Search for extragalactic astrophysical counterparts of IceCube neutrino events

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INTRODUCTION:

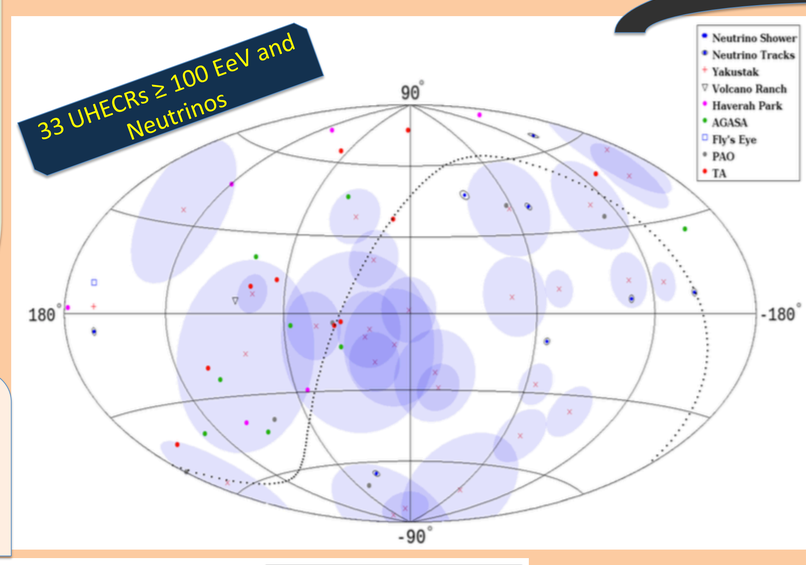
- IceCube Neutrino Observatory, the world's largest neutrino detector, has recently published detection of 37 neutrino events collected over 3-year period with energy in 30 TeV–2 PeV range [1].
- Out of 37 events 15 could be due to atmospheric neutrino $6.6^{+5.9}_{-1.6}$ and $8.4^{+4.2}_{-4.2}$ muon backgrounds.
- A background-only origin of all 37 events has been rejected at 5.7-σ level [1]. Therefore a cosmic origin of a number of neutrino events is robust.
- The track events have on average ~1° angular resolution, but the dominant, shower events have much poorer angular resolution, ~ 15° on average.
- Recently IceCube have updated their number of observed neutrino events to 54, in 4 years [2]. Out of 54, 6 are track events and the rest are showers.

Correlation study of IceCube neutrino events and sources from *Swift*-BAT 70 month X-ray source catalog [4], *Fermi* Third Catalog of Active Galactic Nuclei (3LAC) extended to low galactic latitudes [5], TeVCat [6].

MOTIVATION:

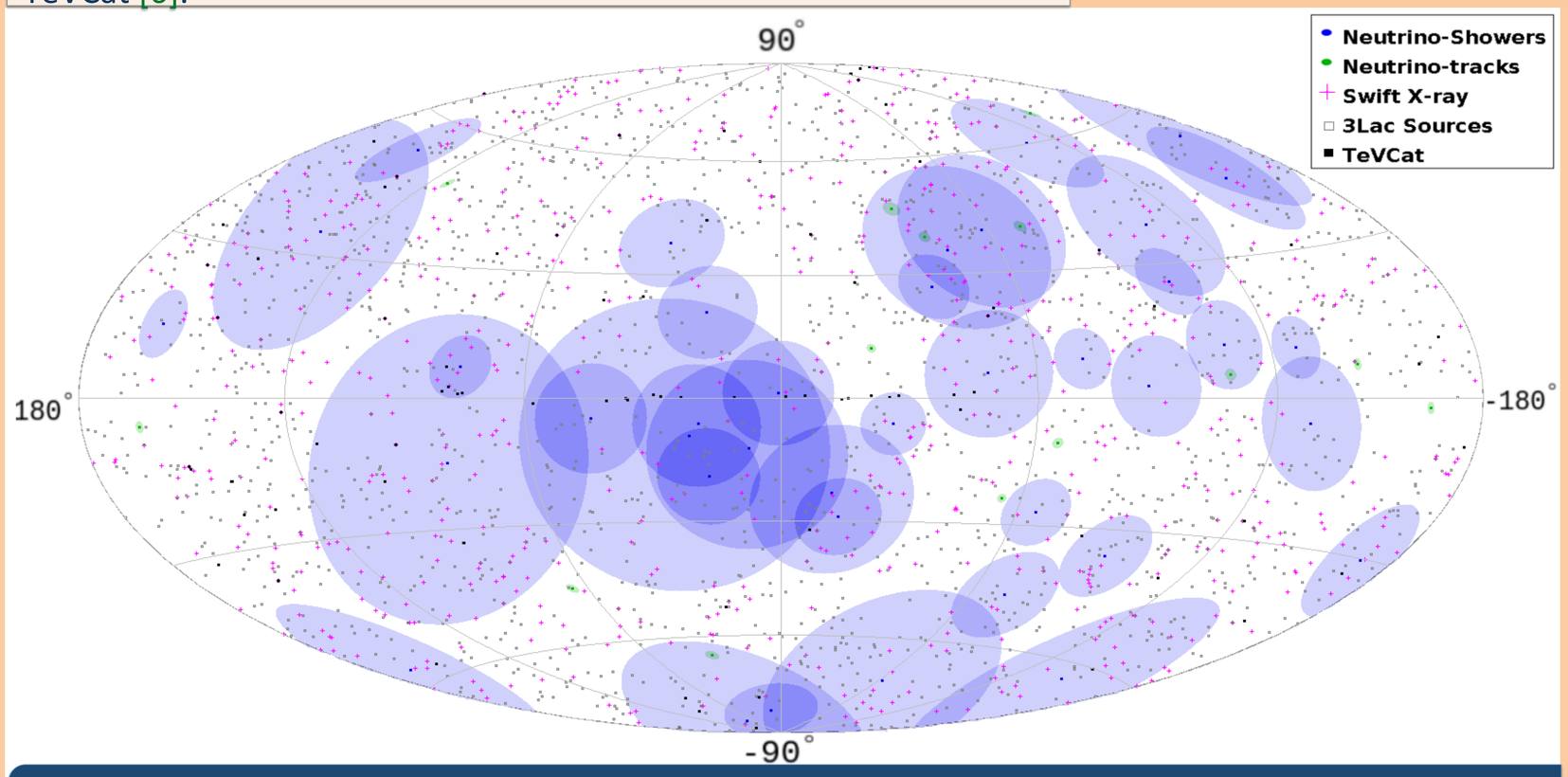
- High energy cosmic rays (CRs) can interact with low energy photons and/or low energy protons to produce neutrinos and high energy gamma rays inside the source or while propagating to earth. So a multi-messenger study of neutrinos, Cosmic Rays and gamma-rays can identify the possible astrophysical sources.
- A correlation of Ultra-High Energy (UHE) CRs with the 37 cosmic neutrino events [3], show 90% CL of 6 only Pierre Auger Observatory [PAO] and all available UHECR events above 100 EeV.

More Results



Neutrino Event #	UHECR RA	UHECR Dec	UHECR Experiment	*Swift* X-ray Source Catalog [24] Name	z	Type
1	45.6	−1.7	PAO	NGC 1142	0.0289	Sy2
				NGC 1194	0.0136	Sy1
				MCG +00-09-042	0.0238	Sy2
				NGC 1068	0.0038	Sy2
11	150.1	−10.3	PAO	2MASX J10084862-0954510	0.0573	Sy1.8
17	241.5	23	AGASA	2MASX J16311554+2352577	0.0590	Sy2
29, 34	295.6	43.52	TA	2MASX J19471938+4449425	0.0539	Sy2
				ABELL 2319	0.0557	GC
				Cygnus A	0.0561	Sy2
21	352.6	−20.2	PAO	PKS 2331-240	0.0477	Sy2
2, 24, 25	294.5	−5.8	AGASA	2MASX J19373299-0613046	0.0103	Sy1.5
34	340.6	12	PAO	MCG +01-57-016	0.0250	Sy1.8
				MCG +02-57-002	0.0290	Sy1.5
				UGC 12237	0.0283	Sy2
	349.0	12.3	AGASA	NGC 7479	0.0079	Sy2/Liner
				2MASX J23272195+1524375	0.0457	Sy1
				NGC 7469	0.0163	Sy1.2
	352.6	−20.2	Haverah Park	NGC 7679	0.0171	Sy2

Neutrino Event #	UHECR RA	UHECR Dec	UHECR Experiment	Kühr Radio Source Catalog [25] Name	z	Type
1	45.6	−1.7	PAO	NGC 1068	0.0038	Sy2
21	352.6	−20.8	PAO	PKS 2331-240	0.0477	Sy2
34	340.6	12	PAO	NGC 7385	0.0255	GC



Sky map of the 53 IceCube cosmic neutrino events with error circles and extragalactic sources from different catalogs in Galactic coordinate system.

STATISTICAL METHOD:

- Right Ascension and Declination (ϕ = RA, θ = π/2 − Dec) of the event directions and sources into unit vectors as,

$$\hat{x} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)^T.$$

- Scalar product of the neutrino and source vectors is independent of the coordinate system, and the angle between them is a invariant measure.

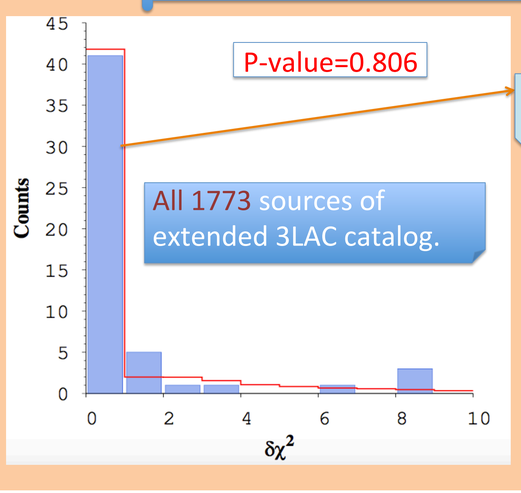
$$\gamma = \cos^{-1}(\hat{x}_{\rm neutrino} \cdot \hat{x}_{\rm source})$$

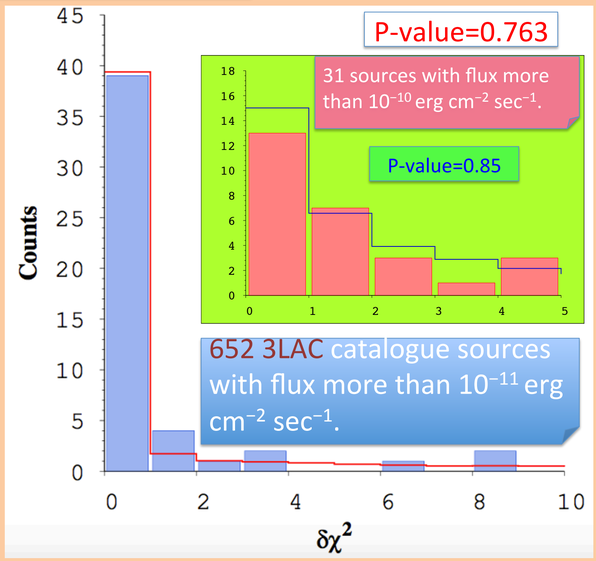
- The static from the angle is done as in [4],

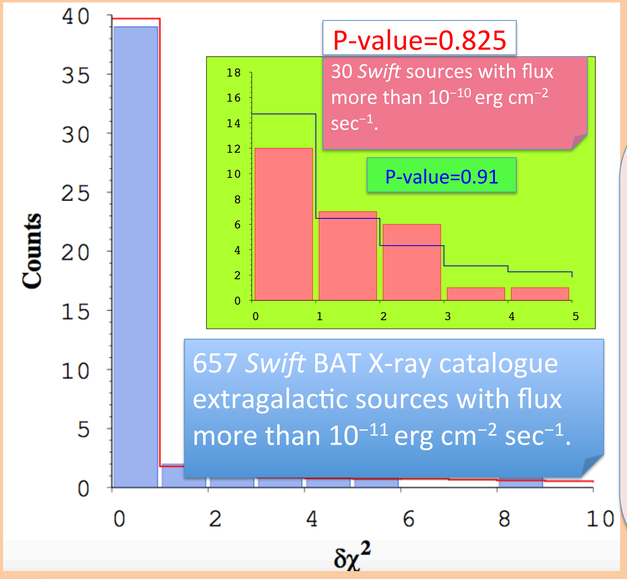
$$\delta\chi_i^2 = \min_j(\gamma_{ij}^2/\delta\gamma_i^2)$$

- A value $\delta\chi2_i \leq 1$ is a "good match" between the *i*-th neutrino and a source arrival directions .

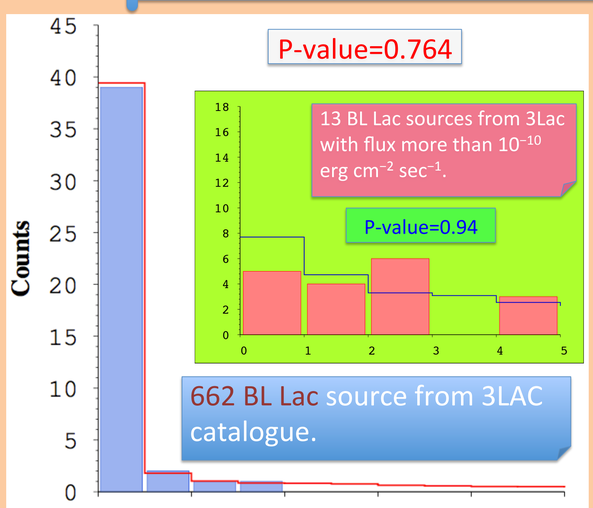
Correlation study with constraints on flux.

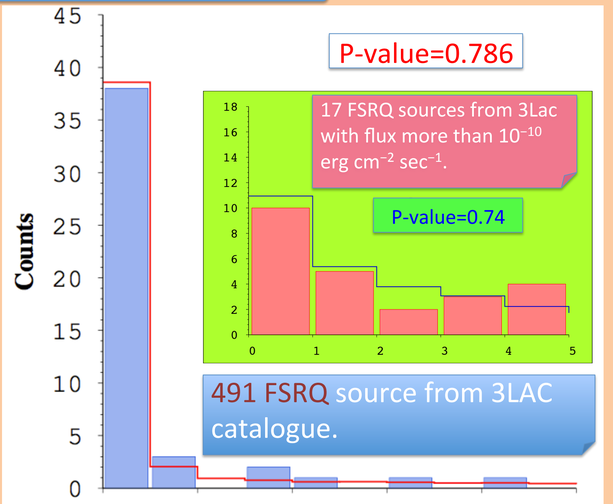


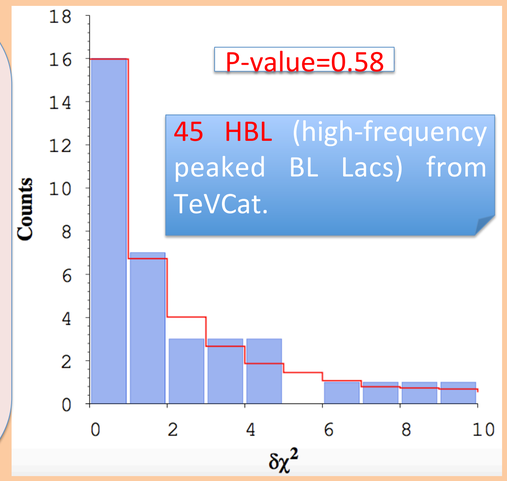




Different class of sources







SUMMARY

- We investigated correlation of the arrival directions of cosmic neutrinos, detected by IceCube, with energy with the arrival directions of ≥ 100 EeV UHECRs.
- We searched for astrophysical sources in the Swift-BAT X-ray catalog, the Kühr radio source catalog and Fermi-LAT 1LAC AGN catalog within 3° error circles of the ≥ 100 EeV UHECRs which are correlated with cosmic neutrino events.
- Galaxy cluster ABELL 2319, NGC 7385 and radio galaxy Cygnus A are the promising candidates of neutrinos as well as UHECRs, others are mostly radio-quite AGNs.
- A correlation of IceCube neutrino events with different source catalogs, 3LAC, TeVCaT has been started.

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