The Progenitor of the TeV Emission from M87

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TeV emission from M87

4σ, discovered by HEGRA in 2003 (1999 observations)

Confirmed by HESS in 2005 (2003, 2004 observations)

First extragalactic source that isn't a blazar

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Observation of the giant radio galaxy M87 at TeV energies with H.E.S.S.

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The giant radio galaxy M 87 was observed at TeV energies with the Cherenkov telescopes of the H.E.S.S. collaboration (High Energy Stereoscopic System). The observations have been performed in the year 2003 during the comissioning phase and in 2004 with the full four telescope setup. The observations were motivated by the measurement of the HEGRA collaboration which reported a $4.7\,\sigma$ excess of TeV γ-rays from the direction of M 87. The results of the H.E.S.S. observations – indicating a possible variability of TeV γ-ray emission from M 87 (compared to the HEGRA result) – are presented.

1. Introduction

The giant radio galaxy M 87 is located at a distance of $\sim 16\,\mathrm{Mpc}$ ($z = 0.00436$) in the Virgo cluster of galaxies. The angle between the parsec scale plasma jet – well studied at radio, optical and X-ray wavelengths – and the observer's line of sight has been estimated to be in the order of $20° - 40°$. The mass of the black hole in the center of M 87 is of the order of $2 - 3 \cdot 10^9\,M_\odot$. M 87 is discussed to be a powerful accelerator of high energy particles, possibly even up to the highest energies [17, 18]. This makes M 87 an interesting candidate for TeV γ-ray emission. M 87 was observed with the HEGRA stereoscopic telescope system in 1998/1999 for a total of 77 h (after quality cuts) above an energy threshold of 730 GeV. An excess of TeV γ-rays has been found with a significance of $4.7\,\sigma$ [9, 10]. The integral flux was calculated to be 3.3% of the flux of the Crab Nebula.

M 87 is of particular interest for observations at TeV energies: The large jet angle makes it different from the so far observed TeV emitting active galactic nuclei (AGN) which are of the blazar type, i.e. with their plasma jets pointing directly towards the observer. Various models exist to describe emission of TeV photons from M 87. Leptonic models (i.e. inverse Compton scattering) are discussed in [11], whereas [12] consider the TeV γ-ray production in large scale plasma jets. From the experimental view, the TeV γ-ray production in large scale jets would be of particular interest since the extension of the M 87 jet structure could be resolved at TeV energies with the typical angular resolution of stereoscopic Cherenkov telescope arrays of $\leq 0.1°$ per event. Hadronic models do also exist [13, 14] as well as TeV γ-ray production scenarios correlated with the cosmic ray population of the radio galaxy [15]. Finally, the hypothesis of annihilating exotic particles (i.e. neutralinos) has been discussed by [16].

Observations with the H.E.S.S. telescopes have been initiated to confirm the HEGRA result and to further clarify the origin of the TeV γ-ray emission.

2. The H.E.S.S. experiment

The High Energy Stereoscopic System (H.E.S.S.) collaboration operates an array of four imaging atmospheric Cherenkov telescopes optimized for an energy range between 100 GeV and 10 TeV. The telescopes are located in the Khomas Highlands in Namibia (23d 16′ 18″ S, 16d 30′ 1″ E) at a height of 1 800 m above sea level, see Fig. 1. Each telescope has a $107\,\mathrm{m}^2$ tessellated mirror surface [2, 3] and is equipped with a 960 photomultiplier tube (PMT) camera with a field of view of $\sim 5°$ [4]. The full four telescope array is operational since December, 2003. Since July 2003 the telescopes are operated in a coincident mode [5] assuring that at least two telescopes record images for each event which is important for an improved reconstruction of the shower geometry, and γ-hadron separation. More information about H.E.S.S. can be found in [6].

3. Observations of M 87 with H.E.S.S.

M 87 has been observed with the H.E.S.S. Cherenkov telescopes between March and May, 2003 and February to May, 2004. The 2003 data were taken during the comissioning phase of the experiment with only two telescopes. The stereo events have been merged offline based on their individual GPS time stamps. The 2004 data were taken with the full four telescope array with the hardware coincidence trigger. The sensitivity of the full setup increased by more than a factor of two compared to the sensitivity of the instrument during the 2003 observation campaign

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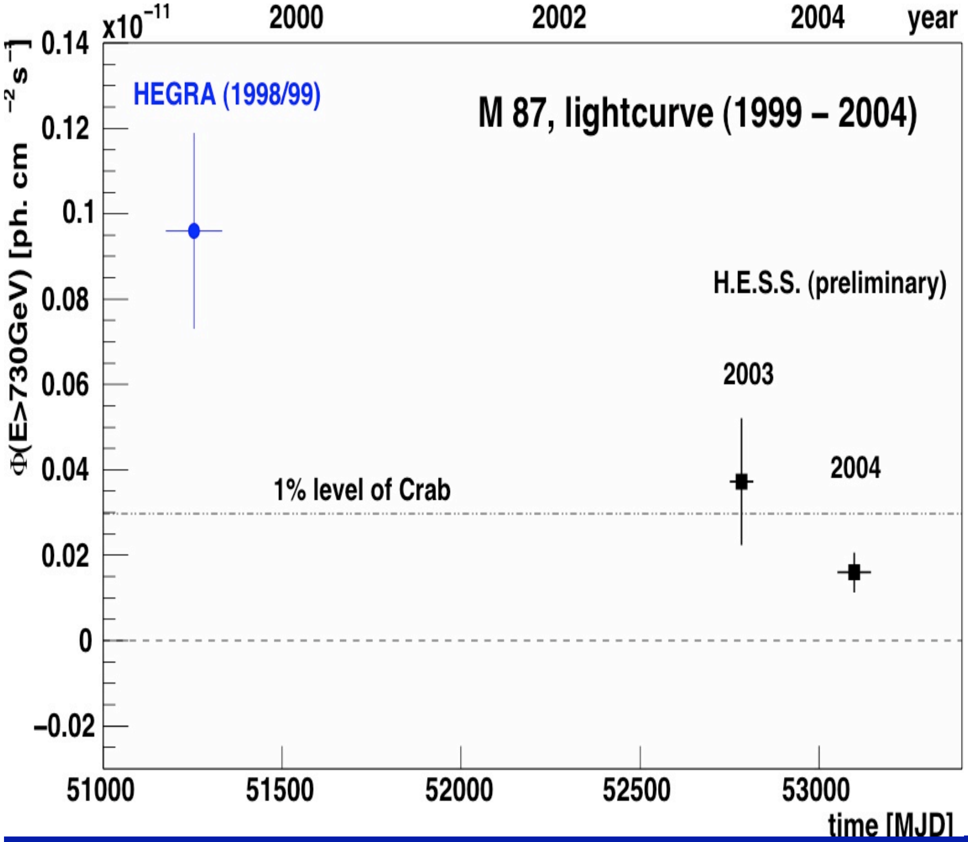
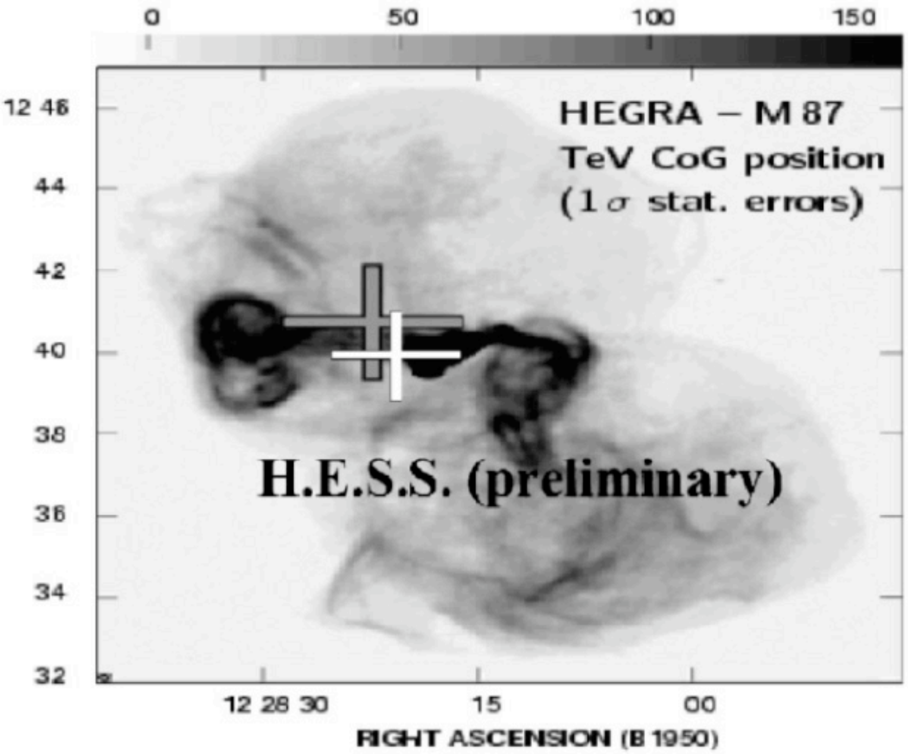




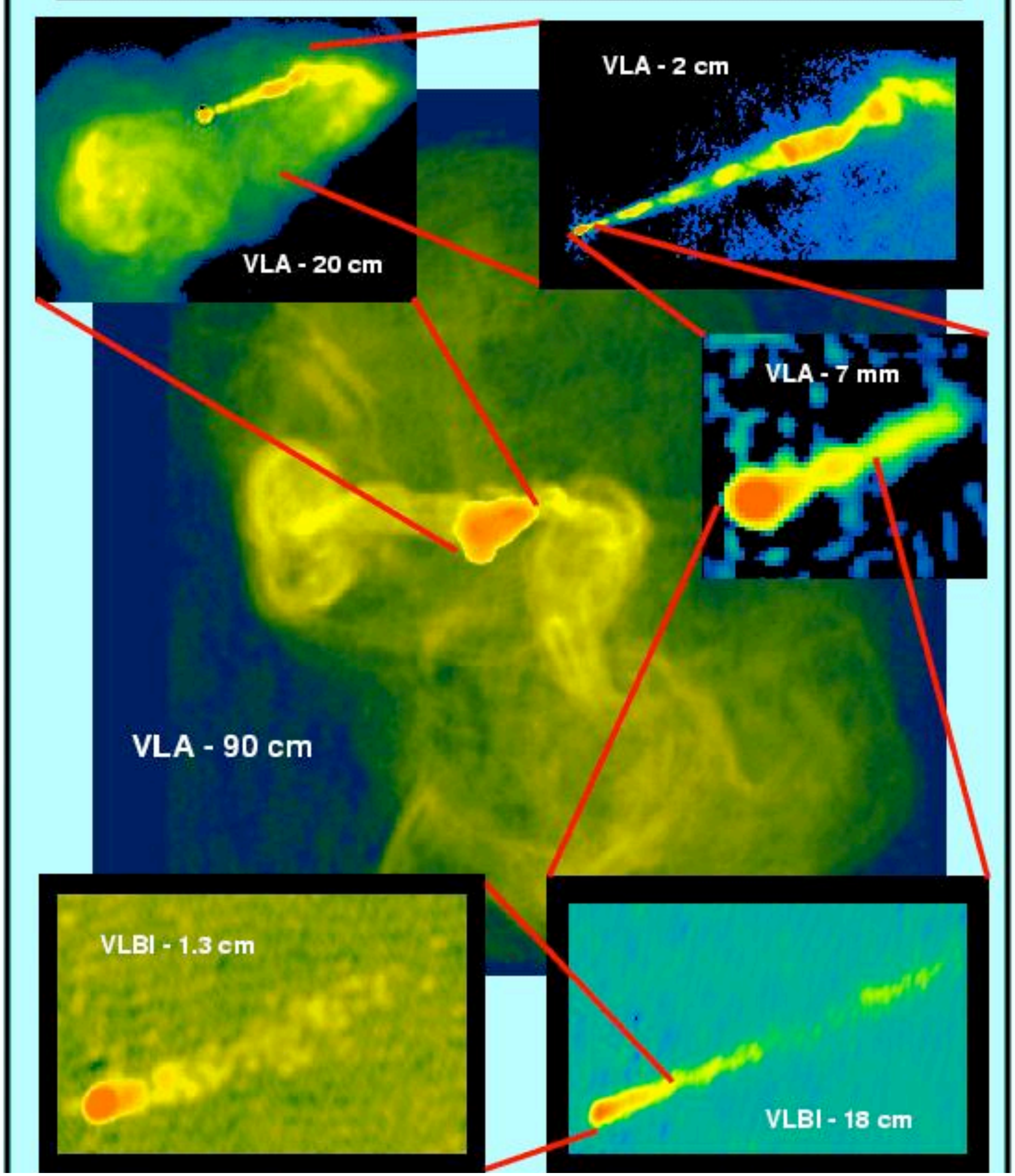
Likely variable

Large positional error circle

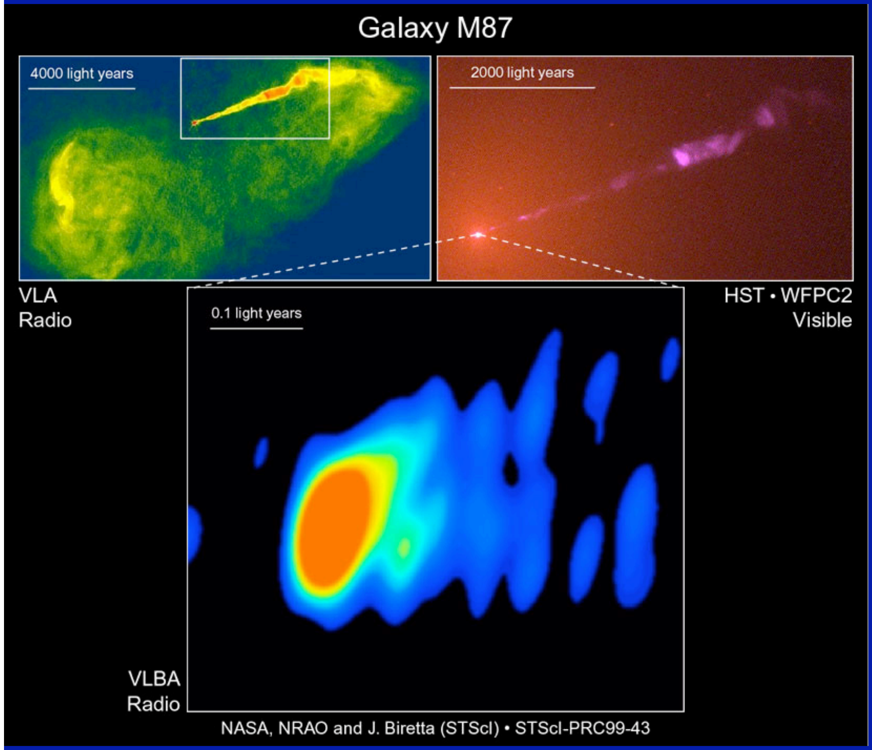
Where does it come from??

How blind are we -- really??

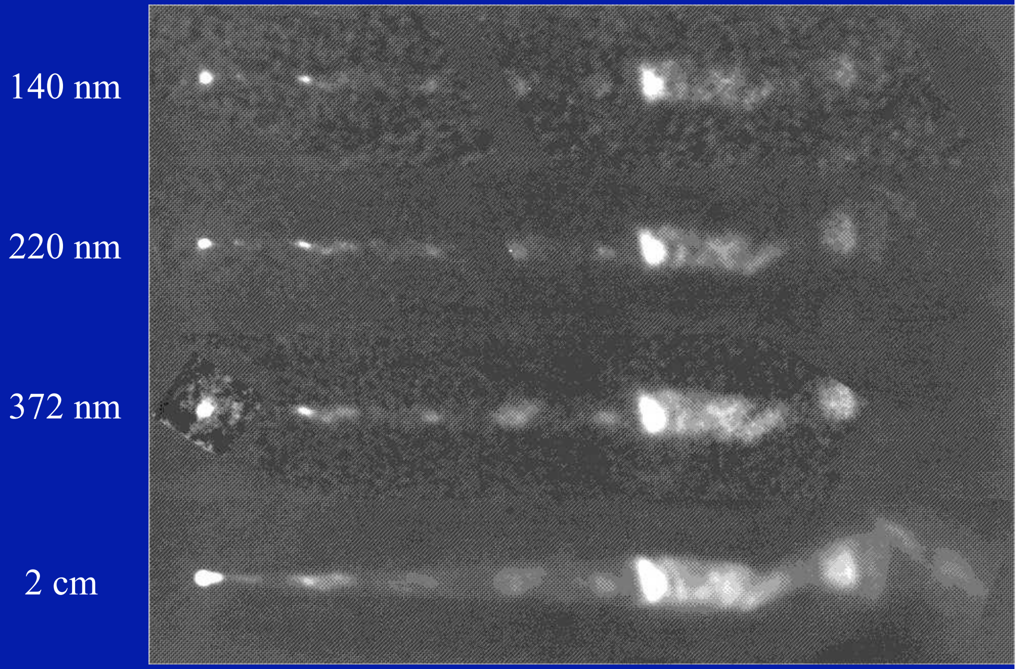
M87 -- From 200,000 Light-Years to 0.2 Light-Year



The Jet of M87



NASA, NRAO and J. Biretta (STScI) • STScI-PRC99-43



Sparks et al. 1996; Junor et al. 1999

Jet extends for >2 kpc to NE of nucleus, well collimated through ~20”.

No visible counter-jet, but there is a hotspot ~25” SW of nucleus.

VLBI maps show a well-collimated jet extending in to 50 R_G.

The jet has several bright knots, seen in the radio, optical and X-rays.

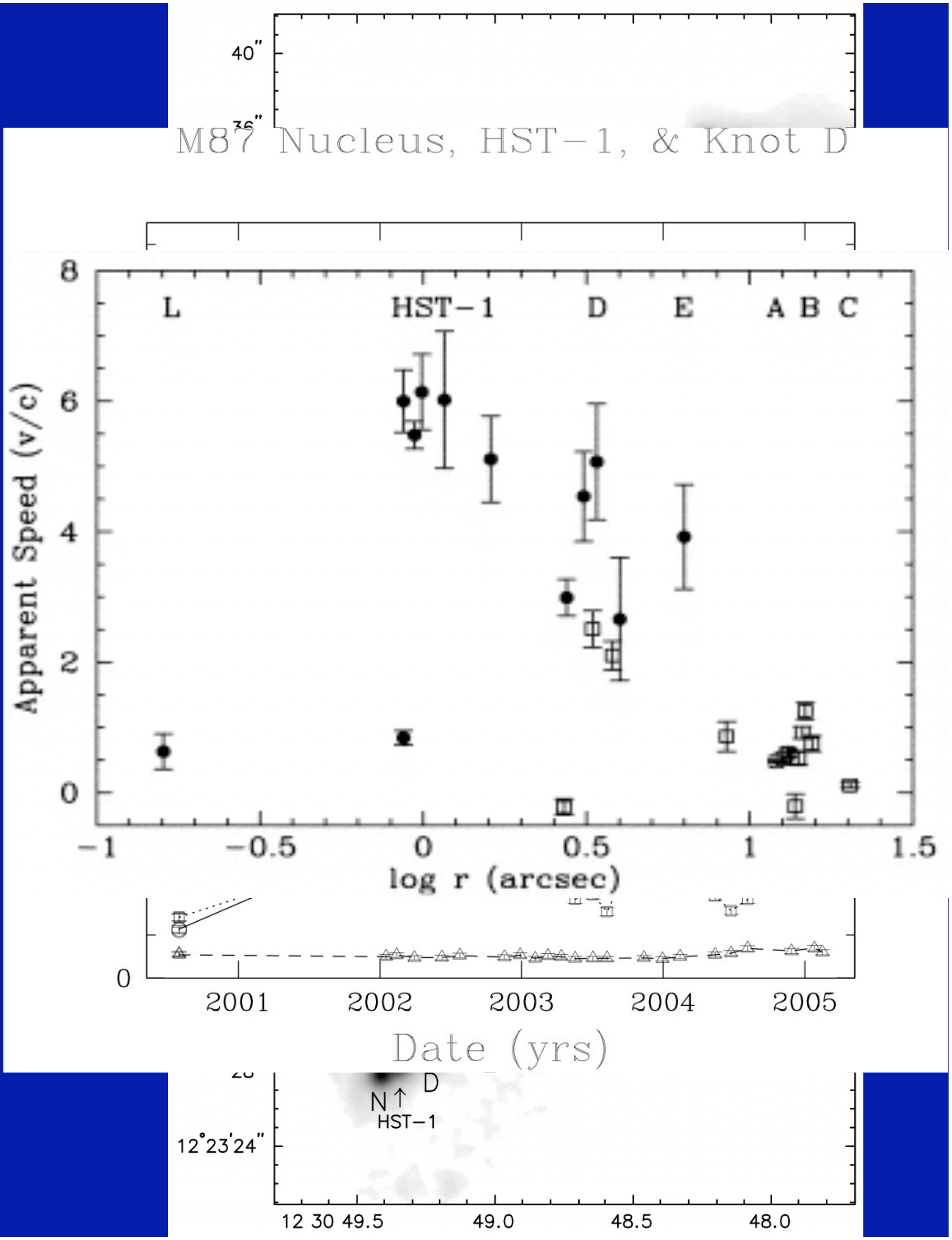
M87 Jet:
key points

Several bright knots seen in radio, optical and X-rays

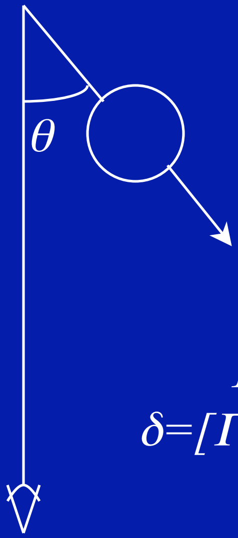
Three features are within a factor ~few in opt/X-ray brightness: nucleus, HST-1 and A.

Two features show strong opt/X-ray variability: nucleus and HST-1.

Apparent superluminal motion (speeds up to 6c) seen throughout inner jet -- key link in unified schemes.



Relativistic Effects



$v=\beta c$

$\Gamma=(1-\beta^2)^{-1/2}$

$\delta=[\Gamma(1-\beta\cos\theta)]^{-1}$

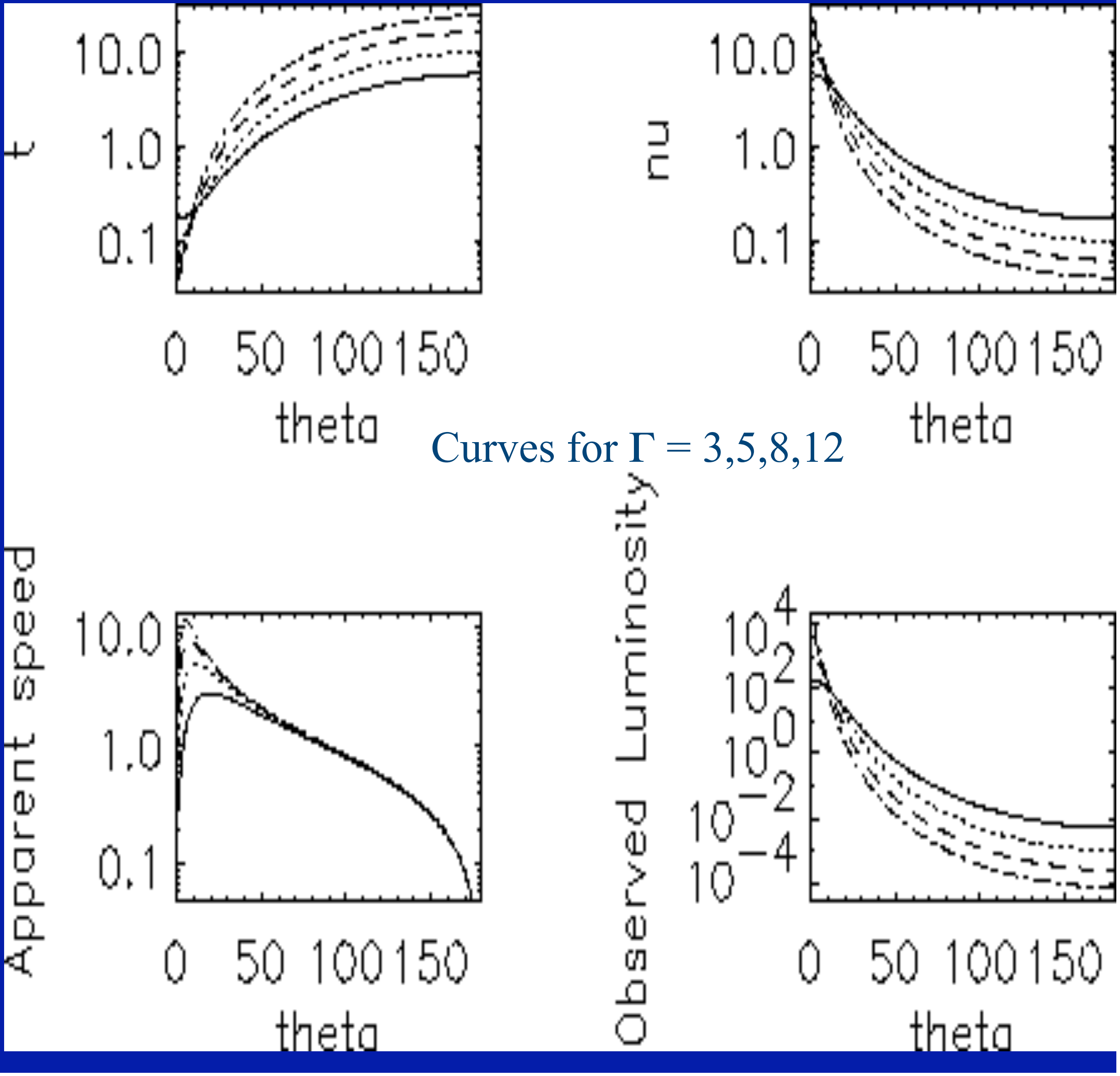
Time dilation: $\tau_{app}=\delta^{-1}\tau$

Blueshifting radiation: $\nu_{app}=\delta\nu$

Apparent Superluminal Motion:

$v_{app}=v\sin\theta/(1-\beta\cos\theta)$

Relativistic beaming: $L_{obs}=\delta^{p}L$, where p~3



Curves for Γ = 3,5,8,12

Whence comes the TeV emission?

Three possibilities: Nucleus/jet base, HST-1, A.

Stawarz et al. (2005) suggested knot A…

…but that model has problems:

Cannot account for possible variability (factor 5 1999-2004).

Requires unrealistically high density of starlight seed photons & B field 10X equipartition value.

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ON THE MAGNETIC FIELD IN THE KILOPARSEC-SCALE JET OF RADIO GALAXY M87

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ABSTRACT

Several low-power kiloparsec-scale jets in nearby radio galaxies are known for their synchrotron radiation extending up to optical and X-ray photon energies. Here we comment on high-energy γ-ray emission of one particular object of this kind, i.e., the kiloparsec-scale jet of the M87 radio galaxy, resulting from Comptonization of the starlight photon field of the host galaxy by the synchrotron-emitting jet electrons. In our analysis, we include the relativistic bulk velocity of the jet, as well as the Klein-Nishina effects. We show that upper limits to the kiloparsec-scale jet inverse Compton radiation imposed by the HESS and HEGRA Cerenkov Telescopes—which detected a variable source of very high energy γ-ray emission within $0\overset{\circ}{.}1$ ($\sim$30 kpc) of the M87 central region—give us an important constraint on the magnetic field strength in this object, namely, that the magnetic field cannot be smaller than the equipartition value (referring solely to the radiating electrons) in the brightest knot of the jet, and most likely, is even stronger. In this context, we point out a need for the amplification of the magnetic energy flux along the M87 jet from the subparsec to kiloparsec scales, suggesting the turbulent dynamo as a plausible process responsible for the aforementioned amplification.

Subject headings: galaxies: individual (M87) — galaxies: jets — galaxies: magnetic fields — radiation mechanisms: nonthermal

1. INTRODUCTION

Because of the pure nonthermal nature of the multiwavelength emission of extragalactic jets, many of the jets' parameters are basically unknown. Intensity of the jet magnetic field is the exemplary unknown in all jet models. The situation is even less clear on large scales ($\geq$1 kpc) than on small (subparsec and parsec) scales, as typically the observed spectrum of large-scale jets consists of the synchrotron emission alone, without synchrotron self-absorption features or the inverse Compton (IC) component. Therefore, the usual approach is to assume energy equipartition between the large-scale jet magnetic field and synchrotron radiating electrons, thus obtaining $B_{\rm eq} \sim 10^{-6}$ to 10^{-3} G. The standard justification for the equipartition assumption is that the IC X-ray emission detected from a number of hot spots and lobes in powerful radio sources often (although not always) yields $B \approx B_{\rm eq}$ (see, e.g., Kataoka & Stawarz 2004 and references therein). This, however, cannot really be taken as a proof for the magnetic field–radiating electrons energy equipartition in the case of the jet flows, as the physical processes responsible for the evolution of radiating particles and magnetic field within terminal shocks and extended lobes can differ substantially from the respective processes that take place within large-scale jets themselves (see, e.g., a discussion on the magnetic field structure within the hot spots and lobes by Blundell & Rawlings 2000).

Unfortunately, the X-ray emission recently detected from a number of large-scale quasar jets (e.g., Schwartz et al. 2000; Siemiginowska et al. 2002, 2003; Sambruna et al. 2004) cannot give us a definite answer on the magnetic field intensity in these objects. First, it is not well established if this X-ray emission is synchrotron or inverse Compton in origin (see a discussion in Stawarz 2003). Second, poorly constrained relativistic bulk velocities of the large-scale jets influence the inferred values of the jet parameters in both cases significantly. As a result, one can only say that if the X-ray emission of large-scale quasar jets is indeed due to the IC scattering of the cosmic microwave background radiation (Tavecchio et al. 2000), then it is possible to find a value of the jet Doppler factor that allows energy equipartition between the magnetic field and the radiating electrons (or even equipartition between magnetic field energy and the total particle's bulk energy; Ghisellini & Celotti 2001) in a certain object. This, however, does not mean that the energy equipartition is fulfilled. In fact, Kataoka & Stawarz (2004) argued that in a framework of the IC hypothesis the more plausible interpretation leads to subequipartition magnetic field within the large-scale quasar jets. We note that the analysis of jet dynamics suggests that the powerful quasar jets are most likely matter-dominated, at least on the large scales (see, e.g., Sikora et al. 2005 and references therein). Still, other models involving Poynting flux–dominated outflows (Blandford 2002) cannot be rejected without uncertainty.

Contrary to the large-scale quasar jets, the synchrotron origin of the X-ray emission of the kiloparsec-scale flows in low-luminosity radio galaxies is well established (see Stawarz 2003 and references therein). In addition, the two-sidedness of the FR I radio structures suggests much lower bulk velocities of these jets compared to their powerful quasar-hosted analogs. All of these constraints give the unique opportunity to more accurately estimate magnetic field intensity within some nearby FR I jets by studying their inevitable IC γ-ray emission. Unfortunately, because of the insufficient sensitivity of the present γ-ray detectors, such analysis can be performed only for the closest FR I sources.

Stawarz et al. (2003) considered very high energy (VHE) γ-ray emission produced by the kiloparsec-scale jets in nearby low-power radio galaxies of the FR I type. Optical and X-ray emission recently detected from a number of such objects indicate that these jets are still relativistic on the kiloparsec scale and that they contain ultrarelativistic electrons with energies up

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Whence comes the TeV emission?

Is it knot HST-1?

Brightest optical, X-ray
source currently

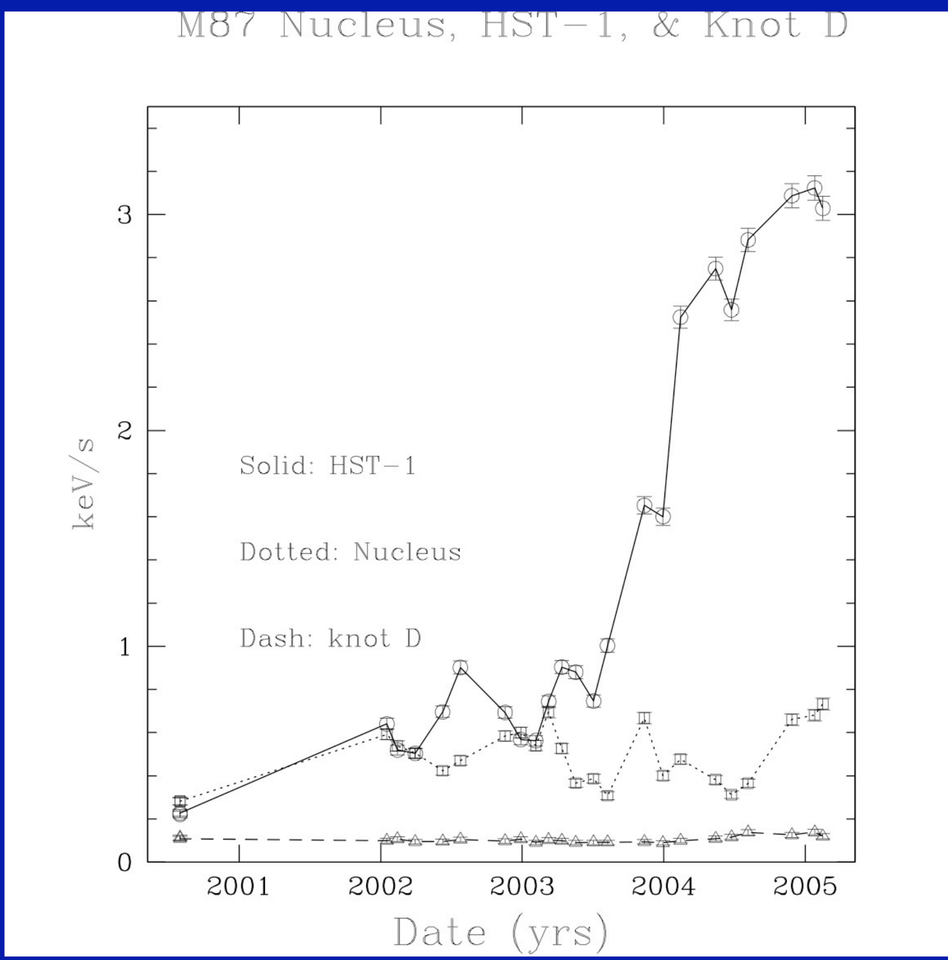
Much fainter in radio

But … variability is all wrong:
between 2000-2005 flared
by X50!

⇒ Cannot be TeV emitter

Nucleus is last possibility

Fortunately lightucurve is ok!



Model I: a homogeneous jet

Synch peak at ν_s=10^{12}–10^{14} Hz (as in Perlman et al. 2001), cooling break at higher freqs

Synch, inverse-Compton cross at ~few keV, IC is SSC only (note apparent change in X-ray slope)

Homogeneous, one velocity

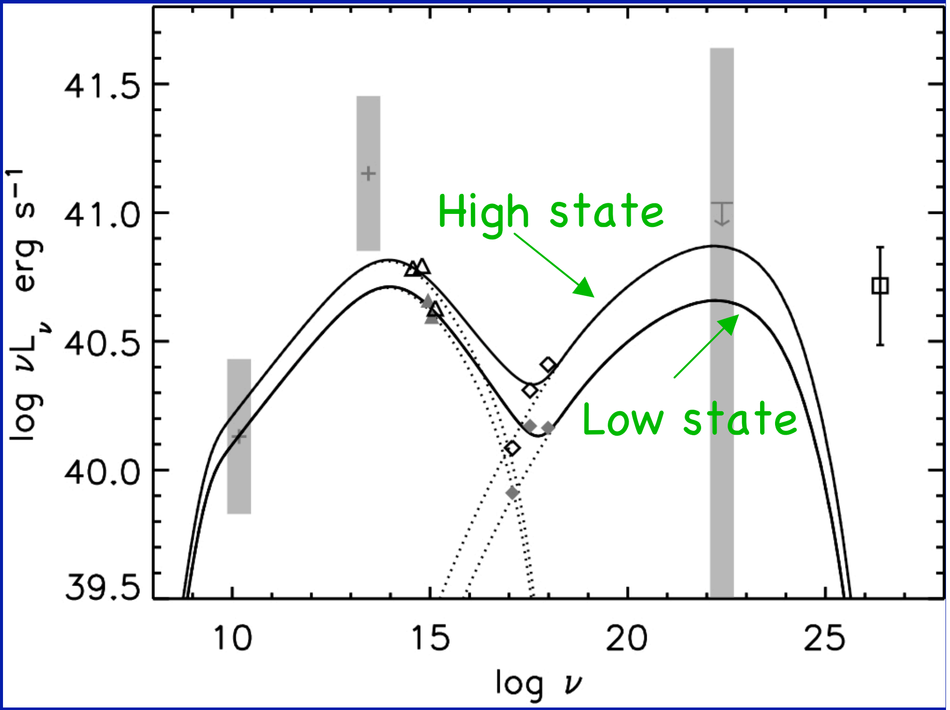
Var. timescale ⇒ $R \approx c\delta t_{var} = 10^{17}\,\delta$ cm

Problem: SED dies at 10^{24}–10^{25} Hz

ν_{IC}~10^{23} Hz is forced thanks to t_{var}

Cutoff at high freq very steep because of reduced KN X-section

CRITICAL PROBLEM



Can we try a decelerating jet?

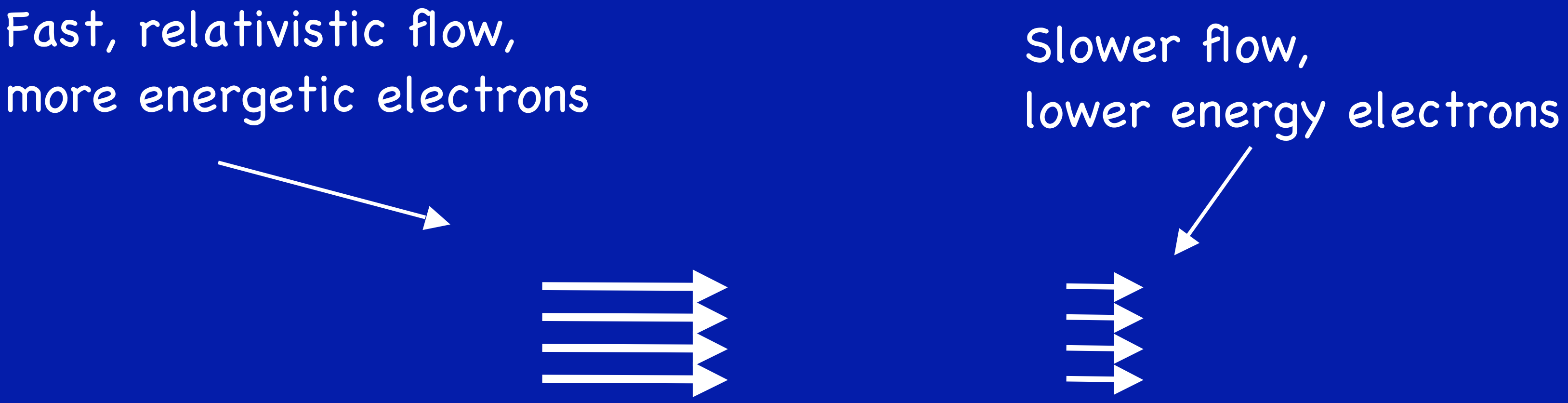
Motivation when applied to TeV BL Lacs (Georganopoulos & Kazanas 2003):

- No superluminal motion
- Homogeneous models require $\delta \approx 50$ to reproduce SED
  - Disastrous for unified schemes

Motivation for applying it to M87 (Perlman et al. 2003):

- Variability timescales in core and HST-1 would have to be boosted to very high δ (>20+) to get BL Lac-like variability

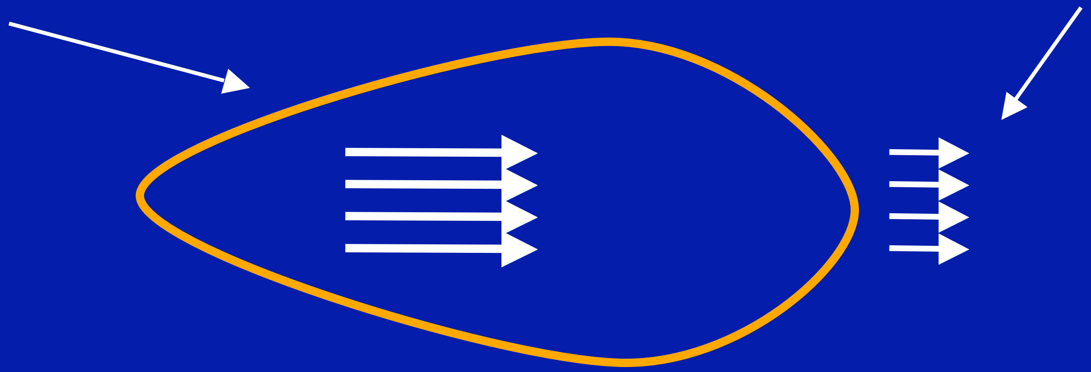
Radiation beaming patterns for a relativistic and decelerating flow.



Fast, relativistic flow,
more energetic electrons

Slower flow,
lower energy electrons

Radiation beaming patterns for a relativistic and decelerating flow.



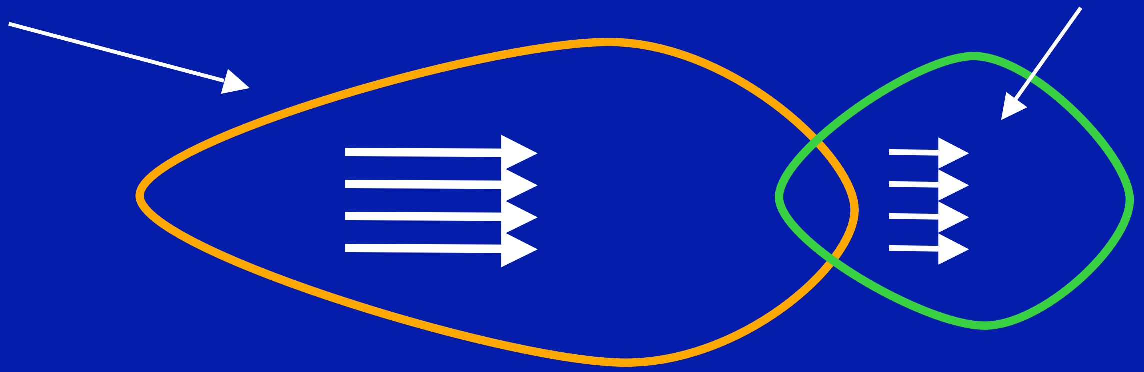
Fast, relativistic flow,
more energetic electrons

Slower flow,
lower energy electrons

Strongly beamed Synchrotron and SSC emission from the fast part of the flow. Dominates the high energy part of the observed synchrotron spectrum in BL Lacs.

The SSC emission contributes to the observed GeV-TeV emission.

Radiation beaming patterns for a relativistic and decelerating flow.



Fast, relativistic flow,
more energetic electrons

Slower flow,
lower energy electrons

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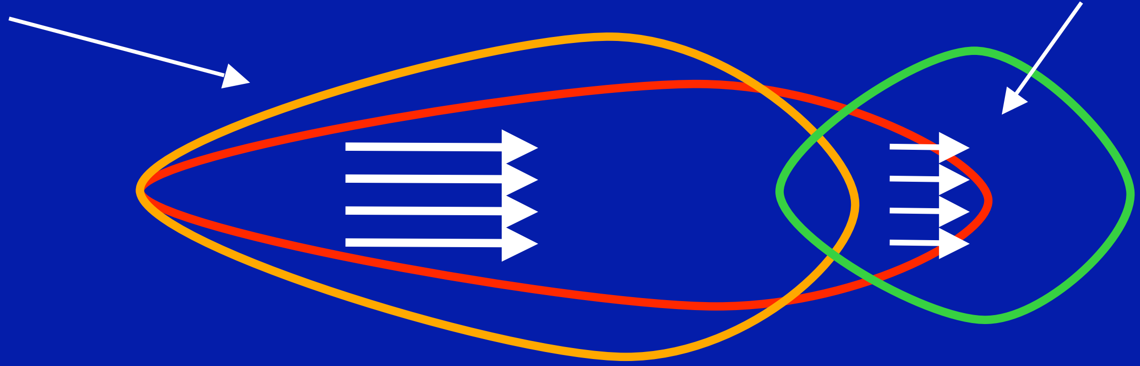
Less beamed radio synchrotron, SSC emission from slow part of the flow.

Dominates the radio and X-ray output in FR Is.

Radiation beaming patterns for a relativistic and decelerating flow.



Fast, relativistic flow,
more energetic electrons

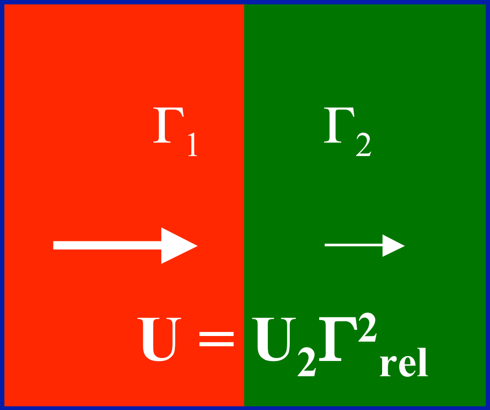
Slower flow,
lower energy electrons

UC emission: Synchrotron seed photons from slow part of the flow are scattered by the upstream energetic electrons of fast part of the flow.

UC is the major contributor to the TeV flux._

Upstream Compton (UC) Scattering

Higher seed photon energy density
Tighter beaming pattern

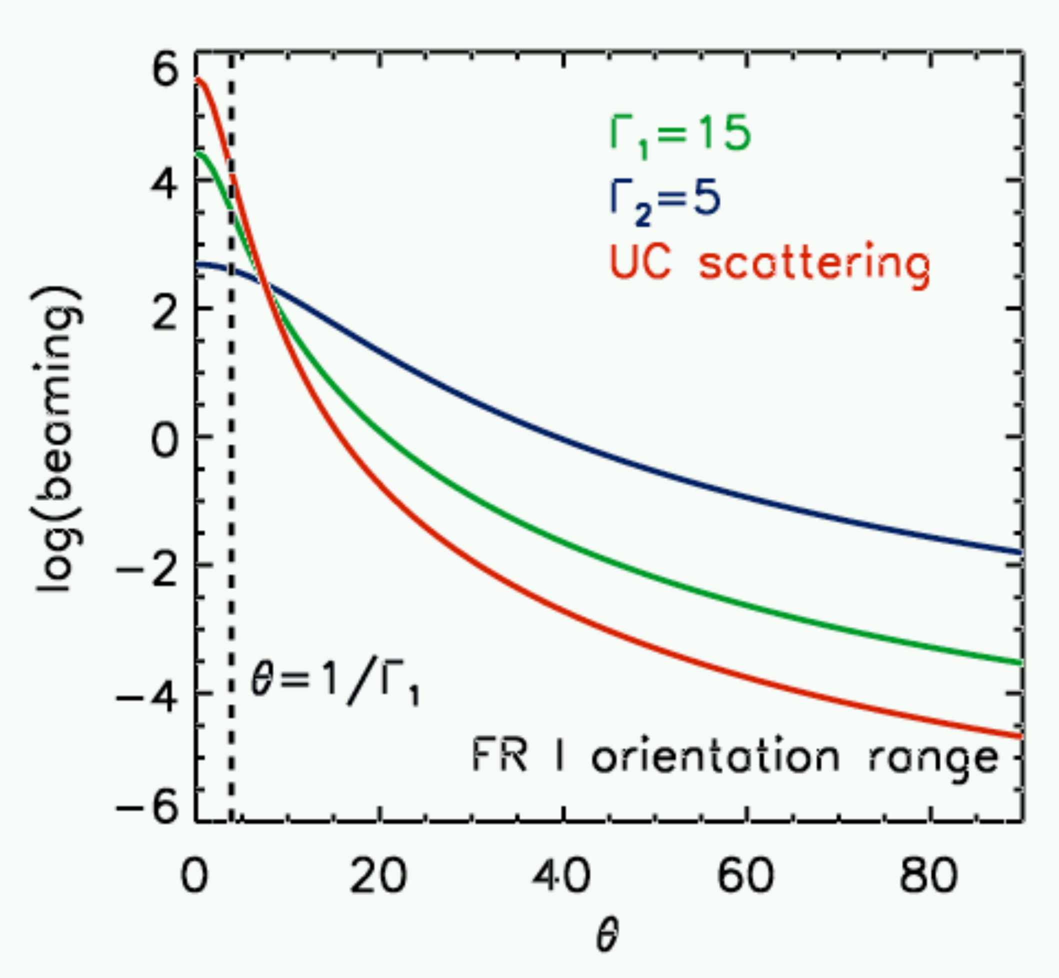


Synchrotron and SSC from each zone:

$L_1 \propto \delta_1^{2+\alpha}, L_2 \propto \delta_2^{2+\alpha}$

UC:

$L_{UC} \propto \delta_1^{3+2\alpha} / \delta_2^{1+\alpha}$

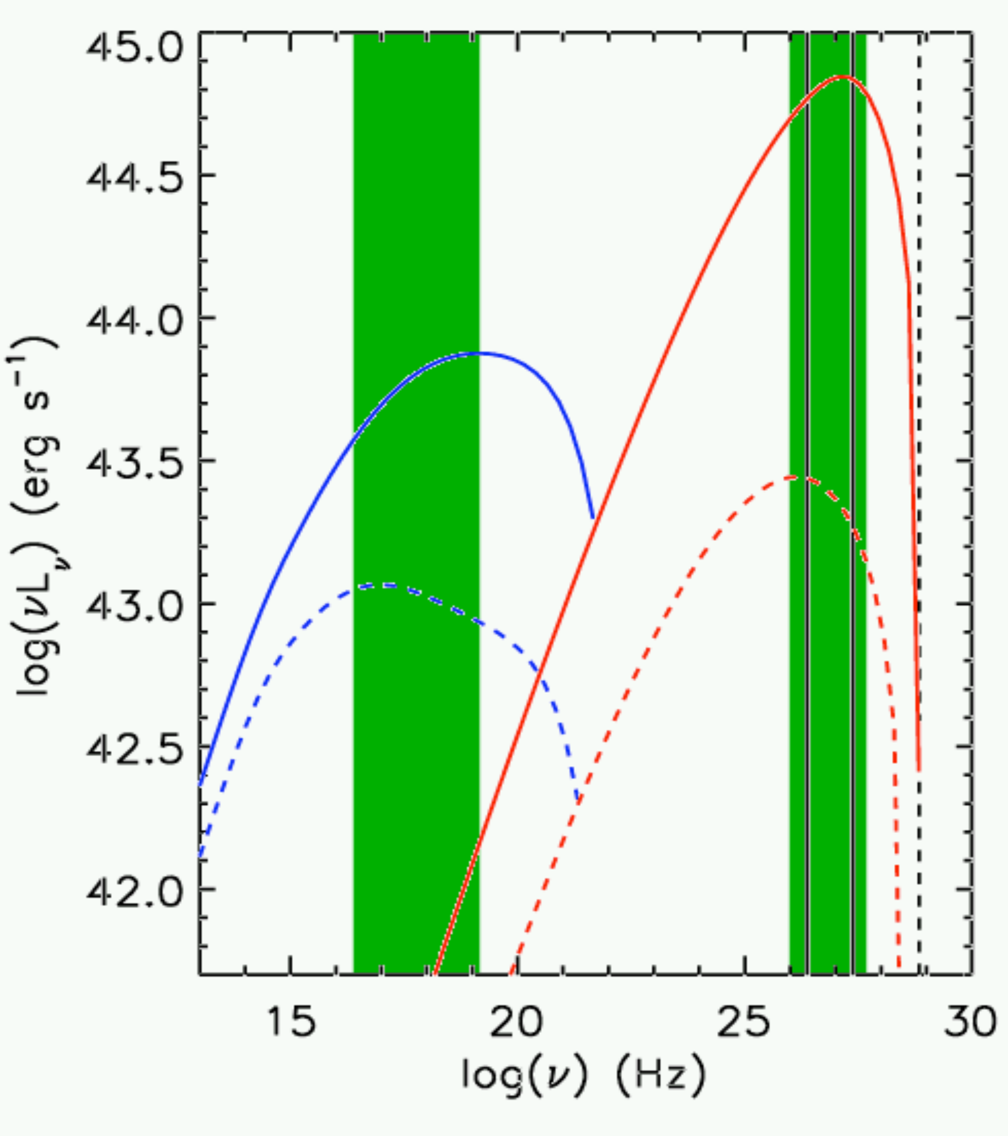


A decelerating relativistic flow

To reproduce typical TeV BL Lac SED requires:

- Flow decelerates from $\Gamma=15$ to $\Gamma=4$, $R=10^{16}$ cm
- $\gamma_{max}=10^7$, $B=0.1$ G
- $\theta_1=3^o$, $\theta_2=6^o$

Georganopoulos & Kazanas 2004



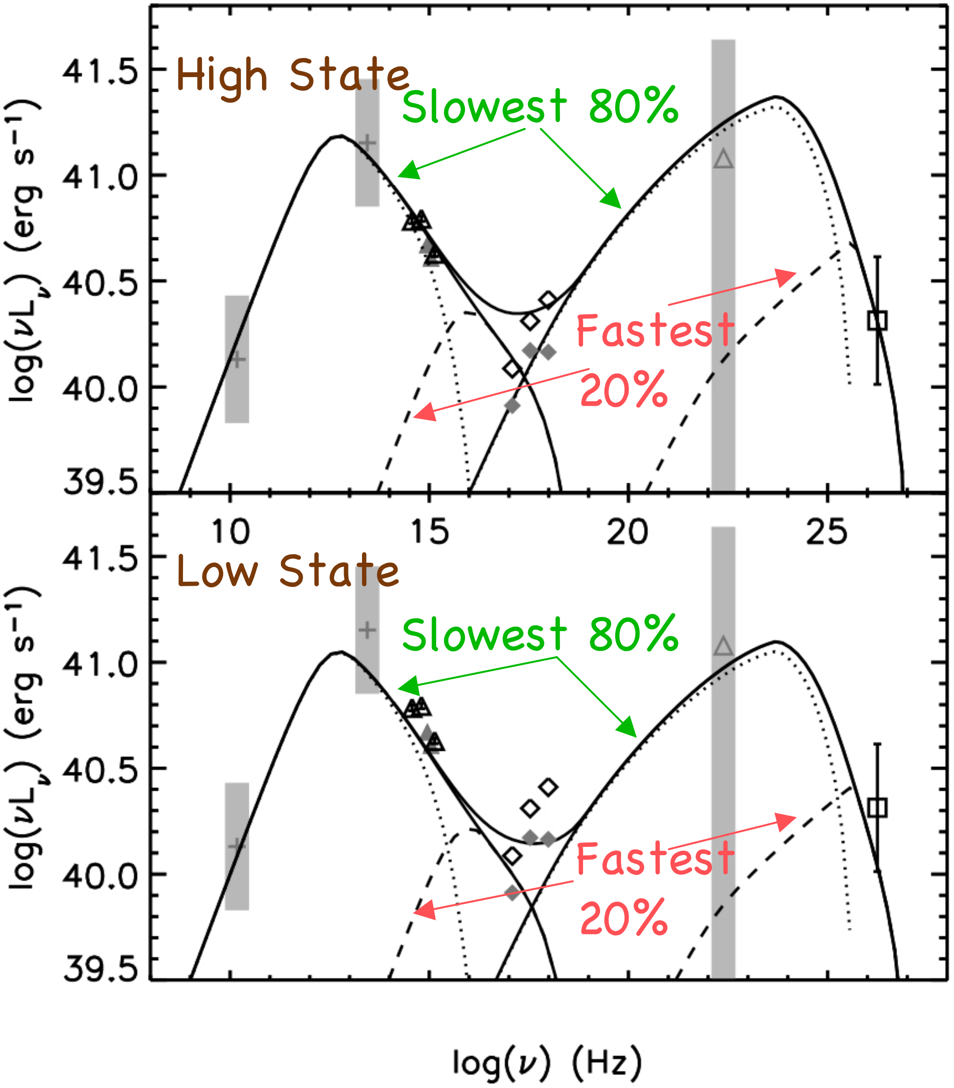
Decelerating flow applied to M87

Higher energy electrons in fast part of flow, cool radiatively as they advect downstream

Lorentz factor decreases from Γ=20→5 (as $1/z^2$) in 0.1 pc

Viewing angle θ=13°

TeV emission is UC.



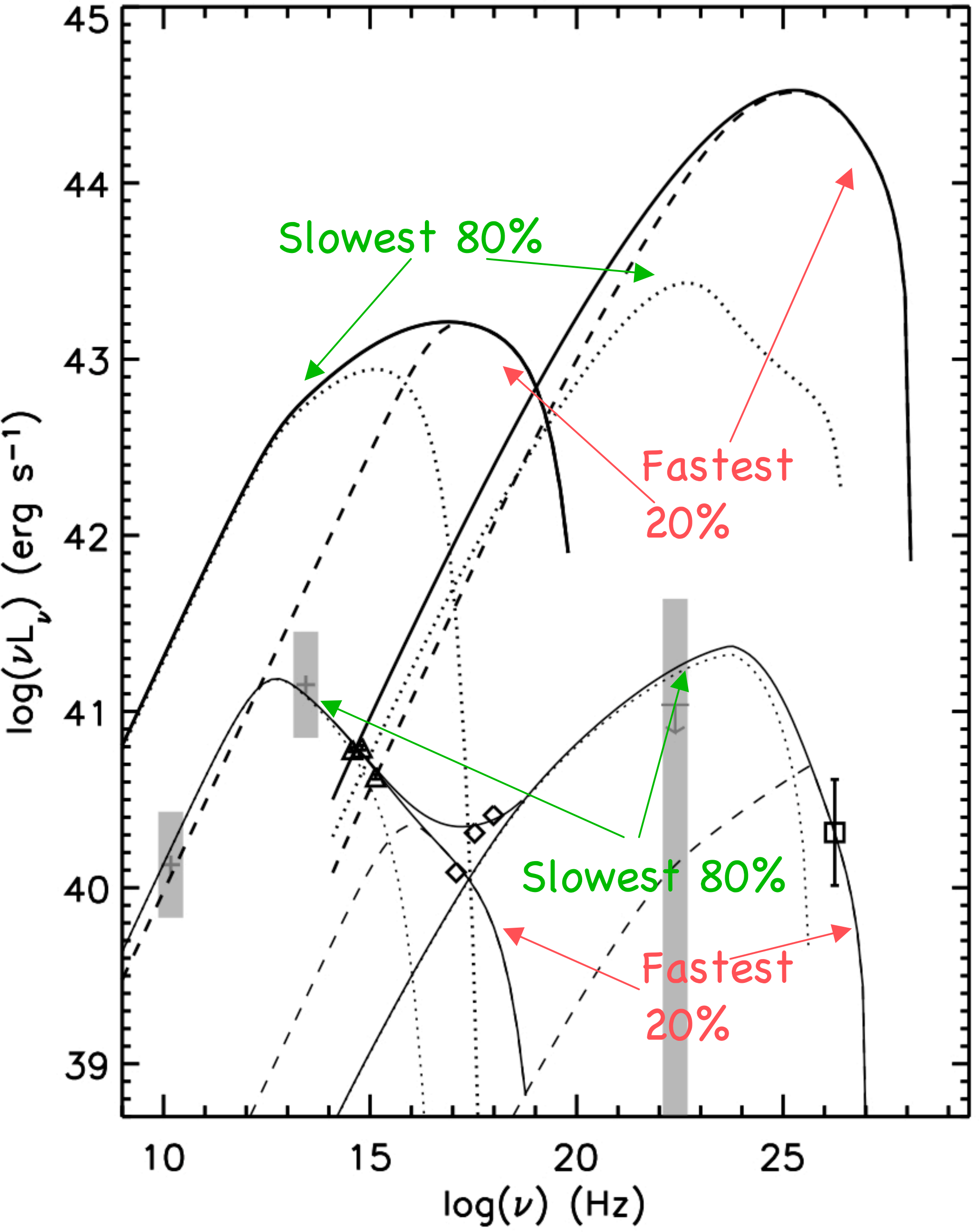
What happens if you beam this?

Upper set of curves are same jet seen at $\theta=1/\Gamma_{fast}=2.9°$

Completely different SED: properties dominated by fast part of flow!

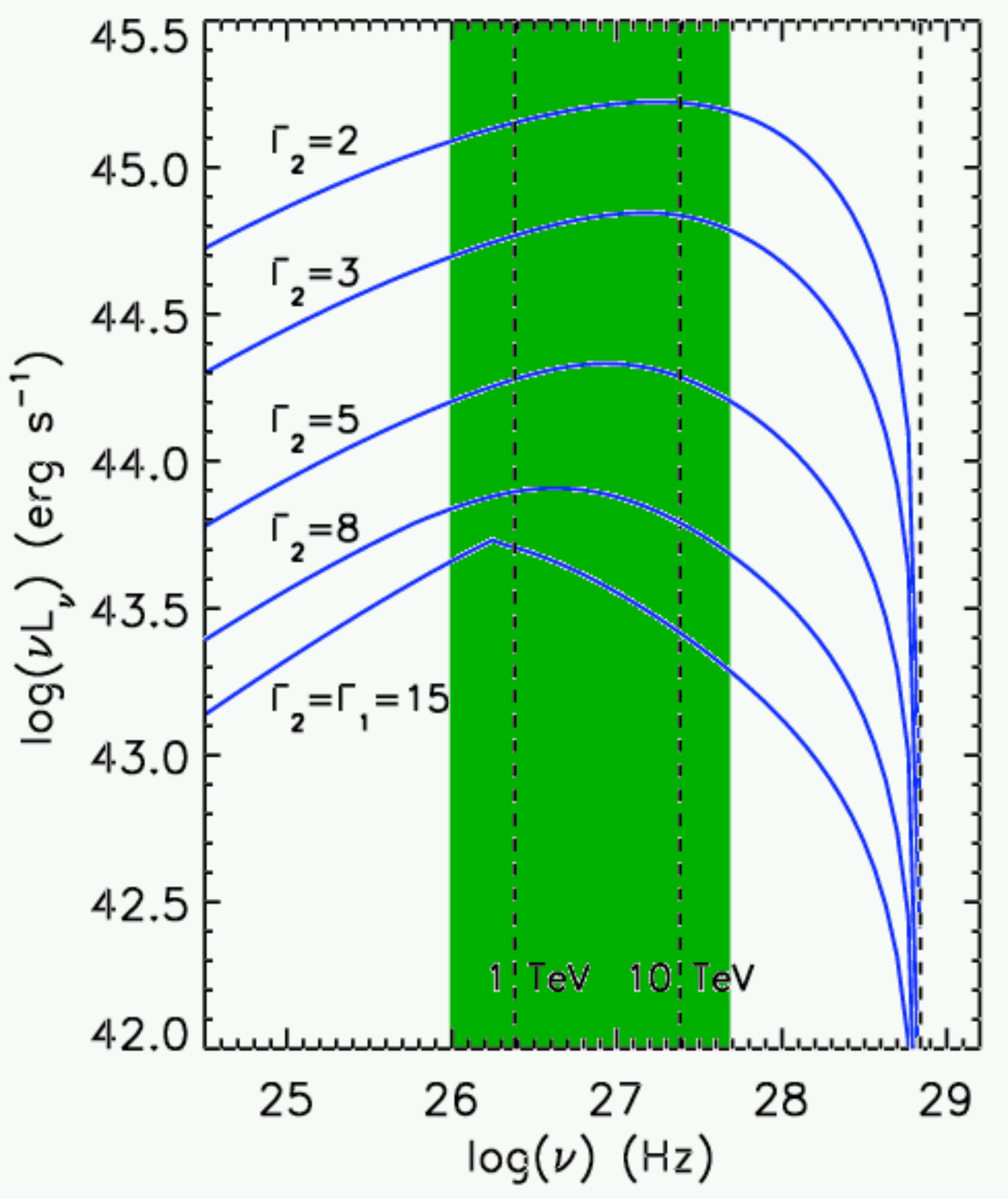
$\nu_s \approx 10^{17}$ Hz, $\nu_{IC} \approx 10^{26}$ Hz, Compton dominance ~30

Similar to TeV BL Lac 1ES1426+428.



Emission from a decelerating relativistic flow

The more a flow decelerates, the higher the UC peak energy and power.



Conclusions

- Nucleus is likely TeV emission site
- Very difficult to model via homogeneous jet
- Decelerating jet (or other velocity structure) is required
- Cautionary note for unified schemes -- Velocity structure may be the way to produce HBLs.

  At distance of Mkn 501 & Mkn 421 HST-1 and nucleus would be 0.06" apart; knot A would be at 0.8" … unresolved in optical from ground and not easily separable with Chandra.