Gamma-Rays from Non-Blazar AGN

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Abstract. Non-blazar Active Galactic Nuclei (AGN) have emerged as a new γ-ray emitting source class on the extragalactic sky and started to deepen our understanding of the physical processes and the nature of AGN in general. The detection of Narrow Line Seyfert 1 galaxies in the Fermi-LAT energy regime, for example, offers important information for our understanding of jet formation and radio-loudness. Radio galaxies, on the other hand, have become particularly interesting at high (HE) and very high (VHE) gamma-ray energies. With their jets not directly pointing towards us (i.e. "misaligned"), they offer a unique tool to probe into the nature of the fundamental (and often "hidden") physical processes in AGN. This review highlights and discusses some of the observational and theoretical progress achieved in the gamma-ray regime during recent years, including the evidence for unexpected spectral hardening in Centaurus A and extreme short-term variability as seen in IC 310 and M87.

INTRODUCTION

Within the last couple of years, the extragalactic sky has become populated by gamma-ray emitting sources. The Fermi-LAT Third AGN catalog (3LAC) now list about 1600 HE (high energy, > 100 MeV) sources [1], while at VHE (very high energy, > 100 GeV) energies the detection of about 70 AGN is currently summarised in the TeVcat catalog1. Most of these sources are of the blazar type, i.e. radio-loud AGN in which the jet is thought to be inclined at small viewing angles i to the line of sight. This goes along with substantial Doppler-boosting of their intrinsic jet emission, \( S(\nu) = D^2 S'(\nu') \) where \( D = 1/[\gamma_b(1 - \beta_b \cos i)] \) is the Doppler factor, \( \gamma_b \), the jet bulk Lorentz factor and \( \alpha \geq 2 \), which favours their detection on the sky by current gamma-ray instruments.

Non-blazar AGN, such as Radio Galaxies or Narrow Line Seyfert 1 galaxies, are much less occurrent, but have in the meantime solidly emerged as new gamma-ray emitting source classes as well (see below): Radio Galaxies (RG) have been conventionally classified as radio-loud (R>10), lower-luminous (\( M_v > -23 \)) AGN, hosted by elliptical galaxies and often revealing broad or narrow emission lines in their spectra (shortened BLRG and NLRG). Morphologically, radio galaxies have also been categorised since long into Fanaroff-Riley I and II sources (FR I, FR II) [2], the former (FR I) class comprising lower luminosity (< 2 × 10^{26} W/Hz at 178 MHz), edge-darkened sources and the latter one (FR II) high luminous (> 2 × 10^{26} W/Hz at 178 MHz), edge-brightened sources where the radio lobes are dominated by bright hot spots. Various considerations suggest that the central engine in FR II might be accreting in a "standard" (geometrically thin, optical thick) mode, while FR I sources are probably supported by a radiatively inefficient accretion flow (RIAF).

Narrow Line Seyfert 1 (NLSy1) galaxies [3], on the other hand, are optically lower luminosity (\( M_v > -23 \)) AGN which are typically found in spiral/disk galaxies, spectroscopically revealing strong emission lines, in particular narrow (FWHM < 2000 km/s) optical Balmer (H\beta) lines from the broad line regime (BLR) and strong Fe II emission (bump). At X-ray energies, NLSy1 are found to exhibit significant variability, a steep intrinsic spectrum and a relatively high luminosity. In view of their smaller black holes masses (10^6-8 \( M_\odot \)), as estimated from reverberation techniques, this would seem to imply accretion rates close to the Eddington one. NLSy 1 are mostly radio-quiet

1http://tevcat.uchicago.edu
(R < 10), with only a small fraction (< 10%) being radio-loud.

CURRENT STATUS AT GAMMA-RAY ENERGIES

At HE gamma-rays, Fermi-LAT has reported the detection of 1591 (1444 in the clean sample) AGN (with TS values > 25) at |b| > 10° in its 3 LAC catalog (published in 2015) based on 48 months of data (see Fig. 1), out of which 467 have been classified as Flat Spectrum Radio Quasars (FSRQs), 632 as BL Lacs, 460 as blazar candidates of uncertain type and 32 as non-blazar AGN (then including 5 NLSy1). In terms of numbers, non-blazar AGN thus make out only a small fraction (≤ 2%) of all extragalactic gamma-ray sources. Despite this, they have started to strongly impact on the field by offering unique insights into the physics and astrophysics of accreting supermassive black hole systems.

![Figure 1](image-url)

**NLSy 1**

While by now the detection of nine NLSy1\(^2\) has been reported at HE gamma-rays, none of them has yet been seen at VHE energies. In the Fermi-LAT energy range, these NLSy1 sources appear relatively bright given their known redshifts (up to \(z ≈ 0.58\)), implying apparent isotropic luminosities of \(L_{\text{GeV}} \sim 10^{44–48}\) erg/s [4]. Current models suggest, though, that the non-thermal emission is non-isotropic and arises in a relativistic jet. There is in fact increasing evidence for the presence of relativistic outflows in some of these radio-loud NLSy1, such as a one-sided core-jet radio structure on pc-scales, superluminal (\(\beta_{\text{app}} \sim 10\)) motion of components (SBS 0846+513, \(z=0.583\)) and intense “blazar-like” variability (optical intraday, HE flaring) suggestive of beaming, e.g. [5].

The spectral energy distributions (SED) of the detected NLSy1 appears to be double-humped shaped, suggestive of a synchrotron-inverse Compton origin, where the HE gamma-rays probably arise due to external Compton scattering of seed photons from the BLR and/or from a dust-torus. The non-detection at VHE energies may then be due to an intrinsic limit or related to the BLR or EBL (Extragalactic Background Light) absorption of their TeV emission. The "unusual" presence of jets in an AGN class believed to be hosted by spiral galaxies provides important information for our common understanding of jet launching in astrophysical sources, e.g., with respect to a putative black hole mass threshold, favourable accretion states and black hole spin (and merger history) requirements and unification scenarios [6, 7].

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\(^2\)1H 0323+342, SBS 0846+513, PMN J0948+0022, PKS 1502+036, PKS 2004-447, FBQS J1644+2619, B3 1441+476, NVSS J124634+023808, 4C +04.42
Radio Galaxies

Out of the tenish radio galaxies detected at HE gamma-rays by Fermi-LAT, cf. also Ref. [8, 9], five have so far been seen at TeV energies (see Fig. 2). M87 \((d \sim 16 \text{ Mpc})\) has been the first detected in VHE gamma-rays, while PKS 0625-35 \((z = 0.055)\) has been the latest addition. At \(d \sim 4 \text{ Mpc}\) Centaurus A (Cen A) is the nearest one, while PKS 0625-35 at \(d \sim 200 \text{ Mpc}\) is farthest away.

The jets in radio galaxies are commonly thought to be substantially misaligned \((i > 10^\circ)\), suggesting rather modest Doppler factors \((D \leq \text{a few})\) and thus moderate Doppler boosting only. In the simplest AGN unification scheme, FR I type sources are taken to resemble BL Lac objects (a blazar subclass) viewed at large viewing angles. The double-humped shaped SEDs of BL Lac-type sources have for long been satisfactorily fitted by (single-zone) leptonic synchrotron-self Compton (SSC) models with high Doppler factors, assuming the second hump to be related to inverse Compton up-scattering of synchrotron photons by the electrons themselves. Earlier application to radio galaxies suggested that their (then available) nuclear SED could be fitted by similar (SSC-jet) processes yet with small Doppler factors ("misaligned BL Lacs") [10]. If this would indeed apply, the emission of only a few radio galaxies are expected to reach into the Fermi-LAT GeV regime (as seems indeed to be the case), and little sources are expected to show up at TeV energies. Yet, despite being relatively small in number, RG have turned out particularly interesting by offering unique insights into some of the fundamental (and often hidden) non-thermal processes in gamma-ray emitting AGN.

In the following a brief description of the individual source status is given.

**PKS 0625-354**

PKS 0625-354 was discovered as a VHE emitter above 250 GeV (at a level of \(\sim 6\sigma\) in 5.5 h of data) in 2012 by H.E.S.S. [11]. Its VHE spectrum extends to \(\sim 2\) TeV and seems rather steep (compatible with a power law of photon index \(\sim -2.8\pm0.5\)). The associated apparent isotropic VHE luminosity is moderate and of the order of \(L_{\text{VHE}} \sim 5\times10^{42}\) erg/s. PKS 0625-354 is an AGN at a distance of about \(d \sim 220 \text{ Mpc}\) with a black hole mass (inferred from the M-bulge relation) of the order of \(M_{\text{BH}} \sim 10^9M_\odot\) [12] and probably accreting in an inefficient mode. It is known as a low excitation line radio-loud object, but there is uncertainty as to whether it resembles more a BL Lac or FR I-RG type...
source, e.g. [13]. Recent TANAMI observations provide evidence for a one-sided parsec-scale jet and superluminal motion with $\beta_{\text{app}} \sim 3$ [14], rather supporting a BL Lac classification along with non-modest Doppler boosting. Its classical "radio galaxy" status may thus have to be re-considered. No evidence for significant VHE variability has been found in the H.E.S.S. data set, although hints for a HE variability on a timescale $\sim 100$ d might be inferred from its Fermi-LAT light curve, cf. also [15]. Given its unclear classification and the limited VHE data set, the current situation seems physics-wise not yet constraining enough to draw robust conclusions on the origin of its non-thermal emission much beyond single zone SSC-type considerations [15]. To some extent PKS 0625-354 may thus remind one of the early stages of VHE blazar research, with future surprises not excluded.

**NGC 1275**

NGC 1275, also known as Perseus A, is the central radio galaxy of the Perseus cluster of galaxies at a distance of $\sim 70$ Mpc. The source was detected as VHE emitter above hundred GeV by MAGIC with a flux level of $\sim 3\%$ of the Crab Nebula, and studied in two observational campaign (the first during 10/2009-02/2010 with $\sim 46h$ at a level of $6.1\sigma$; the second during 08/2010-02/2011 with $\sim 54 h$ at a level of $6.6\sigma$) [16, 17]. Its VHE spectrum, when characterised by a single power law alone, is very steep with photon index of $\sim -4.1$. No signal has been seen above 650 GeV. When HE (Fermi-LAT) and VHE data are combined, the gamma-ray spectrum appears compatible with either a log-parabola or a power-law with a sub-exponential cut-off, suggestive of a common origin and of a peak or cut-off around several GeV. While at VHE energies only hints for month-type variability could be established, the source is known to show significant HE variability on timescales of a few days [18], suggesting that the gamma-ray emission originates in a (possibly, single) compact zone. NGC 1275 hosts a supermassive black hole of mass $\sim 3 \times 10^8 M_\odot$ [19] and shows a pc-scale radio jet orientated at $i \sim 30 - 45^\circ$ [20, 21]. A one-zone SSC interpretation of its SED, assuming the sub-pc scale jet to be misaligned ($i \sim 20 - 30^\circ$) (i.e. the "classical" misaligned BL Lac scenario), appears possible, though some tension may arise with the inferred jet inclination on pc-scales. This could probably be alleviated if e.g. the emitting component follows a non-straight trajectory that relaxes with distances, or if the jet is structured (spine-shear) allowing for a more complex inverse Compton interplay [22].

**Centaurus A**

Being the nearest AGN on the sky at a distance of $d \approx 3.7$ Mpc, Centaurus A (Cen A) is one of the best studied extragalactic objects. It hosts a black hole of mass $(0.5 - 1) \times 10^8 M_\odot$ and shows (under the proviso of adopting a quasar SED template) an estimated bolometric luminosity $L_{\text{bol}} \sim 10^{43}$ erg/s much less than the expected Eddington luminosity $L_{\text{Edd}}$, suggesting that accretion in its inner disk part might occur in a radiatively inefficient mode, cf. also [23]. Observations at radio frequencies have revealed a peculiar morphology with evidence for a sub-pc scale jet and counter-jet, a one-sided kpc jet, two radio lobes and extended diffusive emission. VLBI studies suggest that Cen A is a "non-blazar" source, its inner jet probably being substantially inclined (e.g., $i \sim 12 - 45^\circ$ based on TANAMI jet-counter jet flux ratio measurements, under the proviso of intrinsically symmetric jets) and characterized by moderate (radio) bulk flow speeds $u_j < 0.5 c$ only, e.g. [24, 25]. The detection of VHE gamma-rays (at a level of $5\sigma$) from the core region of Cen A has been reported by H.E.S.S. based on more than 100h of data taken in 2004-2008 [26]. The VHE spectrum extends from 300 GeV up to $\sim 5$ TeV and seems relatively hard (compatible with a single power law index $\Gamma \approx -2.7 \pm 0.5$). The source is relatively weak at VHE energies with an equivalent apparent isotropic luminosity of $L_i(> 250$ GeV) $= 2.6 \times 10^{39}$ erg/s. No significant VHE variability has been detected, so that an extended (within the angular resolution $\sim 0.1^\circ$ of H.E.S.S.) origin of the TeV emission cannot be simply discarded.

At HE, Fermi-LAT has detected gamma-ray emission from both the core (within $\sim 0.1^\circ$) and the giant lobes of Cen A [27, 28, 29, 30]. Together with Fornax A [31], extended HE gamma-ray emission has thus by now been seen in two radio galaxies, allowing to explore the associated plasma dynamics, radiation fields and processes on large scales. The core region of Cen A was initially detected up to 10 GeV (at a level of $4\sigma$) in 10 month of data and the HE spectrum then appeared compatible to a single power law with $\Gamma = 2.67 \pm 0.1$. While this index is very close to what has been seen at VHE, it became soon apparent that a simple HE power-law extrapolation would under-predicted the fluxes measured at TeV energies. The HE and VHE data were taken non-simultaneously, but the absence of variability in both energy bands suggested that the discrepancy might be continuing. An update using 4 year of Fermi-LAT data (allowing for spectral extension up to $\sim 50$ GeV), then found intriguing evidence for an unusual spectral hardening at HE gamma-ray energies with a possible break $E_b \sim 4$ GeV where (in a broken power law approximation) the photon index changes from about $-2.7$ (below $E_b$) to about $-2.1$ (above $E_b$), with associated
apparent luminosities $L(> E_b) \sim 10^{40} \text{ erg/s}, L(< E_b) \sim 10^{41} \text{ erg/s}$, respectively [32]. A recent update using 7.5 year of Fermi-LAT data (enabling spectral extension up to $\sim 150$ GeV) [33], also reported in these Proceedings, is reinforcing this conclusion of spectral hardening at a $> 5\sigma$ level, see Fig. 3. While in the AGN context spectral steepening at gamma-ray energies is familiar, a spectral hardening comes quite unexpected. This spectral feature is most naturally understood as revealing the emergence of an additional emission component that extends into the TeV regime and that is beyond the conventional (single and strongly Doppler-boosted) SSC-contribution which often seems to account for the SEDs in blazars. From a astrophysical points of view, this is particularly interesting and a variety of different (not mutually exclusive) interpretations as to its true origin are encountered in the literature, see e.g. Fig. 4. These include (i) seemingly exotic suggestions such as the self-annihilation of dark matter particles of mass $\sim 3$ TeV in a putative central dark matter (DM) spike) [33], (ii) extended scenarios based on e.g. the hadronic interaction of relativistic protons with ambient matter in the large-scale (halo-size) region ("Fermi-bubble like") [32], the integrated gamma-ray contribution from a supposed population of millisecond pulsars [33], or (leptonic) inverse-Compton processes with various photon fields (SSC, starlight, CMB, EBL) in the kpc-scale jet of Cen A [34, 35], (iii) inner (pc-scale an below) jet models such a multiple (leptonic) SSC-emitting components moving at different angles to the line of sight [36], photo-meson ($p\gamma$) interactions of ultra-high energy protons in strong photons fields (e.g. standard disk-type) on inner jet scales [37, 38, 39] and elaborated lepto-hadronic variants thereof [40, 41], or $\gamma$-ray induced pair-cascades in a putative dusty torus-like region [42], last not least (iv) magnetospheric scenarios based on leptonic inverse Compton processes in an under-luminous ADAF-type environment [43, 44].

All of these models come with some challenges, from e.g. an anomalously high dark matter concentration in DM scenarios, a high required jet power in hadronic models and poorly-known density profiles for pulsars to the deviation from equipartition and internal opacity constraints in leptonic models, the putative absence of a dusty torus in Cen A or external opacity constraints for near black hole scenarios.

There is evidence for variability of the gamma-ray emission below the break $E_b$ on timescale of several months [33],

**FIGURE 3.** The high-energy gamma-ray spectrum of Cen A above 100 MeV based on $\sim 7.5$ year of Fermi-LAT data. The spectrum shows an unexpected spectral hardening at a few GeV, where its index changes by $\sim 0.5$ (assuming a broken power law), see also Refs. [32, 33]. This feature is most naturally interpreted as a physically distinct emission component that emerges towards highest energies and allows to smoothly connect the HE and VHE regimes. Figure courtesy of J. Graham.
Possible Interpretations for the High-Energy Gamma-Ray Component above the Break in Centaurus A:

| Exotic           | Dark Matter (mass ~3 TeV, central spike) Self-Annihilation (Brown+ 2016) |
|------------------|--------------------------------------------------------------------------|
| Extended         | HE from pp-interaction of relativistic p ("Fermi Bubble-like") (Sahakyany+ 2013) |
|                  | EC starlight photons (e.g. Stawarz+ 2006)                                |
|                  | Millisecond Pulsar Population (GeV + IC broadening) (Brown+ 2016)        |
|                  | inverse-Compton processes in the kpc-scale jet (e.g. Hardcastle & Croston+ 2011) |
| Inner Jet        | multiple SSC-emitting components (i.e., differential beaming) (e.g. Lenain+ 2008) |
|                  | pγ-interactions in inner jet (e.g. Kachelrieß+ 2010; Reynoso+ 2011; Sahu+ 2012; Petropolou+ 2014) |
|                  | γ-ray-induced pair-cascades in a torus-like region (Roustazadeh & Bottcher+ 2011) |
| BH vicinity      | rotational acceleration & IC (e.g. Rieger & Aharonian 2009)              |

**FIGURE 4.** Possible scenarios for the nature of the high energy gamma-ray component (above the break) seen in Cen A.

which seems compatible with a standard (e.g. one-zone SSC) jet origin of this emission. At higher energies (i.e., for the so-called 2nd component) no significant variability has yet been detected, though the limited Fermi-LAT statistics and the weakness of the source in the VHE regime are making it difficult to really probe into this. Given the limited angular resolution (~ 5 kpc) of current gamma-ray instruments, uncertainties thus remain as to the true origin of the γ-ray emission above the break, and both extended and inner jet-related scenarios appear possible. We note that possible hints for variability would allow to disfavour the former ones, while the current (apparent) lack of variability does not necessarily provide compelling evidence against an inner jet-related origin if the jet is indeed sufficiently misaligned and Doppler-boosting effects are weak.

Apart from some circumstantial evidence in the case of the gamma-ray blazar Mkn 501, this is the first time that spectral results provide strong evidence for the appearance of a physically distinct component at γ-ray energies. While it seems that up to a few GeV the SED of Cen A could in principle be reasonably well modelled by standard leptonic SSC processes assuming a "misaligned blazar" [10, 27], the true nature of this second component and its relation to the AGN still remains to be disclosed.

**IC 310**

The Perseus Cluster radio galaxy *IC 310* at a distance of *d* ~ 80 Mpc has been detected at VHE energies by MAGIC in about of 21 h data (taken during 10/2009-02/2010)[45]. The source, which is believed to host a black hole of mass \( \sim 3 \times 10^8 M_\odot \) [46], has for a while been classified as a head-tail radio galaxy, but the apparent lack of jet bending along with recent indications for a one-sided pc-scale radio jet structure inclined at \( i \leq 38^\circ \) suggests that IC 310 may instead be a source at the borderline dividing low-luminosity radio galaxies and BL Lac objects [47]. The spectrum at VHE energies, which has been measured up to ~ 10 TeV, is very hard and compatible with a single power law (there is no
evidence for a break) of photon index $\Gamma \approx -2.0$ [48]. The VHE flux in the 2009-2010 campaign has been found to vary from yearly and monthly down to daily time scales. During a strong VHE flare in November 12-13, 2012 IC 310 has shown an exceptional variability behaviour with evidence for extreme short-term variability on (flux doubling) timescales of $\approx 5$ min, see Fig. 5 [46]. Jet orientation (probably $i \sim 10 - 20^\circ$), power and timing constrains have been taken to disfavour jet-star interaction [49] or magnetic reconnection [50] scenarios proposed for blazars as the cause of this VHE variability, and the fact that the VHE flux varies on timescales much shorter than the light travel time across black hole horizon scales $r_g(3 \times 10^8 M_\odot)/c = 25$ min has been interpreted as evidence for the occurrence of gap-type particle acceleration on sub-horizon scales (i.e. with a gap height $h <$ gravitational scale $r_g$), see e.g. Fig. 6 for illustration. The potential of such particle acceleration in vacuum gaps has been explored recently under a variety of conditions, see e.g. [51, 52, 53, 54, 55]. The observed VHE doubling timescale would imply gap sizes of the order of $h \sim 0.2 r_g$ in the case of IC 310. Given that the observed VHE luminosity appears rather high (apparent isotropic VHE luminosity $L_{\text{VHE}} \sim 10^{44}$ erg/s) and that the VHE spectrum is smooth with no indication for absorption up to 8.3 TeV, gap-type particle acceleration scenarios for IC 310 may encounter some challenges as well. Promising work [55] has been started to positively probe its feasibility and further observational characterisation (including the relation of IC 310 to the BL Lac class) may help to disentangle the nature of the non-thermal VHE processes in IC 310. The angular resolution of VHE instruments is moderate only, so that in the absence of variability (e.g. see the case of Cen A) the location of the emitting region is often rather poorly constrained. This if different to IC 310 where the exceptional VHE variability now strongly limits possible scenarios and suggests that it may be magnetospheric in origin. Given its distance and black hole mass, VLBI-type radio observation will not be able to probe deeply into the near-black hole environment of IC 310 (in contrast to the case of M87, see below), so that some uncertainties still remain. We note however, that radio observations appear consistent with the ejection of a new component at the time of the TeV activity [56].

**FIGURE 5.** VHE light curve of IC 310 above 300 GeV as observed with the MAGIC telescopes during November 12/13, 2012. Extreme VHE variability on (doubling) timescale much less then 10 min is apparent from the Figure. The two gray lines indicate flux levels of 1 and 5 Crab units, respectively. From Ref. [46]. Reprinted with permission from AAAS.

*M87*

The Virgo Cluster galaxy *M87* at a distance of $d \approx 16.7$ Mpc was the first radio galaxy detected at TeV energies [57]. Its proximity has made it a prime target to probe jet formation scenarios with high-resolution radio observations down to scales of tens of Schwarzschild radii $R_s$ (approaching the event horizon), and much effort has been recently directed into this, e.g. [58, 59, 60, 61, 62]. M87 is classified as an FR I source and known to host one of most massive black holes with $M_{\text{BH}} \approx (2 - 6) \times 10^9 M_\odot$. At radio frequencies its sub-parsec scale jet appears complex, possibly consisting
FIGURE 6. Unscreened electric field regions ("vacuum gaps" where $\vec{E} \cdot \vec{B} \neq 0$) may form close to the horizon in under-dense black hole environments. Charged seed electrons, injected by e.g. pair-creation processes in the inner accretion flow (RIAF) into these regions, are then quickly accelerated along the fields to high energies and can trigger an electromagnetic pair cascade, that is accompanied by highly variable VHE emission (due to curvature radiation or inverse Compton processes) and that eventually ensures a charge supply high enough to establish the formation of jet like features. A scenario of this type has been proposed to account for the extreme VHE variability in IC 310 [46].

of a slower, mildly relativistic ($\beta \sim 0.5c$) layer and a faster moving spine ($\gamma_b \sim 2.5$), e.g. [59], and to be misaligned by an angle $i \sim (15 - 25)^\circ$. The indications for a parabolic jet shape may indicate that the jet initially experiences some external (e.g., disk wind) confinement [63]. The inferred jet seeds and inclinations are on average consistent with rather modest Doppler boosting $D \sim$ a few (for review, see e.g. [64]). At VHE energies, M87 is known for its particularly interesting characteristics, including rapid day-scale variability (on flux doubling time scales $\Delta t_{\text{obs}} \sim 1$ d) detected during active source states, and a relatively hard spectrum compatible with a power law of photons index $\Gamma_{\text{VHE}} \sim 2.2$ and extending from $\sim 300$ GeV to beyond 10 TeV, e.g. [65, 66, 67, 68]. Both this hard VHE spectrum and the observed rapid variability are remarkable features for a misaligned AGN, and reminiscent of those seen in IC 310. At HE ($> 100$ MeV) gamma-ray energies, Fermi-LAT has reported the detection of gamma-rays form M87 up to 30 GeV based on 10 months of data with a photon index comparable to the VHE one ($\Gamma_{\text{HE}} = 2.26 \pm 0.13$)[69] and no indications for variability down to timescales of $\sim 10$ d. A simple power-law extrapolation from the HE to the VHE regime would however under-predict the (non-simultaneous) VHE fluxes measured during TeV high states, suggesting that the high states might be accompanied by the emergence of a additional component beyond the conventional assumed SSC-type component. Similar to the case of Cen A, numerous models have been proposed to account for this, and the interested reader is directed to Refs. [64, 70] for an overview and discussion of them.

The observed rapid VHE variations in M87 are (still) the fastest compared to those seen at any other waveband. Light travel time arguments point to a compact $\gamma$-ray emitting region ($R < c\Delta t_{\text{obs}}/D$) with a size comparable to the Schwarzschild radius $r_s = (0.6 - 1.8) \times 10^{15}$ cm of its black hole.

Over the years M87 has shown several active states, with VHE high states being reported for 2005, 2008 and 2010, and an elevated (TeV flux level 2-3 times higher than average) state detected in 2012. During all VHE high states, day-scale VHE variability has been seen. For the elevated state in 2012 evidence for VHE variability on timescale of weeks have been reported, hinting to the possibility that the "quiescent" state might perhaps also show some longterm evolution [71]. High-resolution VLBI radio observations, probing scales down to tens of gravitational radii, which have been performed during the active 2008, 2010 and 2012 VHE states provide evidence that the TeV emission is accompanied by (delayed) radio core flux enhancements, and support the conclusion that the VHE emission may originate at the jet base very near to the black hole [72, 73, 74, 61]. The required compactness of the TeV zone and the
noted radio \((R_s\text{-scale})\) – VHE correlation would seem to support models where the observed variable VHE emission is related to gap-type processes occurring in the vicinity of the black hole and signals a (fresh) injection of plasma particle in the jet that could lead to some increased (delayed, and possibly more extended) radio emission \([52, 53, 54]\). To some extent M87 may thus remind one of IC 310, though the radio core inferences seem to make the situation for M87 much more conclusive.

Conclusions

In recent years non-blazar AGN have emerged as a particularly interesting gamma-ray emitting source class on the extragalactic sky. The detection of Narrow Line Seyfert 1 galaxies at Fermi-LAT energies along with related multi-wavelength observations is providing important information for our astrophysical understanding of jet formation and the trigger mechanisms behind radio-loudness. Radio galaxies, on the other hand, continue to significantly impacting on the field. With their jets misaligned and associated Doppler boosting effects only modest, they allow unique insights into otherwise "hidden" environments (e.g. close to the black hole, or in the "background"). Evidence for an unexpected spectral hardening in the gamma-ray regime for Cen A, for example, are most naturally interpreted as indications for the emergence of a new physical component beyond the conventional SSC-type one with possible interpretations ranging from dark matter scenarios to black hole magnetospheric processes. Extreme VHE variability on timescales smaller than or comparable to the light travel time across the horizon of the black hole, as seen for example in IC 310 and M87, on the other hand, suggest that this \(\gamma\)-ray emission may originate in a very compact zone, probably in the vicinity of the black hole itself. Further studies in this regard could allow to probe deeply into the Physics of the Extremes. Non-blazar AGN, and misaligned sources in particular, are thus turning out to be of increasing astrophysical significance by allowing a deep fundamental diagnostic of the non-thermal acceleration and radiation mechanisms, of the link between accretion and jet formation processes, of the near black-hole environment and multi-zone emission models, thereby deepening our understanding of the nature of cosmic reality. All this makes them sources with a very promising physics potential for the upcoming CTA array, both what concerns their spectral as well as their timing characterization.

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