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Extra–galactic jets: a hard X–ray view

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Abstract. Extragalactic jets are the most powerful persistent sources of the universe. Those pointing at us are called blazars. Their relativistically boosted emission extends from radio frequencies to TeV energies. They are also suspected to be the sources of energetic neutrinos and high energies cosmic rays. The study of their overall spectrum indicates that most of the emission of powerful blazars is in hard X–rays or in soft γ–rays. In this band we can find the most powerful jets, visible also at high redshifts. It is found that the jet power is linked to the accretion luminosity, and exceeds it, especially if they produce energetic neutrinos, that require tre presence of ultrarelativistic protons.

Key words. neutrinos – radiation mechanisms: non-thermal – galaxies: active – BL Lacertae objects: general – gamma-rays: galaxies

1. Introduction

About 10% of Active Galactic Nuclei (AGN) have relativistic jets, producing radiation across the entire electromagnetic spectrum, that is beamed along the velocity direction. When the jets are pointing at us, the sources are called blazars. There two flavours of them: powerful jets do have broad emission lines with the same properties of radio–quiet sources, and are called Flat Spectrum Radio Quasars (FSRQs), while less powerful sources have very weak or absent emission lines, and are called BL Lacs. Estimates of black hole masses are available now for a large number of sources, allowing to estimate the accretion disk luminosity in Eddington units: $L_{\rm d}/L_{\rm Edd}$. Therefore we now know that FSRQs have disk emitting in the standard regime (optically thick and geometrically thin), while most BL Lacs are have radiatively inefficient disks (Narayan et al. 1997, Narayan et al. 2000). In this regime, the UV emission is strongly reduced (Mahadevan et al. 1997), and the disk radiation cannot photo–ionize the clouds responsible for the line emission (Ghisellini & Celotti 2001; Ghisellini et al. 2009). This implies that jets can be produced both when the accretion is radiatively efficient (and the disk is geometrically thin) and when instead the disk is radiatively inefficiently (and is geometrically thick).

2. The blazar sequence revisited

All blazars have a spectral energy distribution (SEDs) characterized by two broad emission humps: the first is produced by synchrotron, while the second, at higher energies is probably due the inverse Compton (IC) process.

Fig. 1–3 illustrate the SEDs of three representative blazars of different bolometric luminosity. Fig. 1 shows the SED of the powerful blazar PKS 2149–306, with z = 2.345. In this

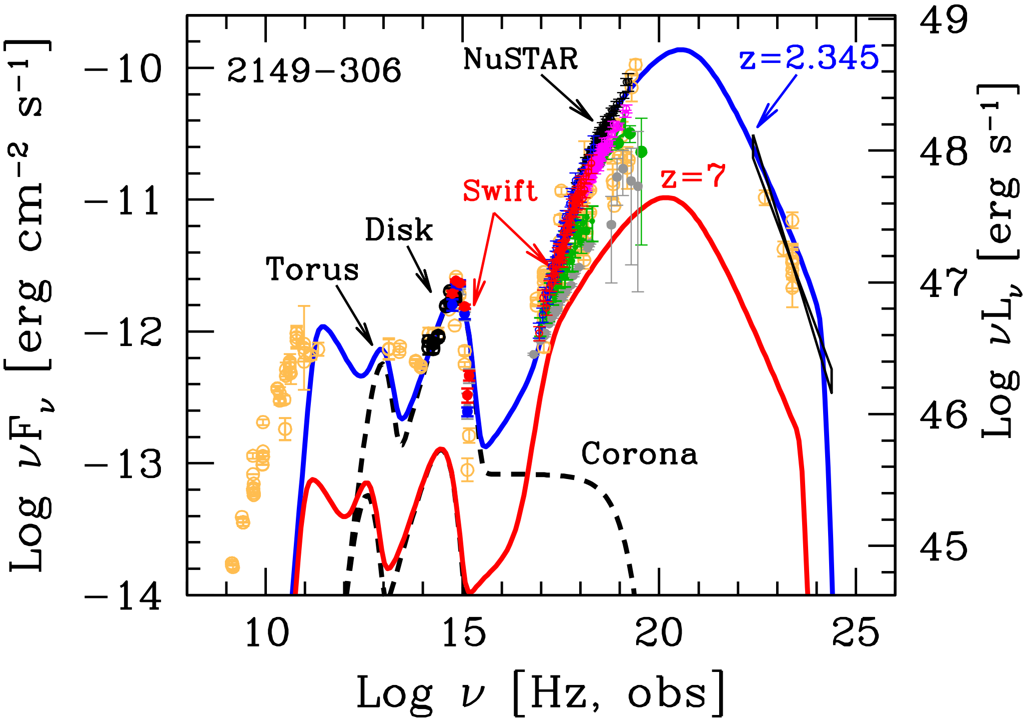

Fig. 1. The SED of the powerful FRSQ 2149–306. The accretion disk emission is clearly visible, together with the IR emission from the molecular torus. The SED is dominated by the high energy bump.

case the synchrotron peak is the far IR, while the largely dominant IC peak is around 1 MeV.

The spectrum beyond both peaks is steep ($F_\nu \propto \nu^{-\alpha}$, with $\alpha > 1$), and this allows the thermal emission of the accretion disk to be clearly visible, together with the infrared emission by the molecular torus assumed to surround the accretion disk, intercepting and re–emitting a large fraction ($\gtrsim 50\%$) of the accretion disk luminosity. The curves correspond to a one–zone model and the bottom one illustrates how the SED would appear if the redshift were $z = 7$. Even at these redshifts the source would be quite bright, especially in hard X–rays, where the flux would be above 10^{-12} erg cm^{-2} s^{-1}.

Fig. 2 shows TXS 0506+056 (with $z = 0.3365$, Paiano et al 2018), the source suspected to be the producer of the high energy neutrino detected by Icecube (Aartsen et al. 2018). Somewhat unexpectedly, this source is an intermediate blazar, with the synchrotron peak in the optical band. However, it has been detected in the TeV band. The high energy luminosity, in this kind of source, is usually of the same order of the synchrotron luminosity. Padovani et al. (2019) argued that this source is not a real BL Lac, but rather a FSRQ with hidden broad emission lines. To this aim, they show (Fig. 1 in their paper), that the synchrotron peak frequency of this source does not agree with the blazar sequence. However, this is not the only blazar showing, especially during flares, anomalous synchrotron peak frequencies with respect to their γ–ray luminosity, as shown in Fig. 4. With PKS 2155–304, 3C 66A and OJ 287 (all classical BL Lacs), TXS 0506+056 is in good company.

Fig. 3 shows the SED of an extreme BL Lac. In this context, "extreme" means that the synchrotron peaks in the X–ray band, and the TeV flux, once de–absorbed, is rising in νF_ν. However, the synchrotron and the high energy luminosity remain usually similar, as in inter-

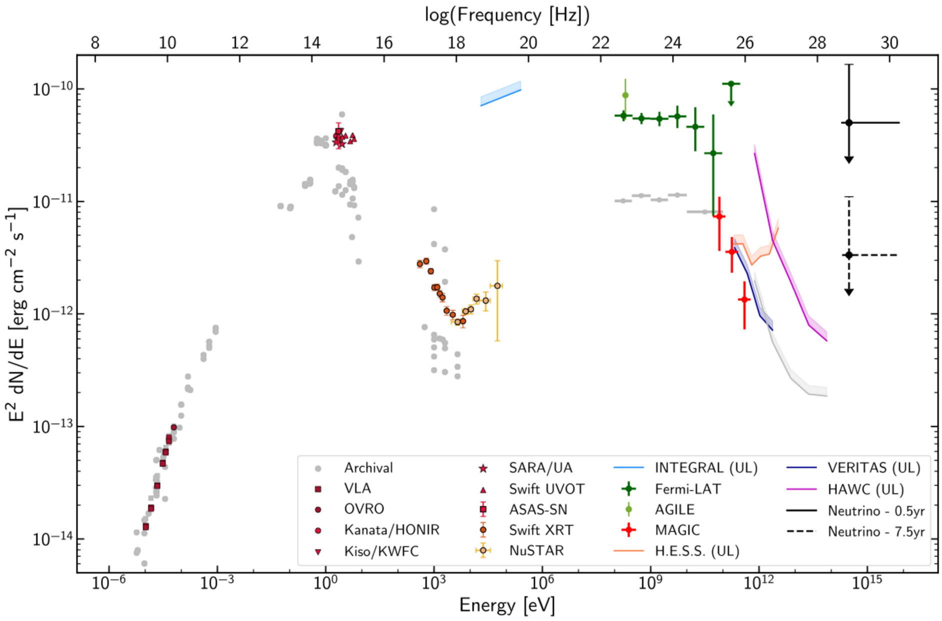

Fig. 2. The SED of TXS 0506+365, the blazars suspected to produce high energy neutrinos. Its SED is intermediate: the synchrotron peak is in the optical band, but the high energy peak is at relatively high energies. From Aartsen et al. (2018).

mediate blazars. These kind of sources are the best candidates to be detected by Cherenkov telescopes and arrays, to test the acceleration mechanisms, to probe the extragalactic infrared and optical background, and possibly new physics (violation of the Lorentz invariance and/or the existence of axions).

The three blazars illustrated in Fig. 1–3 exemplify a common trend among blazars, that we have called "blazar sequence". Increasing the observed (beamed) bolometric luminosity, the frequency of both peaks shift to smaller values, and the high energy hump becomes more dominant. The original blazar sequence (Fossati et al. 1998; Ghisellini et al. 1998) was based on flux limited complete samples in radio and in X–rays, but the γ–ray sources, detected by EGRET onboard the Compton Gamma Ray Observatory, were very few.

The blazar sequence was always a subject of intense debate. The main objection is that it reflects the outcome of selection effects, and therefore is not a real property of blazars. (see Giommi, Menna & Padovani, 1999; Perlman et al. 2001; Padovani et al. 2003; Caccianiga & Marcha 2004; Antón & Browne 2005; Giommi et al. 2005; Nieppola, Tornikoski & Valtaoja 2006; Raiteri & Capetti 2016; Giommi et al. 2012; Padovani, Giommi & Rau 2012; see also the reviews by Padovani 2007 and Ghisellini & Tavecchio 2008).

On the other hand, it has always been confirmed by surveys becoming deeper. We have recently taken advantage of the LAT detected blazars in the 3LAC sample (Ackermann et al. 2015) with measured redshift (about 800 sources) to revisit the blazar sequence. We collected their SED from the archives and divided the blazars according to their γ–ray luminosity (Ghisellini et al. 2017). The main results of this study was a general confirmation of the original sequence, with one important exception. If we study separately FSRQs and BL Lacs, we find that FSRQ have synchrotron and high

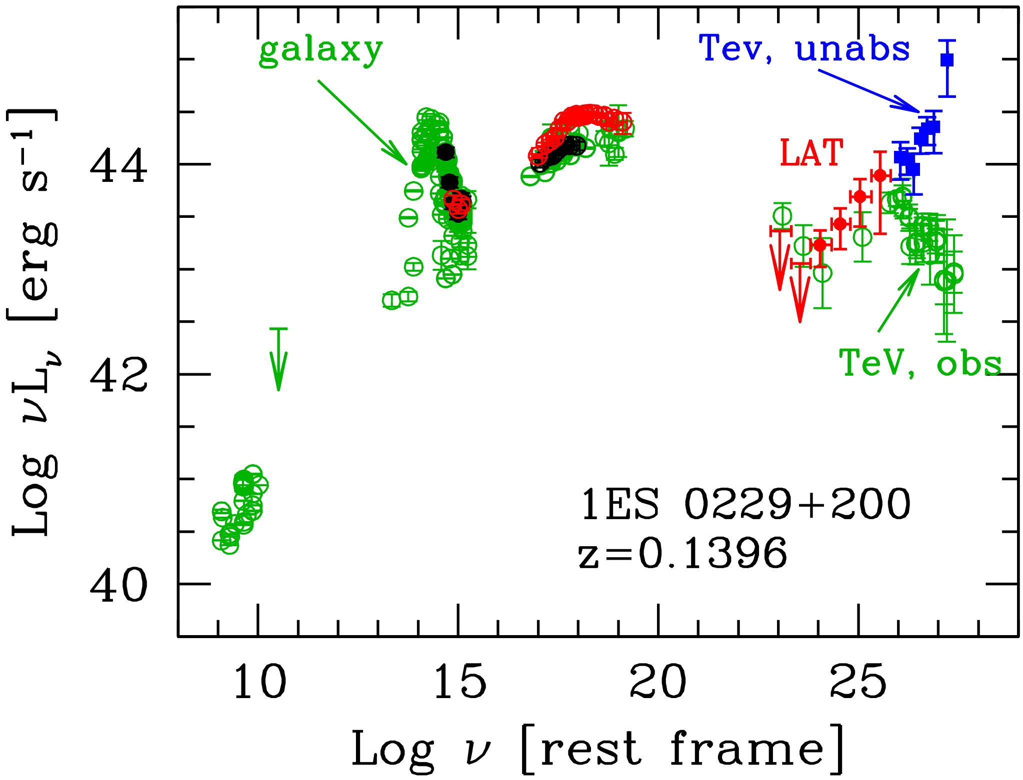

Fig. 3. The extreme BL Lac 1ES 0229+200. These blazars are the best candidates to be observed in the TeV band. Note that its TeV luminosity, once corrected for absorption, is rising in νL_ν.

energy peaks frequency that are approximately constant, while in BL Lacs they shift to smaller values when increasing the observed bolometric luminosity. On the other hand, the Compton dominance, namely the ratio of the high energy to the synchrotron luminosity is strongly dependent from total power, especially in FSRQs.

This agrees with the idea that the observed trend is controlled by the amount of radiative cooling: if in FSRQ the dissipation region is inside the broad line region (BLR) or the molecular torus, the corresponding radiation energy density dominates the cooling of the emitting particles. Both structures have a typical dimension that scales with the square root of the disk luminosity $R \propto L_{\rm d}^{1/2}$), making the radiation energy density $\propto L_{\rm d}/R^2$ constant.

BL Lacs, instead, have no broad lines nor obscuring tori (Chiaberge et al. 1999), and therefore their (internally produced) radiation energy density varies. Fig. 6 shows the random Lorentz fator $\gamma_{\rm peak}$ as a function of the comoving magnetic + radiation energy density: the inverse correlation is clear.

3. Jet power vs accretion disk luminosity

Rawlings, & Saunders (1991) were among the first to study the relation between the jet power and the disk luminosity, albeit in a rather indirect way. They found that the minimum energy contained in the radio lobe, divided by the jet lifetime, correlated with the luminosity of the narrow lines. This, per se, is not surprising, since the two quantities are both dependent on redshift. But the important thing was that this correlation indicates that the jet power is of the same order of the disk luminosity.

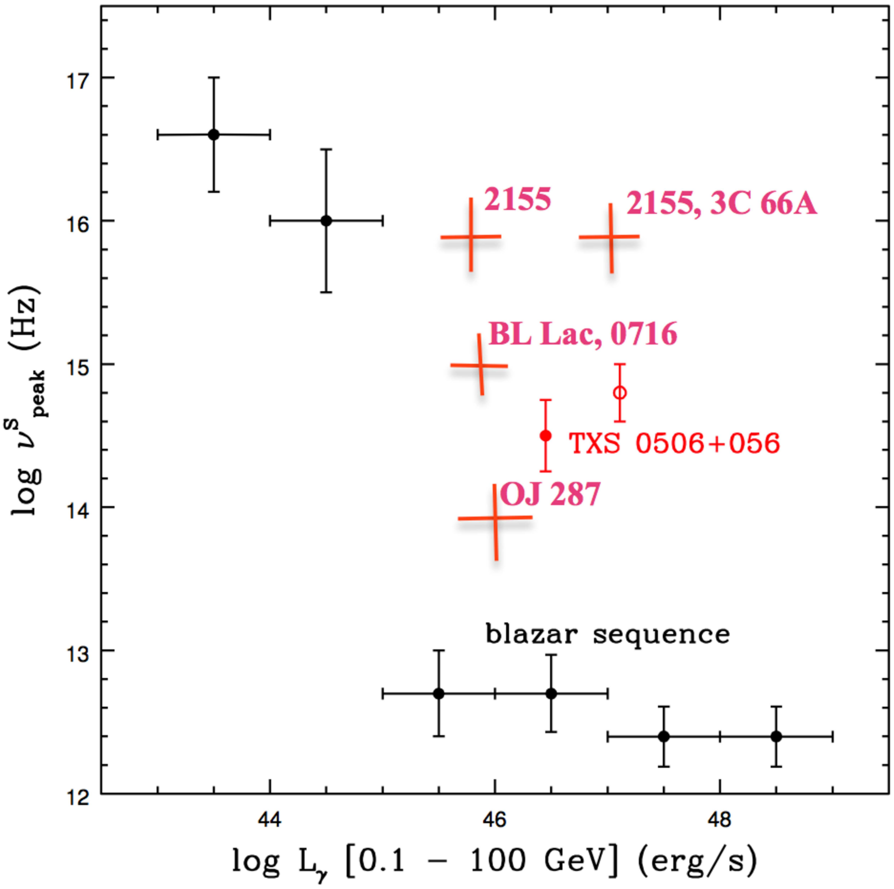

Fig. 4. The peak synchrotron frequency ν^{s}_{peak} as a function of the γ–ray luminosity L_γ. Black points are typical values of the blazars analyzed by Ghisellini et al. (2017). The source TXS 0506+056 appears an outlier, but consider that, especially during high states, other "classical" BL Lacs have similar values of ν^{s}_{peak} and L_γ. Adapted from Padovani et al. (2019).

Soon later, Celotti & Fabian (1993) devised another method to calculate the jet power, calculating the amount of emitting electrons and the bulk Lorentz factor required to explain the radio emission, at the VLBI scale, from blazars. When the first γ–ray data become available, it was realised that i) the γ–ray luminosity dominates the electromagnetic output, and ii) there is often a coordinated variability of the flux in different bands. The first property called for an efficient process for producing high energy radiation, and it was soon proposed that if the dissipating region were located within the BLR, the comoving energy density would be boosted by $\sim \Gamma^2$ (Γ is the bulk Lorentz factor) and thus would outshine the internally produced synchrotron radiation energy density. This enhances the inverse Compton process. The second property is the main motivation for the "one–zone" model, that greatly simplifies the modelling of the source, limiting the number of parameters (with respect to inhomogeneous models).

The jet power can be:

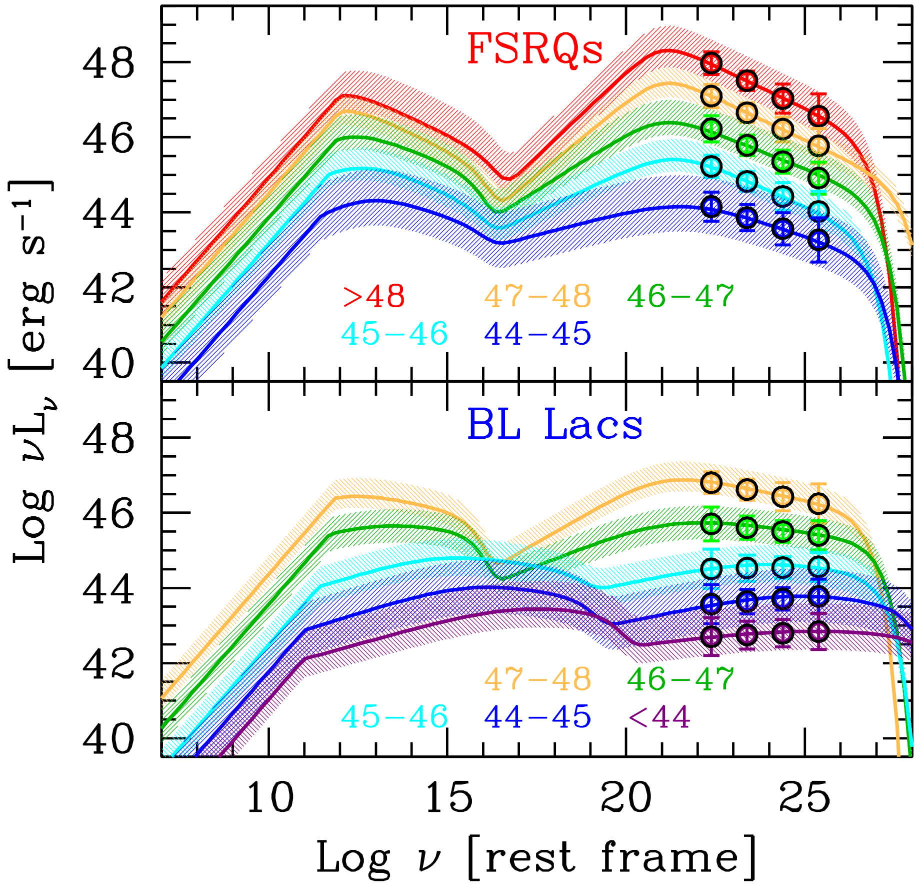

Fig. 5. The new blazar sequence. Note that for both FSRQs and BL Lacs the Compton dominance increases with the bolometric luminosity, while only for BL Lac the emission peaks shift to smaller frequencies as the luminosity increases. From Ghisellini et al. (2017).

1. *magnetic:* We know that the base of the jet is optically thin. Instead, the base of the jet of GRB is completely opaque. In the latter case, therefore, it is possible that the plasma is accelerated by its own pressure with a bulk Lorentz factor increasing linearly with the distance R from the black hole: $\Gamma \propto R$. In blazars, this is not possible. Therefore we *must* invoke a magnetic acceleration. And yet, the synchrotron luminosity is less than the inverse Compton one, requiring that the magnetic field in the dissipating region (at $\sim 10^3$ Schwarzschild radii) is under equipartition. This calls for a very fast magnetic acceleration.
2. *kinetic:* To find out the amount of this power component, we must estimate the number of particles in the jet, and thus we

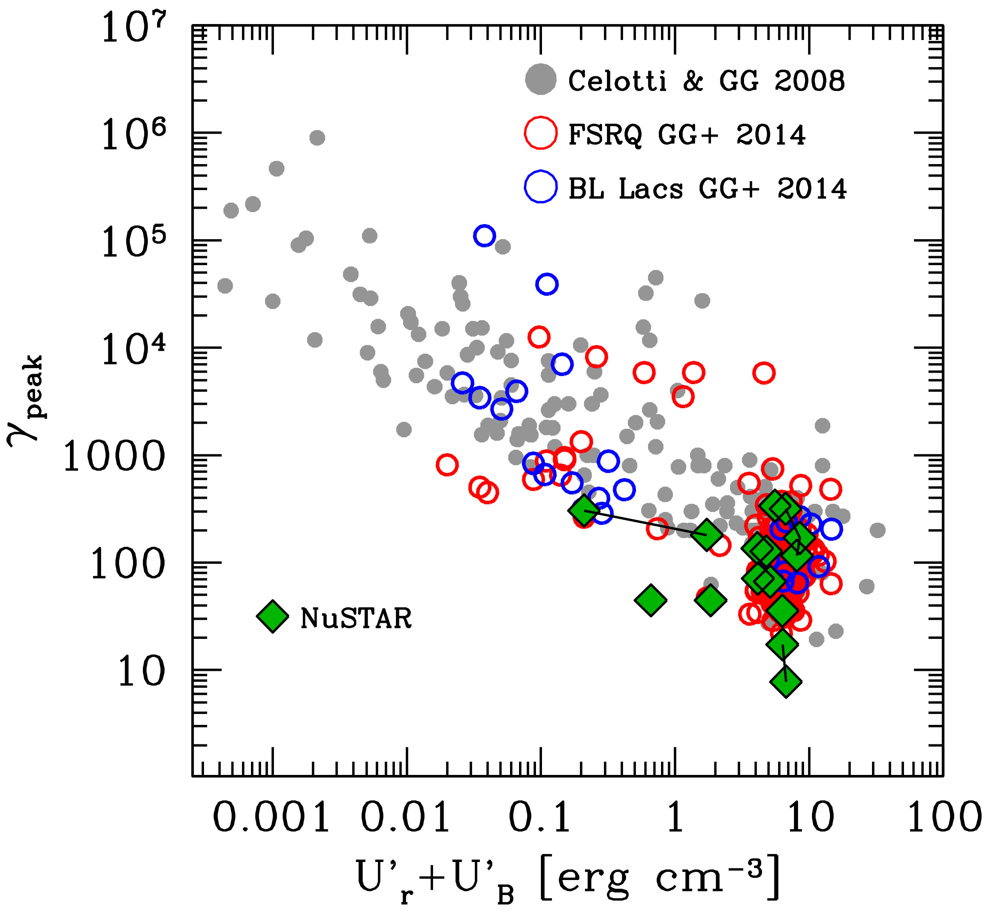

Fig. 6. The random Lorentz factor $\gamma_{\rm peak}$ of the electrons emitting at both the synchrotron and Inverse Compton peak as a function of the comoving magnetic radiation energy density. From Ghisellini et al. (2019).

must assume a radiative model. For a leptonic, one–zone model, this is the dominant form of jet power, if we assume that there is one cold proton per emitting electron. The jet *cannot* be pair dominated, for two reasons: i) without protons, there is not enough power to account for the radiation we see; ii) a pure jet, crossing the BLR zone at high speed, would suffer a strong Compton recoil, and would quickly decelerate.

3. *Radiative:* this form of jet power (let us call it $P_{\rm r}$) is almost model–independent, and therefore is the most reliable. It is simply $P_{\rm r} \sim L_{\rm obs}/\Gamma^2$ and Γ can be estimated independently of the applied model, by e.g. the apparent superluminal motion. $P_{\rm r}$ is a *lower limit* of the total jet power.

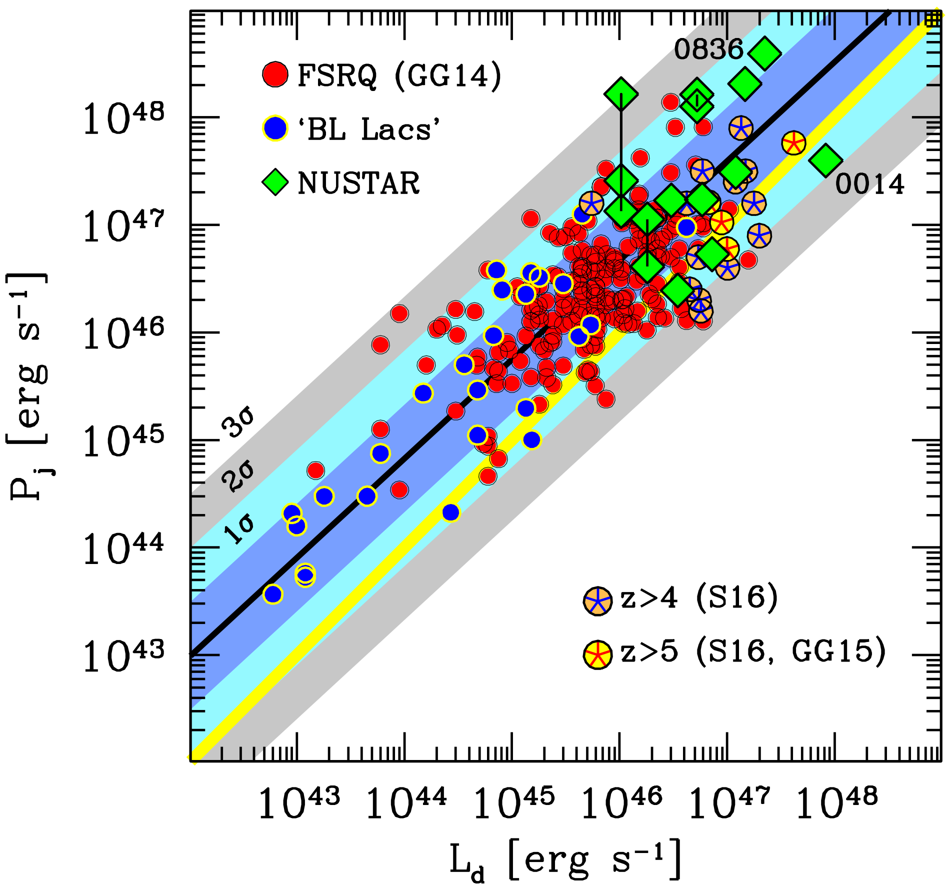

Fig. 7. The jet power as a function of the accretion luminosity. The soursed labelled "BL Lacs" in this figure, although consistent with the formal definition (EW<5Å), do have broad lines in their spectrum, and should be considered as the low luminosity tail of FSRQs. The yellow line is the equality line, the black line is the best fit. From Ghisellini et al. (2014; 2019).

Fig. 7 shows the jet power as a function of the disk luminosity for a large number of blazars. On average, the jet power is ∼10 times larger than the disk luminosity, assuming one cold proton per emitting electron. If the latter is $L_{\rm d} = \eta_{\rm accr}\dot{M}c^2$, with $\eta_{\rm accr} \sim 0.1$, as it is usually assumed, then $P_{\rm j} \sim \dot{M}c^2$. This is born out also by numerical simulations, showing that, on average, $P_{\rm j} \sim 1.5\dot{M}c^2$ (Tchekhovskoy et al. 2012). This strongly suggests that the jet power comes from the spin energy of the black hole (Blandford & Znajek 1977), and not directly from accretion (Cavaliere & D'Elia 2002, Ghisellini & Celotti 2002). Furthermore, we have now evidences that *jets are the result of the most powerful persistent engines of the universe.*

Will the $P_{\rm j} \sim \dot{M}c^2$ relation continue to be valid also when the accretion changes regime, from standard (Shakura–Sunyaev 1973 like) to radiatively inefficient (i.e. ADAF, Rees et al. 1982, Narayan & Yi 1994; or ADIOS, Blandford & Begelman 1999)?

4. Energy crisis?

As mentioned, there is the serious possibility that blazars are the producers of the high energy neutrinos detected by Icecube (Aartsen et al. 2018, see also the review of Gaisser 2018). The production of neutrinos is associated with the production of high energy γ–rays, and it is not clear what is the type of blazar contributing the most (Resconi et al. 2017; Righi et al. 2019).

If the association with blazars is confirmed, it implies that in their jets there are ultra–relativistic protons with energies ~20 times larger than the observed PeV neutrino. Their contribution to the total power is uncertain, being a factor of a few in the case of collision between protons and a boosted external photon field (peaking in the X–ray band, Tavecchio & Ghisellini 2015), and a few thousands if we require that hadrons are required to produce the entire SED (Zdziarski & Böttcher 2015).

If ultra-relativistic protons are indeed present in the jets of AGNs we face an energy crisis, since their power would exceed the disk luminosity by more than one order of magnitude.

One possible solution is that only a small fraction of the gravitational energy dissipated by the accreting $\dot{M}$ is transformed into heat, while the rest goes to power the jet (Jolley & Kuncic 2008; Jolley et al. 2009). The total accretion efficiency η is used to power the jet with an efficiency $\eta_{\rm j}$, and to heat the disk with an efficiency $\eta_{\rm accr}$:

$$P_{\rm j} = \eta_{\rm j}\dot{M}c^2; \quad L_{\rm d} = \eta_{\rm accr}\dot{M}c^2; \quad \eta = \eta_{\rm j} + \eta_{\rm accr} \quad (1)$$

This does not imply that the jet power comes directly from accretion. It may come from the black hole spin, whose rotational energy is extracted by a very large magnetic field, sustained by a large matter density in the vicinity of $R_{\rm ISCO}$, in turn possible because the accretion rate is much larger than what the disk luminosity would naively suggest if we use $\eta_{\rm accr} \sim 0.1$. This has an important consequence: if there is a jet, the disk efficiency can be smaller than what is foreseen for standard accretion models. To produce a given $L_{\rm d}$, $\dot{M}$ must therefore be larger, and this helps jetted sources to have black holes that grow faster (especially at large redshifts, Ghisellini et al. 2013; Sbarrato et al. 2015).

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