Searching for transient astrophysical neutrino sources with the IceCube Neutrino Observatory using a multimessenger approach

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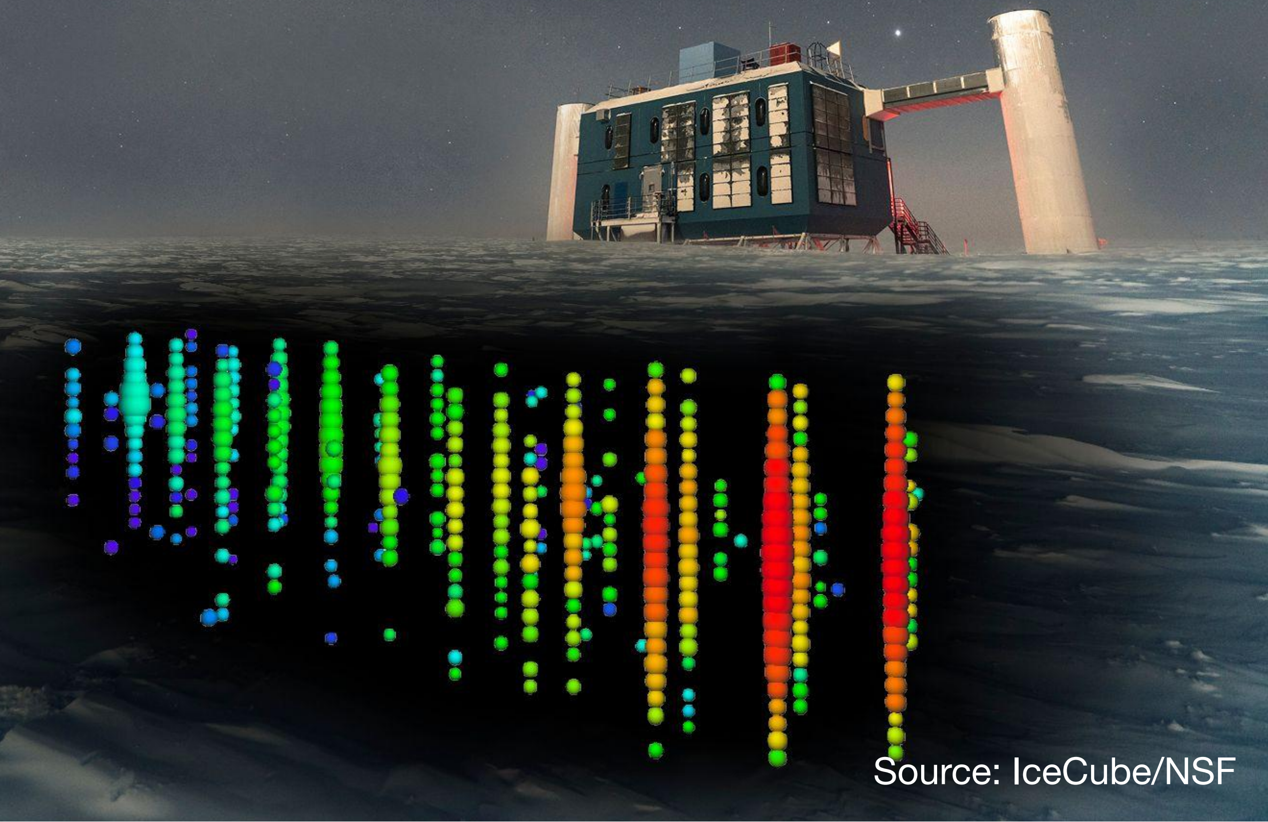
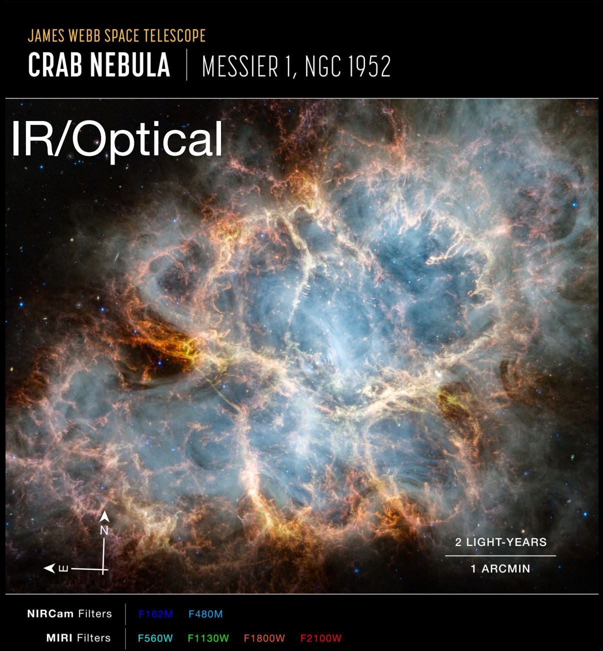
NSF

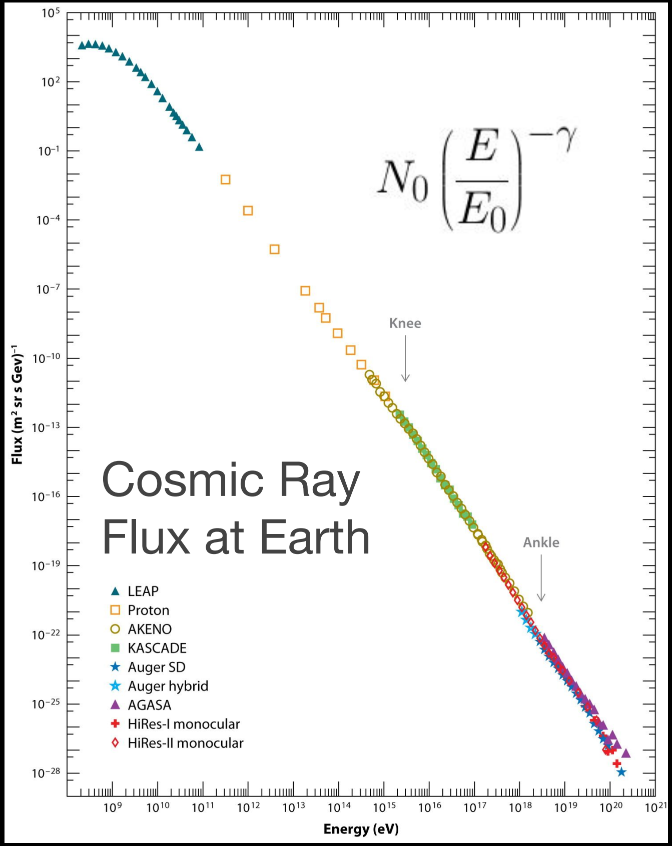
IceCube Neutrino Observatory



Source: IceCube/NSF

Exploring the universe through different messengers can expose new astrophysical processes



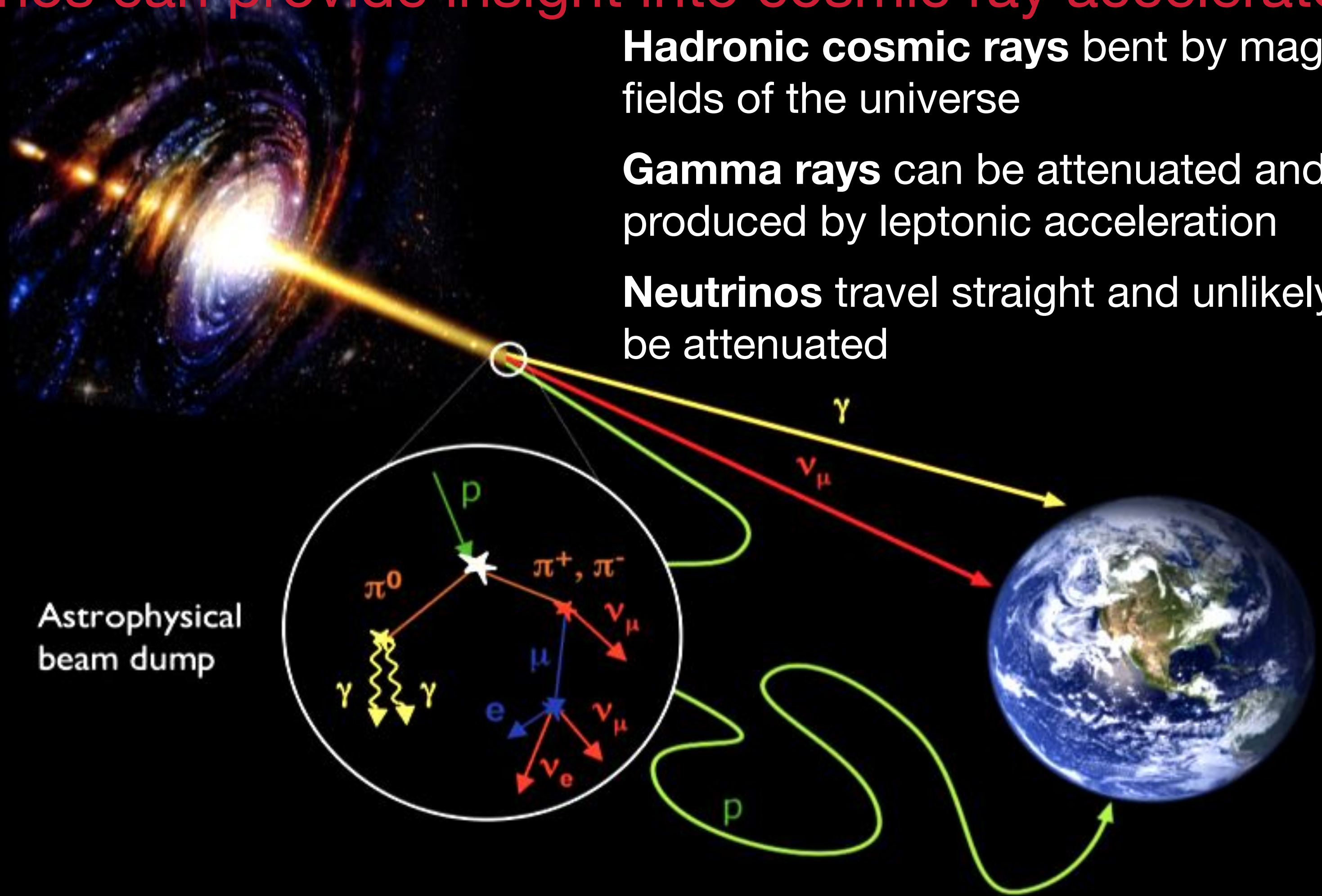


Neutrinos can provide insight into cosmic ray accelerators

Hadronic cosmic rays bent by magnetic fields of the universe

Gamma rays can be attenuated and produced by leptonic acceleration

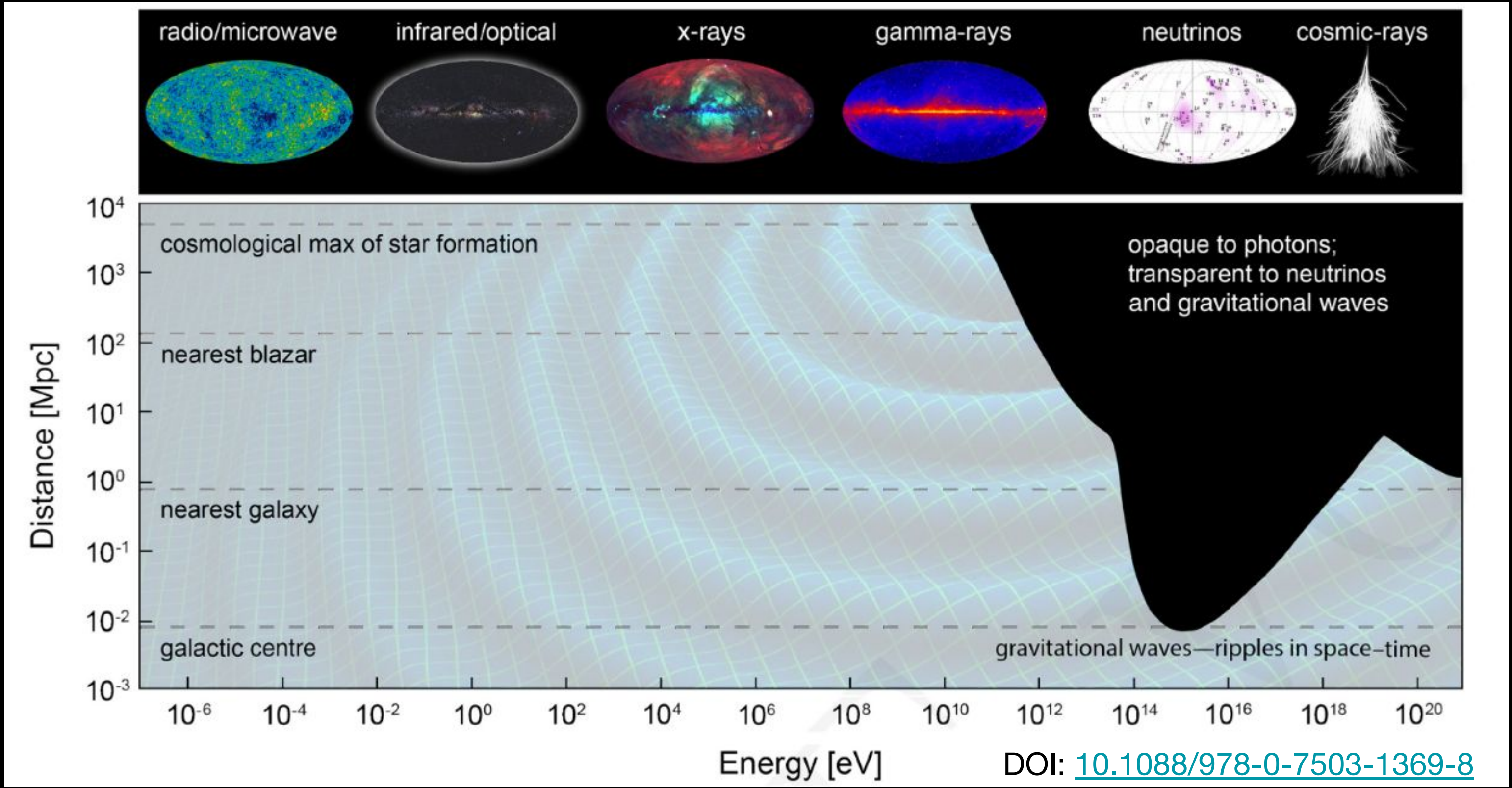
Neutrinos travel straight and unlikely to be attenuated



Neutrino astronomy versus gamma-ray astronomy

Gamma rays attenuated by CMB and other background light in the TeV energy ranges

Gamma rays also produced by cosmic ray electron acceleration (**leptonic acceleration**)



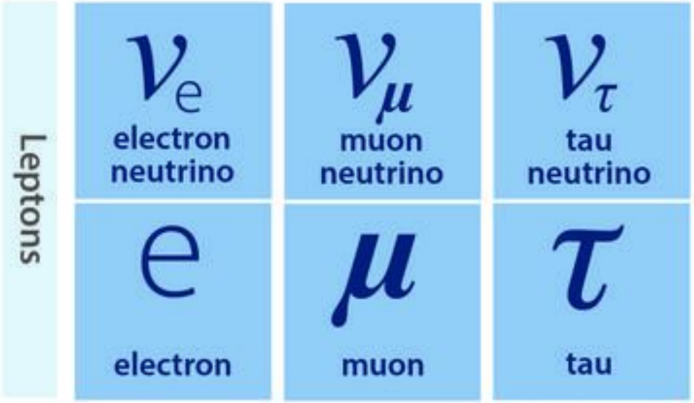
DOI: 10.1088/978-0-7503-1369-8

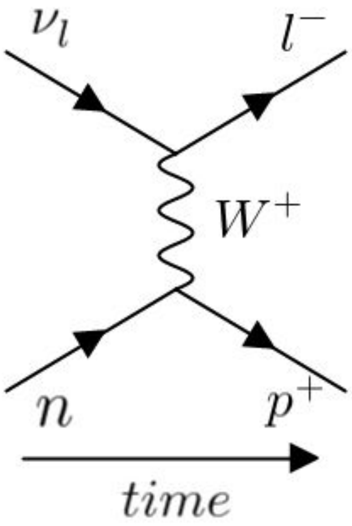
Neutrino Interactions

Cannot observe neutrinos directly

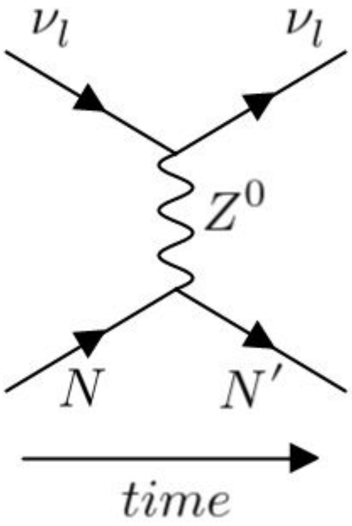
Instead observe the outgoing charged particles from weak neutrino interactions

At IceCube energies, most interactions DIS

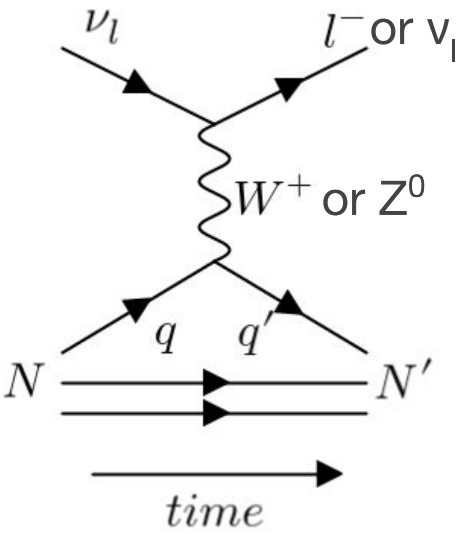




Charged Current (CC)



Neutral Current (NC)



Deep Inelastic Scattering (DIS)

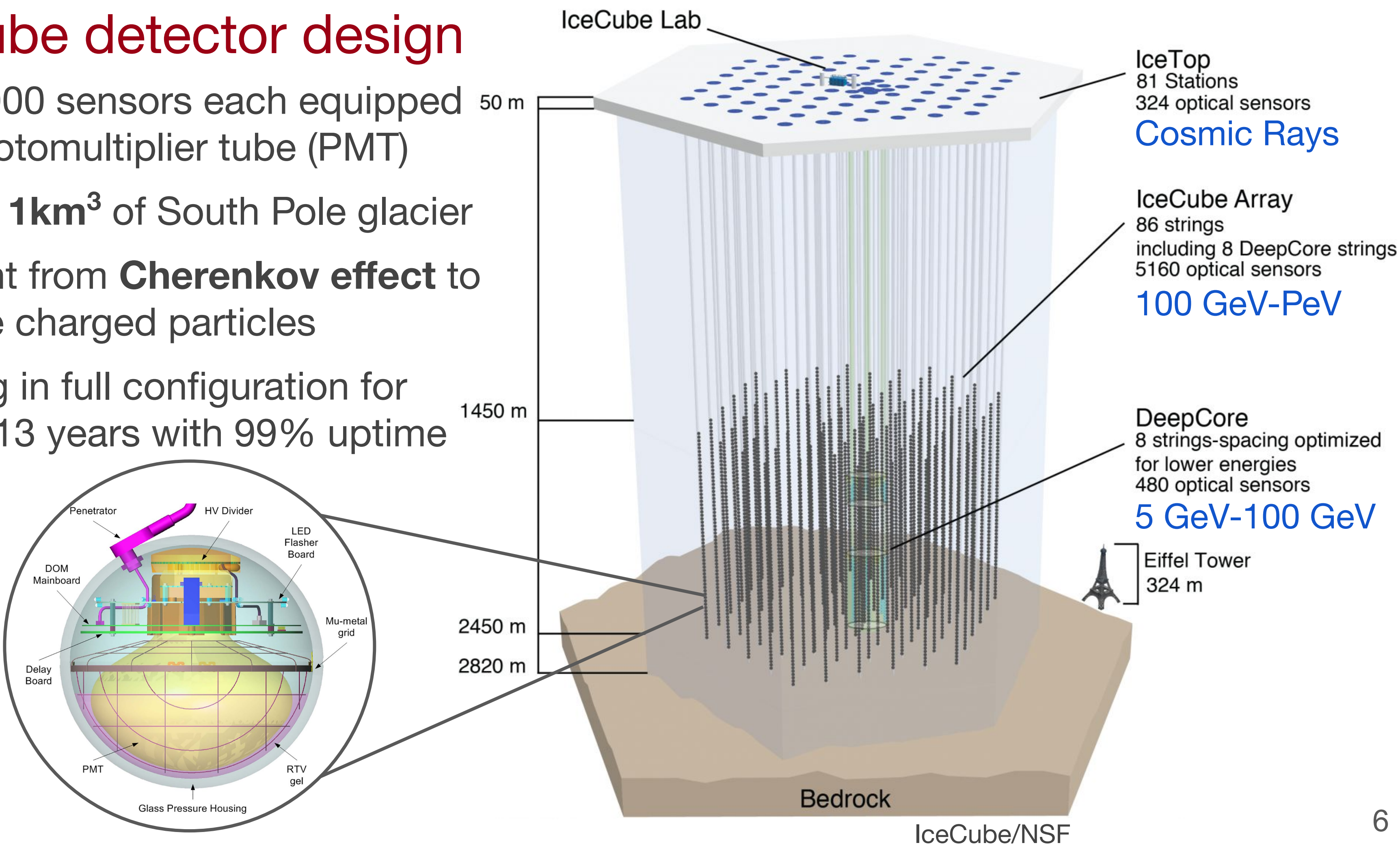
IceCube detector design

Over 5000 sensors each equipped with photomultiplier tube (PMT)

Array in **1km³** of South Pole glacier

Use light from **Cherenkov effect** to observe charged particles

Running in full configuration for almost 13 years with 99% uptime

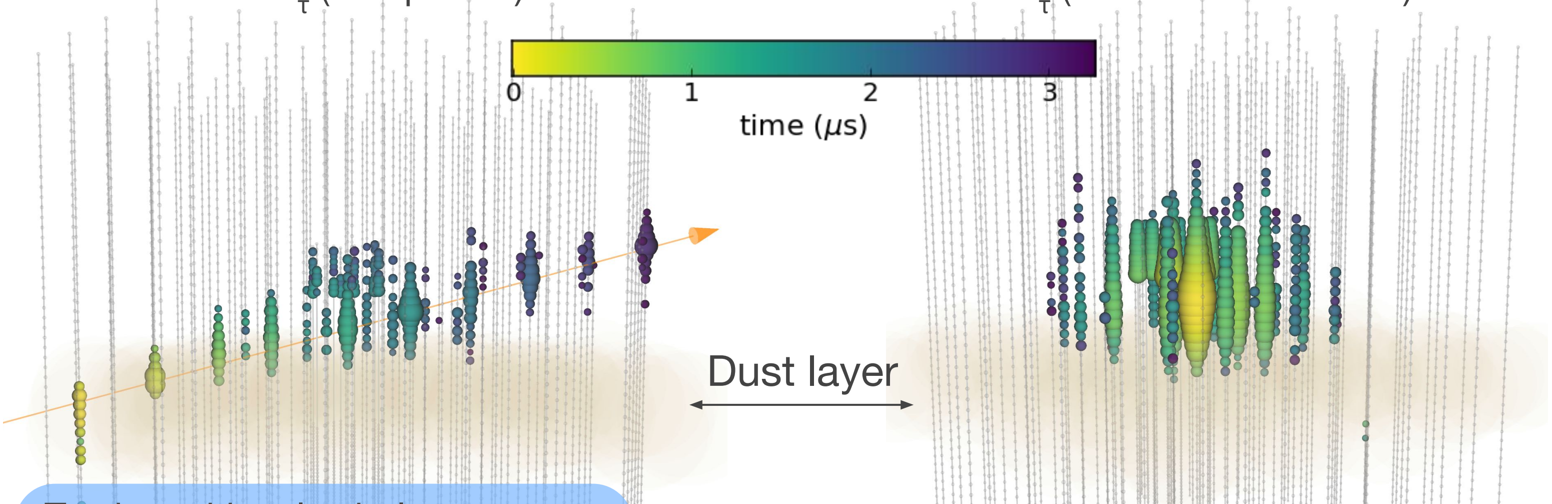


IceCube/NSF

Main TeV particle morphology classifications within IceCube

Muon Track
Angular Resolution: 0.6°
Log Energy Resolution: 20% of muon energy at detector entry
Atmospheric muons, charged current ν_μ and ν_τ ($\tau \to \mu + \nu$'s)

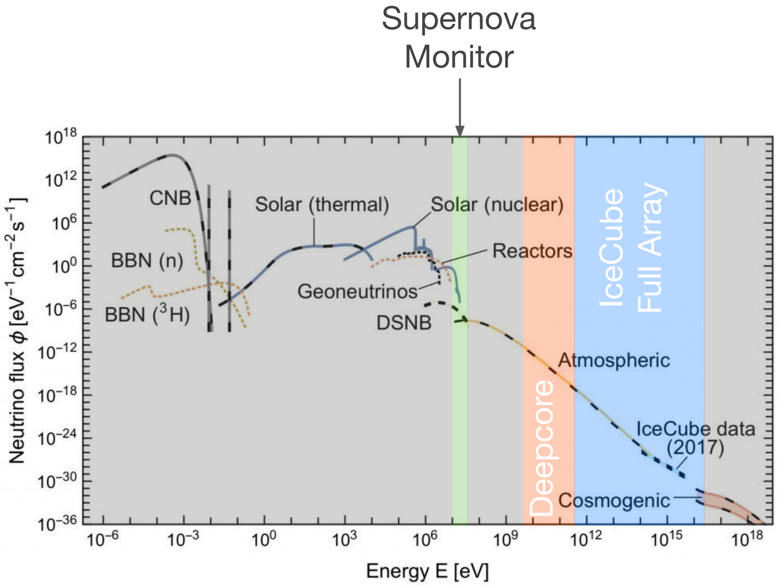
Electromagnetic/Hadronic Cascade
Angular Resolution: 5°-15°
Log Energy Resolution: 15% of neutrino energy
Neutral current ν, charged current ν_e and ν_τ ($\tau \to$ e/hadrons + ν's)



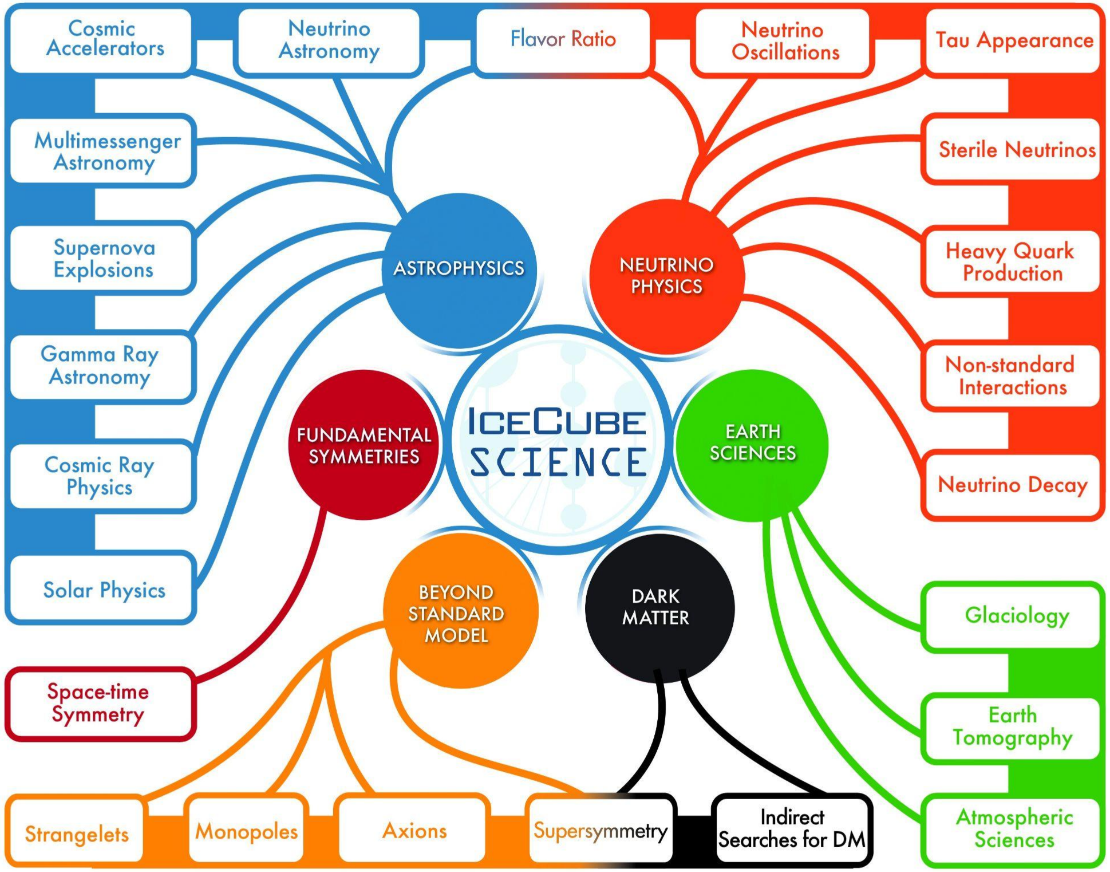
Track positional subclasses:
- Through-going
- Starting
- Stopping
- Skimming

Cascade positional subclasses:
- Contained
- Partially contained

IceCube science covers a broad range of physics topics

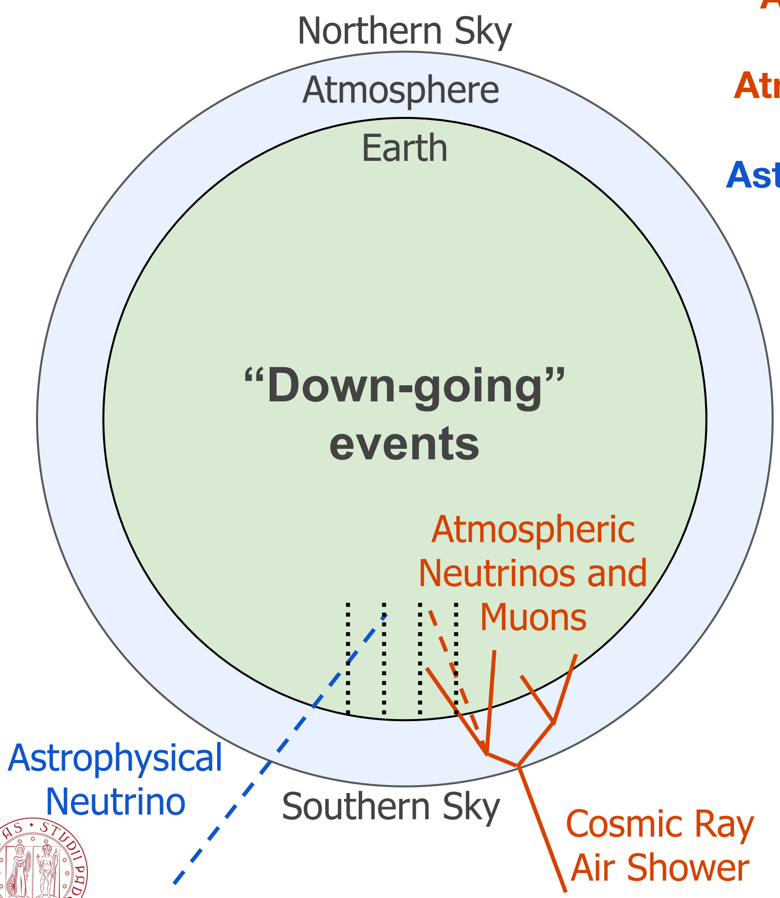


Neutrino fluxes across decades of energy
[Rev. Mod. Phys. 92, 45006 (2020)]

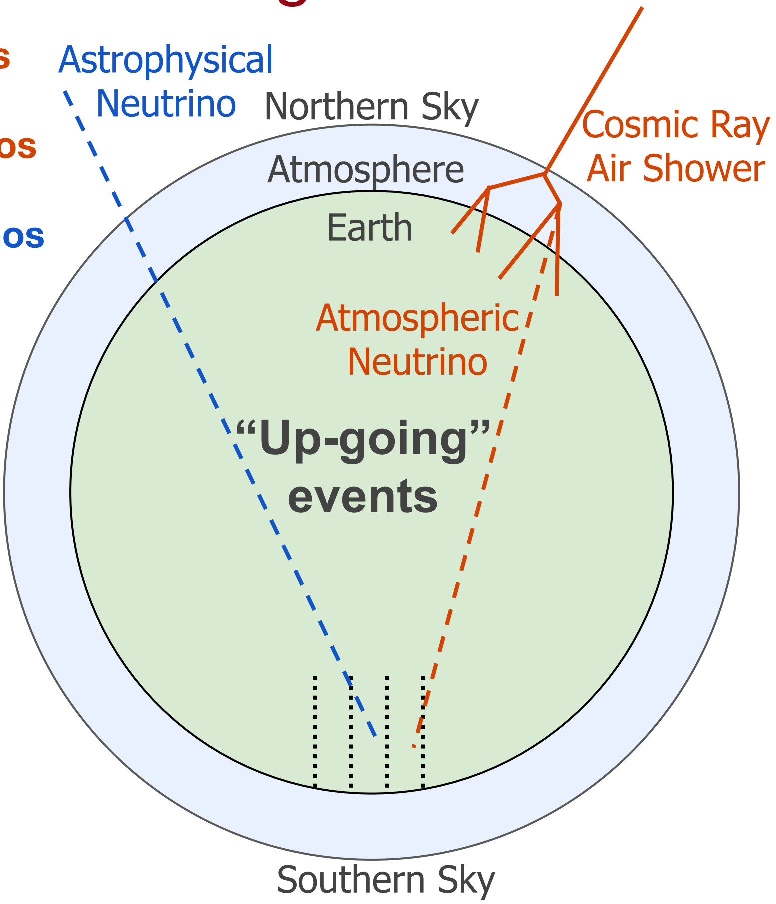


IceCube/NSF

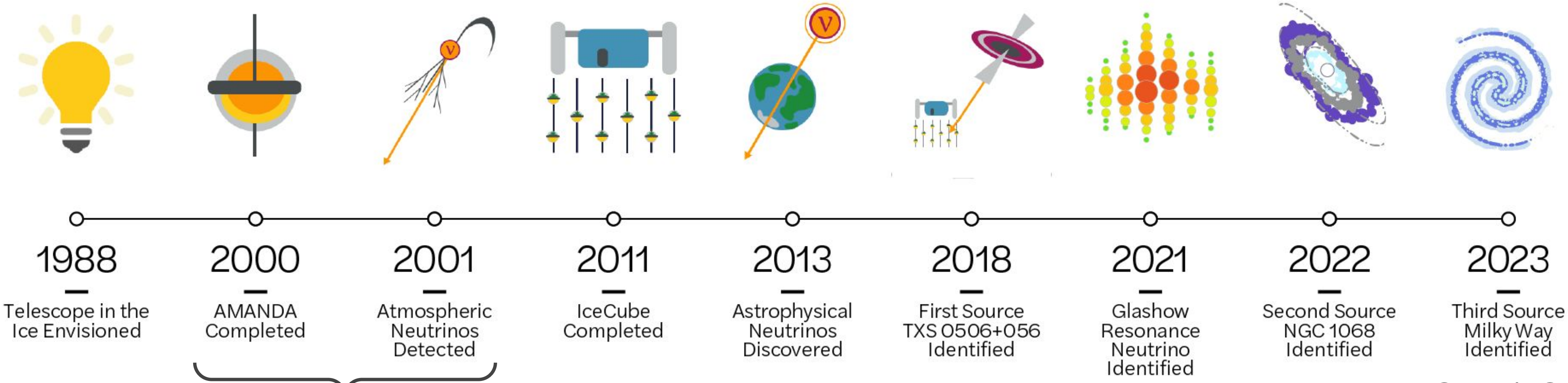
Astrophysical neutrinos and atmospheric backgrounds



Atmospheric Muons
~3000 Hz
Atmospheric Neutrinos
~1 per second
Astrophysical Neutrinos
~1 per day



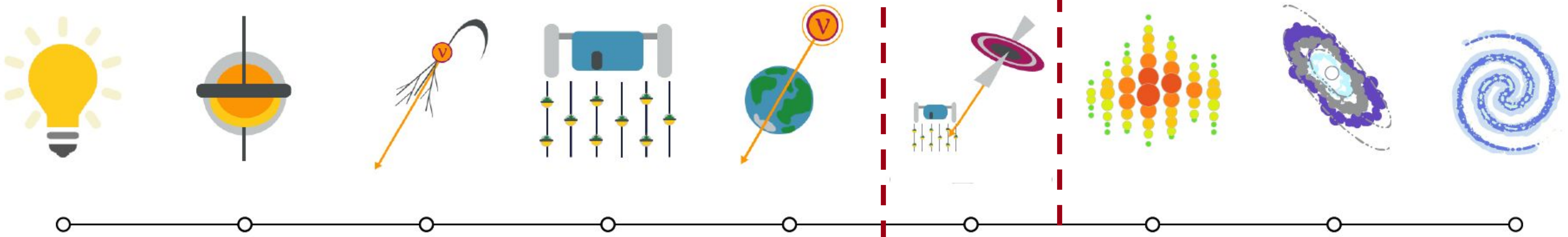
Timeline of neutrino astronomy achievements with IceCube



IceCube predecessor, AMANDA

IceCube/NSF

Timeline of neutrino astronomy achievements with IceCube



1988	2000	2001	2011	2013	2018	2021	2022	2023
Telescope in the Ice Envisioned	AMANDA Completed	Atmospheric Neutrinos Detected	IceCube Completed	Astrophysical Neutrinos Discovered	First Source TXS 0506+056 Identified	Glashow Resonance Neutrino Identified	Second Source NGC 1068 Identified	Third Source Milky Way Identified

IceCube predecessor, AMANDA (2000–2001)

IceCube/NSF

The multimessenger approach to neutrino astronomy

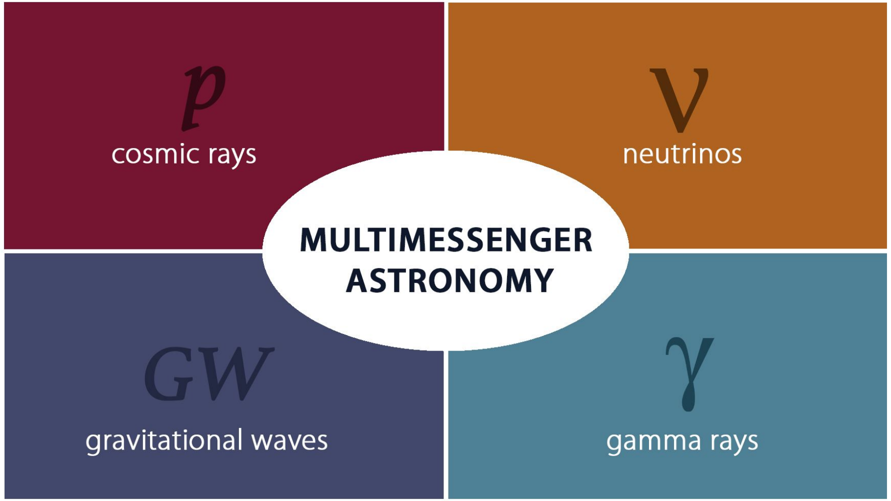
Many hypothesized neutrino sources have variable activity in photons (e.g. blazars)

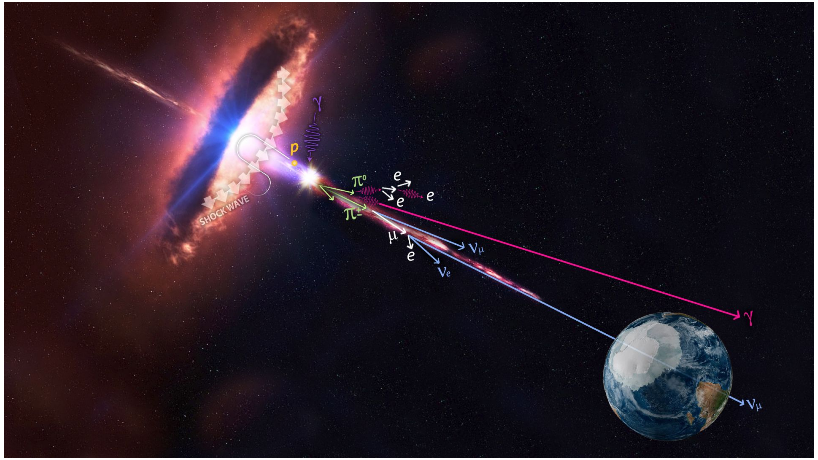
Looking for transient neutrino phenomena difficult due to statistics

Easier to distinguish true signals if observe coincident photon detections

IceCube: >99% uptime and view of full sky
→ acts as sentinel to alert other telescopes

IceCube "realtime" efforts include sending alerts and follow-up of transient phenomena



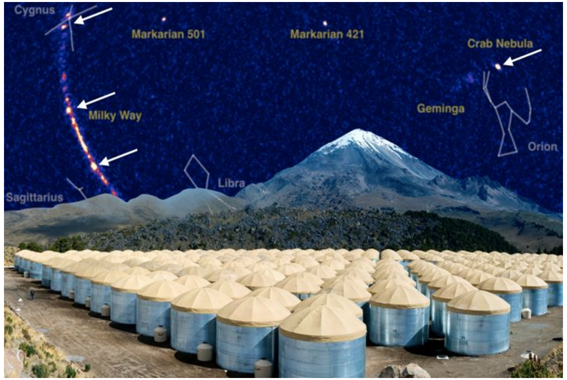


Gamma-ray detector technologies

Satellite

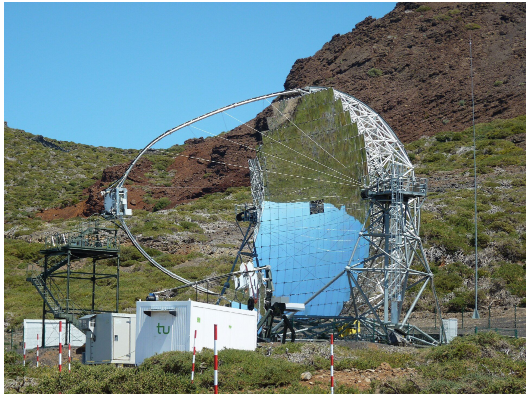
Fermi

Water Cherenkov Tanks



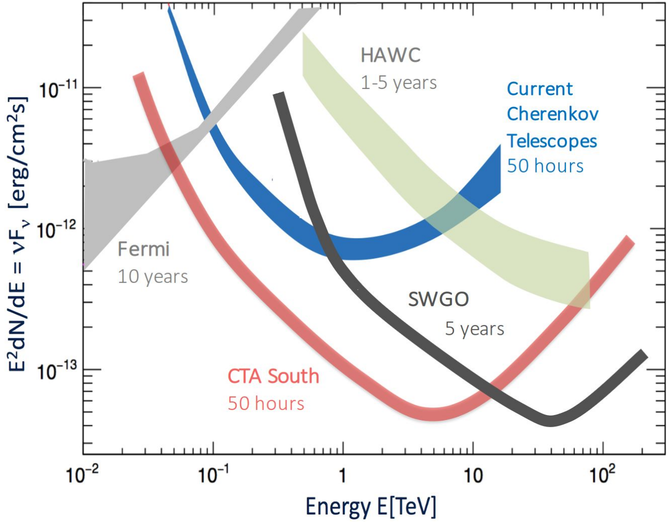
HAWC

Imaging Air Cherenkov Telescopes (IACTs)



MAGIC

DOI:10.1088/1742-6596/1468/1/012096



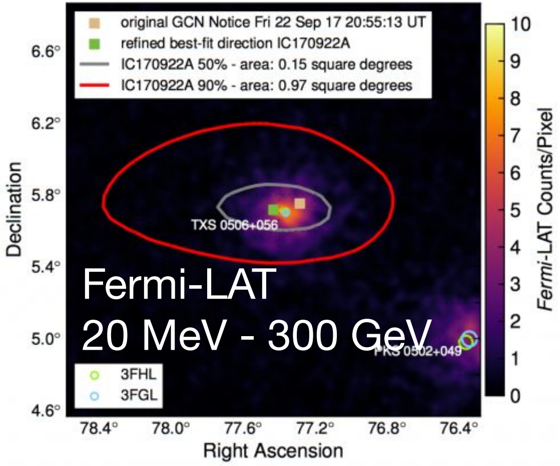
First example of neutrinos in MMA: TXS 0506+056

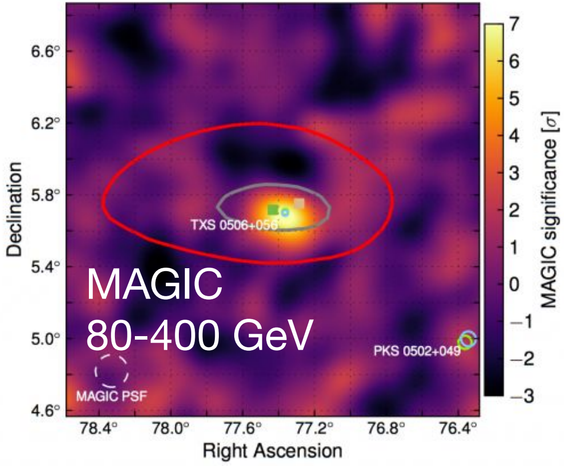
DOI: 10.1126/science.aat1378

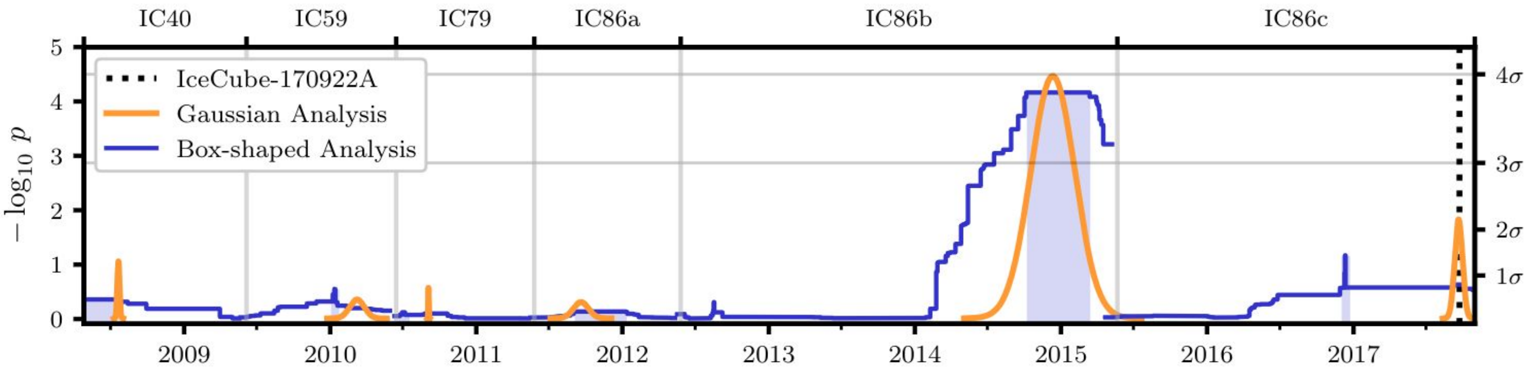
(2017) **high energy neutrino** coincided with **flare from blazar TXS 0506+056** (3σ significance)

Flare observed across electromagnetic spectrum

Archival neutrino flare also found by IceCube (also at 3σ)







DOI: 10.1126/science.aat2890

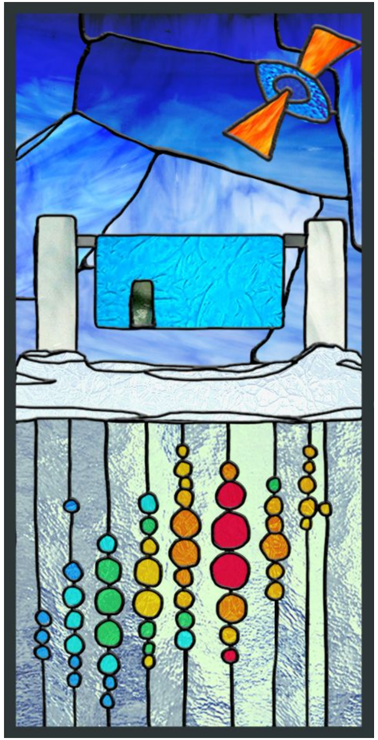
Identifying neutrino flares in realtime with GFU Platform

Gamma-ray Follow-up (GFU) platform looks for clusters of neutrinos in space and time

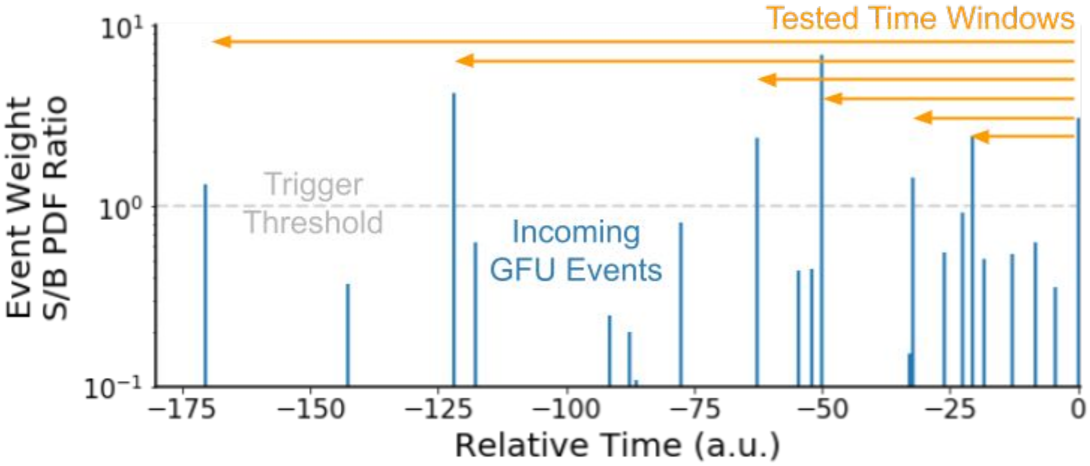
Goals:

- Identify neutrino flares as early as possible
- Send alerts to imaging air cherenkov telescopes (IACTs) for follow-up

Tests time windows of up to 180 days (typical for blazar flares)



Neutrino flare alerts algorithm (GFU alerts)



Alert method:

1. Evaluate if signal over background likelihood > trigger threshold
2. Build time windows with previous trigger events
3. Select time window that results in max test statistic (TS)
4. Calculate local p-value with max TS
5. Send alert if local p-value > defined threshold

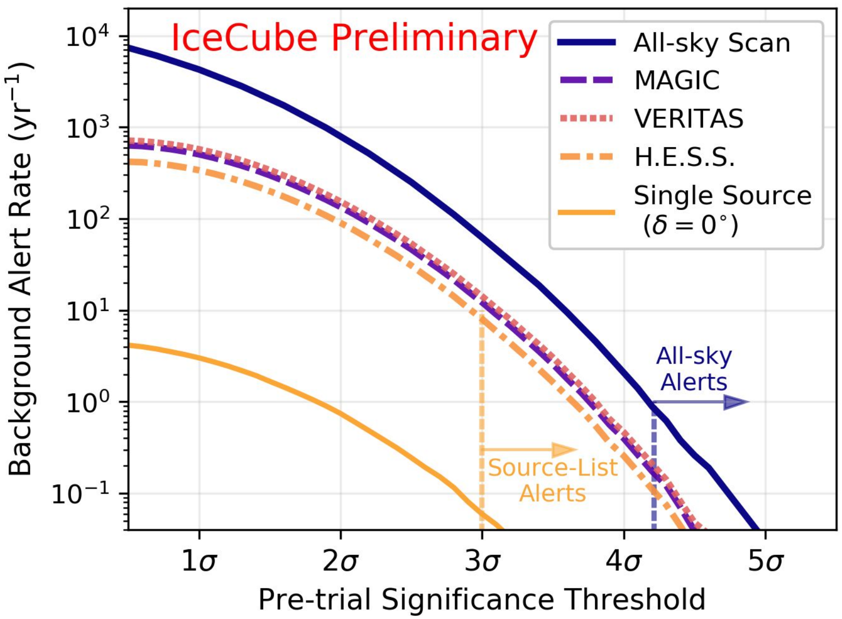
GFU Source list vs. Allsky alerts

GFU alert stream has two different modes: Source list and Allsky

Send out alerts if trigger passes p-value threshold

Source list alerts shared under MoU with IACTs

Allsky alerts not yet shared



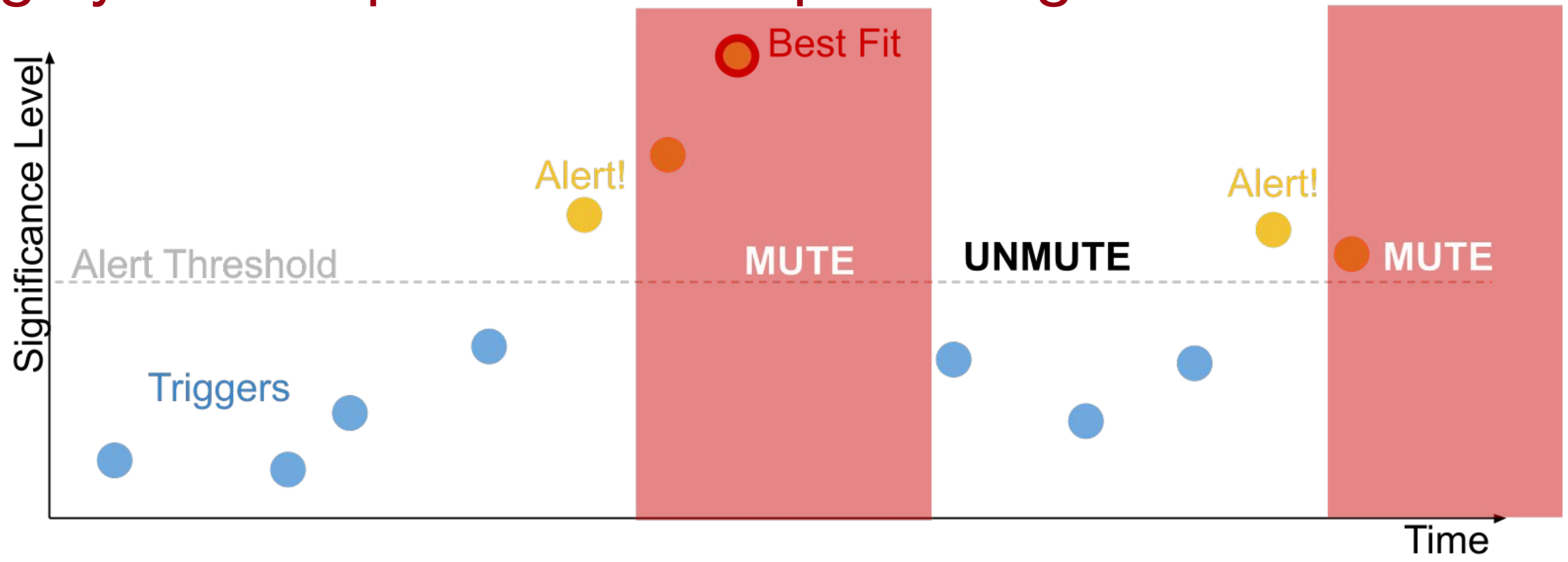
Source list alerts (model dependent)

- Test location of nearby AGN that are highly variable in gamma-rays
- Pro: reduces trials factor
- Con: relies on model assumptions
- Con: $z \leq 1$ bias

Allsky alerts (model independent)

- Test pixels around incoming events
- Pro: can identify previously unknown/unexpected sources
- Con: large number of trials

Muting system to prevent alert spamming

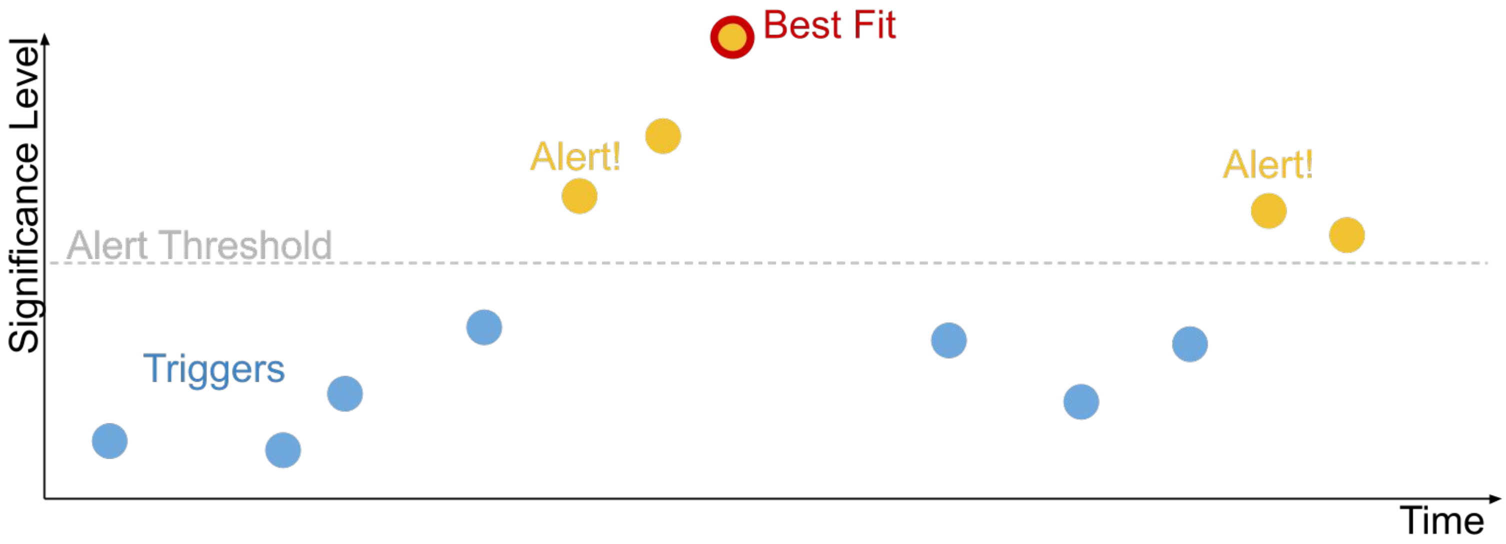


To prevent spamming of alerts:

- MUTE: after first alert level trigger
- UNMUTE: after first sub-alert level trigger

Con: obscures behavior of source after first alert

Offline analysis of GFU alerts



Run source list and allsky analyses on 11.5 years of archival data

Goals:

- study evolution of flares after alert muting
- check for flares which occurred before alert stream activation (2019)

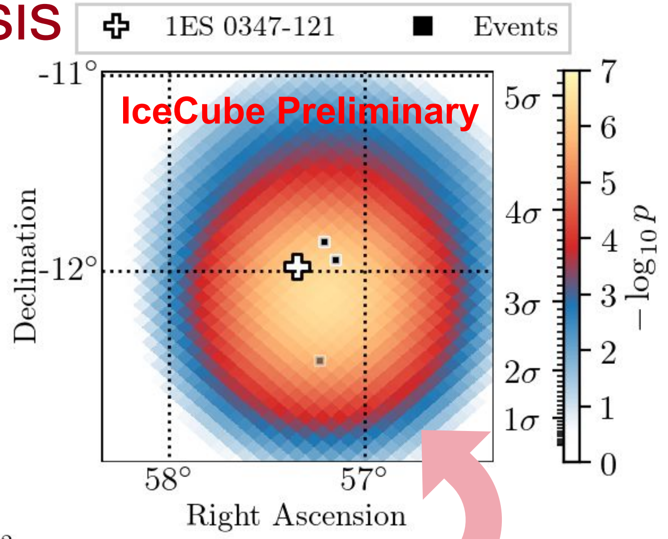
Source list results from the offline analysis

Best fit source: **1ES 0347-121** (δ=-11.98°)

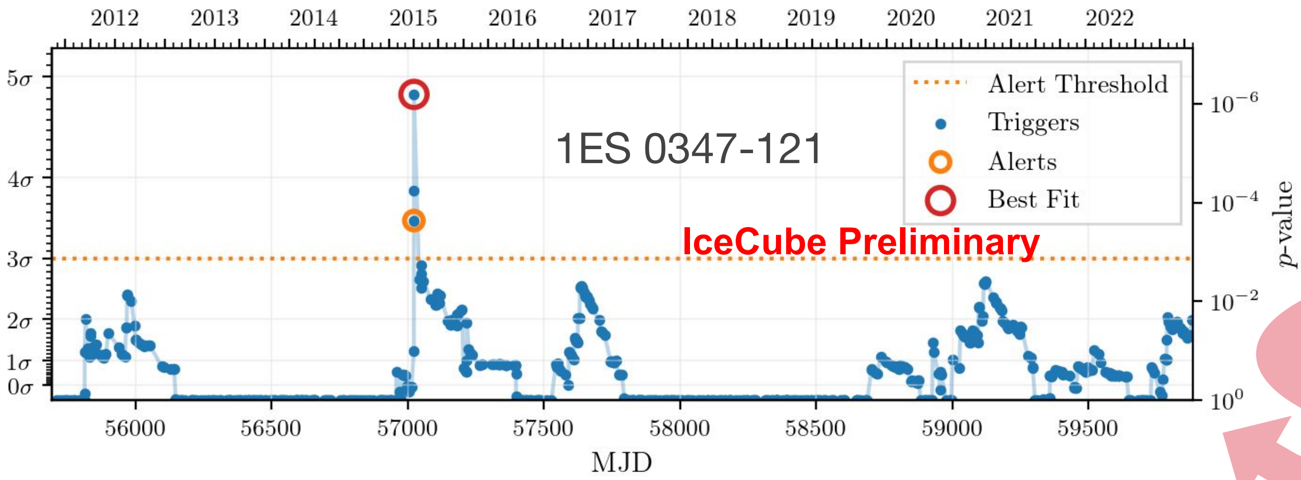
4.84σ local → 1.81σ post-trial significance after correcting for all trials from all triggers for all sources

Best fit flare parameters: 6.9 hours and 3.93 events

Archival alert - occurred before current alert stream



Localization around best fit flare time



Time evolution of GFU p-value around source

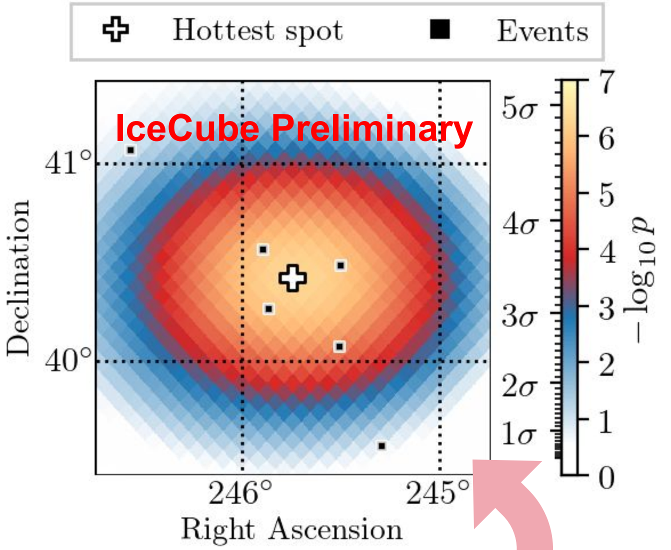
Allsky results from the offline analysis

Most significant flare (hotspot) in allsky found in the **northern sky (δ=40.42°)**

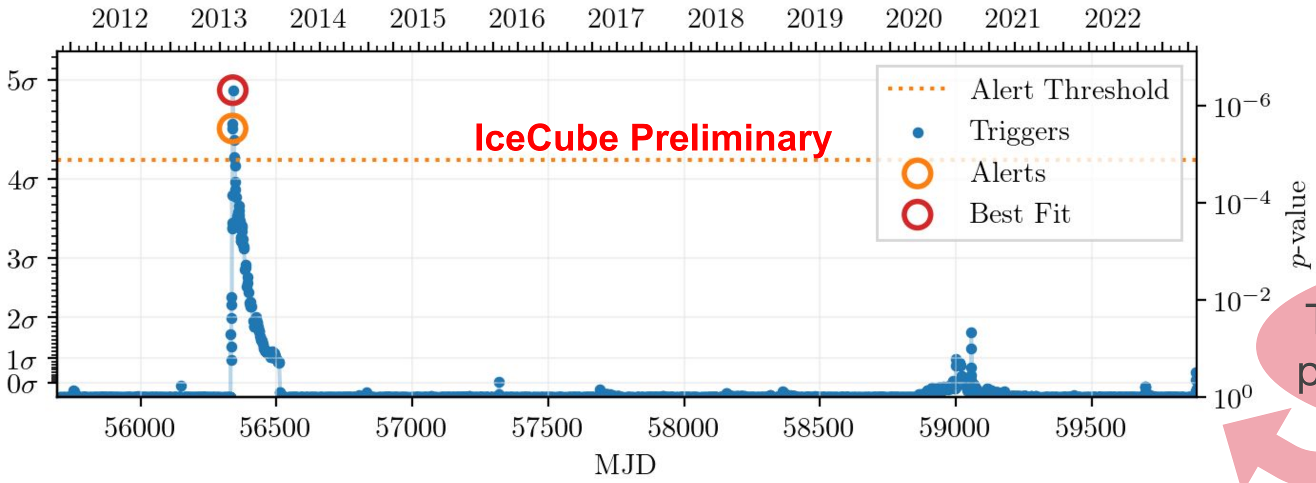
4.90σ local → 0.482σ post-trial significance after correcting for all trials from all triggers across whole sky

Best fit flare parameters: 9.4 days and 10.7 events

Archival alert - occurred before current alert stream



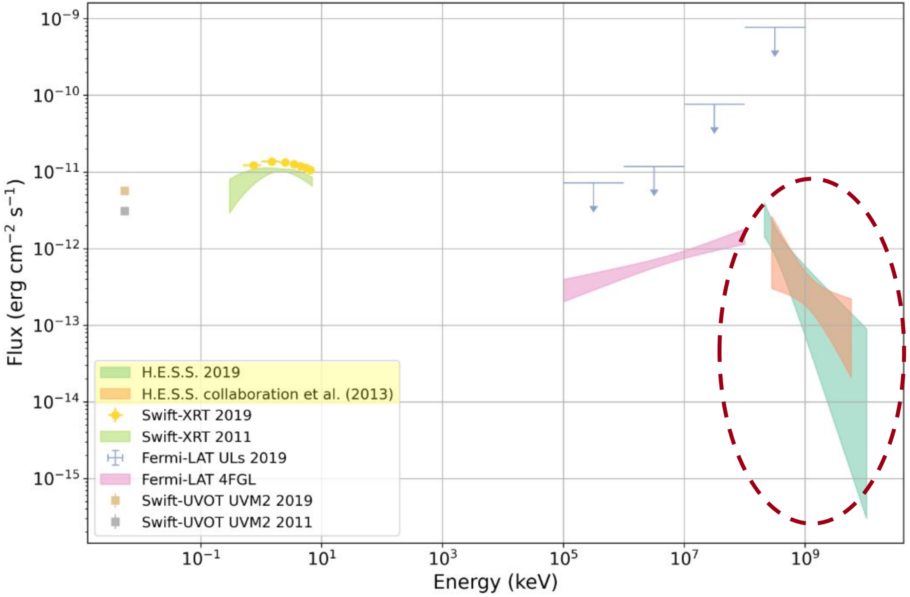
Localization around best fit flare time



Time evolution of GFU p-value around hotspot

Example of IACT follow-up of GFU alert

Source: 1ES 1312-423
Multiwavelength spectral energy distribution (SED) around GFU alert time



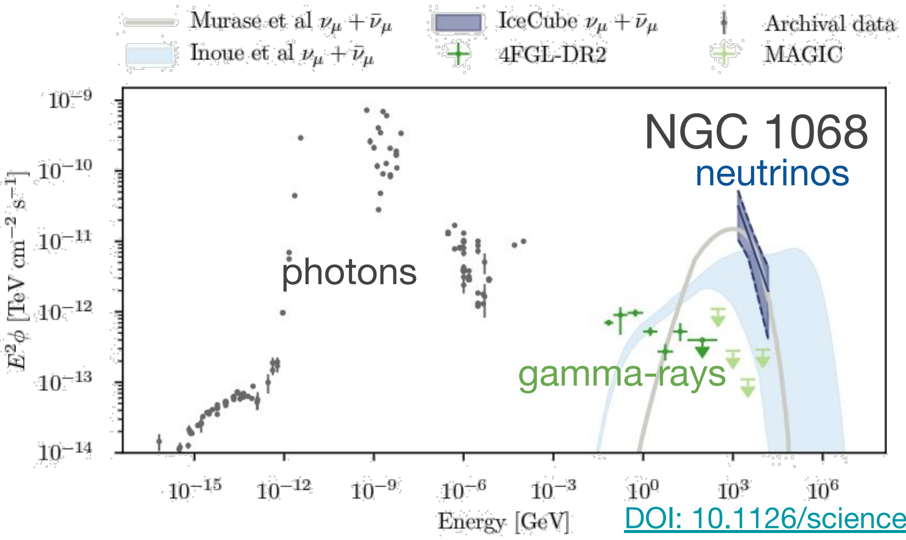
F. Schüssler, PoS (ICRC 2023) 1501

IACTs have been receiving GFU source alerts since May 2019

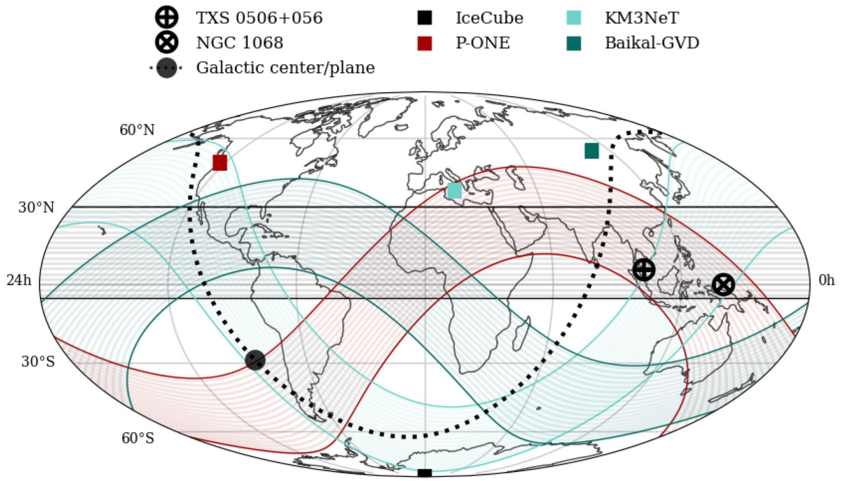
Gamma-ray observations have been performed on subset of the alerts

Have not yet seen significant gamma-ray excesses from direction of sources

Future improvements to the GFU alerts



DOI: 10.1126/science.abg3395

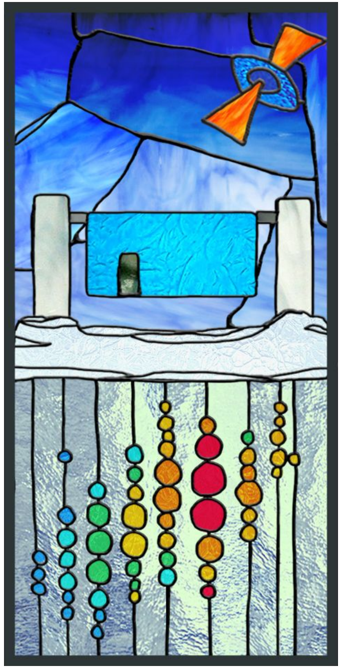


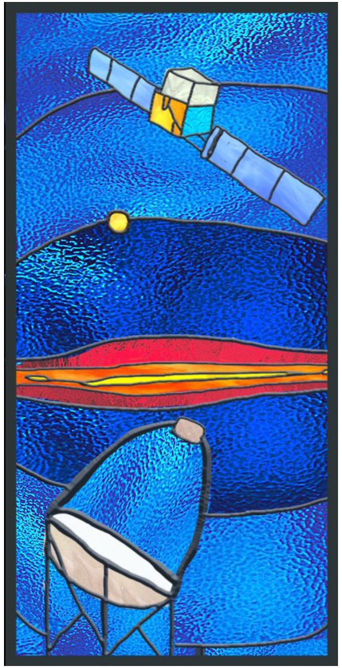
https://doi.org/10.3390/universe10020053

Plans to expand and update the operation of GFU in the future:

- Use more modern event selection, reconstruction, and analysis techniques
- Update source list with increasing knowledge of neutrino sources
- Share alerts publicly for other types of telescopes
- Combine data streams with other neutrino telescopes

Summary



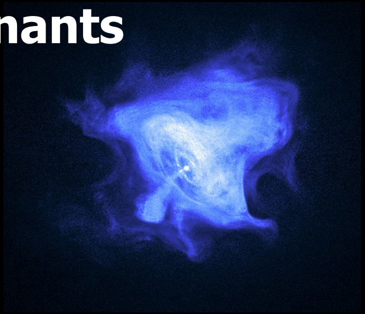


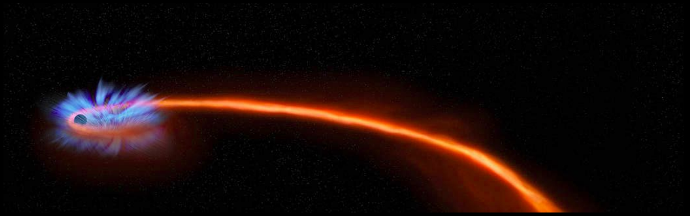
- IceCube looks to identify the sources of astrophysical neutrinos to study the extreme universe
- IceCube has a realtime system implemented to look for transient neutrino phenomena coincident with photon activity
- Gamma-ray Follow-Up (GFU) alerts aim to identify potential neutrino flares
- GFU alerts sent to high energy gamma-ray imaging air cherenkov telescopes (IACT)
- Flares of interest from archival search cannot reject null hypothesis after trials corrections

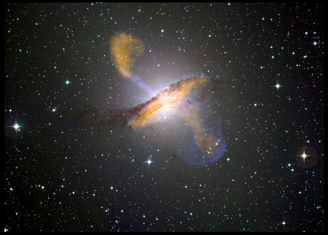
Backup

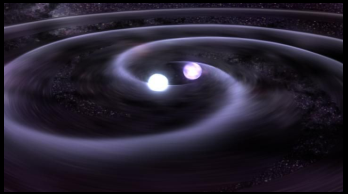
Neutrino Point-Source Candidates

	Steady, Time-Independent	Transient, Time-Dependent
Galactic	**Pulsar Wind Nebula** **Supernova Remnants**	**TeV Binaries** Tidal Disruption Events
Extragalactic	**Active Galactic Nuclei** **Starburst Galaxies**	AGN Flares Neutron Star Merger Gamma Ray Bursts





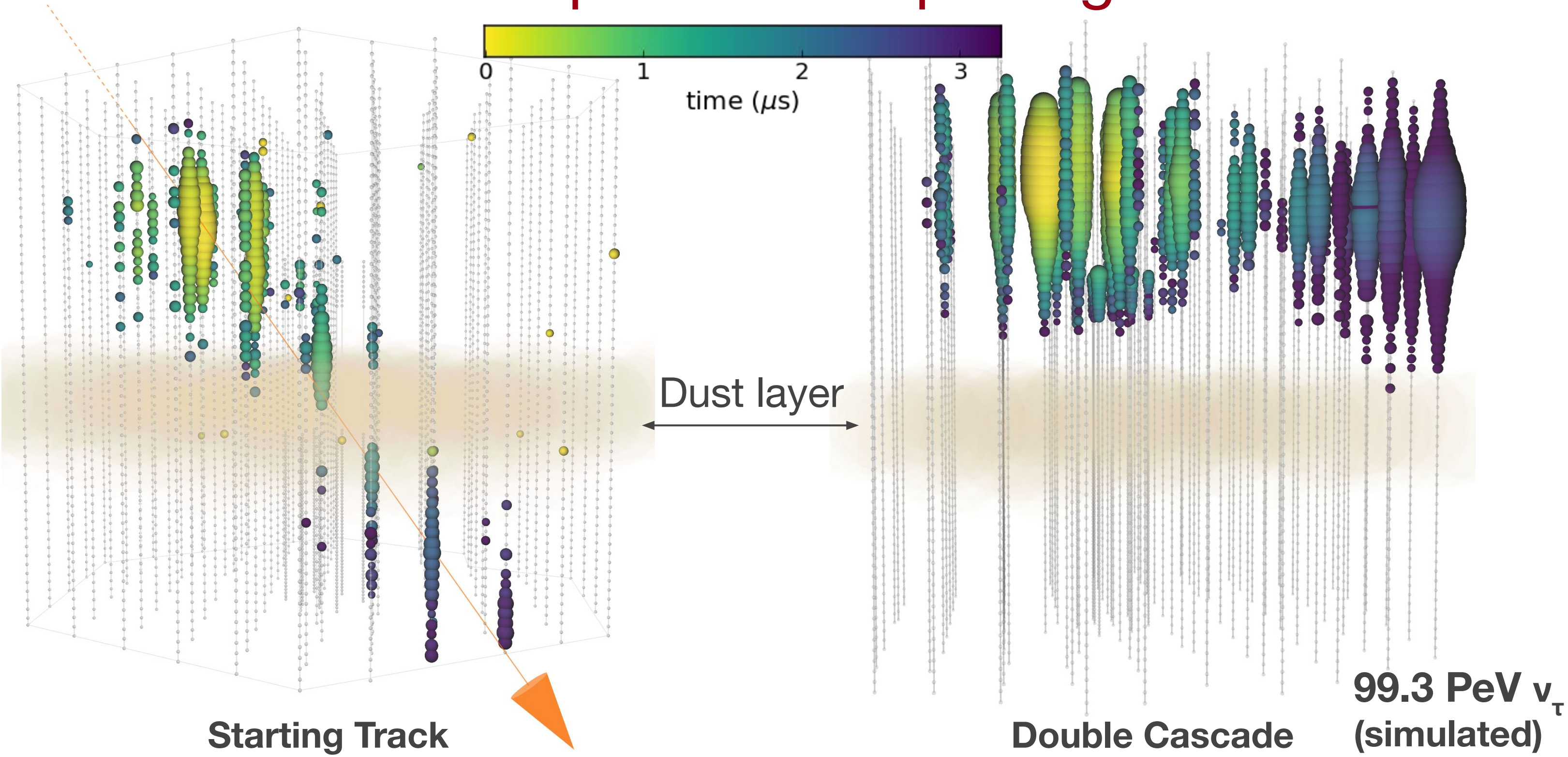




[3], [4], [5], [6], [7]

Unknown sources also possible

Some subclasses of TeV particle morphologies within IceCube



Starting Track

Angular Resolution: 1.5°

Log Energy Resolution: .3 x $\log(E_\nu)$

Charged current ν_μ and ν_τ ($\tau \to \mu + \nu$'s)

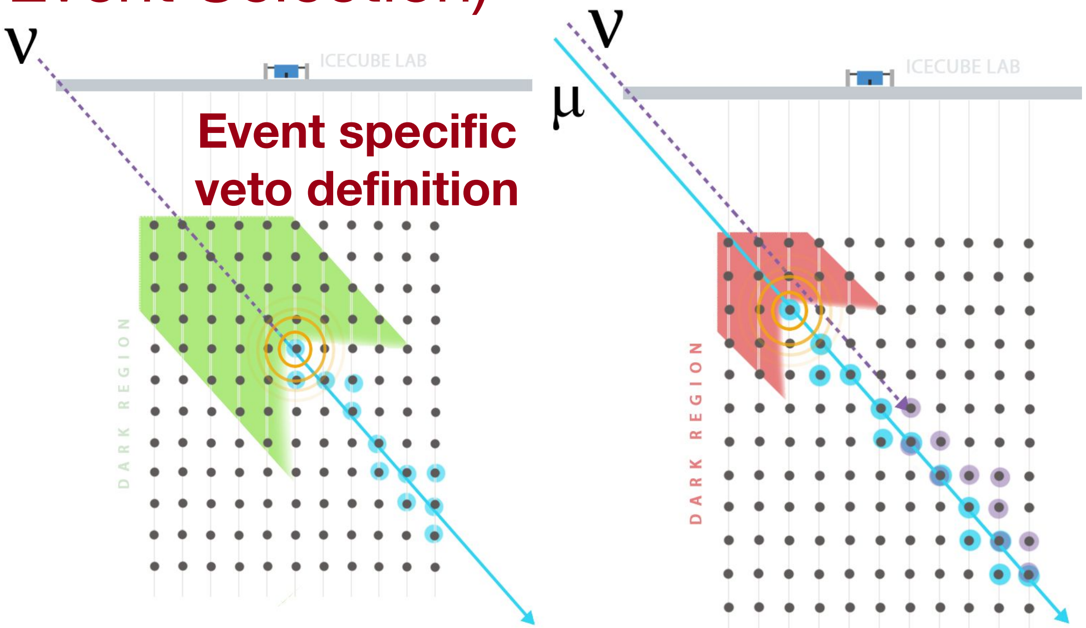
Double Cascade

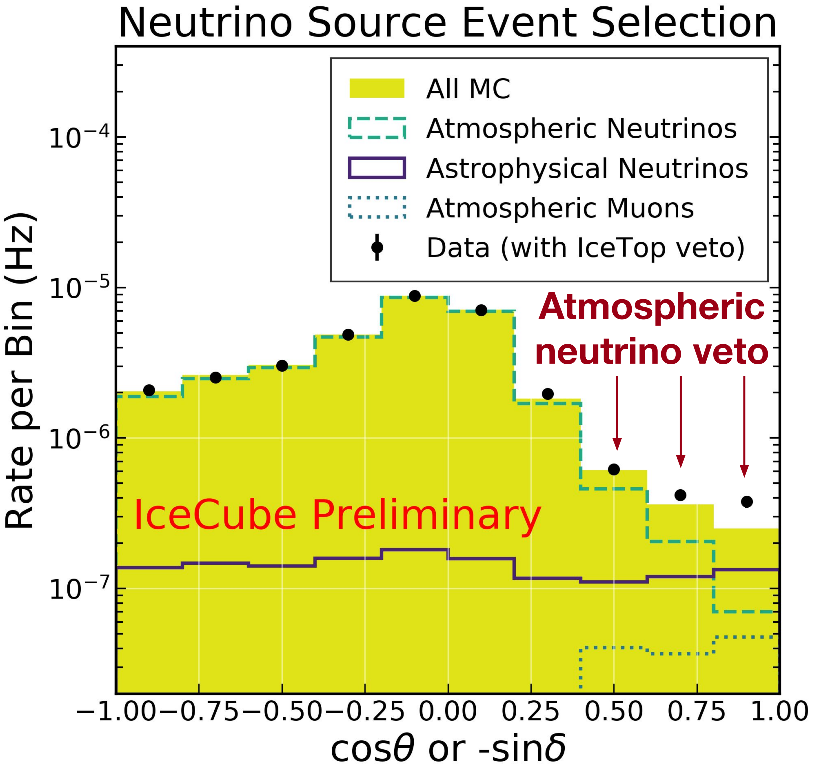
ν_τ ($\tau \to$ e/hadrons + ν's)

Must be high energy to see tau track

At lower energies look for double pulse structure in PMT waveform

ESTES (Enhanced **Starting Track** Event Selection)





Calculate probability that DOMs in the “dark region” would not have seen light from incoming muon

Look for signs of hadronic cascade

Flux assumed from PoS(ICRC2023)1008

Reject atmospheric neutrinos with light from muons

Suppresses atmospheric background in southern sky

~10,000 events in 10.3 years

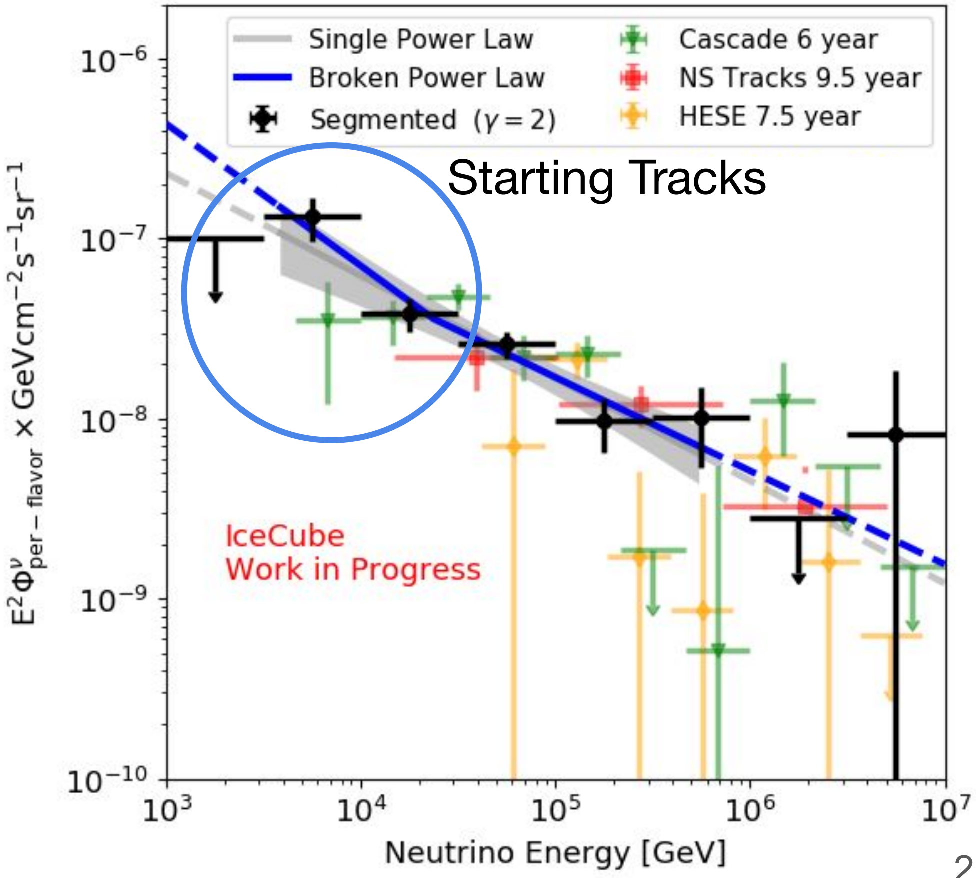
Recent measurements of astrophysical neutrino flux at earth as seen by IceCube

In 2013, IceCube announced discovery of astrophysical neutrino flux

Now have > 10 years of data

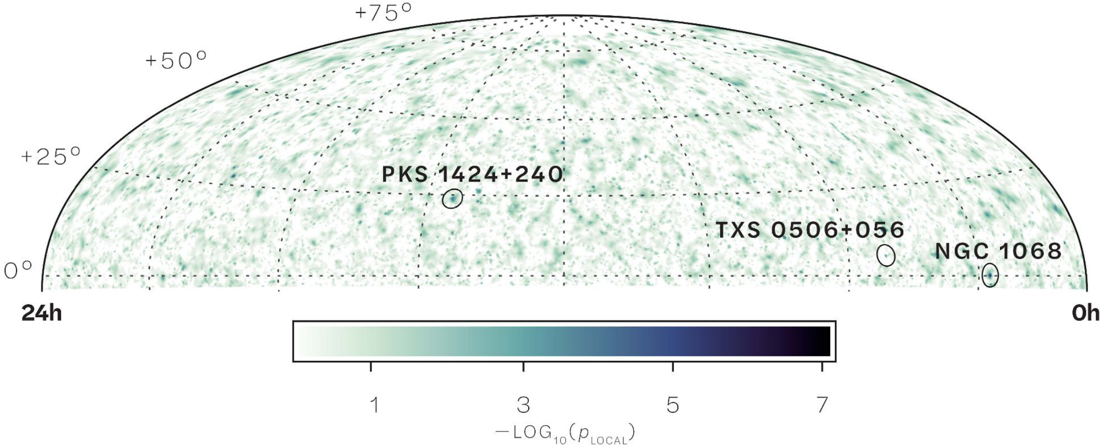
New **starting tracks** and **cascades** samples veto atmospheric neutrino events

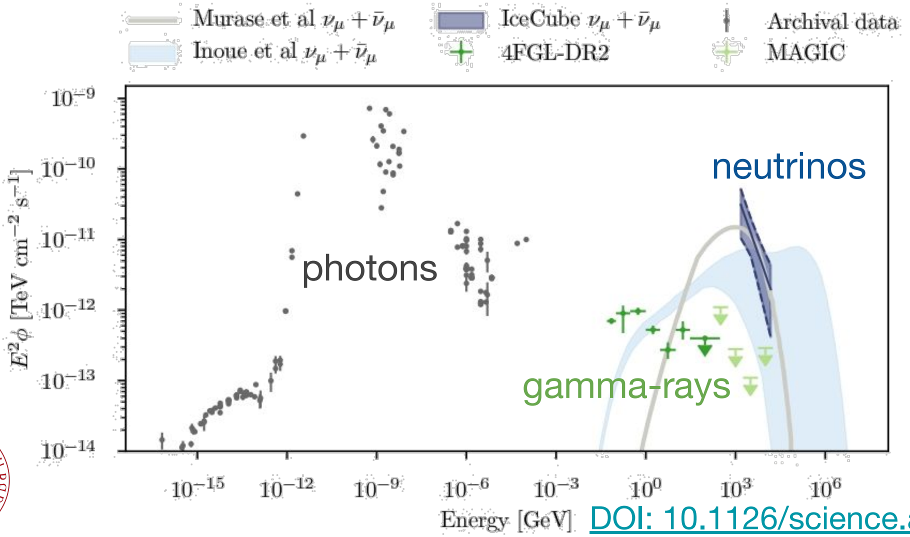
Suppression of atmospheric neutrinos gives insight into 1-100 TeV astrophysical flux



PoS(ICRC2023)1008

IceCube identifies NGC 1068 as likely neutrino source (2022)





Search for significant clustering of events versus isotropic null hypothesis

Brightest point in sky correlates with known seyfert galaxy: **NGC 1068**

NGC 1068 rejects null hypothesis at 4.2 σ after trials correction

Neutrino production environment opaque to gamma-rays?

DOI: 10.1126/science.abg3395

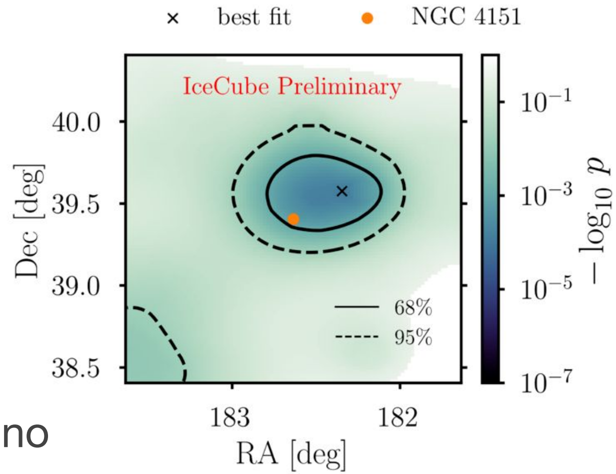
Building from NGC 1068, studies of x-ray bright seyferts

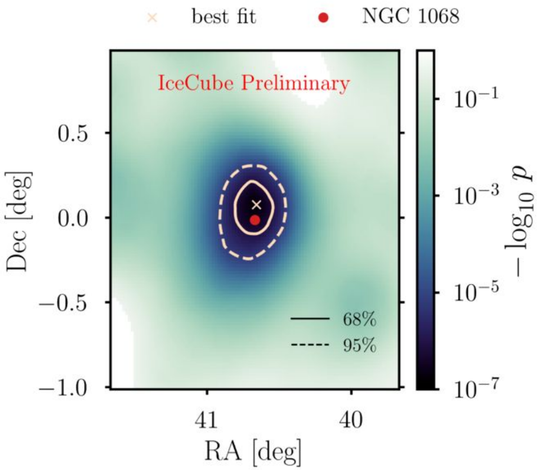
Neutrino production environment opaque to gamma-rays?

New catalogs developed with information learned from NGC 1068

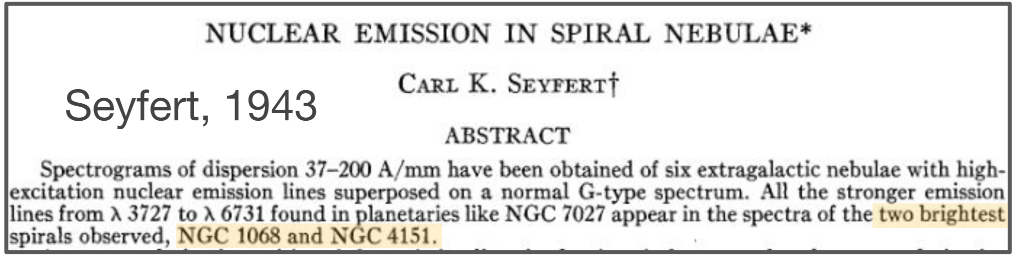
Look at **x-ray bright seyfert galaxies**

Hints that NGC 4151 (2.9σ) also neutrino source





PoS(ICRC2023)1052, PoS(ICRC2023)1032


Seyfert, 1943

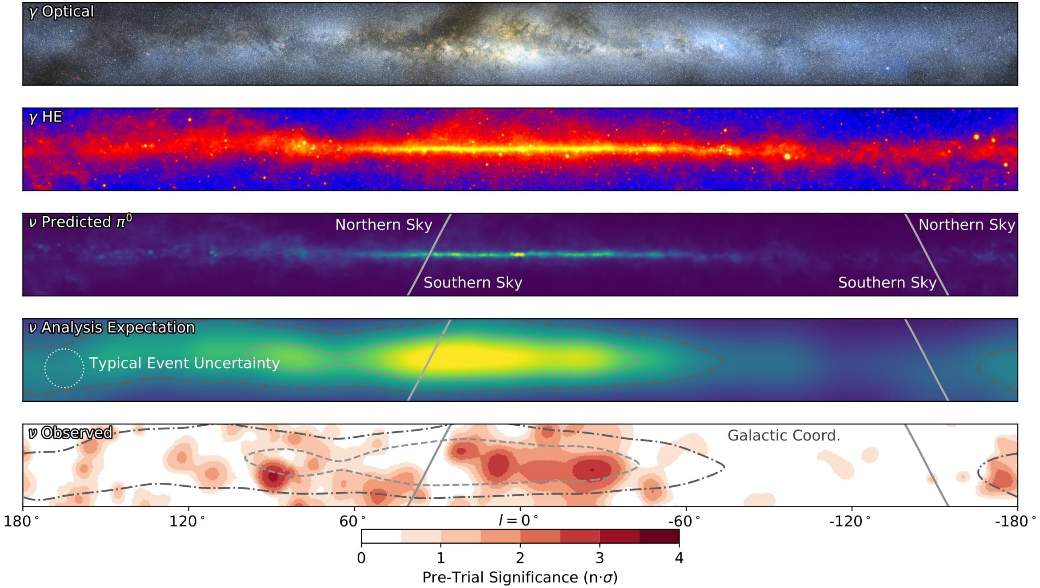
NUCLEAR EMISSION IN SPIRAL NEBULAE*

CARL K. SEYFERT†

ABSTRACT

Spectrograms of dispersion 37–200 A/mm have been obtained of six extragalactic nebulae with high-excitation nuclear emission lines superposed on a normal G-type spectrum. All the stronger emission lines from λ 3727 to λ 6731 found in planetaries like NGC 7027 appear in the spectra of the two brightest spirals observed, NGC 1068 and NGC 4151.

IceCube observes galactic plane in neutrinos (2023)



[DOI: 10.1126/science.adc9818](https://doi.org/10.1126/science.adc9818)

Fermi π^0 Model: [DOI: 10.1088/0004-637X/750/1/3](https://doi.org/10.1088/0004-637X/750/1/3)

Neutrinos can be produced in galactic plane by:

- Galactic accelerators (e.g. supernova remnants)
- Diffuse cosmic ray flux interacting with galactic medium

Used deep neural network to improve **cascade event** angular resolution

Excess of neutrinos found from galactic plane

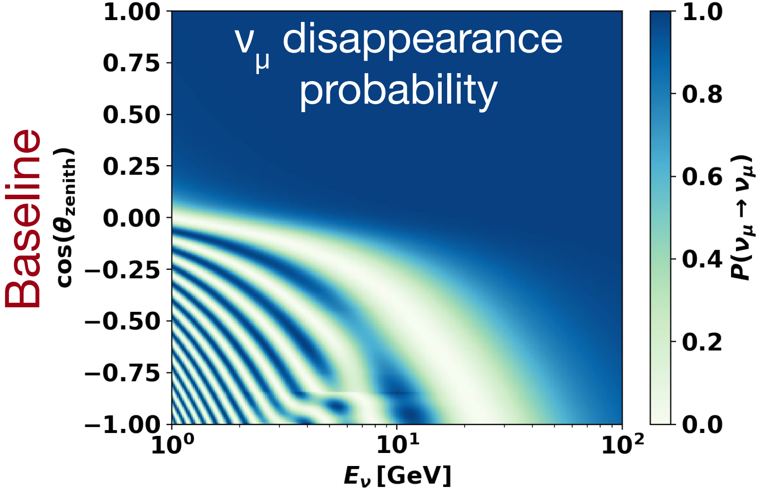
Rejects null hypothesis at 4.5σ assuming the Fermi π^0 model (diffuse)

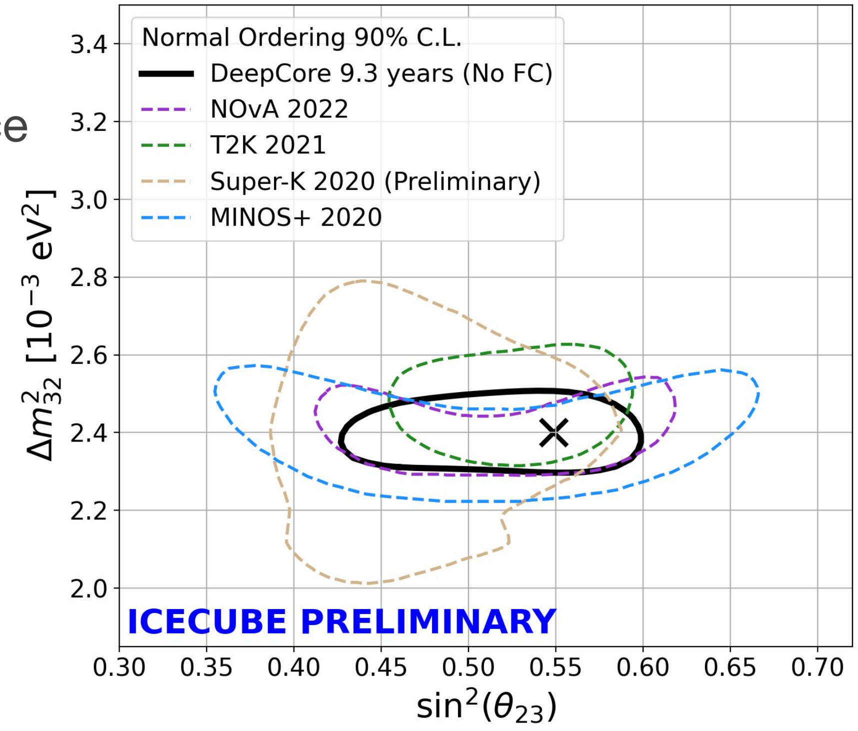
IceCube neutrino oscillation measurement using DeepCore

Here, **atmospheric neutrinos** signal instead of background

Used denser instrumented DeepCore to produce sample of 150,000 5-300 GeV neutrino events

Measure muon neutrino disappearance to constrain Δm_{23}^2 and $\sin^2(\theta_{23})$





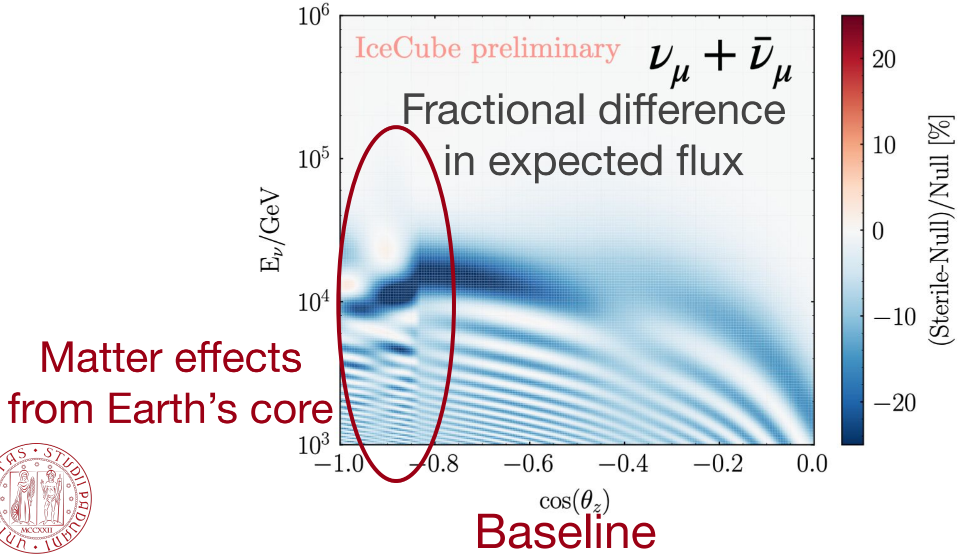
PoS(ICRC2023)1143

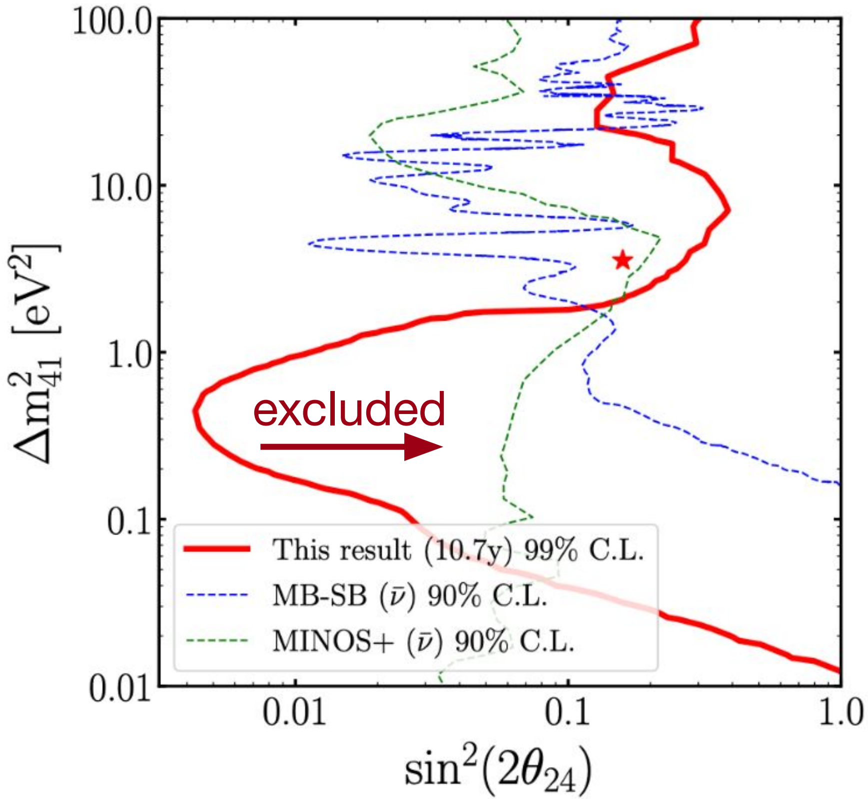
IceCube uses higher energy atmospheric neutrinos to look for oscillations from sterile neutrinos

Use TeV energy atmospheric neutrinos to look for oscillations due to sterile mixing

Employ 3+1 sterile neutrino model

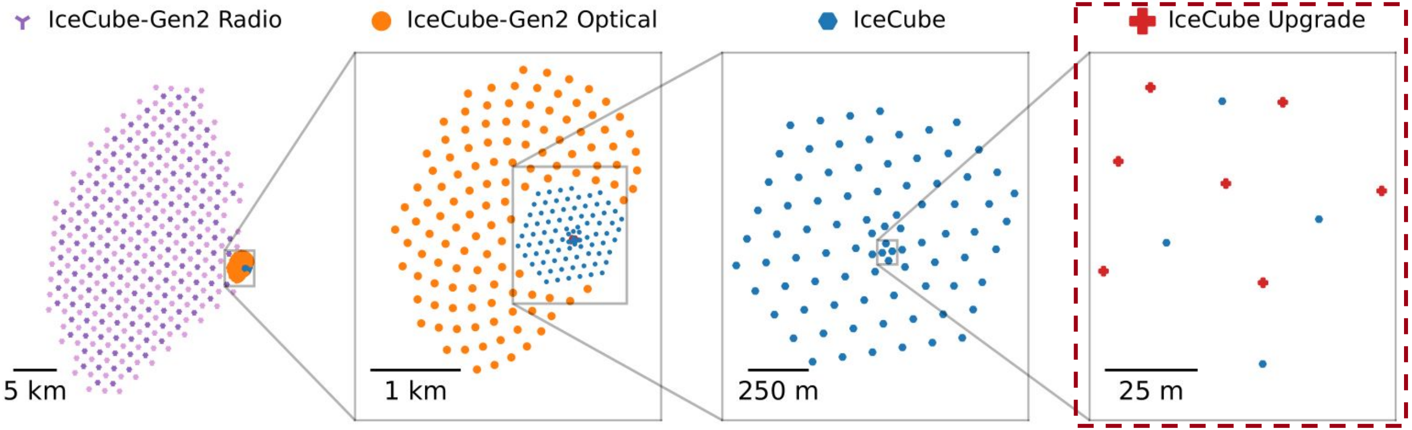
Excludes unique region of sterile mixing parameter space





Garcia, A. TeVPA 2023

The next generation of IceCube: the IceCube Upgrade

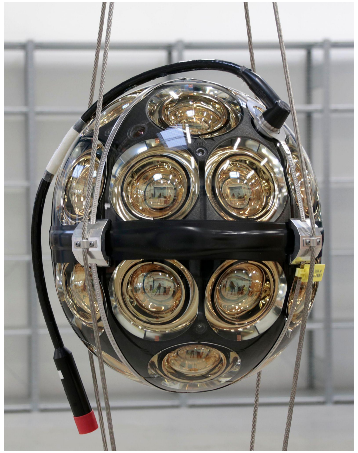


IceCube Upgrade (deployment 2025/26)

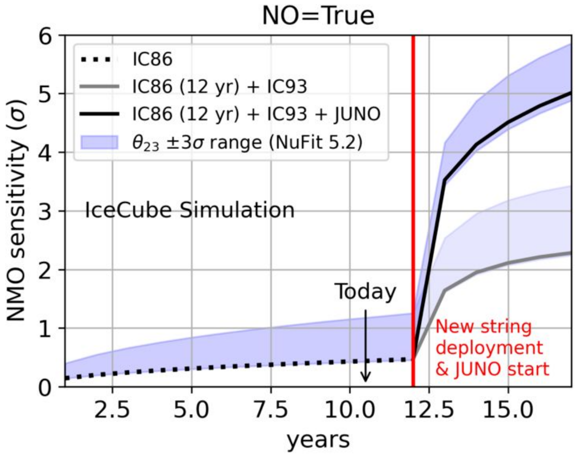
- Denser instrumentation
- Lower minimum energy (~1 GeV)

Goals:

- R&D for IceCube-Gen2
- Calibration of detector systematics
- Oscillation physics

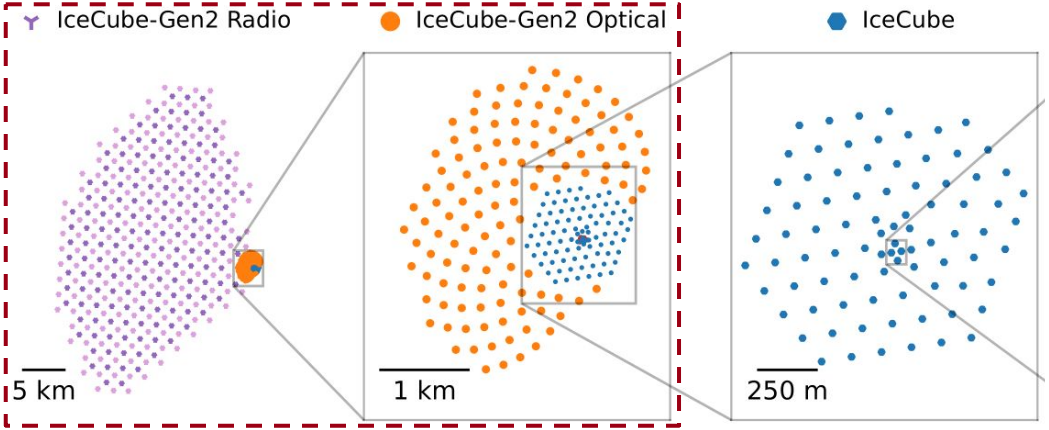


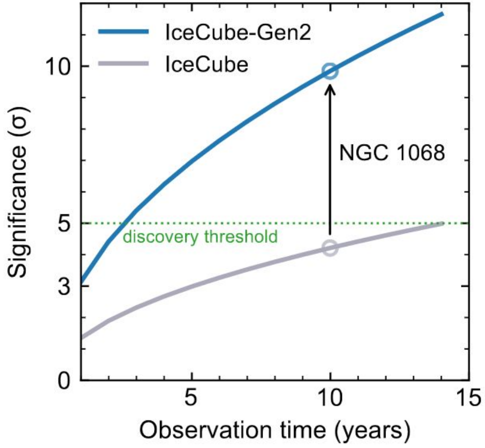
Multi-PMT DOM
PoS(ICRC2023)1183



Neutrino Mass Ordering
PoS(ICRC2023)1036

The next generation of IceCube: IceCube-Gen2



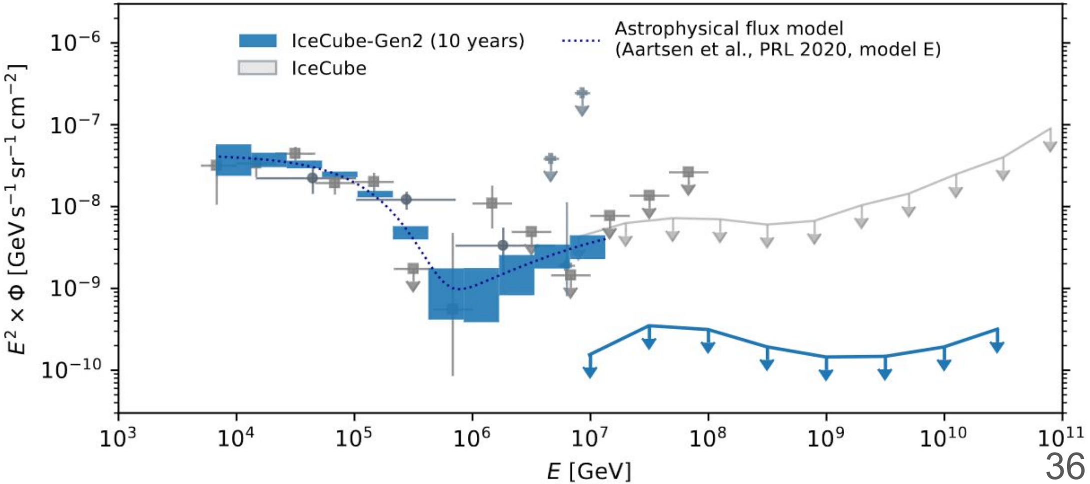


IceCube-Gen2

- Increase effective volume
- Increase upper energy threshold

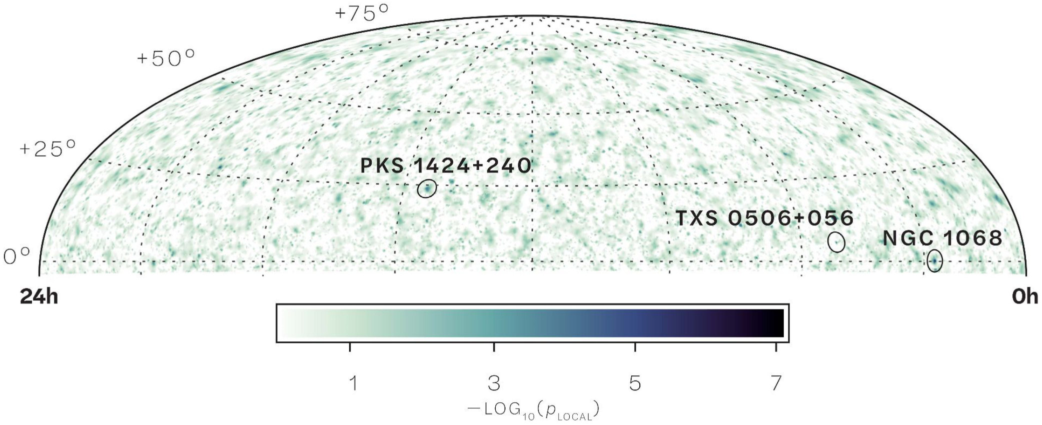
Goals:

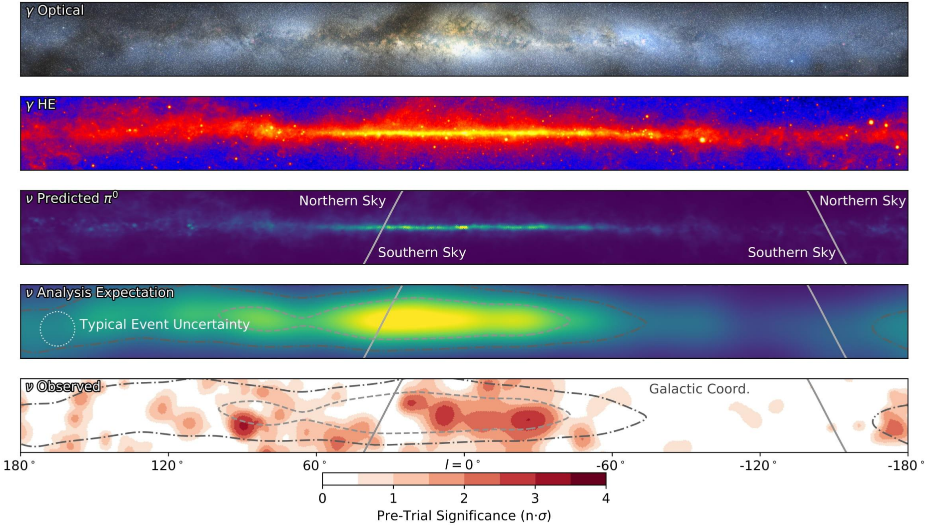
- Measure neutrino flux at extreme energies (PeV+)
- Improve sensitivity to astrophysical neutrino sources by factor of ~5



IceCube-Gen2 TDR

Summary of IceCube review





IceCube has been operating at South Pole for 12+ years

IceCube discovered flux of astrophysical neutrinos

Beginning to identify sources of astrophysical neutrinos:

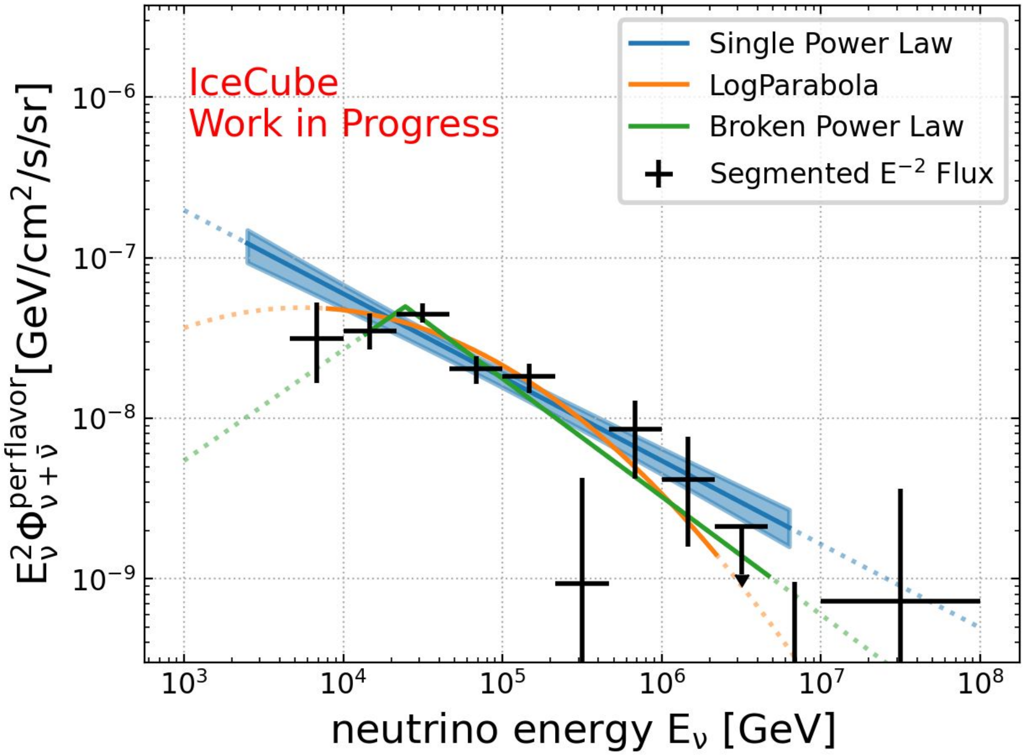
- NGC 1068, x-ray bright seyfert
- TXS 0506+056, blazar flare
- Galactic plane

Study oscillation parameters with atmospheric neutrinos

IceCube-Gen2 to explore cosmic energy frontier

Combined track and cascade measurement of diffuse astrophysical neutrino flux

- Combine diffuse measurement for northern tracks and cascades
- Cascade channel has less atmospheric background, dominates below 100 TeV
- Hints at shape within the diffuse neutrino spectrum?
- Next step is to add more channels for a “global” diffuse neutrino measurement



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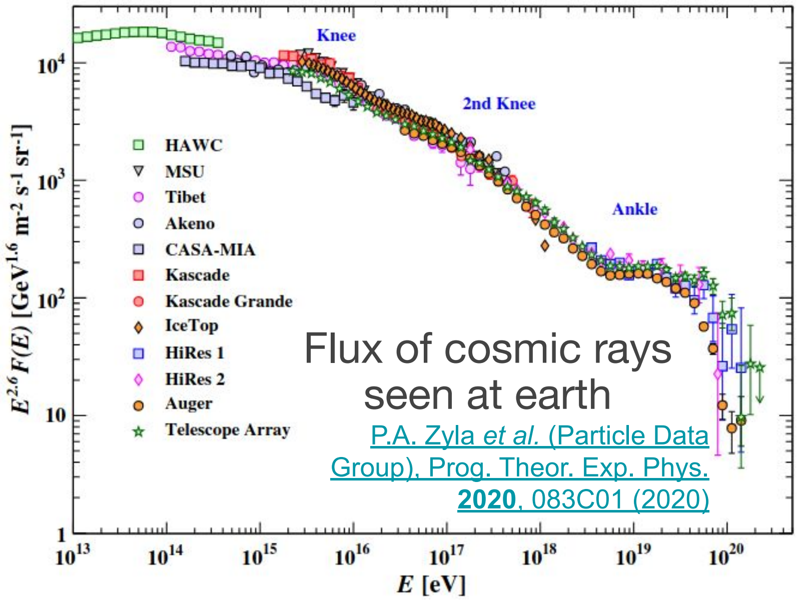
Diffuse Galactic Plane Neutrinos

Observe a flux of cosmic rays at the earth

Cosmic rays interact in the atmosphere and create showers of secondary particles including neutrinos and gamma rays

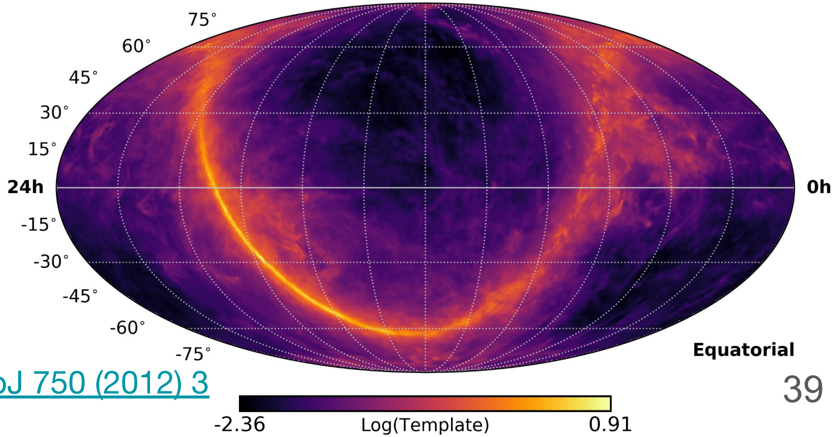
Same interactions should occur with the galactic plane medium

Look for astrophysical neutrinos being produced by diffuse CR interacting with GP matter



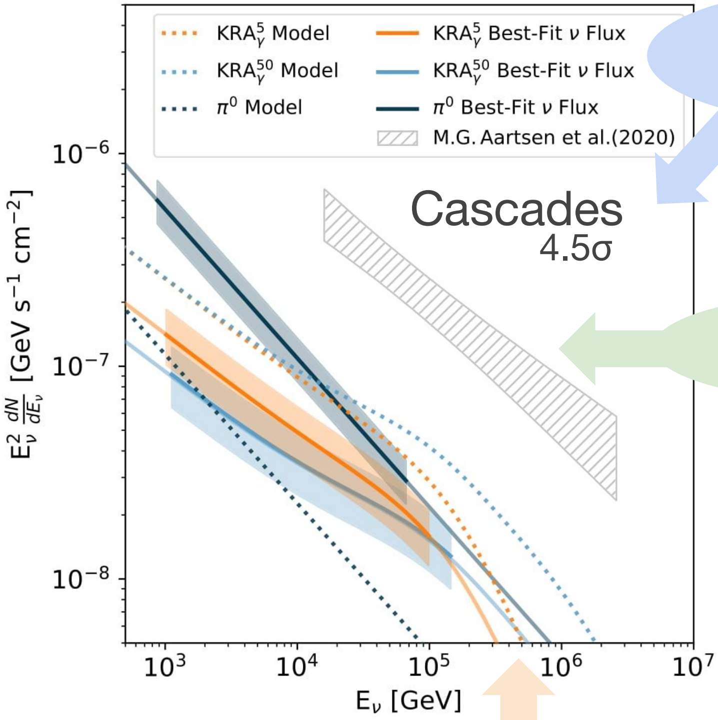
Flux of cosmic rays seen at earth

P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

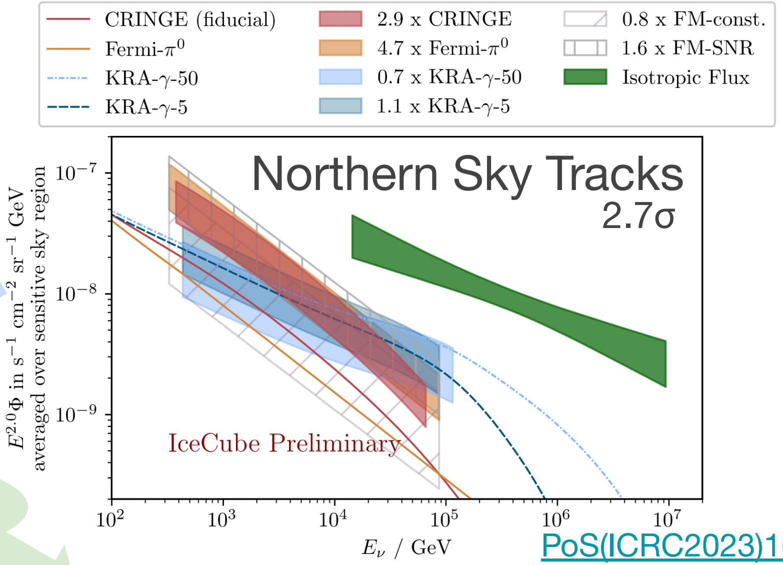


Fermi π^0: ApJ 750 (2012) 3

Measurements and upper limits of the galactic plane neutrino flux



Larger rate of signal events



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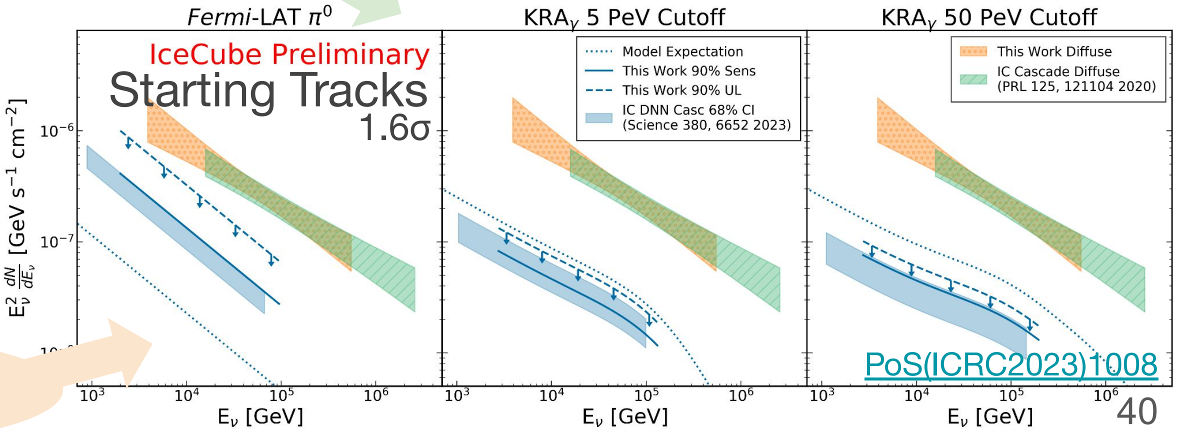
View of Galactic Center



DOI: 10.1126/science.adc9818

Atmospheric ν Background Veto

PoS(ICRC2023)1008

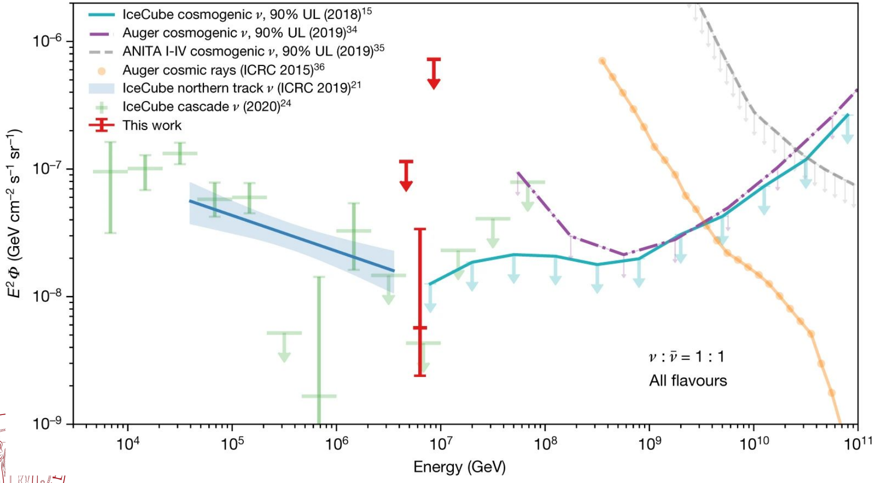
IceCube's Glashow event (2021)

W resonance between electron and electron antineutrino

Partially contained cascade event with 6.3 PeV reconstructed energy

Secondary muons observed consistent with hadronic decay of boson

Insight into PeV neutrino flux



[Nature 591, 220-224 (2021)](#)