ELECTRON-POSITRON PAIR PLASMA IN TXS 0506+056 AND THE “NEUTRINO FLARE” IN 2014 - 2015

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ABSTRACT
The detection of a long flaring activity from blazar TXS 0506+056 in temporal and spatial coincidence with the energetic neutrino IceCube-170922A provided evidence about the photo-hadronic interactions in this source. However, analysis of the archival neutrino and multi-wavelength data from the direction of this blazar between September 2014 and March 2015 revealed a “neutrino flare” without observing quasi-simultaneous activity in the gamma-ray bands, posing challenges to established models. Electron-positron (e±) pairs generated from the accretion disks have been amply proposed as a mechanism of bulk acceleration of sub-relativistic and relativistic jets. These pairs annihilate inside the source producing a line around the electron mass which is expected to be blueshifted in the observed frame (on Earth) and redshifted in the frame of the dissipation region of the jet. The redshifted photons in the dissipation region interact with accelerated protons, producing high-energy neutrinos that contribute significantly to the diffuse neutrino flux in the ∼ 10 - 20 TeV energy range in connection with gamma-rays from photo-pion process which can be detected by future MeV orbiting satellites. Based on this phenomenological model we can explain the “neutrino flare” reported in 2014 - 1015.

Subject headings: Galaxies: active – Galaxies: individual (TXS0506+056) – Physical data and processes: acceleration of particles — Physical data and processes: radiation mechanism: nonthermal – Neutrinos

1. INTRODUCTION
The discovery of a diffuse neutrino flux in the energy range from TeV to PeV by the IceCube telescope has opened a new window in astrophysics at very high energies (VHEs; IceCube Collaboration 2013; Aartsen et al. 2014; The IceCube Collaboration et al. 2015; Kopper and IceCube Collaboration 2017). Because of distinct configurations and strengths of magnetic fields among sources and Earth, cosmic rays (CRs) themselves cannot supply accurate information where these were accelerated (e.g., Pierre Auger Collaboration and et al. 2007). A similar situation due to extragalactic background light (EBL) occurs when TeV photons are emitted from sources at high redshifts (e.g. Franceschini et al. 2008). Whereas CRs are deviated by magnetic fields, and TeV photons are absorbed by EBL, high-energy neutrinos can largely travel and reach Earth giving reliable spatial information about sources.

The IceCube collaboration reported on September 22, 2017 at 20:54:30.43 UTC the detection of a neutrino-induced muon-track event called IceCube-170922A which had an energy of ∼ 290 TeV (IceCube Collaboration et al. 2018a). The reconstructed direction of this event from statistical and systematic effects was R.A.=77°.43±0.95 and Dec=+5°.72±0.50 (J2000.0) which was consistent with the location of blazar TXS 0506+056 when it exhibited very high activity in gamma-rays, X-rays, optical and radio bands. Shortly after the detection, IceCube analyzed the archival muon-neutrino data collected over a period of 9.5 years in the direction of this blazar. This collaboration reported an excess of high-energy neutrinos over the atmospheric background between September 2014 and March 2015 (IceCube Collaboration et al. 2018b). This excess was associated with a large number of neutrinos (13 ± 5) called “neutrino flare” which had energies in the range of ∼ 10 - 20 TeV (Rodrigues et al. 2019). Surprisingly, this “neutrino flare” was detected without significant activity in the electromagnetic bands. This blazar was associated with a redshift of z = 0.3365 ± 0.0010 (Paiano et al. 2018), after the identification of three weak emission lines ([O II] 327.7 mm, [O III] 500.7 mm and [NII] 658.3 mm).

Several interpretations about the IceCube-170922A event and the “neutrino flare” with and without quasi-simultaneous gamma-ray activity have been suggested. Taking into account the Fermi data, Padovani et al. (2018) claimed that during the period of time associated to the “neutrino flare” the broadband spectral energy distribution (SED) of this blazar could have been hardened above 2 GeV. However, Fermi-LAT collaboration et al. (2019) argued that this atypical behaviour might not be relevant. Murase et al. (2018) studied the IceCube-170922A event and the “neutrino flare” with and without quasi-simultaneous gamma-ray activity have been suggested. Taking into account the Fermi data, Padovani et al. (2018) claimed that during the period of time associated to the “neutrino flare” the broadband spectral energy distribution (SED) of this blazar could have been hardened above 2 GeV. However, Fermi-LAT collaboration et al. (2019) argued that this atypical behaviour might not be relevant. Murase et al. (2018) studied the IceCube-170922A event and the “neutrino flare” with and without quasi-simultaneous gamma-ray activity have been suggested. Taking into account the Fermi data, Padovani et al. (2018) claimed that during the period of time associated to the “neutrino flare” the broadband spectral energy distribution (SED) of this blazar could have been hardened above 2 GeV. However, Fermi-LAT collaboration et al. (2019) argued that this atypical behaviour might not be relevant. Murase et al. (2018) studied the IceCube-170922A event and the “neutrino flare” with and without quasi-simultaneous gamma-ray activity have been suggested. Taking into account the Fermi data, Padovani et al. (2018) claimed that during the period of time associated to the “neutrino flare” the broadband spectral energy distribution (SED) of this blazar could have been hardened above 2 GeV. However, Fermi-LAT collaboration et al. (2019) argued that this atypical behaviour might not be relevant.
It has been ample proposed that blazar jets have a large amount of electron-positron (e±) pairs generated from the accretion disks, which serve as a mechanism of bulk acceleration (Phinney 1982; Wardle et al. 1998; Blandford and Levinson 1995). As particular cases, Beloborodov (1999) and Iwamoto and Takahara (2002, 2004) studied pair plasmas ejected with sub-relativistic and relativistic velocities, respectively. Beloborodov (1999) investigated the e± pairs created in gamma-gamma interactions outside the accretion disks. The author found that the pair plasma was ejected with mildly relativistic velocities, and the expected annihilation line produced by the pairs inside the source and observed on Earth was blueshifted and broadening. Iwamoto and Takahara (2002, 2004) considered a pair plasma from a Wein equilibrium state at relativistic temperatures. They found that the pair plasma inside the outflow could be relativistically accelerated and the emission from the photosphere could be detected as MeV-peaked flux. Later, Fraija (2015) computed the hadronic interaction between radiation coming from this plasma and protons accelerated in the dissipation region in order to explain orphan flares reported in some blazars (Daniel et al. 2005; Acciari and et al. 2011).

In this paper we present a phenomenological model, in which photons produced by the pair annihilations at the base of the outflow reach the dissipation region of the jet and interact with accelerated protons. We show that this model can explain a large diffuse neutrino flux in the 10 - 20 TeV energy range and the “neutrino flare” reported in 2014 - 2015. We consider the pair plasma with the features described in Beloborodov (1999) and Iwamoto and Takahara (2002, 2004). The paper is arranged as follows. In Section 2 we introduce the one-zone lepto-hadronic scenario. In Section 3 we compute the neutrino production from a sub-relativistic plasma scenario and a relativistic plasma in a Wein equilibrium state introduced by Beloborodov (1999) and Iwamoto and Takahara (2002, 2004), respectively. In addition, we show the connection between MeV gamma-ray photons and the diffuse neutrino flux. In Section 4 we apply our model, as a particular case, to interpret the “neutrino flare” reported in the source TXT 0506+056, and finally in Section 5 we present the discussion and summary. We will use throughout the paper natural units c = ℓ = 1 and Qν = Q/10^8 in e.g.s.

We consider the Hubble and the cosmological constants given by H₀ = 69.6 km s⁻¹ Mpc⁻¹, ΩΛ = 0.714 and Ωm = 0.286, respectively (Planck Collaboration et al. 2016). Prime quantities are used for the rest frame of the black hole, and unprimed quantities are used in the observer frame and the comoving frame of the dissipation radius and the plasma. For instance, E′ is the energy in the black hole rest frame, E is the energy in the observer frame (on Earth), ε is the energy in the comoving frame of the dissipation radius and ε is the energy in the comoving frame of the plasma.

2. ONE-ZONE LEPTO-HADRONIC SCENARIO

The most extensively accepted scenarios to interpret the broadband SED of blazars are: i) the one-zone SSC model in the leptonic scenario (e.g. Finke et al. 2008; Abdo et al. 2011; Fraija and Marinelli 2016), and ii) the one-zone proton synchrotron (Mücke and Protheroe 2001; Mücke et al. 2003) and photo-hadronic interactions (e.g. Atoyan and Dermer 2003, 2001; Böttcher et al. 2013; Fraija 2014a; Fraija and Marinelli 2015, 2016) in the hadronic scenario. Irrespective of the scenario, the total kinetic luminosity of the jet is estimated through

\[ L_{\text{jet}} = \sum_{i=e,p,B} L_i, \]

where \( L_e, L_B \) and \( L_p \) are the luminosities due to electrons, magnetic field and protons, respectively, which depending on the source the luminosity associated to each set of particles or magnetic field could contribute more than another.

2.1. Leptonic scenario

A homogeneous one-zone model is used considering an electron population described with double-break power laws (Abdo et al. 2011)

\[ \frac{dN_{\gamma}}{d\gamma_e} = N_{0,e} \begin{cases} \gamma_e^{-\alpha_1}, & \gamma_{e,min} \leq \gamma_e \leq \gamma_{e,1} \\ \gamma_e^{-\alpha_2}, & \gamma_{e,1} \leq \gamma_e \leq \gamma_{e,2} \\ \gamma_e^{-\alpha_3}, & \gamma_{e,2} \leq \gamma_e \leq \gamma_{e,max}. \end{cases} \]

with \( N_{0,e} \) the number density of electrons, \( \alpha_1, \alpha_2 \) and \( \alpha_3 \) the spectral indexes, and \( \gamma_{e,min}, \gamma_{e,1}, \gamma_{e,2} \) and \( \gamma_{e,max} \) the electron Lorentz factors for minimum, breaks (1 and 2) and maximum, respectively. This electron population is injected within the spherical dissipation “blob” region of the jet (\( r_b \)) which moves with a constant ultra-relativistic speed \( \beta_b = \sqrt{1 - 1/T_b^2} \) in a collimated jet. The term \( T_b \) corresponds to the bulk Lorentz factor of the dissipation region. The kinetic power ratio between the magnetic field and ultra-relativistic electrons can be estimated through the equipartition parameter \( b_{B,e} = L_B/L_e \), where the luminosities carried by the magnetic field and electrons are (e.g., see Böttcher et al. 2013; Fraija 2014b; Fraija et al. 2019a)

\[ L_B \simeq \frac{1}{8} \pi^2 \Gamma_b B^2, \]

and

\[ L_e \simeq \pi \Gamma_b m_e \int_{\gamma_{e,min}}^{\gamma_{e,max}} \gamma_e \frac{dN_{\gamma}}{d\gamma_e} d\gamma_e, \]

respectively, with \( m_e \) the electron mass.

The electron population confined by the magnetic field (\( B \)) in the dissipation region begins to radiate photons by synchrotron process, and also scatter these photons via inverse Compton scattering. The electron Lorentz factors, the timescales, the synchrotron and inverse Compton scattering spectra with their spectral breaks are explicitly illustrated and discussed in Fraija and Marinelli (2016) and Fraija et al. (2017a).

2.2. Hadronic scenario

Protons are co-accelerated with electrons and confined, in turn, in the dissipation region by the magnetic field. For this scenario, it is important to define the proton luminosity as

\[ L_p \simeq \pi r_b^2 \Gamma_b m_p \int_{\gamma_{p,min}}^{\gamma_{p,max}} \gamma_p \frac{dN_{\gamma}}{d\gamma_p} d\gamma_p, \]

where \( m_p \) is the proton mass and \( \gamma_{p,max} \) is the maximum Lorentz factor for protons. Protons are mainly cooled down by photo-hadronic interactions which encompass two mechanisms: photo-pion production and Bethe-Heitler (BH) pair production.
2.2.1. Photo-pion production

The proton energy loss rate due to photopion production is given by \( p + \gamma \rightarrow \pi^0 + p \) or \( \pi^+ \rightarrow n + (\Delta^+ + ) \). Then, neutral pions decay into two photons (\( n^0 \rightarrow \gamma + \gamma \)) and charge pions decay into neutrinos and anti-neutrinos (\( \pi^+ (\pi^-) \rightarrow \mu^+ (\mu^-) + \nu_\mu (\bar{\nu}_\mu) \)). The efficiency of the photo-pion production calculated through dynamical (\( t_d = \frac{\tau_b}{t_p} \)) and photo-pion (\( t_{p\pi} \)) timescales in the comoving frame is given by (Stecker 1968; Waxman and Bahcall 1997)

\[
f_{p\pi} \simeq \frac{t_d}{t_{p\pi}} = \frac{r_b}{2T_b \gamma_p^3} \int_{\epsilon_{th}}^{\infty} d\sigma_{p\pi}(\epsilon) \frac{n(\epsilon)}{\epsilon} \int_{\epsilon_{th}^2}^{\infty} d\epsilon_{\gamma} n(\epsilon_{\gamma}) \frac{n(\epsilon)}{\epsilon^2}, \tag{5}\]

where \( \sigma_{p\pi} \simeq \sigma_{pk} \frac{\Delta \epsilon_{pk}}{\epsilon_{pk}} \) with \( \sigma_{pk} = 5 \times 10^{-28} \text{ cm}^2 \) is the photo-pion cross section, \( \Delta \epsilon_{pk} = 0.2 \text{ GeV}, \epsilon_{pk} \simeq 0.3 \text{ GeV} \), \( \epsilon_{p\pi} \simeq 0.2 \) and \( n(\epsilon) \) is the photon spectrum. We consider a mono-energetic photon distribution

\[
n(\epsilon) = \frac{u_{\gamma}}{\epsilon_{\gamma}} \delta(\epsilon - \epsilon_{\gamma}) , \tag{6}\]

and the energy density of target photons given by

\[
u_{\gamma} \simeq \frac{L_{\gamma, \text{ph}}}{4\pi \Gamma_{\gamma, \text{ph}} r_b^2} , \tag{7}\]

with \( L_{\gamma, \text{ph}} \) the luminosity of the seed photons. The efficiency of the photo-pion production can be written as

\[
f_{p\pi} \simeq 2 \frac{u_{\gamma}^2 \sigma_{pk} r_b}{\epsilon_{\gamma}} \left[ 1 - \left( \frac{E_{p\pi}^{\text{th}}}{E_p} \right)^2 \right] , \tag{8}\]

where \( E_{p\pi}^{\text{th}} \) corresponds to the threshold of the proton energy.

2.2.2. Bethe-Heitler pair production

The proton energy loss rate due to BH pair production is given by \( p + \gamma \rightarrow e^- + e^+ \). The efficiency of the BH pair production calculated through the dynamical and BH (\( t_{pe} \)) timescales is given by (Petropoulou and Mastichiadis 2015)

\[
f_{pe} \simeq \frac{t_d}{t_{pe}} = \frac{3}{8\pi \gamma_p^2} \sigma_T \alpha \frac{m_e}{m_p} \int_2^{\infty} d\kappa \frac{n(\kappa)}{\kappa^2} \phi(\kappa) , \tag{9}\]

where \( \alpha \) is the fine structure constant, \( \kappa = 2 \gamma_p e_{\gamma} / m_e \), \( \sigma_T = 6.65 \times 10^{-25} \text{ cm}^2 \) is the Thompson cross section, and \( \phi(\kappa) \) is a function defined in Chodorowski et al. (1992). Considering the mono-energetic photon distribution given by eq. (6), the efficiency of the BH pair production can be written as

\[
f_{pe} \simeq \frac{3}{4\pi} \sigma_T \alpha \frac{m_e u_{\gamma}}{m_p} \frac{\phi(\kappa)}{\kappa^2} \epsilon_{\gamma} r_b , \tag{10}\]

2.2.3. Secondary pair productions

Synchrotron emission is expected from secondary pairs created in photo-pion and BH pair production. The characteristic photon energy radiated by synchrotron is \( \epsilon_{\gamma} = \frac{q_e}{2\pi m_e^2} B \epsilon_{\gamma, i} \), where \( q_e \) is the elementary charge and \( \epsilon_{\gamma, i} \) is the energy of the secondary pairs with \( i = p\pi \) and \( pe \) for photo-pion and BH pair production, respectively.

### The secondary pairs from photo-pion process.

The electron energy generated by the photo-pion production is

\[
\epsilon_{e,p\pi} \simeq \frac{1}{4} \frac{\epsilon_p^{	ext{th}}}{\epsilon_p} . \tag{11}\]

The synchrotron spectrum estimated through the proton spectrum and the efficiency of the photo-pion production can be written as (Petropoulou and Mastichiadis 2015)

\[
L_{E_p^\gamma} = \frac{1}{8} f_{p\pi} L_{E_p^\gamma} , \tag{12}\]

with \( f_{p\pi} \) given by eq. (8).

### The secondary pairs from BH process.

The electron energy generated by the HE pair production is (Kelner and Aharonian 2008)

\[
\epsilon_{e,pe} = \frac{\gamma_p}{1 + 4\gamma_p \epsilon_{\gamma}/m_p} (\sqrt{\gamma_p \epsilon_{\gamma}} + \sqrt{\gamma_p \epsilon_{\gamma} - m_e^2}) . \tag{13}\]

The synchrotron spectrum estimated through the proton spectrum and the efficiency of the photo-pion production can be written as (Petropoulou and Mastichiadis 2015)

\[
L_{E_p^\gamma} = f_{pe} L_{E_p^\gamma} , \tag{14}\]

with \( f_{pe} \) given by eq. (10).

### 3. Neutrino Production

In the scenario of the photo-pion and BH processes, neutrinos and anti-neutrinos are generated in the \( \pi^\pm \) decay products. The efficiencies of the photo-pion and BH processes are calculated in eqs. (8) and (10), respectively. The maximum energy that protons can reach in the dissipation region can be estimated comparing the acceleration, the cooling and the dynamical timescales. The acceleration timescale for protons with energy \( \epsilon_p \) is characterized by \( t_{\text{acc}} = \frac{\eta L}{q_e B} \) where \( \eta L \) is order of unity (e.g. Fraija et al. 2012, 2019b).

The maximum of the neutrino spectrum calculated through the photo-pion production can be obtained through the proton spectrum given by (Murase et al. 2014)

\[
E_{\nu, \text{acc}} \simeq 51.3 \text{ GeV} \Gamma_b \Gamma_{\text{rel}} \left( \frac{\epsilon_{\gamma}}{511 \text{ keV}} \right)^{-1} , \tag{15}\]

where \( \epsilon_{\gamma} \) is the energy of the seed photons corresponding to the pair annihilations given in the sub-relativistic and relativistic pair plasma scenarios (see the following subsections), and \( \Gamma_{\text{rel}} \) is the relative Lorentz factor between the pair plasma where the photons emerge and the dissipation region (see eq. 20).

3.1. A sub-relativistic pair plasma scenario

High-energy photons above the electron rest-mass energy (\( m_e = 511 \text{ keV} \)) interact each other to create an electron-positron (\( \gamma + \gamma \rightarrow e^- + e^+ \)) atmosphere around the black hole. Then, electron-positron pair production in a small size \( r \) is expected close to luminous accreting black hole and serve as a mechanism of bulk acceleration of outflows. In the optically
thin outflow, pairs get away without annihilation and the corresponding luminosity in the electron-positron rest mass is estimated through the number of high-energy photons interacting above the disk. In the optically thick case, pairs annihilate before they can escape from the source \( t_{\text{ann}} \approx \frac{1}{n_{\pm} \sigma_{\gamma \gamma}} < 1 \), with \( n_{\pm} \) the density of the pairs. These pairs are in Compton equilibrium with radiation at a temperature of \( \sim 10 \) keV. The plasma at the base of the outflow has a bulk velocity close to the equilibrium \( \beta_p \sim 0.3 \) incrementing to \( \beta_p \sim 0.7 \) at the photosphere (Beloborodov 1999). The escaping photons can be detected by a distant observer as an annihilation line of width equivalent \( \sim 10 \) keV.

The observed luminosity in photons with energy (in the observer frame)

\[
E_\gamma \approx \frac{1}{1 + z} \frac{m_e}{\Gamma_p(1 - \beta_p \cos \theta)} \tag{17}
\]

corresponds to a photon density \( n \approx \frac{L_{\text{ph}}}{\pi^2 m_e}. \) The term \( \theta \) is an arbitrary angle with respect to the line between the source and observer and \( \Gamma_p = 1/\sqrt{1 - \beta_p^2} \) is the bulk Lorentz factor of the pair plasma. The optical depth for interacting photons is \( \tau_{\gamma \gamma} \approx n \sigma_{\gamma \gamma} \), where \( \sigma_{\gamma \gamma} \) is the average cross section for photon interactions.

In the transition zone from the optically thick to thin \( e^\pm \) envelope, pairs are \( n_{\pm} \approx (\sigma_T r_{\text{ph}})^{-1} \) with \( r_{\text{ph}} \) the photosphere radius. The escaping pairs can be estimated as \( F_\pm \approx \frac{1}{\sigma_T r_{\text{ph}}} \) and the corresponding emerging pair luminosity as \( L_\pm = 2\pi r_{\text{ph}}^2 F_\pm \). Numerical calculations of the density profile of the pair outflow generated above a disk with different parameters for an optically thick and thin outflow are given in Beloborodov (1999).

### 3.2. A relativistic plasma in Wein equilibrium state

In this scenario, the base of the jet is connected with the black hole through the Wein fireball. At the initial state, it is made of \( e^\pm \) pairs in quasi-thermal equilibrium inside the initial scale \( r_o = 2r_g = 4GM \), being \( M \) the black hole mass, \( r_g \) the gravitational radius and \( G \) the gravitational constant. At the first state, photons inside the Wein fireball are at relativistic temperature defined through microscopic processes. The internal energy is converted into kinetic energy and the Wein fireball expands by its radiation pressure. As a result of this expansion, the temperature decreases and the bulk Lorentz factor increases at the first state. The initial optical depth is (Iwamoto and Takahara 2002, 2004)

\[
\tau_0 \approx \frac{n_{e,o} \sigma_T r_o}{\Gamma_o},
\tag{18}
\]

where \( \Gamma_o = 1/\sqrt{1 - \beta_o^2} \) is the initial Lorentz factor of the plasma and \( n_{e,o} \) is the initial electron density which is given by

\[
n_{e,o} = \frac{1}{4\sigma_T G M \beta_o^2 \gamma_{\gamma_{o}}} \frac{1}{\beta_o \gamma_{\gamma_{o}}} \left( \frac{m_p}{m_e} \right) \left( \frac{r_g}{r_o} \right)^2 \left( \frac{L_j}{L_{\text{Edd}}} \right),
\tag{19}
\]

where \( L_j \) is the total luminosity of the jet, \( L_{\text{Edd}} = 2\pi m_p r_g / \sigma_T \) is the Eddington luminosity, \( \gamma_{\gamma_{o}} = K_\gamma (1/\theta_o)/K_2 (1/\theta_o) - \theta_o \) is the average Lorentz factor of electron thermal velocity, \( \theta_o = T_o / m_e c \) is the initial temperature normalized to electron mass and \( K_i \) is the modified Bessel function of integral order. By considering the conservation equations of energy and momentum for a steady and spherical flow (Iwamoto and Takahara 2004, 2002), during the expansion of the Wein fireball the number density of photons and pairs evolve as \( n_{e,o} + 2n_{e,o} = 3n_{e,o} \left( \frac{\tau_o}{r_o} \right)^3 \), the temperature as \( \theta = \theta_0 \frac{r}{r_o} \), the bulk Lorentz factor as \( \Gamma_p = 1/\sqrt{1 - \beta_p^2} = \Gamma_o \frac{r}{r_o} \) and the optical thickness as \( \tau = \tau_0 \left( \frac{r}{r_o} \right)^{-3} \). Finally, the quasi-thermal radiation scape at the photosphere (defined at \( \tau = 1 \), for a radius of \( r_{\text{ph}} = \frac{4}{3} \theta_o r_o \). The numerical results of the relevant quantities at the photosphere such as the radius, the temperature and the velocity are \( 2.7 \lesssim r_{\text{ph}} \lesssim 9.9, 0.2 \lesssim \theta_{\text{ph}} \lesssim 1.5, 1.3 \lesssim (\Gamma_p \beta_{p})_{\text{ph}} \lesssim 5.8 \) and \( 0.1 \lesssim \frac{L_j}{L_{\text{Edd}}} \lesssim 25 \), respectively (Iwamoto and Takahara 2002).

### 3.3. Interactions between photons from the pair plasma and protons within the dissipation region

Figure 1 shows a schematic representation of the photon-hadronic interactions between the radiation generated inside the pair plasma and the accelerated proton in the dissipation region. We consider as seed photons those from the annihilation line released from the photosphere. As follows, we describe the dynamics and Lorentz factors evolved in each frame.

Emerging photons generated in the pair plasma and released from the photosphere will have energies given by eq. 17. These are observed on Earth as an annihilation blueshifted line with an equivalent width of some keV (Beloborodov 1999; Iwamoto and Takahara 2002; Siegert et al. 2016). Emerging photons from the plasma are redshifted in the frame of the dissipation region which moves with a Lorentz factor \( \Gamma_b \). The relative Lorentz factor between the pair plasma and the dissipation region is

\[
\Gamma_{\text{rel}} = \Gamma_b \Gamma_p (1 - \beta_b \beta_p).
\tag{20}
\]

In simple terms, the annihilation line is redshifted in the frame of the dissipation radius. For instance, considering a typical value of Lorentz factor for blazars \( \Gamma_b = 10 \) (Murase et al. 2014) and a sub-relativistic velocity with \( \beta_p = 0.3 \) (Beloborodov 1999), the relative bulk Lorentz factor becomes \( \Gamma_{\text{rel}} \approx 7.5 \). Therefore, in the comoving frame of the jet the annihilation line has an energy of dozens of keV corresponding to

\[
E_{\gamma'} \approx 25.1 \text{ keV} \frac{1}{\Gamma_{\text{rel}} - 1} \left( \frac{\epsilon_{\gamma}}{511 \text{ keV}} \right).
\tag{21}
\]

Photons from the photosphere reach the dissipation region and interact with the accelerating protons producing neutrinos. The characteristic energy can be roughly estimated as

\[
E_{\nu,b} \approx 5.1 \text{ TeV} \Gamma_{b,1} \Gamma_{\text{rel},1} \left( \frac{\epsilon_{\gamma}}{511 \text{ keV}} \right)^{-1}.
\tag{22}
\]

If we consider a relativistic plasma with velocity \( \beta_p = 0.98 \), then the Lorentz factor becomes \( \Gamma_{\text{rel}} \approx 1.2 \). In this case, the annihilation line would have an energy of \( \epsilon_{\gamma} \approx 0.3 \text{ MeV} \) and the characteristic neutrino energy becomes \( E_{\nu,b} \approx 0.6 \text{ TeV} \).
3.4. Connection between MeV gamma-ray photons and diffuse neutrino flux

The neutrino and the gamma-ray spectra from extragalactic BL Lac objects can be estimated through the expression

\[
\phi(E_\gamma) = \frac{1}{4\pi H_0} \int_{z_{\text{max}}}^{z_{\text{max}}} \frac{dz}{(1+z)^2 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}} \times \int dL_\gamma \rho(z, L_\gamma) \frac{L_{E_\gamma}}{E_\gamma^4},
\]

(23)

where \(\rho(z, L_\gamma)\) is the gamma-ray luminosity function of BL Lac objects (per comoving volume in the range of \([\log L_\gamma, \log L_\gamma + d\log L_\gamma]\) at a redshift \(z < z_{\text{max}}\)) and \(E_\gamma'\) is the energy of neutrinos \((x = \nu)\) and synchrotron due to secondary pairs \((x = e^\pm)\). We consider the gamma-ray luminosity function reported in Zeng et al. (2014). In order to compute the individual contribution of each BL Lac, we assume a proton distribution described by

\[
\frac{dn_p}{dE_p} = A_p \gamma_p^{-\alpha_p},
\]

(24)

with \(\alpha_p \approx 2\) the spectral proton index and \(A_p\) the normalization constant. This normalization is estimated assuming that the proton luminosity corresponds to a fraction \(n_p\) of the Eddington luminosity \((i.e., L_p = n_p L_{\text{Edd}}^p)\).

The neutrino and gamma-ray synchrotron fluxes from a single source are calculated in accordance with the hadronic model described in section 2. We consider the seed photons as those created inside a sub-relativistic pair plasma scenario and a relativistic plasma in Wein equilibrium state. In both scenarios we describe the seed photons with the nonenergetic distribution function given in eq. (6). In addition, we assume that the gamma-ray luminosities radiated from the photosphere and from the dissipation region are similar. The parameter values used in Figure 2 are reported in Table 1. Figure 2 shows the neutrino and gamma-ray synchrotron spectra from extragalactic BL Lac objects with redshifts \(z < 2\). The neutrino and gamma-ray spectra are shown from a sub-relativistic pair plasma scenario and a relativistic plasma in Wein equilibrium state. The neutrino flux from the sub-relativistic pair plasma scenario is larger than the relativistic plasma and has a significant contribution in the 1 - 30 TeV energy range. The gamma-ray synchrotron flux at few MeV could be observed in eASTROGAM from the sub-relativistic pair plasma scenario but not from the relativistic plasma. Considering both scenarios, gamma-rays from the secondary pairs could be observed in AMEGO experiment.

4. PARTICULAR CASE: TXS 0506+056

4.1. Multiwavelength and neutrino data

The Fermi LAT (Large Area Telescope) gamma-ray fluxes are obtained between the energy range 0.1 - 300 GeV using the Fermi public database. The Swift BAT (Burst Area Telescope), XRT (X-ray Telescope) and UVOT (Ultra Violet/Optical Telescope) data used in this work are publicly available. The Owens Valley Radio Observatory (OVRO; Richards et al. 2011) data are publicly available. All-Sky Automated Survey for Supernovae (ASAS-SN) optical data used in this work are publicly available. Archival data used in this work are publicly available.

Neutrino data collected with the IceCube collaboration, VHE data collected with HESS (High Energy Stereoscopic System), Major Atmospheric Gamma Imaging Cherenkov (MAGIC), Very Energetic Radiation Imaging Telescope Array System (VERITAS) and HAWC (High-Altitude Water Cherenkov) observatory, gamma-ray data collected with the AGILE satellite, X-ray data collected with Nuclear Spectroscopic Telescope Array (NuSTAR) and INTERnational Gamma-Ray Astrophysics Laboratory (INTEGRAL), optical data with Kiso (G-band), Kanata (R-band) and SARA (UA) ground Telescopes and radio data collected with Very Large Area (VLA; 11 GHz) are taken from IceCube Collaboration et al. (2018b).

4.2. Electromagnetic flaring activity in 2017

On 22 September 2017, the IceCube-170922A event triggered the IceCube experiment (IceCube Collaboration et al. 2018b). One week later, the Fermi LAT collaboration announced high activity in spatial coincidence with the blazar RXJ 0506+056 and the IceCube-170922A event. Immediately thereafter, this source was followed up by a multiwavelength campaign covering a wide range of the electromagnetic spectrum. For instance, the MAGIC telescopes monitored this source and detected VHE gamma-ray emission. IceCube Collaboration et al. (2018b) concluded that the blazar jet may accelerate CRs up to energies of several PeV.

Figure 3 shows the multiband (from radio to VHE gamma-ray) light curves of blazar TXS 0506+056 collected from 2008 August 22 to 2017 December 12. The red dashed line shows the IceCube-170922A event. Blow-up of the flaring activity exhibited during IceCube-170922A event is shown in the gamma-ray, X-ray, optical and radio bands. Figure 4 shows the broadband SED of the blazar TXS 0506+056 with different curves corresponding to distinct models and contributions. The multiwavelength data collected during the flaring activity is shown in red color and the observed flux associated to the IceCube-170922A event is shown for 7.5 and 0.5 years in black. The dashed line corresponds to the best-fit curve proposed by Gao et al. (2019). They considered CRs in the jet of TXS 0506+056 and demonstrated that a moderate increase in the CRs during the flaring activity can yield a powerful increase of the neutrino flux with a range of blazar parameters. Several theoretical models have been proposed to interpret the IceCube-170922A event (e.g. see Padovani et al. 2018; Murase et al. 2018; Gao et al. 2019; Reimer et al. 2019; Fermi-LAT collaboration et al. 2019; Righi et al. 2019; Britzen et al. 2019; Keivani et al. 2018).

4.3. Neutrino flare during 2014-2015

The IceCube collaboration reported an excess of high-energy neutrinos with respect to the atmospheric background between September 2014 and March 2015. This excess called “neutrino flare” was associated with a large number of neutrinos \((13 \pm 5)\) with energies in the range of \(\sim 10 - 20\) TeV (Rodrigues et al. 2019). The shadow region in Figure 3 corresponds to the fraction of the multiwavelength light

\[\text{https://asas-sn.osu.edu/variables}\]
curves associated with the timescale during which the “neutrino flare” was observed. Data points in gray color exhibited in Figure 4 correspond to the archival data. These data show an intense flux in the soft X-rays at \( \sim 1 - 2 \) keV which was not collected during the observation of the “neutrino flare” (see Figure 3). Contrary to the flare observed in 2017, the gamma-ray, optical and radio fluxes were not detected in high activity during this period, suggesting different origins.

In order to describe the best-fit curve (black solid line) that describe the broadband SED in TXS 0506+056 (the archival data points), the SSC model presented in Fraija and Marinelli (2016); Fraija et al. (2017a) is used. The Chi-square \( \chi^2 \) minimization method implemented in the ROOT software package (Brun and Rademakers 1997) and the procedure to obtain the values of the bulk Lorentz factor of the jet, the size of dissipation region, the electron density, the strength of the magnetic field and the spectral indexes are shown in Fraija and Marinelli (2016). The fitting and derived parameters are reported in Table 2. For instance, the values of fitting parameters of the bulk Lorentz factor, the size of dissipation region and the strength of the magnetic field are in the range considered for other models (e.g. see Murase et al. 2018; Rodrigues et al. 2019; Reimer et al. 2019).

The value of the minimum electron Lorentz factor \( \gamma_{\text{e, min}} = 8 \times 10^3 \) used in our model to fit the broadband SED indicates that the electron population is efficiently accelerated above the corresponding energy, and below this one these electrons are accelerated by a distinct process that generates a hard electron spectrum. The value of the electron luminosity derived is \( \sim 3 \) times smaller than the Eddington luminosity \( L_{\text{Edd}} = 3.8 \times 10^{46} \text{erg s}^{-1} \) which is estimated considering a black hole mass of \( 3 \times 10^8 M_\odot \) (Padovan et al. 2019). Taking into account the value of the black hole mass, the gravitational radius is \( r_g = 8.9 \times 10^{13} \text{cm} \), which is two orders of magnitude smaller than the dissipation radius. Given the best-fit values of the bulk Lorentz factor and the dissipation radius, the variability timescale becomes \( t_\nu = 0.9 \pm 0.1 \) days. The value of the magnetic and electron luminosity ratio \( \lambda_{\text{B,e}} = 0.03 \) suggests that a principle of equipartition is not present in the jet of TXT 0506+056. We found that the best-fit value of the second break of the electron distribution \( (\gamma_{\text{e}}, \beta) \) is due to synchrotron cooling, and the first break \( (\gamma_{\text{e}}, c) \) could be associated to the acceleration process. Therefore, this model requires that the electron distribution below the second break be accelerated less efficiently.

Based on the IceCube-170922A event (IceCube Collaboration et al. 2018b) and the theoretical models used to interpret it (e.g. see Padovan et al. 2018; Murase et al. 2018; Gao et al. 2019; Reimer et al. 2019), we also assume the existence of protons inside the dissipation region of jet. Given the value derived for the maximum electron Lorentz factor, it is possible to estimate the maximum Lorentz factor for protons \( \gamma_{\text{p}, \text{max}} = \frac{m_e}{m_p} \gamma_{\text{e}, \text{max}} = 2.13 \times 10^{11} \).

Although the Hillas condition is too optimistic, the maximum energy that CRs could reach in the dissipation radius is \( E_{\gamma, \text{max}} = e Z r_d B T \sim 3.46 \times 10^{19} \text{eV} \) for \( Z=1 \) (Hillas 1984). Taking into account the best-fit value of the bulk Lorentz factor \( \Gamma_0 = 20 \) and the numerical results about the velocity range of the \( e^\pm \) outflow \( 0.3 \lesssim \beta_p \lesssim 0.7 \) (Beloborodov 1999), from eqs. (20) and (21), the relative Lorentz factor and the energy of the annihilation line lie in the range of \( 9 \lesssim \Gamma_{\text{rel}} \lesssim 22 \) and \( 15 \lesssim \epsilon_\gamma \lesssim 25 \text{keV} \), respectively. Protons interacting with these seed photons produce neutrinos with the characteristic energy in the range of \( 10 \lesssim E_{\nu, b} \lesssim 20 \text{TeV} \) which corresponds to the range of events observed in the IceCube neutrino telescope. The curve in yellow exhibited in Figure 4 corresponds to the seed-photon flux emitted from the pair plasma. In addition to the 10 - 20 TeV neutrinos, VHE photons in the range of \( \sim 20 - 40 \text{TeV} \) and secondary pairs from photo-pion and BH processes are created. The respective efficiencies of the photo-pion and BH processes are \( f_{\nu, p} \approx 1 \) and \( f_{\nu, \text{BH}} \approx 0.06 \), respectively. The synchrotron energy break and the maximum flux of secondary pairs are \( \approx 0.1 \text{MeV} \) and \( \approx 9 \times 10^{-12} \text{erg cm}^{-2} \text{s}^{-1} \) for photo-pion process, and \( \approx 0.6 \text{keV} \) and \( \approx 5 \times 10^{-15} \text{erg cm}^{-2} \text{s}^{-1} \) for BH process, respectively. It can be observed that the maximum flux generated by secondary pairs in the photo-pion process is \( \sim 3 \) orders of magnitude larger than BH process. The contribution of synchrotron emission from photo-pion process (dotted-dashed line) is shown in Figure 4. The solid red line in this figure represents the total contribution (SSC model, seed photons and the synchrotron radiation from secondary pairs). Given the distance from the blazar TXS 0506+056 to Earth, photons above 20 TeV are drastically suppressed due to EBL absorption. Taking into account the effect of this absorption described in Franceschini et al. (2008), the attenuation factor \( \exp\{-\tau(E_{\nu}, z)\} \) to the photon flux lies in the range of \( \sim 70 - 260 \).

With the parameters reported in Table 2, the proton luminosity associated to the “neutrino flare” is \( 3.5 \times 10^{46} \text{erg s}^{-1} \) which is 3 times lower than the Eddington luminosity. Therefore, from eq. (4), the proton density associated to this flare becomes \( 211 \text{ cm}^{-3} \). This value is very similar to the electron density found with our model after fitting the archival data. We can conclude that within the dissipation region of the jet there is one cold proton per electron (i.e. it has neutral charge \( Z = 1 \)) and enhanced ASTROGAM (e-ASTROGAM; de Angelis et al. 2018) which will explore the sky in the energy bands of \( 0.3 - 100 \text{MeV} \) and \( 0.3 - 3 \text{GeV} \), respectively.

We can conclude that during September 2014 and March 2015, pairs were continuously created outside the disk forming a sub-relativistic outflow with velocities in the range of \( 0.3 \lesssim \beta_p \lesssim 0.7 \) as predicted in numerical simulations (Beloborodov 1999). During this period, the annihilation lines reached the dissipation region and interacted with the accelerating protons, thus producing the 10 - 20 TeV neutrinos detected in the IceCube telescope.

The expected MeV gamma-ray contributions from synchrotron BH pair production and the annihilation lines have a direct impact in the broadband SEDs. Nearby blazars including TXS 0506+056 would be potential candidates for MeV gamma-ray orbiting observatories such as All-sky Energy Gamma-ray observatory (AMEGO; McEnery et al. 2019) and enhanced ASTROGAM (e-ASTROGAM; de Angelis et al. 2018) which will explore the sky in the energy bands of \( 0.3 - 100 \text{MeV} \) and \( 0.3 - 3 \text{GeV} \), respectively.

Our results indicate that for a typical Lorentz factor of \( \sim 20 \), the maximum energy of the characteristic neutrino is \( \sim 20 \text{TeV} \). For sources with a redshift of \( z = 0.5 \) and a typical Lorentz factor \( \Gamma_0 < 30 \), the characteristic neutrino energy in the range of \( 30 - 40 \text{TeV} \) is expected. Therefore, neutrino events with energies \( E_\nu \lesssim 40 \text{TeV} \) reported by the IceCube Collaboration (IceCube Collaboration et al. 2017; Aartsen et al. 2014) might be explained through this phenomenological model.

Neutrino multiplet as detected on February 17, 2016 by the IceCube (Icecube Collaboration et al. 2017) could be expected from this process and would be promising sources
for IceCube-Gen2 (IceCube-Gen2 Collaboration et al. 2014).

5. DISCUSSION AND SUMMARY

We studied the high-energy neutrino production in the inner outflows of blazars. As seed photons, we considered the radiation from a sub-relativistic pair plasma scenario and a relativistic plasma in Wein equilibrium state. This radiation emitted from the photosphere can be detected above $> 511 \text{keV}$ up to a few MeV on Earth (observer frame), and only at dozens of keV in the frame of the dissipation region. These $\gamma$-rays photons reach the dissipation region and interact with accelerating protons producing pion decay products ($\gamma$, $\nu_e$, $\mu$ and $e^\pm$). Depending on the parameter values of the dissipation region and the sub-relativistic and the relativistic pair plasma scenario, gamma-rays, neutrinos and synchrotron photons generated by secondary pairs could be detected by orbiting and ground telescopes on Earth.

We want to emphasize that Murase et al. (2014) calculated the neutrino production considering seed photons originated from the photosphere in different pair plasma scenarios. We calculated the neutrino and gamma-ray spectra from those generated by the annihilation pairs which are released up to $\gamma$-rays at $> 30 \text{ TeV}$ energy range, and also that synchrotron photons and a relativistic plasma in Wein equilibrium state. This radiation from a sub-relativistic pair plasma scenario has a significant contribution in the $1 - 40 \text{ TeV}$ energy range of the electromagnetic counterpart as observed during the neutrino flare reported between September 2014 and March 2015 by the IceCube collaboration. Based on previous models (i.e. Gao et al. 2019), we concluded that the “neutrino flare” reported between September 2014 and March 2015 had a different origin to the flare in 2017 detected in all the electromagnetic bands.

Neutrino multiplet as detected on February 17, 2016 by the IceCube (Icecube Collaboration et al. 2017) could be expected from this process and would be promising sources for IceCube-Gen2 (IceCube-Gen2 Collaboration et al. 2014). For sources with a redshift of $z = 0.5$ and typical Lorentz factors $\Gamma_b < 30$, the characteristic neutrino energies in the range of $30 - 40 \text{ TeV}$ are expected. Therefore, neutrino events with energies $E_\nu \lesssim 40 \text{ TeV}$ reported by the IceCube collaboration (IceCube Collaboration et al. 2017; Aartsen et al. 2014) might be explained through this phenomenological model.

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### TABLE 1

VALUES USED TO COMPUTE THE NEUTRINO FLUX AND THE SYNCHROTRON EMISSION FROM SECONDARY PAIRS

| Parameter                                      | Value |
|------------------------------------------------|-------|
| Blob region                                    |       |
| Bulk Lorentz factor                            | $\Gamma_b$ | 10 |
| Variability (day)                              | $t$     | 1  |
| Proton luminosity ($L_{edd}$)                  | $L_p$   | 0.5|
| Magnetic field (G)                             | $B$ (G) | 1  |
| Maximum proton energy (PeV)                    | $E_{max}$ | 1  |
| Spectral index                                 | $\alpha_p$ | 2.1|

A sub-relativistic pair plasma scenario

| Parameter                                      | Value |
|------------------------------------------------|-------|
| Bulk Lorentz factor                            | $\Gamma_p$ | 1.4 |
| Relative Lorentz factor                        | $\Gamma_{rel}$ | 4.2 |
| Photosphere radius ($r_{ph}$)                  | $r_{ph}$ | 2  |

A relativistic plasma in Wein equilibrium state

| Parameter                                      | Value |
|------------------------------------------------|-------|
| Bulk Lorentz factor                            | $\Gamma_p$ | 1.8 |
| Relative Lorentz factor                        | $\Gamma_{rel}$ | 3.1 |
| Photosphere radius ($r_{ph}$)                  | $r_{ph}$ | 3  |

### TABLE 2

VALUES FOUND IN ESTIMATING THE BEST-FIT CURVE OF THE ARCHIVAL DATA POINTS WITH OUR MODEL.

| Parameter                                      | Value |
|------------------------------------------------|-------|
| Fitting parameters                             |       |
| Bulk Lorentz factor                            | $\Gamma_p$ | 19 ± 3 |
| Dissipation region (cm)                        | $r_d$  | $(3.3 ± 0.41) \times 10^{16}$ |
| Electron density (cm$^{-3}$)                   | $N_e$  | $(2.2 ± 0.5) \times 10^2$ |
| Magnetic field (G)                             | $B$    | $0.16 ± 0.03$ |
| Low-energy electron spectral Index             | $\alpha_1$ | $2.47 ± 0.02$ |
| Medium-energy electron spectral Index           | $\alpha_2$ | $3.69 ± 0.14$ |
| High-energy electron spectral Index             | $\alpha_3$ | $4.50 ± 0.15$ |

Derived parameter

| Parameter                                      | Value |
|------------------------------------------------|-------|
| Minimum electron Lorentz factor*               | $\gamma_{e,\text{min}}$ | 800 |
| Break 1 electron Lorentz factor                | $\gamma_{e,c1}$ | $(6.26 ± 0.71)) \times 10^3$ |
| Break 2 electron Lorentz factor                | $\gamma_{e,c2}$ | $(4.75 ± 0.61) \times 10^4$ |
| Maximum electron Lorentz factor                | $\gamma_{e,\text{max}}$ | $(1.16 ± 0.12) \times 10^8$ |
| Magnetic Luminosity (erg s$^{-1}$)             | $L_B$  | $(3.73 ± 0.59) \times 10^{43}$ |
| Electron Luminosity (erg s$^{-1}$)             | $L_e$  | $(1.91 ± 0.33) \times 10^{46}$ |

* This value was not derive from our model, but rather used an input.
Fig. 1.— Schematic representation of the dynamics of the pair plasma and the dissipation region of TXS 0506+056. Physical distances and radii are not to scale.

Fig. 2.— The neutrino and gamma-ray spectra are shown from a sub-relativistic pair plasma scenario and a relativistic plasma in Wein equilibrium state. The sensitivities of eASTROGAM and AMEGO experiments are taken from de Angelis et al. (2018) and McEnery et al. (2019), respectively. These sensitivities are given in GeV cm$^{-2}$ s$^{-1}$. The IceCube data points are taken from IceCube Collaboration et al. (2017).
Fig. 3.— TXS 0506+056 light curves are shown between 2008 August 22 to 2017 December 12 obtained with multiple orbiting satellites and ground based observatories. From top to bottom: VHE, MeV - GeV γ-ray, X-ray, optical and radio wavelengths are presented. The red dashed line shows the IceCube-170922A event and the shadow area corresponds to the period of time associated to the “neutrino flare”. Blow-up of the flaring activity around the IceCube-170922A event is shown in each electromagnetic band.
Fig. 4.— The broadband SED of TXS 0506+056 with the model curves for lepto-hadronic models presented in this work and in Gao et al. (2019). The archival data points shown in gray correspond to the data before the flare in 2017 and the red data points correspond to the flare. The black dashed line corresponds to the best-fit curve proposed by Gao et al. (2019) and the red solid line to the lepto-hadronic used in this work. The yellow solid line represents the observed seed photons.