Latest Results from IceCube and High-Energy Neutrinos

Jimmy DeLaunay
On behalf of the IceCube Collaboration

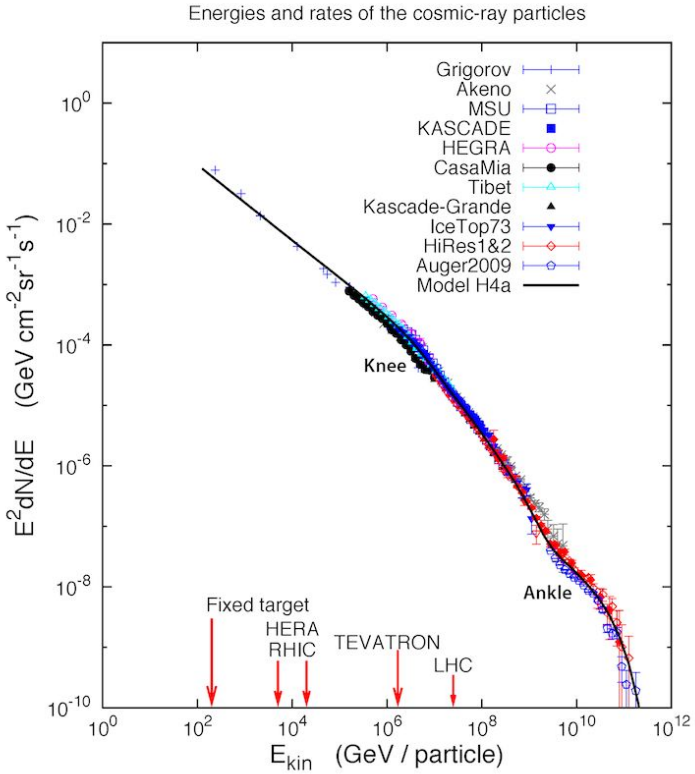
CIPANP 2022
Sep 3rd 2022

THE UNIVERSITY OF ALABAMA®

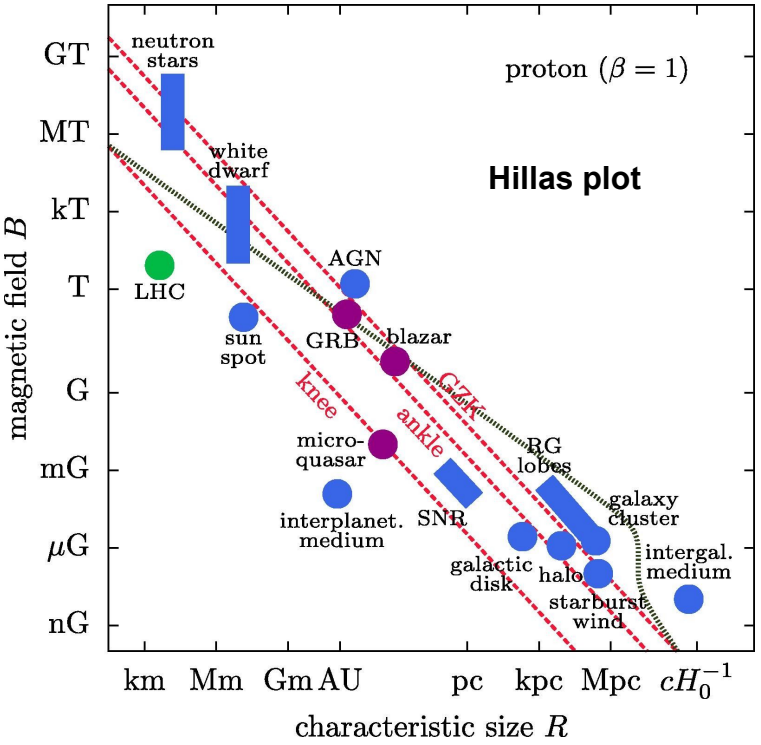
IceCube
South Pole Neutrino Observatory

Why High-Energy Neutrinos? - A Cosmic-Ray Motivation

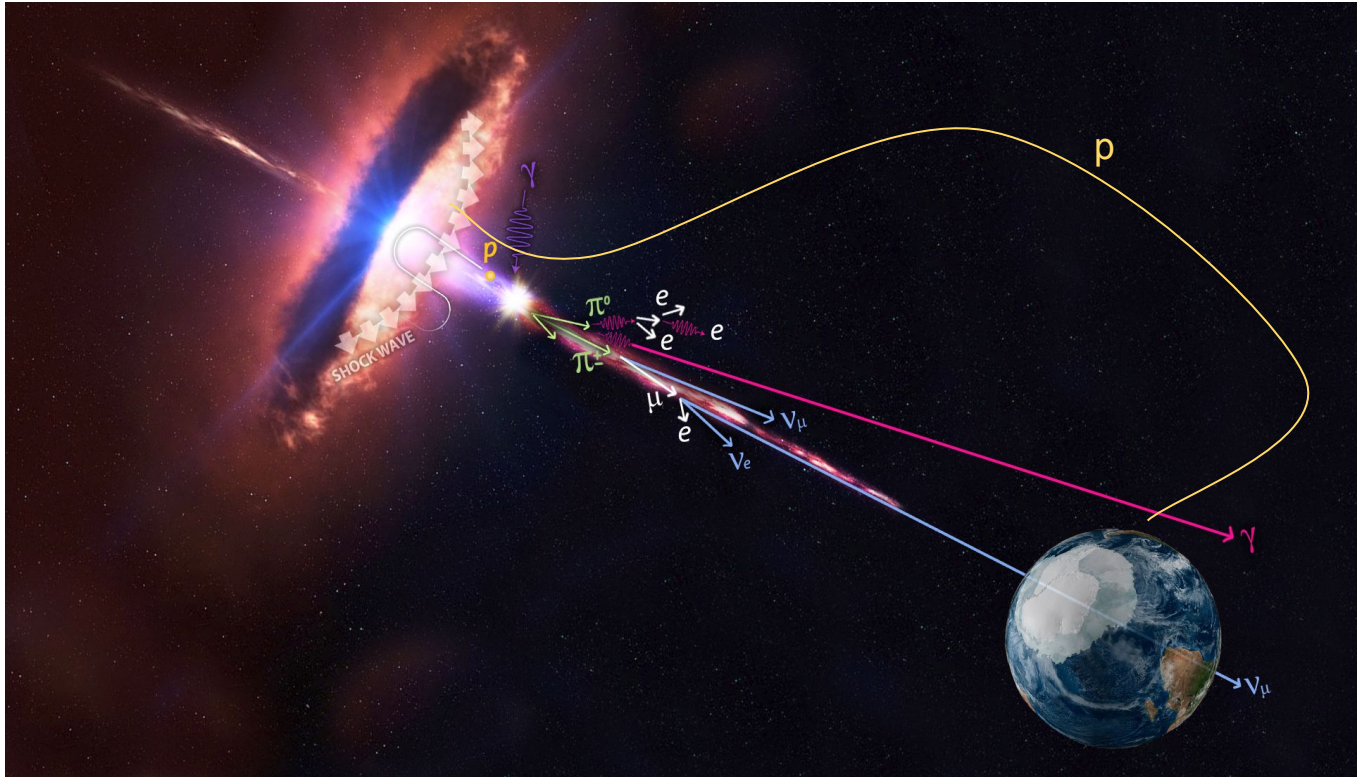
The well measured cosmic-ray flux to > 10^{20} eV



Where could they be accelerated?



Why High-Energy Neutrinos?



Cosmic-rays curve in magnetic fields

CRs interact in photon fields (p-γ) or matter fields (p-p) creating Pions and ultimately neutrinos.

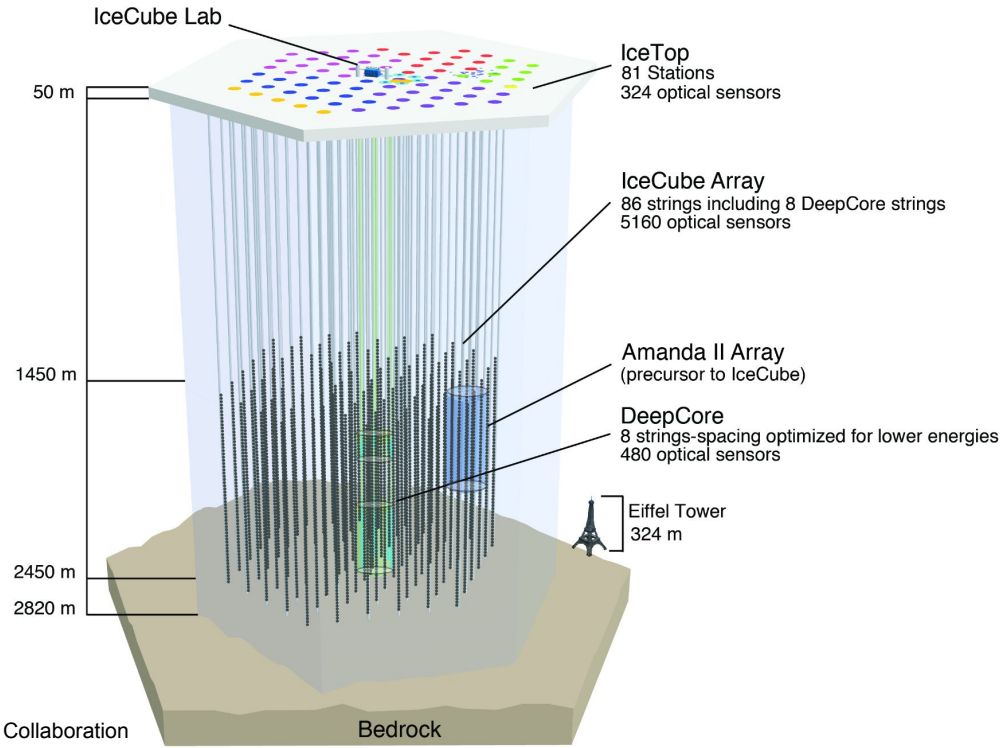
High-energy photons interact with extragalactic background light

- 100 GeV photon horizon at z ~ 1
- High-energy photons can also come from non-hadronic interactions

$$p\gamma \longrightarrow \Delta^+ \longrightarrow \begin{cases} n\pi^+ & \longrightarrow n\mu^+\nu_\mu \longrightarrow ne^+\nu_e\nu_\mu\bar{\nu}_\mu \\ p\pi^0 & \longrightarrow p\gamma\gamma \end{cases}$$

$$pp \longrightarrow \begin{cases} pn\pi^+ & \longrightarrow pn\mu^+\nu_\mu \longrightarrow pne^+\nu_e\nu_\mu\bar{\nu}_\mu \\ pp\pi^0 & \longrightarrow pp\gamma\gamma \end{cases}$$

The IceCube Neutrino Observatory



Credit: IceCube Collaboration

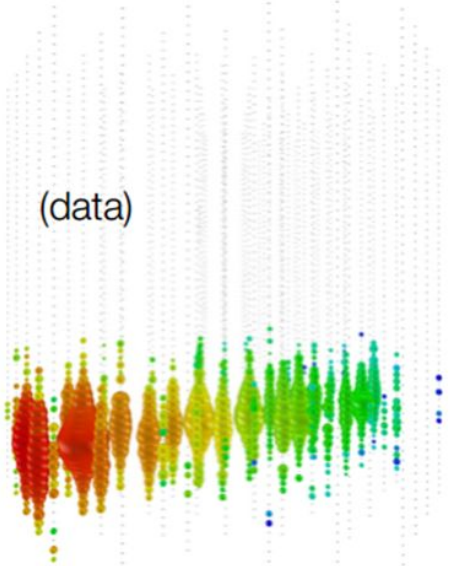
- ~km^3 of ice
- 86 strings of 60 DOMs
- Construction completed in 2011

DOM

Event Topologies

Track

CC ν_μ Interactions
Some CC ν_τ Interactions

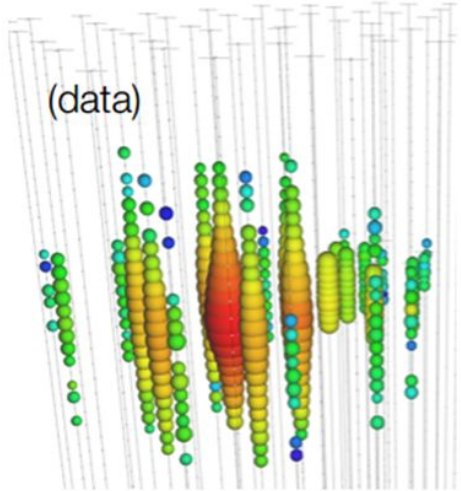


Angular Resolution ~ 0.2 - 1°
Energy Resolution ~ factor of 2

EARLIER **LATER**

Cascade

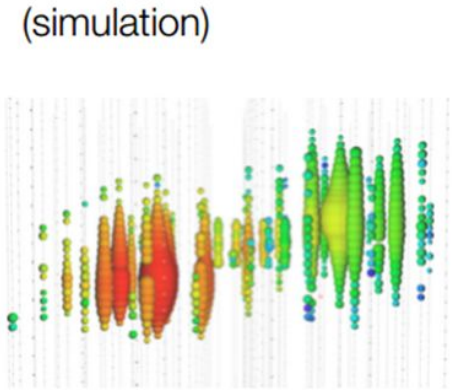
NC Interactions
CC ν_e Interactions
Most CC ν_τ Interactions



Angular Resolution ~ 10°
Energy Resolution ~ 15%

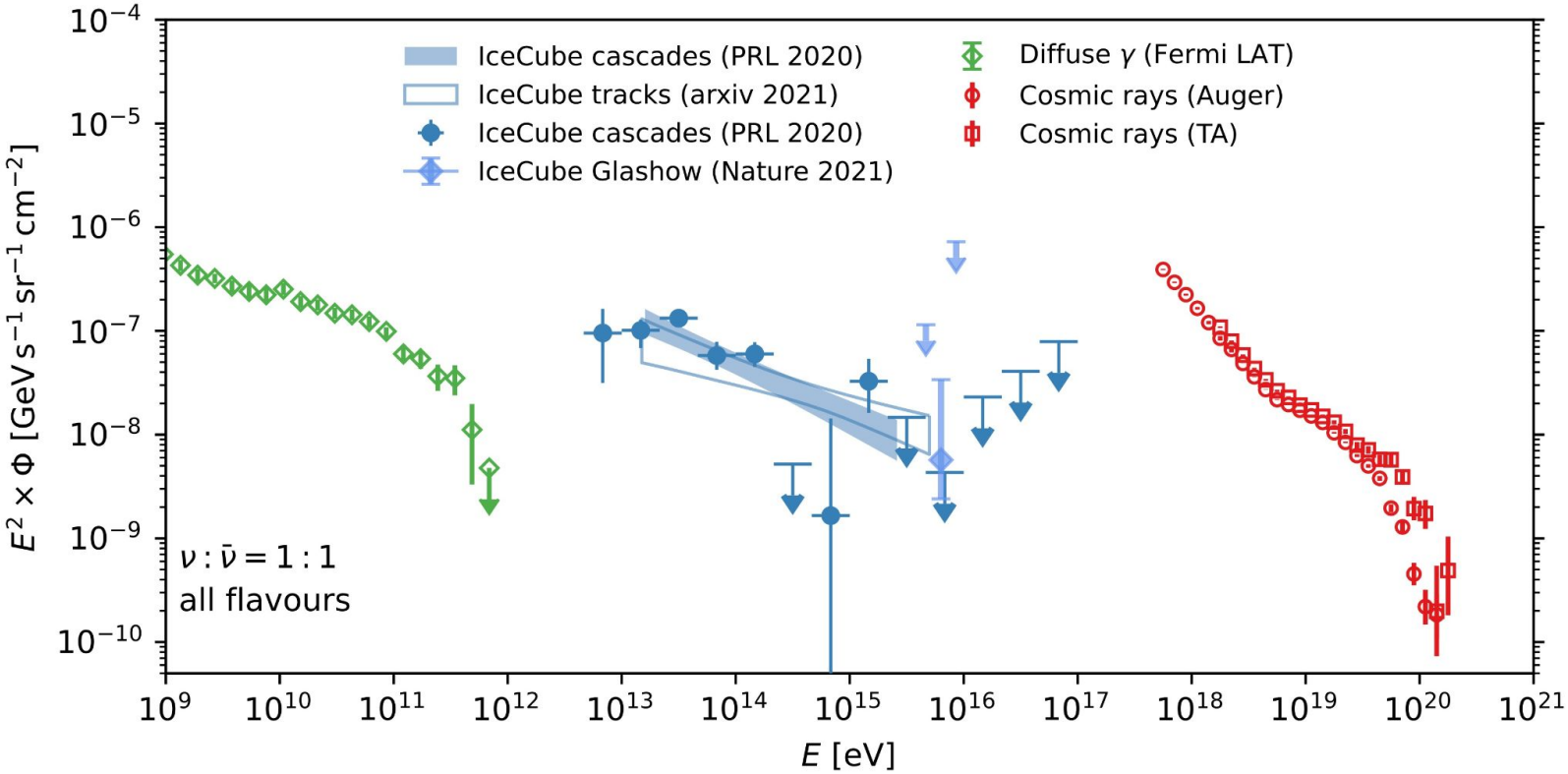
Double-Cascade

Some CC ν_τ Interactions



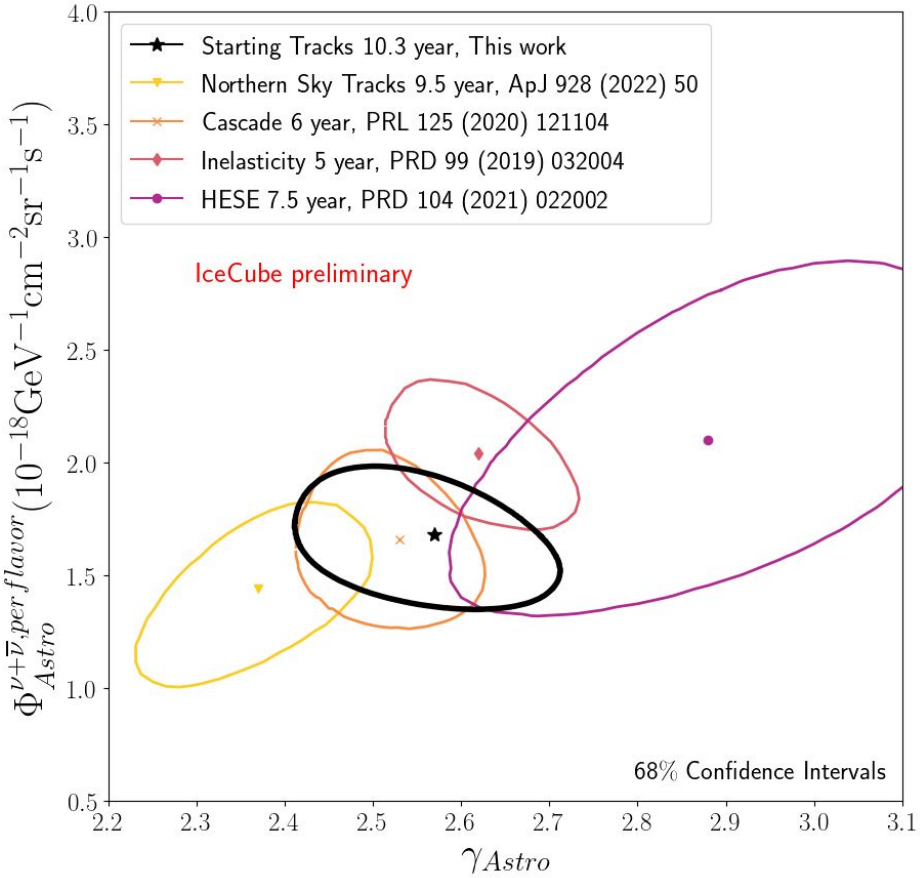
Requires > ~1 PeV
τ decay creates 2nd cascade
L_τ ~ 50 m· E_τ/ PeV

Astrophysical High Energy Neutrino Flux



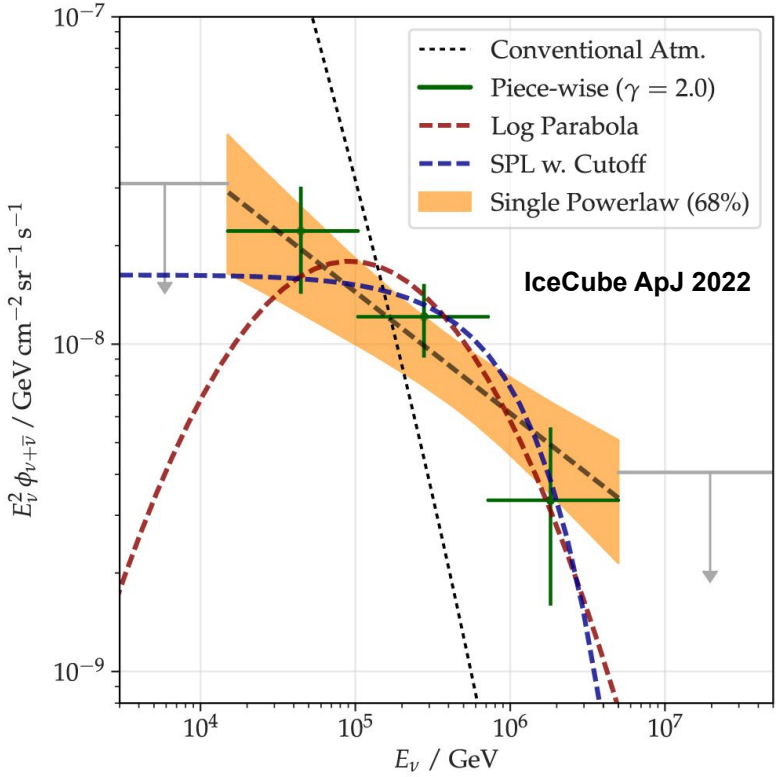
Astrophysical High Energy Neutrino Flux - Power Law

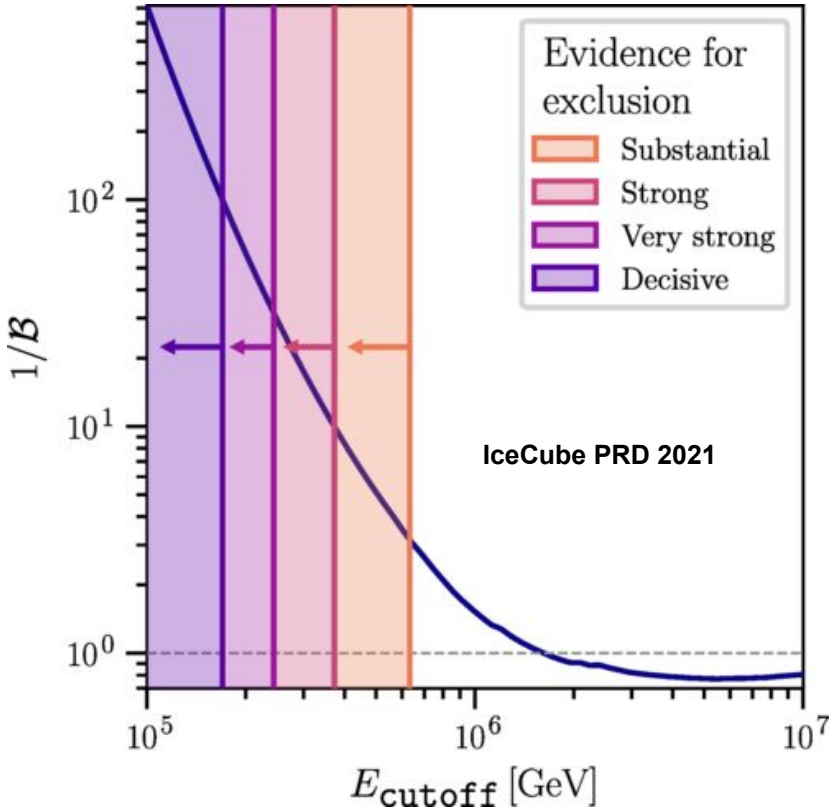
- DIfferent analyses and selections give different results
  - Slight tension but still statistically compatible
- Analyses are sensitive to different:
  - Energy ranges
  - Flavours
  - Sky regions



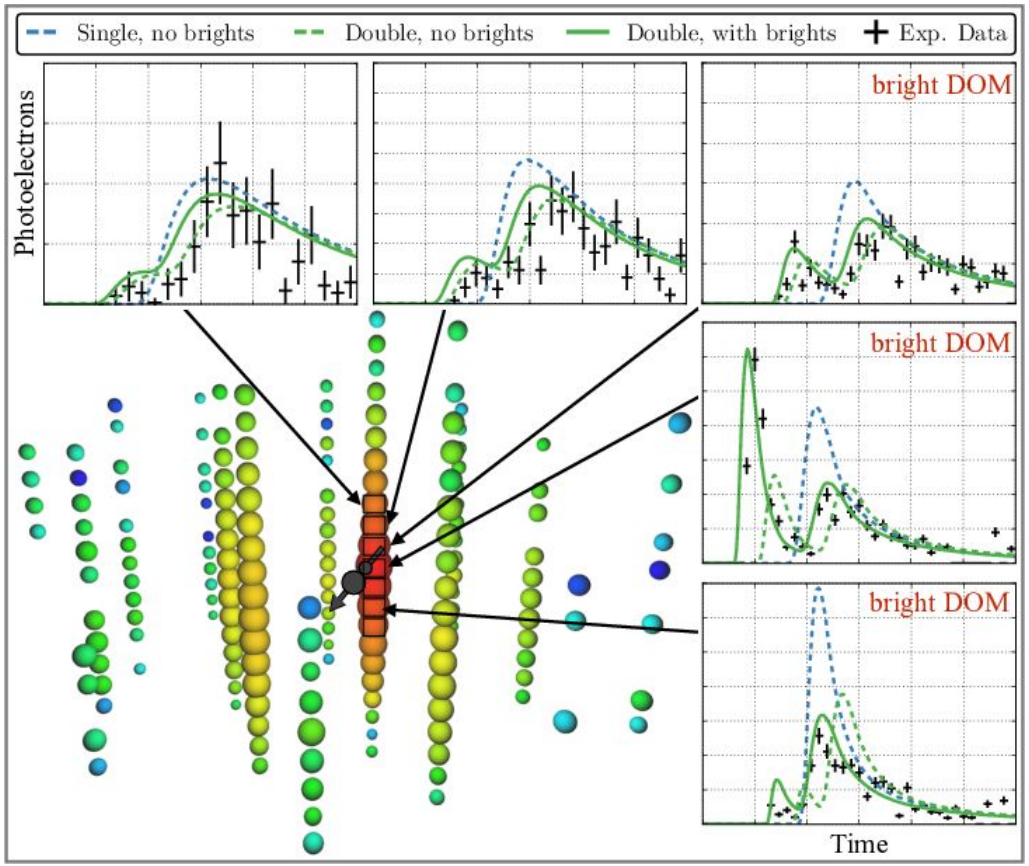
Astrophysical High Energy Neutrino Flux - Beyond Power Law

Nothing significantly favored over simple power law so far





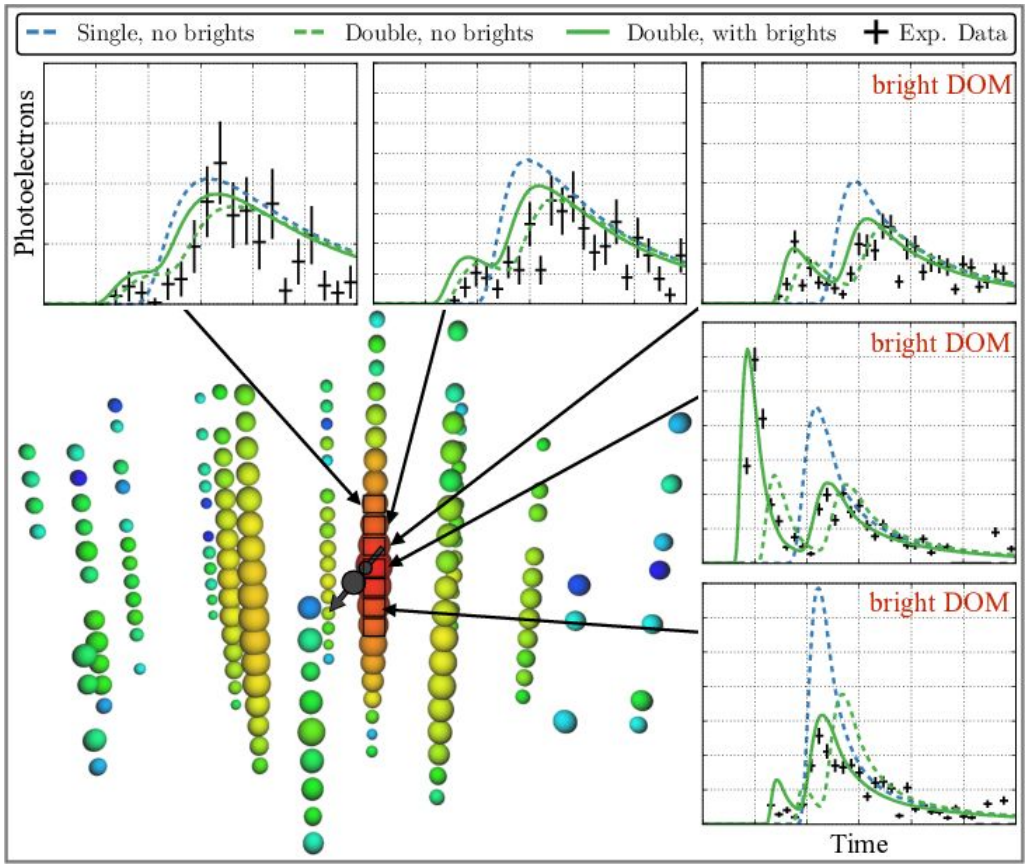
Neutrino Flavors - Taus



- Likelihood reconstruction with double cascade hypothesis used to select ν_τ's
- 2 candidates found
  - 76% and 98% probabilities of being ν_τ's
- Null hypothesis of no astrophysical ν_τ's rejected at 2.8σ

IceCube, arXiv:2011.03561

Neutrino Flavors - Taus



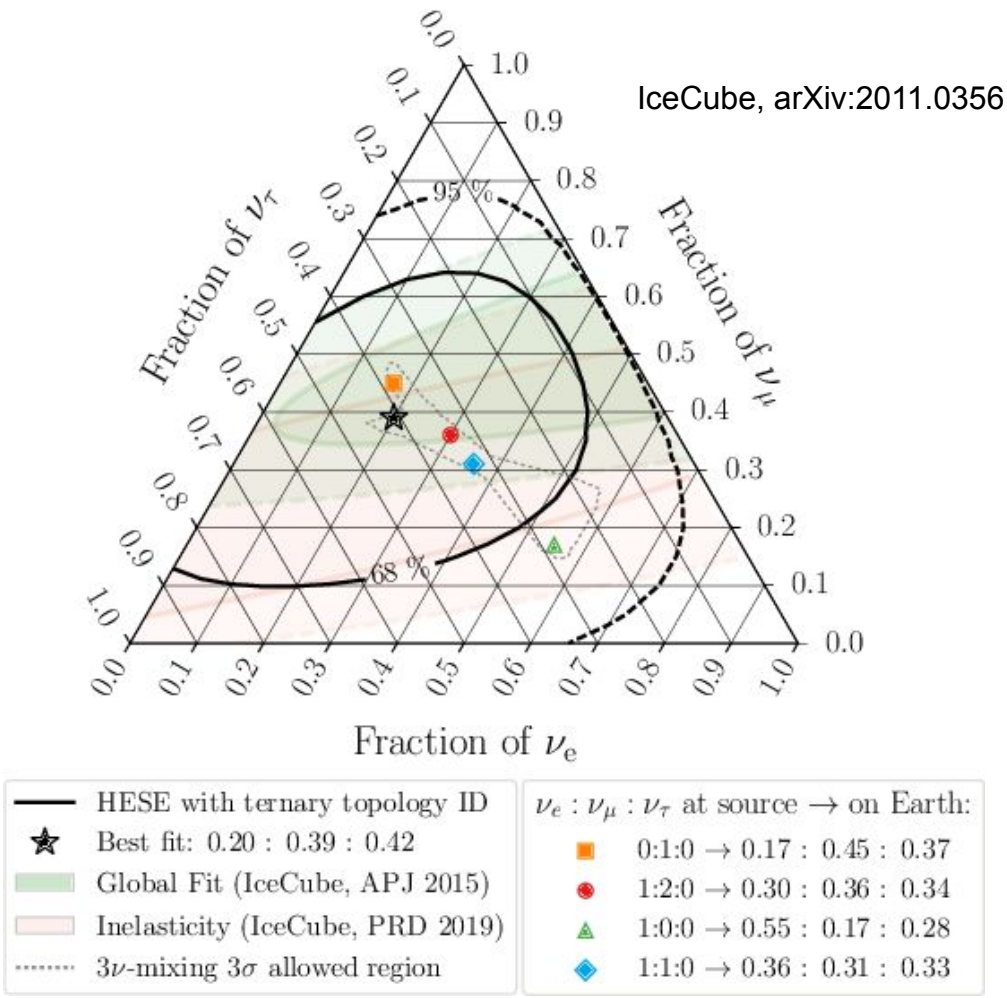
- Likelihood reconstruction with double cascade hypothesis used to select ν_τ's
- 2 candidates found
  - 76% and 98% probabilities of being ν_τ's
- Null hypothesis of no astrophysical ν_τ's rejected at 2.8σ

- New ν_τ results coming soon
- New CNN method expects to find ~5 ν_τ over a background of ~0.5
  - ~50% of 5σ rejection of the null hypothesis

IceCube, arXiv:2011.03561

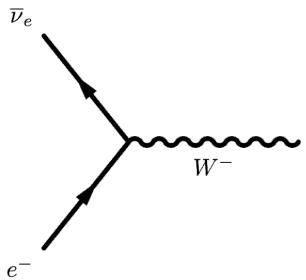
Neutrino Flavors - All

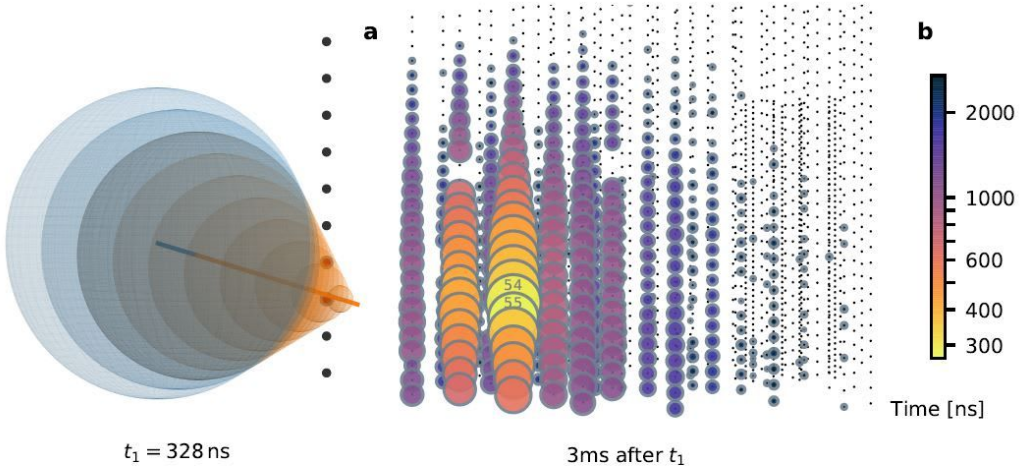
- Using event topology classification can infer the flavor ratio at Earth
- Oscillations change the flavor ratio from at the source, but can still infer the source ratio with enough statistics.



Neutrino Flavors/Anti - $\bar{\nu}_e$

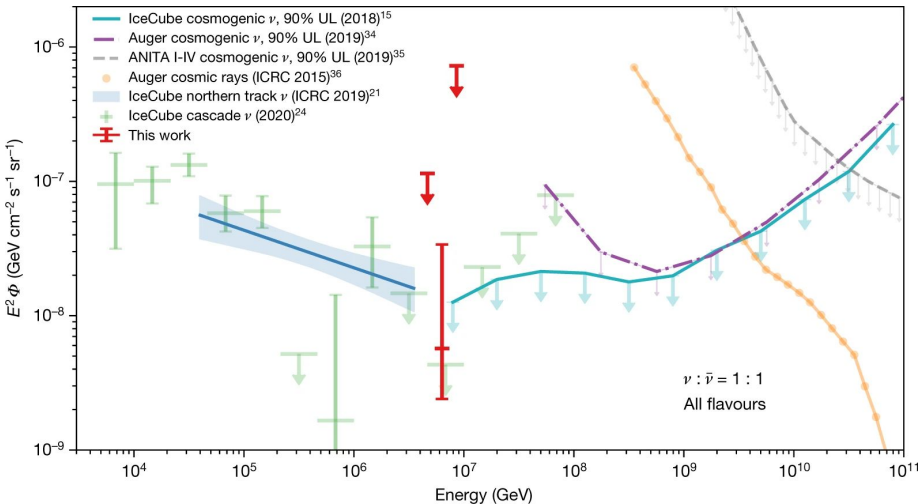
Glashow Resonance
E_R = 6.3 PeV
Confirms $\bar{\nu}_e$





Leading muon outrunning Cherenkov wavefront of shower

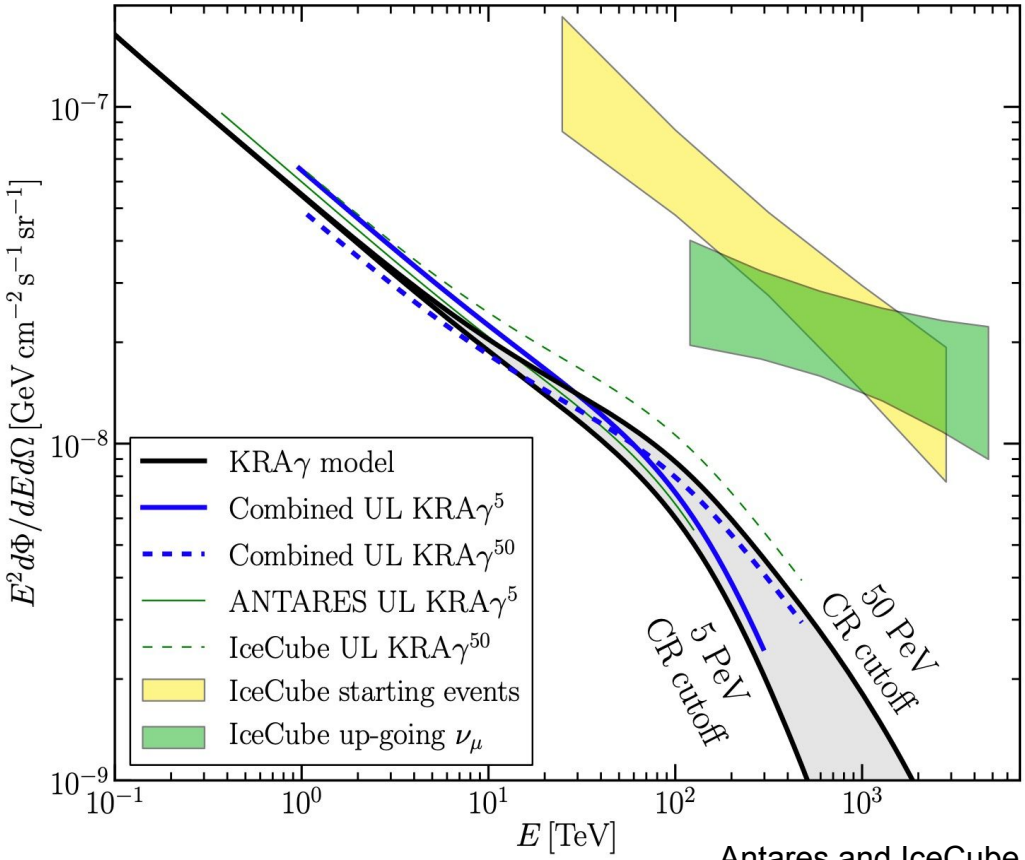
Adds high-energy flux point



- First observation of a Glashow Resonance
- ~6 PeV cascade
- More observations can constrain ratio of $\bar{\nu}_e$: ν_e
  - Then also the production mechanism (pp vs. pγ)

IceCube (Nature, 2021)

Neutrino Sources - Galactic Diffuse



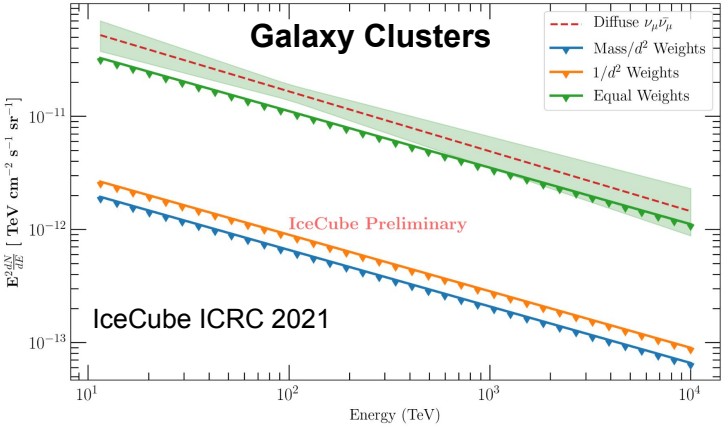
- Diffuse emission from the galactic plane expected at ~10% of isotropic diffuse flux
- Upper limits close to models
- Expect results from new event selections with improved Southern sky sensitivity soon

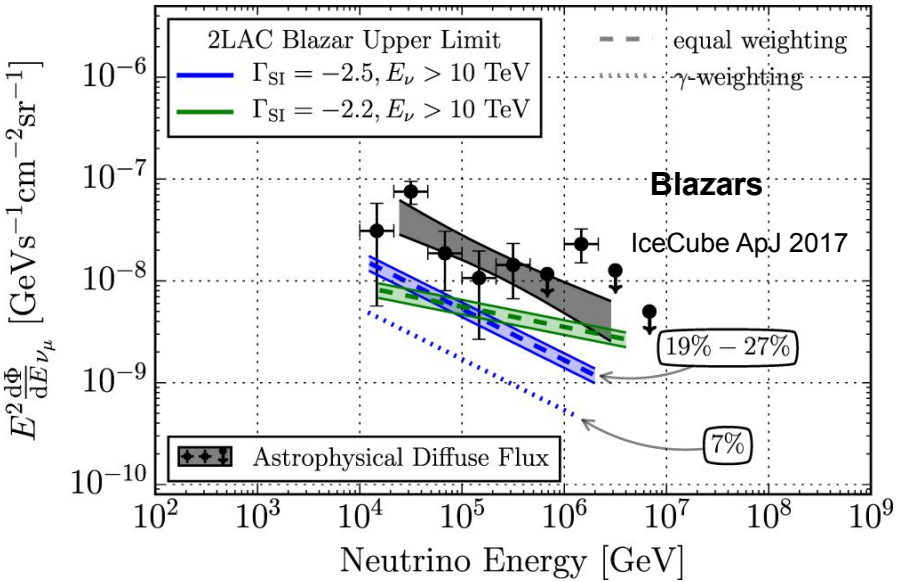
Antares and IceCube Collaboration 2018 ApJL

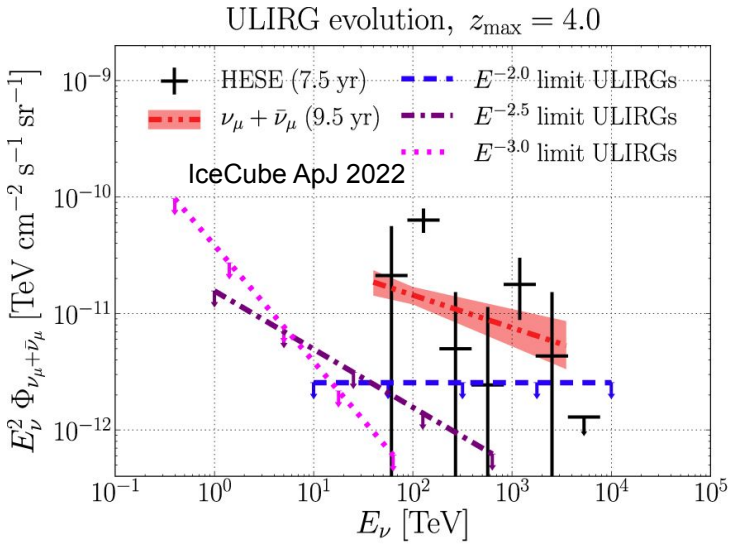
Neutrino Point Sources - Catalogs

Stacking analyses performed on catalogs of sources

Upper limits set on several steady and transient catalogs
Transients: GRBs, Blazar Flares, FRBs, TDEs, …
Steady: AGN, Blazars, Galaxy clusters, …

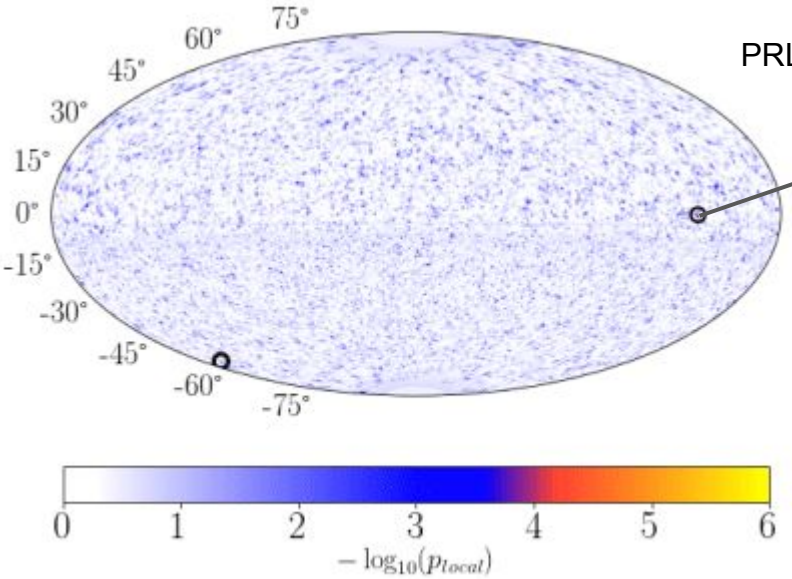




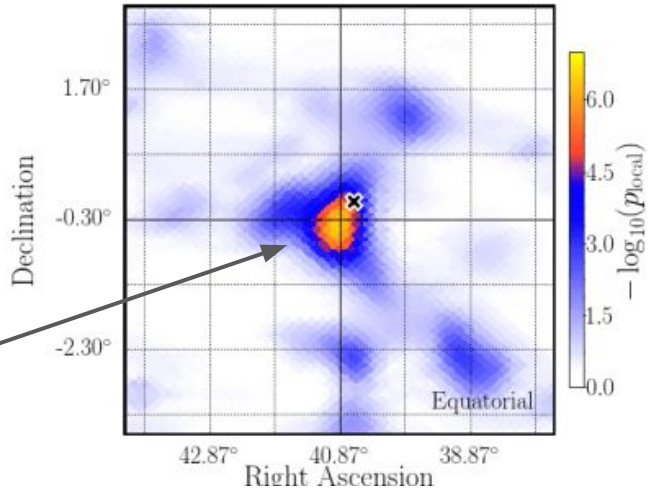


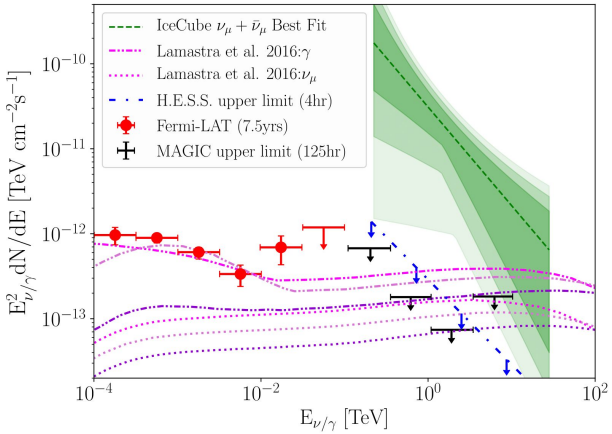
Neutrino Point Sources - All Sky and Source List

- All sky scan with 10 years of track data
- Also tests 110 gamma-ray bright sources
- Hottest spot 0.35° from NGC 1068 (in source list)
- NGC 1068 2.9σ in source list
  - Strongest PS signal for IceCube so far!



PRL 124, 051103 (2020)

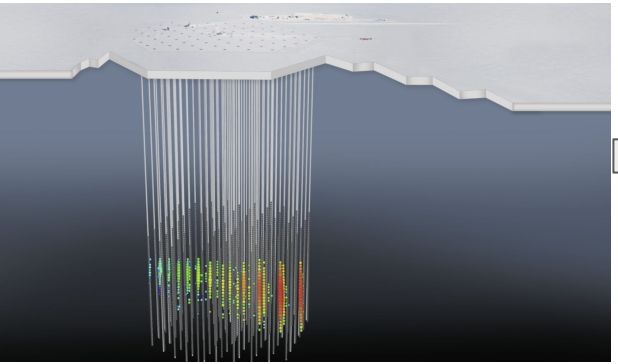


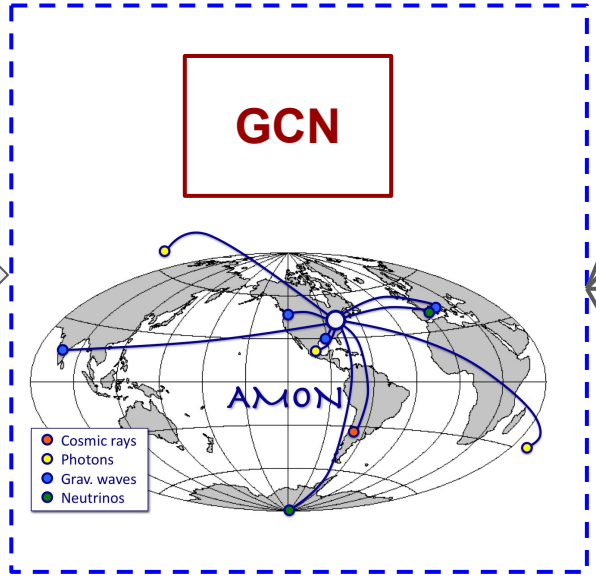


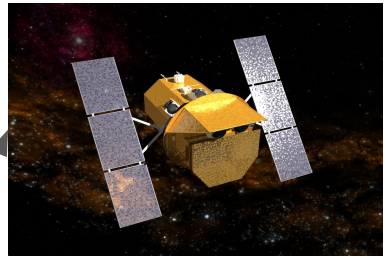
Results from improved data/methods coming soon

High-Energy Neutrino Alerts and Follow Up

- High-energy track alerts sent out to astronomical community in real-time
- Attempt to find any transient counterparts



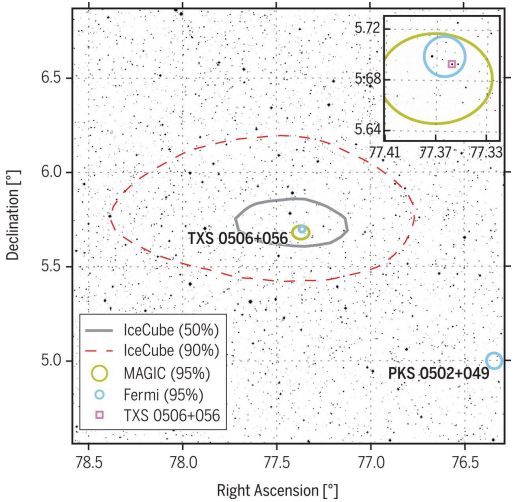




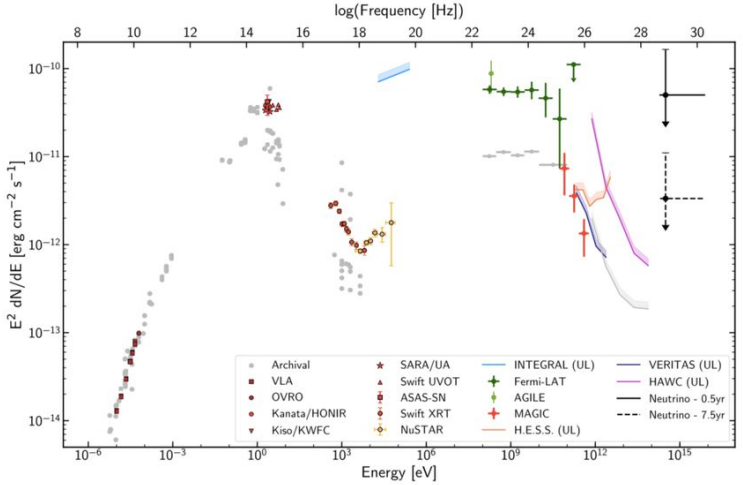
IC 170922A and TXS 0506

High-energy track alert <0.1° from Blazar in gamma-ray flaring state

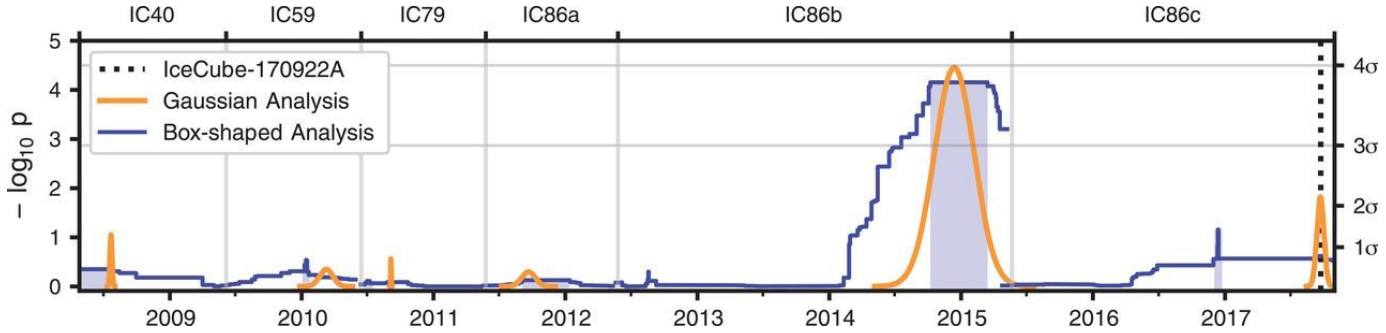
IceCube Science 2018



Extensive multi-wavelength observations



Possible neutrino flare from TXS in 2014-2015



Evidence for a Blazar neutrino point source

Conclusion / Outlook

- The astrophysical flux of high-energy neutrinos has been detected and measured
  - Work in progress to better characterize flux's: spectral shape, flavor composition, and nu/nubar ratio
  - Several source classes ruled out as majority contributor to flux
- Hints of emission for two neutrino point sources
  - Flaring emission from TXS blazar
  - Steady emission from Seyfert NGC 1068
- Many exciting results from new methods coming soon
- Coming further in the future
  - IceCube Upgrade
    - Smaller spacings and new DOM designs
  - IceCube-Gen2
    - Further spacings for much larger detector volume