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Gamma-ray emission in radio galaxies, from MeV to TeV

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Abstract. Thanks to the *Fermi* γ-ray satellite and the current Imaging Atmospheric Cherenkov Telescopes, radio galaxies have arisen as a new class of high- and very-high energy emitters. The favourable orientation of their jets makes radio galaxies extremely relevant in addressing important issues such as: (i) revealing the jet structure complexity; (ii) localising the emitting region(s) of high- and very-high energy radiation; (iii) understanding the physical processes producing these photons. In this review the main results on the γ-ray emission studies of radio galaxies from the MeV to TeV regimes will be presented, and the impact of future Cherenkov Telescope Array observations will be discussed.

Keywords. radiation mechanisms: nonthermal, galaxies: active, galaxies: jets, galaxies: nuclei

1. Introduction

Radio galaxies (RG) are radio-loud Active Galactic Nuclei (AGN) characterised by powerful jets of relativistic plasma whose non-thermal radiation emits from radio frequencies up to TeV energies. RGs have been historically classified by Fanaroff & Riley (1974) on the basis of their radio morphology into FR I and FR II†. Within the Unified Model of AGN (Urry & Padovani 1995), FR Is are considered the parent population of BL Lacs (i.e. their misaligned counterpart) and FR IIs the parent population of Flat Spectrum Radio Quasars (FSRQ). The cause of the FRI/FRII dichotomy is still unknown: external agents, e.g. environment, host galaxy, merging history, etc. (Bicknell 1995) or intrinsic factors, e.g. accretion processes (Ghisellini & Celotti 2001), have been invoked as possible explanations. Jets of RGs are oriented at large inclination angles with respect to the l.o.s. ($\theta >10°$), making these sources unique laboratories where to contemporarily study jets and accretion processes and establish a connection between the two. However, the large jet inclination angle geometrically disfavours the detection of RGs above 100 MeV since their non-thermal radiation does not benefit from the strong Doppler amplification typical of blazars. Indeed, the degree of boosting depends on the relativistic Doppler factor δ=1/Γ(1-βcosθ), that relates the intrinsic and observed flux for a source moving at relativistic speed (Urry & Padovani 1995). The flux enhancement is strongly dependent on the viewing angle and decreases very rapidly for $\theta >$8-10°. This trend was confirmed by the detection of only three possible γ-ray counterparts of RGs by the EGRET telescope onboard the CGRO satellite, i.e. NGC 6251, Centaurus A and 3C 111 (Nolan *et al.* 1996,

† A source is considered a FR I if the separation between the points of the peak intensity in the two lobes is smaller than half of the largest size of the source (R<0.5). If R>0.5 the source is a FR II. This morphological criterium corresponds to a separation at a radio luminosity $P_{178\ MHz}=10^{25}$ W Hz^{-1} sr^{-1}. Sources with a radio luminosity below such a threshold are FR Is, above it are FR IIs.

Mukherjee *et al.* 2002, Sguera *et al.* 2005, Hartmann *et al.* 2008). A huge step forward in this field has been made thanks to the *Fermi* satellite, as predicted by several works suggesting these sources as possible targets detectable by the Large Area Telescope (LAT) instrument onboard *Fermi* (Stawarz *et al.* 2003, 2006, Ghisellini *et al.* 2005, Grandi & Palumbo 2007).

In the following, the main recent results on RGs obtained with the *Fermi*-LAT telescope in the MeV-GeV band (Sec. 2) and with the current Imaging Atmospheric Cherenkov Telescopes in the TeV regime (Sec. 3) will be presented. Within this context, the impact of the future Cherenkov Telescope Array (CTA) on the study of RGs at very-high energies will be also discussed.

2. The MeV-GeV band: Fermi-LAT results

The *Fermi* γ-ray space telescope (Atwood *et al.* 2009) was launched in 2008 June 11th and carries onboard two instruments: (i) the LAT, that operates in the nominal energy band 20 MeV-300 GeV† and (ii) the Gamma-ray Burst Monitor (GBM), that covers the energy range 8 keV-40 MeV. Results presented throughout the paper are based on LAT data.

Radio galaxies are γ-ray emitters

In only 15 months of survey the LAT could detect 11 radio objects, 7 FR Is and 4 FR IIs (e.g. 2 radio galaxies and 2 steep spectrum radio quasars‡), generally referred to as Misaligned AGN (MAGN¶; Abdo *et al.* 2010a), confirming that RGs are GeV emitters (Table 1). Most of the sources are faint ($F_{>0.1\ \rm GeV} \sim 10^{-8}$ ph cm^{-2} s^{-1}) and have steep power-law spectra ($\Gamma >2.4$), in agreement with the Unified Models of AGN in which radio galaxies are considered a de-boosted version of blazars (Fig. 1 *left panel*). The number of radio galaxies caught by the LAT has continuously increased, passing from 11 to 22 in 4 years of operations (3 LAC; Acero *et al.* 2015), with FR Is preferentially detected with respect to FR IIs (Table 1). The discrepancy in the FR I/FR II detection rate does not seem to be related to the larger distance of FR IIs, generally found at higher redshifts (Grandi & Torresi 2012). If a correlation between the radio core flux and the γ-ray flux (Ackermann *et al.* 2011, Ghirlanda *et al.* 2011, Lico *et al.* 2017) is assumed, implicitly implying that the emission in the two bands is mainly from the jet, several FR IIs are expected to be detected above the LAT sensitivity threshold (see also Kataoka *et al.* 2011). This result suggests that the predominance of FR Is in the GeV sky should be related to other causes, for example intrinsic differences in the jet structure, or in the vicinity of the black hole (see, e.g. de Gouveia Dal Pino et al. 2018, these Proceedings).

Localisation of the γ-ray emitting region

One challenging aspect of the high-energy study of MAGN, and of blazars in general, is the localisation of the γ-ray emitting region. Indeed, localising where high-energy photons are dissipated with respect to the black hole has a strong impact on the physical models invoked to explain the γ-ray radiation. The site of emission is not unique: it can occur at sub-pc scales, within the broad-line region (BLR), or outside it on pc

† With the new Pass8 data the LAT energy range extends up to 1 TeV (Atwood *et al.* 2013). For more information about Pass8 https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass8_usage.html

‡ Steep Spectrum Radio Quasars are usually considered as FR II broad line radio galaxies at high redshift.

¶ With the term Misaligned AGN we consider objects characterised by steep radio spectra ($\alpha >0.5$) and possibly showing symmetrical extension in the radio maps, i.e. radio galaxies and steep spectrum radio quasars.

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Table 1. 3LAC MAGN: (i) Source name; (ii) 3FGL name; (iii) right ascension; (iv) declination; (v) redshift; (vi) radio classification; (vii) detected TeV counterpart. 3C 120 has been added to the list since it is a confirmed γ-ray source, and also Tol1326-379 and PKS1718-379 recently associated with 3FGL sources.

Source	3FGL Name	RA (J2000)	Dec (J2000)	z	FR type	TeV source
3C 78	3FGLJ0308.6+0408	03 08 26.22	+04 06 39.3	0.02865	FR I	no
IC310	3FGLJ0316.6+4119	03 16 42.97	+41 19 29.61	0.019	FR I	yes
NGC1275	3FGLJ0319.8+4130	03 19 48.16	+41 30 42.1	0.0175	FR I	yes
ForA(lobes)	3FGLJ0322.5-3721	03 21 37.75	−37 12 49.1	0.00587	FR I	no
4C+39.12	3FGLJ0334.2+3915	03 34 18.41	+39 21 24.4	0.02059	FR I	no
Pictor A	3FGLJ0519.2-4542	05 19 49.72	−45 46 43.85	0.03506	FR II	no
PKS0625-35	3FGLJ0627.0-3529	06 27 06.72	−35 29 15.33	0.05494	FR I	yes
3C 189	3FGLJ0758.7+3747	07 58 28.1	+37 47 11.8	0.04284	FR I	no
3C 221	3FGLJ0934.1+3933	09 35 06.63	+39 42 06.7	–	FR II/SSRQ	no
3C 264	3FGLJ1145.1+1935	11 45 05.0	+19 36 22.74	0.02172	FR I	yes
M87	3FGLJ1230.9+1224	2 30 49.42	+12 23 28.04	0.00428	FR I	yes
CenA(core)	3FGLJ1325.4-4301	13 25 27.61	−43 01 08.8	0.0018	FR I	yes
3C 303	3FGLJ1442.6+5156	14 43 02.76	+52 01 37.29	0.14119	FR II	no
NGC6251	3FGLJ1630.6+8232	16 32 31.96	+82 32 16.39	0.02	FR I	no
3C 111	3FGLJ0418.5+3813c	04 18 21.27	+38 01 35.8	0.0485	FR II	no
CenB	3FGLJ1346.6-6027	13 46 49.04	−60 24 29.35	0.01292	FR I	no
TXS0348+013	3FGLJ0351.1+0128	03 50 57.36	+01 31 04.91	1.12	FR II/SSRQ	no
3C 207	3FGLJ0840.8+1315	08 40 47.58	+13 12 23.56	0.681	FR II/SSRQ	no
PKS1203+04	3FGLJ1205.4+0412	12 06 19.92	+04 06 12.04	0.536	FR II/SSRQ	no
3C 275.1	3FGLJ1244.1+1615	12 43 57.64	+16 22 53.39	–	FR II/SSRQ	no
3C 380	3FGLJ1829.6+4844	18 29 31.78	+48 44 46.16	0.695	FR II/SSRQ	no
3C 120	–	04 33 11.1	+05 21 16	0.033	FR I	no
Tol1326-379	3FGL1330.0-3818	13 29 19.2	−38 14 18	0.028	FR 0	no
PKS1718-649	3FGLJ1728.0-6446	17 23 41.0	−65 00 37	0.014	CSO	no

scales, as attested by several studies performed on blazars (Abdo *et al.* 2010b, Jorstad *et al.* 2010, Agudo *et al.* 2011a, 2011b). MAGN are particularly suitable for this kind of study since they offer the opportunity to observe γ-ray emission processes from sub-pc up to kpc scales: different emission sites imply different seed photons involved in the Inverse Compton process producing the GeV emission‖ (Tavecchio *et al.* 2011). In order to establish where the high-energy radiation is emitted, a multi-wavelength (MW) approach is necessary, as demonstrated by the successful results obtained for the broad-line radio galaxies 3C 111 and 3C 120 ††: in these two sources the radio-to-γ-ray study allowed to establish a clear link between intense γ-ray flares and the expulsion of bright superluminal knots in the radio core. In 3C 111, a MW outburst occurred in late 2008 (Fig. 1 *right panel*) was attributed to the ejection of a new radio blob (Grandi *et al.* 2012): the emitting region was compact ($\leqslant$0.1 pc) and the event was localised in the radio core at $\sim$0.3 pc from the black hole. A similar result was obtained by Tanaka *et al.* (2015) from a six-year MW monitoring of 3C 120. Also in this case the γ-ray flare was related to the ejection of a knot from the radio core at sub-pc distance from the black hole. This finding was further confirmed by Casadio *et al.* (2015) who could better constrain the site of the emitting region within $\sim$0.13 pc by exploiting mm-VLBI data. In the examples above the emitting region is located within the BLR, however, in other cases like M87 different dissipation zones have been found, depending on the event producing the outburst‡‡ (Aharonian *et al.* 2006, Harris *et al.* 2006, Acciari *et al.* 2009,

‖ In the standard leptonic scenario.

†† 3C 111 is a FR II, while 3C 120 although morphologically classified as FR I, is characterised by a powerful accretion disk. Interestingly, these are the only AGN for which a disk/jet connection has been established (Marscher *et al.* 2002, Chatterjee *et al.* 2011).

‡‡ In M87 a long-term MW campaign and very-high energy data have allowed to identify different emitting regions: the TeV flare occurred in 2005 was associated with an X-ray burst of

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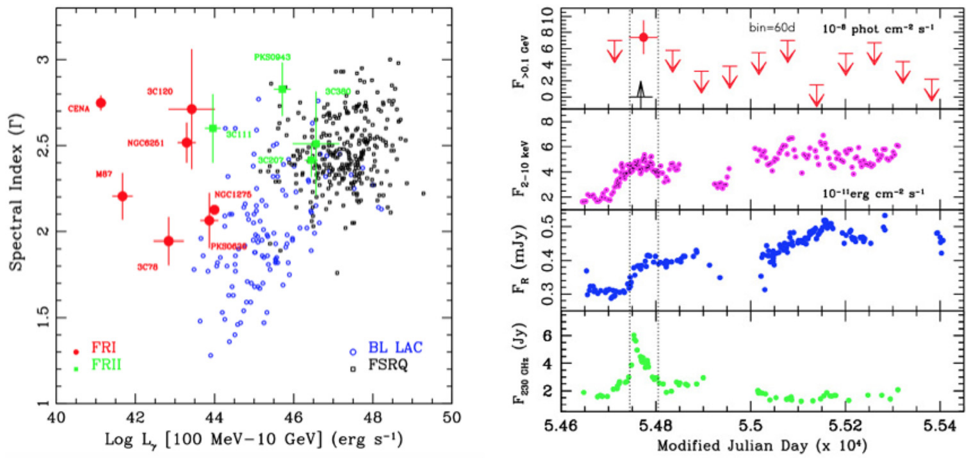

Figure 1. *Left panel:* Power-law photon index (Γ) plotted as a function of the 100 MeV-10 GeV γ-ray luminosity for: BL Lacs (open blue circles), FSRQ (open black squares), FR I (red circles), FR II (green squares). Blazars and MAGN (radio galaxies + SSRQ) occupy different regions of the plot. The two green squares falling in the FSRQ region are the two more distant sources of the sample, i.e. the two SSRQ 3C 207 and 3C 380. *Right panel:* mm (230 GHz; *green*), optical (R; *blue*), X-ray (2.4-10 keV; *magenta*) and γ-ray (0.1-100 GeV; *red*) light curves of 3C 111. mm-to-X-ray data are from Chatterjee *et al.* (2011), γ-ray data are from Grandi *et al.* (2012). The *black dotted lines* limit the flare event in late 2008 (October 4-December 4). The *black arrow* marks the time of ejection of the radio knot. *Red downward arrows* are γ-ray 2σ upper limits.

Abramowski *et al.* 2012). Although the potentiality of such studies is great, MAGN having dedicated long-term MW campaigns are a few. Multi-frequency monitoring is a difficult task that requires a huge effort to collect (quasi-)simultaneous data necessary to find connections among different wavebands. However, it would be very important to have ongoing MW campaigns on MAGN when the CTA observatory will be operative. This would represent a great step forward in the comprehension of the jet structure and evolution.

Extended γ-ray emission

Extended radio lobes represent another possible site of production of high-energy photons (Cheung 2007, Hardcastle *et al.* 2009) as confirmed by the LAT detection of the lobes in the FR I radio galaxy Centaurus A (Abdo *et al.* 2010c). The detection and imaging of extended γ-ray emission is challenging given (i) the PSF of the LAT (the 68% containment PSF is $\sim$0.8 deg at 1 GeV) and (ii) because the emission is isotropic and not boosted by relativistic effects. Indeed, in Centaurus A it was possible to separate the contribution of the two lobes from the core in 10 months of data thanks to the proximity of the source (z=0.001825) and to the total angular extent of its lobes ($\sim$10 deg). The flux above 100 MeV of the two lobes accounts for more than half of the total γ-ray flux of the source and the emission is likely produced through Inverse Compton (IC) scattering of the Cosmic Microwave Background Radiation (CMB). Very recently, γ-ray extended emission was also found in the FR I Fornax A (Ackermann *et al.* 2016) in 6.1 years of data. The source is very nearby (z=0.005871) and the radio lobes

the knot HST-1, at 0.85″ from the nucleus. In 2008, the coincidence of another TeV flare with radio flares confined the VHE photon production region within 10 Schwarzschild radii. Finally, the 2010 TeV flare was not accompanied by an enhancement of the radio flux but by an increase in the *Chandra* X-ray flux 3 days after the flare, making hard to unambiguously interpret the data.

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span $\sim 50'$, but differently from Cen A, the core flux accounts for less than 14% of the total γ-ray flux. However, an IC/CMB-EBL model (Georganopoulos *et al.* 2008, Domínguez *et al.* 2011) alone is not sufficient to reproduce the extended emission because it underestimates the high-energy fluxes. A second component, in addition to the leptonic one, is required and this could be of hadronic origin (McKinley *et al.* 2015). Finally, the *Fermi*-LAT detection of a young Compact Symmetric Object (CSO), i.e. PKS 1718-649 (Migliori *et al.* 2016) further supports the non-thermal γ-ray production in the lobes (for a detailed discussion see Migliori 2018, these Proceedings).

FR I Spectral Energy Distributions

Observations of FR Is at high- (HE) and very-high (VHE) energies† have questioned the pure one-zone SSC model, generally applied to reproduce their spectral energy distributions (SED), because it implies bulk velocities of the jet much lower than BL Lacs ($\Gamma \leqslant 3$). This is at odd with the Unified Scenario in which FR Is are the misaligned counterpart of BL Lacs. The problem is overcome if stratified jets, consisting of different regions moving at different velocities and mutually interacting, are assumed (Georganopoulos *et al.* 2003, Ghisellini *et al.* 2005, Böttcher *et al.* 2010): these models were successfully applied to the SED of M87 (Abdo *et al.* 2009a), NGC 6251 (migliori *et al.* 2011) and NGC 1275 (Abdo *et al.* 2009b), suggesting that in FR Is the presence of slower components could play an important role in amplifying the GeV emission. Interestingly, a limb-brightened jet structure has been observed in M87 (Kovalev *et al.* 2007) and recently in NGC 1275 (Giovannini *et al.* 2018 and Giovannini 2018, these Proceedings). In FR IIs the external layers could be less prominent or even absent and/or the deceleration processes less efficient, explaining their rarity in the GeV sky. Other possible sources of γ-ray photons could be magnetic reconnection events along the jets or in the vicinity of the black hole (Giannios *et al.* 2010, Khiali *et al.* 2015). Hadronic models based on proton-photon interactions have been also developed to provide connections among AGN, ultra-high-energy cosmic rays (UHECR) and neutrinos (Böttcher 2012, Becker & Biermann 2009, Khiali & de Gouveia Dal Pino 2016, Ramirez-Rodriguez et al. 2018, these Proceedings).

Temporal variability

Studying γ-ray variability is a powerful tool to further explore the jet structure issue in FR Is and FR IIs. The two classes show a different temporal behaviour: FR Is are detected, on average, for most of the time by the LAT and their light curves do not show variability structures, as suggested by the 3FGL variability index‡ $TS_{var} < 72.4$ (Grandi *et al.* 2013). On the contrary, FR IIs are observed only when intense and rapid flares occur (Fig. 1 *right panel*). Within this picture an outstanding exception is NGC 1275 which shows a blazar-like behavior and a rapid variability on timescales of days to weeks (Tanada *et al.* 2018).

The FR 0 radio galaxy Tol1326-379

The increased exposure time of the LAT survey combined with recent large-area surveys such as SDSS/NVSS/FIRST (Best & Heckman 2012) allowed to explore for the first time the GeV emission of RGs at low radio fluxes (∼mJy). This is the realm of FR 0 sources (Baldi *et al.* 2015), i.e. compact radio galaxies (radio size $\leqslant 5$ kpc) that represent the bulk of the RL AGN population in the local Universe (Baldi *et al.* 2018). Grandi *et al.* (2016)

† HE: >100 MeV; VHE: >100 GeV (see e.g. Aharonian 2012).

‡ The variability index is an indicator of the variability of a source on timescales of months. For the 3FGL catalog, an index >72.4 indicates that the source is variable at a 99% confidence level.

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proposed the association of a 3LAC source with the FR 0 Tol1326-379, offering the opportunity to investigate for the first time the behavior of these objects in the high-energy domain. FR 0s are similar to FR Is in the optical and X-ray properties, i.e. they are classified as low-excitation galaxies and their X-ray radiation is of non-thermal origin, likely produced by the jet (Torresi *et al.* 2018). In γ-rays, the flux of Tol1326-379 is similar to FR Is, $F_{(>1\ GeV)} = (3.1 \pm 0.8) \times 10^{-10}$ ph cm^{-2} s^{-1} but the spectrum is steeper, Γ=2.78±0.14. The SED of Tol1326-379 resembles that of Cen A, known to lie close to the plane of the sky, $\theta \sim 50 - 80°$. Therefore, also for the compact FR 0 source the orientation angle could be large and the process responsible for the γ-ray emission is likely the same as extended FR Is.

3. Radio galaxies in the TeV regime

Up to now, only a few radio galaxies have a very-high energy counterpart (Table 1): all of them are nearby (z<0.06) FR Is. Despite their limited number, observations of radio galaxies in the TeV band have already produced intriguing results. For example, (i) the synergy between VHE data and MW observations have allowed to localise the emitting regions in M87 (Sec. 2); (ii) the fast (ΔT∼4.8 minutes) TeV variability, recently caught by MAGIC in IC 310 (Aleksić *et al.* 2014), has questioned the classical shock-in-jet scenario (Blandford *et al.* 1979) invoking sub-horizon scale structures as a possible explanation for the extreme temporal behavior (Glawion 2018, these Proceedings); (iii) the extrapolation of *Fermi*-LAT data to higher energies has evidenced that a second hard component, whose nature is still debated, is necessary to account for the H.E.S.S. flux (Sahakian *et al.* 2013). It would be important to observe such a structure in other radio galaxies in order to understand if it is (or not) a common characteristic of MAGN. A major problem at the moment, is the difficulty in extrapolating the model from the GeV to the TeV band since data are often not simultaneous. Hopefully, this issue will be overcome with CTA that working as an observatory in synergy with other facilities, will provide simultaneous data in a very wide energy band from a few MeV up to hundreds TeV. Thanks to the improvement in sensitivity by a factor of 5x to 20x, depending on the energy range, with respect to the current Cherenkov telescopes, CTA will give a significant contribution in characterising MAGN at very-high energies (Angioni *et al.* 2017). Fig. 2 is a diagnostic plot showing the detectability of a source by CTA (northern and southern arrays) given a LAT spectral slope and a flux in the 1-100 GeV band: sources with $\Gamma_{\rm LAT} \leqslant$2.1 can be easily revealed for fluxes down to 10^{-10}ph cm^{-2} s^{-1}. As the slope steepens, larger fluxes are required to overcome the sensitivity threshold of the array. Incidentally, we note that this plot predicted the possible detection of PKS 0625-35 and 3C 264, later revealed by H.E.S.S. and VERITAS, respectively (Dyrda *et al.* 2015, H.E.S.S. Collaboration 2018, Mukherjee 2018).

4. Summary and conclusions

In the last decade our view of RGs above 100 MeV has greatly changed. Indeed, the *Fermi* satellite confirmed RGs as a class of γ-ray emitters, in spite of the unfavourable inclination angle of their jets. Although they are a small number with respect to the blazars detected by *Fermi* (<2% in the 3 LAC), studying RGs at high- and very-high energies is of great importance to understand the jet phenomenon and to reveal the jet structure complexity. In particular, the observation of RGs in the GeV band has evidenced that: (i) γ-ray photons can be produced in different sites and at different scales along the jet and in the radio lobes; (ii) a one-zone SSC model used to reproduce the SED of FR Is is oversimplified: structured jets, magnetic reconnection events or hadronic processes have

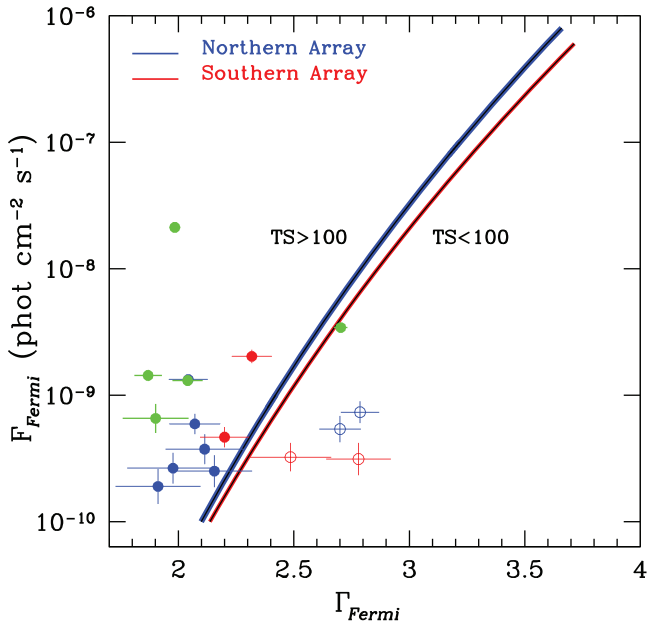

Figure 2. Diagnostic plot for MAGN with known *Fermi*-LAT flux and spectral slope reproduced from Angioni *et al.* (2017). The *blue* and *red lines* define the region where a source can be detected by CTA North and South, respectively, assuming a threshold TS=100. *Green filled circles* are radio galaxies already detected by current IACT telescopes (before the detection of PKS 0625-35 and 3C 264). *Blue filled circles* are TS>100 detections with the northern array and *red filled circles* with the southern array. *Empty circles* represent TS<100 detections.

been invoked to reconcile the data with the Unified Models; (iii) the different detection rate and temporal variability of FR Is and FR IIs suggest possible intrinsic jet differences between these two classes.

RGs in the TeV band are almost unexplored, however the few detections obtained so far with the current IACTs already produced promising results, such as the sub-horizon scale variability in IC 310 or the second hard component found in Cen A. CTA will have a strong impact on our comprehension of RGs as a class by detecting additional sources and better characterising those already known to emit TeV γ-ray photons. This will be very important to shed light on the mechanism producing the VHE radiation, e.g. leptonic or hadronic processes or both. Indeed, RGs are considered good candidates as extragalactic cosmic-ray accelerators, e.g. the relativistic jets and the radio lobes offer an ideal environment where particles can be accelerated, and thus they could be sources of high-energy neutrinos (Fraija *et al.* 2016, Hooper 2016, Murase 2018, Matthews *et al.* 2018).

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