

TXS 0506+056-like blazar sources and their role as possible neutrino emitters

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ABSTRACT

The interest in blazars as candidate neutrino emitters grew after the 3σ evidence for a contemporaneous joint photon and neutrino emission from the flaring blazar TXS 0506+056 in 2017. Blazars, a class of extragalactic sources with relativistic jets pointing toward Earth, present a broadband emission interpretable via leptonic and hadronic processes, the latter relevant for proton acceleration and neutrino production. Several emission models have been developed to explain this multi-messenger observation, but the details of the neutrino production and the nature of TXS 0506+056 are not yet fully understood. In this work we investigate the properties of sources similar to TXS 0506+056. We select a sample of blazars from the Fermi 4LAC-DR2 catalog by constraining a number of key parameters in ranges centered on TXS 0506+056 values. We estimate their disk accretion efficiency and model their spectral energy distribution (SED) in terms of lepto-hadronic emission, gaining information respectively on the potential similarity of their environment with that of TXS 0506+056 and on their neutrino flux and detectability prospects at TeV energies. Our study shows the candidates' high energy emission to be dominated by leptonic processes. Part of them also show a high accretion rate, characteristic of FSRQs. For these sources, the very high energy (VHE) and neutrino fluxes appear undetectable by current and future instruments in an average emission state.

1. Introduction

The origin of cosmic-rays is still an open issue. In this context the detection of high-energy neutrinos can provide a unique signature of cosmic ray interactions and pinpoint genuine cosmic-ray accelerators, given that neutrinos are expected to originate from the interactions of hadrons with ambient matter or radiation fields. Many advancements have been made in the last decade, from the detection of a diffuse neutrino flux [1], to the evidence of the first potential neutrino sources [2–4] by the IceCube Neutrino Observatory [5]. For example, the multi-messenger observation of a high-energy neutrino in coincidence with the flaring blazar TXS 0506+056, in 2017 [2], strengthened the interest in blazars as possible neutrino-emitting candidates [2], as already suggested by e. g. [6–8].

Blazars are a subclass of active galactic nuclei (AGNs) hosting a relativistic jet pointing in the direction of Earth and behaving as a natural accelerator of particles. These sources are thus expected to provide a favorable environment for proton acceleration to very-high energies, and consequent neutrino production via photo-meson interactions inside the jet. They can reach a total luminosity ranging from 10^{44} erg/s

to 10^{48} erg/s. The spectral energy distributions (SEDs) of blazars are characterized by two, broad non-thermal components peaking in the infrared-to-soft X-ray band and γ -ray band, respectively. The former is unanimously explained as originating from synchrotron emission from a population of relativistic electrons in the jet, while the origin of the latter is still debated. It can be interpreted as inverse Compton (IC) scattering of relativistic electrons with soft photons. The target photons involved can be the ones emitted through the synchrotron radiation at lower energies (in this case we talk about synchrotron self Compton, SSC) or can originate in external radiation fields coming from e.g. the accretion disk, the broad line region (BLR) or the torus (in this case we talk about external Compton, EC). Another interpretation invokes hadronic emission processes, as synchrotron emission from relativistic protons or radiation from secondary particles produced via proton-photon or proton-proton interactions. Mixed lepto-hadronic models assuming the high-energy component to be produced by both leptonic and hadronic emission processes are also possible. Among the sources interpreted with such scenarios (see e.g. [9–11]) there is TXS 0506+056, where the high-energy emission was explained as

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dominated by IC scattering, with a minor contribution from hadronic processes in X-rays and VHE γ -rays [12–15].

Blazars are divided into two sub-classes: BL Lac objects and Flat-Spectrum Radio-Quasars (FSRQ). They were initially classified based on the intensity of the emission lines in their optical spectra [16], considering as FSRQs the sources showing prominent emission lines, and as BL Lacs those with faint or absent emission lines. This classification can be related to the efficiency of the accretion flow onto the supermassive black hole [17,18]: FSRQs tend to be more powerful and are thought to have a radiatively efficient accretion flow and a BLR rich in gas, while BL Lacs are thought to have an inefficient disk and a weak BLR. Differences between these two sub-classes can be observed also in their SEDs. FSRQs usually present larger bolometric luminosity, lower frequency of the peaks, larger Compton dominance¹ and softer γ -ray spectra than BL Lacs. This behavior is well highlighted by the so-called blazar sequence, an anticorrelation between the SED luminosity and the peaks frequency firstly observed by Fossati et al. [19]. Here, the authors started from radio and X-ray samples of blazars and divided them into radio luminosity bin, finding the above mentioned anticorrelation together with an increase of the Compton Dominance with frequency. The same behavior was later confirmed from [20], who used a larger sample comprising γ -ray sources and divided it into γ -ray luminosity bins. The However, since its first proposal in 1998, the blazar sequence has been subject of active debate, with different authors arguing it to be the result of selection effects and observational biases (see e. g. [21,22]). However, the division between the two sub-classes is not sharp and the classification of a single blazar is often not straightforward. For example, TXS 0506+056 is usually referred to as a BL Lac object, but in the last years a potential nature as FSRQ was suggested [23], making it a so-called masquerading BL Lac. These kinds of sources are intrinsically FSRQ with an efficient accretion disk and prominent optical emission lines which appear faint due to a highly boosted non-thermal continuum. After TXS 0506+056, other blazars have been reclassified as potential masquerading BL Lacs (see e. g. [24–27]).

In this work we present the selection of a sample of blazars similar to TXS 0506+056 aiming to investigate their accretion efficiency and their potential multi-messenger role as possible neutrino-emitting candidates. In Section 2 the details of the candidates selection are explained, with Section 2.3 showing the estimation of the accretion rate of the sources. Section 3 reports information on the data and the analysis methods used. Analysis results for each single candidate are reported in Section 4. The modeling of the SEDs of the candidates in the context of a lepto-hadronic emission is reported in Section 5 for each object. Finally in Section 6 we present the interpretation and discussion of our results.

2. Sample of candidates

This Section is dedicated to the selection of candidates with similar features to those of TXS 0506+056.

2.1. Selection from Fermi 4LAC-DR2 catalog

The sources have been selected from the second release of the Fourth Catalog of Active Galactic Nuclei (4LAC-DR2, [28,29]) from the *Fermi* Large Area Telescope (LAT), based on the second release of the Fourth *Fermi*-LAT catalog (4FGL-DR2, [30,31]).² The 4FGL-DR2

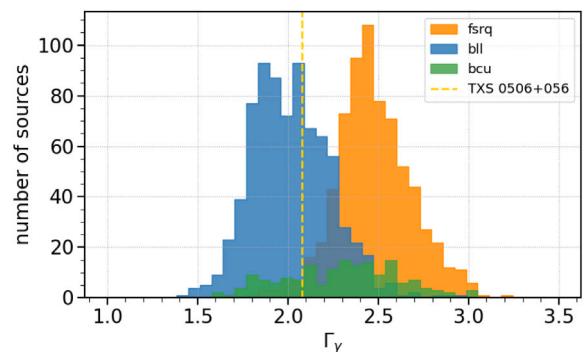


Fig. 1. Histogram of the photon indexes of all sources in 4LAC-DR2 with known redshift. The legend reports: BL Lacs (bll), FSRQs (fsrq), blazar candidate of unknown type (bcu) and TXS 0506+056.

contains γ -ray sources detected in the energy range from 50 MeV to 1 TeV in the first 10 years of *Fermi* activity, from 2008, August 4 to 2018, August 2. The 4LAC catalog was developed to identify AGN counterparts to 4FGL γ -ray sources. The new catalog contains 285 additional AGNs with respect to the first release, the majority of which are blazars. In particular, the 4LAC-DR2 contains 689 FSRQs, 1111 BL Lacs, 1277 blazar candidates of uncertain type (bcu) and 70 non-blazar AGNs.

Assuming the existence of the blazar sequence and taking its results as starting point for our selection, we first investigated the distribution of three source parameters linked to the SED shape of blazars. The chosen parameters are the γ -ray photon index, Γ_γ , the γ -ray luminosity (integrated in the 1 – 100 GeV range), L_γ , and the synchrotron peak frequency, ν_{syn} . In order to compute the luminosity, we took into account all blazars in the catalog with a known redshift. The distributions of the two blazar subclasses are shown in Figs. 1, 2, and 3. Although overlapping, the distributions of the photon index, Γ_γ , and γ -ray luminosity, L_γ , show clearly distinct values with the FSRQs tending to have higher values of both Γ_γ and L_γ with respect to BL Lacs. For the synchrotron peak frequency, FSRQs show smaller values than BL Lacs, with a very narrow distribution peaked around $\sim 10^{13}$ Hz, while the distribution of BL Lacs spans a wider range (from $\sim 10^{13}$ Hz to $\sim 10^{18}$ Hz). These distributions are in line with the behavior highlighted by the blazar sequence. Looking at these distributions, TXS 0506+056 seems not to hold the properties of neither a pure FSRQ, nor a pure BL Lac, being it more likely to be sampled from the BL Lac distribution in Figs. 1 and 3, and from the FSRQ distribution in Fig. 2. Its classification may therefore be non-straightforward. Indeed, given the discrepancy between its usual classification as a BL Lac and the interpretation from [23], the nature of TXS 0506+056 is not firmly established and it is possible that the source has transitional properties between the two subclasses of blazars.

Motivated by these arguments, we performed a selection based on the above-mentioned parameters, which are related to the SED characterization and the emission properties of these sources and, consequently, on their internal environment and possible classification into FSRQs and BL Lacs. We note that observational biases might be introduced with the used criteria, as well as with other criteria that might be adopted. The photon index and the synchrotron peak frequency were extracted directly from the catalog, while the luminosity was derived according to Ghisellini et al. [17]. Since we chose the luminosity as a selection parameter, all sources without a known redshift are excluded a priori from the selection. The chosen parameters were constrained to be close to those of TXS 0506+056, within reasonable uncertainties in their values, in order to plausibly select sources with the same properties. The defined ranges are:

$$\Gamma_{\gamma,0506} - 0.5 < \Gamma_\gamma < \Gamma_{\gamma,0506} + 0.5,$$

¹ The Compton dominance is defined as the ratio between luminosity of the SED at the two peak frequencies (higher-energy peak divided by the lower-energy one).

² At the time of this analysis, the 4LAC-DR2 catalog was the latest available resource. Following the recent release of the 4LAC-DR3 catalog [32], we compared the spectral parameters between the 4LAC-DR2 and 4LAC-DR3 versions. This comparison confirmed that no significant changes were observed for the selected sources.

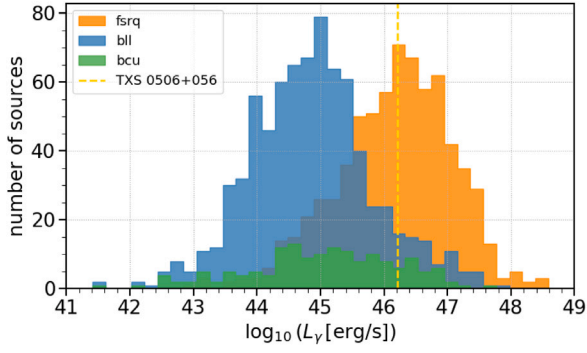


Fig. 2. Luminosity histogram of all sources in 4LAC-DR2 catalog with known redshift. The legend is the same as in Fig. 1.

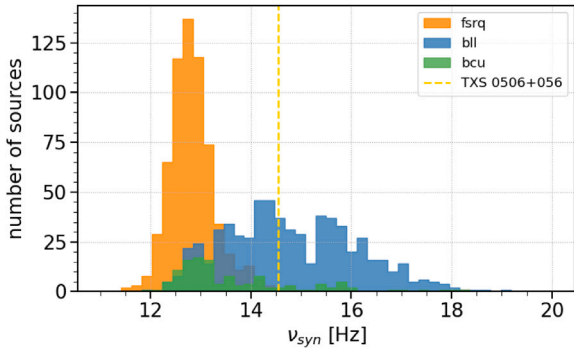


Fig. 3. Histogram of the synchrotron peak frequencies of all sources in 4LAC-DR2 catalog with known redshift. The legend is the same as in Fig. 1.

$$\log_{10}(L_{\gamma,0506}) - 0.5 < \log_{10}(L_{\gamma}) < \log_{10}(L_{\gamma,0506}) + 0.5,$$

$$\log_{10}(\nu_{S,0506}) - 0.7 < \log_{10}(\nu_S) < \log_{10}(\nu_{S,0506}) + 0.7,$$

where $\Gamma_{\gamma,0506} = 2.079 \pm 0.014$, $L_{\gamma,0506} = (1.62 \pm 0.04) \times 10^{46}$ erg/s, and $\nu_{S,0506} = 3.55 \times 10^{14}$ Hz, are referred to TXS 0506+056.³ With this choice we expect to select blazars belonging to the same γ -ray luminosity bin of the blazar sequence [20] and source class as TXS 0506+056. Note that this is not the only possible choice for the selection but it represents a reasonable and reliable possibility since the chosen parameters act as effective proxies for the SED shape.

The sample resulting from this selection contains 27 sources, of which 25 are blazars, and, in particular, 23 are classified as BL Lac objects. The full list of the selected sources can be found in Table 1, together with TXS 0506+056 for comparison.

2.2. Selected sources

Since the aim of this work is to find a sample of sources with similar physical properties to TXS 0506+056, we intend to give an estimate of the accretion rate of the candidates. For the computation of this quantity we need not only the redshift value of the candidates but also information on the emission lines in their optical spectra, in particular the luminosity of the lines. For this reason we will keep in the sample only those sources satisfying these requirements, although this reduce significantly the number of selected candidates.

Starting from the sources in Table 1, we applied a further selection in order to only keep objects having a detailed spectral analysis in the optical and/or ultraviolet band. For each object we performed a

search in the literature to inspect the reliability of the redshift value reported in the 4LAC-DR2 catalog and the presence of information on the emission lines. Details are reported in the last column of Table 1 and listed in the following. We found that almost half of the sources in the sample (13 objects) do not report any optical/UV spectral analysis in the literature; 7 sources have a reliable redshift but no detailed information on their spectral lines is reported. The redshift of some of these objects has been reviewed by Foschini et al. [40] through photometric measurements. However, the absence of a detailed spectral analysis limits their suitability for our purposes, since they do not include information on the single spectral lines. In addition, within these sources, one went out of the selection after the redshift inspection (4FGL J0908.9+2311): the redshift reported in the catalog for this source is $z = 1.184$, while the one provided in the Ref. [37] is $z = 0.431$. With this new value, the luminosity of the source does not lie anymore in the range defined for the selection. Within the remaining seven sources, three only have a redshift lower limit given by the absorption lines of the host galaxy. Finally, there are three sources, besides TXS 0506+056, that have a detailed optical/UV spectral analysis. All of them are classified as BL Lac objects. Our work is then based on the comparison of these 3 sources, namely 4FGL J0050.7-0929, 4FGL J1309.4+4305, and 4FGL J0114.8+1326, with TXS 0506+056 (4FGL J0509.4+0542). In Table 2, for each of them, we report the selection parameters (photon index Γ_{γ} , synchrotron peak frequency ν_S , luminosity L_{γ}) as derived from the 4LAC-DR2 catalog, together with the information on their redshift and spectral lines and the related references. We also report the associated counterpart and include TXS 0506+056 for comparison. From this moment on, we will refer to each of them using the counterpart name.

2.3. Estimation of the accretion rate

From the optical/UV spectral observations, we are interested in the luminosity of the emission lines, which can be exploited to estimate different useful quantities such as the photon energy density within the BLR and the dusty torus (see Section 5), or the accretion rate. In this section we give an estimate of the accretion rate of the candidates in order to understand if they could share the same accretion mechanism and the same nature as TXS 0506+056.

Starting from the luminosity of the lines we extrapolated the luminosity of the BLR, L_{BLR} , of the source through the use of the lines ratios reported in ([41], Table 1) where the authors estimate the strength of the emission lines with respect to the Ly α line (to which a reference value of 100 is assigned) in a composite spectrum of >700 quasars. These ratios are used to estimate L_{BLR} through the relation

$$L_{\text{BLR}} = \sum_i L_{i,\text{obs}} \frac{\langle I_{\text{BLR}}^* \rangle}{\sum_i I_{i,\text{est}}}, \quad (1)$$

reported in ([42], Eq. 1) where $L_{i,\text{obs}}$ is the observed luminosity, $L_{i,\text{est}}$ is the line ratio and $\langle I_{\text{BLR}}^* \rangle$ is the sum of the ratios. Since one of our sources shows H α emission, we added this contribution (not included in the list of [41]) to the line ratios, as it was done in [42]. L_{BLR} is a reliable tracer of the disk emission, since the broad emission lines observed in the spectrum arise from the plasma directly ionized by the disk radiation. Thus, we estimated the luminosity of the accretion disk assuming that the BLR reprocesses about 10% of the disk emission: $L_{\text{disk}} \simeq 10 L_{\text{BLR}}$. Finally, from the disk luminosity, we recovered the accretion rate, defined as the quantity of matter accreted by the black hole by unit of time and given by $\dot{M} = L_{\text{disk}}/(\eta c^2)$, with η the accretion efficiency. In terms of the Eddington luminosity, the accretion rate becomes:

$$\dot{m} = \frac{1}{\eta} \frac{L_{\text{disk}}}{L_{\text{Edd}}}, \quad (2)$$

where L_{Edd} can be written as $L_{\text{Edd}} = 1.3 \times 10^{38} \frac{M}{M_{\odot}} \frac{\text{erg}}{\text{s}}$, and η is the accretion efficiency, which we assume to be $\eta = 0.1$ for black holes [43,44].

³ Note that the 4LAC-DR2 catalog does not report an error on the synchrotron peak frequency.

Table 1

Parameters of the 27 selected sources. All of them except the luminosity are directly extracted from the 4LAC-DR2 catalog. The columns report: name of the source from the catalog, photon flux, photon index, source type (bll = BL Lac object, fsrq = flat spectrum radio quasar, bcu = blazar candidate unknown, css = Compact Steep Spectrum radio source), redshift, SED class, frequency of the synchrotron peak, luminosity in 1–100 GeV energy range, information on spectral analysis in the literature (z ll = redshift lower limit, z only = only redshift value provided, yes = both redshift and information on spectral lines provided), and related references. The sources highlighted in bold represent those we chose after the redshift inspection.

4LAC-DR2 name	Photon Flux [$10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$]	Photon index	Type	Redshift	SED class	ν_s [10^{14} Hz]	L_γ [10^{46} erg/s]	Spectral analysis	Refs.
4FGLJ0509.4+0542	80 ± 2	2.08 ± 0.01	bll	0.3365	ISP	3.55	2.00 ± 0.05	Yes	[33,34]
4FGLJ0004.0+0840	1.9 ± 0.4	2.0 ± 0.1	bll	2.057	ISP	3.02	4.3 ± 0.8	z ll	[34]
4FGLJ0035.2+1514	11.6 ± 0.7	1.9 ± 0.04	bll	1.090	ISP	9.71	5.9 ± 0.4	z ll	[35]
4FGLJ0050.7-0929	39 ± 1	2.02 ± 0.02	bll	0.635	ISP	1.32	4.8 ± 0.2	Yes	[34]
4FGLJ0114.8+1326	11.1 ± 0.6	2.11 ± 0.04	bll	0.583	ISP	6.31	1.02 ± 0.06	Yes	[36]
4FGLJ0153.9+0823	16.2 ± 0.8	1.95 ± 0.03	bll	0.681	ISP	8.91	2.5 ± 0.1	z only	[37]
4FGLJ0253.2-0124	2.9 ± 0.4	2.1 ± 0.1	bll	1.480	ISP	2.24	2.8 ± 0.4	No	–
4FGLJ0434.1-2014	3.4 ± 0.4	2.27 ± 0.08	bll	0.928	ISP	1.12	0.9 ± 0.1	z only	[37]
4FGLJ0528.7-5920	2.8 ± 0.3	2.06 ± 0.09	bll	1.13	HSP	15.85	1.4 ± 0.2	No	–
4FGLJ0849.5+0456	5.4 ± 0.5	2.08 ± 0.07	bll	1.06959	ISP	2.45	2.3 ± 0.2	No	–
4FGLJ0908.9+2311	4.8 ± 0.5	1.82 ± 0.07	bll	1.184	ISP	5.07	3.1 ± 0.3	z only	[37]
4FGLJ0921.7+2336	3.6 ± 0.4	2.06 ± 0.09	bll	1.062	ISP	2.00	1.5 ± 0.2	No	–
4FGLJ1003.4+0205	1.5 ± 0.3	2.0 ± 0.2	bcu	2.075	ISP	5.72	3.5 ± 0.7	No	–
4FGLJ1103.0+1157	12.2 ± 0.6	2.41 ± 0.03	fsrq	0.914	ISP	1.27	3.0 ± 0.2	No	–
4FGLJ1107.8+1501	5.8 ± 0.5	1.95 ± 0.06	bll	0.6	ISP	3.63	0.65 ± 0.06	z only	[37]
4FGLJ1155.8+6137	0.9 ± 0.2	1.9 ± 0.2	bll	1.525	ISP	2.66	1.0 ± 0.3	No	–
4FGLJ1213.6+1306	6.1 ± 0.5	2.47 ± 0.05	fsrq	1.14	LSP	0.87	2.7 ± 0.2	z only	[38]
4FGLJ1215.1+5002	3.9 ± 0.4	1.88 ± 0.07	bll	1.545	ISP	7.94	4.5 ± 0.4	No	–
4FGLJ1245.1+5709	3.6 ± 0.3	2.13 ± 0.07	bll	1.545	ISP	7.94	3.8 ± 0.3	No	–
4FGLJ1253.8+6242	4.1 ± 0.3	1.99 ± 0.06	bll	0.867	LSP	0.09	1.1 ± 0.1	z only	[37]
4FGLJ1309.4+4305	16.4 ± 0.7	1.90 ± 0.03	bll	0.691	ISP	5.19	2.7 ± 0.1	Yes	[34]
4FGLJ1459.0+7140	2.9 ± 0.3	2.50 ± 0.06	css	0.91	ISP	3.83	7.12 ± 0.07	z only	[38]
4FGLJ1509.7+5556	3.4 ± 0.3	1.88 ± 0.07	bll	1.68	ISP	1.41	4.9 ± 0.5	No	–
4FGLJ1530.9+5736	2.2 ± 0.3	2.06 ± 0.09	bll	1.1	ISP	2.00	1.0 ± 0.1	No	–
4FGLJ2116.2+3339	34 ± 1	1.90 ± 0.02	bll	0.35	ISP	7.94	1.13 ± 0.04	z ll	[39]
4FGLJ2145.5+1006	1.0 ± 0.3	1.8 ± 0.2	bll	2.826	ISP	1.82	5 ± 2	No	–
4FGLJ2156.9-0854	2.7 ± 0.4	2.1 ± 0.1	bll	1.017	ISP	1.74	1.0 ± 0.2	No	–

Table 2

Final sample of selected sources with information on selection parameters as extracted or derived from the 4LAC-DR2 catalog, on their redshift and emission lines. The columns are: source name, associated counterpart name, photon index reported in 4LAC-DR2 catalog, synchrotron peak frequency reported in 4LAC-DR2 catalog, luminosity derived from energy flux and redshift reported in 4LAC-DR2 catalog, redshift found in the literature, emission lines observed in the optical spectrum, luminosity of each line, references. The references are: [33] = Paiano et al. [33], [34] = Landoni et al. [34], [36] = Shaw et al. [36].

γ -ray Source	Counterpart	Γ_γ	ν_s [10^{14} Hz]	L_γ [$10^{46} \text{ erg s}^{-1}$]	z_{ref}	Emission lines	L_{lines} [$10^{41} \text{ erg s}^{-1}$]	Refs
4FGL J0509.4+0542	TXS 0506+056	2.079 ± 0.014	3.55	2.00 ± 0.05	0.3365	[O II] [O III] [N II]	1.0 0.05 0.05	[33,34]
4FGL J0050.7-0929	PKS 0048-09	2.016 ± 0.018	1.32	4.77 ± 0.15	0.635	[O II] [O III] H α	1.0 0.94 1.6	[34]
4FGL J0114.8+1326	GB6 J0114+1325	2.11 ± 0.04	6.31	1.02 ± 0.06	0.685	H β [O III]	124 245	[36]
4FGL J1309.4+4305	B3 1307+433	1.90 ± 0.03	5.19	2.68 ± 0.13	0.693	[O II] [O III]	20.0 5.5	[34]

The exact value of the black hole mass of the candidates is not known. Therefore, in order not to provide a result depending too strongly on given assumptions, we decided to select two reasonable values for the black hole mass, i. e. $M_{\text{BH}} = 10^8, 10^9 M_\odot$, defining a possible range in which the accretion rate can lie. This choice is in accordance with the black hole mass estimations from [45]. In addition the chosen mass range is consistent with the mass value estimated by Paliya et al. [46] for PKS 0048-09. The results we found are summarized in Table 3. Taking into account the division proposed by Ghisellini et al. [18], we suppose a dividing value between FSRQs and BL Lacs of $\dot{m}_d \sim 5 \times 10^{-2}$, assuming FSRQs to have a higher $\dot{m}$ value while BL Lacs a lower one. Despite the expectations, we can see that the estimated accretion rates are quite different from source to source. In particular, B3 1307+433 and GB6 J0114+1325 show high values, lying above the dividing line, while PKS 0048-09 show values below the threshold, although quite close to it. This may suggest a different internal environment for the selected objects. Regarding TXS 0506+056, the estimated range is

consistent with the value found in [23] ($L_{\text{BLR}}/L_{\text{Edd}} \sim 10^{-3}$, which in our case translates into $\dot{m} \sim 10^{-1}$), who proposed the source to be a FSRQ. However, the situation seems more delicate, since, with the assumed mass values, the estimated accretion rate range lies around $\dot{m}_d$. If we assume the source host galaxy to be a giant elliptical with absolute magnitude in the R-band of $M_R = -22.9$ (as done in e. g. [33,35,47]), then the black hole mass can be estimated to be $M_{\text{BH}} \sim 3 \times 10^8$ [48]. By taking into account the redshift lower limit of $z > 0.3$ by Paiano et al. [33], this mass value results to be an upper limit. With these additional assumptions, therefore the low edge of the accretion rate range can be estimated as $\dot{m}_{\text{low}} = 6.55 \times 10^{-2}$, lying this time above the threshold values, although very close to it. The results obtained for PKS 0048-09 and TXS 0506+056 are very interesting themselves, as they suggest that close to the critical accretion rate value the assumptions usually made for the BLR may break down. Indeed, The H α line observed for PKS 0048-09 is usually associated with the BLR. Possible explanations of the results obtained for the accretion rate can be related to the

Table 3

Estimated values of BLR luminosity (L_{BLR}), disk luminosity (L_{disk}) and accretion rate ($\dot{m}$).

Source	L_{BLR} [erg s ⁻¹]	L_{disk} [erg s ⁻¹]	$\dot{m}_{\text{low}}$	$\dot{m}_{\text{high}}$
TXS 0506+056	2.55×10^{43}	2.55×10^{44}	1.96×10^{-2}	1.96×10^{-1}
PKS 0048-09	2.42×10^{42}	2.42×10^{43}	1.86×10^{-3}	1.86×10^{-2}
GB6 J0114+1325	3.66×10^{44}	3.66×10^{45}	2.82×10^{-1}	2.82
B3 1307+433	3.39×10^{44}	3.39×10^{45}	2.61×10^{-1}	2.61

possibility that these objects host a non-standard BLR, where factors such as a reduced covering factor, lower gas density, or an atypical geometry (e.g., non-spherical or incomplete coverage of 4π) could lead to discrepancies between the expected and estimated values. This makes these sources interesting for further studies.

3. Data analysis

For each source, we analyzed public data from *Fermi*-LAT, *Swift*/XRT and *Swift*/UVOT.

3.1. Fermi-LAT

The LAT is the main instrument onboard the *Fermi* satellite [49]. The LAT detects photons by conversion into electron-positron pairs and has an operational energy range from 20 MeV to more than 300 GeV.

We performed a dedicated analysis of the *Fermi*-LAT data of each selected source (namely B3 1307+433, GB6 J0114+1325, PKS 0048-09 as well as TXS 0506+056) using 12 years of LAT observations taken between 2008, August 4 and 2020, August 4. We then repeated the analysis on shorter time intervals based on the γ -ray activity of the selected sources as well as on the availability of quasi-simultaneous multi-wavelength observations (see second and third columns of Table 4 for further details).

For the data selection, we used P8R3 (v3) Source class events [50], in the energy range between 100 MeV and 1 TeV, in a region of interest (ROI) of $15^\circ \times 15^\circ$ centered on the source position. The low energy threshold is motivated by the large uncertainties in the arrival directions of the photons below 100 MeV, leading to a possible confusion between point-like sources and the Galactic diffuse component (see [51] for issues at low energies with *Fermi*-LAT and a possible alternative analysis method).

The analysis consists of the following steps: model optimization, and source localization, spectrum and emission variability studies. It was performed with *Fermipy*⁴ (v1.0.1, [52]), a python library making use of the Fermi Tools, of which the version 2-0-18 was used. We created counts maps using a pixel size of 0.1° . All γ -rays with zenith angle larger than 105° were excluded in order to limit the contamination from secondary γ -rays from the Earth's limb [53]. We applied different cuts for the data selections at low energies and selected event types with the best point spread function⁵ (PSF). In particular, for energies below 300 MeV we excluded events with zenith angle larger than 85° , and photons from PSF0 and PSF1 event types. Between 300 MeV and 1 GeV we excluded events with zenith angle larger than 95° , as well as photons from the PSF0 event type. Above 1 GeV we use all events with zenith angles less than 105° .

We used the P8R3_SOURCE_V3 instrument response functions. The model used to describe the sky includes all point-like and extended

sources located at a distance $<15^\circ$ from the source position and listed in the 4FGL-DR2 [30], as well as the Galactic diffuse and isotropic emission. For the two latter contributions, we adopted the same templates⁶ adopted to derive the 4FGL-DR2 catalog. The spectral analysis was performed leaving free to vary the diffuse background template normalization and the spectral parameters of the sources within 3° from our targets. For the sources in a radius between 3° – 5° and all variable sources only the normalization was fit, while we fixed the parameters of all the remaining sources within the ROI at larger angular distances from our target. We modeled the spectrum of the sources using the same spectral function adopted in the 4FGL-DR2 catalog. A log-parabola function

$$\frac{dN}{dE} = N_0 \times \left(\frac{E}{E_b} \right)^{-(\alpha + \beta \ln(E/E_b))}$$

was used for TXS 0506+056, B3 1307+433 and PKS 0048-09, while a power-law function

$$\frac{dN}{dE} = N_0 \times \left(\frac{E}{E_b} \right)^{-\Gamma}$$

was used for GB6 J0114+1325. Finally we extracted a light curve using time bins with a duration of two months.

3.2. Swift

The *Neil Gehrels Swift observatory* satellite [54] is a multiwavelength satellite observatory equipped with 3 instruments: the X-ray Telescope (XRT; [55], 0.2–10 keV) the Ultraviolet/Optical Telescope (UVOT; [56], 170–600 nm) and the Burst Alert Telescope (BAT; [57], 15–150 keV). For our sources, we took data from the XRT and UVOT. Similarly to what we did for the *Fermi*-LAT analysis, we firstly performed a dedicated analysis of each selected source using all available observations. Then, we repeated the analysis on smaller time intervals chosen based on the activity of the source (see Section 4 for more details on the selection of the period). In the first case the single observations were analyzed, while in the second one all observations belonging to the selected period were summed.

All XRT observations were performed in photon counting mode [58], providing photon counts within specific energy ranges defined by the instrument channels. The spectrum data of the source were taken from the UK Swift Science Data Centre⁷ and analyzed by using the HEASOFT v. 6.29 and XSPEC v. 12.12.0g software packages. Each spectrum was rebinned in energy using the grppha tool of HEASOFT in order to have at least 25 counts per bin to apply the χ^2 test. When counts were not sufficient, as in the observations of GB6 J0114+1325, the Cash statistic was used [59]. All XRT spectra were analyzed in the 0.3 – 10 keV energy range and modeled with an absorbed power-law with a fixed Galactic column density N_H , measured according to Kalberla et al. [60]. For all sources, the spectral parameters obtained from the fit, i.e. the normalization K and the photon index Γ_X , as well as the value used for N_H and the total exposure time are reported in Table 5.

Simultaneous UVOT observations were performed during the XRT pointings. The UVOT is composed of 6 broad-band filters, three of which in the visible band (v , b , u) and three in the ultraviolet ($w1$, $m2$, $w2$). All of them were used in the observation of the selected sources. Photometric data were downloaded from the High Energy Astrophysics Science Archive Research Center (HEASARC⁸). Data were analyzed with the uvotimsum and uvotsource tasks and the 20201215 CALDB-UVOTA release of the calibration database. We used uvotimsum to integrate the available images and uvotsource to recover the

⁴ <http://fermipy.readthedocs.io/en/latest/>.

⁵ A measure of the quality of the direction reconstruction is used to assign events to four quartiles. In Pass 8 data, γ -rays can be separated into 4 PSF event types: 0, 1, 2, 3, where PSF0 has the largest point spread function and PSF3 has the best one.

⁶ <https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html>.

⁷ https://www.swift.ac.uk/user_objects/index.php.

⁸ <https://heasarc.gsfc.nasa.gov/cgi-bin/W3Browse/w3browse.pl>.

Table 4

Fermi-LAT results in the 0.1–1000 GeV energy range. For TXS 0506+056, PKS 0048-09 and B3 1307+433 a log-parabola function was used for fitting their spectra using a E_0 of 1.07 GeV, 924 MeV and 1.39 GeV, respectively. A power-law function with $E_0 = 1.4$ GeV was used for GB6 J0114+1325. The reported flux values are in unit of 10^{-8} ph cm $^{-2}$ s $^{-1}$, while normalization values are in unit of 10^{-12} MeV $^{-1}$ cm $^{-2}$ s $^{-1}$.

Source	Period [days]	MJD	TS	Flux [10^{-8} ph cm $^{-2}$ s $^{-1}$]	Spectral values		
					N_0 [10^{-12} MeV $^{-1}$ cm $^{-2}$ s $^{-1}$]	α (Γ)	β
TXS 0506+056	12 years	54 682–59 065	15 400	7.97 ± 0.28	7.62 ± 0.13	2.03 ± 0.02	0.051 ± 0.008
PKS 0048-09	12 years	54 682–59 065	7500	3.31 ± 0.15	4.97 ± 0.12	1.91 ± 0.02	0.062 ± 0.010
	Low	55 100–55 600	610	2.04 ± 0.34	8.11 ± 1.14	1.97 ± 0.11	0.044 ± 0.005
	High	55 880–55 950	230	6.00 ± 1.22	3.30 ± 0.26	1.92 ± 0.09	0.089 ± 0.040
B3 1307+433	12 years	54 682–59 065	2930	0.76 ± 0.07	0.76 ± 0.03	1.74 ± 0.04	0.093 ± 0.017
	Average	59 488–59 759	80	0.65 ± 0.30	0.76 ± 0.19	1.59 ± 0.23	0.090 ± 0.085
GB6 J0114+1325	12 years	54 682–59 065	1260	1.39 ± 0.10	0.56 ± 0.03	2.09 ± 0.03	
	Average	55 450–55 600	95	2.54 ± 0.66	0.86 ± 0.15	2.18 ± 0.13	

Table 5

Values of the parameters obtained from the fit and total exposure time for each source.

Source	State of activity	n_H [cm $^{-2}$]	Γ_x	K [keV $^{-1}$ cm $^{-2}$ s $^{-1}$]	Exp. time [ks]
PKS 0048-09	High	3.10×10^{20}	2.16 ± 0.17	$(7.0 \pm 0.5) \times 10^{-4}$	2.94
	Low		2.12 ± 0.07	$(8.7 \pm 0.4) \times 10^{-4}$	6.69
GB6 J0114+1325	Average	3.27×10^{20}	4.0 ± 0.7	$(7.7 \pm 3.6) \times 10^{-5}$	1.18
B3 1307+433	Average	1.85×10^{20}	2.38 ± 0.18	$(6.9 \pm 0.6) \times 10^{-5}$	21.29

Table 6

Recovered magnitudes in the Vega system for each source in the selection. For PKS 0048-09 we report both the magnitudes obtained in the chosen low state (upper line) and high state (lower line).

Source	State of activity	v [mag]	b [mag]	u [mag]	$w1$ [mag]	$m2$ [mag]	$w2$ [mag]
PKS 0048-09	High	16.4 ± 0.04	16.81 ± 0.03	15.99 ± 0.02	16.02 ± 0.03	16.05 ± 0.03	16.18 ± 0.02
	Low	14.85 ± 0.03	15.22 ± 0.02	14.39 ± 0.02	14.41 ± 0.02	14.41 ± 0.03	14.69 ± 0.02
GB6 J0114+1325	Average	16.85 ± 0.1	17.21 ± 0.07	16.29 ± 0.05	16.29 ± 0.05	16.27 ± 0.06	16.28 ± 0.04
B3 1307+433	Average	17.31 ± 0.04	17.72 ± 0.03	16.86 ± 0.03	16.86 ± 0.03	16.9 ± 0.03	17.01 ± 0.02

sources magnitudes through differential photometry techniques. They were applied for each filter to photometric images belonging to the same observation date. For each candidate, the source counts were extracted from a circular region centered on the source, with a radius of 5 arcsec; while background counts were obtained from a circular region with radii between of 40 and 60 arcsec located in a source-free area. All the computed magnitudes were then corrected for Galactic extinction, given by the relation $A_\lambda = E(B - V) [a_\lambda R_v + b_\lambda]$ [61], where $E(B - V)$ is taken from the NASA/IPAC Infrared Science Archive⁹ according to Schlafly and Finkbeiner [62], while the other coefficients are reported in [61]. The corrected magnitudes were finally converted into energy fluxes by using the parameters in [63]. For each source the detection was obtained in all photometric bands.

4. Analysis results

In the following we report the results from our *Swift* and *Fermi* analyses. For each source we firstly recovered the multiwavelength emission over time in order to identify low and high or flaring states of activity. As a criterion to define a gamma-ray emission state as low or high, we used the condition that the flux in the bi-monthly time bins of the *Fermi*-LAT light curve differed by at least two sigma from the flux estimated over the 12-year period, as shown by the values reported in Table 4. Then, once identified, we chose a period for both low and high states for which we have contemporaneous multiwavelength data. Quasi-simultaneous observations in AGN modeling are crucial for accurately capturing the variability of the active galactic nucleus across different wavelengths, ensuring that changes in emission are correctly

correlated, and therefore related to same emission mechanism, and not misinterpreted due to time lags between observations. Among our sources, B3 1307+433 and GB6 J0114+1325 do not show significant variability in their lightcurves, so for these sources we just created a SED in their average state. The source PKS 0048-09 is the only one for which we could define both a low and a high state period, given that it is the only source in our sample showing significant variability. For all sources, the spectral results from *Fermi*-LAT and *Swift*/XRT analyses have been collected in Tables 4 and 5 respectively, while the magnitudes obtained from UVOT analysis are presented in Table 6. The multi-wavelength SEDs containing the contemporaneous data in the selected periods are shown in Fig. 7 for each source.

4.1. PKS 0048-09

The source was observed by *Swift* 9 times between 2008, June 4 (MJD 54621) and 2012, January 13 (MJD 55939) with both XRT and UVOT. The multiwavelength lightcurve of the source is quite peculiar, since it shows three flares, one in each of the energy ranges analyzed (*Fermi*-LAT, *Swift*/XRT, *Swift*/UVOT) which are not coincident in time. Indeed they happened in different periods and do not correspond to the brightest activity in the other bands, so it is not easy to define a unique high state of activity for the source. The *Fermi*-LAT flare has no coincident *Swift* simultaneous observations, so we cannot say anything about the source activity in the other bands in that period and cannot consider it to build the simultaneous high-state SED of the source. Regarding the brightest XRT flare, it happened in May–June 2009 (MJD $\sim 54952 - 55012$) and is not coincident with the brightest activity in UVOT bands. The same happens for the optical–UV flare observed by UVOT between December 2011 and January 2012 (MJD $\sim 55896 - 55939$): it corresponds to a relatively high activity of the

⁹ <https://irsa.ipac.caltech.edu/applications/DUST/>.

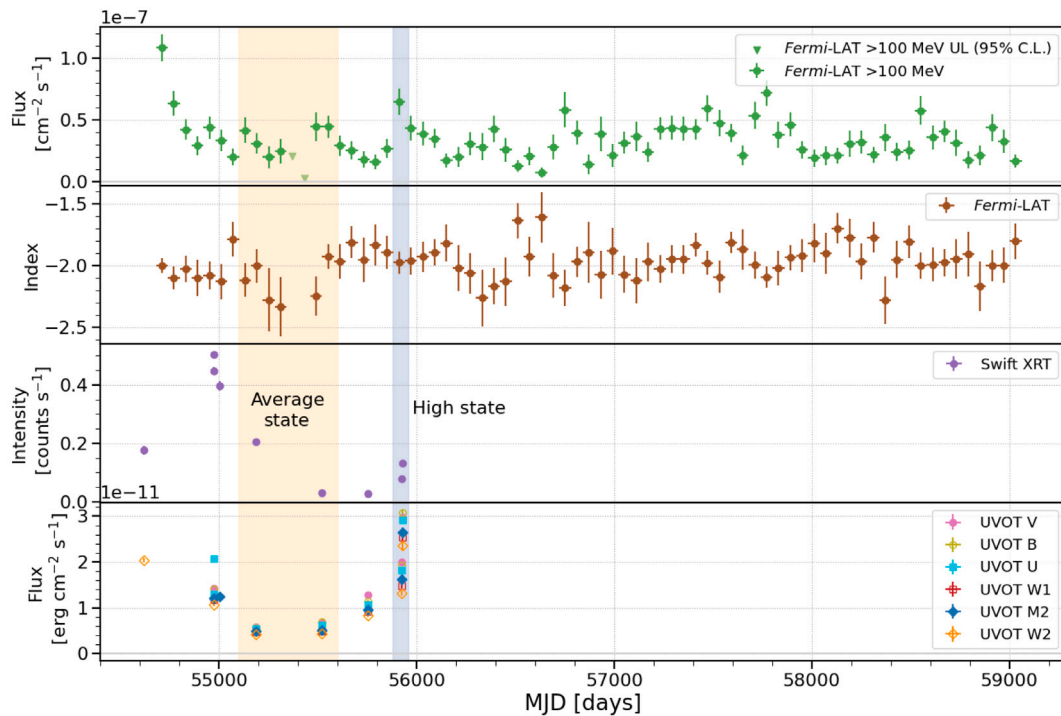


Fig. 4. Multiwavelength lightcurve of the source PKS 0048-09. From top to bottom, the panels show: *Fermi*-LAT flux in 60-days bins, values assumed by the γ -ray spectral index in the same bins, *Swift*/XRT flux in daily bins, *Swift*/UVOT flux in daily bins. The shaded areas identify the boundaries of the low (orange) and high (blue) state periods chosen to build the SED.

source in the X-ray band, but not to the brightest X-ray flux. We finally decided to consider as a high state a period of few months coincident with the *UVOT* flare because of a simultaneous slightly-enhanced activity observed in *Fermi*-LAT data at the same time. The full period we considered for *Fermi*-LAT analysis in the high state ranges from 2011 November 15 to 2012 January 24 (MJD 55880 – 55950, see the blue shaded area in Fig. 4). Instead, given that a clearly visible low state cannot be identified from the source LC, we concentrated on an average state of activity. We considered the period between 2009 September 26 and 2011 February 8, containing two *Swift* pointings (MJD 55100 – 55600, see the yellow shaded area in Fig. 4). The full multi-wavelength lightcurve of this source is shown in Fig. 4.

PKS 0048-09 is significantly detected with *Fermi*-LAT in the 12-years period ($TS = 7500$, $> 85\sigma$) and presents flux and spectral parameters in agreement with the results for this source in the 4FGL-DR3 catalog [64], similarly based on 12 years of *Fermi*-LAT data. During the high-state period the source presents a slightly higher flux (about twice the one derived in our 12-years analysis) while the log-parabola indexes are compatible within the statistical uncertainties. The spectral parameters recovered from the analysis are reported in Table 4, while the values reported in the 4FGL-DR3 catalog are $\alpha = 1.92 \pm 0.03$, $\beta = 0.06 \pm 0.01$.

4.2. GB6 J0114+1325

The source was observed by *Swift* only 4 times between 2010, November 22 (MJD 55522) and 2020, July 17 (MJD 59047), with both the XRT and UVOT. Like for the other sources, we first built the lightcurve of the candidate in order to identify suitable low and high states of activity, finding no a clear variation in the source flux (see Fig. 5). However, since the data are so sparse in time, it is not possible to select a time interval with a large number of *Swift* pointings for the construction of the SED, and thus we consider the average state of the SED. We decided to consider an interval ranging from 2010, September 11 and 2011, February 8 (MJD 55450 – 55600).

The chosen interval lies around the first *Swift*/XRT observation (on 2010, November 22), which is one of the most significant ones. The *Fermi*-LAT analysis is then performed over the selected period. The XRT observations show a low total exposure (see Table 5), because of which the number of counts obtained in each energy bin created with *grppha* is not enough to apply the χ^2 statistic, so in this case the Cash statistic is used. With *Fermi*-LAT, GB6 J0114+1325 is detected with a $TS = 1260$, corresponding to a significance of $> 35\sigma$. The flux and spectral parameters (see Table 4) are in agreement with the 4FGL-DR3 results ($\Gamma = 2.06 \pm 0.04$) for this source. During the selected period the source presents a slightly higher flux (less than twice the one derived in the 12-years analysis) and a power-law index compatible within the statistical uncertainties.

4.3. B3 1307+433

This source was observed by *Swift* 18 times between 2010, September 2 (MJD 55441) and 2021, December 10 (MJD 59558), with the majority of the pointings in 2021, thanks to a dedicated observation proposal submitted by the authors. In particular, we have 13 observations in the period from 2021, October 4 to 2021, December 10 (MJD 59491 – 59558). We firstly generated the daily lightcurve of the source for both XRT and UVOT. In the first case the lightcurve was generated with the flux in units of counts s^{-1} with the data product generator tool available at the UK *Swift* Science Data Centre, while in the second case we performed the analysis of the photometric images for each observation date. The lightcurves in each band are shown in Fig. 6. Since neither the *Fermi*-LAT nor the *Swift* light curves show significant variations of the source flux in the period from October to December 2021 and given the large number of observations in this period, we chose these data to build the SED of the source in its average state. *Fermi*-LAT analysis was performed in the whole period from 2021, October 1 to 2021, December 31 (MJD 59488 – 59579).

Analyzing 12 years of *Fermi*-LAT data (see Table 4 for spectral results) the source is detected in γ rays with a $TS = 2931$, corresponding

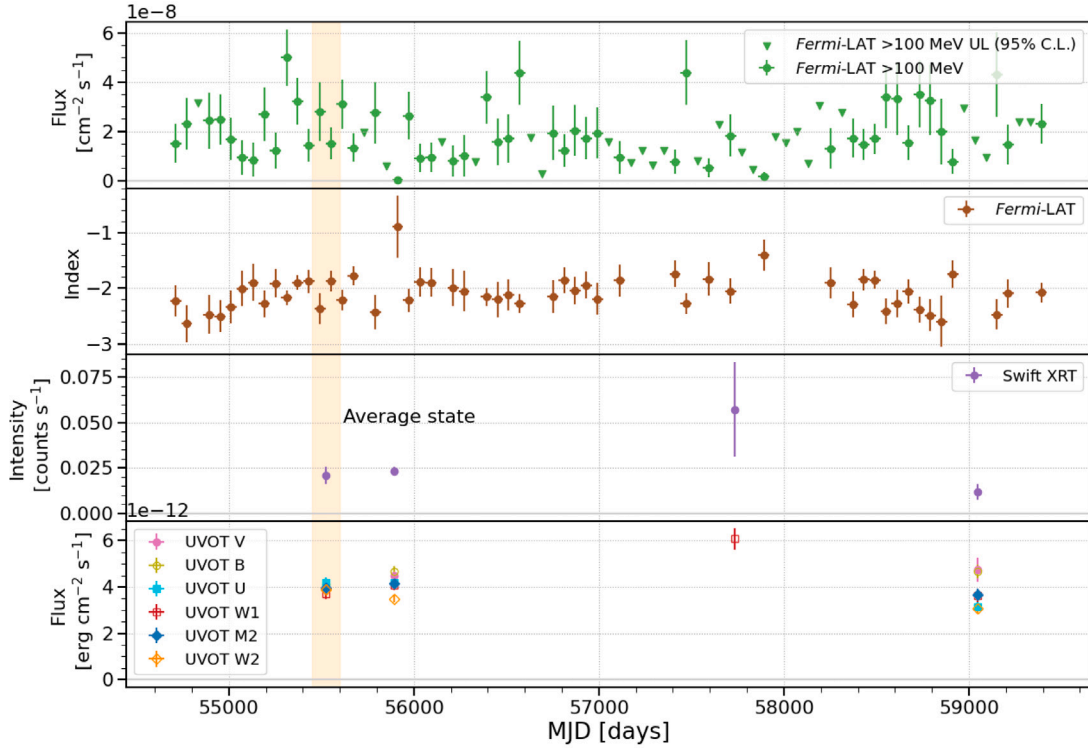


Fig. 5. Multiwavelength lightcurve of the source GB6 J0114+1325. The reported information are the same as in Fig. 4.

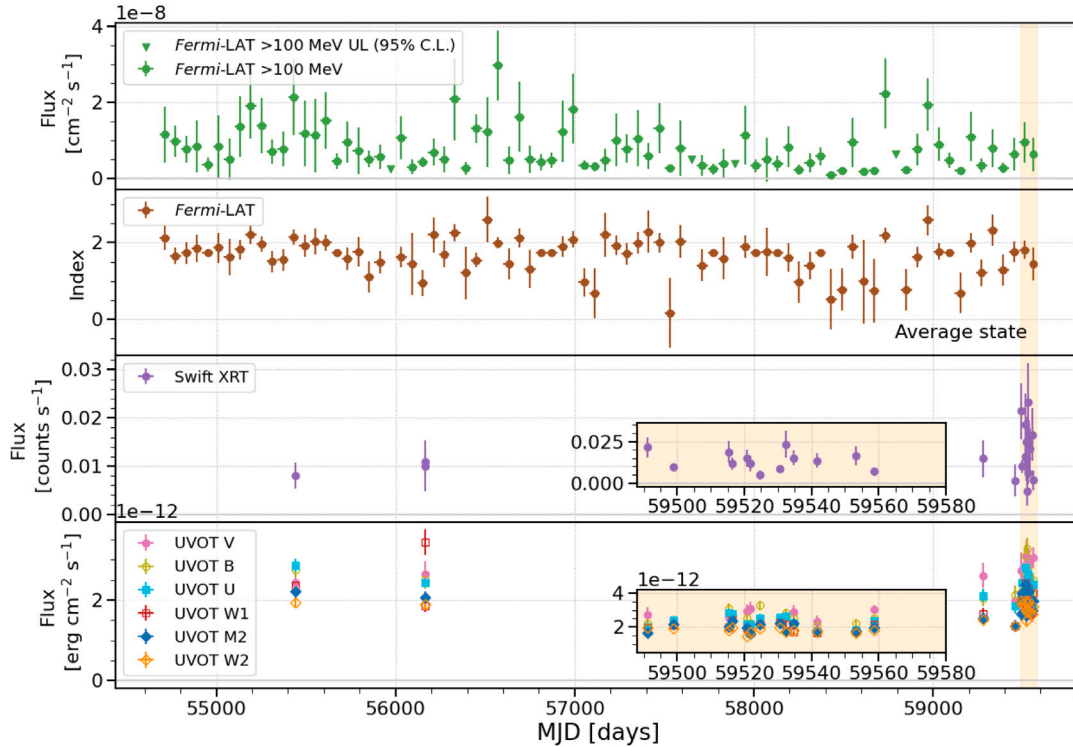


Fig. 6. Multiwavelength lightcurve of the source B3 1307+433. The reported information are the same as in Fig. 4. The insets show the trend of the source in X-ray and optical/UV bands during the selected period.

to a significance $> 50\sigma$. The spectral parameters of this source are in agreement with the 4FGL-DR3 results, which are $\alpha = 1.76 \pm 0.04$ and $\beta = 0.09 \pm 0.02$. For the selected average-state period the source presents a similar emission with flux and spectral parameters compatible within the uncertainties with the one that we obtained using 12 years.

5. Modeling

The modeling of the TXS 0506+056 multi-messenger campaign in 2017 indicates that the most likely emission scenario is a mixed lepto-hadronic one, in which the origin of the γ -ray SED component is

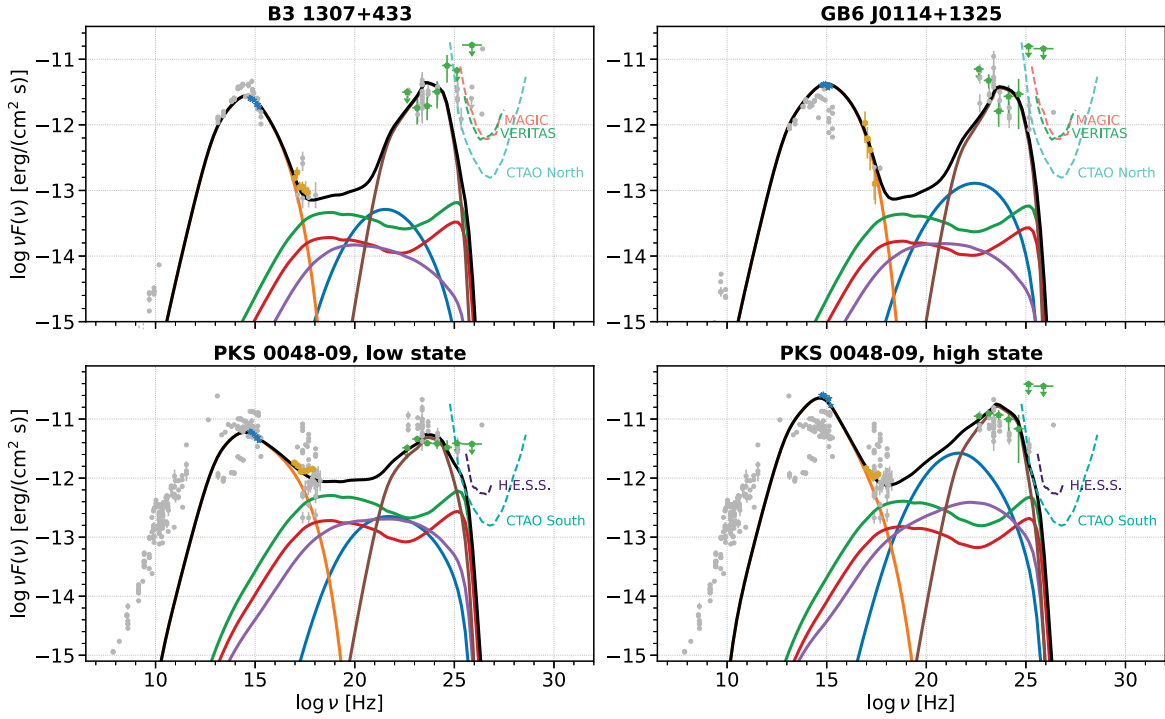


Fig. 7. Multi-wavelength SED of the candidates in the selected periods and modeling in lepto-hadronic context. Gray points show the archival data from ASI ASDC [65], while light-blue stars, gold hexagons, and green pentagons show *UVOT*, *XRT* and *Fermi-LAT* data in the selected periods, respectively. The model lines show: electron synchrotron emission (orange), synchrotron self Compton emission (blue), external Compton emission (brown), Bethe-Heitler cascades (violet), cascades from π^0 (green), and $\pi^\pm$ (red) decay. For the two sources in the northern hemisphere (GB6 J0114+1325, B3 1307+433) a comparison with the sensitivity of MAGIC (salmon dashed line, [66]), VERITAS (light-green dashed line, [67]), and the CTAO Northern array (cyan dashed line, [68]) for 50 h of observation, are also shown, while for the only source in the southern hemisphere (i.e. PKS 0048-09), the comparison is done with H.E.S.S. (purple dashed line [69]) and CTAO Southern array (seagreen dashed line).

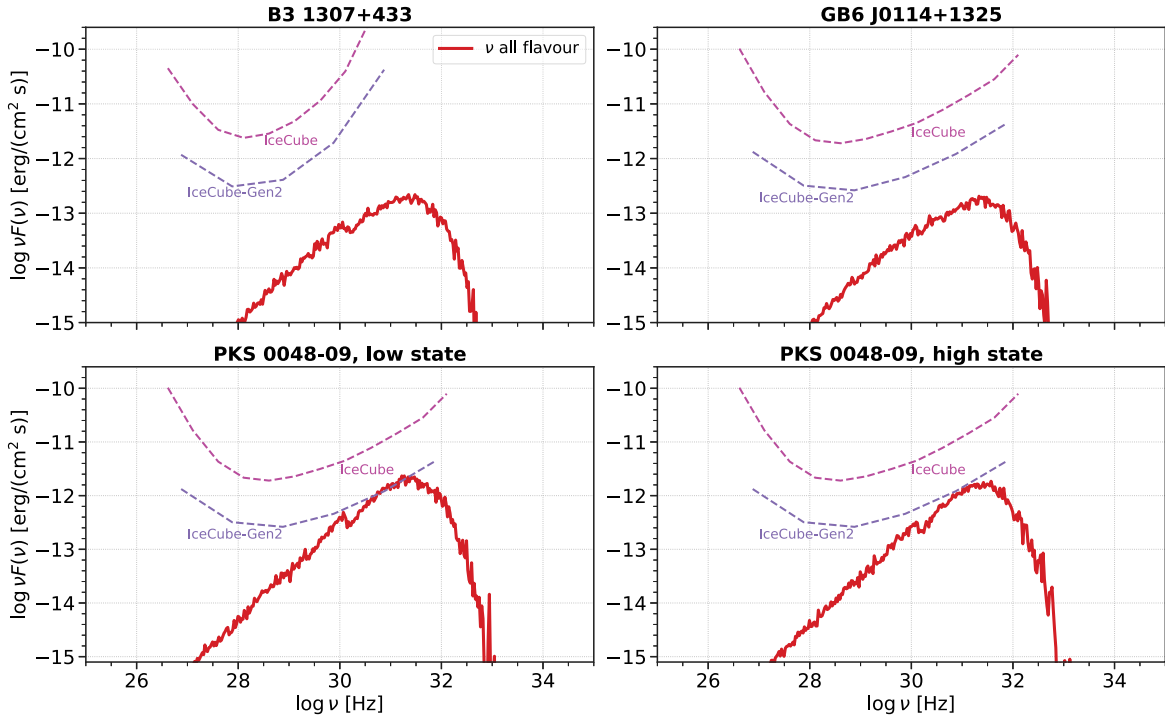


Fig. 8. Neutrino spectrum expected from the model in Fig. 7 of the sources under consideration, compared with the IceCube sensitivity for point-source searches for 8 years of exposure [70]. The sensitivity is shown for a declination of 30° in the upper left panel and of 0° in the other panels, based on the proximity to the source declination.

predominantly leptonic (inverse Compton scattering by primary electrons), with subdominant hadronic emission by $e^\pm$ cascades triggered by pion decay and Bethe–Heitler pair production. Due to energetic constraints, the target photon field for $p\text{-}\gamma$ interactions is more likely to be external to the jet, and relativistically boosted in the reference frame of the emitting plasmoid in the jet. In this section we model the SED of the three targets that share similar observational properties (see Section 2), within the same framework. The numerical code we use here is *LeHa* [71], that was already applied in the study of TXS 0506+056, albeit assuming a single-zone scenario (i.e. in absence of external photon field, [14]), and for a spine-layer structured jet [72]. The code calculates the photon and neutrino emission from a spherical plasmoid in the jet, parametrized by its Doppler factor δ , its radius R' , and average magnetic field B' . The energy distributions of primary electrons and protons are both described by a broken power law with exponential cut-off at the maximum energy. $p\text{-}\gamma$ interactions include photo-meson (computed using SOPHIA, [73]), and Bethe–Heitler pair-production. *LeHa* is a stationary code, that computes SEDs assuming that all particles have the time to reach equilibrium between injection and cooling. Arbitrary external photon fields can be provided as input for both $p\text{-}\gamma$ and $\gamma\text{-}\gamma$ interactions.

For the purposes of this work, the important parameter is the radiation energy density of the broad emission line photons. In order to compute this quantity we need information on the luminosity and radius of the BLR. We gave an estimation for the former in Section 2.3 thanks to our study on the spectral lines, while the latter can be recovered from the disk luminosity by assuming a simple scaling relation: $R_{\text{BLR}} = 10^{17} L_{\text{disk},45}^{1/2}$ cm [74], where $L_{\text{disk},45}$ is the luminosity of the disk in units of 10^{45} erg s $^{-1}$. The recovered values for each source are the following: 1.84×10^{17} cm for B3 1307+433, 1.91×10^{17} cm for GB6 J0114+1325 and 1.56×10^{16} cm for PKS 0048-09. This relation implies that, within the BLR, the energy density, u_{BLR} , of the line photons is constant and equal for all sources. The value obtained in the observer's frame is

$$u_{\text{BLR}} = \frac{L_{\text{BLR}}}{4\pi c R_{\text{BLR}}^2} \times 2.24 = 5.95 \times 10^{-2} \text{ erg cm}^{-3}. \quad (3)$$

In order to recover the value of the photon energy density in the jet frame ($u'_{\text{ph,BLR}}$) one needs to multiply the above result by the square of the bulk Lorentz factor, Γ^2 . A similar procedure can be followed in order to obtain the luminosity and photon energy density within the torus. In this case we assume that the accretion luminosity reprocessed by the torus is about 40%, so $L_{\text{torus}} = 0.4 L_{\text{disk}}$. As in the case of the BLR, we assume a scaling relation between the luminosity of the disk and the one of the torus: $R_{\text{torus}} = 2.5 \times 10^{18} L_{\text{disk},45}^{1/2}$ cm [74]. For B3 1307+433 we obtain $L_{\text{torus}} = 1.36 \times 10^{45}$ erg s $^{-1}$ and $R_{\text{torus}} = 4.60 \times 10^{18}$ cm, for GB6 J0114+1325 we obtain $L_{\text{torus}} = 1.46 \times 10^{45}$ erg s $^{-1}$ and $R_{\text{torus}} = 4.78 \times 10^{18}$ cm, for PKS 0048-09 we obtain $L_{\text{torus}} = 9.68 \times 10^{42}$ erg s $^{-1}$ and $R_{\text{torus}} = 3.89 \times 10^{17}$ cm.

For the purpose of the numerical modeling, the free parameters are the energy densities of photons from the BLR and the torus in the reference frame of the plasmoid. We compare them to the predicted energy densities as a function of the location of the emitting region r , the bulk Lorentz factor Γ , and $R_{\text{BLR}}, L_{\text{BLR}}, R_{\text{torus}}, L_{\text{torus}}$ as provided above. The energy distributions of the external fields are assumed to be a delta function for the BLR (we consider for simplicity that the whole BLR is dominated by the Ly α line), and a black body with temperature $T = 420$ K for the torus [75]. The energy densities as a function of r are computed following a modified version of Nalewajko et al. [76] approach, where the BLR is considered as a shell with an opening angle of $\pi/4$ along the jet direction. Here, we consider a BLR full shell with internal and external radii of $0.9 R_{\text{BLR}}$ and $1.1 R_{\text{BLR}}$ respectively (see [77], for details), as well as a torus reprocessing fraction of 0.4.

The modeling of the SEDs is provided in Fig. 7, the expected neutrino spectrum is shown in Fig. 8, and the detailed list of model parameters in Table 7. The modeling for TXS 0506+056 can be found

in [72]. For all sources, we start by performing a leptonic modeling with a fixed value of $\delta = 30$. The energy density of the BLR photon field in the reference frame of the emitting region (u'_{BLR}) is a free parameter of the model, as it depends on the location of the emitting region and the Lorentz factor; on the other hand, we assume that the emitting region is always within R_{torus} , which gives thus $u'_{\text{torus}} = 0.028$ erg cm $^{-3}$. Once the leptonic component is able to reproduce the data, we then add a hadronic contribution, maximized in order not to overshoot the constraints in the X-rays. In all cases, the modeling results are in line with the observed data, and the discrepancy between data and model at most 2σ at HE. This applies also in the case of B3 1307+433, which shows a spectral hardening at HE, that, however, cannot be fully reproduced by the Inverse Compton emission from a single-zone model such as the one adopted here.

We stress here that the solutions computed for all our sources are sample models. We show that a leptonic-hadronic modeling inspired by the ones developed for TXS 0506+056, and assuming as target photon field the radiation from the BLR and the torus, can reproduce the SED, and provide the estimated neutrino spectrum from these objects. We do not perform an extensive study of the parameter space, nor perform a minimization. In particular, the hadronic component here is not constrained by the data, and the underlying proton distribution is assumed for all models to be a power-law with index $\alpha_p = 2$, and high-energy exponential cut-off at the Lorentz factor $\gamma_{p,\text{max}} = 10^8$.

6. Discussion and conclusions

In this work we searched for blazar sources with similar observational properties to TXS 0506+056, with the goal of identifying potential similarities in their accretion mechanism and non-thermal processes at work in their jet emission.

We selected the sources from the 4LAC *Fermi*-LAT catalog of AGNs, based on their γ -ray luminosity, γ -ray photon index and synchrotron peak frequency. These selection criteria excluded a priori all sources without an established value of their redshift, which represent $\sim 63\%$ of the BL Lac population in the catalog. The initial sample we obtained consisted of 27 objects. However, the need for precise information on the spectral emission lines of the selected sources for the determination of their accretion rate brought us to only three blazars, in addition to TXS 0506+056, all classified as BL Lacs. Indeed, the great majority of the 27 objects in the initial sample lack a detailed spectral analysis in the literature, and almost half of them lacks any measurement of their optical/UV spectra. Therefore, we strongly support detailed spectroscopic measurements of the blazars which we had to rule out from the sample, as well as campaigns aimed at measuring the redshift of *Fermi*/LAT blazars. These measurements will be essential for the knowledge of the luminosity of the sources in the catalog and for a deeper investigation of the selected objects, which will allow us to enlarge the number of sources in the sample and to perform statistical studies. New spectroscopic measurements of blazars can have an important role also for blazar studies with the upcoming Cherenkov Telescope Array Observatory (CTAO; see e.g. [78]).

For each of the selected sources we provided a simple estimation of their accretion rate starting from the information on their optical emission lines. For two out of four sources in the selection (i. e. B3 1307+433, and GB6 J0114+1325) the values we found for the accretion rate lie above the dividing line set by Ghisellini et al. [18], which may point to a more efficient accretion process and be more consistent with FSRQs, while for one source, PKS 0048-09, values below the threshold are found, appearing more compatible with an inefficient accretion flow, suggestive of a BL Lac. The accretion rate range derived for all selected sources is based on the assumption of two typical mass values for AGNs and is consistent with typical accretion rate estimates in AGNs. However, for TXS 0506+056 the situation is more delicate, based also on the assumptions made, so a precise measurement of its mass would be needed for a better understanding of its nature.

Table 7

Parameters of the lepto-hadronic models. The quantities flagged with a star (*) are derived quantities, and not model parameters. The luminosity of the emitting region was calculated as $L = 2\pi R^2 c \Gamma^2 (u'_B + u'_e + u'_p)$, where u'_B , u'_e , and u'_p are the energy densities of the magnetic field, the electrons, and the protons, respectively.

Source	PKS 0048-09 low	PKS 0048-09 high	GB6 J0114+1325	B3 1307+433
z	0.635	0.635	0.685	0.693
δ	30	30	30	30
Γ	20	20	20	20
R' [10^{16} cm]	1.25	1.25	1.25	1.25
* τ_{var} [h]	6.3	6.3	6.5	6.5
B' [G]	1	1	1	1
* u'_B [erg cm $^{-3}$]	0.04	0.04	0.04	0.04
$\gamma'_{e,\text{min}}$	300	300	300	300
$\gamma'_{e,\text{break}}$	1.6×10^3	2.6×10^3	3.0×10^3	2.2×10^3
$\gamma'_{e,\text{max}}$	5×10^4	7×10^4	1.6×10^4	1.5×10^4
$\alpha_{e,1} = \alpha_{p,1}$	2.0	2.0	2.0	2.0
$\alpha_{e,2}$	3.35	4.1	3.0	3.5
K'_e [cm $^{-3}$]	1.6×10^3	4.5×10^3	8.0×10^2	8.0×10^2
* u'_e [erg cm $^{-3}$]	3.0×10^{-3}	9.5×10^{-3}	1.8×10^{-3}	1.5×10^{-3}
$\gamma'_{p,\text{min}}$	1	1	1	1
$\gamma'_{p,\text{max}}$ [10^8]	1	1	1	1
K'_p [cm $^{-3}$]	800	630	80	56
* u'_p [erg cm $^{-3}$]	21.4	16.9	2.1	1.5
u'_{BLR} [erg cm $^{-3}$]	7.0×10^{-2}	7.0×10^{-2}	0.12	0.20
u'_{torus} [erg cm $^{-3}$]	2.8×10^{-2}	2.8×10^{-2}	2.8×10^{-2}	2.8×10^{-2}
* $r[R_{\text{BLR}}]$	2.0	2.0	1.9	1.7
* u'_e/u'_B	0.077	0.24	0.045	0.039
* u'_p/u'_B	540	420	54	38
* L [10^{46} erg s $^{-1}$]	16.6	13.1	1.7	1.2

Public multiwavelength data from the selected sources were analyzed, searching for contemporaneous high and low emission activity. A flaring state could be identified only for PKS 0048-09, while for the other sources simultaneous periods of average activity were selected. The SED of the candidates in the selected periods was built with the available multiwavelength data and modeled in the same framework used for TXS 0506+056, assuming a lepto-hadronic emission. Under the hypothesis that the emitting region is located either within the BLR or beyond it but still within the torus, and thus assuming that the external photon fields from these structures contribute non-negligibly to the emitting region itself, the resulting SED modeling is compatible with a dominant contribution from the EC process.

For PKS 0048-09, the only source that shows a flaring behavior and for which we modeled two different flux states, a successful modeling of the high state is achieved by changing, with respect to the low state, only the energy distribution of primary electrons in the emitting region, without modifying the parameters of the jet, nor of the external photon field. This explains the higher SSC contribution in the SED of the flaring state of PKS 0048-09 compared to the other sources.

The hadronic component in the models maximizes the neutrino emission without having a high impact on the electromagnetic emission in most of the cases. This component emerges mainly in X-rays as the contribution of pion decay and Bethe–Heitler pair production, coming from photo-meson interactions, but the obtained SEDs can be fitted also with a purely leptonic model. For the source PKS 0048-09, the hadronic component is visible also at VHE, where it arises as the result of photo-meson interactions mostly. A detection in that band would therefore be crucial in constraining this component (see below for a more detailed discussion). Regarding the X-ray band, for B3 1307+433 the observations we took thanks to our *Swift* monitoring program play a relevant role in constraining the contribution of the hadronic component, thanks to their high photon statistics and the slope resulting from the analysis. Therefore, additional measurements in this band are essential for a more precise characterization of the X-ray emission of these sources and to rule out the possibility of a purely leptonic emission. In particular, additional data from *Swift*/*XRT* for the objects with few observations would provide a better characterization of the 0.3 – 10 keV band, while data from e. g. *NuSTAR* are essential to

characterize the higher energies, since no data in this band are available at the moment for the selected sources.

The models were computed assuming both the BLR and the dusty torus as target photon fields, the photon energy densities of which were free model parameters. The target photon field energy density in the reference frame of the emitting region depends on its position with respect to the accretion disk, the BLR, and the torus. It can thus be used to infer the position of the emitting region in the jet. The values used in the models constrain the emitting region to be just outside the BLR, at a few R_{BLR} , since the fit value (see Table 7) is lower than the one estimated thanks to our study on the emission lines, which assumes a region located inside the BLR. The value obtained from this estimation is: $u'_{\text{BLR}} = u_{\text{BLR}} \Gamma^2 = 23.8$ erg cm $^{-3}$, where u_{BLR} is given by Eq. (3) and Γ is the same as is used in the fit.

The SEDs and models obtained for the sources were compared with the sensitivities, for 50 h of observation, of the imaging air Cherenkov telescopes (IACT) H.E.S.S., MAGIC, VERITAS, and the upcoming Cherenkov Telescope Array Observatory (CTAO), in order to provide perspectives for VHE observations (see Fig. 7). Two of the selected sources (i.e. B3 1307+433 and GB6 J0114+1325) appear to be out of reach for IACTs in their average state. B3 1307+433, was observed by VERITAS with an exposure time of 9.4 h, obtaining a flux upper limit of 17.8×10^{-12} cm $^{-2}$ s $^{-1}$ TeV $^{-1}$ at 256 GeV [79]. This is in line with a potential nature as masquerading BL Lacs, for which a stronger absorption at VHE from the source environment is expected with respect to standard, bare, BL Lacs. Differently, the source PKS 0048-09 exhibit a more pronounced VHE emission, due to the hadronic component. It appears out of reach for the current generation of IACTs, but at the edges of CTAO sensitivity, being therefore detectable by CTAO with about 50 h of observations in both its low and high states. The same comparison is also made for the obtained neutrino spectra with the sensitivity of the IceCube Neutrino Observatory for 8 years of data-taking [70] and for the future IceCube-Gen2 for 10 years of data-taking [80]. For both we considered a declination of 0° or 30° (we chose the closest to the source declination). This comparison is reported in Fig. 8. Similarly to the VHE detection, the neutrino fluxes expected from B3 1307+433 and GB6 J0114+1325 appear not detectable by

the current IceCube Neutrino Observatory and the future IceCube-Gen2, while PKS 0048-09 shows the highest neutrino flux, placing at the edge of IceCube-Gen2 sensitivity and being therefore potentially detectable. Taking into account the ongoing effort in neutrino astronomy, this source could be a good target for future experiments, as e.g. HUNT [81], expected to have a volume of about 30 km³.

It is worth noting that this source is also the only one showing a sub-threshold value of the accretion rate, which may suggest the presence of a non-standard BLR in its environment, as discussed in Section 2.3. This, together with its detectability prospects at VHE, makes it an interesting target for future studies.

Although in this work we decided to concentrate on photo-meson interaction models, which are the most common for blazars, it is worth mentioning that also p-p models can well describe the neutrino emission from blazars. It was pointed out e.g. in [82–84], where the authors considered a general target with typical density and radius values, the BLR clouds, and cold protons in the jet respectively as target material. This kind of models require a lower proton power of the jet with respect to p- γ ones, allowing the production of lower-energy neutrinos. Therefore, even if dense target matter is usually not abundant in blazars environment, it may be interesting investigating also this kind of processes for these objects in future studies.

Finally, a comparison with the blazar PKS 0735+17 is worth mentioning, since this object was proposed as the counterpart of the neutrino event IceCube-211208A,¹⁰ which was coincident with flaring activity of the source in several wavebands, and was shown to have a SED very similar to the one of TXS 0506+056 in the work of (Sahakyan et al. [25], see Fig. 5 of the paper). After an inspection of the source parameters reported in the 4LAC-DR2 catalog, we found that the γ -ray luminosity and spectral index lie in the ranges we defined in Section 2. Regarding the synchrotron peak frequency ν_S , it was found to be quite close to the TXS 0506+056 value during the period of the flare ($\log \nu_S = 15.17$) and shortly after ($\log \nu_S = 14.13$; [25]). However, in the catalog this blazar is classified as a BL Lac of the LSP type and the reported value of ν_S is too low to include the source in the selection ($\log \nu_S = 13.43$). The value in the 4LAC-DR2 refers to an average emission state of the source. Therefore, the similarities observed in its flaring state are due to the variability of ν_S with the source activity and the SED in its average state results to be not as similar as suggested. A further investigation of this object is needed for a better understanding of its similarities and differences with TXS 0506+056. Indeed, while this study focuses on the averaged emission, where quasi-simultaneous data is more readily available, future research will compare the characteristics of the high state of TXS 0506+065 — during which the neutrino event was detected — with those of other gamma-ray AGNs. This comparison aims to shed light on the mechanisms potentially responsible for neutrino emission during their flaring episodes.

CRediT authorship contribution statement

I. Viale: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **G. Principe:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **C. Righi:** Supervision, Methodology, Conceptualization. **M. Cerruti:** Writing – review & editing, Writing – original draft, Software, Investigation. **F. Tavecchio:** Supervision, Methodology, Conceptualization. **E. Bernardini:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

All observational data used in this work are publicly available, modeling results can be made available upon request to the authors.

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