Review of and recent results from the IceCube South Pole Neutrino Observatory

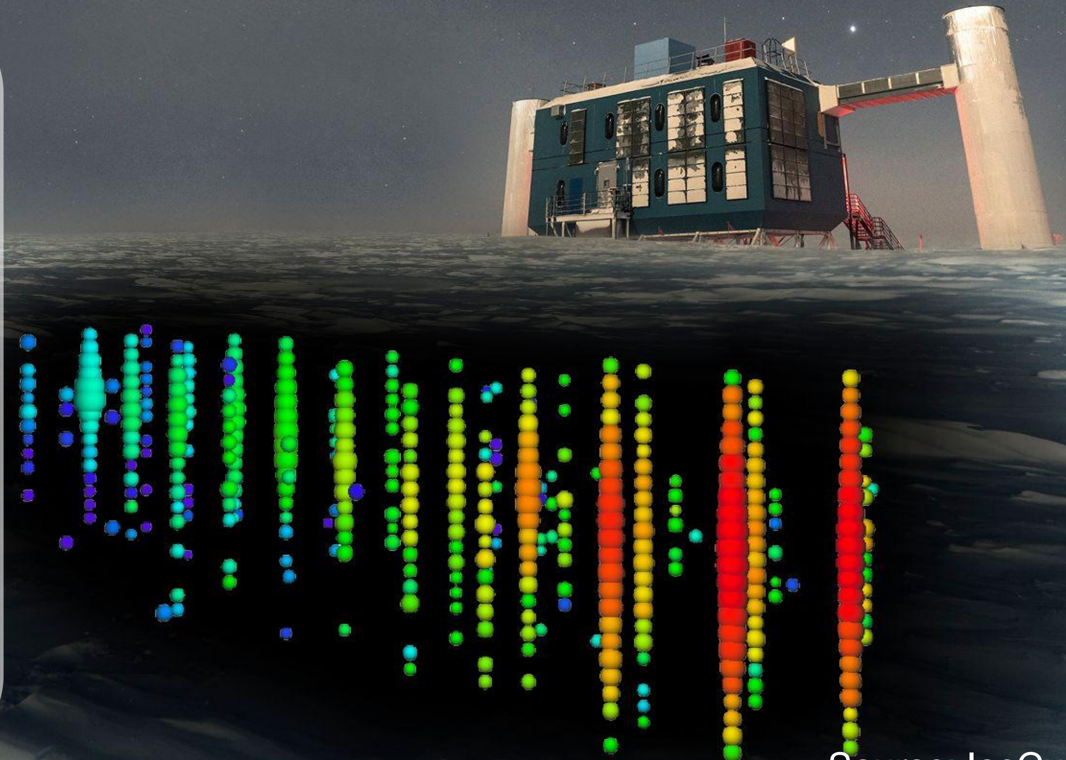
Sarah Mancina on behalf of the IceCube Collaboration

Les Rencontres de Physique de la Vallée d'Aoste
La Thuile
March 4th, 2024

Università degli Studi di Padova

NSF

IceCube Neutrino Observatory



Source: IceCube/NSF

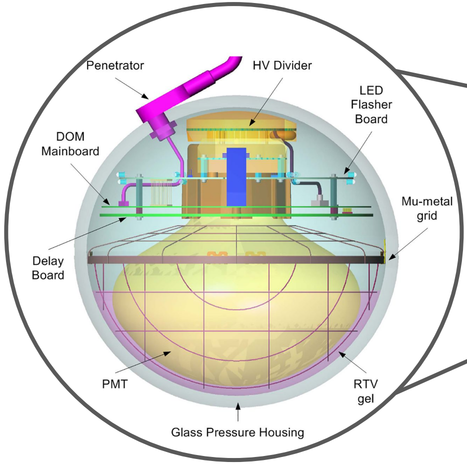
IceCube detector design

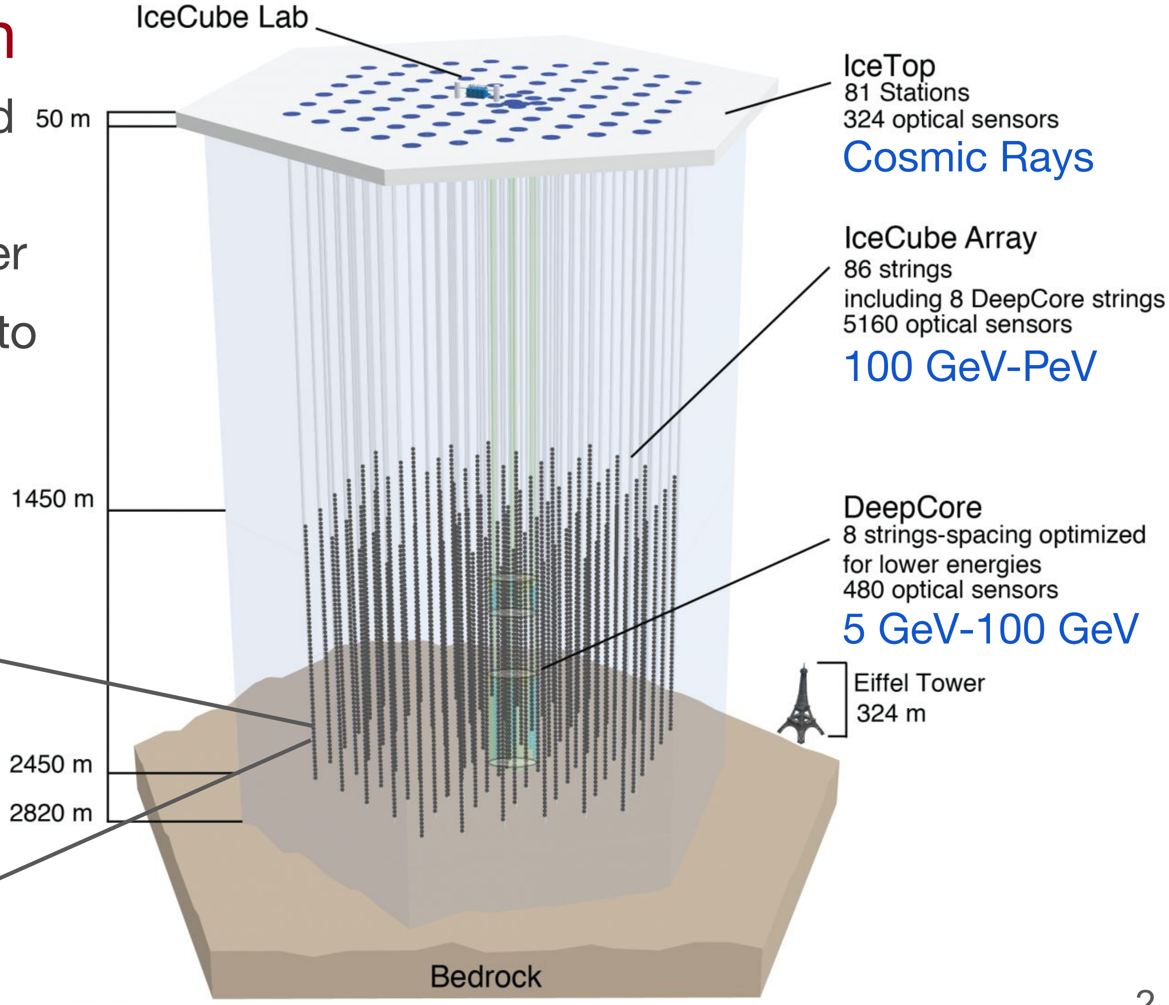
Over 5000 sensors each equipped with photomultiplier tube (PMT)

Array in **1km^3** of South Pole glacier

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

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

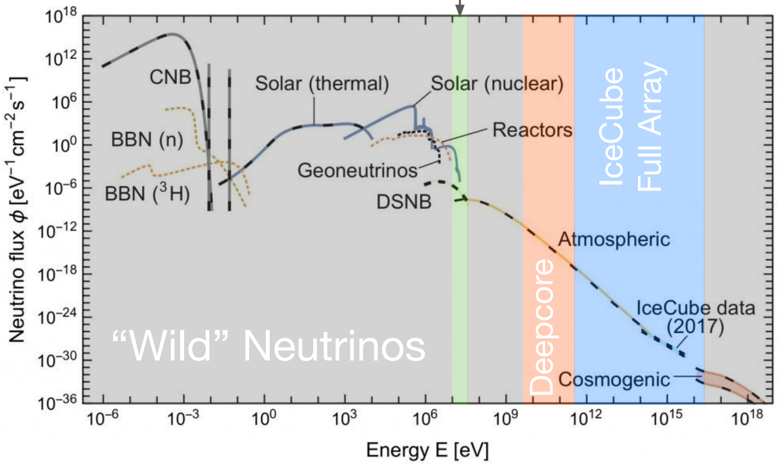




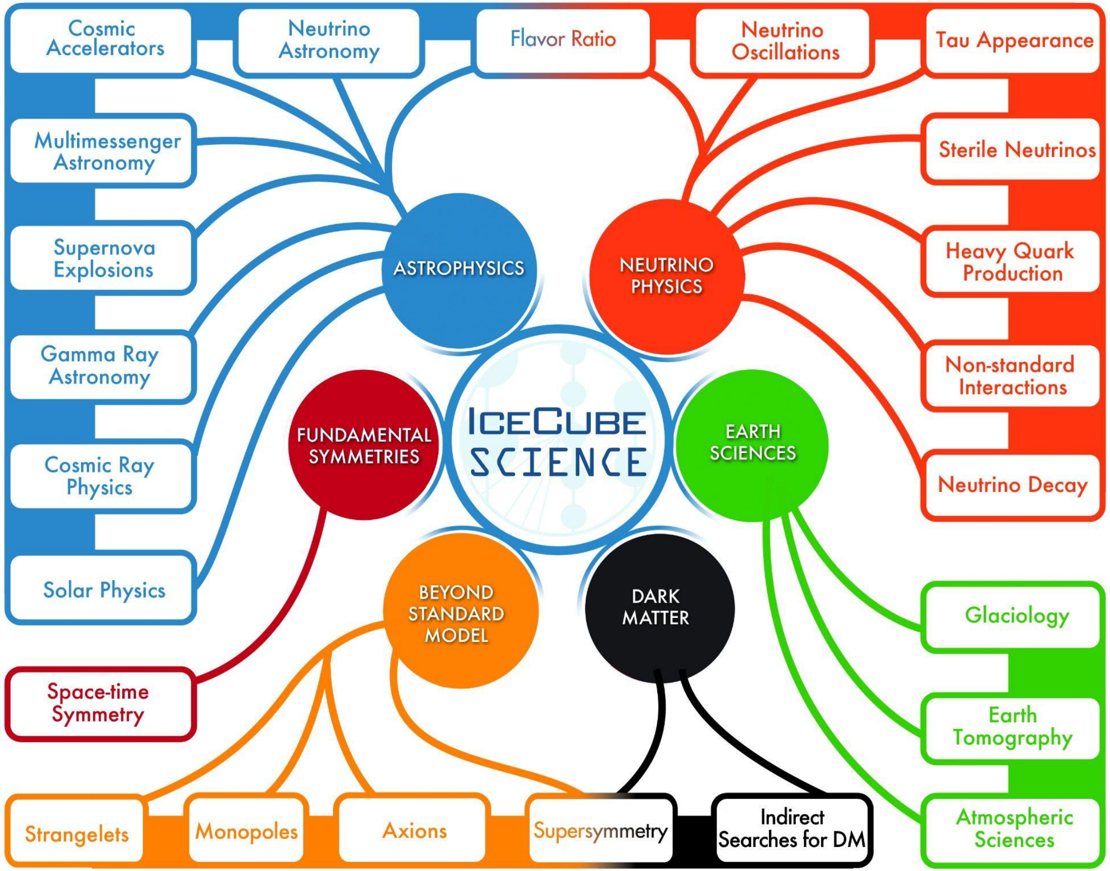
IceCube/NSF

IceCube science covers a broad range of physics topics

Supernova
Monitor



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



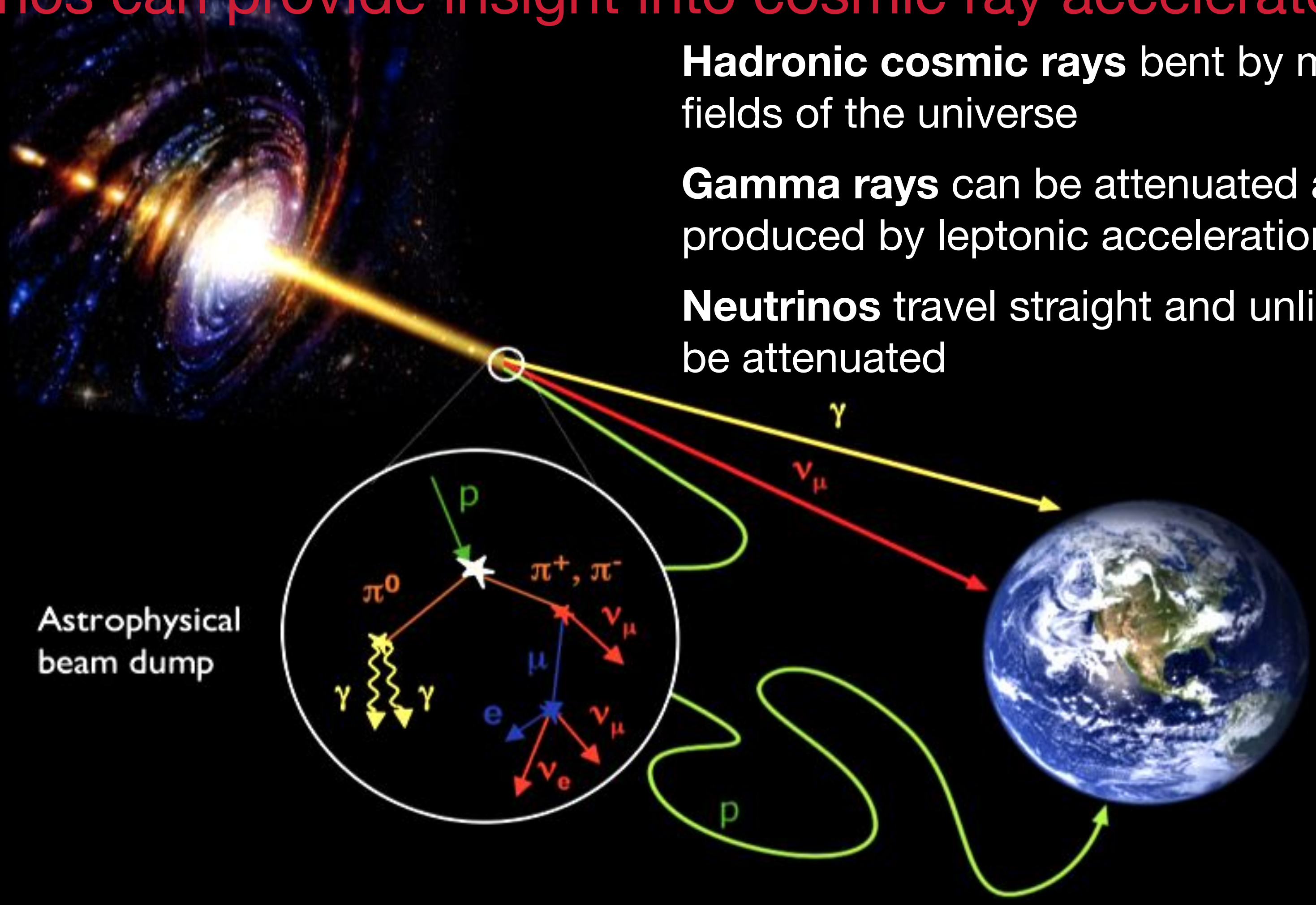
IceCube/NSF

Neutrinos can provide insight into cosmic ray accelerators

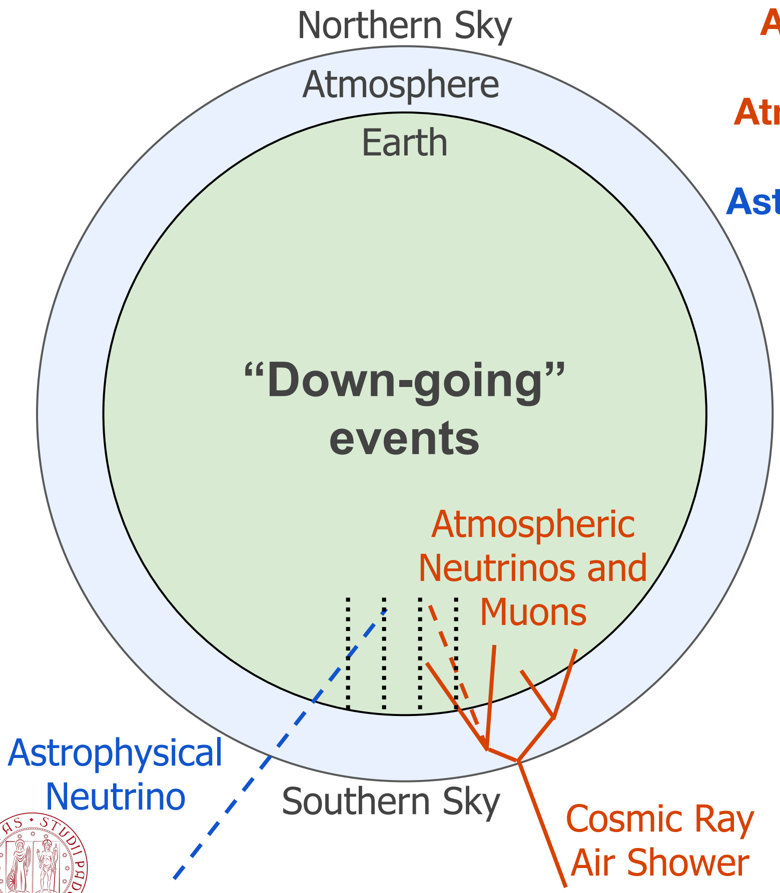
Hadronic cosmic rays bent by magnetic fields of the universe

Gamma rays can be attenuated and produced by leptonic acceleration

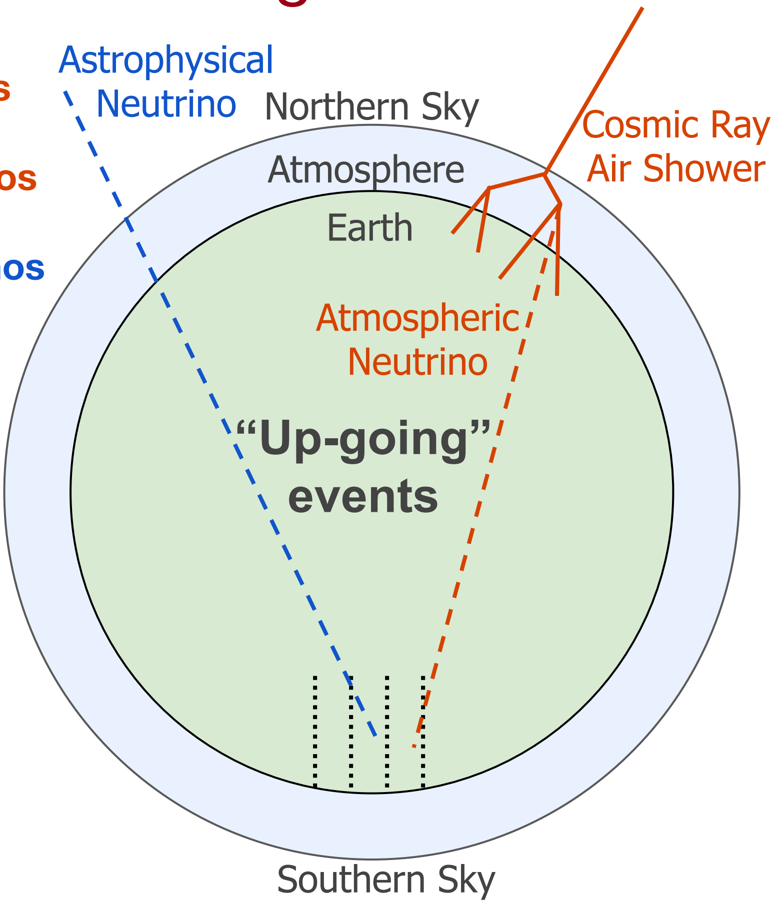
Neutrinos travel straight and unlikely to be attenuated



Astrophysical neutrinos and atmospheric backgrounds



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



Main TeV particle morphology classifications within IceCube

Muon Track

Angular Resolution: 0.6°

Log Energy Resolution: 20% of muon energy at detector entry

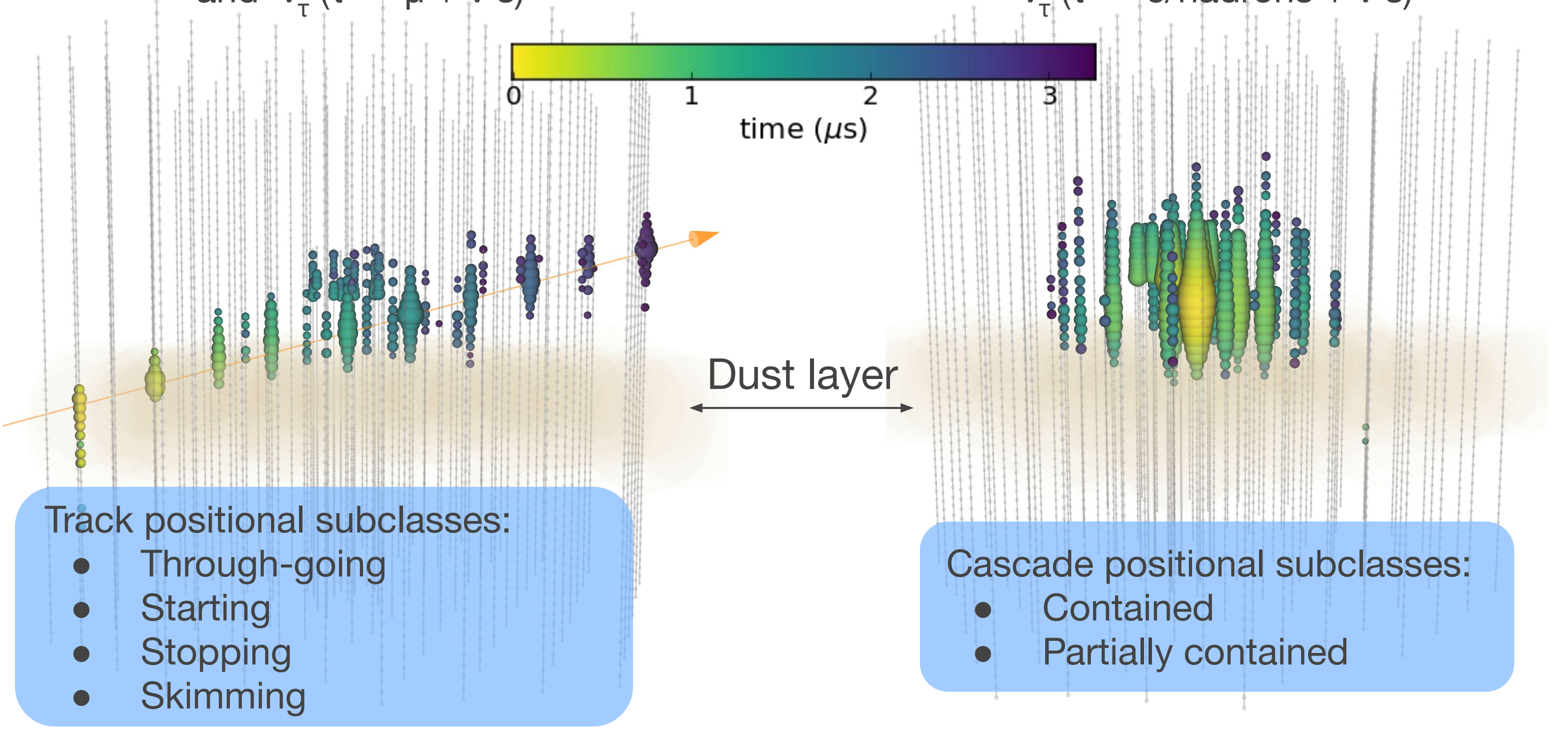
Atmospheric muons, charged current ν_μ and ν_τ ($\tau \rightarrow \mu + \nu$'s)

Electromagnetic/Hadronic Cascade

Angular Resolution: 5°-15°

Log Energy Resolution: 15% of neutrino energy

Neutral current ν, charged current ν_e and ν_τ ($\tau \rightarrow$ e/hadrons + ν's)



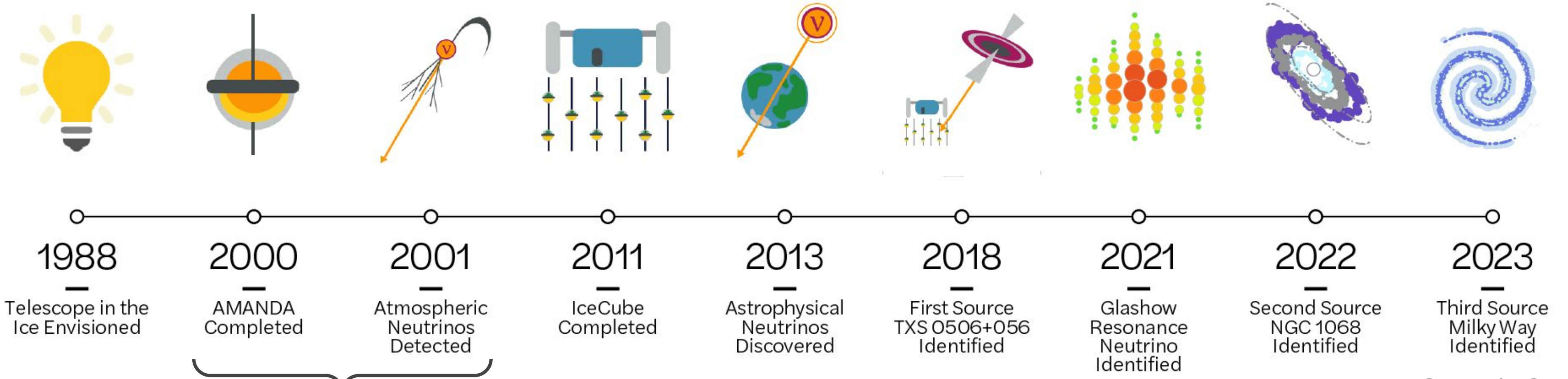
Track positional subclasses:

- Through-going
- Starting
- Stopping
- Skimming

Cascade positional subclasses:

- Contained
- Partially contained

Timeline of neutrino astronomy achievements with IceCube



IceCube predecessor, AMANDA

IceCube/NSF

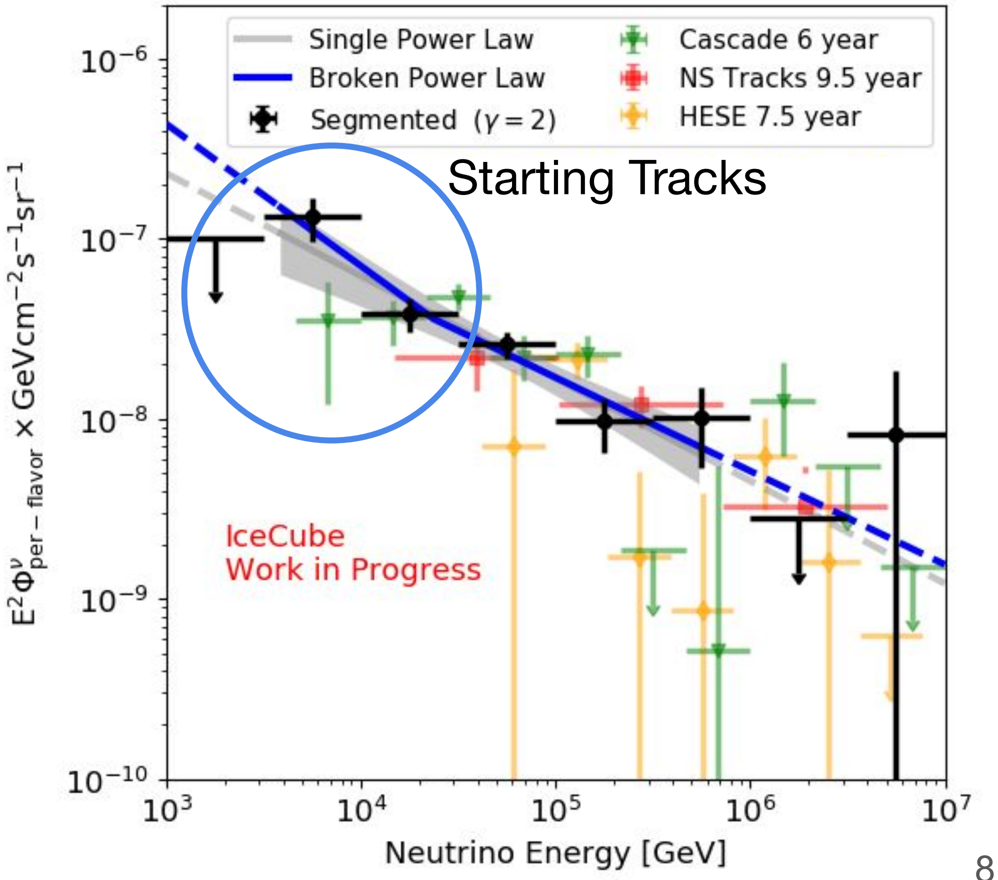
Recent measurements of astrophysical neutrino flux at earth as seen by IceCube

In 2013, IceCube announced discovery of astrophysical neutrino flux

Now have > 10 years of data

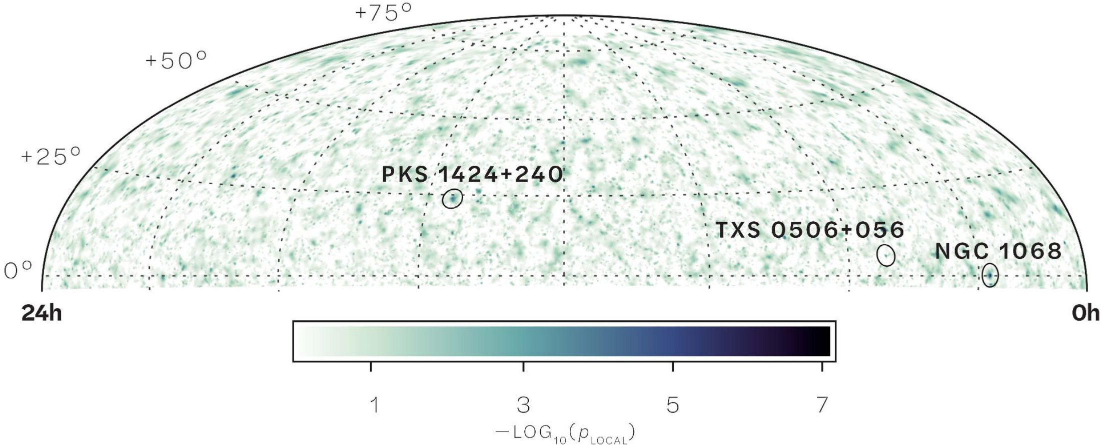
New **starting tracks** and **cascades** samples veto atmospheric neutrino events

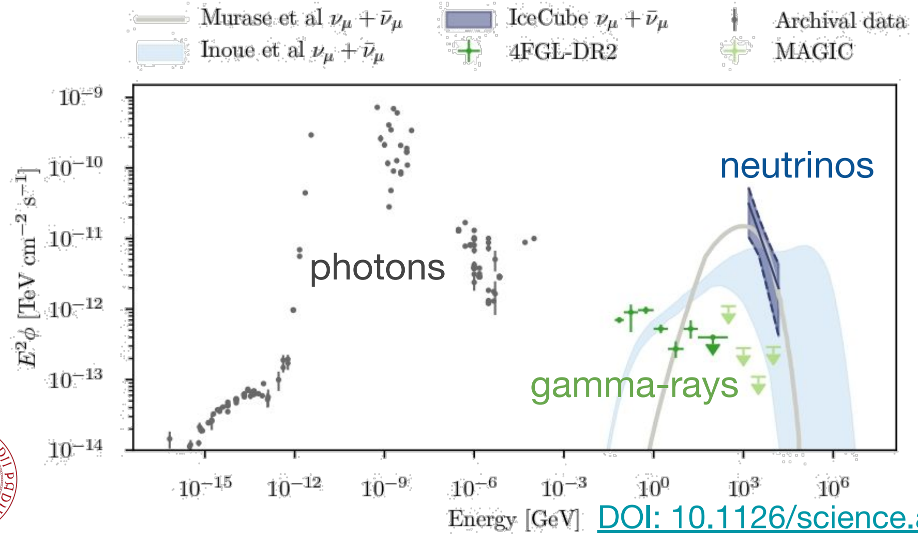
Suppression of atmospheric neutrinos gives insight into 1-100 TeV astrophysical flux



PoS(ICRC2023)1008

IceCube identifies NGC 1068 as likely neutrino source (2022)





DOI: 10.1126/science.abg3395

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?

NASA/ESA Hubble

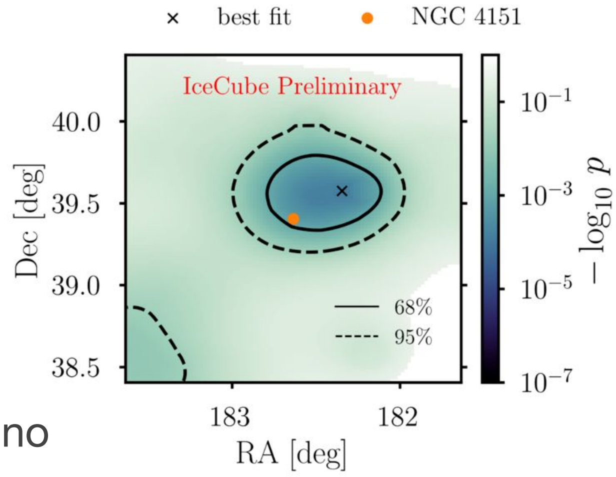
Building from NGC 1068, studies of x-ray bright seyferts

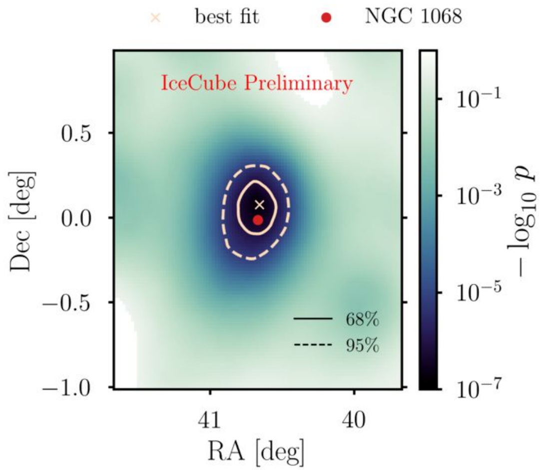
Neutrino production environment opaque to gamma-rays?

New catalogs developed with information learned from NGC 1068

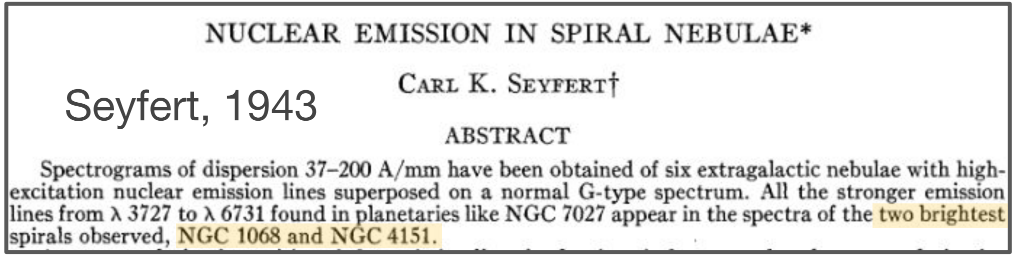
Look at **x-ray bright seyfert galaxies**

Hints that NGC 4151 (2.9σ) also neutrino source





PoS(ICRC2023)1052, PoS(ICRC2023)1032



Seyfert, 1943

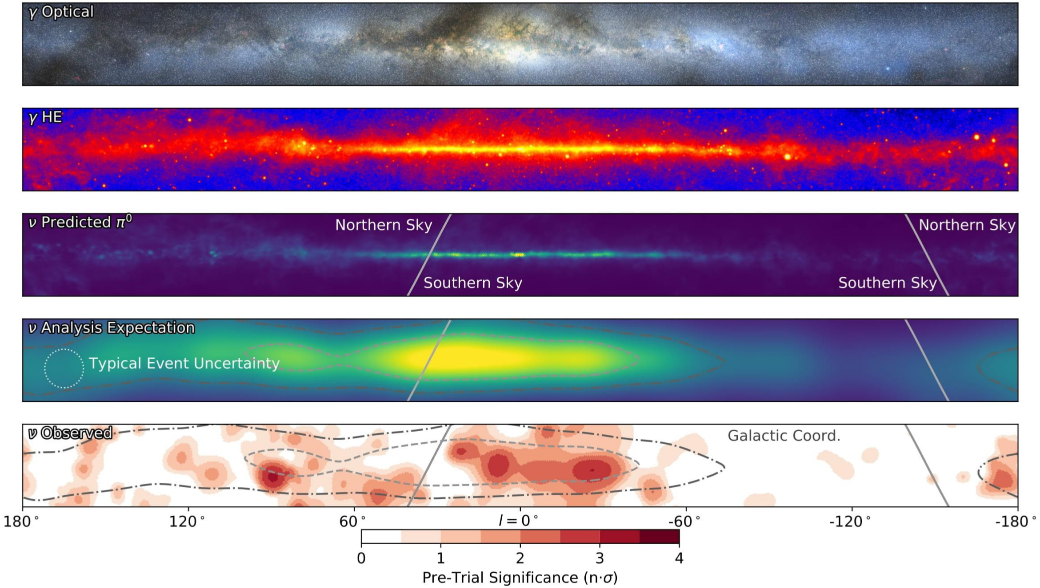
NUCLEAR EMISSION IN SPIRAL NEBULAE*

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

Fermi π^0 Model: DOI: 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

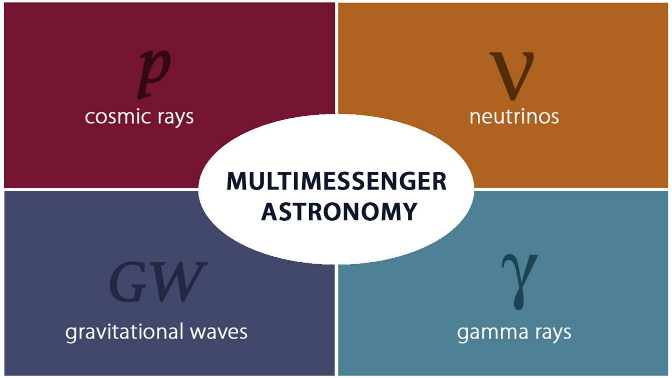
Excess of neutrinos found from galactic plane

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

TXS 0506+056 and the multimessenger approach to neutrino astronomy

IceCube has >99% uptime and view of full sky
→ can act as sentinel to alert other telescopes

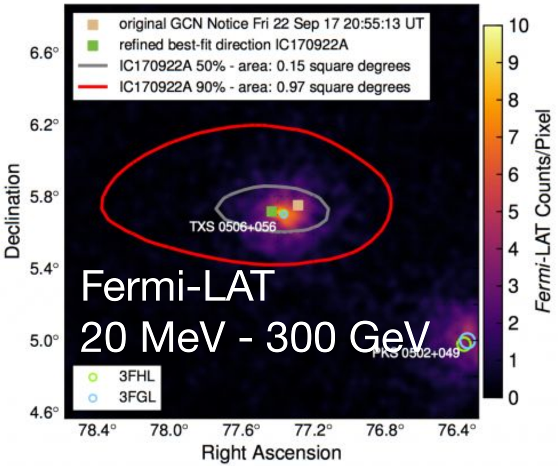
IceCube "realtime" efforts include sending alerts and follow-up of transient phenomena

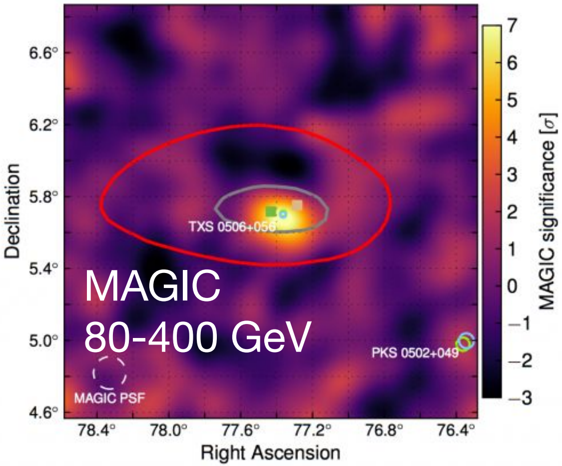


(2017) **high energy neutrino** coincided with **flare from blazar TXS 0506+056** (3σ significance)

Flare observed across electromagnetic spectrum

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





DOI: 10.1126/science.aat1378

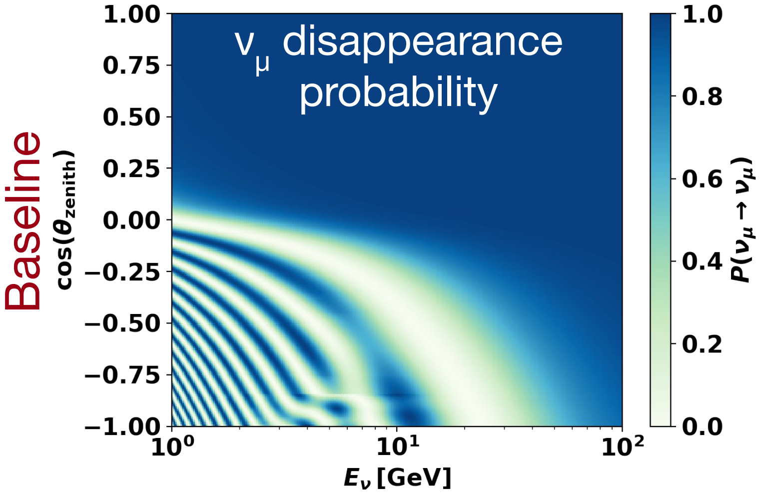
DOI: 10.1126/science.aat2890

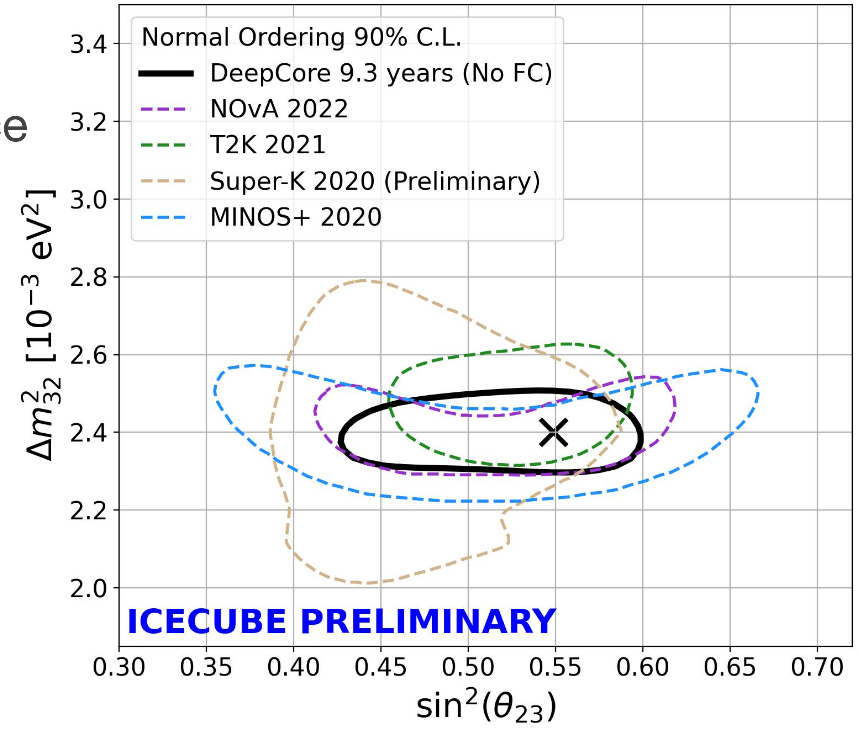
IceCube neutrino oscillation measurement using DeepCore

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 $\sin^2(\theta_{23})$





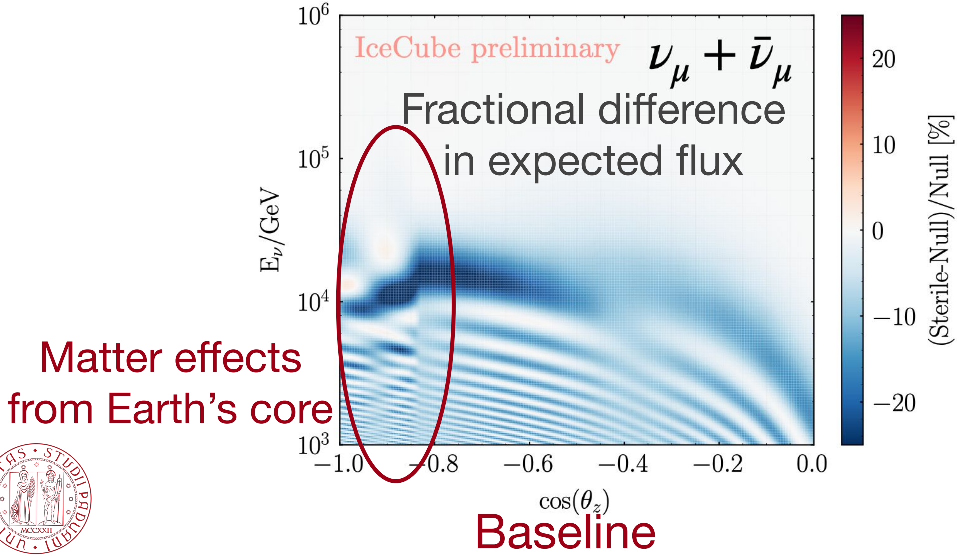
PoS(ICRC2023)1143

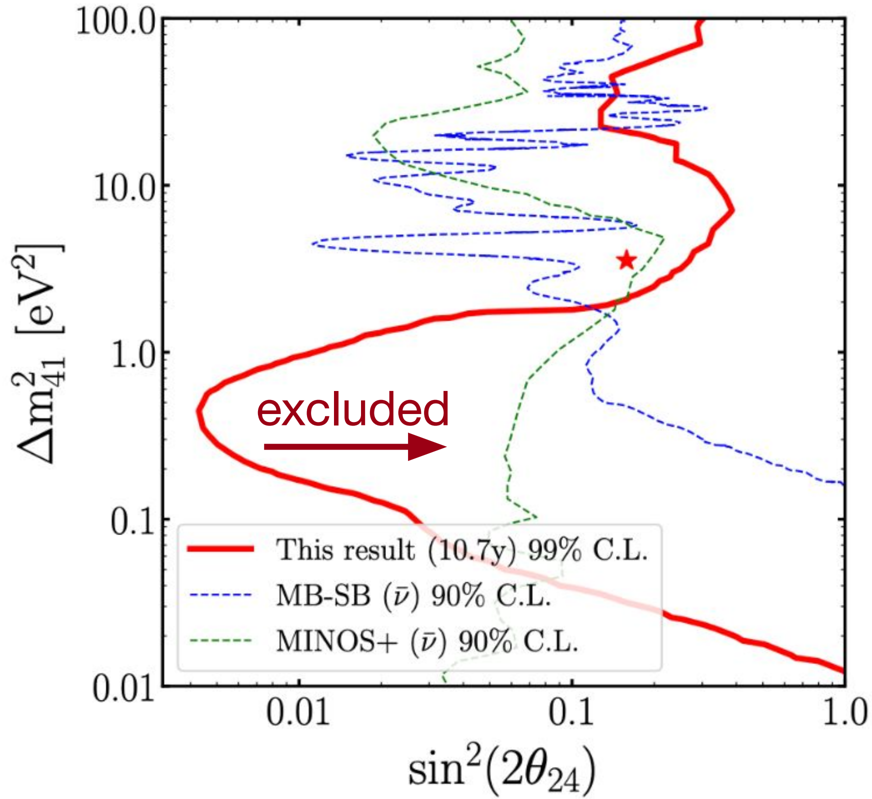
IceCube uses higher energy atmospheric neutrinos to look for oscillations from sterile neutrinos

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

Employ 3+1 sterile neutrino model

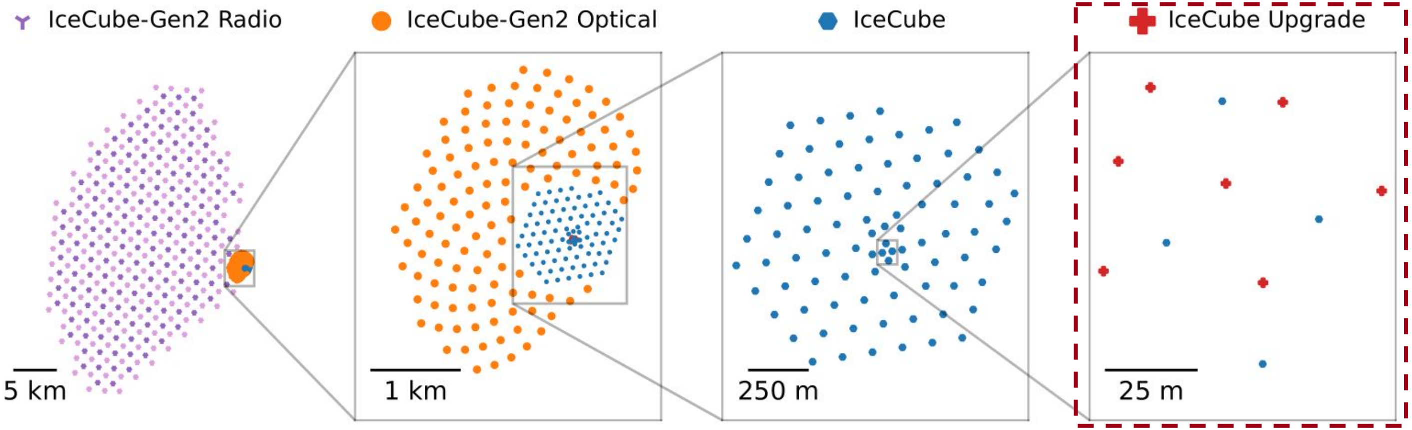
Excludes unique region of sterile mixing parameter space





Garcia, A. TeVPA 2023

The next generation of IceCube: the IceCube Upgrade

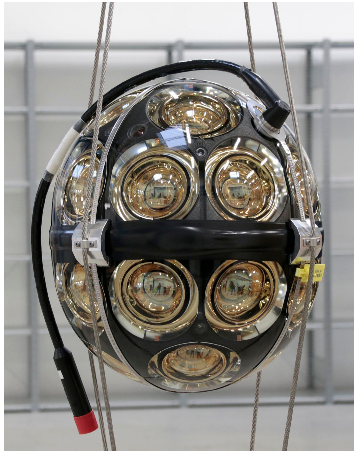


IceCube Upgrade (deployment 2025/26)

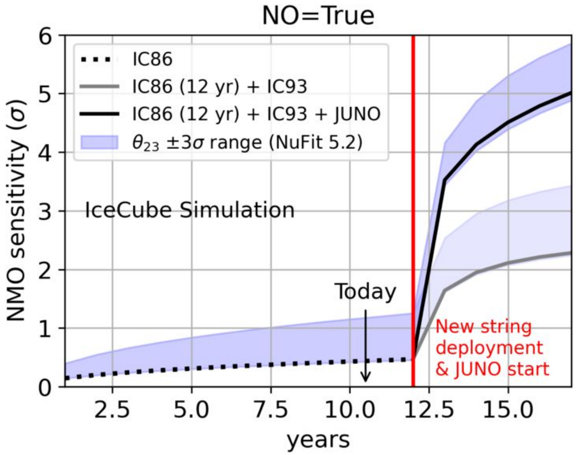
- Denser instrumentation
- Lower minimum energy (~1 GeV)

Goals:

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

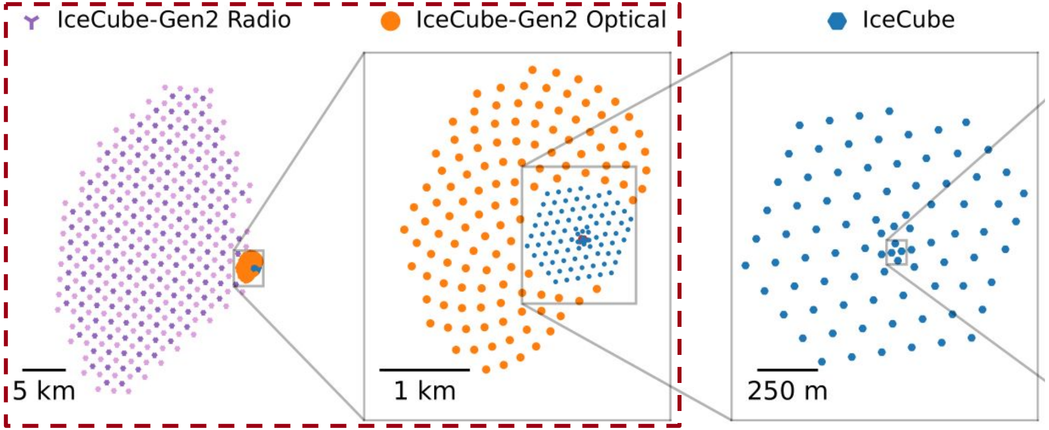


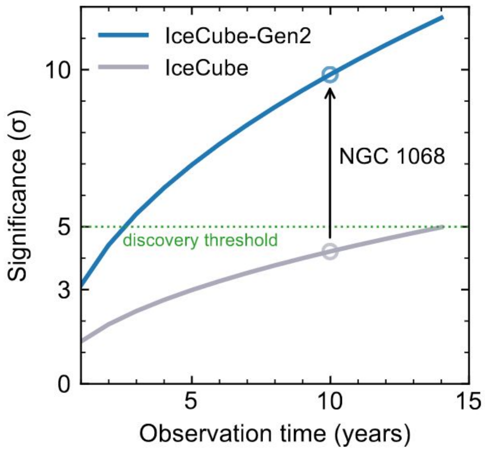
Multi-PMT DOM
PoS(ICRC2023)1183



Neutrino Mass Ordering
PoS(ICRC2023)1036

The next generation of IceCube: IceCube-Gen2



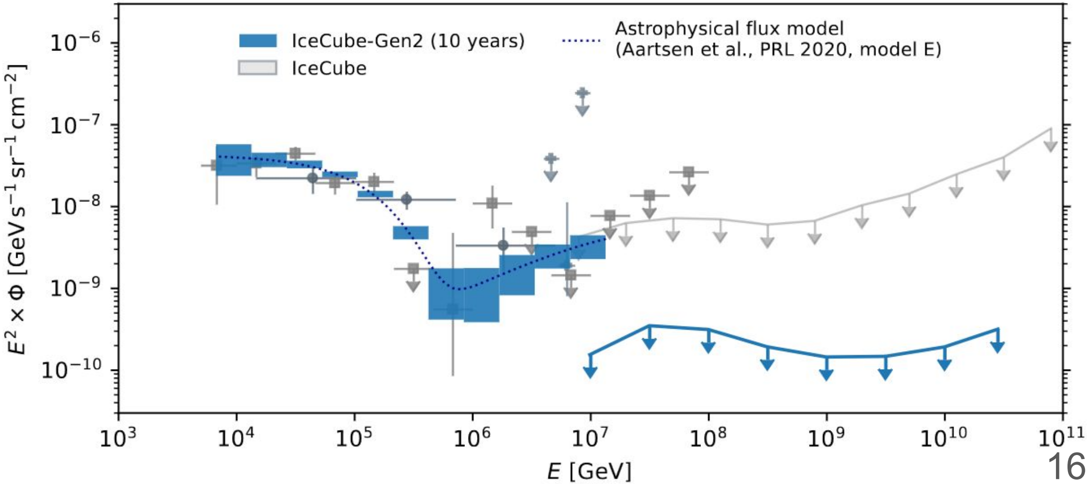


IceCube-Gen2

- Increase effective volume
- Increase upper energy threshold

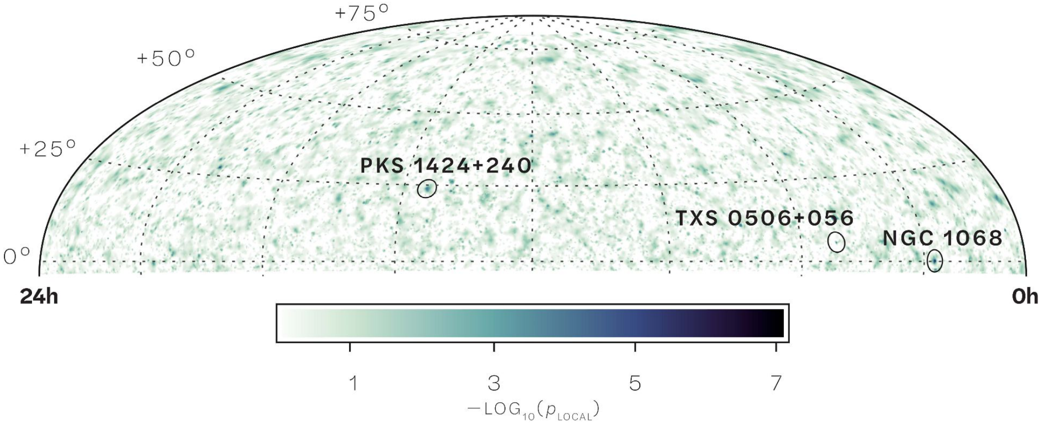
Goals:

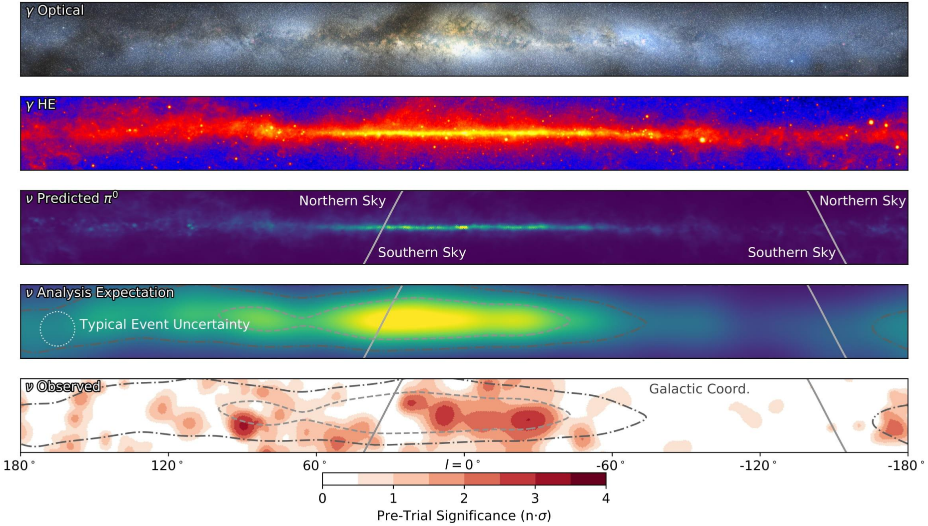
- Measure neutrino flux at extreme energies (PeV+)
- Improve sensitivity to astrophysical neutrino sources by factor of ~5



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

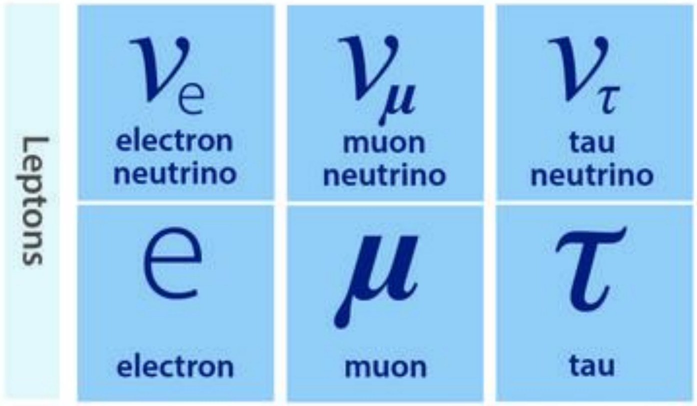
Backup

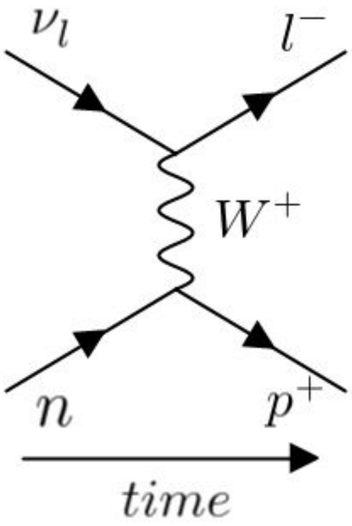
Neutrino Interactions

Cannot observe neutrinos directly

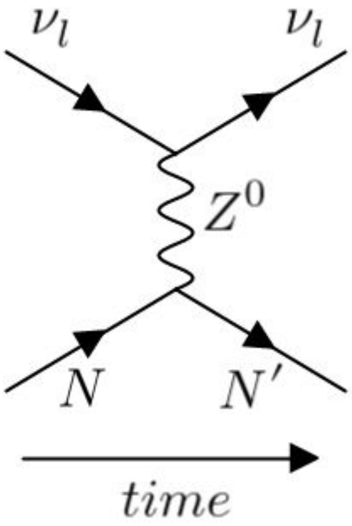
Instead observe the outgoing charged particles from weak neutrino interactions

At IceCube energies, most interactions DIS

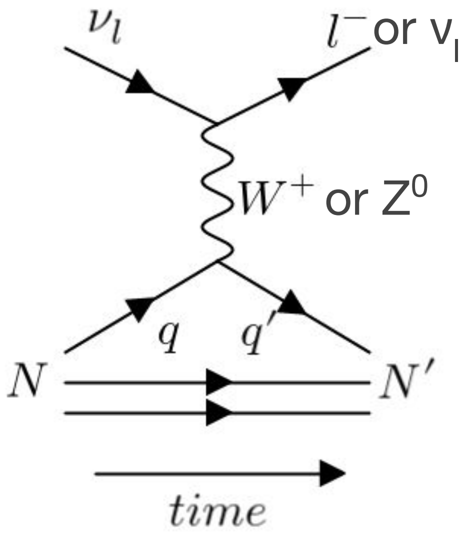




Charged Current (CC)



Neutral Current (NC)

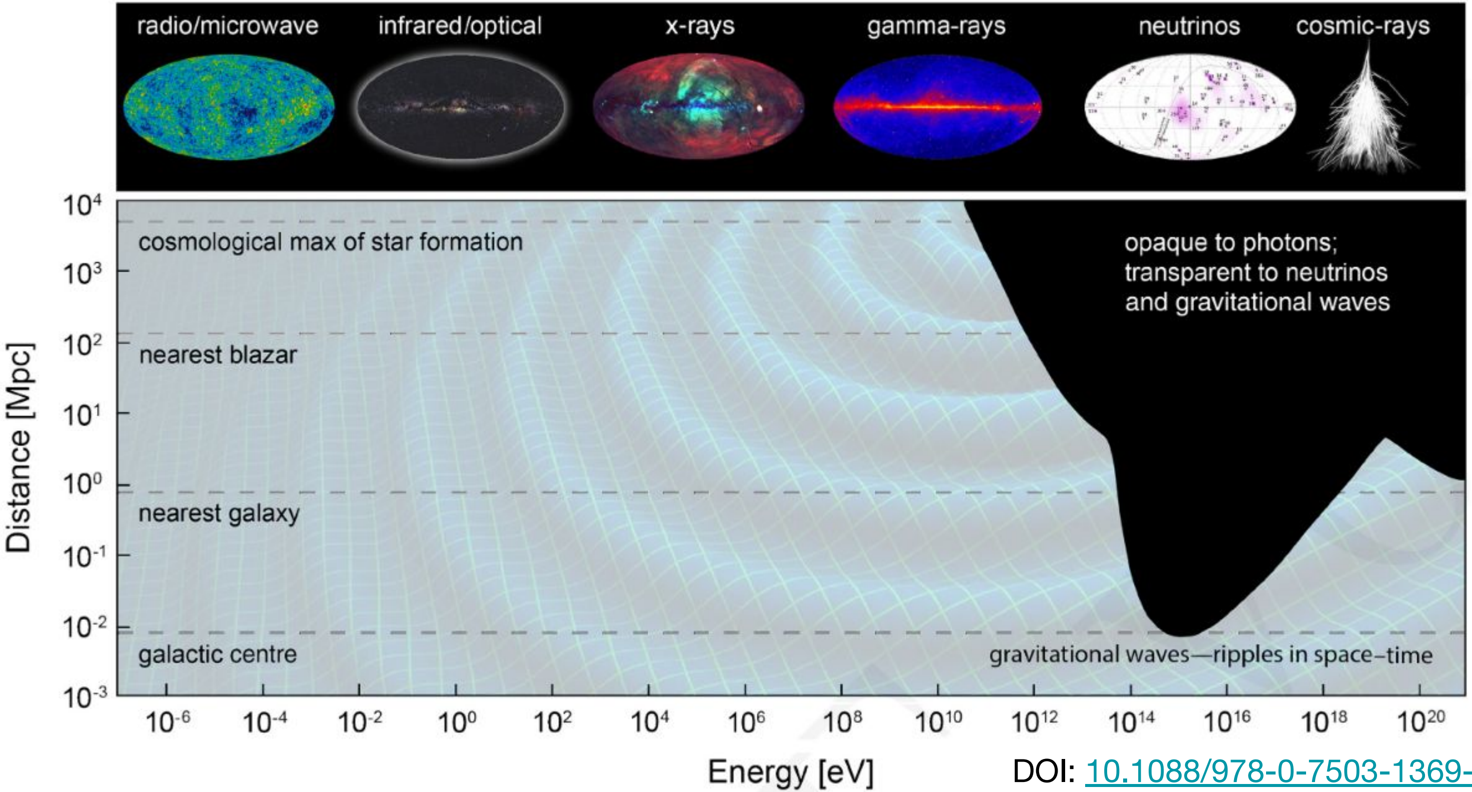


Deep Inelastic Scattering (DIS)

Neutrino astronomy versus gamma ray astronomy

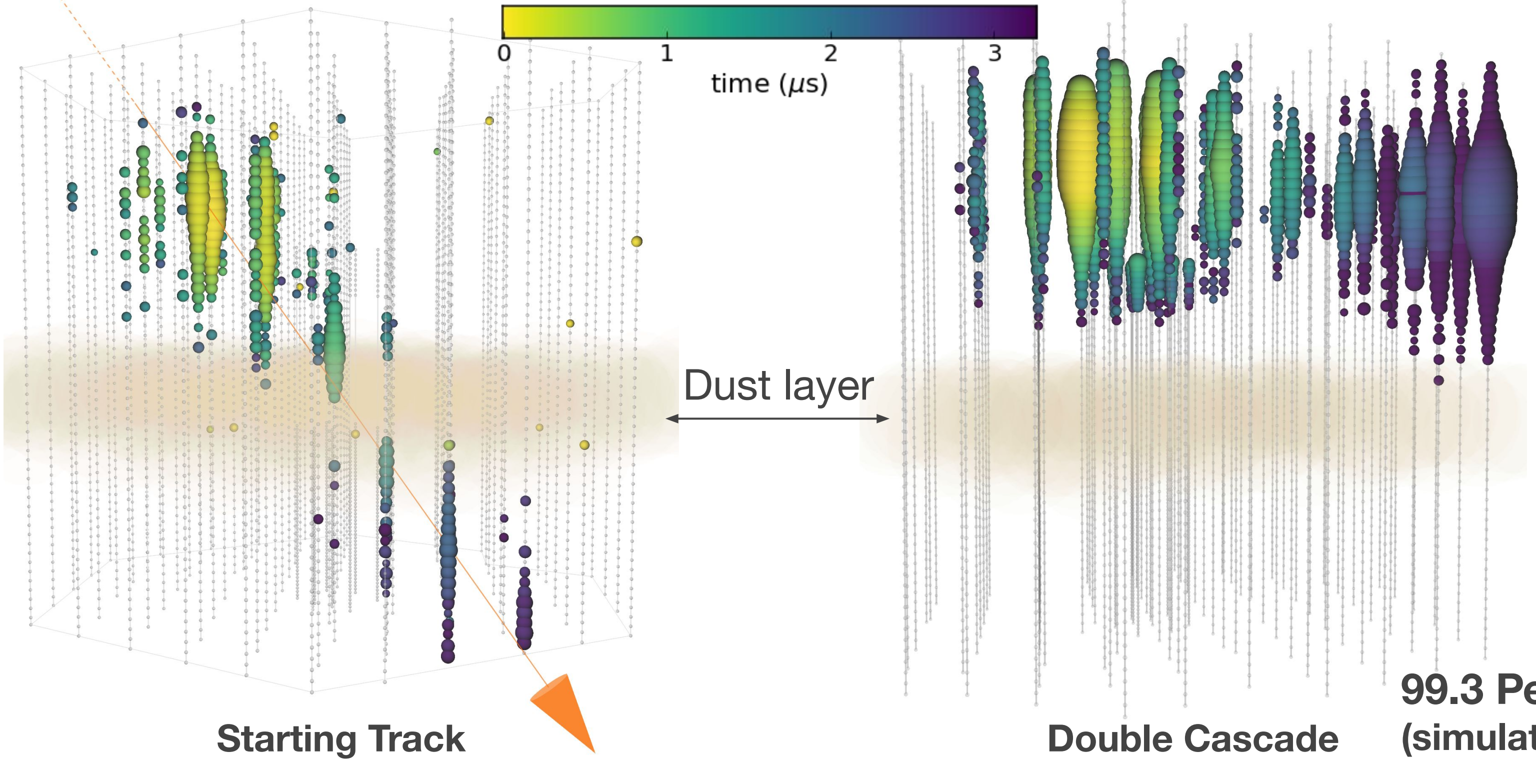
Gamma rays attenuated by CMB and other background light in the TeV energy ranges

Gamma rays also produced by cosmic ray electron acceleration, **leptonic acceleration**



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

Some subclasses of TeV particle morphologies within IceCube



99.3 PeV ν_τ (simulated)

Starting Track

Angular Resolution: 1.5°

Log Energy Resolution: .3 x log(E_ν)

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

Double Cascade

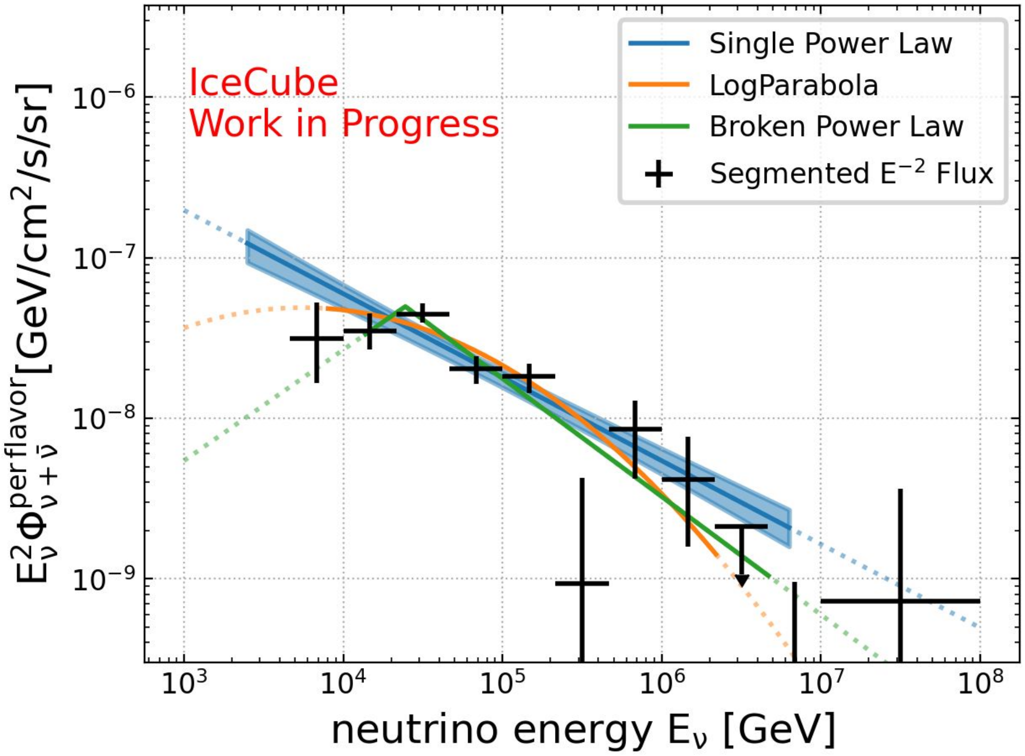
ν_τ ($\tau \rightarrow$ e/hadrons + ν's)

Must be high energy to see tau track

At lower energies look for double pulse structure in PMT waveform

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



PoS(ICRC2023)1064

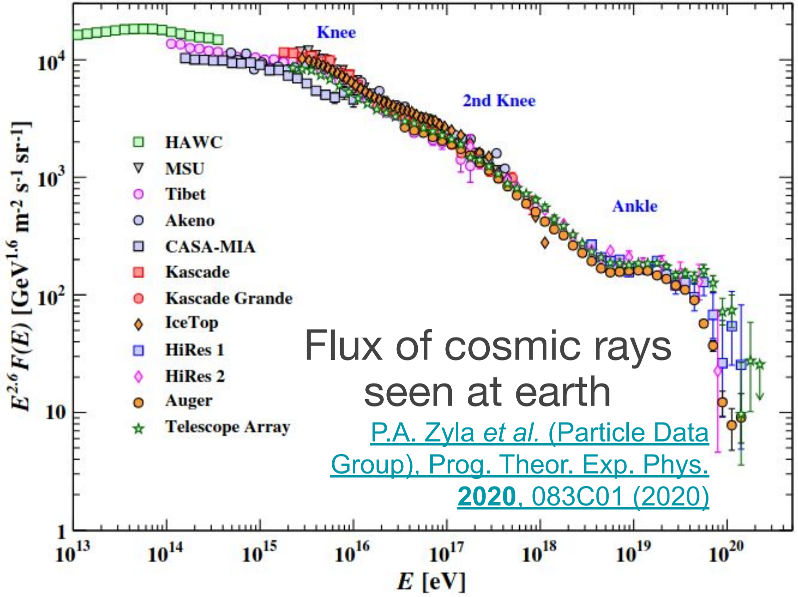
Diffuse Galactic Plane Neutrinos

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

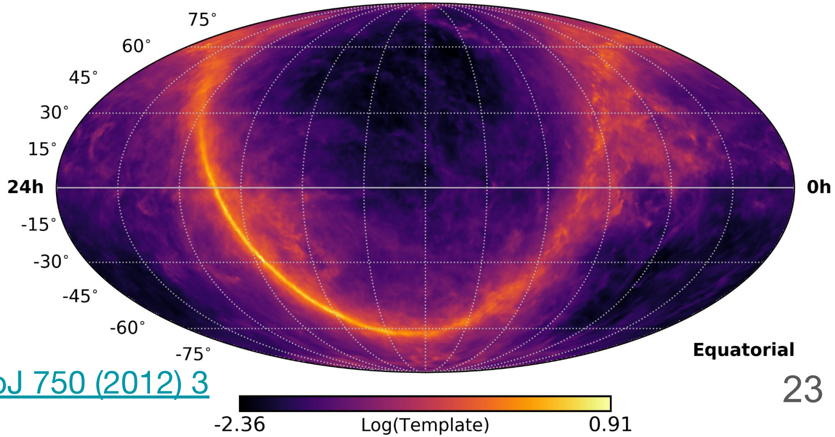
Same interactions should occur with the galactic plane medium

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



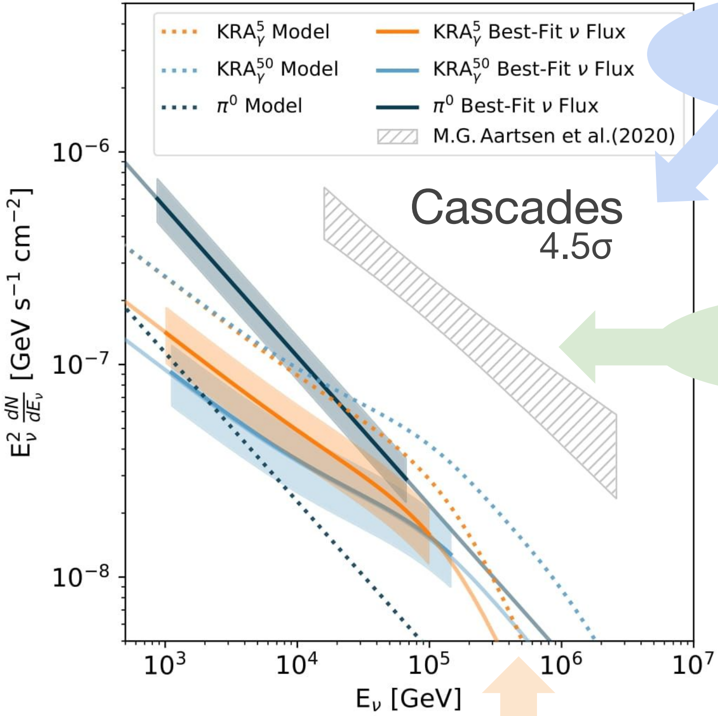
Flux of cosmic rays seen at earth

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

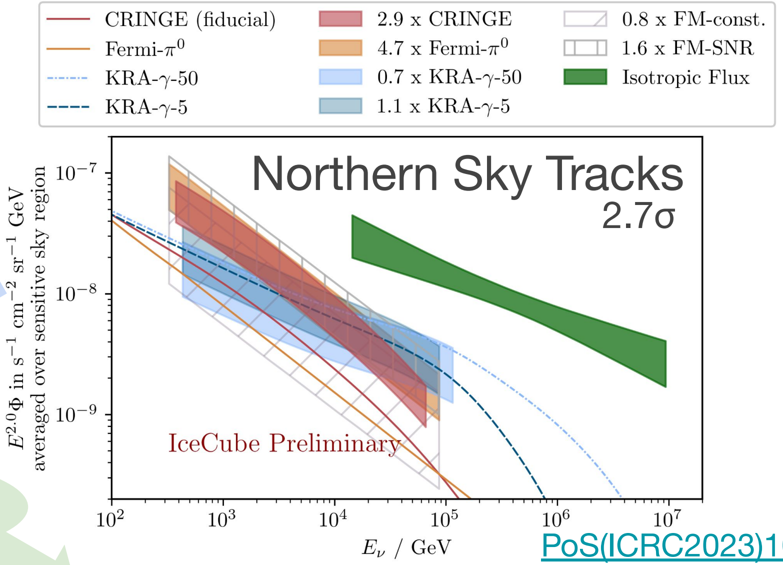


DOI: 10.1126/science.adc9818

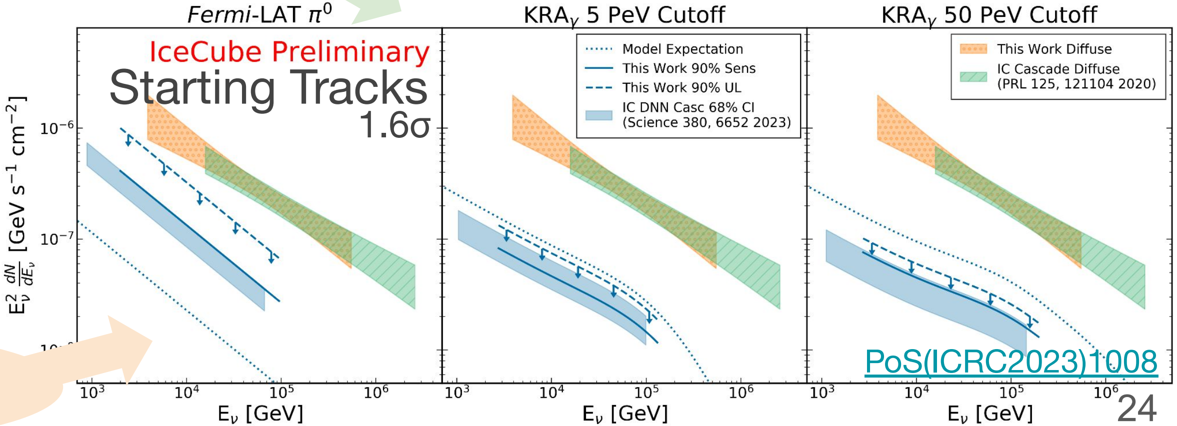
Larger rate of signal events

View of Galactic Center

Atmospheric ν Background Veto



PoS(ICRC2023)1046



PoS(ICRC2023)1008

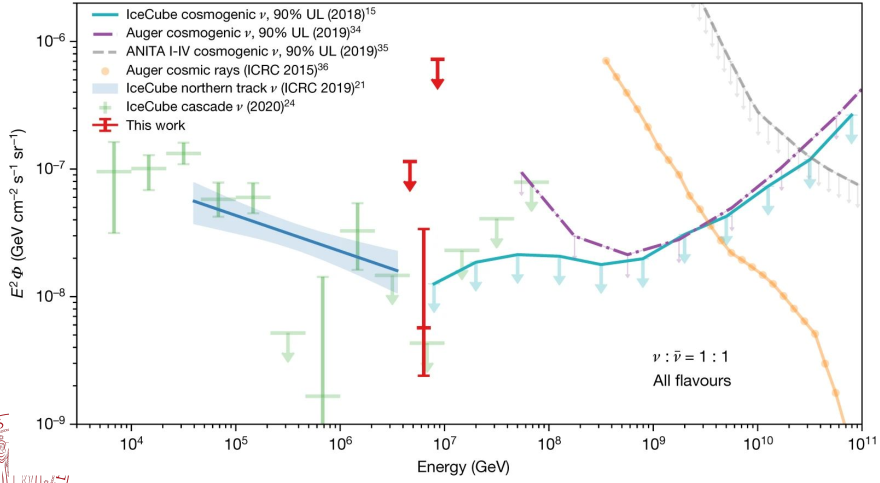
IceCube's Glashow event (2021)

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)]