Particle Acceleration in Extragalactic Jets

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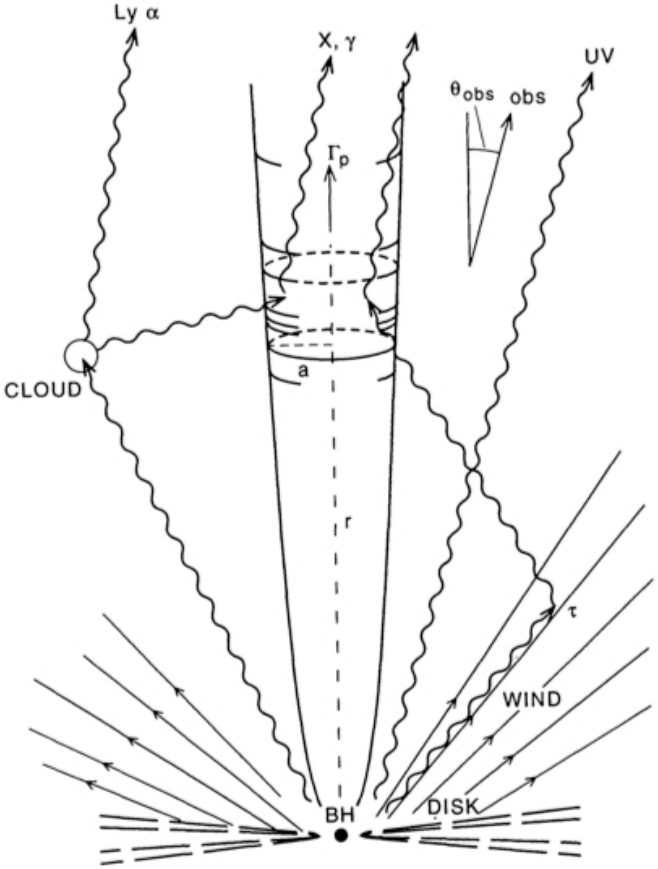
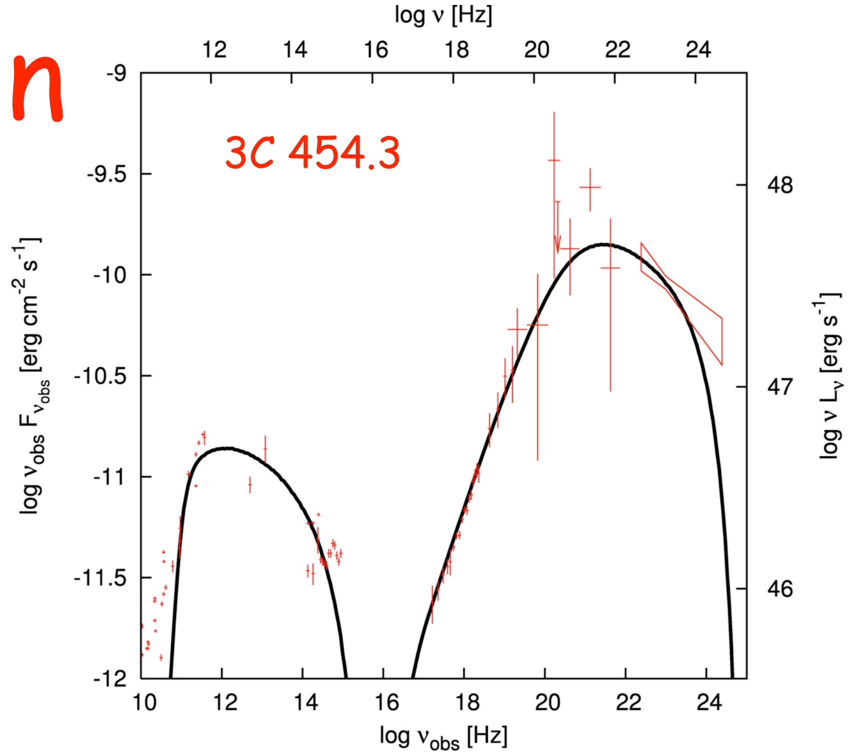
Outline of the Talk

- What are the types of particle (electron) spectra produced in extragalactic jets?
- What are the particle acceleration / energy dissipation processes involved?
- Need for multiwavelength (radio-to-gamma-ray) observations !

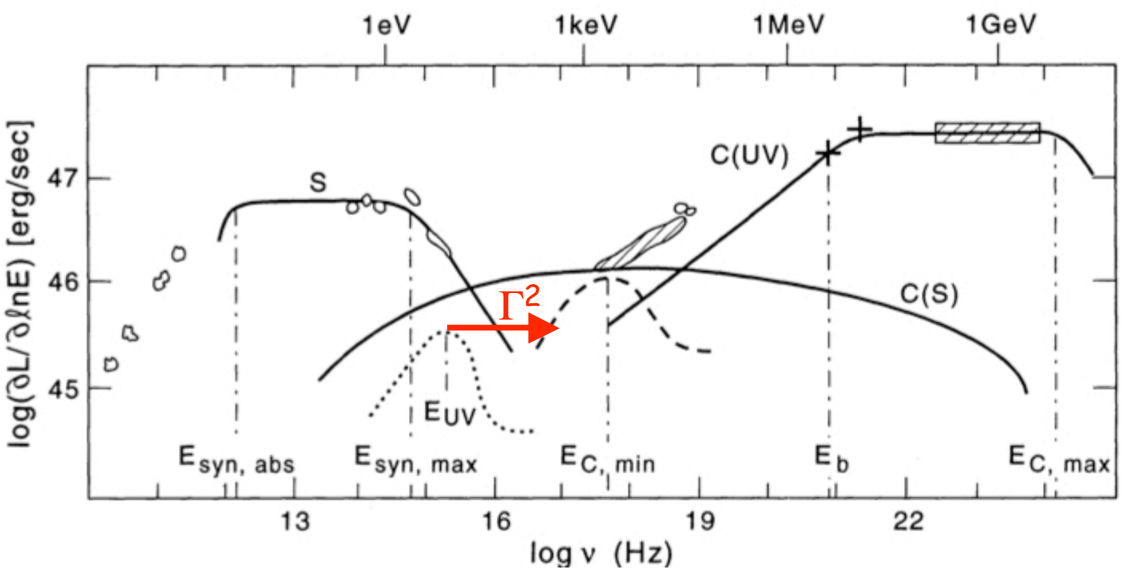
Blazar Phenomenon



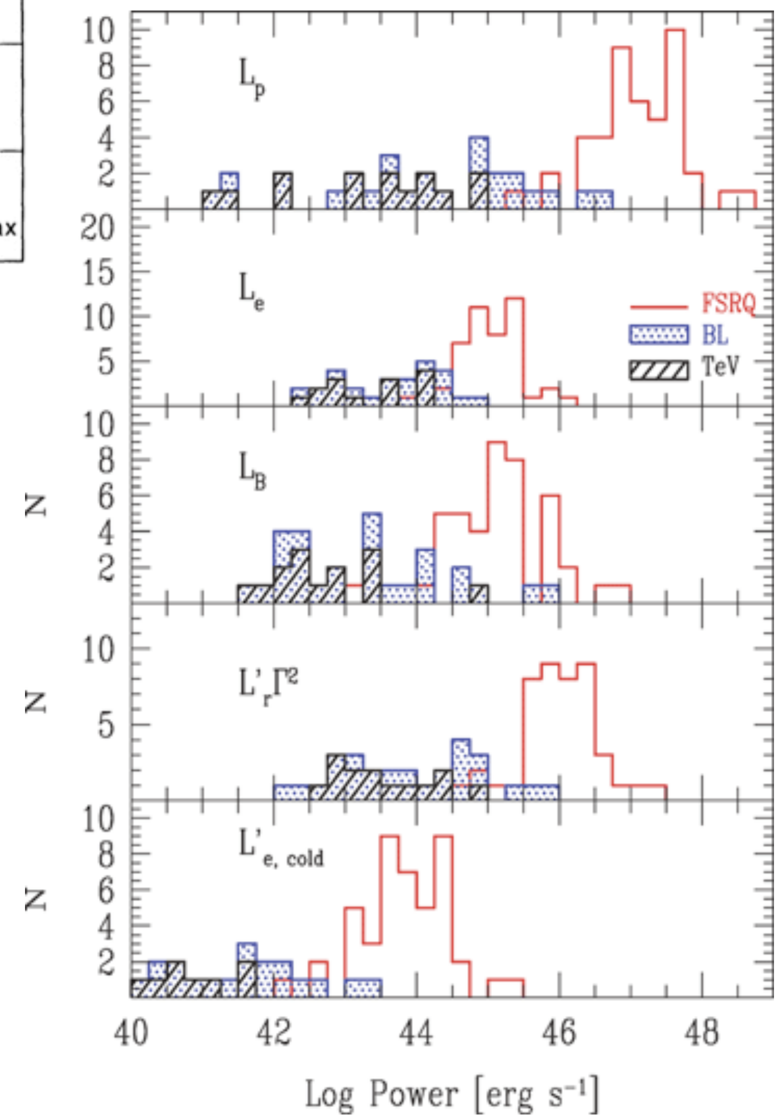


Modelling of the broad-band blazar emission (and its variability) in a framework of the leptonic scenario (**Dermer & Schlickeiser 1993, Sikora, Begelman & Rees 94, Blandford & Levinson 95)** allows to put some constraints on the physical parameters of the blazar emission region. In particular, such modeling indicate that:

1) Emission regions are compact, $R \sim 10^{16}$ cm .
2) Implied highly relativistic bulk velocities of the emitting regions, $\Gamma \sim 10$-30 , are in agreement with the ones inferred from the observed superluminal motions of VLBI jets on pc (kpc?) scales.
3) Energy density of MF is typically below energy density of radiating ultrarelativistic electrons, $U_B \leq U_{e,rel}$.
4) The implied MF intensity $B \sim 0.1$-1 *G* is consistent with the one inferred from the SSA features in flat spectra of compact radio cores.



Jet Power



In addition, the power carried by ultrarelativistic electrons cannot account for the total radiated power of blazars, or for the kinetic power of quasar jets deposited far away from the active nucleus (e.g., **Celotti & Ghisellini 08**). So either

(1) MF is dominating dynamically, while blazar emission is produced in small jet sub-volumes with MF intensity lower than average (?), or

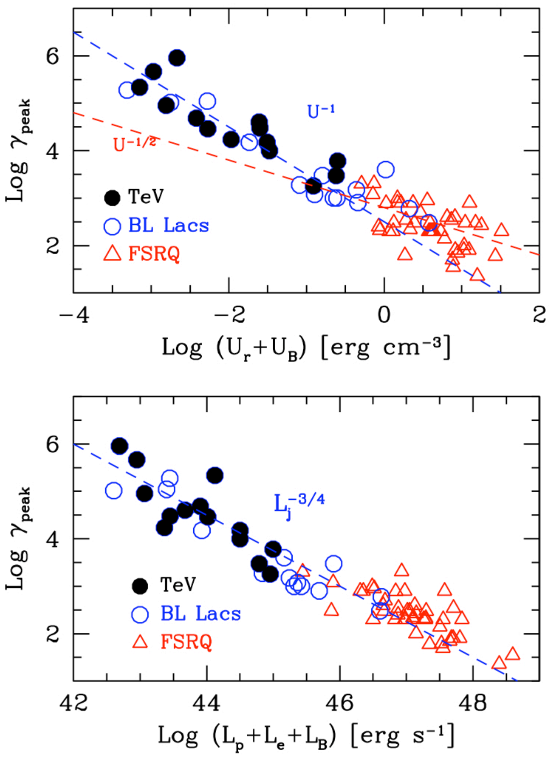
(2) jets on blazar scales are dynamically dominated by protons and/or cold electrons.

However, lack of bulk-Compton features in soft-X-ray spectra of blazars (**Begelman & Sikora 87, Sikora+97, Sikora & Madejski 00, Celotti+07**) indicates that

(3) cold electrons cannot carry bulk of the jet power.

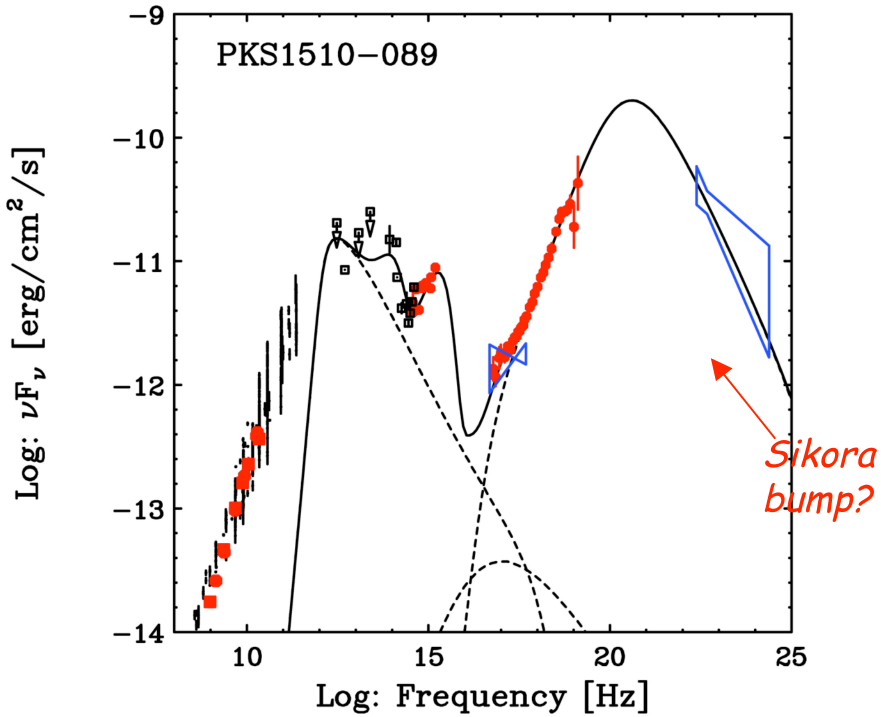
All of these conclusions regard only powerful sources.

Powerful Blazars: Shock Spectra



In the "internal shock model" (**Sikora+94, Spada+01**) one should expect blazar emission zone located at the distances $r \sim \Gamma^2 r_g \sim (10^2 - 10^3)\, r_g \sim 0.01\text{-}0.1$ pc .

In the "reconfinement shock model" (**Sikora+07, Bromberg & Levinson 08**) one can expect the blazar emission zone located at larger distances $r \sim 0.1\text{-}1$ pc .



Kataoka+08: parameters of blazar PKS 1510-089

$\Gamma \sim 20$, $r \sim 1$ pc , $R \sim 10^{16}$ cm , $N_e/N_p \sim 10$, $B \sim 0.6$ G
$L_p \sim 2 \times 10^{46}$ erg/s , $L_e \sim 0.1 \times 10^{46}$ erg/s , $L_B \sim 0.6 \times 10^{46}$ erg/s

$N_e(\gamma) \propto \gamma^{-1.35}$ **for** $\gamma < \gamma_{br} \sim 100$
$\propto \gamma^{-3.35}$ **for** $\gamma > \gamma_{br} \sim 100$

Low-Power Blazars (TeV BL Lacs)

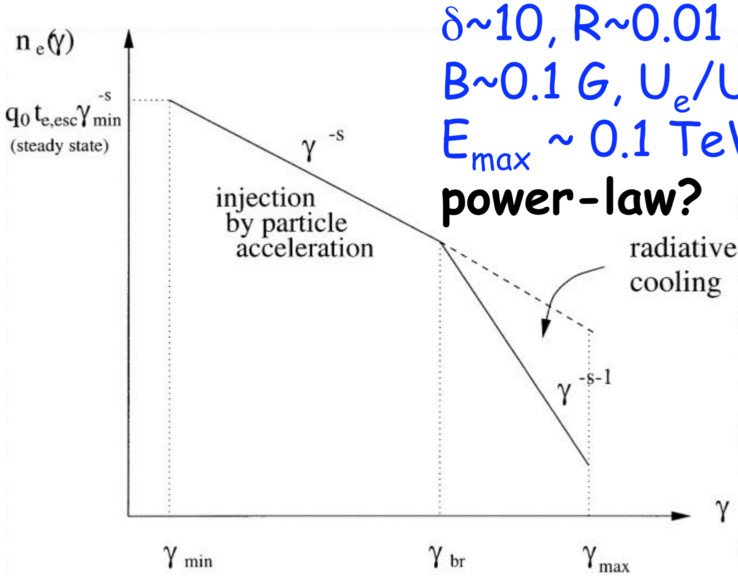
Kino+02:

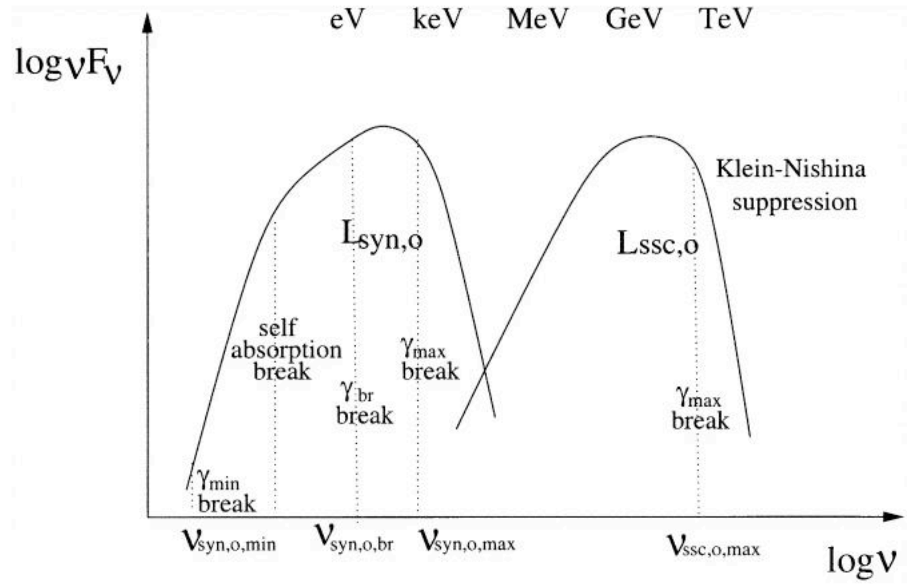
$\delta \sim 10$, $R \sim 0.01$ pc

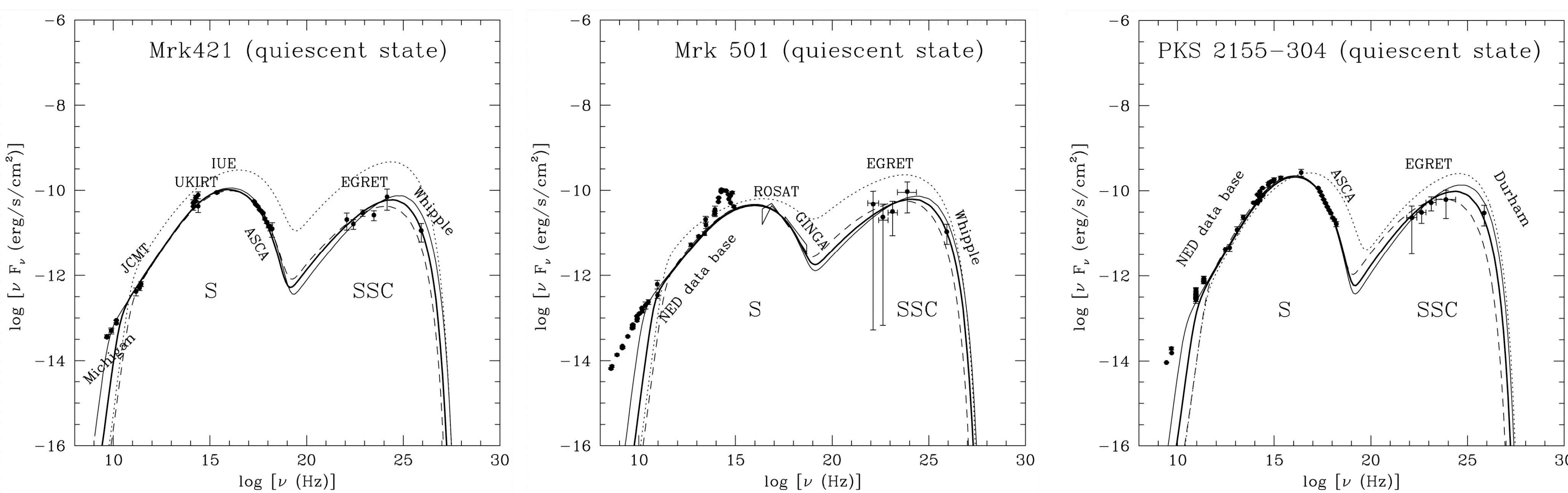
$B \sim 0.1$ G, $U_e/U_B \sim 10$

$E_{max} \sim 0.1$ TeV

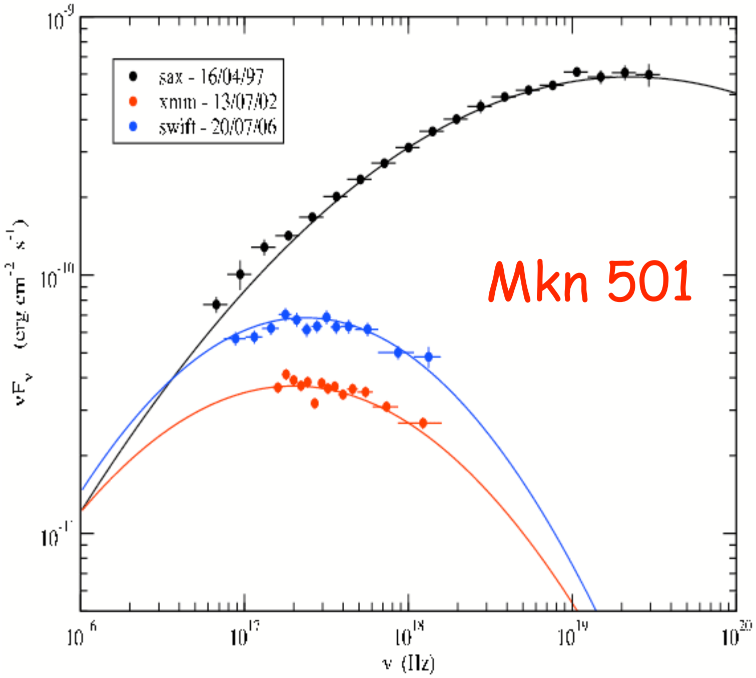
power-law?

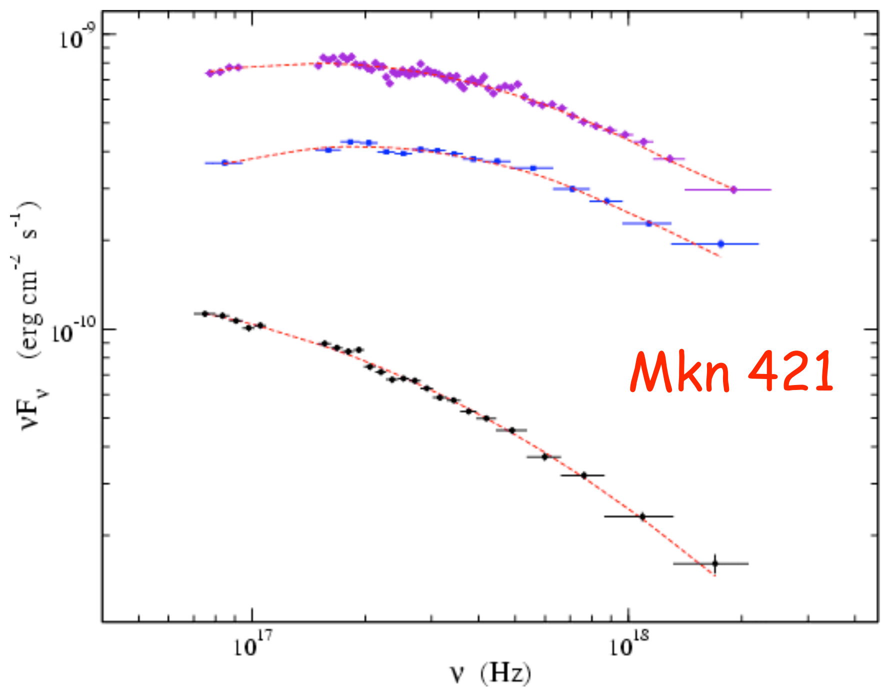






X-ray synchrotron spectra of BL Lacs

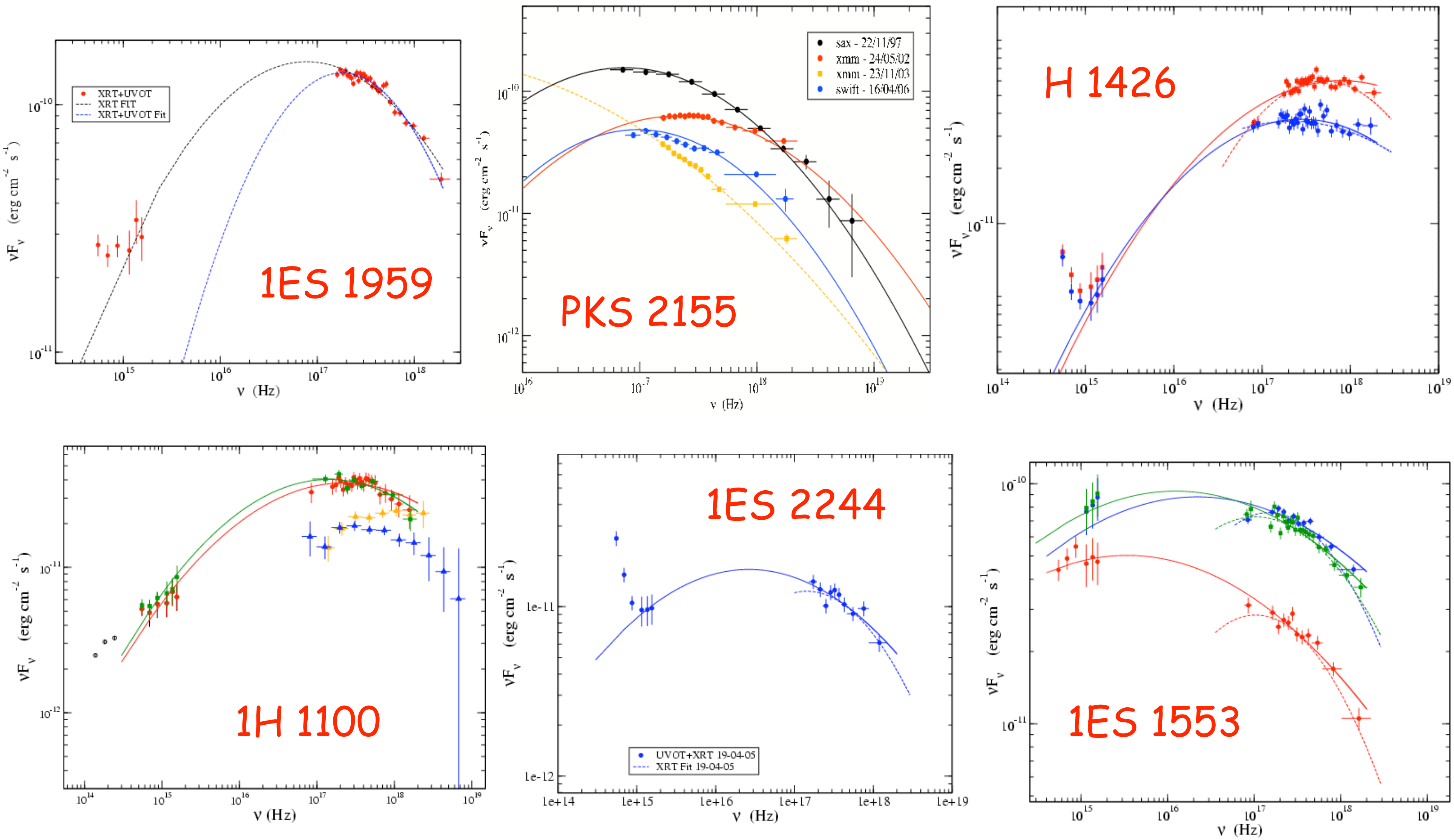




X-ray spectra of BL Lacs are smoothly curved. They cannot be really fitted by "a power-law and an exponential cut-off" form, $F(E) \propto E^{-\Gamma}\exp(-E/E_{cr})$. Instead, "log-parabolic" shape represents the X-ray continua well, $F(E) \propto E^{-a + b\cdot\log(E/Ecr)}$ (Massaro+03,08; Landau+86; Krennrich+99; Giommi+02; Perri+03; Tramacere+07).

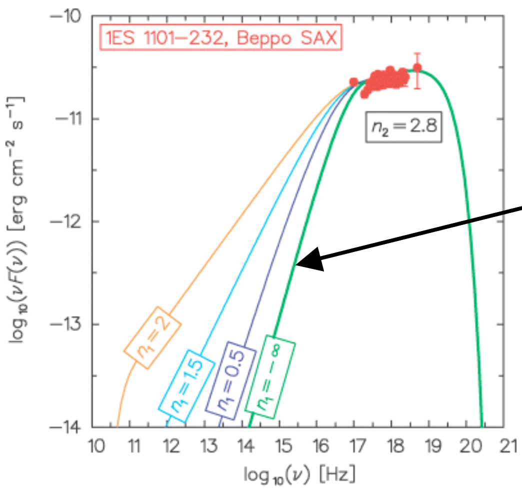
Caution: analysis of the X-ray spectra is hampered by the unknown/hardly known intrinsic absorbing column density. In the case of BL Lacs, on the other hand, such absorption is not expected to be significant. Analysis of the optical spectra are hampered by the contribution of the elliptical host.

Curved optical-to-X-ray spectra…



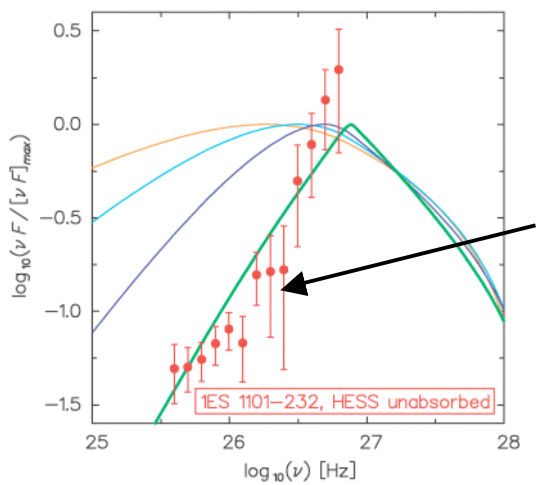
… of all TeV-emitting BL Lacs (Tramacere + 07)

TeV spectra of BL Lacs



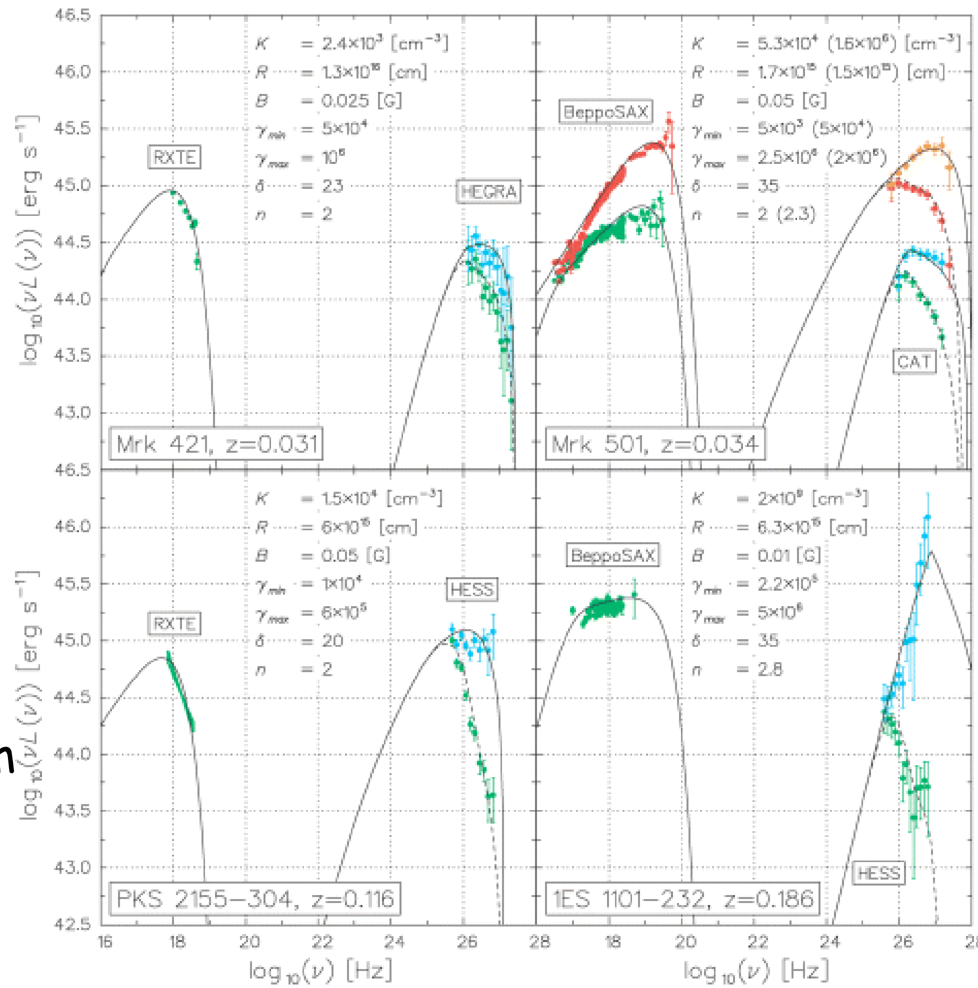
the flattest synchrotron spectrum

$\alpha = - 1/3$



the corresp. (Th. regime) SSC spectrum

$\alpha = - 1/3$



Analysis of the TeV spectra of blazars is hampered by the gamma-ray absorption on the extragalactic background light (spectral energy distribution of EBL is hardly known!). Typically, low photon statistics and rapid spectral variability make such studies even more difficult. However, recent H.E.S.S. observations of a distant blazar 1ES 1101-232 (z = 0.186; Aharonian+06), and subsequent modeling (Katarzynski +06), suggest that the intrinsic TeV spectrum of this source have to be unusually flat, possibly even of the pile-up form.

"Universal" particle spectrum: Modified Ultrarelativistic Maxwellian

As long as particle escape from the acceleration region is inefficient, stochastic acceleration of ultrarelativistic particles undergoing radiative losses $t_{rad} \propto p^x$ tends to establish modified ultrarelativistic Maxwellian spectrum

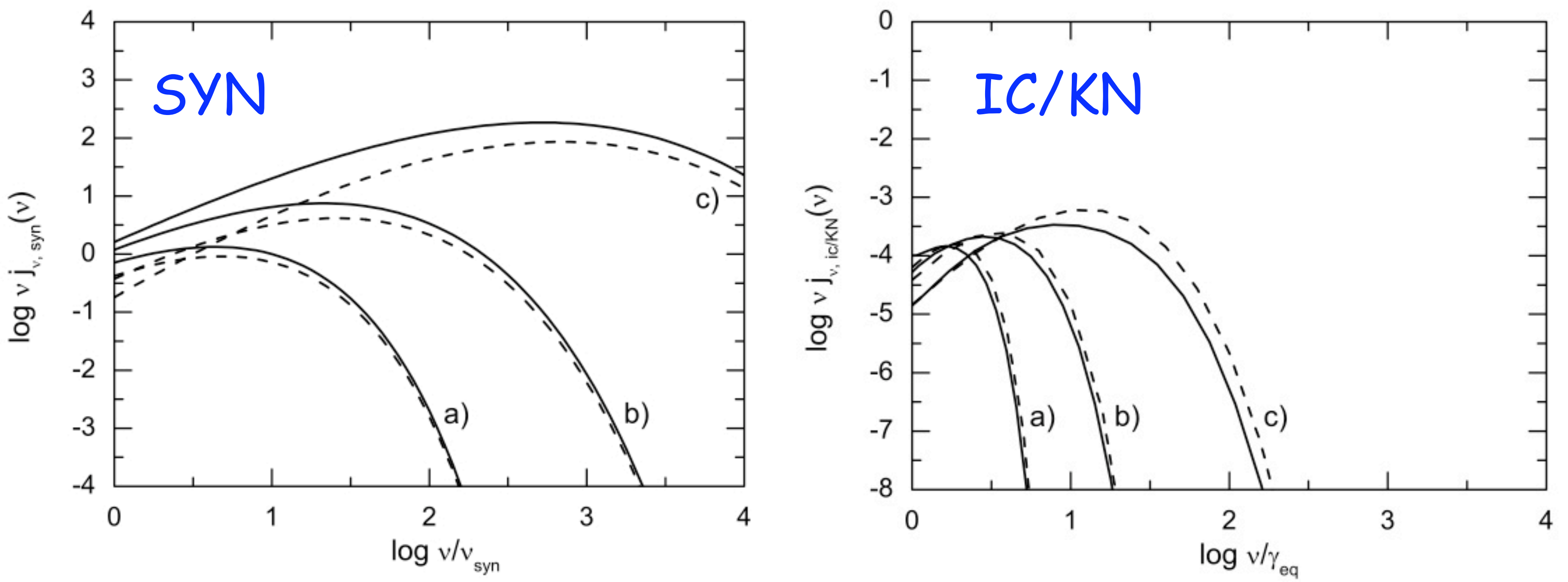
$$n(p) \propto p^2 \times \exp[- (1/a) (p/p_{eq})^a]$$

where $W(k) \propto k^{-q}$ is the energy spectrum of the turbulence, $a = 2-q-x$, and p_{eq} is the maximum particle energy defined by the balance between the acceleration and losses timescales,

$$t_{acc}(p_{eq}) = t_{rad}(p_{eq})$$

(Stawarz & Petrosian 08; also Schlickeiser 84, Bogdan & Schlickeiser 85, Park & Petrosian 95).

Fermi II: Emission spectra



a) dominant synchrotron losses, $q = 1$ (i.e., $a = 2$)

$j_{syn}(\nu > \nu_{syn}) \propto \nu^{+0.5} \exp[-1.4\ (\nu/\nu_{eq})^{+0.5}]$

$j_{ic/kn}(\nu > \gamma_{eq}) \propto \nu^{+2.5} \exp[-0.5\ (\nu/\gamma_{eq})^{+2.0}]$

b) dominant synchrotron losses, $q = 2$ (i.e., $a = 1$)

$j_{syn}(\nu > \nu_{syn}) \propto \nu^{+0.83} \exp[-1.9\ (\nu/\nu_{eq})^{+0.3}]$

$j_{ic/kn}(\nu > \gamma_{eq}) \propto \nu^{+2.5} \exp[-(\nu/\gamma_{eq})^{+1.0}]$

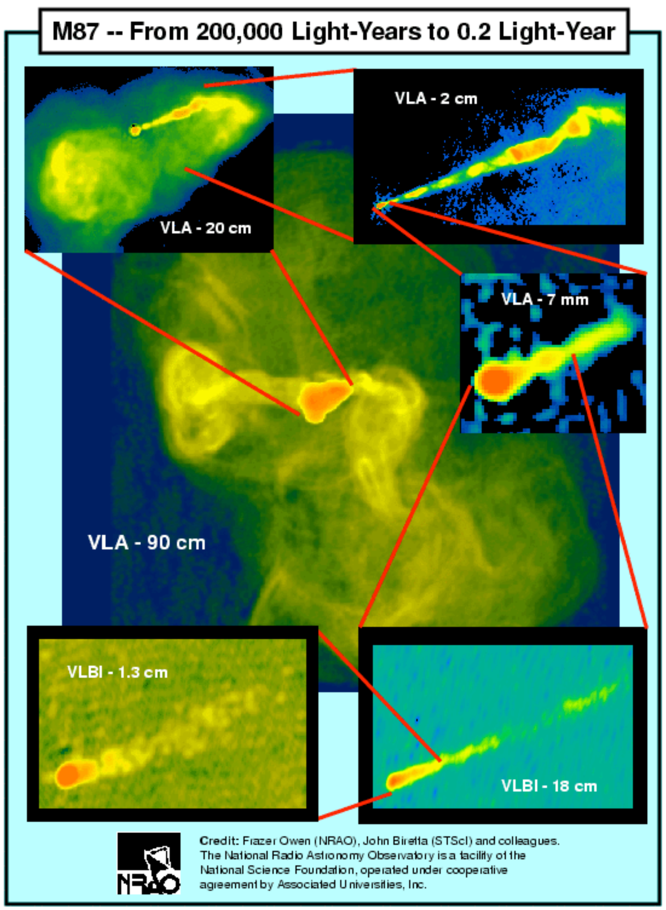
c) dominant IC/KN losses, $q = 1$ (i.e., $a = 0.5$)

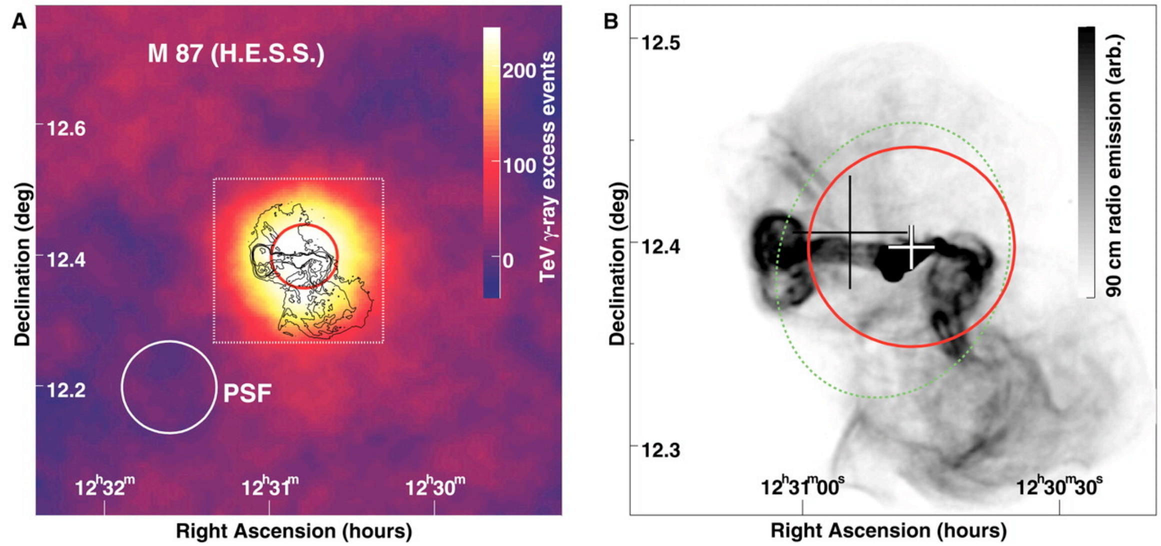
$j_{syn}(\nu > \nu_{syn}) \propto \nu^{+1.1} \exp[-2.9\ (\nu/\nu_{eq})^{+0.2}]$

$j_{ic/kn}(\nu > \gamma_{eq}) \propto \nu^{+2.5} \exp[-2.0\ (\nu/\gamma_{eq})^{+0.5}]$

H.E.S.S. Observations of M87

First detected by HEGRA.
Later observed by H.E.S.S.
(**Aharonian+07, for the HESS Collab.**). Recently detected also
By MAGIC and VERITAS.



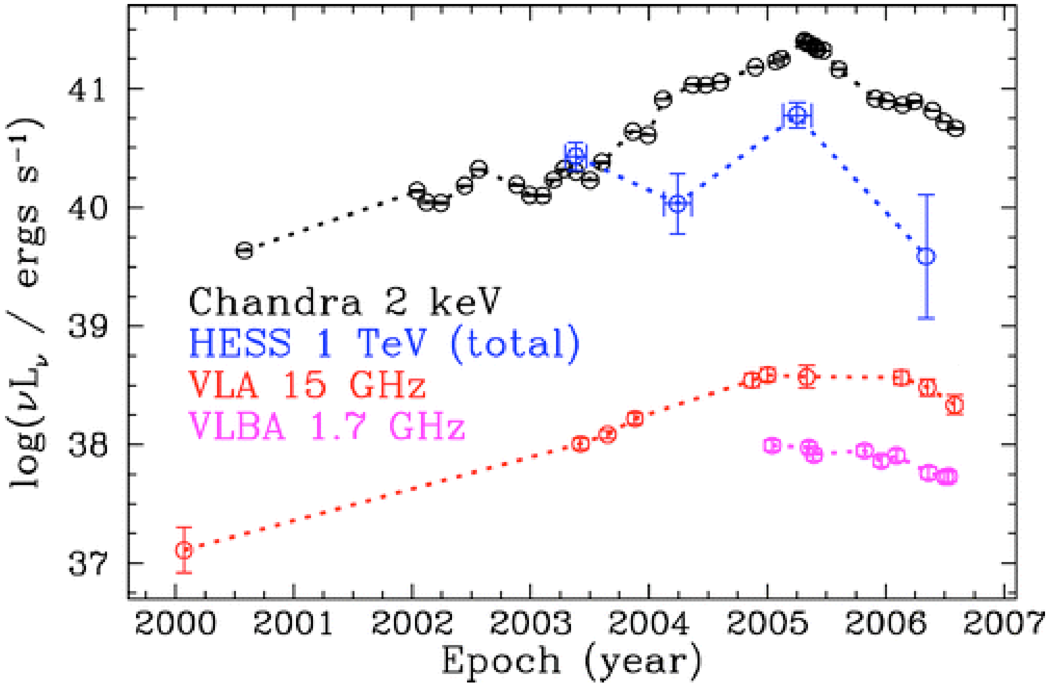


What can be the source of the TeV emission detected from M87?

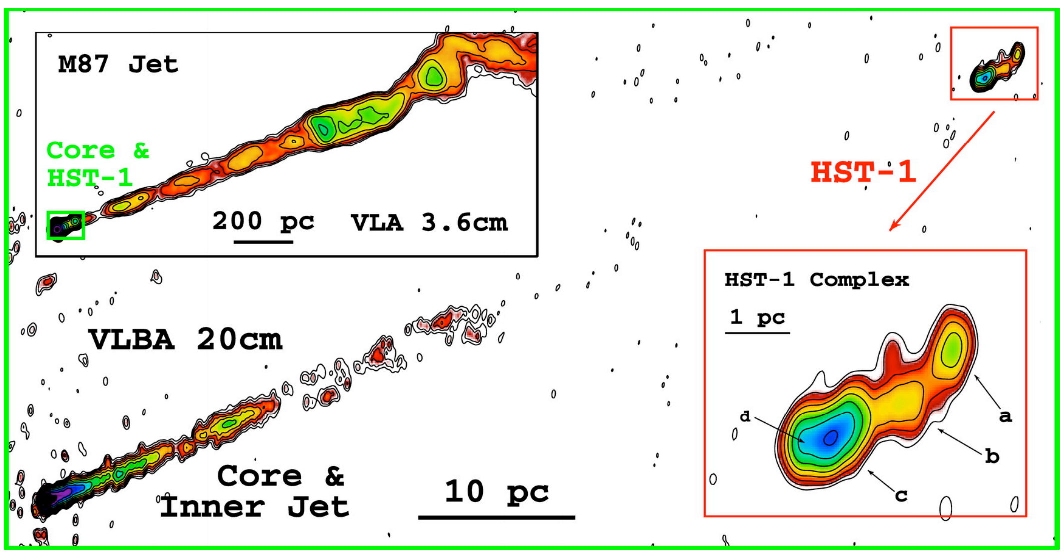
Inner (sub-pc scale) jet?
Large-scale (kpc-scale) jet?
Virgo A cluster?
Central SMBH (M_{BH} ~ 3×10^9 M_{sun}) ?

Only the ~kpc-scale jet is the guarantee TeV emitter, because it is known to accelerate electrons up to TeV energies (synchrotron X-rays with B~0.1-1 mG!).

TeV emission Far Away From SMBH?

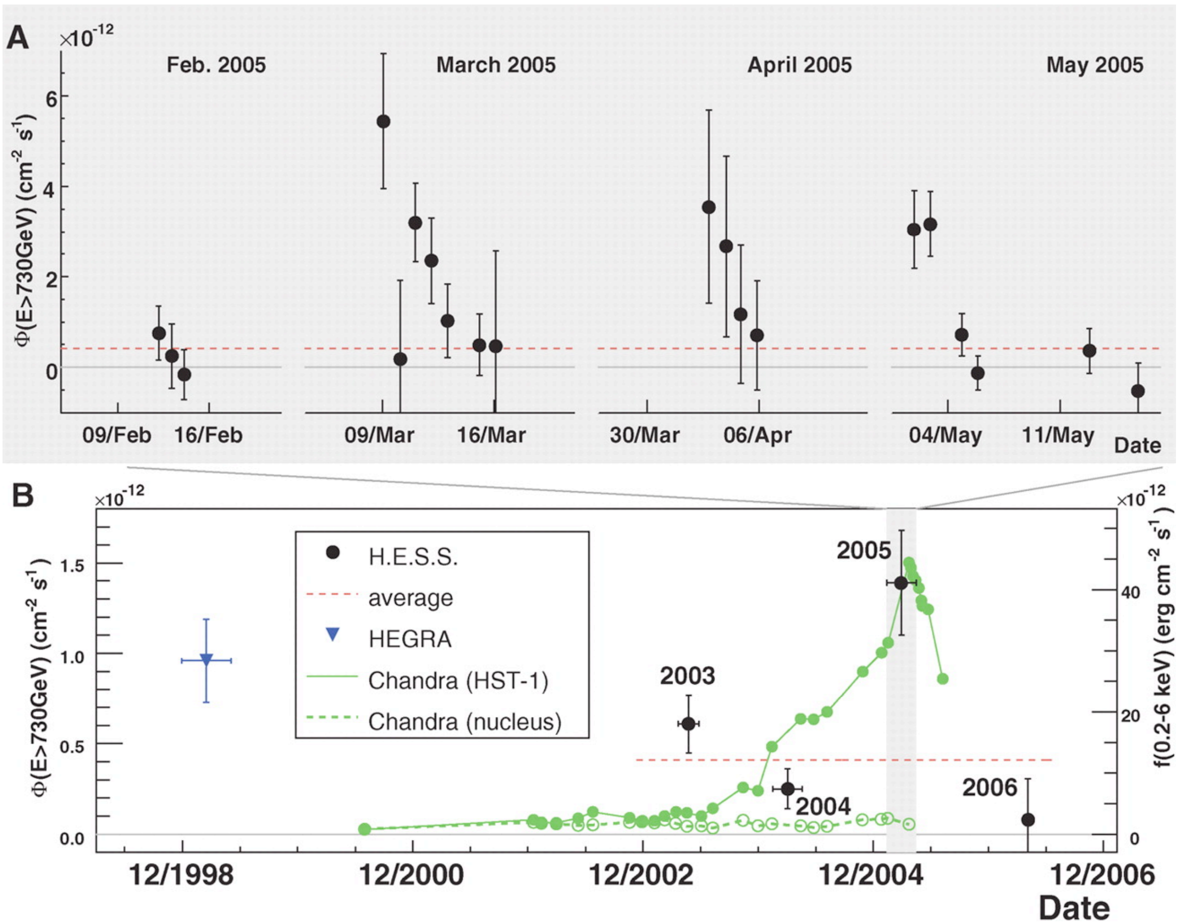


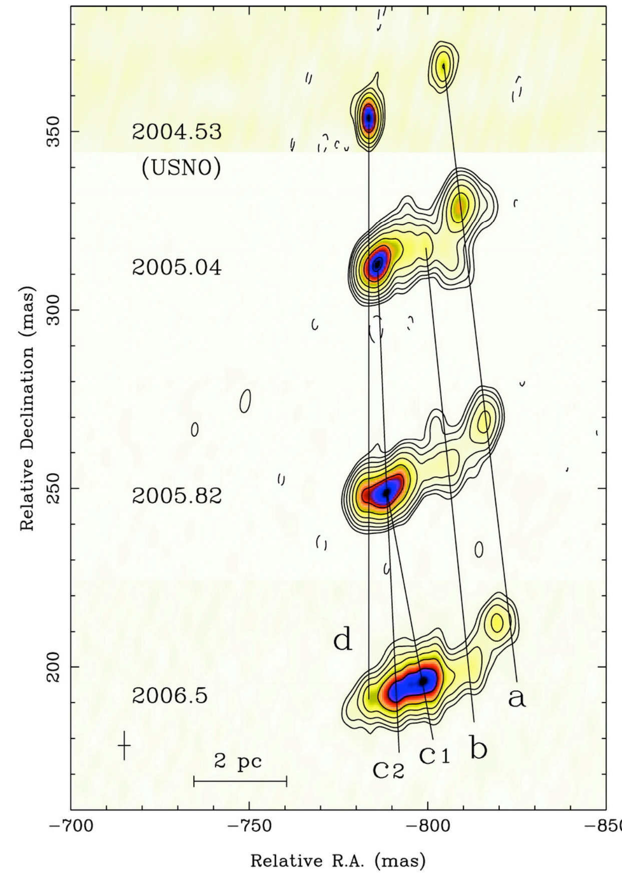
Monitoring of the jet in M87 radio galaxy with VLBA, Hubble Space Telescope, and Chandra X-ray Observatory resulted in the detection of a huge outburst (in radio, optical, and X-ray photon energies) of HST-1 knot, placed ~100 pc from the central black hole. Just after the outburst, the knot started to eject superluminal ($\beta_{app} \leq 4$) radio components **(Cheung, Harris & Stawarz07)**.



Knot HST-1 can be understood as a nozzle formed within the outflow by a converging reconfinement shock driven in the expanding jet by the high pressure ambient medium (**Stawarz+06**).

Variable TeV Emission from M87





Short variability of the TeV emission observed from M87 implies linear size of the emission region $R_\gamma < 0.002\ \delta$ pc ~ $10\ \delta\ R_g$

HST-1 knot:

r ~ 100 pc ~ $10^6\ R_g$

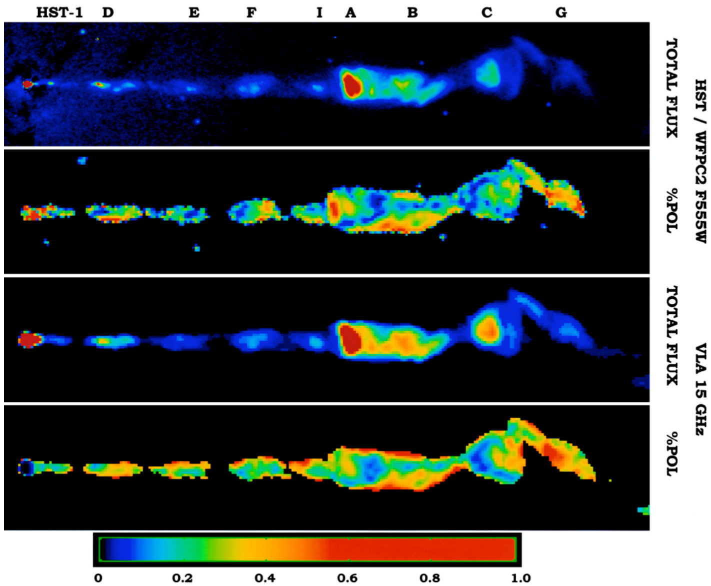
$R_{HST} < 0.15$ pc

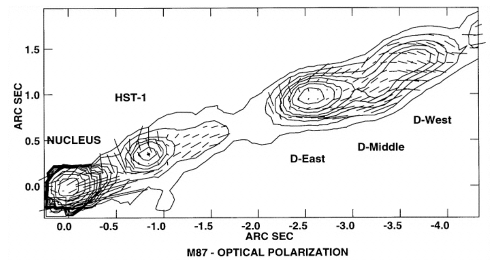
$R_X < 0.02\ \delta$ pc

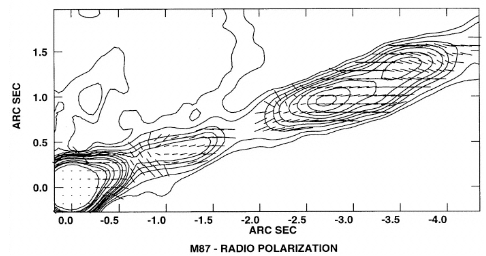
$\delta > 2$

FR I Jets

2-kpc-long jet in M87 radio galaxy (d_L = 16 Mpc) observed at radio, optical, and X-ray frequencies.





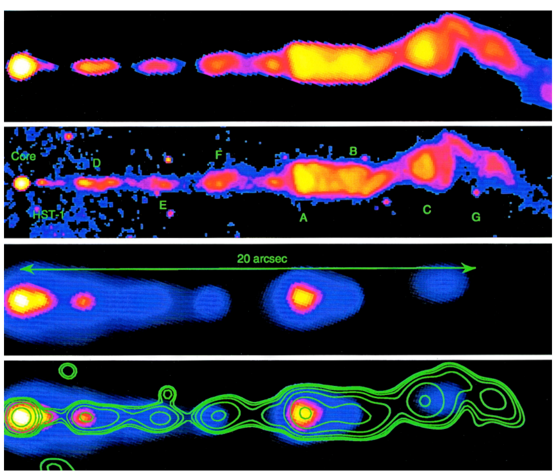


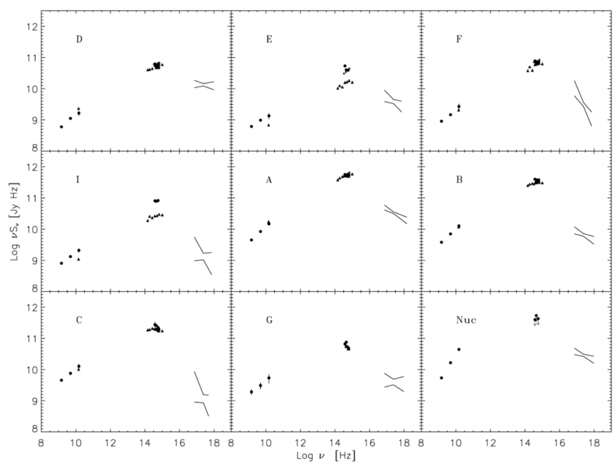
(Perlman+99)

Radio and optical polarized emission: internal structure consistent with the spine – boundary shear layer morphology.

Radio-to-X-ray synchrotron emission:

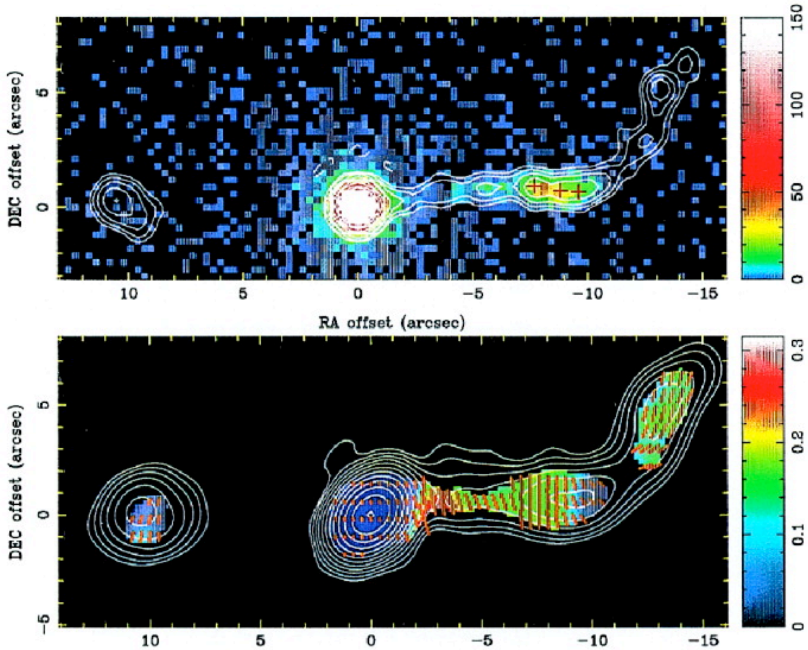
- presence of $\gamma = 10^8$
- electrons (E_e = 100 TeV);
- broad-band knots' spectra hardly consistent with the standard shock acceleration models;
- a need for continuous electron acceleration along the whole jet ($\ell_{rad,\,X} \sim 10$ pc « 2 kpc).



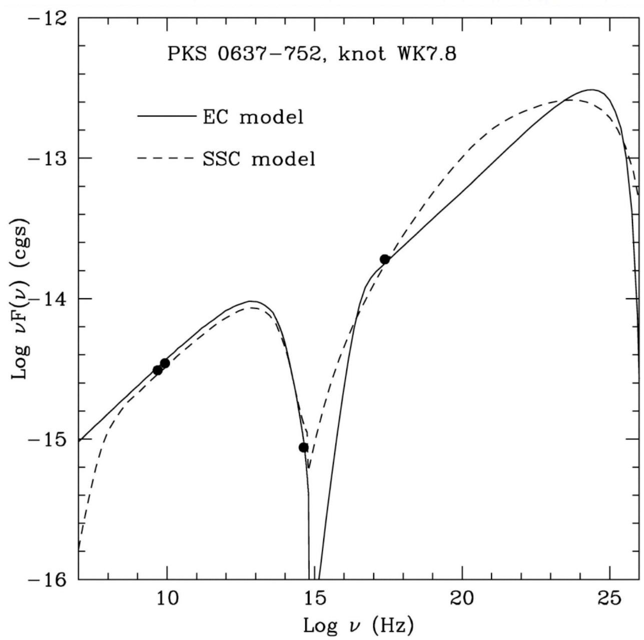


(Marshall+02, Wilson & Young 02)

Chandra Quasar Jets



Chandra X-ray Observatory detected surprisingly intense X-ray emission from large-scale (100 kpc – 1 Mpc) quasar jets ($L_X \sim 10^{44}$-10^{45} erg/s). Many examples (e.g., **Schwartz+00, Cheung+, Hardcatle+, Harris+, Jorstad+, Kataoka+, Kraft+, Marshall+, Sambruna+, Siemiginowska+**).



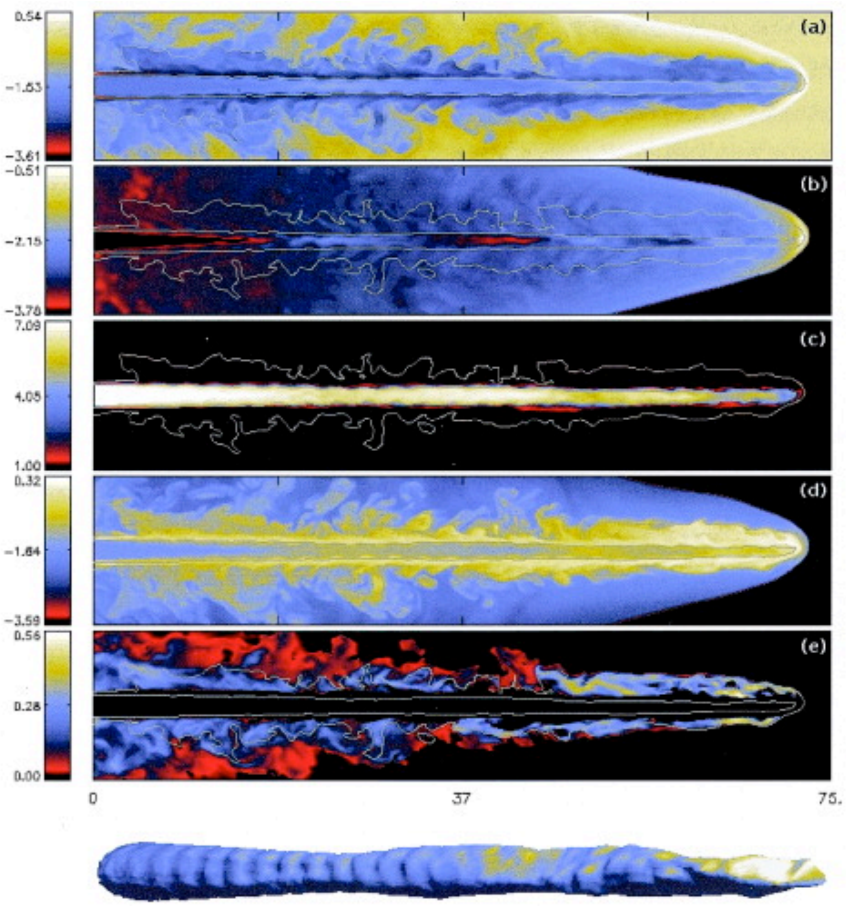
It was proposed that this X-ray emission is due to inverse-Compton scattering of the CMB photons by low-energy jet electrons, $E_e \sim 100$ MeV. (**Tavecchio+00, Celotti+01**).

IC/CMB model requires highly relativistic bulk velocities ($\Gamma > 10$) on Mpc scales, and dynamically dominating protons,

$L_p > L_e \sim L_B$

with $B \sim B_{eq} \sim 1$-$10\ \mu$G. Note that for Γ<10 the IC/CMB model would imply $B \ll B_{eq}$

Non-standard electron spectra?



Relativistic 3D-HD simulations indicate presence of highly turbulent shear boundary layers surrounding relativistic jets **(Aloy+99)**.

Relativistic large-scale jets are highly turbulent, and velocities of turbulent modes thereby may be high. As a result, stochastic (2nd order Fermi) acceleration processes may be dominant. Assuming efficient Bohm diffusion (i.e. turbulence spectrum $\delta B^2(k) \propto k^{-1}$), one has

$t_{acc} \sim (r_g/c)\,(c/v_A)^2 \sim 5 \times 10^2\ \gamma\,[s]$

$t_{esc} \sim R_j^2/\kappa \sim 6 \times 10^{24}\ \gamma^{-1}\,[s]$

$t_{rad} \sim 6\pi m_e c \,/\, \sigma_T \gamma B^2 \sim 8 \times 10^{18}\ \gamma^{-1}\,[s]$

$r_g \sim \gamma m_e c^2 / eB$, $\kappa \sim r_g c / 3$,

$v_A \sim B / (4\pi m_p n)^{1/2} \sim 10^8$ cm/s,

$B \sim 10^{-5}$ G, $R_j \sim 1$ kpc .

$t_{esc}/t_{rad} \sim 10^6$

$t_{acc} \sim t_{rad}$ for $\gamma_{eq} \sim 10^8$

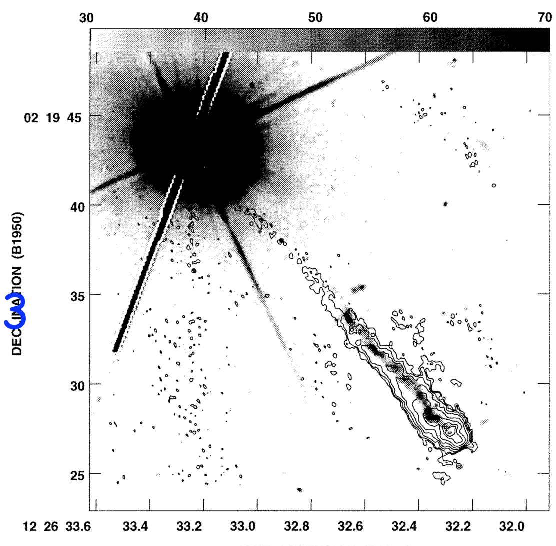
Pile-up synchrotron X-ray emission expected!
(Stawarz & Ostrowski 02, Stawarz+04)

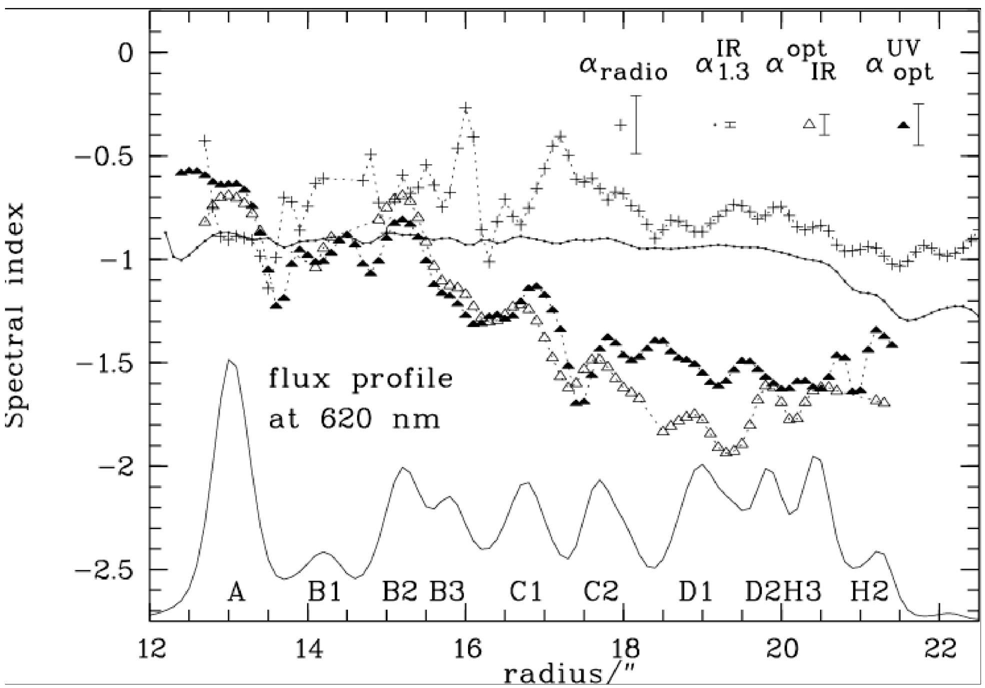
Quasar 3C 273

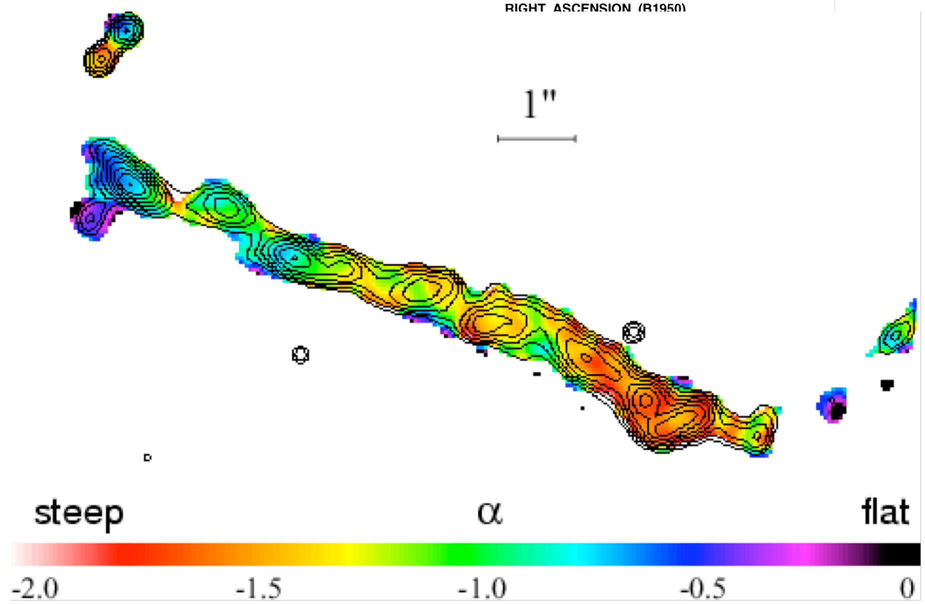
Radio-to-UV emission of 3C 273 jet is polarized, and therefore synchrotron.
Optical-to-X-ray continuum seems to form additional synchrotron component.
Does it indicate single but `non-standard' electron energy distribution? Or rather two distinct electron populations?
Spectral profiles inconsistent with the shock scenario.

(Jester+02, 05, 07)

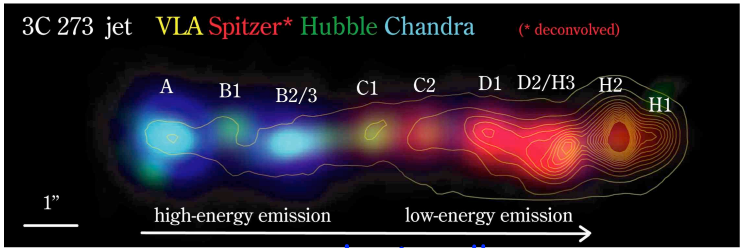
~100-kpc jet in quasar 3C 273 (d_L ~ 750 Mpc)





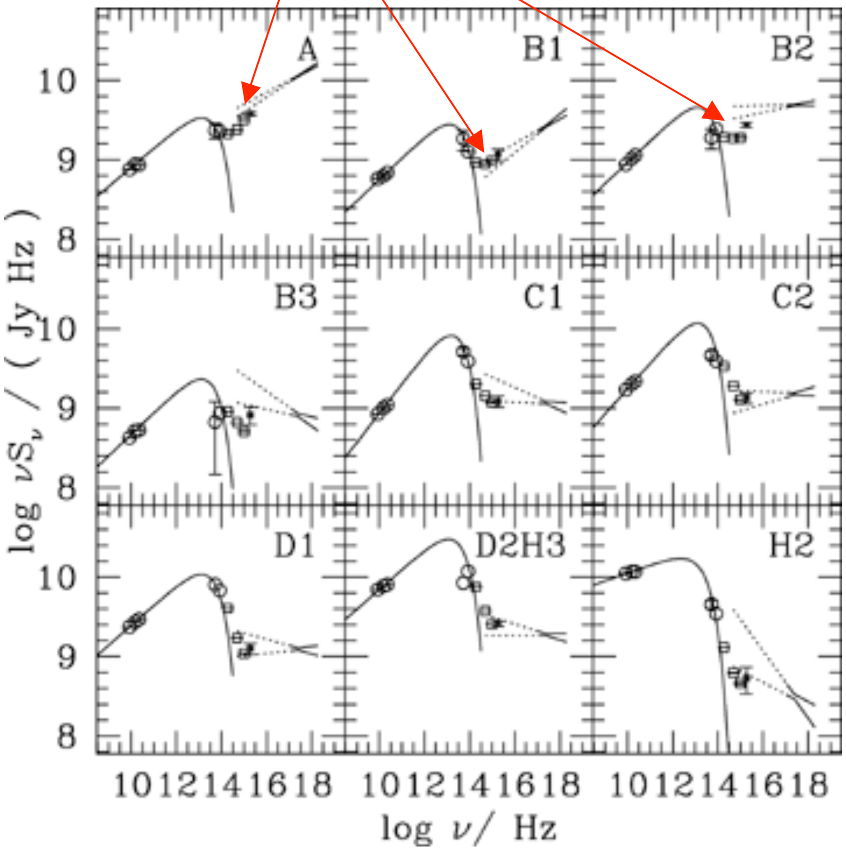


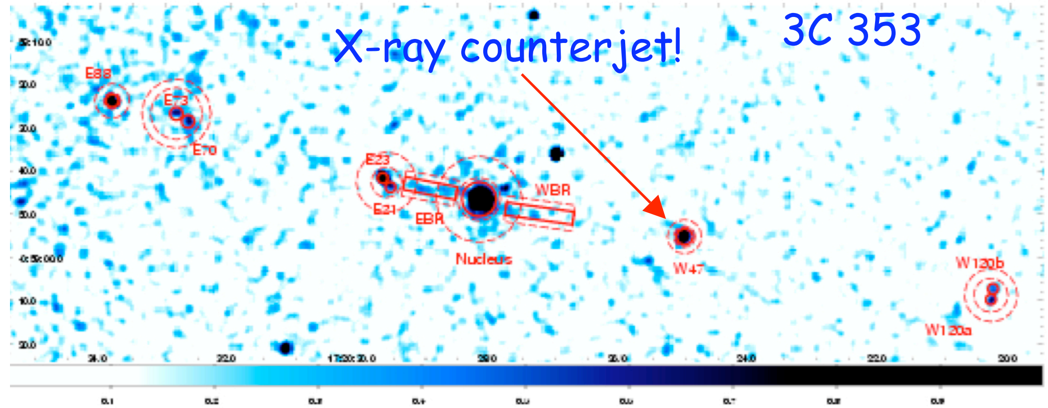
Synchrotron X-rays?

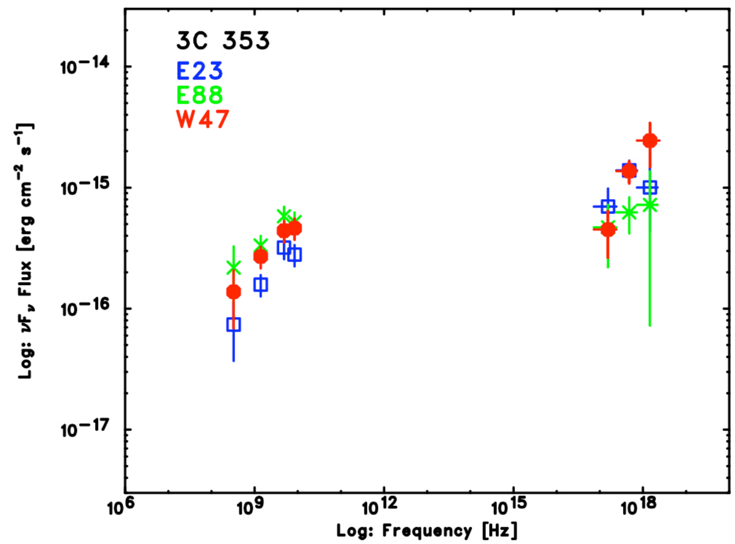


3C 273

polarized!



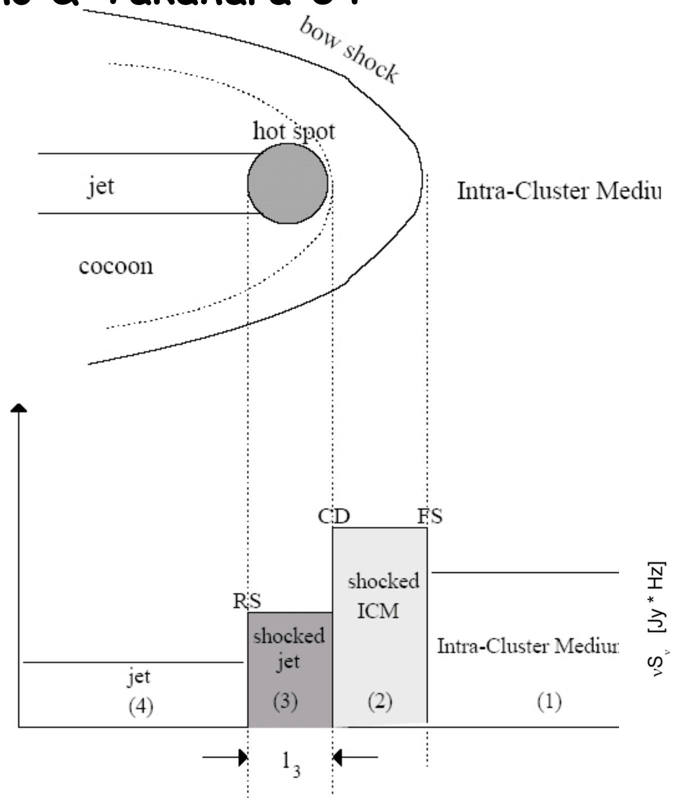


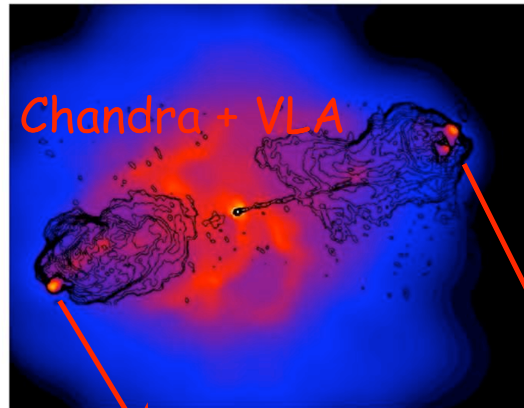


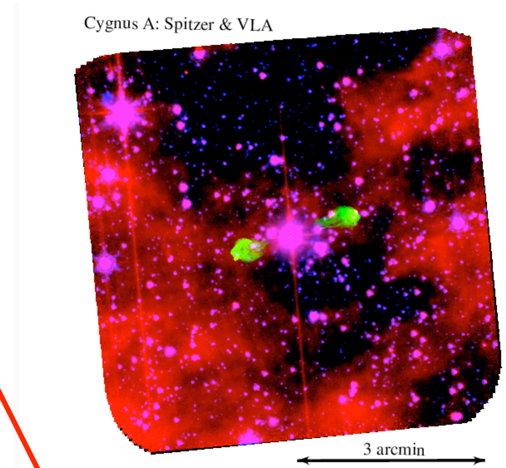
The spectral character of the broad-band emission of 3C 273 jet (**Jester+ 07**), as well as the detection of the X-ray counterjet in FR II radio galaxy 3C 353 (**Kataoka+08**), indicates that the synchrotron scenario for the X-ray emission of Chandra quasar jets may be more likely than the IC/CMB model.

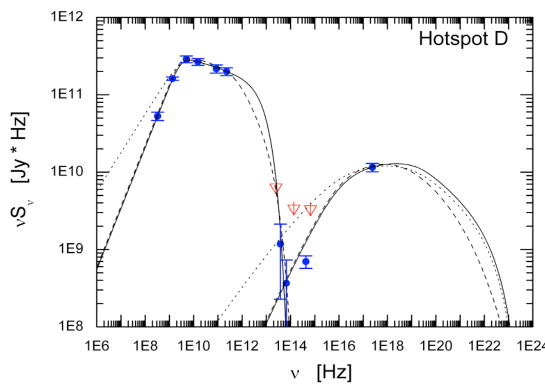
Terminal Hotspots

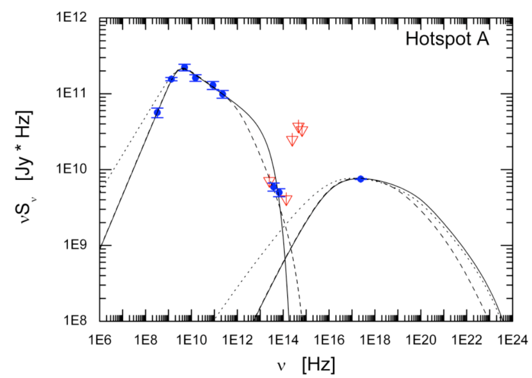
Kino & Takahara 04









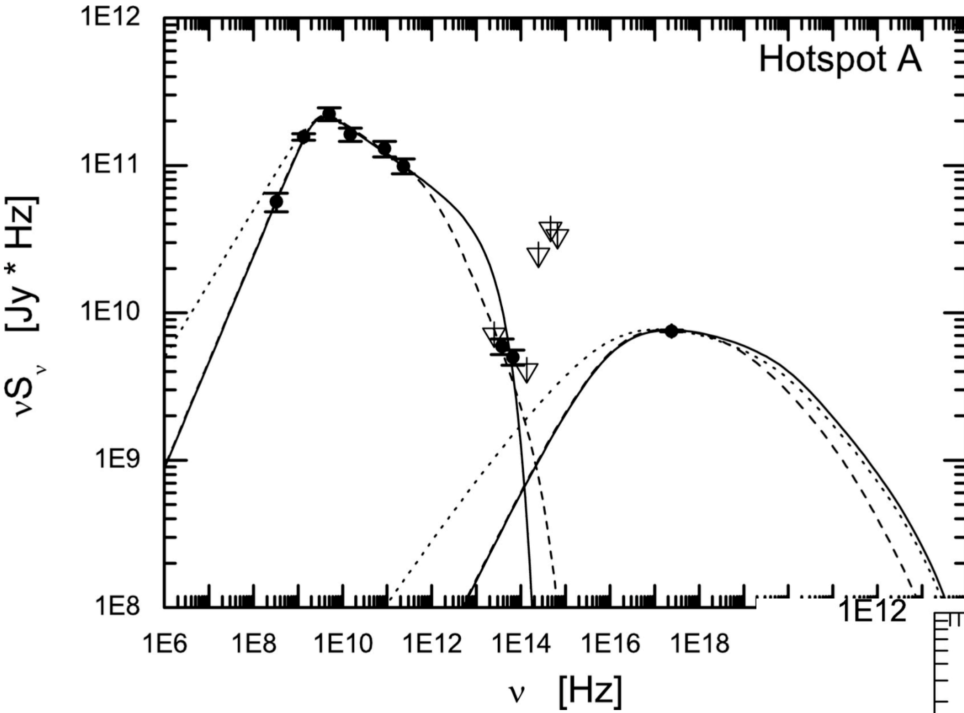


Hotspots in powerful radio sources are understood as the terminal regions of relativistic jets, where bulk kinetic power transported by the outflows from the active centers is converted at a strong shock (formed due to the interaction of the jet with the ambient gaseous medium) to the internal energy of the jet plasma.

Hotspots of exceptionally bright radio galaxy Cygnus A (d_L = 250 Mpc) can be resolved at different frequencies (VLA, Spitzer, Chandra), enabling us to understand how (mildly) relativistic shocks work ***(Stawarz+07)***.

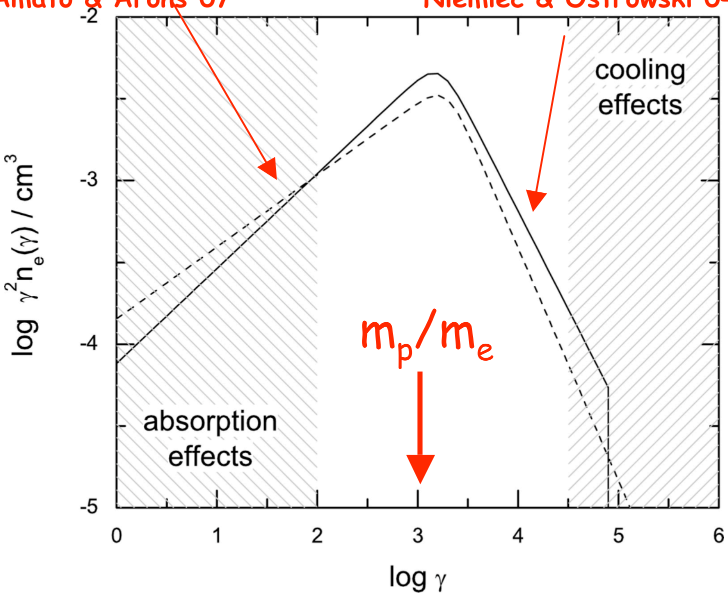
Shocks

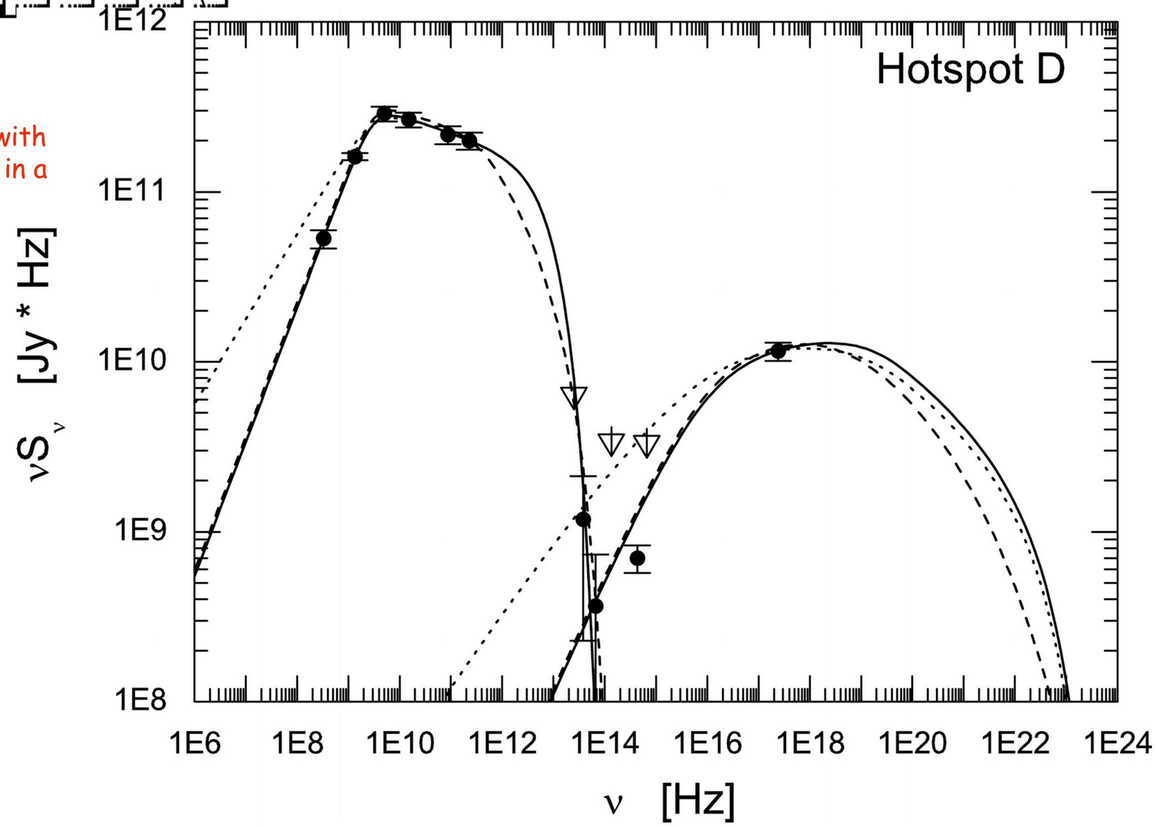
Stawarz+07: analysis of the broad-band emission of hotspots in the exceptionally bright radio galaxy Cygnus A indicates $U_B \sim U_e$ and terminal shocks dynamically dominated by protons.



Resonant acceleration of the type discussed by **Hoshino+92** **Amato & Arons 07**

Mildly-relativistic shock with perpendicular MF results in a Steep particle spectrum: **Niemiec & Ostrowski 04**





Conclusions

- Varity of particle (electron) spectra are produced in extragalactic jets.
- Variety of particle acceleration / energy dissipation processes are involved. (Not only shocks, but also turbulent processes.)
- Need for multiwavelength (radio-to-gamma-ray) observations and detailed modeling of the observed spectra.
- Variety of emission spectra for different jet regions (blazars, resolved jet knots, inteknot regions, terminal shocks, etc.).