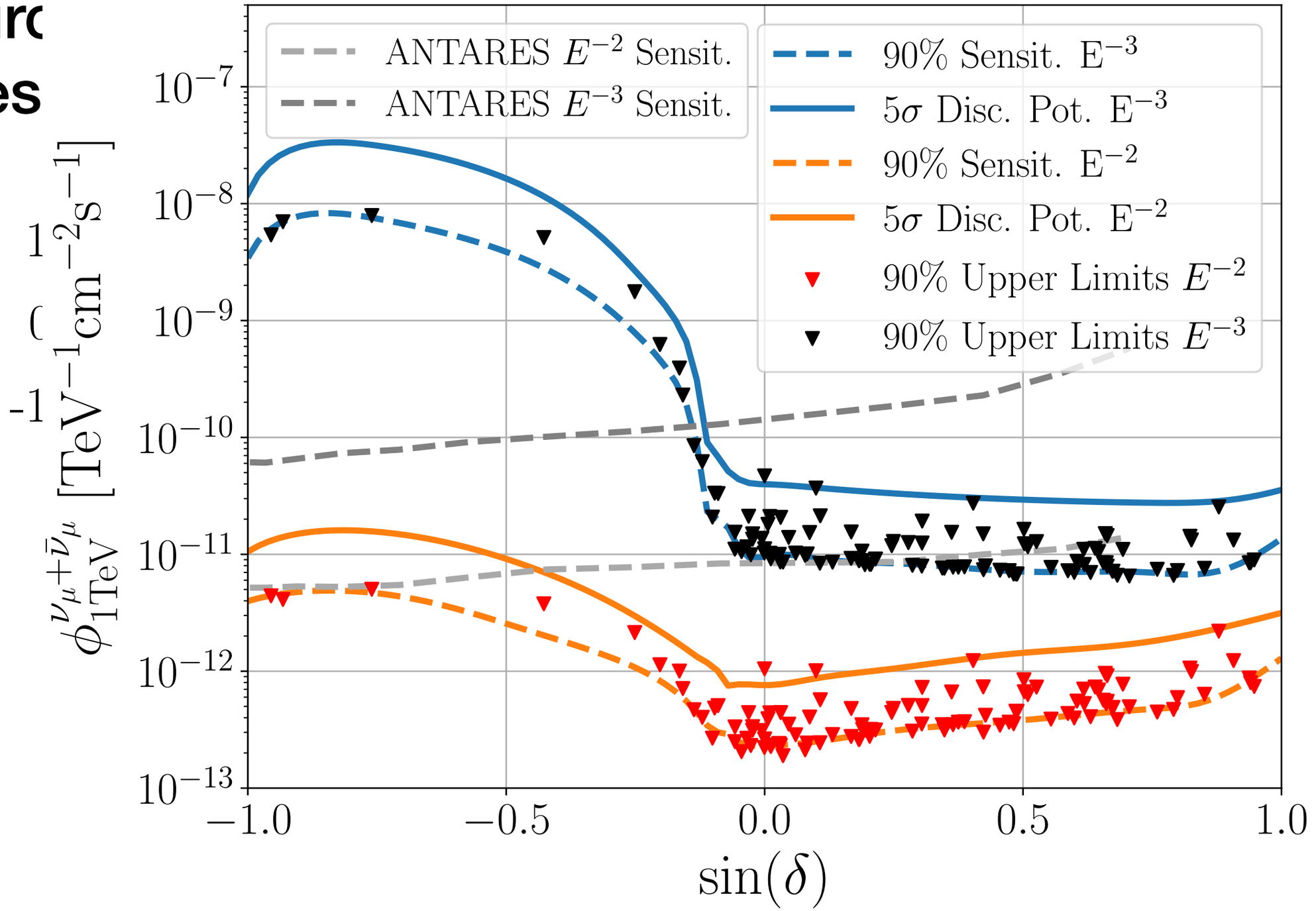
All-sky source search (10 yr data):

-No significant source found (N/S p-values: 0.10/0.75)

-No correlation with list of 74 known HE gamma-ray sources in both hemispheres. Galactic & Extragalactic

IceCube, Phys. Rev. Lett. 124, 051103 (2020)

Point Sourc Searches



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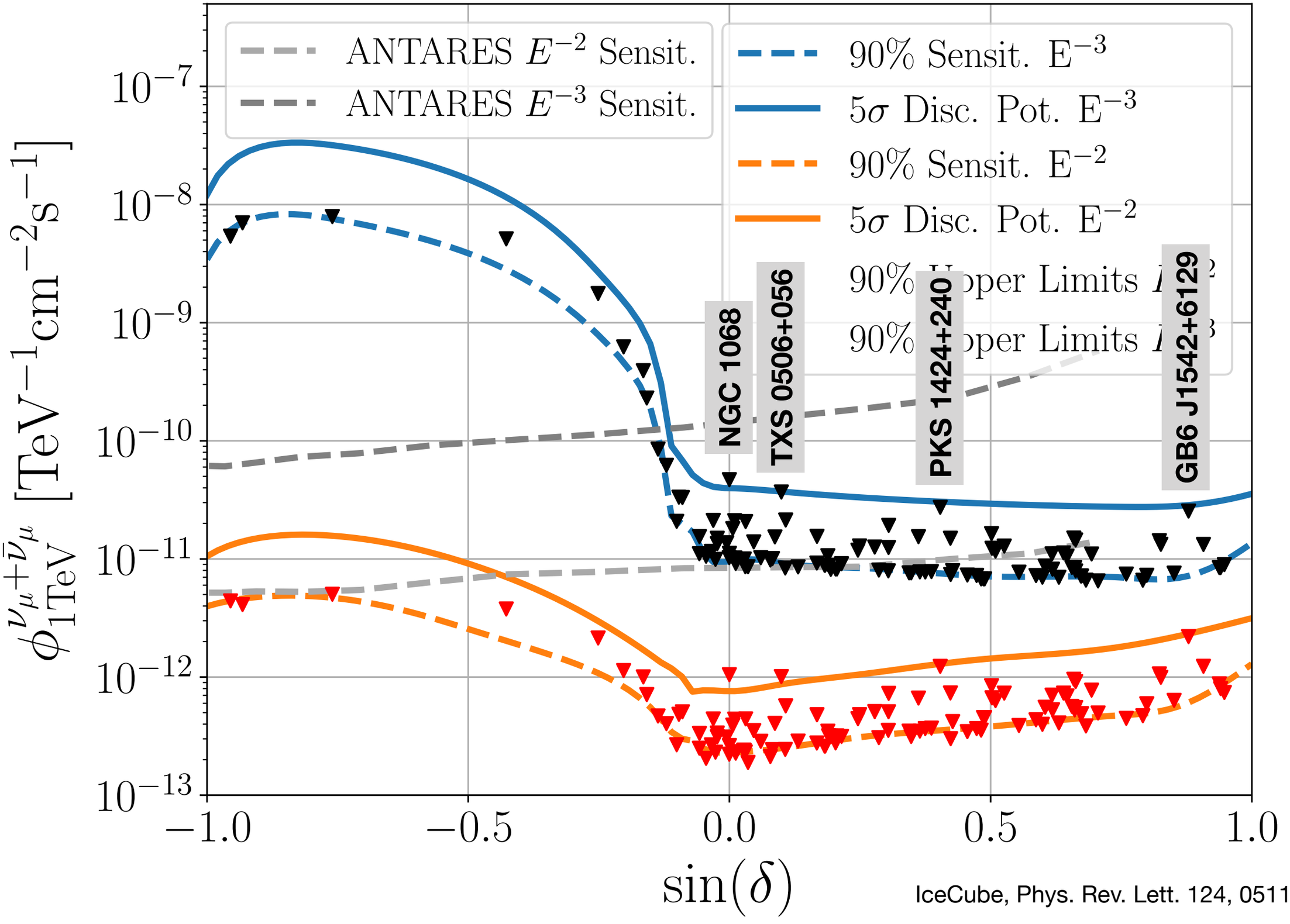
IceCube, Phys. Rev. Lett. 124, 051103 (2020)

Hints of sources after 10 years?

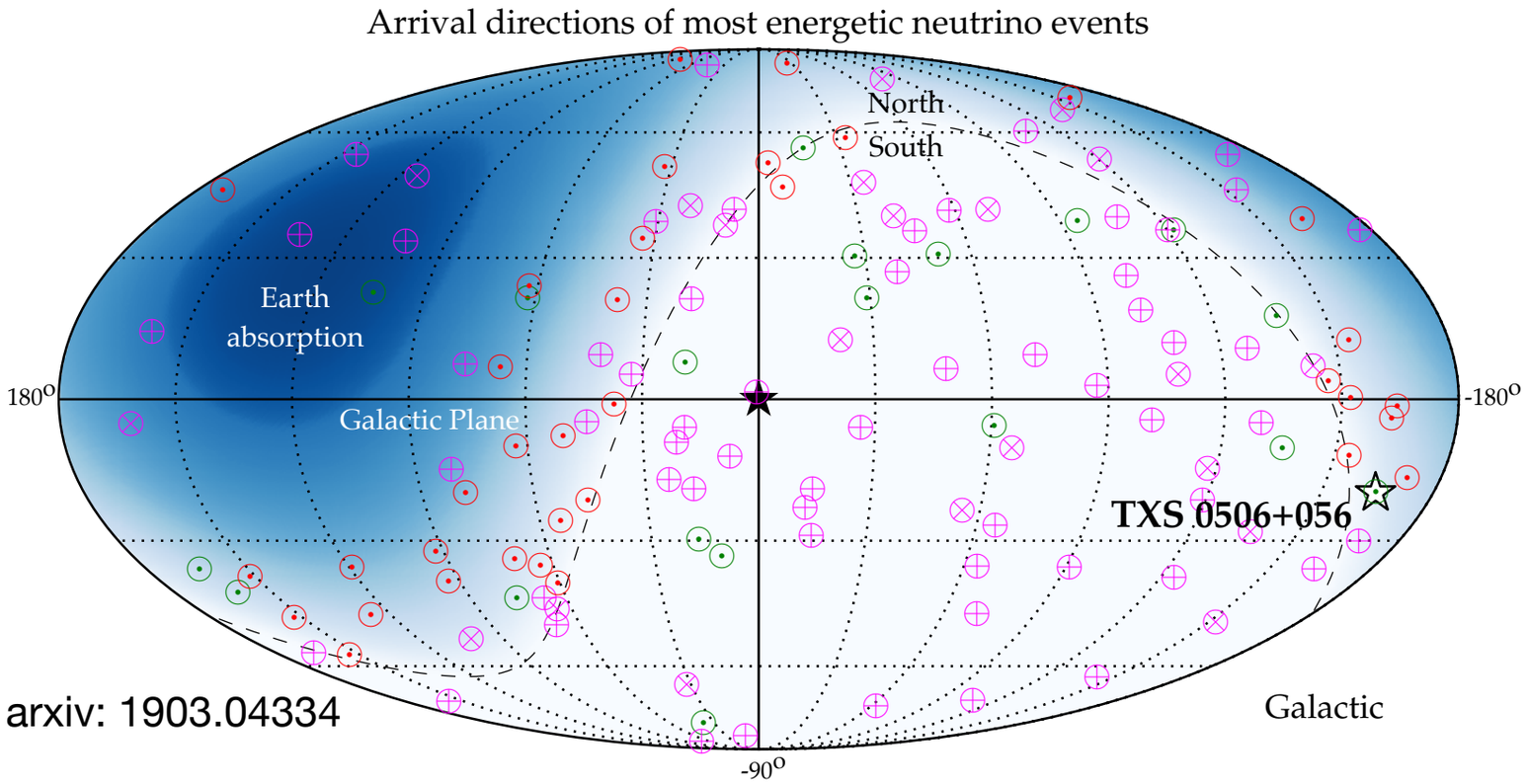


IceCube, Phys. Rev. Lett. 124, 051103 (2020)

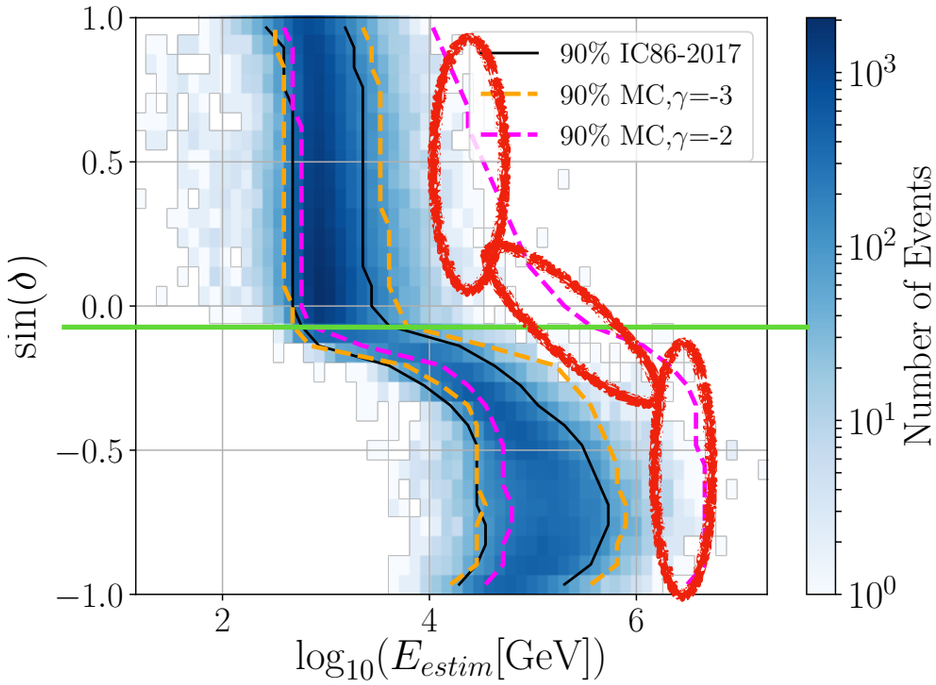
Identifying sources

- While hints of sources starting to appear, no significant (>5σ) evidence yet found for a point source signal in IceCube data alone.
- A multi-messenger strategy is needed:
  - Look for neutrino signals correlated with well-known potential sources
    - Galactic plane or catalogs of known high-energy sources
  - Look in realtime for transient photon signals in correlation with detection of an astrophysical neutrino
    - Realtime neutrino alert program
  - Search in realtime for neutrinos from other transient phenomena
    - TOO searches: Gravitational wave events, etc…

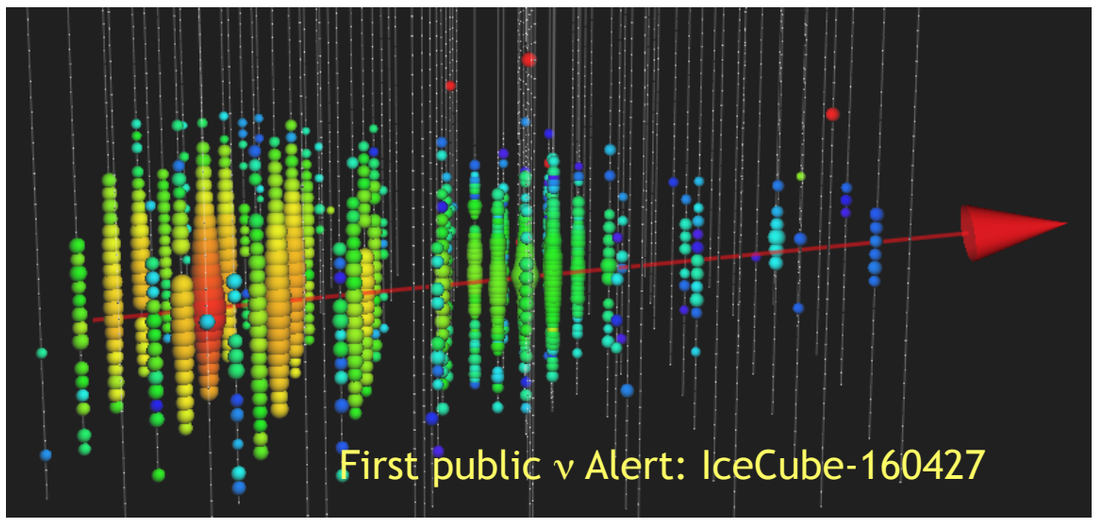
IceCube Astrophysical neutrino alerts



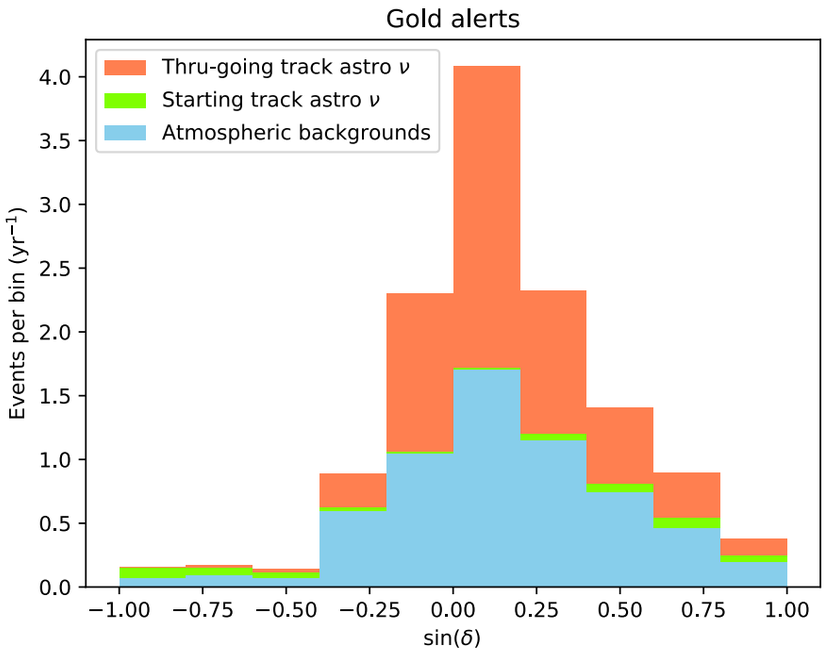
arxiv: 1903.04334

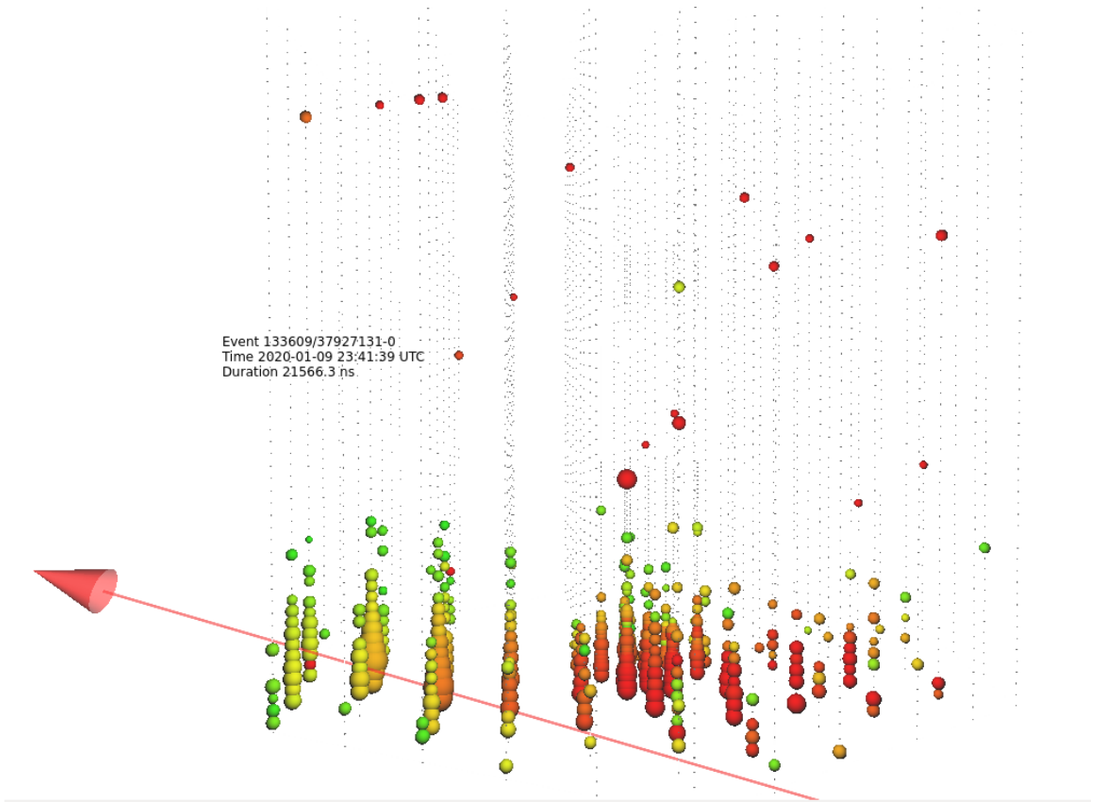


- Identify well reconstructed, high-energy neutrino candidates in real-time
- Transmit them to the North and advertise
    - Latency from detection to alert typically less than 1 minute
- Community observations to search for multi-messenger signals
- In operation since April 2016

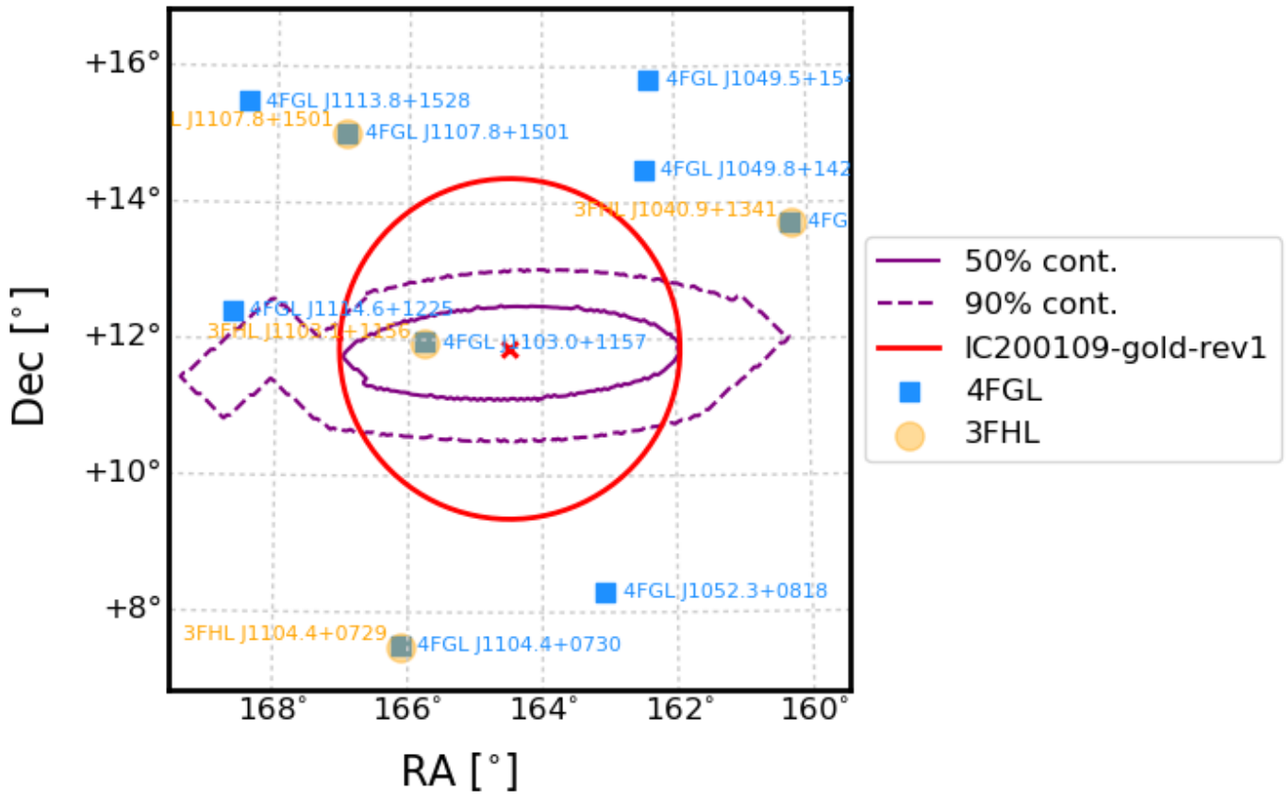


IceCube Realtime Track Alerts





- Expanded and improved alert selection compared to first alert selection
- Targeting starting and through-going tracks
  - Neutrinos with smallest angular uncertainty
- Two selection levels
  - Gold alerts : average 50% likely astrophysical origin
  - Bronze alerts: average 30% likely astrophysical origin
- More alerts per year
  - Gold: 12/yr expected
  - Bronze 18/yr additional expected

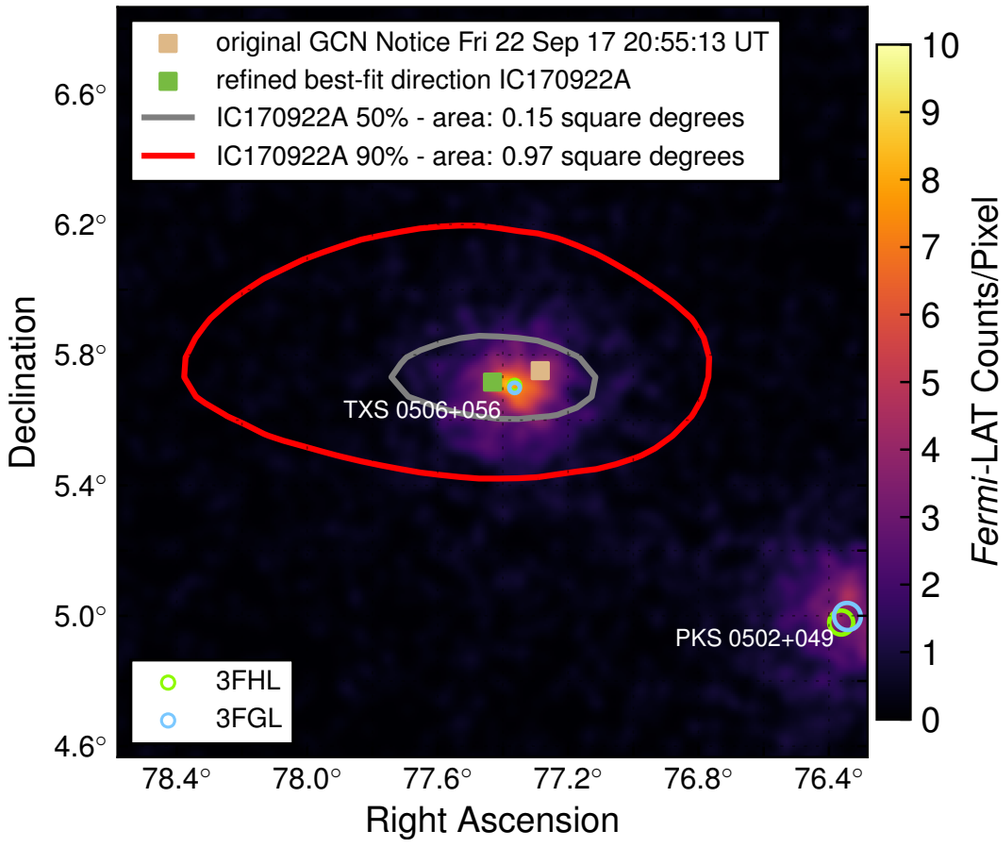


Updated selection active since May 2019

Multi-messenger alerts: TXS 0506+056

On September 22, 2017, IceCube issued a neutrino alert:

- ~290 TeV track alert neutrino (IceCube-170922A)
- Spatially coincident with a known blazar (TXS 0506+056) that was in a flaring state (~3σ significance)
- Blazar was also detected by the MAGIC air-Cherenkov telescope with γ-rays up to 400 GeV.
- Very active multi-messenger follow-up campaign that included observations from radio to γ-rays.



TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE: 17/09/23 01:09:26 GMT
FROM: Erik Blaufuss at U. Maryland/IceCube <blaufuss@icecube.umd.edu>

Claudio Koppe
Maryland) rep
icecube.wisc.

On 22 Sep, 20
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was in a norm
interaction ve
the detector

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845,

Tweet

We searched f
neutrino event
10787) with al
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175, 97). Radi
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http://www.phy

Because Fermi
region will c
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collaboration b
Italy, Japan and

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

Tweet Recommend 448

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays are measured from a direction consistent with a detected neutrino event. Several follow up observations from other observatories have been reported in ATels: #10773, #10787, #10791, #10792, #10794, #10799, #10801, GCN: #21941, #21930, #21924, #21923, #21917, #21916. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) E. Bernardini (elisa.bernardini@desy.de), K.Satalecka (konstancja.satalecka@desy.de). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

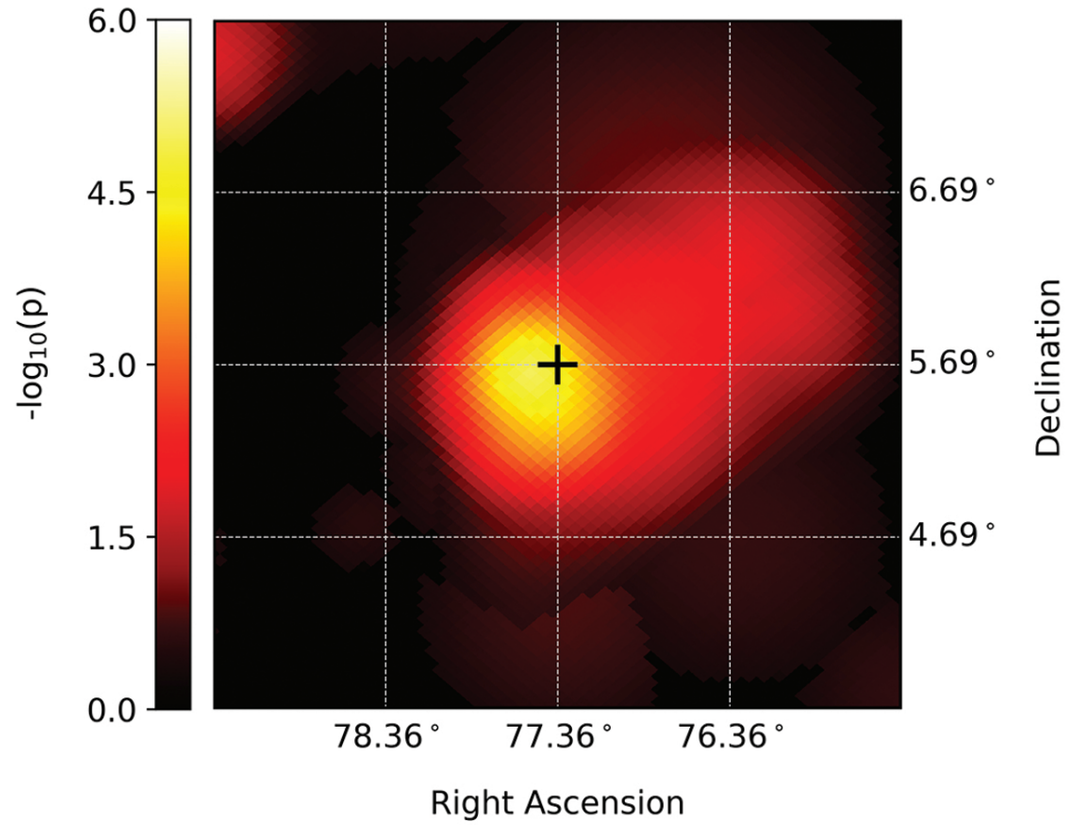
Published: Science 361 (2018)

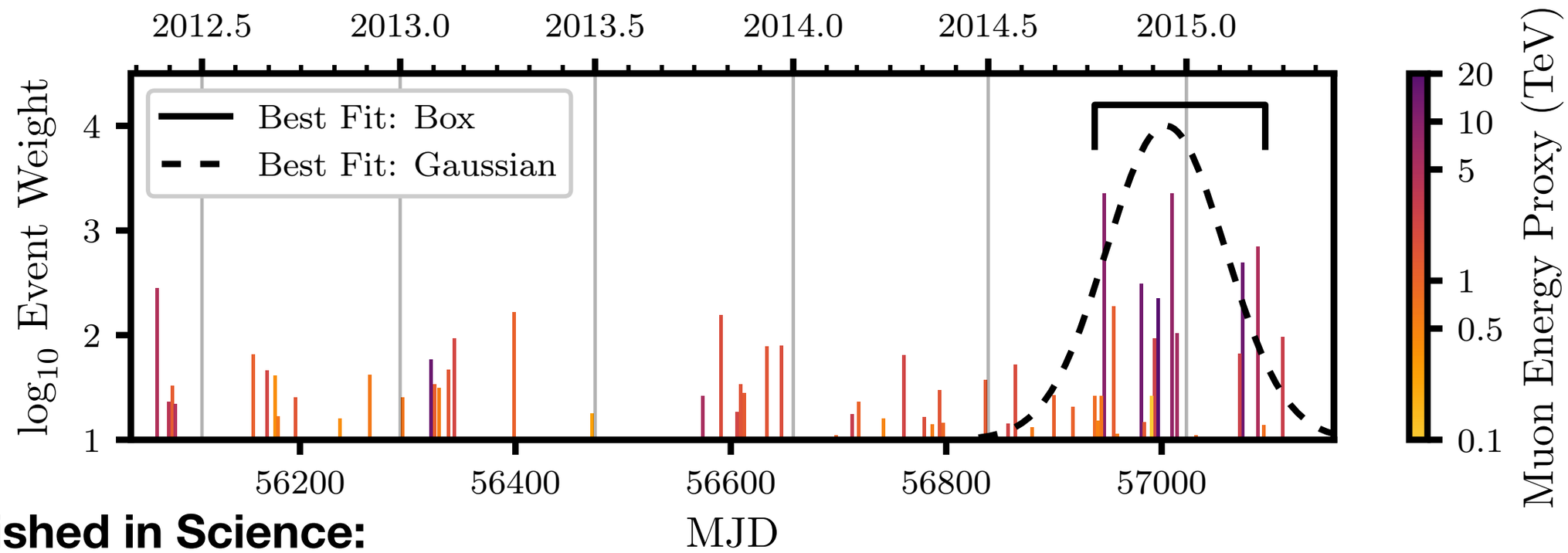
IceCube point source search: TXS 0506+056

Based on the neutrino alert - performed a search of historical neutrino track events

Evidence of time-dependent emissions is observed:

- September 2014 - March 2015
  - Independent of, and prior to neutrino alert
- 3.5σ excess over expected background
- 13 ± 5 events over background



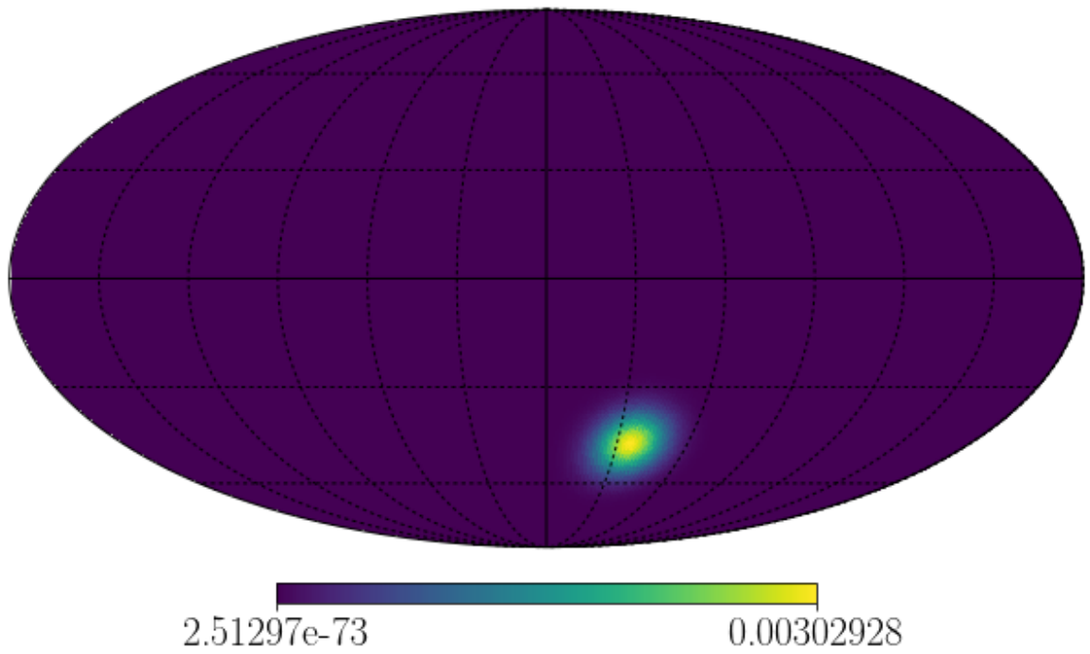


Published in Science:
IceCube Coll. Science 361 (2018) 147

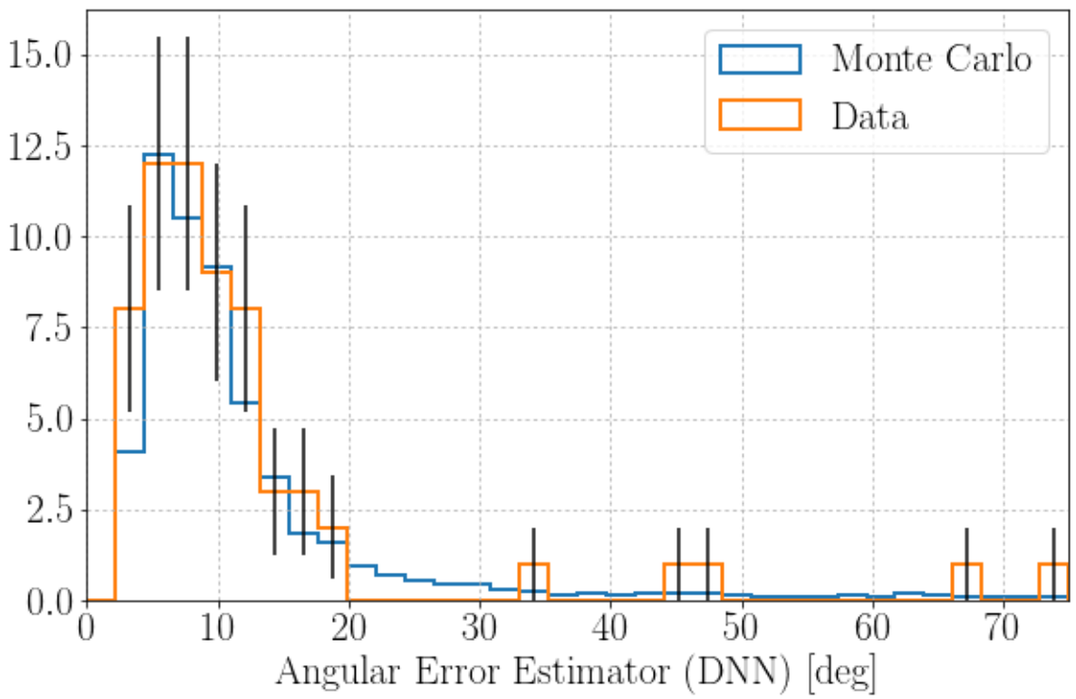
Alerts from Cascades

New Cascade neutrino alert stream added to GCN in July 2020

- Dominated (~85%) by astrophysical neutrinos
- Novel DNN tools used for event reconstruction
- Skymap probability maps published with GCN alert as FITS files



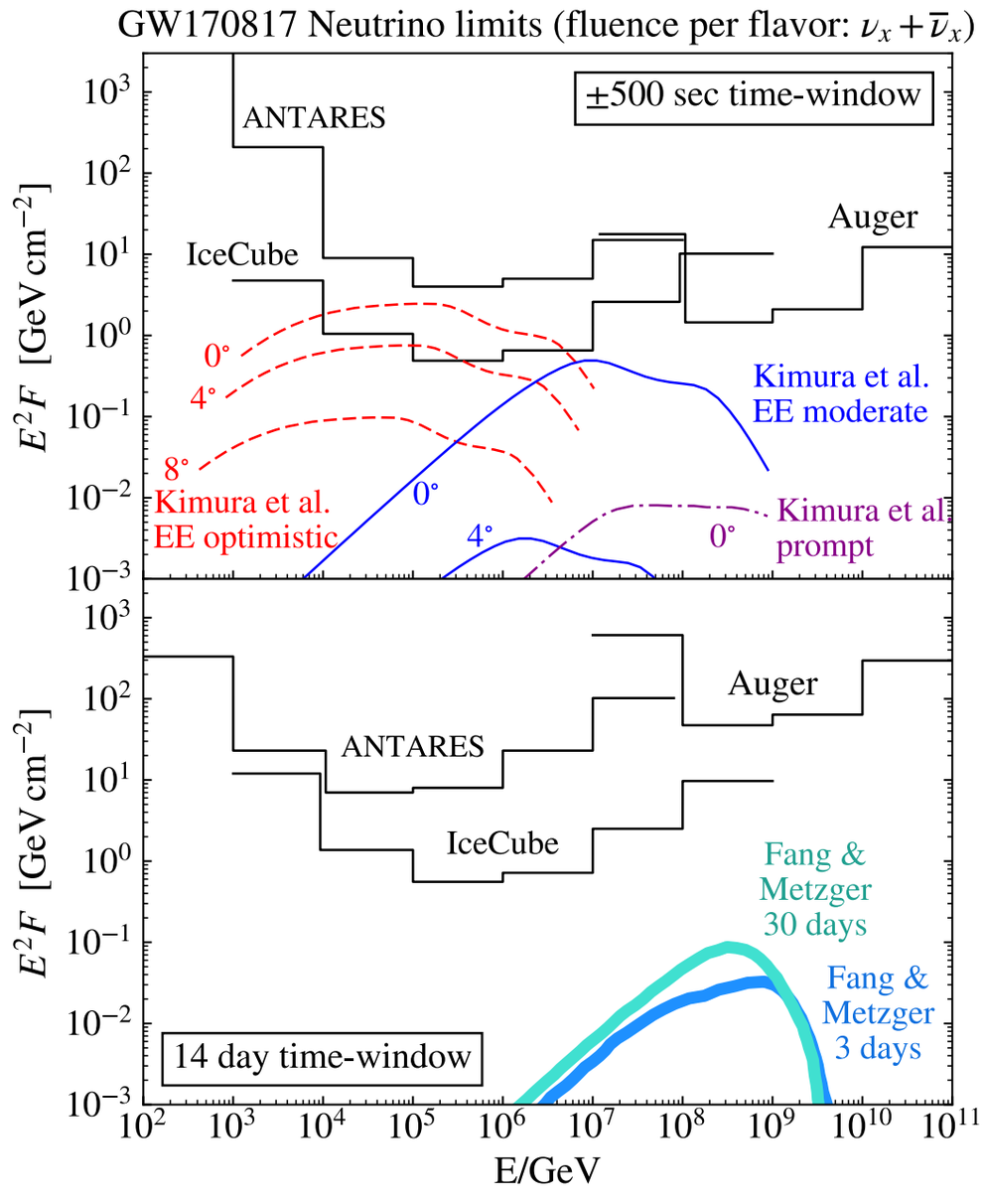
		Number of events/year	Proportion
Astrophysical	Cascades	6.7	85%
	Tracks	0.1	1%
	Total	6.8	86%
Atmospheric	Neutrinos	1.1	14%
	Muons	0.0	0.0%
Total Monte Carlo		7.9	100%
Data		8.1±1.0	

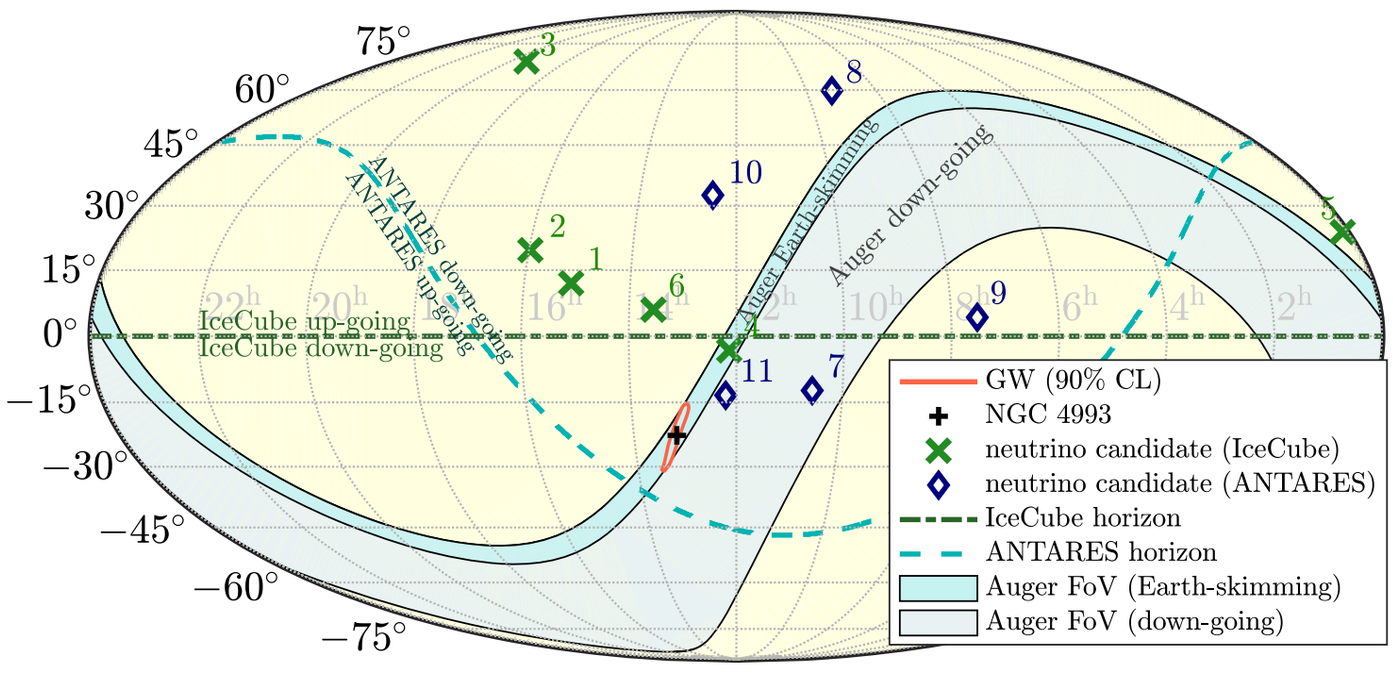


GCN High Energy Cascade Alert Documentation

TOO search: Neutrinos from gravitational wave events with IceCube

- High-energy neutrinos can provide important information:
  - Coincident detection could reduce localization uncertainty and aid follow-up optical source searches
  - Provide understanding of particle acceleration and high-energy emission from compact objects
- Plans to search in realtime for neutrinos in Run O4 now in development





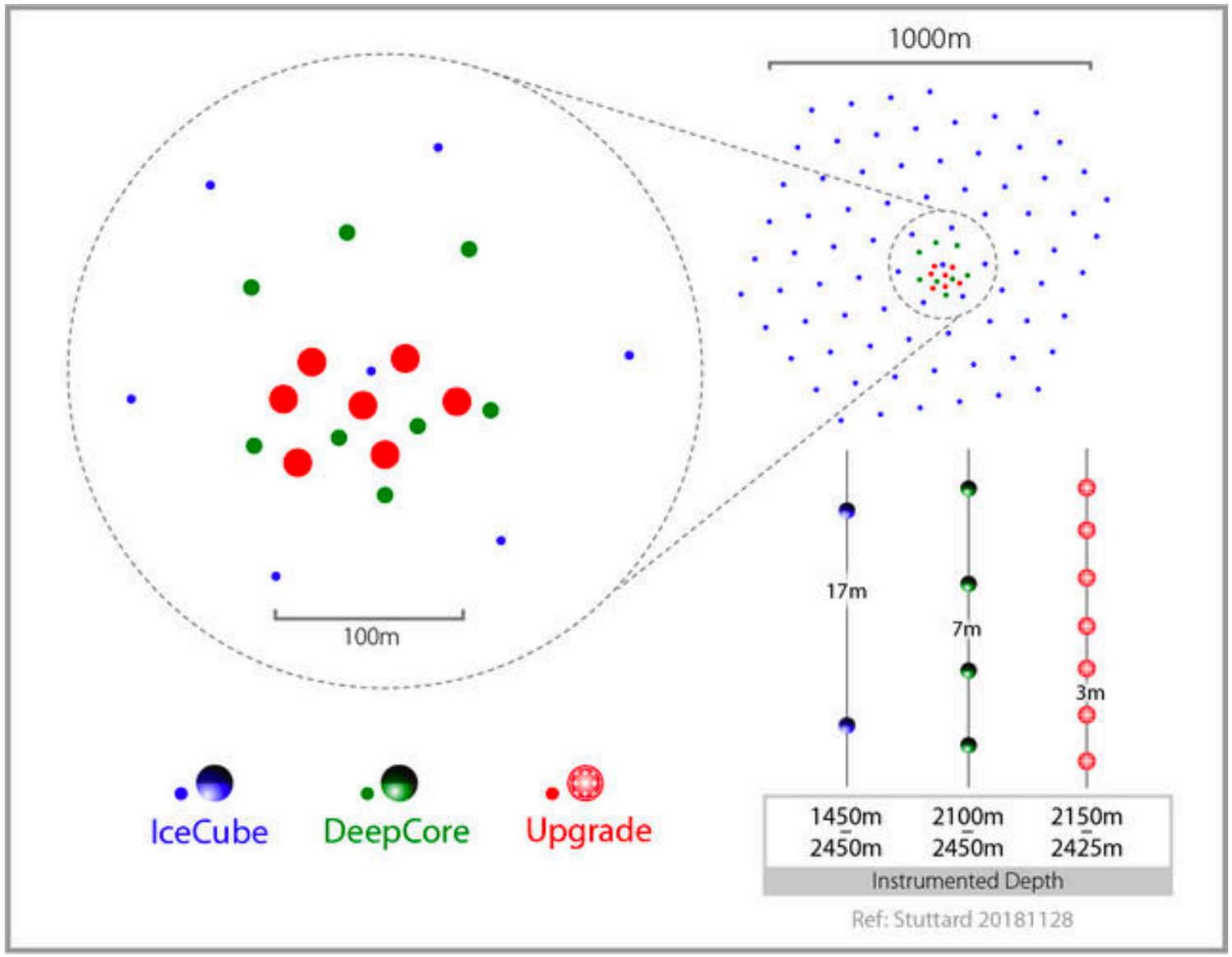
Astrophys.J. 850 (2017)

Challenges for multi-messenger neutrino astrophysics

- Neutrino detection backgrounds
    - Most alerts, especially tracks, have a chance of being of atmospheric origin
    - “Signalness” depends on an assumed spectral index for the neutrino signal.
- Source confusion
    - IceCube angular resolution is typically poorer than most photon observations. Can lead to significant source confusion for a single event
    - Neutrinos have small cross sections, single events can arrive from large redshifts
- Model confusion
    - Some models predict that neutrinos should be favored from obscured sources
        - Target material responsible for neutrinos obscures gamma-rays. (Murase+, Fang+, others..)
- High energy astrophysical neutrinos are rare, even in a km^3 detector!

Upgrade plans

- Two-tier effort
  - IceCube Upgrade - funded
    - Focus on improved calibration and low energy neutrino physics
    - Test new technologies
    - Deployment now 2025/26
- IceCube Gen2
  - Focused on larger samples of astrophysical neutrinos over a wide energy range

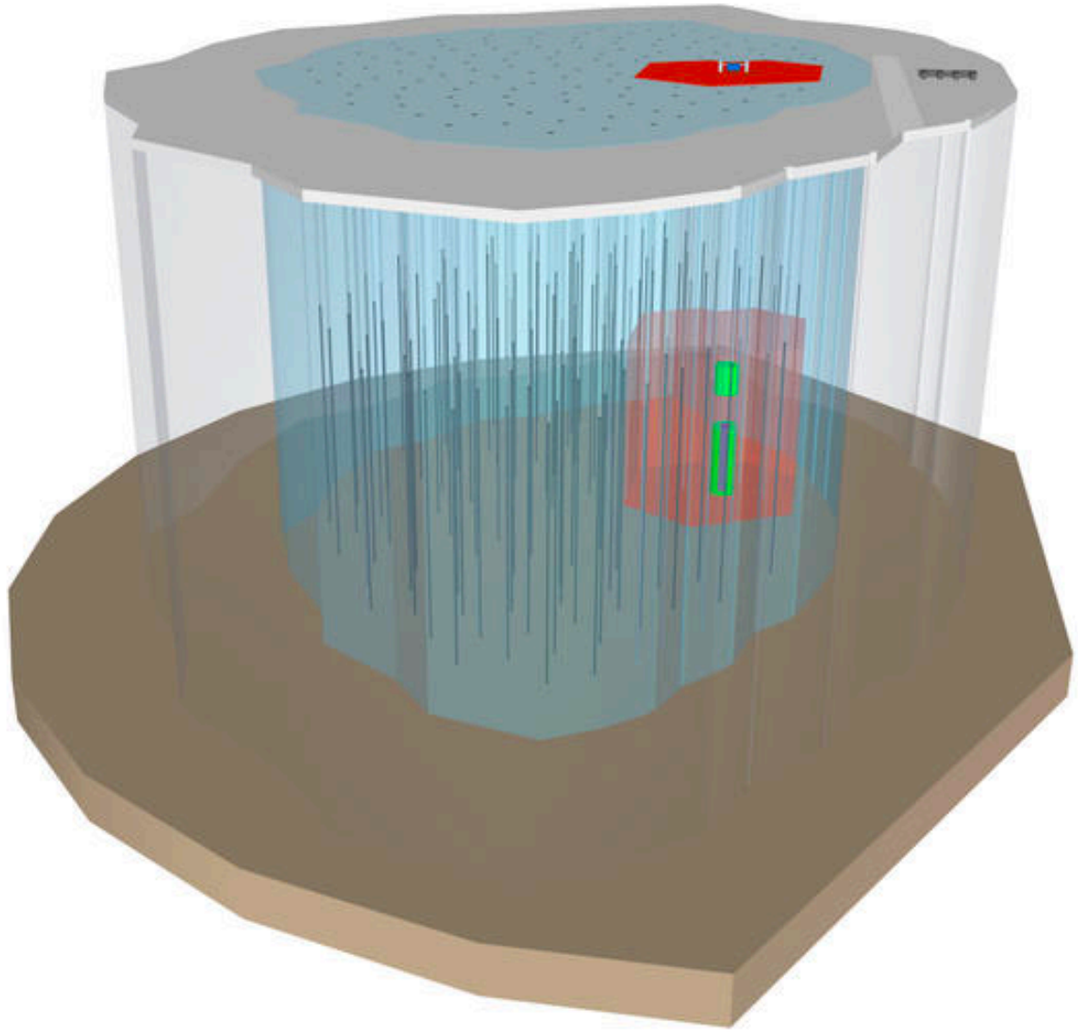


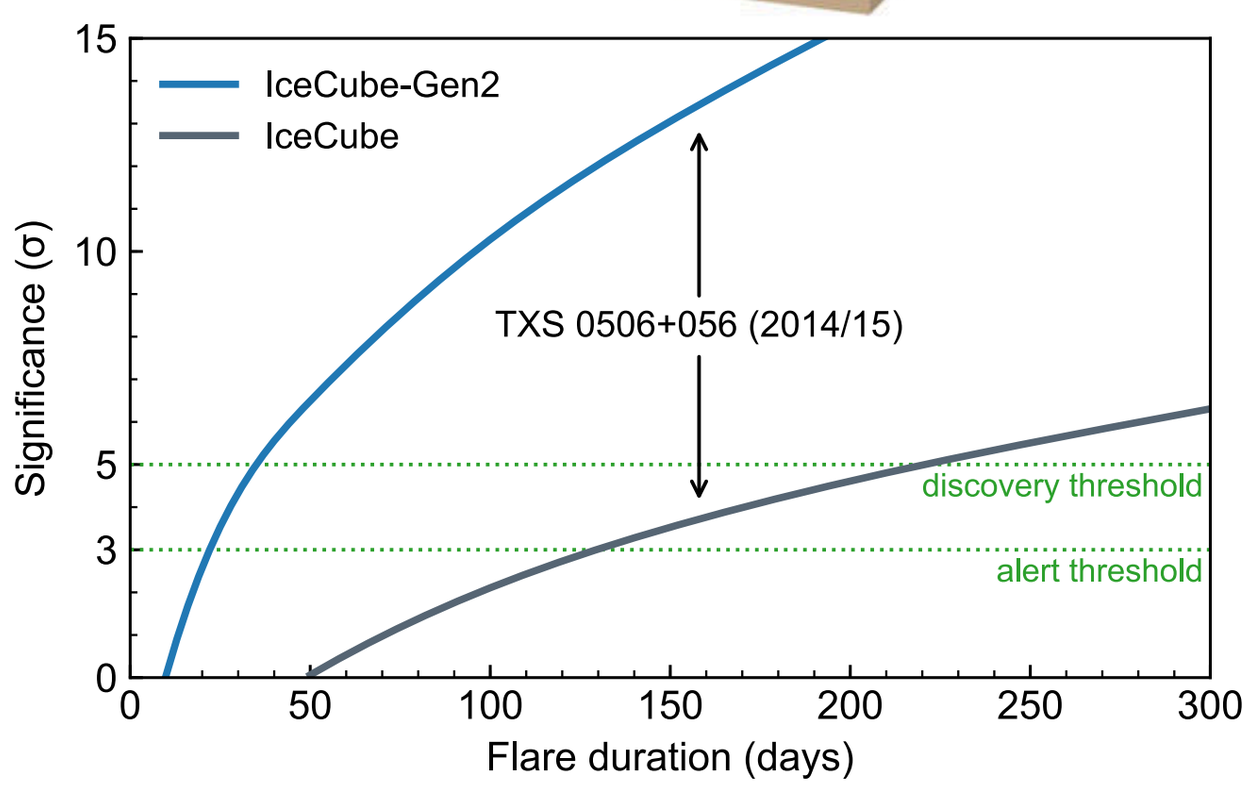
IceCube Upgrade

Ice is stable: Able to reprocess decade+ of neutrinos with improved analyses and systematics

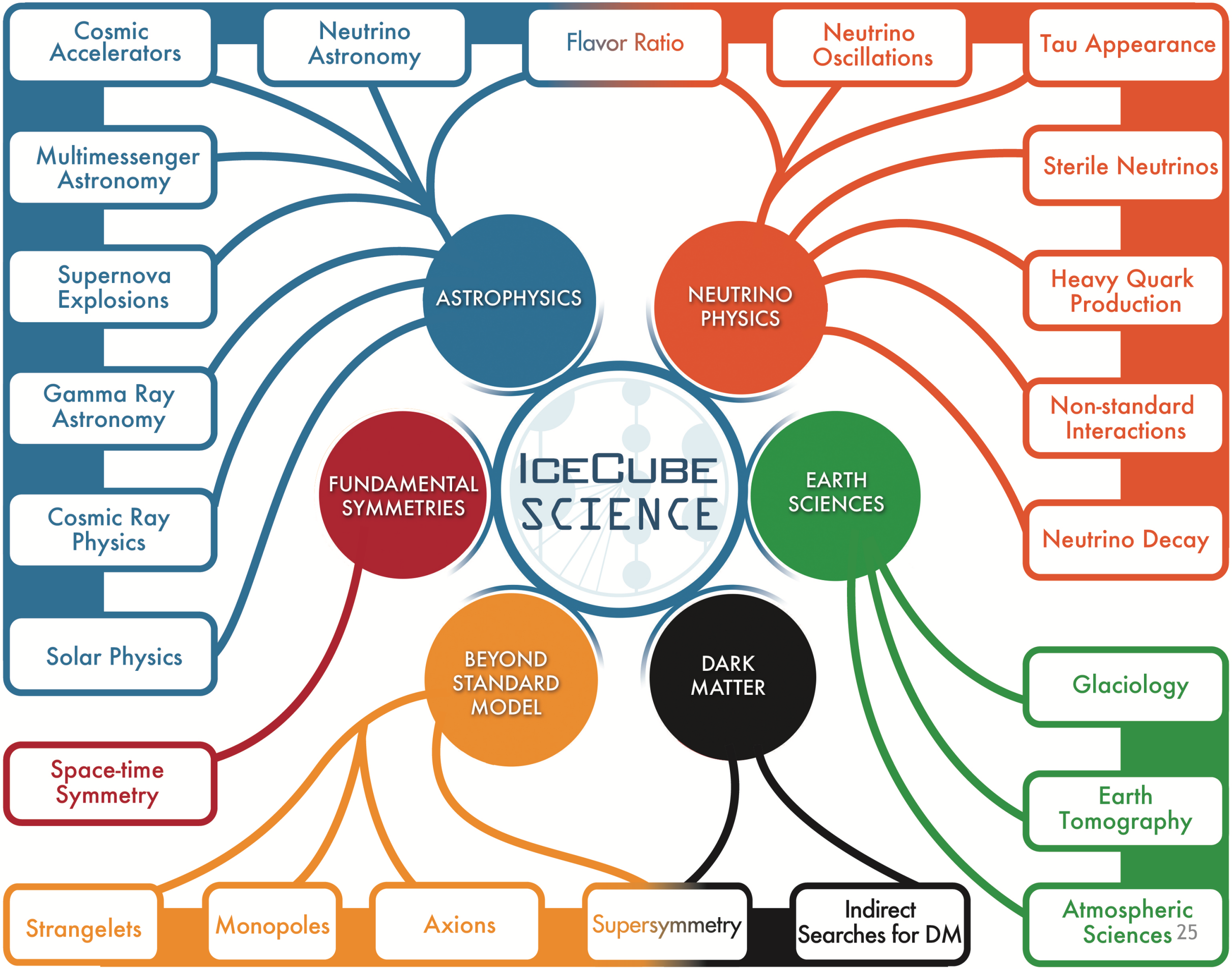
IceCube Gen

- Looking forward, to get larger and better samples of astrophysical neutrinos, a larger detector is needed
- Envision a wide-band neutrino observatory
  - 8-10 x larger optical Cherenkov detector
    - Neutrino astronomy and multi-messenger astrophysics
  - Askaryan radio detector array
    - Probe neutrinos beyond EeV energies
  - Surface particle detector
    - Detailed cosmic ray spectrum and composition measurements and veto capabilities





arXiv:2008.04323


Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Multimessenger Astronomy
Sterile Neutrinos
Supernova Explosions
Heavy Quark Production
Gamma Ray Astronomy
Non-standard Interactions
Cosmic Ray Physics
Neutrino Decay
Solar Physics
ASTROPHYSICS
NEUTRINO PHYSICS
FUNDAMENTAL SYMMETRIES
ICECUBE SCIENCE
EARTH SCIENCES
BEYOND STANDARD MODEL
DARK MATTER
Glaciology
Space-time Symmetry
Earth Tomography
Strangelets
Monopoles
Axions
Supersymmetry
Indirect Searches for DM
Atmospheric Sciences

Summary

- Over more than 10 years of operation, IceCube has developed strong evidence for an astrophysical flux of neutrinos
    - While first hints for sources (TXS 0506+056, NGC 1068,…) are developing, no overwhelming evidence in neutrinos alone
- IceCube has developed a strong multi-messenger component
    - Realtime alerts: High energy tracks and cascade to community
        - Have delivered some interesting and tantalizing correlations.
    - TOO neutrino searches following interesting alerts in other messengers.
- Coming next: IceCube Upgrade and the path toward IceCube Gen2

The future looks bright for Neutrino Astronomy!

Thanks!

THE ICECUBE COLLABORATION

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Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

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University of Copenhagen

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Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
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US National Science Foundation (NSF)

IceCube South Pole Neutrino Observatory

icecube.wisc.edu

Weather for South Pole Station

Today is Saturday, July 4th 12:32am

Temperature

-78.3 °C -108.9 °F

Windchill

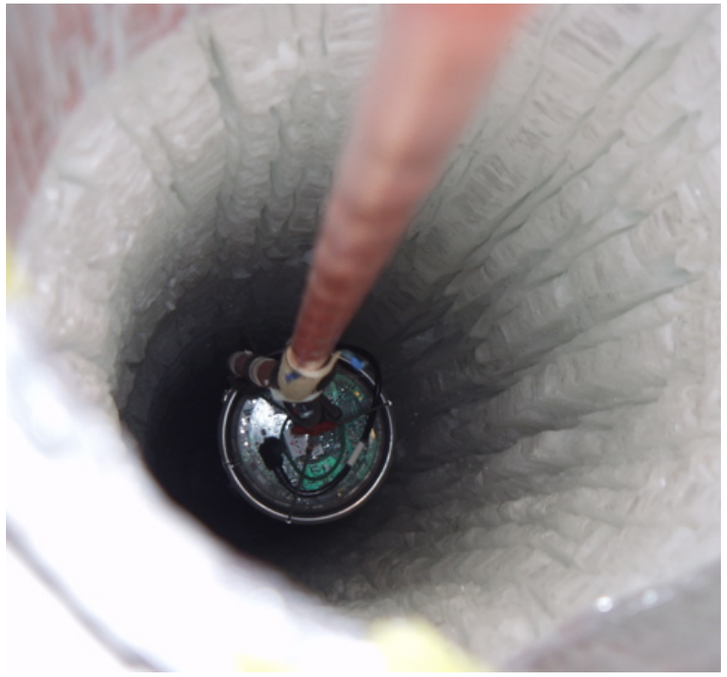
-108.8 °C -163.9 °F

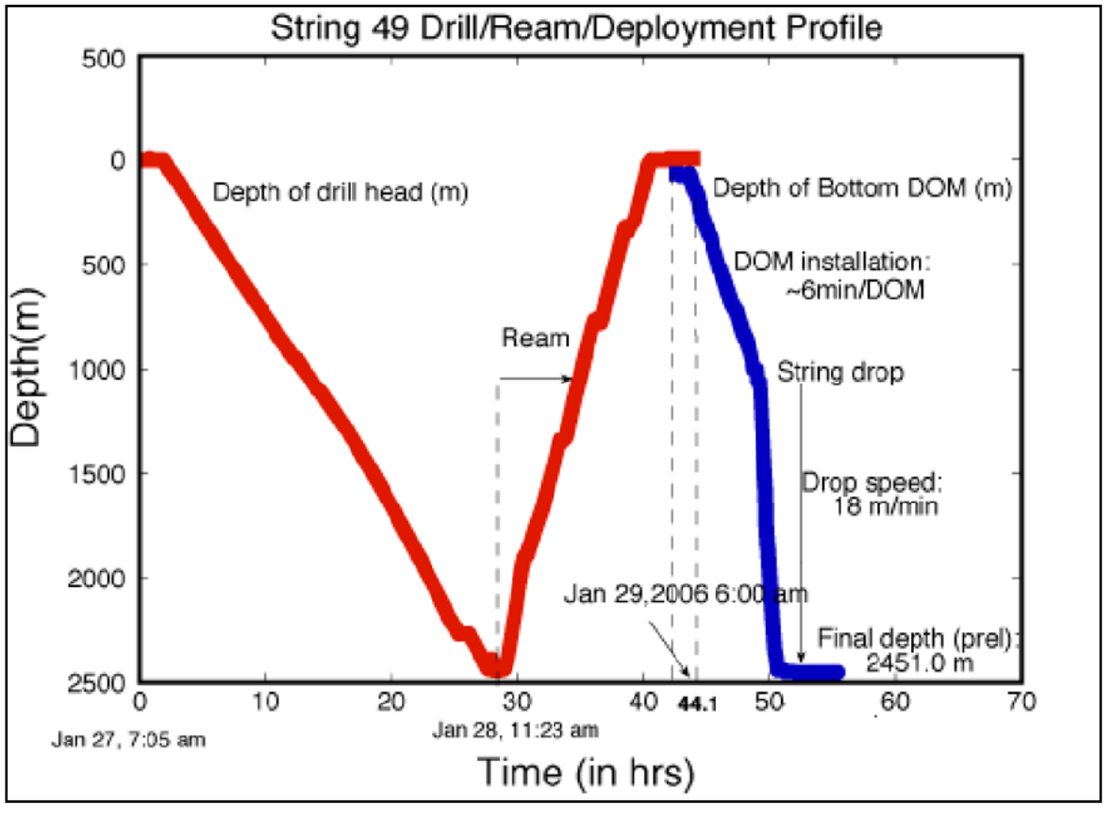
Wind

16.6 kts Grid 143

Barometer

671.3 mb (3,340 m/10,958 ft)




String 49 Drill/Ream/Deployment Profile
Depth of drill head (m)
Depth of Bottom DOM (m)
DOM installation:
~6min/DOM
Ream
String drop
Drop speed:
18 m/min
Jan 29,2006 6:00 am
Final depth (prel):
2451.0 m
Depth(m)
Time (in hrs)
Jan 27, 7:05 am
Jan 28, 11:23 am
44.1
500
0
500
1000
1500
2000
2500
0
10
20
30
40
50
60
70