Jets Lecture 6

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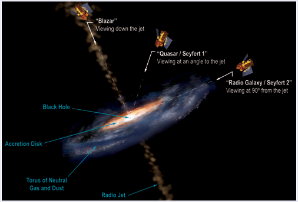
Outline

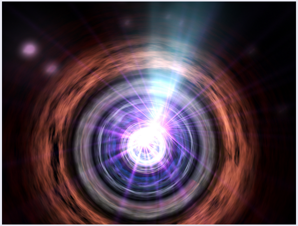
Blazars

Blazar phenomenon - An AGN jet seen (almost) end-on

- A powerful jet seen in end-on → relativistic boosting amplifies the jet emission

Credit: A. Simonnet, Sonoma State U.





Credit: NASA GSFC

Blazar phenomenon - An AGN jet seen (almost) end-on

- A powerful jet seen in end-on $\rightarrow$ relativistic boosting amplifies the jet emission
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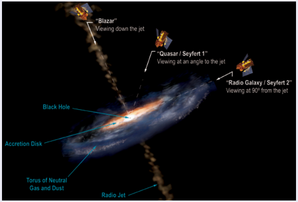

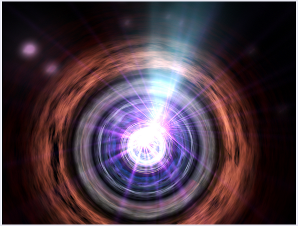

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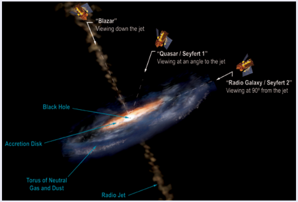

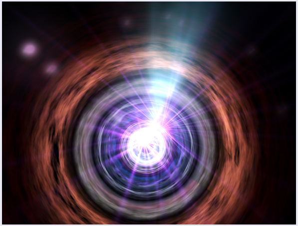

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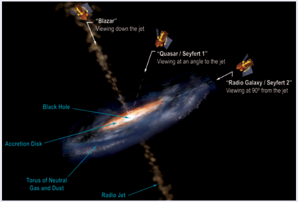

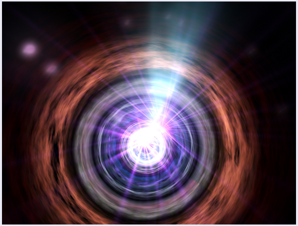

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- Significance: allow detailed studies of the jets (across a wide redshift range)

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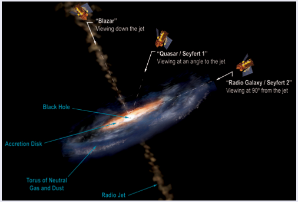

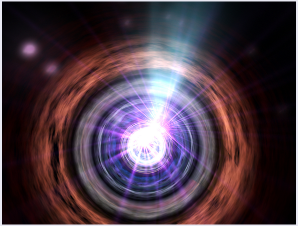

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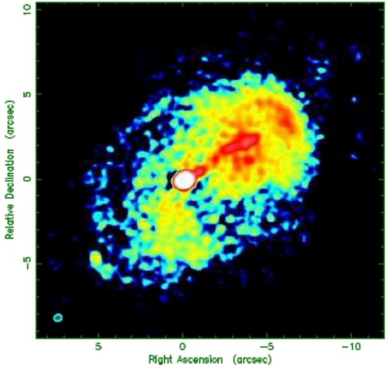
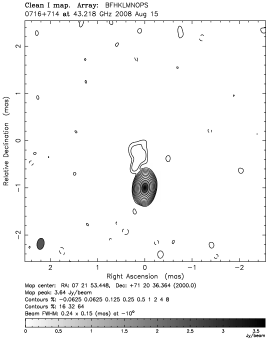
Compact morphology of blazars



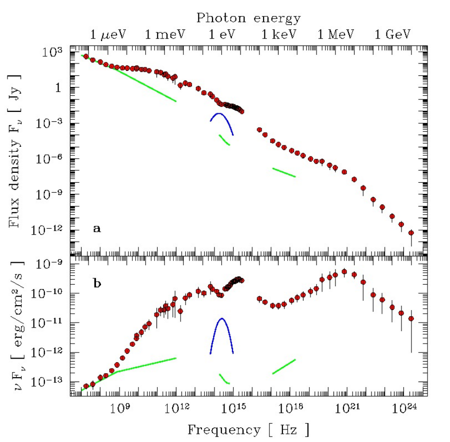


Left: Large scale radio structure of blazar 0716+714. (Credit: U. Bach) Right: 43 GHz VLBA image of the innermost part of the jet in 0716+714. (Credit: Boston Uni. blazar monitoring program) Note how almost all the flux density is concentrated within a few milliarcsecond-size compact jet!

Blazar spectral energy distribution - an example

- In the SED: two broad "humps" – synchrotron hump between radio and optical/X-rays + high energy emission hump from X-rays to GeV/TeV γ-rays (which dominates the SED!)

FSRQ 3C 273. Blue line: host galaxy – green line: approximate contribution from the outer jet (Credit: M. Türler)



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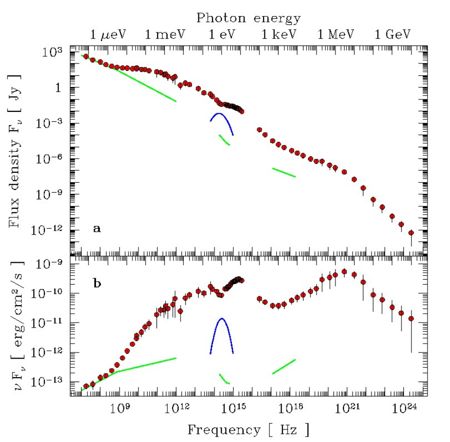

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- Note the flat part in the radio/mm-spectrum

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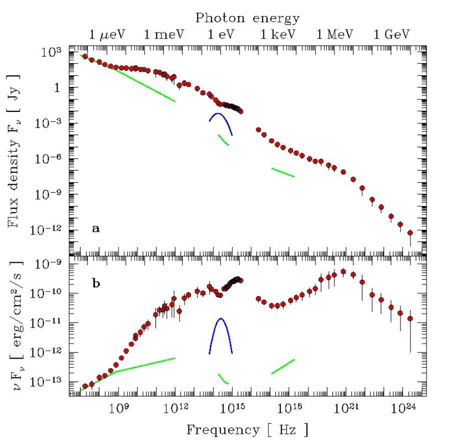
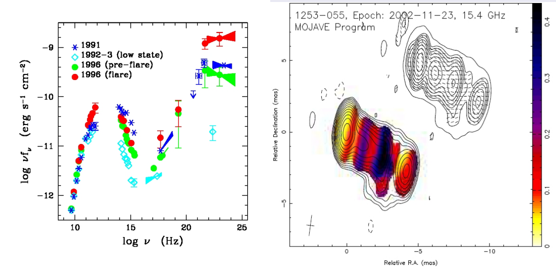


Types of blazars: Flat-spectrum radio quasars

- Highly luminous sources. High energy component dominates.

3C279 [Wehrle et al. (1998) / MOJAVE]



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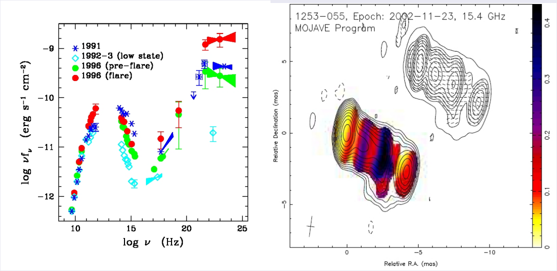

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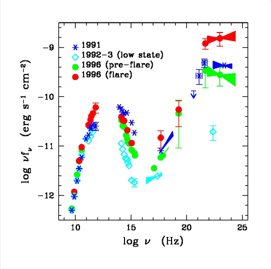

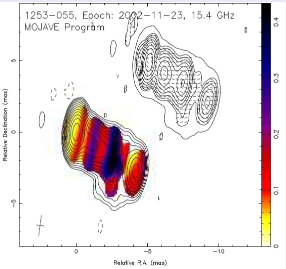

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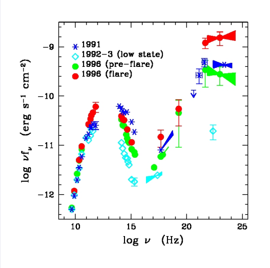

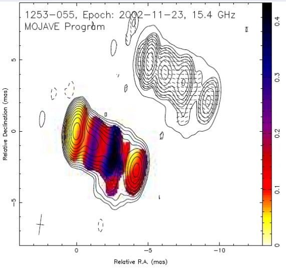

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- "Knotty" parsec-scale jets

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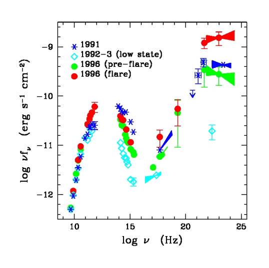
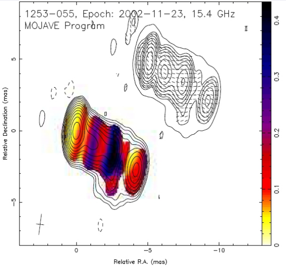
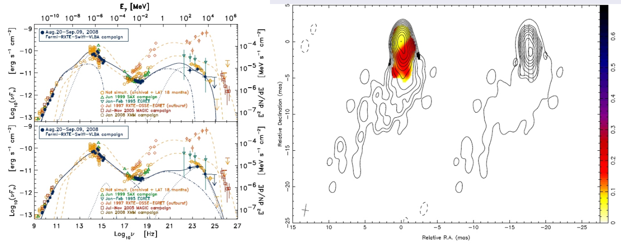




Types of blazars: BL Lac objects

- Named according to a prototype source BL Lacertae

BL Lac [Fermi-LAT team / Savolainen]



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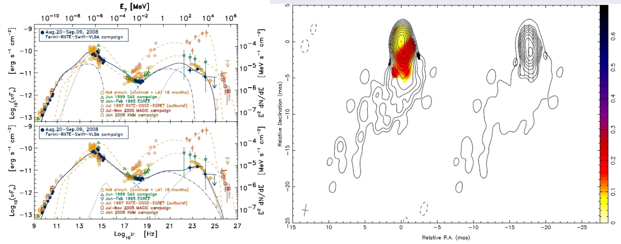

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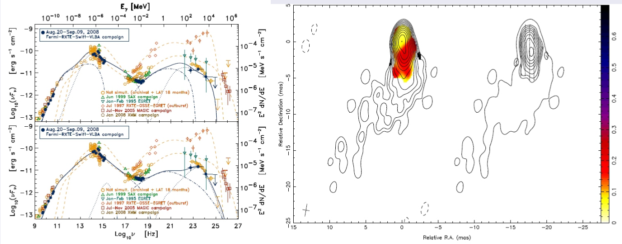

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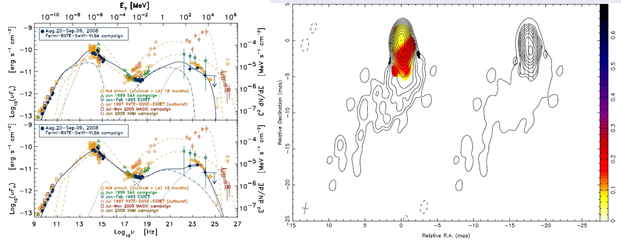

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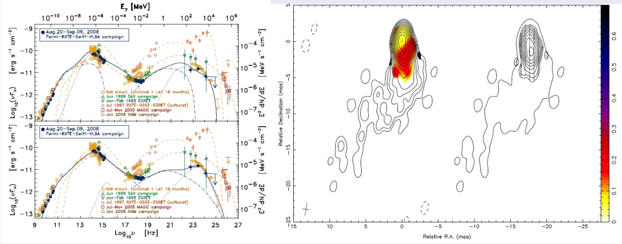
- Wide range of SED synchrotron peak frequencies: LBL ($< 10^{14}$ Hz), IBL (10^{14} Hz$< \nu_m < 10^{15}$ Hz), HBL ($> 10^{15}$ Hz)

BL Lac [Fermi-LAT team / Savolainen]



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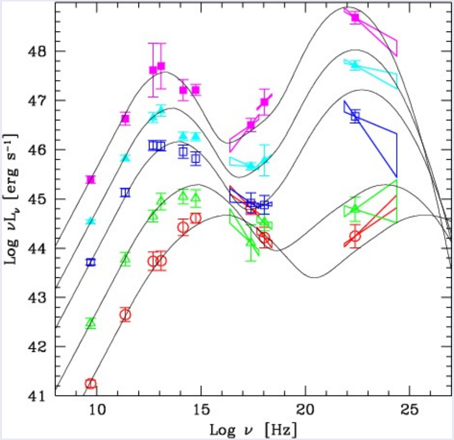

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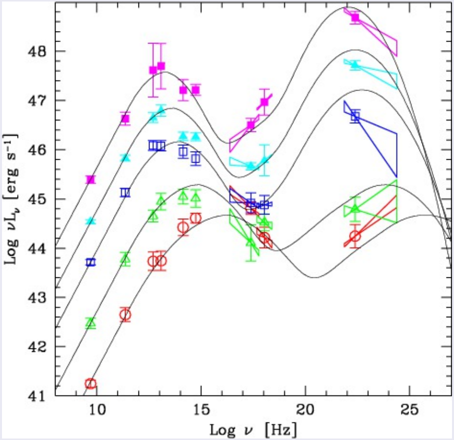

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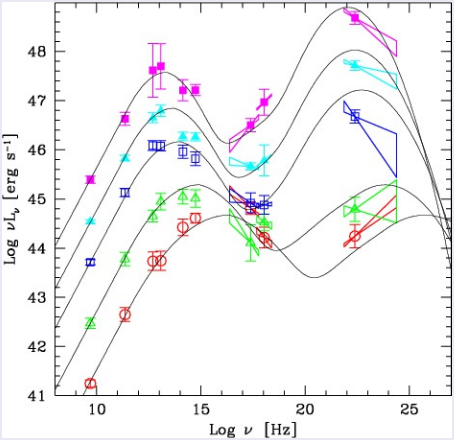

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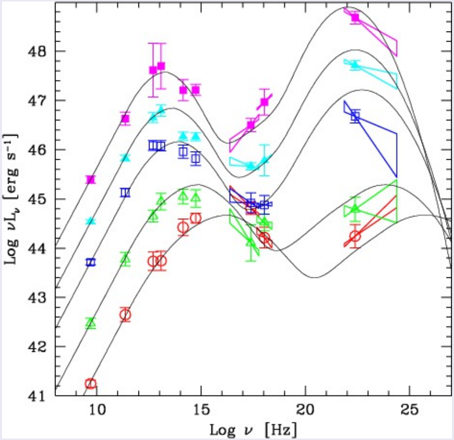

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- Does luminosity alone describe all the blazar properties?

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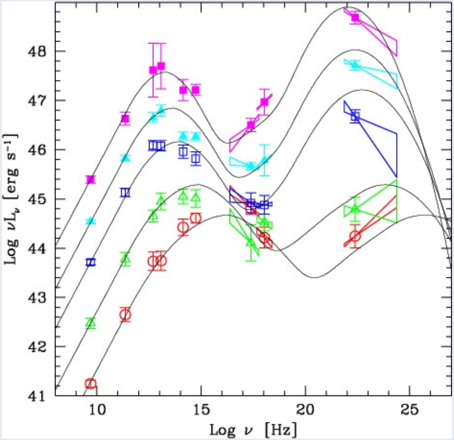
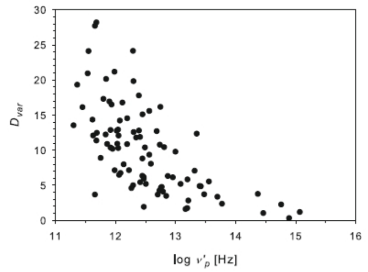


Blazar sequence – explanations and criticism

- Classical explanation (Ghisellini): all high frequency peaking blazars are BL Lacs with weak or absent emission lines → they have less external seed photons for IC scattering → radiative losses are not as severe as in FSRQs and electrons achieve higher energies

Nieppola et al. (2008)



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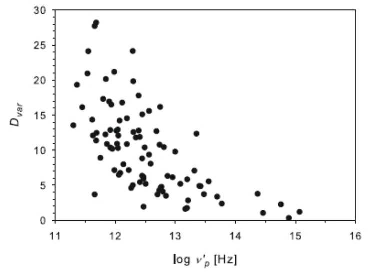

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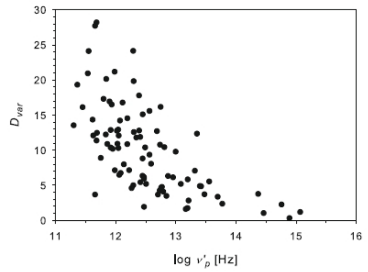

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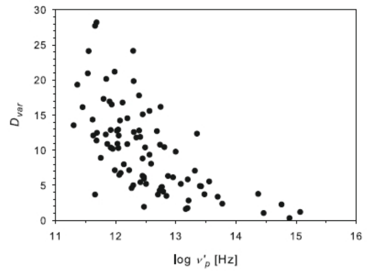
- Criticism 2: Giommi et al. (2011) recently proposed that the sequence is due to selection effects from comparing shallow radio and X-ray surveys. "There

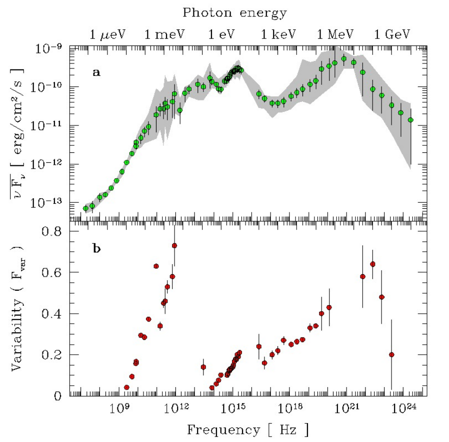
Nieppola et al. (2008)



Blazar variability

- Blazars are highly variable throughout the electromagnetic spectrum

Credit: M. Türler



Blazar variability

- Blazars are highly variable throughout the electromagnetic spectrum
- Radio-to-optical part has typically: 1) larger variability amplitudes and 2) faster time scales at higher frequencies. Similar behaviour can be seen in the high energy hump.

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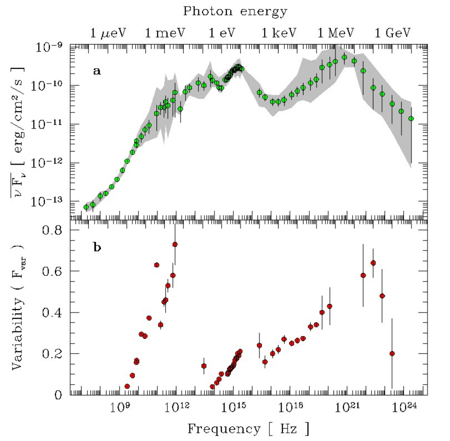

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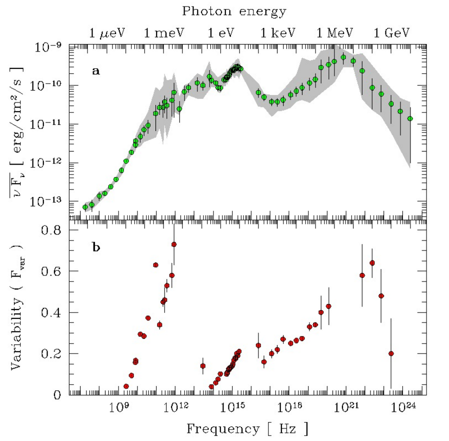
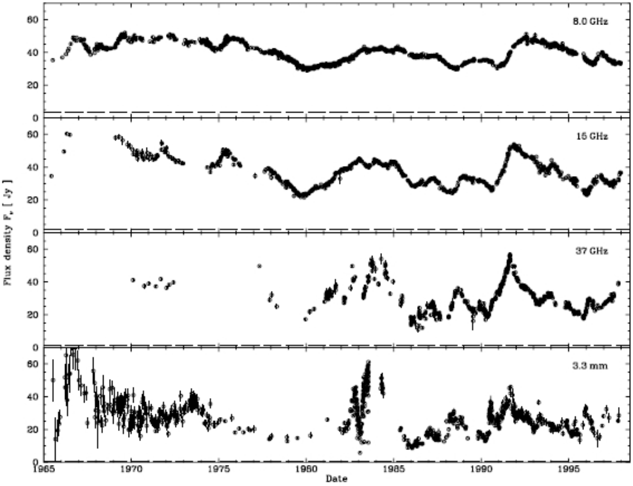
- Radio-to-optical part has typically: 1) larger variability amplitudes and 2) faster time scales at higher frequencies. Similar behaviour can be seen in the high energy hump.
- The variations at different bands are correlated, but in a complicated way and with delays: 1) In the synchrotron part, flares typically propagate from high to low frequencies. 2) Correlations between synchtron and high energy hump exist but are complicated

Credit: M. Türler

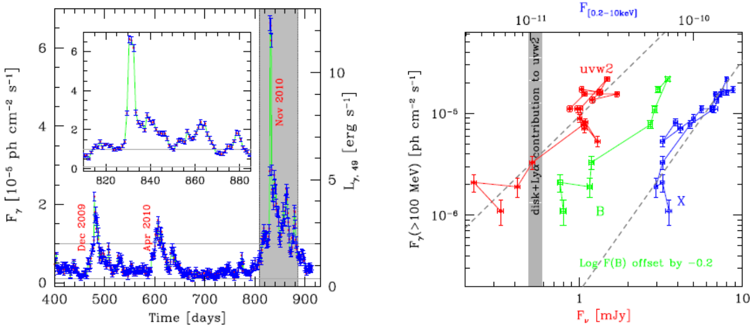


Blazar variability – an example of 3C273 light curves



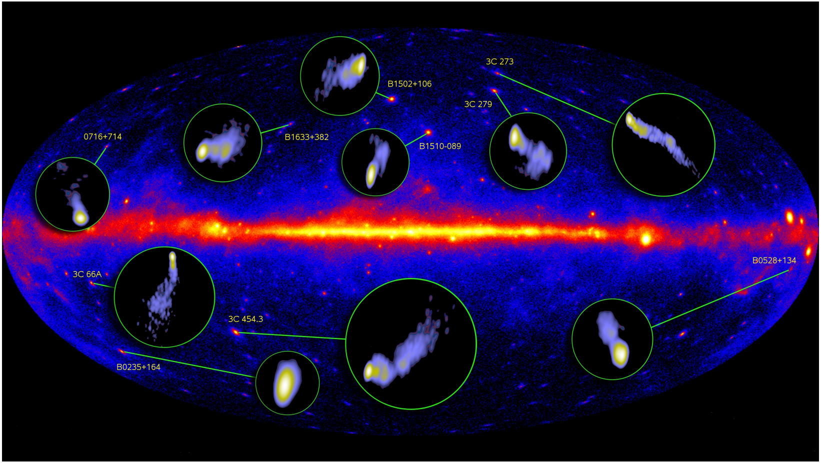
Türler et al. (1999)

Blazar variability – correlations



Strong GeV-optical correlation in 3C454.3 during the flaring period in 2010: the same emission region! [Tavecchio et al. (2010); Bonolli et al. (2010)] There are also correlations (although more complicated) between mm-emission and GeV γ-rays as we shall see later.

GeV emission from blazars



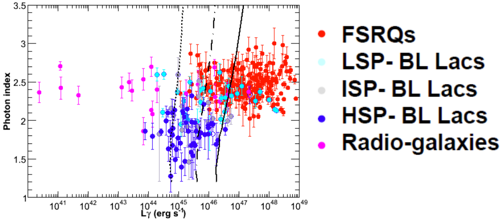
1-yr Fermi-LAT γ-ray sky with VLBI-scale jets from the MOJAVE survey as insets.

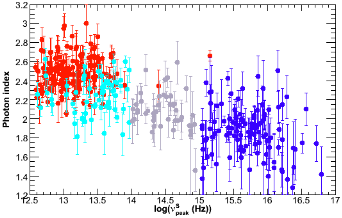
Being an all-sky monitor, Fermi is a fantastic tool for detecting flaring blazars!

1FGL – Properties of γ-ray AGN

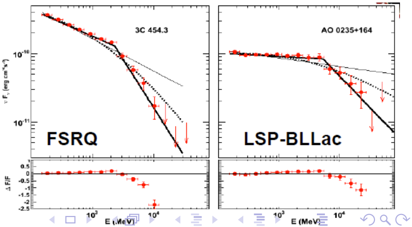
- Gamma-ray spectra:
  - Photon index correlates with blazar class

Lott+





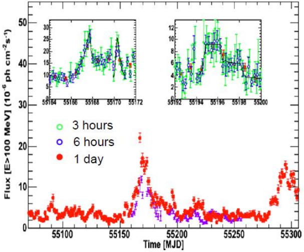
- Many FSRQs and LSP-BL Lacs show broken power-law spectra
  - $\Delta\Gamma \sim 1 \rightarrow$ not from radiative cooling
  - Due to a break in the underlying particle energy distribution?
  - KN-effect?
  - Photon-photon absorption: Intrinsic? Or on HeII Lyman recombination continuum + lines (Poutanen & Stern 2010) ?

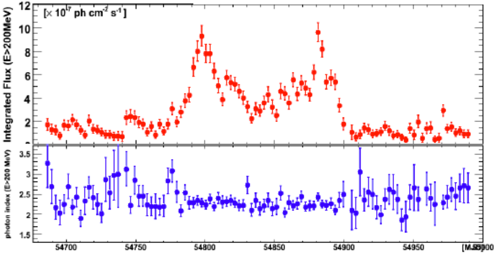


1FGL – Properties of γ-ray AGN

- Revolution in GeV variability studies – "All the sky (almost) all the time"
- Variability time scale range from months to hours
- Power-law PSD of slope -1..-2
- Relative constancy of photon index

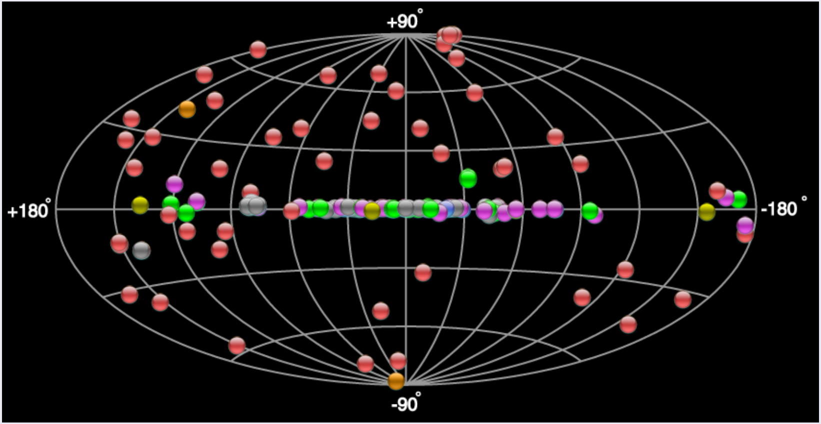
3C454.3





Lott+

TeV emission from blazars



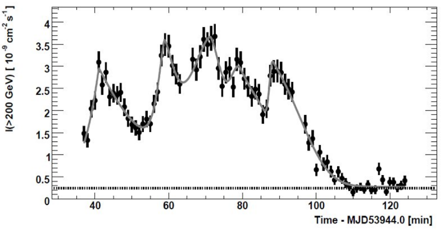
From tevcat.uchicago.edu. Red symbols mark TeV AGN.

- More than 40 blazars detected in TeV γ-rays, mostly HBLs, but also three FSRQs! 3C279 is the highest z detection (by MAGIC telescope)

Rapidly variable TeV emission

- Minutescale TeV variability observed in some sources requires (in one-zone models) very high Lorentz factors in order to avoid too high photon densities making the source opaque due to pair production

Minutescale TeV variability in 2155-304 observed by H.E.S.S.



Aharonian et al. 2007 (H.E.S.S. Collaboration)

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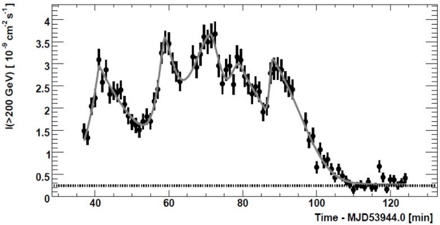

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- On the other hand, these same sources have very slow apparent jet speeds when measured with VLBI!
- Lorentz factors in excess of ~ 50 are not likely based on superluminal motions – therefore minutescale variability suggests emission regions much smaller than the cross sectional radius of the jet

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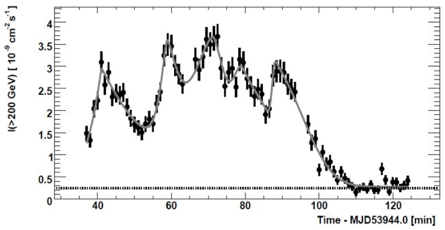

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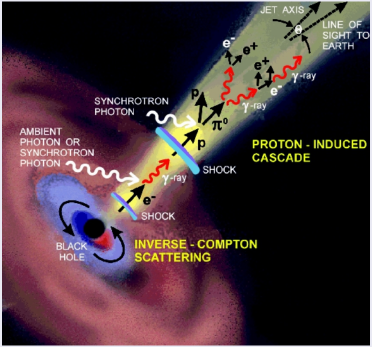
Blazar emission models

Blazar γ-ray emission

- While there is a general agreement that the low-energy hump in blazars is due to synchrotron emission, the origin of the high energy hump is less clear



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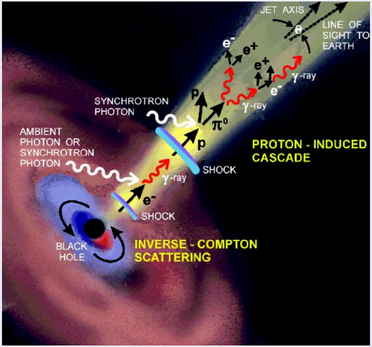

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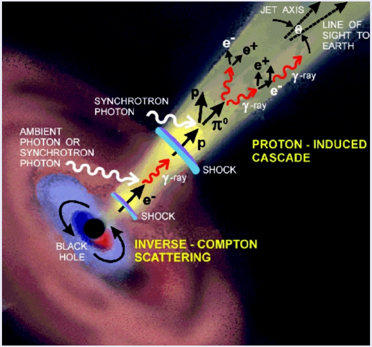

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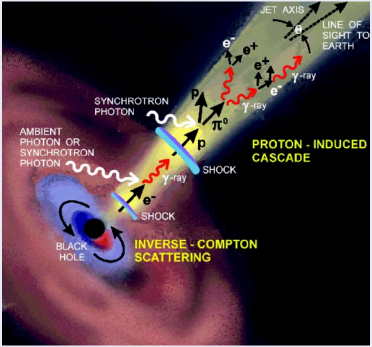
- In hadronic models, relativistic protons are also present in the jet. Interaction with photons can lead to production of neutral pions that will decay into gamma-rays (and then pair produce and then IC-scatter... a cascade). Another route involves neutrons and charged pions which will produce positrons and neutrinos.



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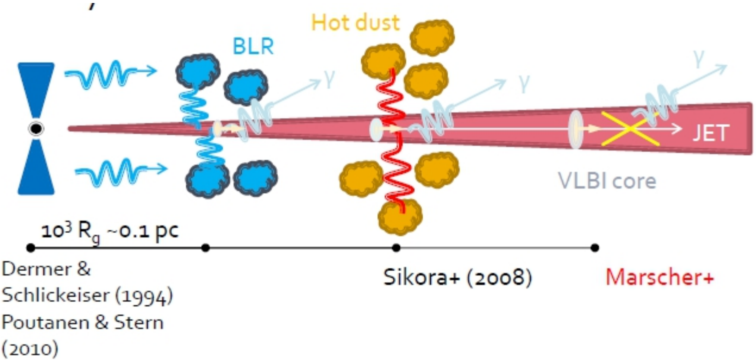
- (Evolve the electron spectrum – time-dependent case)
- Compare with measured SEDs and adjust parameters to fit

Question of the actual γ-ray emission site

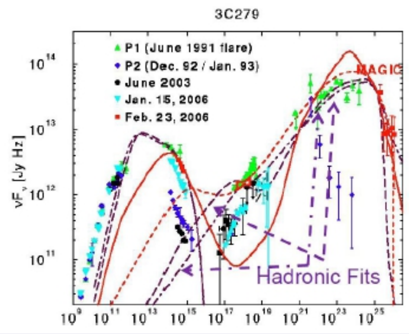


The question about the actual location of the emission region is important, since at different distances from the central engine, there are different radiation environments. Are γ-rays coming from a single or from multiple regions? Different regions dominate in different sources? Currently under hot debate.

Lepto-hadronic models

- To exceed p-γ pion production threshold on interactions with synchrotron photons: $E_p > 7 \times 10^{16} E_{\mathrm{ph}}^{-1}$ eV
- For proton-synchrotron emission at multi-GeV energies: E_p up to 10^{19} eV (UHECR) and high magnetic field ($B > 10\,\mathrm{G}$)
- Provide a succesful fit to 3C279 SED during TeV detection, but have problems in explaining fast variability, and also require high jet luminosities

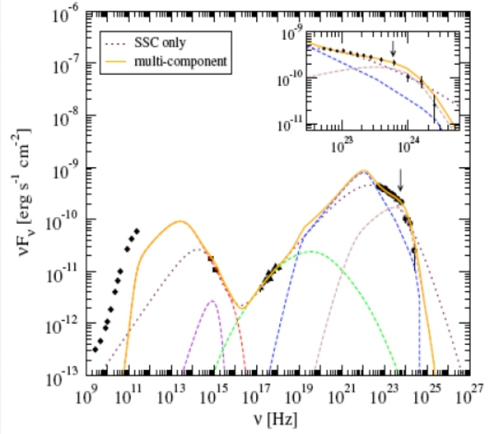
Credit: M. Böttcher



General problem with most (single-zone) SED models

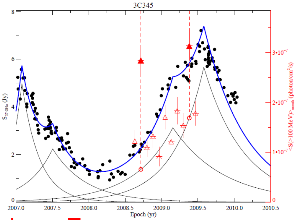
They model optical-γ-ray part of the SED, but not radio-FIR part, which is assumed to be optically thick and not due to the same region as opt-γ part. However... there are correlated γ-ray and mm-wave emission events!

Credit: Finke & Dermer

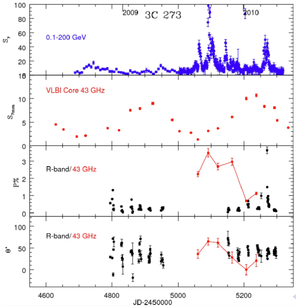


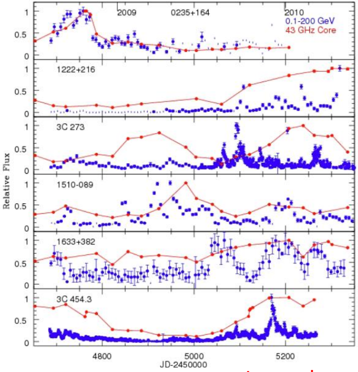
Localization…: mm – optical - gamma-ray connection

- Extended high gamma-ray states coincide with increase in mm-core flux (Jorstad+)
- Strongest gamma-ray flares typically during rise/peak of mm flare (Valtaoja+)
- Degree of linear polarization in mm-core increases during gamma-ray activity. Flare in degree of optical pol. at the time of a large gamma-ray flare (Jorstad+, Agudo+)



Leon-Tavares+





Jorstad+

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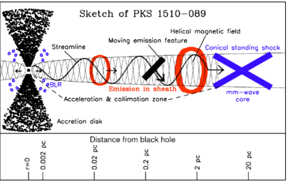
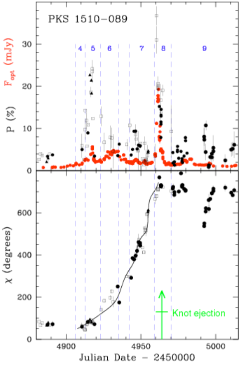
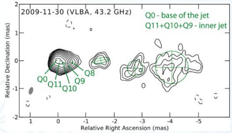
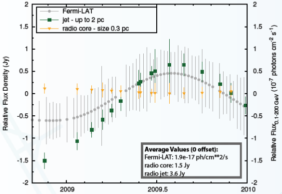




- PKS1510-089: >700 deg rotation in optical EVPA – ends at the time large gamma-ray flare. Simultaneously, a VLBI knot is ejected from the core. Single knot responsible for the outburst.
- Model: Emission feature following a spiral path through toroidal B field and finally colliding with a standing shock 17 pc from the BH.
- Disturbance sees different local seed photon fields during its propagation. (Marscher+)



- 3C345: Increasing trend in gamma-rays matches that of the inner jet at 43 GHz – not the core! Not a single emission region. (Schinzel+)

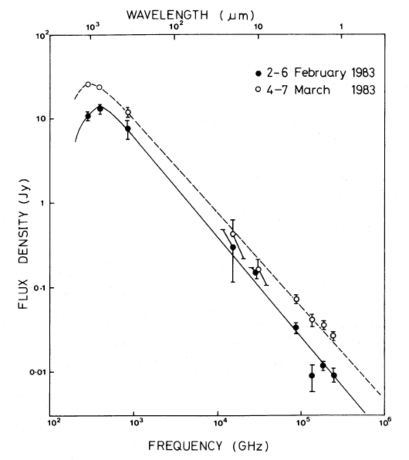


Physical models of the emission region(s) in blazars

First model: adiabatically expanding synchrotron plasmon

- The simplest model for synchrotron variations is an adiabatically expanding magnetized plasmon containing energized electrons (Shklovsky; van der Laan in the 1960s).
- Adiabatic losses dominate the spectral evolution – the predicted behaviour is decreasing synchrotron peak flux density with decreasing synchrotron peak freaquency
- Cannot explain the initial evolution of many flares in mm-regime where the peak flux increases initially with decreasing peak frequency

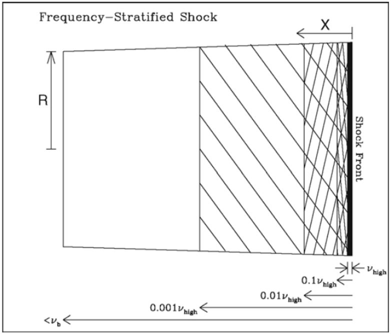
Marscher & Gear (1985)



Shock-in-jet (Marscher & Gear 1985)

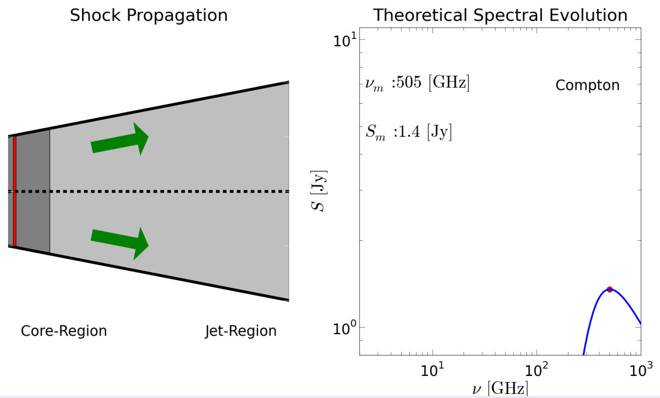
- A frequency-stratified shock model: 1) particles accelerated only at the shock front, 2) they advect away from it experiencing radiative losses, 3) highest energy electrons cool fastest $\rightarrow$ are confined to a thin layer behind the shock
- Thickness of a shell of electrons emitting at ν: $x(\nu) \propto \nu^{-1/2}$
- Causes steepening of the optically thin spectral index by 0.5
- Affects the spectral evolution: three different stages according to the dominant cooling mechanism: 1) inverse Compton, 2) synchrotron, 3) adiabatic
- Remarkably successful model in explaining radio-mm variability

Marscher & Gear (1985)



Spectral evolution in MG85 model

Courtesy of C. Fromm



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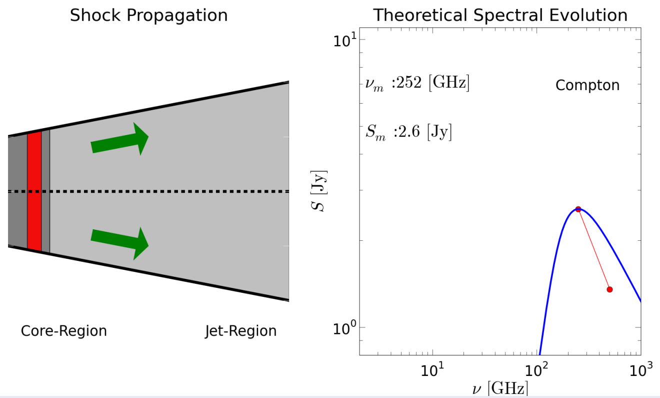

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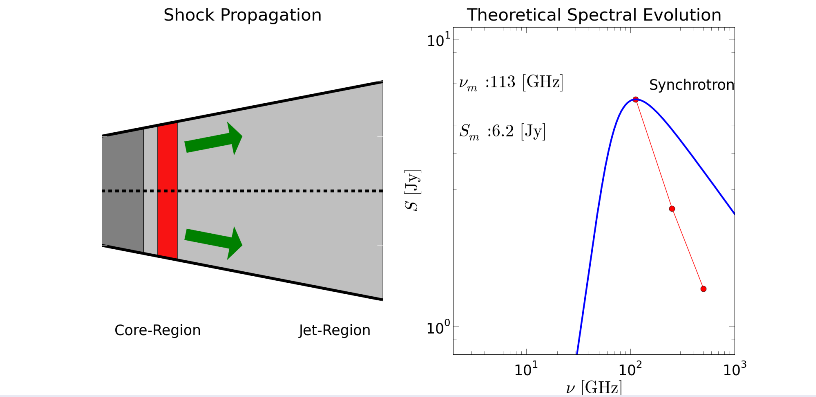

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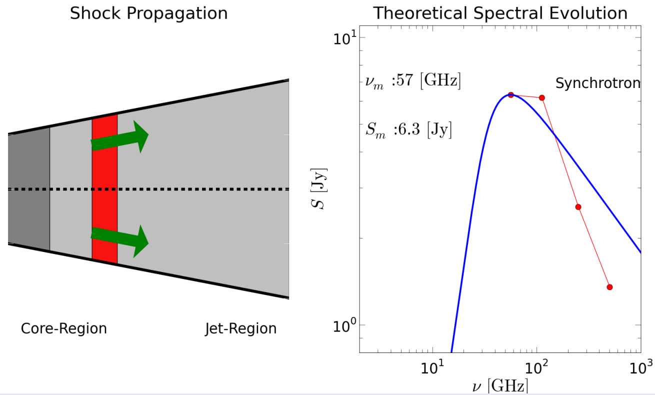

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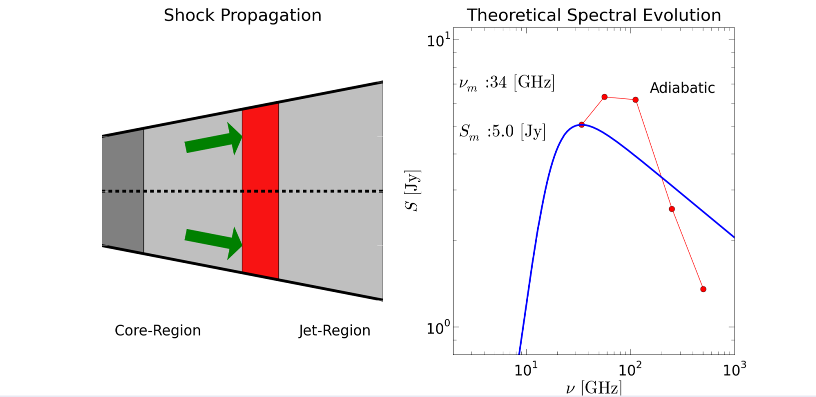

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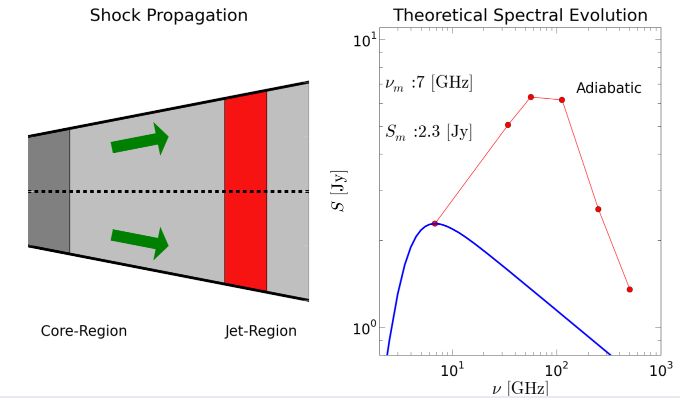

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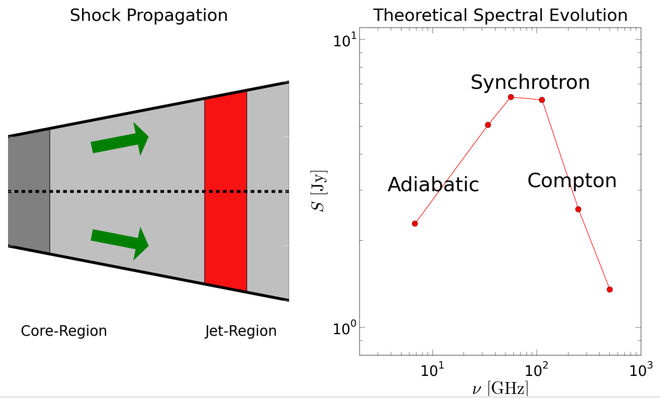
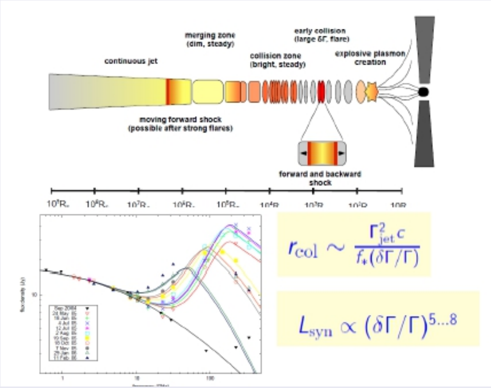


Internal shock (or colliding shells) model

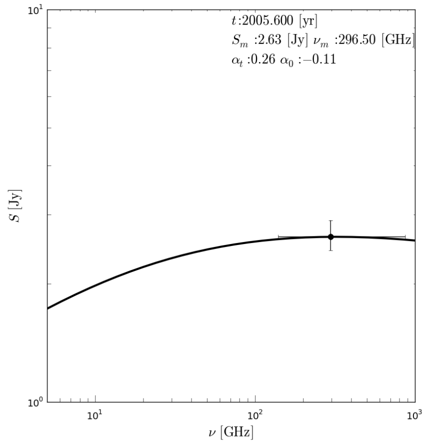


$$r_{\rm col} \sim \frac{\Gamma_{\rm jet}^2 c}{f_*(\delta\Gamma/\Gamma)}$$

$$L_{\rm syn} \propto (\delta\Gamma/\Gamma)^{5\ldots8}$$

Central engine works intermittently ejecting shells of variety of velocities. These collide producing rapid emission. [Spada et al. (2001), Rachen et al. (2010)]

Traveling shock – standing shock interaction in CTA102?



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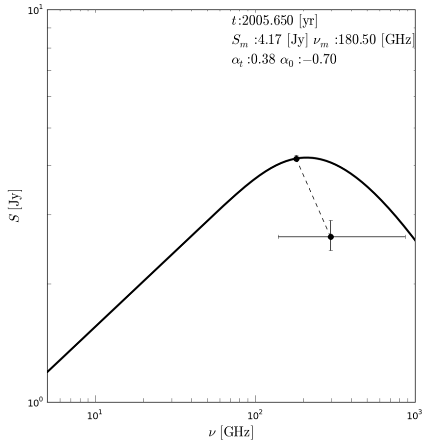

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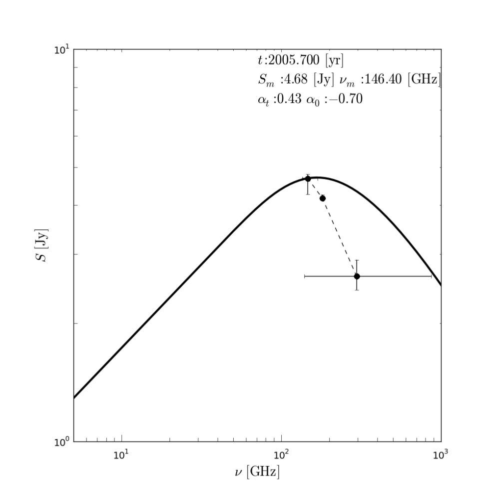

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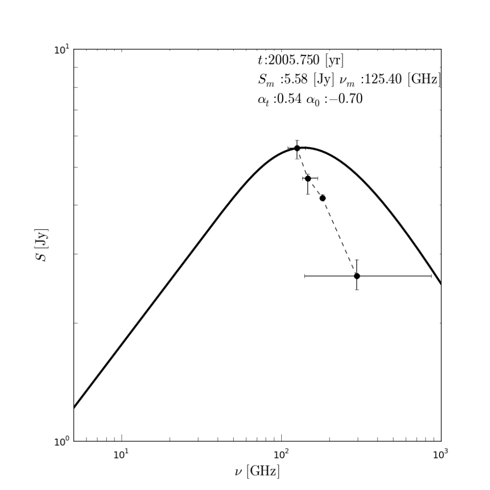

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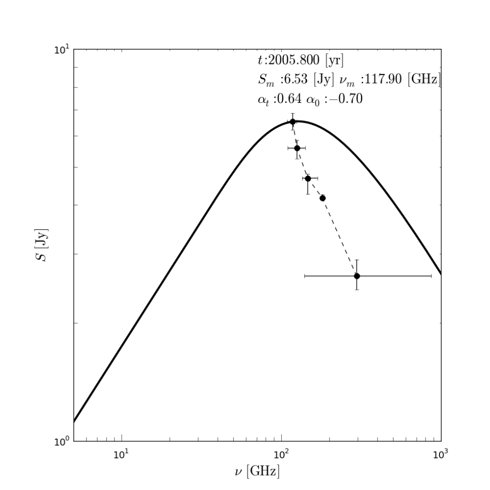

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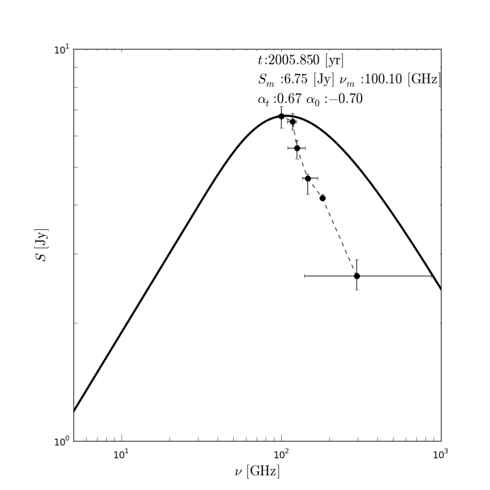

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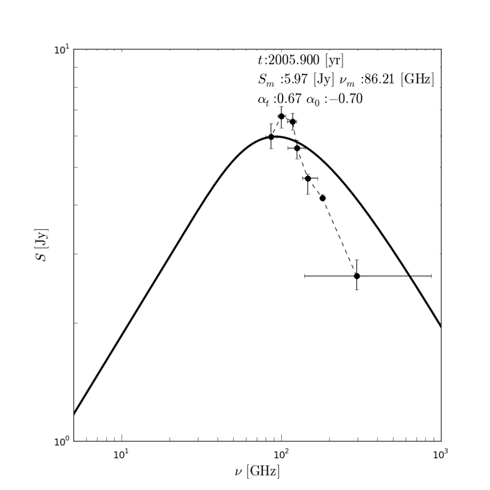

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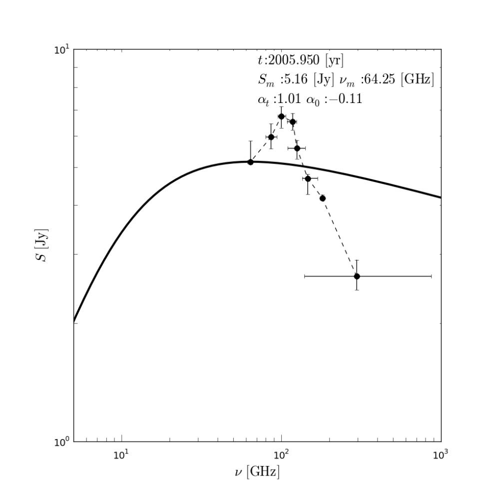

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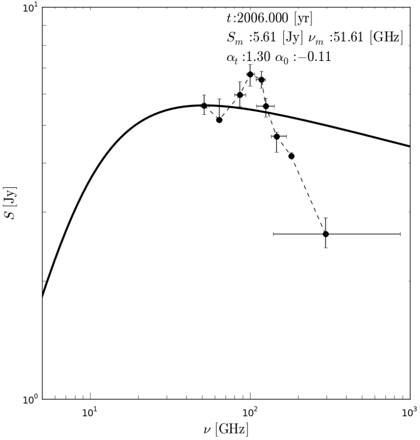

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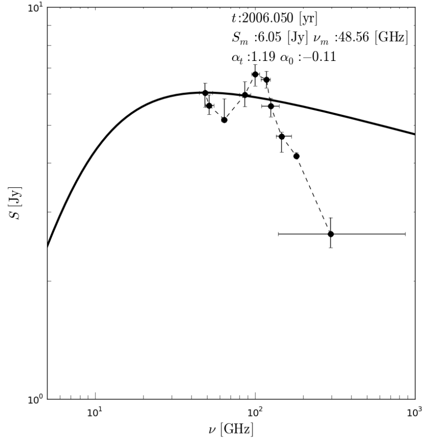

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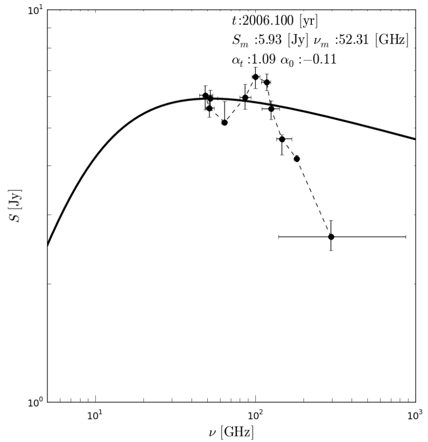

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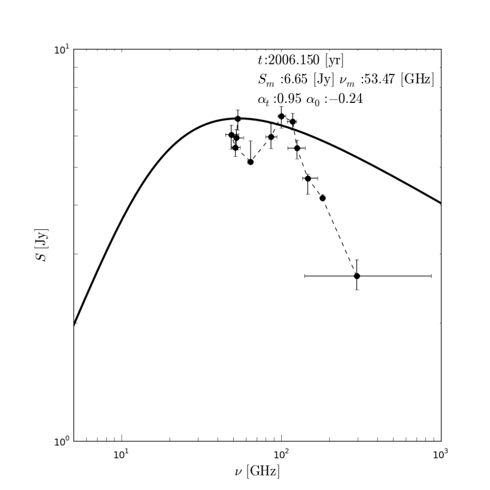

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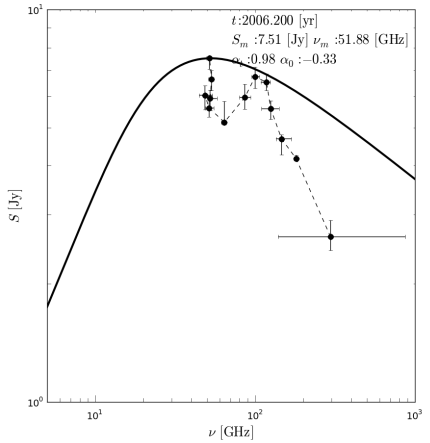

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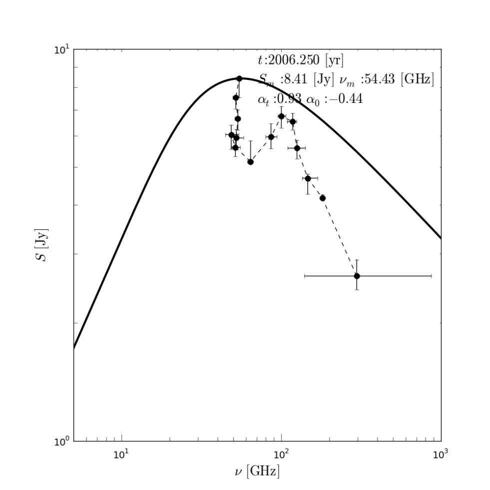

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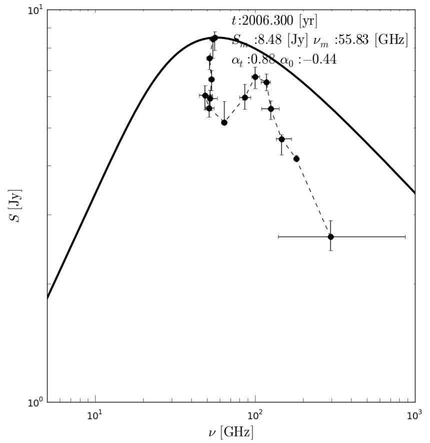

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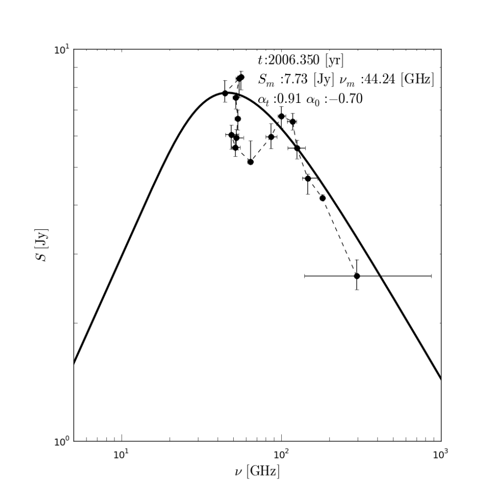

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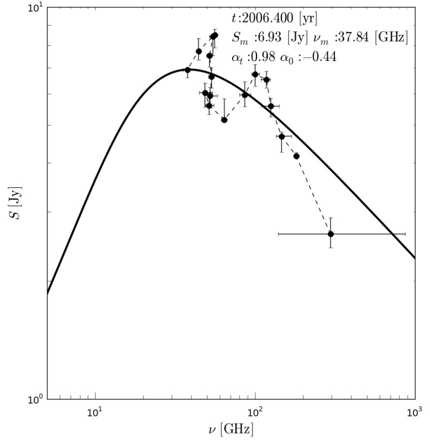

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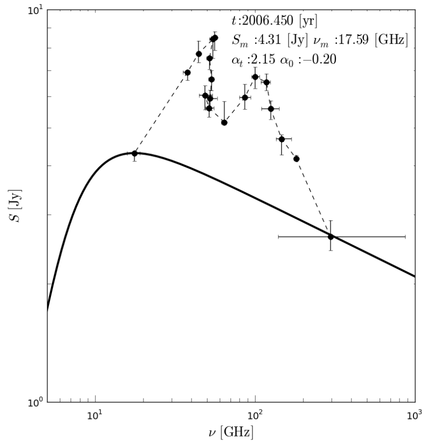

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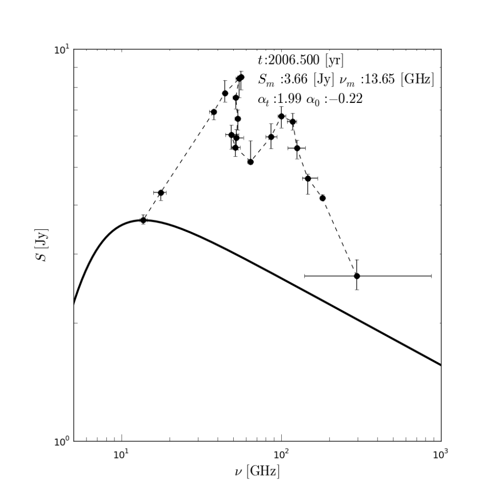

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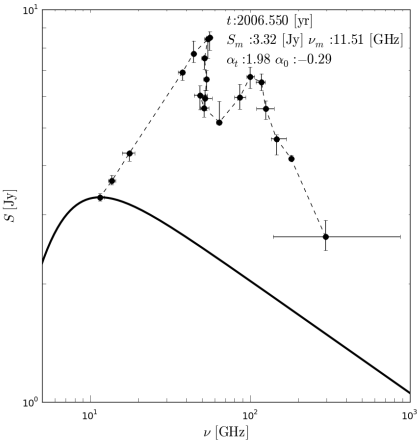

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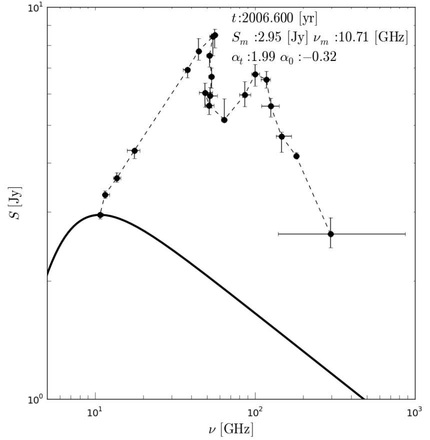

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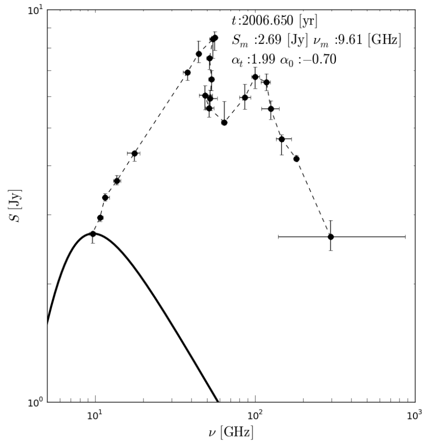

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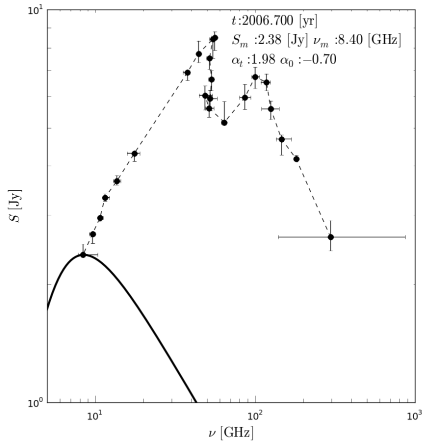

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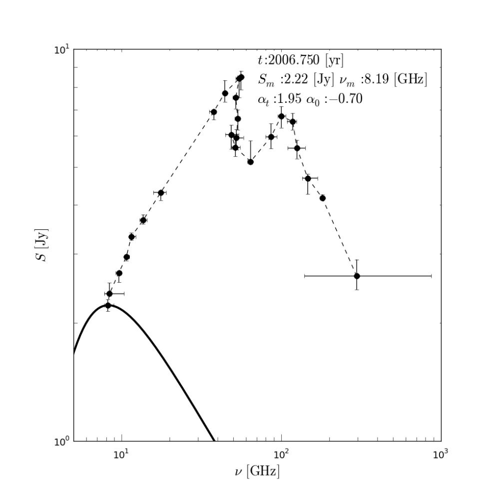

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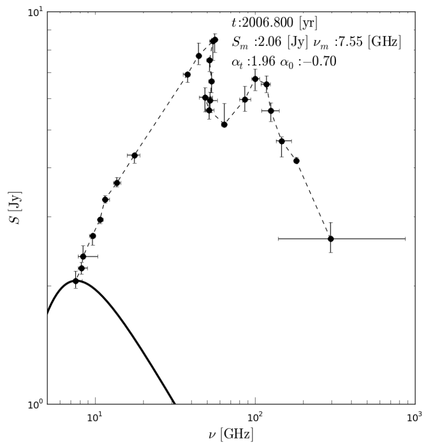
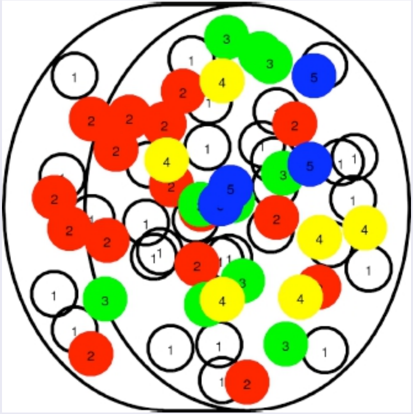


Courtesy of C. Fromm

Turbulent cell model by Marscher (2010)

- Standing shock energizes turbulent flow; maximum energy varies from cell to cell
- Number of emiting cells depends on frequency; shorter variability time scales at higher frequencies
- Higher and more variable linear polarization at high frequencies (as observed)

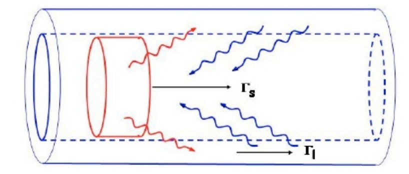
Credit: A. Marscher



Structured jet model

- Attempted solution for fast variability of TeV sources
- Fast spine ($\Gamma \sim 20$) – slow sheath ($\Gamma \sim$ a few)
- Synchtrotron photons from slow sheath can act as targets for IC scattering by spine electrons – and vice versa
- Relative velocity $\rightarrow$ enhanced IC emission, faster time scales

Credit: Ghisellini et al. (2005)



Jet-in-jet models

- Another attempt to explain fast TeV variability
- Emission due to small "mini-jets" moving relativistically in the rest frame of the Poynting-flux dominated jet
- Emission region does not fill the jet
- $\Gamma_{em} \sim \Gamma_j \Gamma_{co}$
- Powered by magnetic reconnection

Credit: Uzdensky et al. (2009)