A Search for Ultra-high-energy Neutrinos from TXS 0506+056 Using the Pierre Auger Observatory

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ABSTRACT

Results of a search for ultra-high-energy neutrinos with the Pierre Auger Observatory from the direction of the blazar TXS 0506+056 are presented. They were obtained as part of the follow-up that stemmed from the detection of high-energy neutrinos and gamma rays with IceCube, *Fermi*-LAT, MAGIC, and other detectors of electromagnetic radiation in several bands. The Pierre Auger Observatory is sensitive to neutrinos in the energy range from 100 PeV to 100 EeV and in the zenith angle range from $\theta = 60^\circ$ to $\theta = 95^\circ$, where the zenith angle is measured from the vertical direction. No neutrinos from the direction of TXS 0506+056 have been found. The results were analyzed in three periods: One of 6 months around the detection of IceCube-170922A, coinciding with a flare period of TXS 0506+056, a second one of 110 days during which the IceCube collaboration found an excess of 13 neutrinos from a direction compatible with TXS 0506+056, and a third one from 2004 January 1 up to 2018 August 31, over which the Pierre Auger Observatory has been taking data. The sensitivity of the Observatory is addressed for different spectral indices by considering the fluxes that would induce a single expected event during the observation period. For indices compatible with those measured by the IceCube collaboration the expected number of neutrinos at the Observatory is well- below one. Spectral indices as hard as 1.5 would have to apply in this energy range to expect a single event to have been detected.

Keywords: neutrinos — multi-messenger — blazar

1. INTRODUCTION

On 2017 September 22, a through-going muon that deposited 23.7 TeV was detected at the IceCube telescope (Aartsen et al. 2017) in Antarctica, likely to be produced by a neutrino. The most probable energy for the neutrino is 290 TeV (Aartsen et al. 2018a) assuming a spectrum compatible with the measured diffuse flux (Aartsen et al. 2015, 2016). Within a minute, the arrival direction and energy estimates were reported through the Gamma-ray Coordinates Network Circular (Kopper et al. 2017) as part of the routine of the multi-messenger that is being established in high-energy astrophysics. Six days later, flaring activity in the γ-ray band was observed in the Fermi Large Area Telescope (*Fermi*-LAT), from TXS 0506+056 (RA= 9h 55.6m, Dec= +5° 41.6'), a powerful blazar at relatively high redshift of 0.3365 ± 0.0010 (Paiano et al. 2018) and only 0.1° away from the deduced neutrino direction (Tanaka et al. 2017). The chance possibility of this correlation was estimated to be $\sim 0.3\%$ (3σ level) which motivated further scrutinizing of this object in practically all bands of the electromagnetic spectrum and in neutrinos (Aartsen et al. 2018a; Padovani et al. 2018).

The remarkable multi-messenger effort that followed revealed a complex variable activity. Most notably, the search of archival IceCube data for signal correlations from the same direction also revealed an excess flux of 13 ± 5 through-going muons between December 2014 and February 2105, dominating the background neutrino flux from this region, which was interpreted as a burst of neutrinos over a time window of about 110 days from the same object (Aartsen et al. 2018b). The significance of such an excess localized in the reported time window being due to background atmospheric neutrinos is estimated to be at the 3.5σ level. A Very-High-Energy (VHE) signal between 80 and 400 GeV was detected in the MAGIC telescope when integrating observation between 2017 September 24 and 2017 October 4, confirming the flaring activity observed by *Fermi*-LAT (Ansoldi et al. 2018).

The detection of neutrinos from the direction of TXS 0506+056 illustrates the potential of multi-messenger observations (Aartsen et al. 2018a). The follow-up studies have attracted a lot of attention since the detection of neutrinos from blazars would provide the first robust evidence of hadronic acceleration in astrophysical jets, potentially explaining the diffuse high-energy neutrino excess detected by IceCube over the atmospheric background, and providing much insight into the modeling of these powerful objects. While the energy of the gamma rays that can reach us from such an extragalactic source is limited by pair production in the background radiation fields, neutrinos are not prone to similar interactions and will travel unimpeded up to the highest energies. Moreover, TXS 0506+056 is listed among the 50 brightest objects in the third catalog of active galactic nuclei detected by *Fermi*-LAT (Ackermann et al. 2015), suggesting that neutrino emission may be highly non-uniform within the blazar population (Halzen et al. 2019). Naturally, other neutrino searches have followed with other facilities spanning different energy bands, such as ANTARES (Dornic & Coleiro 2017) and Kamiokande (Hagiwara et al. 2019). These searches have reported no signals.

Ultra-High-Energy (UHE) neutrinos have been searched for with the Pierre Auger Observatory since 2004 (Abraham et al. 2008) by looking for inclined showers that develop deep in the atmosphere. The Observatory has been shown to have a similar sensitivity to that of IceCube for UHE neutrinos of energies above 100 PeV (Aab et al. 2019a). Moreover, it has been shown to have a distinctive directional sensitivity which can have a unique potential to search for transient events from point sources that are at preferred declinations (Aab et al. 2019b). This is partly due to the enhanced capability of the Observatory to trigger on air showers produced by the decay of tau leptons originating from Earth-skimming tau neutrino interactions near the surface of the Earth. The search for correlated neutrinos from the direction of TXS 0506+056 with the Pierre Auger Observatory has lead to a negative result (Pedreira 2019). In this article we describe the search made and the implications for the possible neutrino flux that could be emitted from this object in the UHE band.

2. THE SEARCH OF NEUTRINOS WITH THE PIERRE AUGER OBSERVATORY

Ultra-high-energy neutrinos arriving with high zenith-angles can induce air showers deep in the atmosphere. These can be detected with arrays of particle detectors, such as those operated within the Pierre Auger Observatory located in the Mendoza province, Argentina. This Observatory is the largest and highest-precision detector available to measure cosmic rays of EeV energies and above (Aab et al. 2015a). It consists of a 3000 km^2 array of water-Cherenkov detectors, the Surface Detector (SD), at ground level arranged on a triangular grid with 1600 detectors 1.5 km apart. The SD samples the front of the extensive air- showers that develop when UHE cosmic rays interact in the upper layers of the atmosphere. The Pierre Auger Observatory also includes a Fluorescence Detector (FD) comprising 27 telescopes that are used to view the atmosphere over the array and capture the fluorescence light that is emitted as the shower passes through the atmosphere. The Observatory was designed to detect cosmic-ray showers, produced by nuclei or protons interacting in the upper layers of the atmosphere.

When regular cosmic-rays (i.e. protons, nuclei, photons) arrive with zenith angles exceeding about 60°, their induced showers are largely absorbed in the atmosphere, well-before reaching ground level. As a result, the shower front at observation level is mostly composed of ultra-relativistic muons that have small time spreads, giving characteristic sharp signals in the particle detectors of the array. Neutrinos, on the other hand, can interact deeper in the atmosphere so that when the neutrino-induced shower front reaches ground level it still has a large fraction of electrons, positrons, and photons (the electromagnetic component), which gives a signal in the detectors which is typically distributed over a larger time interval (Capelle et al. 1998). For instance, while an 80° proton shower has a signal spread of ~ 100 ns about 1 km from the shower axis, a neutrino shower can reach over 1 μs.

The identification of the electromagnetic signals in the SD stations provides the basis for the discrimination between neutrino-induced showers and those from the background of hadronic cosmic-rays. This is basically done using variables related to the ratio of the integrated signal to its peak value in selected stations which provide a measure of the time-width of the signal. For optimization purposes the search is carried out using three distinct groups of events. Each group is selected from the data with its own set of criteria, based on variables that relate to the zenith angle and broadly correspond to zenith angles between 60° and 75°, "Downward-Going Low" (DGL), those between 75° and 90°, "Downward-Going High" (DGH), and those between 90° and 95°, "Earth-Skimming" (ES). The method devised for each group, in addition to the selection of events, includes the search for neutrino candidates within, as explained in detail in (Aab et al. 2015b, 2019a). The ES search provided the most competitive limit for diffuse flux of UHE neutrinos in the 100 PeV to 10 EeV range in 2008 (Abraham et al. 2008), before IceCube had been fully completed. Later updates including the DGH and DGL searches have set limits (Aab et al. 2015b, 2019a) comparable to contemporary bounds from IceCube in the same energy range (Aartsen et al. 2018c).

For the bounds reported here, we make the implicit assumption that the fluxes of all neutrino flavors are equal because of flavor oscillations as they travel to Earth (Learned & Pakvasa 1995), corresponding to a flavor ratio of $\nu_e : \nu_\mu : \nu_\tau$ of 1:2:0 at the source. It is however possible that the actual flavor ratios at the source are significantly different, as has been for instance argued in case of acceleration of secondaries in flares (Klein et al. 2013; Winter et al. 2014). These could result in modified flavor ratios at Earth that would require reevaluation. The remarkable sensitivity of the Observatory to UHE neutrinos is in part due to the Earth-skimming channel (Bertou et al. 2002), in which tau neutrinos traveling through the Earth interact just below the surface, producing a tau lepton that exits to the atmosphere and induces an upcoming air shower. Because of this channel, the Pierre Auger Observatory provides complementary information to IceCube relative to the tau flavor.

There are a number of coincidences that make this channel most effective. The matter depth of the Earth's chord is a rapidly varying function as the nadir angle of the upcoming tau neutrino, $180° - \theta$, approaches the horizontal ($\theta = 90°$). Depending on this angle there is a characteristic neutrino energy, $E_{\rm ch}(\theta)$, at which the matter depth matches the neutrino mean free path. This angle roughly optimizes the search for neutrinos of energy $\sim E_{\rm ch}(\theta)$. On the other hand, for the SD to detect these showers, they must be nearly horizontal so that the shower develops at a very low altitude and the shower front reaches the ground as it extends laterally. It turns out that for nadir angles between $85°$ and $90°$, the values of $E_{\rm ch}(\theta)$ are in the 100 PeV to 10 EeV range, large enough to induce showers that can be detected by such a sparse array. Moreover, at about 1 EeV, there is a sweet-spot in which the probability for the tau neutrino to convert and for the tau lepton to exit the Earth and to be detected in the SD is maximal (Alvarez-Muñiz et al. 2019). This is because of a combination of different effects: Up to about 1 EeV, the matter depth the tau lepton is able to traverse before exiting the Earth is mainly governed by the tau decay length, which increases linearly with energy, enhancing the effective detector volume. Above about 1 EeV, energy losses in the Earth start to dominate in the exit path of the tau lepton so that its range only rises logarithmically with energy. In addition, because of the increased tau decay length in the atmosphere, showers more often start developing at higher altitudes making the detection of the shower front by the surface detector array less likely (Zas 2005).

As a result, for the Earth-skimming detection, the neutrino arrival directions must be within a very small angular range of few degrees below the horizon. For these directions, the effective area of the Observatory for detecting tau-flavor neutrinos is very much enhanced relative to the search method for downward-going neutrinos (DGH and DGL). This is the reason why the Pierre Auger Collaboration could set the best limit to UHE neutrinos from GW170817 (Albert et al. 2017), the binary neutron star merger event detected in gravitational waves and followed up in most bands of the electromagnetic spectrum (Abbott et al. 2017). The instantaneous effective area is highly dependent on the arrival zenith-angle which is a function of the source declination and the hour-angle, so that the sensitivity of the Observatory is highly directional and time-dependent (Aab et al. 2019b). This can be appreciated in Fig. 1 where the three wide coloured bands span the instantaneous effective area of the Observatory within the zenith angle intervals corresponding to the three search channels. For the Earth-skimming channel the width is largest, reflecting the rapid variation of effective area as the zenith angle changes by only 5 degrees from $90°$ to $95°$ reaching a maximum at $\sim 91°$.

The search for neutrinos from the direction of TXS 0506+056 will be considered for periods much longer than a day. Thus, the effective area for neutrino detection must be integrated over time as the source position transits over different zenith angles. In Fig. 1 we have also shown the daily average of the effective area for the Observatory in each of the three search channels for the blazar declination of $5.7°$ (full colored lines), where they are compared to the effective area of IceCube detector for the same source (Aartsen et al. 2018b). Due to the location of the IceCube detector, the effective area for a fixed position in space depends only on its declination and is otherwise independent of time for each configuration. The width of the IceCube band here is due to the different configurations achieved after different construction stages (Aartsen et al. 2018b). The effective exposure can be approximately calculated by multiplying the daily average of the effective area for the corresponding declination, by the length of the time period under consideration (Aab et al. 2019b). The daily average depends strongly on declination and this is partly because the source is only "visible" in neutrinos during a varying fraction of the day in each zenith angle range. This fraction is displayed in Fig. 2 as a function of the declination for each of the three types of searches. The black arrow marks the declination of TX0506+056, indicating that the source is not at a declination that maximizes the observation time. This effect also contributes to the large variations in effective area as a function of the source declination. For periods much larger than a sidereal day the approximation is very accurate because variations in effective area with time have been relatively small since the Observatory was completed in 2008 June.

3. RESULTS AND DISCUSSION

All the data collected with the Pierre Auger Observatory were searched for candidate neutrino events in the direction of TXS 0506+056 with negative results. Instead of providing a flux limit we calculate the expected flux that would have been deduced if a single neutrino had been observed, assuming a steady flux over a given period of time. This illustrates the expected sensitivity to a given flux and can be easily converted to a flux limit at 90% confidence multiplying it by a factor 2.39 (Feldman & Cousins 1998). The results naturally depend on the assumptions that are made with respect to the time period over which the search is integrated. Two benchmark scenarios have been discussed in the original article addressing the correlated detection in neutrinos and in the HE and VHE gamma-ray bands (Aartsen et al. 2018a). The first is of half a year and it is motivated by the time window that gave the largest significance to a search for an excess of neutrino-compatible events in the archival data of IceCube,

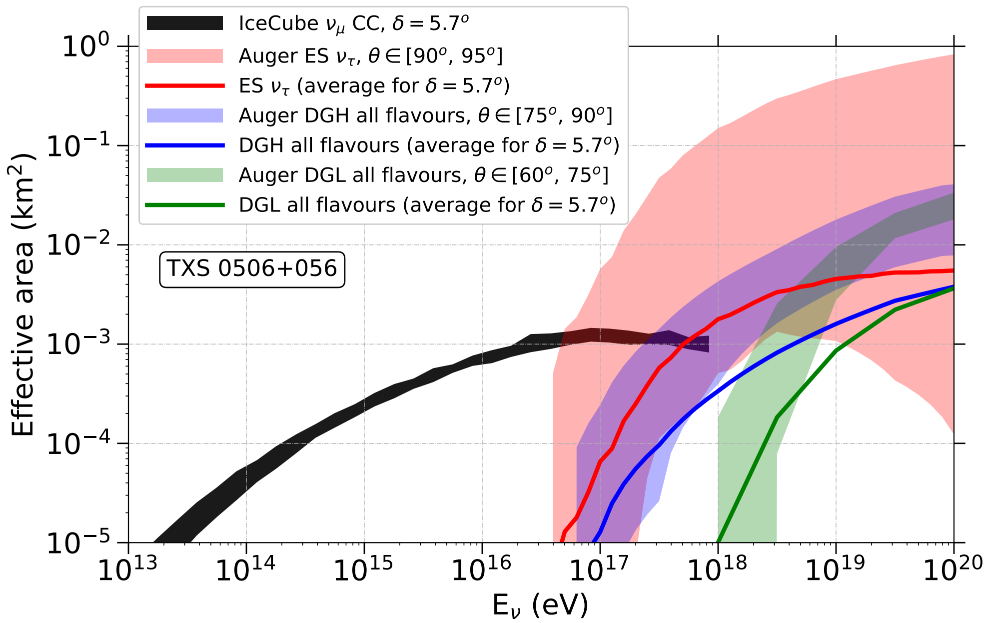

Figure 1. Effective area of the Pierre Auger Observatory as a function of neutrino energy for each search channel. The shaded bands bound the instantaneous effective area for each neutrino detection channel and indicate the variation with zenith angle in the corresponding range. TXS 0506+056 at a declination $\delta \simeq 5.7^\circ$ is viewed at the SD of Auger for a limited amount of time (see Fig. 2) and with a range of zenith angles from $\theta = 60^\circ$ to $\theta = 95^\circ$, the sensitivity being largest below the horizon ($\theta > 90^\circ$). The full lines represent the effective area for the different detection channels when averaging over a full day, i.e. when including the periods during a day, when the source cannot be seen. The instantaneous effective area of IceCube for the declination of TXS 0506+056 is also shown for comparison. For IceCube at the South Pole the zenith angle of TXS 0506+056 is practically constant over time and given by $\theta = 90^\circ + \delta$. The width of the grey band corresponds in this case to different stages of IceCube construction and configuration which depend on the period under consideration.

interpreted as a neutrino flare (Aartsen et al. 2018b). The second period corresponds to 7.5 years, the whole observation time that the IceCube detector had been in operation at the time of detection. We here address similar scenarios of half a year and the whole observation period of the Pierre Auger Observatory which is 15 years from 2004 January 1 to 2018 August 31. We note that periods over which the SD was unstable have been removed from the analysis and that during the first four years of operation the effective area was a rapidly growing function of time because the Observatory was under construction until 2008 June.

The average spectral fluxes of UHE neutrinos with a fixed spectral index ($\sim E^{-\gamma}$) that would produce a single event at the Observatory for these two periods are displayed in Fig. 3 for a spectral index of $\gamma = 2.0$, assumed to hold in the energy range between 100 PeV and 10 EeV and to be constant in time during the corresponding time period. In this plot they are compared to the fluxes obtained from the neutrino detected in 2017 September 22 and inferred to have energy of order few hundred TeV, considering a period of half a year and 7.5 years. The plot also displays the average VHE gamma-ray flux detected with *Fermi*-LAT and MAGIC over periods within a couple of weeks around the neutrino detection date of 2017 September 22 (Aartsen et al. 2018a). These gamma-ray fluxes correspond to the reported flaring activity and have not been corrected for absorption in the extragalactic background light. They are considerably larger than the average gamma-ray fluxes that had been recorded to date from this source, and which are also illustrated for comparison (Acero et al. 2015). The sensitivity of the Auger Observatory to UHE neutrinos is about an order of magnitude below extrapolations with E^{-2} spectra, partly due to the non optimal position of the source.

We have also compared the sensitivity of the Observatory to the neutrino flux observed by IceCube between 19 October 2014 and 6 February 2015. The analysis of this period resulted in constraints for the normalization and spectral index of the observed fluence (Aartsen et al. 2018b). This period of increased neutrino flux in IceCube was not coincident with a VHE gamma-ray flare from the same source, although a hardening of the spectrum in the GeV region was reported (Padovani et al. 2018). In Fig. 4 we display the 1σ and 2σ bands of the average flux obtained from the fluence reported assuming an activity period of 110 days as obtained from the IceCube data analysis using a Gaussian window. The bands are calculated using the whole parameter

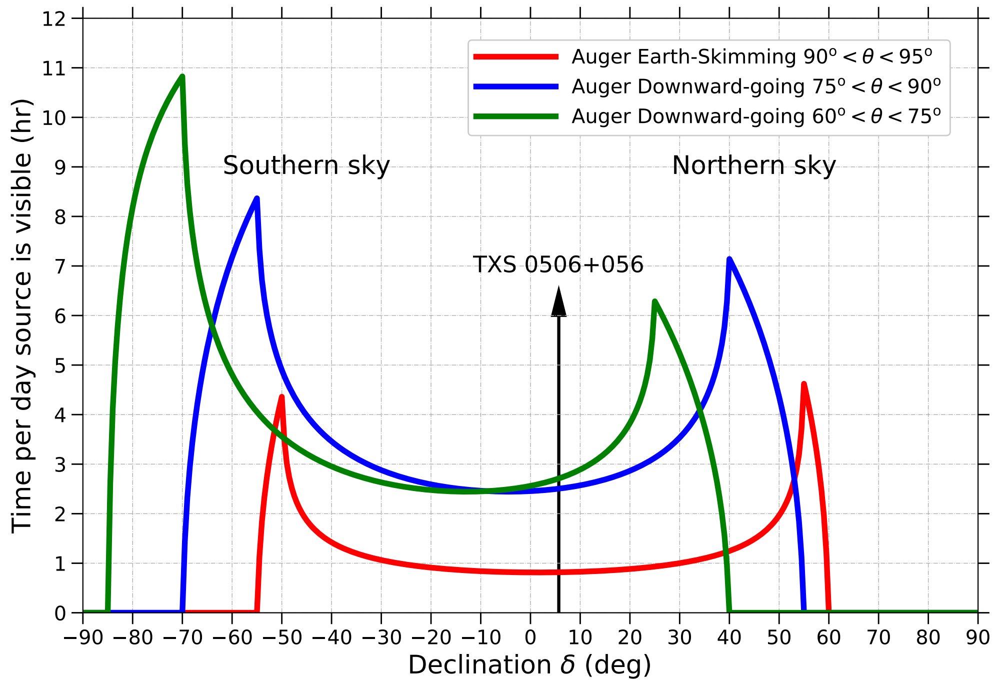

Figure 2. Hours per day a source is visible in each of the search channels as a function of declination. The declination of TXS 0506+056 is marked with an arrow.

space allowed at 68% and 95% confidence levels in the IceCube analysis. The extreme values of the spectral index are $\gamma \sim 1.75$ and $\gamma \sim 2.45$ (~ 1.5 and ~ 2.7) for the 68% (95%) CL contour plot (Aartsen et al. 2018b). The figure also displays the average gamma-ray flux obtained for this period illustrating the reported hardening (Padovani et al. 2018). The results obtained indicate that the Pierre Auger Observatory could only be expected to have detected a signal if the flux extrapolated to the EeV regime with spectral indices harder than $\gamma \sim 1.5$.

With the Pierre Auger Observatory it is also possible to search for UHE photons (Aab et al. 2016; Niechciol 2017; Aab et al. 2019c). For a source as distant as TXS 0506+056, any UHE photon flux that could have been produced is expected to be strongly attenuated through interactions with the cosmic photon-background fields, unless new physics would occur. The data have been searched for UHE photons between 10 and 300 EeV in coincidence with IceCube-170922A over a period of half a year and also in coincidence with the 110 day interval interpreted by (Aartsen et al. 2018b) as burst of neutrinos. No event has been found with an angular distance to the source below 2°. The shower with closest angular distance to the source (2.1°) was observed for the latter period and the corresponding value of the Principal Component (PC) for photon discrimination (Rautenberg 2019) is very low, so that less than 0.1% of the simulated photons have a smaller PC value. As a result, the probability of this event to be a correlating photon is less than 6×10^{-5}. Assuming an E^{-2} spectrum, the photon energy flux that would give one expected photon event at the Observatory is 1.8×10^{-12} erg cm^{-2} s^{-1}. For the half a year period in 2017 the closest event, at an angular distance of 3.0°, has an even lower probability to be a photon, and the reference energy flux for one detected photon becomes 1.0×10^{-12} erg cm^{-2} s^{-1}.

In summary, we have studied the implications of the non-observation of UHE neutrinos with the Pierre Auger Observatory. The source is not located at one of the preferential declinations for observation so the flux constraints that can be obtained are rather limited. The neutrino flux from TXS 0506+056 at 100s of TeV sampled by IceCube with event IceCube-170922 was converted to a flux using a half a year period (Aartsen et al. 2018a). If the flux from the source had an E^{-2} spectrum extending to the EeV and if it had remained constant over the lifetime of the Observatory with the same normalization, one neutrino event could be expected to have been observed at the Pierre Auger Observatory. We have also shown that the Observatory could have a chance to detect UHE neutrinos produced between October 2014 and February 2015 only in case the spectrum extended to the EeV range with a spectral index harder than $\gamma \sim 1.5$ (Aartsen et al. 2018b).

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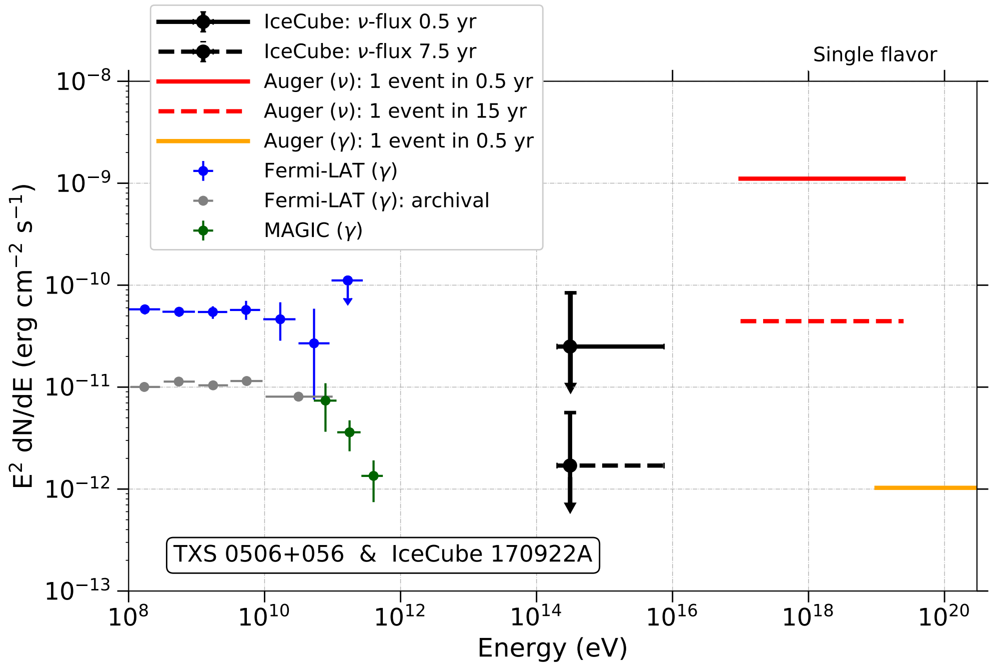

Figure 3. UHE flux reference that would give one expected neutrino event at the Pierre Auger Observatory over a period of half a year (2017 March 22 - September 22) for a spectrum $dN/dE \propto E^{-2}$ in comparison to the flux that would produce on average one detection like the IceCube-170922A event over the same period (solid red and black lines). Flux references are also shown for the Pierre Auger Observatory for a period of ~15 years during which it has taken data (2004 January 1 - 2018 August 31) and for a period of 7.5 years for IceCube (Aartsen et al. 2018a) (dashed red and black lines). The average VHE and UHE photon fluxes measured with *Fermi*-LAT, and MAGIC around 2017 September 22 (Aartsen et al. 2018a), and the archival photon measurement from *Fermi*-LAT (Acero et al. 2015), as well as the UHE photon flux from this direction that would give one expected photon event in half a year at the Pierre Auger Observatory, are also shown for comparison.

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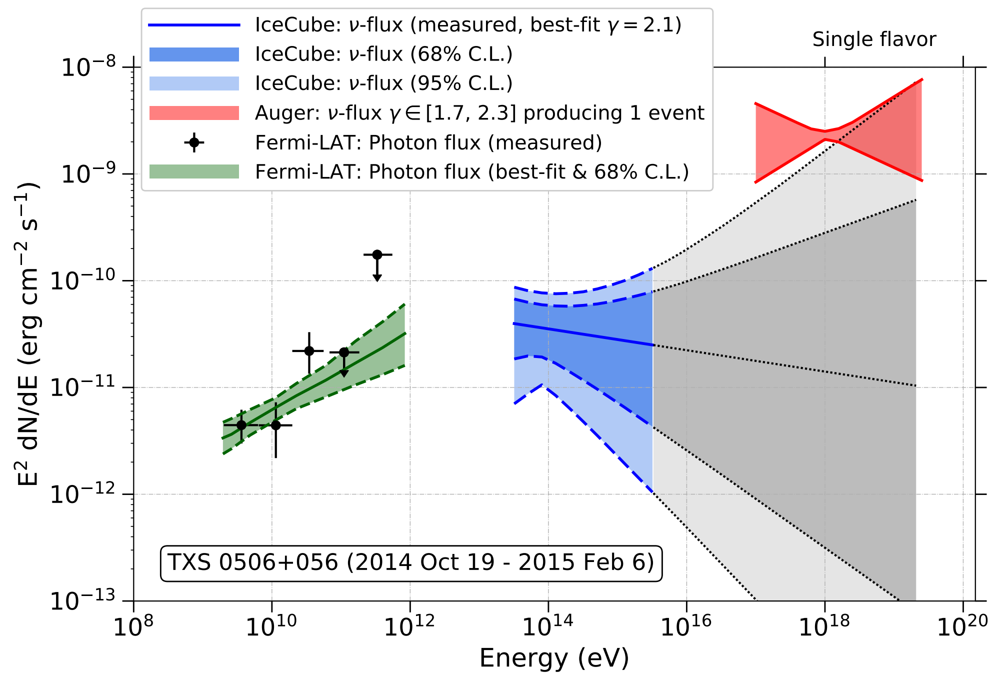

Figure 4. UHE neutrino flux sensitivities for the Pierre Auger Observatory (one event expected) assuming a constant flux during a period of 110 days from 19 October 2014 to 6 February 2015 in comparison to the measured photon flux (Padovani et al. 2018) and to the neutrino flux inferred with IceCube during the same period with a spectral index of $\gamma = 2.1 \pm 0.2$ (Aartsen et al. 2018b). The band shown for IceCube is obtained using the extreme values of γ ($\sim$1.75, $\sim$2.45) from the given one-sigma contour plot and ($\sim$ 1.5 and $\sim$ 2.7) from the two-sigma contour.

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