GeV Photon Emission from Blazars with the Stochastic Electron Acceleration

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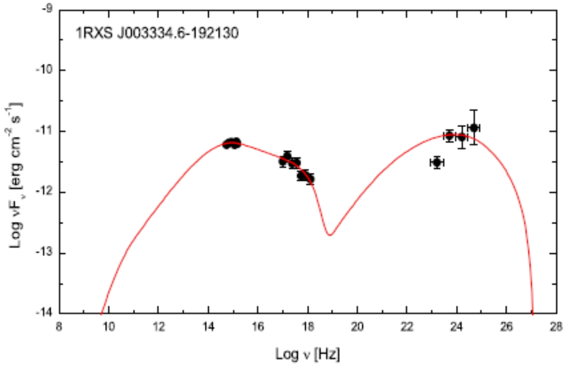
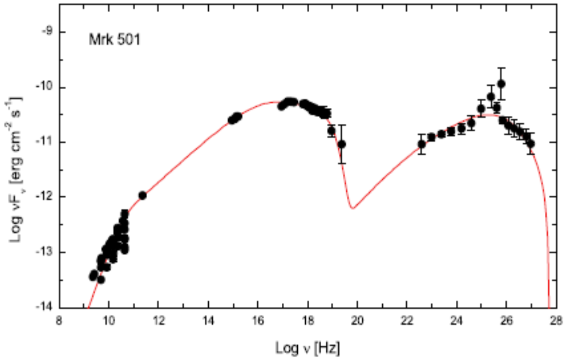
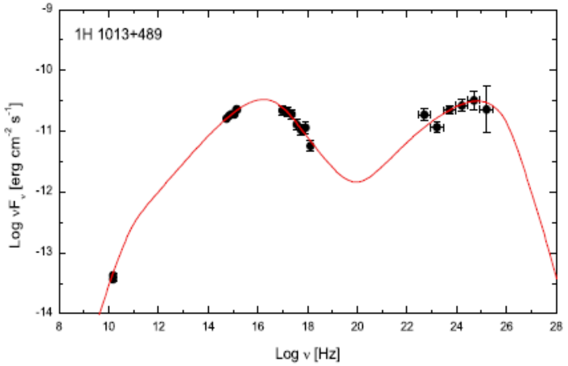
AGN:Fermi BL Lacs

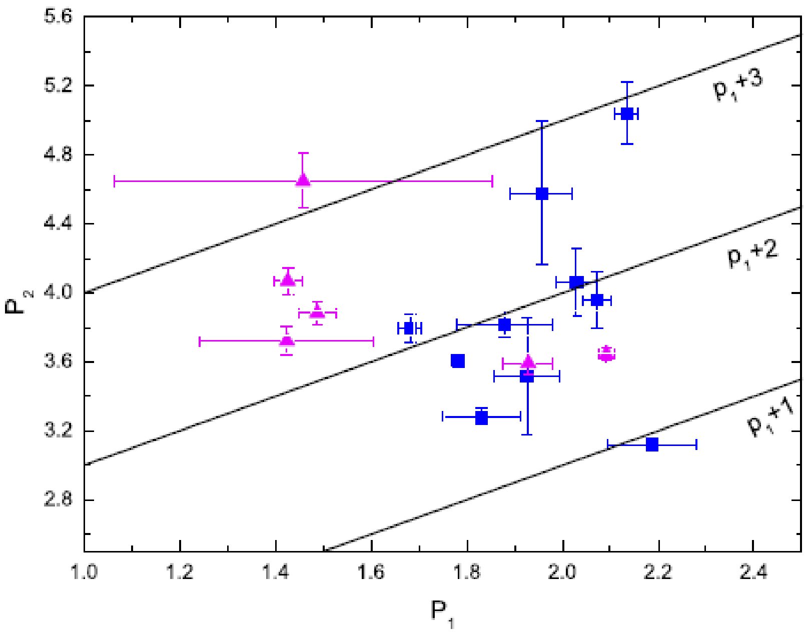


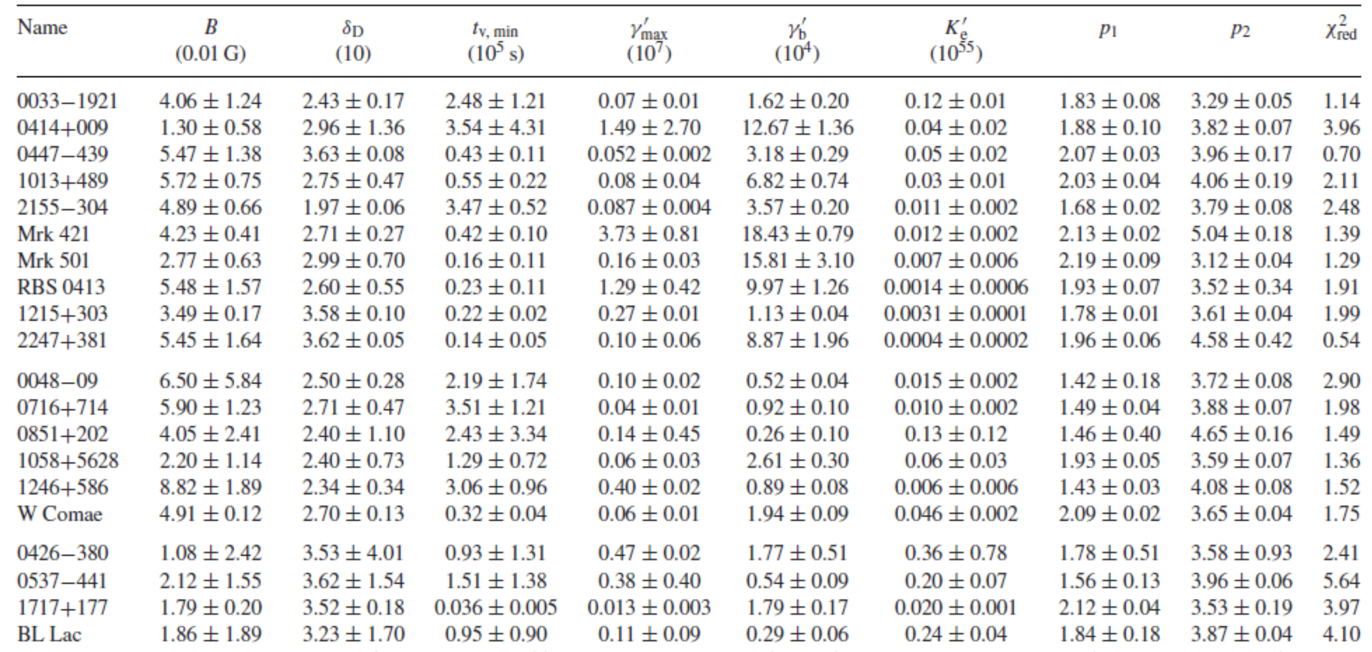




Yan+

MNRAS 439, 2933–2942 (2014)



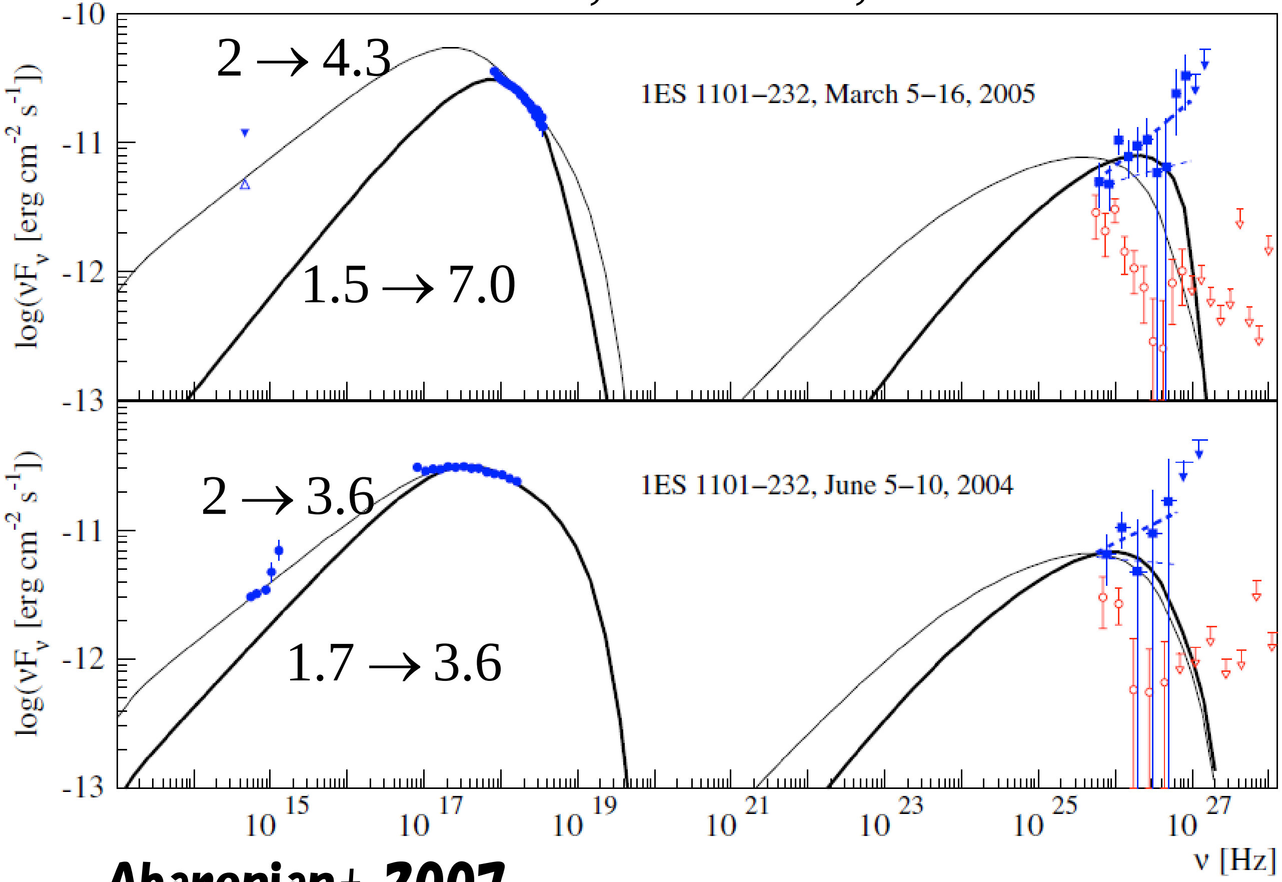


Name	B (0.01 G)	δ_D (10)	$t_{v,\min}$ (10^5 s)	$\gamma'_{\max}$ (10^7)	γ'_b (10^4)	K'_e (10^{55})	p_1	p_2	$\chi^2_{\rm red}$
0033−1921	4.06 ± 1.24	2.43 ± 0.17	2.48 ± 1.21	0.07 ± 0.01	1.62 ± 0.20	0.12 ± 0.01	1.83 ± 0.08	3.29 ± 0.05	1.14
0414+009	1.30 ± 0.58	2.96 ± 1.36	3.54 ± 4.31	1.49 ± 2.70	12.67 ± 1.36	0.04 ± 0.02	1.88 ± 0.10	3.82 ± 0.07	3.96
0447−439	5.47 ± 1.38	3.63 ± 0.08	0.43 ± 0.11	0.052 ± 0.002	3.18 ± 0.29	0.05 ± 0.02	2.07 ± 0.03	3.96 ± 0.17	0.70
1013+489	5.72 ± 0.75	2.75 ± 0.47	0.55 ± 0.22	0.08 ± 0.04	6.82 ± 0.74	0.03 ± 0.01	2.03 ± 0.04	4.06 ± 0.19	2.11
2155−304	4.89 ± 0.66	1.97 ± 0.06	3.47 ± 0.52	0.087 ± 0.004	3.57 ± 0.20	0.011 ± 0.002	1.68 ± 0.02	3.79 ± 0.08	2.48
Mrk 421	4.23 ± 0.41	2.71 ± 0.27	0.42 ± 0.10	3.73 ± 0.81	18.43 ± 0.79	0.012 ± 0.002	2.13 ± 0.02	5.04 ± 0.18	1.39
Mrk 501	2.77 ± 0.63	2.99 ± 0.70	0.16 ± 0.11	0.16 ± 0.03	15.81 ± 3.10	0.007 ± 0.006	2.19 ± 0.09	3.12 ± 0.04	1.29
RBS 0413	5.48 ± 1.57	2.60 ± 0.55	0.23 ± 0.11	1.29 ± 0.42	9.97 ± 1.26	0.0014 ± 0.0006	1.93 ± 0.07	3.52 ± 0.34	1.91
1215+303	3.49 ± 0.17	3.58 ± 0.10	0.22 ± 0.02	0.27 ± 0.01	1.13 ± 0.04	0.0031 ± 0.0001	1.78 ± 0.01	3.61 ± 0.04	1.99
2247+381	5.45 ± 1.64	3.62 ± 0.05	0.14 ± 0.05	0.10 ± 0.06	8.87 ± 1.96	0.0004 ± 0.0002	1.96 ± 0.06	4.58 ± 0.42	0.54
0048−09	6.50 ± 5.84	2.50 ± 0.28	2.19 ± 1.74	0.10 ± 0.02	0.52 ± 0.04	0.015 ± 0.002	1.42 ± 0.18	3.72 ± 0.08	2.90
0716+714	5.90 ± 1.23	2.71 ± 0.47	3.51 ± 1.21	0.04 ± 0.01	0.92 ± 0.10	0.010 ± 0.002	1.49 ± 0.04	3.88 ± 0.07	1.98
0851+202	4.05 ± 2.41	2.40 ± 1.10	2.43 ± 3.34	0.14 ± 0.45	0.26 ± 0.10	0.13 ± 0.12	1.46 ± 0.40	4.65 ± 0.16	1.49
1058+5628	2.20 ± 1.14	2.40 ± 0.73	1.29 ± 0.72	0.06 ± 0.03	2.61 ± 0.30	0.06 ± 0.03	1.93 ± 0.05	3.59 ± 0.07	1.36
1246+586	8.82 ± 1.89	2.34 ± 0.34	3.06 ± 0.96	0.40 ± 0.02	0.89 ± 0.08	0.006 ± 0.006	1.43 ± 0.03	4.08 ± 0.08	1.52
W Comae	4.91 ± 0.12	2.70 ± 0.13	0.32 ± 0.04	0.06 ± 0.01	1.94 ± 0.09	0.046 ± 0.002	2.09 ± 0.02	3.65 ± 0.04	1.75
0426−380	1.08 ± 2.42	3.53 ± 4.01	0.93 ± 1.31	0.47 ± 0.02	1.77 ± 0.51	0.36 ± 0.78	1.78 ± 0.51	3.58 ± 0.93	2.41
0537−441	2.12 ± 1.55	3.62 ± 1.54	1.51 ± 1.38	0.38 ± 0.40	0.54 ± 0.09	0.20 ± 0.07	1.56 ± 0.13	3.96 ± 0.06	5.64
1717+177	1.79 ± 0.20	3.52 ± 0.18	0.036 ± 0.005	0.013 ± 0.003	1.79 ± 0.17	0.020 ± 0.001	2.12 ± 0.04	3.53 ± 0.19	3.97
BL Lac	1.86 ± 1.89	3.23 ± 1.70	0.95 ± 0.90	0.11 ± 0.09	0.29 ± 0.06	0.24 ± 0.04	1.84 ± 0.18	3.87 ± 0.04	4.10
OT 081	9.82 ± 9.80	2.31 ± 5.16	0.12 ± 0.55	2.00 ± 2.10	0.52 ± 0.58	0.007 ± 0.022	1.75 ± 0.66	3.76 ± 0.59	1.69
4C 01.28	10.56 ± 19.20	2.47 ± 3.42	0.66 ± 6.02	0.12 ± 0.43	0.30 ± 0.18	0.06 ± 0.13	1.69 ± 0.64	3.70 ± 0.32	0.96

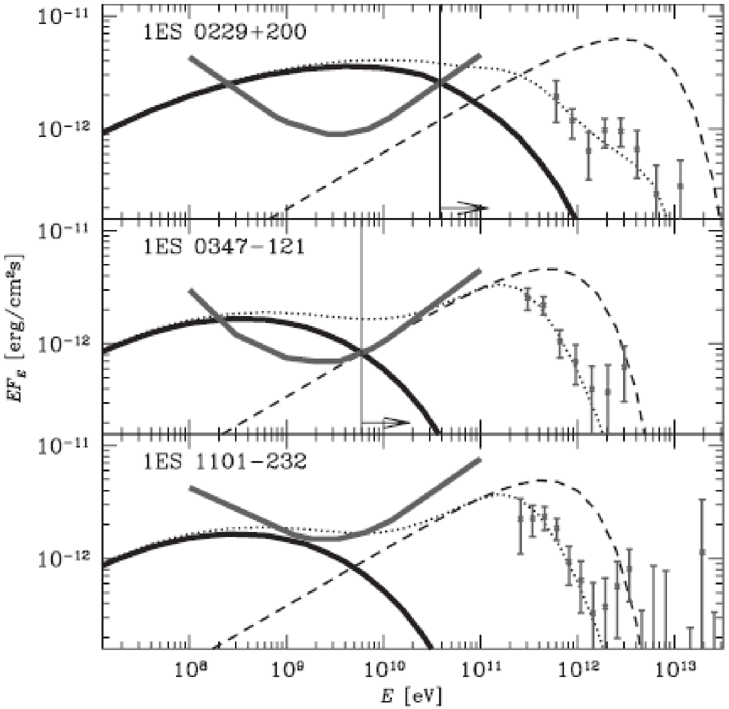
Hard spectrum blazar

The spectral index is harder than the usual shock acceleration models.

$$\delta = 25,\ B' = 0.1\mathrm{G},\ R = 2.8\times10^{16}\,\mathrm{cm}$$



Aharonian+ 2007



Neronov & Vovk 2010

Problems in SSC with shock acceleration

- Low maximum electron energy (far below the Bohm limit)
- Hard spectrum ($p<2$)
- Multiple breaks in electron spectrum
- Spectral break is inconsistent with the cooling break
- The emission seems to be composed of steady and flare components.

Stochastic acceleration

Stawarz & Petrosian 2008

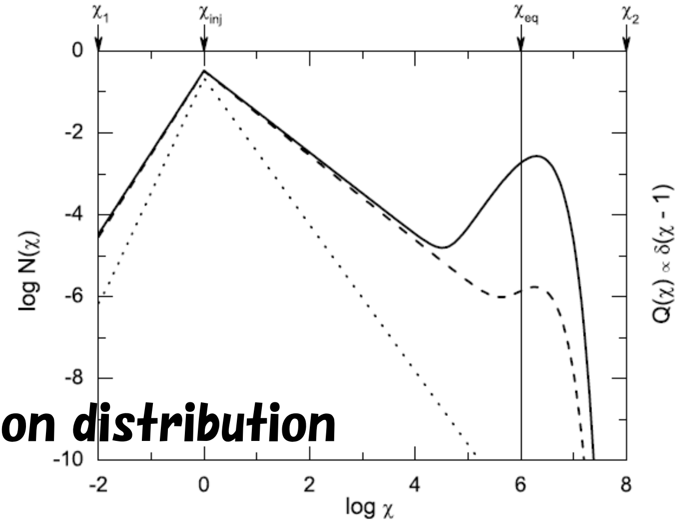
$$\frac{\partial n(p,t)}{\partial t} = \frac{\partial}{\partial p}\left[D(p)\frac{\partial n(p,t)}{\partial p}\right] - \frac{\partial}{\partial p}\left[\left(\frac{2D(p)}{p} + \langle \dot{p} \rangle\right) n(p,t)\right] - \frac{n(p,t)}{t_{\rm esc}} + \tilde{Q}(p,t).$$

$$D(p) \approx \frac{\zeta \beta_{\rm A}^2 p^2 c}{r_g^{2-q} \lambda_2^{q-1}} \propto p^q$$

λ_2: Maximum wave length

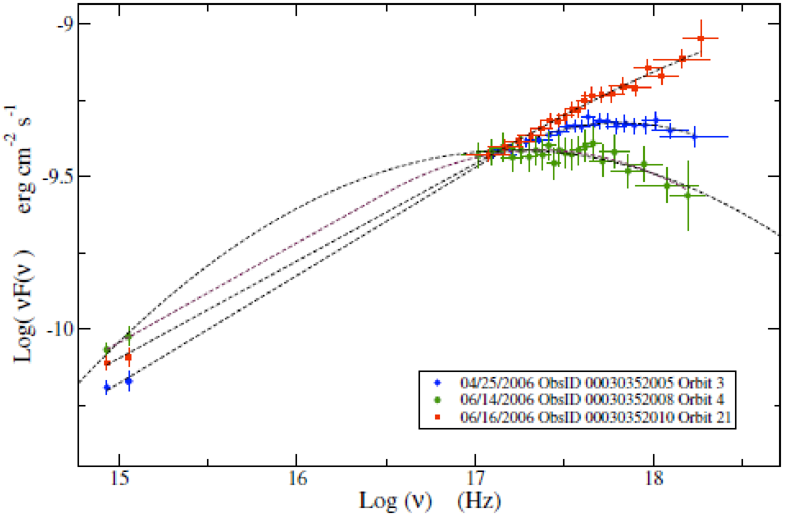
$$\zeta \equiv (\delta B)^2/B_0^2 < 1.$$

$$t_{\rm acc} \equiv p^2/D(p) \propto p^{2-q}/\beta_{\rm A}^2$$



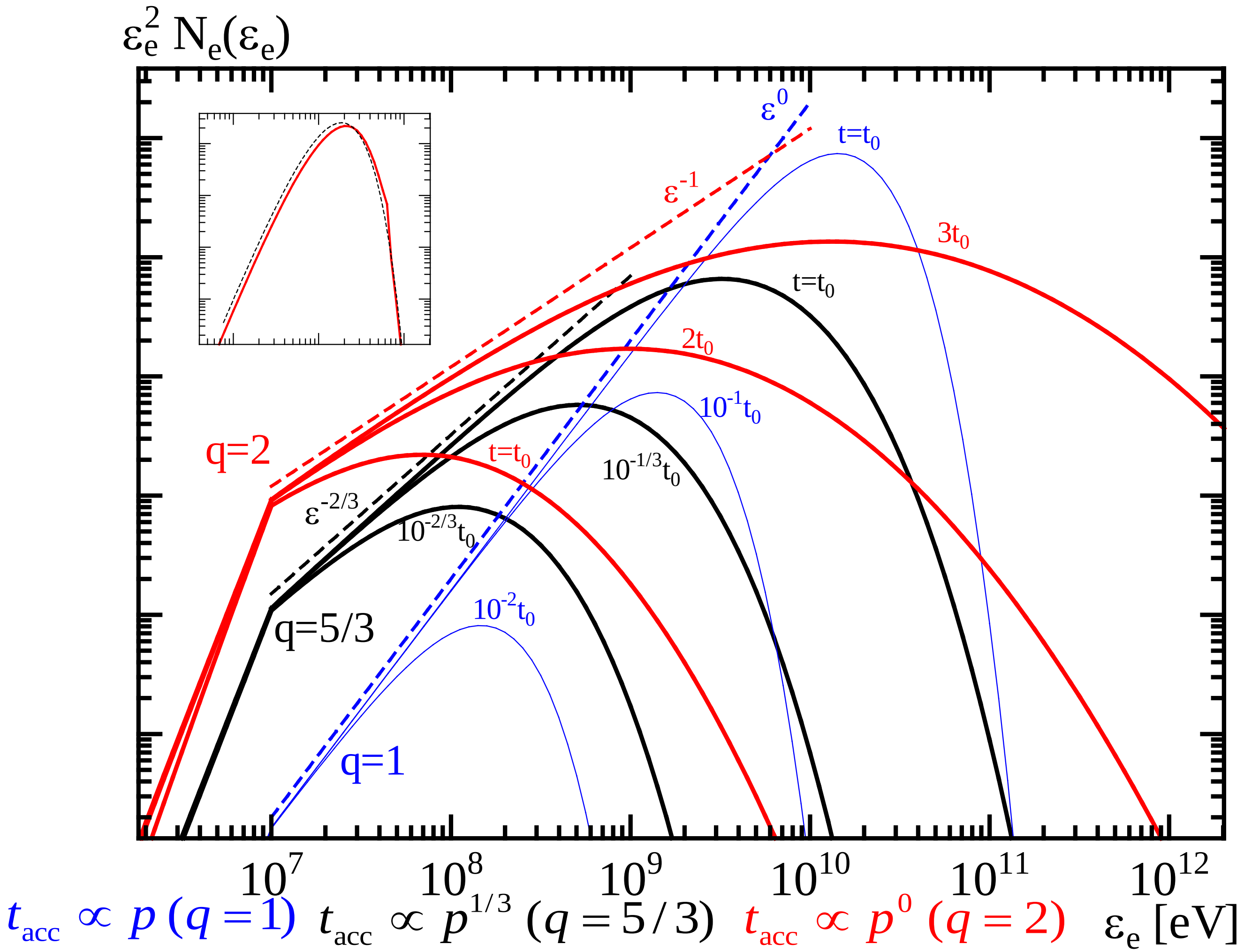
Electron distribution

- **Stochastic acceleration (2nd order Fermi acceleration) can produce harder electron spectra.**
- **This is slower process than the usual shock acceleration.**
- **The log-parabola shape in observed photon spectra may indicate the stochastic acceleration (Tramacere+ 2009)**



$$\begin{aligned} n(\gamma) &= K\,(\gamma/\gamma_c)^{-s}, & \gamma \le \gamma_c \\ n(\gamma) &= K\,(\gamma/\gamma_c)^{-(s+r\,{\rm Log}(\gamma/\gamma_c))}, & \gamma > \gamma_c \end{aligned}$$

Temporal evolution of electron spectrum



$$D(\varepsilon_e) = \frac{\bar{\xi}\pi e c \varepsilon_e k |\delta B^2|_k}{8B} \equiv K\varepsilon_e^q$$

$$|\delta B^2|_k \propto k^{-q}$$

$$t_{acc} \sim \varepsilon_e^2/2D(\varepsilon_e) \propto \varepsilon_e^{2-q}$$

Steady state solution

$$N_e(\varepsilon_e) \propto \varepsilon_e^{1-q}$$

Solution when the cooling and acceleration balances

$$N_e(\varepsilon_e) \propto \varepsilon_e^2 \exp\{-(\varepsilon_e/\varepsilon_c)^{3-q}\}$$

Hard spectra & lower maximum energy

Maxwellian distribution?

Lefa+ 2011

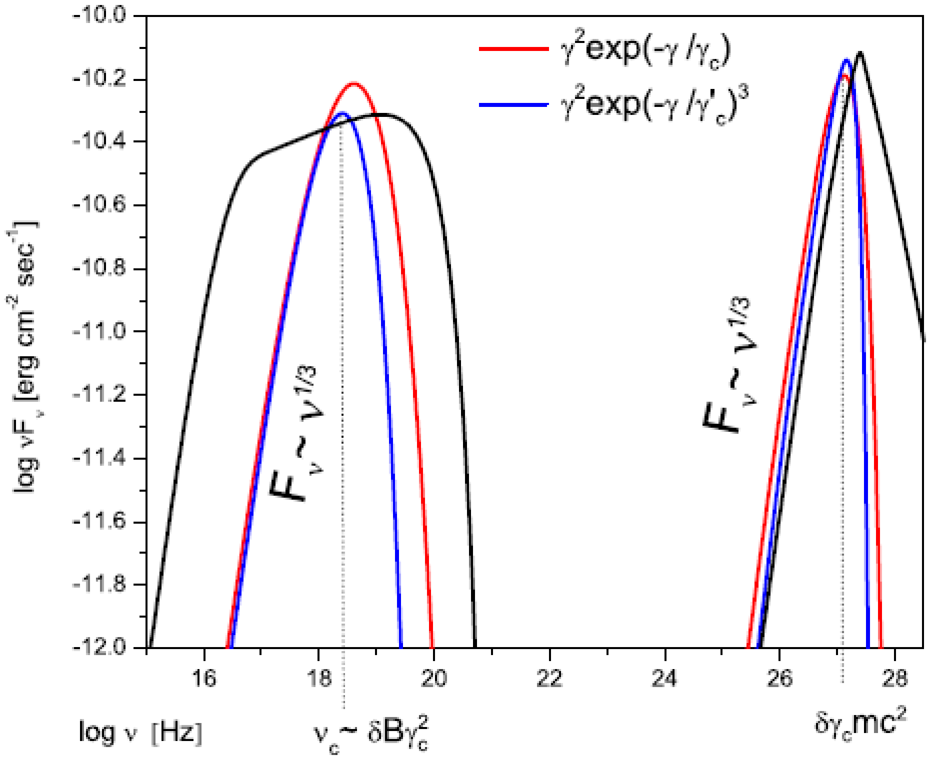
In extreme cases, the acceleration & cooling balance each other, then we have very hard spectrum.

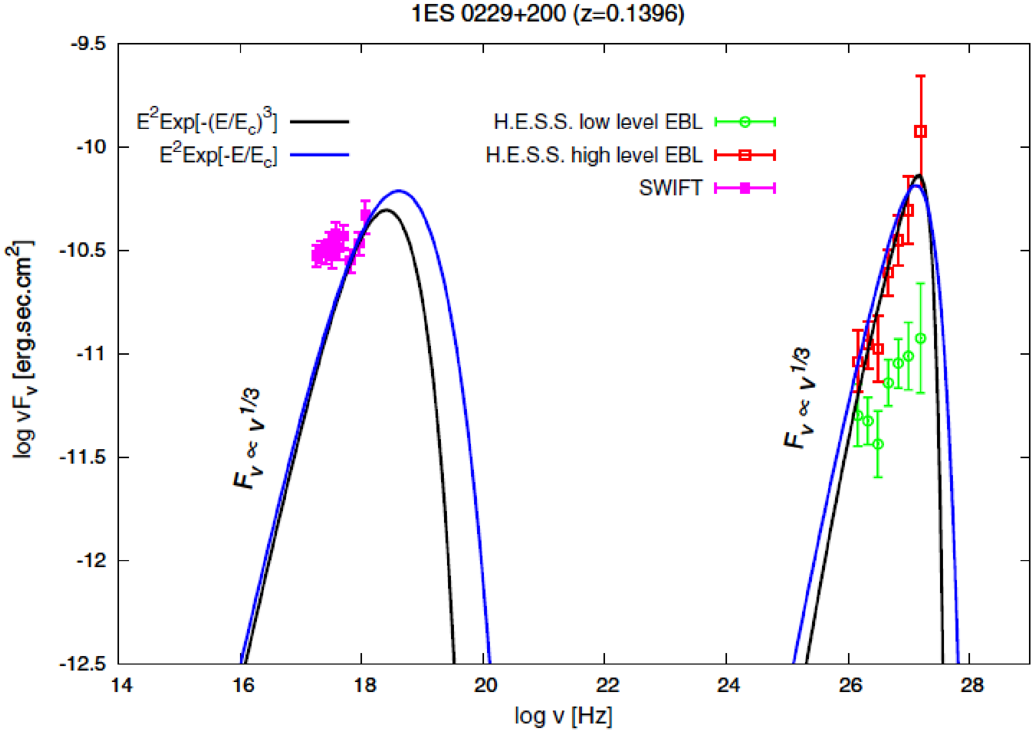
$$\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_p \frac{\partial f(p)}{\partial p}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}(\beta_s p^4 f(p)) = 0$$

$$t_{cool} = 1/\beta_s p$$

$$f(\gamma) = A\gamma^2 e^{-(\frac{\gamma}{\gamma_c})^{1+\alpha_p}} \qquad D_p \propto p^{2-\alpha_p}$$

$\alpha_p = 1/3$ **for Kolmogorov**

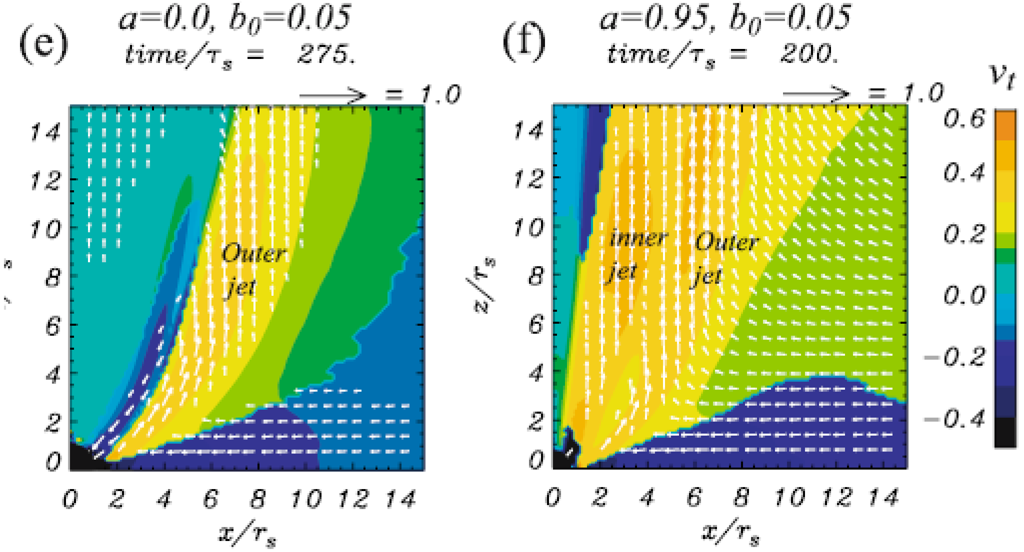




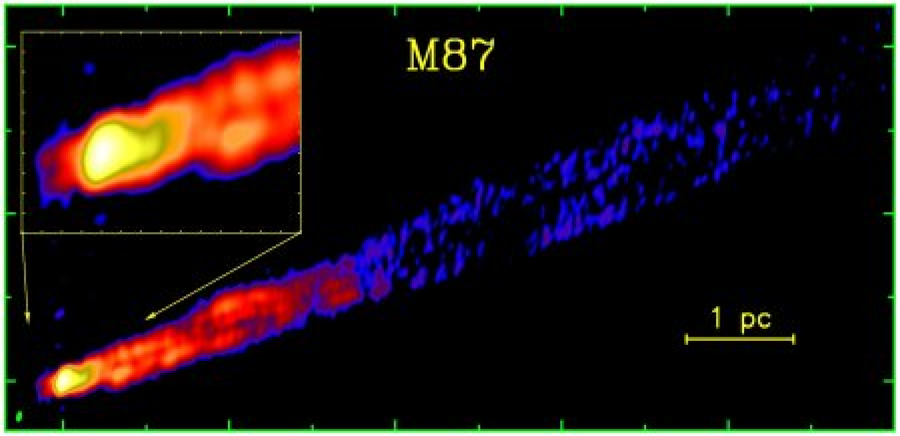
Turbulence in AGN jets

Spine-Sheath structure

Hardee+ 2007 MHD simulation

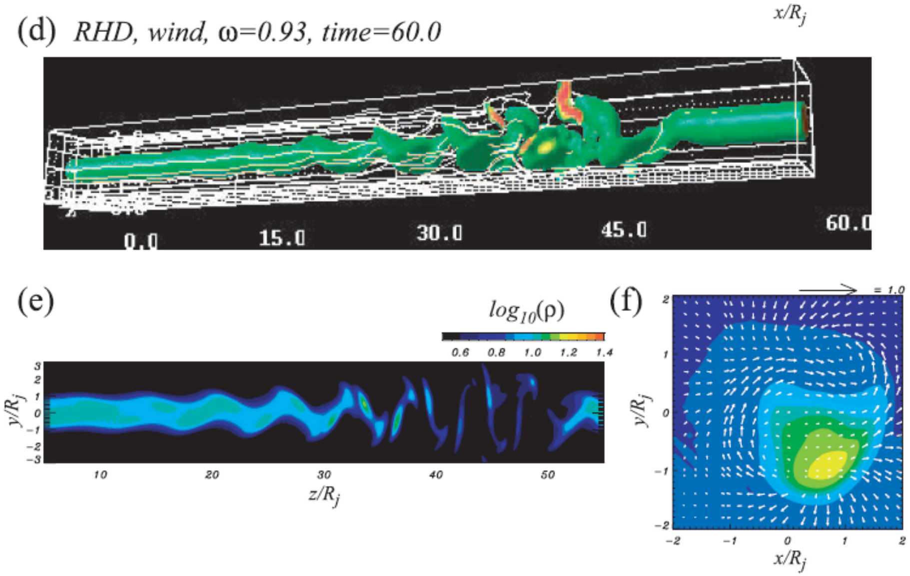


Double layer in M87 jet



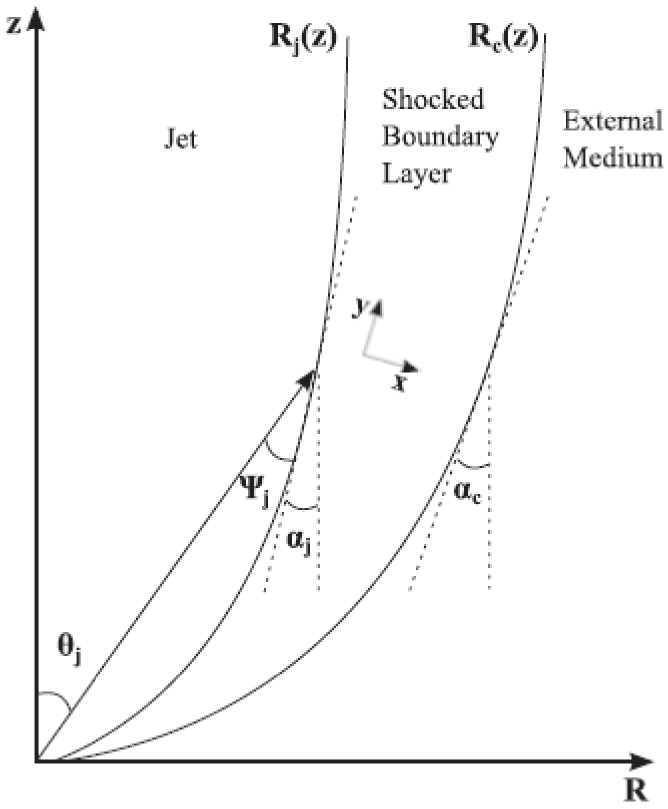
Kelvin Helmholtz Instability

Mizuno+ 2007



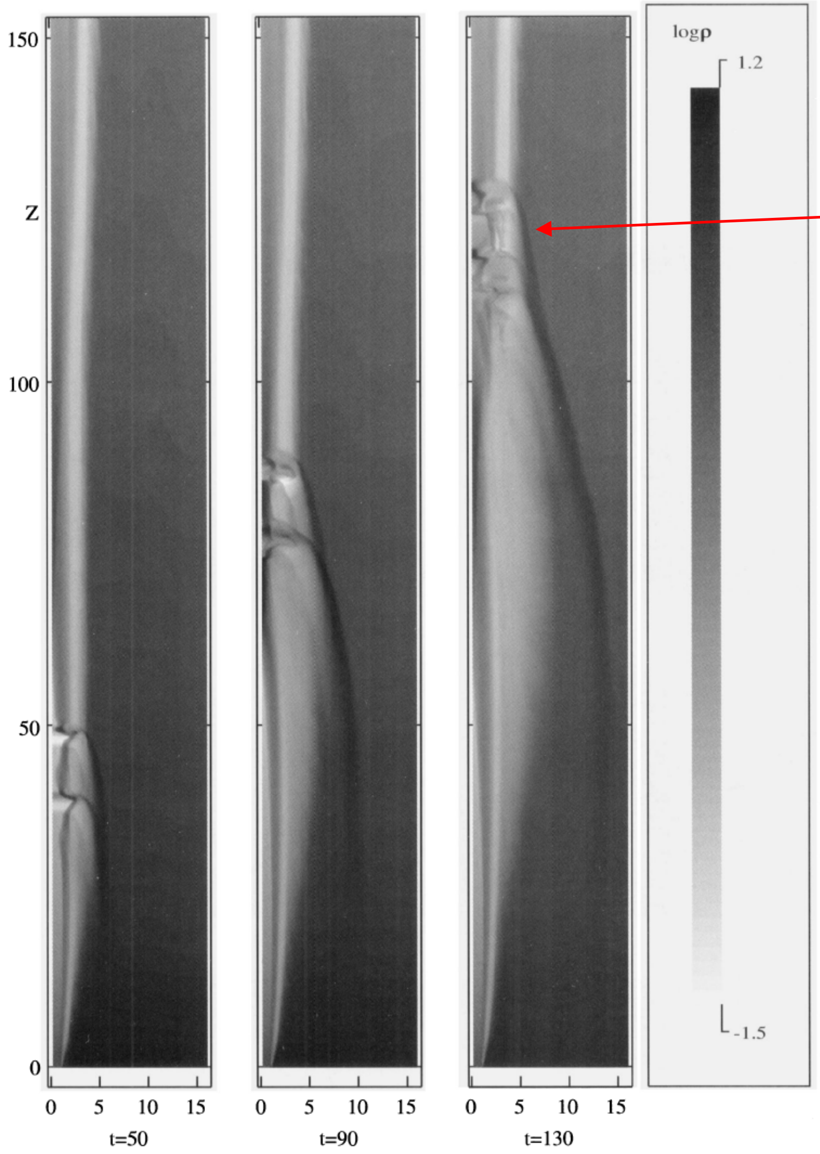
Recollimation

Recollimation of the jet may induce turbulences.



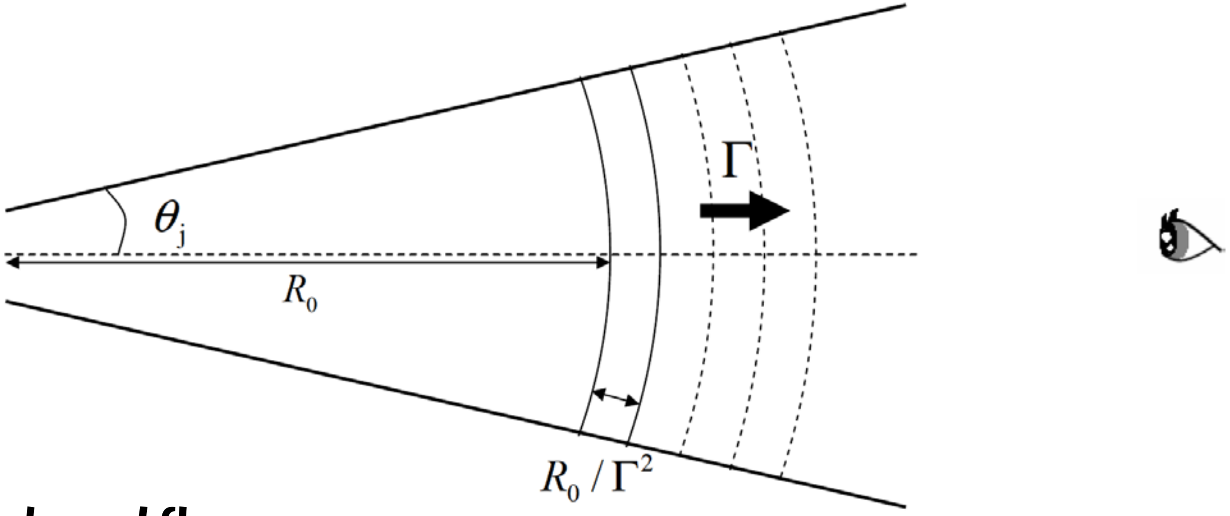
Kohler+ 2012

Komissarove & Falle 1997



Induce turbulence?

Model



- *Steady outflow*
- *Continuous shell ejection with a width of R_0/Γ in commoving frame*
- *Elecrton injection from $R=R_0$ to $2R_0$ with stochastic acceleration*
- *Turbulence Index: Kolmogorov $q=5/3$*
- *Both injection and acceleration stop at $R=2R_0$*

Physical Processes

- *Electron injection*
- *Stochastic acceleration*
- *Synchrotron emission and cooling*
- *Inverse Compton emission and cooling*
- *Adiabatic cooling ($V \propto R^2$)*
- *Photon escape*
- *No electron escape!*

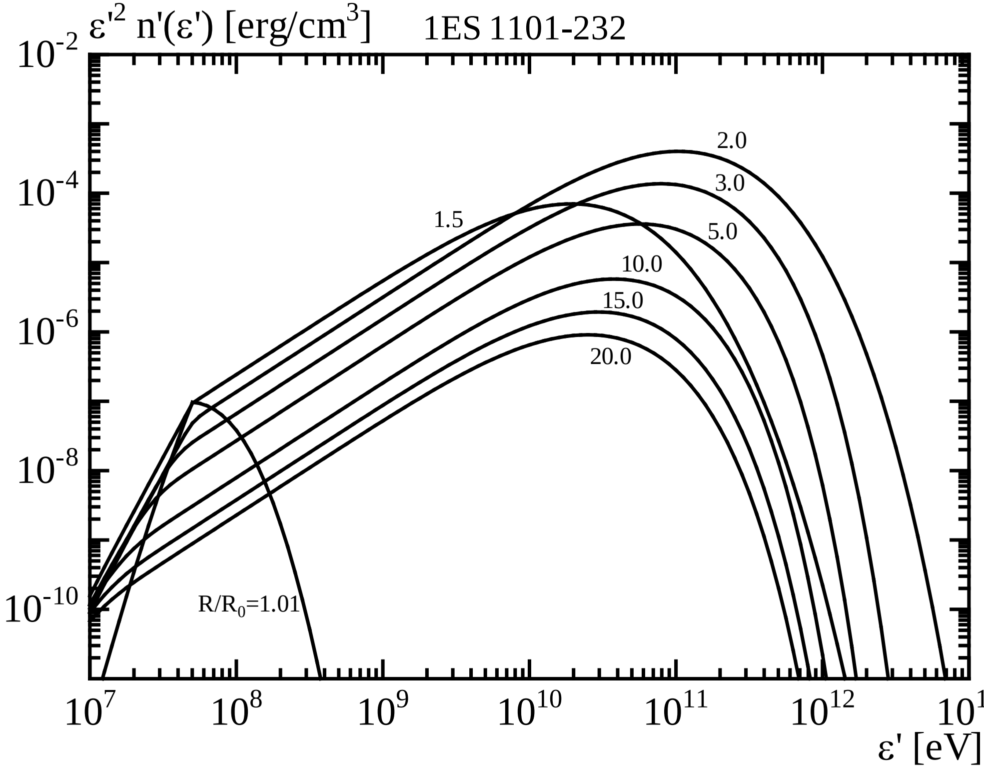
$$D(\varepsilon) = \frac{\bar{\xi}\pi e c \varepsilon k \delta B_k^2}{8B} \equiv K\varepsilon^q.$$

Hereafter, $q = 5/3$, $\theta_{\rm j} = 1/\Gamma$, $\gamma_{\rm inj} = 100$.

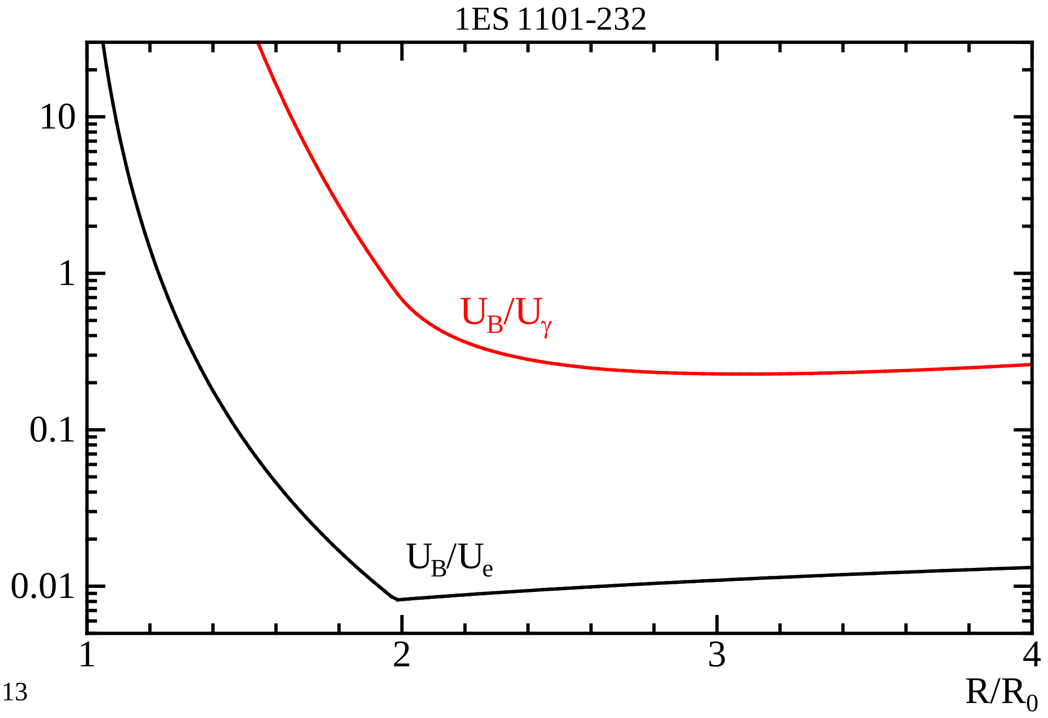
$$B' = B_0(R/R_0)^{-1}$$

Simple case

Electron spectrum



Energy density ratio



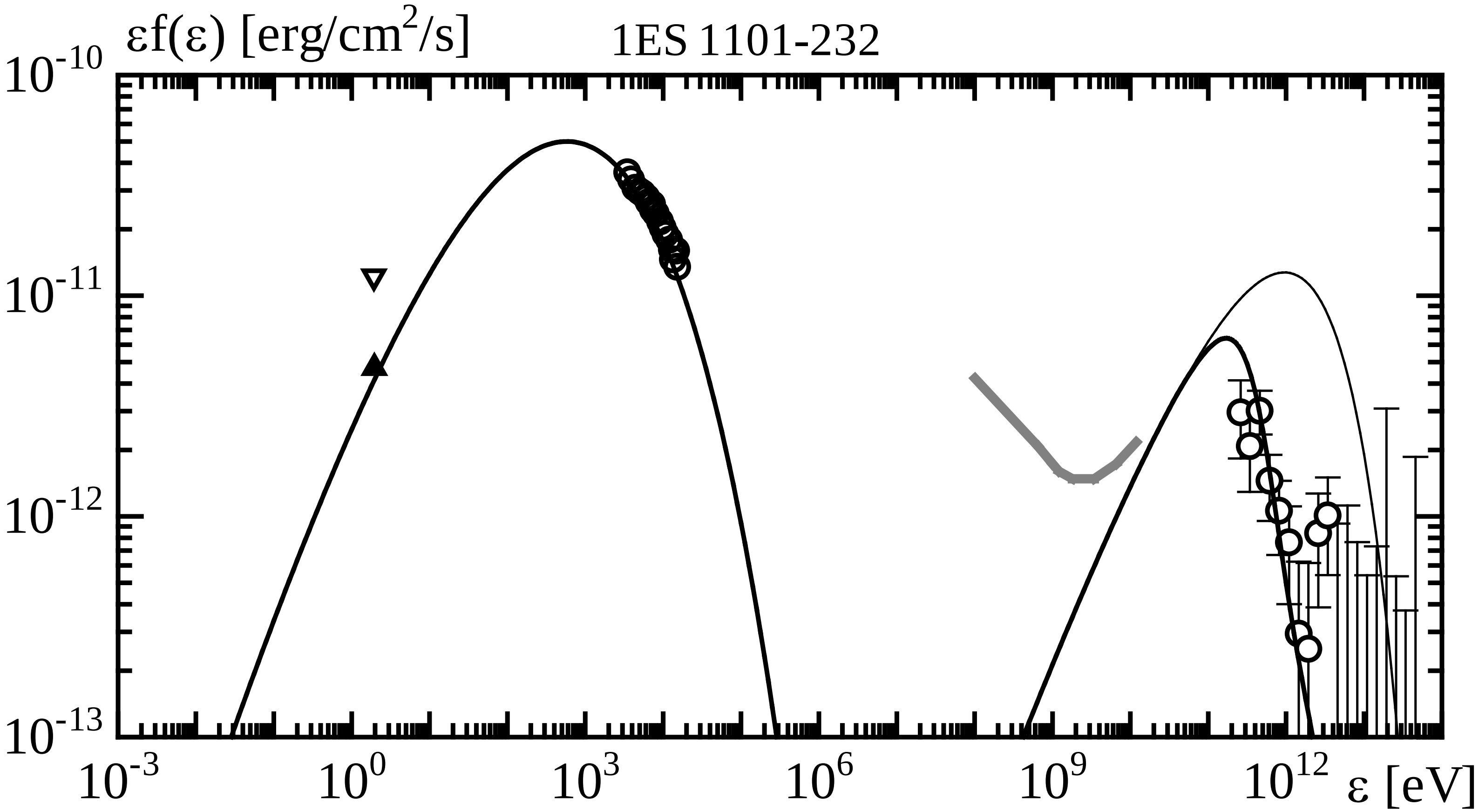
Constant injection & constant diffusion coefficient

The model parameters: $\Gamma = 25$, $B_0 = 0.03$ G, $W' = R_0/\Gamma = 2.8\times10^{16}$ cm, $\Delta T'_{\rm inj} = W'/c$, $K = 4.3 \times 10^{-3}$ eV$^{1/3}$ s^{-1}, $\dot{N}_0 = 1.5 \times 10^{46}$ s^{-1}

Kolmogorov turbulence (q=5/3) is assumed.

1ES 1101-232

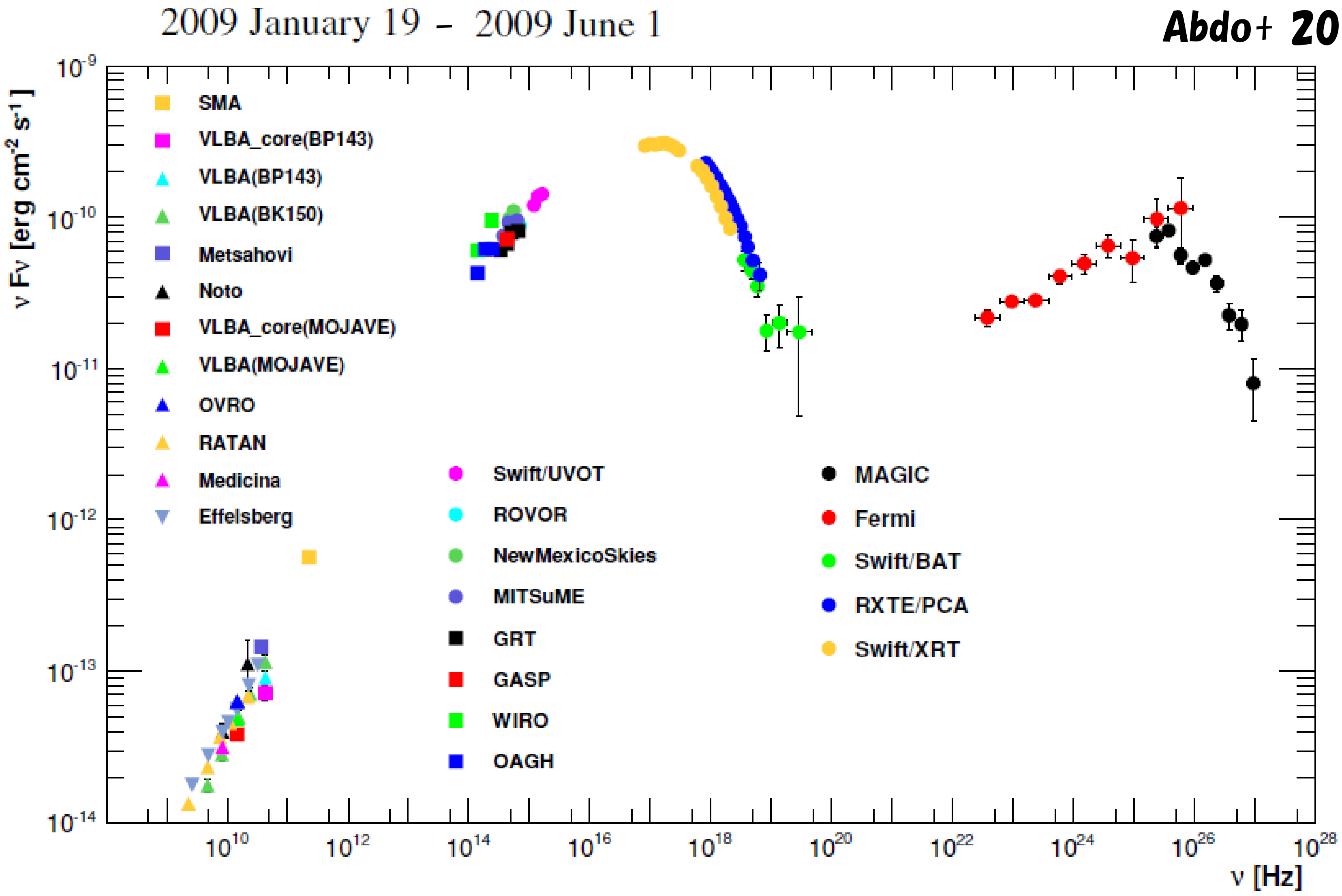
$L_\gamma = 2.6 \times 10^{43}\,\mathrm{erg\,s^{-1}}$



The simple model can reproduce the spectrum of 1ES 1101-232

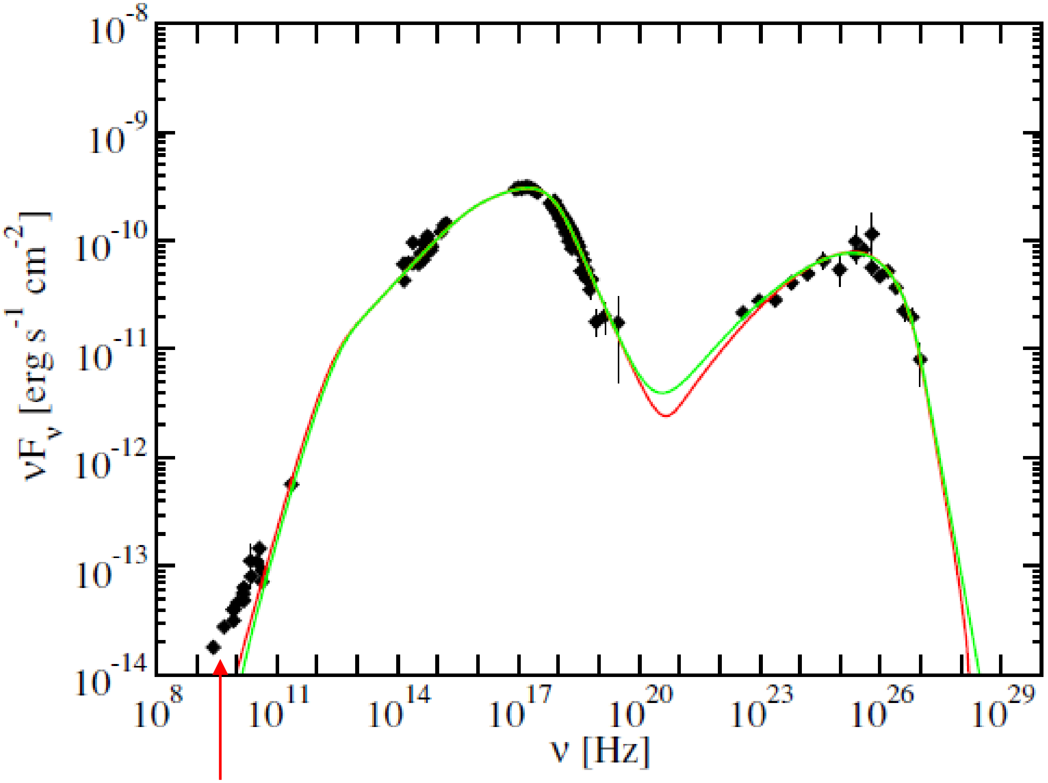
Mrk 421

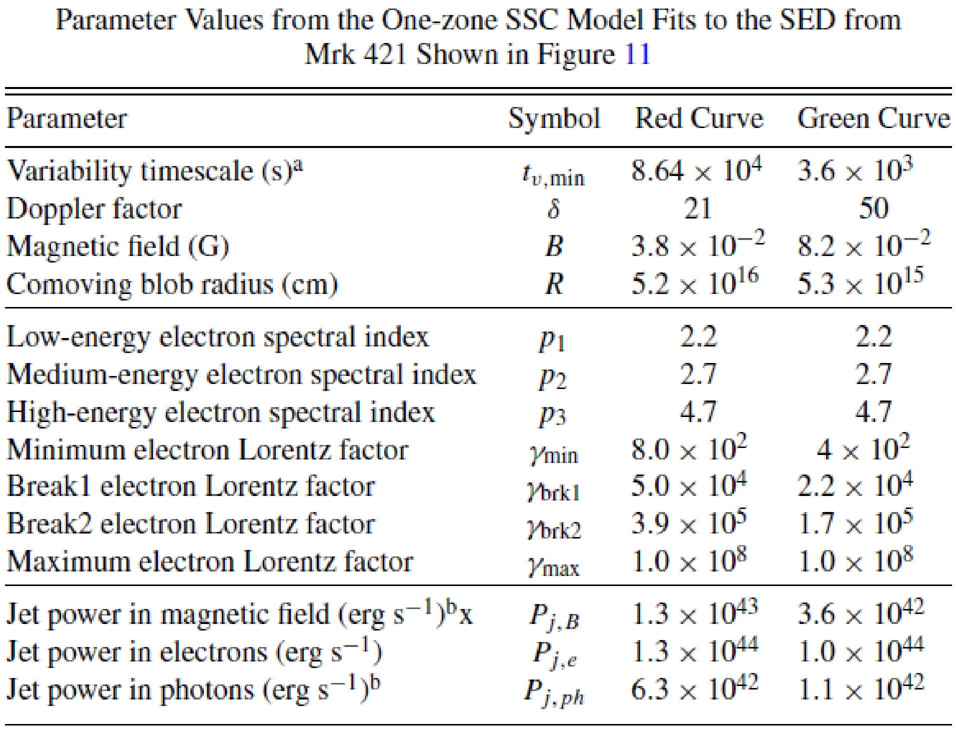
Abdo+ 2011



Best example of Wide-band spectra

Borken-power-law fit





Parameter Values from the One-zone SSC Model Fits to the SED from Mrk 421 Shown in Figure 11

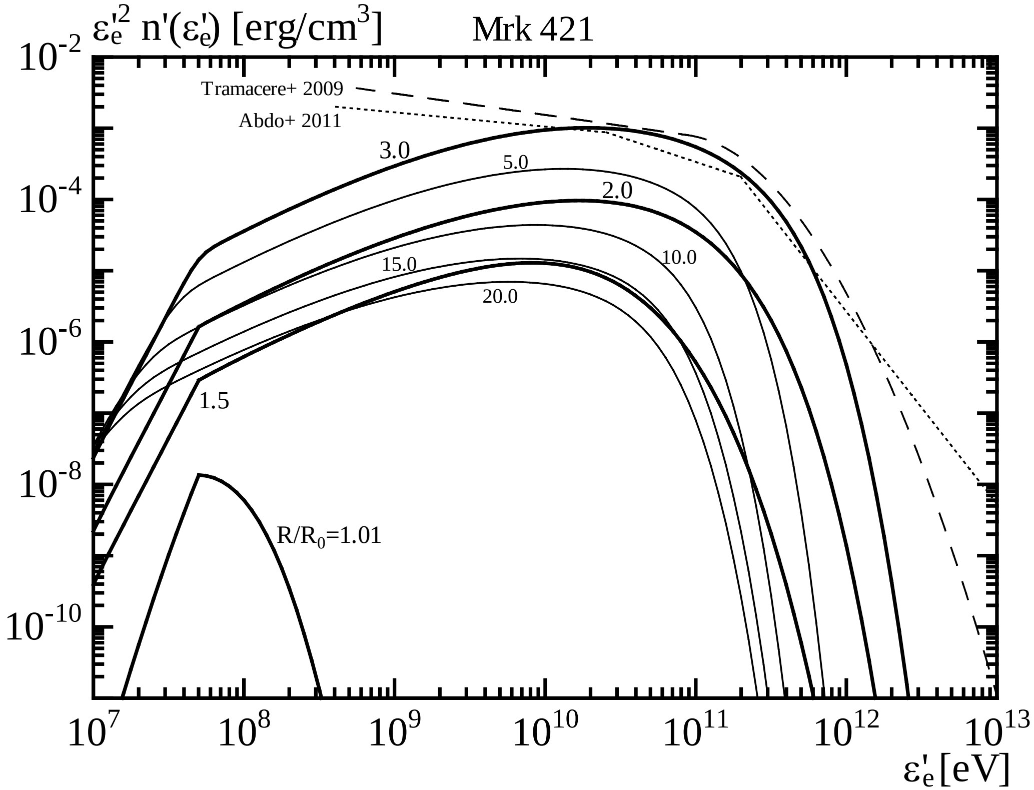
Parameter	Symbol	Red Curve	Green Curve
Variability timescale (s)[a]	$t_{v,\min}$	8.64×10^4	3.6×10^3
Doppler factor	δ	21	50
Magnetic field (G)	B	3.8×10^{-2}	8.2×10^{-2}
Comoving blob radius (cm)	R	5.2×10^{16}	5.3×10^{15}
Low-energy electron spectral index	p_1	2.2	2.2
Medium-energy electron spectral index	p_2	2.7	2.7
High-energy electron spectral index	p_3	4.7	4.7
Minimum electron Lorentz factor	$\gamma_{\min}$	8.0×10^2	4×10^2
Break1 electron Lorentz factor	γ_{brk1}	5.0×10^4	2.2×10^4
Break2 electron Lorentz factor	γ_{brk2}	3.9×10^5	1.7×10^5
Maximum electron Lorentz factor	$\gamma_{\max}$	1.0×10^8	1.0×10^8
Jet power in magnetic field (erg s^{-1})[b]x	$P_{j,B}$	1.3×10^{43}	3.6×10^{42}
Jet power in electrons (erg s^{-1})	$P_{j,e}$	1.3×10^{44}	1.0×10^{44}
Jet power in photons (erg s^{-1})[b]	$P_{j,ph}$	6.3×10^{42}	1.1×10^{42}

Radio should be different component in this case

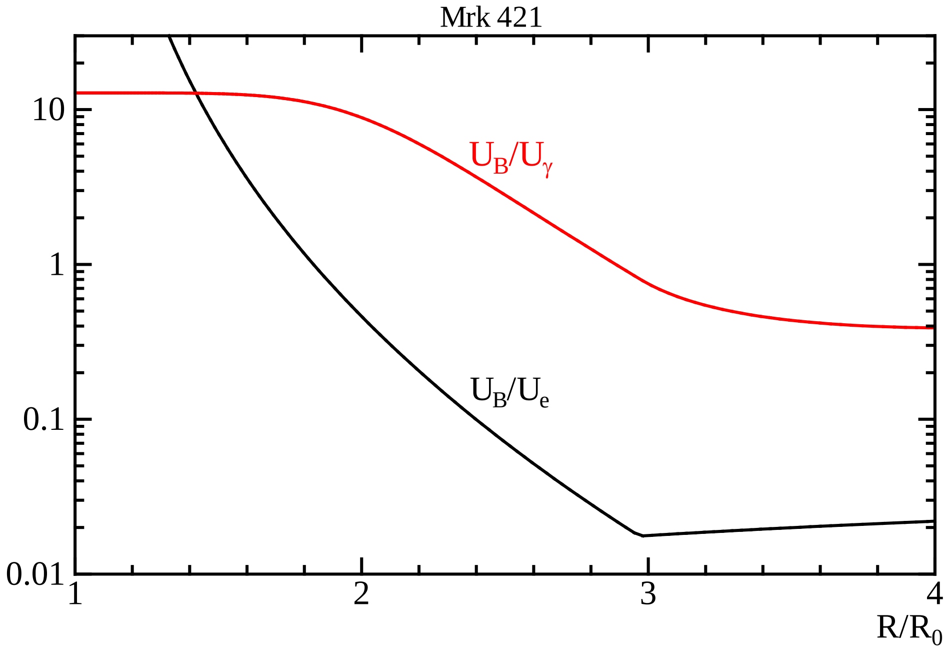
Need double break and low-energy cut-off

Radial evolution in the stochastic acceleration model

Electron spectrum



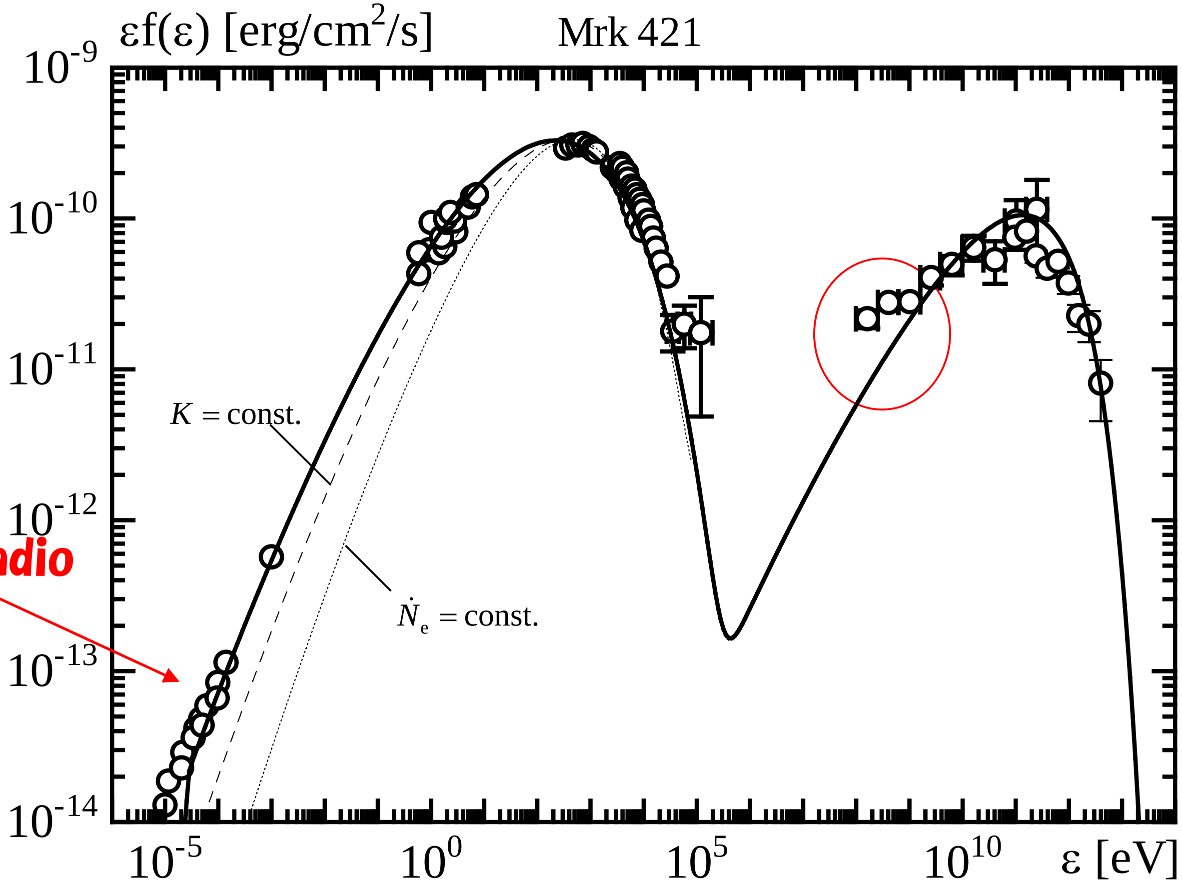
Energy density ratio



- The radial evolution of electron injection and diffusion coefficient can generate soft electron spectra.
- The spectral shape $>10^{10}$eV is similar to those in previous studies.
- We do not need a low-energy cut-off.

Kolmogorov turbulence ($q=5/3$) is assumed.

Fit with stochastic acceleration



Hard to reconcile GeV data.

Agree with radio

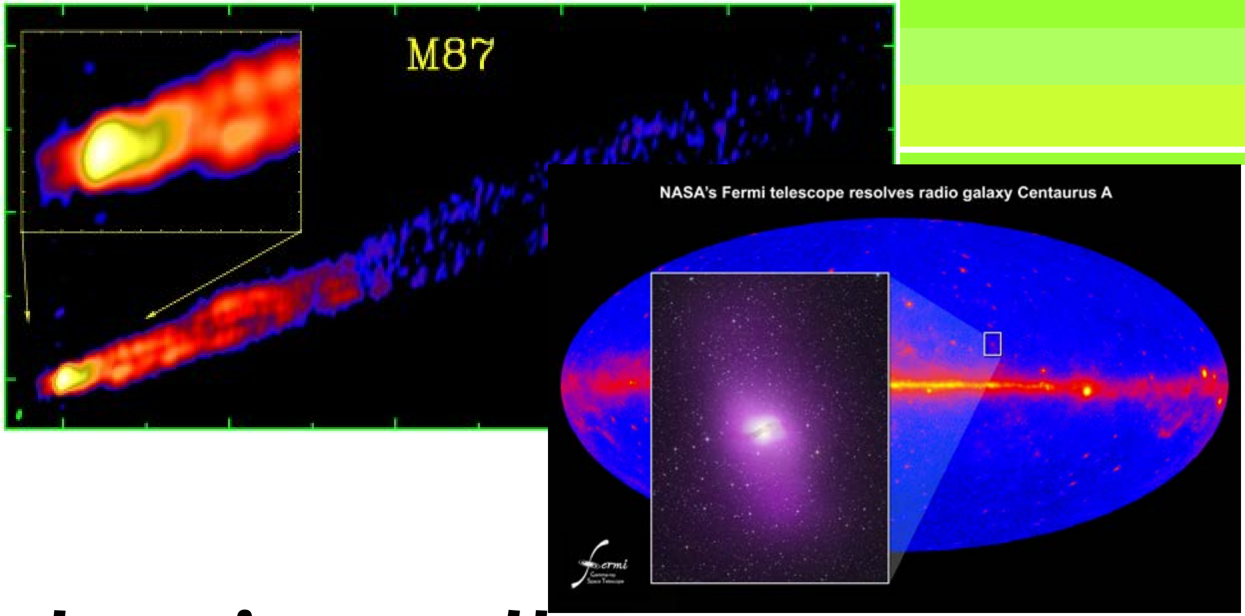
$$\dot{N}_\mathrm{e} = \dot{N}_0 (R/R_0)^7$$

$$K = K_0 (R/R_0)^{-1}$$

To produce a soft spectrum, increasing injection rate with radius is assumed.
(If q>5/3, such strong evolutions may be not required.)

The model parameters: $\Gamma = 15$, $B_0 = 0.13$ G, $W' = R_0/\Gamma = 1.0 \times 10^{16}$ cm, $\Delta T'_\mathrm{inj} = 2W'/c$, $K = 1.3 \times 10^{-2}$ eV$^{1/3}$ s^{-1}, $\dot{N}_0 = 9.8 \times 10^{43}$ s^{-1}

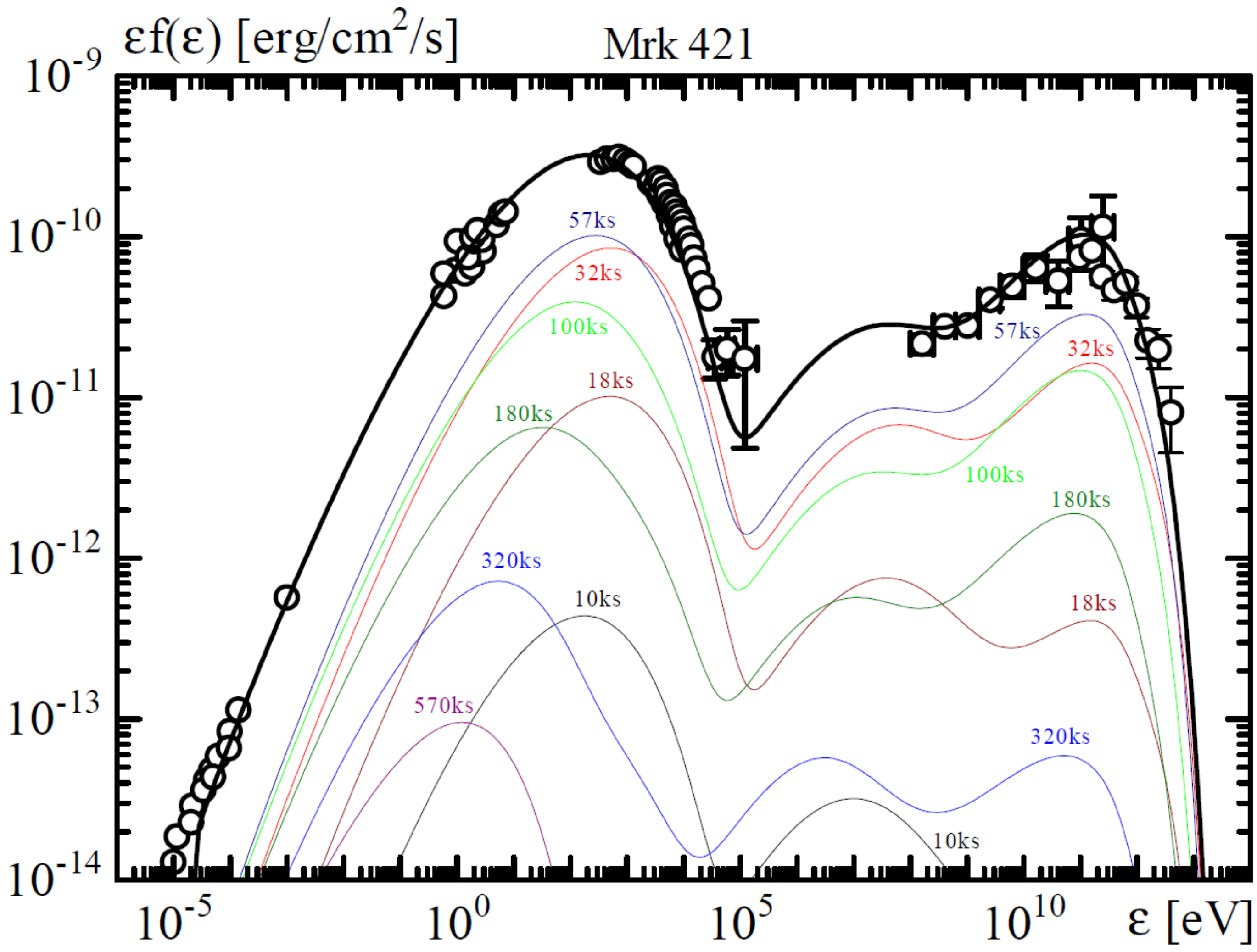
Possible Solutions



- Two-zone model:
  - Spine & Sheath?
  - Gamma-ray lobe?
  - But, the spectral shape is smooth.
- External Compton
  - Optical seed photons from BLR

    ⇒too hard (peak > GeV)
  - Radio photons?

SSC+EIC



- External radio photons can be seed photons for GeV-IC emission.
- Thin lines show temporal evolution of photon spectrum from "one shell".
- The steady spectrum is a superposition of contributions from multiple shells at different radii.

External photon: $L_{\rm ex} = 4.9 \times 10^{38}$ erg s^{-1}, the spectral peak at 10^{-6} eV (240 MHz)

Summary

- SA model can naturally explain hard spectra as seen in 1ES 1101-232.
- Radial evolution of the electron injection rate & diffusion coefficient can produce softer spectra such as that in Mrk 421.
  - We do not need artificial spectral-breaks.
  - The spectral cut-off shape is naturally reproduced.
  - The radio spectrum is also fitted.
  - External IC may be required to fit the GeV flux
- Seed photons for external IC are radio.