Possible extragalactic astrophysical counterparts of IceCube neutrino events.

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with

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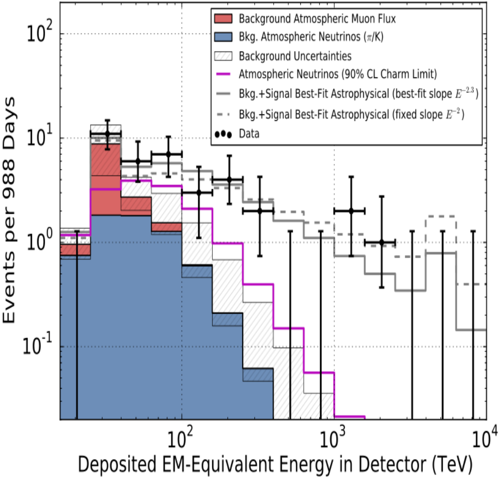
June 10, 2015

IceCube Neutrinos

- Icecube results 2010-2013.
- Total 37 events detected, 28 cascades, 9 tracks of which 1 coincident muon event.
- Over background expectation $15.0^{+7.2}_{-4.5}$ of which atmospheric muons 8.4 ± 4.2 and atmospheric neutrinos $6.6^{5.9}_{-1.6}$.
- Rejecting only background origin with 5.7σ level.
- Best fit flux $E^2\phi = (0.95 \pm 0.3) \times 10^{-8}[\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}]$ with hard cutoff at 2 PeV or a softer spectra with spectral index $\gamma = 2.3 \pm 0.3$.

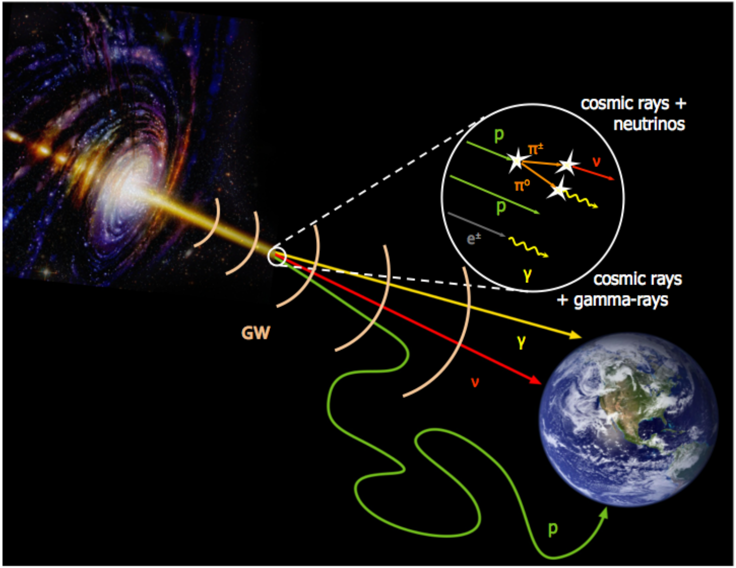


M.G. Aartsen et.al., PRL 113, 2014

ID	Dep. Energy (TeV)	Observation Time (MJD)	Decl. (deg.)	R.A. (deg.)	Med. Angular Error (deg.)	Event Topology
1	$47.6^{+6.5}_{-5.4}$	55351.3222143	−1.8	35.2	16.3	Shower
2	117^{+15}_{-15}	55351.4659661	−28.0	282.6	25.4	Shower
3	$78.7^{+10.8}_{-8.7}$	55451.0707482	−31.2	127.9	$\lesssim 1.4$	Track
4	165^{+20}_{-15}	55477.3930984	−51.2	169.5	7.1	Shower
5	$71.4^{+9.0}_{-9.0}$	55512.5516311	−0.4	110.6	$\lesssim 1.2$	Track
6	$28.4^{+2.7}_{-2.5}$	55567.6388127	−27.2	133.9	9.8	Shower
7	$34.3^{+3.5}_{-4.3}$	55571.2585362	−45.1	15.6	24.1	Shower
8	$32.6^{+10.3}_{-11.1}$	55608.8201315	−21.2	182.4	$\lesssim 1.3$	Track
9	$63.2^{+7.1}_{-8.0}$	55685.6629713	33.6	151.3	16.5	Shower
10	$97.2^{+10.4}_{-12.4}$	55695.2730461	−29.4	5.0	8.1	Shower
11	$88.4^{+12.5}_{-10.7}$	55714.5909345	−8.9	155.3	16.7	Shower
12	104^{+13}_{-13}	55739.4411232	−52.8	296.1	9.8	Shower
13	253^{+26}_{-22}	55756.1129844	40.3	67.9	$\lesssim 1.2$	Track
14	1041^{+132}_{-144}	55782.5161911	−27.9	265.6	13.2	Shower
15	$57.5^{+8.3}_{-7.8}$	55783.1854223	−49.7	287.3	19.7	Shower
16	$30.6^{+3.6}_{-3.5}$	55798.6271285	−22.6	192.1	19.4	Shower
17	200^{+27}_{-27}	55800.3755483	14.5	247.4	11.6	Shower
18	$31.5^{+4.6}_{-3.3}$	55923.5318204	−24.8	345.6	$\lesssim 1.3$	Track
19	$71.5^{+7.0}_{-7.2}$	55925.7958619	−59.7	76.9	9.7	Shower
20	1141^{+143}_{-133}	55929.3986279	−67.2	38.3	10.7	Shower
21	$30.2^{+3.5}_{-3.3}$	55936.5416484	−24.0	9.0	20.9	Shower
22	220^{+21}_{-24}	55941.9757813	−22.1	293.7	12.1	Shower
23	$82.2^{+8.6}_{-8.4}$	55949.5693228	−13.2	208.7	$\lesssim 1.9$	Track
24	$30.5^{+3.2}_{-2.6}$	55950.8474912	−15.1	282.2	15.5	Shower
25	$33.5^{+4.9}_{-5.0}$	55966.7422488	−14.5	286.0	46.3	Shower
26	210^{+29}_{-26}	55979.2551750	22.7	143.4	11.8	Shower
27	$60.2^{+5.6}_{-5.6}$	56008.6845644	−12.6	121.7	6.6	Shower
28	$46.1^{+5.7}_{-4.4}$	56048.5704209	−71.5	164.8	$\lesssim 1.3$	Track
29	$32.7^{+3.2}_{-2.9}$	56108.2572046	41.0	298.1	7.4	Shower
30	129^{+14}_{-12}	56115.7283574	−82.7	103.2	8.0	Shower
31	$42.5^{+5.4}_{-5.7}$	56176.3914143	78.3	146.1	26.0	Shower
32	—	56211.7401231	—	—	—	Coincident
33	385^{+46}_{-49}	56221.3424023	7.8	292.5	13.5	Shower
34	$42.1^{+6.5}_{-6.3}$	56228.6055226	31.3	323.4	42.7	Shower
35	2004^{+236}_{-262}	56265.1338677	−55.8	208.4	15.9	Shower
36	$28.9^{+3.0}_{-2.6}$	56308.1642740	−3.0	257.7	11.7	Shower
37	$30.8^{+3.3}_{-3.5}$	56390.1887627	20.7	167.3	$\lesssim 1.2$	Track

Motivation

- Propagation of UHECRs, Gamma rays and Neutrinos.

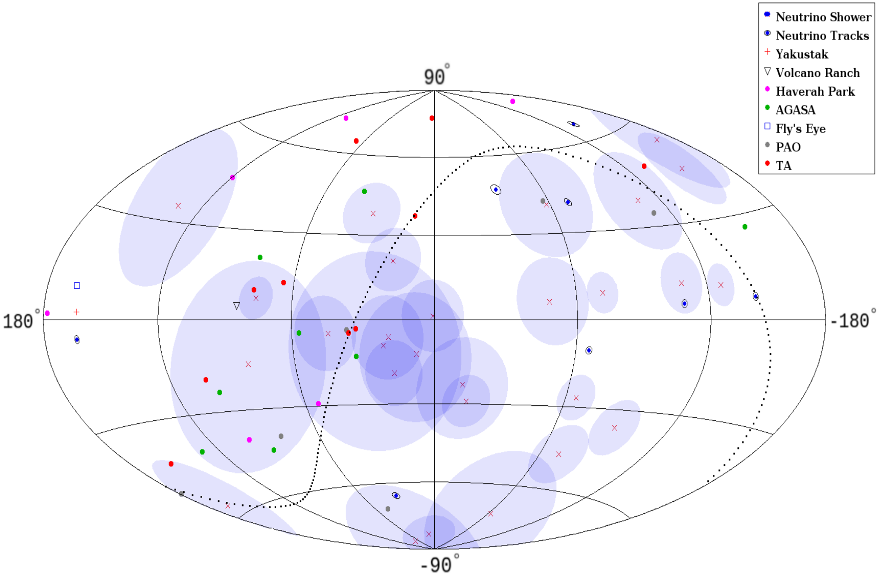


- PAO covers southern sky, $-90^{\circ} \leq Dec \leq 45^{\circ}$.
- Telescope Array (TA), Utah. More than 500 scintillator detectors covering 700 km^2 area. It covers Northen part of the sky with declination, $-10^{\circ} \leq Dec \leq 90^{\circ}$.
- Angular resolution for PAO above 10 EeV is 0.9°, while for TA it is $1.0 - 1.7^{\circ}$
- PAO has detected 6 events above 100 EeV in 10 yrs while Telescope array has detected 10 in 5 yrs of its operation, and in total 33 public events by other past experiments.

Experiment	Reference	Energy (EeV)	RA (°)	Dec (°)
Haverah Park	[10]	101	201	71
Haverah Park	[10]	116	353	19
Haverah Park	[10]	126	179	27
Haverah Park	[10]	159	199	44
Haverah Park	[11]	123	318.3	3.0
Haverah Park	[11]	115	86.7	31.7
Yakutsk	[10]	110	75.2	45.5
AGASA	[12]	101	124.25	16.8
AGASA	[12]	213	18.75	21.1
AGASA	[12]	106	281.25	48.3
AGASA	[12]	144	241.5	23.0
AGASA	[12]	105	298.5	18.7
AGASA	[12]	150	294.5	-5.8
AGASA	[12]	120	349.0	12.3
AGASA	[12]	104	345.75	33.9
Volcano Ranch	[10]	135	306.7	46.8
Fly's eye	[10]	320	85.2 ± 0.5	$48.0^{+5.2}_{-6.3}$
Pierre Auger	[2]	108.2	45.6	-1.7
Pierre Auger	[2]	127.1	192.8	-21.2
Pierre Auger	[2]	111.8	352.6	-20.8
Pierre Auger	[2]	118.3	287.7	1.5
Pierre Auger	[2]	100.1	150.1	-10.3
Pierre Auger	[2]	118.3	340.6	12.0
Telescope Array	[3]	101.4	285.74	-1.69
Telescope Array	[3]	120.3	285.46	33.62
Telescope Array	[3]	139.0	152.27	11.10
Telescope Array	[3]	122.2	347.73	39.46
Telescope Array	[3]	154.3	239.85	-0.41
Telescope Array	[3]	162.2	205.08	20.05
Telescope Array	[3]	124.8	295.61	43.53
Telescope Array	[3]	135.5	288.30	0.34
Telescope Array	[3]	101.0	219.66	38.46
Telescope Array	[3]	106.8	37.59	13.89

(2) *A.Aab et al., [Pierre Auger Collaboration] arXiv: 1411.6111*
(3) *R. U. Abbasi et al., [Telescope Array Collaboration] APJ 790, 2014*
(10) *M Nagano and A.A Watson, Rev. Mod. Phys. 2000*
(11) *M. Ave et al., PRL 85 2000*
(12) *M. Takeda et al., APJ 522, 1999*

33 UHECRs > 100 EeV and Neutrinos



Statistical method for analyzing correlation

A. Virmani et al., Astropart. Phys. 17, 2002

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

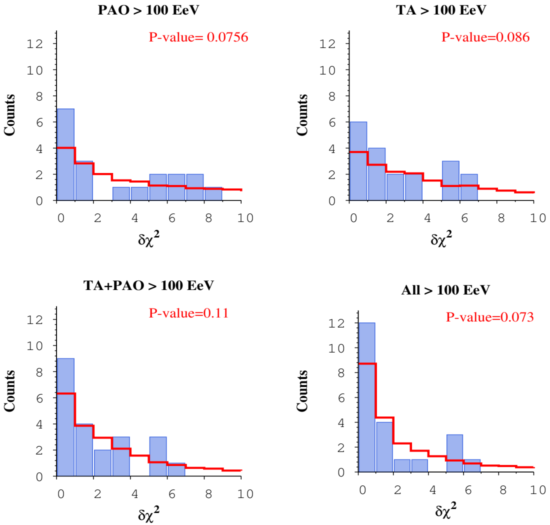
where $\phi = RA$ and $\theta = \pi/2 - Dec$.
Angle between neutrino and UHECR vectors $(\hat{x}_{\rm neutrino}, \hat{x}_{\rm UHECR})$

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

For each neutrino direction $\hat{x}_i$ and UHECR direction $\hat{x}_j$ pair as

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

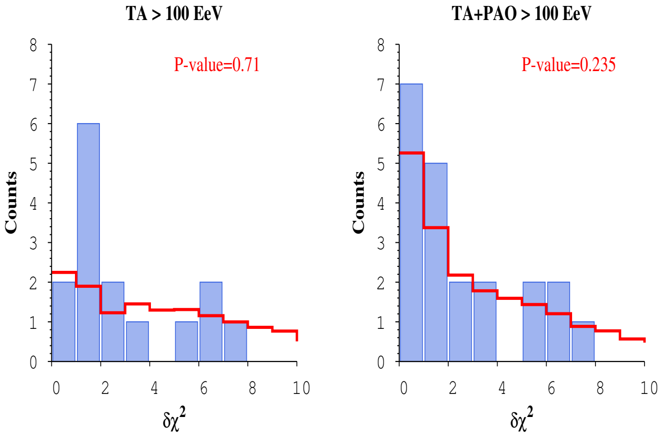
which is minimized for all j.
The distribution with observed data giving a number of "hits" or $N_{\rm hits}$ with $\delta\chi^2 \leq 1$ therefore forms a basis to claim correlation.
Statistical significance of correlation in real data or p-value can be calculated, using frequentists' approach, by counting the number of times we get $N_{\rm hits}$ or more with $\delta\chi^2 \leq 1$ in simulated events divided by the number of realizations.



Reetanjali Moharana & Soebur Razzaque, arXiv:1501.05158

Energy calibrated Analysis of correlation.

A. Aab et. al., APJ 794, 2014



ν event no. [1]	$\delta\chi^2$	Energy (EeV)	RA (°)	Dec (°)	Experiment
1	0.41	108.2	45.6	−1.7	PAO
	0.95	106.8	37.59	13.9	TA
2	0.97	150	294.5	−5.8	AGASA
11	0.10	100.1	150.1	−10.3	PAO
16	0.006	127.1	192.8	−21.2	PAO
17	0.77	144	241.5	23.0	AGASA
21	0.55	111.8	352.6	−20.8	PAO
24	0.78	101.4	285.74	−1.7	TA
	0.97	150	294.5	−5.8	AGASA
25	0.06	150	294.5	−5.8	AGASA
	0.07	101.4	285.74	−1.7	TA
	0.10	135.5	288.3	0.34	TA
	0.12	118.3	287.7	1.5	PAO
	0.58	105	298.5	18.7	AGASA
	0.62	123	318.3	3	Haverah Park
29	0.18	124.8	295.6	43.52	TA
31	0.35	101	201	71	Haverah Park
33	0.34	118.3	287.7	1.5	PAO
	0.40	135.5	288.3	0.34	TA
	0.74	101.4	285.74	−1.7	TA
	0.84	105	298.5	18.7	AGASA
34	0.20	104	345.75	34	AGASA
	0.22	135	306.7	46.8	Volcano Ranch
	0.25	122.2	347.7	39.46	TA
	0.34	118	340.6	12	PAO
	0.34	124.8	295.61	43.53	TA
	0.36	105	298.5	18.7	AGASA
	0.45	123	318.3	3	Haverah Park
	0.47	116	353	19	Haverah Park
	0.50	120	349	12.3	AGASA
	0.55	120.3	285.5	33.62	TA
	0.71	134	281.25	48.3	AGASA

Astrophysical source search

Astrophysical source search

- Sources correlated with neutrinos and UHECRs simultaneously.
- Galactic and extragalactic magnetic field can deflect UHECRs to at least 3°
- Source search within a comoving volume with its radius set by the GZK effect (limiting sources within redshift $z = 0.06$)
- Swift-BAT 70 month X-ray source catalog
- the catalog includes 1210 objects of which 503 objects are within redshift ≤ 0.06. Out of these 503 X-ray selected objects at least 18 are simultaneously correlated with the neutrino events and UHECRs above 100 EeV
- Extragalactic radio sources with flux density nearly 1 Jy at 5 MHz from Kuhr Catalog. 61 Sources within redshift 0.06. Only 3 sources correlated.

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- Extragalactic radio sources with flux density nearly 1 Jy at 5 MHz from Kuhr Catalog. 61 Sources within redshift 0.06. Only 3 sources correlated.

Neutrino Event #	UHECR			Swift X-ray Source Catalog [24]		
	RA	Dec	Experiment	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			Kühr Radio Source Catalog [25]		
	RA	Dec	Experiment	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

[24]*W.H. Baumgartner et., al., arXiv:1212.3336*

[25]H. Kuhr et., al, A & A Suppl. Ser 45, 1981.

Neutrino luminosity

Neutrino power-law flux,

$$J_{\nu_\alpha}(E_\nu) = A_{\nu_\alpha} \left(\frac{E_\nu}{100 \text{ TeV}} \right)^{-\kappa} .$$

Normalization factor from the number of neutrino events, N_ν for all 3 flavors, α

$$A_{\nu_\alpha} = \frac{1}{3} \frac{N_\nu}{T \sum_\alpha \int_{E_{\nu 1}}^{E_{\nu 2}} dE_\nu \, A_{\text{eff},\alpha}(E_\nu) \left(\frac{E_\nu}{100 \text{ TeV}} \right)^{-\kappa}},$$

where T is the time period of IceCube.
Neutrino luminosity for the particular source with luminosity distance d_L

$$L_\nu = 4\pi d_L^2 \sum_\alpha \int_{E_{\nu 1}(1+z)}^{E_{\nu 2}(1+z)} dE_\nu \, E_\nu \, J_{\nu,\alpha}(E_\nu).$$

UHECRs luminosity

UHECR power-law flux,

$$J_{\rm uhecr}(E_{\rm cr}) = A_{\rm uhecr}\left(\frac{E_{\rm cr}}{\rm EeV}\right)^{-4.3} \;;\; E_{\rm cr} \geq 28.8 \ {\rm EeV},$$

Normalization factor from the number of UHECR events, N_{UHECRs}

$$A_{\rm uhecr} = \frac{N_{\rm uhecr}}{\frac{\Xi\omega(\delta)}{\Omega}\int_{E_{\rm cr1}}^{E_{\rm cr2}} dE_{\rm cr}\left(\frac{E_{\rm cr}}{\rm EeV}\right)^{-4.3}}.$$

Here Ξ is the total integrated exposure, Ω is the solid angle of the detector and $\omega(\delta)$ is the relative exposure for particular declination angle δ.

Extrapolating cosmic-ray flux to energy 500 TeV,

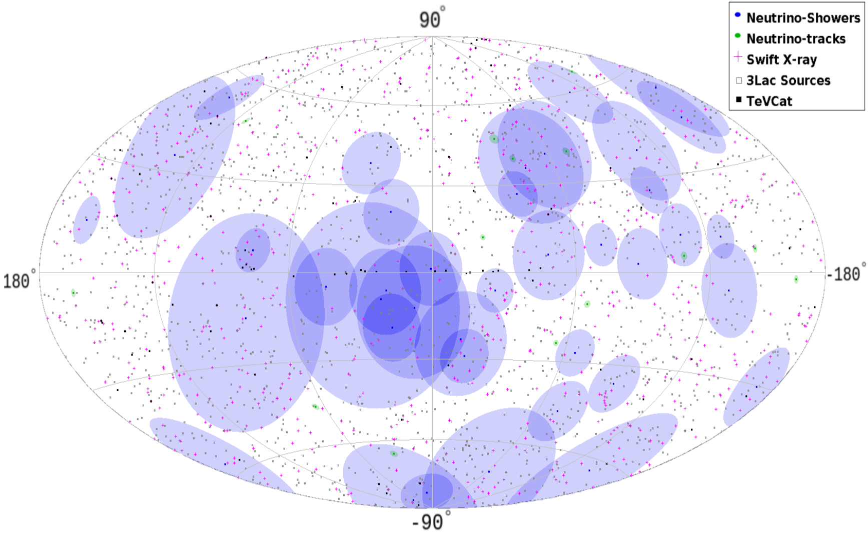
$$J_{\rm cr}(E_{\rm cr}) = \frac{L_{\rm cr}(1+z)}{4\pi d_L^2}\frac{(\kappa-2)(E'_{\rm cr1}E'_{\rm cr2})^{\kappa-2}}{E'^{\kappa-2}_{\rm cr2} - E'^{\kappa-2}_{\rm cr1}} E'^{-\kappa}_{\rm cr}\left(\frac{dE'_{\rm cr}}{dE_{\rm cr}}\right).$$

$E'_{\rm cr1} = 500$ TeV and $E'_{\rm cr2} = 180$ EeV with $\propto E'^{-\kappa}_{\rm cr}$

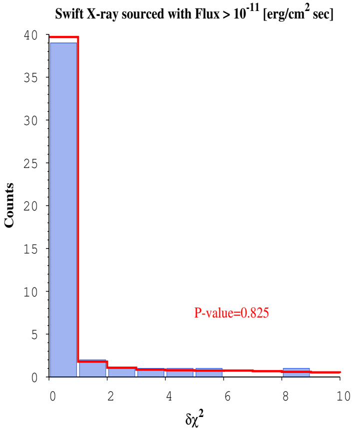
Source name	L_X (10^{44} erg/s) $/L_R$ (10^{41} erg/s)	L_ν (10^{44} erg/s) $\kappa = 2.1$	$= 2.3$	L_{cr} (10^{44} erg/s) $\kappa = 2.1$	$= 2.3$
NGC 1142	1.58/0.012(74 GHz)	0.95	1.0	0.7	5.4
NGC 1194	0.12/0.00012(1.4 GHz)	0.2	0.2	0.04	0.2
MCG +00-09-042	0.17/0.0043(1.4 GHz)	0.64	0.71	0.3	2.1
NGC 1068	0.031/0.0034(31.4 GHz)	0.016	0.017	0.001	0.007
2MASX J10084862-0954510	1.04/0.0028(1.4 GHz)	3.9	4.32	44	578
2MASX J16311554+2352577	0.79/0.0048(1.4 GHz)	4.1	4.6	1600	22000
2MASX J19471938+4449425	1.66/0.0045(1.4 GHz)	6.8	7.6	211	26000
ABELL 2319	1.78/0.0046(1.4 GHz)	3.7	4.1	270	3500
Cygnus A	11.2/314(14.7 GHz)	3.7	4.1	290	3700
PKS 2331-240	0.81/1.32(31.4 GHz)	2.6	2.9	9.5	102
2MASX J19373299-0613046	0.055/0.0012(1.4 GHz)	0.24	0.26	1.3	7.3
MCG +01-57-016	0.23/0.0026(1.4 GHz)	0.71	0.78	0.5	3.6
MCG +02-57-002	0.25/0.00084(1.4 GHz)	0.95	1.1	1.0	7.5
UGC 12237	0.23/0.0011(1.4 GHz)	0.91	1.	0.9	6.6
NGC 7479	0.029/0.04(22 GHz)	0.07	0.08	0.3	1.4
2MASX J23272195+1524375	0.51/0.24(1.4 GHz)	2.4	2.7	280	2900
NGC 7469	0.4/0.0056(365 MHz)	0.3	0.3	2.2	14
NGC 7679	0.1/0.00033(1.4 GHz)	-	-	-	-
NGC 1068	0.031/0.0034(31.4 GHz)	0.016	0.017	0.001	0.007
PKS 2331-240	0.81/1.32(31.4 GHz)	2.6	2.9	9.5	102
NGC 7385	- /0.17(31.4 GHz)	0.7	0.8	0.5	4.0

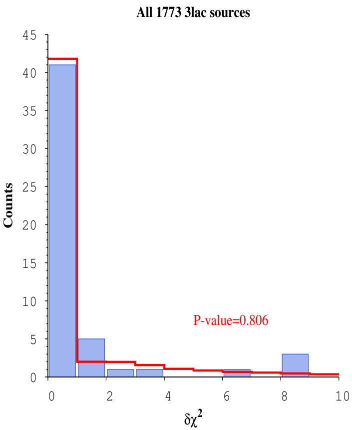

4 year HESE
ICECUBE PRELIMINARY
Galactic
TS=2log(L/L0)
where do they come from?

1773 3Lac sources (*M. Ackermann et., al, arXiv: 150106054*), *687 Swift BAT X-ray sources, TeVCat sources*



Neutrino and source correlation





Summary

Summary

- We have investigated whether the arrival directions of cosmic neutrinos, detected by IceCube, with energy ~ 30 TeV–2 PeV are correlated with the arrival directions of UHECRs with energy $\gtrsim 100$ EeV.
- We found that IceCube cosmic neutrinos are correlated with UHECRs with energy ≥ 100 EeV with significance at 90% CL.
- We have 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 has been started.

Thank you

Synchrotron loss of pion/muon energy

- The charged pion and muon, lose energy due to synchrotron radiation.

  $*$ Synchrotron loss time of pion in magnetic field energy density (U_B) in CM frame,

$$t_{\rm syn} = \frac{3m_\pi^4 c^3}{4\sigma_T m_e^2 \varepsilon_\pi U_B'}.$$

  $*$ pion lifetime for decay,

$$\tau_\pi \approx 2.6 \times 10^{-8}\ \varepsilon_\pi'/(m_\pi c^2)\ \mathrm{s}$$

- Comparing two, the break energy in neutrino spectrum due to synchrotron loss of muon energy,

(as pion loss is 10 times of muon loss due to synchrotron radiation).

$$\epsilon_{\nu,\mu}^s = 2.56 \times 10^6 \epsilon_e^{1/2} \epsilon_B^{-1/2} L_{\gamma,51}^{-1/2} \Gamma_{300}^4 t_{v,-3} \mathrm{GeV}$$

Cont...

The break energy in neutrino spectrum due to synchrotron loss of muon energy, (as pion loss is 10 times of muon loss due to synchrotron radiation).

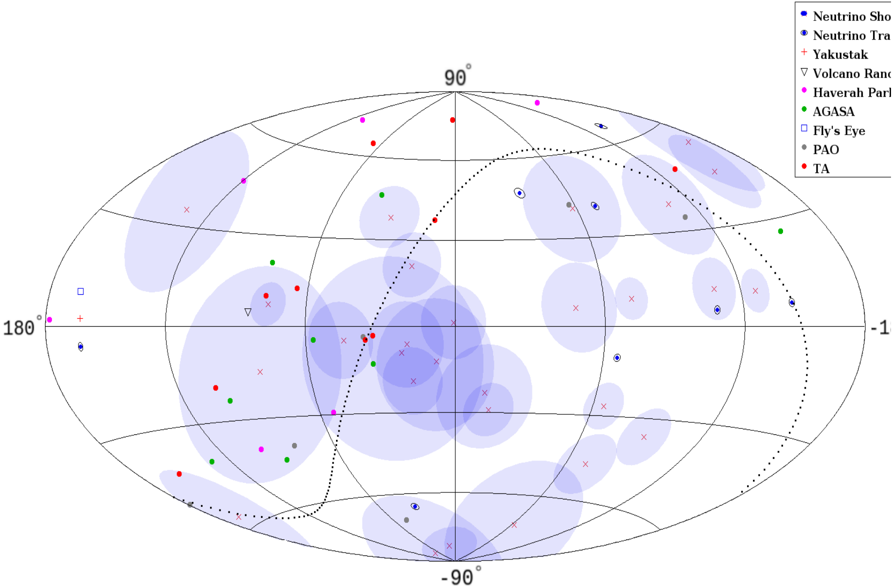
$$\epsilon^s_{\nu,\mu} = 2.56 \times 10^6 \epsilon_e^{1/2} \epsilon_B^{-1/2} L_{\gamma,51}^{-1/2} \Gamma_{300}^4 t_{v,-3} \mathrm{GeV}$$

• Synchrotron loss time of pion in magnetic field energy density (U_B) in CM frame,

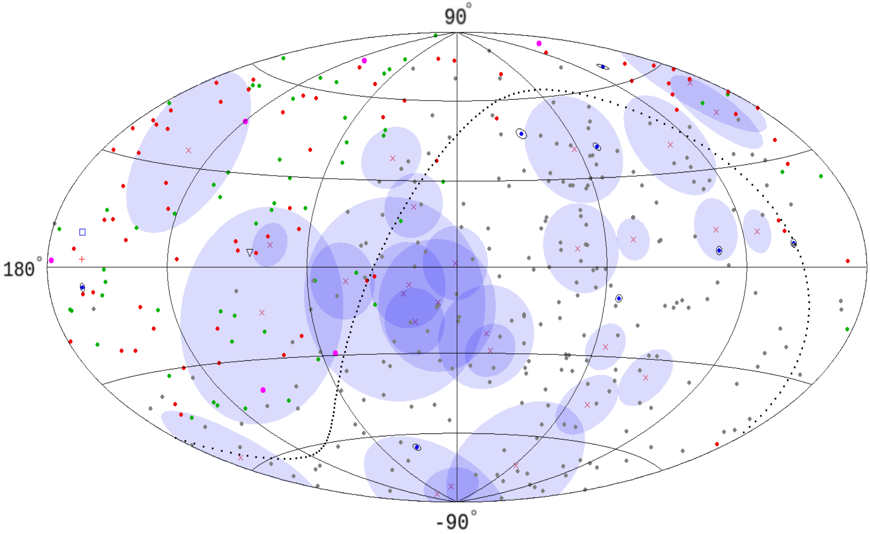
$$t_{\rm syn} = \frac{3 m_\pi^4 c^3}{4 \sigma_T m_e^2 \varepsilon_\pi U_B}.$$

• pion lifetime for decay,

$$\tau_\pi \approx 2.6 \times 10^{-8}\ \varepsilon'_\pi/(m_\pi c^2)\ \mathrm{s}$$



Neutrino Sho
Neutrino Tra
Yakustak
Volcano Ranc
Haverah Parl
AGASA
Fly's Eye
PAO
TA
90°
180°
-1
-90°

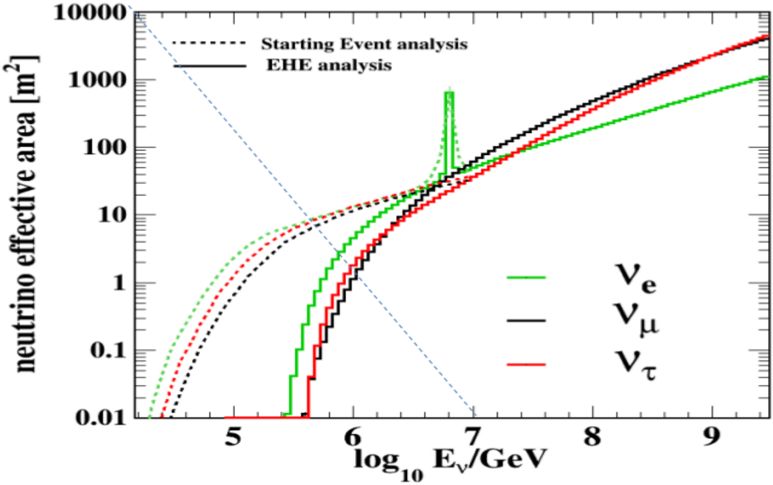


90°
180°
-90°

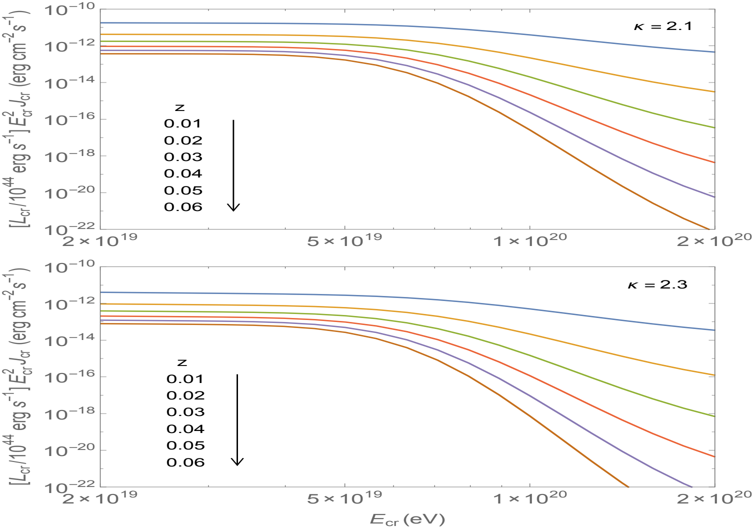
$$\delta\theta_{\rm IG} \approx 1.1^\circ Z \left(\frac{E_{\rm cr}}{100\ {\rm EeV}}\right)^{-1} \left(\frac{B_{\rm rdm}}{1\ {\rm nG}}\right) \left(\frac{D}{200\ {\rm Mpc}}\right)^{1/2} \left(\frac{\lambda_{\rm coh}}{100\ {\rm kpc}}\right)^{1/2}$$

$$A_{\text{eff},e} = \left[0.493\,(E_\nu/\text{TeV})^{0.5} - 2.227\right]\ \text{m}^2,$$
$$A_{\text{eff},\mu} = \left[0.466\,(E_\nu/\text{TeV})^{0.5} - 3.393\right]\ \text{m}^2,$$
$$A_{\text{eff},\tau} = \left[0.504\,(E_\nu/\text{TeV})^{0.5} - 3.020\right]\ \text{m}^2.$$

Area x ν flux x 4π x livetime = event rate



Here Ξ is the total integrated exposure, as mentioned in ref. [31], Ω is the solid angle of the detector and $\omega(\delta)$ is the relative exposure for particular declination angle δ. For reference, we use for PAO, $\Xi_{\mathrm{PAO}} = 66,000$ km^2 yr sr and $\Omega_{\mathrm{PAO}} = 1.65\pi$ sr [2]; for TA, $\Xi_{\mathrm{TA}} = 3,690$ km^2 yr sr and $\Omega_{\mathrm{TA}} = 0.85\pi$ sr [3]; for AGASA, $\Xi_{\mathrm{AGASA}} = 1,000$ km^2 yr sr and $\Omega_{\mathrm{AGASA}} = 0.59\pi$ sr [32]. We do not use the Haverah Park event that is correlated with a neutrino event. We calculate $\omega(\delta)$ from ref. [33] but adapt it for different experiments by using their respective geographical locations and zenith angle ranges. For the lower and upper limits of integration in Eq. (4.9), we use $E_{\mathrm{cr}1} = 80$ EeV and $E_{\mathrm{cr}2} = 180$ EeV, allowing a 20% uncertainty for the 100 EeV threshold energy used to search correlation and 150 EeV maximum energy found for


$\kappa = 2.1$
$\kappa = 2.3$
z
0.01
0.02
0.03
0.04
0.05
0.06
$[L_{cr}/10^{44}\,\mathrm{erg\,s^{-1}}]\,E_{cr}^2 J_{cr}\,(\mathrm{erg\,cm^{-2}\,s^{-1}})$
E_{cr} (eV)
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
2×10^{19}
5×10^{19}
1×10^{20}
2×10^{20}