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Blazar as neutrino emitters

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Active galactic nuclei with a relativistic jet pointing to the Earth, also called blazars, are natural accelerators of particles, as witnessed by the strong non-thermal emission. This makes them good candidate sources for extragalactic cosmic rays and neutrinos at high-energy. The recent detection of IceCube-170922A, a ~ 300 TeV neutrino potentially correlated with the flaring blazar TXS 0506+056, directs attention toward this kind of objects as neutrino emitters. This coincidence event shed light on the structure and dynamics of the sources confirming the presence of cosmic rays inside the jet. In particular it offers a unique opportunity to explore the interplay between energetic photons, neutrinos and cosmic rays in the jet.

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1. Introduction

High-energy (> 60 TeV) neutrinos were observed for the first time in 2010 by the world's largest neutrino detector IceCube, a km^3-scale detector constructed deep within the ice at the geographical South Pole [1]. Two main types of signals, *tracks* and *cascades*, are measured by IceCube. The former are produced by muons, mostly due to charged current interactions of muon neutrinos with matter. Tracks are reconstructed with angular uncertainties of $\sim 0.5° - 1°$. Cascades, products of all other neutrino interactions, result from particle, that are very short, together with showers. For this reason typical angular uncertainty for cascades is quite big, $10 - 20°$. On average, 8 track-like high-energy neutrino events with a high probability of being astrophysical are detected and published as alerts per year. In 2016, in fact, IceCube Collaboration set up a real time alert system [2]. Any track-like event with sufficient energy to have a high probability of being an astrophysical neutrino generates an alert in the form of a public Gamma-ray Coordinate Network circular within a minute of the event for possible follow-up by astronomical telescopes.

After $\sim$ ten years of observation the origin of these neutrinos is still unknown. The main channels to produce high-energy neutrinos are the interaction of relativistic protons with matter (pp channel) or with radiation ($p\gamma$ reaction or photo-meson) and for this reason there are several kind of sources that can be considered as neutrino emitters (see [3] or [4] for a review). The quite isotropic distribution of arrival directions suggests an extragalactic component.

Here we focused on Blazars, a quite small fraction of the entire population of active galactic nuclei (AGN) with a relativistic jet pointed to us [5]. Their defining phenomenology includes the presence of a compact core, extreme variability at all frequencies (but generally being more extreme at the highest frequencies), high degree of optical and radio polarization ([6],[7] for a review). The most distinctive feature, however, is the intense emission in the γ-ray band, often dominating the bolometric radiative power output. Indeed, blazars are the most numerous extragalactic γ-ray sources, both at GeV and TeV energies. The 4-years catalogue of Fermi-LAT (4FGL, [8]) reports more than 1700 blazars, to be compared with about 30 non-blazar extragalactic sources. Similar is the situation at higher energies ([9]).Their spectral energy distribution (SED) is characterised by two peak in the νF_ν plot. Synchrotron emission from the relativistic electrons produced the first bump peaking in the IR-optical-UV band. The origin of the second peak, in the γ-ray band, is still under debate. It can be produced by the Inverse Compton emission (leptonic model) or by the synchrotron emission of relativistic protons or photomeson cascade (hadronic model).

Blazars are divided into two subclasses: flat spectrum radio quasars (FSRQ) showing broad emission lines in the optical spectrum and generally powerful in the γ-ray band, and BL Lac objects, less powerful, with weak or absent emission lines and with the two peak of the SED at the same luminosity. The favourite channel to produce high-energy neutrino from these sources is the $p\gamma$ reaction due to the abundance of photons produced inside the jet and in the environment.

At present there is only one case[1] for which there is a strong evidence of a spatial correlation between the direction of a neutrino event observed by IceCube and a flaring blazars [12] (hereinafter TXS event). In 2017, the blazar object TXS 0506+056 was the only γ-ray source within the well reconstructed direction region of the IceCube event IC-170922A [12], and simultaneously in an

[1] In 2016 a possible correlation between a neutrino with high angular uncertainty and a flaring FSRQ was reported by [10]. However there are several arguments excluding this correlation (see e.g. [11]).

elevated flux state in the Fermi-LAT energy range [12] at the time this event was detected. A multiwavelenth campaign dedicated to this source showed a global high-state during the neutrino event [12]. Moreover, for the first time, this blazar was observed at very-high energy by MAGIC telescopes [13].

In the following, after a sketch of the general framework, we review the theoretical and observational status concerning the neutrino emission from both FSRQs and BL Lacs.

2. The general framework

AGN are composed by a central supermassive black hole ($M_{BH} = 10^8 - 10^9 M_{\odot}$) accreting matter from the surroundings (see [5] for more details).

The phenomenological division between FSRQ and BL Lac objects can be interpreted as a difference in the nature of the accretion flow [14] [15]. In FSRQ, which show bright thermal features (optical lines) and, in some cases, a bump at optical-UV frequencies (thought to mark the direct emission from the hot accreting gas), the accretion likely occurs through a radiatively efficient (optically thick) accretion disk [16]. The luminous UV continuum emitted by the disc is responsible for the photoionization of the gas confined in "clouds" rapidly orbiting the black hole and occupying the so-called broad line region (BLR). Farther out (1-10 pc), dust grains, probably organised in a geometrical torus, intercept a fraction $\varepsilon \approx 0.5$ of the disk continuum, reprocessing it as thermal IR emission (with temperature close to that corresponding to the sublimation of dust, $T \approx 10^3$ K).

The lack of strong thermal components in BL Lac optical spectra is generally interpreted as an evidence of a radiatively inefficient accretion flow (RIAF). At very low accretion rates the particle density is so low that the energy exchange time scale between electrons and protons becomes larger than the accretion time scale. Most of the dissipated energy remains stored within the protons/ions, and an effective radiating disc model is no more plausible. In this case the accretion flow can achieve temperature higher than the accretion disc, for this reason it is also called "hot accretion flow". It occurs at lower mass accretion rates, and is described by models such as the advection-dominated accretion flow (ADAF) and luminous hot accretion flow (LHAF) (see [17] for more details). For this reason the emission lines in the optical spectra are weak or absent. The presence of this kind of accretion in BL Lac is only theorised and there is no observational evidence to support this interpretation.

This scheme can explain the presence of broad emission lines in case of FSRQs and the absence or weakness of these thermal features in case of BL Lacs. It is also able to explain the difference between the GeV γ-ray spectra of BL Lacs (generally displaying hard spectra) and those of FSRQ (characterised by soft - photon index larger than 2 - spectra), as the effect of the different radiative losses characterising the high-energy electrons in the two kind of sources.

More generally, the interplay between radiative losses of the emitting electrons in the jet and the accretion rate onto the black hole could be at the base of the so-called "blazar sequence" [18] [19], i.e. the trend between the observed luminosity (progressively increasing from BL Lacs to FSRQ) and the synchrotron and high-energy SED peak frequencies (decreasing from BL Lacs to FSRQ) displayed by the blazar population. However this trend could be a selection effect, see for examples [20] for an alternative scenario.

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3. Main models

Neutrino emission from both FSRQs and BL Lac objects is attributed to the $p\gamma$ interaction in which relativistic protons, or more generally cosmic rays (CR), interac with photons produced in the jet itself or with an external radiation field (emission from BLR, torus, disc, other). Their interaction produces pions, where neutral pions decay into two γ-ray, while charged pions produced neutrinos through the decay: $\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu} \rightarrow e^{\pm} + \nu_{e} + 2\nu_{\mu}$ (note that we do not distinguish between ν and $\bar{\nu}$). Due to the threshold of the $p\gamma$ reaction, the typical energy of protons and photons involved is of the order of $E_p \approx 10^{16} - 10^{17}$ eV and $E_\gamma \approx 1 - 10$ eV, respectively to produce neutrinos at ~ 100 TeV -10 PeV.

The most simple neutrino emission model from Blazars assumes a single region of the jet in which relativistic protons interact with photons produced in the jet itself by the synchrotron emission of the electrons. However this simple case leads to disfavour blazars as main neutrino emitters, e.g. [21] or [22]. Due to the different environment of FSRQs and BL Lacs it is convenient to consider them separately to understand the main photon field possibly involved in the neutrino production.

As already said previously, FSRQs are powerful Blazars, with an accretion disk that irradiate the BLR. Following [23], we can reasonably assume that the spectral shape of the BLR emission observed in the jet frame frame is a blackbody peaking at a factor Γ times the (rest-frame) frequency of the Lyman α line. The external radiation can be responsible for the photomeson reaction if relativistic protons are accelerate before the BLR. Figure 1 shows the SED of a generic FSRQ (solid blue line) and the expected neutrino emission using different photon population involved in the $p\gamma$ reaction. Note that we assumed a population of protons distribution parameterised by a cut-offed power-law with the total injected luminosity of $L_p = 10^{45}$ erg s^{-1}, a spectral index $n = 2$ and an energy cut at $E_{cut} = 10^{17}$ eV (see [21] for a more complete discussion).

For BL Lac objects the situation is less clear because of the weakness or absence of external radiation coming from BLR or torus. However, TXS 0506+056, the flaring blazar associated to the muon neutrino event in 2017, is classified as a BL Lac object. In particular BL Lac are divided in three subclasses due to the position of the synchrotron peak, ν_S of the SED. TXS 0506+056 is classified as an intermediate/low BL Lac (IBL/LBL, or, ISP/LSP, see [24]). BL Lac was already took into account as neutrino emitters before this event. In [21] the so-called spine-layer scenario was proposed to produce neutrino. This view, which adopts a structured relativistic jet with a fast core and a slower shield, is based on both observations, e.g. [25], and theoretical motivations, e.g. [26]. In this scenario the protons inside the core can interact with the photons produced in the external region, amplified by relativistic motion effects. This scenario was proposed in [13] to explain the TXS event of 2017. Another external radiation population that can be involved in the $p\gamma$ reaction are those produced by RIAF. In this case the relativistic protons should be accelerated close to the accretion flow in order to have an efficient neutrino production. This scenario is already suggested for other kind of AGN, as in [27] and it was suggested for the first time for BL Lac in [28]. In [28] the neutrino emission using the RIAF radiation is considerable in comparison with the internal jet radiation, only for the LBL objects. A paper in which this scenario is applied to TXS 0506+056 is on preparation. Other alternative scenarios were presented to explain the TXS event (see [29], [30], [31], [32], [33], [34]). The common feature that comes up from the models of the

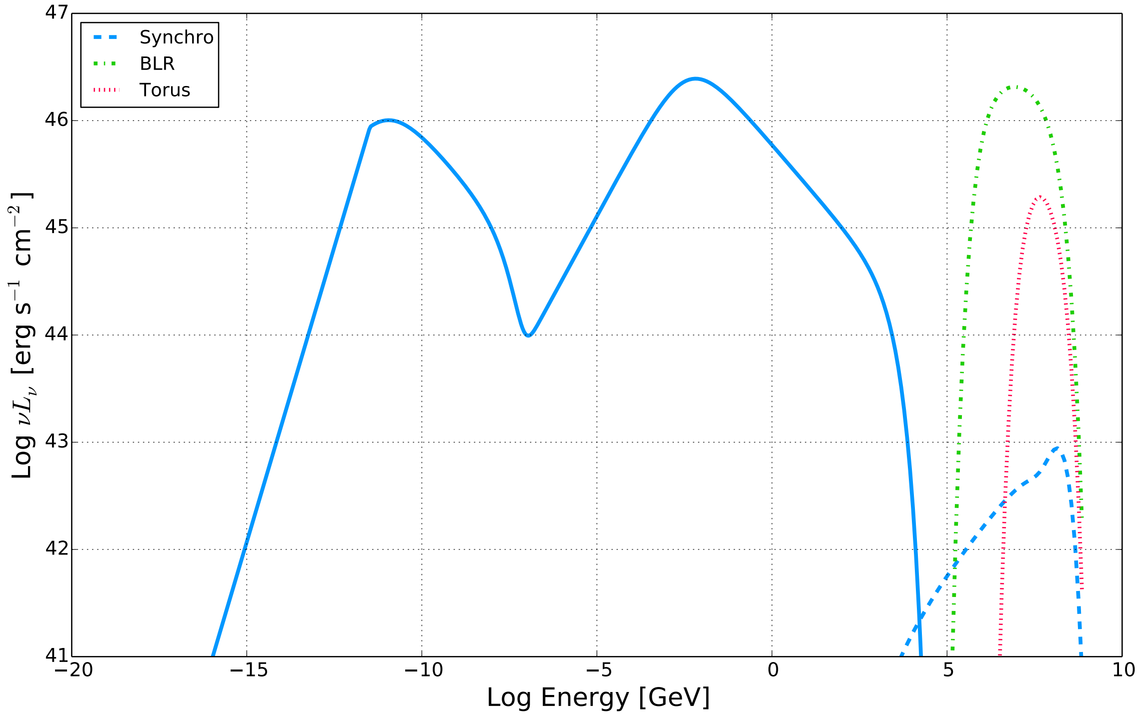

Figure 1: SED for a typical FSRQs belonging to the luminosity bin 10^{45} erg s^{-1} $< L_{LAT} < 10^{46}$ erg s^{-1} of the blazar sequence [19]. Blue solid line shows the average SED of this luminosity bin derived with the phenomenological model. Red dotted line, green dash-dotted line and blue dashed line are respectively the neutrino spectrum obtained using the radiation of the torus, of the BLR and the internal synchrotron radiation as targets for the $p\gamma$ reaction.

SED of TXS 0506+056 during the neutrino event is that the high-energy electromagnetic emission is dominated by leptonic emission (Inverse Compton), while the radiation emitted via hadronic processes (Bethe-Heitler cascade, synchrotron by relativistic protons and cascade of photo-meson reaction) is not relevant. The reprocessed hadronic component can come up in the X-ray band (between the two peaks of the SED) and at high-energy (TeV band). Another important feature that comes up is that the shape of the X-ray spectrum could give information on the relative role of leptonic and hadronic processes.

More exotic scenarios were presented to explain the neutrino emission from this BL Lac, such as the pp reaction ([33] or [35]).

4. Open issues

The study of blazars as high-energy neutrino sources is becoming increasingly interesting after the observation of a coincidence event with the flaring blazar TXS 0506+056 by IceCube in 2017. However there are several open issue still under debate. Here we present some of these:

- Several studies suggest that the neutrino background observed by IceCube is a sum of several components (see for example [36] or [37]). In particular the IceCube Collaboration estimates a maximum contribution of $\sim 20\%$ of the observed neutrino background from blazar. However, due to the relatively high angular uncertainty of the neutrino arrival direction, it should be easier find an electromagnetic counterpart if the source is a transient. For this reason blazar are in any case good neutrino sources to monitor. In fact, recently indications of Ice-Cube Collaboration, suggest that in the neutrino sky map there is a hint of clustering at the 4σ level for four sources. Three of these are blazar, while another is a Seyfert galaxy NCG 1068 (see [38], [39]).

- Recent [40] argued that TXS 0506+056 is not a BL Lac object, but a so-called "masquerading FSRQ": a FSRQ with hidden broad lines and a standard accretion disc. The motivations are both observational that theoretical. The nature of TXS 0506+056 has an impact on the theoretical modelling of this source and on our understanding of neutrino emission in blazars. According to the blazar sequence TXS 0506+056 is probably an intermediate object between FSRQ and BL Lac. Fig.2 shows a preliminary plot of the energy index α_γ versus the γ-ray luminosity L_γ for a selected objects of 4LAC catalogue of Fermi [41]. The blazars were selected based on the luminosity at the synchrotron-peak frequency L_S given in the catalogue, the γ-ray spectral index and the γ-ray luminosity. The region around the grey line ($\alpha_\gamma = 1.2$) can be interpreted as a division of the changing accretion regime of the underlying accretion disk from radiatively efficient to inefficient [15]. The green cross is TXS 0506+056, that stays below the grey line.

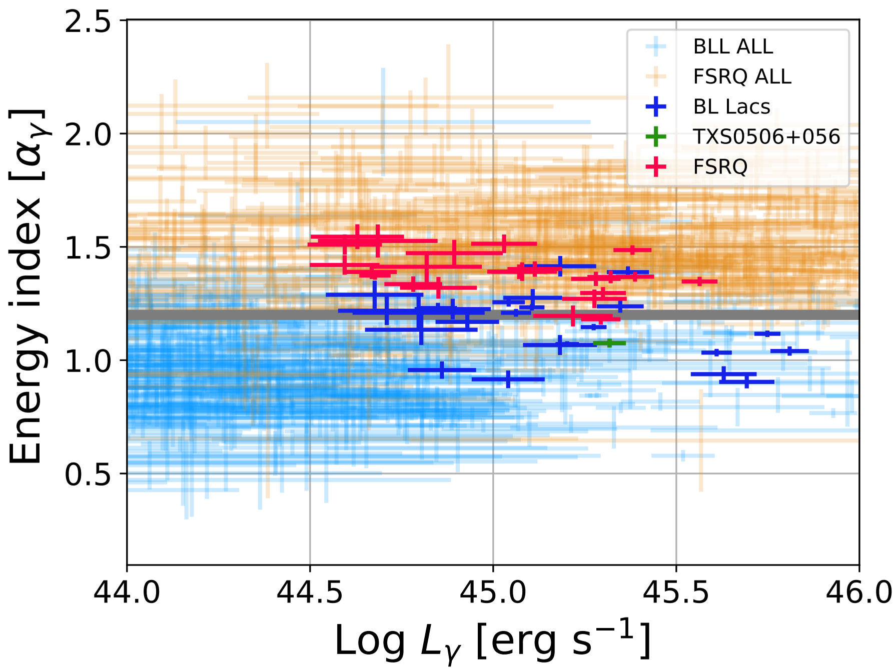

Figure 2: The energy spectral index α_γ vs of the γ-ray luminosity L_γ in the band [0.1- 100 GeV] for a selected blazars with known redshift present in the 4LAC sample. The red crosses are FSRQs; blue crosses are BL Lacs, and TXS 0506+056 is the green cross. The horizontal grey line marks $\alpha_\gamma = 1.2$. With light color are represented all the FSRQ (orange) and BL Lac (light blue) of the 4LAC catalogue.

- After the TXS event, the IceCube Collaboration presented the evidence for an extended neutrino excess coming from the same direction of TXS 0506+056 consisting of ~ 13 neutrino events detected in a period between September 2014 - March 2015 ([42]). Differently from the IC-170922A event, there is no evidence for a γ-ray flare, and not enough data at other wavelength showing an high-state ([43]). Moreover the previous lepto-hadronic models used to explain the single event in 2017 seems to be challenged because of the steep spectrum of this neutrino flare (see for example [44], [45], [46]).

- Even if high peaking BL Lac object (HBL or HSP) such as Mkn 501 or Mkn 421 are more prominent in γ-ray than IBL/LBL, we still do not have clear cases of neutrinos possibly associated with these kind of sources. [47] shows the upper limits to the energy density of any radiation field for this kind of sources. With this work is evident that HBL can produce neutrinos but their production efficiency is very low.

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