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Linking electromagnetic observations to neutrino astrophysics

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Abstract. The incontrovertible evidence of the existence of cosmic sources producing neutrinos has opened the quest for the identification of those emitters. Observations of the electromagnetic emission from astrophysical objects prove to be an important complement to the neutrino information and can be used to place constraints on the source population contribute to the cosmic diffuse neutrino flux observed by the IceCube observatory. While no single neutrino point source has been pointed out with high confidence so far, a promising ground for discovery is the search for transient and variable neutrino/electromagnetic sources, in which case the atmospheric neutrino and muon backgrounds can be reduced by taking time- and space-coincidence. A first encouraging result in this direction is the positional and time coincidence of the high-energy neutrino IceCube-120922A and the flaring gamma-ray blazar TXS 0506+056.

Key words. galaxies: active — galaxies: jets — gamma-rays: galaxies — radiation mechanisms: non-thermal — relativistic processes — neutrinos

1. Introduction

The detection of a diffuse high-energy neutrino flux of cosmological origin in the energy range from 30 TeV to 2 PeV (Aartsen et al. 2013) by the IceCube observatory has prompted the quest for the identification of the astrophysical sources responsible for it. The observed total diffuse neutrino flux follows a differential spectrum not harder than $dN/dE \propto E^{-2}$ above a few tens of TeV and ranging to almost 10 PeV (Aartsen et al. 2015). The observed signal is consistent with an isotropic distribution, suggesting that the majority of the contribution is of extragalactic origin (Aartsen et al. 2014).

The production of high-energy neutrinos involves the acceleration of cosmic rays. Two main categories of high-energy neutrino / cosmic rays production models have been proposed: ”cosmic-ray accelerators”, where neutrinos are produced within the cosmic ray source and mesons are typically produced by interactions of cosmic rays with radiation, and ”cosmic ray reservoirs”, where neutrinos are produced by inelastic hadronuclear collisions while confined within the environment surrounding the cosmic ray source (for more details see e.g., Murase and Waxman 2016). For instance, the former models have been suggested for relativistic jets of gamma-ray bursts and blazars, while the second ones for starburst galaxies, galaxy clusters and active galactic nuclei (AGN).

So far, single neutrino point source candidates have eluded the detection. No strong steady or variable neutrino point source, nor a correlation with the Galactic plane has been reveled by the IceCube dataset (Aartsen et al. 2014).

2. Neutrino and electromagnetic signal

While neutrino astronomy has turned into a helpful means of investigation, more can be learned by using it in synergy with other mature probes. In particular, the combination of neutrino/electromagnetic information is motivated by the fact that both radiations may be pictured in the same astrophysical particle-cascades scenario, cascades that are ultimately originated by cosmic rays. As further support in this direction, the diffuse gamma-ray and neutrino backgrounds are comparable, suggesting a common origin (Murase 2013). Building on these assumptions, limits have been placed on the known astrophysical source classes contribution to the diffuse neutrino flux. Stringent constraints derived on steady source candidate classes and limits on source density inferred by non-observation of neutrino multiplets (Murase and Waxman 2016) indicate that even the brightest neutrino sources are still out of reach to the sensitivity of currently operating neutrino detectors.

An important exception to this pessimistic scenario are potential variable neutrino emitters. If the emission of neutrinos is related to time-dependent processes, a relatively short-lived but intense neutrino emission could overcome the atmospheric neutrino background, unveiling its astrophysical origin through position/time correlation studies.

3. AGN as multi-messenger sources

AGN with relativistic jets, powered by accretion of mass onto the central supermassive black hole (SMBH), have long being endorsed as high-energy cosmic-ray accelerators and, in turn, neutrino emitters (Mannheim & Biermann 1989; Stecker et al. 1991; Mannheim et al. 1992). Blazars, AGN with the jet pointing close to the line of sight of the observer, are the most numerous sources in the extragalactic GeV-TeV γ-ray sky (e.g., Reimer & Böttcher 2013; Acero et al. 2015; Ackermann et al. 2016). Their powerful jets are capable of accelerating electrons to relativistic energies, and their electromagnetic emission is often explained within the framework of leptonic scenarios. However, it is reasonable assuming that in such environments hadrons are present too and, at least at some extent, accelerated as well. This idea has fostered the development of lepto-hadronic scenarios, where emission by hadrons interactions contribute to the electromagnetic radiation observed at the highest energies.

In hadronic interactions, high-energy photons / pairs and neutrinos are produced in equal power (by order of magnitude, e.g., Mannheim & Schlickeiser 1994; Mücke et al. 2000), making gamma-ray blazars plausible source candidates of the observed high-energy neutrinos. It has been shown that one-zone blazar emission models, where neutrinos are produced in photo-hadronic interactions, typically predict the peak of the neutrino spectra at or beyond PeV-energies (e.g., Mücke et al. 2003; Dermer et al. 2012), energies that can be directly probed by the current neutrino detectors.

3.1. A promising hint

In the literature, several studies claim a hint for connection between individual gamma-ray blazars and high-energy neutrino events, although with marginal correlation significance (e.g. Kadler et al. 2016; Padovani et al. 2016; Krauss et al. 2018; Lucarelli et al. 2019). To date, the most compelling one is the observation of a IceCube event, i.e., IceCube-170922A, in spatial and time coincidence with the flaring gamma-ray blazar (Aartsen et al. 2018a). The high-energy neutrino IceCube-170922A was detected on 2019 September 22. Information about its sky localization were reported by the IceCube collaboration to the astrophysical community almost in real time and prompted an extensive multi-messenger campaign to pinpoint the potential astrophysical counterpart. High-energy gamma-ray emission from the candidate neutrino counterpart, the blazar TXS 0506+056, was first reported by the *Fermi*-Large Area Telescope (Tanaka, Buson, and Kocevski 2017), and further confirmed by the MAGIC and VERITAS Cherenkov detectors (Ansoldi et al. 2018; Abeysekara et al. 2018). At the time of the neutrino detection, TXS 0506+056 was undergoing an enhanced activity state (see Fig. 1). Assuming a direct correlation between the gamma-ray and neutrino emission, a spatial chance coincidence of the neutrino and blazar was disfavoured at 3 σ significance. The rich multi-wavelength dataset collected enabled an avalanche of theoretical efforts directed to model the neutrino emission in coincidence with the electromagnetic blazar flare (see e.g., Gao et al. 2019; Ansoldi et al. 2018; Cerruti et al. 2019; Keivani et al. 2018).

A subsequent follow up analysis of the IceCube archival data evidenced the presence of additional neutrinos positionally consistent with TXS 0506+056 (Aartsen et al. 2018b). The neutrino excess was constituted by 13 low-energy events clustered in a four months time interval, between October 2014 and March 2015. The energy of the events was on average $\sim$ 10 TeV, and the most energetic one had a deposited energy of 20 TeV. The spatial coincidence and previous gamma-ray/neutrino connection has motivated the idea that the blazar could be responsible also for these observed neutrinos. Intriguingly, during this period of time, the blazar did not display remarkable activity over the electromagnetic spectrum and its emission was compatible with a lower/quiescent state (green shaded area in Fig. 1), although there exists some debate about the presence of a potential hardening in its gamma-ray spectrum (Fermi-LAT collaboration et al. 2019; Padovani et al. 2018).

3.2. A complicated interplay

Many theoretical models that have been applied to the spectral energy distribution (SED) of TXS 0506+056 successfully explain the simultaneous multi-wavelength emission and IceCube-120922A neutrino detection from the blazar. However, the detection of one single neutrino event, like in the case of IceCube-120922A, makes it difficult (if not impossible, see Strotjohann, Kowalski, and Franckowiak 2019) to derive robust estimates on the neutrino spectrum. The latter is a necessary ingredient to reliably anchor any theoretical model. In this respect, the archival neutrino excess observed in 2014 – 15 offers an ideal opportunity. It includes a sufficient statistics to derive spectral constraints and thus allows us to test predictions for photo-hadronically produced neutrinos from TXS 0506+056 and place constraints on the associated broad-band electromagnetic SED.

The neutrino flux from the 2014 – 15 neutrino excess positionally consistent with TXS 0506+056 was best represented by a power-law spectrum between 32 TeV and 3.6 PeV represented by $\Phi_\nu(E_\nu) = \Phi_0\, E_{14}^{-2.1}$ with $\Phi_0 = 2.2 \times 10^{-15}$ cm^{-2} s^{-1} TeV^{-1} and $E_{14} \equiv E_\nu/(100\,\mathrm{TeV})$ (Aartsen et al. 2018b). In the photo-hadronic scenario of jetted AGN, the high-energy photons and electron-positron pairs accompanying the neutrino emission are expected to develop electromagnetic cascades. It can be shown that the efficiency is directly linked to the observed neutrino production rate and the observable photon radiation is theoretically expected to be shifted in the keV to MeV band.

Efforts have been directed into comparing the contemporaneous neutrino and electromagnetic observations for the October 2014 / March 2015 dataset. During the archival neutrino flare only sparse observations in optical, X-rays and gamma rays are available. Nevertheless, this limited information accessible are yet remarkably constraining for photon-hadronic predictions. Several authors applied different approaches to explain the multi-messenger data of TXS 0506+056 during 2014 – 15 and find it difficult to reconcile the large number of neutrino events detected with the observed photon SED of TXS 0506+056, if neutrinos are produced via photo-pion production (Reimer, Boettcher and Buson 2018; Rodriguez et al. 2019).

The only viable scenario (following the work of Reimer, Boettcher and Buson 2018), appears to be a stationary soft X-ray pho-

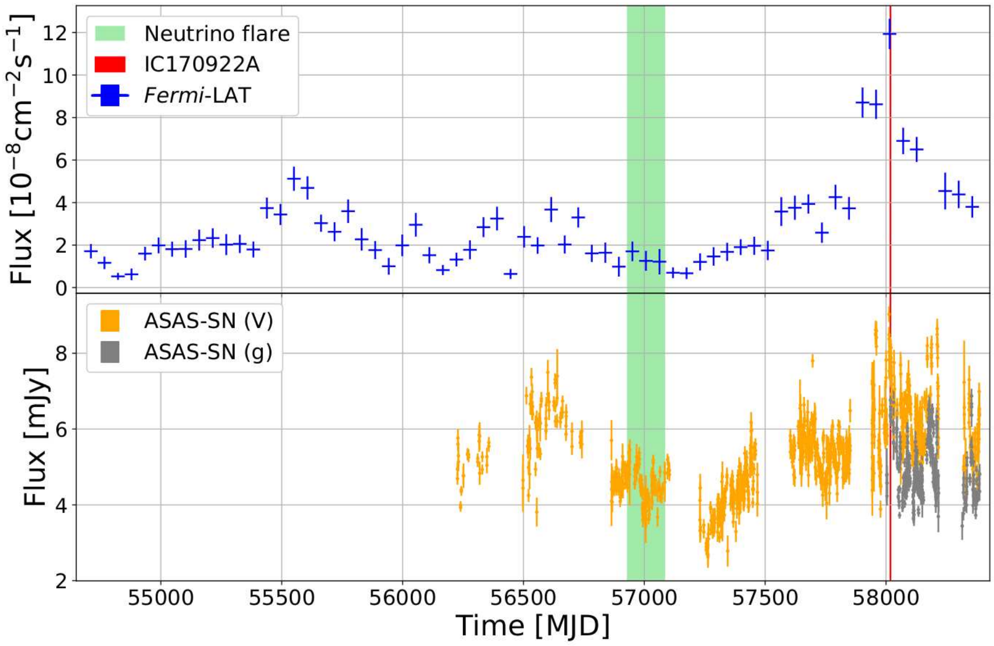

Fig. 1. Light curve of TXS 0506+056 in the gamma-ray band (top, *Fermi*-LAT) and optical (bottom, ASAS-SN). The vertical red line indicates the arrival time of IceCube-170922A, the green shaded area highlights the period of time when in 2014–15 IceCube observed an excess of low-energy neutrinos ("neutrino flare"). From Reimer, Boettcher and Buson (2018)

ton field providing the seed targets for photopion production of the observed neutrinos with the resulting cascades being driven by inverse Compton radiation only. In this framework, the predicted electromagnetic emission does not exceed the limits imposed by the observations, and the required proton kinetic power is compatible with that resulting from a jet powered by accretion into a supermassive black hole. However, the production of neutrinos is very inefficient during the neutrino flare and the predicted GeV-flux too low to explain the LAT observation, implying that the bulk of the gamma-rays can not originate from the same mechanism that is producing the neutrinos. Further, simulations indicate that the electromagnetic signatures accompanying the neutrino emission are shifted into the keV to MeV band where no simultaneous observations are available (Reimer, Boettcher and Buson 2018).

4. Future perspective: looking ahead

The progresses made in the past years have turned neutrino astrophysics into a promising ground for future discoveries. The possible TXS 0506+056 / IceCube-170922A association is a tantalizing clue in support of hadronic acceleration in blazars, and the identification of the first neutrino emitter. Nevertheless, detailed investigations of the 2014 – 15 blazar/neutrino dataset suggest that a direct correlation between gamma-ray activity and neutrino emission is not necessarily straightforward and warrants further investigation. The signatures of the expected cascade electromagnetic emission accompanying the neutrino production are likely encoded in the X-ray - soft gamma-ray band, making the keV band and above the crucial energy range to decipher the multi-messenger information.

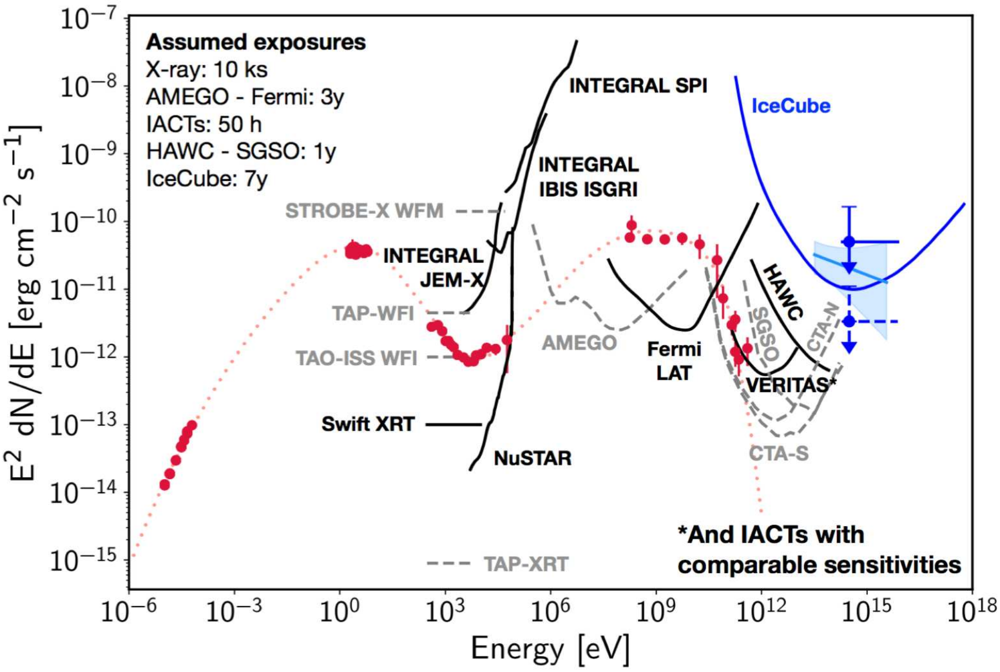

Fig. 2. SED of TXS 0506+056 (red points) with overlaid the sensitivity of current and upcoming observational facilities (from Buson et al. 2019).

Current wide-field instruments such as INTEGRAL (Ubertini & Bazzano 2014) and MAXI/GSC (Kawamuro et al. 2018) provide larger sky coverage, offering a good complement to more sensitive instruments as e.g., *Swift* and *NuSTAR* (see Fig. 2). Significant progresses are expected in future, when instruments like IXPE (Weisskopf et al. 2016) and possibly the All-sky Medium Energy Gamma-ray Observatory (AMEGO Moiseev A. et al. 2018) will enable us with increased sensitivity and the capabilities of providing the first X-ray/gamma-ray polarimetry results, disentangling leptonic and hadronic contributes in the blazar SED.

In general, a pre-condition for likely astrophysical very-high-energy (> 100 TeV, VHE) neutrino sources is that they generate VHE cosmic rays as well, making the quest for neutrino sources even more rewarding. New neutrino observatories planned for the upcoming decade, such as the KM3NeT (Adrin-Martnez et al. 2016) and GVD (Avrorin et al. 2018) in the northern hemisphere, and IceCube-Gen2 in the South Pole (IceCube-Gen2 Collaboration et al. 2014), will have a sensitivity similar or improved by a factor of two to the IceCube detector one. These next-generation detectors promise to shed light in the identification of hadronic sources, possibly providing the first definite clues into the Universe' PeV proton accelerators. Notwithstanding that such emitters could also be naturally related to the sources of ultra-high energy cosmic rays detected by the Auger and Telescope Array observatories, for the current (and near future) detected maximum neutrino energies of $\lesssim 3$ PeV, it is only necessary to have sources capable of accelerating cosmic rays up to $\lesssim 100$ PeV (Meszaros 2017; Bttcher 2019).

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