Cosmic Identity Card

Name: Astrophysical high-energy Neutrino

Date of Birth: ???

Place of Birth: ???

The First Search for High-Energy Neutrino Emission from Galaxy Mergers

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arXiv: 2404.06539

Motivation

- What are the sources of the highest energy particles in our universe, the high-energy ($\gtrsim 10^{15}$ eV) cosmic-rays?

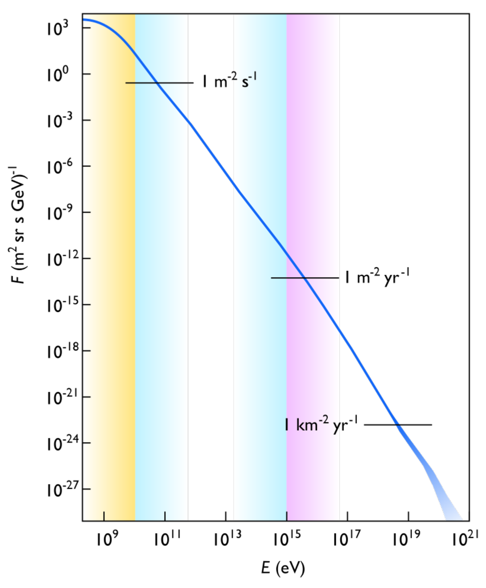


Fig: Cosmic-ray flux versus particle energy at the top of Earth's atmosphere [Fig. courtesy: wikipedia]

Why search for astrophysical neutrinos?

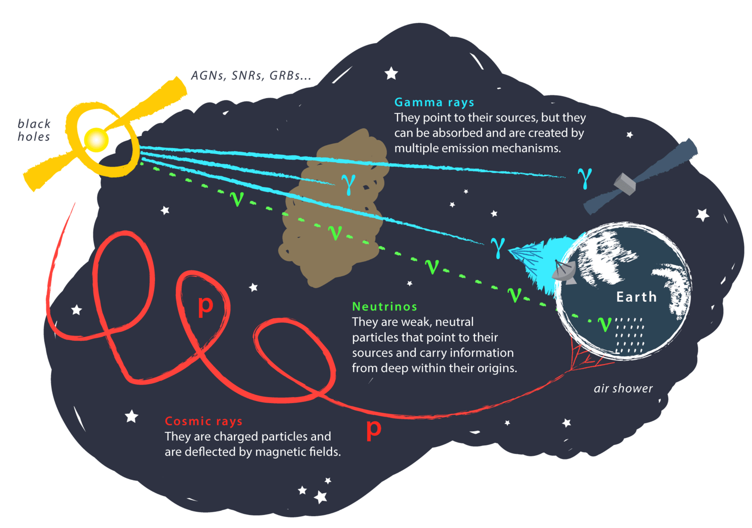


Fig: Cosmic-ray particles interact with matter and radiation at/ near the source, or during propagation to produce neutrinos and anti-neutrinos that travel cosmic distances in straight paths pointing back to where they were produced. Charged cosmic-ray particles bend in astrophysical magnetic fields and do not point back to their sources. Photons may get absorbed while propagation. **[courtesy: IceCube/WIPAC]**

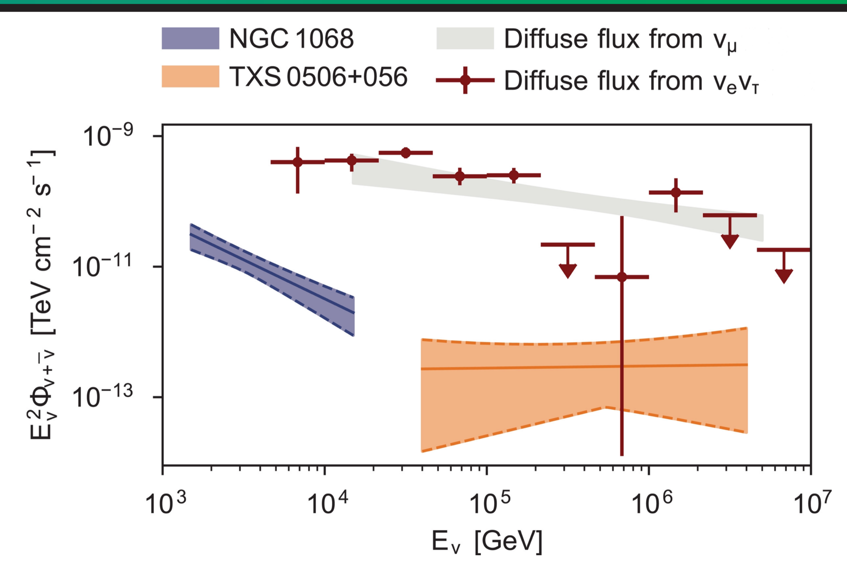


Fig: The high energy neutrino flux observed by IceCube. TXS 0506+056 and NGC 1068 are confirmed high-energy astrophysical neutrino sources till now. IceCube has recently reported strong evidence for diffuse neutrino emission from the Galactic plane. We also observe a high-energy diffuse astrophysical neutrino (in all flavors) flux. Currently, we do not know what sources contribute entirely to the high-energy diffuse astrophysical neutrino flux. **[courtesy: 2211.09972]**

Neutrino telescope: IceCube and high energy neutrino sources

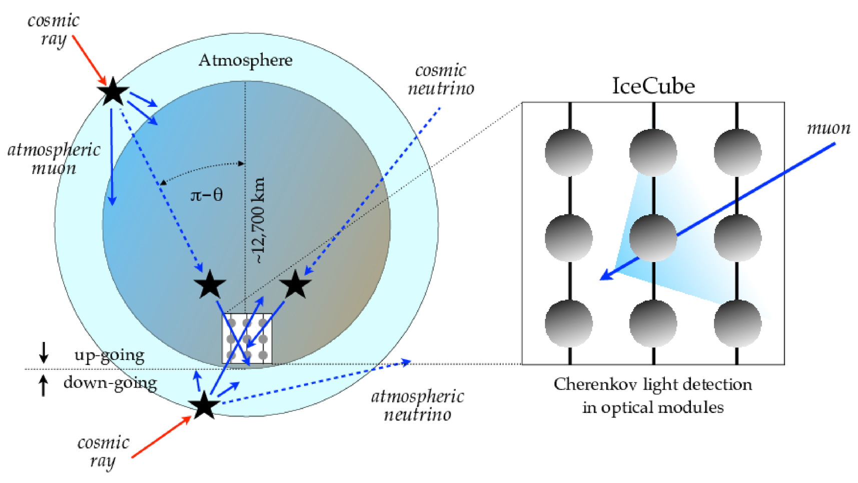


Fig. courtesy:2202.00694

How IceCube detects neutrinos?

$\nu_l + N \rightarrow l +$ hadrons (Charged Current interaction)

$\nu_l + N \rightarrow \nu_l +$ hadrons (Neutral Current interaction)

Similar types of interactions happen for anti-neutrinos.

Glashow resonance: $\bar{\nu}_e + e^- \rightarrow W^-(\mathrm{on-shell})$

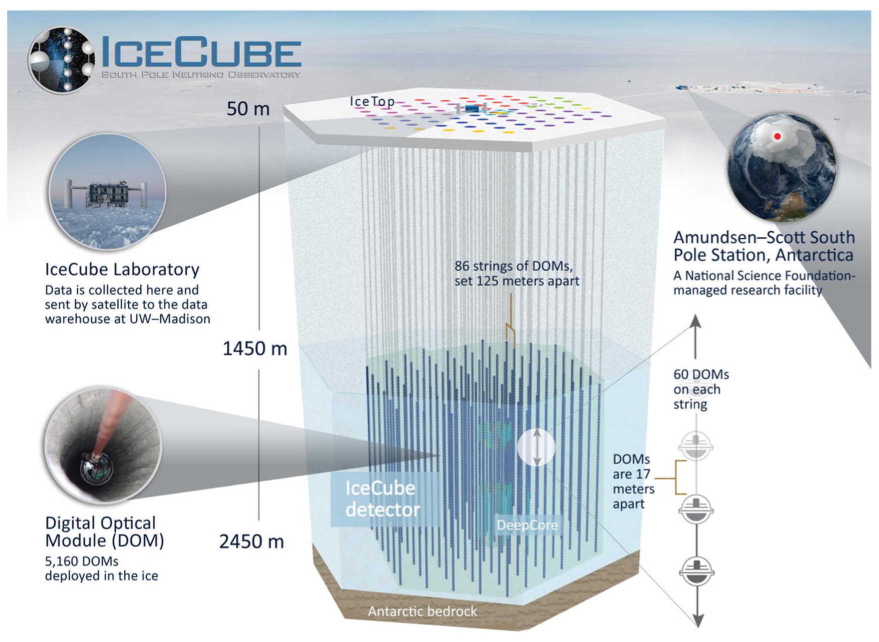


Fig: The IceCube Neutrino Observatory [courtesy: 2202.00694]

Expected number of $(\nu_\mu + \bar{\nu}_\mu)$ events:

$$\hat{n}_s = 2\pi \sum_k t_k \int d\sin\delta \int A^k_{\rm eff}(E_\nu, \delta)\, \frac{dF}{dE_\nu}(E_\nu)\, dE_\nu$$

$$\frac{dF(E_\nu)}{dE_\nu} = \Phi_0 \times \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{\Gamma}$$

Φ_0 is the flux normalization at 100 TeV.

δ is the declination of the source.

t_k is the detector uptime and $A_{\rm eff}$ is detector effective area.

Γ is the spectral index which quantifies how the flux of neutrinos varies with their energy.

Proposed neutrino sources

- Blazars [arXiv: 1904.06371, 2004.09686, 2007.12706, 2309.03115]
- Gamma-ray bursts [arXiv: 1101.1448, 1412.6510, 1601.06484, 1702.06868]
- Radio bright AGN [arXiv: 2103.12813]
- Choked Jet Supernovae [arXiv: 1706.02175, 1809.09610]
- Fast radio bursts [arXiv: 1712.06277, 2212.06702]
- Seyfert galaxies [arXiv: 2306.09018]

Theoretical papers have proposed the existence of high-energy neutrinos originating from galaxy mergers. However, research in the literature has been undertaken to investigate these claims. Our study aims to determine whether galaxy mergers can indeed be identified as the sources of such neutrinos.

Galaxy mergers as high-energy neutrino sources

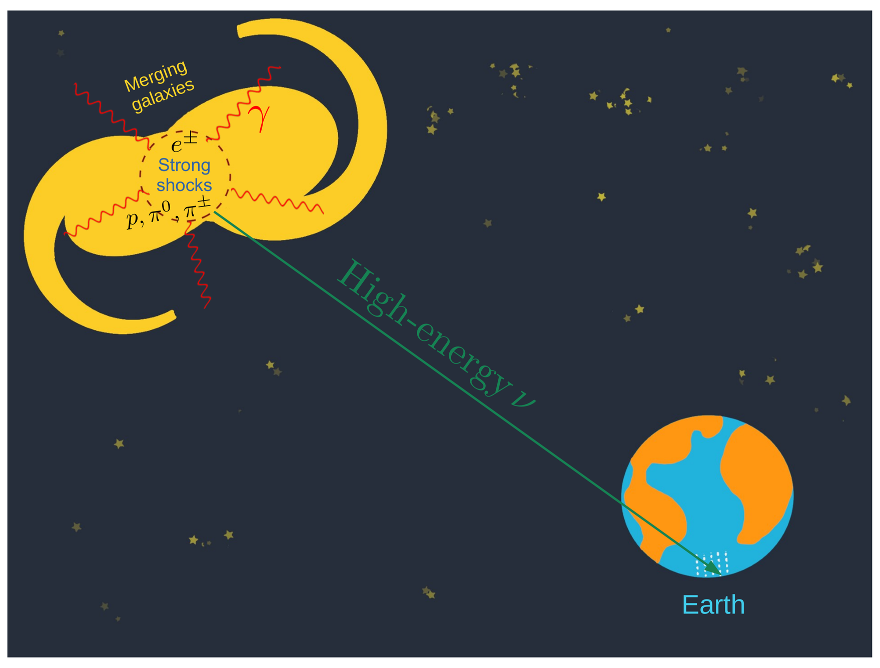


Fig: Schematic figure showing the merger of two galaxies. The shock is in the core region where interactions occur and neutrinos as well as electromagnetic radiation are produced.

Galaxy merger: source of astrophysical neutrino?

- By shock acceleration of particles in massive galaxy mergers or collisions, cosmic-rays can be accelerated up to the energy $(0.1-1)\times 10^{18}$ eV. [arXiv: 1405.3262, 1712.09754]
- Such cosmic-rays lose their energy via hadronuclear interactions within a dynamical timescale of the merger shock, producing gamma rays and neutrinos as a by-product.

Production of high-energy neutrino:

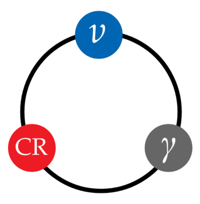
$$p + p_{\rm target} \rightarrow n_\pi[\pi^+ + \pi^- + \pi^0] + X$$

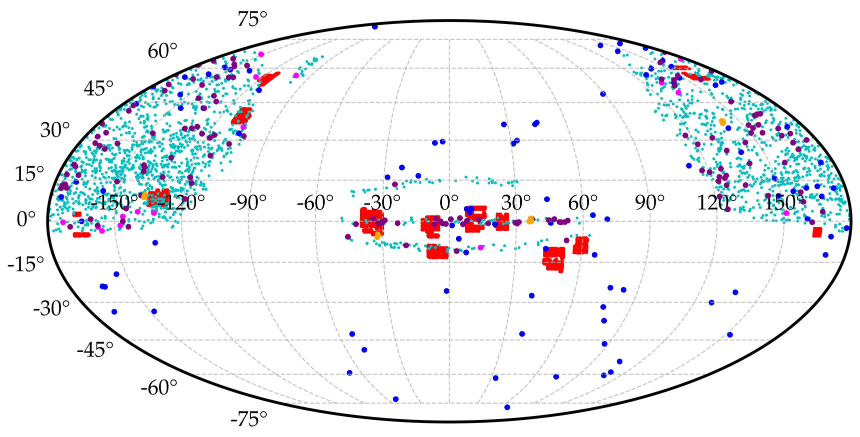
$$p + \gamma_{\rm target} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, \mathrm{BR} = 2/3 \\ n + \pi^+, \mathrm{BR} = 1/3 \end{cases}$$

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

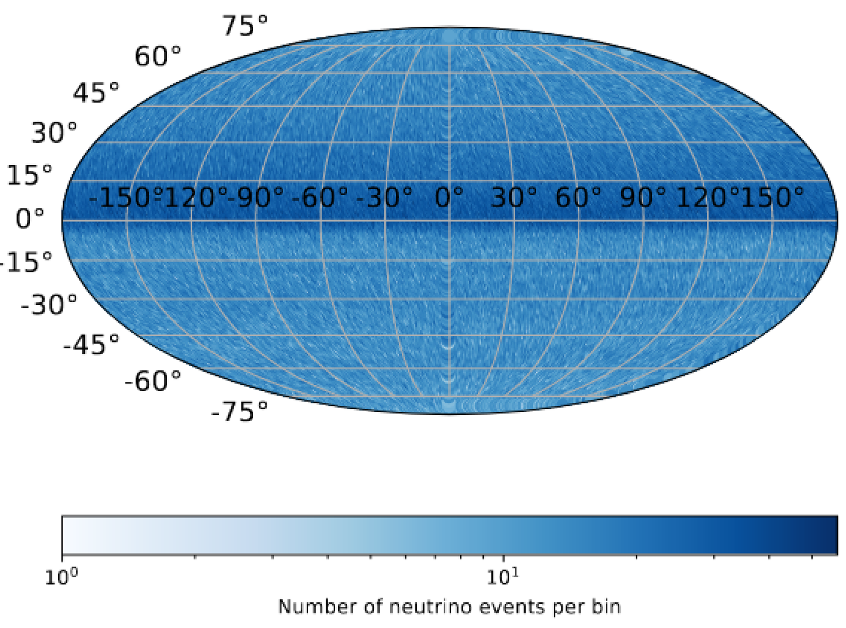
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

$$n\ (\text{escapes}) \rightarrow p + e^- + \bar{\nu}_e$$





Distributions of galaxy mergers



Distributions of muon neutrino events observed by IceCube

We look into the statistical correlation between six galaxy mergers catalogs and the 10 years IceCube skymap

The Test Statistic

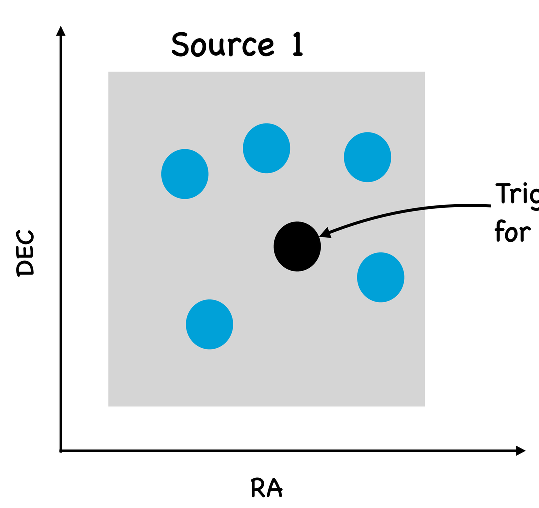
- Test Statistic is,

$$\mathrm{TS}(n_s) = 2\ln\frac{\mathcal{L}(n_s)}{\mathcal{L}(n_s = 0)}$$

- $\mathcal{L}$ is the likelihood function. The denominator is the background or null hypothesis that all events come from the background. The best-fit number n_s of signal events is obtained by maximizing the TS value (TS_{max}). If the background hypothesis is true, the probability distribution for TS_{max} is approximately a χ^2 distribution,

$$\mathrm{PDF}(\mathrm{TS}_{max}) \approx \chi^2_1(\mathrm{TS}_{max})$$

Analysis Formalism



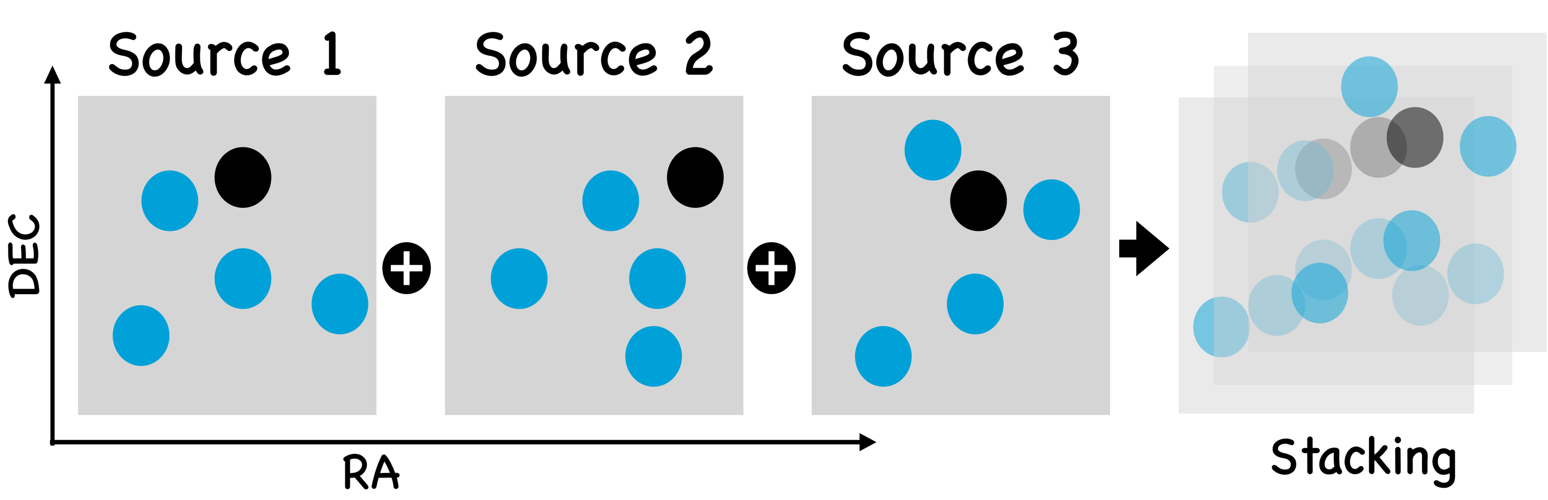


Fig: Schematic representation of single source analysis and stacking analysis, respectively. Stacking analysis is a search for collective neutrino emission from a catalog/class of sources.

Results

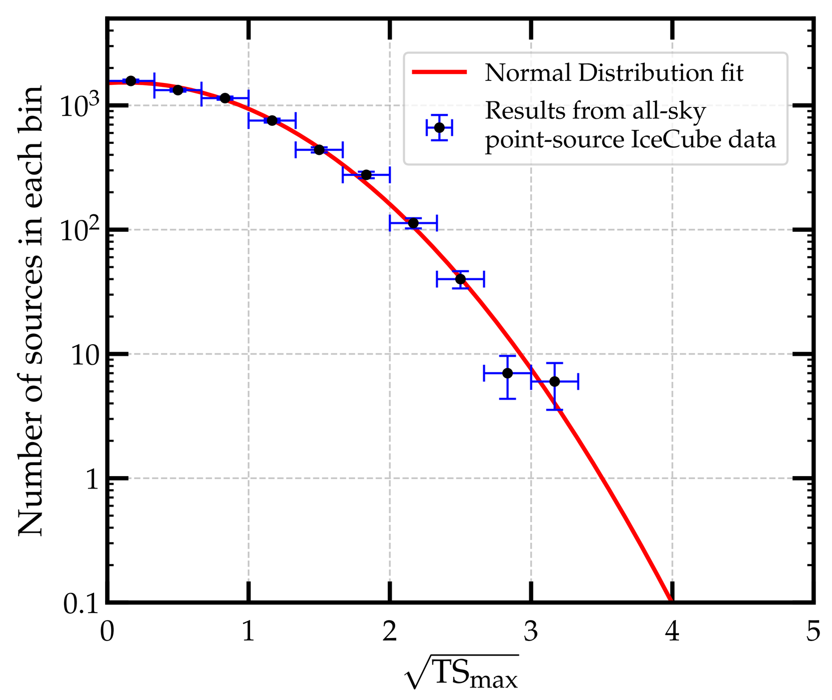


Fig: Distribution of maximized TS values for all galaxy mergers from our likelihood analysis with 10 years of IceCube muon-track data. The normal distribution favours the null hypothesis implying high-energy astrophysical neutrinos are not coming from galaxy mergers. (our work)

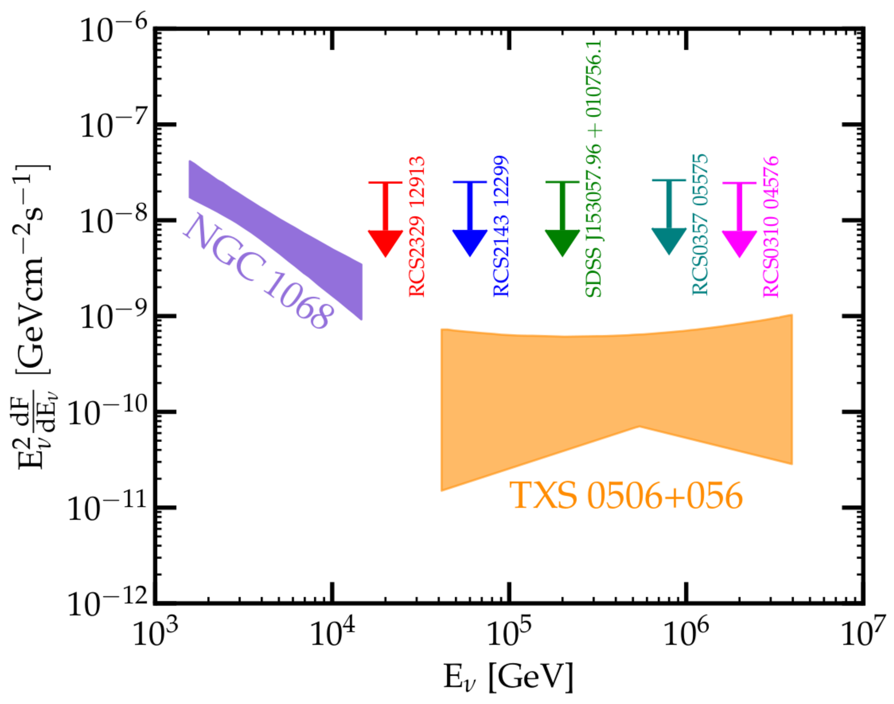


Fig: We present upper limits on the neutrino flux for the five most significant galaxy mergers, ranked according to their test statistics, based on our analysis of 10 years of muon event data from IceCube. We assume a spectral index of -2 for the neutrino flux. Additionally, we include the observed flux by IceCube for NGC 1068 and TXS 0506+056 for the purpose of comparison. (our work)

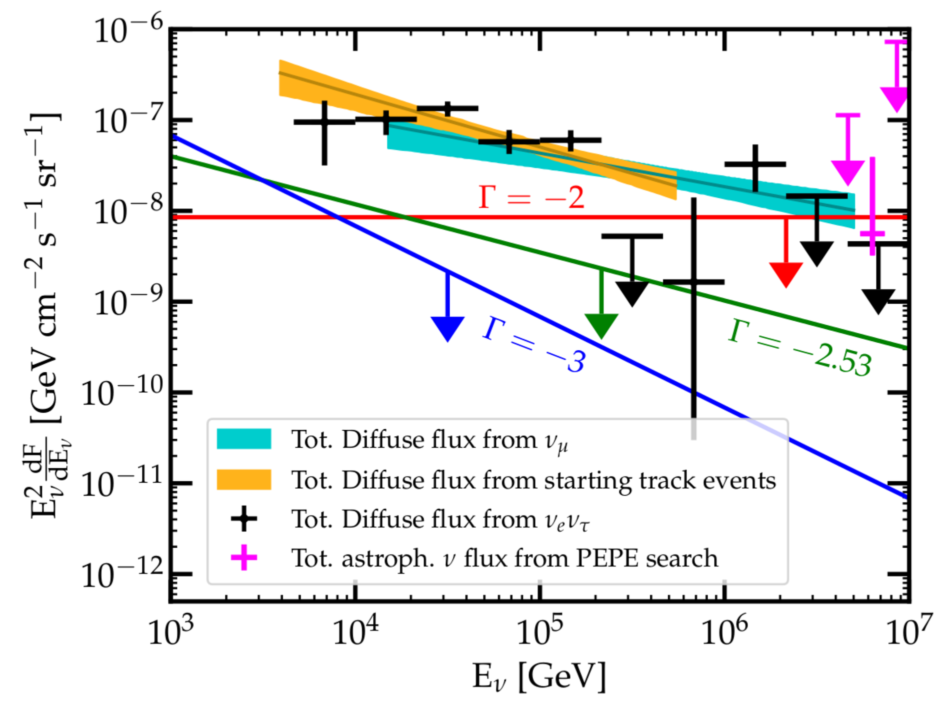


Fig: All six-flavor neutrino energy fluxes vs. neutrino energy combining all the galaxy mergers in the six catalogs for the luminosity distance weighting scheme. The cyan-shaded and orange regions indicate the astrophysical diffuse high-energy neutrino flux measured by IceCube using muon-neutrino and starting track events, respectively. The black data points with error bars represent the total measured astrophysical diffuse high-energy neutrino flux from electron and tau neutrino channels combined by IceCube. The magenta points show the measured total astrophysical neutrino flux from the PEPE analysis. The spectral index of signal neutrinos is Γ. (our work)

Conclusions

- We search for high-energy neutrinos from various galaxy mergers. We do not find high-energy astrophysical neutrinos from any of the galaxy mergers that we consider.
- Our stacking analyses show no significant correlation between our selected galaxy mergers and IceCube neutrinos with the current data set. At 100 TeV, these catalogs accounts for at most 19.69% (Γ = -2.00) of the tot. astroph. diffuse flux measured by IceCube measured from muon-neutrino channel for luminosity distance weighting.
- We conclude that known galaxy mergers from the six catalogs do not contribute significantly to the diffuse neutrino flux detected by IceCube. Our study implies strong constraints on very high-energy hadronic cosmic-ray acceleration in galaxy mergers. Near future searches of neutrinos from galaxy mergers can either discover their neutrino production or produce even more stringent constraints on their very high-energy hadronic acceleration mechanism.

References

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2. Kazumi Kashiyama and Peter Meszaros, The Astrophysical Journal 790 L14 (2014) [arXiv:1405.3262]
3. Chengchao Yuan et al 2018 ApJ 857 50 [arXiv:1712.09754]
4. R. Abbasi et al., Science 378, 6619, 538-543 (2022) [arXiv:2211.09972]
5. My thesis in pictures, Kunal Deoskar