Unveiling the Mysteries of Astrophysical Neutrinos with IceCube

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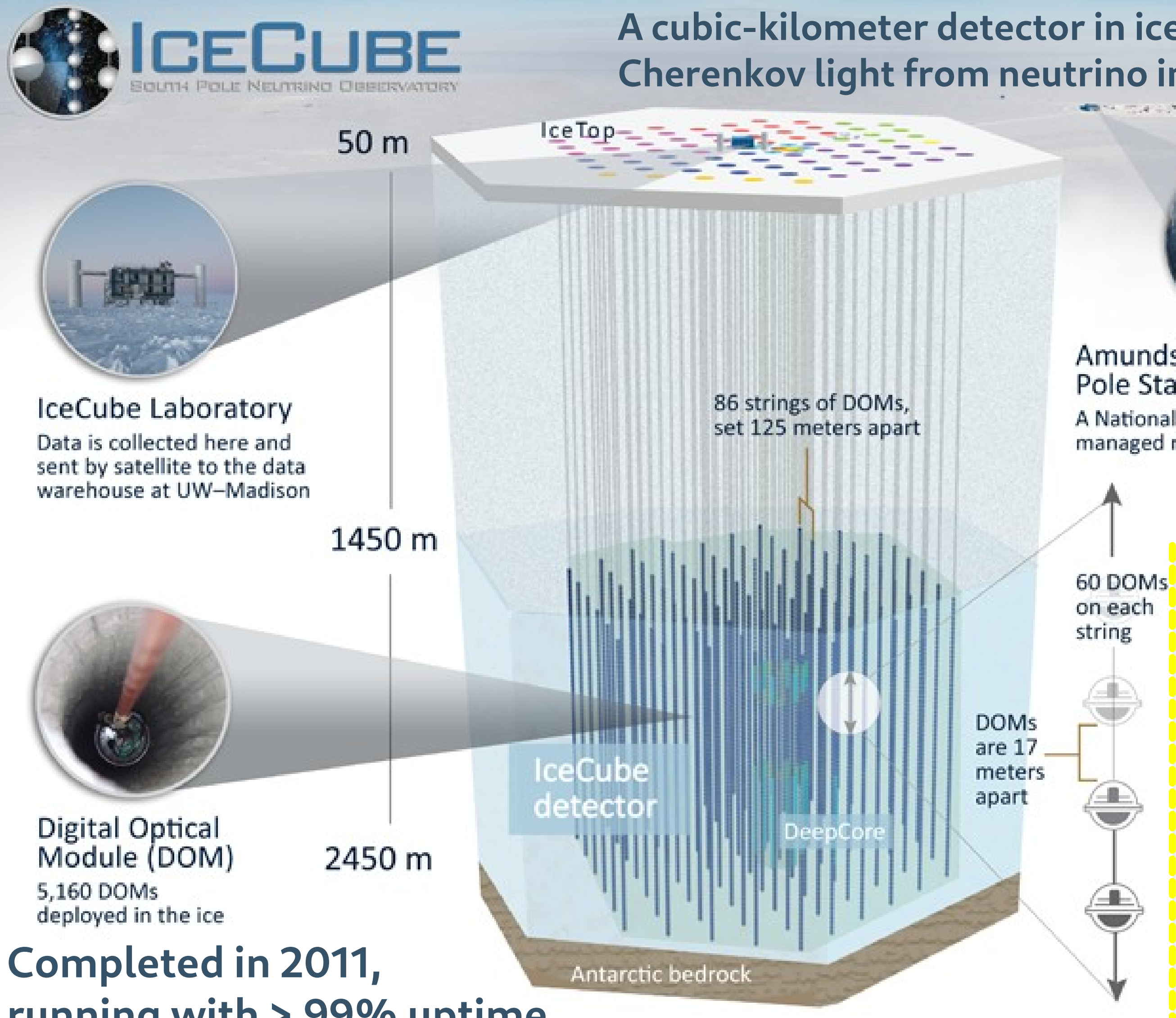
Tata Institute of Fundamental Research, November 24 2025

Outline

- IceCube Neutrino Observatory
- Diffuse astrophysical neutrinos
- Searching for sources of neutrinos
- Future projects

A cubic-kilometer detector in ice to detect Cherenkov light from neutrino interactions



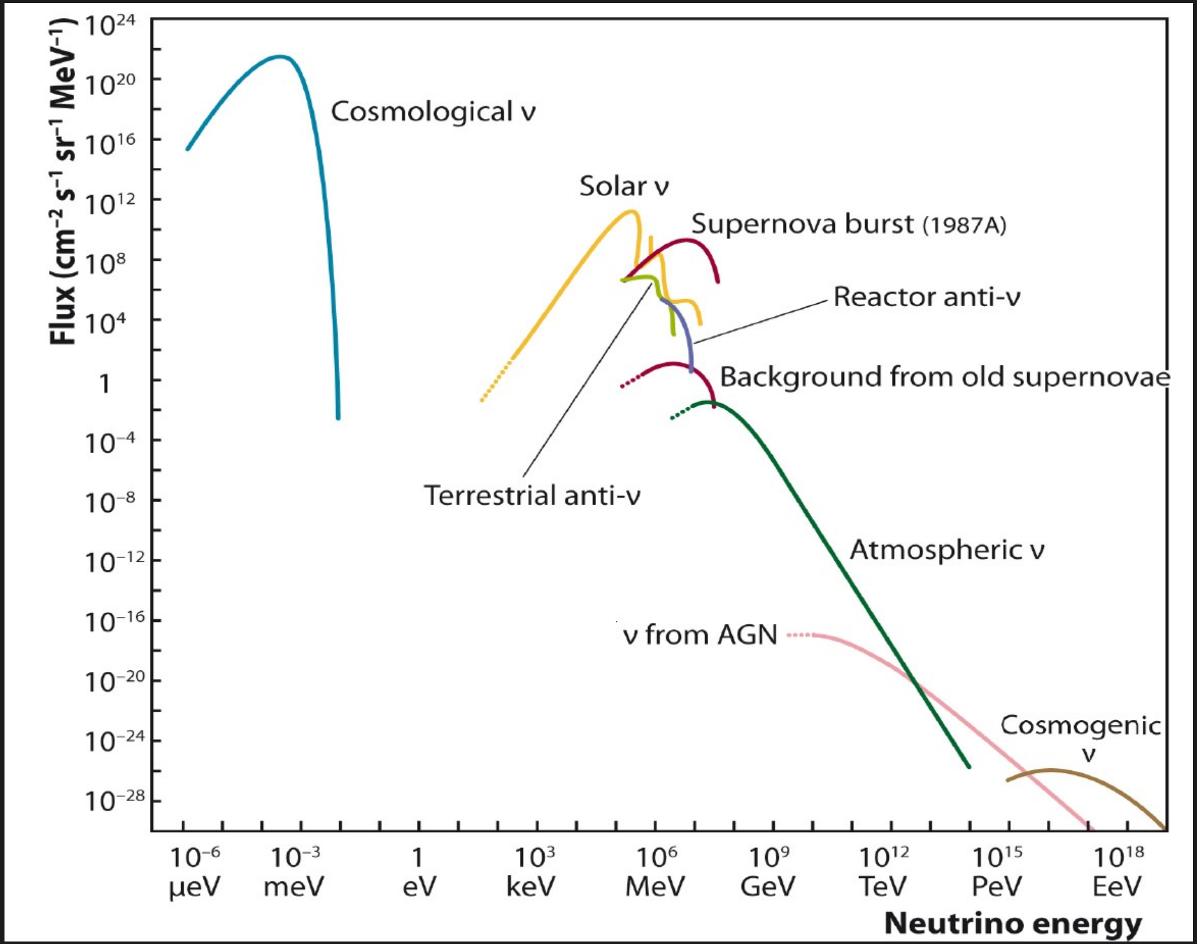
5160 Digital Optical Modules (DOMs)

86 strings, dense infill array with 6 strings, called DeepCore

Cosmic-ray array IceTop on the surface

Completed in 2011, running with > 99% uptime

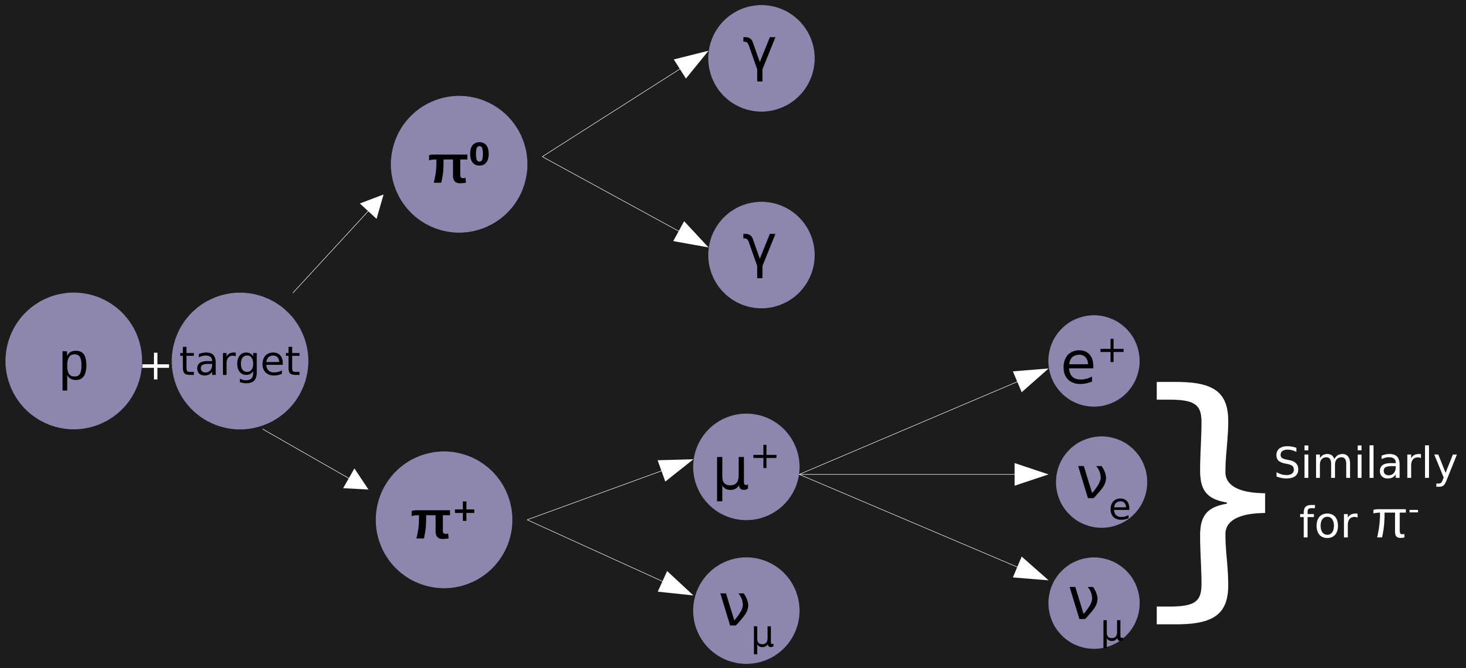
Where Do Neutrinos Come From?

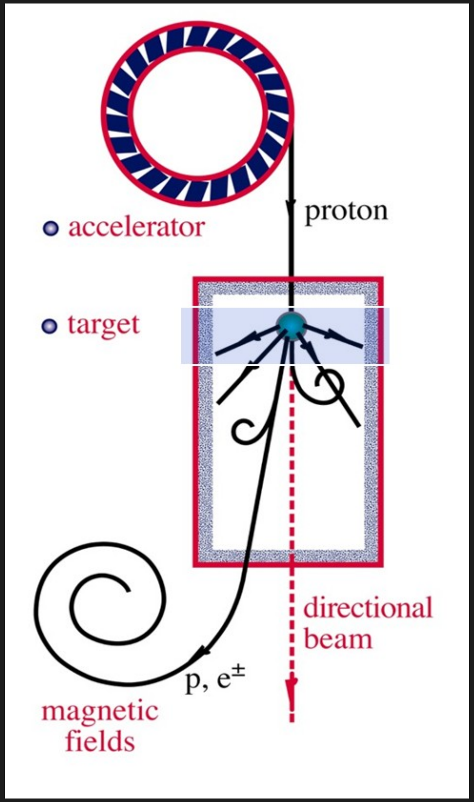


Around 100 trillion neutrinos pass through your body every second!

Production Mechanism of Astrophysical Neutrinos

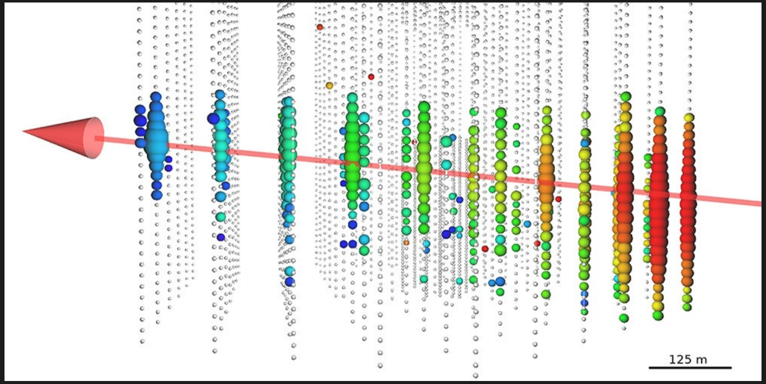
- Neutrinos (and gamma rays) are produced by the interactions of cosmic rays with target material in cosmic accelerators
- We can use neutrinos to look for cosmic-ray sources!





Neutrino Detection with IceCube

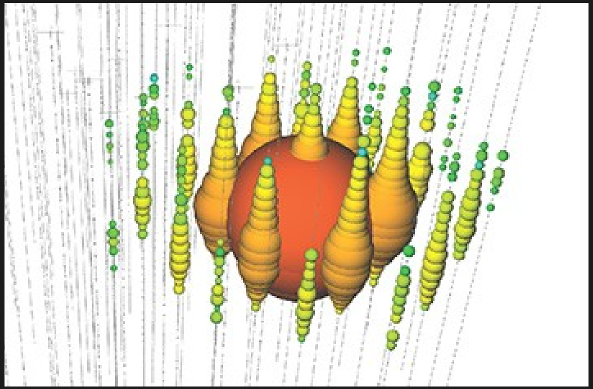
Track



ν_μ + N -> μ+X

Angular resolution ~ 0.5° @10TeV
Energy resolution ~ 29%

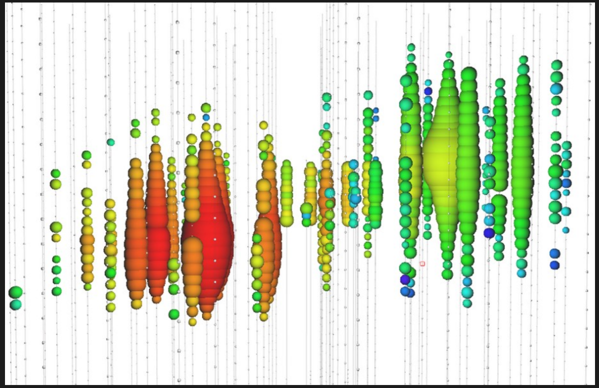
Cascade



ν_e + N -> e+X
ν_x + N -> ν_x+N

Angular resolution ~ 5°@ 50 TeV
Energy resolution ~ 15%

Double cascade

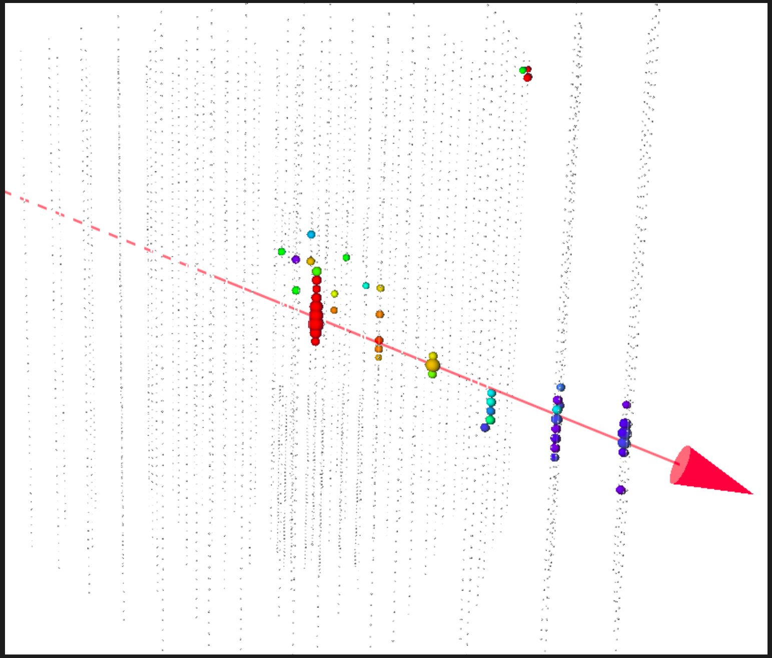


ν_τ + N -> τ+X
τ -> X or e

Decay length ~ 50 m E_τ/PeV

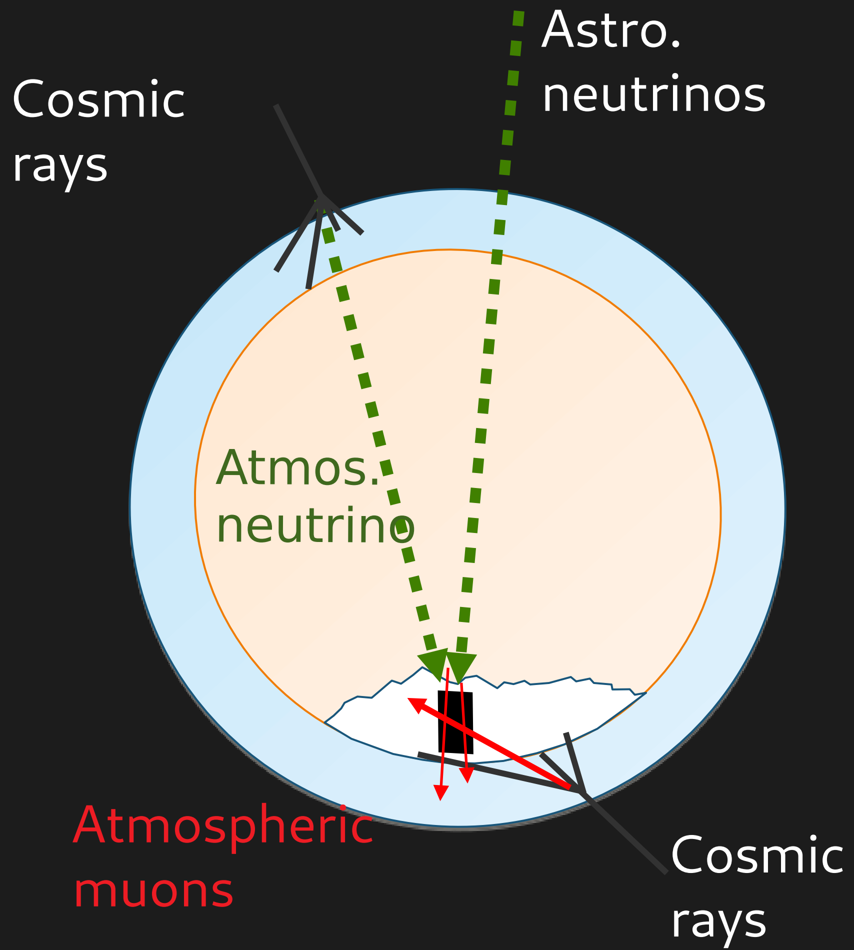
Special case: Starting Events

- Neutrino events with "contained vertices", starting inside the detector
- Called starting cascades/starting tracks
- Have good energy resolution due to the energy deposit of the initial hadronic cascade
- Can be used to distinguish neutrinos from atmospheric muons

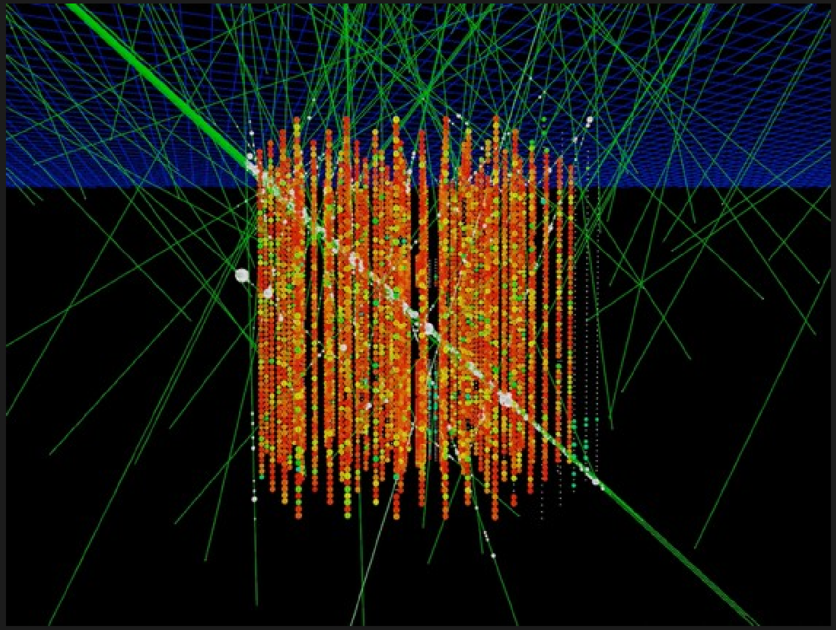


A starting track, E~11 TeV

What IceCube sees



3000 cosmic-ray muons in 1 second
1 atmospheric neutrino in a minute
1 astrophysical neutrino in a day



10 ms of IceCube data

Diffuse Astrophysical Neutrinos

Topics of Interest

1 Diffuse astrophysical flux of neutrinos

→ What is the relation between energy and number of neutrinos?

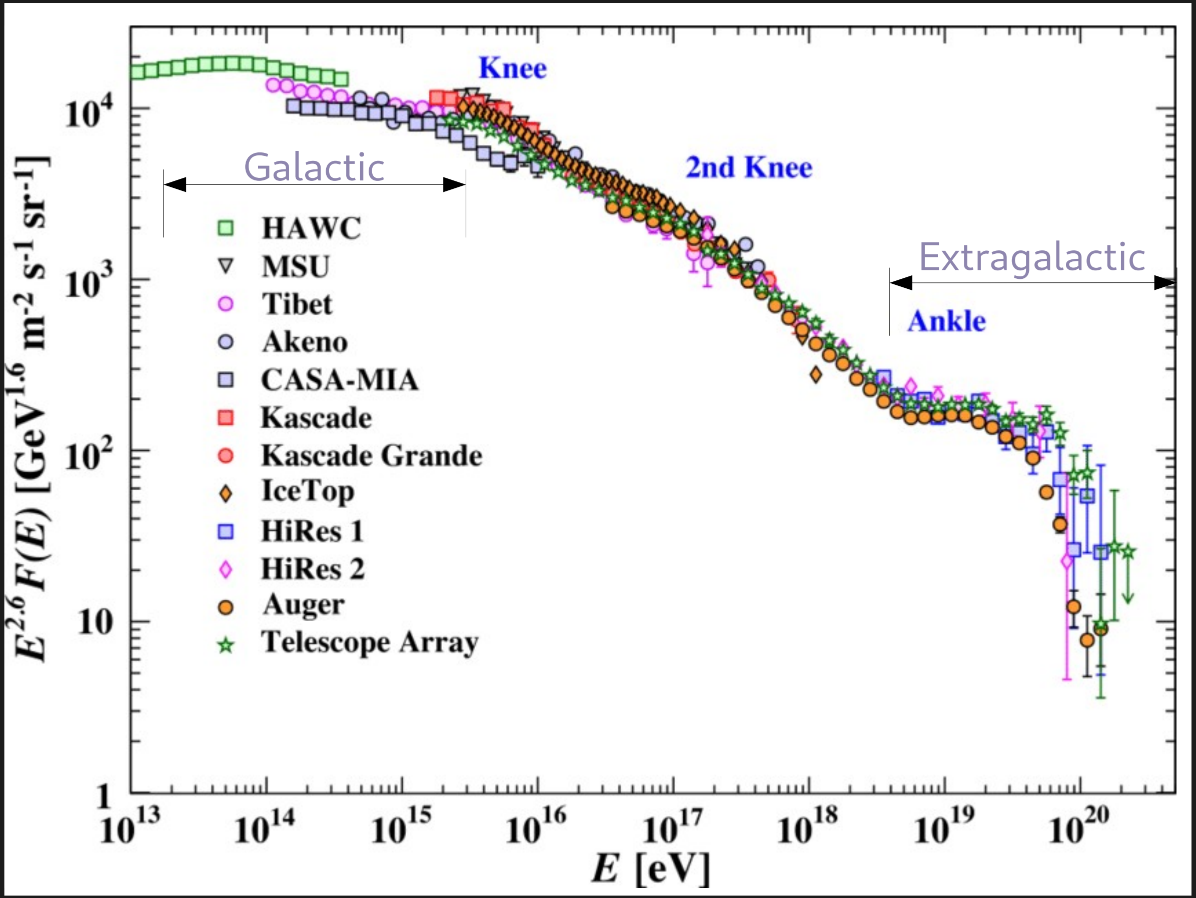
2 Flavor ratio of astrophysical neutrinos

→ How many neutrinos of each flavor exist?

Why diffuse flux?

Structures in the spectrum are related to contributions from different source populations

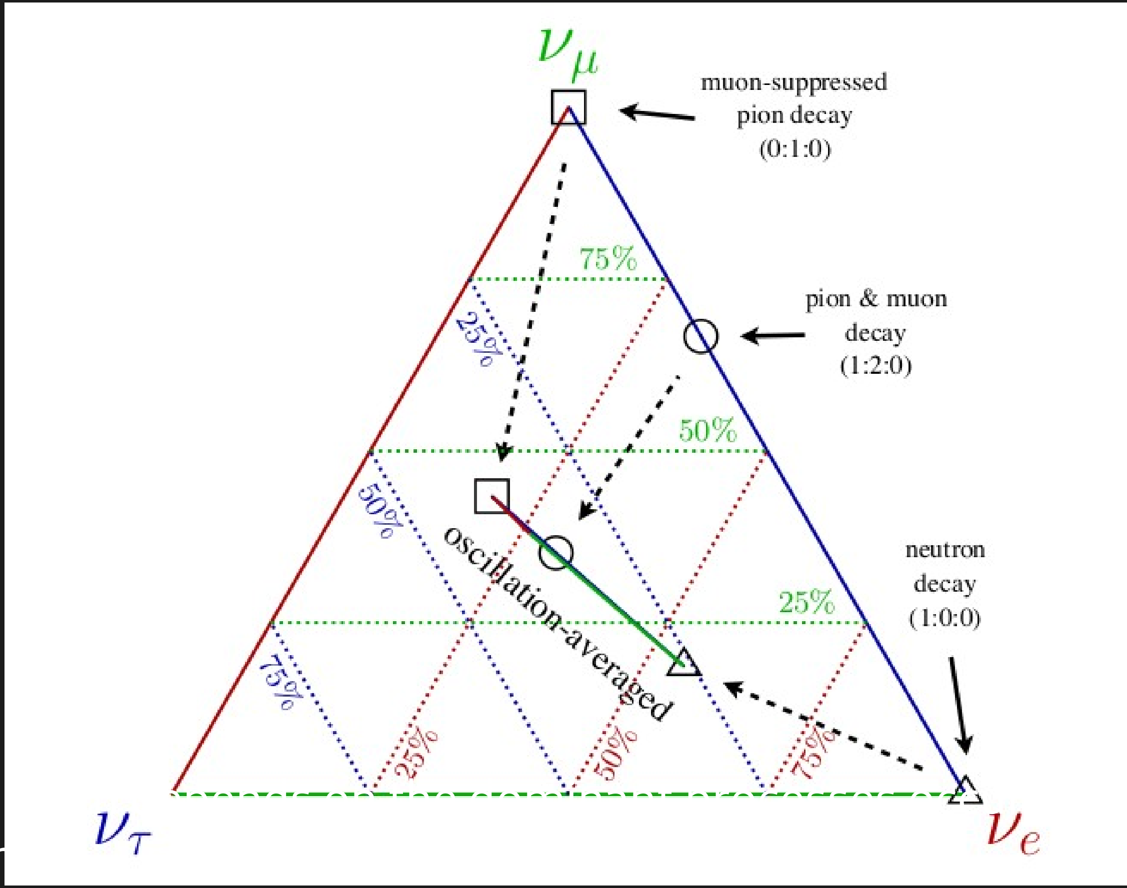
Ex: Flux of cosmic rays



Structures can also indicate changes in the dominant production processes in sources

Flavor ratio as a probe of source mechanisms

Diffuse astrophysical flavor ratio measured at Earth depends on the dominant processes occurring in cosmic sources (probe of source mechanism)



$$\pi^{(\pm)} \rightarrow \mu^{(\pm)} + \overset{(-)}{\nu}_\mu$$

$$\pi^{(\pm)} \rightarrow \mu^{(\pm)} + \overset{(-)}{\nu}_\mu$$
$$\mu^{(\pm)} \rightarrow e^{(\pm)} + \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

l at
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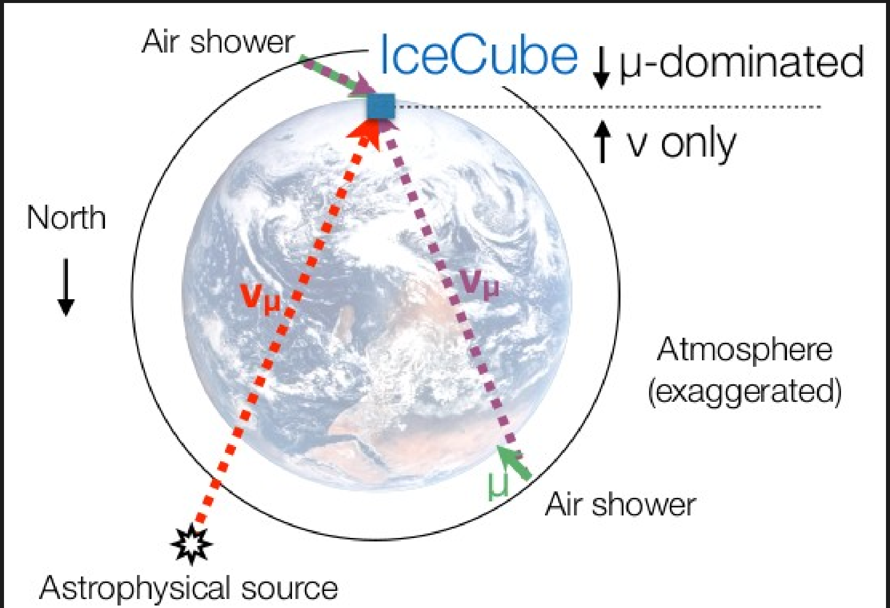
Flavor ratio is also a probe of new physics!

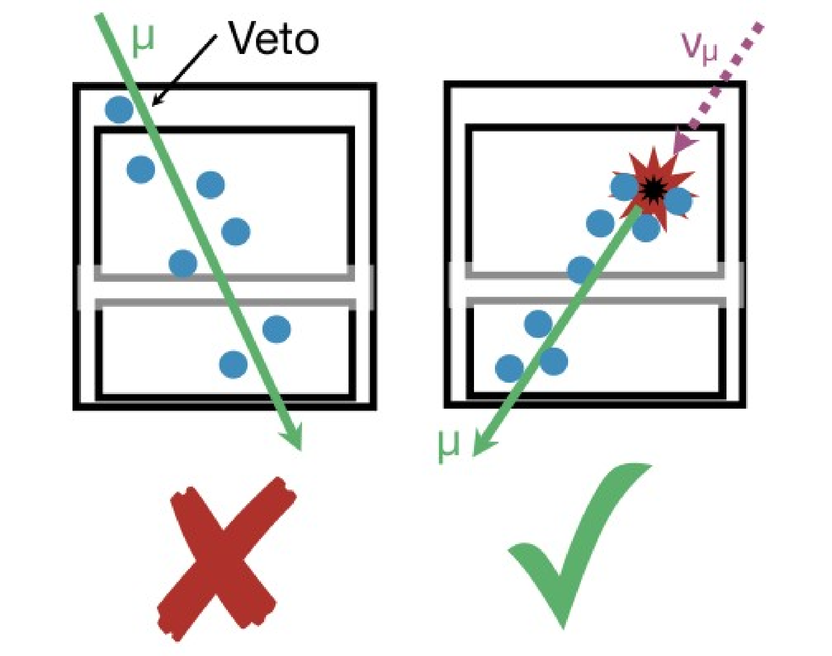
Selection Strategies

"Upgoing tracks"



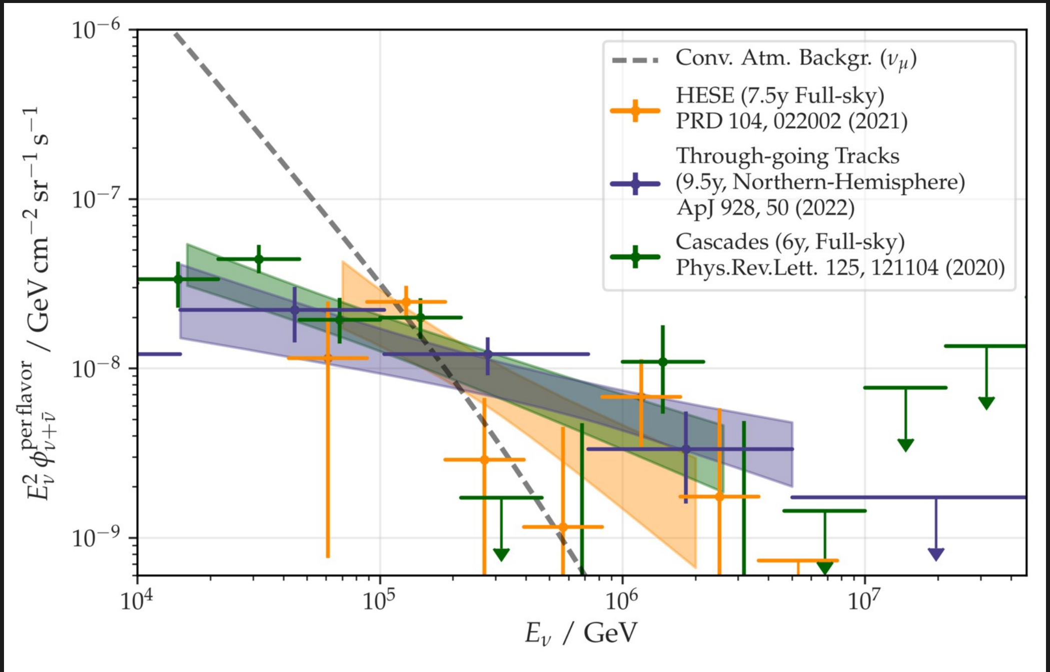
Use the Earth as a shield against muons
Large effective volume
Only ν_μ, only Northern sky

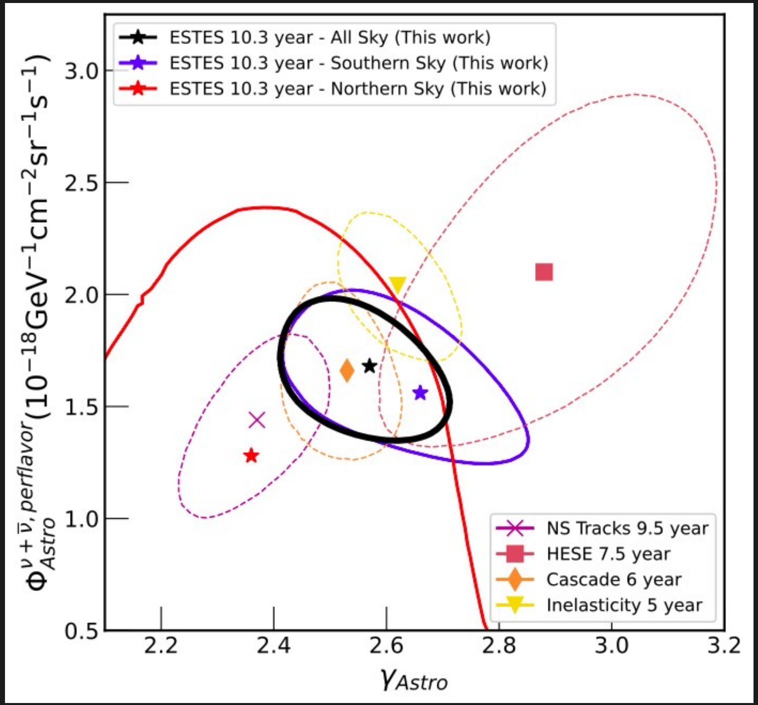
"Fiducial veto"



Use outer detector layers to separate muons
Effective volume smaller than the detector
All flavours, all sky

Spectral shape IceCube saw for a decade



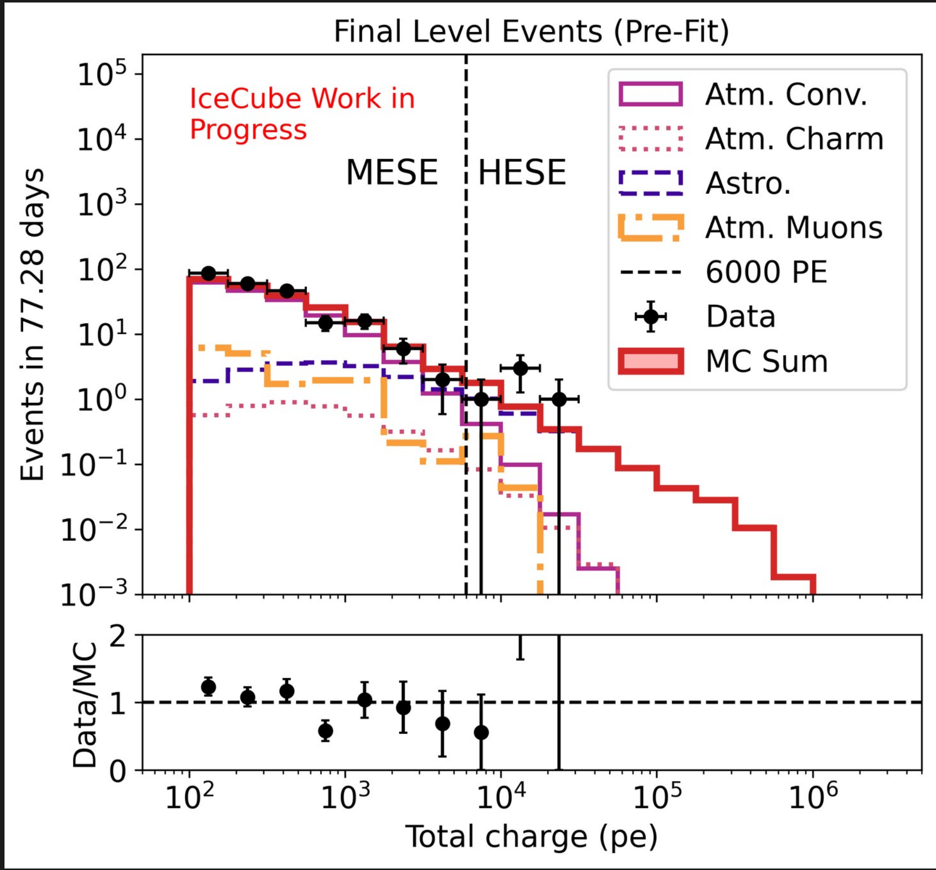


All measurements done until 2022 consistent with single power law model from a few TeV to several PeV

Phys. Rev. D 110, 022001 (2024)

Medium Energy Starting Events (MESE)

- Dataset built selecting starting events with 1 TeV and above energy, extending the concept of HESE to lower energies
- Series of vetoes to reduce the muon background
- Cascades and tracks discriminated with a DNN

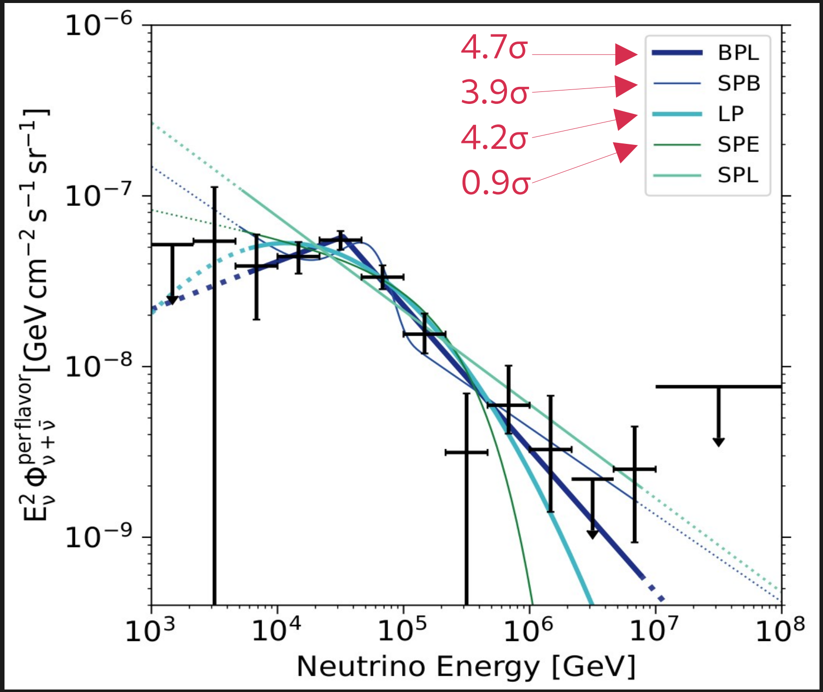


Burn sample

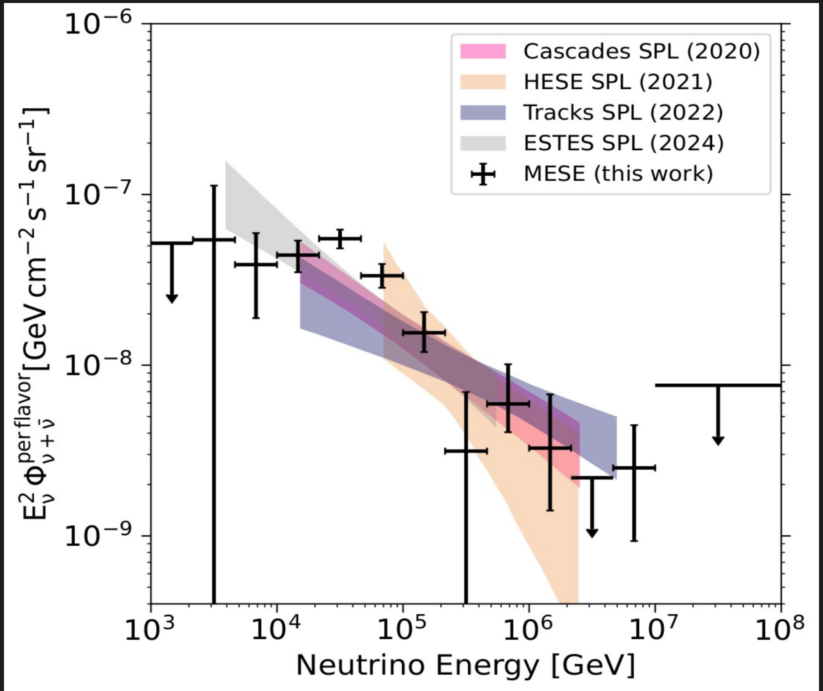
Work with V. Basu (student supervision)

Diffuse astrophysical neutrino spectrum

[IceCube paper submitted to PRD]



Fits of tested spectral models. Broken power law is prefered the most (4.7 σ wrt SPL)

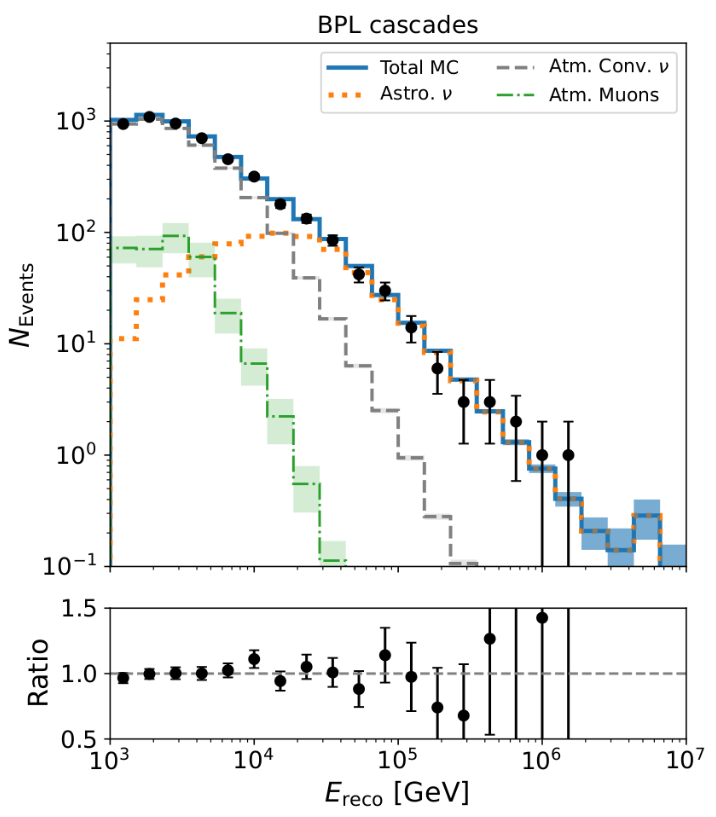


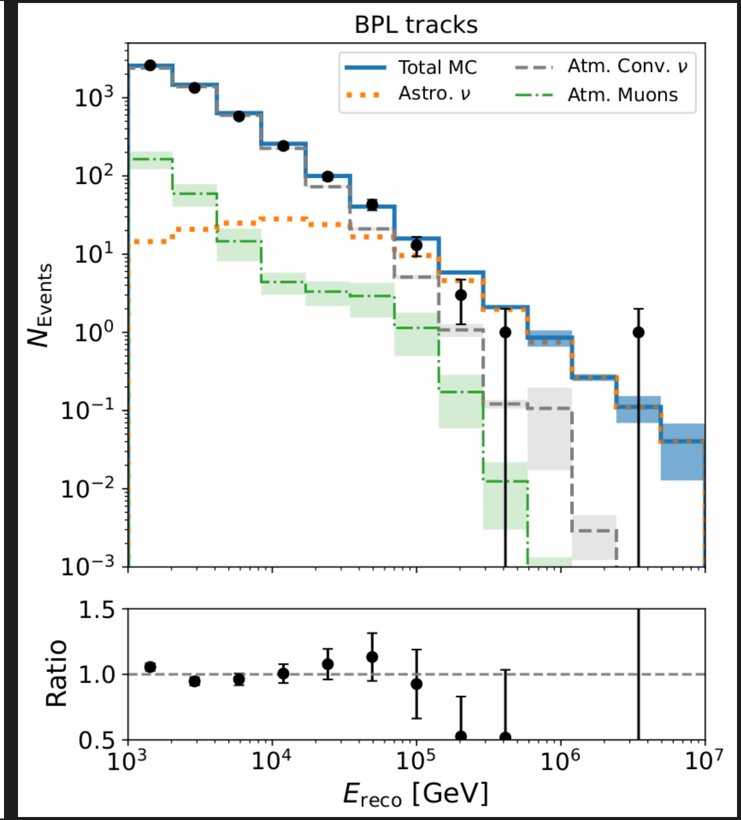
Segmented spectral fit of MESE compared to previous IC measurements

MESE Data/MC Comparison

Best fit astro. flux of 2.27 x $\begin{cases} (E/33.1\mathrm{TeV})^{-1.72}, & E< 33.1 \mathrm{~TeV} \\ (E/33.1\mathrm{TeV})^{-2.84}, & E> 33.1 \mathrm{~TeV} \end{cases}$

Atm. Flux model: GaisserH4a + Sibyll 2.3c

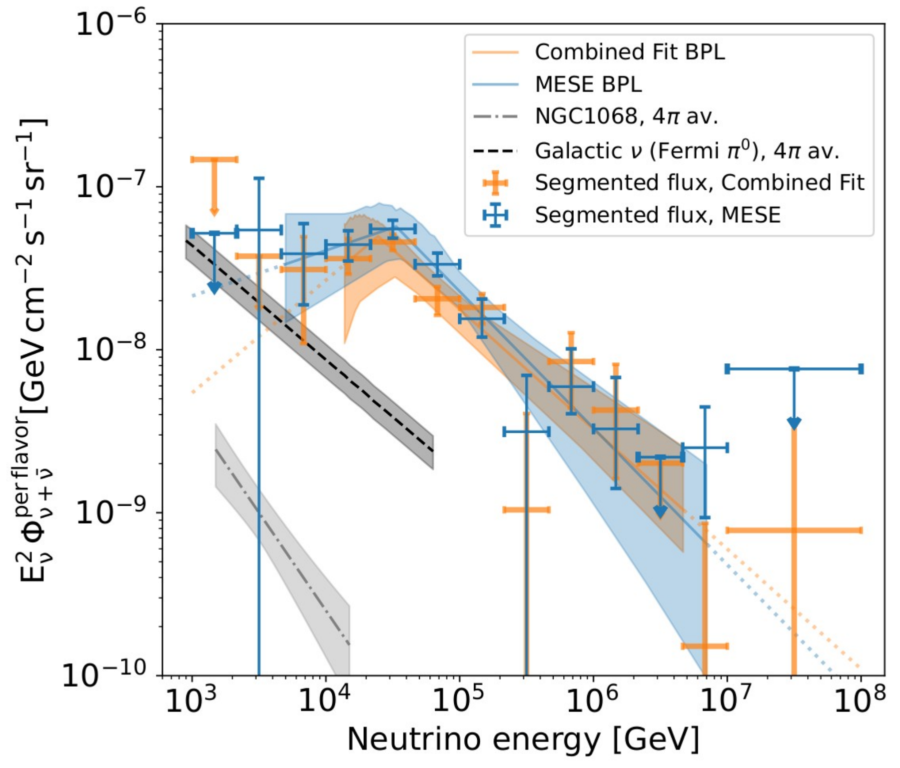




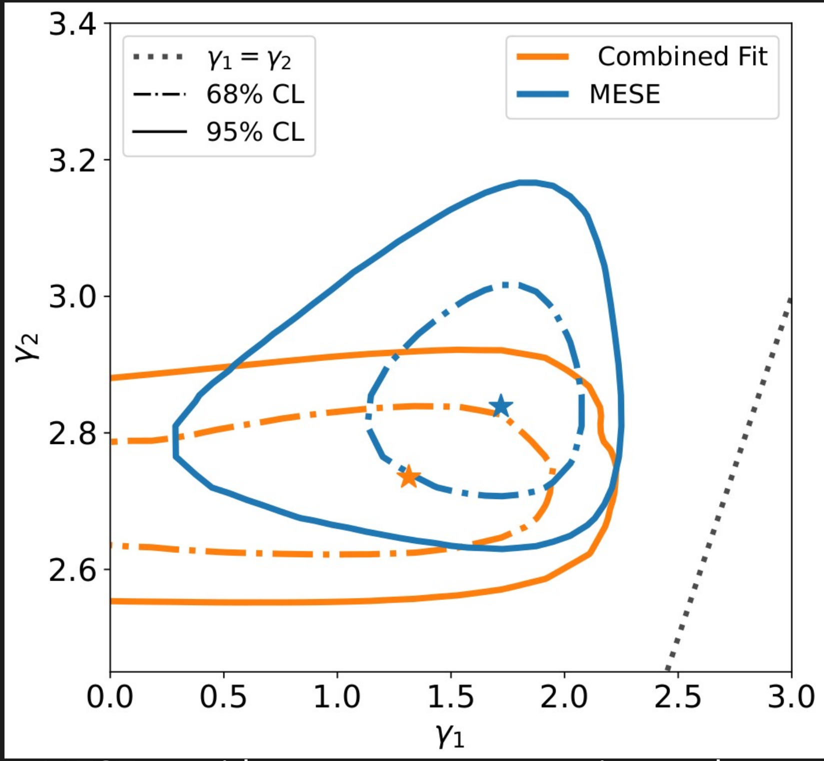
Observed
4968 cascades
and
4920 tracks

Spectral Break/Curvature Seen in Two Measurements!

Combined Fit with cascades and upgoing tracks datasets also measures a break with 4.4σ



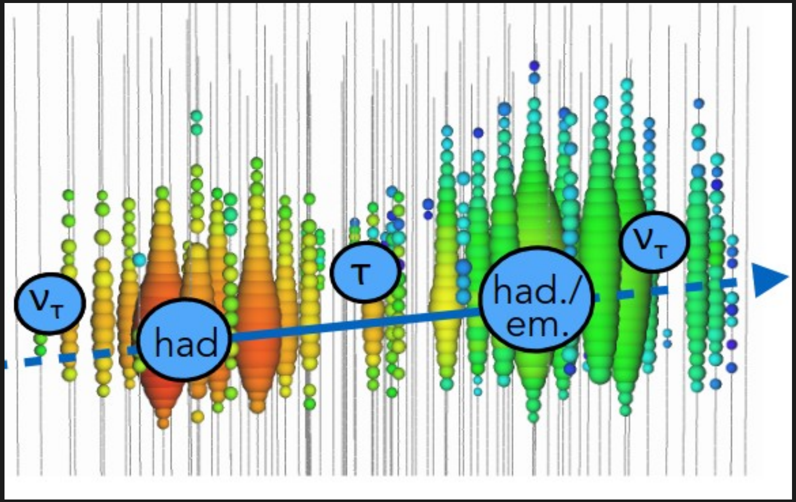
[A. Balagopal V., V. Basu, E. Ganster, R. Naab]
[IceCube paper accepted at PRL]



MESE provides a stronger constraint on the lower energy spectral index while Combined Fit provides a stronger constraint on the higher energy index

What about tau neutrinos in MESE?

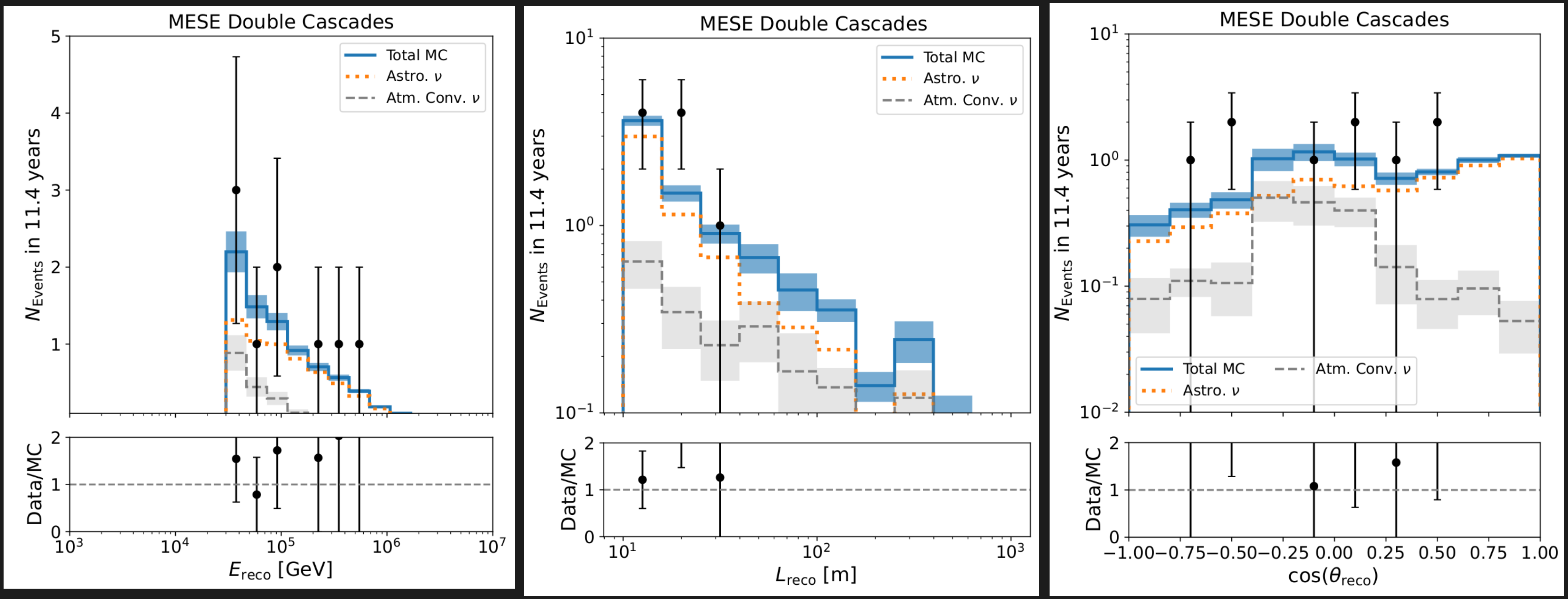
- Dataset has neutrinos of all flavors. So additional tau tagging (along with the cascades/tracks classification) can help in making a 3-flavor measurement
- We do additional likelihood-based classification (taupede) of double cascade events



Likelihood-based approach that selects double-cascade events

Data/MC distributions

- Double cascades observables: energy, zenith, tau-decay length
- Cascades & tracks observables: energy, zenith (not shown here)

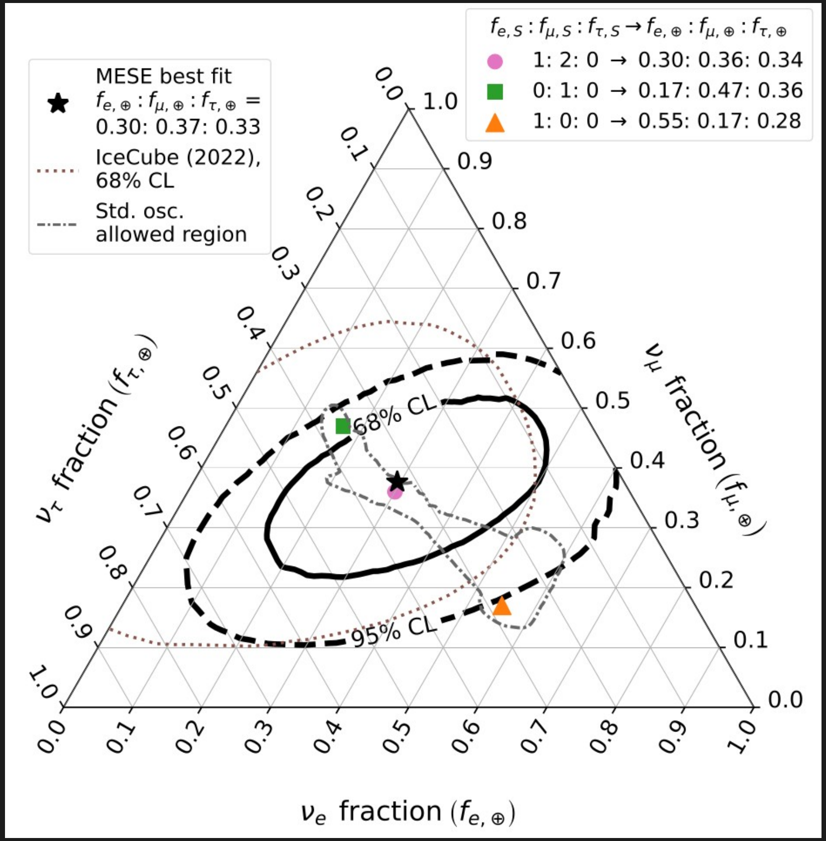


Data count: 4960 cascades, 4919 tracks and 9 double cascades

Astrophysical Flavour Ratio

- BPL assumed as the flux model for the measurement of the flavor ratio
- Best fit close to pion decay scenario
- Best fit consistent with standard theory of oscillations

With 11.4 years of data, IceCube obtains a closed 1σ contour for the first time!



[A. Balagopal V.]

[IceCube paper submitted to PRL]

Comparison of BPL and SPL fits

BPL fit:

φ_{astro} 2.72

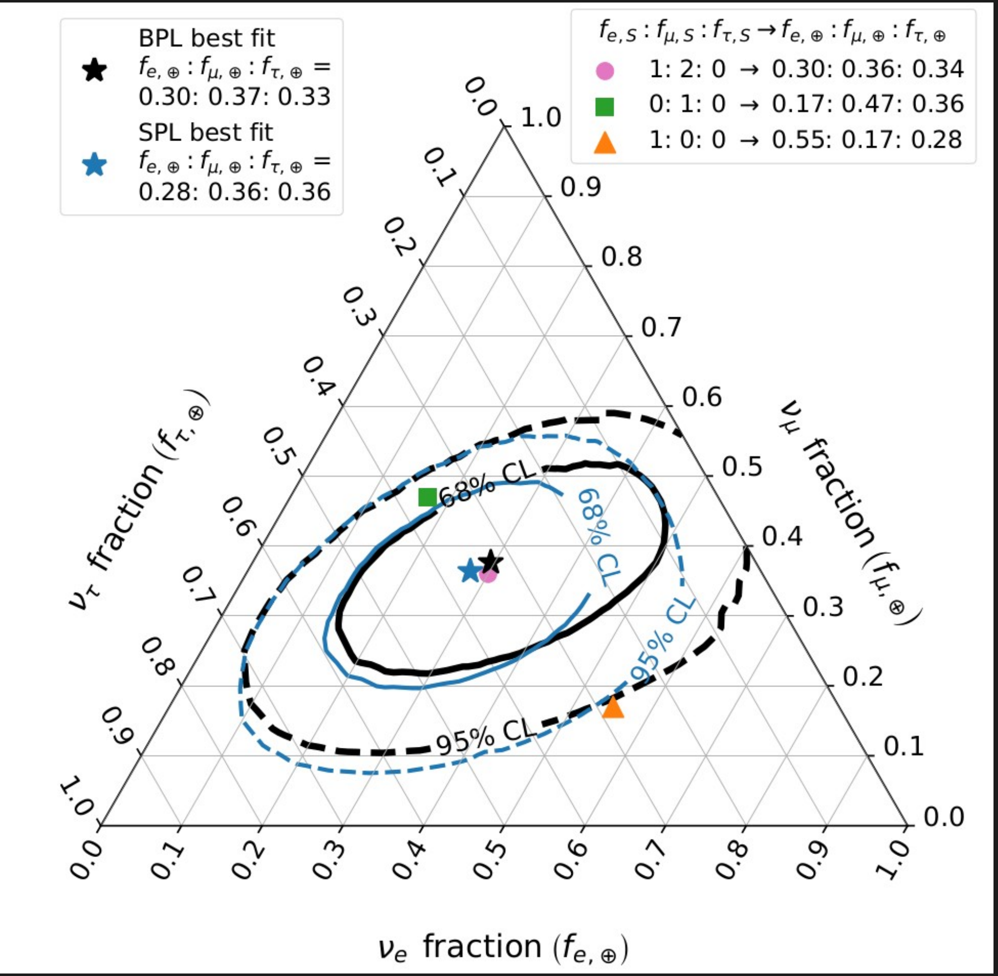
γ1: 1.75, γ2: 2.81

SPL fit:

φ_{astro} 2.55

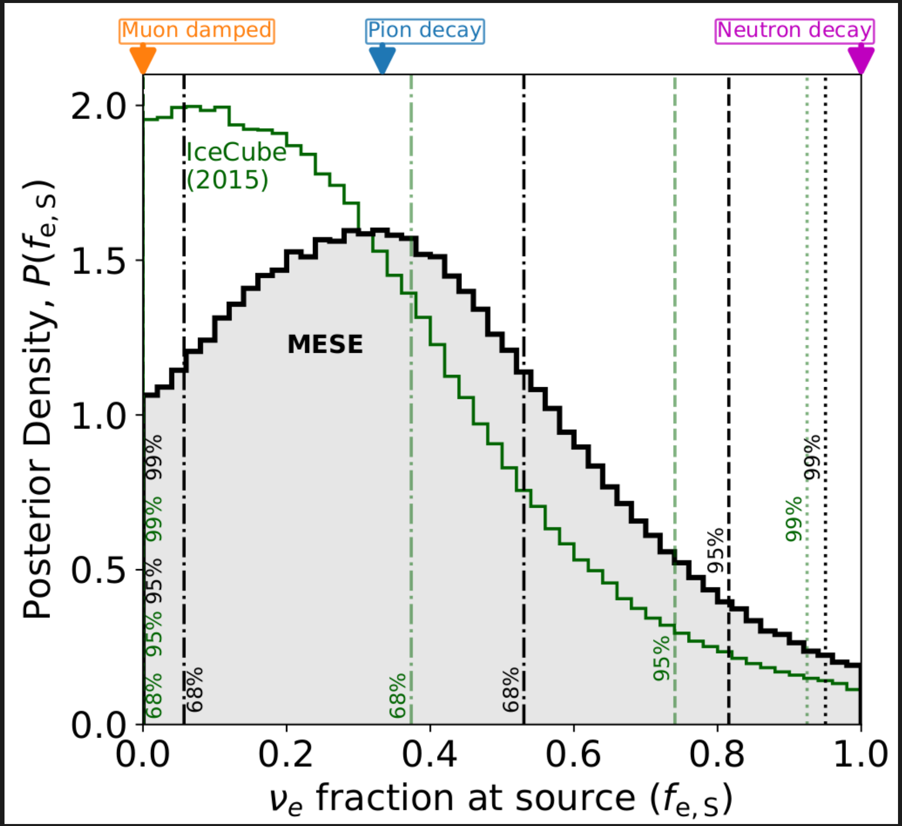
γ: 2.54

Softer index at high energies for BPL responsible for the non-closure of the 95% contour



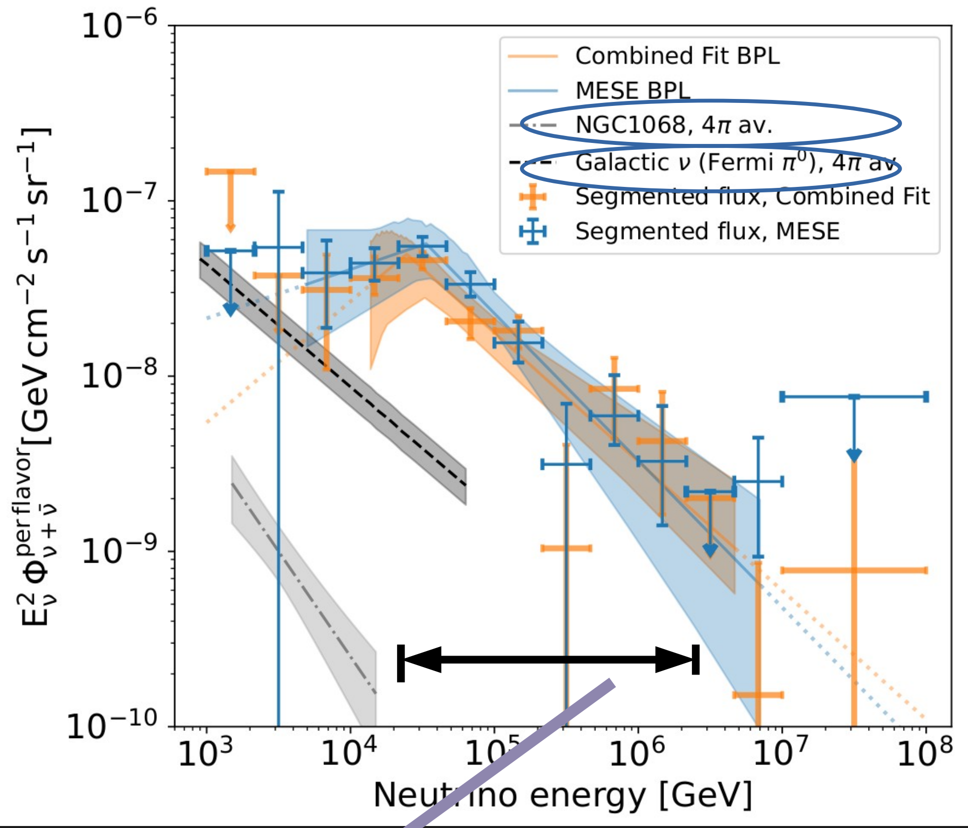
Flavor composition at astrophysical sources

- Inferred by including information of neutrino mixing parameters
- Assuming no tau neutrinos at production
- Neutron decay scenario rejected with > 99% confidence!



Searches for Sources of Neutrinos

Where are the sources?



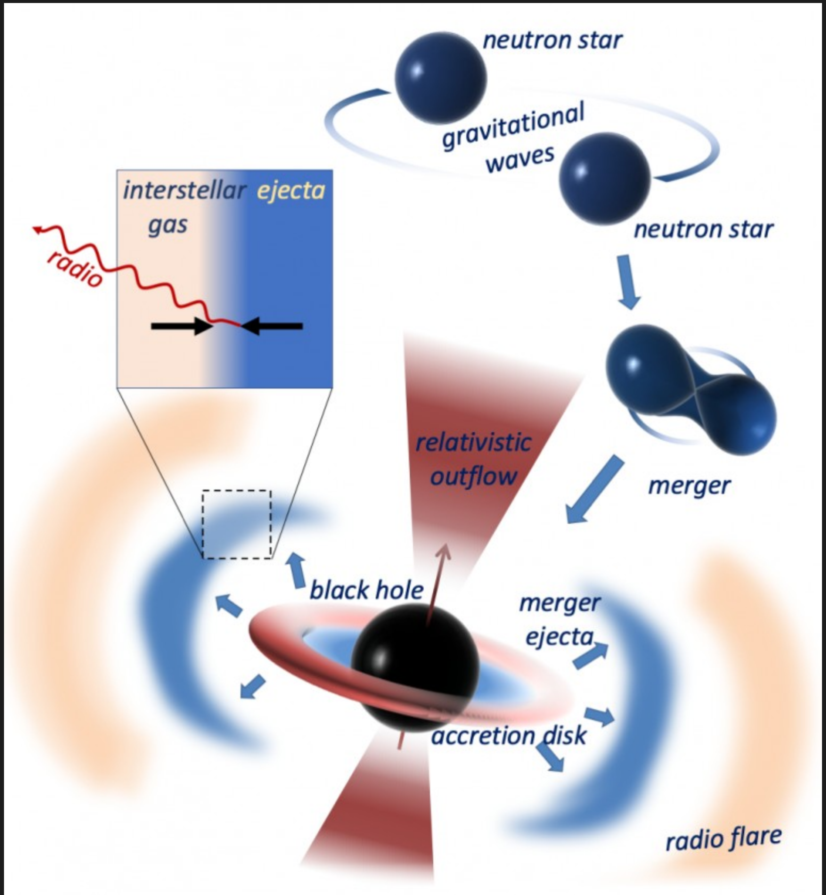
Three known sources, but cannot explain the bulk of the observed neutrino flux

So the search continues…

TXS 0506+056 approx. here

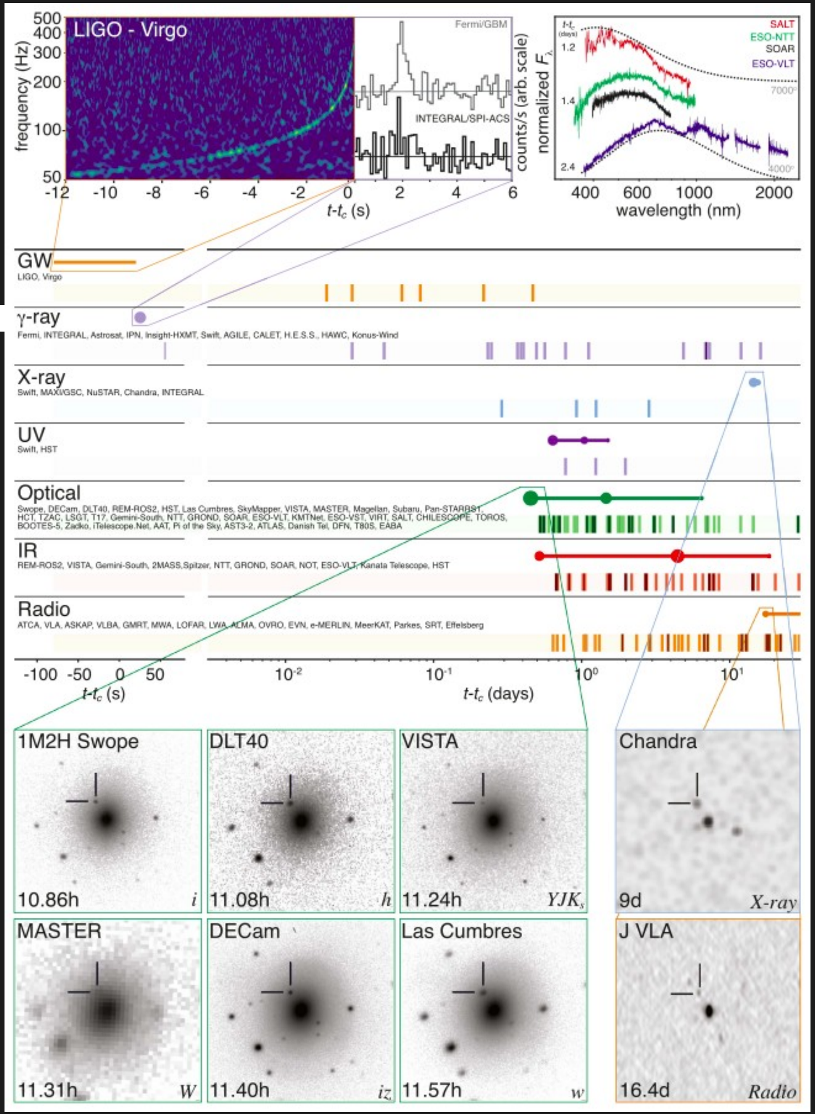
Binary mergers and neutrinos

- Several predictions for the production of neutrinos from binary mergers
- Mainly from BNS and NSBH mergers
- Focus on GW170817 to understand such systems



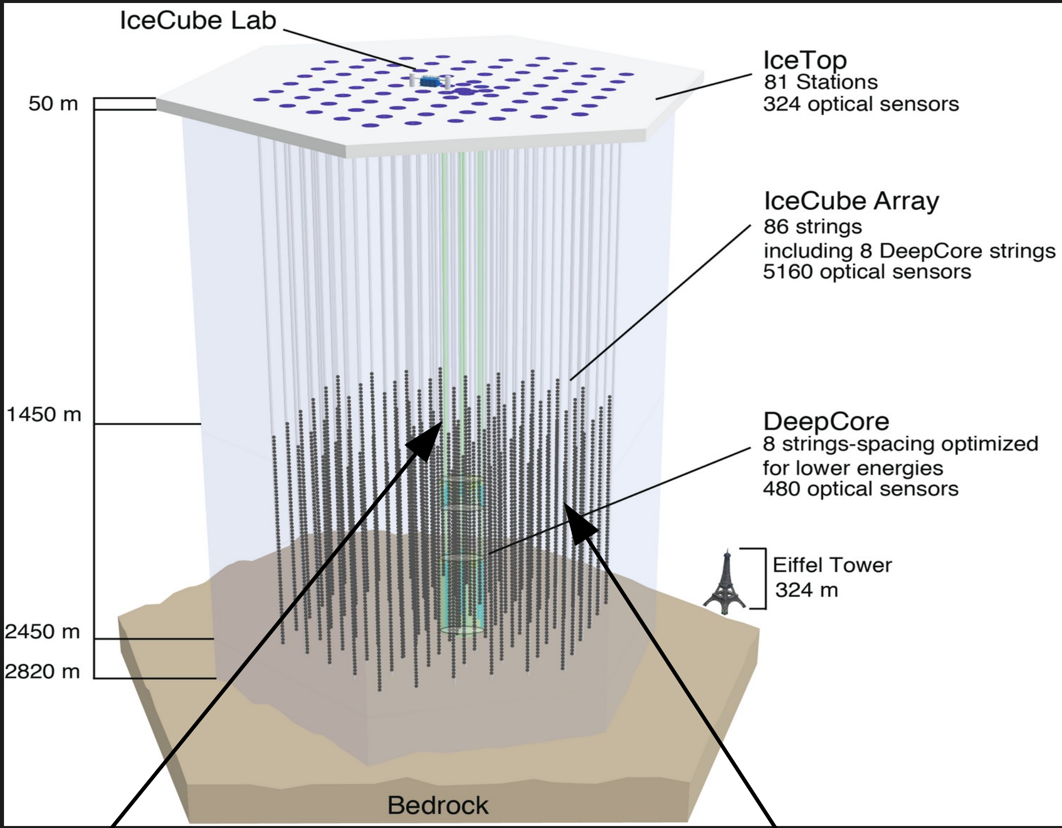
GW170817

- GW event/GRB that was observed by several EM telescopes
- Identified as a kilonova
- Originating from host galaxy NGC 4993
- Neutrino searches done by IceCube, ANTARES, Pierre Auger Observatory
- No neutrinos were found



GW events and neutrinos

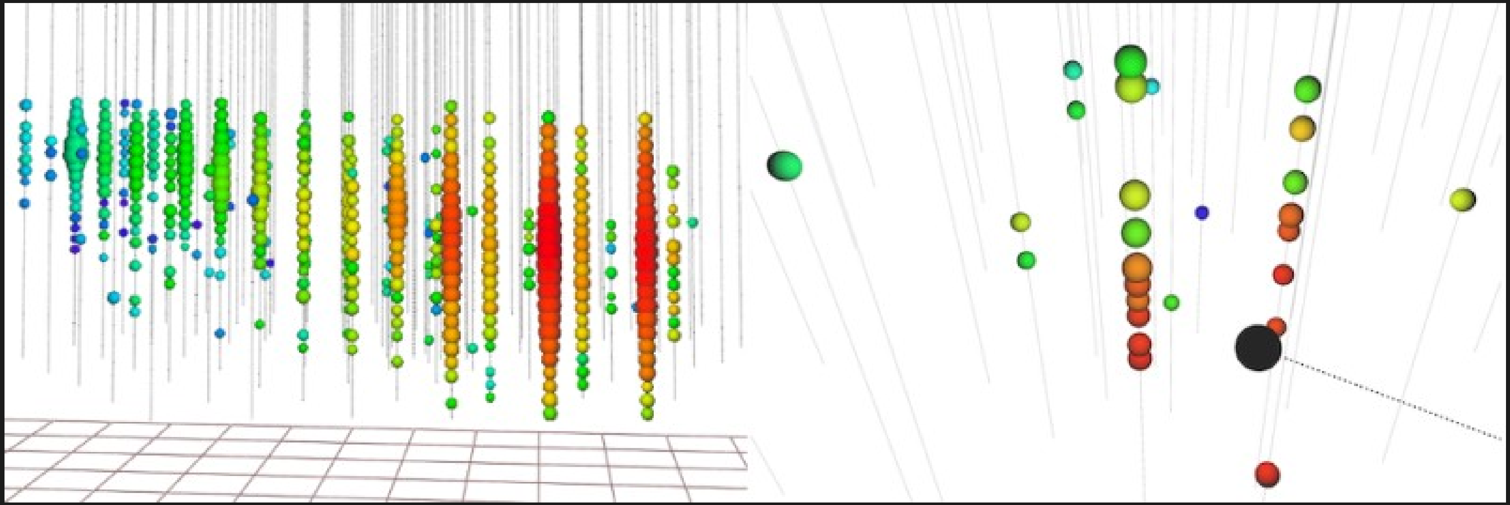
- We search for neutrino events detected by IceCube as possible conterparts to GW events detected by LIGO-Virgo
- Searches done in the high energy (> 1 TeV), low energy (<1 TeV) regime
- Search for neutinos within ±500 s wrt GW event



DeepCore to detect low energy neutrinos

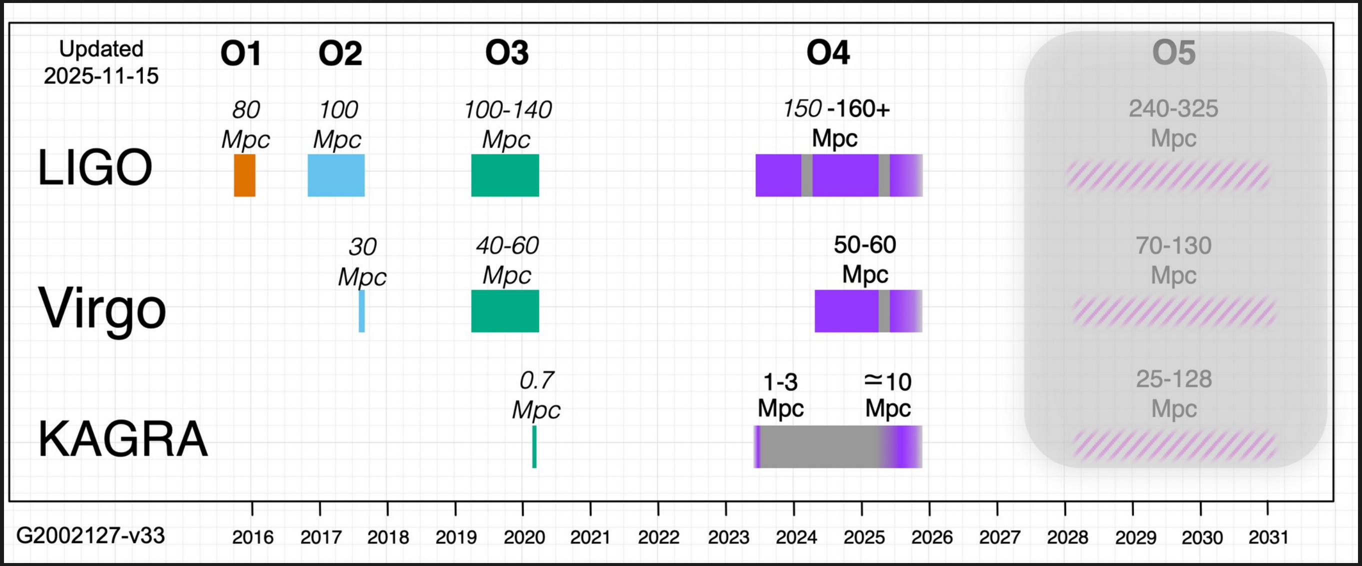
High energy neutrinos from the whole detector

Event Signatures in IceCube & DeepCore



A 290 TeV event compared to a 25 GeV event

GW events from LIGO/Virgo/Kagra



GWTC-1 catalog

GWTC-2.1, GWTC-3 catalogs Realtime alerts from LVK

Realtime alerts from LVK

[Source: LVK]

Catalog search with IceCube

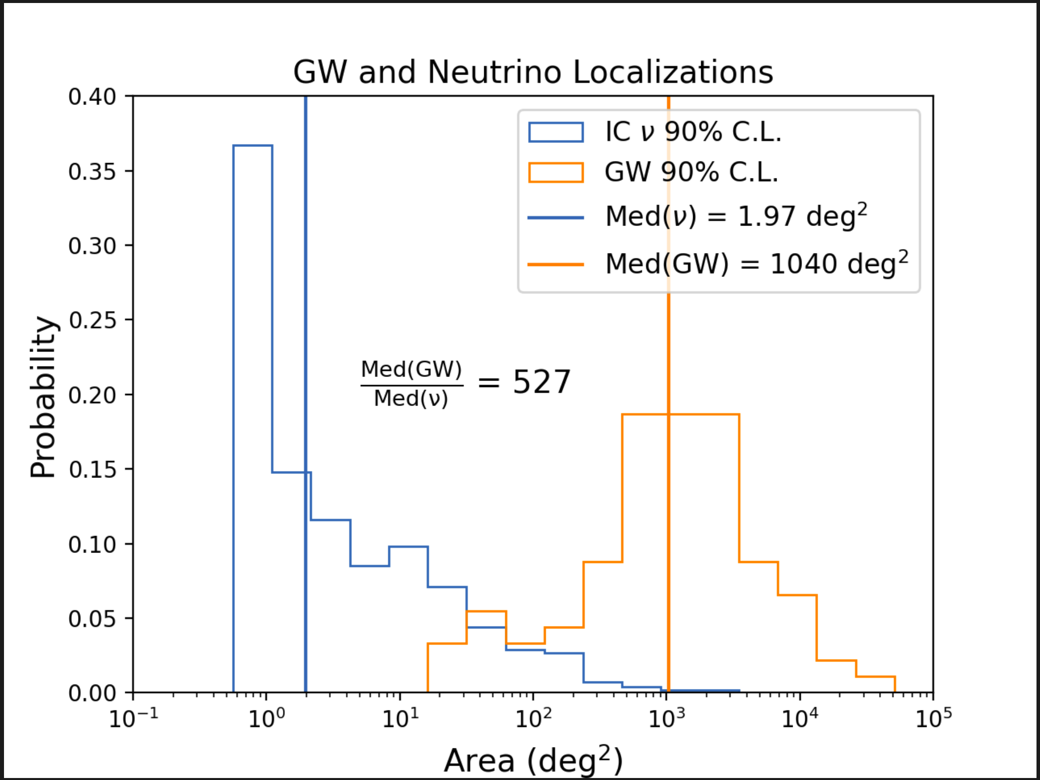
Catalog and realtime searches with IceCube

Realtime search with IceCube

*Realtime follow-up is done only with high energy neutrinos

GW & neutrino localizations

- Area of GW probabilities in sky is large
- High-energy neutrinos (shown here) have much smaller area in sky
- Low-energy neutrinos have similar areas compared to GW areas

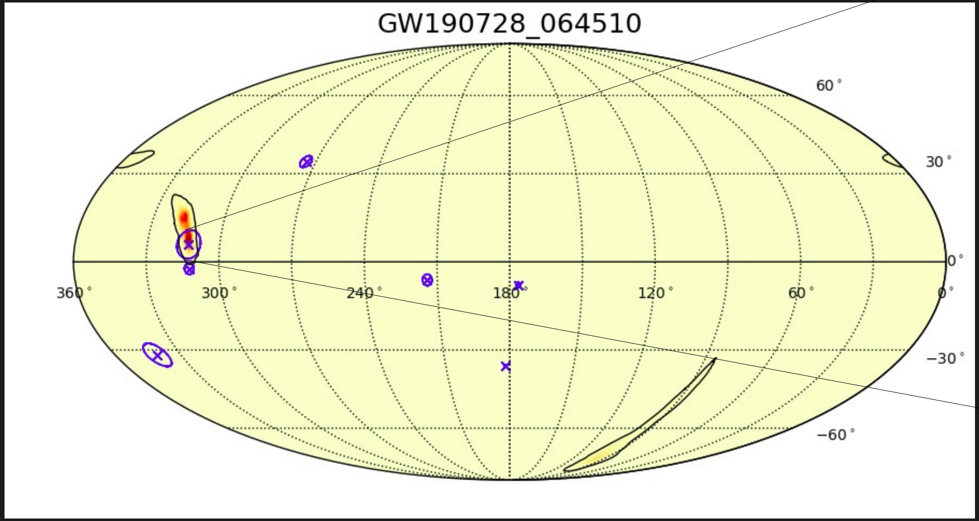


[R. Abbasi et al 2023 ApJ 944 80]

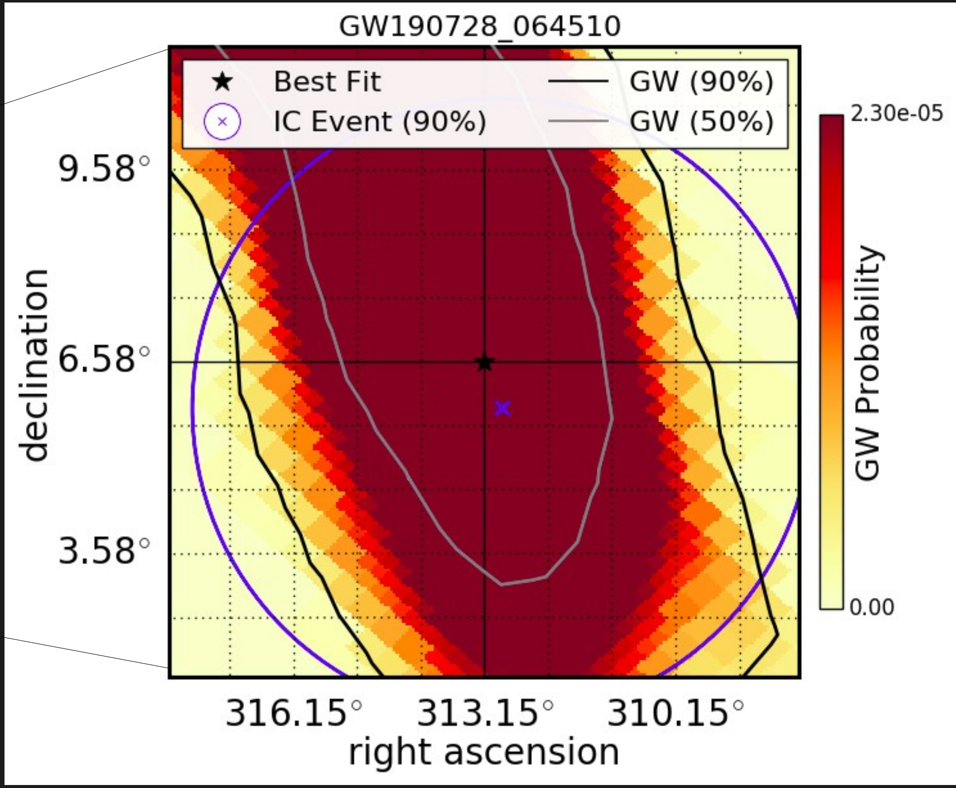
An example event: High Energy Analysis (realtime)

- Neutrino arrived 360 s before the GW merger
- Had a reconstructed energy of 601 GeV
- No counterparts found from other observatories
- pre-trial p-value for this event: 0.04

[A. Balagopal V., R. Hussain]



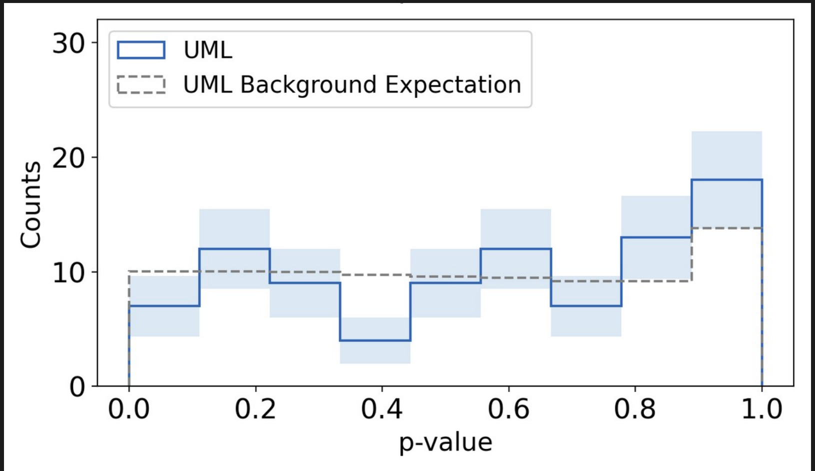
7 neutrinos within ±500 seconds



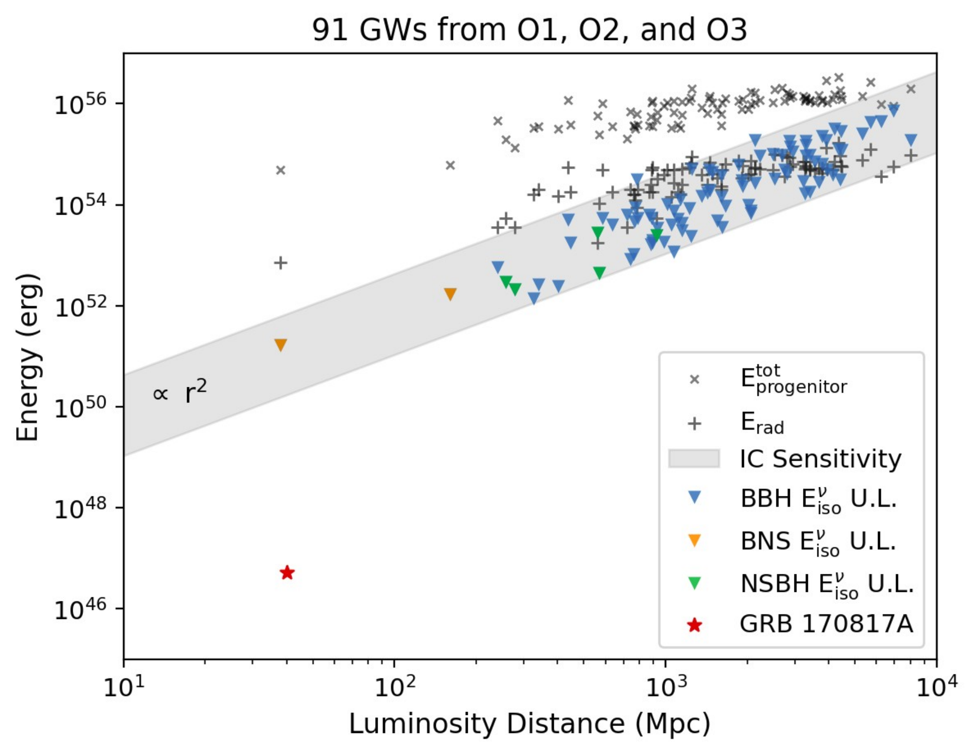
[R. Abbasi et al 2023 ApJ 944 80]

Results: High Energy Analysis (catalog search)

91 GWs from O1,O2,O3



No significant neutrino emission was seen in GWTC-1, GWTC-2.1 and GWTC-3



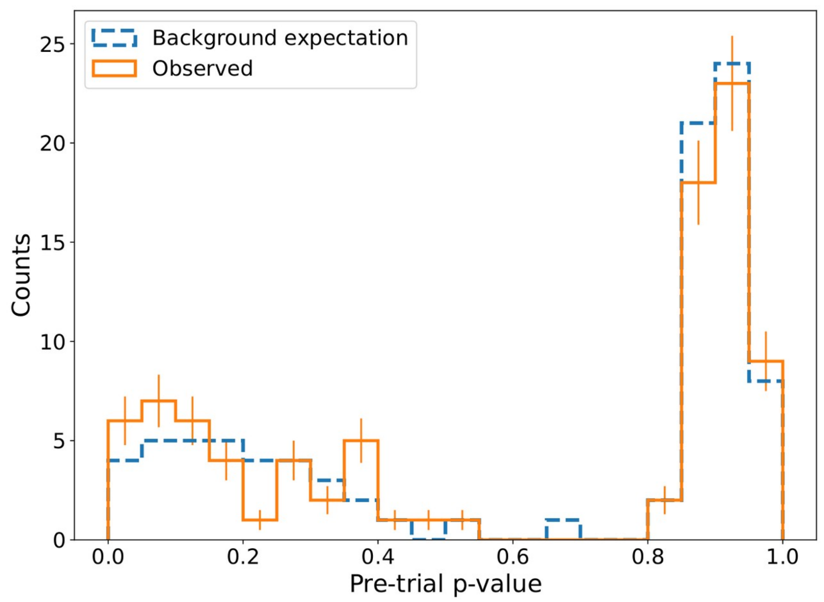
90% UL on the isotropic equivalent energy emitted in high-energy muon neutrinos

[A. Balagopal V., R. Hussain]

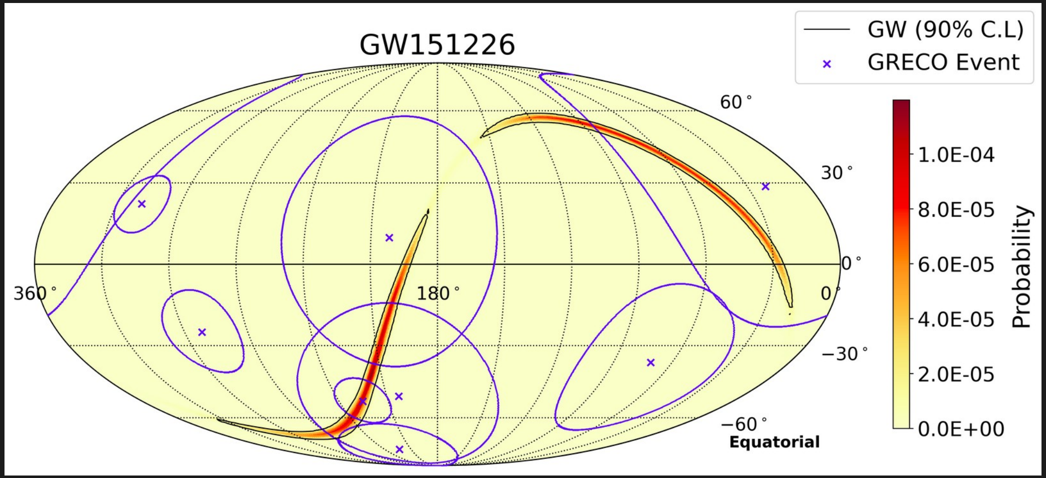
[R. Abbasi et al 2023 ApJ 944 80]

Results: Low Energy Analysis (catalog search)

No significant emission was found



90 GW events from O1, O2, O3

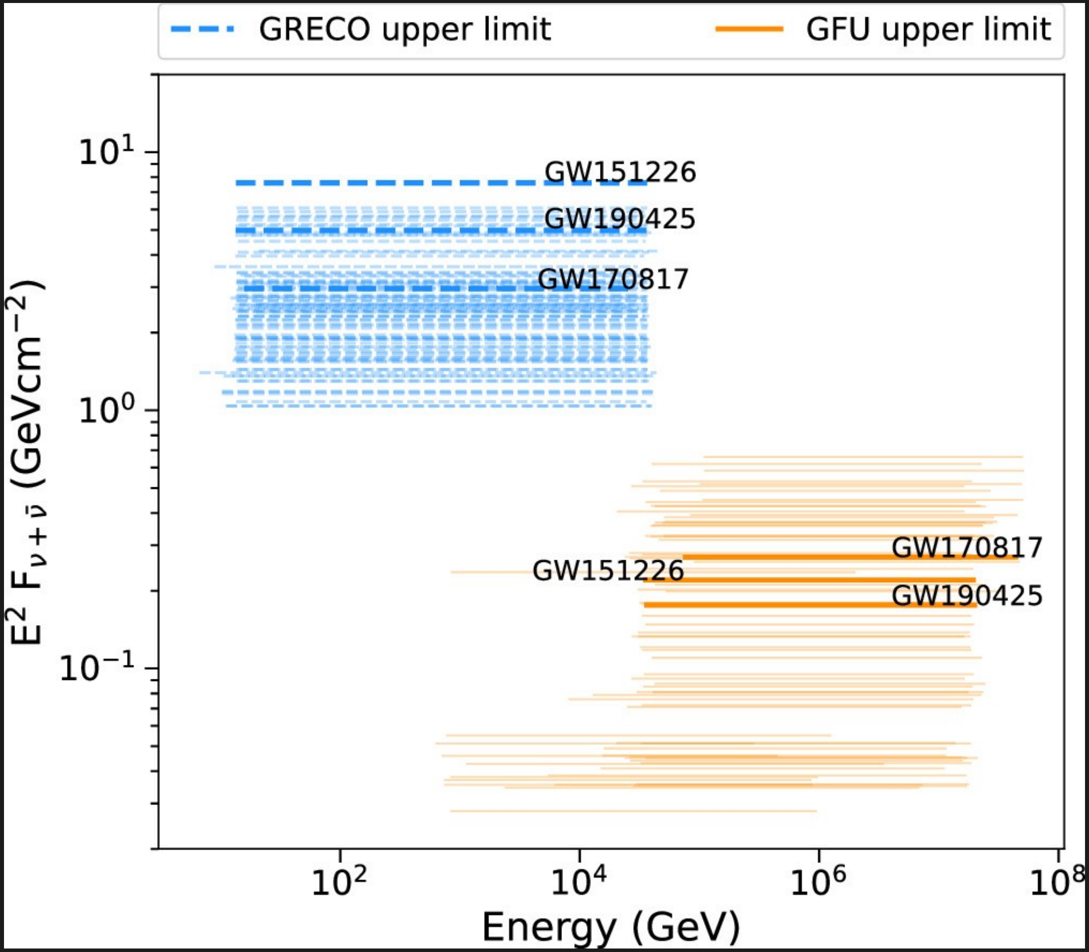


Event with lowest pre-trial p-value of 0.008
(out of 90 GW events)

[R. Abbasi et al 2023 ApJ 959 96]

[A. Balagopal V.]

Flux upper limits (high & low-energy)



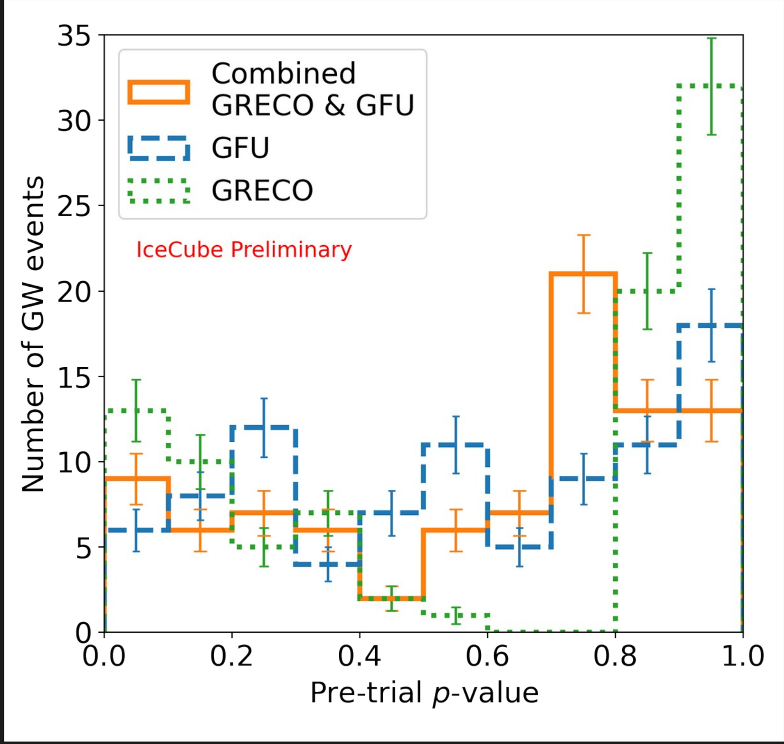
[A. Balagopal V.]

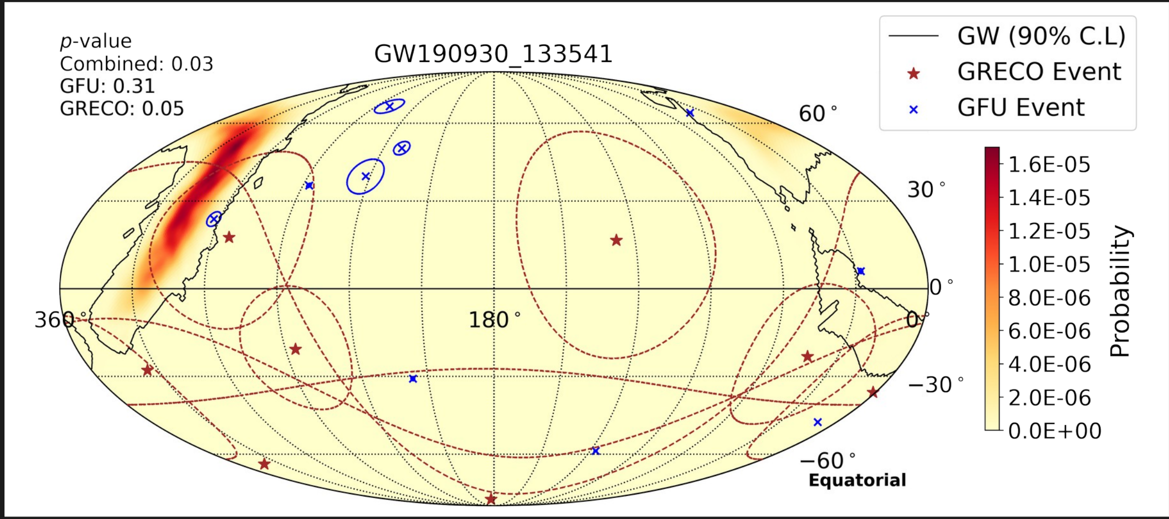
- Upper limits assuming spectral index=2
- GW151226: event with the lowest pre-trial p-value in low-energy
- GW190425: only BNS event with pre-trial p-value < 0.1
- GW170817: first observed BNS event with associated gamma-ray emission

[R. Abbasi et al 2023 ApJ 959 96]

Combined low & high energy searches

- Motivated by individual searches, found some events with p-value < 0.1 in both searches
- Joint-likelihood search with both neutrino data samples, fixed spectral index of 2.5
- No significant detection

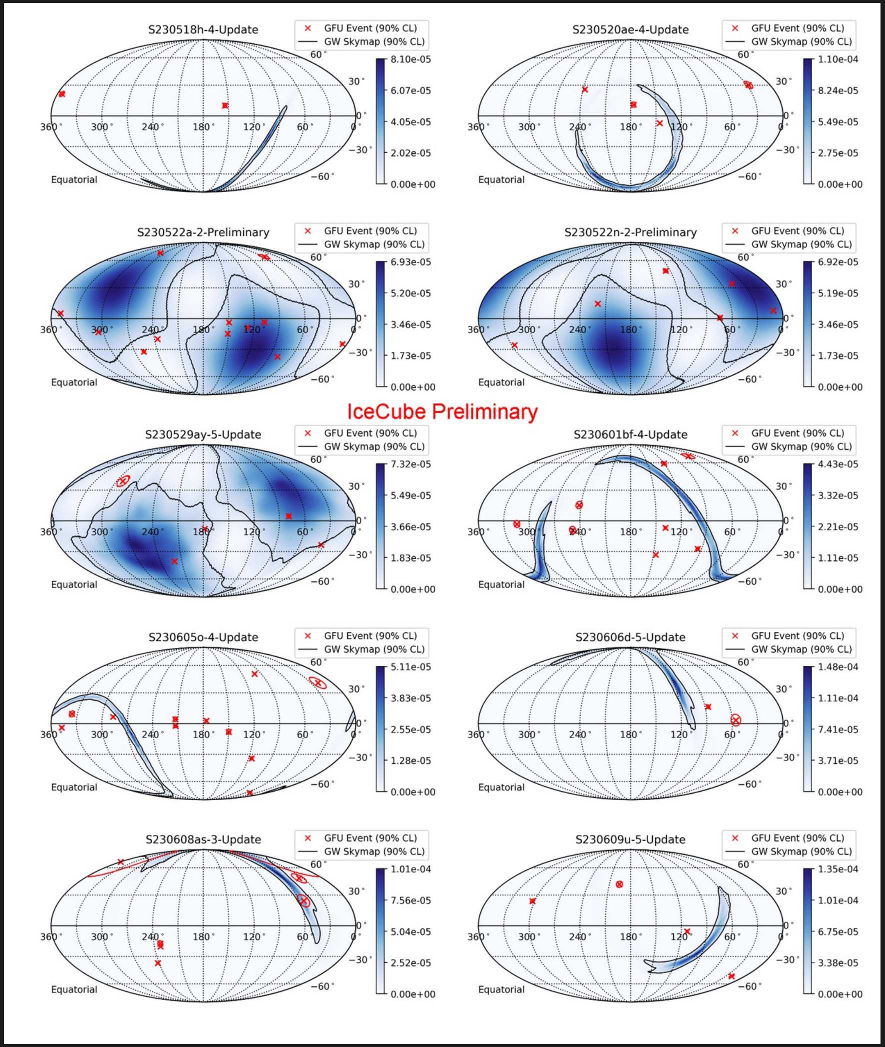




[A. Balagopal V.]

Paper under preparation

GW events in the O4 run (realtime)



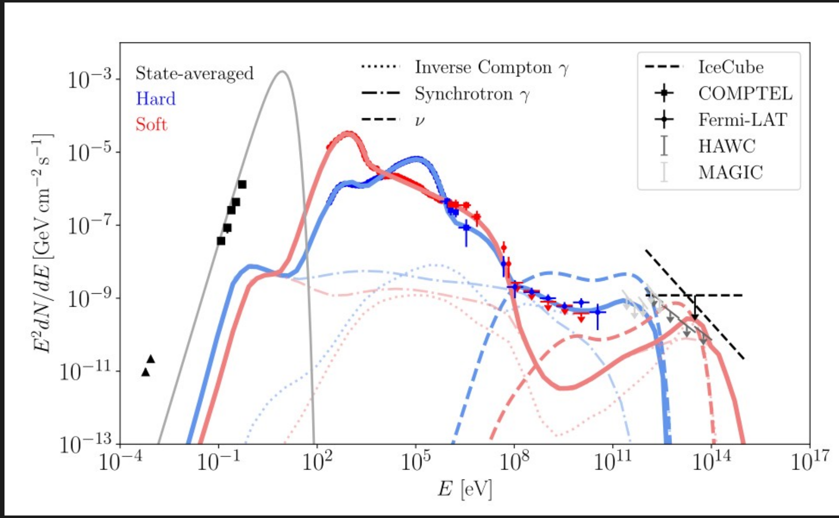
- IceCube sends GCN notices of each follow-up
- In case of detection with p-value < 0.01, will also release neutrino information
- Improves localization information for EM follow-up

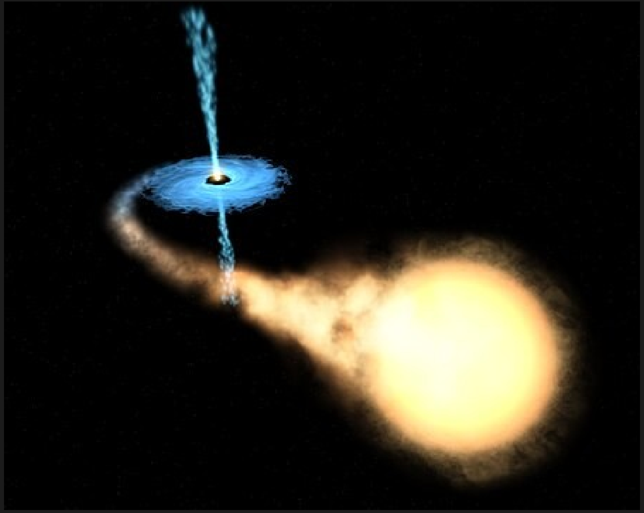
J. Thwaites
(student supervision)

Future Focus

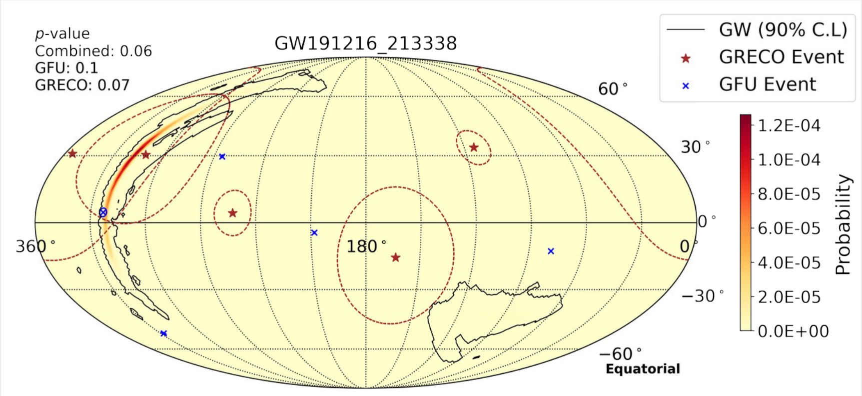
Continuing the search for sources

- Identification of Galactic sources using low-energy neutrinos
- Gamma-ray and X-ray emitting binaries (microquasars, pulsars) are good candidates
- Currently developing a multi-messenger search with such systems
- Fermi-LAT and VERITAS gamma-rays, SWIFT X-rays, GeV-TeV scale IC neutrinos

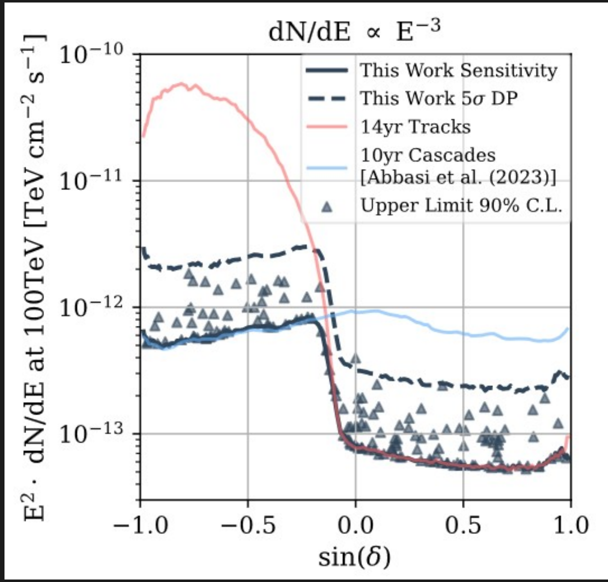




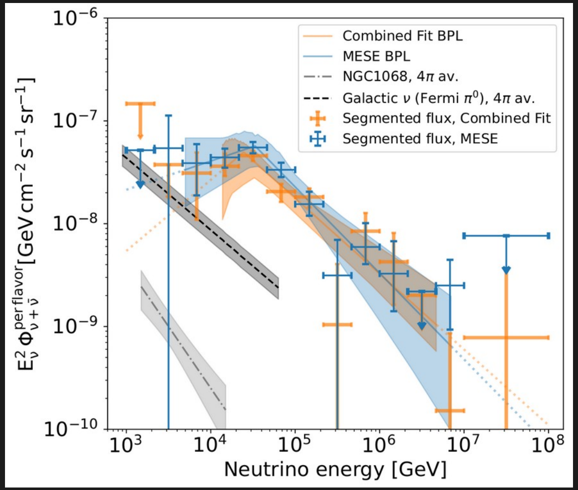
Combined analyses unlocks more information



Low+high energy neutrinos associated with GW events [A. Balagopal V.]



Cascades+tracks for source searches [R. Shah]



Cascades+tracks for diffuse spectrum [E. Ganster, R. Naab]

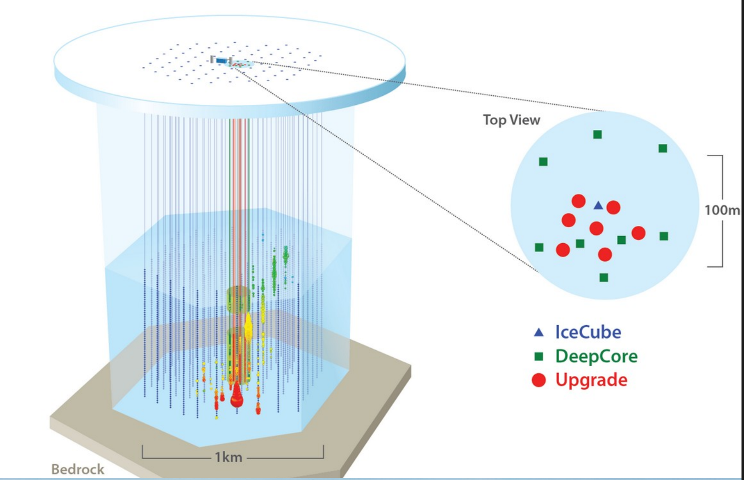
Plan to take this forward, by not only combining information from different neutrino datasets, but also other messengers!

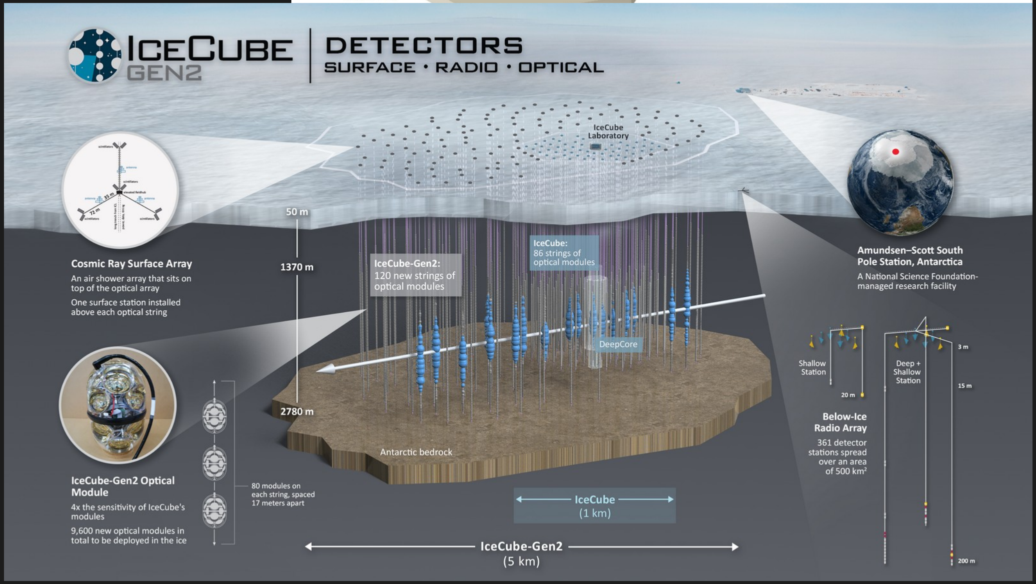
Plans for combined analyses

- Combined 3 neutrino datasets for targeting GeV-TeV scale neutrinos (binary study)
- Joint-likelihood study with photon experiments (public data, MoU)
- Combining datasets for enhanced flavor ratio measurements, including energy dependent measurements

Other analyses plans

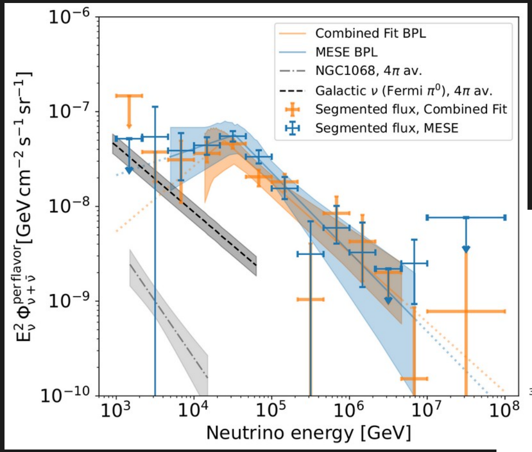
- Improved, fast reconstructions for low-energy neutrinos and inclusion of these events in the real time alert stream of IceCube
- IceCube Upgrade efforts:
    - Astrophysical source searches of low-energy neutrinos (transients)
    - Characterization of low-energy Galactic Plane flux
- IceCube-Gen2:
    - Flavor and spectrum studies at EHE energies
    - EHE neutrino identification, search for association with lower energy neutrinos

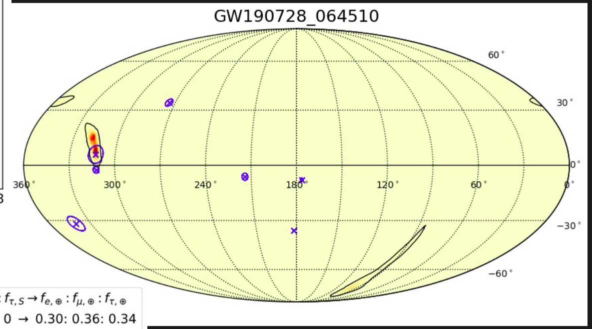


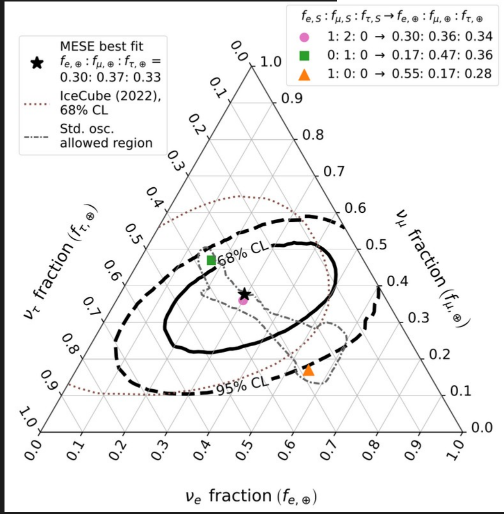


Summary

- Worked on several aspects of neutrino astrophysics, multi-messenger astrophysics, and cosmic-ray physics (not shown in this talk)
- Plan to bring this forward by working with people at TIFR and multi-messenger community in general

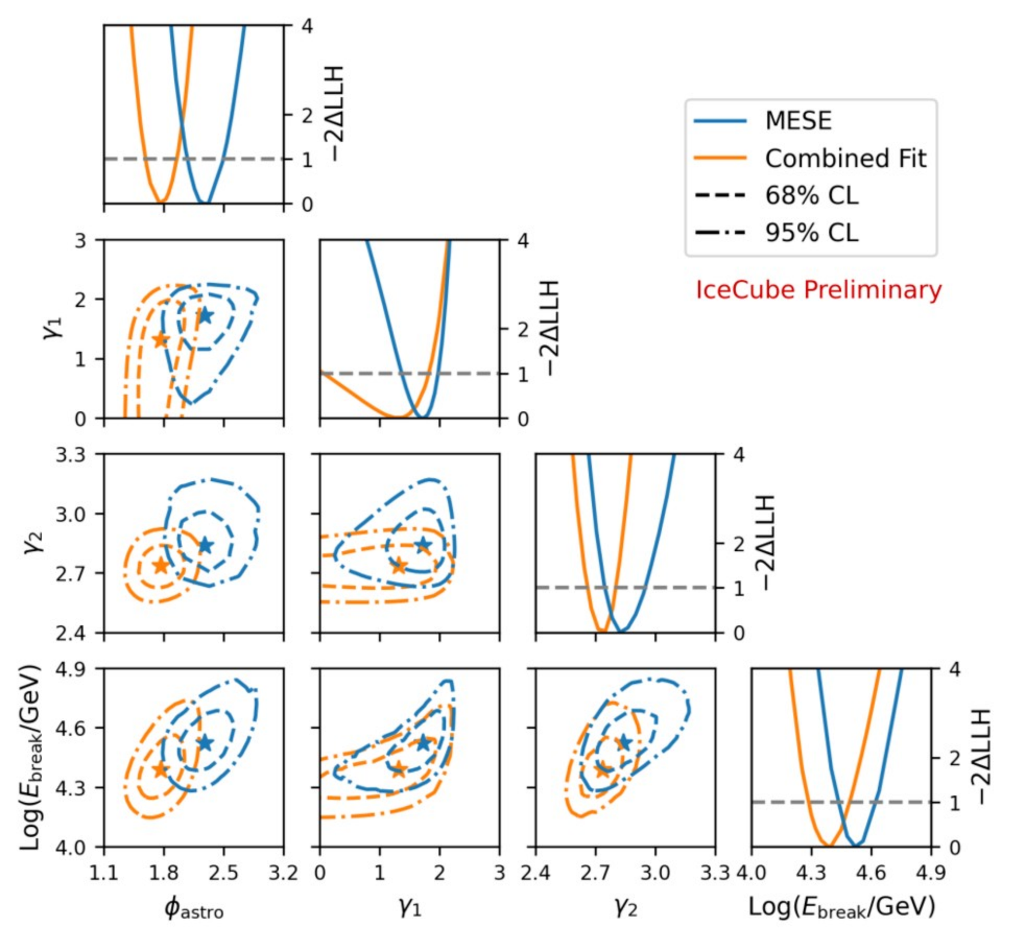




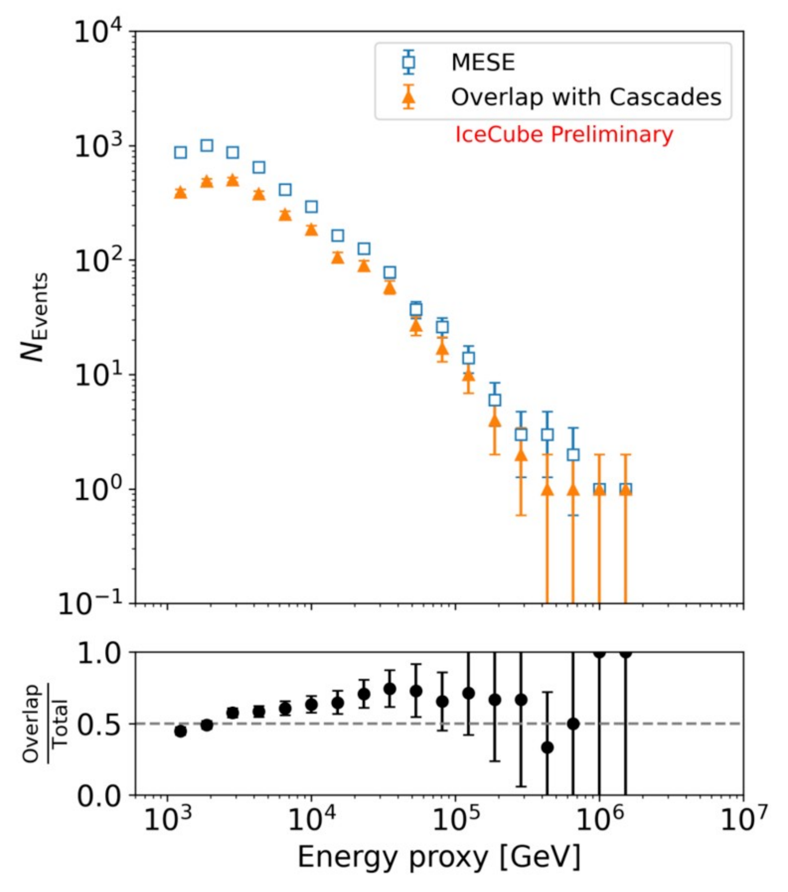


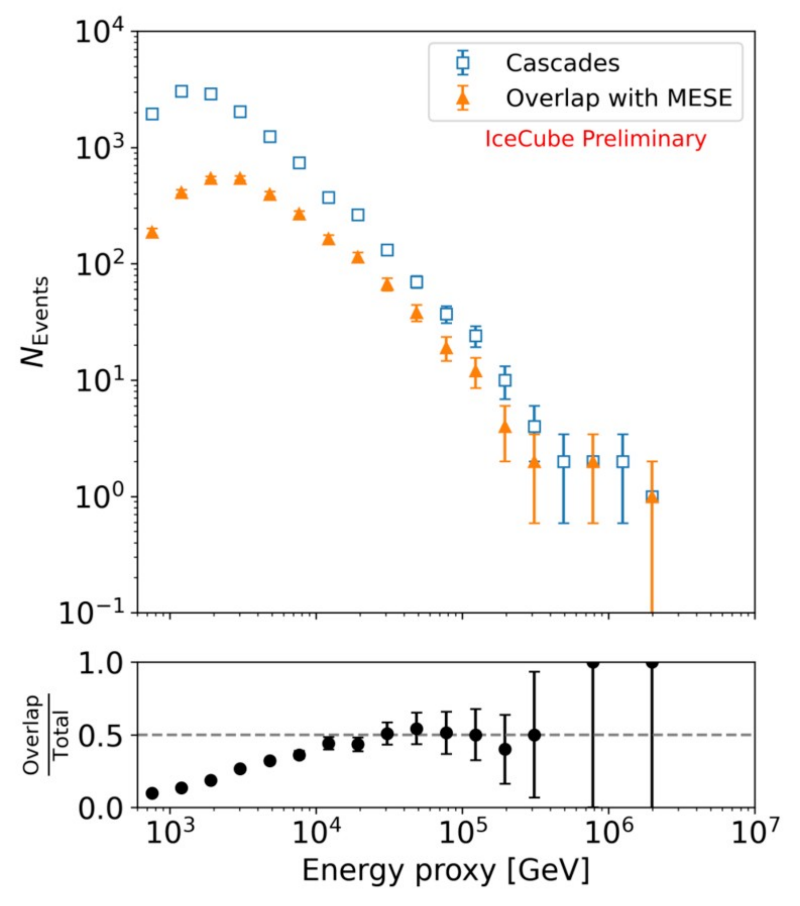
Backup

Comparison of Combined Fit and MESE

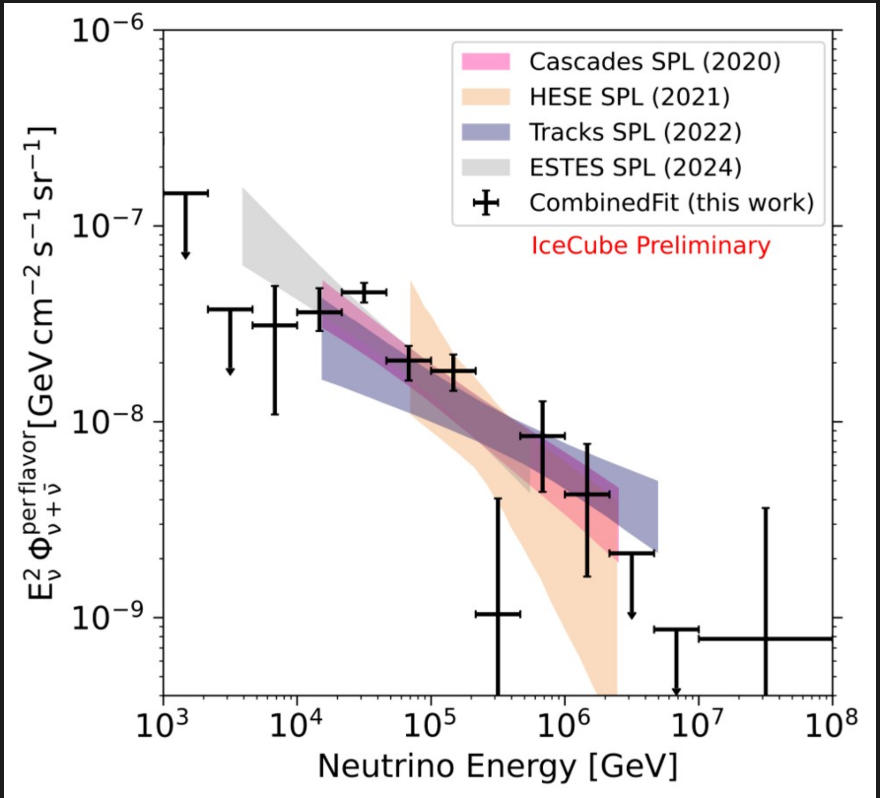


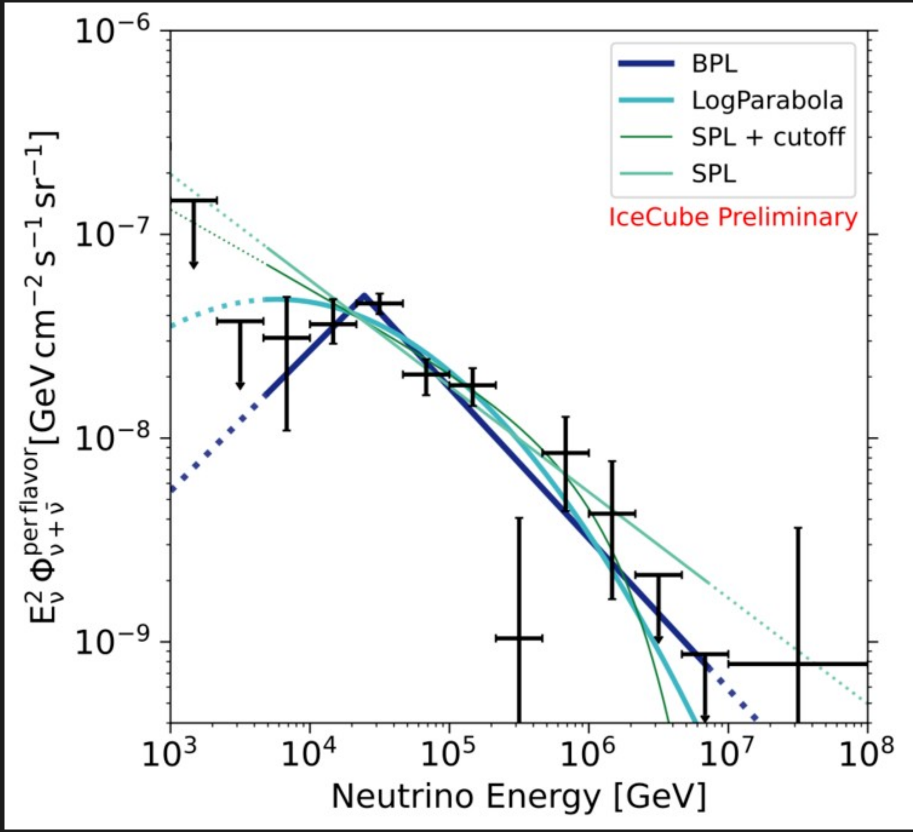
Overlap of Combined Fit and MESE





Combined Fit Segmented Flux





What about ESTES?

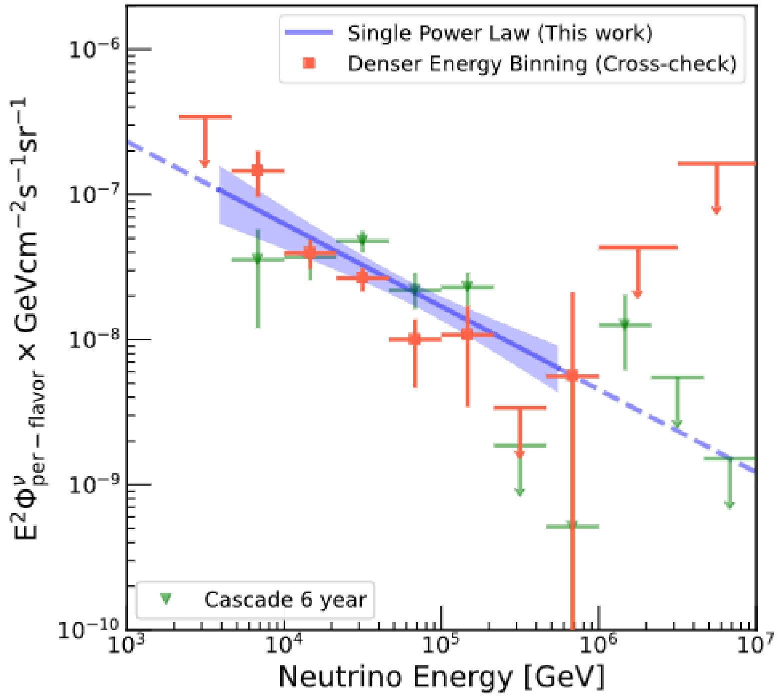
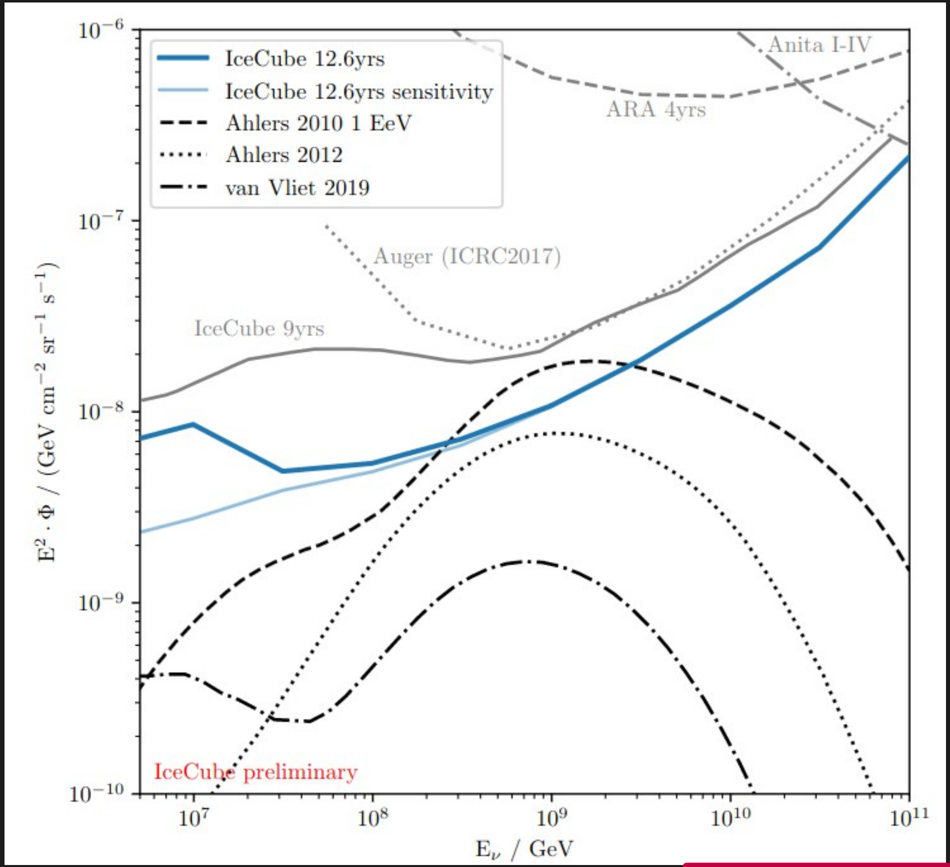


FIG. 22. Distribution of the unfolded flux as first shown in Fig. 17. The red points are the segmented flux measurement using denser energy binning as a cross-check to compare directly with 6-year IceCube cascade result [49]. There is no sensitivity to the astrophysical flux in the 1-2.15 TeV bin.

Tracks alone seem to be insufficient to measure the break

Segmented Fit with MESE tracks only is consistent with ESTES

EHE Limits

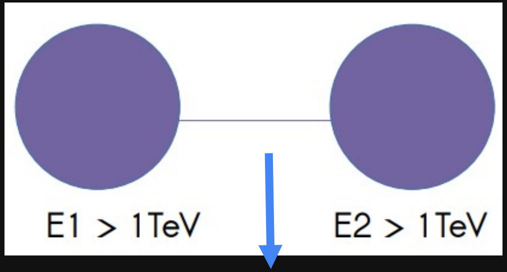


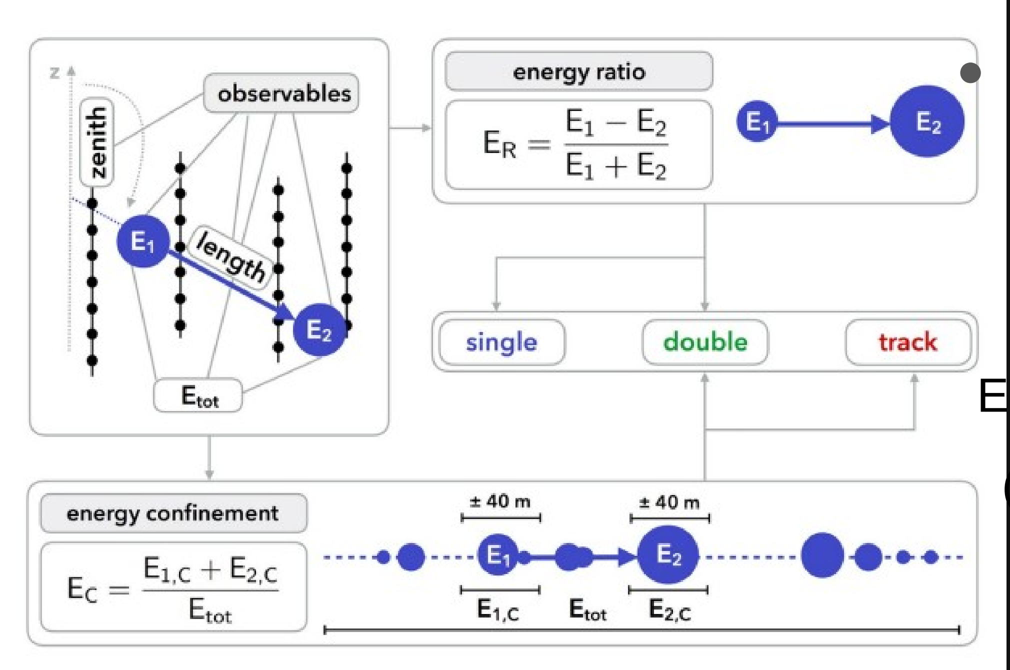
- **New analysis focused on EHE events**
- **3 events found in the sample**
- **Events are consistent with no cosmogenic neutrinos**
- **Most stringent limits set in this energy range**

1 TeV	10TeV	100TeV	1 PeV	10 PeV	100 PeV	1 EeV

> 1 PeV

Tau neutrino tagging





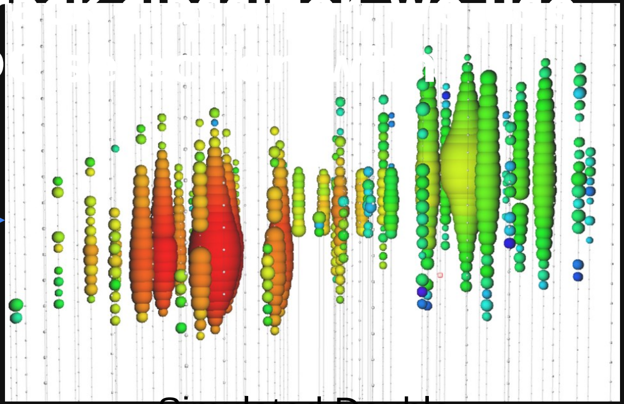
- Using Taupede: likelihood-based fitter for double cascades (DC), previously used in HESE (M. Usner DOI:10.18452/19458
 J. Stachurska DOI:10.18452/21611)

- MESE has a DNN-based cascade/tr
only the D
Taupede

(EC≥0.99)

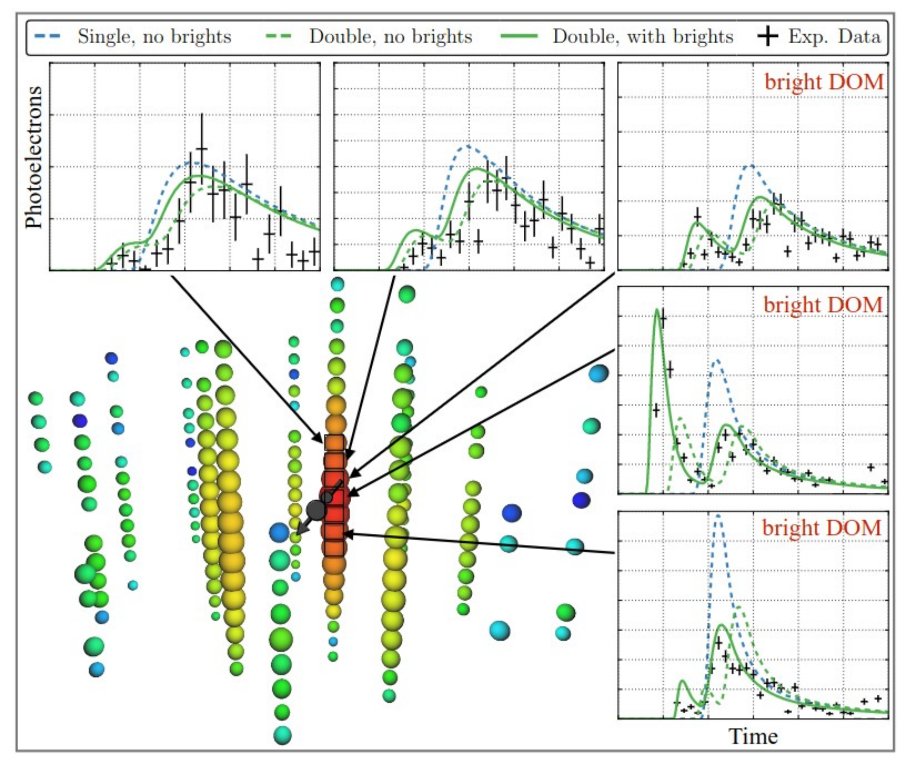
ER ϵ (0.98,0.3)

(E_{tot}≥ 30TeV)



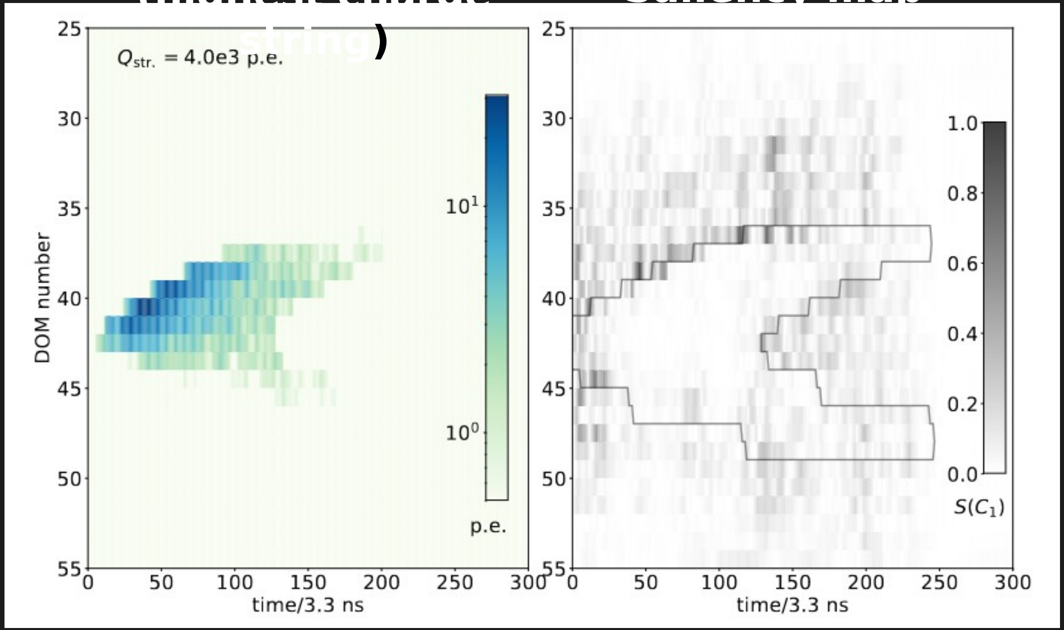
Simulated Double Cascade Event

Tau neutrinos in IC



Charge deposited (highest charge string)

Saliency map

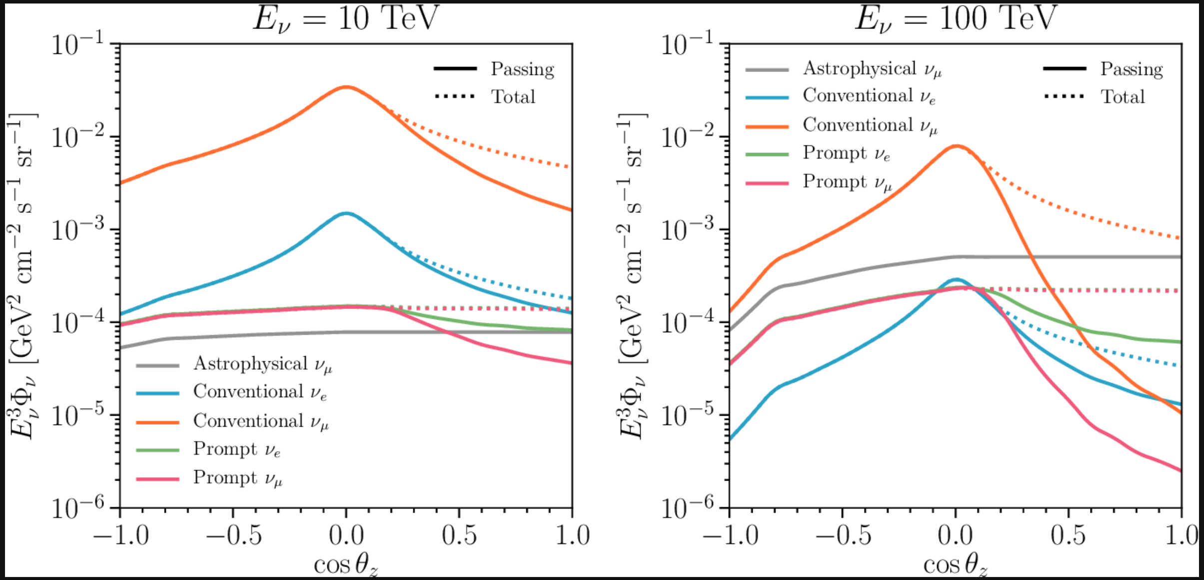


Likelihood approach: Two candidate neutrinos with 2.9 σ (7.5 years HESE)

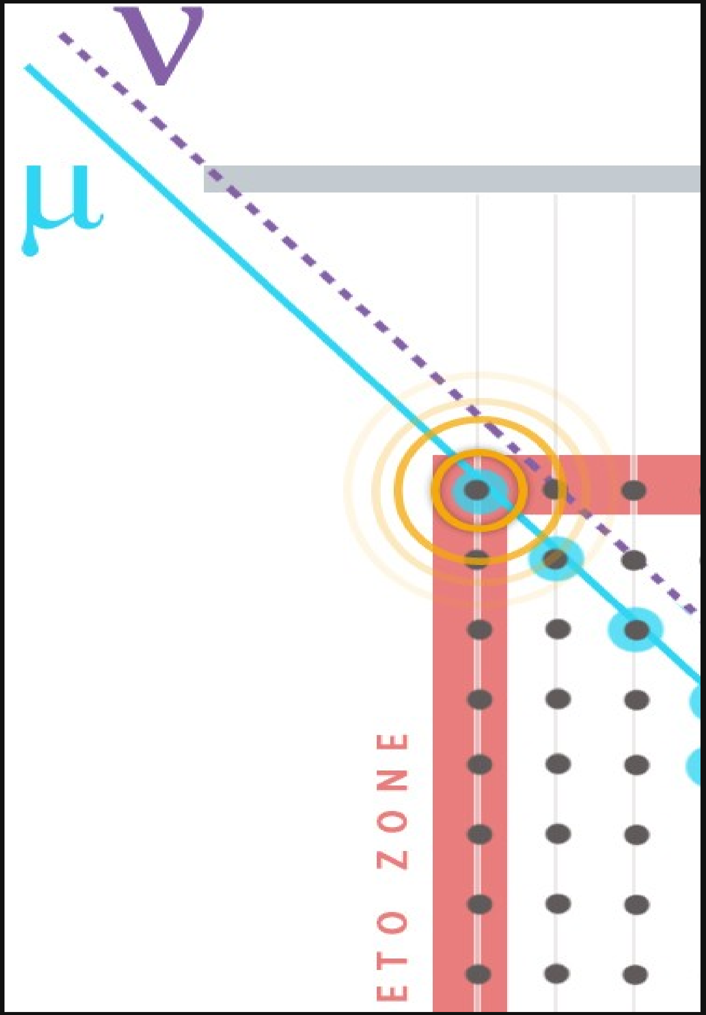
CNN approach: Seven candidate neutrinos with 5 σ (9.7 years)

Neutrino self-veto

- **Neutrinos from CR showers often accompanied by muons.**
- **Vetoing these muons suppresses atm. neutrino background**
- **Accurate modeling of the self-veto suppression via muon bundle injection.**



Argüelles, Carlos A., et al.*Journal of Cosmology and Astroparticle Physics* 2018.07 (2018): 047.

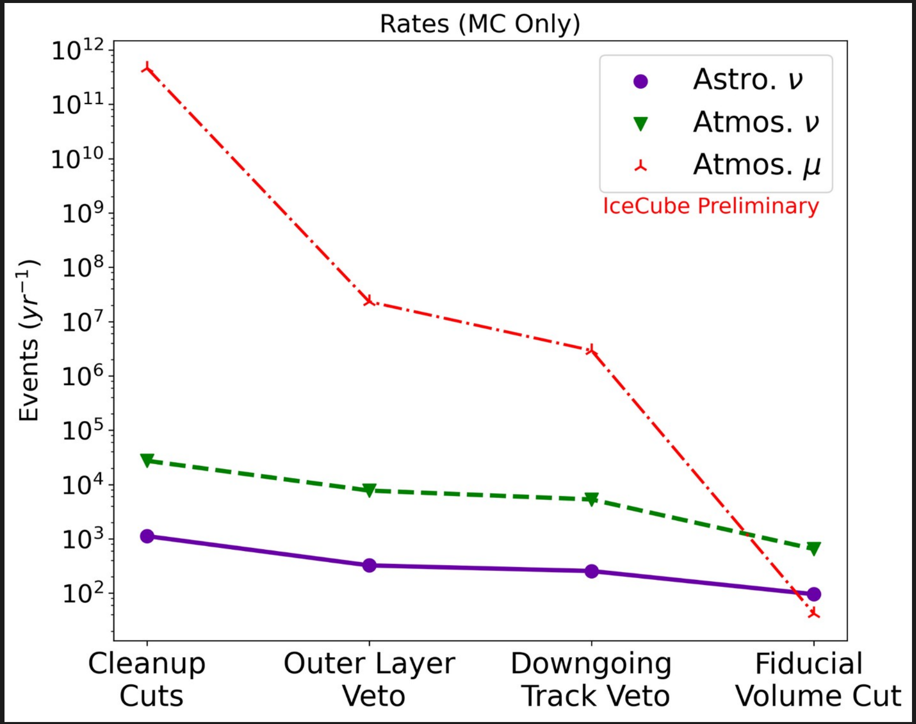


Measurements with MESE

Rate of muons reduced by several orders of magnitude

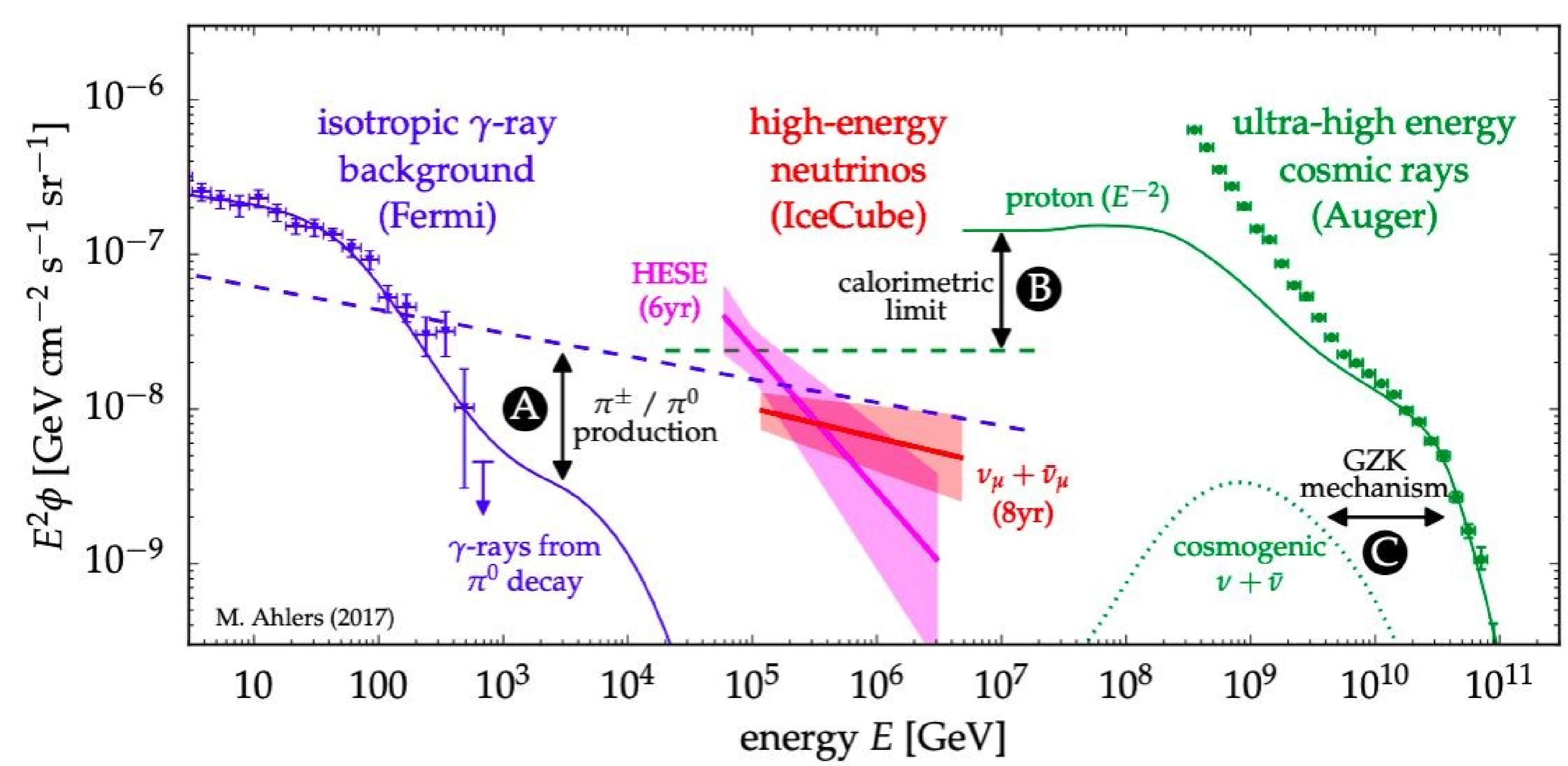
Two measurements with MESE dataset (livetime: 11.4 years):

- M1 All-flavor astrophysical spectrum of neutrinos
- M2 Flavor ratio of cosmic neutrinos

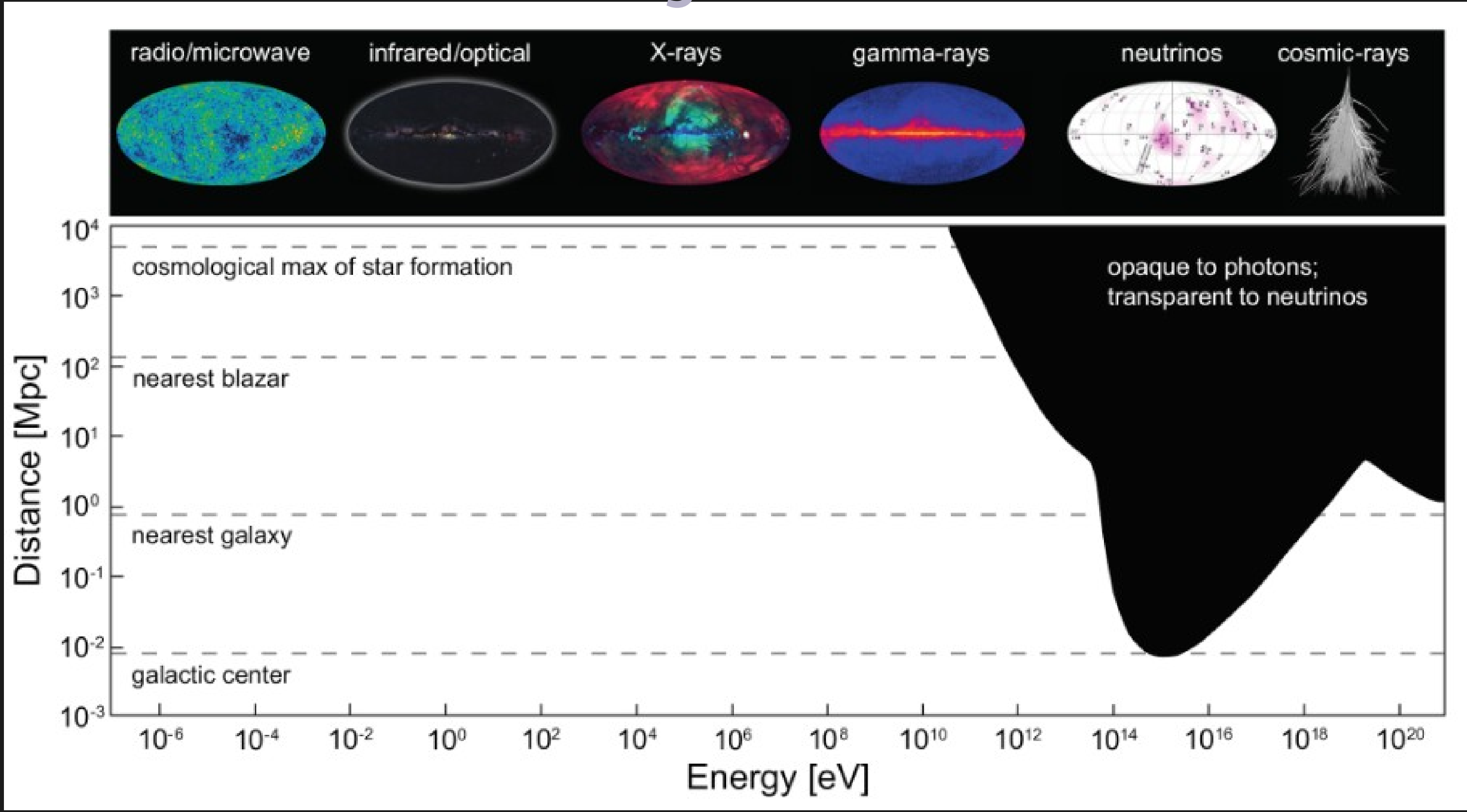


Connection with other messengers

Energy density of high energy neutrinos similar to γ-ray flux, and Ultra High Energy Cosmic Rays (UHECRs) -> could indicate related production mechanisms

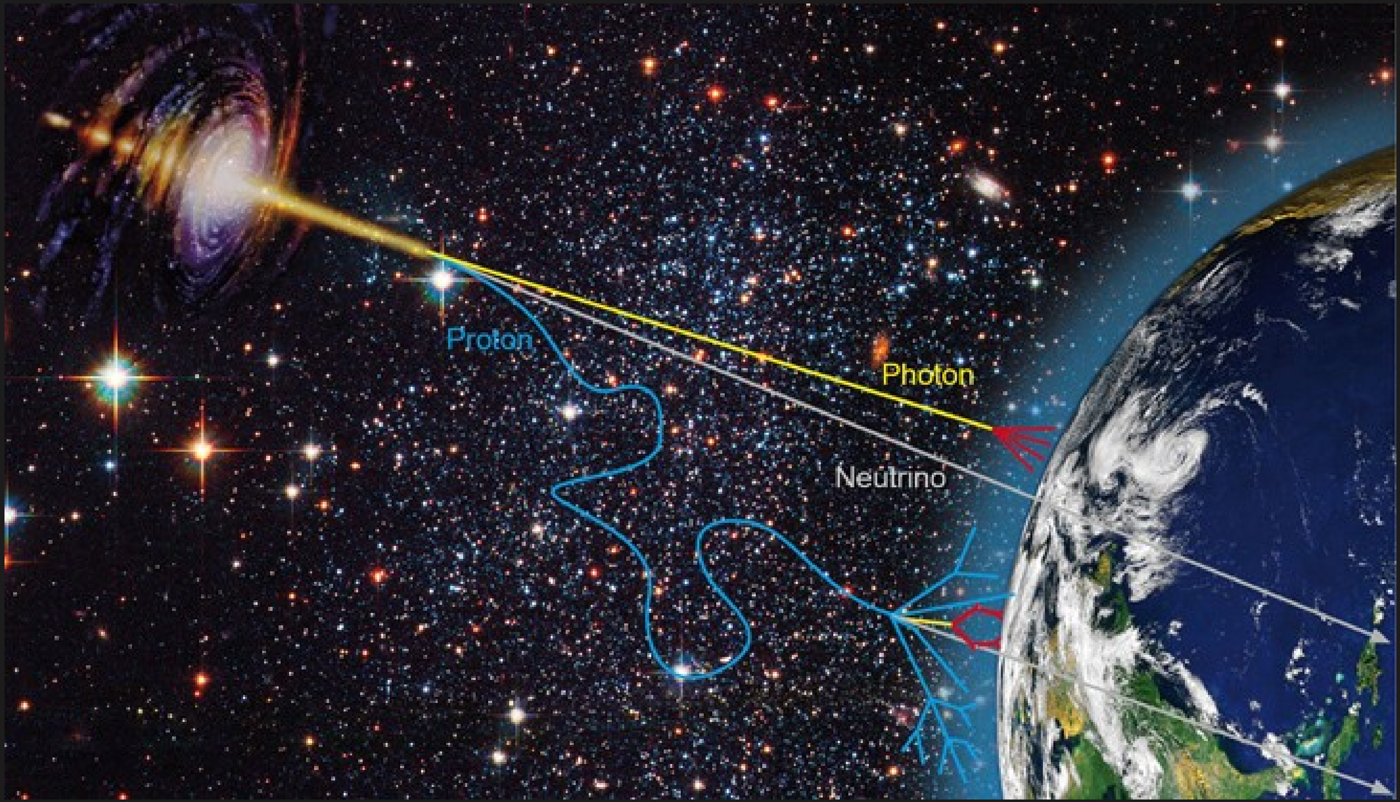


Neutrinos: a messenger of the extreme Universe



20% of the Universe is opaque to the EM spectrum. Can be probed by gravitational waves, neutrinos and cosmic rays

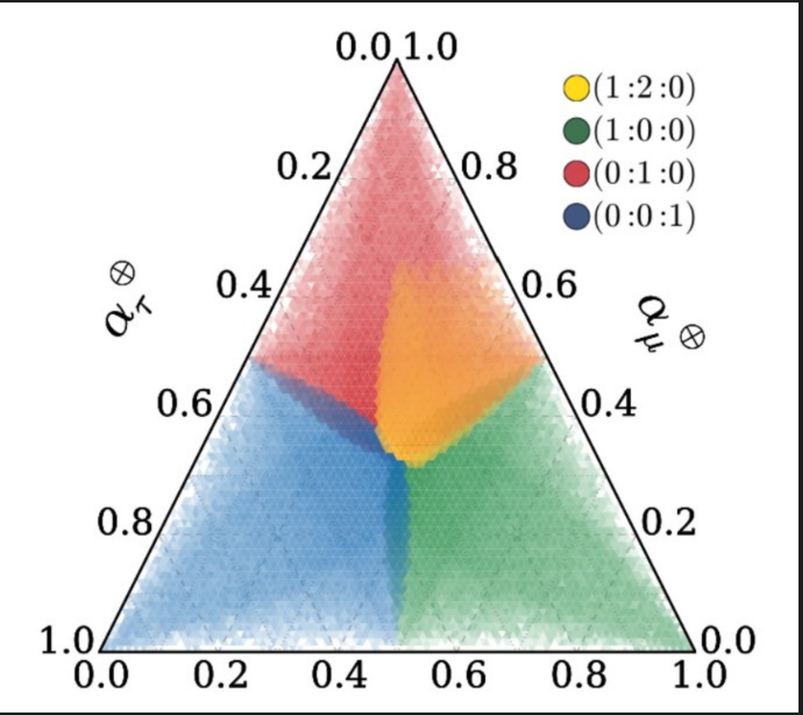
Cosmic Connection



Astrophysical sources can produce energetic particles like cosmic rays, gamma rays and neutrinos

Flavor Ratio as a Probe of New Physics

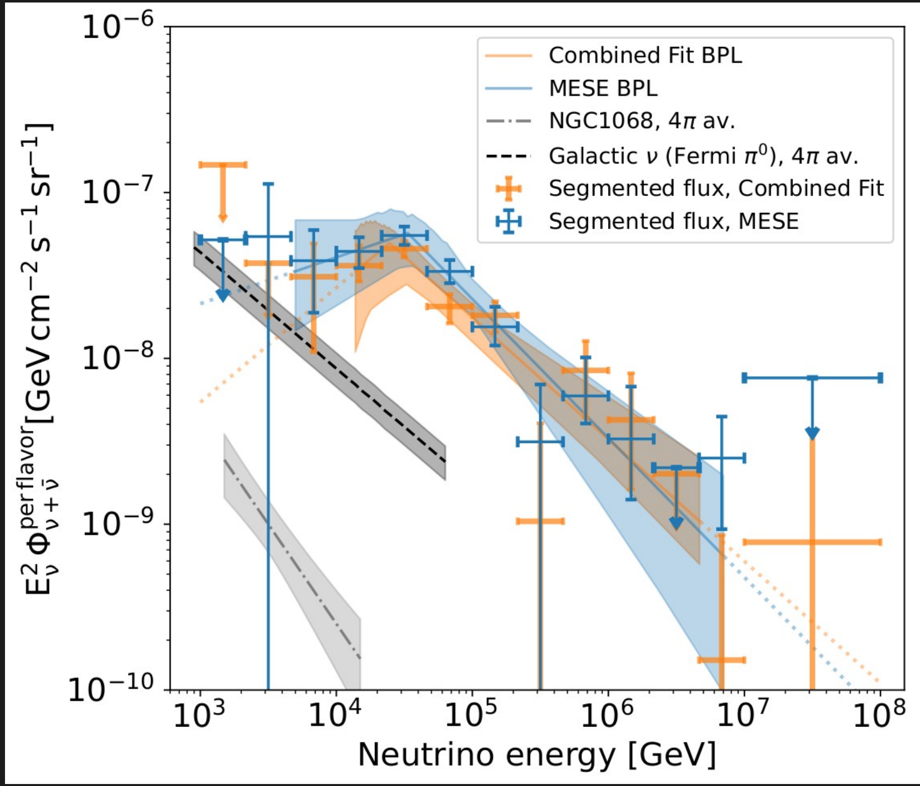
Expected ratio at Earth changes under new physics assumptions (LI & CPT violation, equivalence principle, cosmic torsion, non-standard interactions)



Phys. Rev. Lett. 115, 161303 (2015)

M1 Spectral Break/Curvature Seen in Two Measurements!

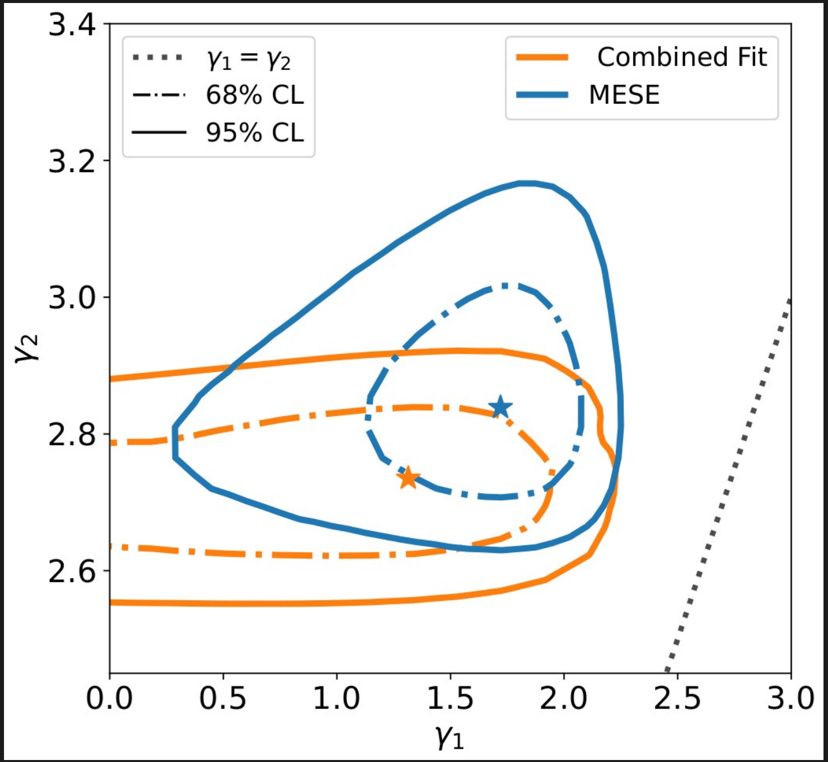
- Combined Fit with cascades and upgoing tracks datasets
- Measured the break in the spectrum with 4.4σ
- Consistent measurement from two analyses



[A. Balagopal V., V. Basu, E. Ganster, R. Naab]

[IceCube paper accepted at PRL]

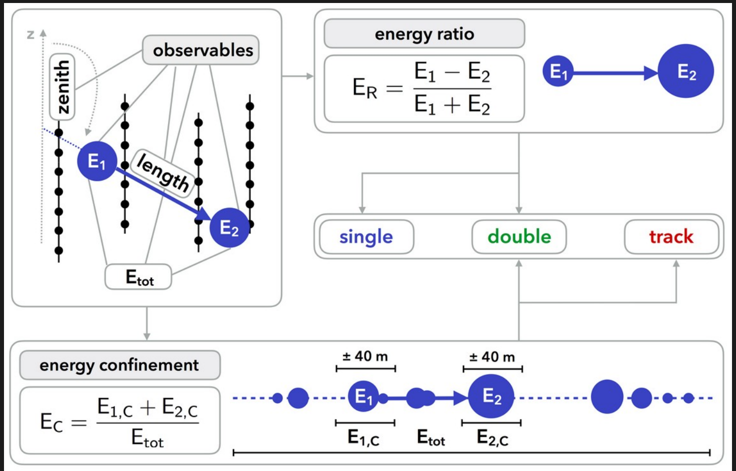
M1 Likelihood contours of the two spectral indices



MESE provides a stronger constraint on the lower energy spectral index while Combined Fit provides a stronger constraint on the higher energy index

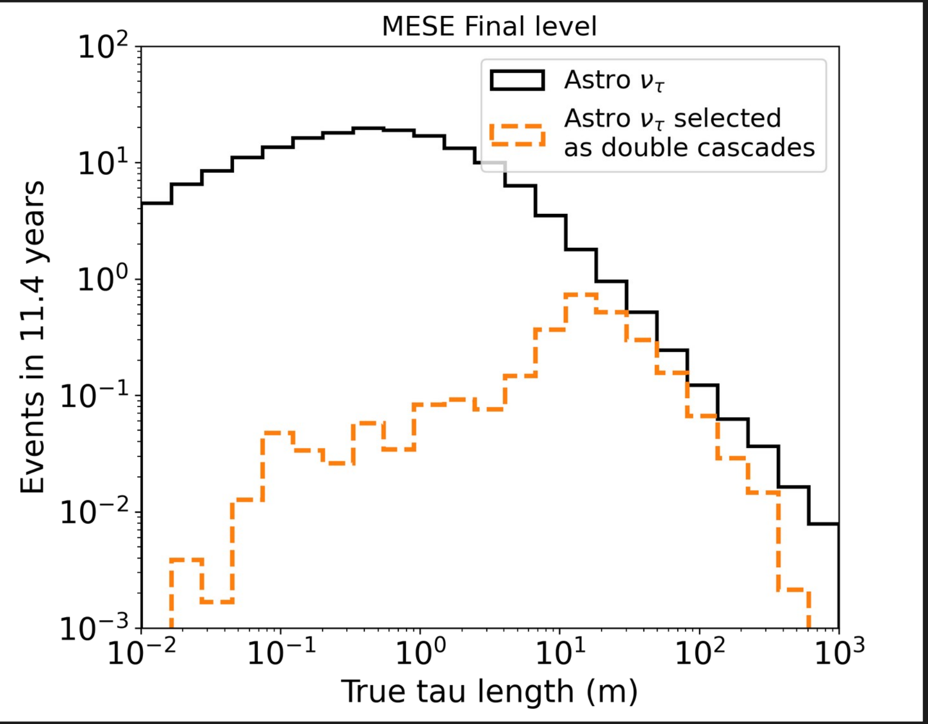
Double cascade selection

- Selection cuts based on taupede reconstruction (derived from previous HESE studies)
- Cuts focused on energy of each cascade, energy asymmetry, energy confinement
- Retain events with E > 30 TeV, L> 10 m as double cascades, rest are kept as cascades/tracks. Final purity ~ 72%



Energy confinement (EC): ratio of energy in each cascade within 40 m distance wrt total energy

Energy ratio: relative energy deposited in each cascade

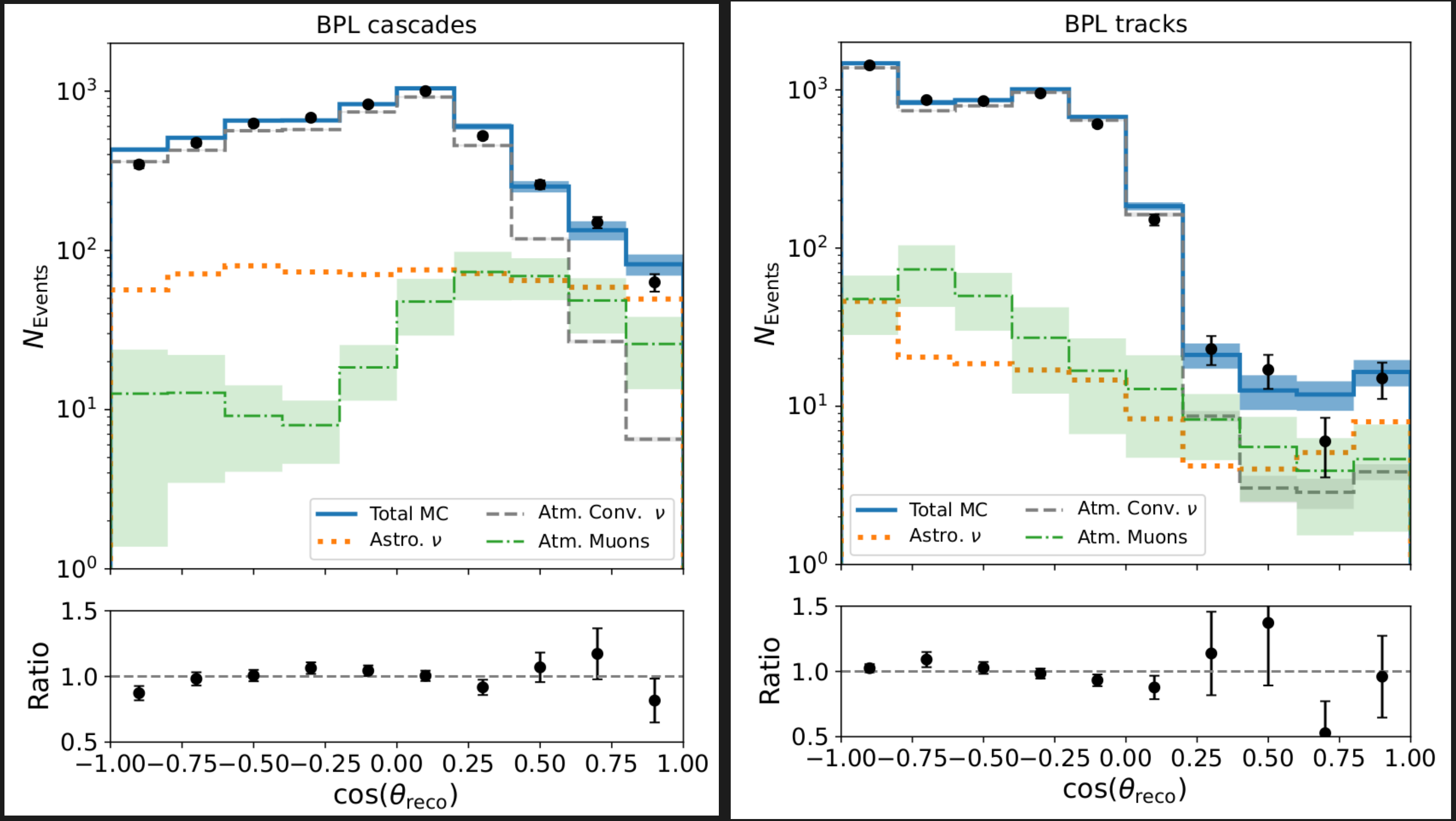


M1

MESE Data/MC Comparison

Best fit astro. flux of 2.27 x $\begin{cases} (E/33.1\mathrm{TeV})^{-1.72}, & E < 33.1\ \mathrm{TeV} \\ (E/33.1\mathrm{TeV})^{-2.84}, & E > 33.1\ \mathrm{TeV} \end{cases}$

Atm. Flux model: GaisserH4a + Sibyll 2.3c

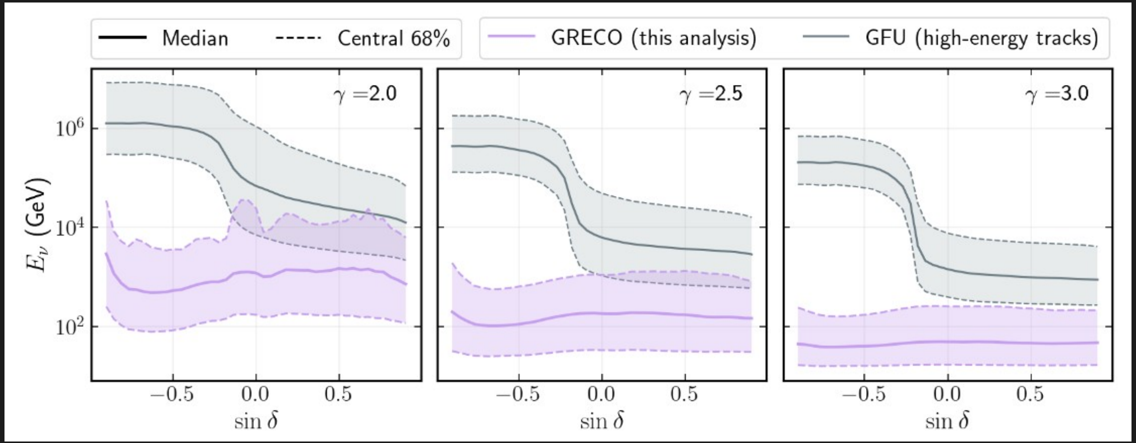


Observed
4968 cascades
and
4920 tracks

Neutrino datasets

High-energy dataset

- Energy range: $5x10^5$ GeV to $7x10^7$ GeV in the southern hemisphere and $5×10^3$ GeV-10^5 GeV in the northern hemisphere
- Muon neutrinos only
- Angular resolution ~ 1 degree



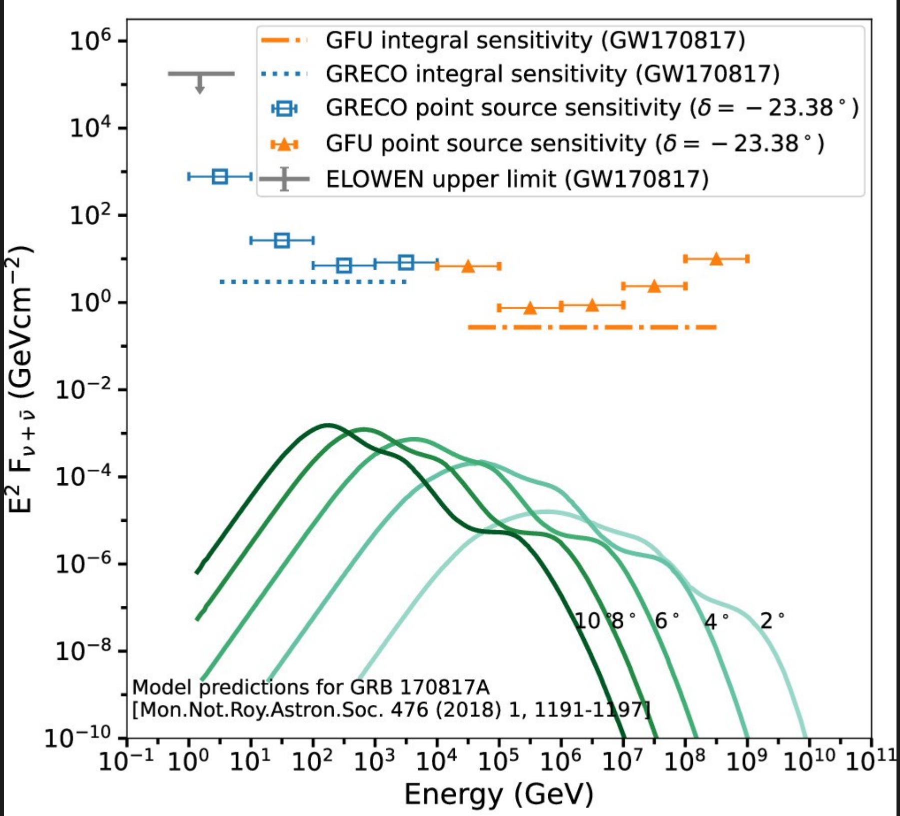
Low-energy dataset

- Energy range: ~8 GeV – $3x10^4$ GeV in the whole sky
- Neutrinos of all flavour
- Median angular resolution ~ 50 degrees

[R. Abbasi et al 2023 ApJ 953 160]

Sensitivities

Comparison of sensitivites of various GW follow-up analyses, with model predictions (selected)



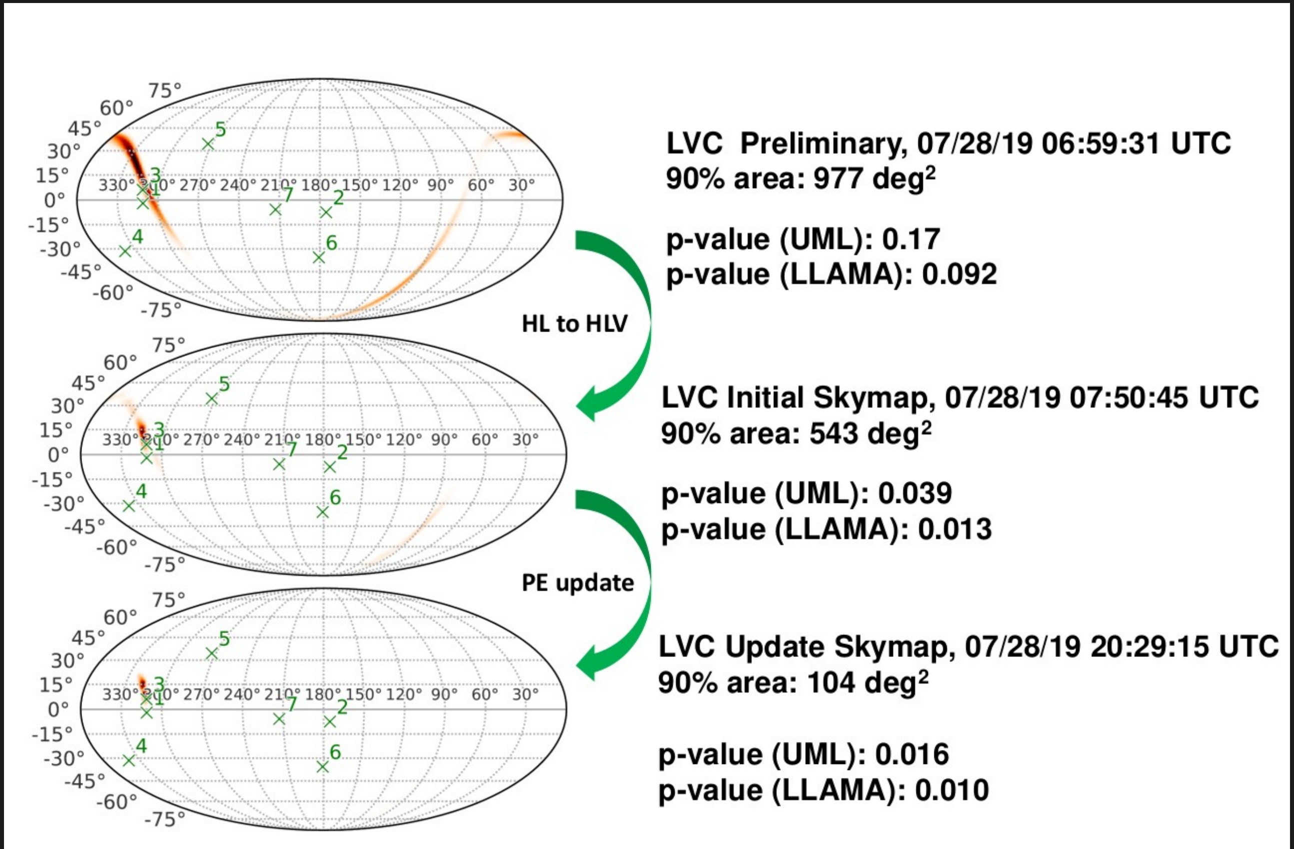
[A. Balagopal V.]

Sensitivities within a 1000 s time window

Injected flux $F \propto E^{-2}$

[R. Abbasi et al 2023 ApJ 959 96]

An example event: High Energy Analysis (realtime)

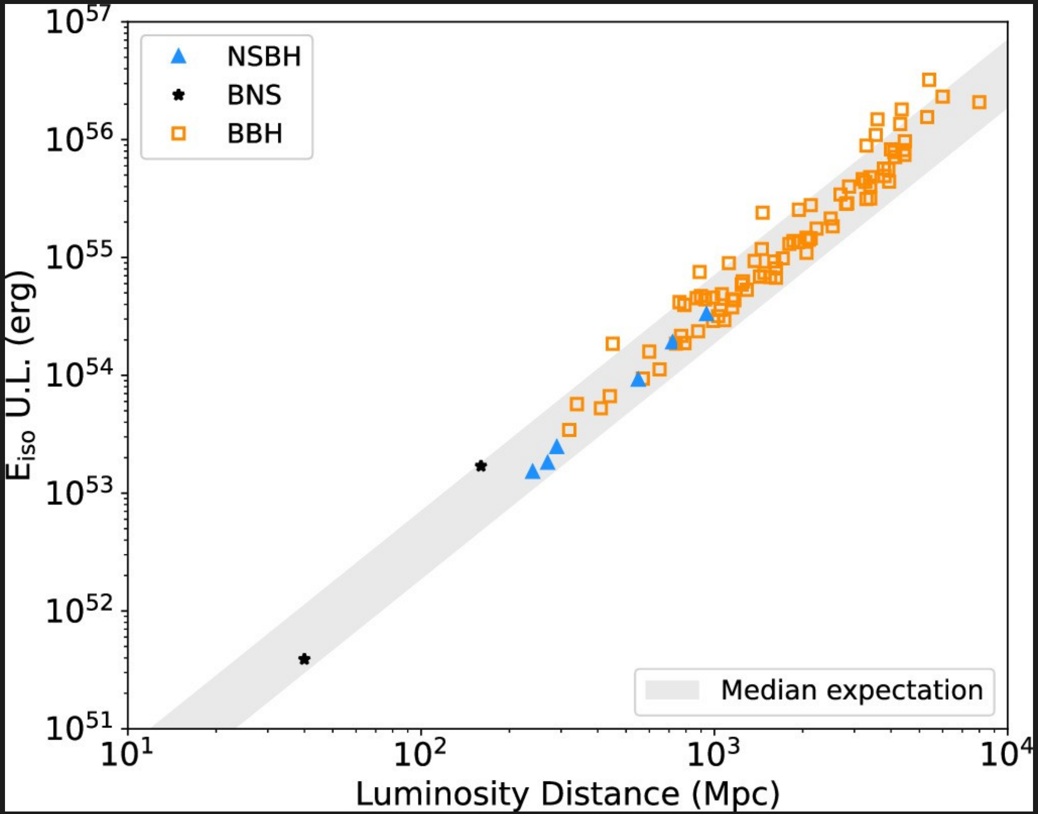


[R. Abbasi et al 2023 ApJ 944 80]

Improved localization of the GW event improved the p-value

E_{iso} upper limits (low-energy)

90 GWs from O1,O2,O3



Upper limits on isotropic equivalent energy emitted in neutrinos of all flavors

[R. Abbasi et al 2023 ApJ 959 96]