

# M 87 and Centaurus A: laboratories for VHE physics of jets and near supermassive black holes

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**Abstract.** In the recent years radio-galaxies have emerged as a new class of extragalactic very-high energy  $\gamma$ -ray emitters (VHE;  $E > 100$  GeV). Their proximity and well studied multi-wavelength behavior enable unique studies of the physics of relativistic plasma jets and the immediate surroundings of super-massive black holes. Here, the two most prominent and nearby sources - Centaurus A and M 87 - are presented and their VHE properties are discussed. Special attention is given to the location of the VHE emission, where recent observational results from a joined multi-wavelength campaign on M 87 can offer new insights.

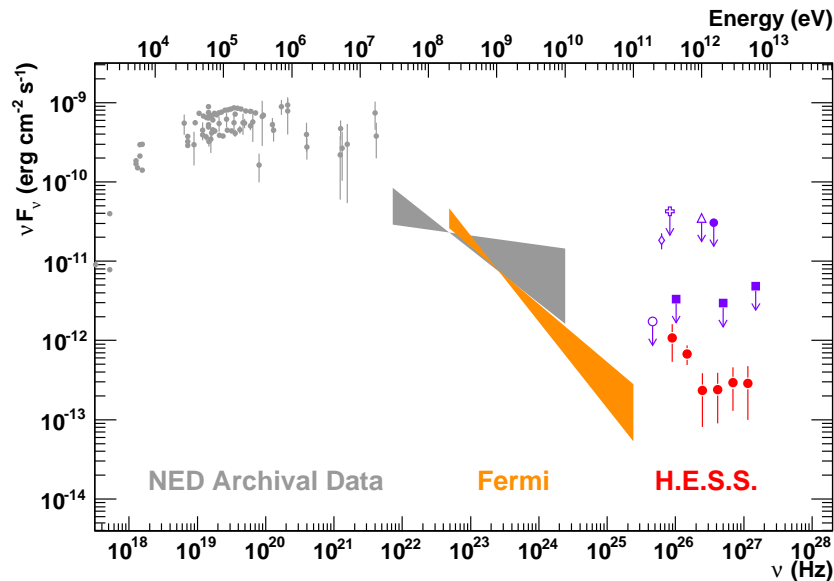
## 1. Introduction

Up to now, the known extra-galactic very-high energy sky (VHE;  $E > 100$  GeV) is almost exclusively populated by a single source class: the VHE blazar. VHE blazars are active galactic nuclei (AGN) with their relativistic jets pointing close to the line of sight of the observer, resulting in a boosting of the flux and energy of the emitted photons. This boosting enables to detect these source up to large distances, with the furthest VHE source currently ranging at a redshift  $> 0.5$  [1], and thereby also giving the means to study the intervening diffuse radiation fields (e.g. [2]).

Recent discoveries of VHE emission from the radio-galaxies M 87 and Centaurus A opened up a new source class for studies. Radio-galaxies also belong to the AGN class, but their jets make a larger angle to the line of sight and therefore the emission is less boosted. The different geometry also enables to study the individual components of the AGN system in greater details. Even more importantly: the most nearby AGN are radio galaxies. The detection of VHE emission from these source enable unique studies of the spatial origin of the VHE emission with unprecedented resolution.

## 2. Centaurus A

Centaurus A (Cen A) is the closest active radio galaxy (for a review see [3]). At radio wavelengths rich jet structures are visible, extending from the core and the inner pc and



**Figure 1.** High energy part of the spectral energy distribution of Cen A.

kpc jet to giant outer lobes with an angular extension of  $8^\circ \times 4^\circ$ . The inner kpc jet has also been detected in X-rays, revealing a complex structure of bright knots and diffuse emission [4]. Recent estimates for the mass of the central supermassive black hole give  $(5.5 \pm 3.0) \times 10^7 M_\odot$  [5]. Cen A has also been proposed as a possible source of ultra-high energy cosmic rays.

Centaurus A has been observed by the H.E.S.S. experiment for over 115 h between 2004 and 2008 resulting in a detection of VHE  $\gamma$ -ray emission with a flux of  $\sim 0.8\%$  Crab [6]. The measured differential photon spectrum is well described by a power-law function  $dN/dE = \Phi_0 \cdot (E/1 \text{ TeV})^{-\Gamma}$  with normalization  $\Phi_0 = (2.45 \pm 0.52_{\text{stat}} \pm 0.49_{\text{sys}}) \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$  and photon index  $\Gamma = 2.73 \pm 0.45_{\text{stat}} \pm 0.2_{\text{sys}}$ . No significant variability has been found on time-scales of 28 min, nights and months (moon periods). Fig. 1 shows the spectral energy distribution of Cen A ranging from X-rays to the VHE regime. The flux measured by H.E.S.S. is clearly below all previous upper limits in the VHE regime. Recently, the *Fermi* LAT team reported a detection of Cen A at GeV energies [7] (Fig. 1 orange bow-tie). A simple extrapolation of the reported power law function would result in a too low flux at  $\sim$ TeV energies.

Several authors have predicted VHE emission from Cen A, and more generally discussed VHE emission from radio galaxies. A first class of models proposed the immediate vicinity of the supermassive black hole as the region of VHE emission, e.g. in pulsar-type scenarios [8, 9]. A second class of models propose a mechanism similar to the mechanism at work in other VHE blazars [10, 11]. [12] discussed a two-flow type model [13, 14], with a fast spine and a slower, mildly relativistic sheath propagating within the jet, which has been successfully applied to M87 [15]. [16] modeled the VHE emission of Cen A with a multi-blob SSC model. Extended VHE emission may also be expected from Cen A. In this context, [17] proposed that  $\gamma$ -rays emitted in the immediate vicinity

of the active nucleus are partly absorbed by the starlight radiation in the host galaxy and initiated pair production cascades. The created  $e^\pm$  pairs are quickly isotropized and radiate VHE  $\gamma$ -rays by inverse Compton scattering the starlight radiation, resulting in an extended VHE emission. Hadronic models have also been invoked to predict VHE emission from radio galaxies [18]. Given the weakness of the signal for the current generation instruments the H.E.S.S. results do not yet strongly constrain these models.

Recently, [19] reported the detection of non-thermal X-ray synchrotron emission from the shock of the southwest inner radio lobe. They investigated inverse Compton scattering the starlight radiation and the CMB from high energy particles in this lobe and predicted a VHE emission well compatible with the H.E.S.S. measurement. This would imply that the VHE emission from Cen A is produced analogous to a gigantic supernova remnant (SNR). While the position is  $\sim 3\sigma$  away from the best fit position of the VHE excess, it is well within the upper limit of the extension.

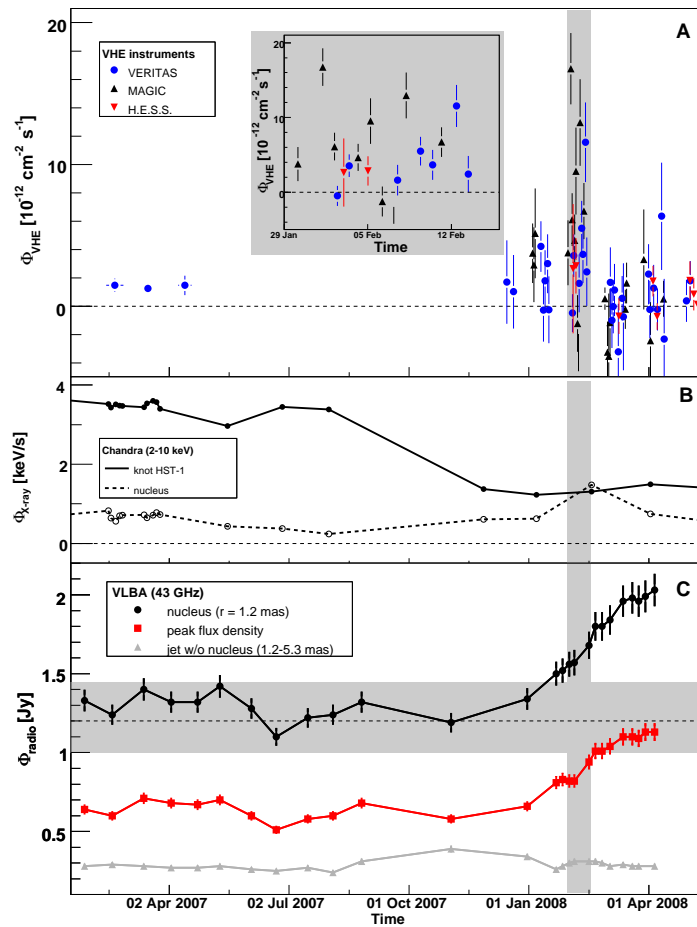
### 3. M 87

The giant radio galaxy M 87 is located in the Virgo cluster at a distance of 16 Mpc [21]. The angle between the plasma jet in M 87 and the line of sight is estimated to lie between  $20^\circ - 40^\circ$  [22]. With its proximity, its bright and well resolved jet, and its very massive black hole with  $6 \times 10^9 M_\odot$  [23], M 87 provides an excellent opportunity to study the inner structures of the jet, which are expected to scale with the gravitational radius of the black hole. Substructures of the jet are resolved in the X-ray, optical and radio wavebands [24] and high-frequency radio very long baseline interferometry (VLBI) observations with sub-milliarcsecond (mas) resolution are starting to probe the collimation region of the jet [25].

A first indication of VHE  $\gamma$ -ray emission ( $> 4\sigma$ ) from the direction of M 87 in 1998/99 was reported by HEGRA [26]. The VHE  $\gamma$ -ray emission was confirmed by H.E.S.S. [27], establishing M 87 as the first non-blazar extragalactic VHE  $\gamma$ -ray source. Utilizing causality arguments, the reported day-scale variability strongly constrains the size of the  $\gamma$ -ray emission region. VERITAS detected M 87 in 2007 in a low flux state [28] but did not find variability in their data-set.

The measured flux variability rules out large-scale emission from dark matter annihilation or cosmic-ray interactions as dominant origin of the VHE emission. Leptonic [29, 16] and hadronic [18] jet emission models have also been proposed to explain the VHE emission. The location of the VHE  $\gamma$ -ray emission is still unknown, but the nucleus [8], the inner jet [18, 29, 16, 15] or larger structures in the jet [30] have been suggested as possible sites. The 2005 VHE  $\gamma$ -ray flare was detected during an exceptional, several years lasting X-ray outburst of the innermost knot in the jet 'HST-1' [31].

To further investigate the origin of the VHE emission the three major VHE instruments H.E.S.S., MAGIC and VERITAS joined for a coordinated monitoring campaign on the source in winter/spring of 2008. During the campaign a strong VHE flux outburst of M 87 was detected [32], again showing variability at the time scale of days. At the same time, further observations at X-ray with Chandra and at radio with VLBA have been performed [33, 34]. The high resolution VLBA observations at 43 GHz achieved a direct imaging of the innermost jet region and the immediate surrounding of the central supermassive black hole with a resolution  $< 100 R_s$  (0.2 mas or 0.016 pc



**Figure 2.** Results of the joined M87 monitoring campaign in 2008 combining observations at VHE (H.E.S.S./MAGIC/VERITAS; top panel), X-rays (CHANDRA; middle panel), and radio (VLBA; bottom panel). From [20]. Reprinted with permission from AAAS.

at 16 Mpc).[33]. The results of this joined multi-wavelength effort have recently been published [20] and are summarized below:

The combined lightcurve of the 2008 data-set is shown in Fig. 2. At VHE energies (top row) the sources is mostly in a quiet state with the very notable exception of February/March 2008, where several strong outburst of the source were detected, again with variability on time-scales  $\sim$ day. In X-rays (middle panel) the lightcurve for the innermost resolvable X-ray bright knot in the jet HST-1 and the core are shown. Contrary to the VHE flare in 2005, the X-ray flux from HST-1 is in a low state, while the core shows a minor increase in flux contemporaneous with the VHE flare. The lowest panel shows the radio flux for the core, which is associated with the black hole and its immediate surrounding at scales  $< 100 R_s$ . The radio flux of the core shows a significant increase coinciding with the VHE flare. The detected multi-wavelength

behavior and its comparison with previous observations leads to the conclusion that there is strong indication for a connection between the radio and the VHE emission - readily explained by a simple model - and that therefore the central black hole and its immediate surrounding are the most likely production site of the VHE emission [20].

These findings lend support to models preferring the immediate vicinity of the central black hole or the jet base as origin of the VHE emission.

#### 4. Conclusion & Outlook

The discovery of VHE emission from the nearby radio galaxies Centaurus A and M 87 enables unique studies of acceleration processes in relativistic jets and in the vicinity of supermassive black holes. Given the proximity of the sources (3.8 and 16 Mpc) and the larger jet angle to the line of sight compared to VHE blazars, the outer and inner kpc jet structures will be resolvable by future VHE experiments like CTA, enabling to further spatially pin down the site of the emission. With the help of simultaneous multi-wavelength observations and (temporal) correlation studies, different section of the jet and the core can be probed, down to the smallest sub-pc (milli-arcsecond) scale, only accessible to VLBA radio observations.

The multi-wavelength behavior observed from M 87 during the 2008 joined campaign points towards the immediate surrounding of the central super-massive black hole as origin of the VHE emission. While this surely needs further observational confirmation, it demonstrates the potential of such joined campaigns to probe VHE emission sites.

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