

Dissecting the region around IceCube-170922A: the blazar TXS 0506+056 as the first cosmic neutrino source

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Abstract. On MJD 58018 the IceCube neutrino observatory detected a highly-energetic, well-reconstructed neutrino, IceCube-170922A, at a distance of 0.1° to a γ -ray flaring blazar, TXS 0506+056. Follow-up searches in archival data additionally revealed a larger flare of neutrinos from the same direction. In order to complete the picture we present here a full multi-wavelength study of the region around IceCube-170922A. While we identify also other non-thermal counterpart candidates, we show that all the evidence points to TXS 0506+056 as the dominant neutrino emitter. Additionally, an analysis of all the available *Fermi*-LAT data indicates a hard spectrum/low flux of TXS 0506+056 during the neutrino flare in contrast to a soft spectrum/high flux at the arrival time of IceCube-170922A. Putting all the pieces together we conclude that the SED of TXS 0506+056 can be energetically reconnected for both neutrino observations.

1 Introduction

The IceCube Neutrino Observatory has recently found evidence for an astrophysical neutrino flux above ~ 100 TeV [1]. The detection of these neutrinos mainly happens in two channels: *starting* events and *through-going* tracks. Despite many efforts the origin of these neutrinos is still unknown [2]. Complementary to the usual point-search searches, IceCube has therefore constructed a realtime alert system [3]. It is triggered by the highest-energy tracks with very good angular resolution and sends an alert to the astronomical community to allow for time simultaneous follow-ups.

On MJD 58018 a highly-energetic, up-going muon-track, IceCube-170922A, passed the realtime event selection and was send out as an alert through the Gamma-ray Coordinates

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Network. It has a most probable neutrino energy of ~ 290 TeV and a best-fit direction of right ascension $77.34^{+0.95}_{-0.65}$ and declination $+5.72^{+0.50}_{-0.30}$. Most notably, a radio bright and flaring γ -ray blazar, TXS 0506+056 (IBL/HBL at $z = 0.3365$ [4]), was found at a distance of 0.1° . The post-trial chance of such a coincidence is $3 - 3.5\sigma$ [5]. Searches in archival IceCube data additionally revealed a flare of neutrinos during a 5-month period in 2014-2015¹ spatially consistent with the neutrino alert. The fluence of this flare is $2.1^{+0.9}_{-0.7} \times 10^{-4}$ TeV cm⁻², which results in a post-trial significance of 3.5σ [6]. Due to the absence of emission lines TXS 0506+056 was originally classified as BL Lac. Recent studies suggest, however, that it is intrinsically an FSRQ with hidden broad line regions [8].

Despite TXS 0506+056 we identified another *known* γ -ray source, PKS 0502+049, as well as five non-thermal objects in the vicinity of IceCube-170922A. Based on their radio to X-ray emission ratio *a priori* all of them are also good counterpart candidates. Hence, in order to complete the observational picture we present here what we call a *dissection* of the region around IceCube-170922A. All available astronomical data are collected and analyzed in order to identify and characterize the neutrino's multi-wavelength counterpart(s) over the entire energy spectrum.

2 Multi-Messenger Data Analysis

Most important for the identification of the multi-wavelength counterpart candidates, data of several telescopes have been analyzed using the VOU-Blazar Tool that has been developed in the framework of the "Open Universe"². The tool selects sources that emit in both, radio and X-ray with a blazar like emission ratio, as determined in the BZCAT [9]. Input Radio and optical data are taken from the Owens Valley Radio Observatory (OVRO7), the Catalina Real time Transient Survey (CRTS8) and the All Sky Automatic Survey (ASAS9) online services. The largest fraction of the X-ray data in a radius of 80 arc-minutes around IceCube-170922A comes from observations of the *Neil Gehrels Swift* observatory and the *NuSTAR* hard X-ray observatory. The preparation of all the data has been done using the standard pipelines of the respective telescopes.

In Figure 1 the region around IceCube-170922A is shown with the corresponding 90% error contour and all the identified counterpart candidates. Despite the two γ -ray blazars (source 1 and 5), there is another known HBL, 2WHSP J050833.3+05310 (source 3), as well as an HBL candidate (source 4). Visual inspection of the remaining SEDs revealed that source 7 is a cluster of galaxies, source 6 is a steep-radio object and source 2 is a nearby elliptical galaxy. These sources are in general not capable of accelerating protons to very high energies or provide enough target material for neutrino production, hence we can exclude them.

2.1 γ -ray Analysis

The production spectra of neutrinos and γ -rays in astrophysical sources are closely connected over the process of pion decay. Hence, in the following, we study the connection of the two messengers for the remaining counterpart candidates. The presented analysis is based on 9.5 years of *Fermi*-LAT data and uses the standard pipelines implemented in the Fermi Science Tools. The sensitive energy range of *Fermi*-LAT starts at 100 MeV and ends at 100 GeV - exactly where the energy range of IceCube begins. Hence we are naturally interested in

¹Using two different parameterizations of the flare's shape the time window is evaluated to MJD 56939 to MJD 57096 (158 days) for a box-shape and MJD 56949 to MJD 57059 (110^{+35}_{-24} days) for a Gaussian shape, respectively [6]. Both approaches are consistent within errors. While the 110 days period was extensively discussed in [7], we will present in this proceeding the analogous results for the 158 day period.

²<http://www.openuniverse.asi.it/>

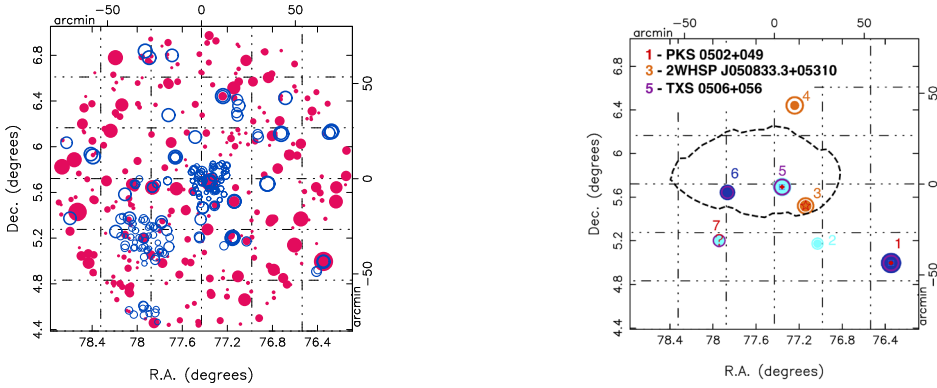


Figure 1. **Left:** Radio and X-ray sources within 80 arc-minutes of the position of IceCube-170922A. Symbol diameters are proportional to source intensity. Radio sources appear as red filled circles, X-ray sources as open blue circles. **Right:** Known and candidate blazars around IceCube-170922A. Dark blue circles represent LBL type candidates, cyan symbols are for IBL candidates, and orange symbols are for HBL candidates. Known blazars are marked by a red diamond if they are included in the BZCAT catalogue or a star if they are part of the 2WHSP sample. The dashed line shows the 90% error contour of IceCube-170922A.

the high-energy part of the *Fermi*-LAT range. Additionally, in order to avoid any source confusion due to wrongly modeled sources, we mostly exclude photon energies below 2 GeV (see figure captions and [7] for more details). The test-statistic (TS) maps in Figure 2 show the γ -ray emission for the time windows around the neutrino alert and during the neutrino flare (significance $\sigma \sim \sqrt{TS}$). It can be seen that there is no obvious emission from the direction

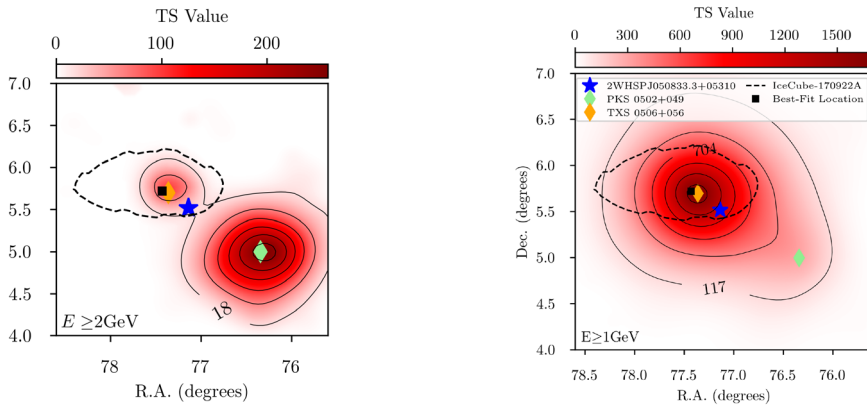


Figure 2. **Left:** The test-statistic map of the region during the neutrino flare in 2014/2015. PKS 0502+049 is the dominant γ -ray emitter in the sky. Above 2 GeV the sources are disentangled and above 5 GeV TXS 0506+056 is the dominating source. This is due to the log-parabola spectrum of PKS 0502+049 that softens above 934 MeV [10]. For symbol explanation see right plot. **Right:** The TS map between MJD 57908 and 58018, just before the neutrino alert. Here TXS 0506+056 dominates already at 1 GeV.

of 2WHSP J050833.3+05310. This result is confirmed by a dedicated analysis at the source's

location. For the other two source the picture differs between the two time periods around the neutrino flare and the neutrino alert, respectively. During the neutrino flare PKS 0502+049 dominates the sky below several GeV. A dedicated light curve (Figure 3, right) reveals the time evolution of this emission. There are two peaks in the photon flux only before and after

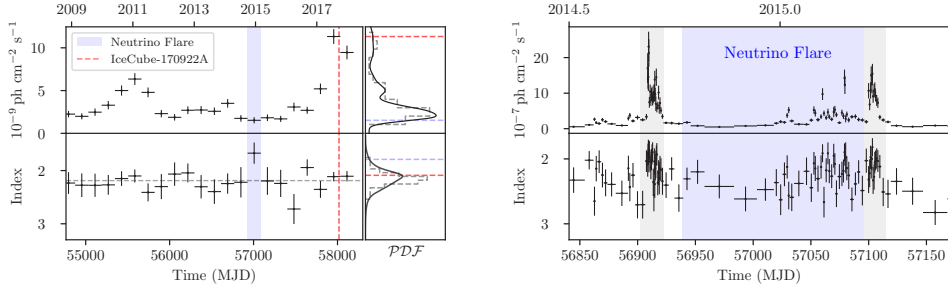


Figure 3. Left: The 158 days, (fixed-binning) γ -ray light curve of TXS 0506+056 above 2 GeV. The kernel density estimate of the flux and spectral index distribution are shown as black lines on the plots on the top- and bottom-right, respectively. **Right:** An adaptive bin light curve for PKS 0502+049 above $E_{\text{min}} = 214$ MeV (see [11] for technical explanation). Note that we go down to lower energies since the PKS 0502+049 strongly dominates in this energy regime. Going to higher energies it quickly softens above 934 MeV [10]. The grey shaded area shows the time windows of an increased photon flux. In both plots the blue band indicates the time window of the neutrino flare.

the neutrino flare. Assuming a certain level of time synchronized emission this is an argument *against* a connection of the IceCube neutrinos and the γ -ray flare of this object. At the same time the γ -ray flux from TXS 0506+056 is low, but shows a hard spectrum with photon index of 1.67 ± 0.2 . The probability of observing such a hard state under the hypothesis of a constant flux is evaluated from a kernel density estimation to $\sim 1\%$. At the arrival time of IceCube-170922A, TXS 0506+056 is clearly the dominating object in the region with a γ -ray flux around 6 times higher than in the quiescent state. The SEDs of TXS 0506+056 during the two relevant time windows are shown in Figure 4. Additionally to the spectrum above 2 GeV as discussed in [7], we additionally tried to model the source down to 100 MeV. The blue band indicates a fit to the data between 100 MeV and 31.6 GeV when using the shape of the best-fit 9.5 year spectrum and only leave the normalisation free. It can be seen that this well reproduces the low-energy part of the SED, while being in tension with the SED above 30 GeV.

3 Conclusion

IceCube has published two cases of neutrino emission that are spatially well consistent with emission from the IBL/HBL Blazar TXS 0506+056. Looking into all the available multi-wavelength data we provide additional information that supports this picture. While there are other non-thermal sources close by, only one of them, PKS 0502+049, is also a γ -ray emitter. The flare of PKS 0502+049 is shown to be not synchronized with the neutrino emission. Furthermore the γ -ray spectra of TXS 0506+056 during both neutrino emission periods are well consistent with the flux level observed in neutrinos. In fact a hardening of the spectrum during the neutrino flare could point to a direct connection of neutrinos and γ -rays. Although statistically still weak, this provides potentially important insights in the

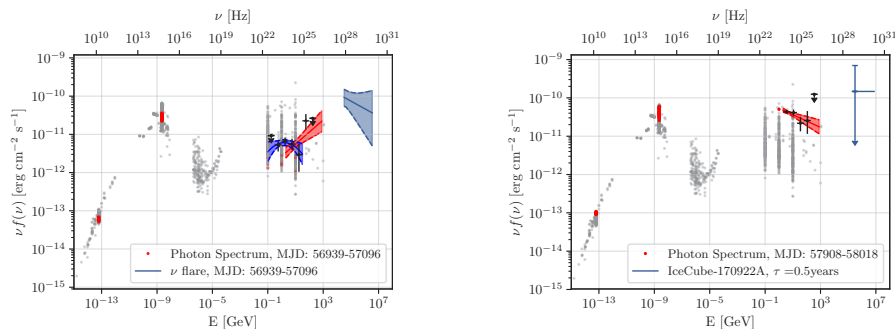


Figure 4. Left: The hybrid SED of electromagnetic emission and neutrinos during the period of the neutrino flare. Archival and time simultaneous data are shown in grey and color, respectively. The red band shows the γ -ray spectrum for neutrino energies above 2 GeV, while the blue band shows a fit to the data between 100MeV and 30GeV when fixing the spectrum to the 9.5 year *Fermi*-LAT best-fit shape and only leaving the normalization free. **Right:** The same as the left plot around the time of the neutrino alert. As there is only one event observed we can only place an upper limit for the neutrino flux derived from Poisson statistics for half a year of IceCube exposure. In both plots the SED points are EBL de-absorbed using the model of [12].

production mechanisms of neutrinos in blazar jets. This scenario is also discussed in several theoretical work, e.g. [13] [14].

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