Introduction

Blazars are broadband emitters and the most natural targets for multi-wavelength astronomy!

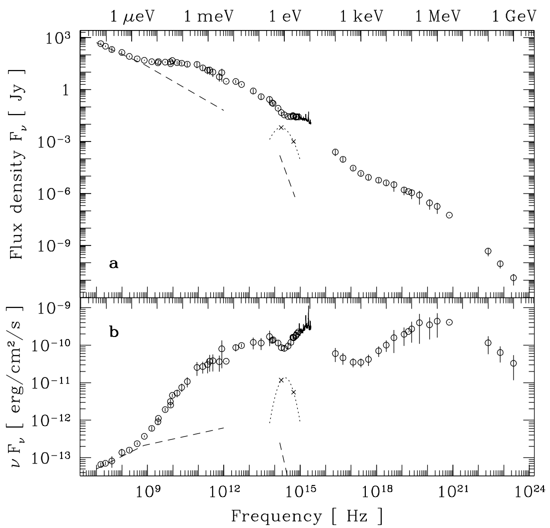
The expression *Blazar* was first used in 1978 to express that optically violently variable quasars (OVVs) and BL Lac objects share their extreme variability characteristics.

Although been first detected in the optical and radio, a large portion of their total energy output is at high energies: hard X-rays, γ-rays, and up to the very high energy (VHE) regime.

The *Compton Gamma-Ray Observatory (CGRO)* with its main detector EGRET revolutionized blazar research by the finding that blazars are the dominant population of extragalactic gamma-ray sources.

The short variability time scales (days!) indicated that the gamma-ray emission comes from beamed plasma (jets) to avoid photon-photon pair production in otherwise too dense gamma photon fields.

Prototypical Example: 3C 273, I

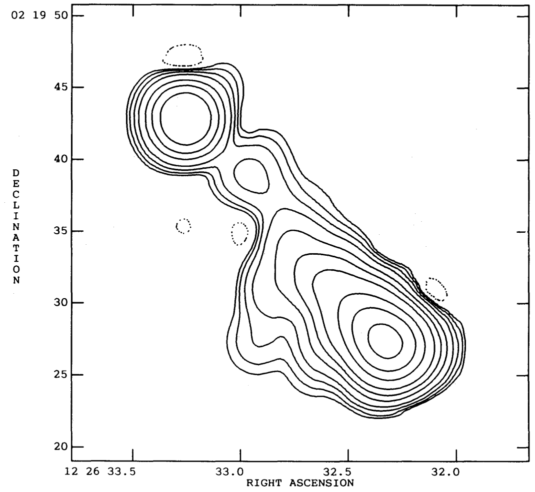


(Türler et al., 1999)

3C 273:

- First detected and brightest (and probably best studied) quasar
- Bright throughout the whole electromagnetic spectrum
- Prominent "big blue bump"
- Huge public database: Türler et al. (1999); Soldi et al. (2008)

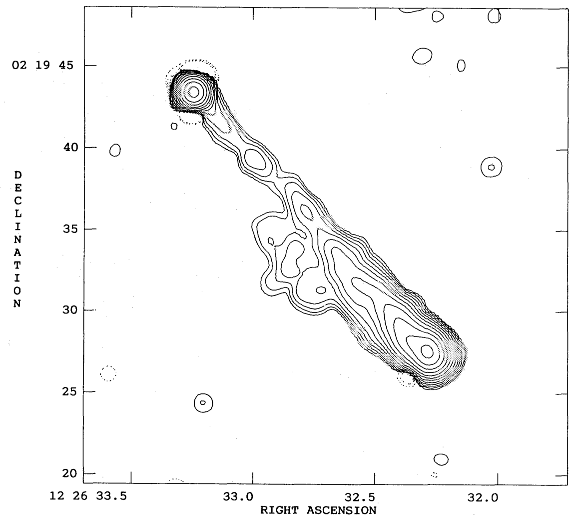
Prototypical Example: 3C 273, II



(Conway et al., 1993)

The kpc-scale jet of 3C 273 seen at $\lambda = 198$ cm with MERLIN

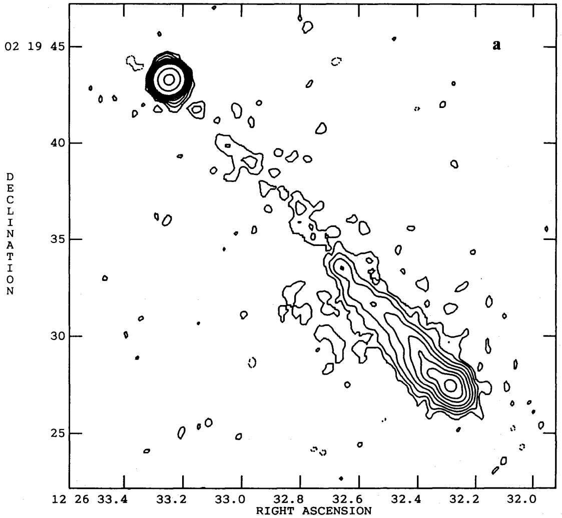
Prototypical Example: 3C 273, III



(Conway et al., 1993)

The kpc-scale jet of 3C 273 seen at $\lambda = 73$ cm with MERLIN

Prototypical Example: 3C 273, IV

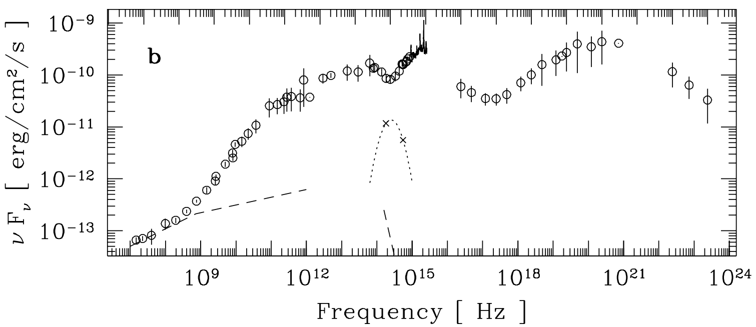


Contribution of large-scale jet negligible above ~ 5 GHz.

The kpc-scale jet of 3C 273 seen at $\lambda = 2$ cm with the VLA

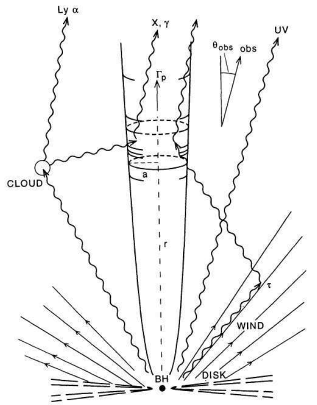
(Conway et al., 1993)

Prototypical Example: 3C 273, V



- Radio: low-frequency emission from large-scale jet; high-frequencies from compact jet (flat spectrum in F_ν)
- up to IR: synchrotron emission from compact jet (possibly plus dust component (dusty torus?))
- "big blue bump" in the optical: accretion disk (?)
- X-rays and up: inverse Compton emission (possibly from multiple seed photon fields)

Broadband Emission Models, I



Geometry in leptonic models (Sikora, Begelman & Rees, 1994)

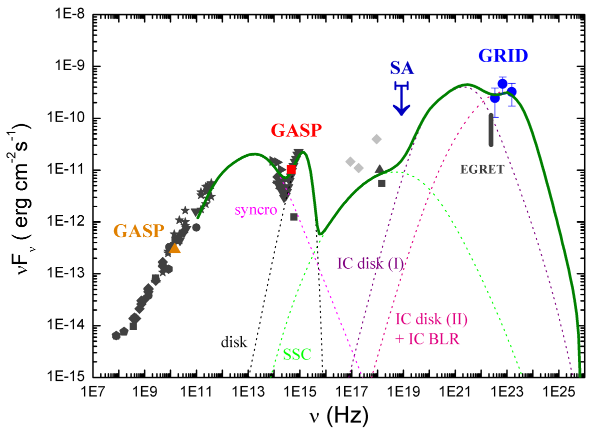
General agreement that the low-energy component is jet-synchrotron emission.

High-energy photons are produced in

- Leptonic models through IC scattering of soft seed photons by the same relativistic electrons responsible for the synchrotron emission. Seed photons are
  - the synchrotron photons themselves (SSC, e.g. Tavecchio, Maraschi & Ghisellini, 1998), or
  - external, e.g., from the accretion disk or the BLR (EC, e.g. Sikora, Begelman & Rees, 1994)
- Hadronic models through reactions involving high-energy protons (hadron-hadron or photon-hadron collisions, pair production and subsequent e^+e^- cascades (e.g. Mannheim, 1993))

Hadronic models are attractive because they can explain the observed ultra-high energetic (UHE) cosmic rays but they have problems explaining the observed blazar X-ray spectra.

Broadband Emission Models, II



Pucella et al. (2008)

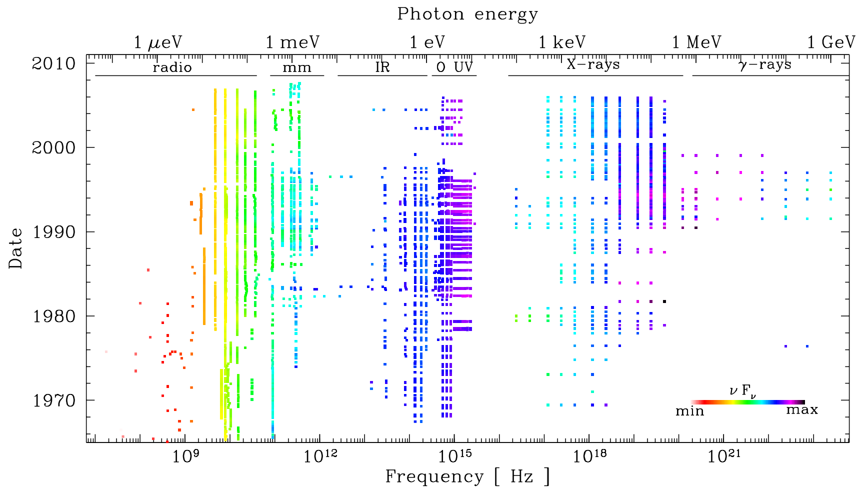
This is an SED of PKS B 1510-089; see below

Modeling the broad-band SED:

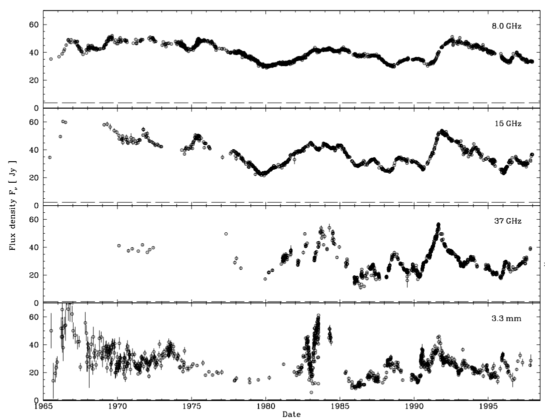
- Consider primary components: synchrotron, disk, scattered BLR emission
- Inverse-Compton components from SSC and EC (of the dominating external photon fields)

Prototypical Example: 3C 273 (continued), I

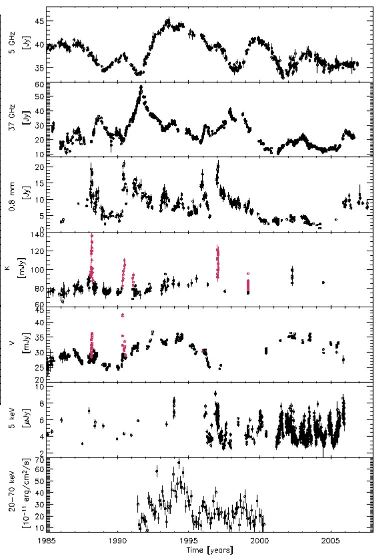
Almost 40 years of multiwavelength observations of 3C 273 (Soldi et al., 2008)



Prototypical Example: 3C 273 (continued), II



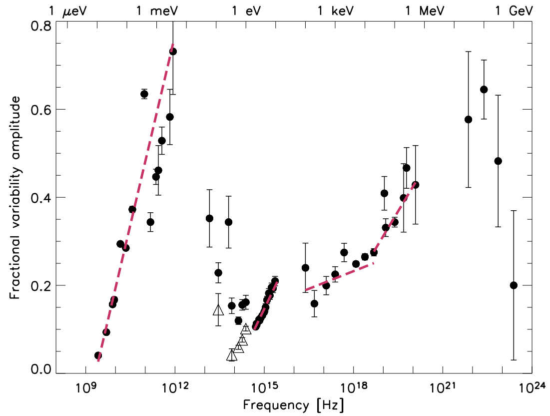
(Türler et al., 1999)



(Soldi et al., 2008)

Variability at all wavelengths but with different time scales and amplitudes ⇒ multiple emission components and/or mechanisms

Prototypical Example: 3C 273 (continued), III



(Soldi et al., 2008)

Fractional variability amplitude:

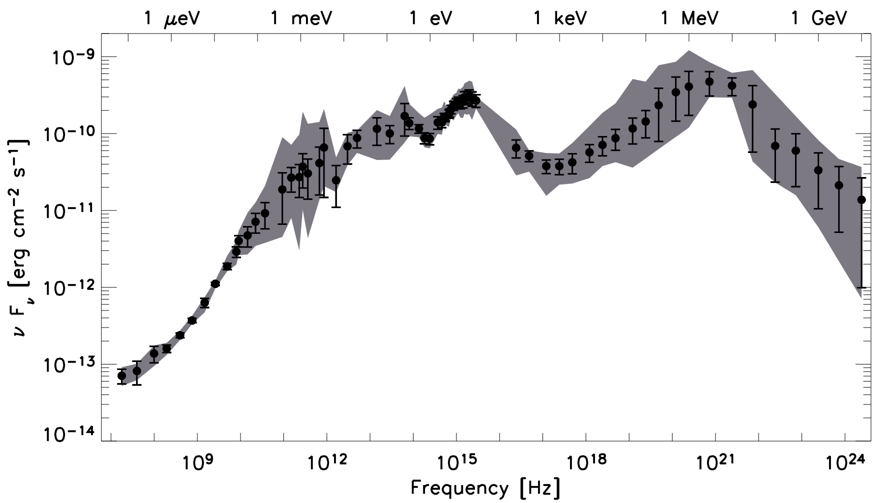
$$F_{\rm var} = \sqrt{\frac{S^2 - \bar{\varepsilon}^2}{\bar{x}^2}} \qquad (3.50)$$

with the sample variance of the light curve S^2, the average flux $\bar{x}$, and the mean of the squared measurement uncertainties $\bar{\varepsilon}^2 = \frac{1}{N}\sum_i \varepsilon_i^2$.

The fractional variability amplitude strongly depends on frequency, rising towards the high-energy end of the synchrotron and IC components. Less-variable IR emission (from dust?).

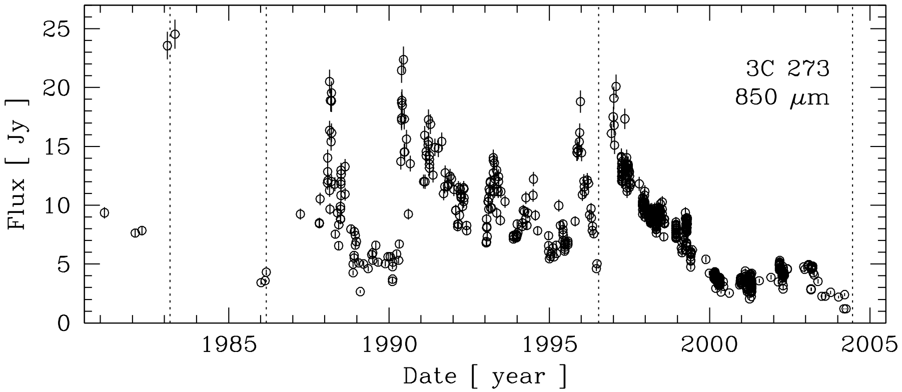
Prototypical Example: 3C 273 (continued), IV

Almost 40 years of multiwavelength observations of 3C 273 (Soldi et al., 2008)



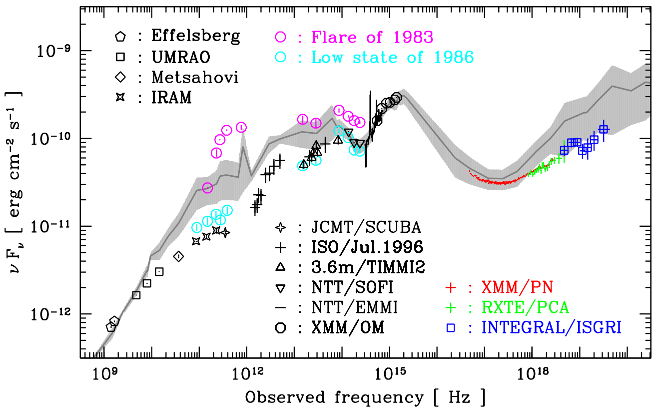
Prototypical Example: 3C 273 (continued), V

A historic jet-emission minimum (Türler et al., 2006)



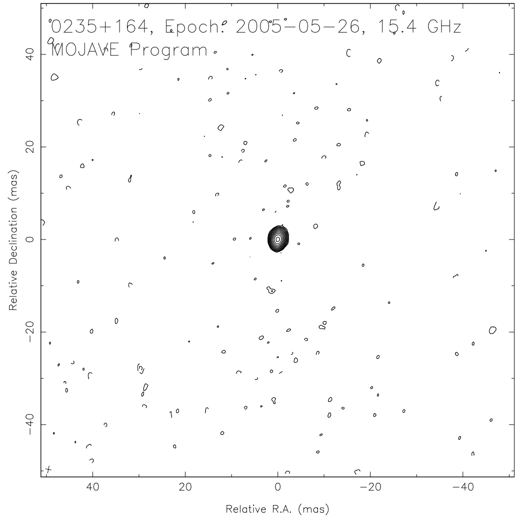
Prototypical Example: 3C 273 (continued), VI

A historic jet-emission minimum (Türler et al., 2006)



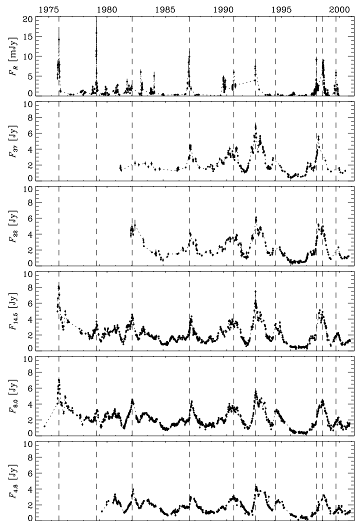
When the jet is weak, Seyfert-like features appear: Thermal dust, iron line; blue bump not directly coupled to jet emission

Pathological Example: AO 0235+16, I

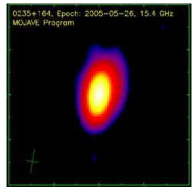


VLBI: always unresolved even with sub-milliarcsecond resolution

Pathological Example: AO 0235+16, II

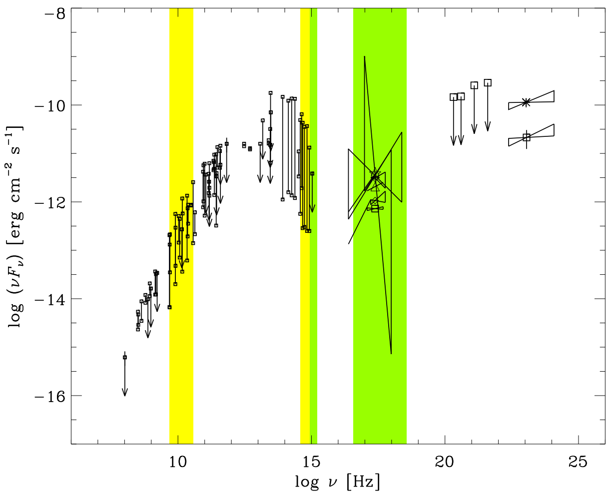


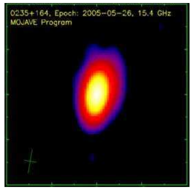
(Raiteri et al., 2001)



- Lightcurves: extremely variable with repeated multiwavelength outbursts
- Shown here: Optical R-band (top), Radio 37/22/15/8/5 GHz (2nd from top to bottom)
- Raiteri et al. (2001) claimed a 5–6 year periodicity

Pathological Example: AO 0235+16, III



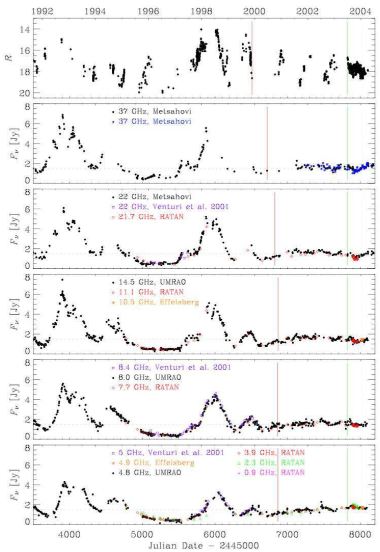


SED (as known in 2003):

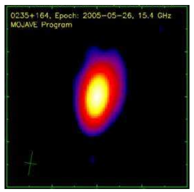
- Messy!
- Well studied radio–optical spectrum
- Confusing X-ray situation
- Bright gamma-ray spectrum

Yellow spectral regions targeted by a large observing campaign in 2003/04 (Epoch of the next predicted outburst)

Pathological Example: AO 0235+16, IV

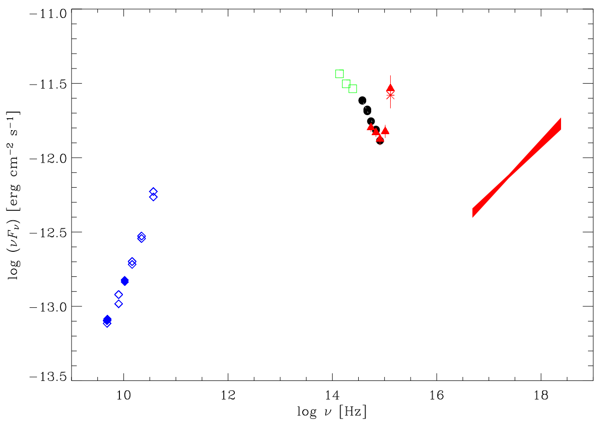


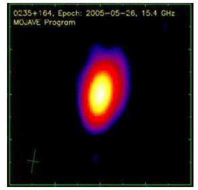
(Raiteri et al., 2005)



- AO 0235+16 in 2003/04: No outburst!
- Still: Campaign collected a wealth of multiwavelength data

Pathological Example: AO 0235+16, V



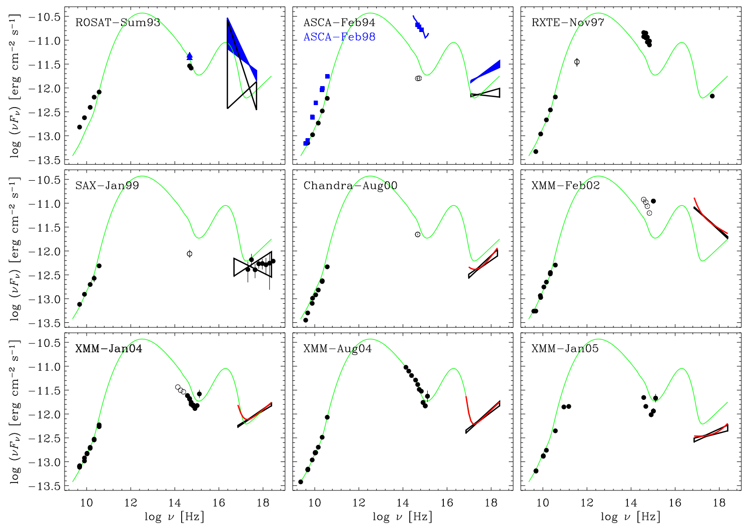


SED (measured in 2003/04 campaign):

- 24 optical/IR telescopes and 4 radio telescopes plus *XMM-Newton* were waiting for the outburst that never happened

Blazar SED with a primary (synchrotron) component in the radio–optical, secondary (IC) rising in the X-ray regime and an additional "bump" in the UV (Raiteri et al., 2005).

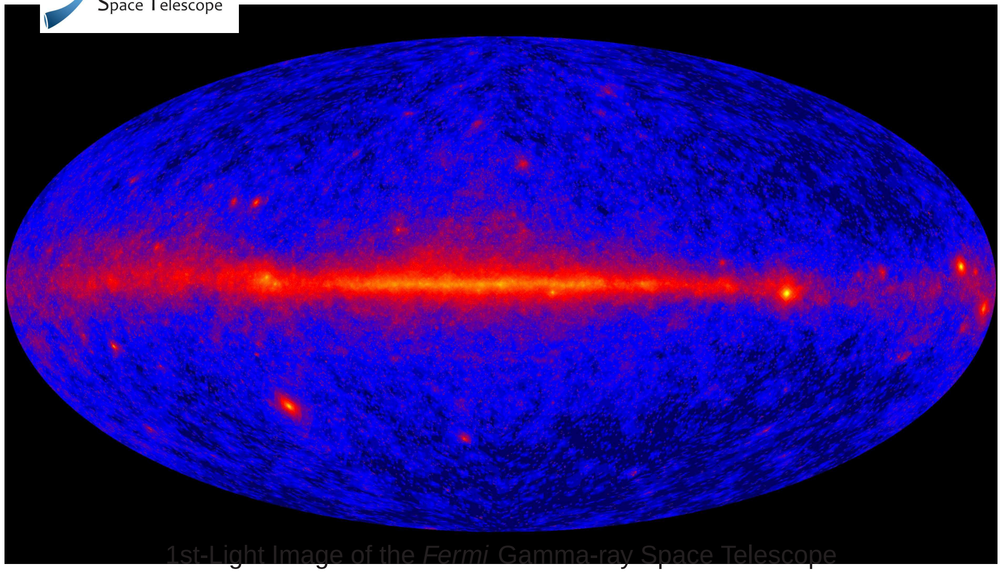
Pathological Example: AO 0235+16, VI



Long-term SED analysis: Raiteri et al. (2006)

Pathological Example: AO 0235+16, VII

The next big flare of AO 0235+16 occured in February 2007, close to the end of the optical visibility season...



1st-Light Image of the *Fermi* Gamma-ray Space Telescope
(one week of data in August 2008)

The *Fermi* and *Agile* Era, I

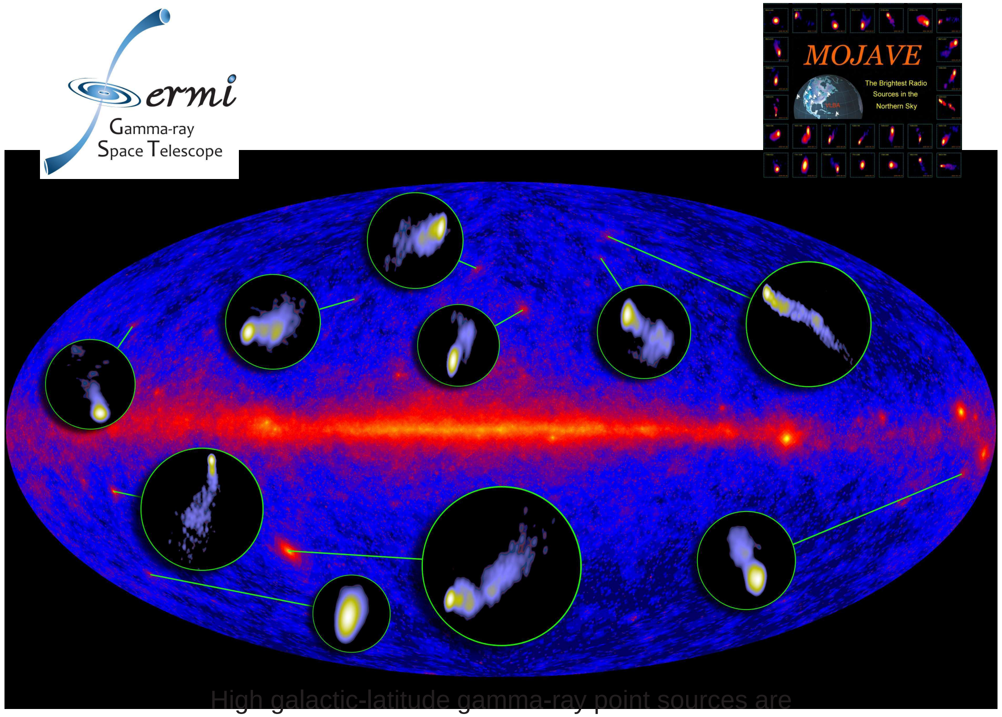
The elusive gamma-ray regime is much better covered than ever before:

Agile launched in April 2007. Now in routine pointed observations mode.

`http://agile.rm.iasf.cnr.it/`

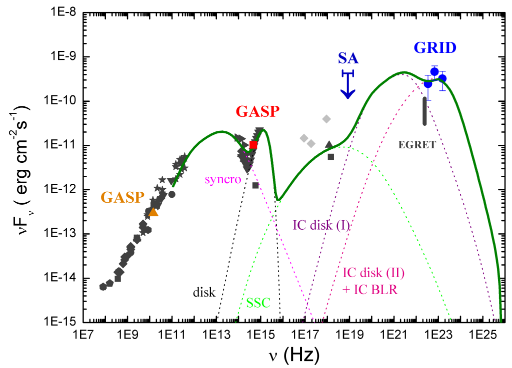
GLAST (Gamma Ray Large Area Space Telescope) launched in June 2008. Now renemed to *Fermi Gamma-Ray Space Telescope* and in routine all-sky monitoring mode.

`http://fermi.gsfc.nasa.gov/`



High galactic-latitude gamma-ray point sources are flat-spectrum radio quasars and BL Lac objects

The *Fermi* and *Agile* Era, IV



Agile+GASP observation of PKS B1510-089: Pucella et al. (2008)

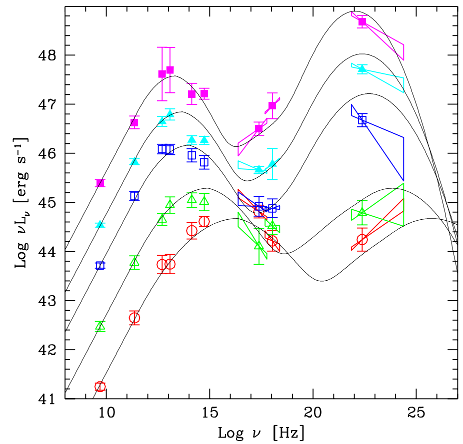
GASP: GLAST-Agile Support Program

Quasar PKS B 1510-089:

- 100 MeV to 1 GeV spectrum: PL with $\Gamma \sim 2$
- SED modeled with a synchrotron+SSC+IC model (external photon field from the disk and from BLR) for a jet with Lorentz factor $\gamma = 20$ observed at the critical angle $1/\gamma$.

MOJAVE speed for 1510-089: $\sim$ 20c!
Maybe even faster at 43 GHz (46 c)

The Blazar Sequence, I

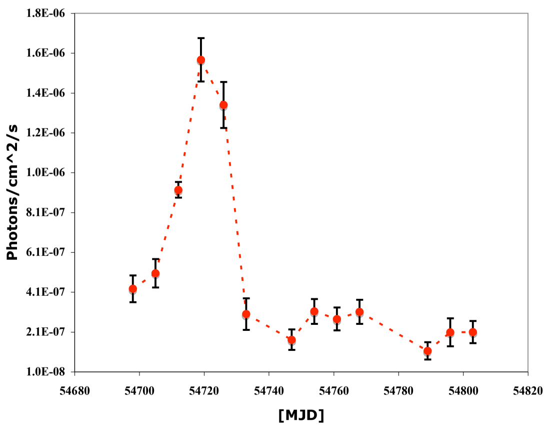


Construction of average blazar SEDs binned according to radio luminosity (Fossati et al., 1998; Donato et al., 2001)

- For all luminosity classes, two broad peaks
- High-luminosity sources peak at lower frequencies (IR and MeV range): LBL objects
- Low-luminosity sources peak at higher frequencies (UV/X-rays and up to TeV energies): HBL objects

(Donato et al., 2001, based on Fossati et al. (1998))

The *Fermi* and *Agile* Era, V



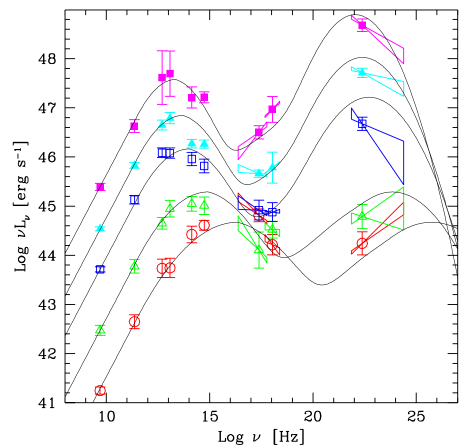
Fermi light curve of PKS B1510-089 (shown are weekly data points starting in late August 2007, about 1 year after the *Agile* pointed observation.)

- Bright flare of 1510-089 detected by *Fermi* in September 2008 (Tramacere, 2008)
- Analysis of follow-up multiwavelength observations going on
- LAT still in calibration phase ⇒ only photons/cm^2/s are published

The LAT detector onboard *Fermi* operates in all-sky scanning mode.

With *Fermi* it is now much easier to detect source flares and compare flaring and non-flaring SEDs.

The Blazar Sequence, II



Analytic parametrization:

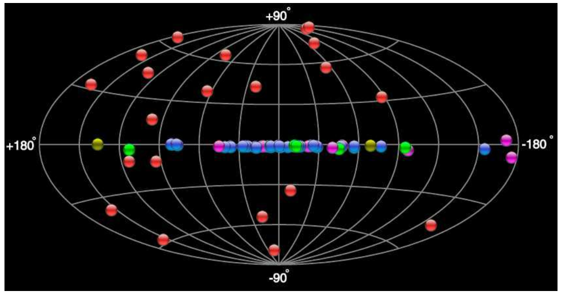
- Peak frequencies are inversely proportional to luminosity
- Constant ratio of the two peak frequencies
- Strength of the second peak proportional to luminosity

Attention: EGRET detected preferentiall blazars during outbursts ⇒ Bias in high-energy data.

Ongoing debate about the validity of the blazar sequence. A (small) number of sources does not fit in.

(Donato et al., 2001, based on Fossati et al. (1998))

Blazars at Very High Energies, I



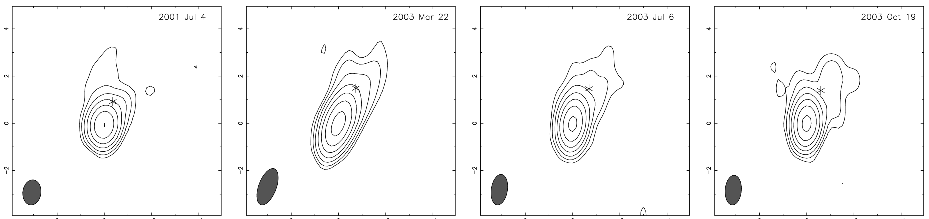
The blazar sequence predicts a dominance of HBL objects at very high energies. This is confirmed by recent blazar detections of TeV telescopes (H.E.S.S., MAGIC, VERITAS, CANGAROO):

- Currently 17 HBL objects detected and only two LBL objects (W Comae and BL Lac; check `http://tevcat.uchicago.edu/` for updated lists)
- Only non-blazar TeV source: M 87

Blazars at Very High Energies, II

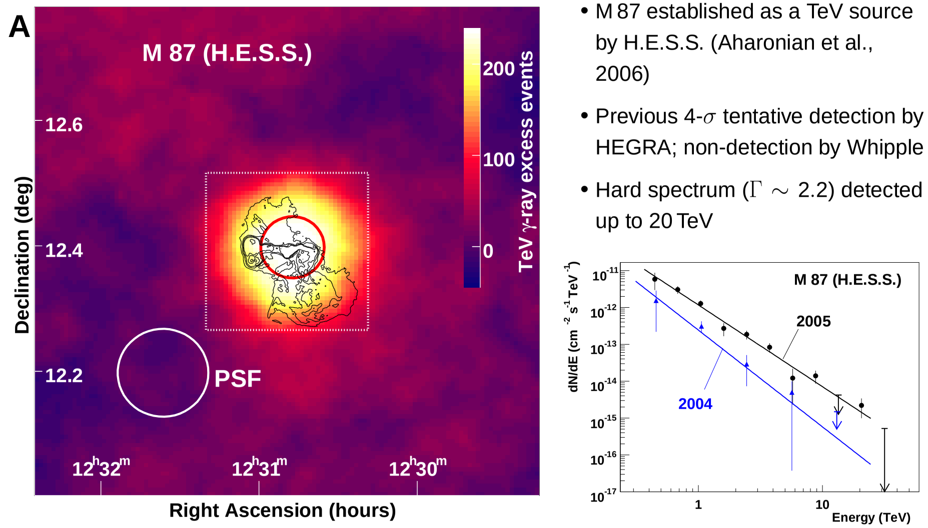
TeV blazars are weak radio sources, because the cm-range is so far left of their synchrotron peak and because they are low-luminosity objects.Similarly, they are bright X-ray sources and relatively weak in the MeV/GeV range.

Despite their variability and SEDs require very high Doppler factors, VLBI measures slow jets (barely superluminal Piner, Pant & Edwards, 2008, and references therein) $\Rightarrow$ 1) extremely small angles or 2) jet deceleration from the "blazar scale" to the "VLBI scale", or 3) another sign of jet-stratification (spine-sheath structure).



(Piner, Pant & Edwards, 2008)

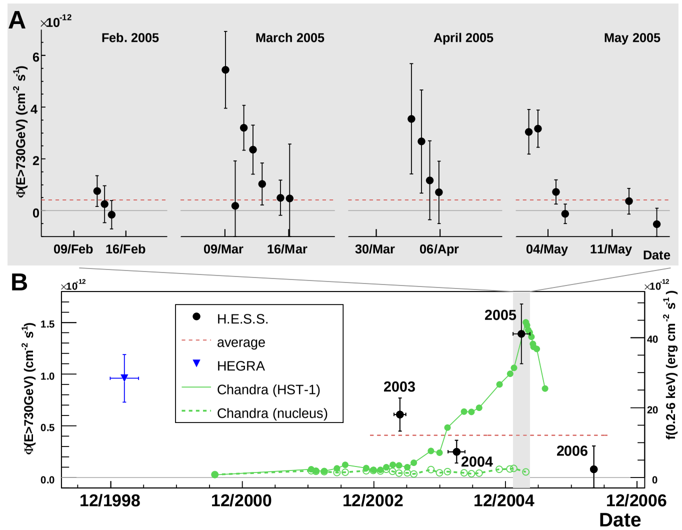
The Only TeV Galaxy: M 87



(Aharonian et al., 2006)

- M 87 established as a TeV source by H.E.S.S. (Aharonian et al., 2006)
- Previous 4-σ tentative detection by HEGRA; non-detection by Whipple
- Hard spectrum ($\Gamma \sim 2.2$) detected up to 20 TeV

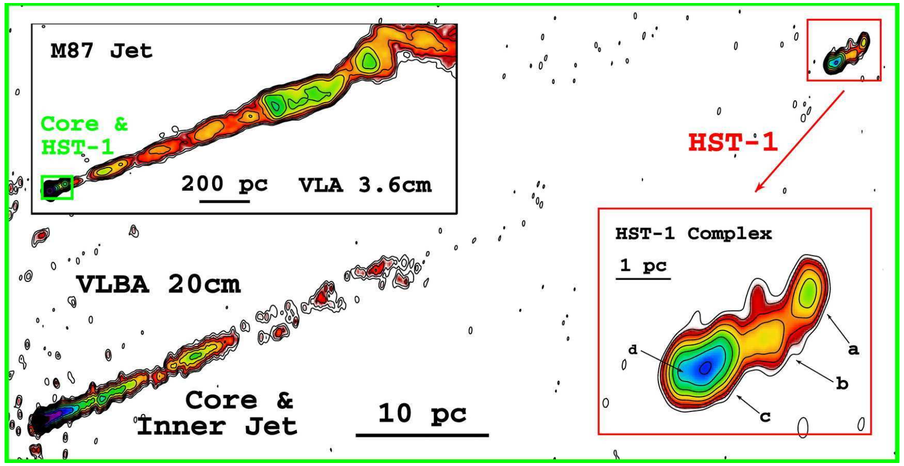
The Only TeV Galaxy: M 87



(Aharonian et al., 2006)

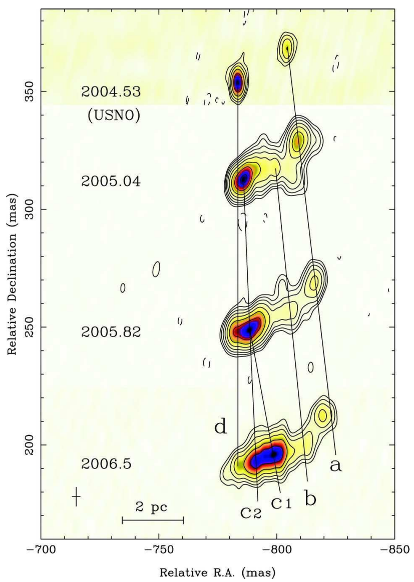
- TeV flux variable on time scales from years down to days
- Emission region must be compact
- Highest measured fluxes coincide with a flare of the HST-1 knot in the M 87 jet as measured by *Chandra* (Harris et al., 2006) (at this epoch brighter than the nucleus!)

The Only TeV Galaxy: M 87



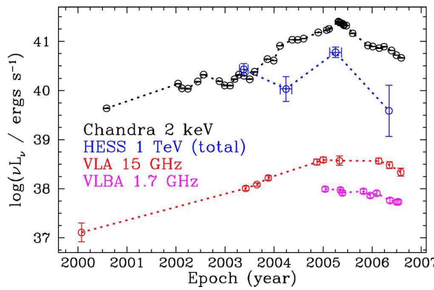
HST-1 resolved by VLBI, but still compact sub-structure (Cheung, Harris & Stawarz, 2007)

The Only TeV Galaxy: M 87



- HST-1 has moving sub-components with superluminal speeds up to $\sim\ 4c$ in agreement with optical measurements by Biretta, Sparks & Macchetto (1999).

$\Rightarrow$ Relativistic bulk motion $>$ 120 pc downstream from the central engine and coinciding with the flaring putative TeV emission region



(Cheung, Harris & Stawarz, 2007)

The Only TeV Galaxy: M 87

A new TeV flare of M 87 has been seen in early 2008 by MAGIC (Albert et al., 2008). The M 87 jet was under intense VLBA monitoring at the time of the flare. To be continued...

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