Some possible sources of IceCube TeV-PeV neutrino events

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Abstract

The IceCube Collaboration has observed 37 neutrino events in the energy range $30\text{ TeV} \lesssim E_{\nu} \lesssim 2\text{ PeV}$ and the sources of these neutrinos are unknown. Here we have shown that positions of 9 high energy blazars and the position of the FR-I galaxy Centaurus A, coincide within the error circles of 10 IceCube events, the later being in the error circle of the highest energy event so far observed by IceCube. Two of the above blazars are simultaneously within the error circles of the Telescope Array hotspot and one IceCube event. We found that the blazar H2356-309 is within the error circles of three IceCube events. We propose that photohadronic interaction of the Fermi accelerated high energy protons with the synchrotron/SSC background photons in the nuclear region of these high energy blazars and AGN are probably responsible for some of the observed IceCube events.

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Introduction — In November 2012, the IceCube Collaboration announced the detection of two showerlike events with energies slightly above 1 PeV by analyzing the data taken during May 2010 - May 2012. These data were taken using the detectors from 79 strings and completed 86 strings with a total combined live time of 662 days. A follow-up analysis of the same data published in November 2013, revealed additional 26 events in the energy range \( \sim 30 \text{ TeV} - 250 \text{ TeV} \). The reconstruction of these 26 events shows that 21 events are showerlike, mostly caused by electron and tau neutrinos and 7 are muon track events. As claimed by the IceCube Collaboration, these 28 events have flavors, directions and energies inconsistent with those expected from the atmospheric muon and neutrino backgrounds and probably this is the first indication of extraterrestrial origin of high energy neutrinos. While the track events have uncertainty of order one degree in their arrival directions, the angular resolution for 21 shower events is poor, ranging from \( \sim 10^\circ \) to \( \sim 50^\circ \). The IceCube point source analysis of all these events ruled out any spatial clustering of events. Very recently, the third year (2012-2013) data analysis is announced which revealed additional 9 events of which two are track events and rest are shower events. The event 35 is the most energetic one so far and has energy \( \sim 2 \text{ PeV} \). In the full 988-day data, the muon background is expected to be \( 8.4 \pm 4.2 \) and the atmospheric neutrino is \( 6.6^{+5.9}_{-1.8} \). Five events are downgoing muons and are consistent with the expected background muon events. This shows that the IceCube events are predominantly shower events. As it is anticipated, the atmospheric neutrinos up to TeV energies exhibit a muon flavor dominance but the IceCube result contradicts this and is consistent with equal fluxes of all the three flavors. Observation of these neutrino events triggered a lot of excitement to understand their origin, production mechanism etc. While interpreting these events in terms of astrophysical models seems challenging, several possible galactic and extra galactic sources have been discussed in the literature which includes, sources from Galactic center, Gamma-ray bursts (GRBs), core of active galactic nuclei (AGN), high energy peaked blazars (HBLs), starburst galaxies etc. (See [18] for a recent review). In ref.[14] many positional correlations of BL Lac objects and galactic pulsar wind nebulae with the IceCube events are shown. Also it is very natural to expected that these neutrinos might come from diverse sources having different production mechanisms and different power-law and this information can probably be extracted from the directionality of the observed neutrino events. The largest concentration of 7 events are around the Galactic center. It is also argued that the
possible clustering of the events could be associated to the Norma arm of the Galaxy \[19\]. But as the statistics is too sparse, it is premature to draw any conclusion regarding the galactic origin of these events. There are also nonstandard physics interpretations of these IceCube events from the decay of superheavy dark matter particles \[20, 21\], leptoquark interaction and decay of exotic neutrinos \[18, 22–24\].

We found coincidence of nine TeV emitting HBL positions and the AGN Centaurus A (Cen A) within the error circle of ten IceCube events. Because of the multi-TeV emission, these HBLs and the FR-I galaxy Cen A are believed to be sources of ultra high energy cosmic rays (UHECRs). Therefore, in this work we focus our analysis on these objects to find out how these events with the desired energy can be produced through photohadronic interaction within the core region of the emanating jets.

In the framework of the unification scheme of AGN, blazars and radio galaxies \[25–27\], all are intrinsically the same objects, viewed at different angles with respect to the jet axis. The double-peak spectral energy distribution (SED) structure is observed in all these objects. Blazars have jets pointing towards the Earth. These peaks are explained through the leptonic model. In the leptonic model, the emitting region in the jet is a blob with comoving radius \( R'_b \) and moving with a relativistic velocity corresponding to a Lorentz factor \( \Gamma \). This is viewed by an observer at an angle \( \theta_{ob} \) results in a Doppler factor \( \delta \simeq \Gamma^{-1}(1 - \cos \theta_{ab})^{-1} \). In this scenario, the multi wavelength emission originates from the blob region. The low-energy peak in radio to optical wavelengths is due to the non-thermal synchrotron radiation from a population of relativistic electrons in the jet, while high-energy emission from X-rays to very high energy (VHE) gamma-rays are from the Compton scattering of the above seed synchrotron photons by the same population of electrons. This model is found very successful in explaining the multi-wavelength emission from BL Lac objects and FR-I galaxies such as NGC 1275, M87, 1ES1959+650, \[28, 29\], Cen A \[30, 31\]. However, it is unable to explain the multi-TeV emission, both non-flaring and flaring from these objects.

\textbf{Hadronic Model —} Observations of variable, non-thermal high energy emission from AGNs imply that these sources are efficient accelerators of particles through shock or diffusive Fermi acceleration processes with a power-law spectrum given as \( dN/dE \propto E^{-\alpha} \), with the power index \( \alpha \geq 2 \) \[32\]. While efficient electron acceleration is limited by high radiative losses, protons and heavy nuclei can reach ultra high energy (UHE) through the same acceleration mechanism. Fractions of these particles escaping from the source region can
constitute the UHECRs arriving on Earth. The astrophysical objects producing UHECRs also produce high energy γ-rays and neutrinos due to interaction of the cosmic rays with the background through $pp$ or $p\gamma$ interactions \cite{33,35}. The core region of the jet (the blob) in the blazars and the FR-I galaxies are close to the supermassive black hole where seed photon density is high. So, if the protons in the region are accelerated enough, can undergo deep inelastic collision with the seed photons. On the other hand in the $pp$ interaction, the UHECR will collide with the low density hydrogen cloud far away from the core region which shows that in blazars (particularly in HBLs) and FR-I galaxies high energy γ-rays and neutrinos are produced more efficiently in $p\gamma$ process than in the $pp$ process. It is observed that multi-TeV emission from AGNs\cite{36} and blazars\cite{37} can be well explained by invoking hadronic model through $p\gamma$ interactions between Fermi-accelerated protons with the seed photons in the self-synchrotron Compton (SSC) regime through the intermediate $\Delta$-resonance and is given by

\[
p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases}  
p \pi^0, & \text{fraction } 2/3 \\
n \pi^+, & \text{fraction } 1/3 
\end{cases},
\]

which has a cross section $\sigma_{\Delta} \sim 5 \times 10^{-28} \text{ cm}^2$. The $\pi^+$ and $\pi^0$ will decay through $\pi^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ and $\pi^0 \rightarrow \gamma\gamma$ respectively. The produced neutrinos and photons are in the GeV-TeV range energy and are correlated. The kinematical condition for the production of $\Delta$-resonance in the observer’s frame is

\[
E_p\epsilon_\gamma = 0.32 \Gamma\delta(1+z)^{-2}\text{GeV}^2,
\]

where $E_p$ and $\epsilon_\gamma$ are the proton and the seed photon energies respectively. In the decay of the $\Delta^+$- resonance to nucleon and pion, each pion carries $\sim 0.2$ of the proton energy and from the pion decay each neutrino and photon carries $1/4$ and $1/2$ of the pion energy respectively. Finally each individual neutrino and photon energies are respectively $E_p/20$ and $E_p/10$. Putting this condition back in Eq.(2) gives

\[
E_\nu\epsilon_\gamma = 0.016 \Gamma\delta(1+z)^{-2}\text{GeV}^2.
\]

The $\epsilon_\gamma$ of a HBL can be calculated for a given neutrino energy if the above parameters are known. The positional correlation of few IceCube events with HBLs, the success of photohadronic interaction to explain the multi-TeV emission from the flaring of some HBLs
and the emission from Cen A opens an avenue to review the same hadronic model to give a possible explanation to these correlated IceCube events. For this reason, we use this model to estimate the $\epsilon_\gamma$ for objects having the positional correlations with the IceCube events.

Results — We found coincidence of the positions of 9 HBLs and one radio galaxy, Cen A within the error circles of 10 IceCube events. These HBLs and AGN are taken from the online catalog for TeV astronomy [38] and are observed in multi-TeV $\gamma$-rays. But redshift, Lorentz factor and doppler factor of some of these HBLs are not yet known. On the other hand whichever HBL has known $z$, $\Gamma$, $\delta$ and SED, and lie within the error circle of the IceCube event we calculate the seed photon energy $\epsilon_\gamma$ necessary to produce the desired neutrino energy $E_\nu$ through photohadronic interaction. The efficiency of this process is also checked by estimating the comoving photon density $n'_\gamma$ in the blob of the HBL/AGN jet. All these correlated events are shower events with sub-PeV energy except the event 35 which is the only PeV event with $E_\nu \simeq 2$ PeV. The skymap in the equatorial coordinates is also shown in FIG. 1, where we have shown all the 37 IceCube events with their individual error circles. Except the HBLs, KUV00311-1993 and HESSJ1934+213 [38], all other have their $z$, $\Gamma$ and $\delta$ measured/fitted and SEDs are calculated from the leptonic models. We observed that most of the cases $\epsilon_\gamma$ lies between the synchrotron peak energy and the forward falling tail of synchrotron energy with the exception of RGBJ0192+017 [39] and 1ES1011+496 [40] for which $\epsilon_\gamma$ lies in the beginning of the SSC energy, 179 keV and 69 keV respectively with the corresponding $n'_\gamma \sim 3 \times 10^3 cm^{-3}$ and $\sim 8 \times 10^4 cm^{-3}$. The HBL, H2356-309 [41] is within the error circles of three IceCube events 7, 10 and 21 having the corresponding synchrotron energies 111 keV, 39 keV and 125 keV respectively. We found $n'_\gamma \gtrsim 2.4 \times 10^5 cm^{-3}$ for these events. Another two HBLs, SHBLJ001355.9 [42] and KUV00311-1938 are also within the error circle of the event 21. While SHBLJ001355.9 has the corresponding synchrotron energy $\epsilon_\gamma \simeq 45$ keV, the redshift and SED of KUV00311-1938 [38] are not known yet. The synchrotron photon density for SHBLJ001355.9 is $\sim 4.2 \times 10^3 cm^{-3}$. The HBL, HESSJ1934+213 [38] is within the error circle of the event 33 but the redshift and the SED of this HBL is also not known yet.

The blazar PKS2005-489 [43] is in the error circles of the events 12 and 15 and to produce these neutrino events the photon energy is in the range 30 keV-53 keV which is near the synchrotron peak and the corresponding proton energy is in the range $1.2 PeV \leq E_p \leq 2.1 PeV$. In these cases, the comoving background photon density found to be $n'_\gamma < 250 cm^{-3}$. 

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The SED of the blazar PKS2005-489 is fitted by taking the blob radius $R'_b \sim 4 \times 10^{17}$ cm\(^4\) which is very high compared to other HBLs that we consider here. Also $n'_\gamma \propto R^{-2}_b$, which makes the photon density very low in this case. This very low photon number density implies that probably the blob in the jet of HBL PKS2005-489 is inefficient to produce $\Delta$-resonance. At the same time these two events are also spatially correlated with the Fermi bubble and is possible that supernova remnant in this region can accelerate protons to high energy to produce neutrinos through $pp$ interaction. The event 17 is correlated with the the HBL, PG1553+113\[^4\] which is the farthest one in our list with a redshift of $z = 0.4$, the corresponding $\epsilon_\gamma \sim 50$ keV and $n'_\gamma \sim 7.4 \times 10^6$ cm\(^{-3}\).

Very recently the Telescope Array (TA) observed an UHECR hotspot with energies above 57 EeV in a region within 20° radius circle centered at R. A. = 146.7° and Dec. = 43.2°\[^4\]. This region correlates with three neutrino events (events 9, 26 and 31) observed by IceCube which is shown in the skymap in FIG. 1. Interestingly positions of two blazars, Mrk 421\[^4\] and 1ES1011+496\[^4\] are also simultaneously within the error circle of the IceCube event 9 and within the TA hotspot. The correlation of Mark 421 with both IceCube events and TA hotspot is discussed very recently\[^14, 47\]. In terms of hadronic model, the required $E_p$ and $\epsilon_\gamma$ for Mrk 421 are 1.3 PeV and 46 keV and $n'_\gamma \sim 1.5 \times 10^6$ cm\(^{-3}\). Similarly for 1ES1011+496 these values are 1.3 PeV and 69 keV and $\sim 7.7 \times 10^4$ cm\(^{-3}\) respectively to produce a 63.2 TeV neutrino event.

Cen A is the nearest active radio galaxy with FR-I morphology and long been proposed as the source of very high energy cosmic rays. Few years ago Pierre Auger (PA) Collaboration reported two UHECR events above 57 EeV within 3.1° around Cen A\[^48\] and using this the expected high energy neutrino event rate in IceCube\[^49, 50\] and the diffuse neutrino flux were estimated\[^51\]. Again, the Cen A position coincides within the error circle of the IceCube event 35 having the highest neutrino energy of 2 PeV so far observed by IceCube. In terms of the hadronic model discussed above the 2 PeV neutrino energy corresponds to a proton energy of $\sim 40$ PeV which will collide with the seed photons with energy $\epsilon_\gamma \sim 56$ eV in the valley formed by the synchrotron and the SSC photons with $n'_\gamma \sim 5.3 \times 10^7$ cm\(^{-3}\). For $\epsilon_\gamma < 56$ eV synchrotron emission dominates and the seed photon density increases rapidly\[^36\]. So in principle, in Cen A, $E_\nu > 2$ PeV can be produced more efficiently. But non-observation of neutrinos above 2 PeV from Cen A can be due to (i) very low flux of UHECR above 40 PeV and/or (ii) there is a cut-off energy around 40 PeV beyond which
FIG. 1. The skymap in the equatorial coordinates showing the 37 IceCube events with their individual error circles (only for shower events). The shower events are shown by + sign and the track events by × sign with their corresponding event number. We have also shown the position of the HBLs with their names which are within the error circle of the IceCube events. Except KUV00311-1938 and H1722+119 all other HBLs have their SED measured/fitted. The TA hotspot is shown as a shaded closed contour and the galactic plane is shown as a dashed line.

the relativistic jet is unable to accelerate protons. Probably many more years of data are necessary to shed more light on this possible correlation between the IceCube event and the position of Cen A.

Conclusions — The astrophysical interpretation of the 37 TeV-PeV neutrino events by IceCube is challenging and several viable candidates have been proposed and HBL is one of them. The HBLs are the sources capable of producing multi-TeV γ-rays. The synchrotron and SSC photons are the dominant background in these objects. Also in the hadronic model scenario, the TeV emission is due to the interaction of Fermi accelerated high energy
| ID | $E_\nu$/TeV | Object | Decl. | R. A. | z   | $\delta$ | $\epsilon_\gamma$/keV |
|----|-------------|--------|-------|-------|-----|---------|-------------------|
| 1  | 47.6        | RGBJ0152+017 [39] | 1.77  | 28.14 | 0.08| 25      | 179.              |
| 7  | 34.3        | H2356-309 [41] | -30.62 | 358.79 | 0.165| 18      | 111.              |
| 10 | 97.2        | H2356-309 | 0.165 | 18    | 39.  |         |                   |
| 21 | 30.2        | H2356-309 | -18.89 | 3.46  | 0.095| 10      | 45.               |
|    | SHBLJ001355.9 [42] | -19.35 | 8.39  | -     | -     | -       |                   |
|    | KUV00311-1938 | -19.35 | 8.39  | -     | -     | -       |                   |
| 9  | 63.2        | Mrk421 [46] | 38.19 | 166.01 | 0.03| 14      | 46.               |
|    | 1ES1011+496 [40] | 49.43  | 153.77 | 0.212| 20    | 69.     |                   |
| 12 | 104         | PKS2005-489 [43] | -48.83 | 302.36 | 0.071| 15      | 31.               |
| 15 | 57.5        | PKS2005-489 | 0.071 | 15    | 53.  |         |                   |
| 17 | 200         | PG1553+113 [44] | 11.19 | 238.94 | 0.4  | 35      | 50.               |
| 33 | 385         | HESSJ1934+213 | 21.3  | 295.98 | -    | -       | -                 |
| 35 | 2004        | Cen A (FR-I) [36] | -43.01 | 201.36 | 0.00183 | 1 | 0.056 |                   |

TABLE I. The Table shows the IceCube event ID in first column with the corresponding neutrino energy $E_\nu$ in the second column. In the third column we have shown the object (HBL/AGN) present within the error circle of the respective event and fourth and fifth columns are for their coordinates, declination(Decl.) and R. A both in degree. All the objects here are HBLs except Cen A (event 35) which is a FR-I galaxy. The columns 6, 7 and 8 respectively show the redshift $z$, Doppler factor $\delta$ and the background photon energy $\epsilon_\gamma$ which is responsible for the production of neutrino with energy $E_\nu$ from photohadronic interaction.

protons with the background photons through the process in Eq. (1). These TeV $\gamma$-rays are accompanied with multi-TeV neutrinos from the decay of charged pions and kaons. By analyzing the TeV emitting HBLs from the online catalog [38] we found coincidence of 9 HBLs and one FR-I galaxy, Cen A positions within the error circle of 10 IceCube events. All these events are found to be shower events. The position of the HBL, H2356-309 coincides with three IceCube events. We found positions of Mrk 421 and 1ES1011+496 are within the error circle of the IceCube event 9 as well as within the error circle of the TA hotspot. The observed highest energy PeV event by IceCube found to coincide with the position of Cen A. In the context of hadronic model we calculated the background photon energy $\epsilon_\gamma$ and the
UHECR proton energy which produces the desired TeV-PeV neutrinos. A detail analysis of these correlations are in progress. Many more years of data are necessary to confirm or reject these positional correlations of the HBLs/AGN with the IceCube events.

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[1] M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 111, 021103 (2013) [arXiv:1304.5356 [astro-ph.HE]].
[2] M. G. Aartsen et al. [IceCube Collaboration], Science 342, no. 6161, 1242856 (2013) [arXiv:1311.5238 [astro-ph.HE]].
[3] M. G. Aartsen et al. [IceCube Collaboration], [arXiv:1405.5303 [astro-ph.HE]].
[4] S. Razzaque, Phys. Rev. D 88, 081302 (2013) [arXiv:1309.2756 [astro-ph.HE]].
[5] M. Ahlers and K. Murase, Phys. Rev. D 90, 023010 (2014) [arXiv:1309.4077 [astro-ph.HE]].
[6] C. Lunardini, S. Razzaque, K. T. Theodoseau and L. Yang, [arXiv:1311.7188 [astro-ph.HE]].
[7] A. M. Taylor, S. Gabici and F. Aharonian, Phys. Rev. D 89, 103003 (2014) [arXiv:1403.3206 [astro-ph.HE]].
[8] K. Murase and K. Ioka, Phys. Rev. Lett. 111, no. 12, 121102 (2013) [arXiv:1306.2274 [astro-ph.HE]].
[9] K. Murase, K. Ioka, S. Nagataki and T. Nakamura, Astrophys. J. 651, L5 (2006) [astro-ph/0607104].
[10] R. Y. Liu and X. Y. Wang, Astrophys. J. 766, 73 (2013) [arXiv:1212.1260 [astro-ph.HE]].
[11] W. Winter, Phys. Rev. D 88, 083007 (2013) [arXiv:1307.2793 [astro-ph.HE]].
[12] F. W. Stecker, Phys. Rev. D 88, no. 4, 047301 (2013) [arXiv:1305.7404 [astro-ph.HE]].
[13] K. Murase, M. Ahlers and B. C. Lacki, Phys. Rev. D 88, no. 12, 121301 (2013) [arXiv:1306.3417 [astro-ph.HE]].
[14] P. Padovani and E. Resconi, [arXiv:1406.0376 [astro-ph.HE]].
[15] F. Krau, M. Kadler, K. Mannheim, R. Schulz, J. Trstedt, J. Wilms, R. Ojha and E. Ros et al., [arXiv:1406.0645 [astro-ph.HE]].
[16] F. Tavecchio, G. Ghisellini and D. Guetta, [arXiv:1407.0907 [astro-ph.HE]].
[17] X. C. Chang and X. Y. Wang, arXiv:1406.1099 [astro-ph.HE].

[18] L. A. Anchordoqui, V. Barger, I. Cholis, H. Goldberg, D. Hooper, A. Kusenko, J. G. Learned and D. Marfatia et al., Journal of High Energy Astrophysics 1-2, 1 (2014).

[19] A. Neronov, D. V. Semikoz and C. Tchernin, Phys. Rev. D 89, 103002 (2014) arXiv:1307.2158 [astro-ph.HE].

[20] K. Murase and J. F. Beacom, JCAP 1210, 043 (2012) arXiv:1206.2595 [hep-ph].

[21] A. Esmaili and P. D. Serpico, JCAP 1311, 054 (2013) arXiv:1308.1105 [hep-ph].

[22] A. Esmaili and Y. Farzan, JCAP 1212, 014 (2012) arXiv:1208.6012 [hep-ph].

[23] P. Baerwald, M. Bustamante and W. Winter, JCAP 1210, 020 (2012) arXiv:1208.4600 [astro-ph.CO].

[24] S. Pakvasa, A. Joshipura and S. Mohanty, Phys. Rev. Lett. 110, 171802 (2013) arXiv:1209.5630 [hep-ph].

[25] G. Ghisellini, A. Celotti, G. Fossati, L. Maraschi and A. Comastri, Mon. Not. Roy. Astron. Soc. 301, 451 (1998) astro-ph/9807317.

[26] G. Fossati, L. Maraschi, A. Celotti, A. Comastri and G. Ghisellini, Mon. Not. Roy. Astron. Soc. 299, 433 (1998) astro-ph/9804103.

[27] M. Chiaberge, A. Capetti and A. Celotti, Mon. Not. Roy. Astron. Soc. 324, L33 (2001) astro-ph/0105159.

[28] G. Tagliaferri and L. Foschini, Astrophys. J. 679, 1029 (2008) arXiv:0801.4029 [astro-ph].

[29] K. Gutierrez et al. [VERITAS Collaboration], Astrophys. J. 644, 742 (2006) astro-ph/0603013.

[30] A. A. Abdo et al. [Fermi Collaboration], Astrophys. J. 719, 1433 (2010) arXiv:1006.5463 [astro-ph.HE].

[31] P. Roustazadeh and M. Bottcher, Astrophys. J. 728, 134 (2011)

[32] C. D. Dermer and R. Schlickeiser, Astrophys. J. 416, 458 (1993).

[33] M. Kachelriess, S. Ostapchenko and R. Tomas, New J. Phys. 11, 065017 (2009)

[34] C. Isola, M. Lemoine and G. Sigl, Phys. Rev. D 65, 023004 (2002) astro-ph/0104289.

[35] M. Honda, Astrophys. J. 706, 1517 (2009).

[36] S. Sahu, B. Zhang and N. Fraija, Phys. Rev. D 85, 043012 (2012) arXiv:1201.4191 [astro-ph.HE].

[37] S. Sahu, A. F. O. Oliveros and J. C. Sanabria, Phys. Rev. D 87, 103015 (2013) arXiv:1305.4985.
[hep-ph]]

[38] See the website: [http://tevcat.uchicago.edu/]

[39] F. Aharonian [HESS Collaboration], Astron. Astrophys. 481, L103 (2008) [arXiv:0802.4021 [astro-ph]].

[40] J. Albert et al. [MAGIC Collaboration], Astrophys. J. 667, L21 (2007) [arXiv:0706.4435 [astro-ph]].

[41] F. Aharonian et al. [H.E.S.S. Collaboration], Astron. Astrophys. 455, 461 (2006) [astro-ph/0607569].

[42] A. Abramowski et al. [HESS Collaboration], Astron. Astrophys. 554, A72 (2013).

[43] A. Abramowski et al. [H.E.S.S. Collaboration], Astron. Astrophys. 533, A110 (2011) [arXiv:1111.3331 [astro-ph.HE]].

[44] J. Aleksic et al. [MAGIC Collaboration], Astrophys. J. 748, 46 (2012) [arXiv:1101.2764 [astro-ph.CO]].

[45] R. U. Abbasi et al. [Telescope Array Collaboration], Astrophys. J. 790, L21 (2014) [arXiv:1404.5890 [astro-ph.HE]].

[46] M. Blazejowski, G. Blaylock, I. H. Bond, S. M. Bradbury, J. H. Buckley, D. A. Carter-Lewis, O. Celik and P. Cogan et al., Astrophys. J. 630, 130 (2005) [astro-ph/0505325].

[47] K. Fang, T. Fujii, T. Linden and A. V. Olinto, arXiv:1404.6237 [astro-ph.HE].

[48] The Pierre Auger Collaboration, Science 318, 938 (2007).

[49] F. Halzen and A. O’Murchadha, [arXiv:0802.0887 [astro-ph]].

[50] A. Cuoco and S. Hannestad, Phys. Rev. D 78, 023007 (2008).

[51] H. B. J. Koers and P. Tinyakov, Phys. Rev. D 78, 083009 (2008).