EeV Astrophysical neutrinos from FSRQs?

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ABSTRACT
Flat Spectrum Radio Quasars (FSRQ) are the most powerful blazars in the $\gamma$-ray band. Although they are supposed to be good candidates in producing high energy neutrinos, no secure detection of FSRQs has been obtained up to now, except for a possible case of PKS B1424-418. In this work we compute the expected flux of high energy neutrinos from FSRQs using standard assumptions for the properties of the radiation fields filling the regions surrounding the central supermassive black hole. We obtain as a result that high energy neutrinos are naturally expected from FSRQs in the sub-EeV–EeV energy range and not at PeV energies. This justifies the non-observation of neutrinos from FSRQs with the present technology, since only neutrinos below 10 PeV have been observed. We found that for a non-negligible range of the parameters the cumulative flux from FSRQs is comparable to or even exceeds the expected cosmogenic neutrino flux. This result is intriguing and highlights the importance to disentangle these point-source emission from the diffuse cosmogenic background.

Key words: astroparticle physics — neutrinos — Flat Spectrum Radio Quasars: general — radiation mechanisms: non-thermal — $\gamma$–rays: galaxies

1 INTRODUCTION
The extreme phenomenology displayed by Active galactic nuclei (AGN) is ultimately associated with the gravitational energy released by gas falling onto a supermassive black hole ($M_{\text{BH}} = 10^7–10^9 M_\odot$) residing at the center of the host galaxies. AGN with relativistic jets, although a minor fraction of the total population, represent the most powerful persistent sources of electromagnetic radiation in the Universe (Blandford et al. 2019). Blazars (Romero et al. 2017) are a subclass of jetted AGNs in which the jet is closely aligned with the line of sight. Under this favorable geometry, the non-thermal emission of the jet is highly amplified by relativistic effects (relativistic beaming). The observed electromagnetic emission of these sources extends over the entire electromagnetic spectrum and it is characterized by strong variability that can enhance the luminosity by several orders of magnitude during flares. The spectral energy distribution (SED) of blazars – dominated by the non-thermal emission of the relativistic jet – typically shows a double bump shape. The first peak is in the IR-UV band, the high-energy one has the maximum in the $\gamma$-ray band. While the first bump originates from the synchrotron emission of relativistic electron in the jet, the physical interpretation of the second peak is still under debate, also in view of the neutrino detection associated with one of these objects (Aartsen et al. 2018). In the pure leptonic model gamma rays are produced through the inverse Compton scattering by the synchrotron-emitting relativistic electrons. In pure hadronic scenarios, on the other hand, high-energy photons are supposed to be produced through synchrotron emission of relativistic protons (Aharonian 2000) or the reprocessed radiation produced in photomeson interactions (e.g. Aharonian 2000, Mücke et al. 2003).

Blazars can be divided into two subclasses: Flat Spectrum Radio Quasars (FSRQ) and BL Lac objects. Their classification is historically based on the width of the emission lines observed in the optical spectra (the traditional division corresponds to an equivalent width of 5 Å). FSRQs display broad lines and are generally more powerful than BL Lac, especially in the $\gamma$-ray band. On the other hand, BL Lacs, although less powerful, can emit photons at higher energies (up to the multi-TeV band). At present, there are pieces of evidence supporting the existence of a continuous trend (or sequence) between the SED of the two subclasses (see Fossati et al. 1998, Ghisellini et al. 2017, G17 hereafter).

The detection by IceCube of a high energy neutrino ($E_\nu \sim 290$ TeV) in the direction of a flaring blazar (whose precise nature is debated, see Padovani et al. 2019), TXS 0506+056, on September 2017 (Aartsen et al. 2018), has lead the community to focus on this class as electromagnetic...
counterparts of astrophysical neutrinos (Palladino et al. 2019; Murase et al. 2018; Padovani et al. 2016), although many other candidates have been proposed (see Ahlers & Halzen 2014, Mészáros 2017 or Gaisser 2018 for reviews). The production of neutrinos requires the existence of a population of relativistic protons (with energies $E_p \simeq 20 \times E_c$) creating charge pions in collisions with target protons/ions or photons (the latter case is usually referred as photons reaction). Relativistic protons are thought to be co-accelerated with the electrons, although the details of the mechanisms involved are not completely clear. Considering the low particle density inferred for the relativistic outflows, pion production through the collision with gas is widely considered unlikely (but see e.g. Sahakyan 2018 for possible scenarios) and, therefore, neutrino production is expected to proceed mainly through the photomeson channel. This reaction is characterized by a well-defined threshold for energies very close to that corresponding to the $\Delta$ resonance, $(p\gamma \rightarrow \Delta^+)$ followed by the quick decay to $p\pi^0$ or $n\pi^+$ and this allows one to derive a useful rule-of-thumb relating the energy of the target photons involved in the reaction, $\epsilon$, and the proton energy, $E_p$, as: $E_p \simeq 1.3 \times 10^{17}/\epsilon$ eV (where $\epsilon$ is expressed in eV). From this relation, and taking into account that the typical neutrino energy is 1/20 of that of the parent proton, one can link the efficient production of neutrinos with energy in the range 0.1-10 PeV with target photons in the optical-soft X-ray bands.

While suggested to be potential good neutrino emitters (e.g. Murase et al. 2012, Dermer et al. 2014; Kadler et al. 2016), FSRQ are not favoured by current data. In particular, being powerful but relatively rare in the sky, one should expect to detect multiplets of neutrino events from single FSRQ already in the current samples (e.g. Murase & Waxman 2016). This rules out the possibility that FSRQs represent the bulk of the sources of the neutrinos detected by IceCube, in the 0.1-10 PeV energy range. Interestingly, this conclusion is consistent with the current picture of the structure of FSRQ. In fact, the most intense radiation field expected to interact with relativistic protons in the inner regions of the jet has typical frequencies corresponding to the UV-optical-IR bands, corresponding to relatively large $E_p$ which, in turn, imply $E_\nu$ above the PeV band. In view of the physics programs of existing and future neutrino telescopes, this expectation deserves to be discussed carefully and quantitatively.

In this work we focus on FSRQ using the state-of-the-art knowledge on their structure and demography to infer their potential neutrino emission. In section 2 we describe the population and the structure of FSRQs we consider in the work, section 3 describes the calculation of the neutrino emission we used, while section 4 describes the set-up of our models. We report the resulting cumulative predicted spectra in 5 in which we also compared our results with the most updated IceCube data, the expected spectra for cosmogenic neutrinos and the sensibility of the future telescope GRAND. Finally in section 6 we conclude with a discussion.

Figure 1. Sketch of the geometry we assumed for FSRQ. Region 1 is the emission region containing cosmic rays and photons from the synctrotron emission of electrons. Region 2 and region 3 are the torus and the broad line region that produce external photon populations. See text for a more detailed description.

2 PROPERTIES OF FSRQS

2.1 Structure

A sketch of the structure of the central regions (distances less then few pc) of FSRQ is reported in Fig.1. We represent the different region of interest in our work. Accretion of gas occurs through a standard, optically thick and geometrically thin accretion disk, showed in yellow in fig.1 (Shakura & Sunyaev 1973). The emission from the disk, peaking in the optical-UV band, irradiates small clouds of gas moving in keplerian orbits around the SMBH. The photoionized gas of the clouds re-emit the intercepted flux in prominent emission lines (with average energy $\epsilon_{\text{BLR}} \simeq 10$ eV), whose observed profile is broadened by Doppler shift. The (usually assumed shell-like) region filled by these clouds is generally named Broad Line Region, BLR, represented in blue in the sketch of figure 1. The geometry of the BLR can be probed by the reverberation mapping technique, which allows direct measurements of the distance of the clouds (Kaspi et al. 2007). Beyond the BLR, at a typical distances 1-10 pc we find a thick structure of dust, traditionally assumed to have a toroidal shape (region 2 of figure 1 in purple). Dust grains are powerful absorbers of radiation and the torus obscures the central regions for observers lying at large angles. Dust heated by the central UV radiation re-emit it as a black-body spectrum at a temperature $T_{\text{IR}} \simeq 500 - 10^3$ K, peaking in the IR band.

As discussed in Ghisellini & Tavecchio (2009) an approximate estimate of the typical size of the BLR ($R_{\text{BLR}}$) and the torus ($R_{\text{torus}}$) can be expressed as a function of the disk luminosity $L_{\text{d}}$ as:

$$R_{\text{BLR}} \simeq 10^{17} \left( \frac{L_{\text{d}}}{10^{45} \text{ erg/s}} \right)^{1/2} \text{ cm} \quad (1)$$

and

$$R_{\text{torus}} \simeq 2.5 \times 10^{18} \left( \frac{L_{\text{d}}}{10^{45} \text{ erg/s}} \right)^{1/2} \text{ cm.} \quad (2)$$

These distances are very important since, together with the
corresponding luminosities, determine the photon density, a critical parameter for the efficiency of the photopion reactions. Note that, since the radiation energy density is proportional to $L/R^2$, the simple scaling above implies fixed energy densities for all $L_\gamma$, i.e. for all FSRQ.

Jets of FSRQ propagate through the different structures discussed above. In the reference frame of the outflowing plasma, moving with constant bulk Lorentz factor $\Gamma$, the energy density of the radiation fields is modified by the relativistic boosting. At distances for which the jet is totally immersed in the (nearly isotropic) radiation field of the BLR or of the torus, the relativistic boosting results in the shift of the frequencies by a factor $\approx \Gamma^2$ with respect to the value measured by an external observer at rest (e.g. Sikora et al. 1994). Although the spectrum emitted by the BLR clouds is rather complex, with the presence of lines and continuum, the boosted emission as observed in the jet rest frame can well approximated by a peaked, black-body like spectrum with the maximum corresponding to the Lyman $\alpha$ line, i.e. at an energy $\epsilon_{\text{BLR}} \approx 10\Gamma$ eV (Tavecchio & Ghisellini 2008).

In the calculation of the neutrino spectra we will use this approximation.

2.2 Sites of neutrino production

The radiation we observe from FSRQ emerges from an emission region inside the jet. For simplicity we assume a spherical region, at a distance $d$ from the central SMBH and with a radius $R$ as reported in figure 1. We assume a conical jet with semi-aperture angle $\theta_j$, so that $R = d \theta_j$. The location of the emission region is FSRQ is a subject of debate. While standard models assume that the emission mainly occurs at distances lower than $R_{\text{BLR}}$ (thus within the dense radiation field of the BLR), the absence of spectral features related to absorption of gamma rays by the UV continuum (e.g. Poutanen & Stern 2010, Costamante et al. 2018), together with the detection of few FSRQ at TeV energies during flares (e.g. MAGIC Collaboration et al. 2018 or H. E. S. Collaboration et al. 2019) indicates that, at least in some cases and/or during high-activity states, the electromagnetic radiation is produced beyond the BLR (e.g. Tavecchio et al. 2011).

In the following we will calculate the neutrino output expected for two cases, namely assuming the emission region located at a distance $d < R_{\text{BLR}}$ and $R_{\text{BLR}} < d < R_{\text{torus}}$. We will distinguish the two scenarios calling them “inside BLR” and “outside BLR”. For the torus we assume $T_{\text{IR}} = 500$ K.

2.3 Population

To characterize the entire population of FSRQs, we consider the results of Ajello et al. (2012). They offer a parametrization of the cosmological evolution of FSRQs, in terms of their gamma-ray luminosity, redshift and spectral index of the spectrum between 0.1-100 GeV. In our model we are only interested to the distribution in redshift and luminosity, therefore the spectral index dependence is integrated out. According to Ajello et al. (2012) these high luminosity objects are characterized by a positive evolution and it becomes very strong for the most luminosity FSRQs, that are distributed as $\sim (1 + z)^3$ for $z < 1$. These objects are quite rare in the Universe, being characterized by a local density lower than 1 Gpc$^{-3}$. Moreover they are very brilliant varying in the range $L_\gamma \sim 10^{44} - 10^{46}$ erg/s.

In this work we divide the FSRQ population in 5 different luminosity bins: from $10^{44}$ erg s$^{-1} < L_\gamma < 10^{45}$ erg s$^{-1}$ to $L_\gamma > 10^{46}$ erg s$^{-1}$. This classification is the same reported in G17 and it will be useful in the next section to derive the neutrino emission for each bin of FSRQs. One possible realization of the distribution given in Ajello et al. (2012) is shown in the first panel of Fig. 2. In this plot we show the redshift and the gamma-ray luminosity of 1167 sources$^1$.

We also illustrate the separation between resolved and unresolved sources, using as a splitting point a luminosity at Earth of $4 \times 10^{42}$ erg cm$^{-2}$ s$^{-1}$, similarly to Palladino et al. (2019). In principle, one can expect that the bolometric (i.e. total) neutrino output is related to the power emitted in the electromagnetic channel. In Murase & Waxman (2016) or Righi et al. (2017) for example authors assume a linear relation between the $\gamma$-ray luminosity and the neutrino one. Here we will find a non-linear relation between the two luminosities because of the models we considered (see section 4).

Center and right panels of fig.2 show the expected contribution to the neutrino flux for different parameters studied in this work and for the two scenarios “inside” and “outside” BLR. In all the scenarios, high luminosity sources contribute most on the expected total neutrino flux from FSRQs.

3 FORMALISM FOR NEUTRINO PRODUCTION

To derive the spectrum of the neutrino emission of FSRQ, we start from the (observed) total, or bolometric, electromagnetic non-thermal luminosity of the jet, $L_{\text{bol}}$, and the (measured or inferred) disk luminosity, $L_{\text{d}}$. The latter can be directly translated into the BLR and torus radii through Eq. 1 and 2 above. This uniquely provide the external photon densities as a function of distance along the jet.

The other ingredient we need is the energy distribution of the relativistic cosmic rays (protons, for simplicity). We describe it as a power law with exponential cut-off (see below). We normalize the total proton luminosity (i.e. total energy injected into the proton population per unit time) as measured in the jet frame, $L'_p$, (primes denote quantities measured in the jet frame), to the electromagnetic luminosity, $L'_{\text{em}}$, i.e. we impose $L'_p = \xi L'_{\text{em}}$ (we assume this relation as a purely phenomenological description, although it can be justified by simple physical arguments, e.g. Righi et al. 2017). The jet-frame electromagnetic luminosity can be derived from the observed luminosity with $L_{\text{bol}} = L'_{\text{em}} \delta^4$, where $\delta$ is the relativistic Doppler factor that depends on the bulk Lorentz factor $\Gamma$ and the angle $\theta$ between the jet velocity and the line of sight as: $\delta = [\Gamma(1-\beta \cos \theta)]^{-1}$. Using these relations we can finally write:

$$L'_p = \frac{L_{\text{bol}} \xi}{\delta^4}$$

$^1$ The total number of sources comes directly from the theoretical distribution.
We solve the integral of equation (5) using as cross section $n_\gamma$. Figure 2. Left panel: cosmological evolution of FSRQs, according to Ajello et al. (2012). Center and right panels: Contribution to the neutrino flux for different parameters we considered in this work. Central panel refers to the “inside” BLR scenario, while right one, the “outside” scenario.

For a given photomeson efficiency $f_{p\gamma}$, the luminosity channelled into neutrinos as measured in the jet frame is proportional to $f_{p\gamma}L'_\nu$.

To derive the observed electromagnetic luminosity $L_{\text{bol}}$, we exploit the averaged SED constructed for sources of different $\gamma$-ray luminosity by G17. Specifically, G17 consider a sample of 448 FSRQs with known redshift extracted from the third catalog of AGN detected by Fermi/LAT, 3LAC (Ackermann et al. 2015), grouped them in 5 bins of gamma-ray luminosity and for each bin they derive an averaged SED using a suitable phenomenological function (see Eq. 11 of G17).

The SED models can be used to derive the average observed bolometric luminosity, $L_{\text{bol}}$, of the five FSRQ categories. These luminosity bins are representative of the entire population of FSRQs.

We then calculate the neutrino spectrum adopting the same calculations described in Tavecchio et al. (2014). Here we describe schematically the main assumptions:

- The proton population is characterized by a total luminosity in the jet frame, $L'_p$, and the energy distribution is parametrised by a cut-offed power-law in energy:

$$L'_p(E'_p) = k_p E'_p^{-n} \exp \left( - \frac{E'_p}{E'_{\text{cut}}} \right)$$  \hspace{1cm} (4)$$

- The photomeson production efficiency $f_{p\gamma}$ is calculated as the ratio between the time-scales of the adiabatic losses ($t_{\text{dynam}} \approx R/c$, with $R$ is the radius of the jet region) and the cooling rate $t_{p\gamma}(E'_p)$ of protons which is given, in the jet frame, by:

$$t_{p\gamma}^{-1}(E'_p) = c \int_{v_{\text{th}}/2c}^{\infty} dv \frac{n_t(v)}{2v^2} \int_{v_{\text{th}}}^{2v'} dv' \sigma_{p\gamma}(v')K_{p\gamma}(v')v'$$ \hspace{1cm} (5)$$

where $n_t$ is the numerical density of the target photons, $\gamma'_p = E'_p/m_p c^2$ and $\epsilon_{\gamma}$ is the threshold energy of the process. We solve the integral of equation (5) using as cross section $\sigma_{p\gamma}$ and the inelasticity $K_{p\gamma}$ provided in Atoyan & Dermer (2003).

- The neutrino luminosity $L'_\nu$ in the jet frame is given by (e.g., Murase et al. 2014):

$$E'_\nu L'_\nu(E'_\nu) \simeq \frac{3}{8} f_{p\gamma}(E'_p) E'_p L'_p(E'_p)$$ \hspace{1cm} (6)$$

- From the decay of $\pi^0$ produced in the photomeson reaction, we expect a production of $\gamma$-rays with a luminosity $L'_\gamma$ given by:

$$E'_\gamma L'_\gamma \simeq \frac{1}{2} f_{p\gamma}(E'_p) E'_p L'_p(E'_p)$$ \hspace{1cm} (7)$$

- Finally we obtain the neutrino luminosity $L_\nu$ in the observer frame using the Doppler factor $\delta$:

$$E_\nu L_\nu(E_\nu) = E'_\nu L'_\nu(E'_\nu) \delta^4$$ \hspace{1cm} (8)$$

Summarizing, the free parameters entering in the calculation are: the index and the maximum energy of the proton distribution, $n$ and $E'_{\text{cut}}$, the distance of the region along the jet where the emission occurs, see Fig. 1, the Lorentz factor $\Gamma$ and the Doppler factor $\delta$. To reduce the number of free parameters, we fixed the Lorentz factor $\Gamma = 13$ following Ghisellini & Tavecchio (2015) and we assume $\delta = \Gamma$ (i.e. we fix the observing angle to $1/\Gamma$).

4 MODELS

In the following we consider two different regions inside the jet in which the photopion production occurs. In the first case (“inside BLR”) we assume that the region is at a distance $d < R_{\text{BLR}}$ (where the BLR radius is given by eq. 1) and, for definiteness, we will consider $d = R_{\text{BLR}}/2$. In this case there are three different photon target populations involved in the $p\gamma$ reaction: the synchrotron radiation produced inside the jet (assumed to be coispatial with the protons), the radiation from the BLR clouds and the thermal torus radiation. In the second case (“outside BLR”) we assume the region to be beyond the BLR radius: in this case there are only the synchrotron radiation and the torus emission as photon targets for the $p\gamma$ reaction (the BLR radiation is strongly de-amplified in the jet frame, see e.g. Ghisellini & Tavecchio 2009). In this case we fix $d = R_{\text{Torus}}/2$ with $R_{\text{Torus}}$ given by Eq. 2.

$R_{\text{BLR}}$ and $R_{\text{Torus}}$ (and, therefore, the distance of the emission region in the two scenarios) can be derived from the disk luminosity. We link the disk luminosity to the bolometric non-thermal luminosity of the jet following Ghisellini & Tavecchio (2009) (see also Ghisellini et al. 2014), i.e. we assume $L_{\text{disk}} \approx L_{\text{bol}}/\Gamma^2$.
Assuming a jet semi-aperture angle $\theta_j$, the radius of the emission region in the “inside BLR” case is:

$$R = \theta_j d = \frac{R_{\text{BLR}}}{2\Gamma}$$

(9)

where we set the aperture angle to the standard value $\theta_j = 1/\Gamma$. For the case outside the BLR we use the same equation with $R_{\text{Torus}}$ instead of $R_{\text{BLR}}$. In this way, we have fixed the distance and the size of the emission region, $d$ and $R$, to $L_{\text{bol}}$ for each bin.

Concerning the maximum energy of the proton distribution, $E_{\text{cut}}$, we derive it using the condition of equality between cooling and acceleration time-scales $t_{\text{cool}} \approx t_{\text{acc}}^{\prime}$ in the jet frame. This condition corresponds to the equilibrium between losses and gains suffered by relativistic protons in the emission region. Losses include photomeson losses with time scale $t_{\text{p}}^{\prime}$, eq. 5 and adiabatic losses with characteristic timescale

$$t_{\text{dyn}} \approx \frac{R}{c}$$

(10)

with $R$ is the radius of the emission region (e.g. Tavecchio & Ghisellini 2015).

The acceleration time can be expressed by:

$$t_{\text{acc}}^{\prime}(E_p) = \eta_{\text{acc}} \frac{R}{c} \simeq 1.36 \times 10^7 \eta_{\text{acc}} \frac{E_{15}^\prime}{B} \text{s}$$

(11)

where $E_{15}^\prime$ is the proton energy normalized to $10^{15}$ eV, $B$ is the magnetic field we set $B = 5$ G, and $\eta_{\text{acc}}$ is a parameter depending on the details of the acceleration process and it is estimated to be in the range of 1-100 (e.g. Rieger et al. 2007). Figure 3 shows the relevant cooling (blue and orange lines) and acceleration timescales (green lines) for different values of $\eta_{\text{acc}}$ for an intermediate luminosity bin, $10^{46}$ erg $s^{-1} < L < 10^{47}$ erg $s^{-1}$. The intersection between the curve corresponding to the shorter cooling timescale and that for the acceleration timescale fixes the maximum energy attainable by accelerated protons. The vertical black dashed lines indicates to the value of $E_{\text{cut}}^{\prime}$ for different values of $\eta_{\text{acc}}$. Except for the highest luminosity bins, the cooling is dominated by the adiabatic losses (horizontal orange line).

In this way the free parameters are now $\xi$ (the parameter linking $L_{\text{bol}}$ with the cosmic ray luminosity, eq. 3), $n$ the index of the proton energy distribution (eq. 4) and $\eta_{\text{acc}}$, the acceleration efficiency (eq. 11). Fig. 4 shows how the neutrino spectrum changes for different values of $n$ and $\eta_{\text{acc}}$ and two luminosity bins of FSRQs (the highest one $L_\gamma > 10^{48}$ erg $s^{-1}$, left panel, and the intermediate one, $10^{46}$ erg $s^{-1} < L_\gamma < 10^{47}$ erg $s^{-1}$, right panel) considering the scenario inside the BLR.

In Fig. 4 is clearly visible that the bulk of the neutrino output lies at energies above 1 PeV for the “inside the BLR case” and at even larger energies in the other case. This is a combined effect of the threshold and of the spectrum of the target photons. For instance, in the case in which the BLR photon field is dominant, the photons have an energy of $\epsilon_{\text{BLR}} \approx 10 \Gamma \approx 130$ eV and, by using the rule-of-thumb, only protons with $E_p^{\prime} > 10^{15}$ eV can interact. The neutrino produced through photomeson reactions will have an energy $E_{\nu}^{\prime} > 5 \times 10^{13}$ eV and, in the observer frame, $E_\nu = E_p^{\prime} \delta > 5 \times 10^{13}$ eV $\approx 10^{15}$ eV. When IR photons from the torus are dominant, the threshold imposes an even larger energy for protons and, in turn, for the produced neutrinos. We remark that this result is completely independent on the details of the proton energy distribution (slope, maximum energy) but it is solely the result of the spectral properties of the photons fields.

### 4.1 Limits from electromagnetic cascades

As discussed in the previous paragraph, photomeson reactions produce neutrinos from the decay of charged pions and $\gamma$-rays from the $\pi^0$ decay. We can derive the spectrum of these photons using eq. 7. Photons with these energies interacting with low-energy targets are promptly absorbed through the pair production reaction $\gamma \gamma \rightarrow e^+e^-$. The resulting pairs produce high-energy gamma-rays through inverse Compton scattering, triggering the development of an electromagnetic cascade inside the emission region. When the energy is degraded below the energy $E_{\text{cascade}}$ for which the optical depth is unity, photons can leave the source. The observed spectrum for saturated cascades is characterized by a universal spectrum with slope $\approx 1$ (i.e. “flat” in the SED representation) extending from a low energy end $E_{\text{min}}$ to $E_{\text{cascade}}$.

The flat cascade component can provide a substantial contribution in the “valley” between the two SED bumps (as extensively discussed for the case of TXS 0506+056, e.g. Ansoldi et al. 2018, Cerruti et al. 2018). The very well know observational fact of the absence of features associated to cascades in the observed SED of FSRQ (e.g. G17) therefore implies a robust upper limit to the luminosity of the cascade component and, in turn, to the neutrino emission.

A detailed calculation of the expected cascade spectrum is beyond our aims. For our purposes a good approximation of the cascade luminosity can be obtained assuming that the total UHE photon luminosity $L_\gamma^\prime$ injected by the $\pi^0$ decay (which in the observer frame is $L_\gamma^\prime \delta^4$) is re-emitted as a
flat $\propto E^{-1}$ component extending from $E_{\text{min}}$ to $E_{\gamma \gamma}$. The latter energy can be derived from the condition that the optical depth of the emission region is $\tau(E) = 1$. $E_{\text{min}}$ is more difficult to assess, but the normalization of the cascade spectrum has a very weak dependence on it. For definiteness we assume $E_{\text{min}} = 10^{33}$ eV.

As an example, in fig. 4 we report (horizontal dotted lines) the cascade spectra derived for two luminosity bins and a set of parameters, together with the corresponding SED. For the high-luminosity bin ($L_\gamma > 10^{46}$ erg s$^{-1}$, left panel) the cascade components are relatively more luminous than those corresponding to the lower luminosity bin ($10^{45}$ erg s$^{-1} < L_\gamma < 10^{47}$ erg s$^{-1}$, right panel). Therefore, each set of parameters ($\eta_{\text{acc}}, n, \xi$) fulfilling the condition that the cascades lie below the “valley” for the most powerful sources, automatically satisfies the constraint for the entire population. We define this the low model.

Another possibility would be instead to adopt different sets of parameters for the different luminosity bins, tuning them so that for each bin the cascade provide the maximum contribution to neutrinos allowed by the SED. Clearly, this case describes the highest total neutrino flux allowed for the entire FSRQ population (high case). For simplicity, in this scenario we fixed the power index $n = 2$ and the acceleration efficiency $\eta_{\text{acc}} = 5$. What we obtain is therefore a different value of $\xi$ for each luminosity bin of FSRQs in a range between $9 \times 10^{-1} < \xi < 2 \times 10^3$. This implies that low power FSRQs should be relatively more efficient than the high power ones in injecting power on relativistic protons.

To give a comparison between the two cases, “high” and “low”, we plot the neutrino spectra for all luminosity bins (inside the BLR case) in figure 5. In both panels solid lines are the electromagnetic SED from G17, while dashed lines are the neutrino spectra. The neutrino spectra are obtained using the same values $n = 2, \eta_{\text{acc}} = 5$ and $\xi = 0.3$ for all bins (low case). The right panel instead shows the high scenario with the same values of $n$ and $\eta_{\text{acc}}$, but with $\xi$ variable for each bin (as above). It is clear that in this high scenario, the low luminosity FSRQs are more efficient in producing neutrinos than for the low case.

A remark is in order. Even if the low case provides a neutrino flux lower than the maximum potentially possible (constrained by the cascade component), it should be considered a relatively optimistic scenario, since we are assuming that protons are accelerated and injected with a relatively large luminosity. Of course, an entire class of models with $\xi$ lower than the minimum assumed are possible, for which the predicted neutrino luminosity would therefore be lower than that derived here.

5 CUMULATIVE NEUTRINO EMISSION

Figures 6 and 7 show the cumulative diffuse neutrino emission from FSRQs for the different scenarios that we consider in this work obtained by convolving the neutrinos spectra with the luminosity functions. In all cases we compare our results with the IceCube data (blue points for HESE events and light blue band for throughgoing muons, Aartsen et al. 2017), the sensitivity of the future experiment GRAND, black dashed lines (Álvaro-Muñiz et al. 2020), and the expected flux from cosmogenic neutrinos, gray region (Alves Batista et al. 2019). Those neutrinos are produced by the interaction of ultra-high-energy cosmic rays, UHECR, interacting with the intergalactic backgrounds including the cosmic microwave background (CMB) and the extragalactic background light (EBL) (Berezinsky & Zatsepin 1990). The expected spectrum of the cosmogenic neutrinos displays a tail at low energies due to the interaction of cosmic rays with the UV component of EBL. In fact, the contribution of the interaction of UHECR with EBL is below $10^{18}$ eV, while at higher energies, the contribution of UHECR interacting with CMB dominates. In fig.6 we report our results considering the “inside” (left panel) and “outside” (right panel) scenarios in the “low” case. We predicted neutrino emission from 10 different models (5 “inside” BLR, 5 “outside” BLR). All scenarios are compatible with the current limits given by IceCube.

In the left panel of 6, in which we are considering the emission region inside the BLR, we have two cases in which the maximum plateau of the emission by FSRQs is observable with 3 years of observation by GRAND and it is not
interfering with the peak of the cosmogenic neutrinos (best expectation). Moreover, these two scenarios, in which we have respectively $n = 2$, $\xi = 0.3$ and $\eta_{\text{acc}} = 1$ (red solid line) or $\eta_{\text{acc}} = 5$ (yellow solid line), are the only two scenarios, among those we considered, providing fluxes clearly detectable with only 3 years with GRAND. For other scenarios (considering softer proton spectra, smaller $\xi$ or low acceleration efficiency) we predict spectra which are amidst in the cosmogenic neutrino region and more years are needed to clearly identified them.

In the right panel of fig. 6 we show the “outside” BLR scenario. In this case the predicted spectra peak at higher energies than the cosmogenic neutrino emission, because of the low-energy target photon energy from the torus. For this reason, we expect an easily distinction between the cosmogenic component and FSRQ neutrino emission. In addition to, we expect an isotropic flux of cosmogenic neutrinos, while we expect that neutrinos from FSRQs point back to the sources.

In figure 7, the neutrino emission in case of the high scenario for both “inside” (green solid line) and “outside” (yellow line) are shown. In the first case the cosmogenic neutrino peak is below our prediction, while in the “outside” case, our spectrum is peaking at higher energy, allowing a possible detection of the cosmogenic neutrinos in case of the most optimistic scenario.

In view of the physics programs of existing and future neutrino telescopes, this expectation deserves to be discussed carefully and quantitatively.

6 CONCLUSION

Flat Spectrum Radio Quasars (FSRQs) are the most luminous blazars in the $\gamma$-ray band. Their nuclear region, that is naturally rich of photons, is the ideal environment to produce high energy neutrinos via photoproduction interactions. In this work we compute the neutrino flux expected from

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Figure 5. Electromagnetic SED of all categories of FSRQs, solid lines, with the expected neutrino spectra, dashed lines. Left panel: Scenario with $n = 2$, $\eta_{\text{acc}} = 5$ and $\xi = 0.3$. Right panel: Maximum scenario with $n = 2$, $\eta_{\text{acc}} = 5$ and $\xi$ variable for each luminosity bin.

Figure 6. Diffuse neutrino case in the luminosity dependent case, assuming $\eta_{\text{acc}} = 5$ in the left panel and $\eta_{\text{acc}} = 50$ in the right panel. The results are compared with the IceCube data (HESE as blue points, throughgoing muons as light blue band) plus the sensitivity of the future experiment named GRAND.
FSRQs, using standard assumptions on their structure and trying to use a limited set of the parameters.

In order to compute the diffuse flux, we use the FSRQs population (i.e. luminosity function and evolution) described by Ajello et al. (2012). We considered two different scenarios, in which neutrinos are produced inside the broad line region (BLR), with three different photon target populations for the photomeson reaction, or outside the BLR, where only synchrotron and torus radiation contribute to the neutrino production. In both cases we derive the neutrino emission investigating 5 different scenarios in which the three main free parameters, the spectral index of relativistic protons $\alpha$, the acceleration efficiency $\eta_{\text{acc}}$, and the parameters $\xi$ that links the bolometric luminosity to the proton luminosity, are varying.

The neutrino luminosity is constrained by the photons produced through the decay of $\pi^0$ that trigger an electromagnetic cascade. The resulting reprocessed photon emission is characterized by a flat spectrum extending over several decades in frequency, contributing especially in the X-ray band, i.e. in the region of the “valley” between the two SED peaks. The condition that the reprocessed flux lies below the observed (hard) X-ray continuum provides a stringent upper limit to the photomeson reactions. In particular, this provides a constraint on the parameters that we used in our luminosity independent model. In particular, the highest luminosity bin provides the most stringent constraint.

Then we considered a more complex model for both “inside” and “outside” scenario, in which all the luminosity bins of FSRQs are producing the maximum neutrino emission allowed without exceeding the limit given by the electromagnetic emission. In this model each luminosity bin had a different value of $\xi$ that implies that low-power FSRQs are relatively more efficient to inject power on relativistic protons than the high-power FSRQs.

We remark that a possible dominant component of neutrinos well above 1 PeV is naturally related to the nature of the radiation fields filling the central regions of FSRQ. In fact, due to the threshold which characterizes the photopion reaction, only protons with energies above the PeV range (as measured in the jet frame) can interact and produce pions. Lower neutrino energies would require the existence of an unobserved intense field at soft/medium X-ray energies. This prediction is in agreement with the non-detection of FSRQ by the current generation of high-energy neutrino detectors.

We showed the cumulative neutrino flux for the entire population of FSRQ, and, in all scenarios we considered the FSRQ could be detectable by future neutrino telescopes in the subEeV-EeV energy region. Moreover, in several cases the neutrino flux is higher than the cosmogenic neutrino flux estimates discussed in the literature. Our results are in agreement with the results obtained in Rodrigues et al. (2018) in which authors identified high-luminous FSRQs as best neutrino emitters among blazar objects.

Our results can be easily tested using future neutrino telescope, since cosmogenic neutrinos are expected to be isotropically distributed, while EeV neutrinos from FSRQs should point back to the source, particularly to FSRQs having a gamma-ray luminosity between $10^{47}$ and $10^{49}$ erg/s.

ACKNOWLEDGEMENTS

AP has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (Grant No. 646623). CR and FT acknowledge contribution from the grant INAF CTA-SKA, “Probing particle acceleration and gamma-ray propagation with CTA and its precursors” and the INAF Main Stream project “High-energy extragalactic astrophysics: toward the Cherenkov Telescope Array”. This work was partially supported by the research grant number 2917W4H7A7S “NAF-NEF: Neutrino and Astroparticle Theory Network” under the program PRIN 2017 funded by the Italian Ministero dell’Università e della Ricerca (MUR).

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