Recent results from the IceCube Neutrino Observatory and the prospects for IceCube-Gen2

Erik Blaufuss
Brookhaven National Lab
Colloquium
March 12, 2024

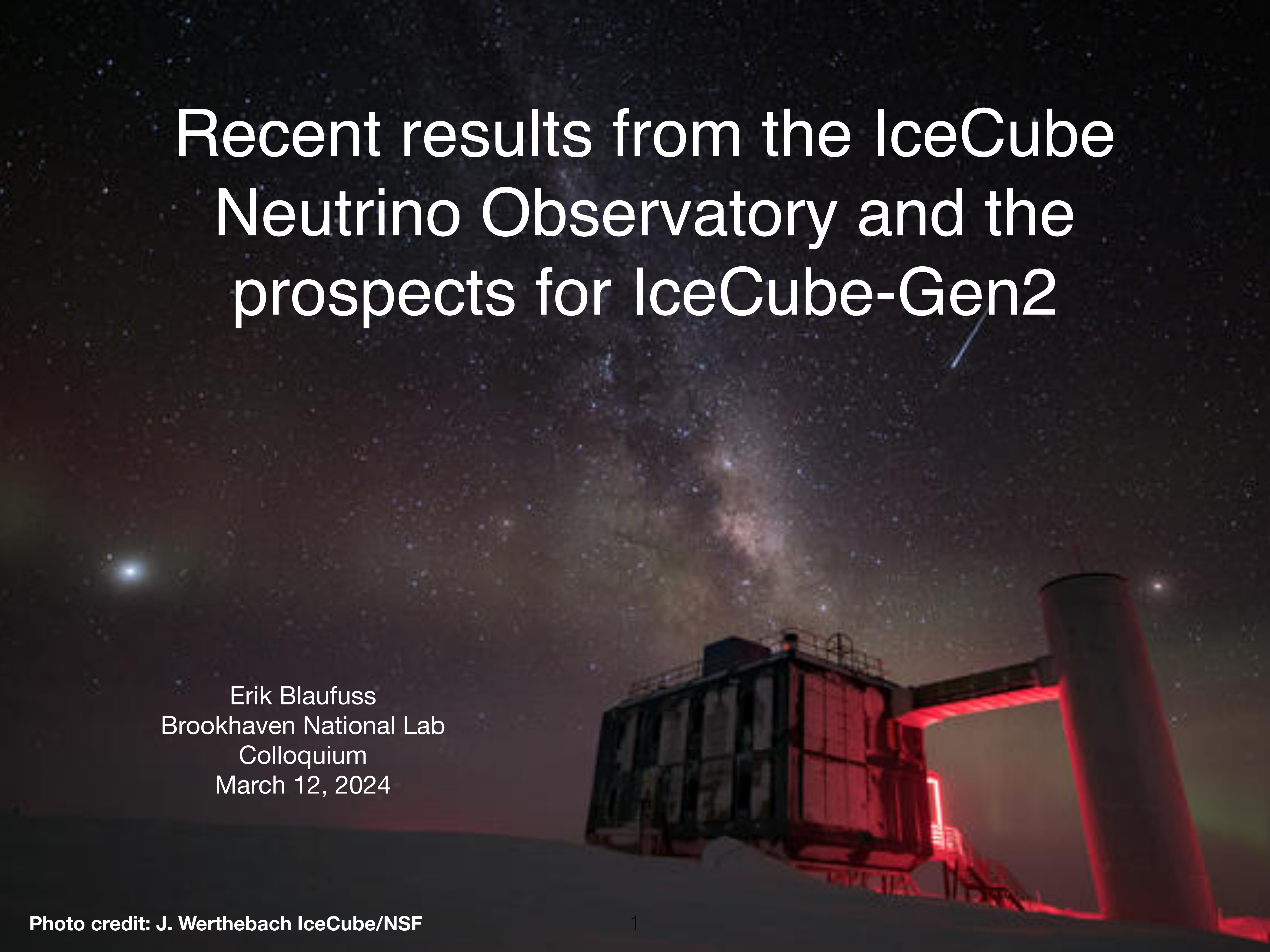
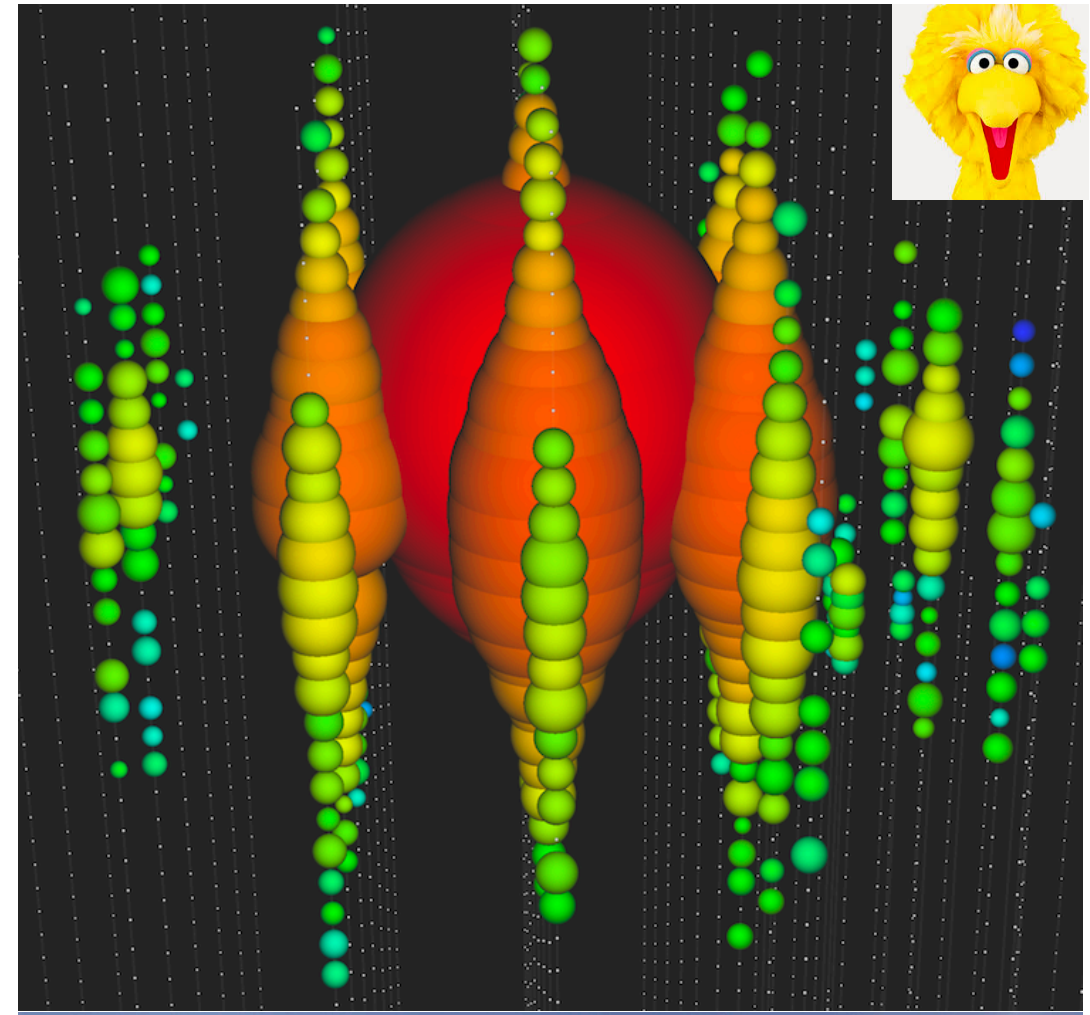


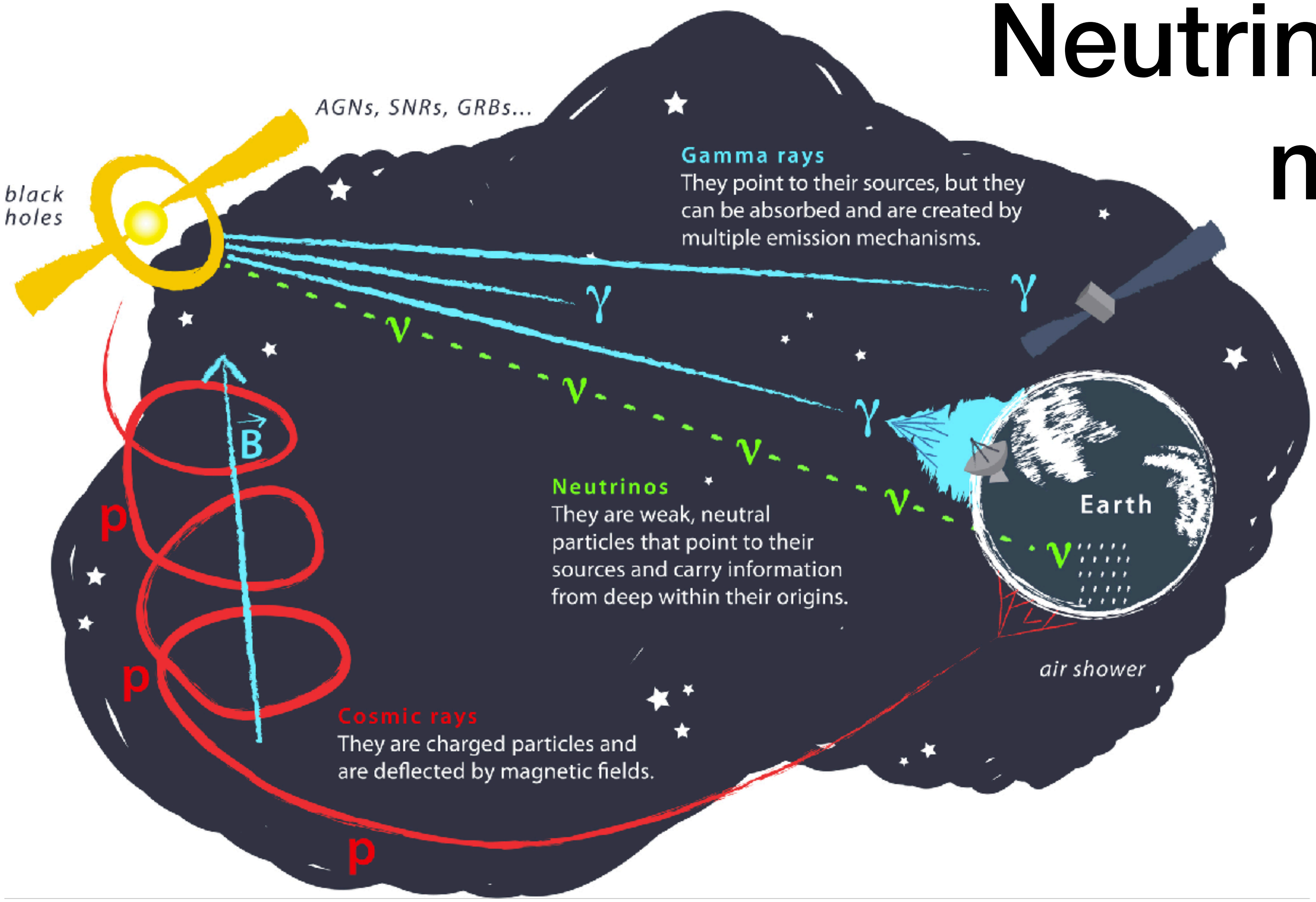
Photo credit: J. Werthebach IceCube/NSF

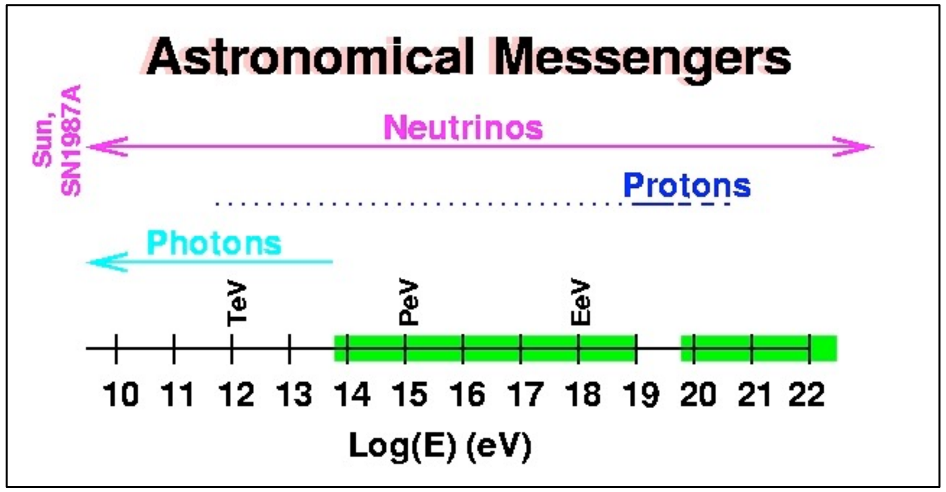
IceCube Astrophysical neutrinos

- Over a decade ago, IceCube announced the discovery of astrophysical high-energy neutrinos.
  - Many questions still remain!
- Today I'll cover:
  - What is IceCube and how does it work?
  - IceCube's measurement of astrophysical neutrinos
  - Recent source search results
  - Realtime alerts, TOO neutrino searches
  - Future prospects

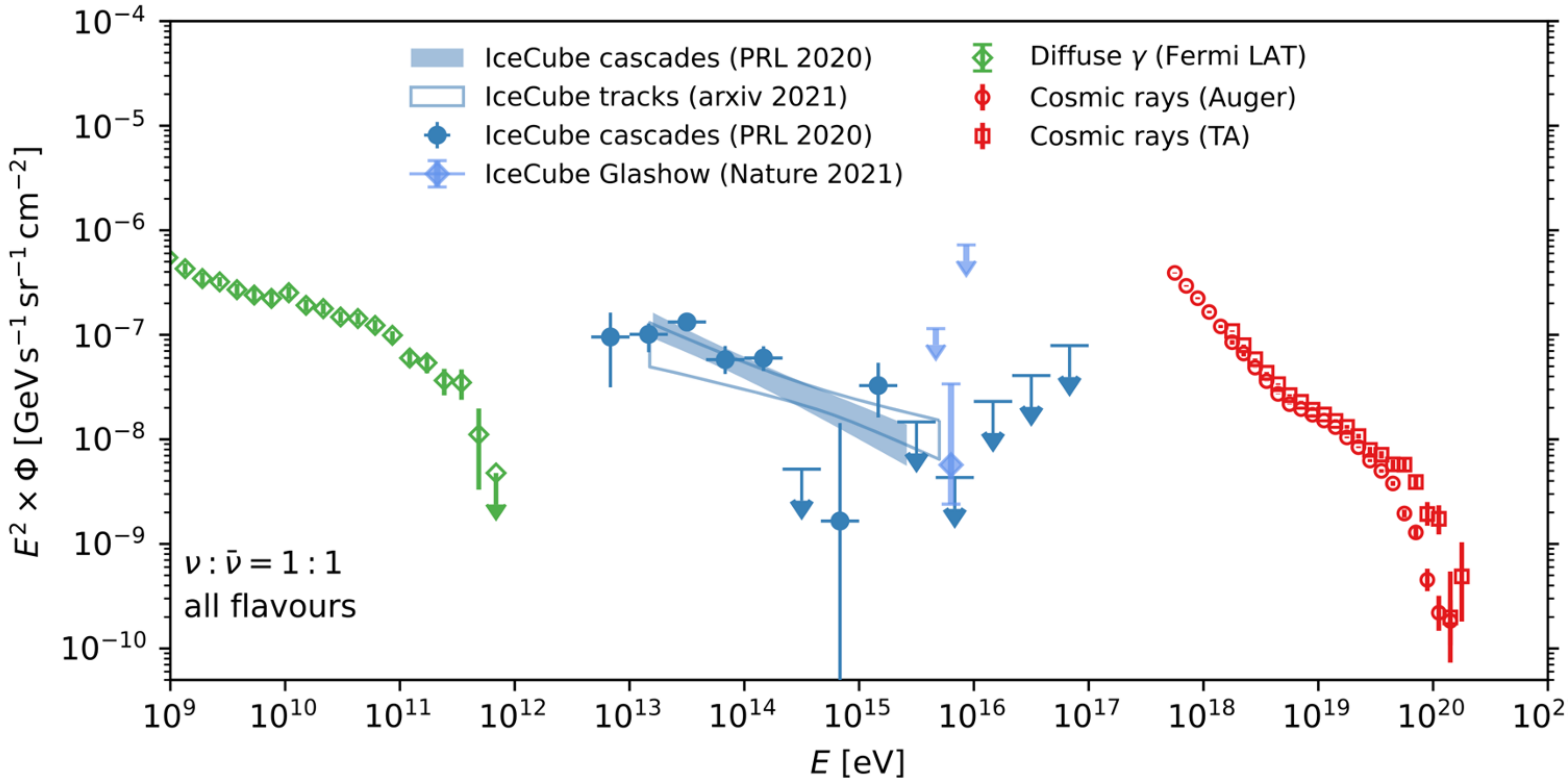


Neutrinos: Astronomical messengers



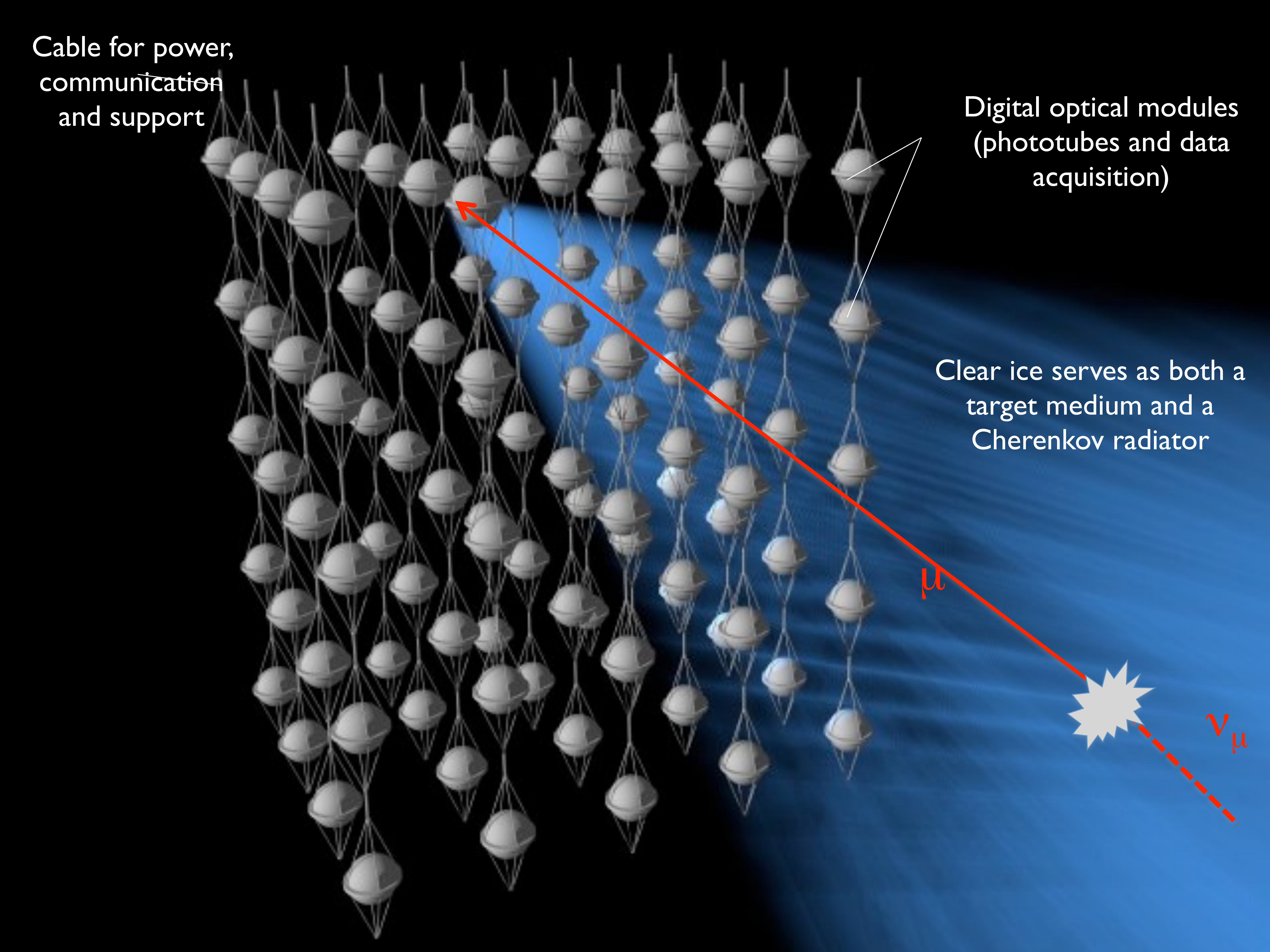


- Neutrinos can be created by hadronic interactions with protons or photons within or near cosmic accelerators
- At the highest energies, neutrinos are an astronomical messenger with several advantages:
    - Neutral
    - Freely propagate from source regions

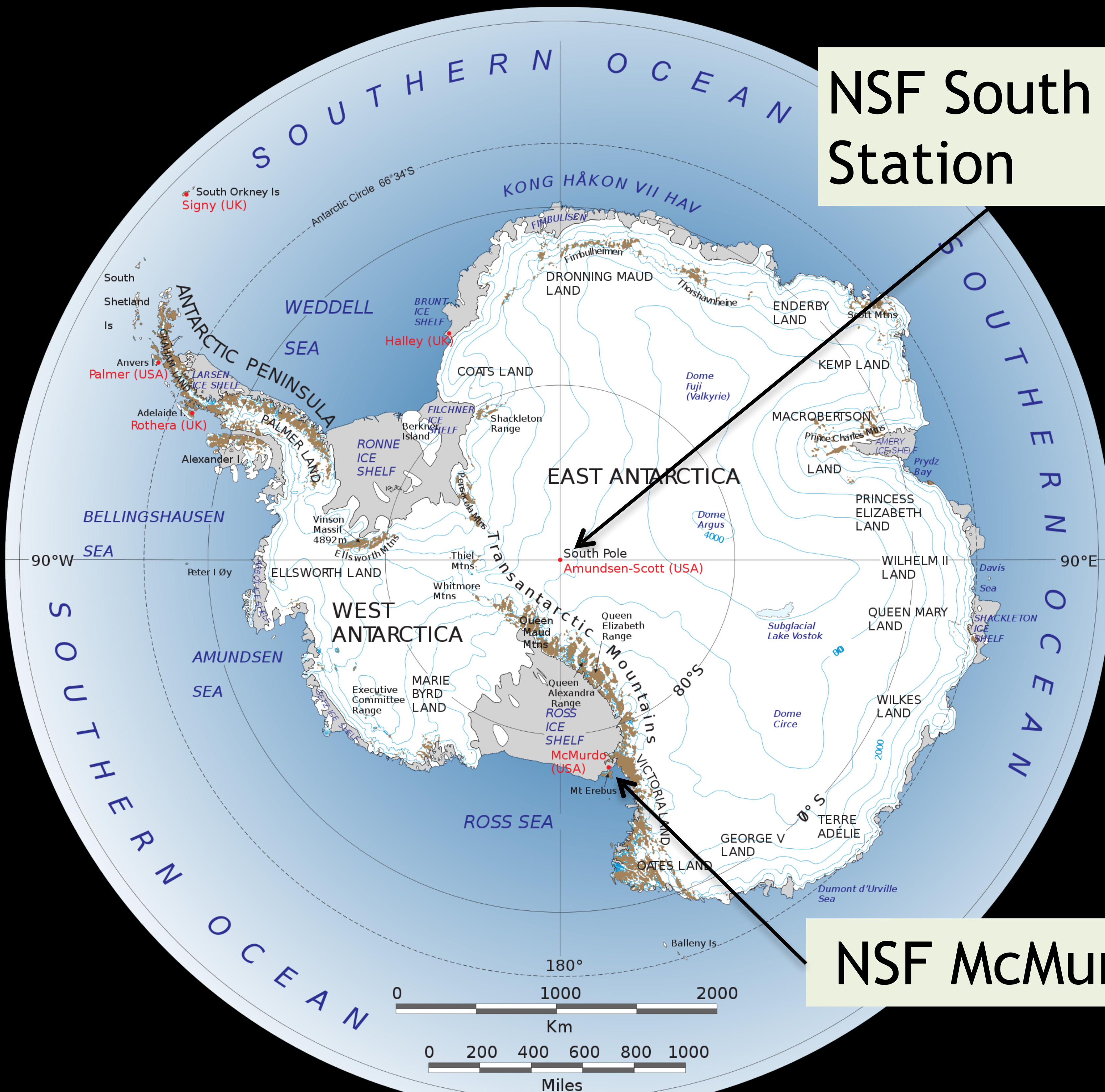


- Similar energy densities observed for extra-galactic components
    - Diffuse gamma-rays
    - Extra-galactic cosmic rays
    - Astrophysical neutrinos
- All potentially arising from a common source class

arxiv: 1903.04334

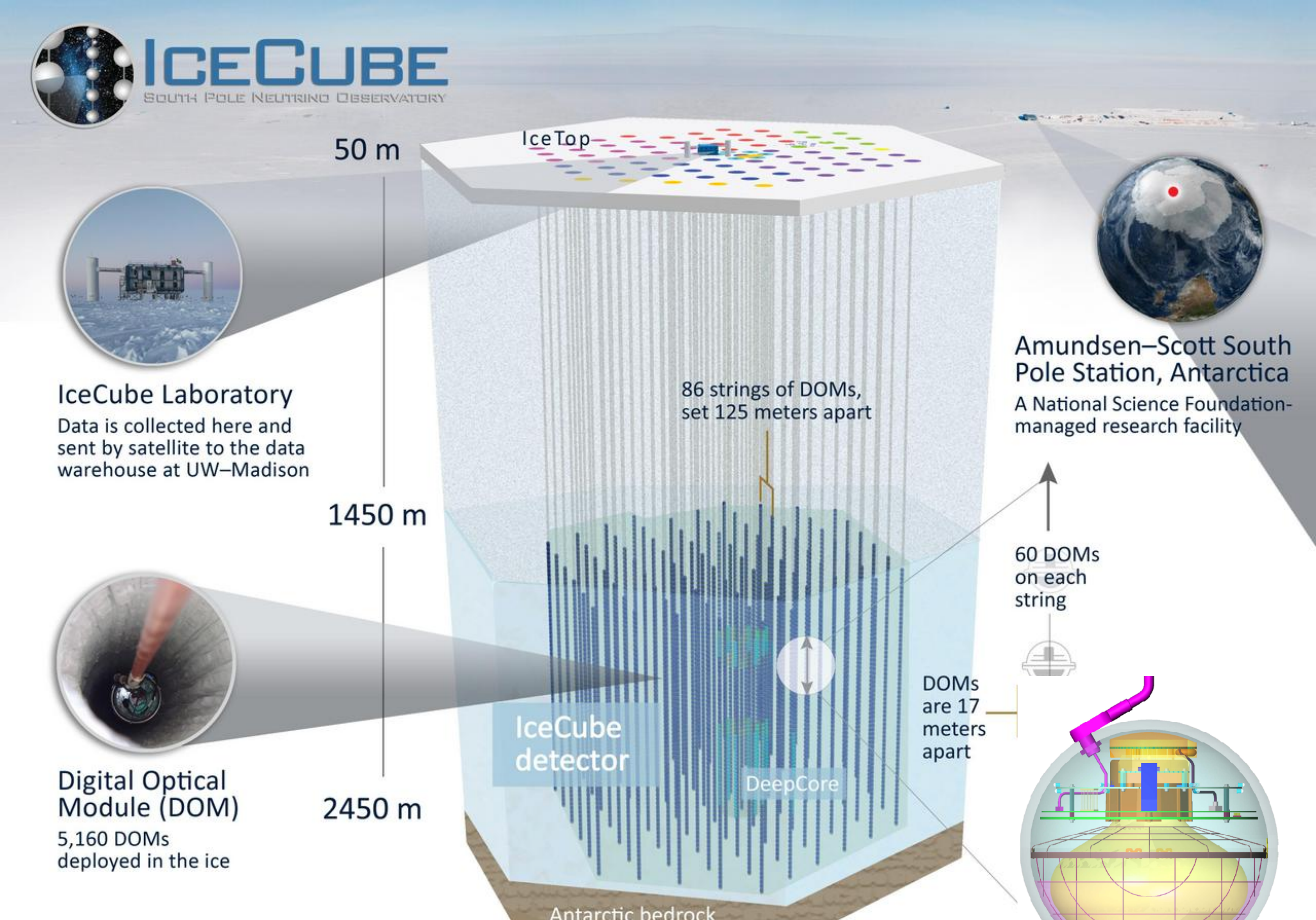

Cable for power, communication and support
Digital optical modules (phototubes and data acquisition)
Clear ice serves as both a target medium and a Cherenkov radiator
μ
ν_μ

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

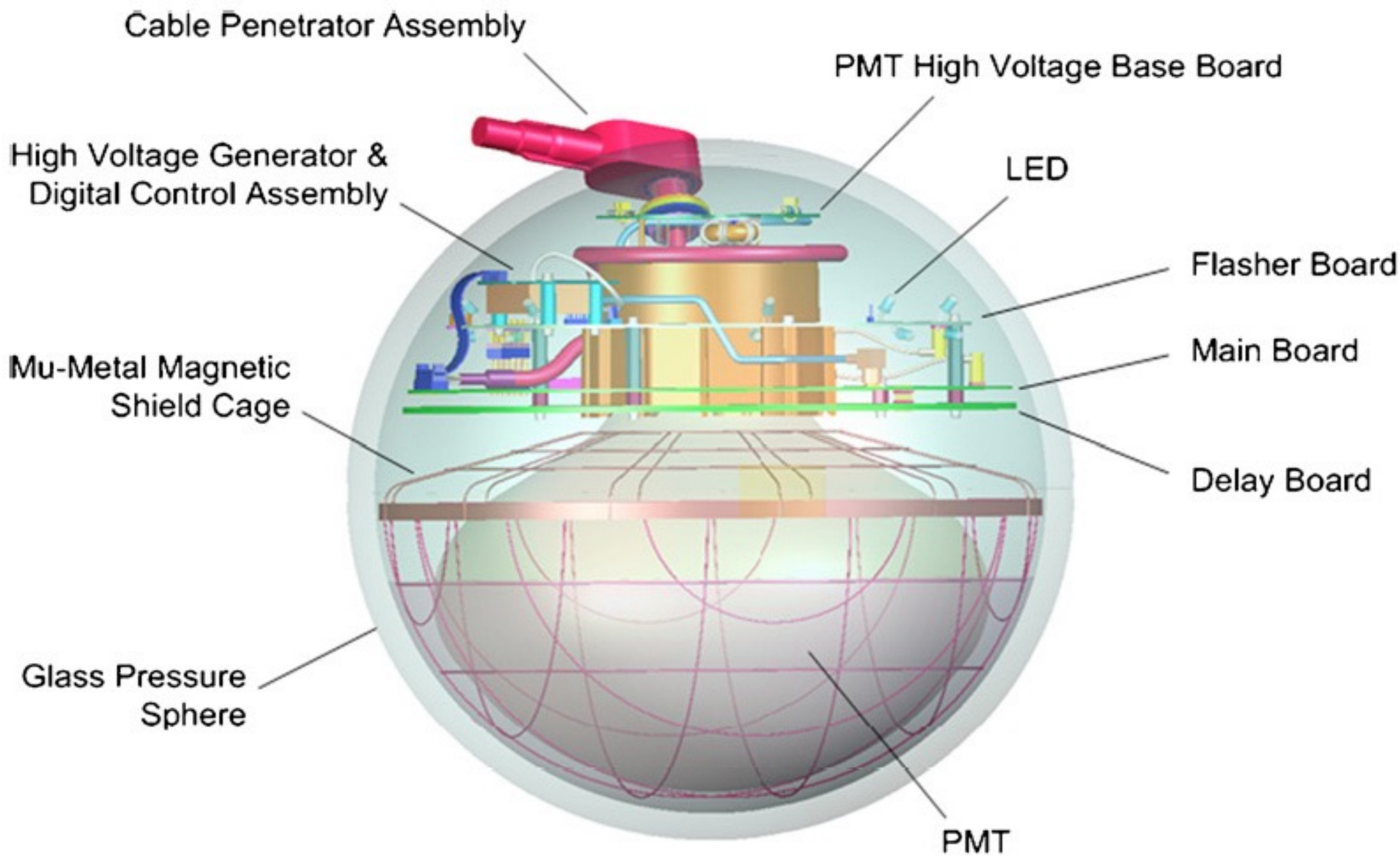


NSF South Pole Station

NSF McMurdo Station



Completed and taking data since Dec 2010



The IceCube Digital Optical Module (DOM)

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

Cable Penetra

High Voltage Generato
Digital Control Assem

Mu-Metal Magnetic
Shield Cage

Glass Pressure
Sphere

Base Board

Flasher Board

Main Board

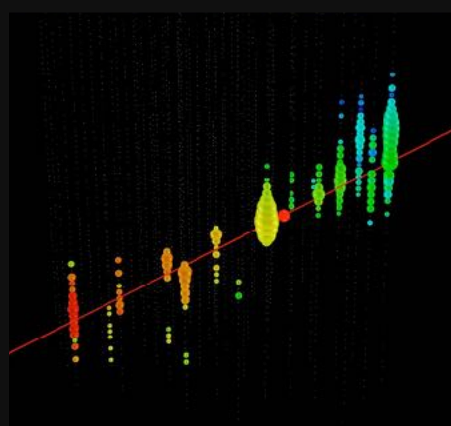
Delay Board

T

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

IceCube sensitive to all ν flavors

CC Muon Neutrino

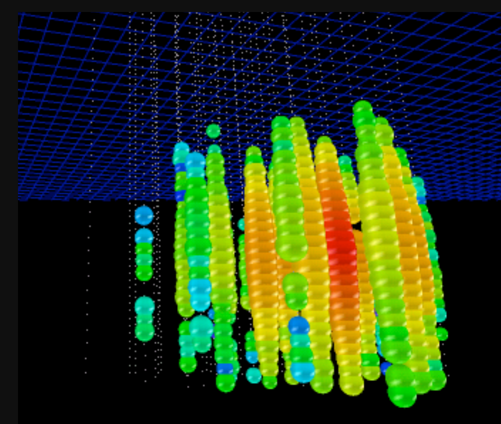


$$\nu_\mu + N \to \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

Neutral Current / CC Electron Neutrino



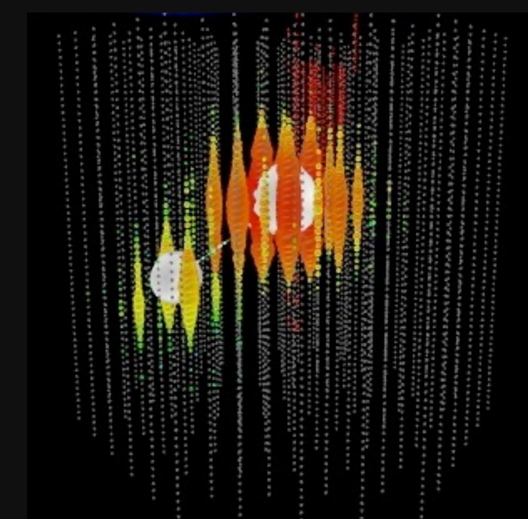
$$\nu_\mathrm{e} + N \to \mathrm{e} + X$$

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

shower (data)

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

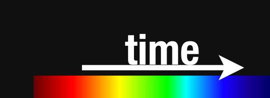
CC Tau Neutrino



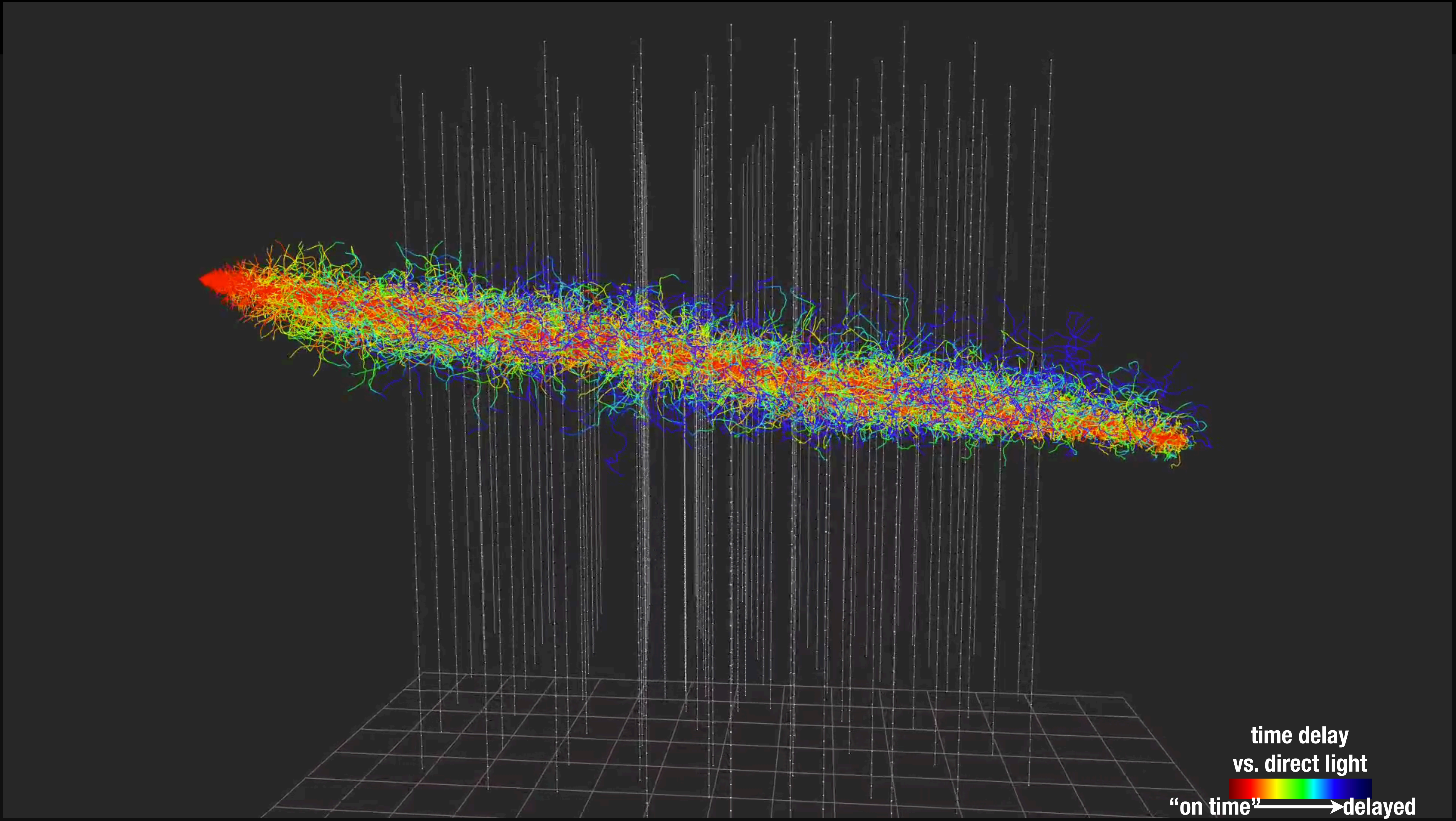
$$\nu_\tau + N \to \tau + X$$

"double-bang" and other signatures (simulation)

(not observed yet)

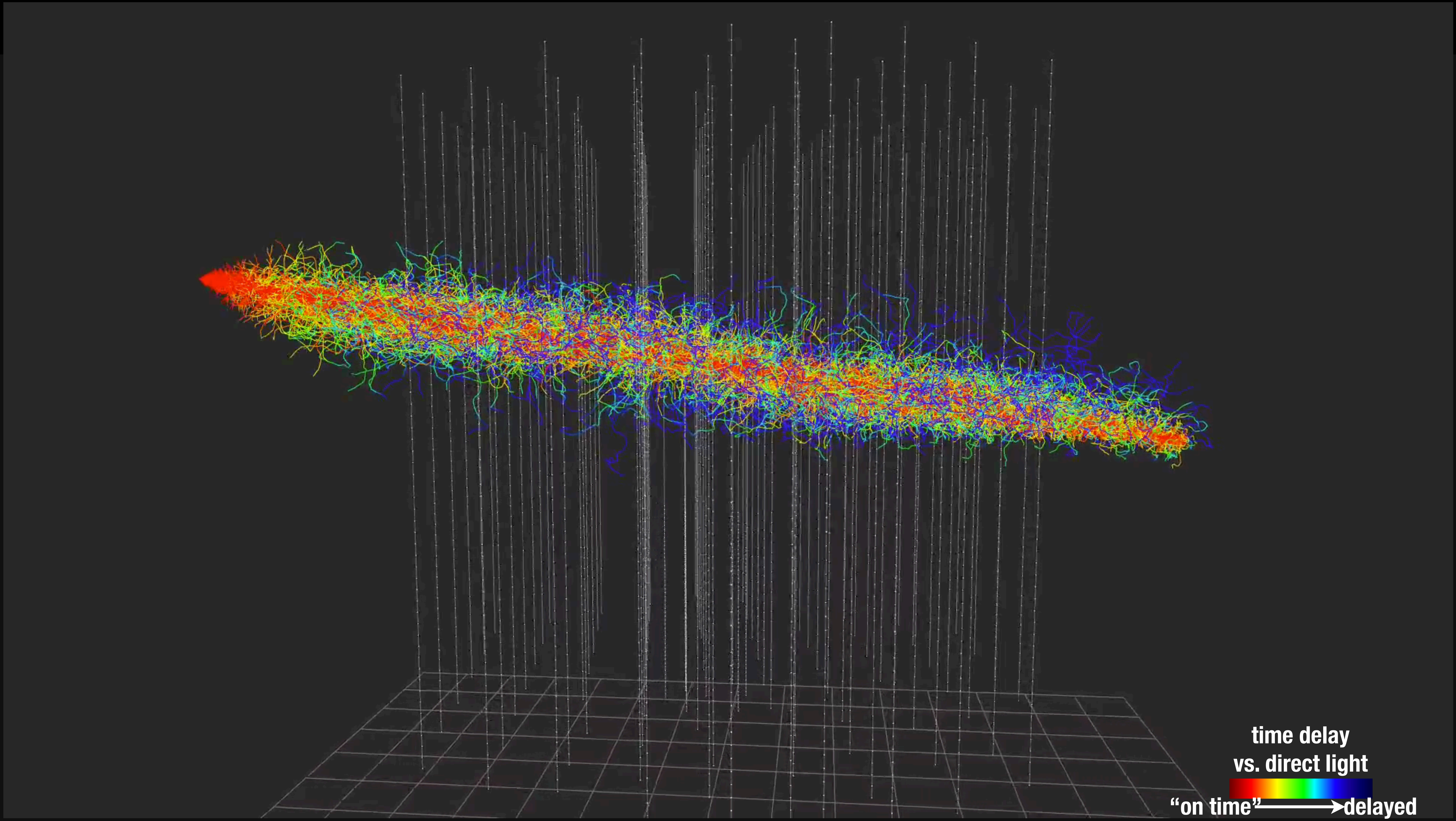


Observing charged particles in Ice.



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

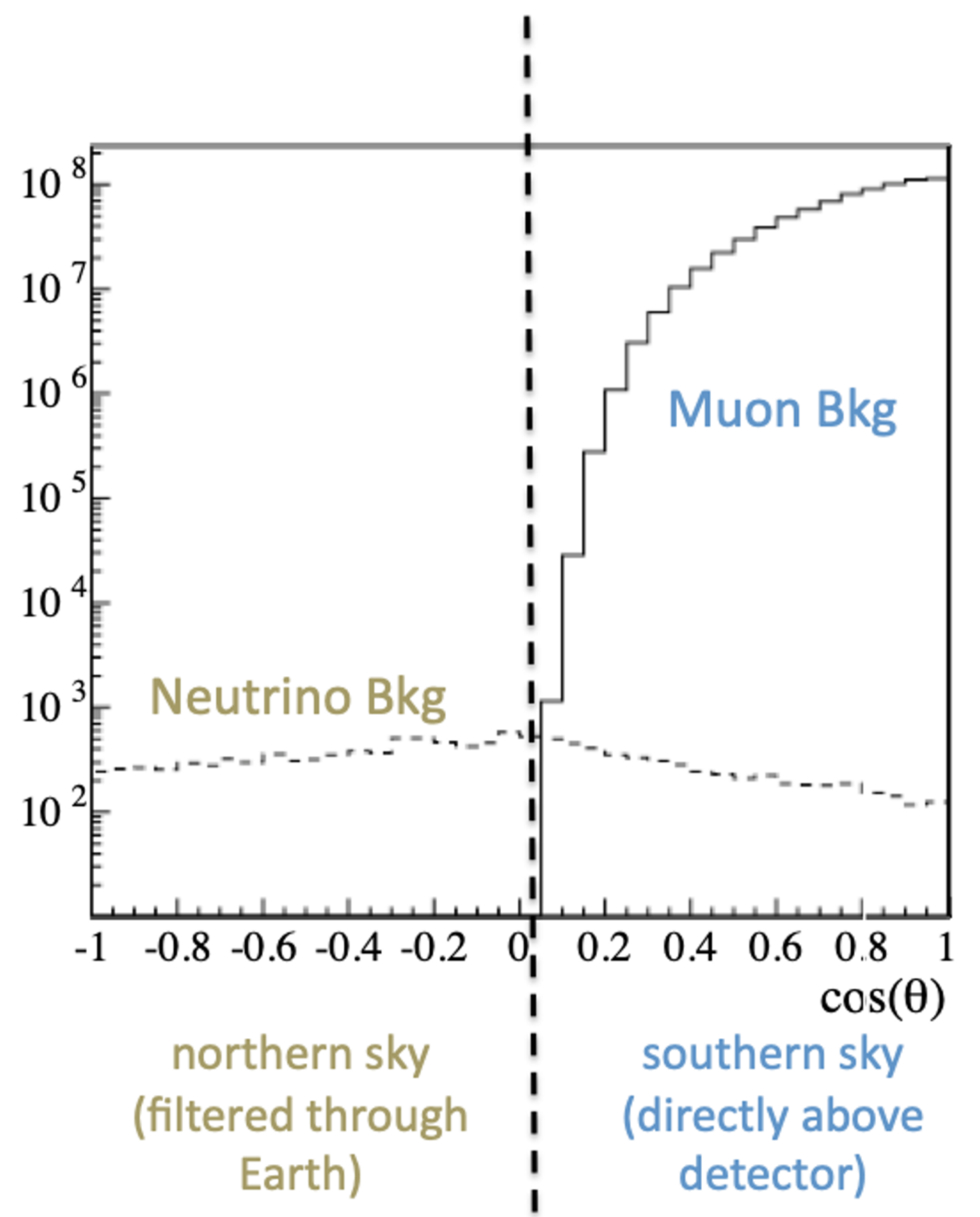
Observing charged particles in Ice.

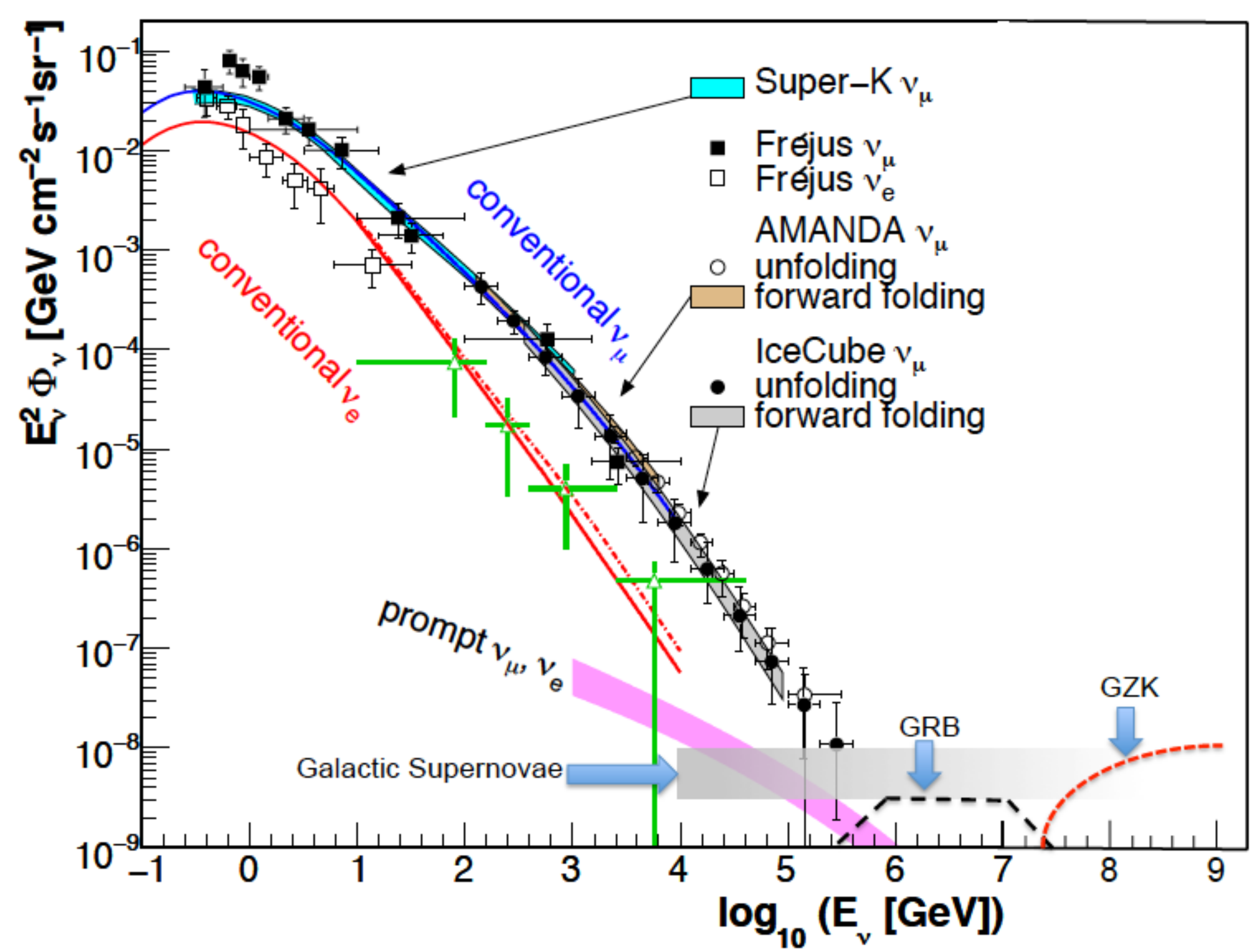


0.01% of all Cherenkov photons generated by a 100 TeV muon in ice.

Identifying Astrophysical Neutrinos

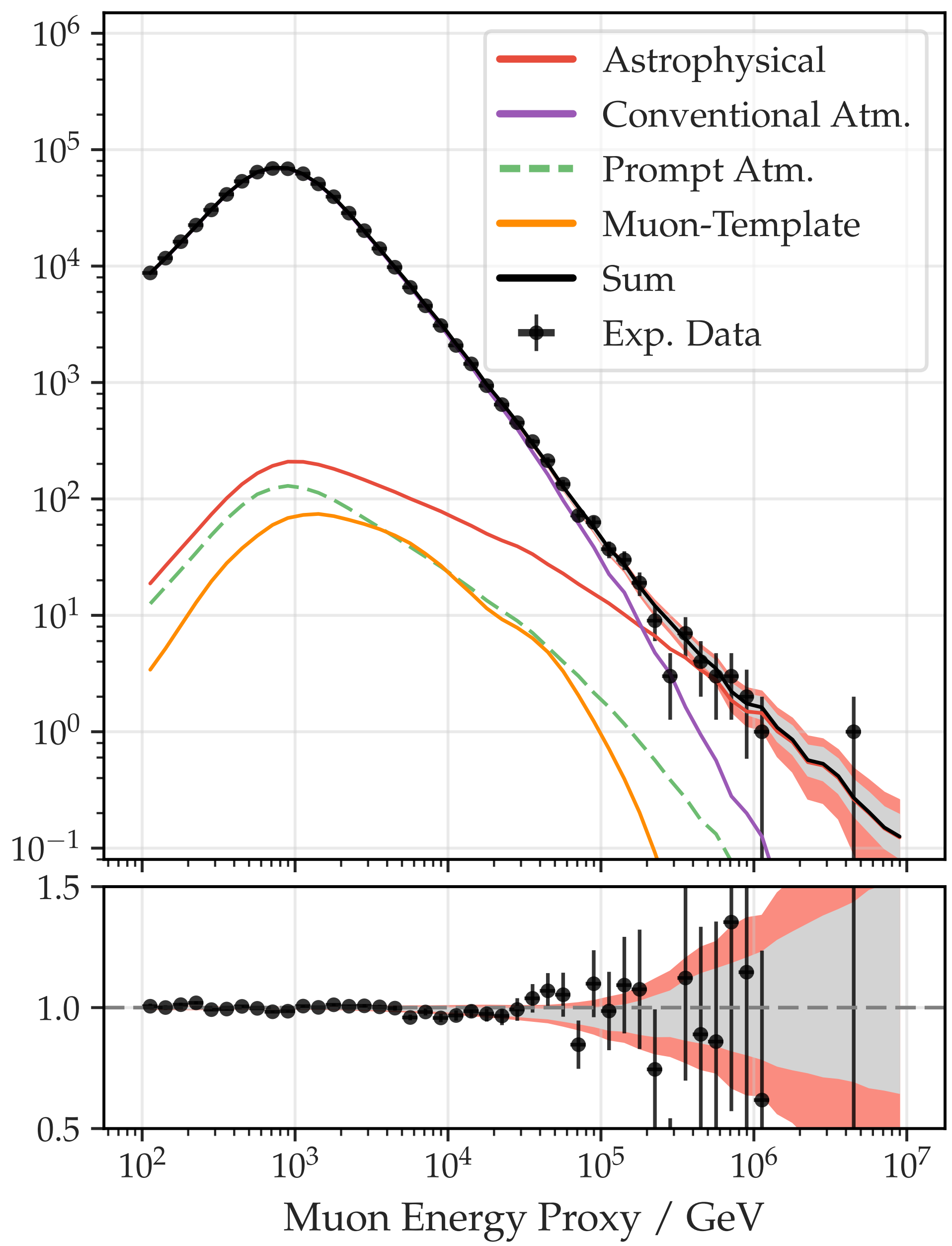
- At lower energies, backgrounds dominate detection
  - Atmospheric muons (Southern hemisphere)
  - Atmospheric neutrinos (Northern hemisphere)
- Prefer high energy events
  - Through-going tracks
  - High-Energy Starting Events
  - Cascade/Shower Events





An established diffuse astrophysical neutrino flux

9.5 yr Up-going tracks

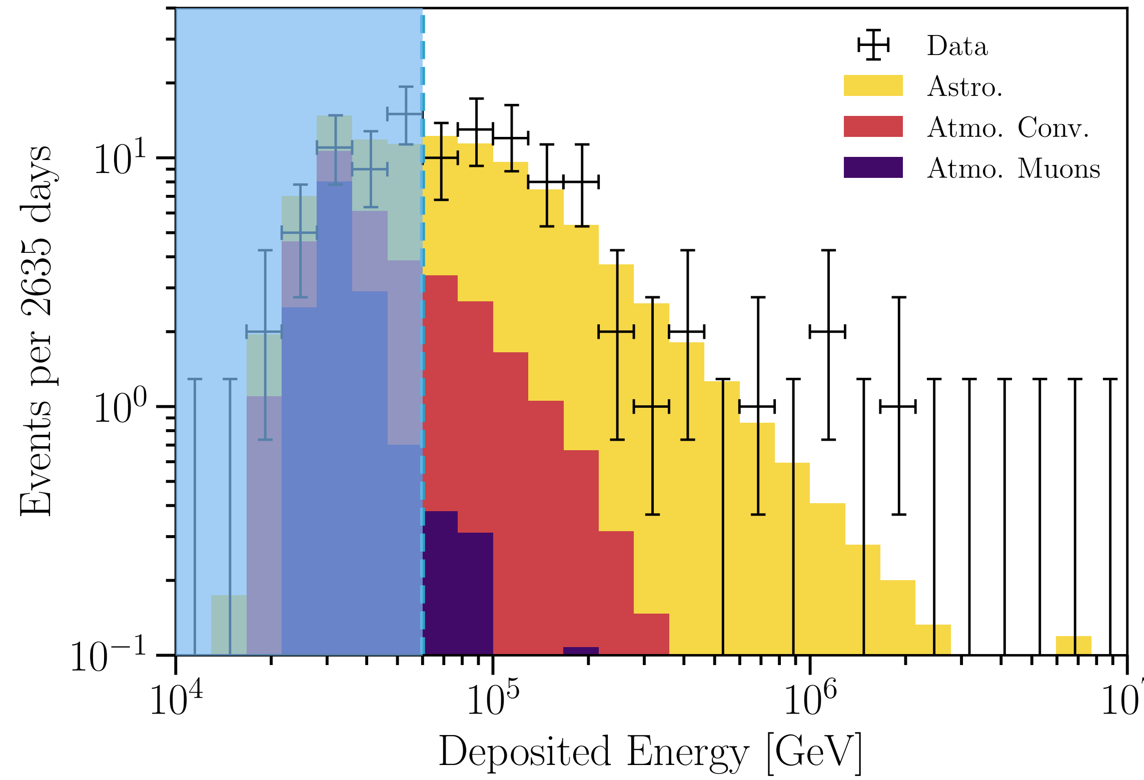


Spectral index: -2.37
Atm-only hypothesis rejected at 5.6σ

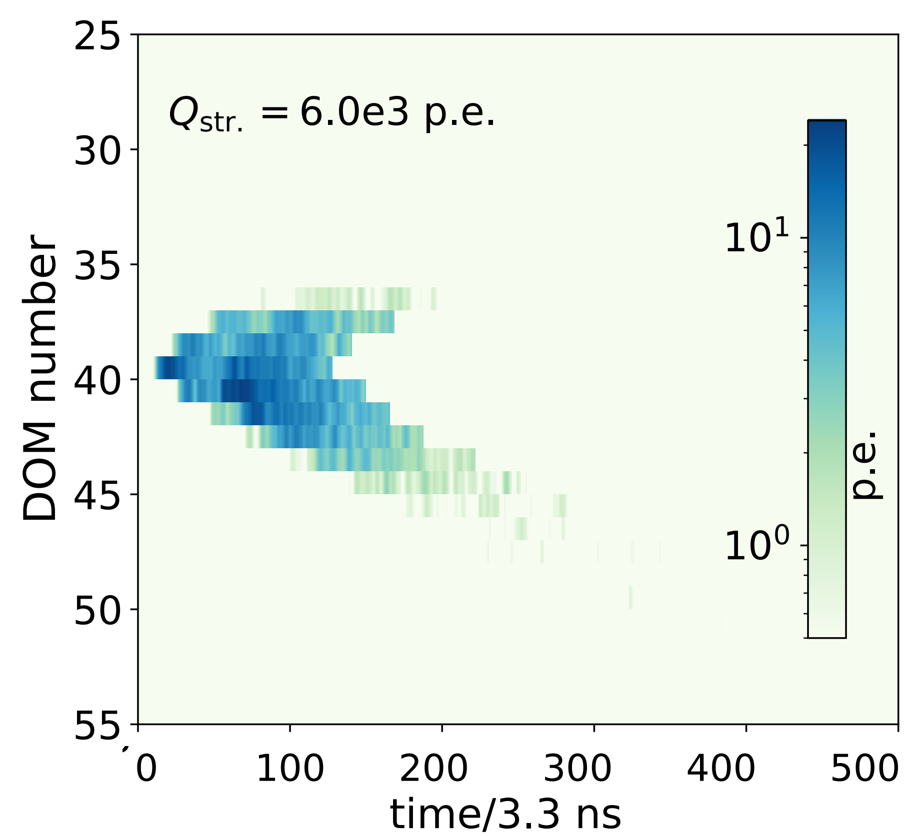
IceCube, Astrophys. J. 928 (2022) 50

7.5 yr Starting tracks

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



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



Identified 7 ν_τ candidates in 10yr
Reject no-Tau hypothesis at 5σ

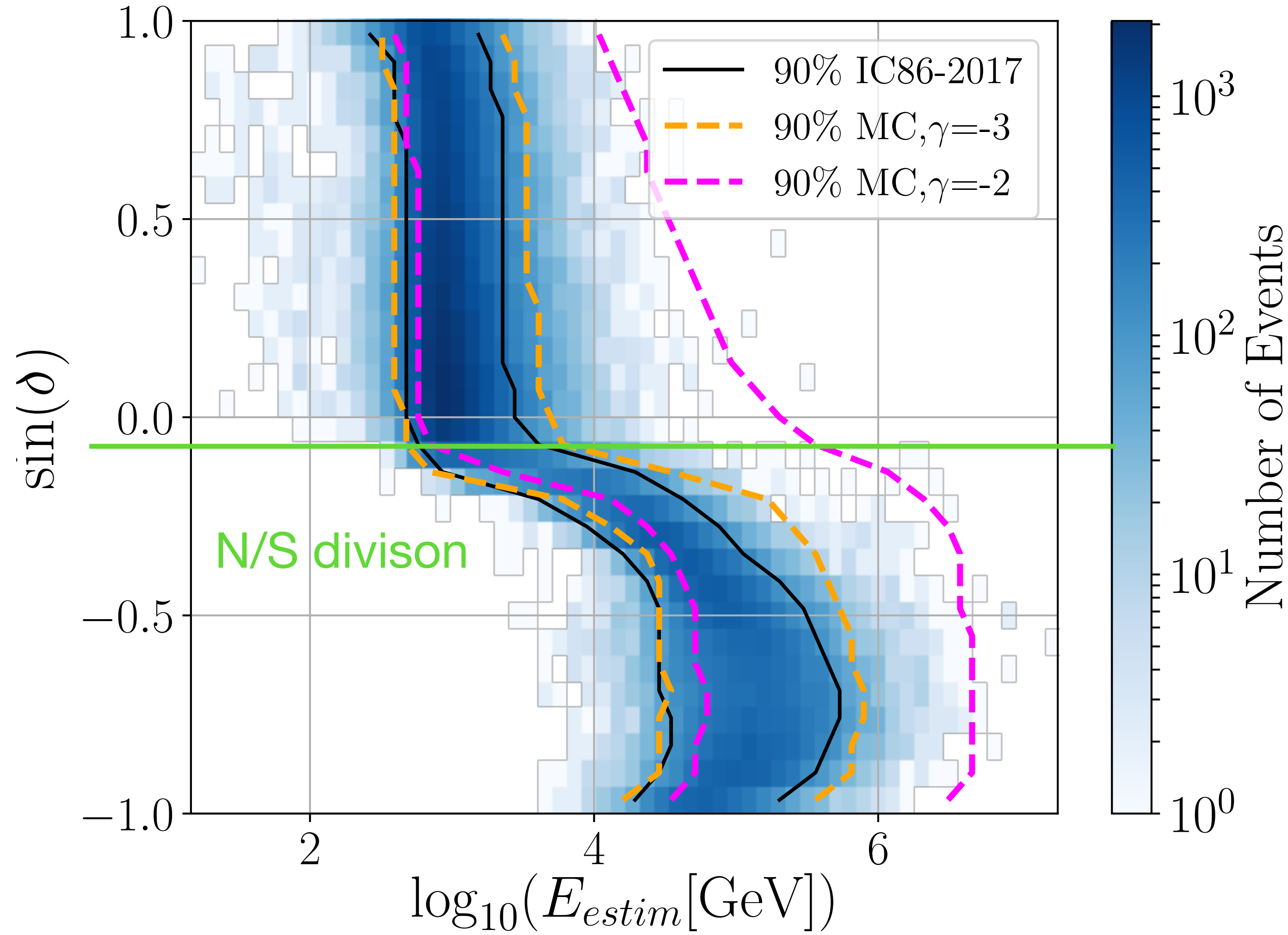
arXiv:2403.02516

Identifying sources of astrophysical neutrinos

- Several strategies used to find evidence for sources
  - Search for excess of events from a single point or source region in the sky
    - Including coincidences with a catalog of known high-energy sources
  - Look in realtime for transient photon signals in correlation with detection of a likely astrophysical neutrino
    - Realtime neutrino alert program
  - Search in realtime for neutrinos from indenfied transient phenomena
    - TOO searches: GRBs, Gravitational wave events, etc…

Neutrino events - Tracks

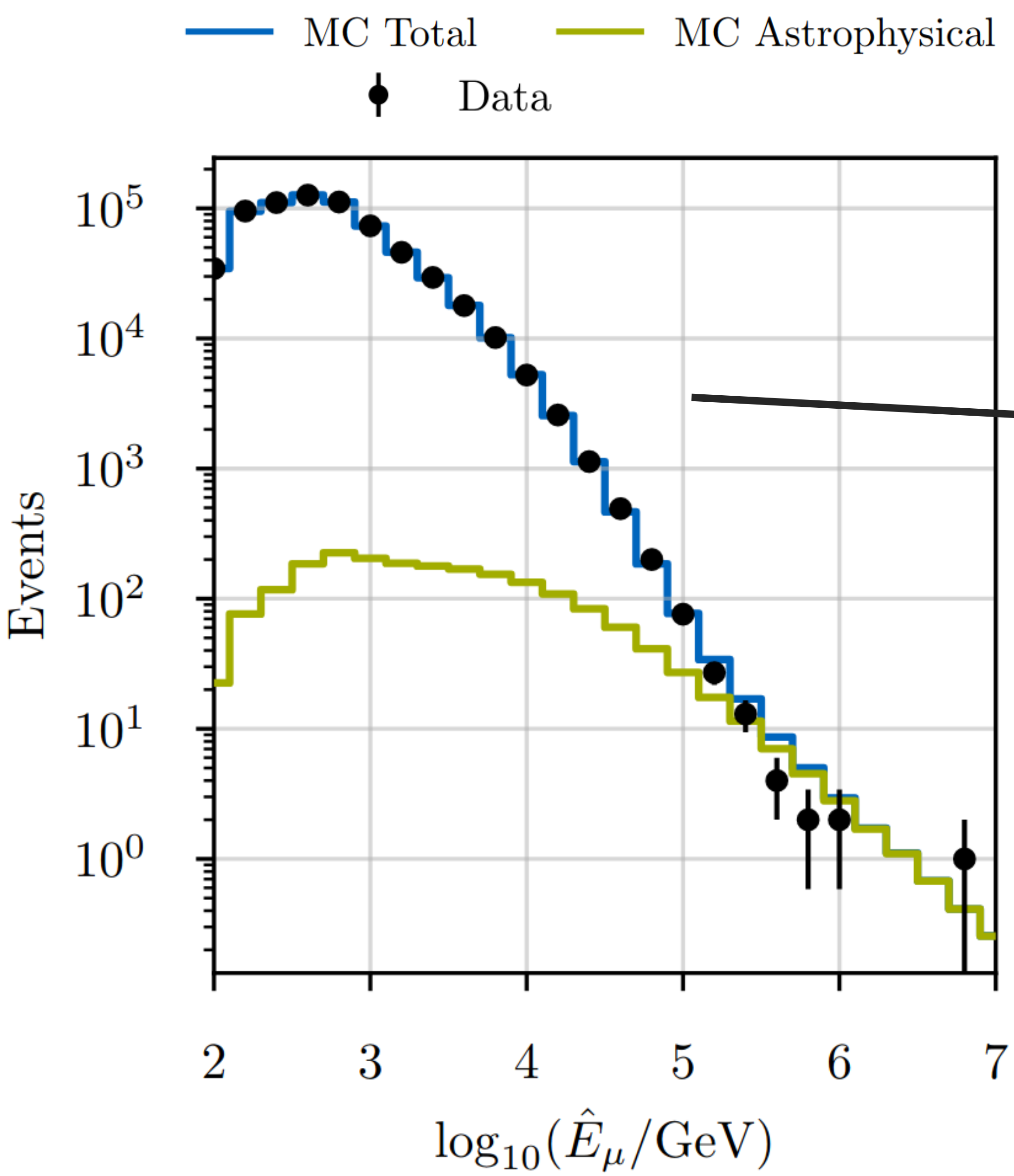
- Through-going muon tracks give preferred for astronomy
    - Best angular resolution and largest effective volumes
- All-sky sensitivity.
    - Different backgrounds in Northern/ Southern skies.
    - Sensitivity to different energies
- South Pole location:
    - Stable operations - 99% uptime
   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

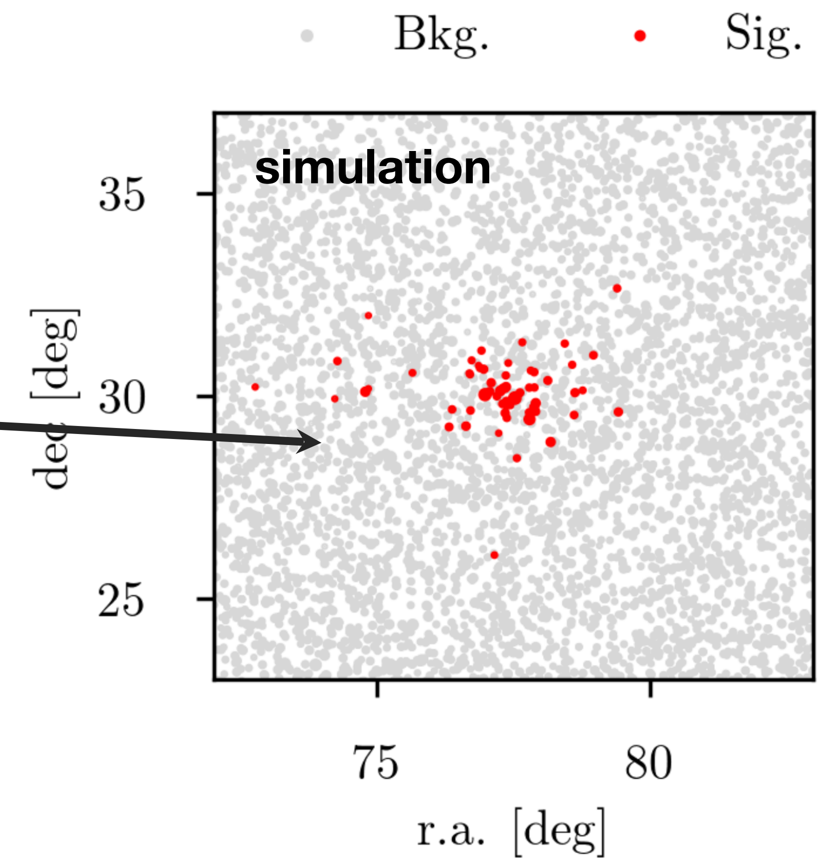


(Muon Energy)

10 Years of IceCube Point Source data sample

Searching for neutrino sources

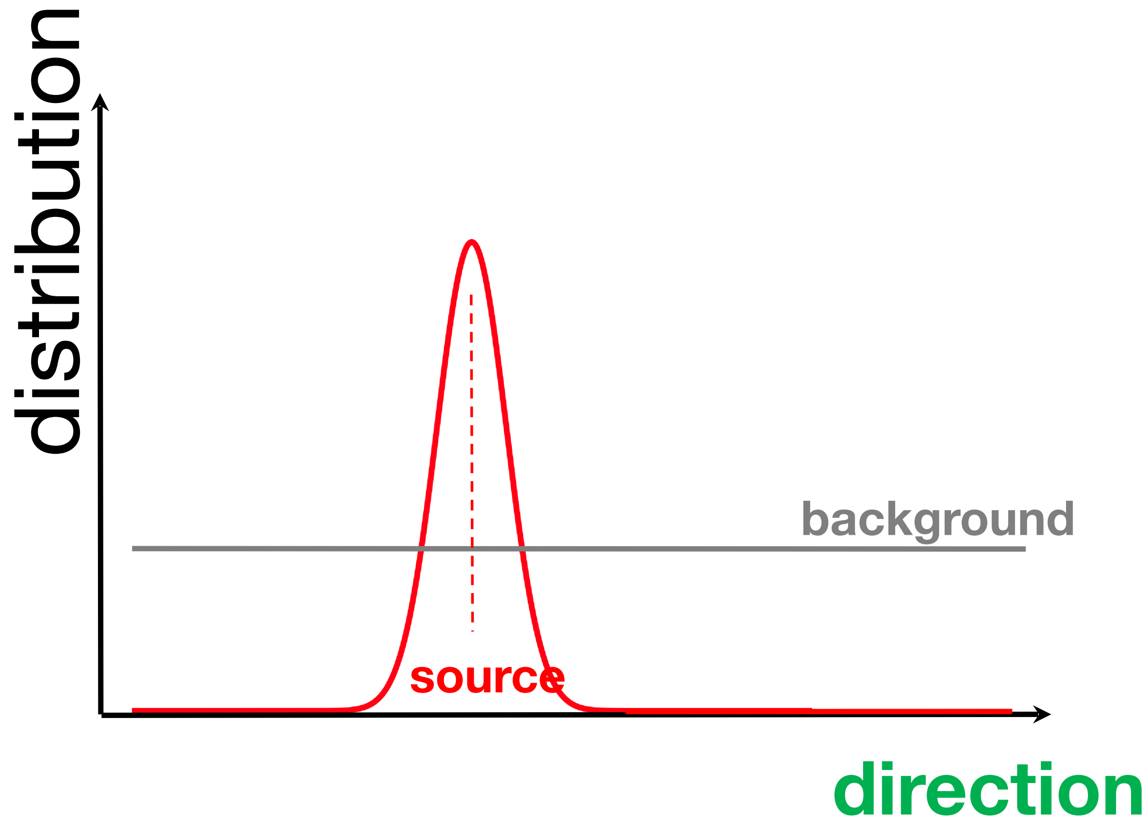


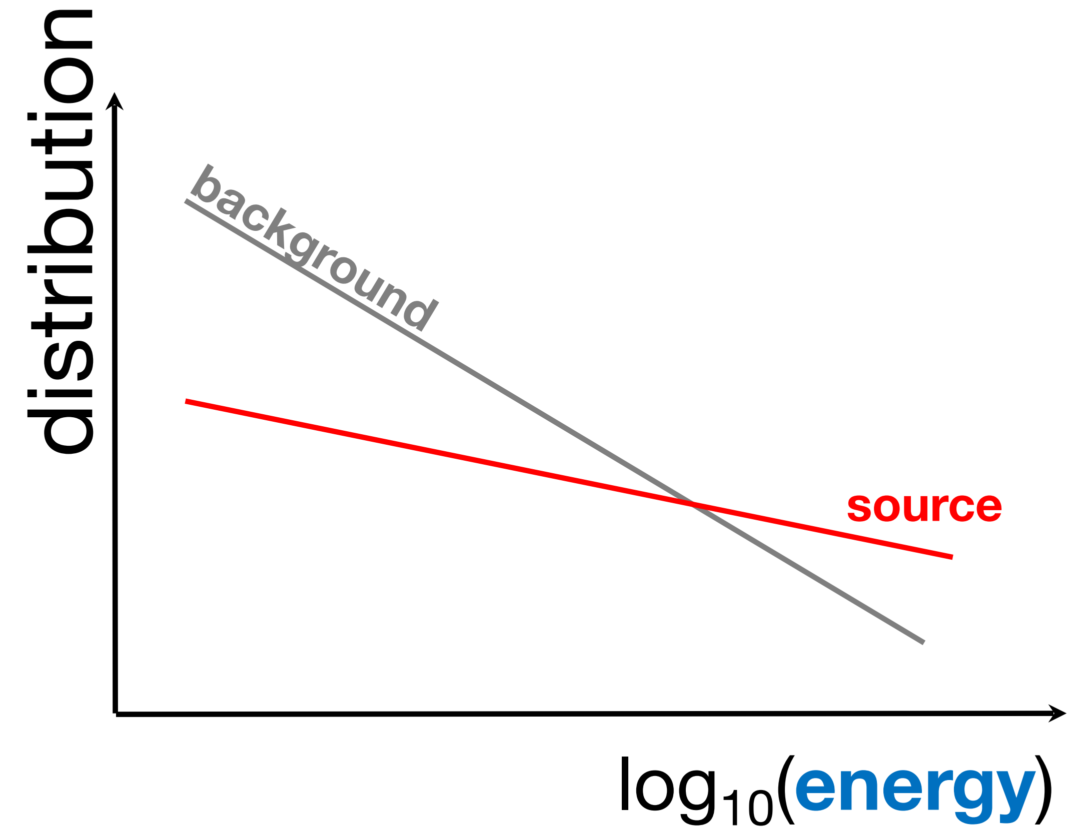


Majority of the events are background in searches for neutrino sources

Credit: H. Niederhausen

Searching for neutrino sources





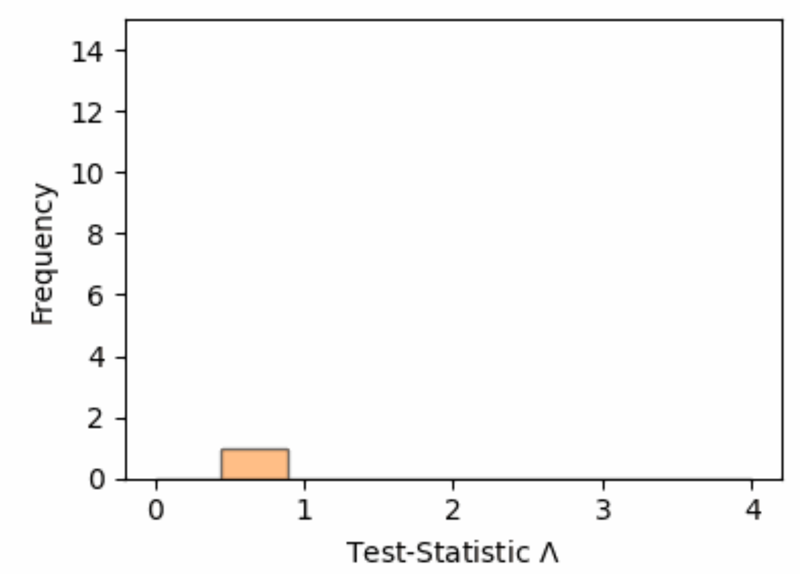
Combine knowledge of background and source properties to better identify sources

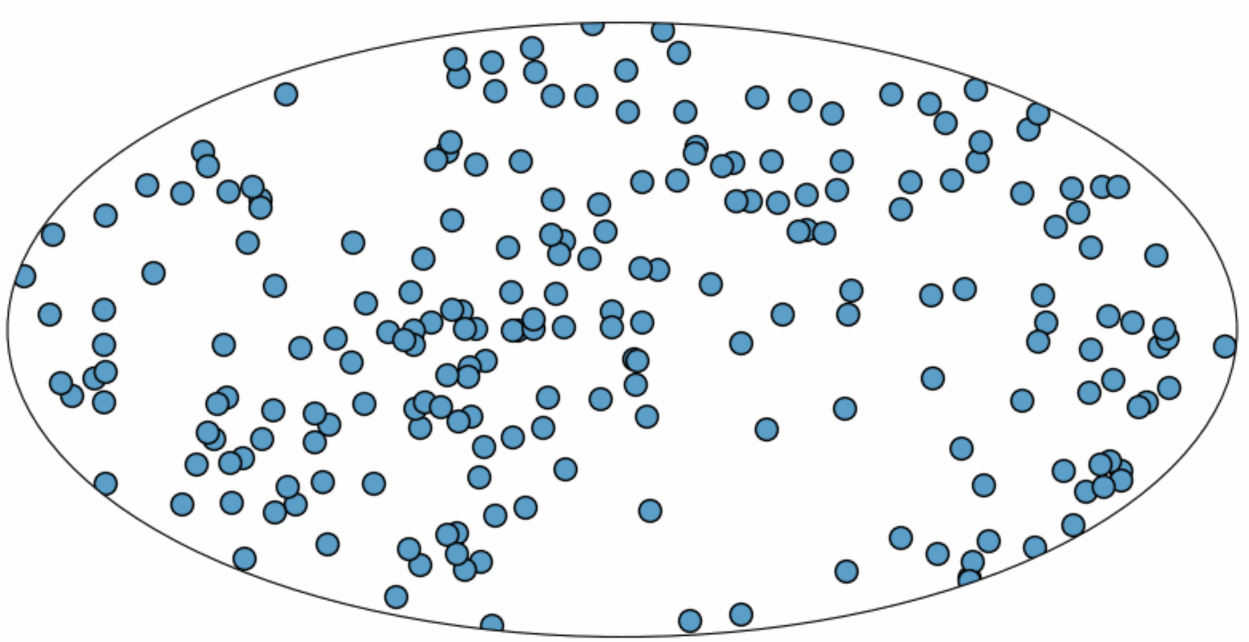
Unbinned maximum likelihood search technique on a fine grid over the entire sky

Credit: H. Niederhausen

Searching for neutrino sources

- Blind analysis
- Backgrounds are modeled in **data-driven** approach
- Randomization in time removes accumulation along source region due to Earth's rotation
  - Example: Source is Galatic plane
- Chance probability of final analysis calculated from distribution of randomized pseudo-experiments





Credit: S. Sclafani

Searching for neutrino sources

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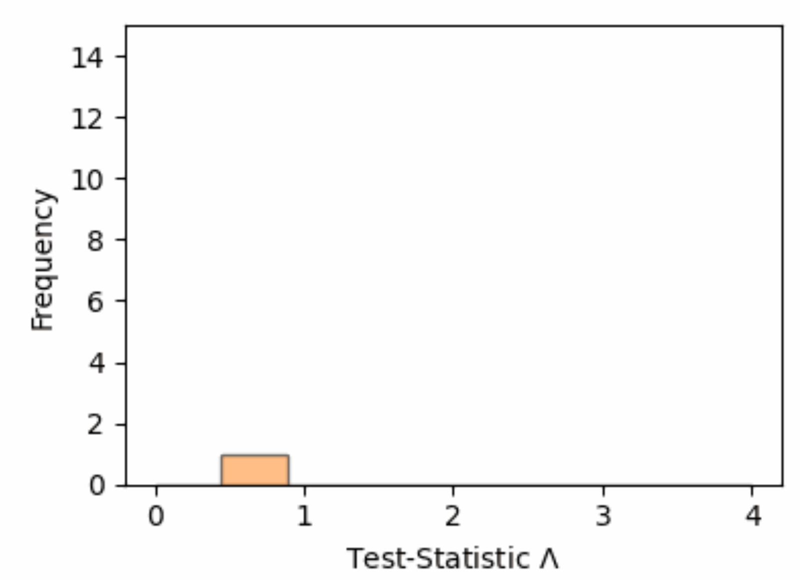
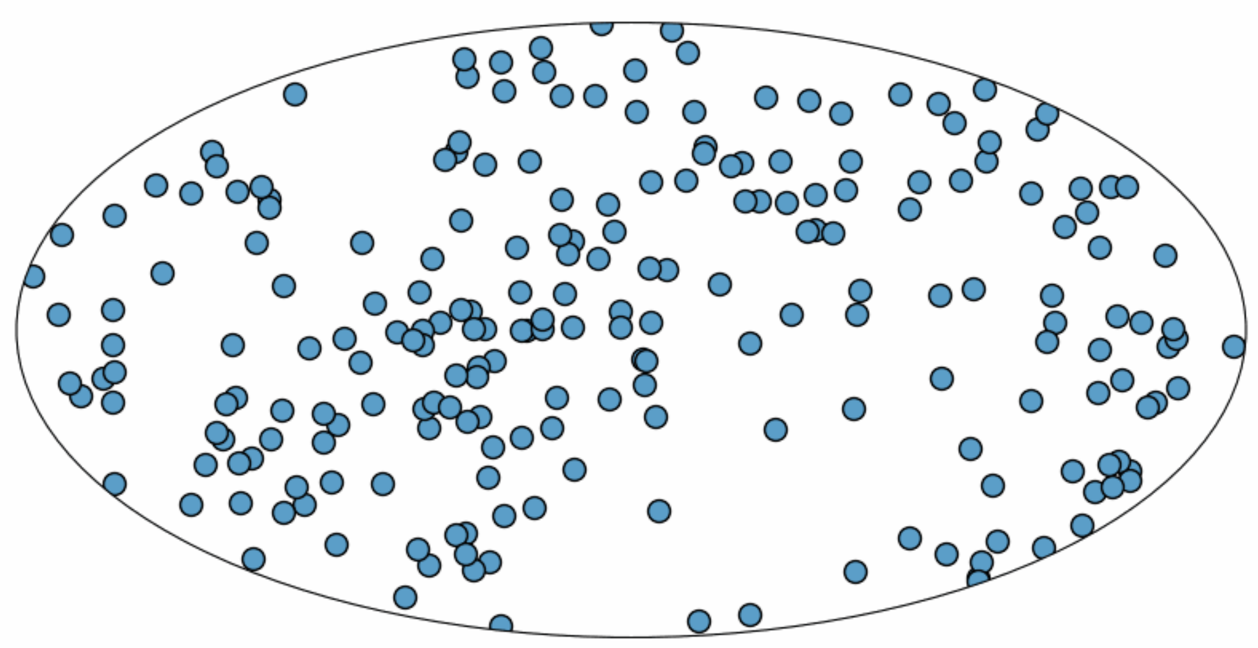
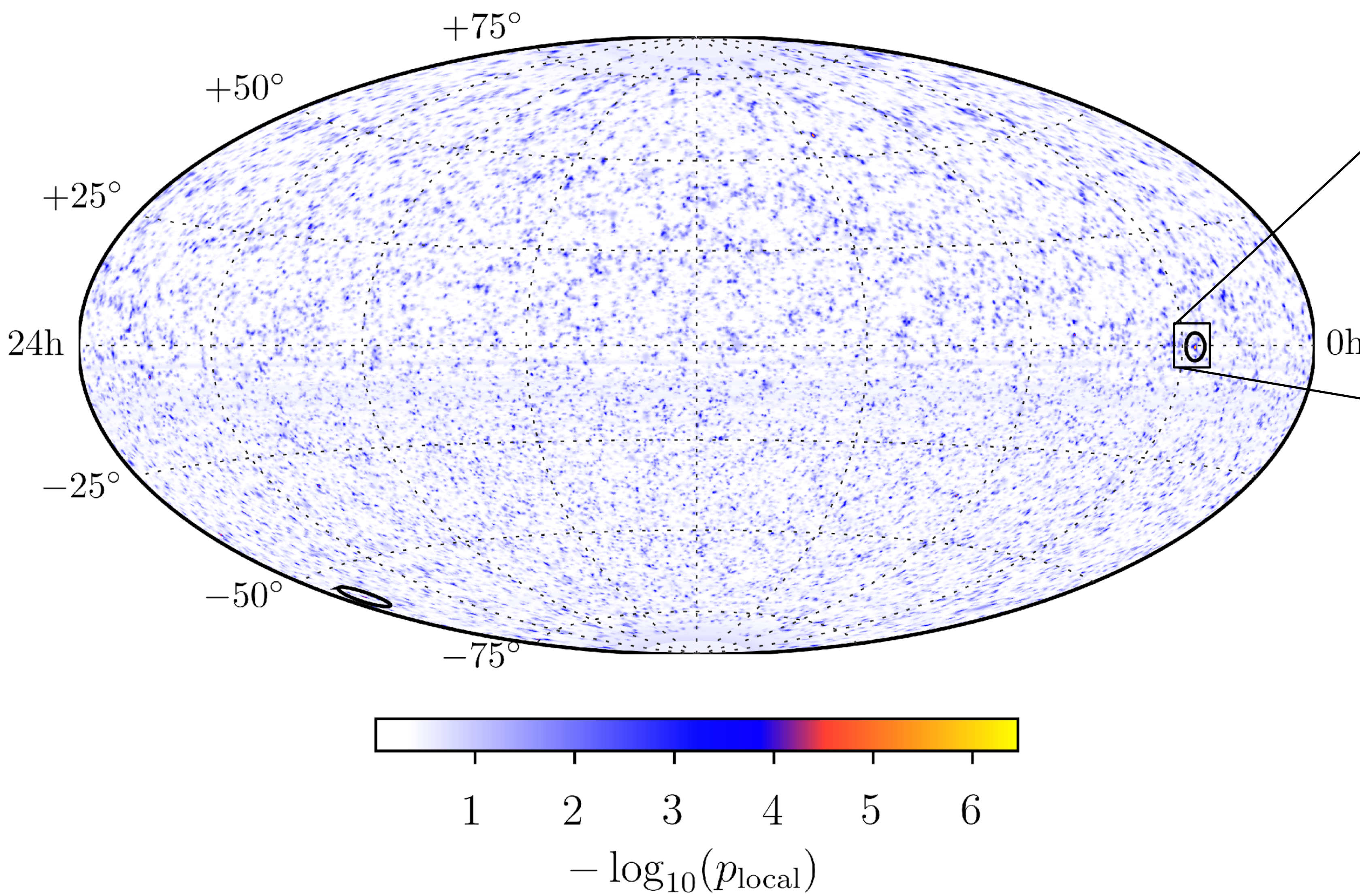




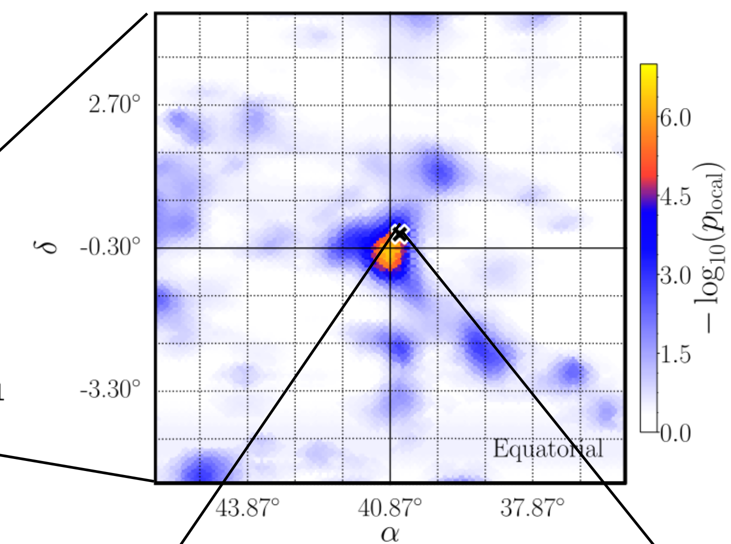
Credit: S. Sclafani

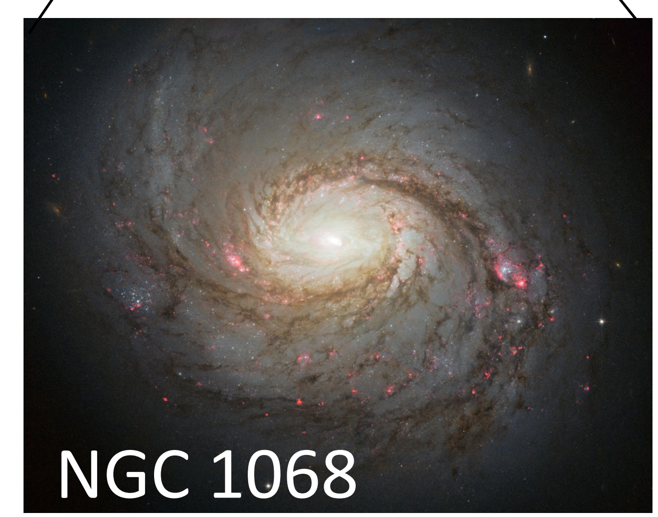
Previous Point Source Results



IceCube, PRL 124, 051103 (2020)

50 neutrinos



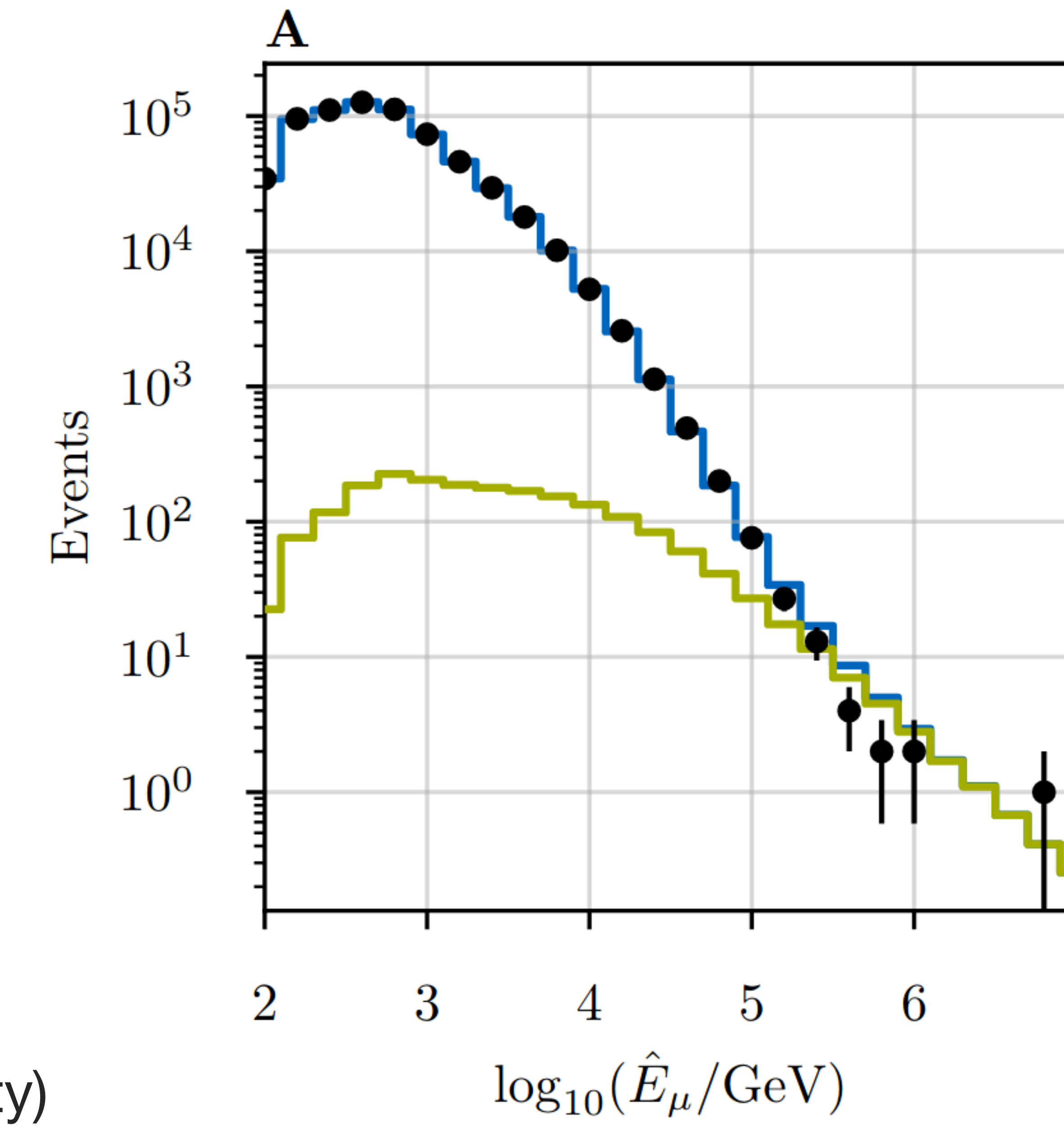


2.9σ excess over background

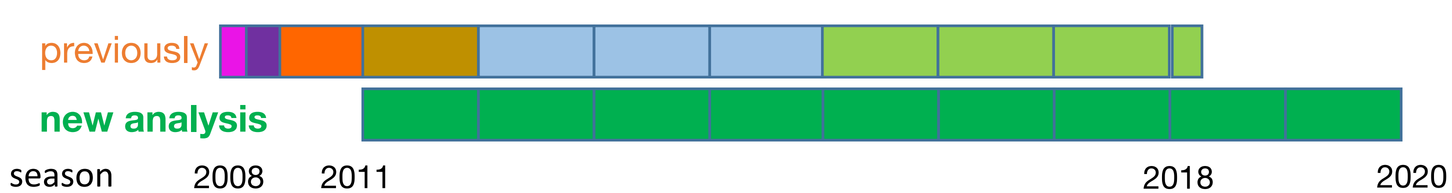
Per year:
90 billion atmospheric muons
80 thousand atmospheric neutrinos

An improved track dataset

- Improved calibrations and uniform processing
- 2 additional years of data from complete detector
- Improved energy and angular uncertainty estimates
- Focus on events from more sensitive northern sky



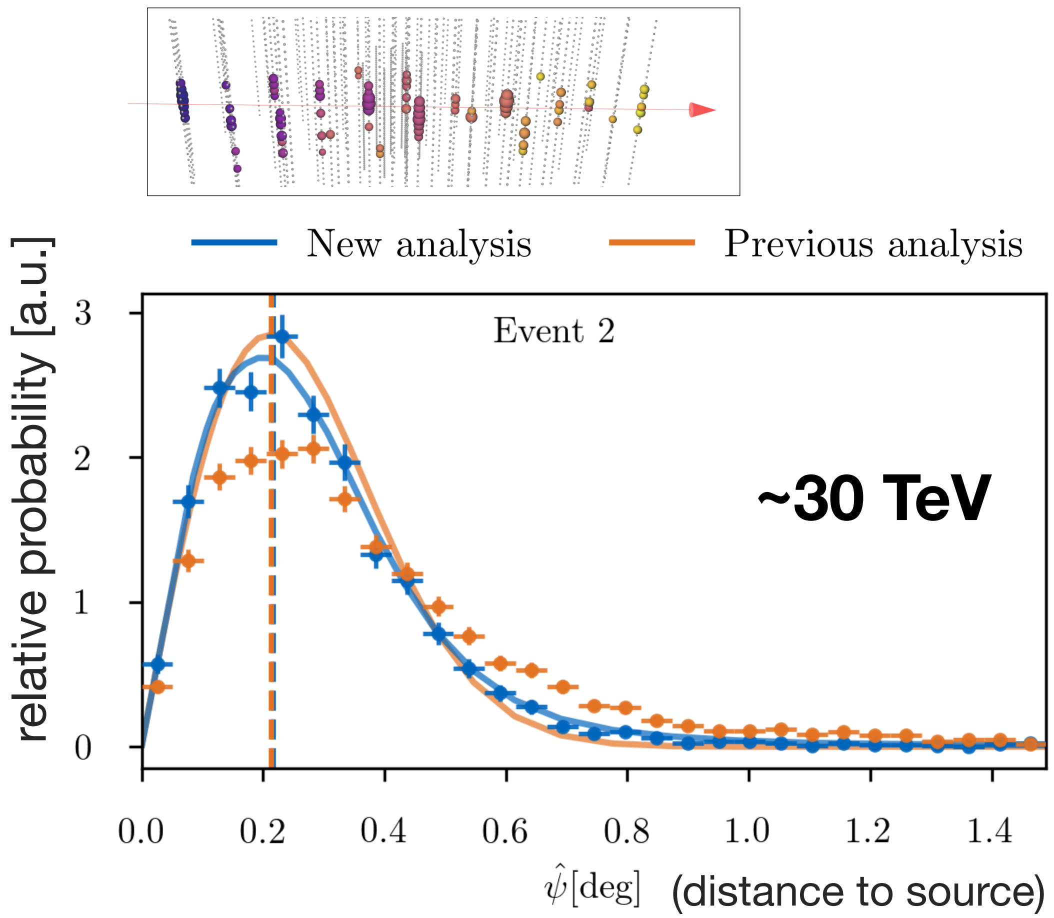
Data: May 2011 to May 2020
~99% detector uptime
~670,000 neutrinos selected (99.7% purity)
out of ~1 trillion events recorded

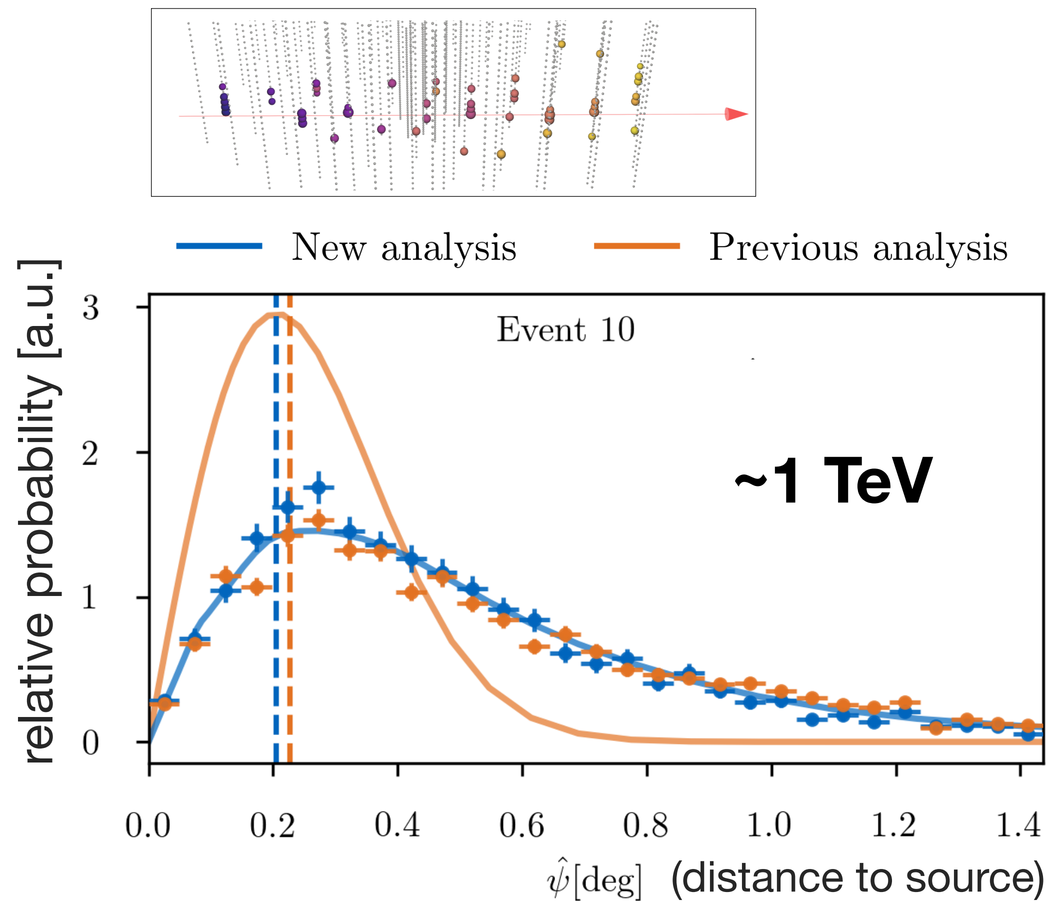


IceCube Pass 2 data

Improved detector calibration, data filtering and processing applied to ALL years

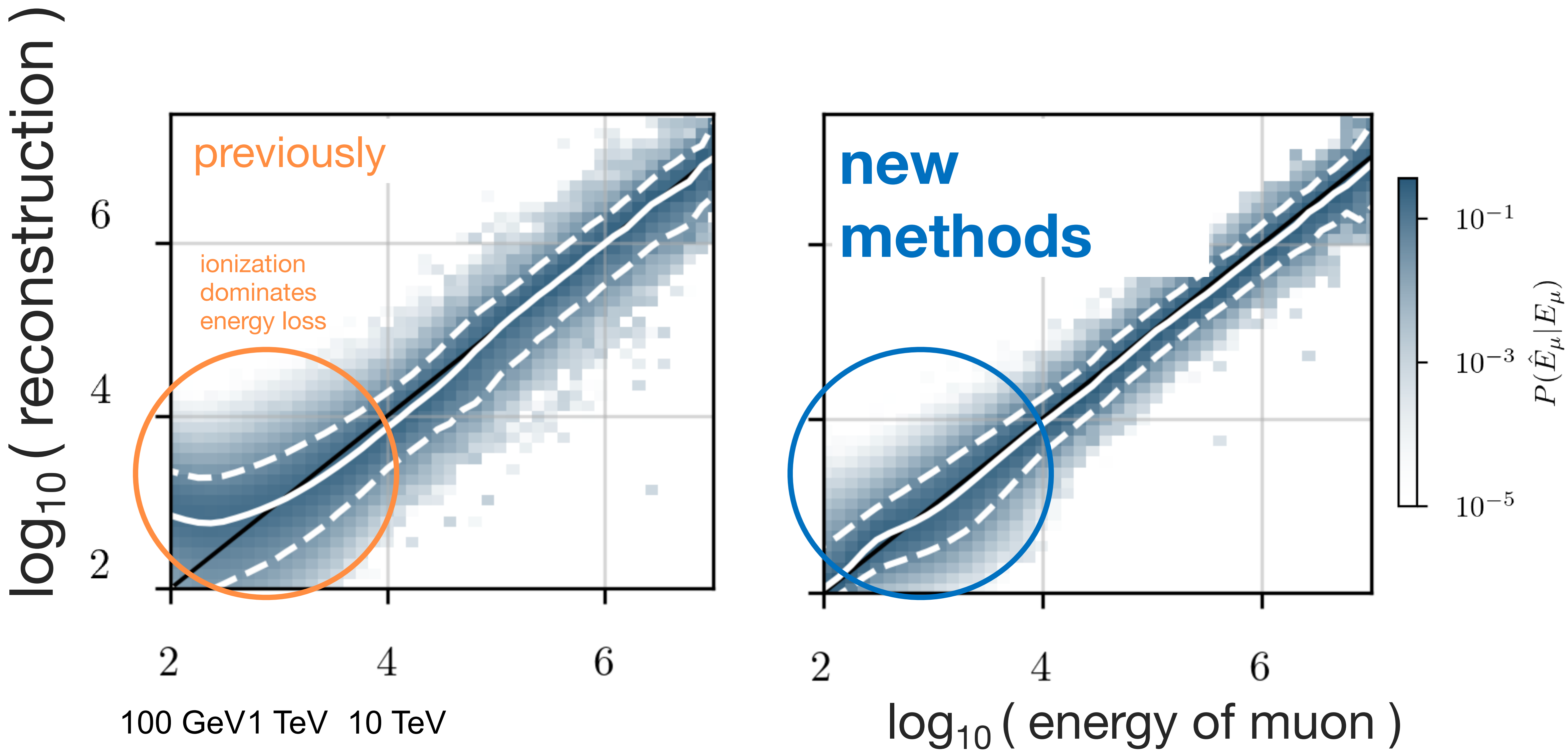
An improved track dataset
Angular uncertainty





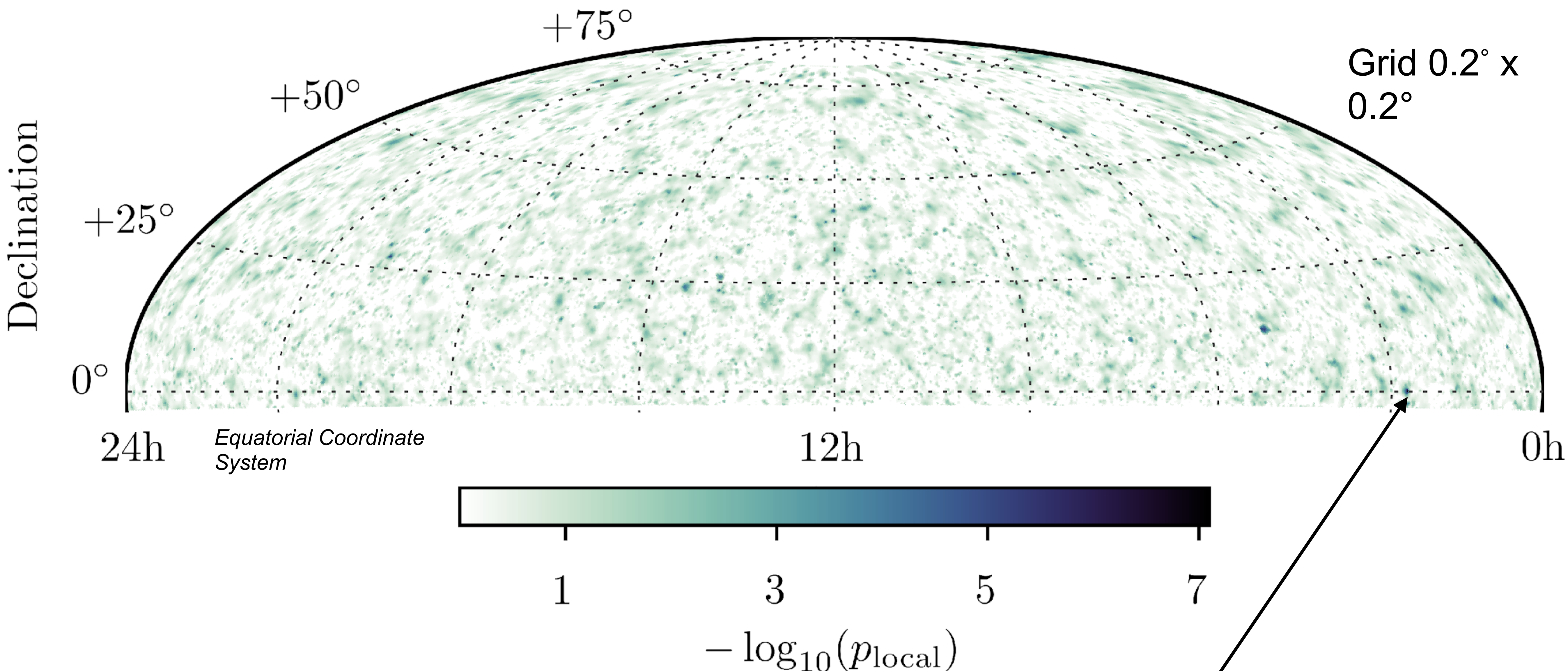
KDE methods used to better quantify expected angular spread of signal events

An improved track dataset
Energy reconstruction



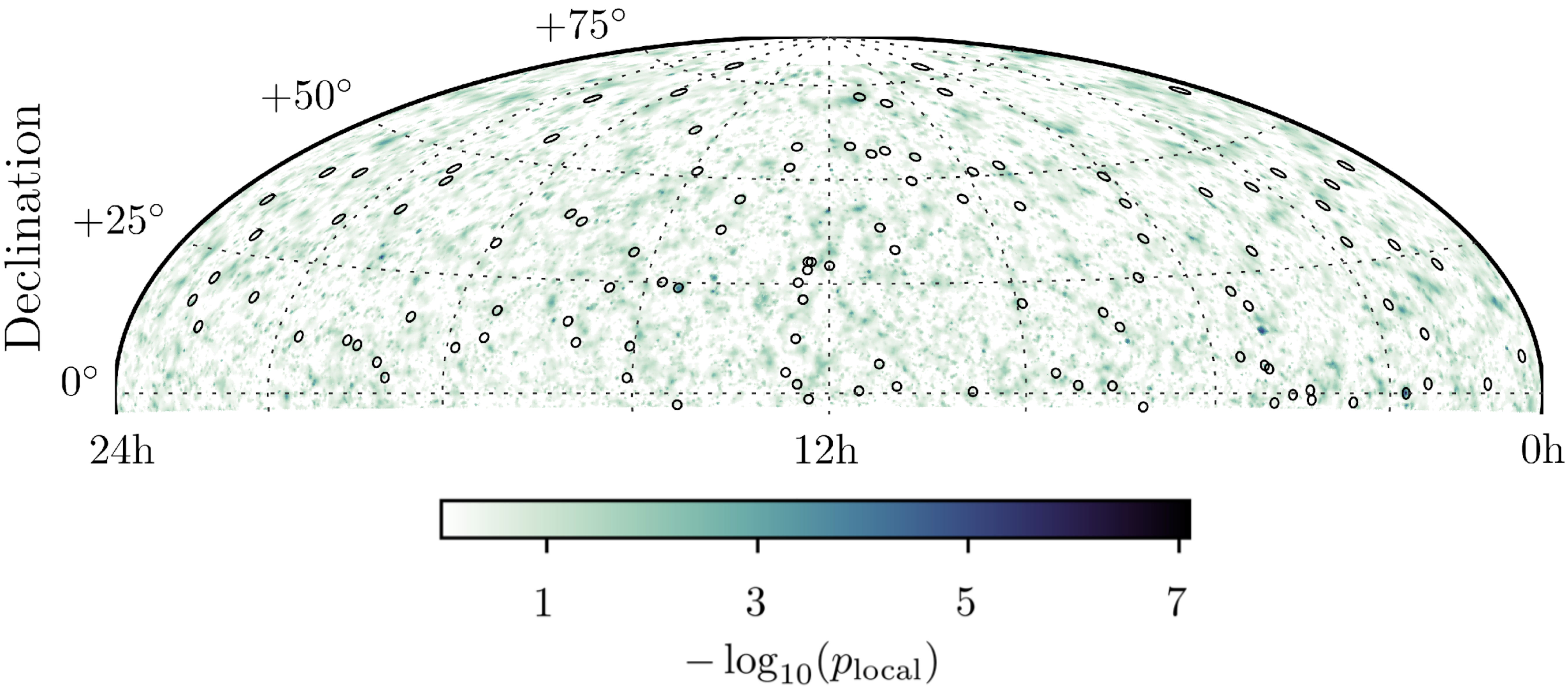
New machine learning techniques provide more accurate energy estimates, especially at TeV-energies

Updated IceCube neutrino sky



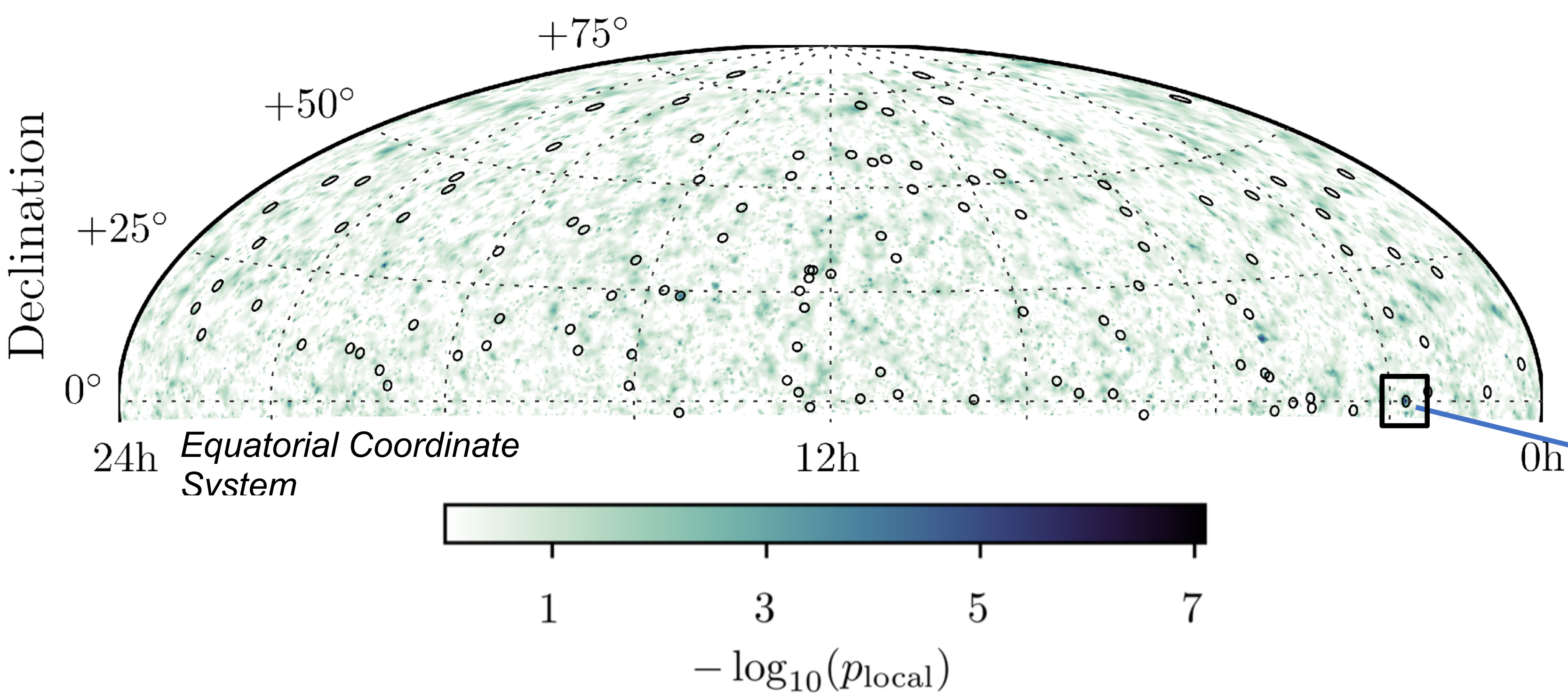
Hottest spot all sky
Local p-value: 5×10^{-8}
After accounting for trials searching entire sky: **2.0σ**

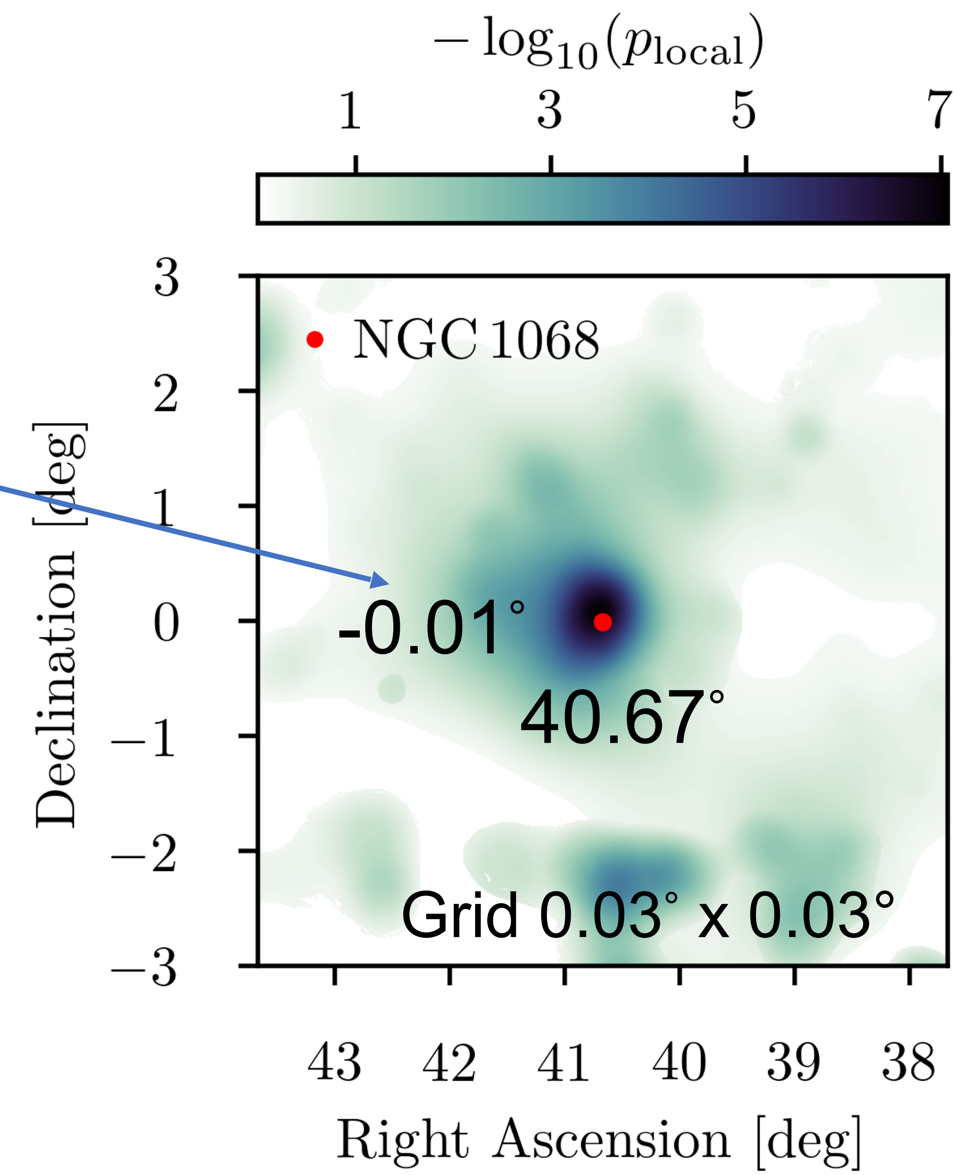
Catalog of known high-energy sources



110 candidate sources defined a-priori

Hottest spot coincides with NGC 1068



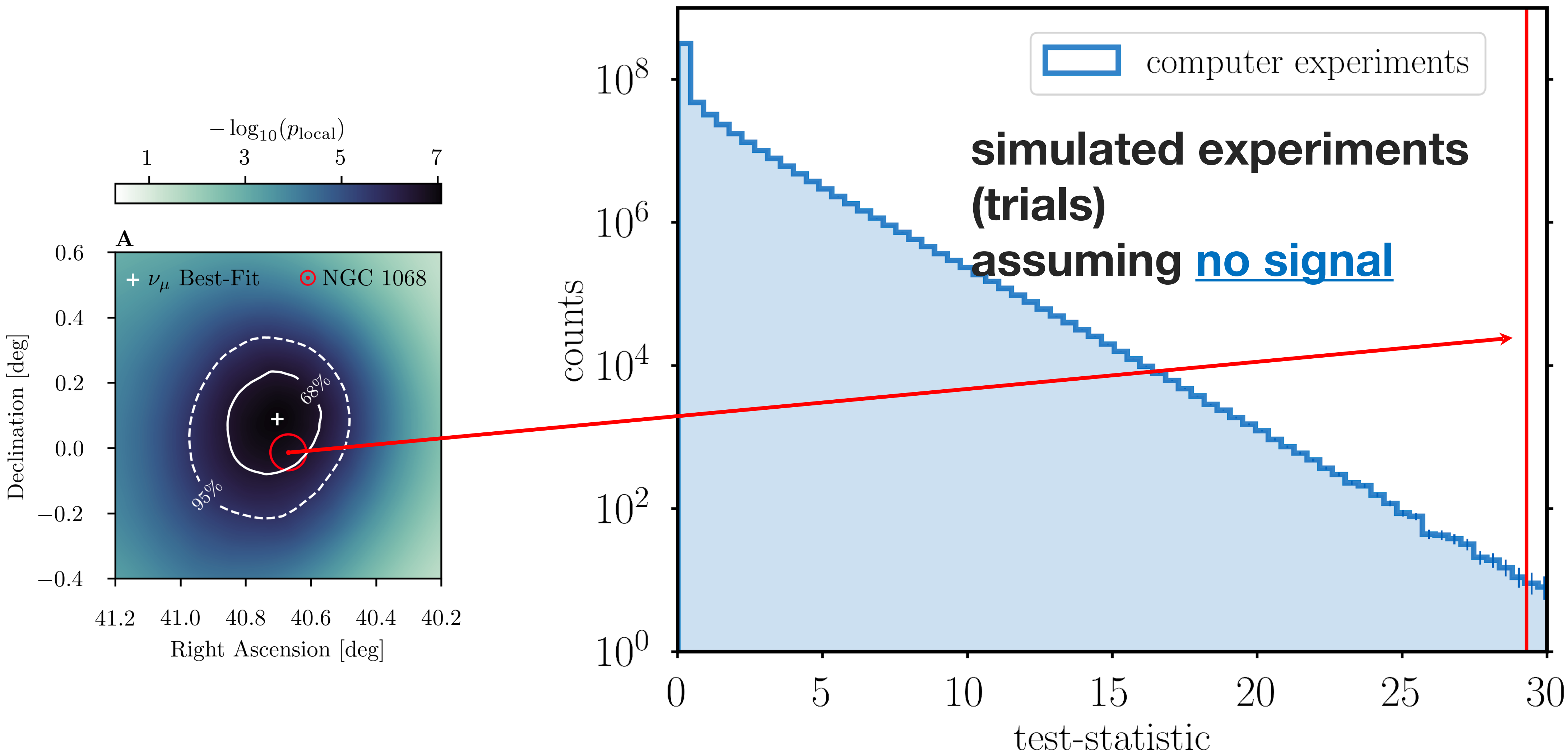


At the NGC 1068 location:

Astrophysical neutrino events = 79^{+22}_{-20}

Spectral index = -3.2 ± 0.2

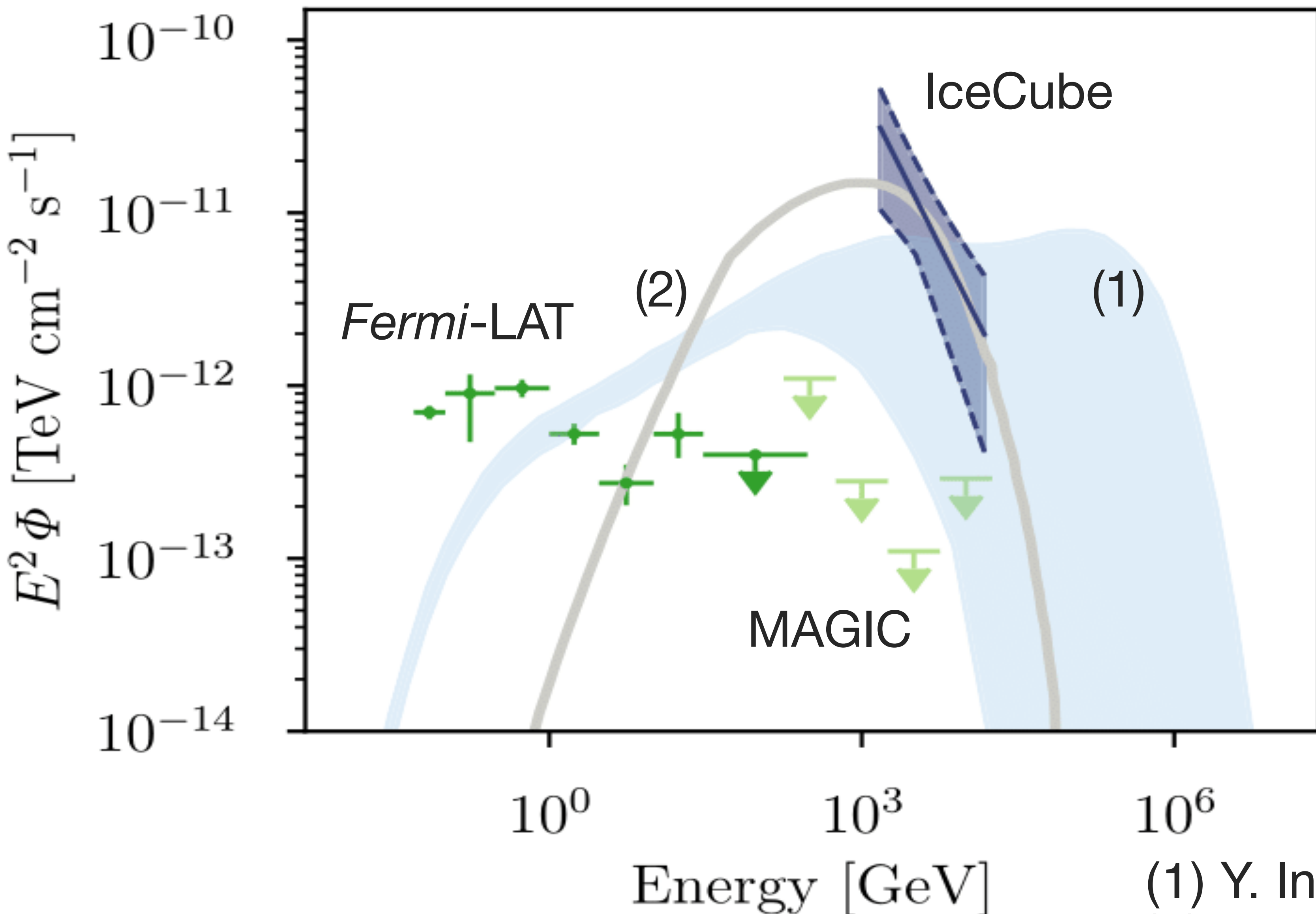
Hottest spot coincides with NGC 1068



Using 500 x 10^6 simulated experiments generated from simulated exp and accounting for catalog size (110 candidate sources) yields:

p-value: 1.1×10^{-5} (**4.2σ**)

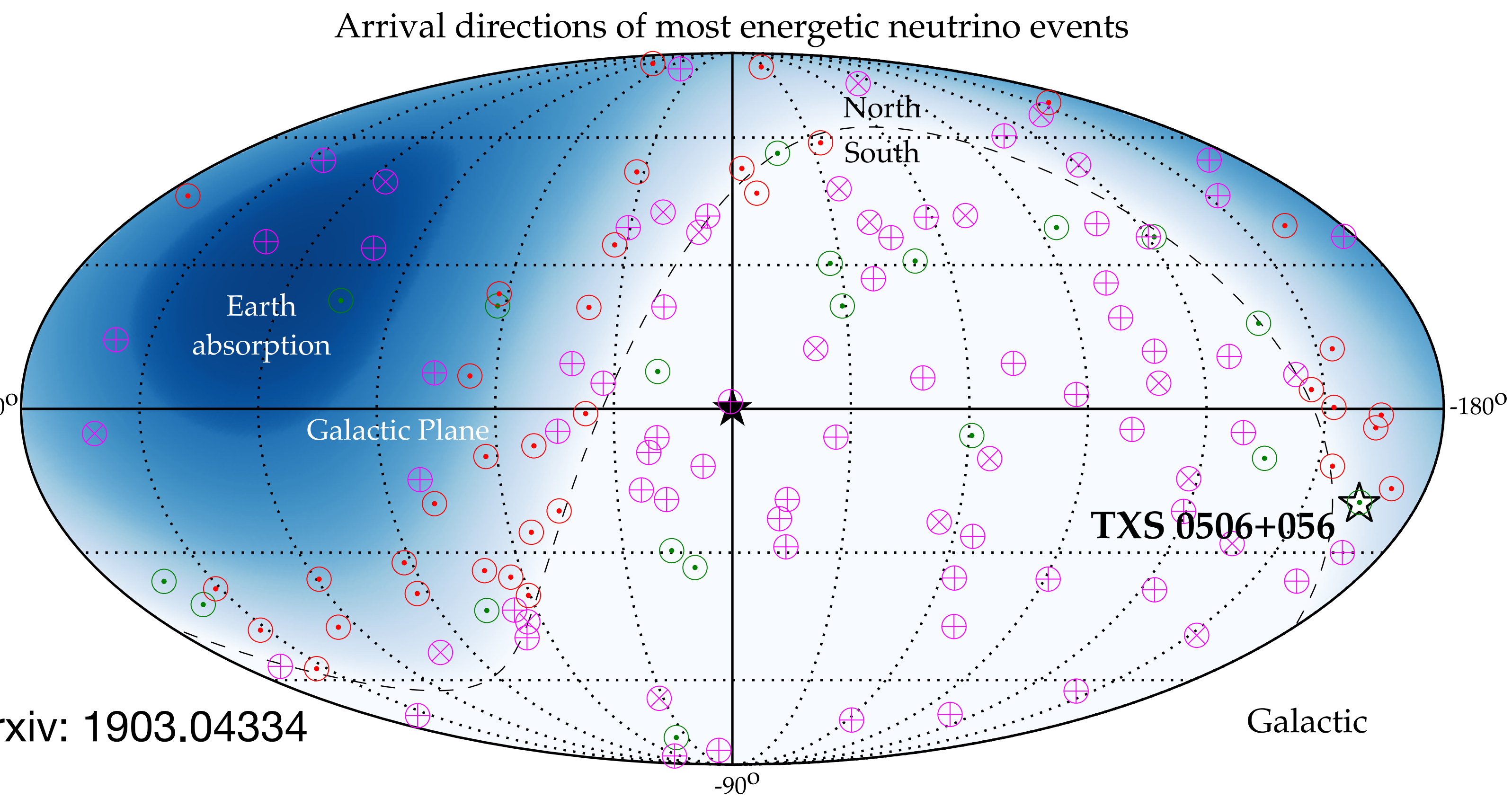
NGC 1068 - Multimessenger observations



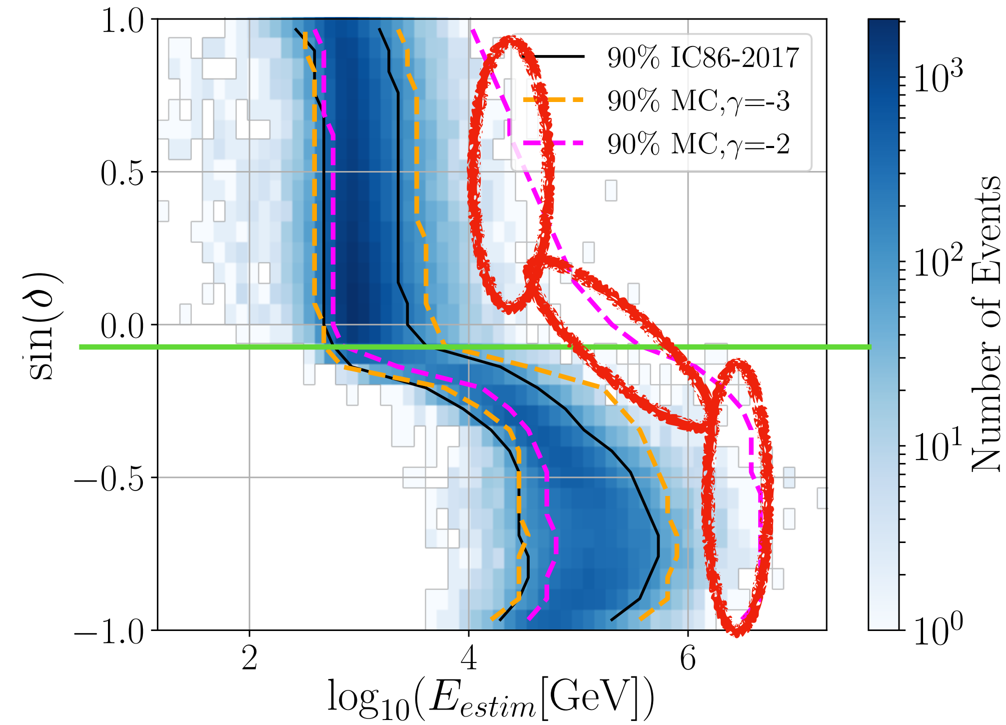
(1) Y. Inoue et al., ApJL'20
(2) K. Murase et al., PRL'20

NGC 1068 - long-studied, nearby AGN
Intense photon fields near AGN core modeled to prevent a strong gamma-ray signal and provide targets for p-γ neutrino production

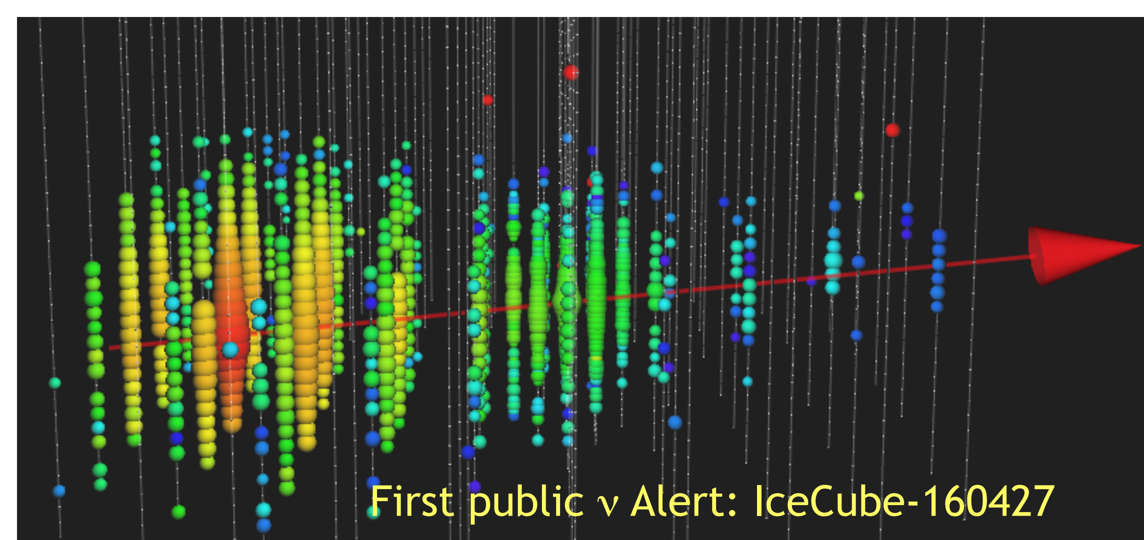
IceCube Astrophysical neutrino alerts



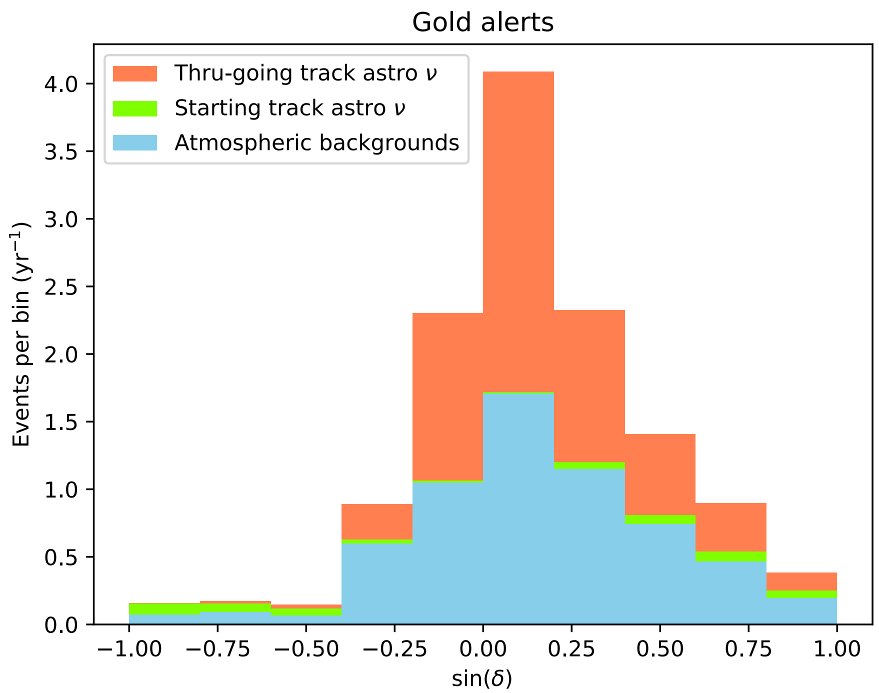
arxiv: 1903.04334

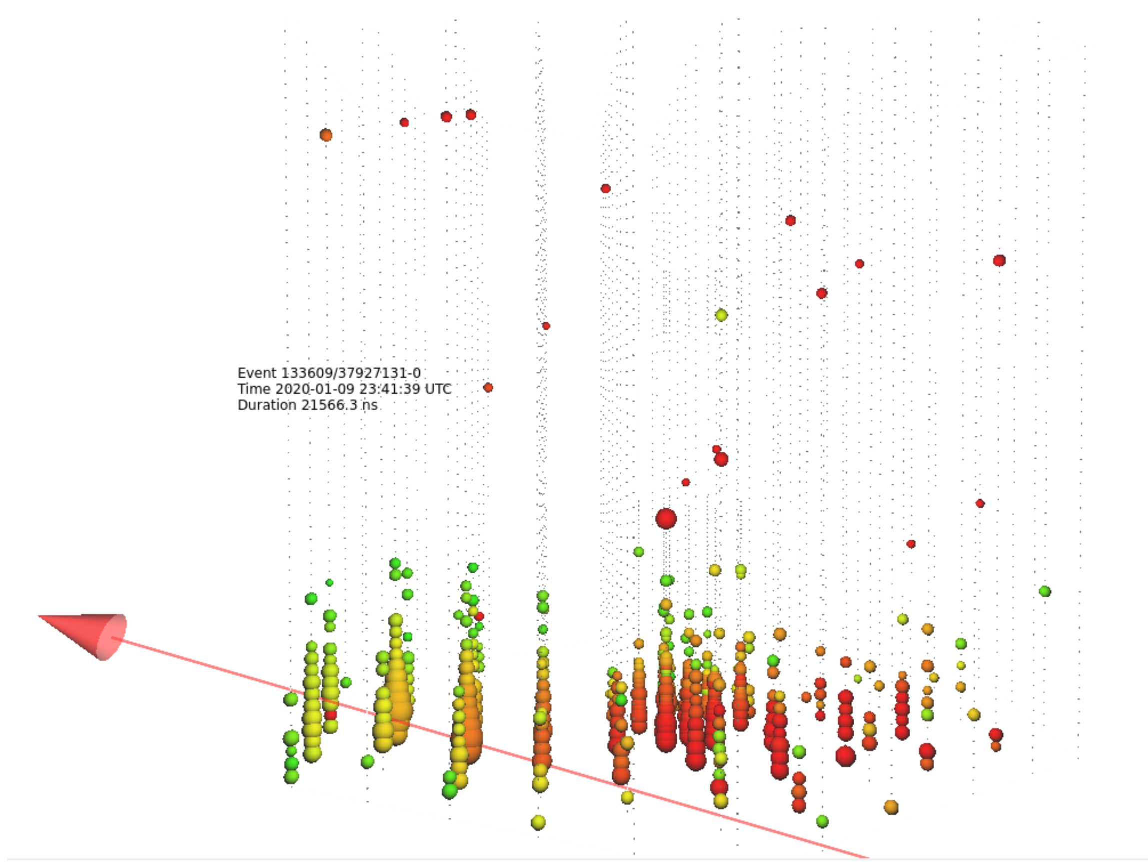


- Identify well reconstructed, high-energy neutrino candidates in real-time
- Transmit them to the North and advertise
    - Latency from detection to alert typically less than 1 minute
- Community observations to search for multi-messenger signals
- In operation since April 2016

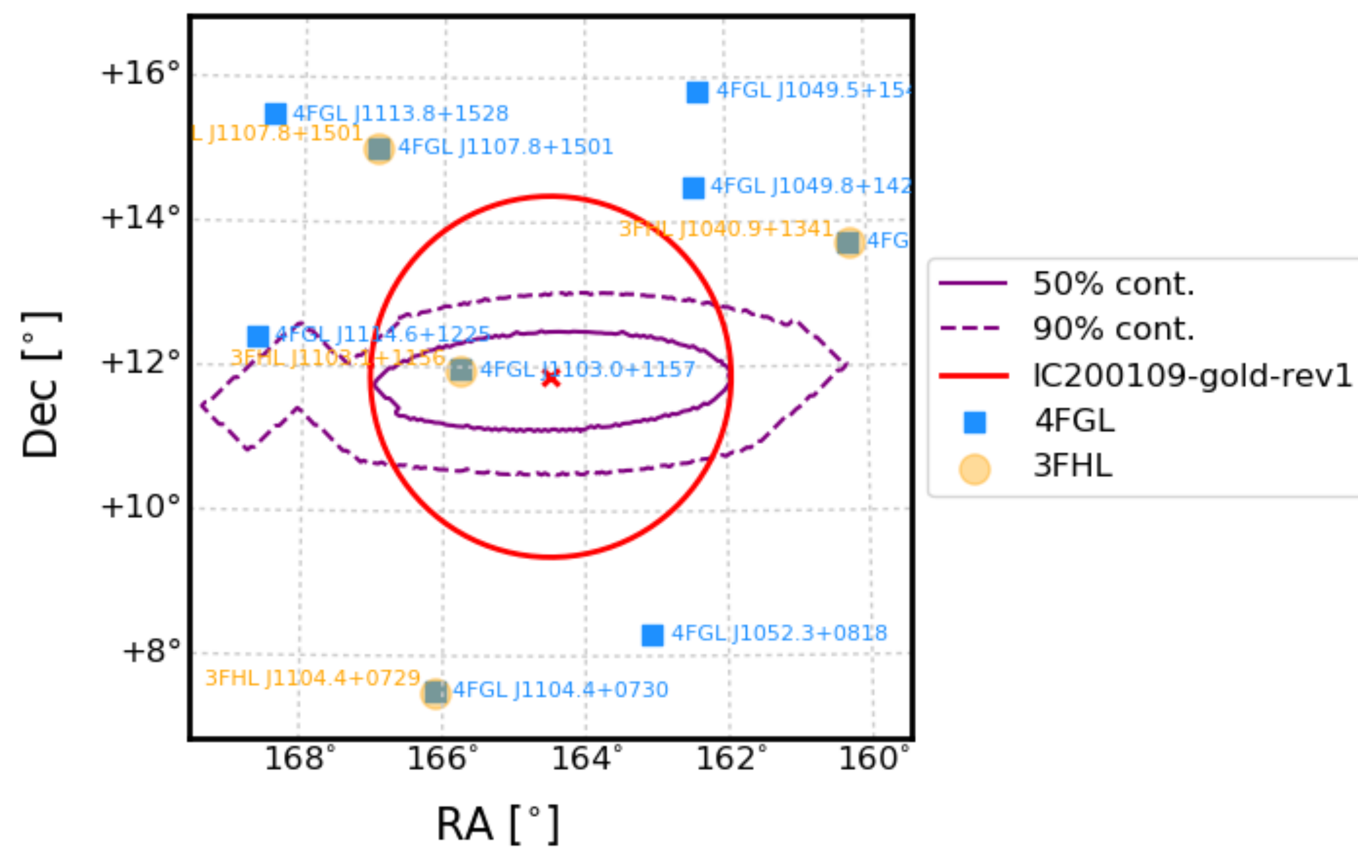


IceCube Realtime Track Alerts





- Expanded and improved alert selection compared to first alert selection since 2019
- 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

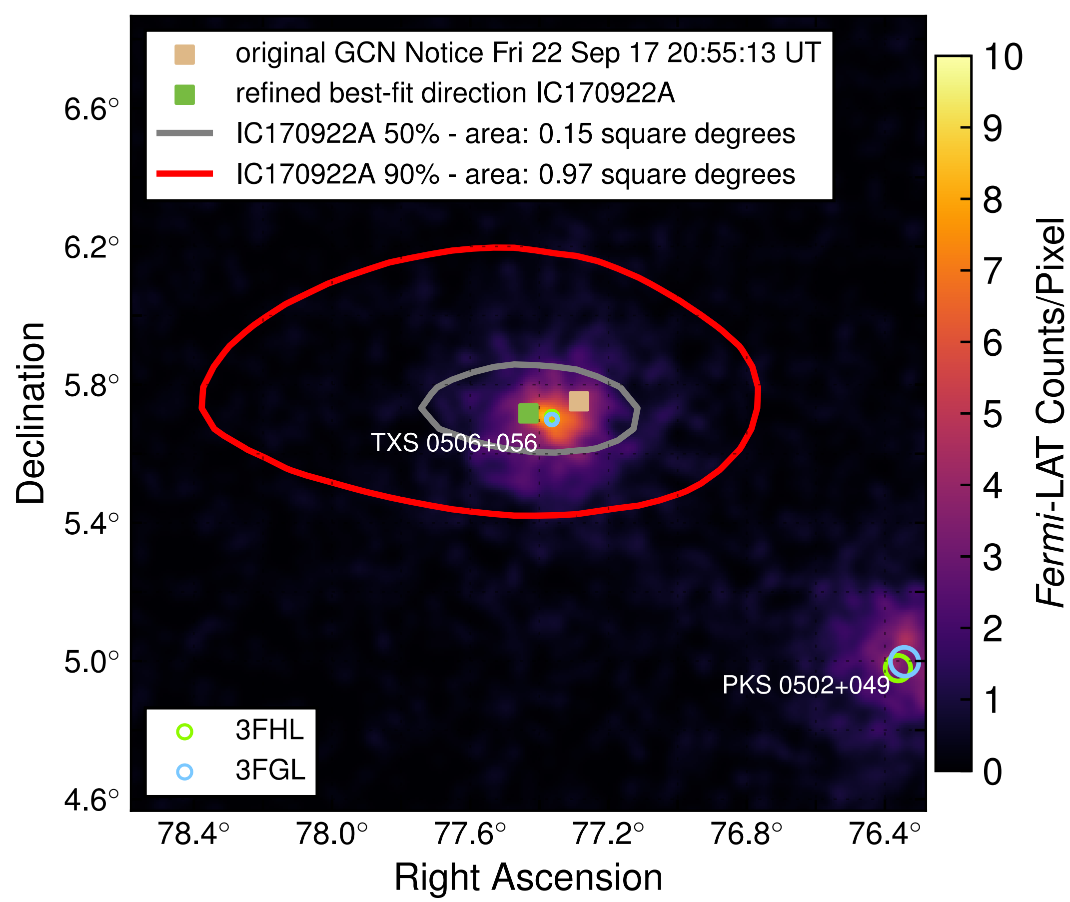


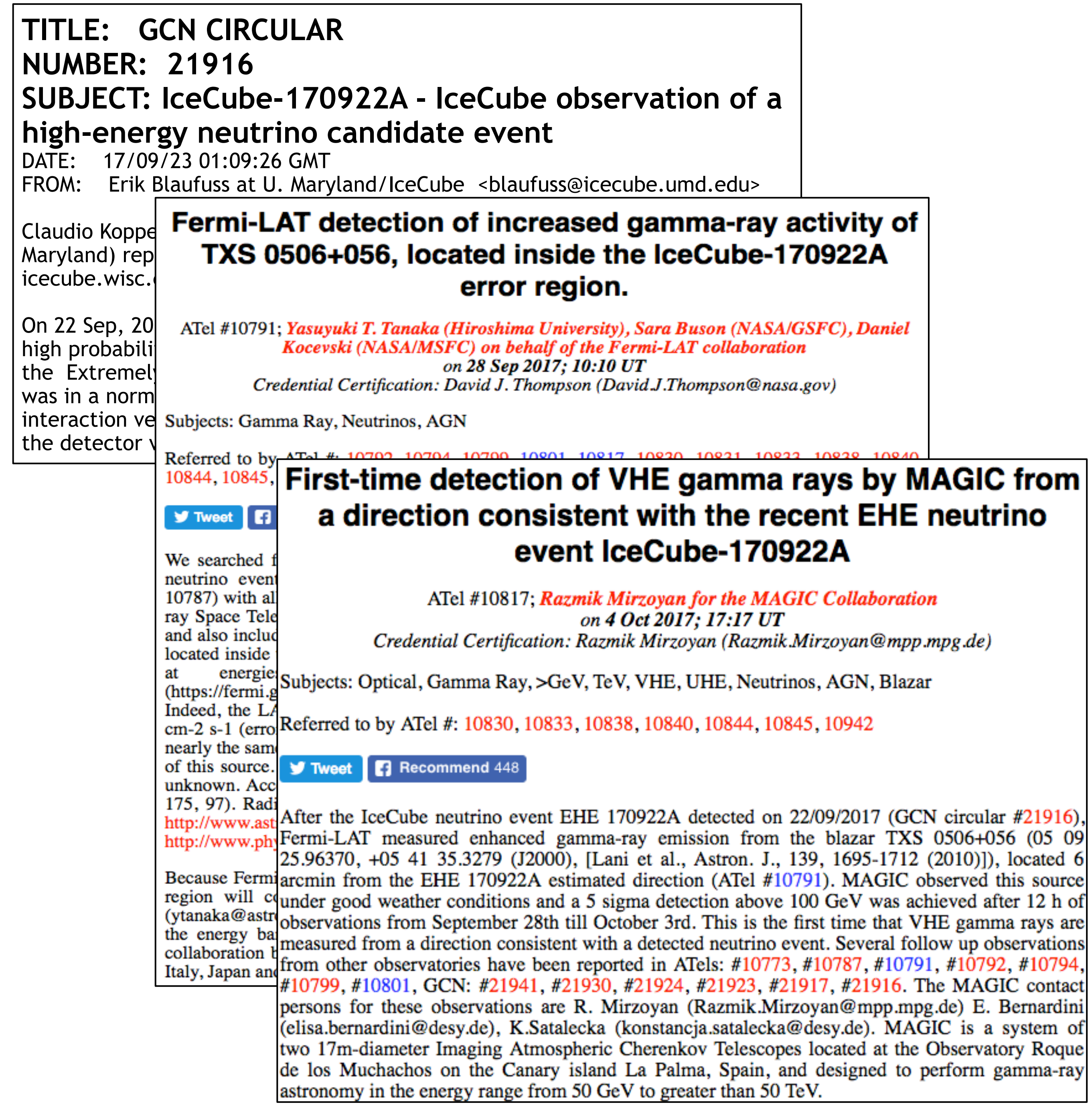
IceCat-1 https://arxiv.org/abs/2304.01174

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… high probabili… the Extremel… 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 … 10844, 10845, …

Tweet

We searched f… neutrino event… 10787) with al… ray Space Tele… and also inclu… located inside … at energie… (https://fermi.g… Indeed, the LA… cm-2 s-1 (erro… nearly the sam… of this source. … unknown. Acc… 175, 97). Radi… http://www.ast… http://www.ph…

Because Fermi… region will c… (ytanaka@astr… the energy ba… collaboration … Italy, Japan an…

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.

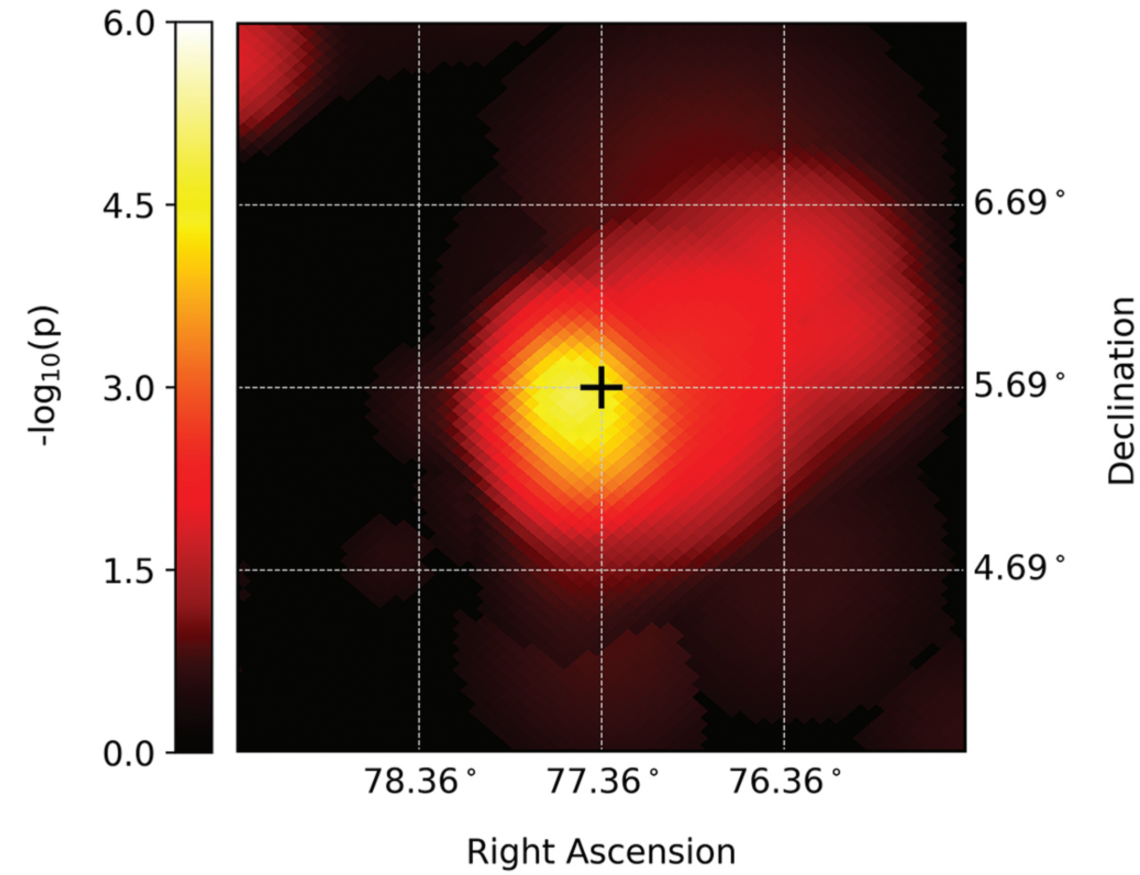
Published: Science 361 (2018)

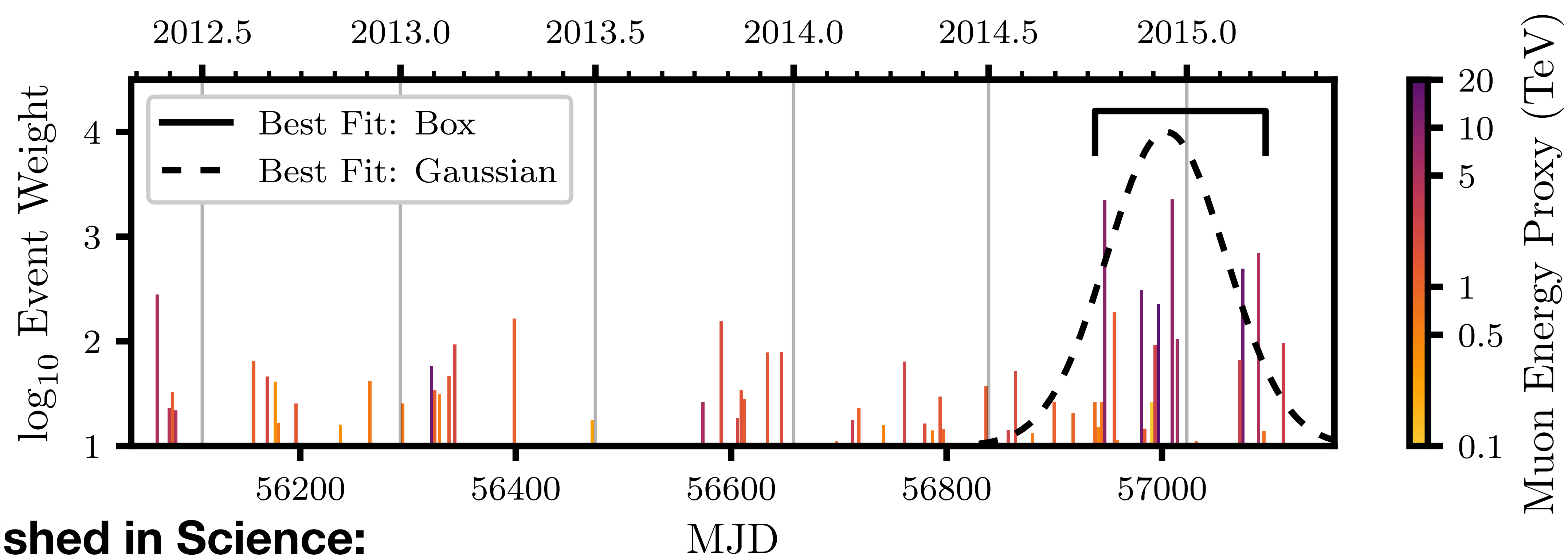
IceCube point source search: TXS 0506+056

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

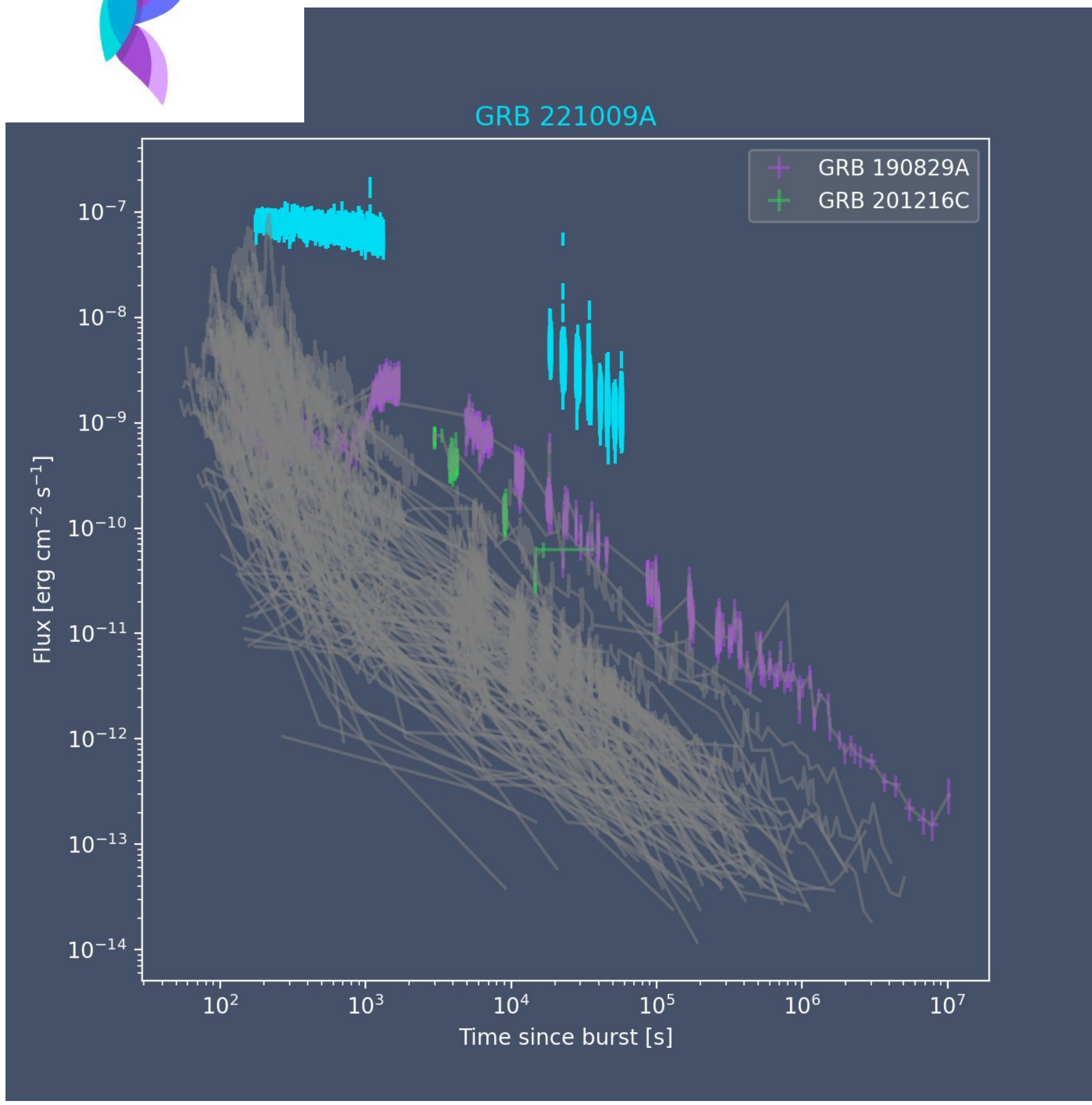




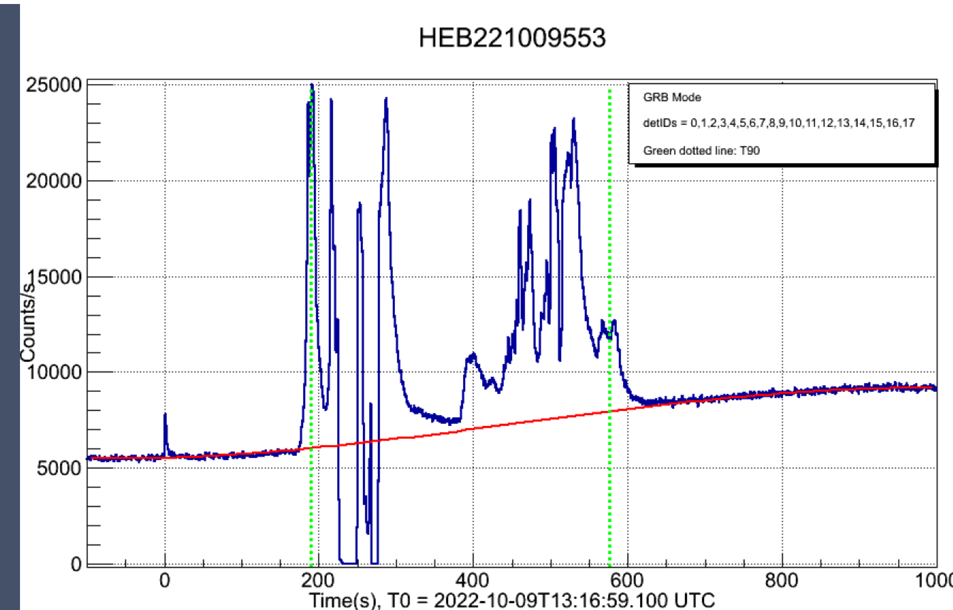
Published in Science:
IceCube Coll. Science 361 (2018) 147

GRB221009A - A nearby, bright GRB

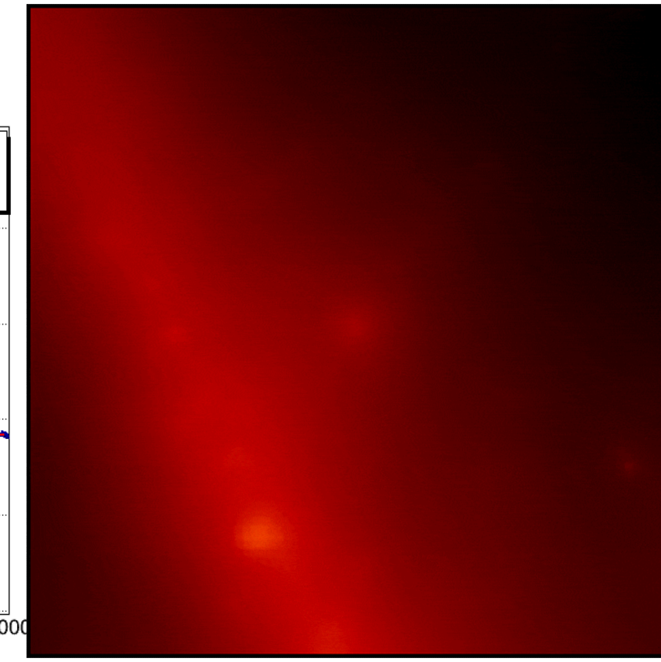
@AstroColibri



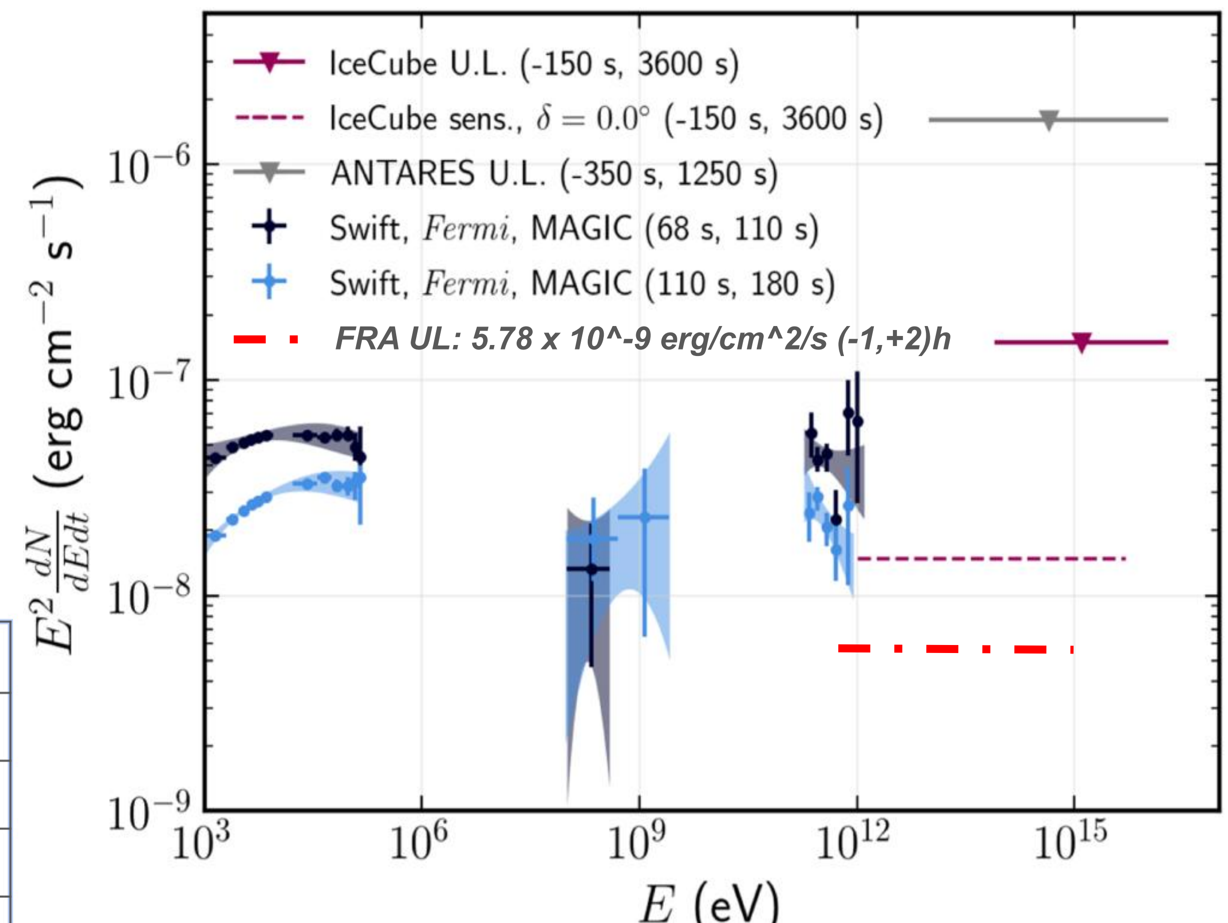
Swift XRT GRB observations



ATEL 15660



Fermi LAT nasa.gov



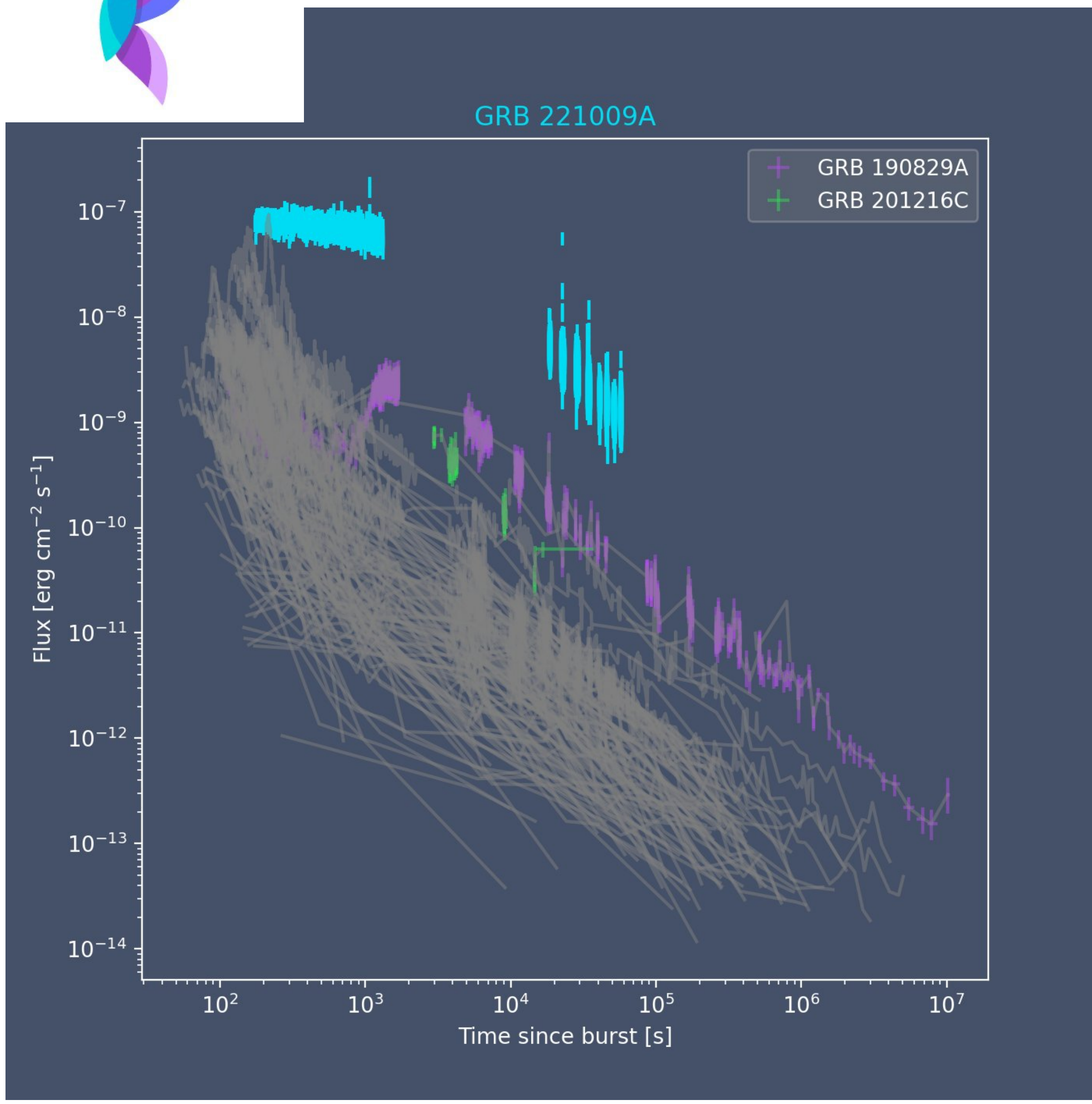
Plot from R. Abbasi *et al* 2021 *ApJ* **910** 4 (GRB 190114C)

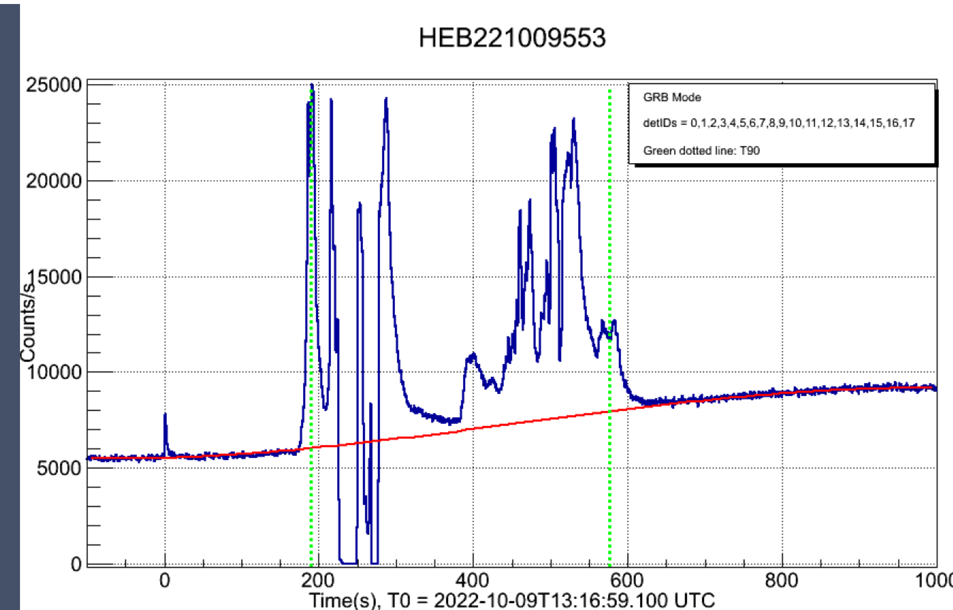
Right Ascension	288.263
Declination	+19.803
z	0.151 (GCN 32648)
T0	09 October 2022 13:16:59.99 UTC
T90 (Fermi-GBM Burst Cat.)	325.8 +/- 6.8 s

J. Thwaites - IceCube

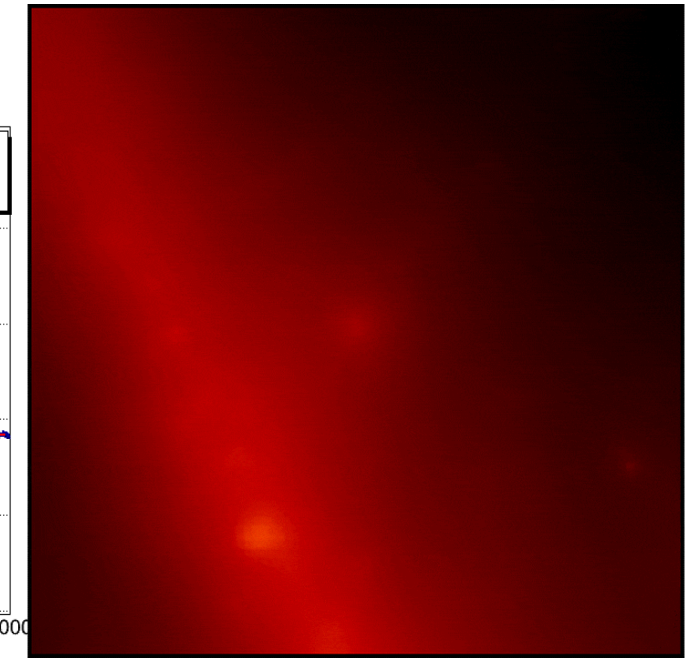
GRB221009A - A nearby, bright GRB

@AstroColibri

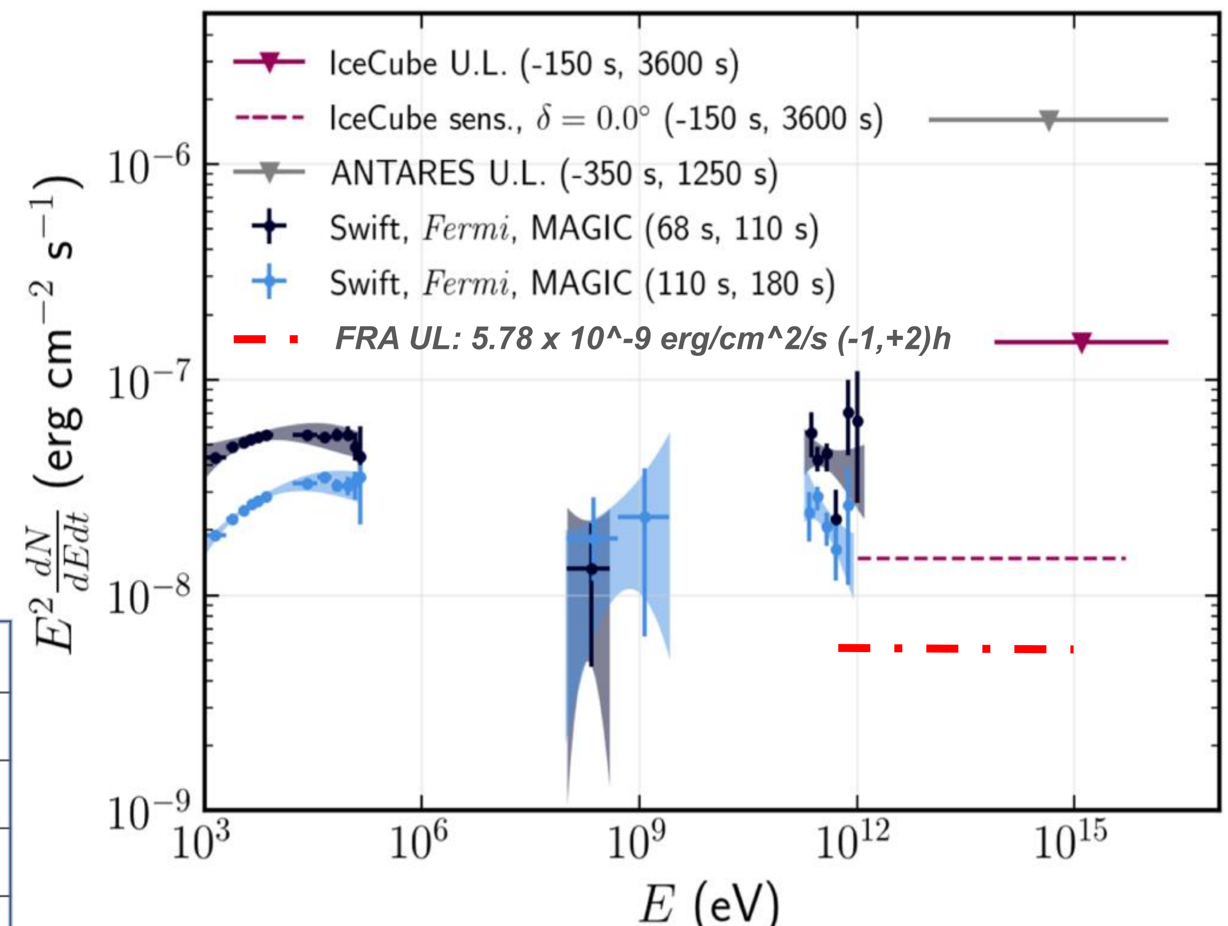




ATEL 15660



Fermi LAT nasa.gov



Swift XRT GRB observations

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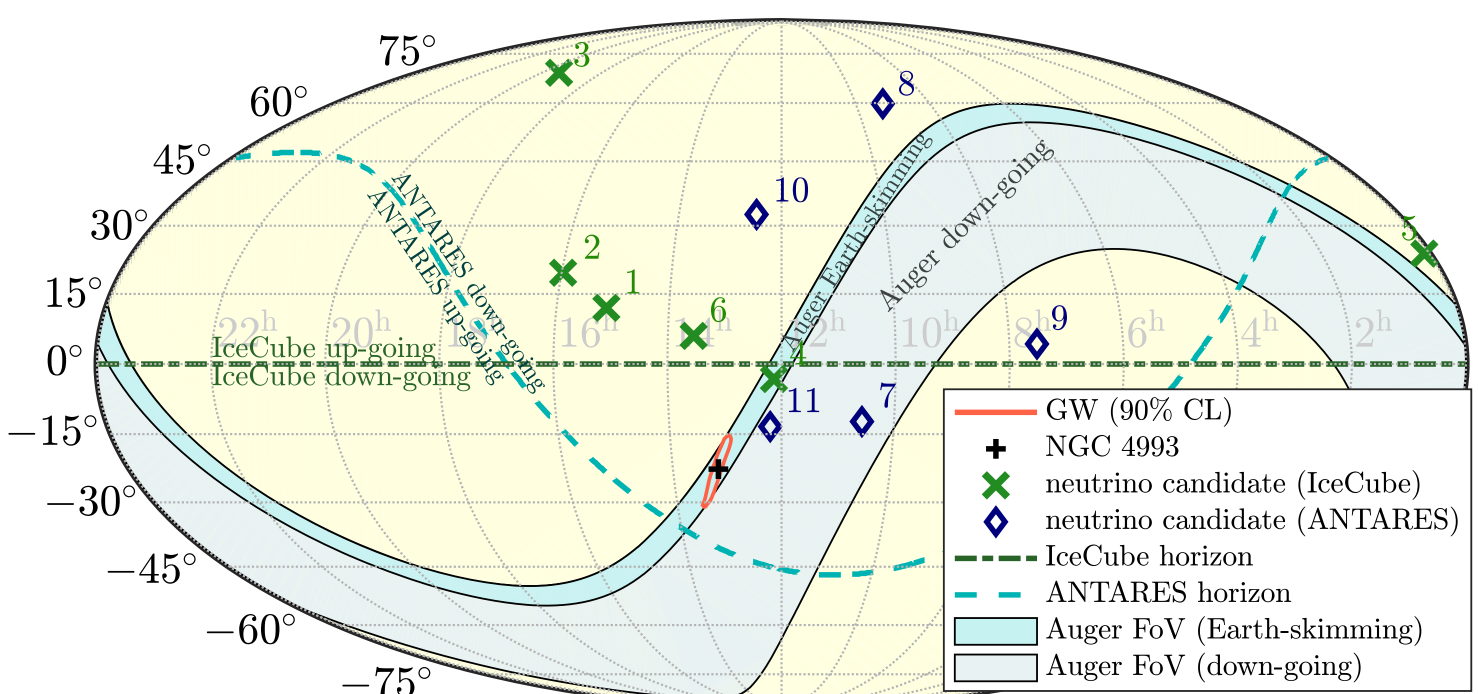
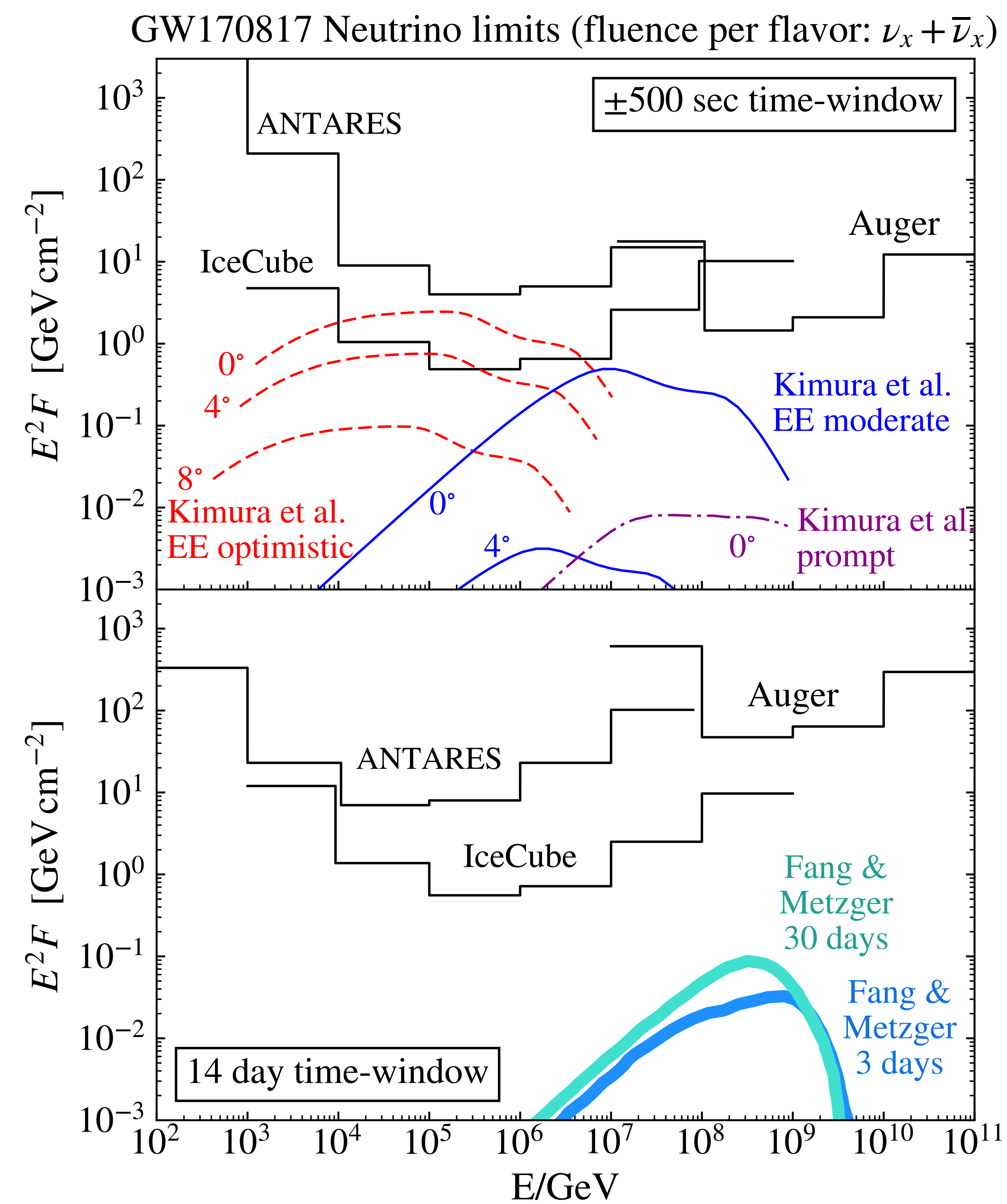
Plot from R. Abbasi *et al* 2021 *ApJ* **910** 4 (GRB 190114C)

J. Thwaites - IceCube

TOO: 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
- Realtime searches for neutrinos in Run O4 now ongoing



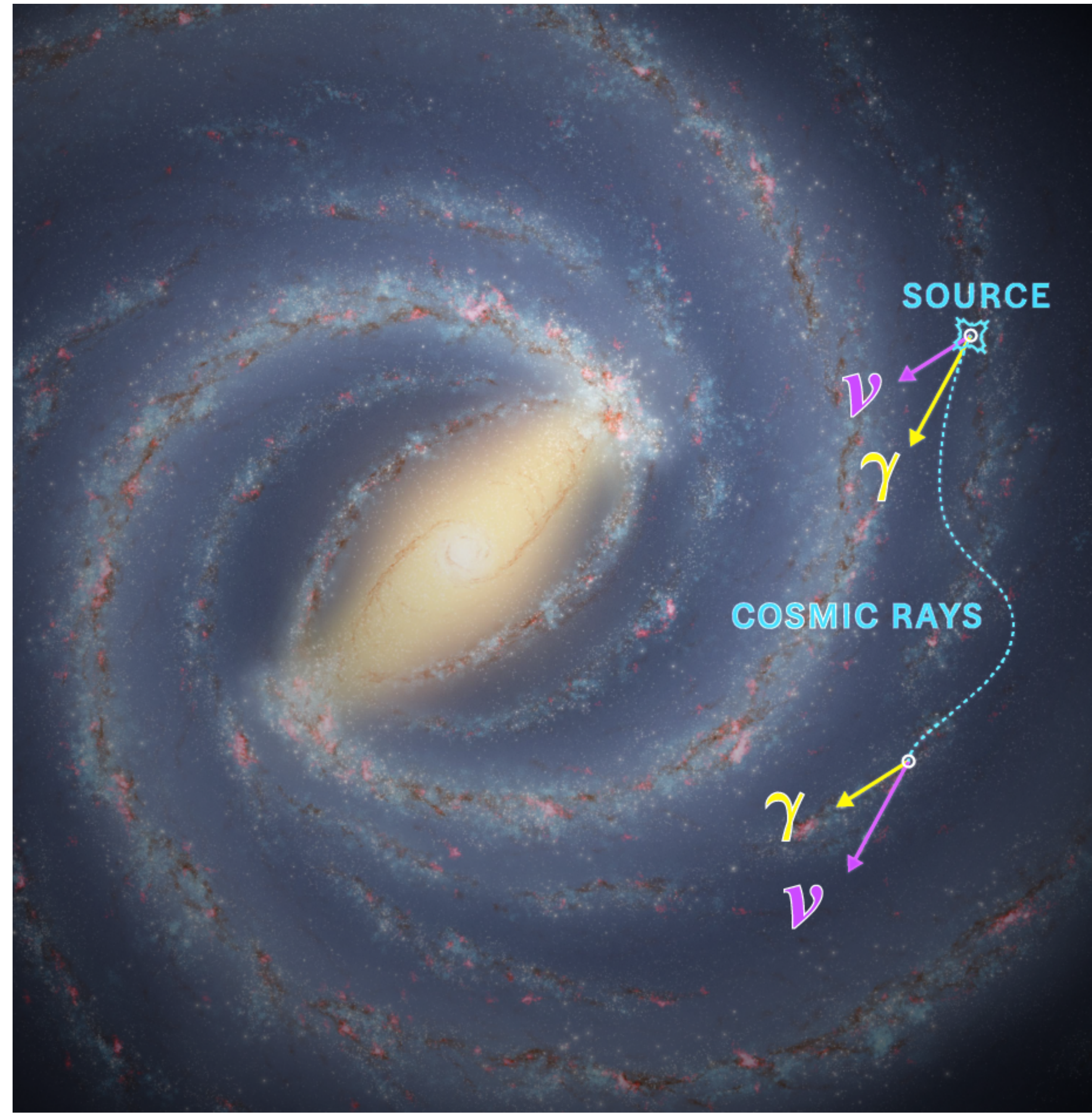


Astrophys.J. 850 (2017)

Galactic Neutrinos

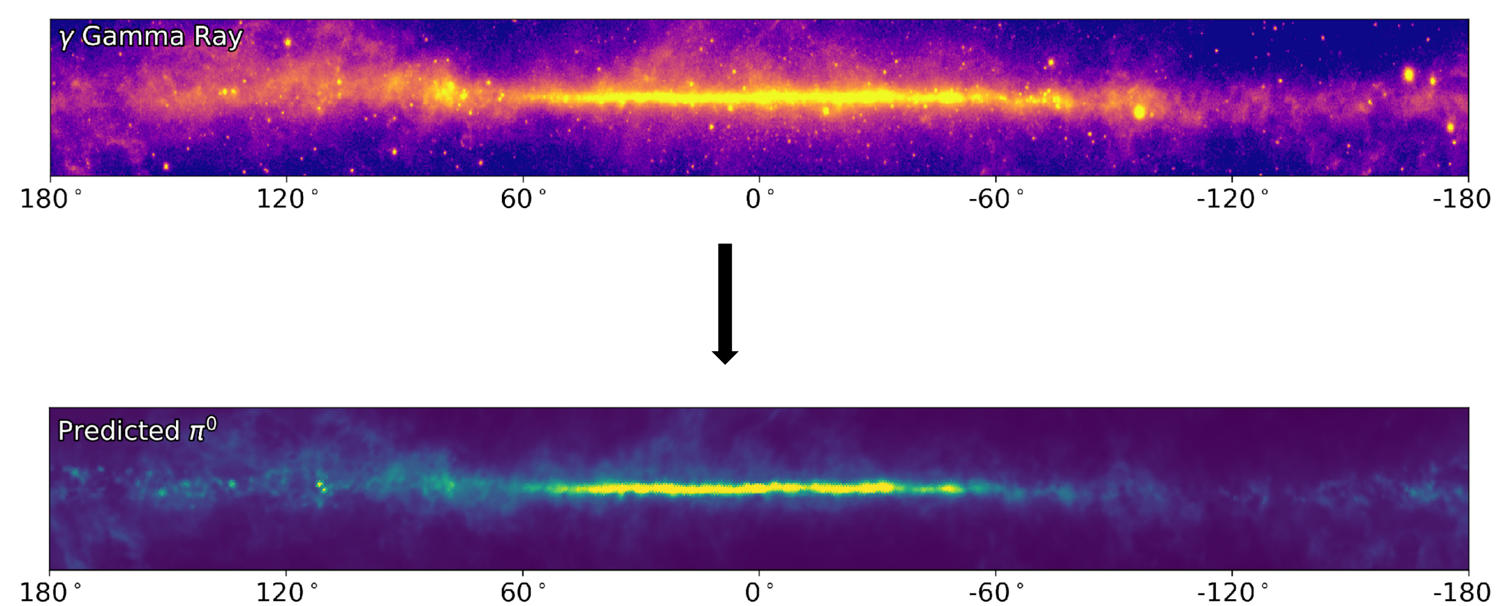
- Galactic neutrino sources
  - Cosmic ray accelerators
  - Not yet identified
  - Use gamma ray emission as a proxy

- Diffuse galactic neutrino emission
  - Cosmic ray measurement
  - Gamma ray measurements
  - Cosmic ray diffusion
  - Gas density



Diffuse Galactic Neutrinos

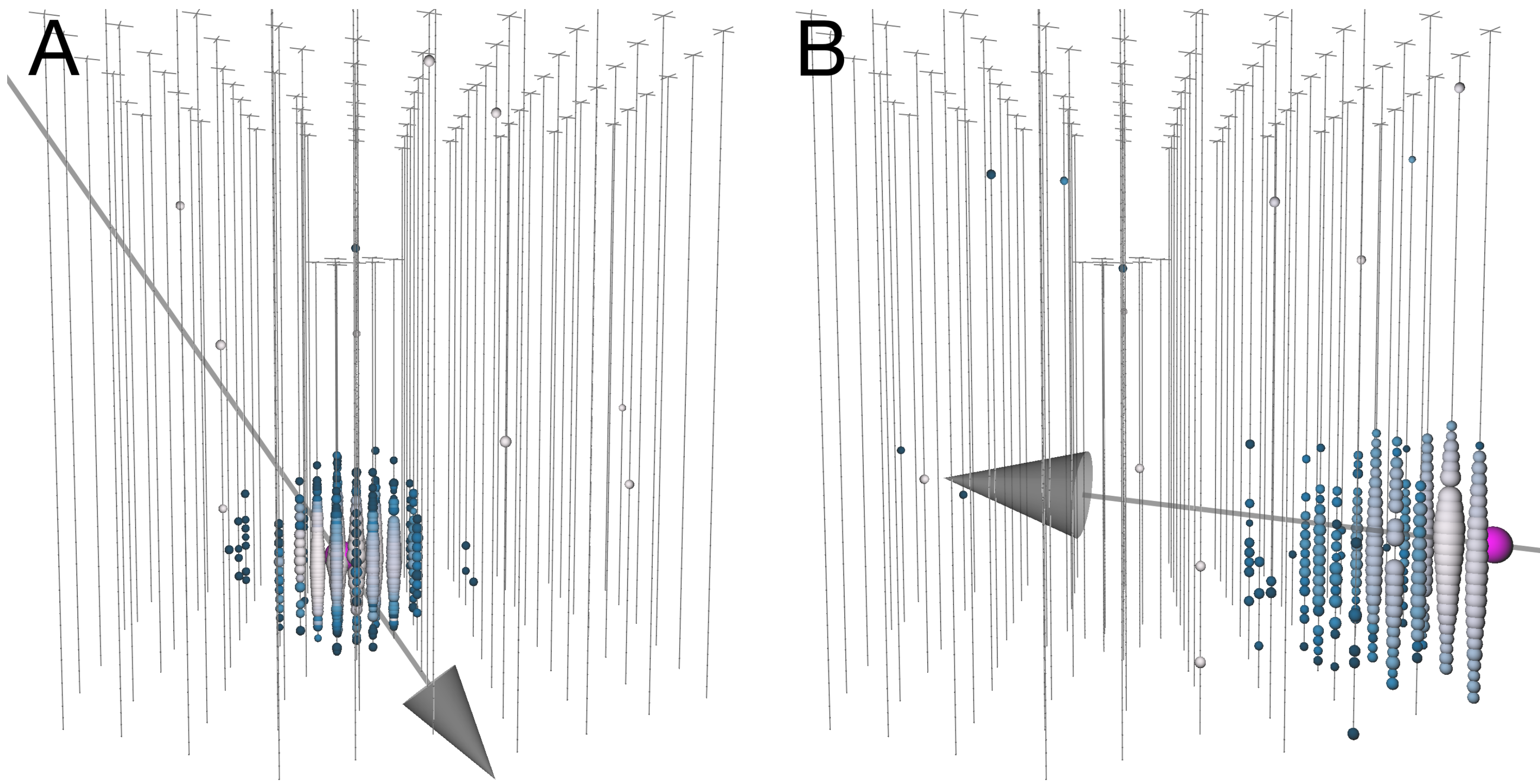
- Expected signal, but strength is low
- *Fermi*-LAT π^0 spectrum ($E^{-2.7}$)
  - Neutrinos expected from π^+/π^-
- Concentrated in southern sky
- Challenging region to probe for IceCube
- **How do we see the galaxy with any sensitivity?**



1. NASA/DOE/Fermi LAT Collaboration: https://svs.gsfc.nasa.gov/11342

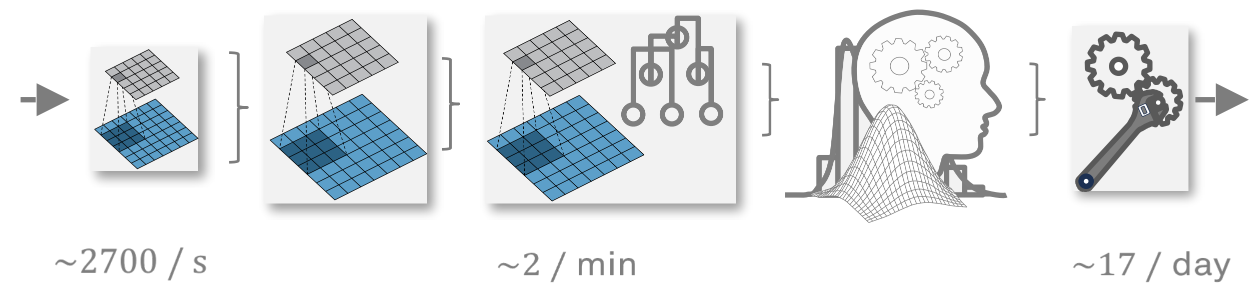
New Cascade Selection

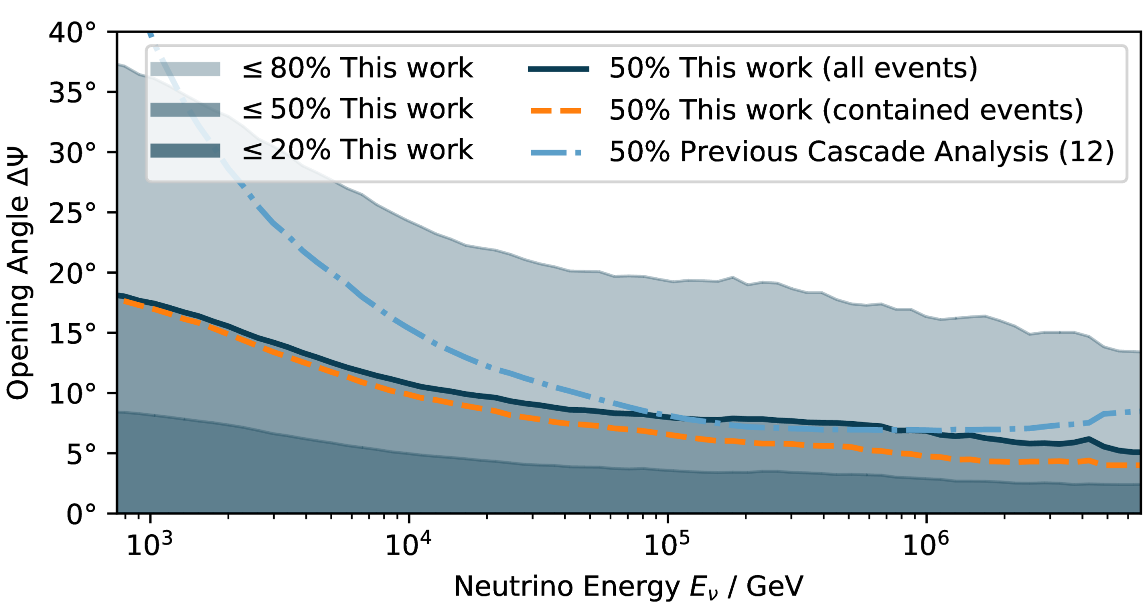
- Goals of a new selection:
  - Increase efficiency to low energy events by using ML
  - Take more events at high energy that aren't fully contained
  - **Tailor background cuts at final level to galactic source sensitivity**

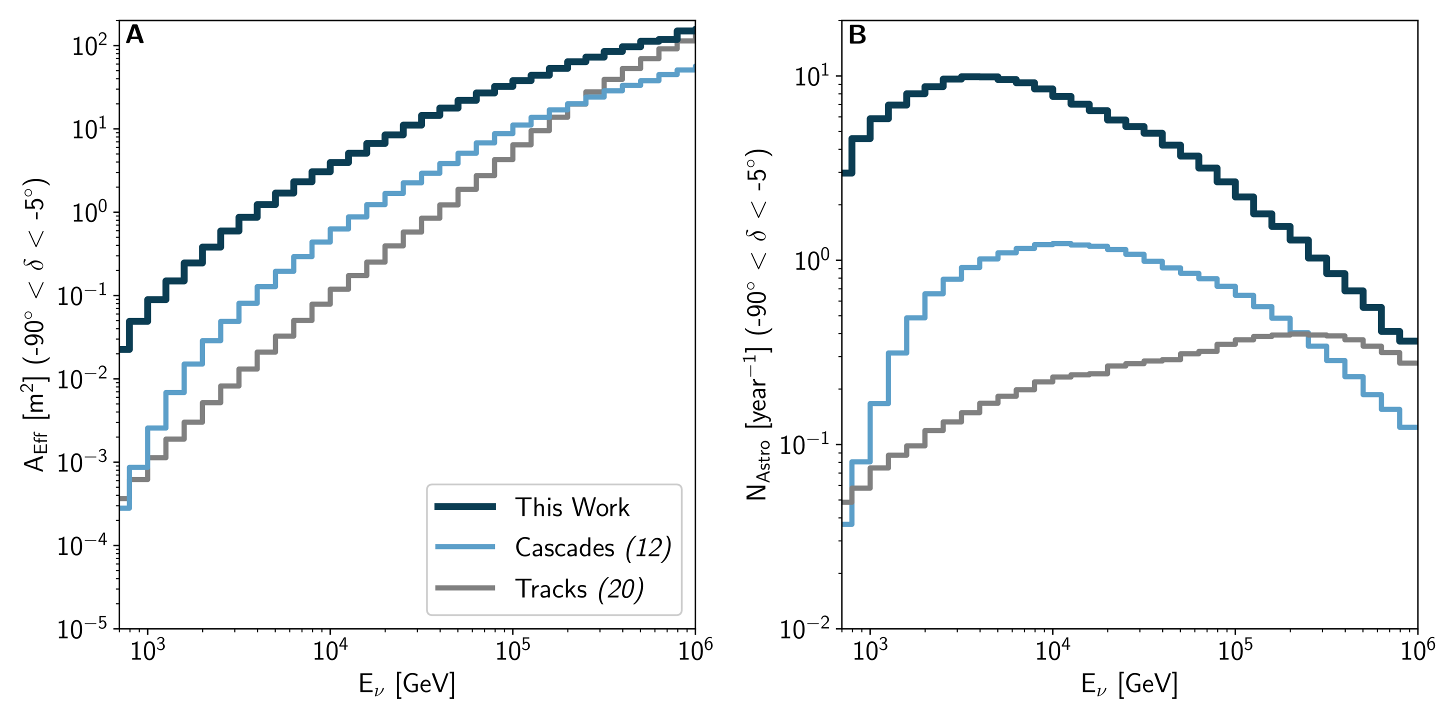


Analysis Level Sample

- 10 years of cascade-like events
  - Machine learning selection and reconstruction
  - 60,000 events
  - 30x more events than previous cascade selection
- Improved angular resolution
- **3-4x Sensitivity**







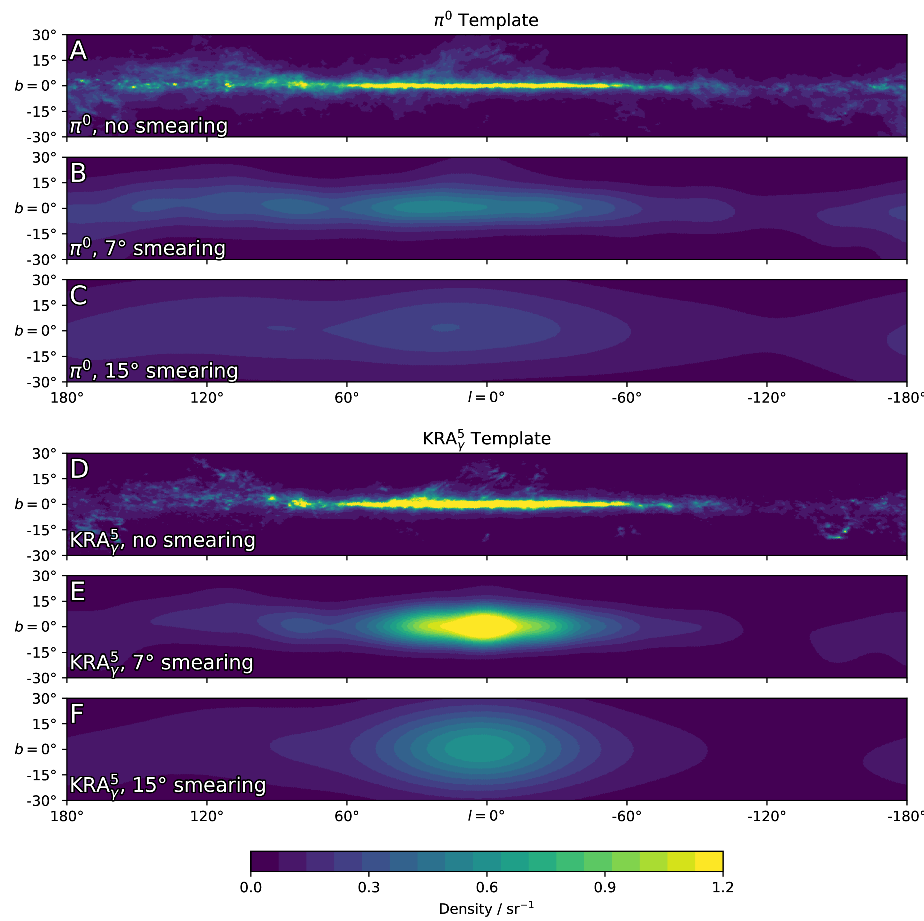
IceCube Collaboration*† *Science* **380**,6652 1338-1343(2023).DOI:10.1126/science.adc9818

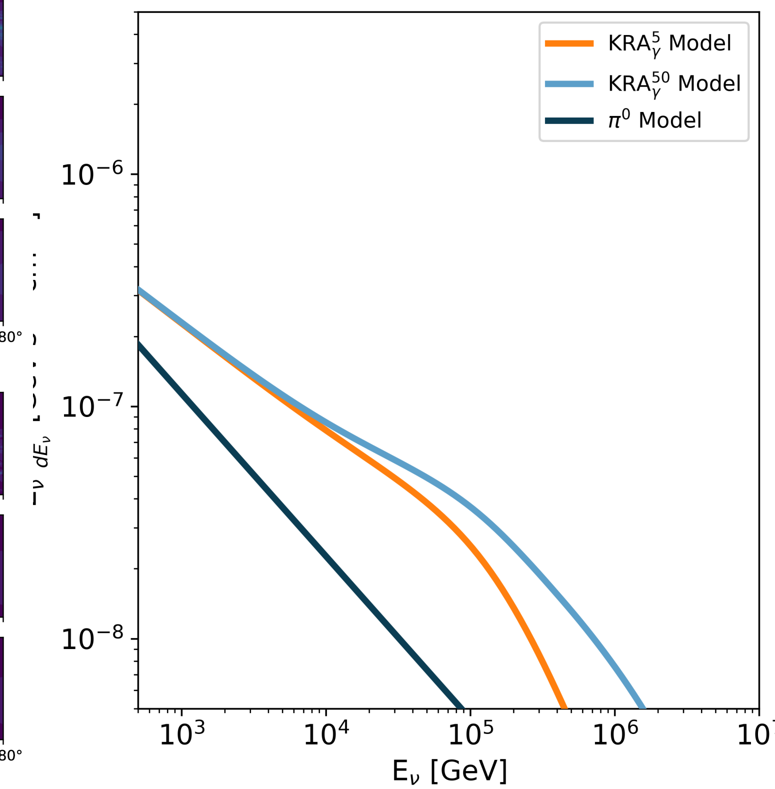
IceCube Collaboration, M. Huennefeld et al. PoS ICRC2021 (2021) 1065

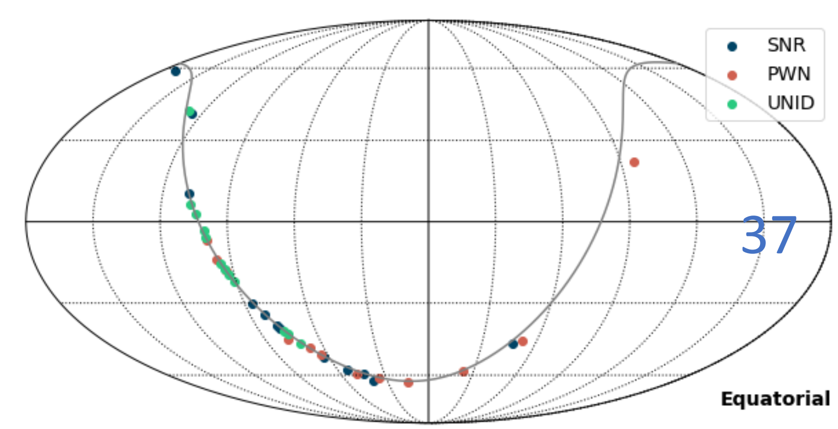
Models of Galactic Emission

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

- (3) diffuse models as spatial templates
  - Point Source → Template
  - (1) *Fermi* π^0
  - (2) KRA$_\gamma$
  - Fixed spectrum
  - Fit for flux normalization
- (3) stacking source searches
  - Supernova Remnants
  - Pulsar Wind Nebulae
  - Unidentified Gamma-Ray Sources





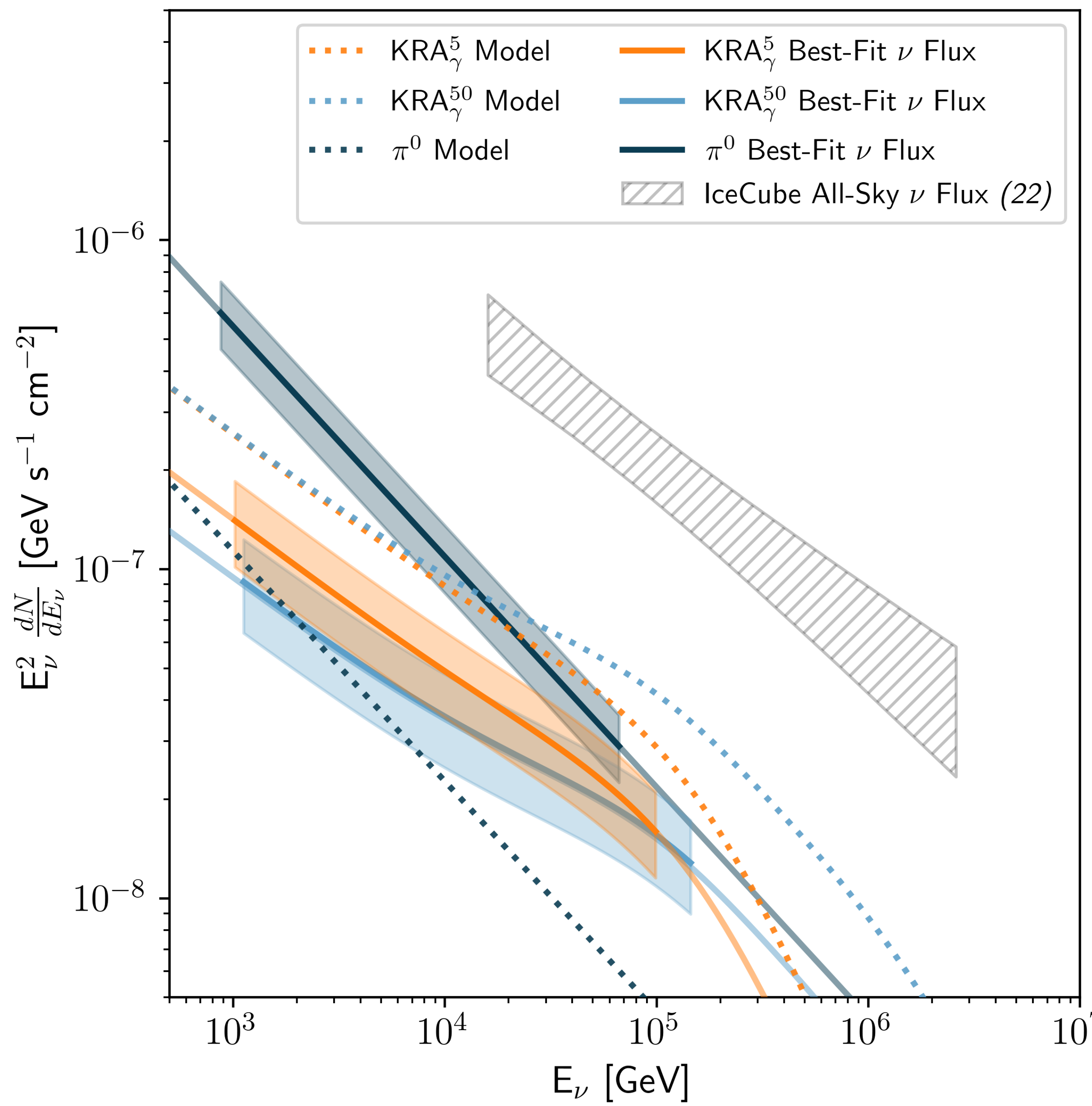


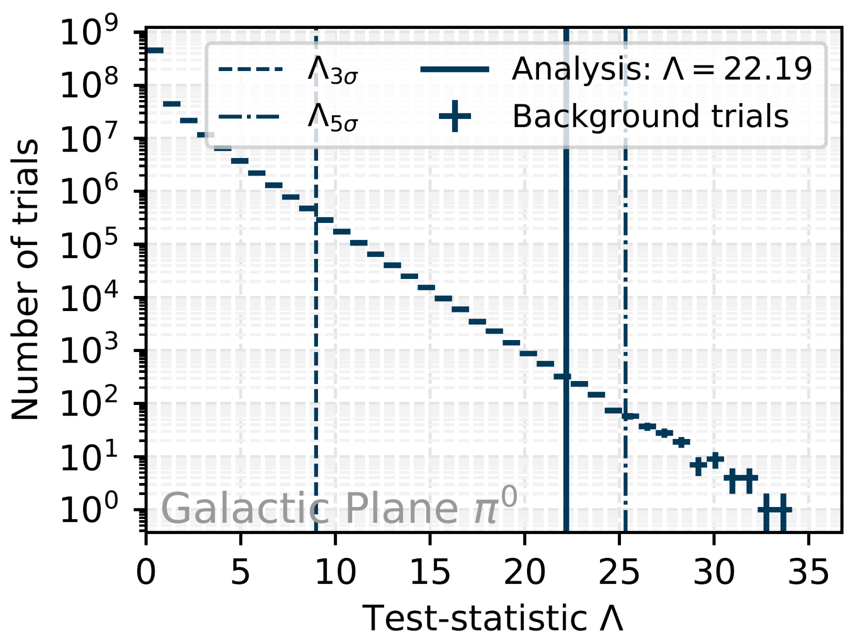
1. Ackermann et al. *The Astrophysical Journal* 750, no. 1 (April 2012): 3. https://doi.org/10.1088/0004-637X/750/1/3.

2. Gaggero et al *The Astrophysical Journal* 815, no. 2 (December 2015): L25. https://doi.org/10.1088/2041-8205/815/2/L25.

Results

- **Identified High-Energy neutrinos from the Milky Way galaxy for the first time**
  - Global significance of 4.5σ
  - 3σ significance from stacking catalogs

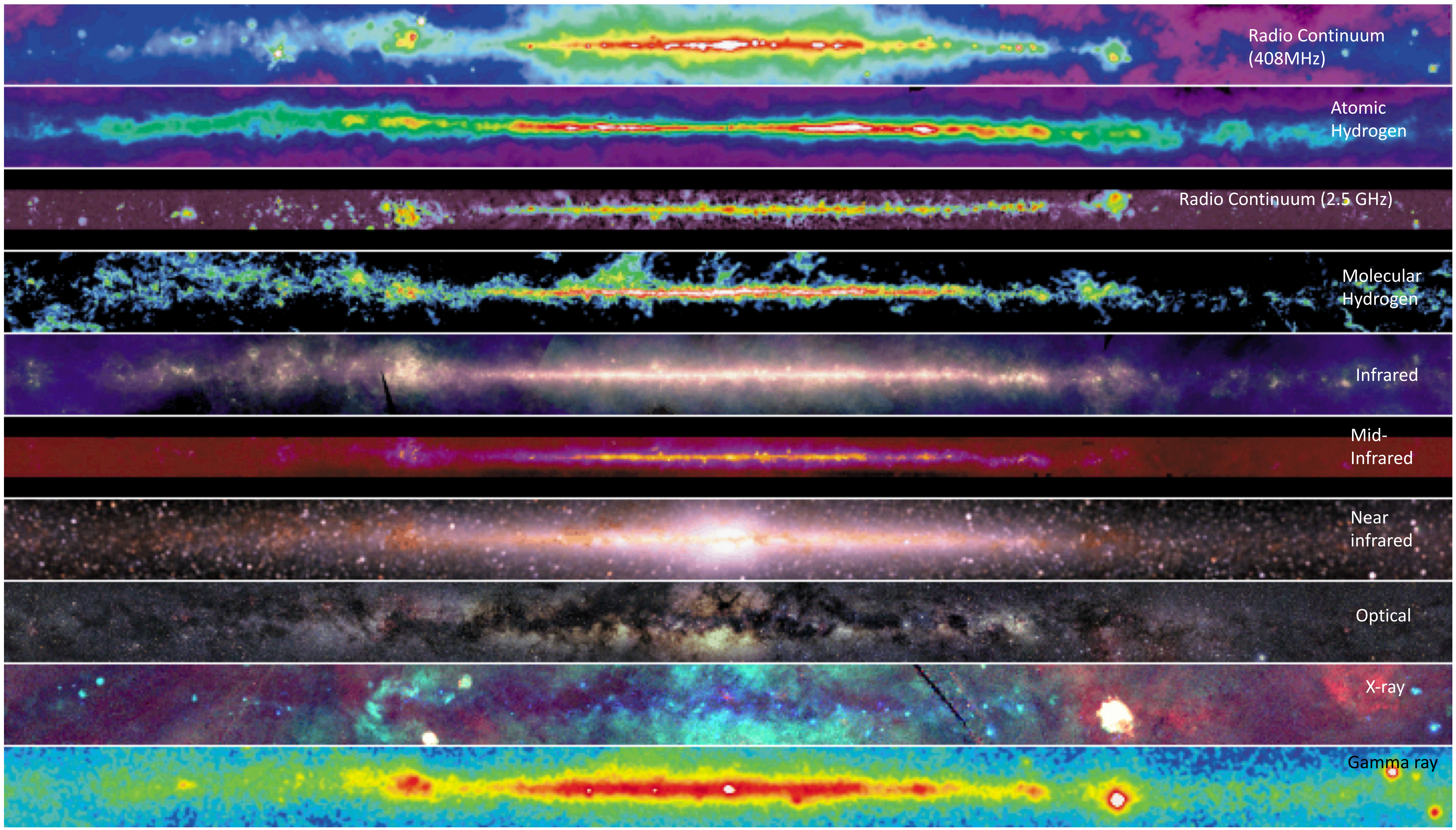




Diffuse Galactic plane analyses	Flux sensitivity Φ	p-value	Best-fitting flux Φ
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA_γ^5	$0.16\times$MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15}\times$MF
KRA_γ^{50}	$0.11\times$MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11}\times$MF
Catalog stacking analyses		**p-value**	
SNR		5.90×10^{-4} (3.24σ)*	
PWN		5.93×10^{-4} (3.24σ)*	
UNID		3.39×10^{-4} (3.40σ)*	

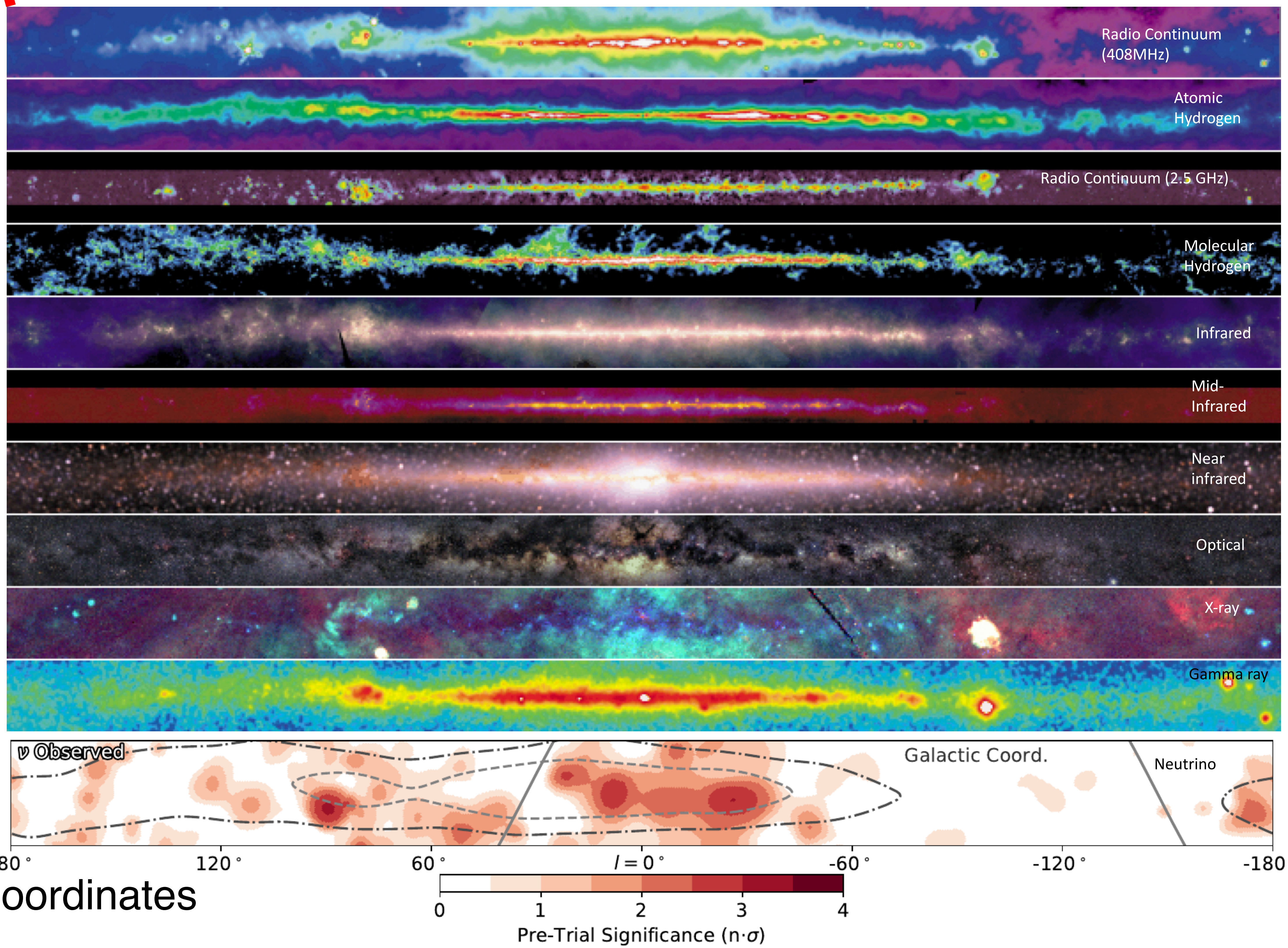
DOI: 10.1126/science.adc9818

Multi-Wavelength Milky Way



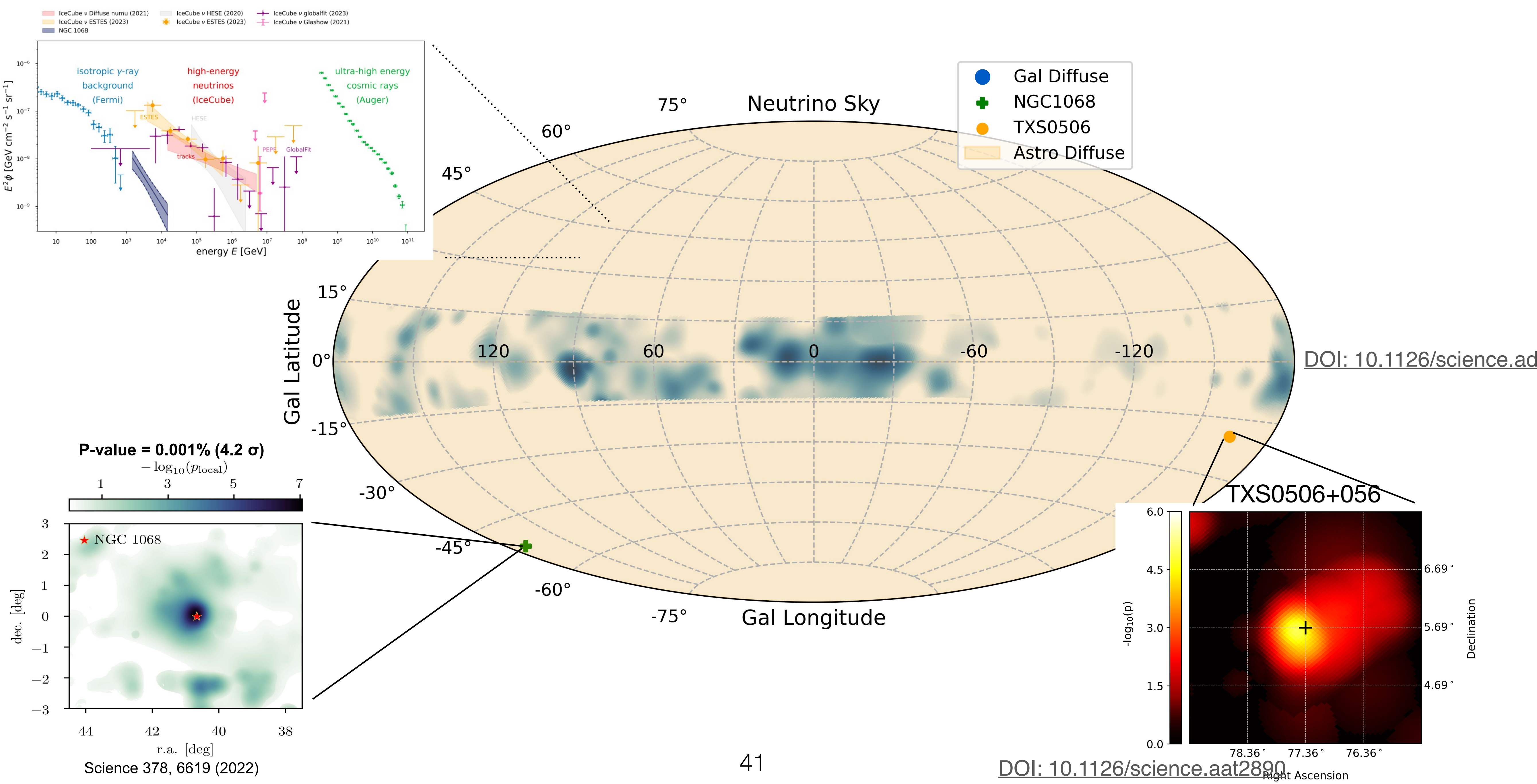
- Galactic Coordinates
- +/- 10 deg

Multi-~~Wavelength~~ Messenger Milky Way



- Galactic Coordinates
- +/- 10 deg

The High Energy Neutrino Sky



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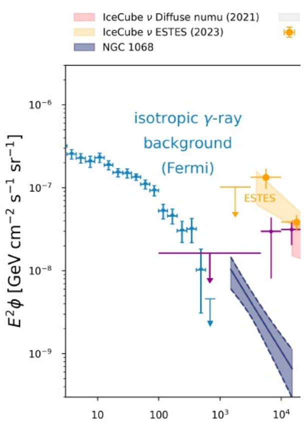
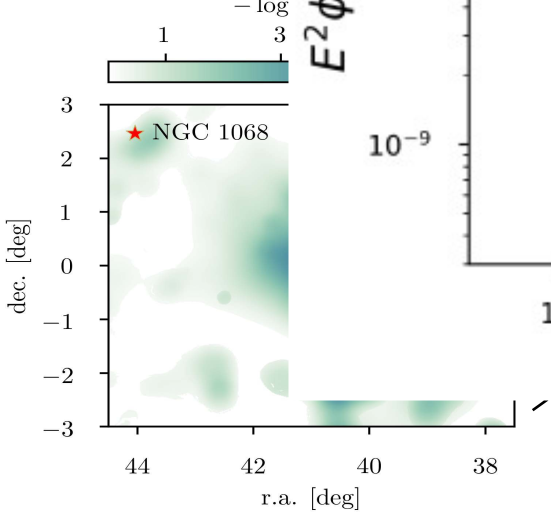
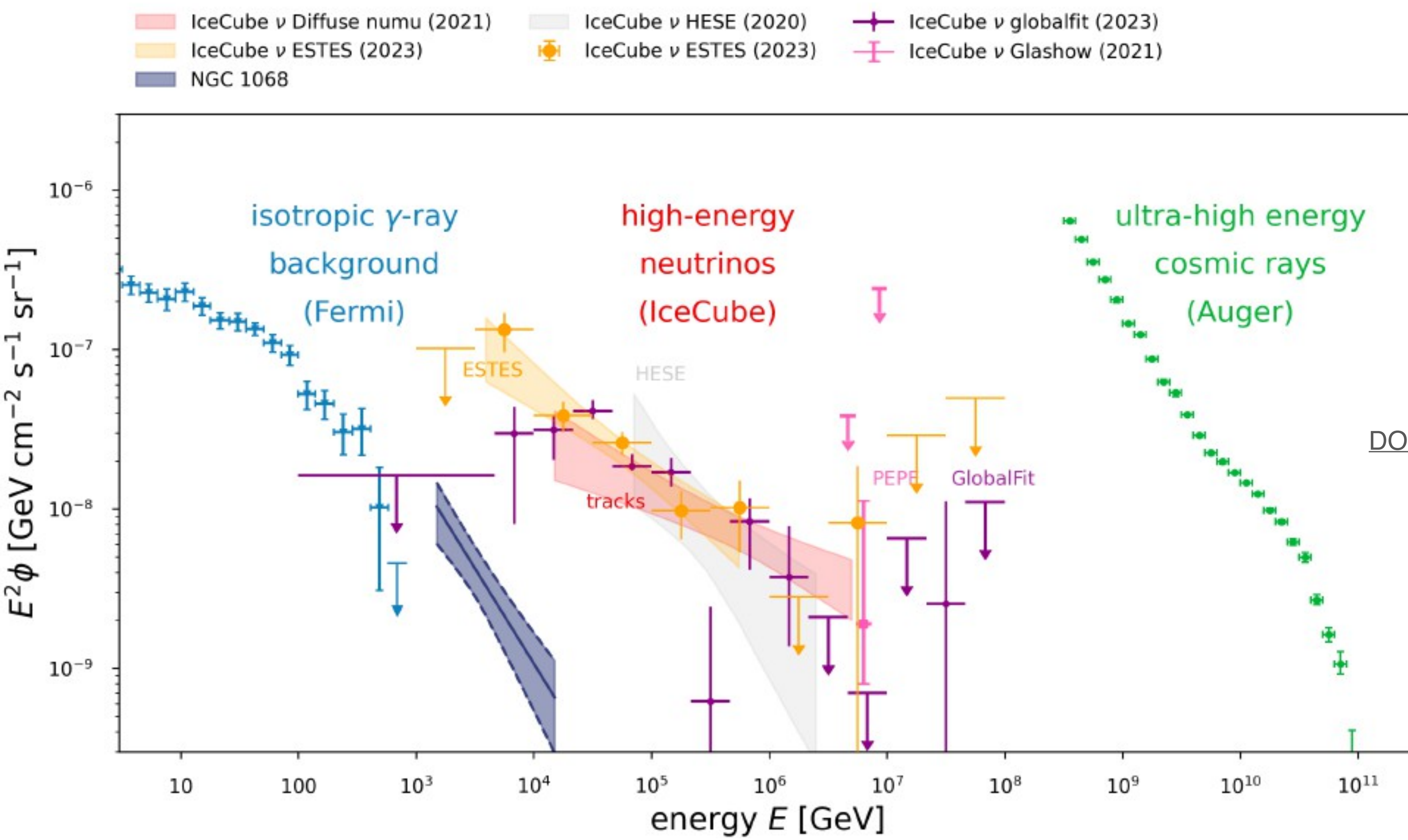
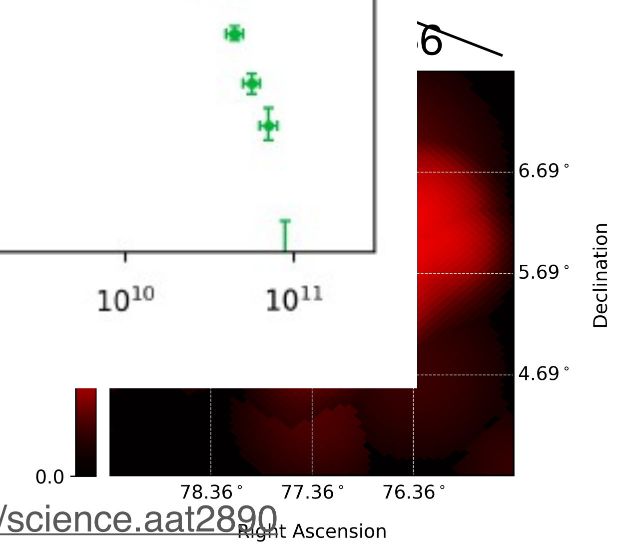






Science 378, 6619 (2022)

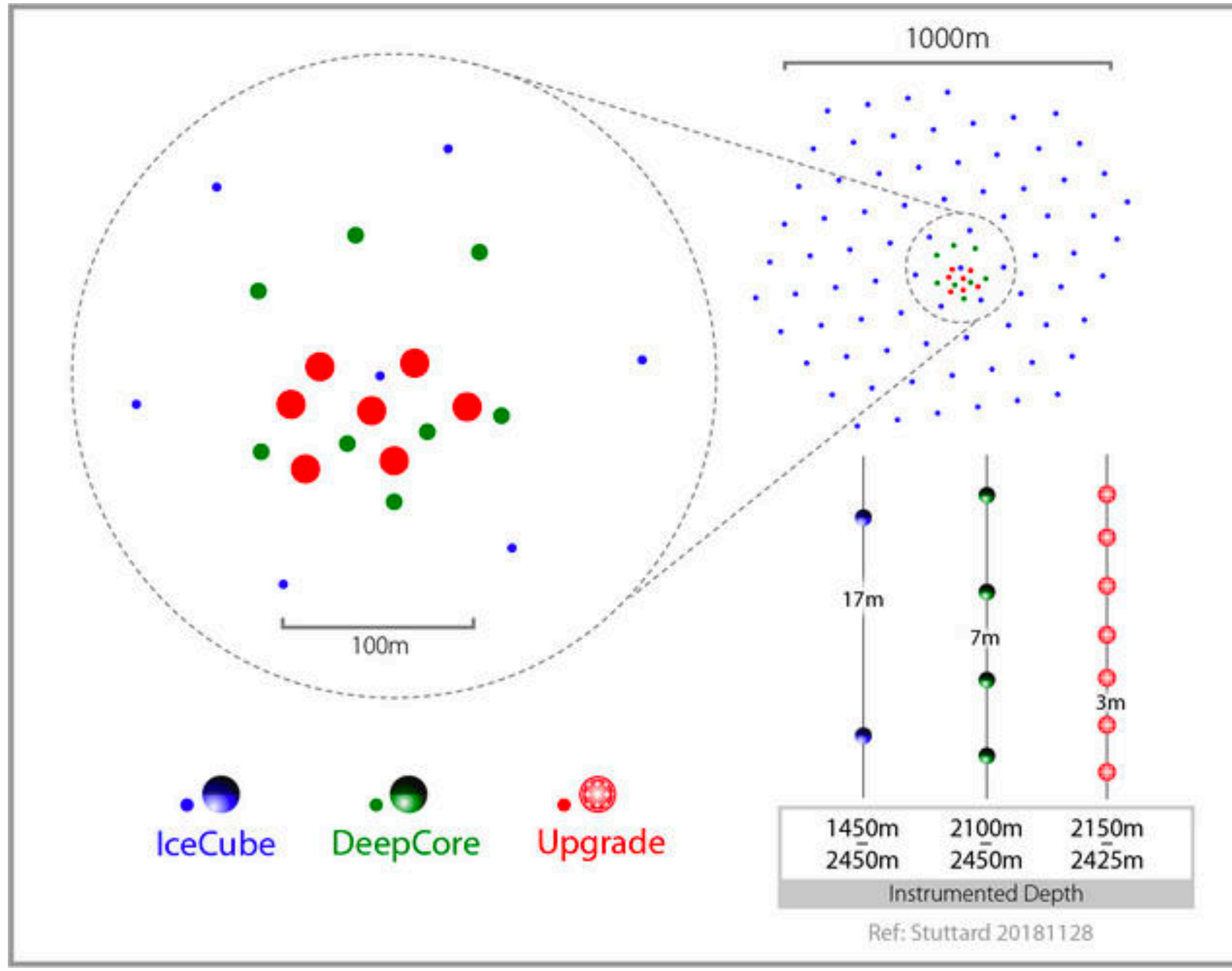
DOI: 10.1126/science.ad



DOI: 10.1126/science.aat2890

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

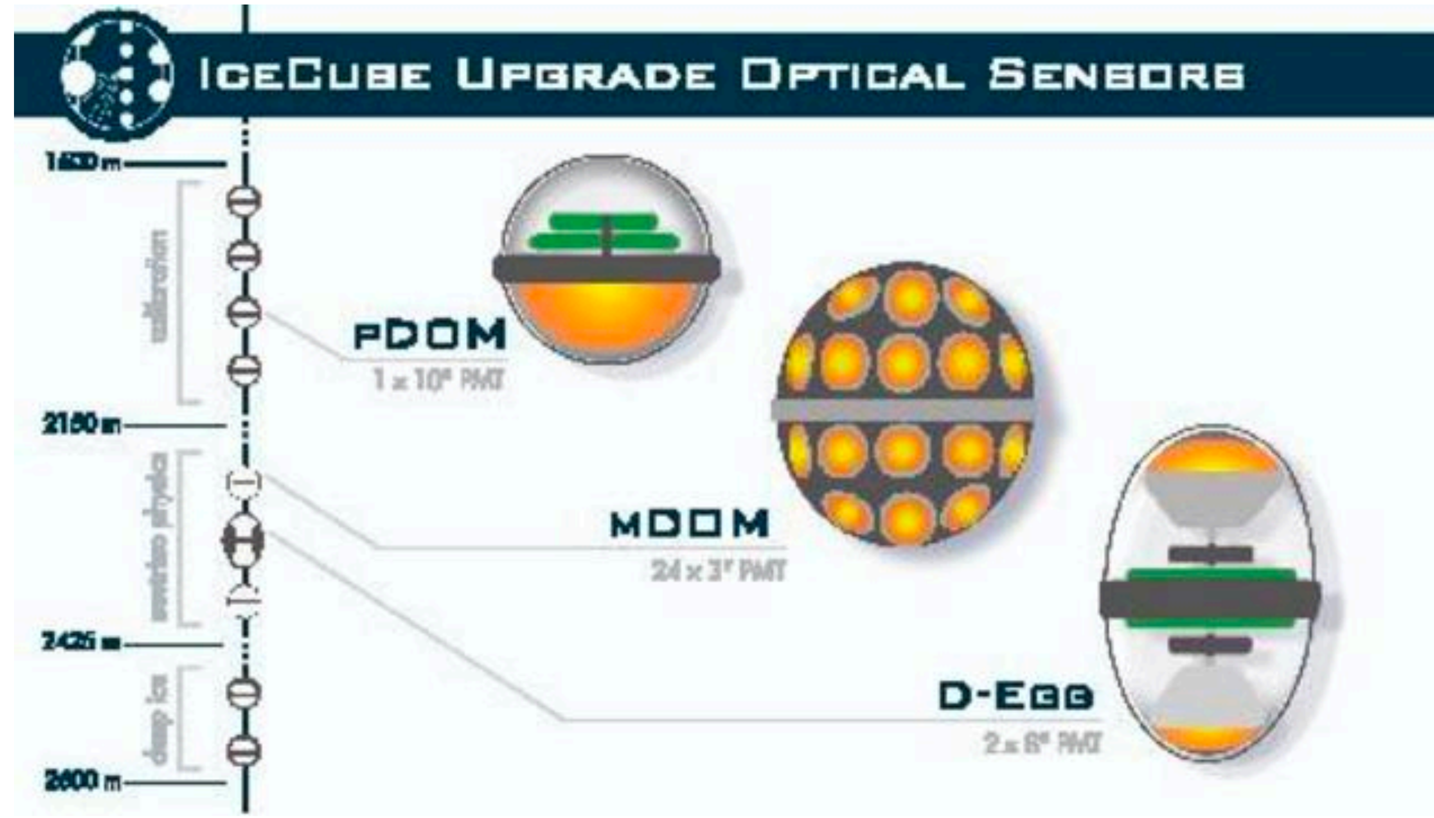


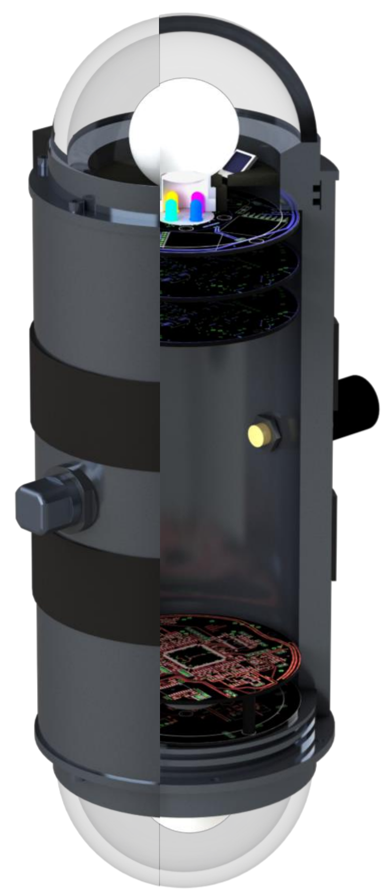
IceCube Upgrade

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

New instrumentation

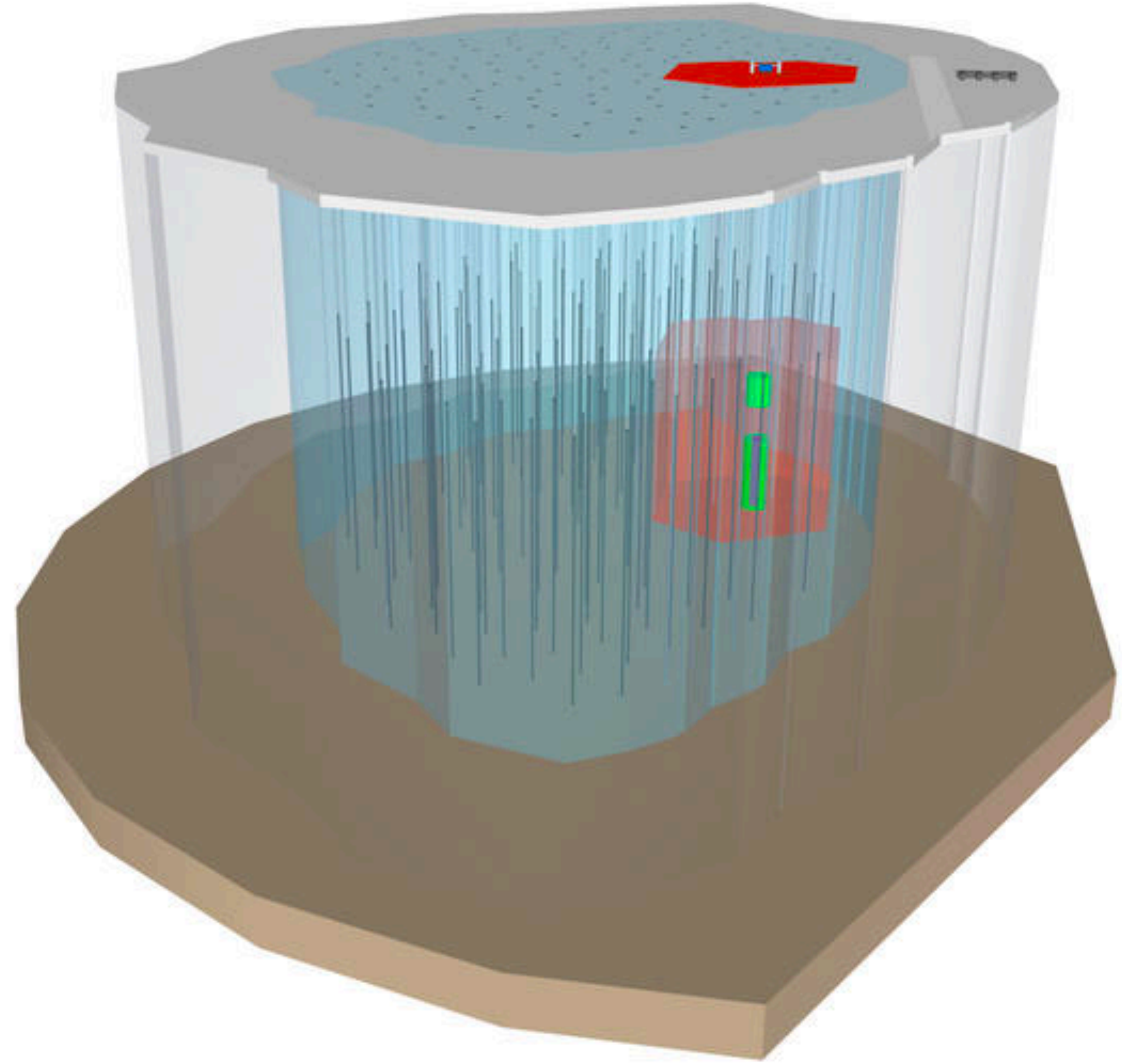
- Several new optical sensors planned for IceCube Upgrade
  - pDOM - refurbished DOMs
  - mDOM - 24 x 3” PMTs
  - DEgg - 2 x 8” PMTs
- New electronic designs for future detectors
- New Calibration devices
  - Built-in Flashers
  - Dedicated light sources

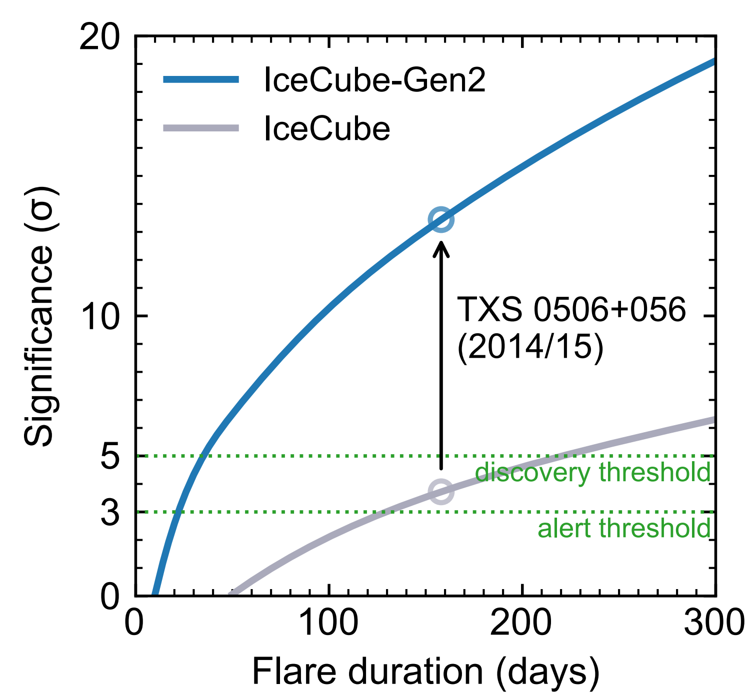


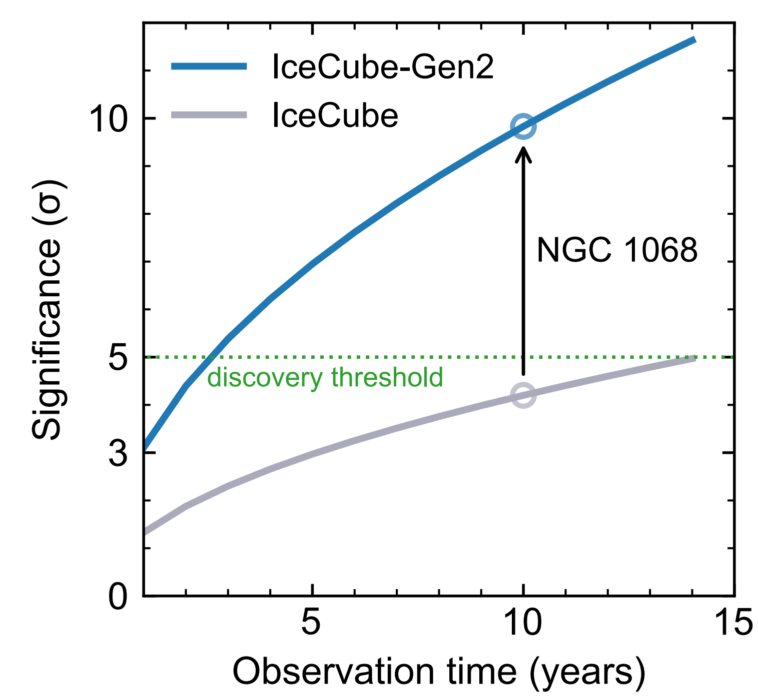


IceCube Gen

- 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

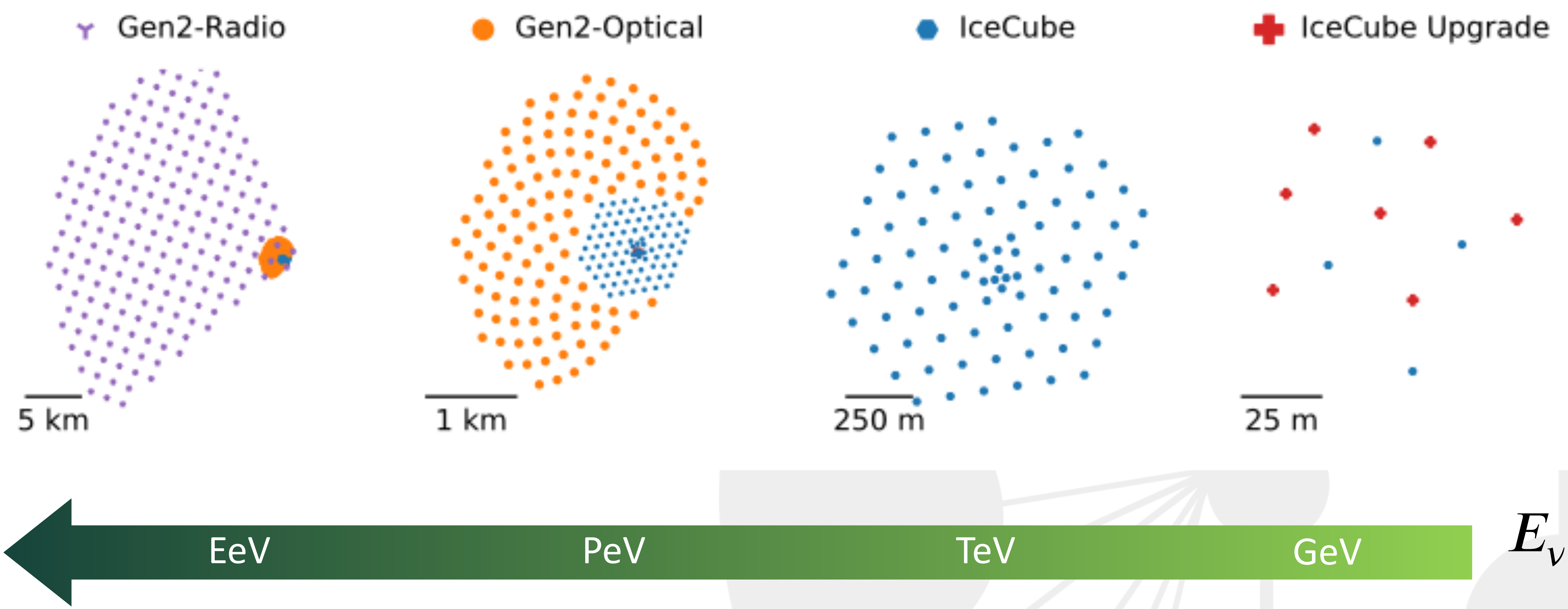


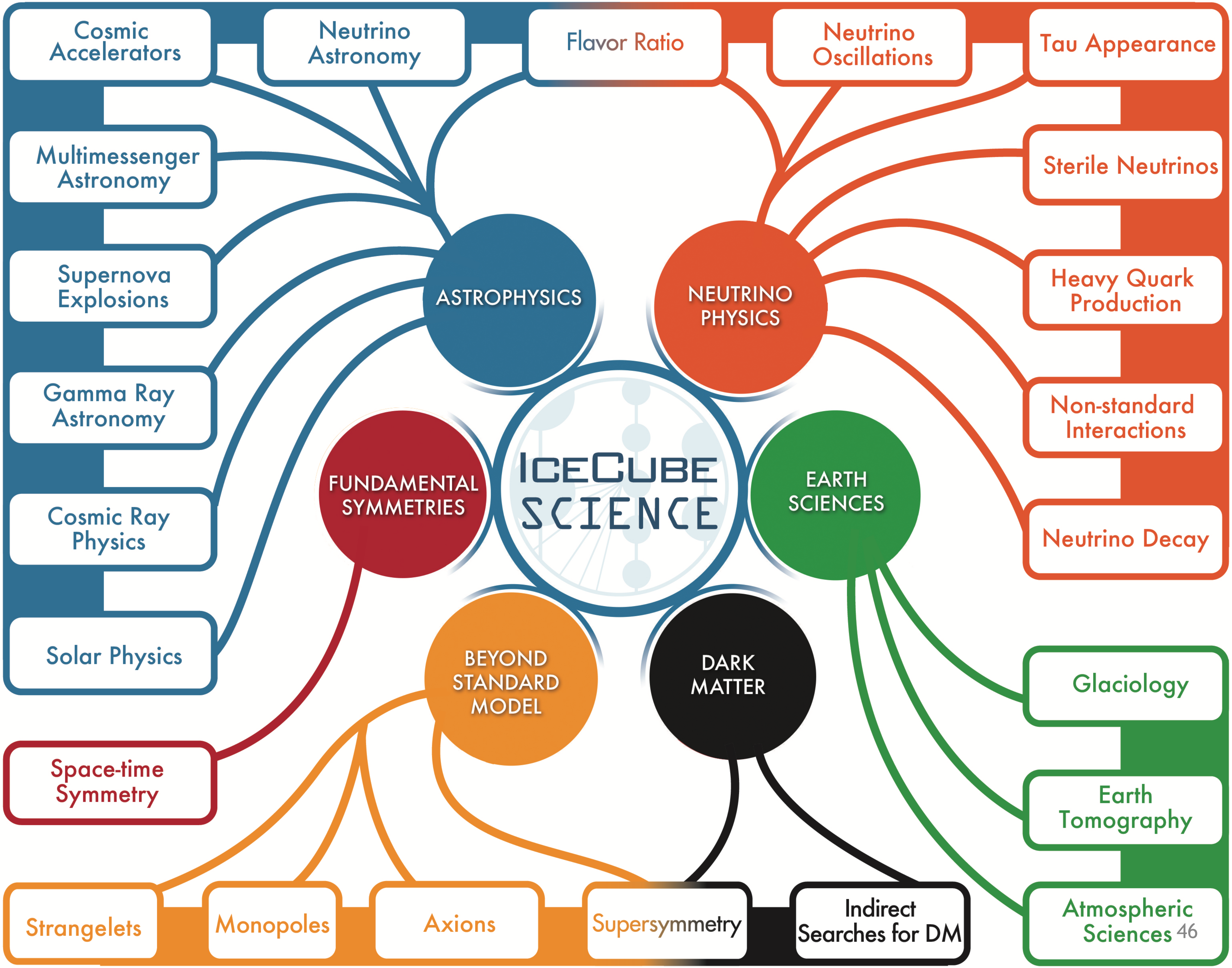




Gen2 TDR - 2023

Future of IceCube




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
  - First evidence for point sources (TXS 0506+056, NGC 1068,…) are emerging, pointing to AGN as source class
  - Galactic plane revealed in neutrinos - more detailed studies underway
- IceCube continues a strong multi-messenger effort
  - 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!

Thanks!


THE ICECUBE COLLABORATION
AUSTRALIA
University of Adelaide
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UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel
CANADA
SNOLAB
University of Alberta–Edmonton
DENMARK
University of Copenhagen
GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
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Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
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)