On behalf of the IceCube Collaboration

Recent Results from IceCube with GeV to PeV Neutrinos

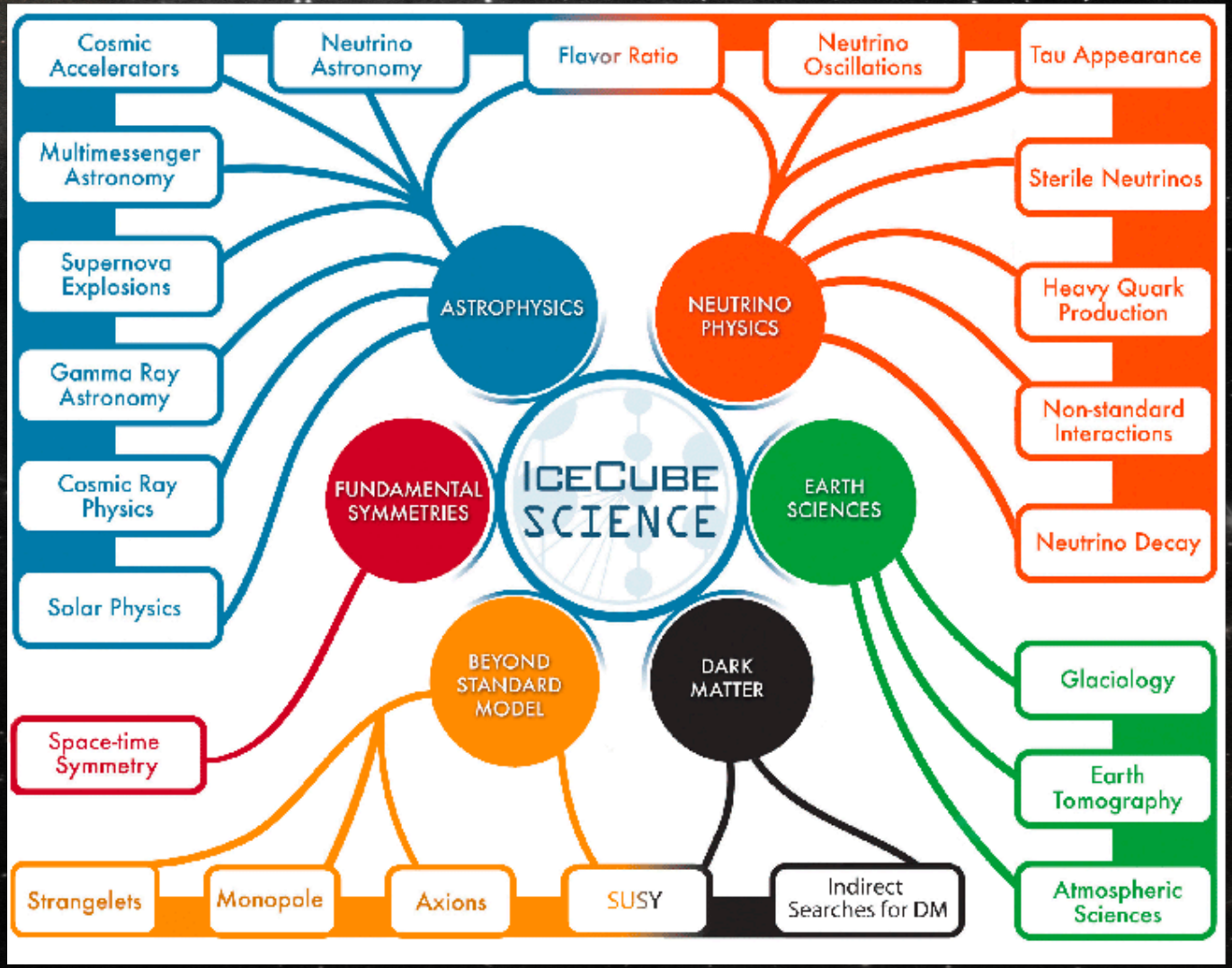
Michigan State University

Shiqi Yu

July 3rd, 2023

WIN 2023, SYSU Zhuhai, China

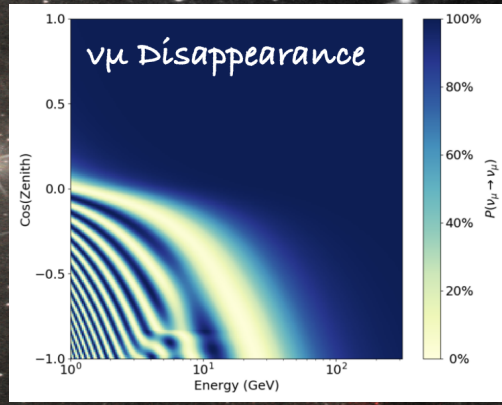

What can we see with IceCube…

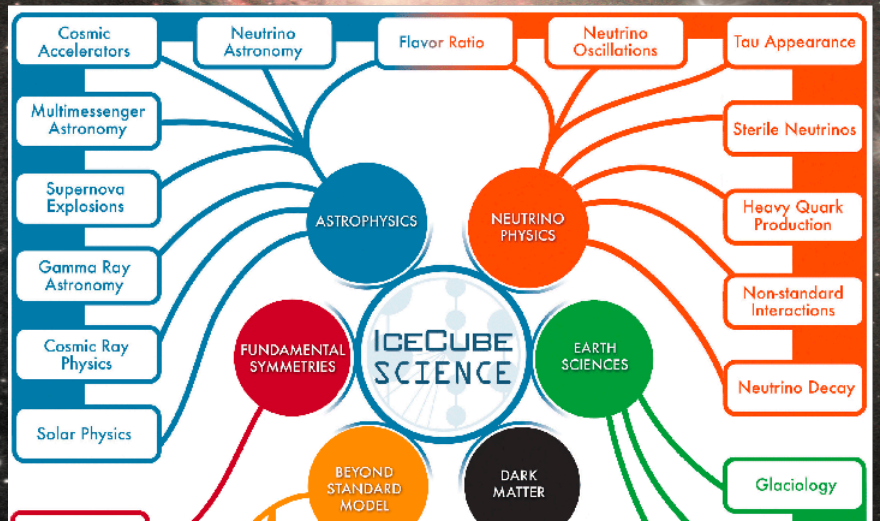

ICECUBE SCIENCE
ASTROPHYSICS
NEUTRINO PHYSICS
FUNDAMENTAL SYMMETRIES
EARTH SCIENCES
BEYOND STANDARD MODEL
DARK MATTER
Cosmic Accelerators
Neutrino Astronomy
Multimessenger Astronomy
Supernova Explosions
Gamma Ray Astronomy
Cosmic Ray Physics
Solar Physics
Flavor Ratio
Neutrino Oscillations
Tau Appearance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

What I am covering today…

Neutrino astronomy

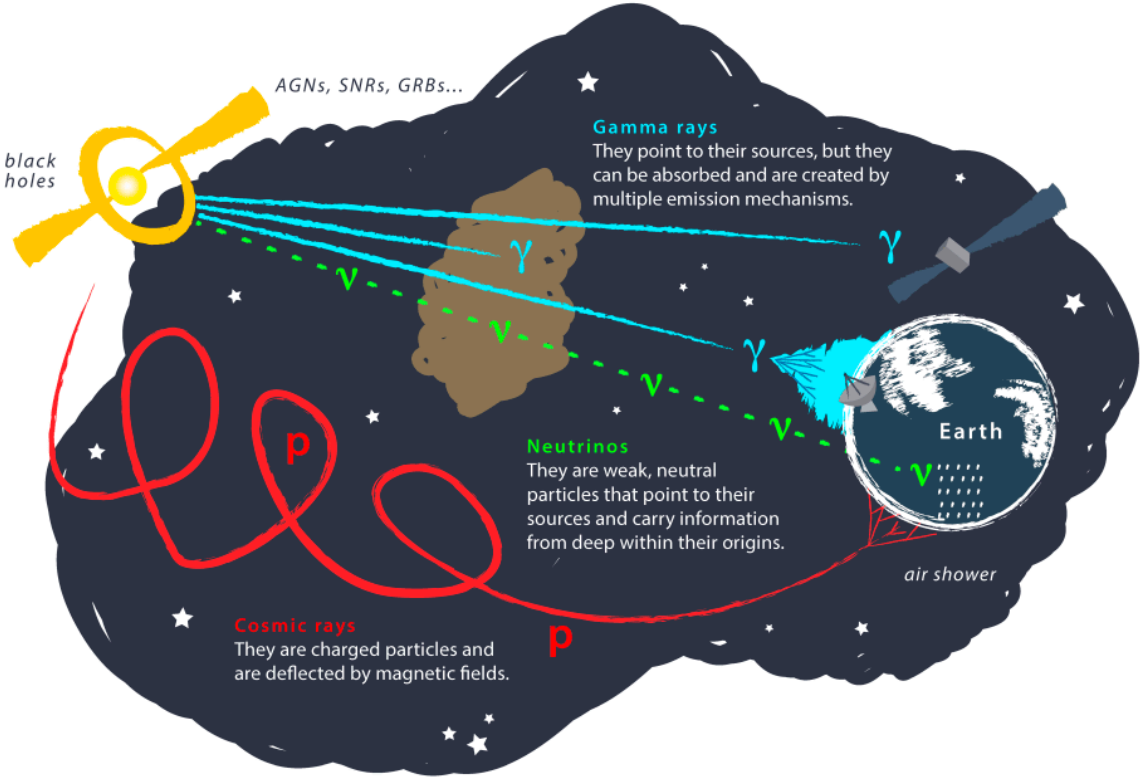
Neutrino physics






Neutrino: Messenger of the Universe

Astronomical Messengers

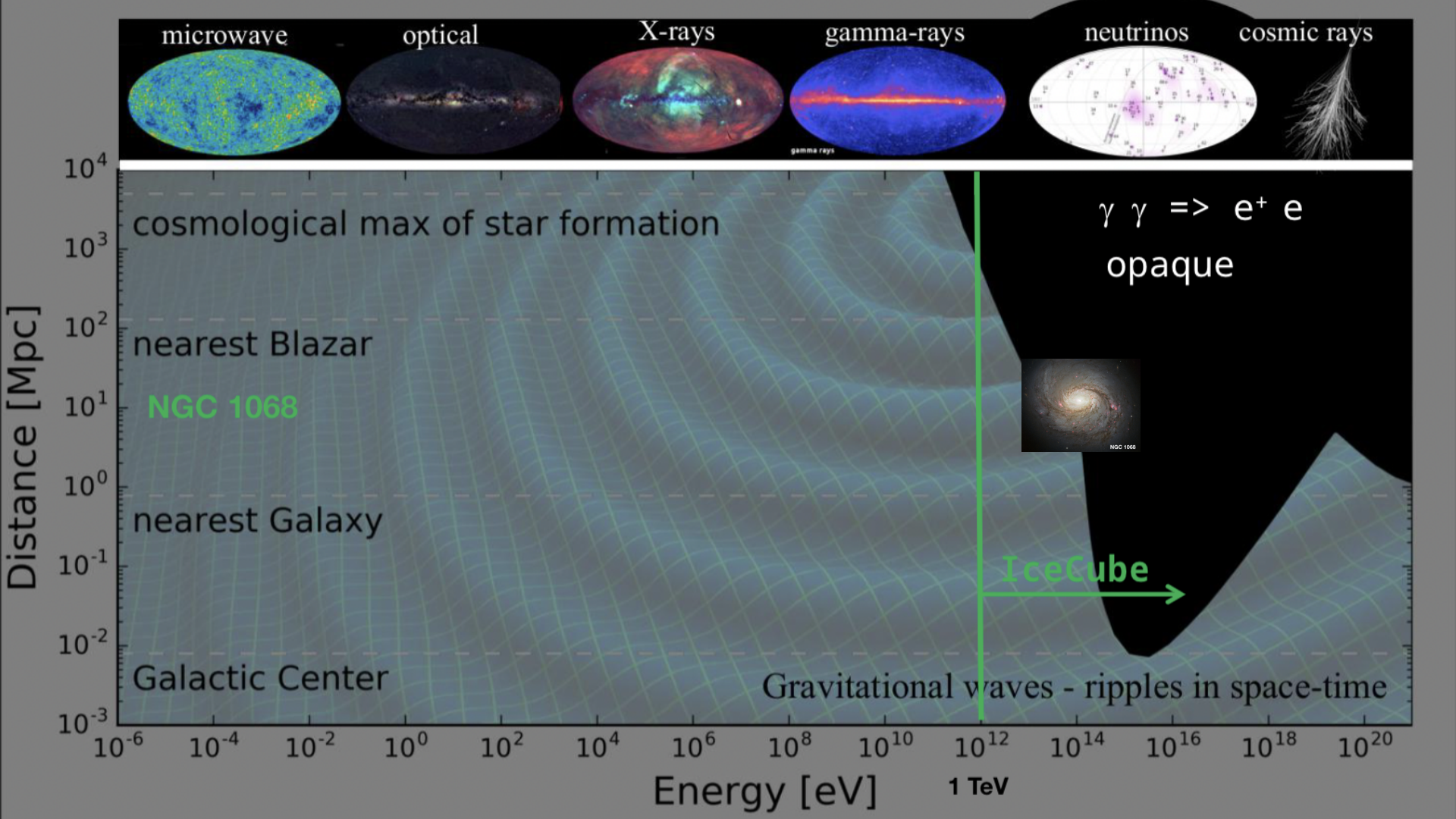


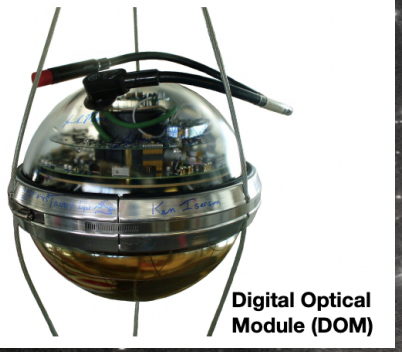
Neutrinos:

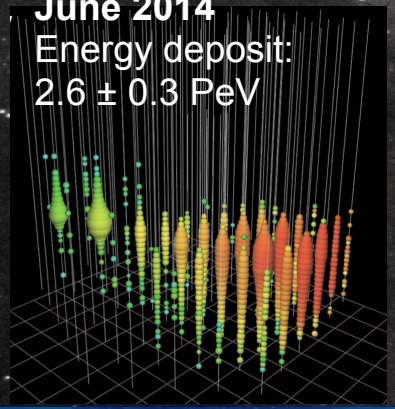
Smoking gun of **hadronic process**

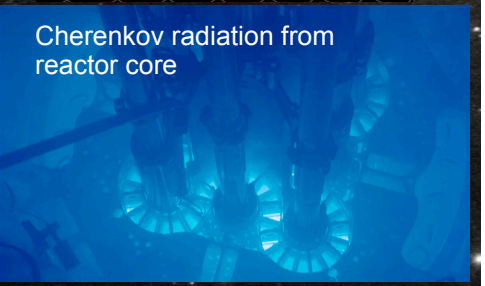
Pointing to their **sources**

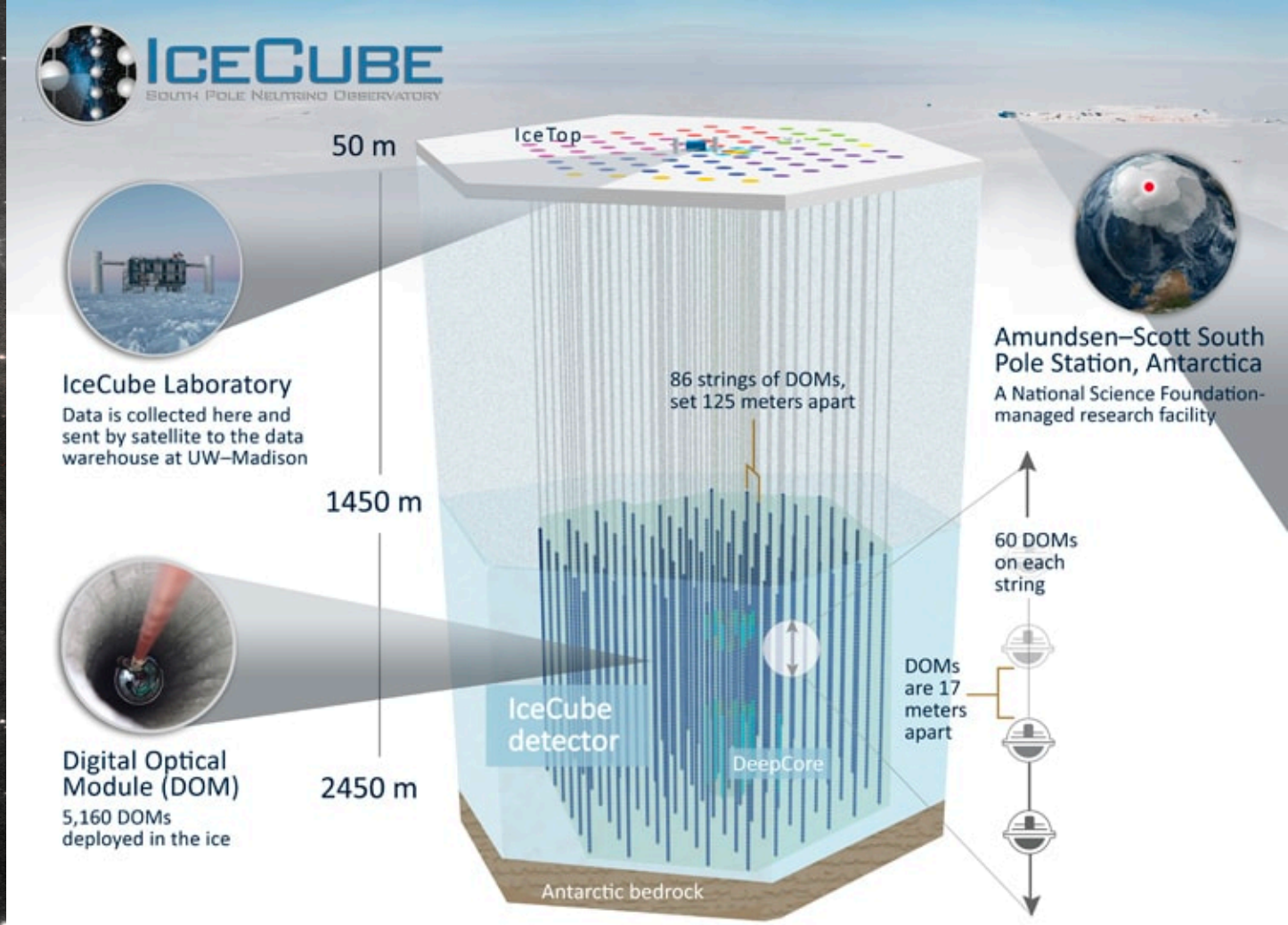
Hard to detect: need **giant detector**!


microwave
optical
X-rays
gamma-rays
neutrinos
cosmic rays
gamma rays
cosmological max of star formation
nearest Blazar
NGC 1068
nearest Galaxy
Galactic Center
γ γ => e+ e
opaque
IceCube
Gravitational waves - ripples in space-time
Distance [Mpc]
Energy [eV]
1 TeV



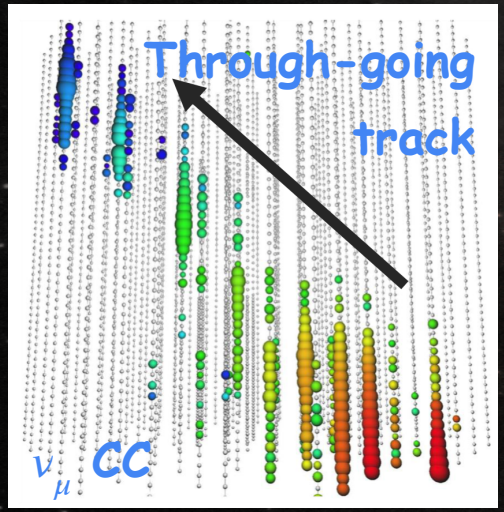






1 km^3 instrumented with 5160 PMT (10 inch) below 1,450m

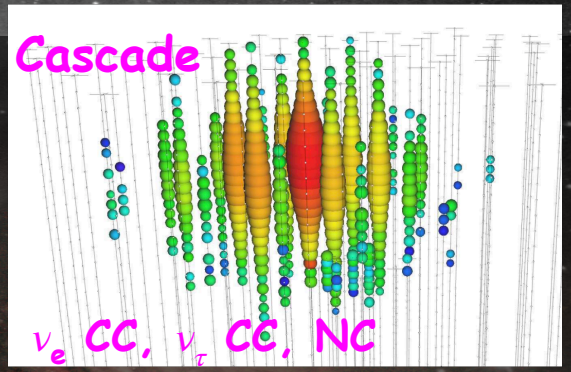
Typical Events in IceCube



Angular resolution: < 1 deg

E_{reco}: muon energy (lower bound on neutrino energy)

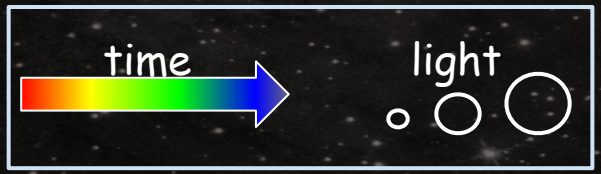
Excellent for Northern sky analysis

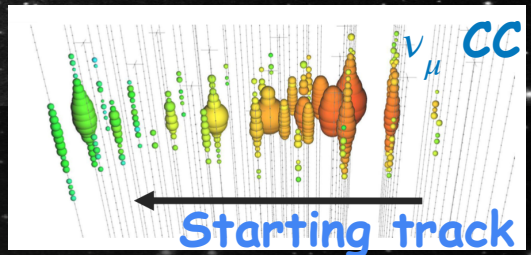


Angular resolution ~ 10 deg

Energy resolution ~15%

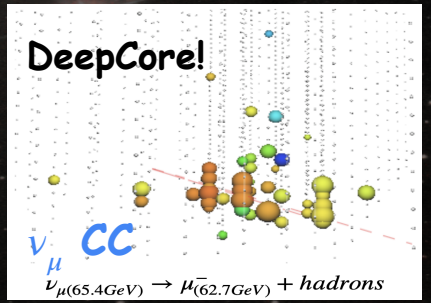
Great to study Southern sky





Better angular resolution than cascades

Great in Southern sky



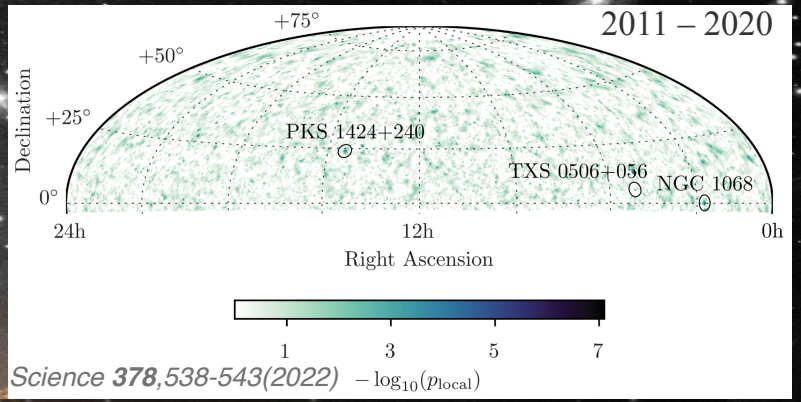
RESEARCH

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

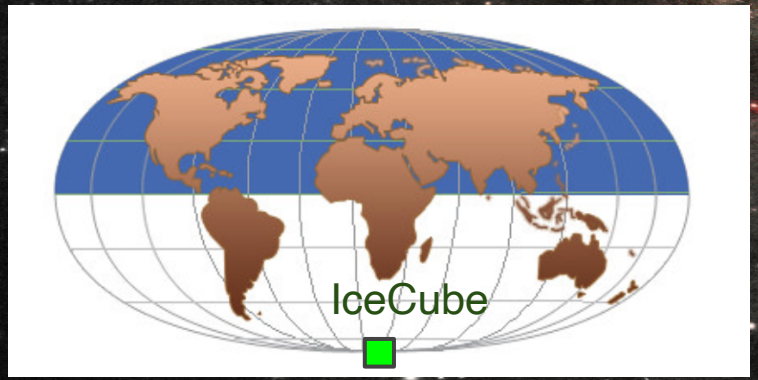
Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†

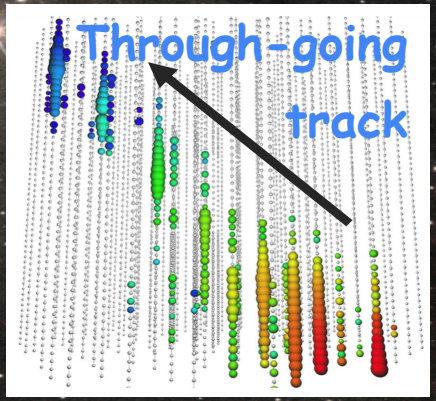


Science ***378***,538-543(2022)

Northern Hemisphere



Earth absorption helps removing muon background



NGC 1068

Science **378**,538-543(2022)

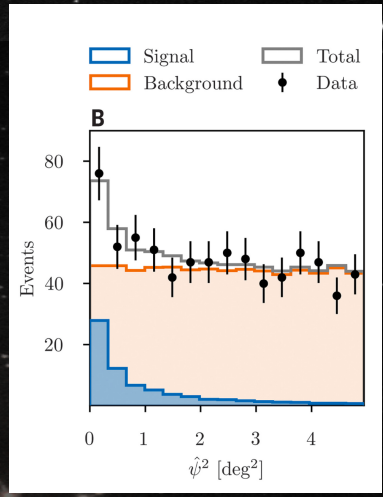
All-sky scan found hot spot at NGC 1068 location.

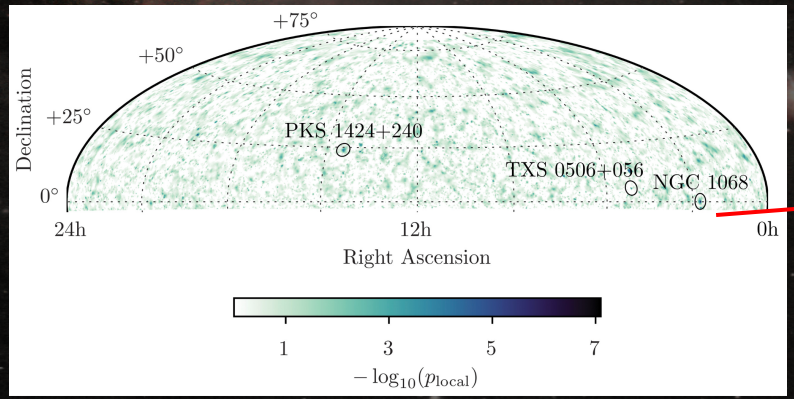
In catalog search (110 sources), at NGC 1068:

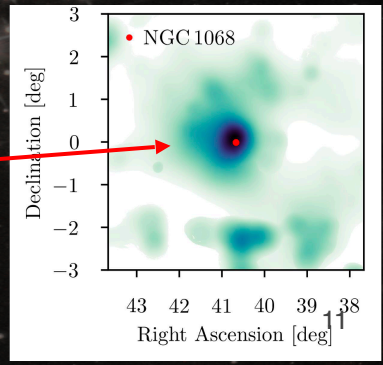
- ➢ 79 candidates; spectral index = 3.2 ± 0.2
- ➢ single source significance 5.2 σ (local)

1 in 100,000
background-only
datasets have object ≥
5.2 σ

→ **4.2 σ evidence !**







Why NGC 1068?

- Seyfert galaxy

NUCLEAR EMISSION IN SPIRAL NEBULAE*

CARL K. SEYFERT†

1940's

ABSTRACT

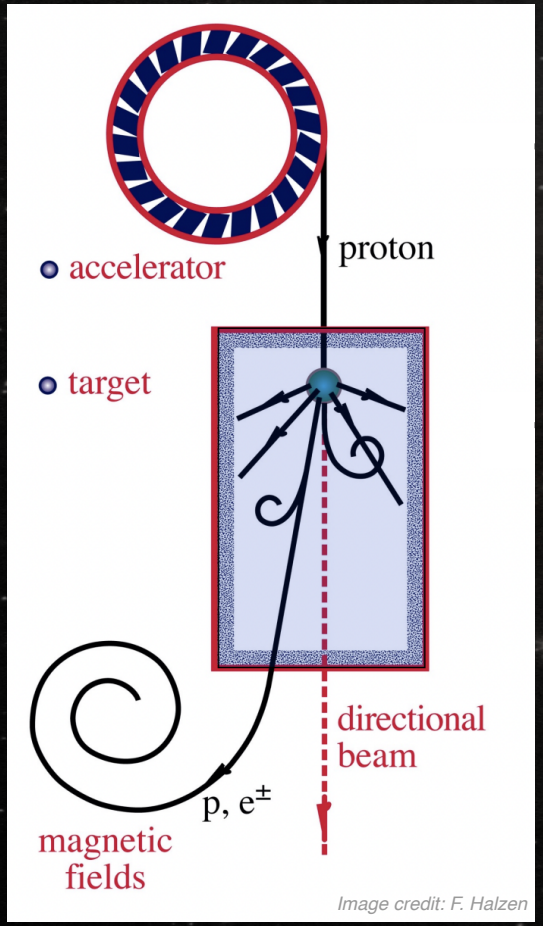
Spectrograms of dispersion 37–200 A/mm have been obtained of six extragalactic nebulae with high-excitation nuclear emission lines superposed on a normal G-type spectrum. All the stronger emission lines from λ 3727 to λ 6731 found in planetaries like NGC 7027 appear in the spectra of the two brightest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

Where could neutrinos be produced?

- ? starburst activity
- ? AGN outflows/winds
- ? faint jet
- ? AGN core region (e.g. corona)

Picture credit: NASA/JPL-Caltech

Accelerator powered by large gravitational energy



→ supermassive black hole

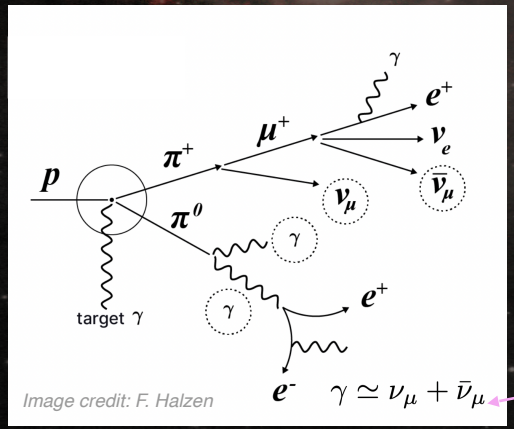
Image credit: IceCube/NASA

active galactic nucleus (AGN)

Accelerated cosmic rays lead to neutrinos and γ-rays:

$$p + p \text{ (or } \gamma) \rightarrow \ldots + \pi^+ \rightarrow \nu$$

$$\rightarrow \ldots + \pi^0 \rightarrow \gamma + \gamma$$



γ-rays production:

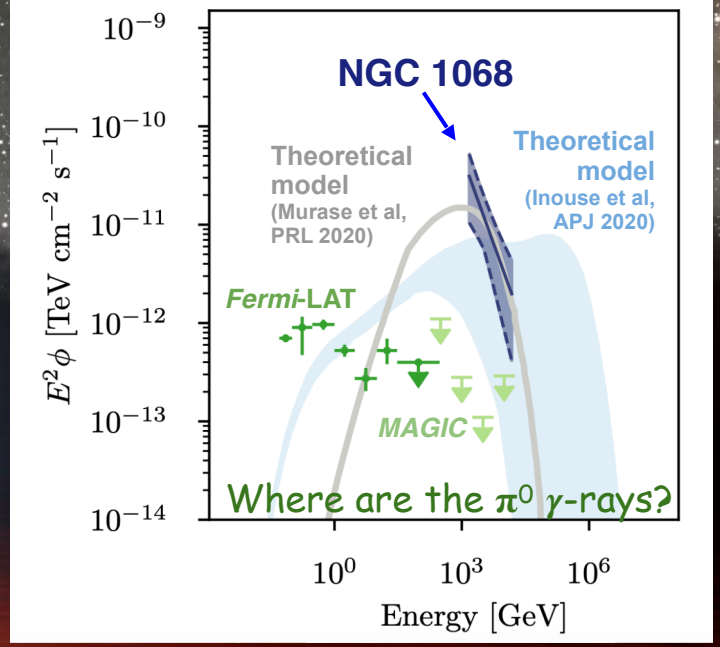
Leptonic process : Inverse compton effect with relativistic particles (e^-)

Hadronic process: decay of π^0

Neutrinos could be produced in the optically thick corona in the vicinity of the black hole.

black hole

accretion disk

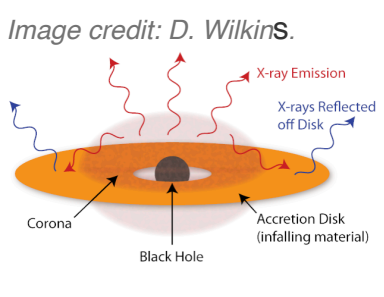


Measured neutrino flux exceeds TeV γ-ray **upper limits!**

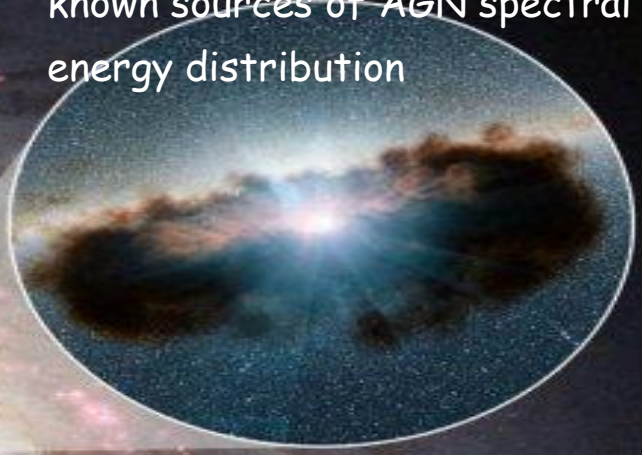
? γ-ray obscured environment: matter & radiation-rich

?! Corona gas and radiation

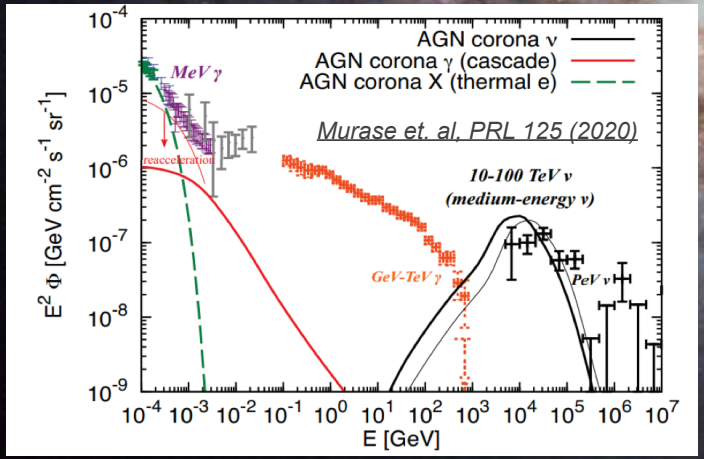
Picture credit: NASA/JPL-Caltech



Accretion disk and corona are the known sources of AGN spectral energy distribution



Bright intrinsic X-ray emission at 2-10 keV



If the coronal models are correct, i.e. particles are accelerated within corona:

=> **population of Seyfert galaxies could explain part of diffuse neutrino flux**

without creating tension with Fermi observations

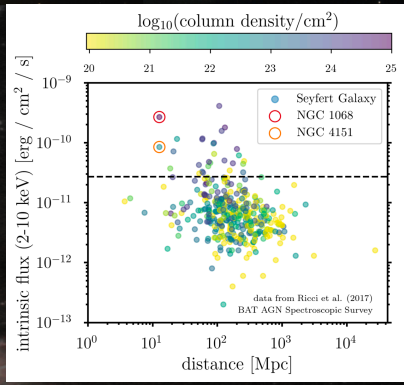
Are there more galaxies similar to NGC 1068 ?

Seyfert Galaxies

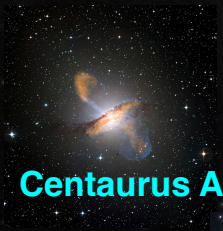
Looking for similar sources to NGC 1068 in full sky:

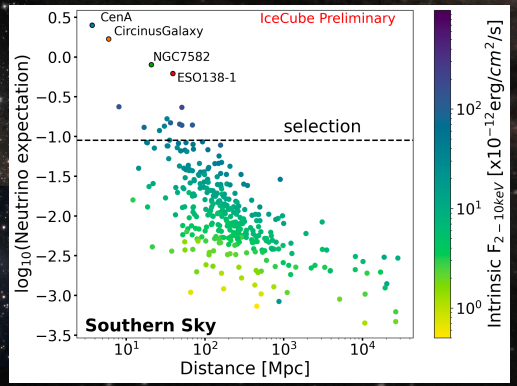
- ➔ Hot coronae and dense environment — Seyferts;
- ➔ Bright on intrinsic X-ray;
- ➔ TeV γ-ray obscured

Select from BASS (BAT AGN Spectroscopic Survey)

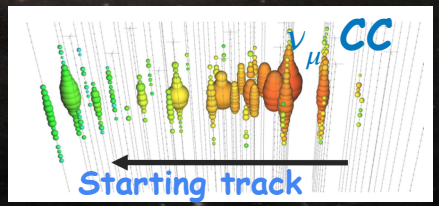


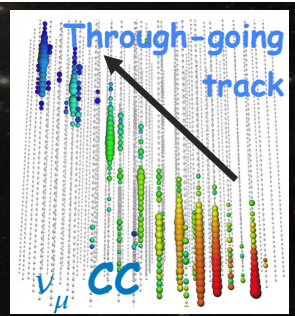
Northern Hemisphere



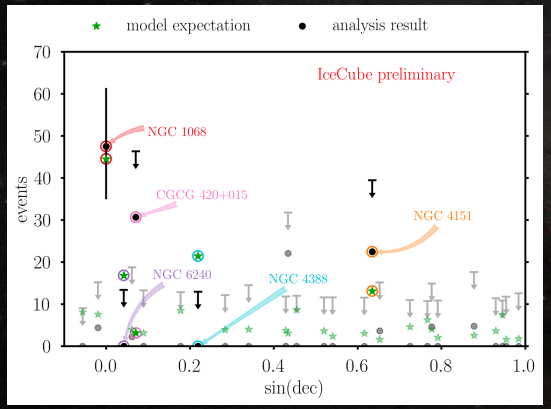


Southern Hemisphere



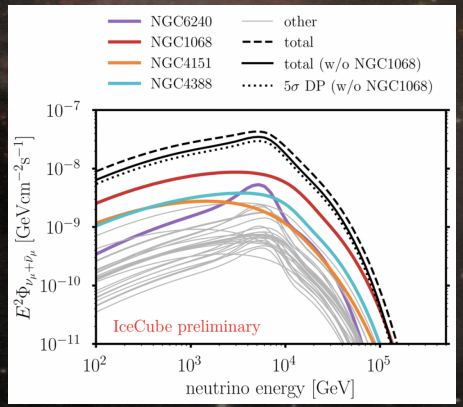


More Seyferts?

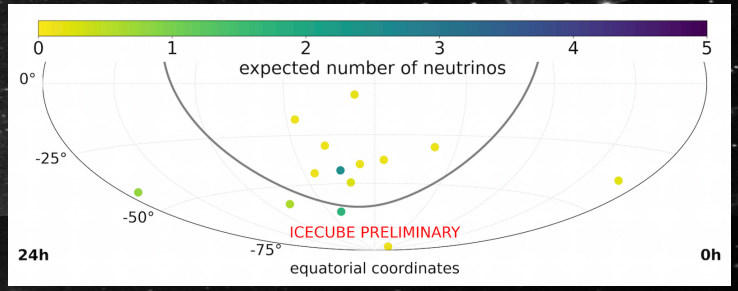


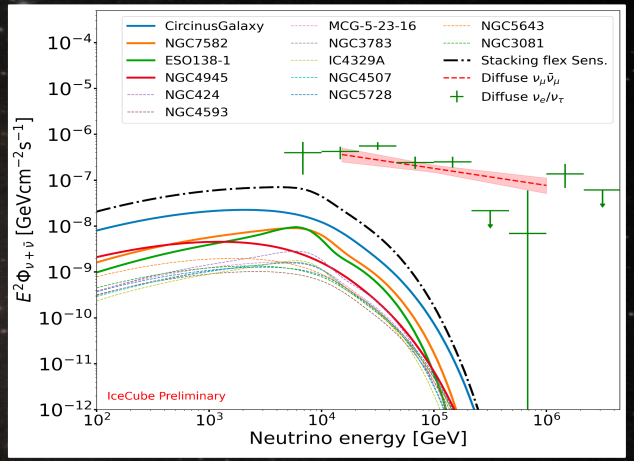
Catalog of 27 Seyfert galaxies (w/o NGC 1068) inconsistent with background **@ 2.7σ significance.**

Northern Hemisphere

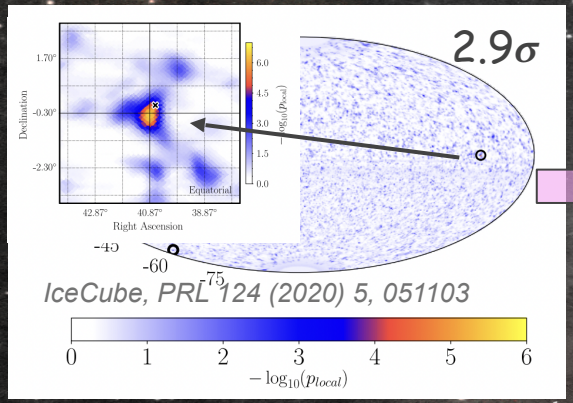


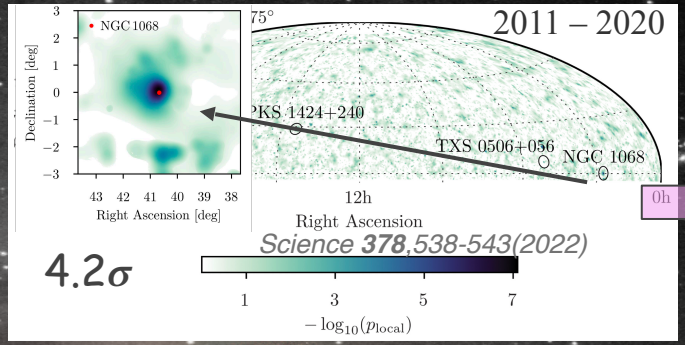
Stacking analysis (combining all sources w/o NGC 1068) consistent with background expectations.





Southern Hemisphere coming soon!
→post-unblinding checks.

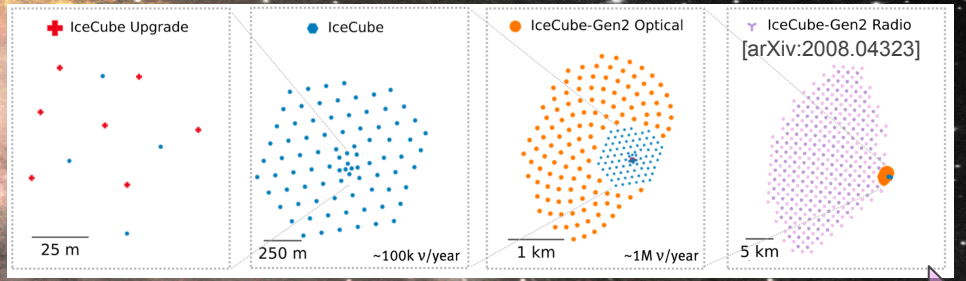




Looking for Seyferts using caronal model

2025-2026

2027 - 2035



GeV TeV (1 km³) PeV (8 km³) EeV (500 km²)

Improved sample (detection, calibration, statistics, reconstruction…)

Future

Improve theoretical models (multi-messengers, parameterization…)

More extragalactic sources (or …)

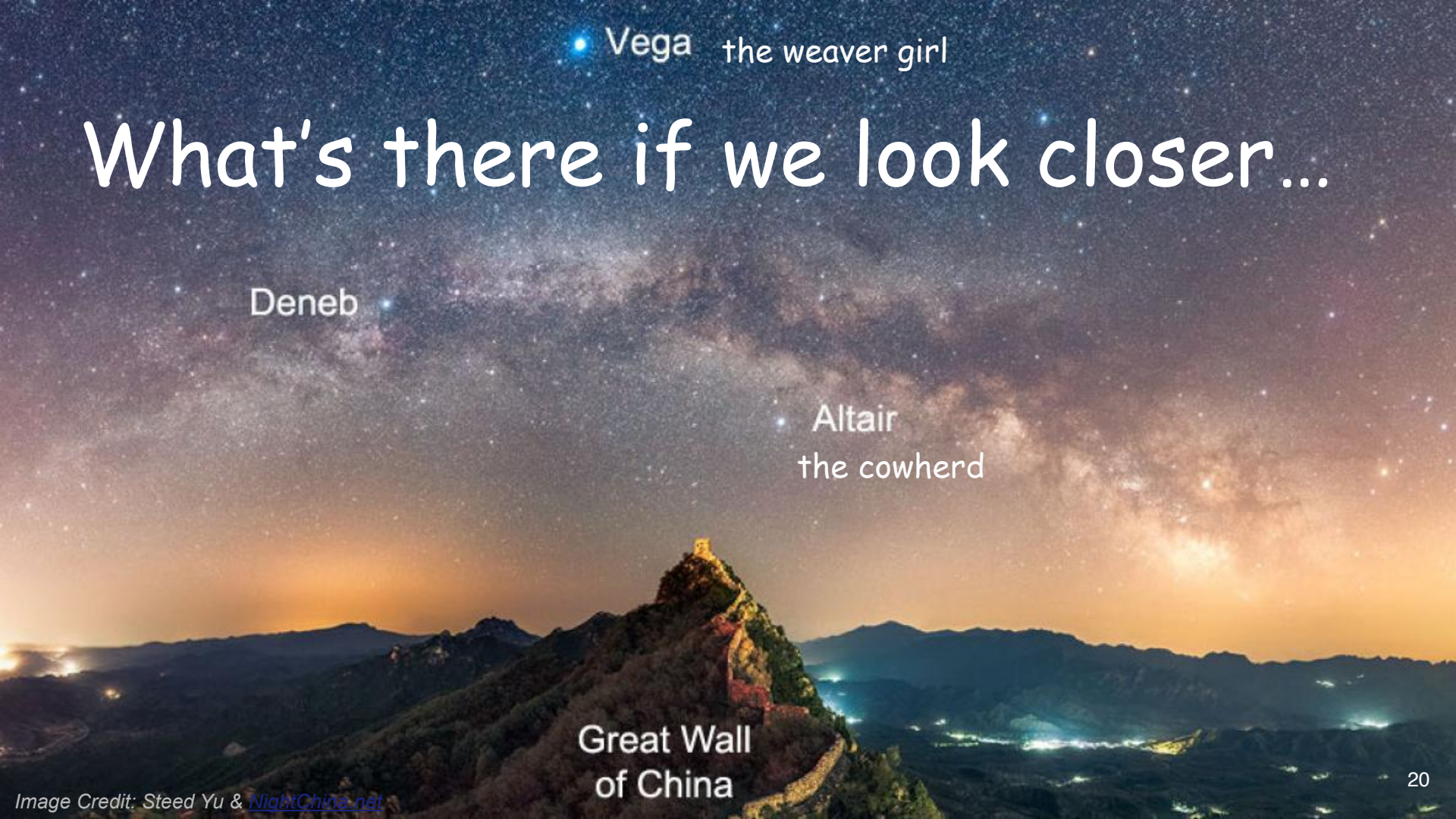
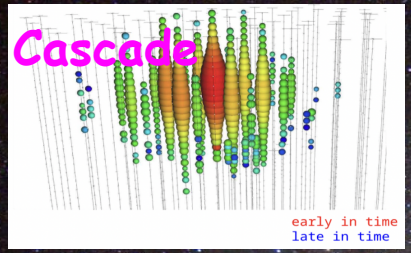


Image Credit: Steed Yu & NightChina.net



Southern Hemisphere

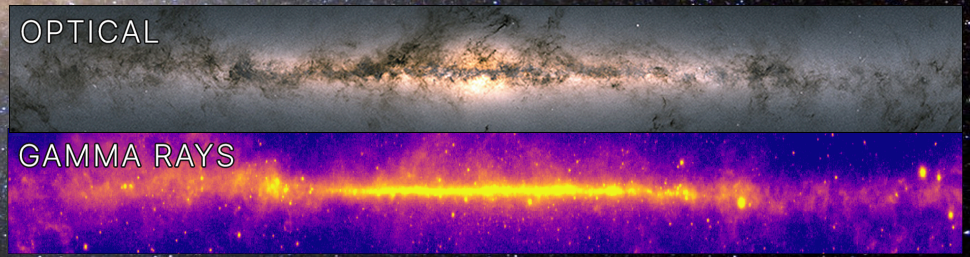
RESEARCH

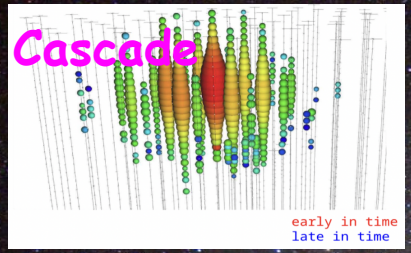
RESEARCH ARTICLES

NEUTRINO ASTROPHYSICS

Observation of high-energy neutrinos from the Galactic plane

IceCube Collaboration*†





Southern Hemisphere

RESEARCH

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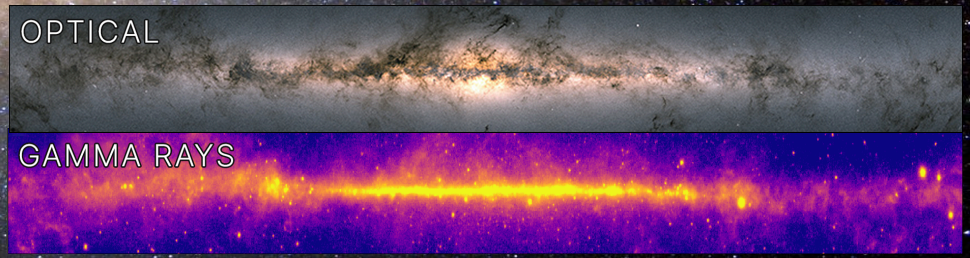
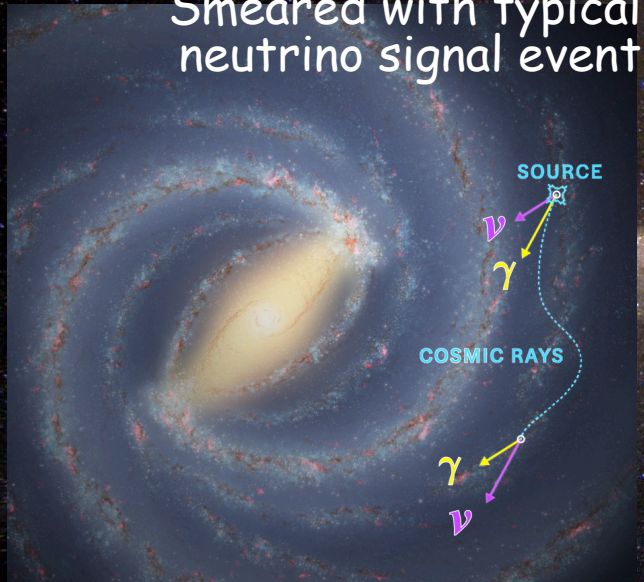
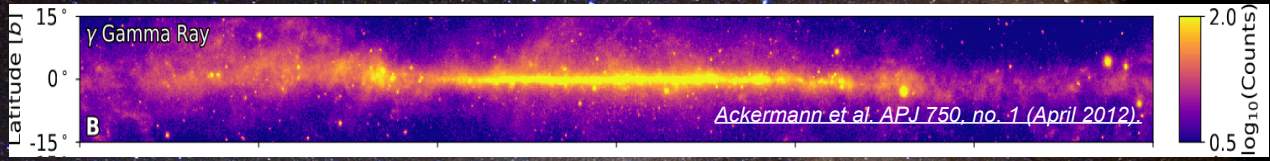


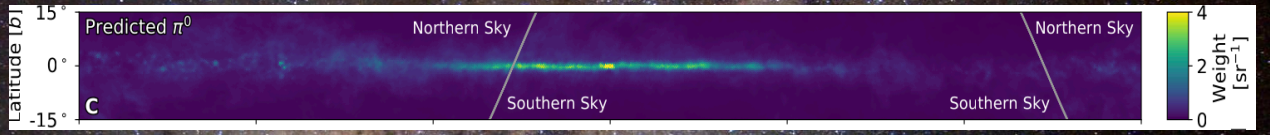
Galactic diffuse emission

Neutrino counterpart to diffuse γ-rays using different models

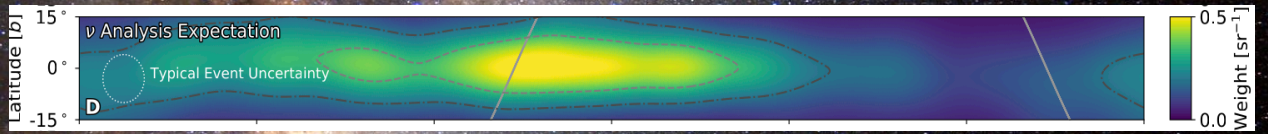
Smeared with typical neutrino signal event

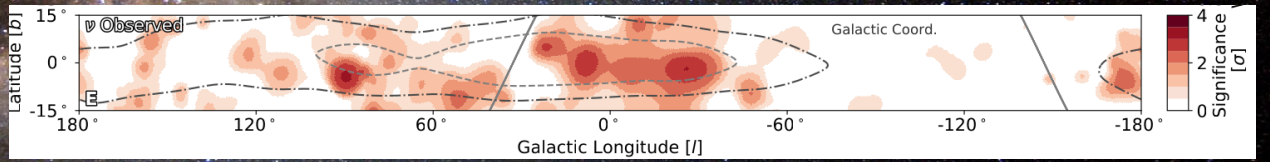






Another theoretical template: Gaggero et al *The Astrophysical Journal* 815, no. 2 (December 2015)





→ 4.5 σ evidence

after accounting for multiple tests

Next question: where/what are the sources?
->Future detectors and improved models

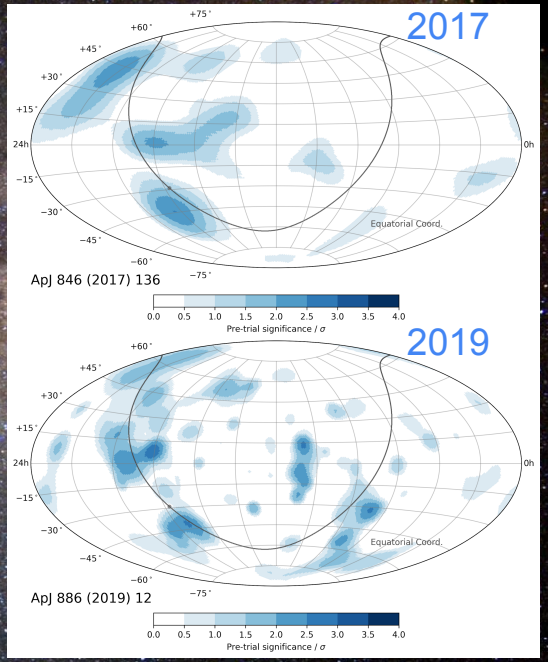
Improved sample (detection, calibration, statistics, reconstruction…)

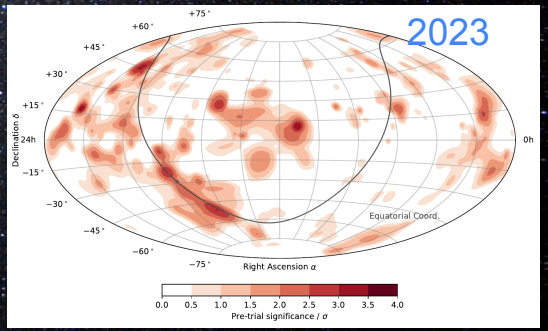
Future

Improve theoretical models (multi-messengers, parameterization…)

More sources!

More statistics and better reconstruction sharpen the view of the cascade sky.

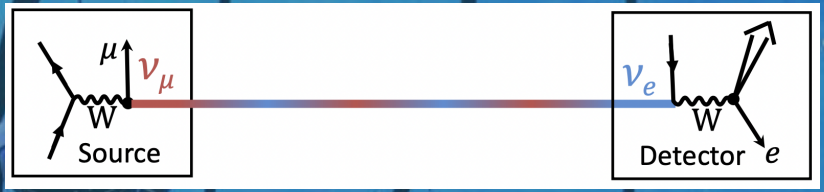


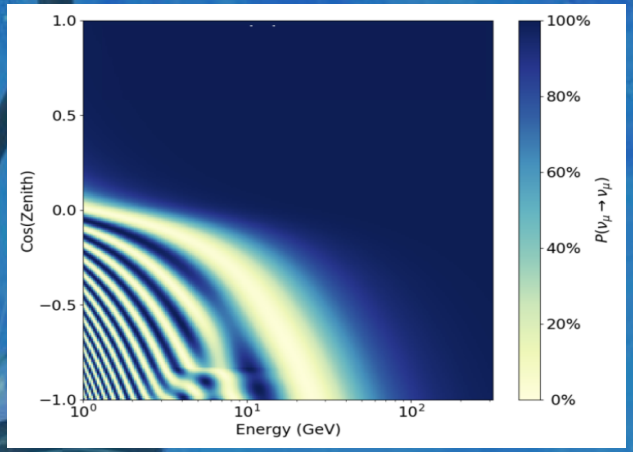


What else can IceCube do…

~~Someone needs to recycle the atmospheric neutrinos…~~

Study neutrino oscillations with **DeepCore**!

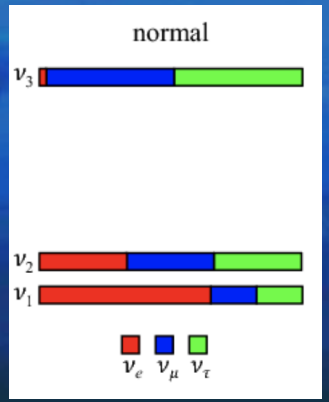




Each flavor (e, μ, τ) is a superposition of masses (1, 2, 3)

Oscillations are described by:

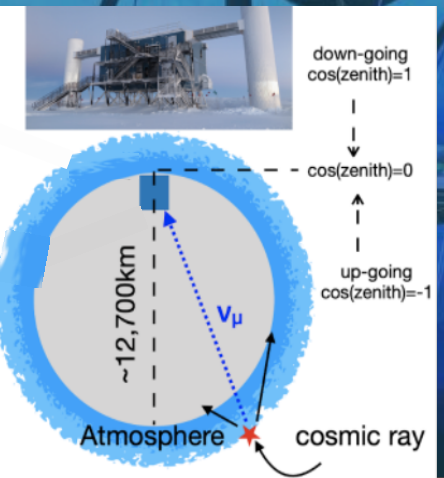
- Mixing angles ($\boldsymbol{\theta_{23}}$, θ_{13}, θ_{12}), δ_{CP}
- Squared mass differences: $\boldsymbol{\Delta m^2_{32}}$, Δm^2_{21}



ν_μ Disappearance with DeepCore

Atmospheric muon neutrinos from cosmic ray interactions:

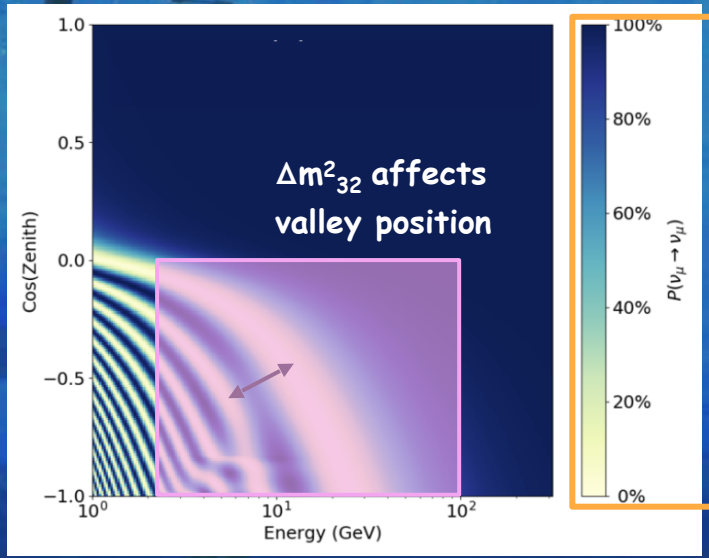
- Wide ranges of both energy (E) and baseline (L), and largest values.



Neutrino distance of travel (L) calculated using arrival direction (zenith).

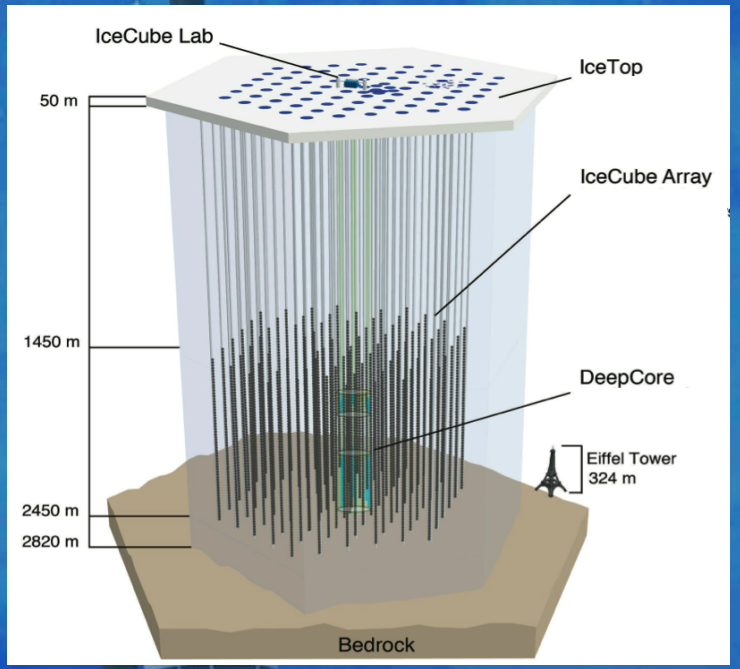
ν_μ survival probability (two flavor approx.):

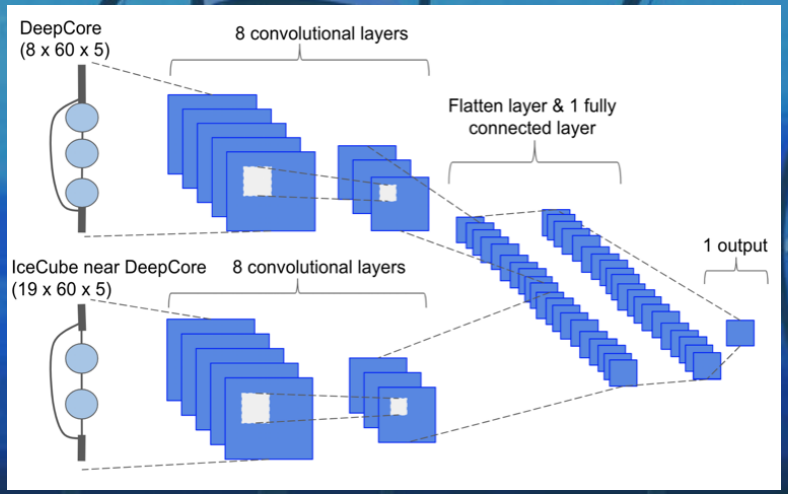
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27 \Delta m^2_{32} L}{E}\right)$$



Low-energy (< 100 GeV) reconstruction is critical to oscillation analysis

DeepCore: denser configured sub-detector, can observe GeV-scale neutrinos.





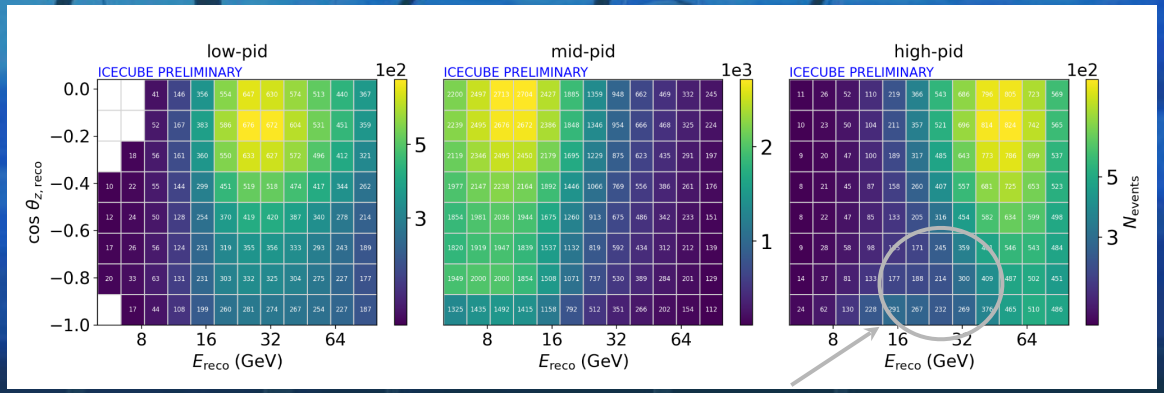
Machine-learning techniques are developed and employed

- Better reconstruction near DeepCore region
- ~3,000 times faster than the current LLH-based method

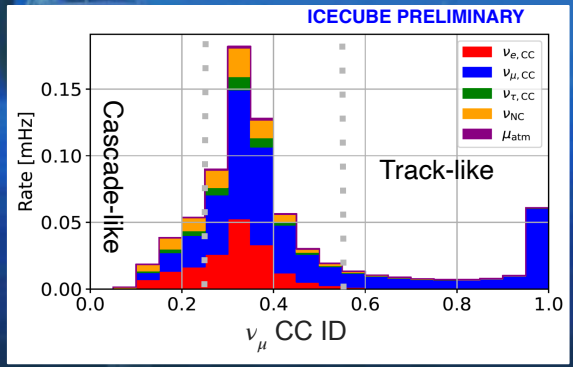
Analysis

Measure 3D distortions in reconstructed [energy, cos(zenith), PID]:

- PID discriminates ν_μ CC vs. other neutrino interactions;
  - 27,352 tracks; 22,963 cascades.
- Robust against systematic uncertainties;

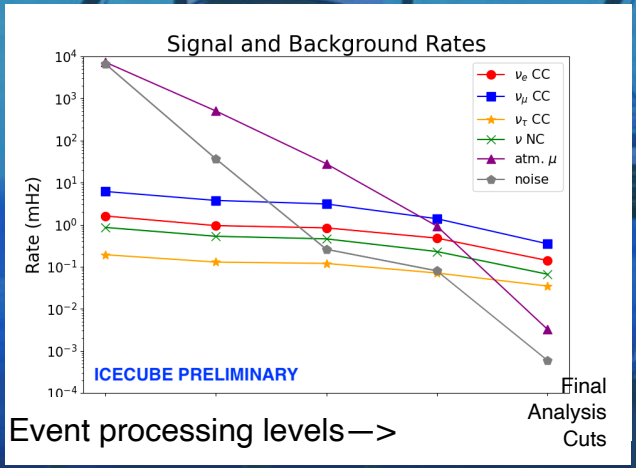


ν_μ **disappearance signal**



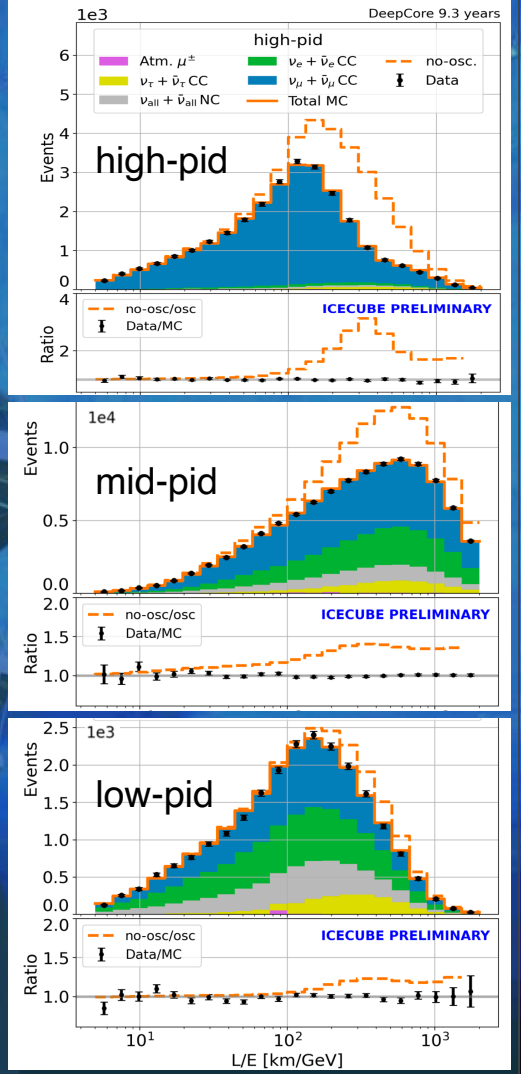
Result

- Data taken over ~3,390 days between 2012-2021;
- Total of 150,257 events;



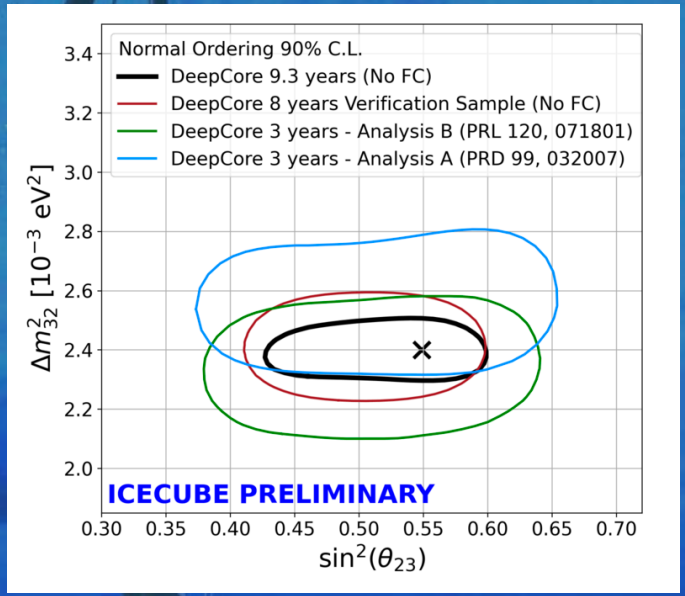
High signal (ν_μ CC) and low background (noise & atm. muon) rates (~0.6%):

- Low levels of selection eliminate atm. muons and noise backgrounds (shared with previous result)



Result

- Consistent with the previous IceCube results.
- Big updates on MC models and calibration since DeepCore 3-year results.
- Compared to DeepCore 8-year result: New reconstruction, including mixed- and low-pid bins into analysis.



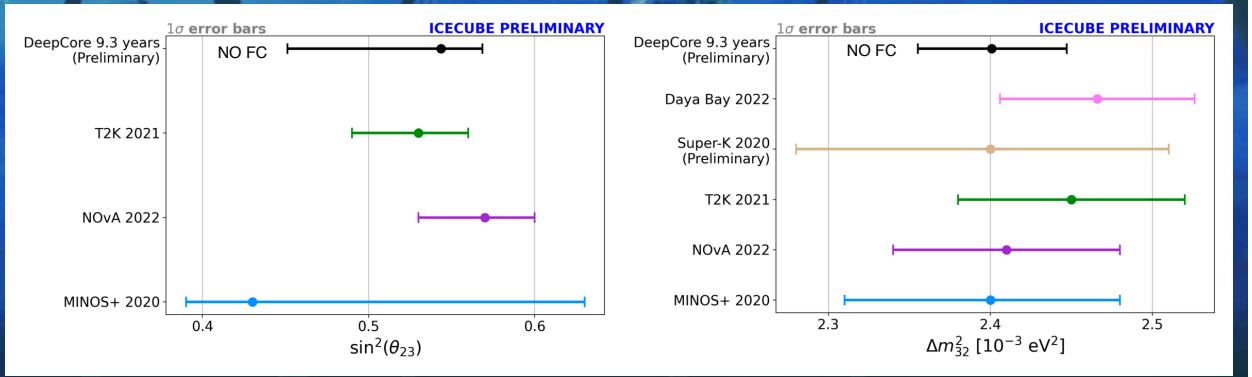
8 years result has been submitted to PRD
arxiv: 2304.12236

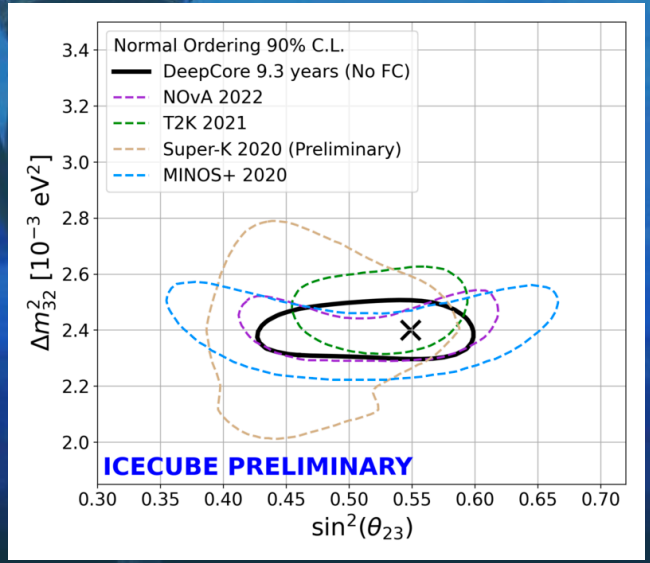
Proceedings about this work: MORIOND EW 2023, NuFACT2022, ICRC 2021

Result

The new result is compatible and complementary with the existing measurements:

- Very high energy sample relative to other experiments and detector technology is unique —〉 observed consistency is a strong validation!

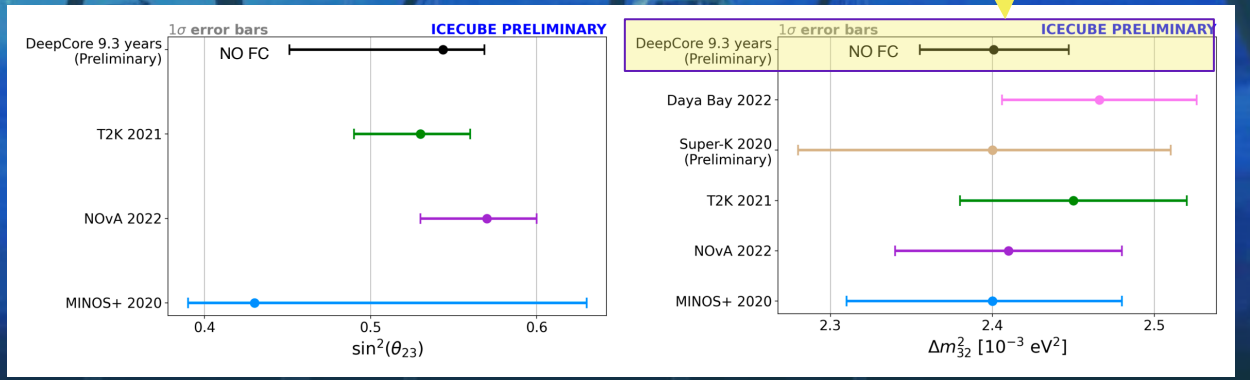


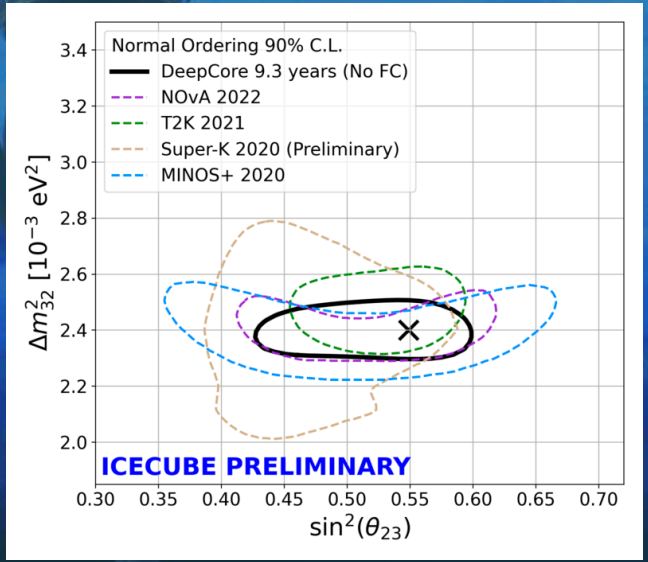


Result

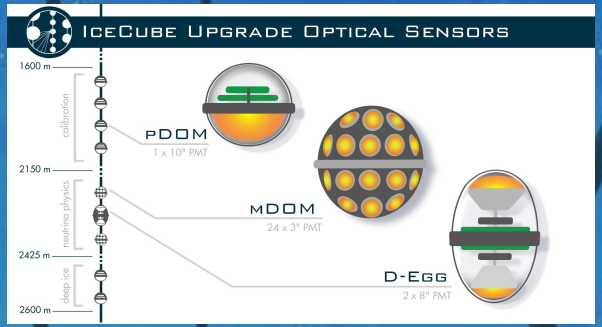
The new result is compatible and complementary with the existing measurements:

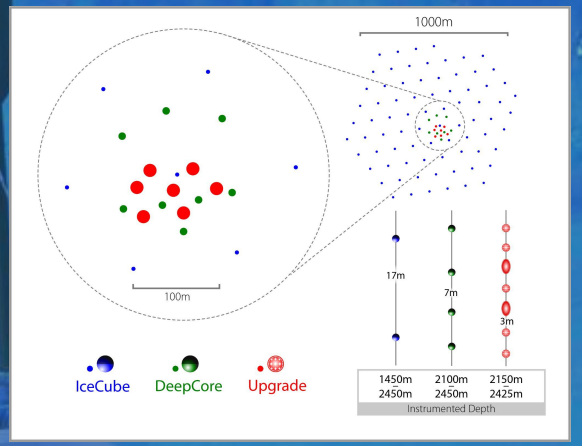
- Competitive on Δm^2_{32} measurement.
- Room for future improvements!
  - Flux model; calibration, etc





Future



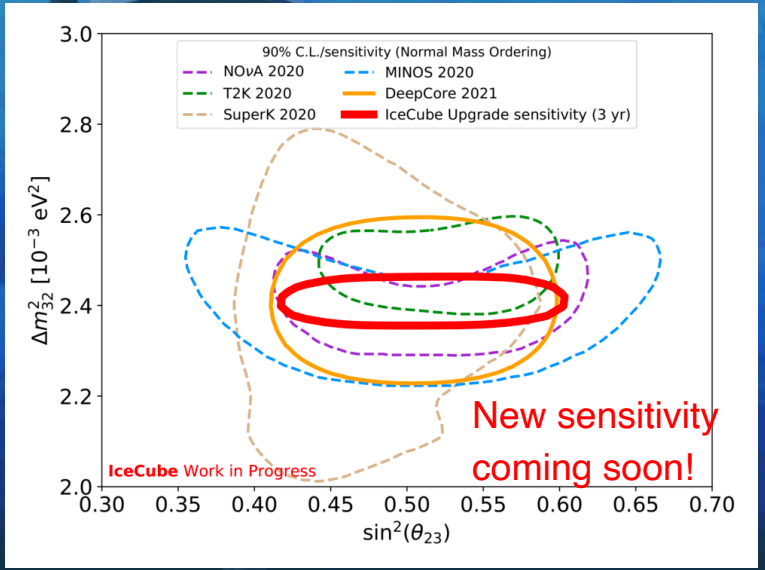


Upcoming results of neutrino physics:

- mass ordering, non-standard interaction, etc…

The Upgrade detector:

- More densely instrumented strings in the center
  - Better event resolution!
- DOM: multiple PMT designs
  - Great for calibration studies!
- Target deploying 2024/25



Summary and Outlook

Astrophysics

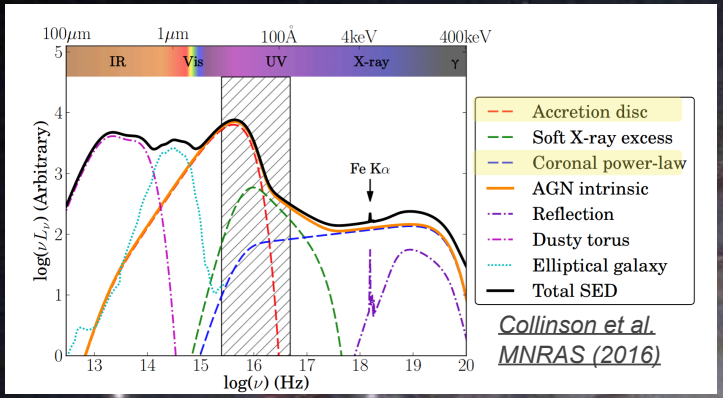
- Evidence of neutrino emissions from NGC 1068 and are working on finding more extra-galactic sources.
- Observation of the Galactic Plane in neutrinos.
- Studying specific models with data is becoming feasible and important.
- The future detectors with improved sensitivities will advance searches.

Neutrino physics

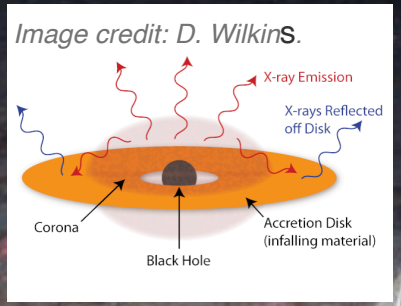
- Muon neutrino disappearance measurement is consistent with our previous results.
- Compatible and complementary with the existing measurements.
  - Competitive constraint on Δm^2_{32}
- More results/sensitivities coming soon!
- Future improvements: calibration (Upgrade), MC models, reconstruction. etc.

Thank you!

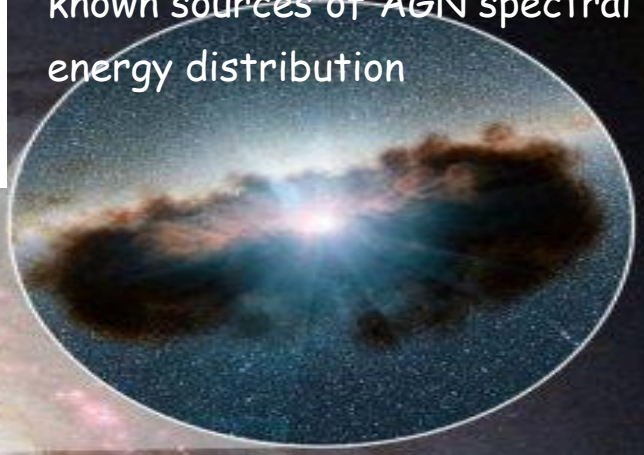

Overflow slides



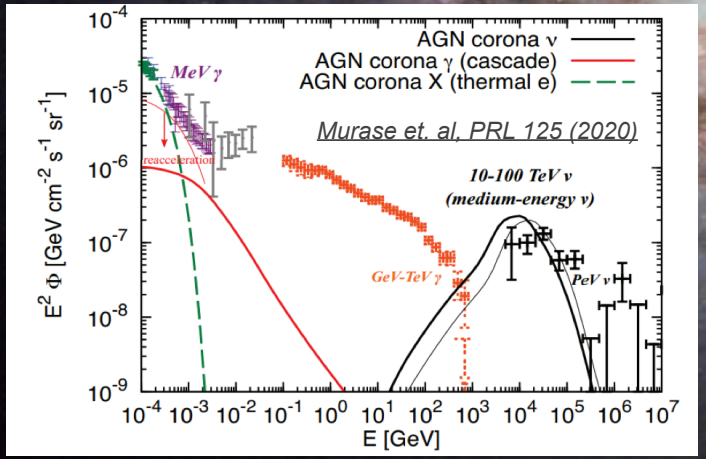
Collinson et al. MNRAS (2016)



Accretion disk and corona are the known sources of AGN spectral energy distribution



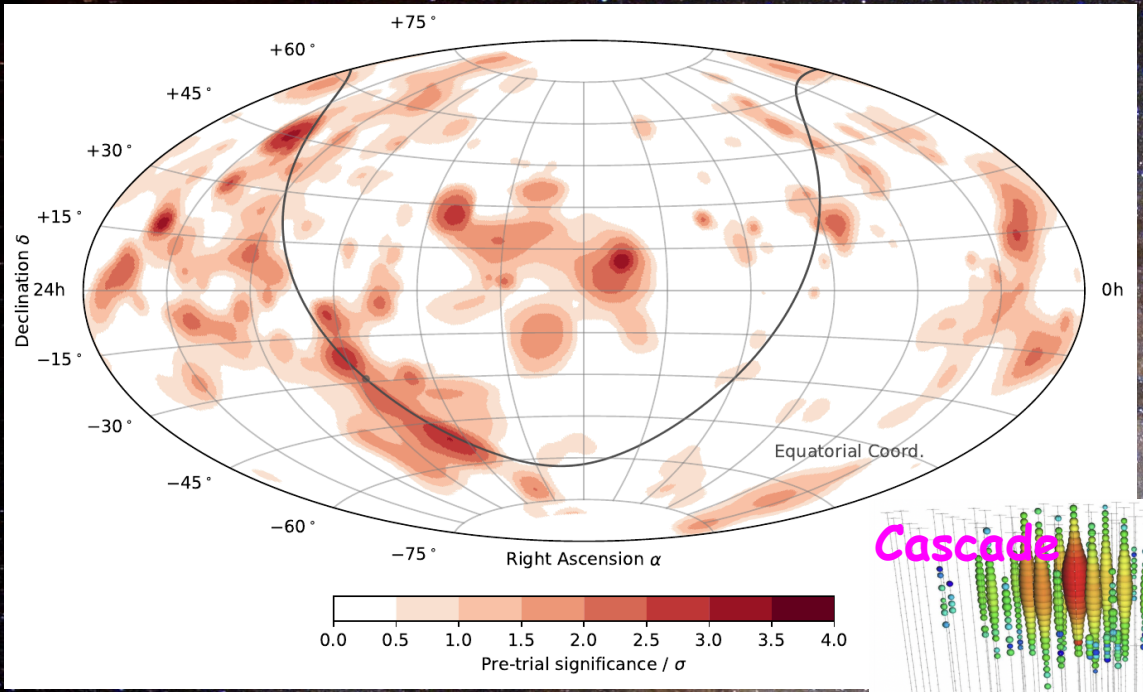
Bright X-ray emission at 2-10 keV



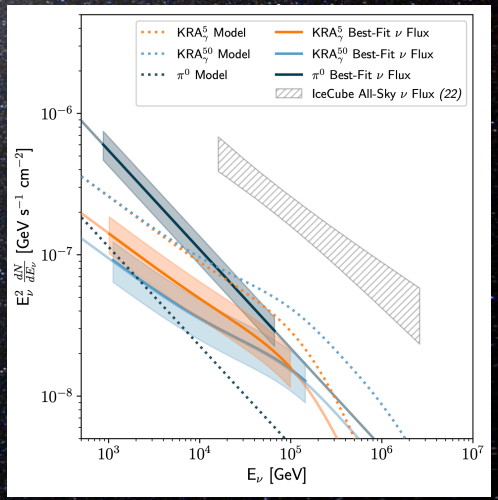
If the coronal models are correct, i.e. particles are accelerated within corona:

=> **population of Seyfert galaxies could explain significant part of diffuse neutrino flux**

without creating tension with Fermi observations

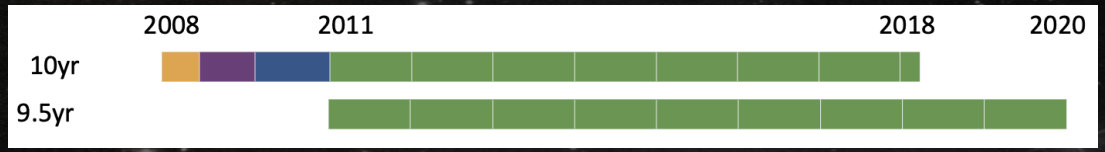


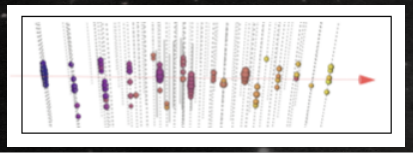
All-sky scan shows no significant spots emitting neutrinos but clusters along galactic-plane.

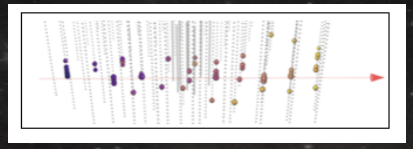


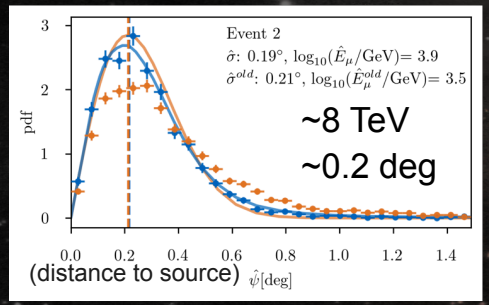
No strong preference on which template is the best.

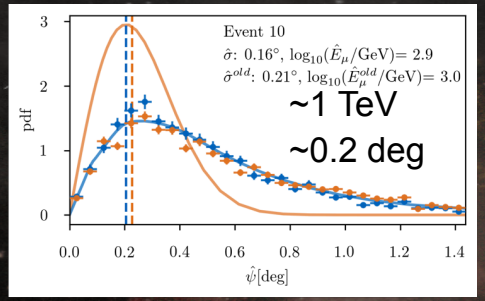
NGC 1068





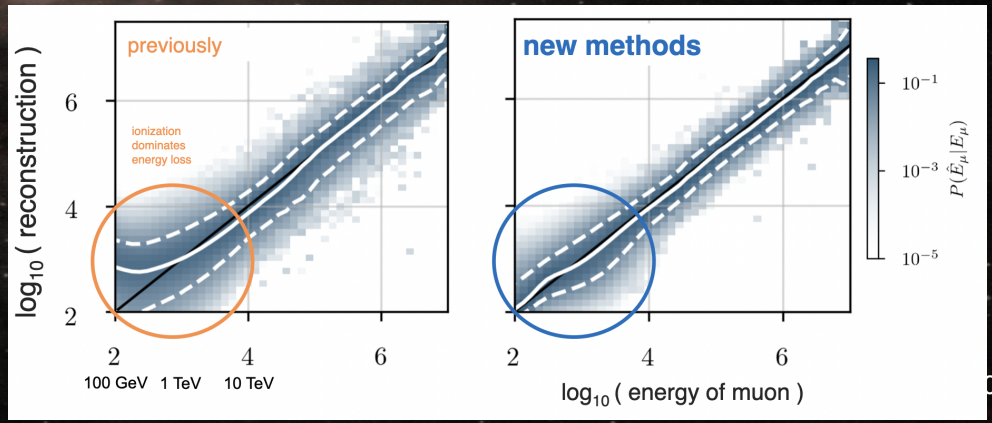




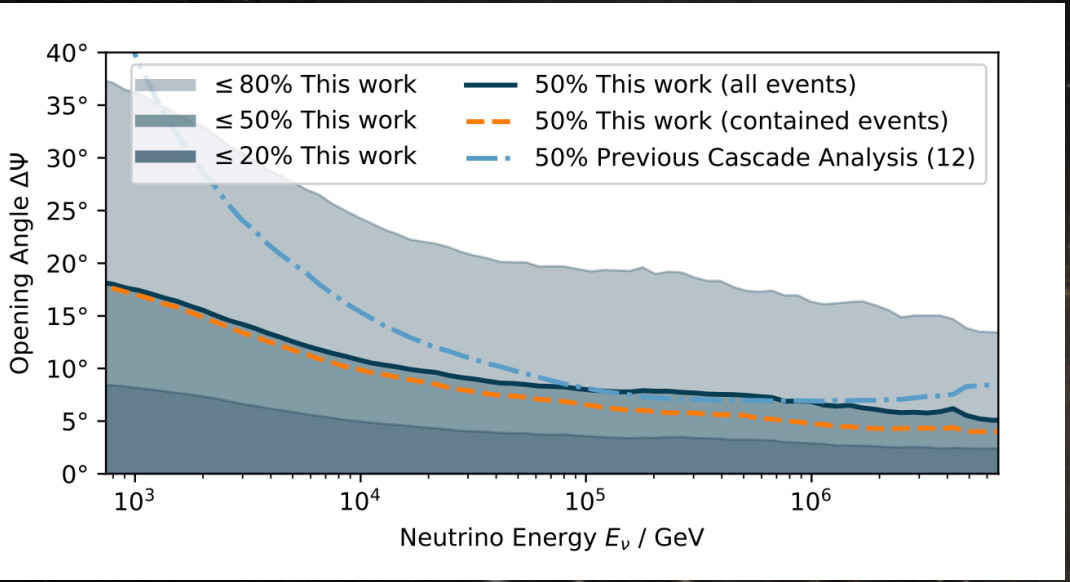


better modeling of directional distributions of individual neutrinos in particular well reconstructed events (at TeV energies)

energy reconstruction: neural network provides more accurate and more precise energy estimates especially at TeV energies

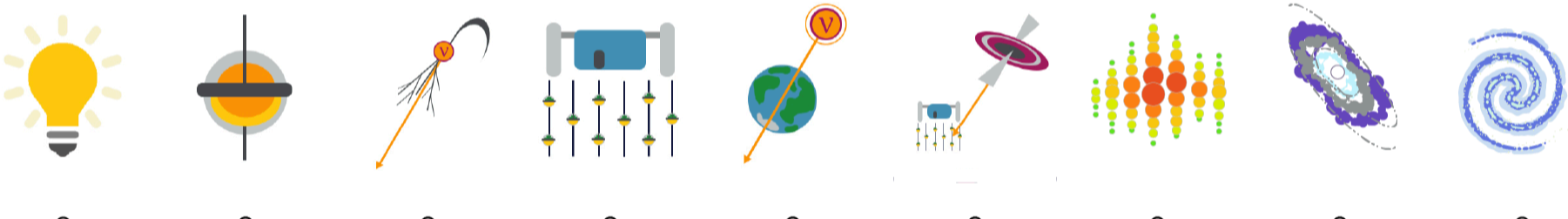


GP reconstruction



energy reconstruction: neural network provides more accurate and more precise energy estimates in all energy range especially at TeV energies

A History of Neutrino Astronomy in Antarctica



1988 — Telescope in the Ice Envisioned

2000 — AMANDA Completed

2001 — Atmospheric Neutrinos Detected

2011 — IceCube Completed

2013 — Astrophysical Neutrinos Discovered

2018 — First Source TXS 0506+056 Identified

2021 — Glashow Resonance Neutrino Identified

2022 — Second Source NGC 1068 Identified

2023 — Third Source Milky Way Identified