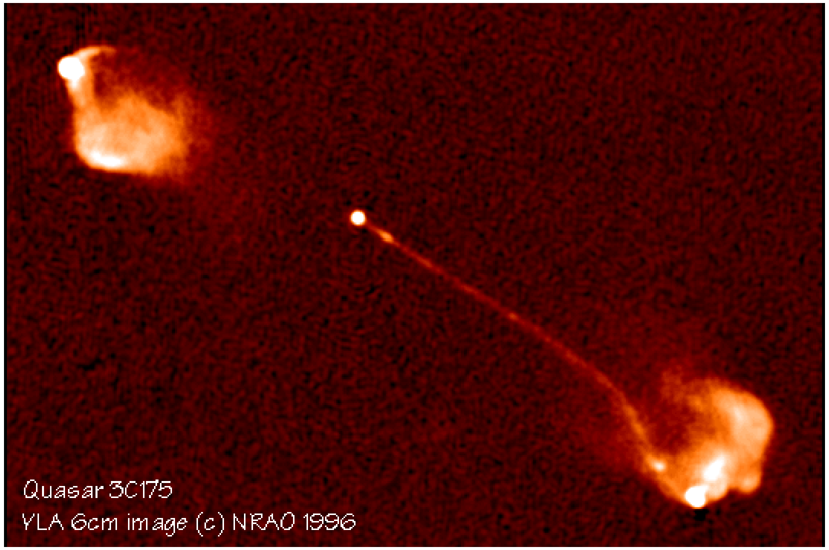
Multiwavelength Spectral and Polarization Signatures of Shocks in Relativistic Jets


Quasar 3C175
VLA 6cm image (c) NRAO 1996

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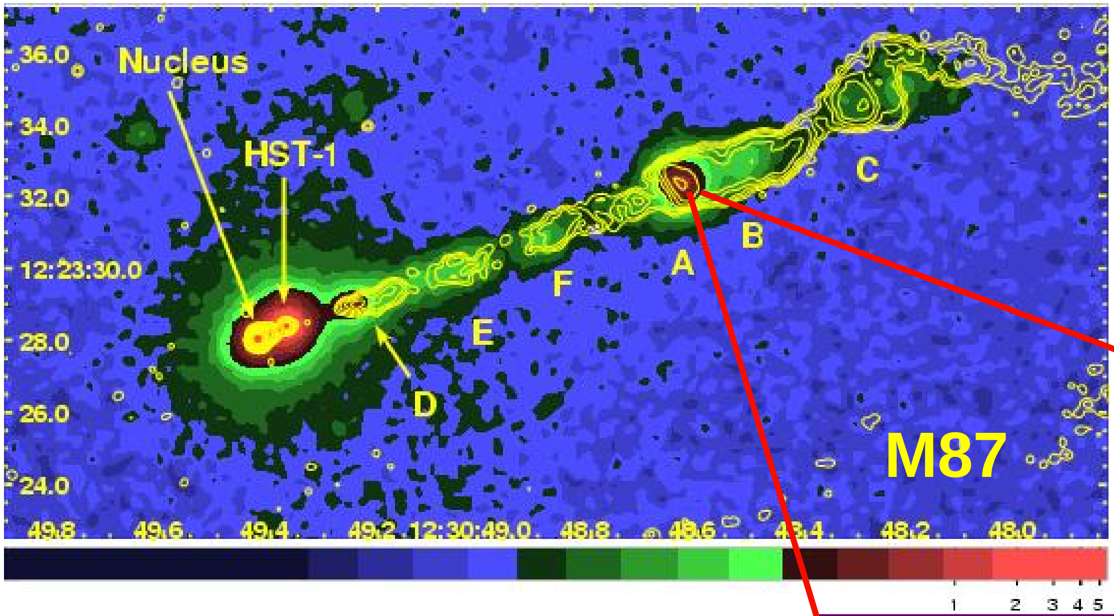
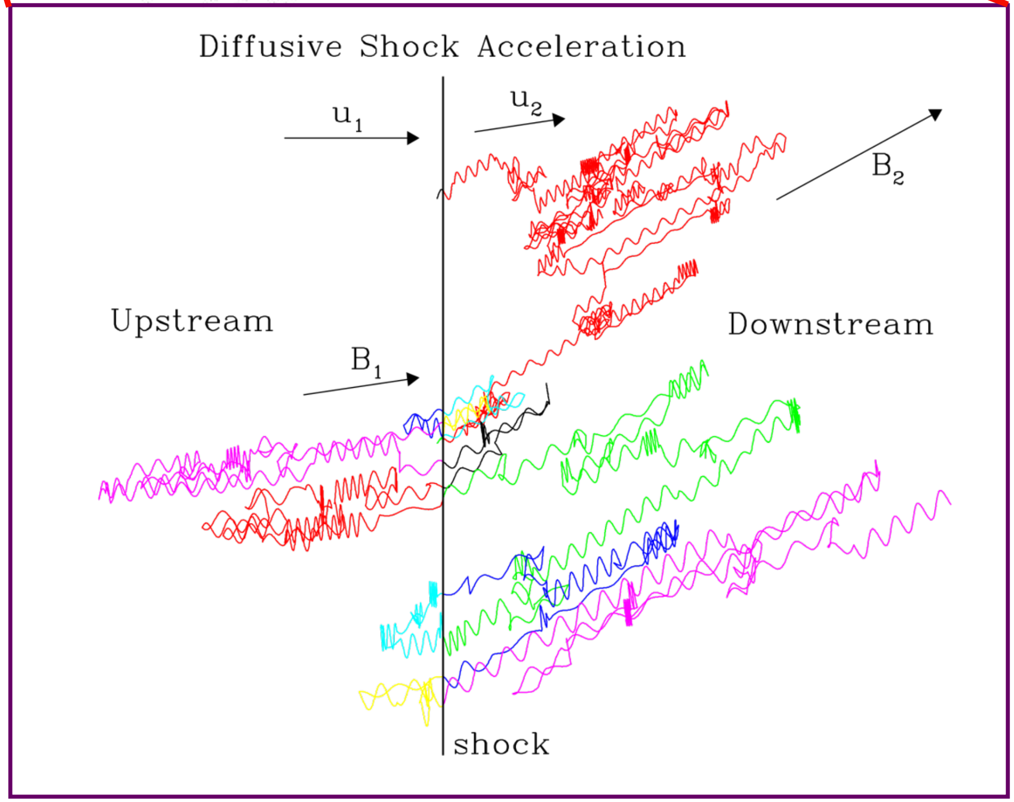
Confined Acceleration Zones



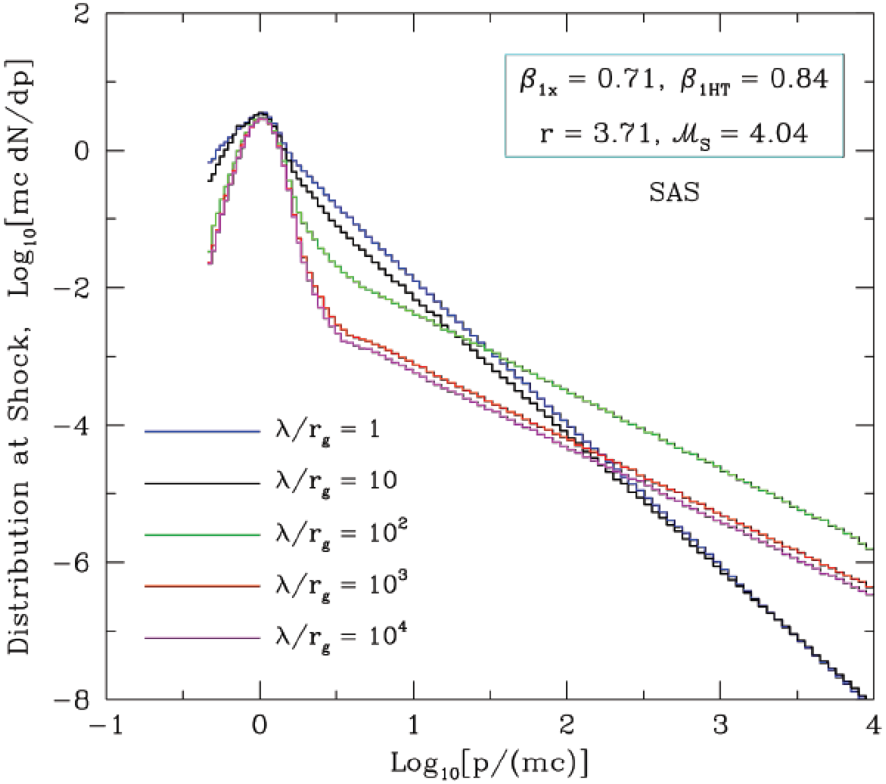
- Shock crossings produce net energy gains according to principle of first-order Fermi mechanism.
- Simulation technique due to Ellison & Jones; detailed in Summerlin & Baring (2012).



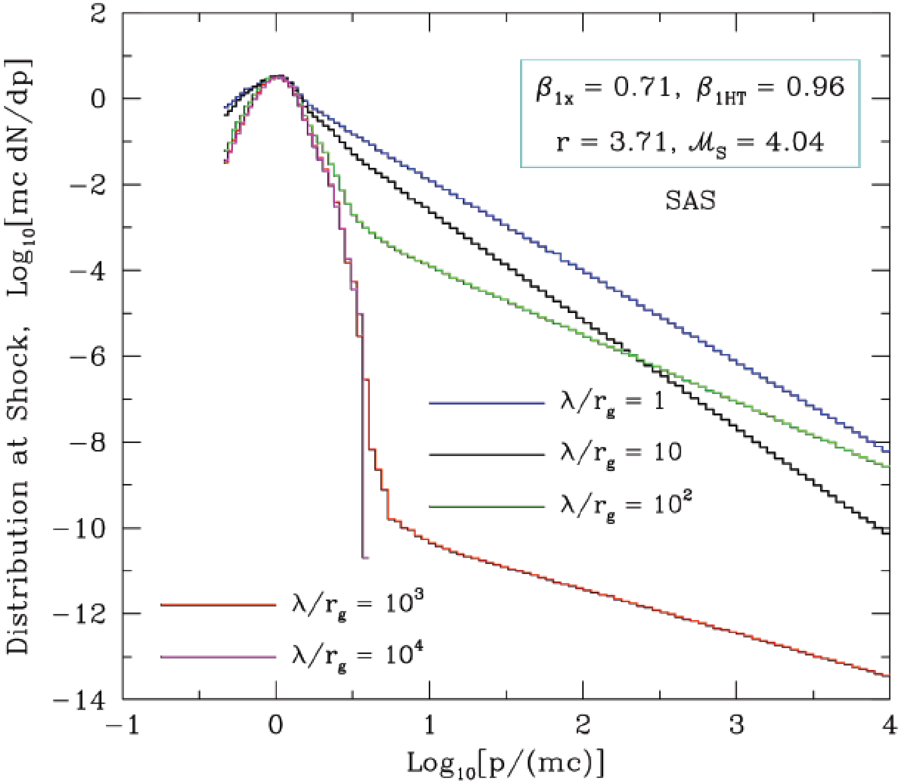
Most critical parameter:
$\lambda = \eta^* r_g$ = Pitch-angle scattering mean free path

Electron Spectra from Diffusive Shock Acceleration

$\lambda = \eta^* r_g$ = Pitch-angle scattering mean free path



Moderately sub-luminal
($\beta_{1HT} = \beta_{1x}/\cos\Theta_{Bf1} < 1$)

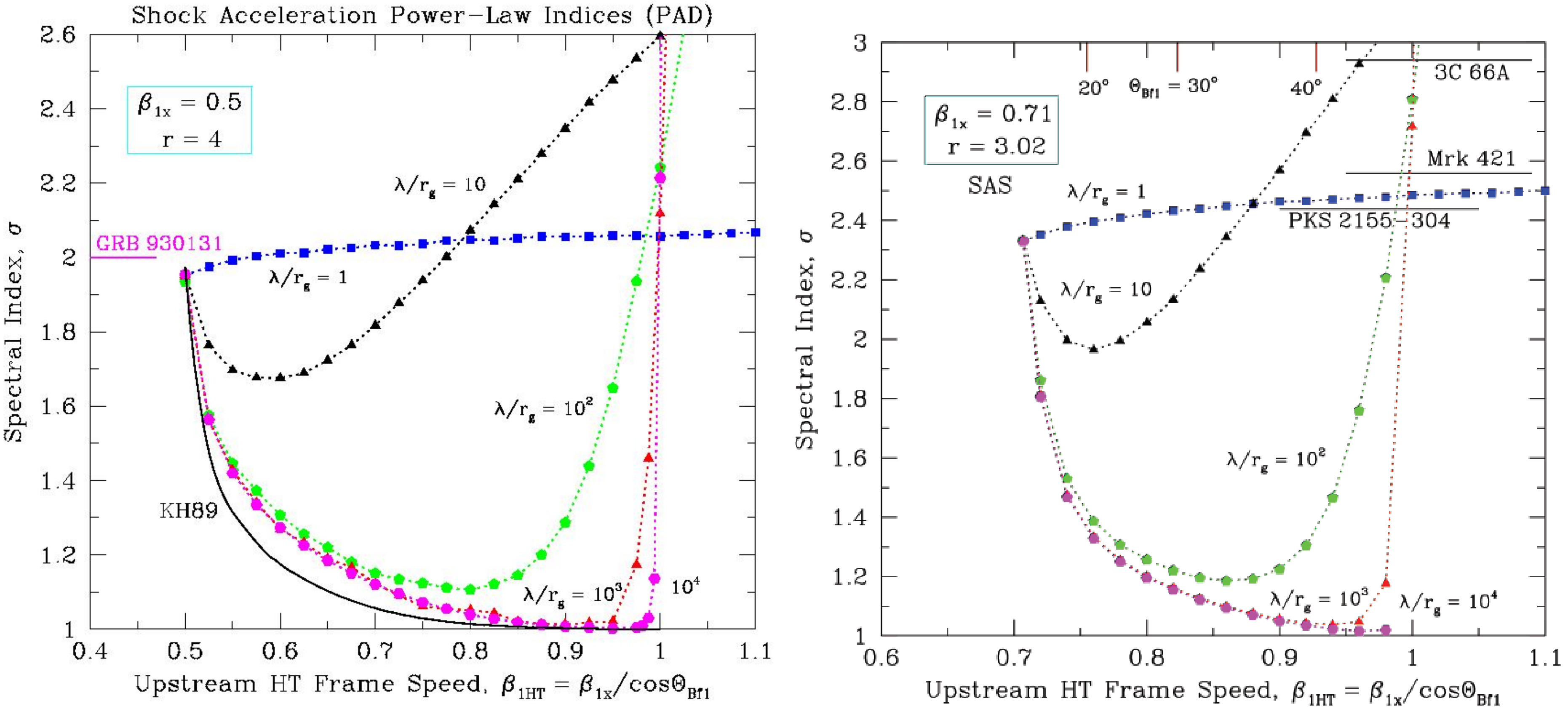


Marginally sub-luminal
($\beta_{1HT} = \beta_{1x}/\cos\Theta_{Bf1} \sim 1$)

(Summerlin & Baring 2012)

Asymptotic Particle Spectral Index

$n(\gamma) \sim \gamma^{-\sigma}$

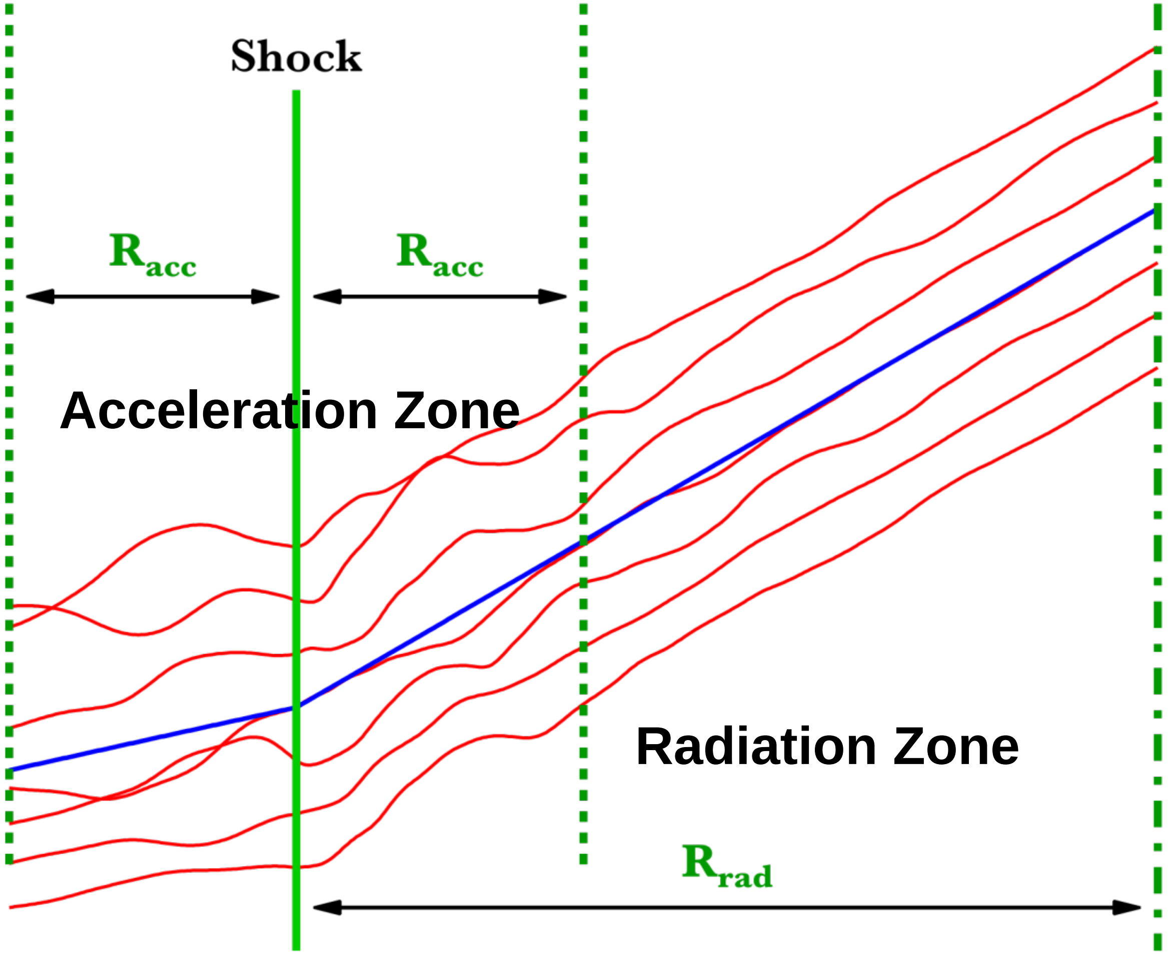


(Summerlin & Baring 2012)

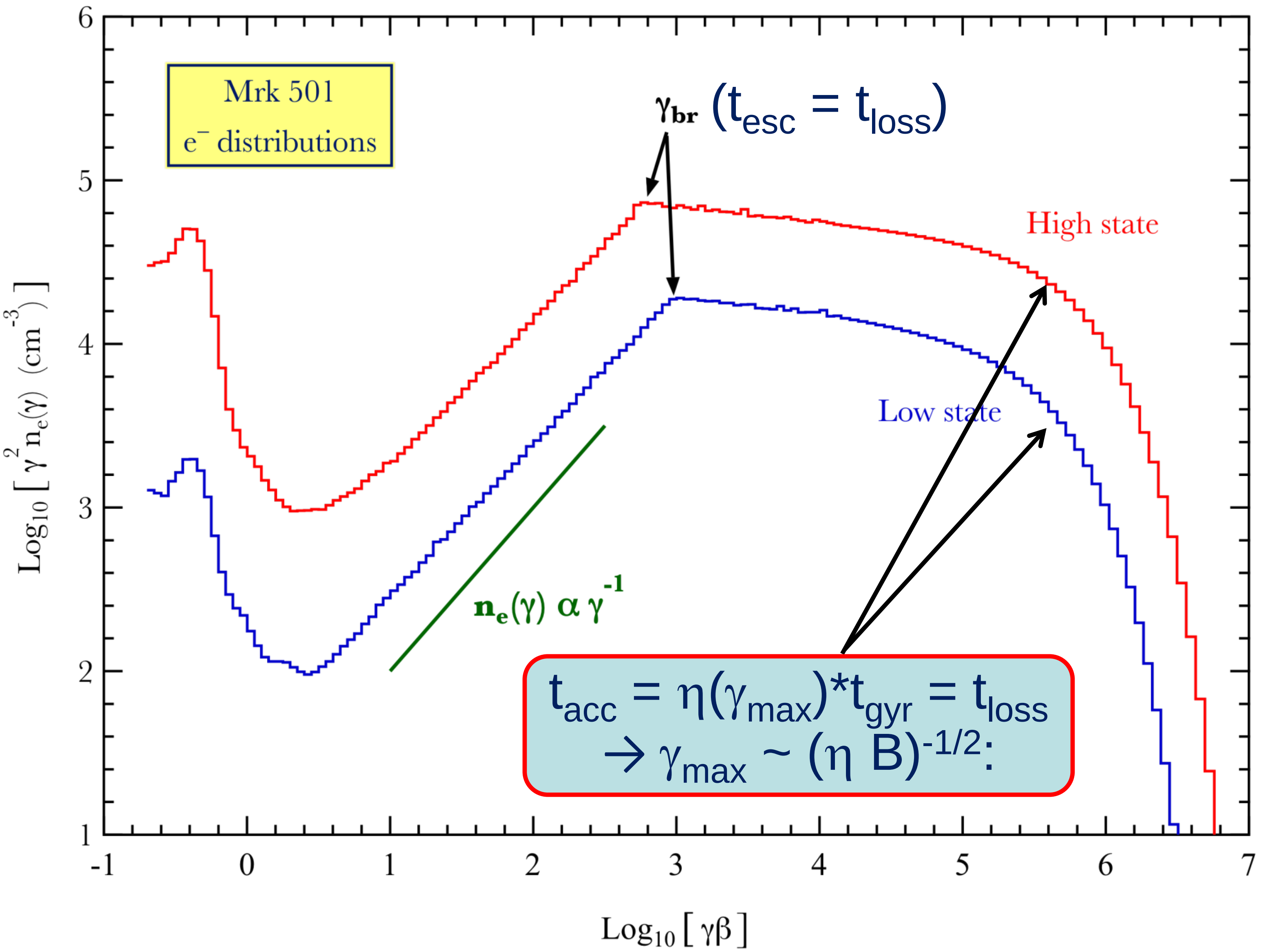
Radiation Modeling

Electron spectra from equilibrium between acceleration (= injection term in Fokker-Planck equation), radiative cooling, and escape

Radiation using synchrotron, SSC, + external Compton modules of Böttcher et al. (2013)



Electron Energy Distributions

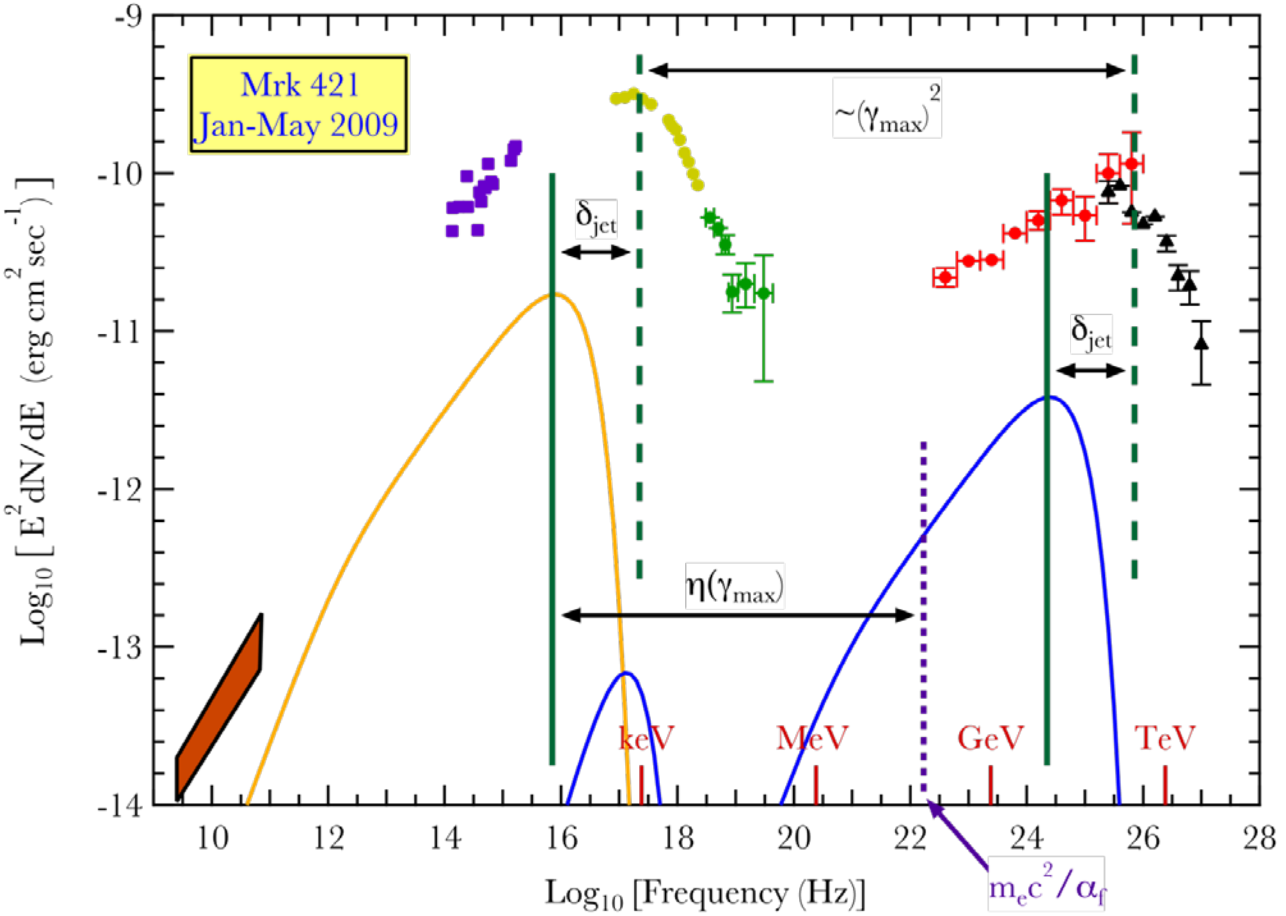


γ_{br} $(t_{esc} = t_{loss})$

$t_{acc} = \eta(\gamma_{max}) * t_{gyr} = t_{loss}$
$\rightarrow \gamma_{max} \sim (\eta\ B)^{-1/2}$:

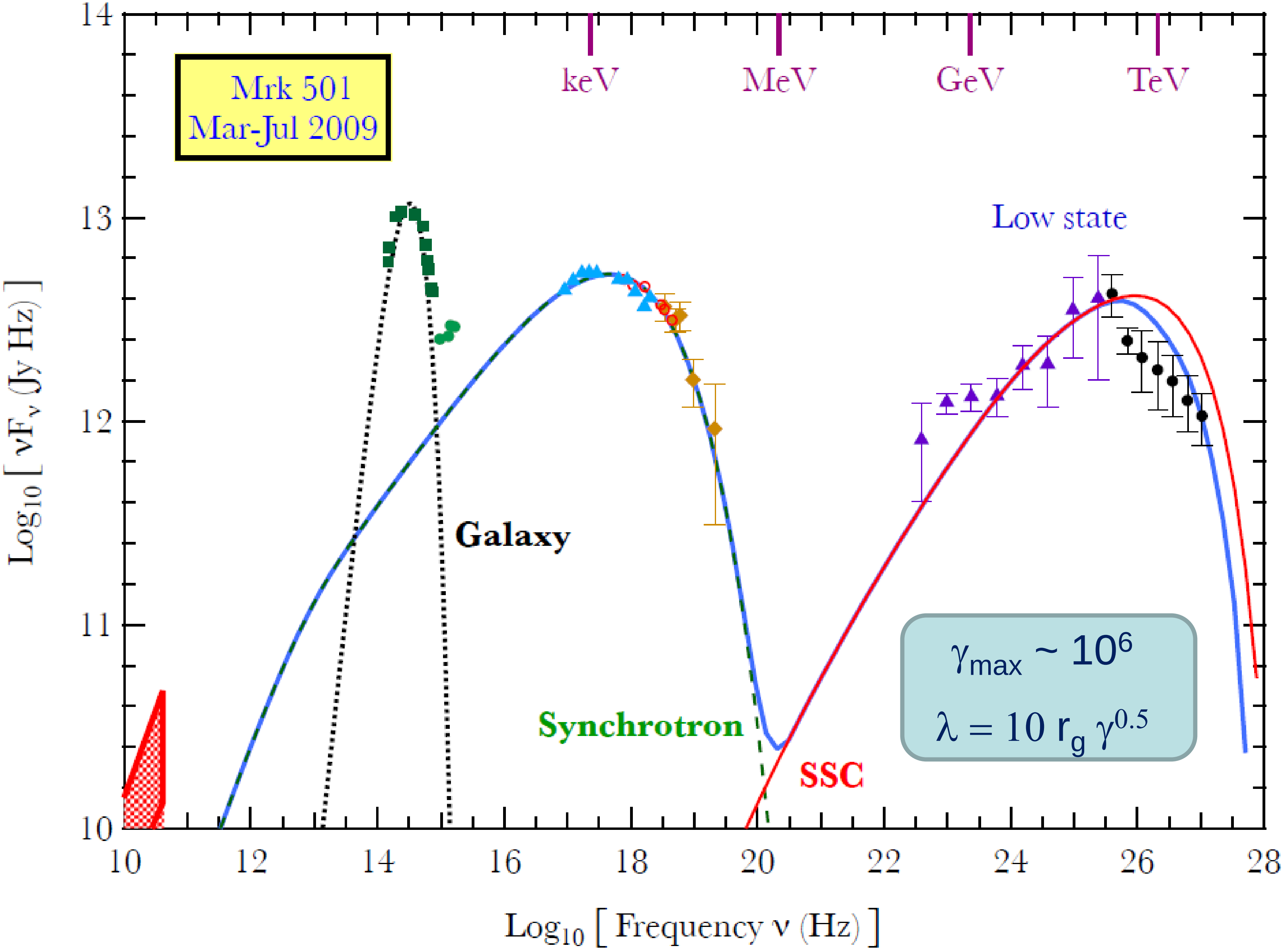
Constraining SSC Model Parameters

- $\eta(p) = \lambda/r_g \sim \eta_1\,(p/mc)^{\alpha} \sim \eta_1\,\gamma^{\alpha}$
- Multiwavelength modeling to constrain η_1 and α.



- Large $\eta\ (\gamma_{max})$ needed to move synchrotron peak $E_{max} \sim \delta m_e c^2/(\eta\alpha_f)$ into X-rays.

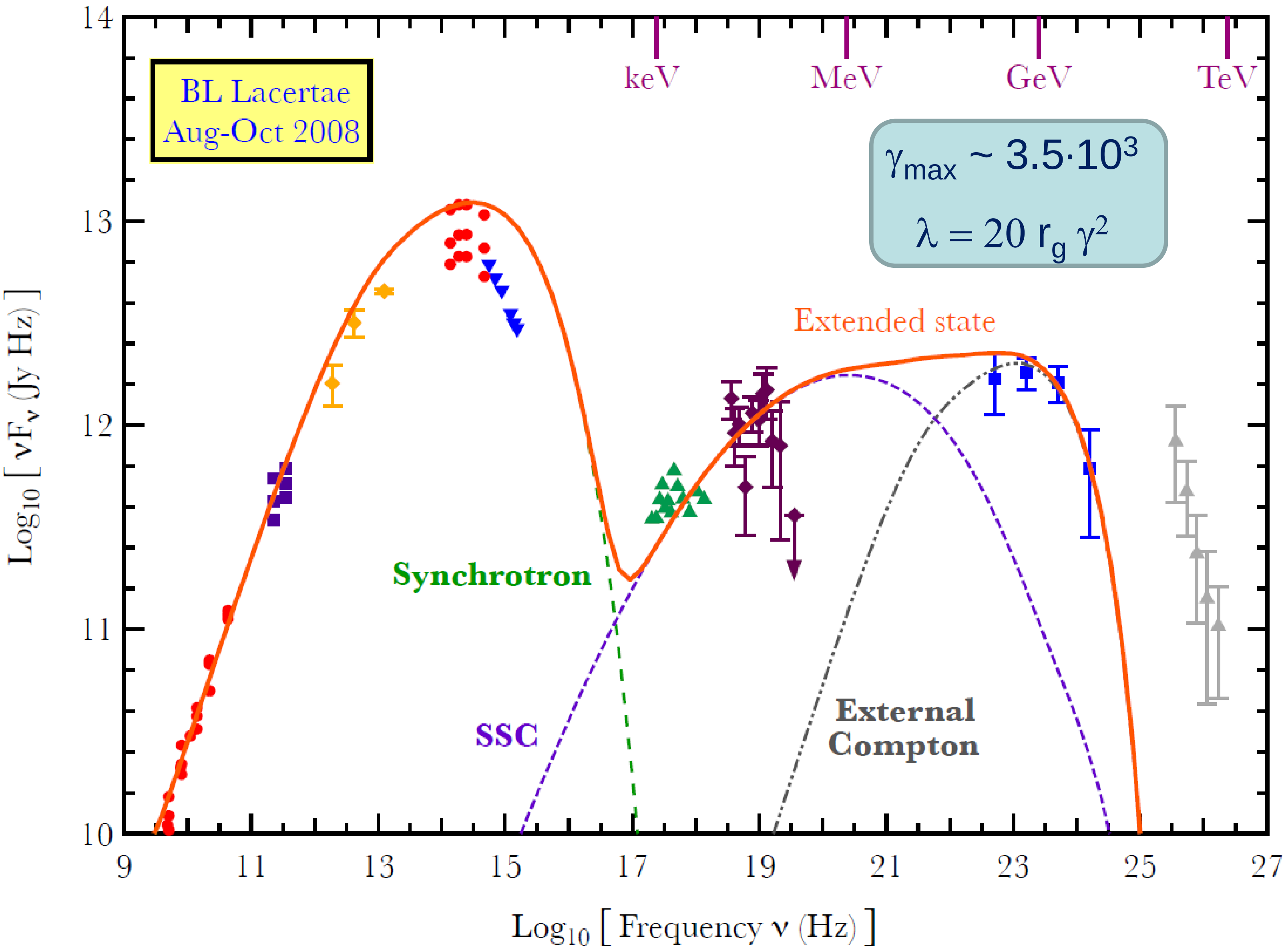
Model Fit to Mrk 501



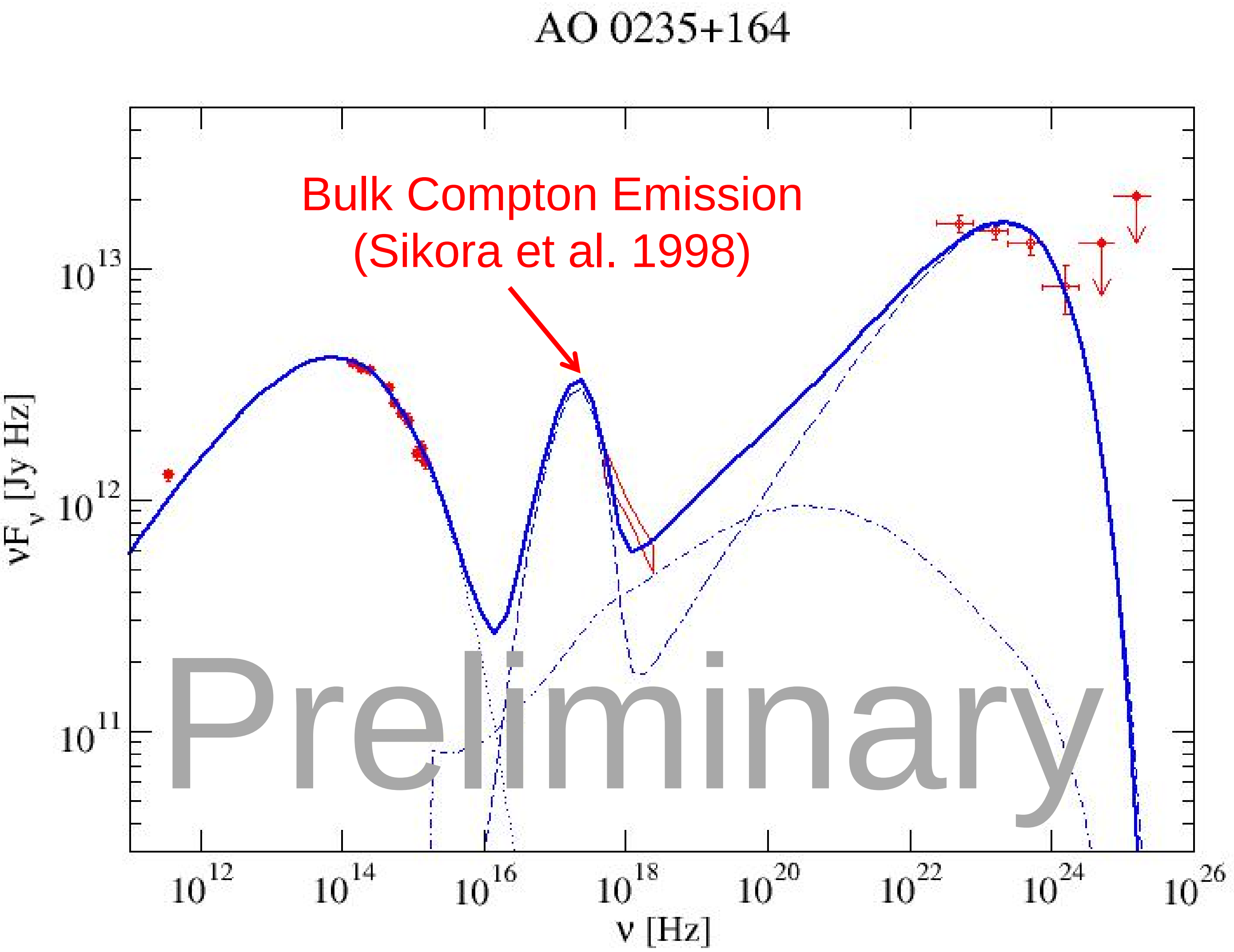
$\gamma_{max} \sim 10^6$

$\lambda = 10\, r_g\, \gamma^{0.5}$

Model Fit to BL Lacertae



Model Fit to AO 0235+164



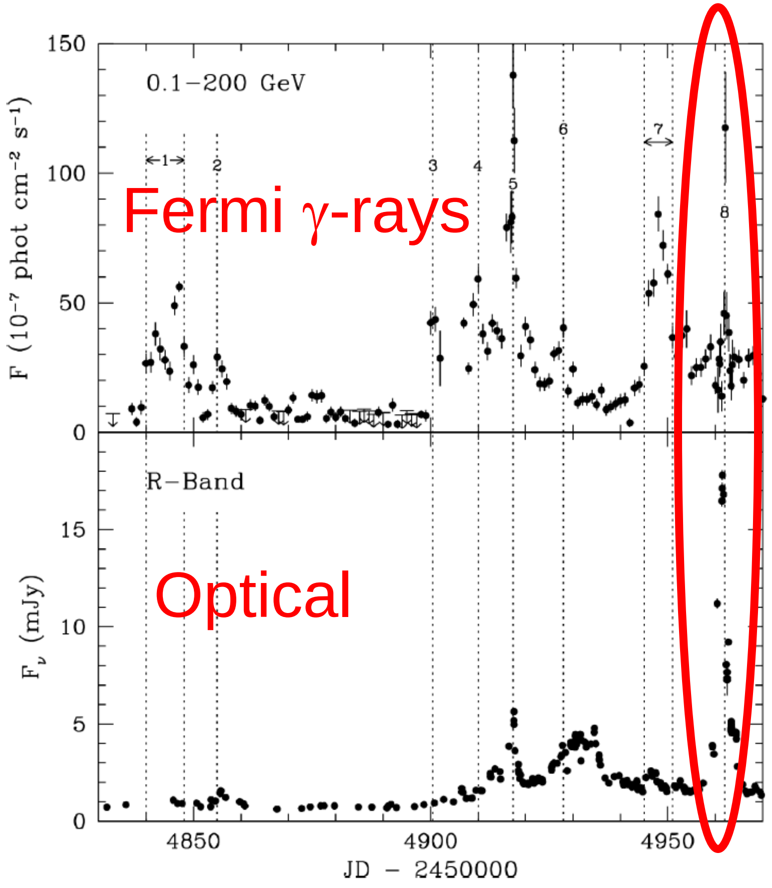
$\eta \sim 10^8$ needed at $\gamma_{max} \sim 10^4$

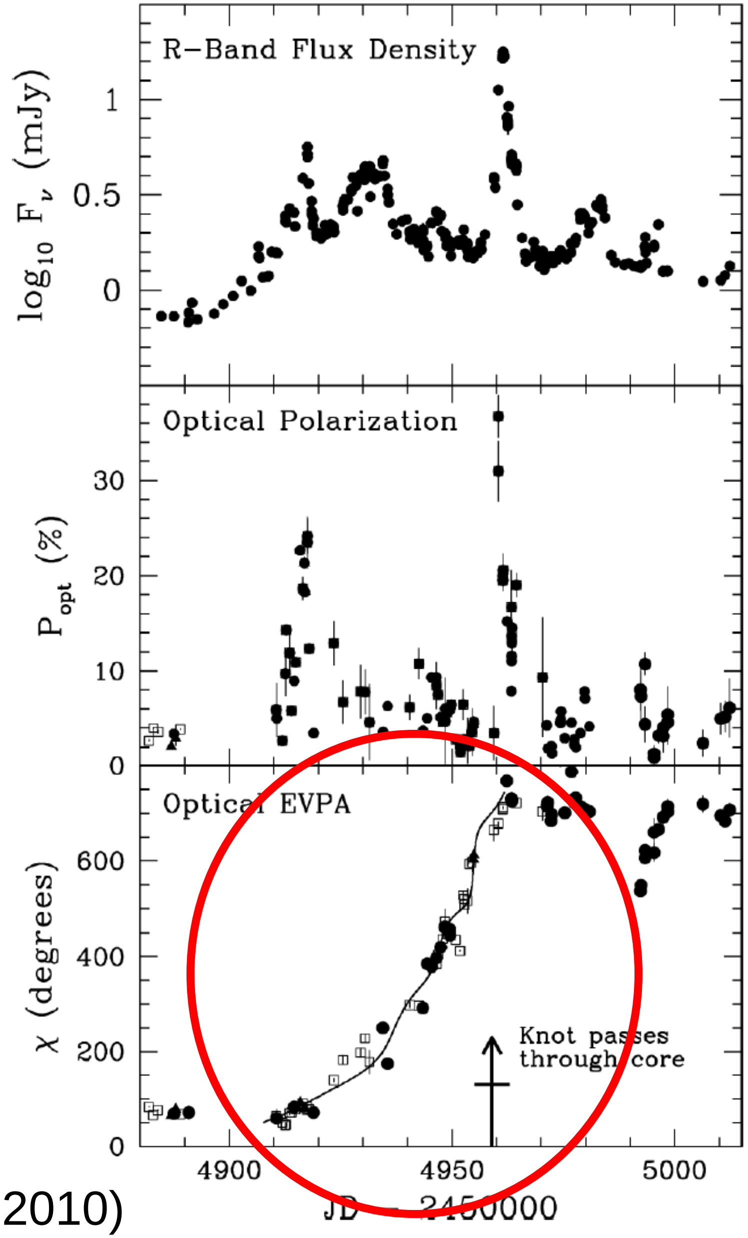
Plausibly achievable only with η increasing with γ:

$\lambda = 3\, r_g\, \gamma^2$

Optical Polarization Angle Swings

- Optical + γ-ray variability of LSP blazars often correlated
- Sometimes O/γ flares correlated with increase in optical polarization and multiple rotations of the polarization angle (PA)





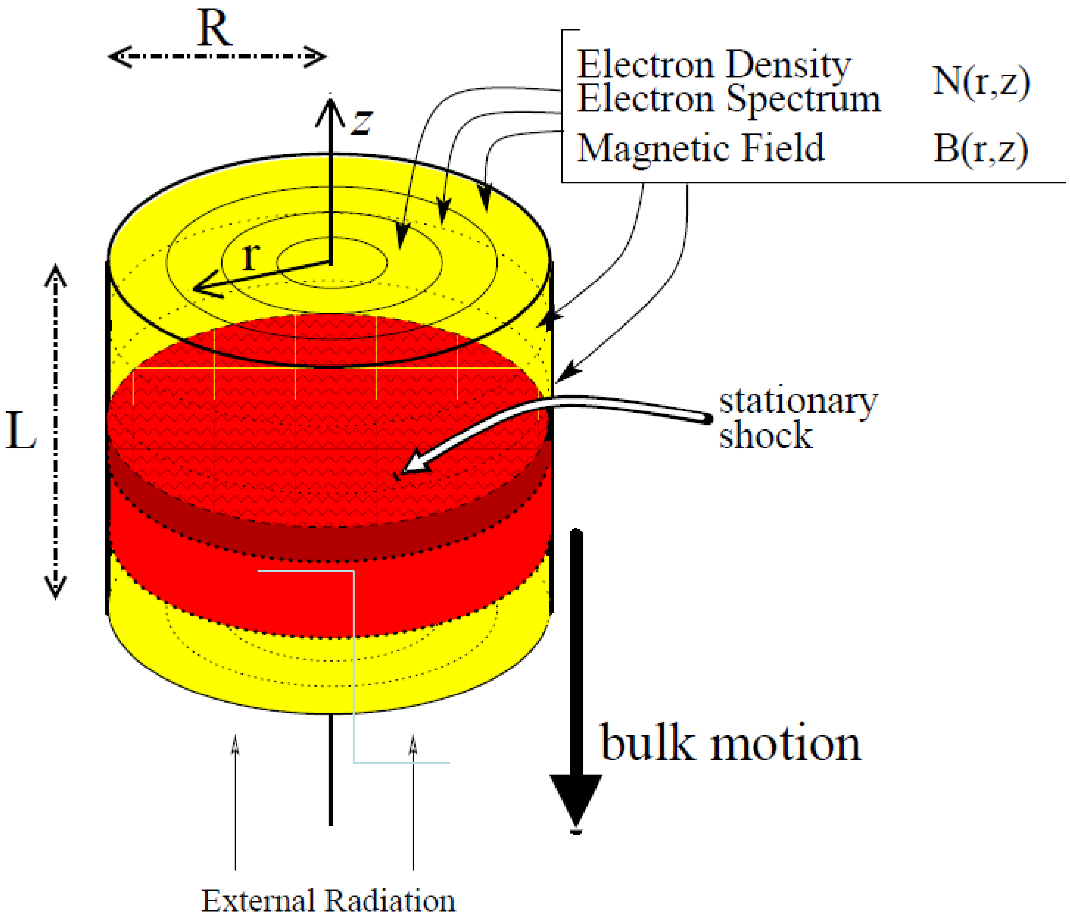
PKS 1510-089 (Marscher et al. 2010)

Tracing Synchrotron Polarization in the Internal Shock Model

- Particle Dynamics (Fokker-Planck) and radiationt ransfer (Monte-Carlo) using code of Chen et al. (2011, 2012)

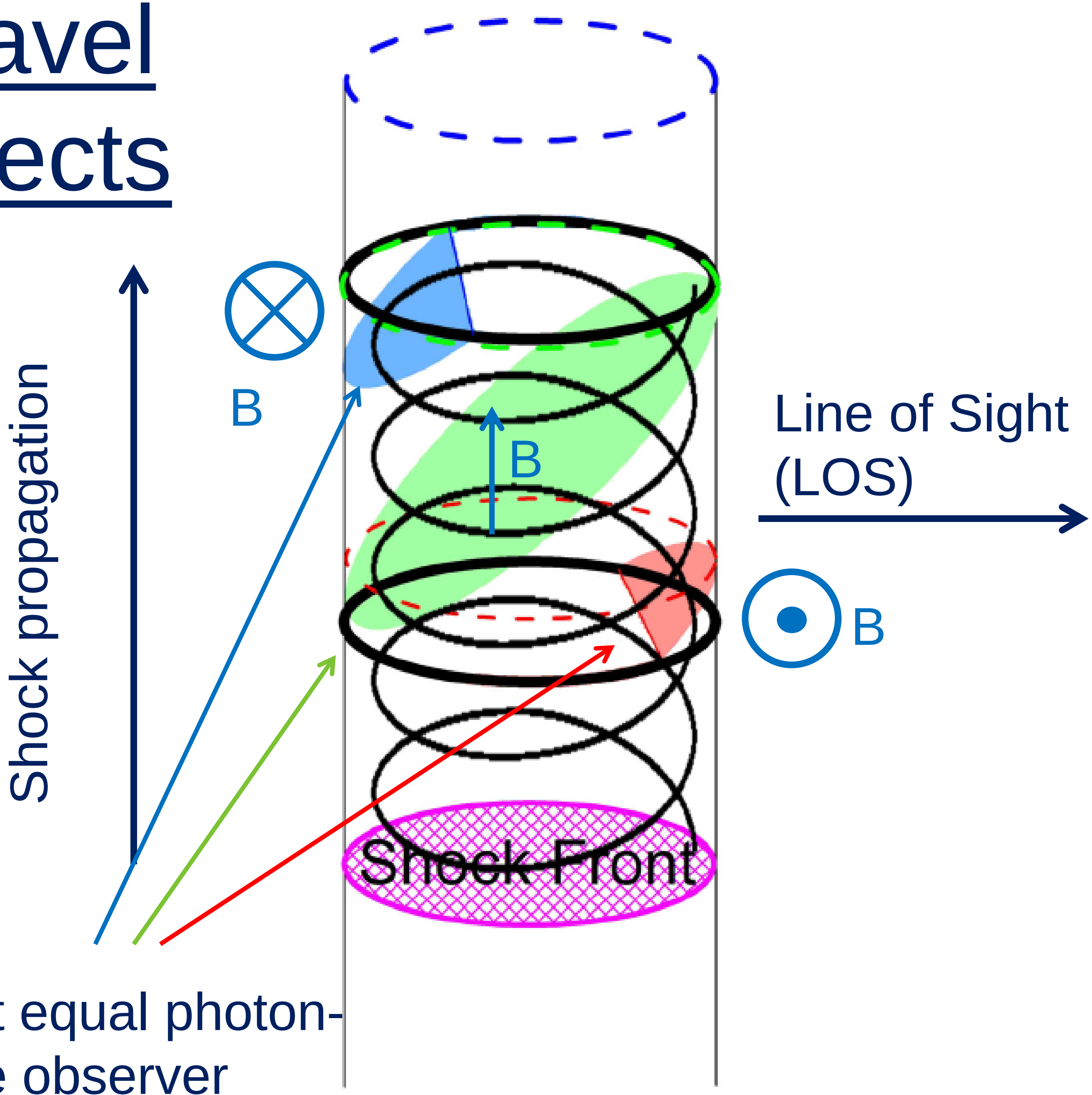
Coupled with

- Time-, space-, and polarization-dependent ray tracing code 3DPOL (Zhang et al. 2014, 2015)



Light Travel Time Effects

Haocheng Zhang
(Ohio University /
Los Alamos)

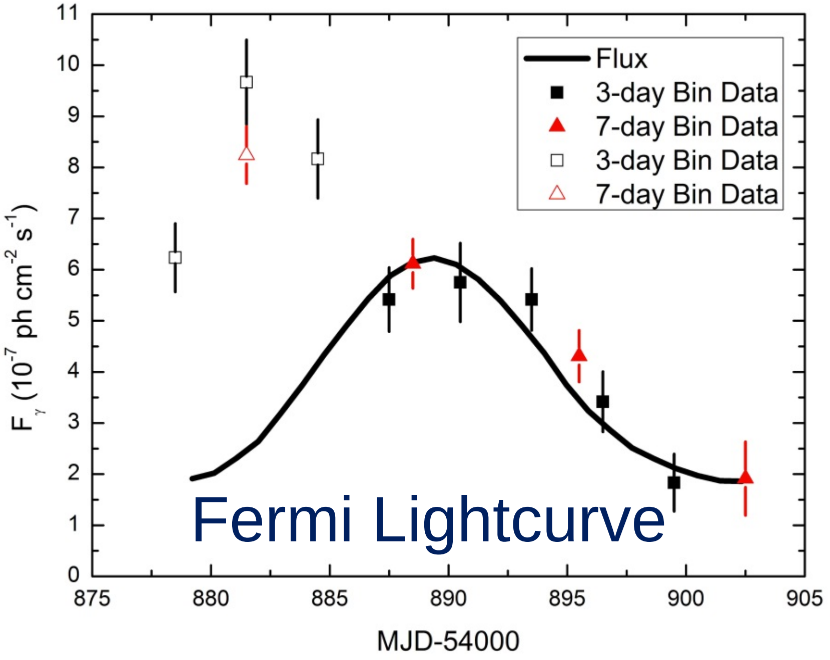


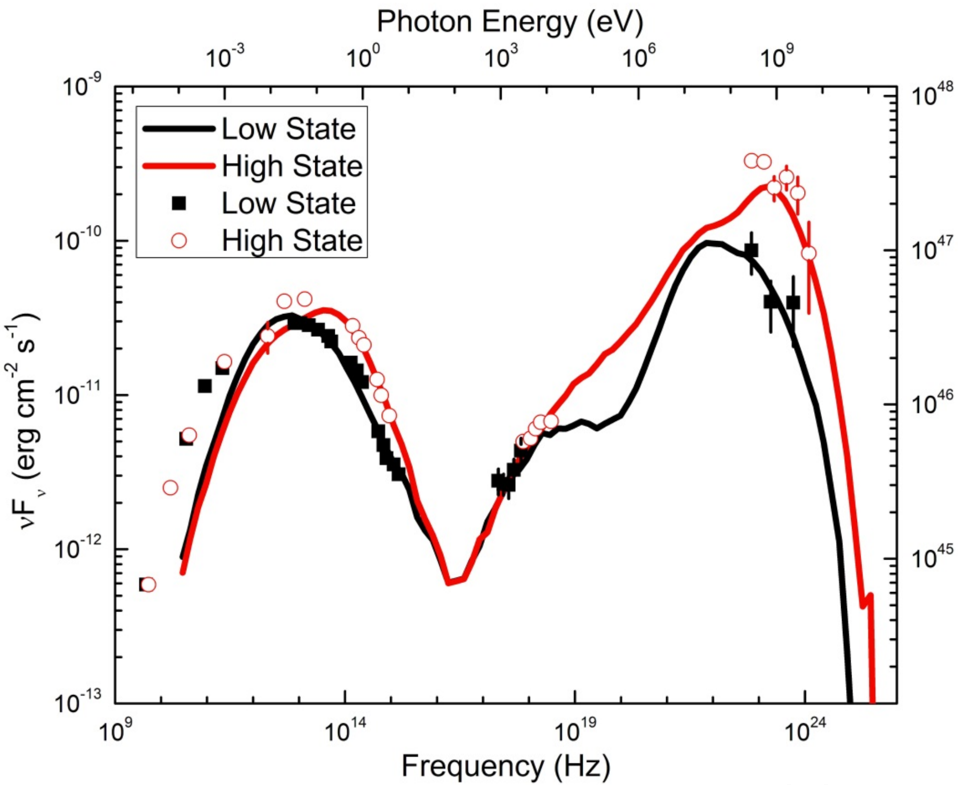
Shock positions at equal photon-arrival times at the observer

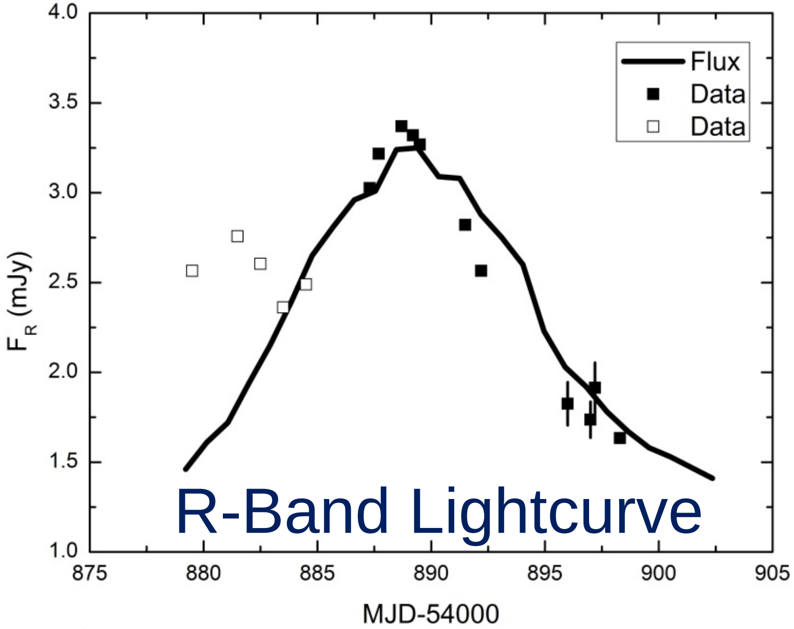
(Zhang et al. 2014, 2015)

Application to 3C279

Simultaneous fit to SEDs, light curves, polarization-degree and polarization-angle swing



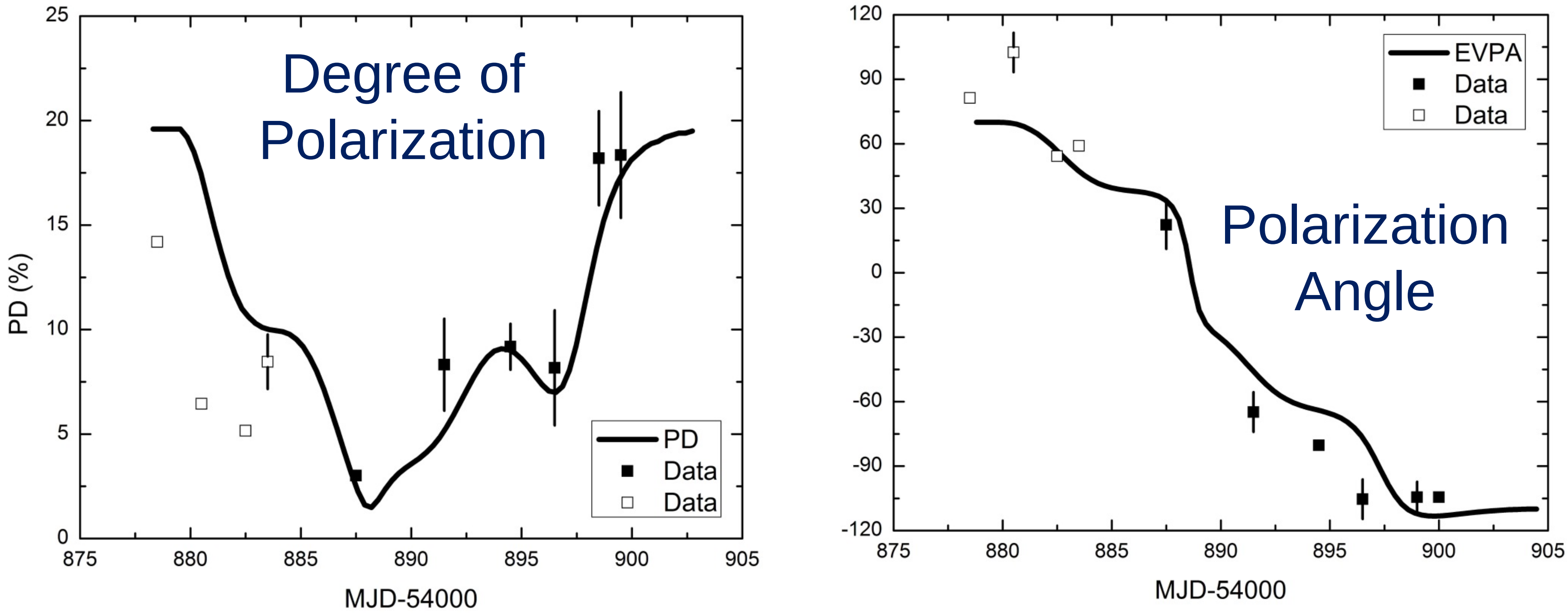




(Zhang et al. 2015)

Application to 3C279

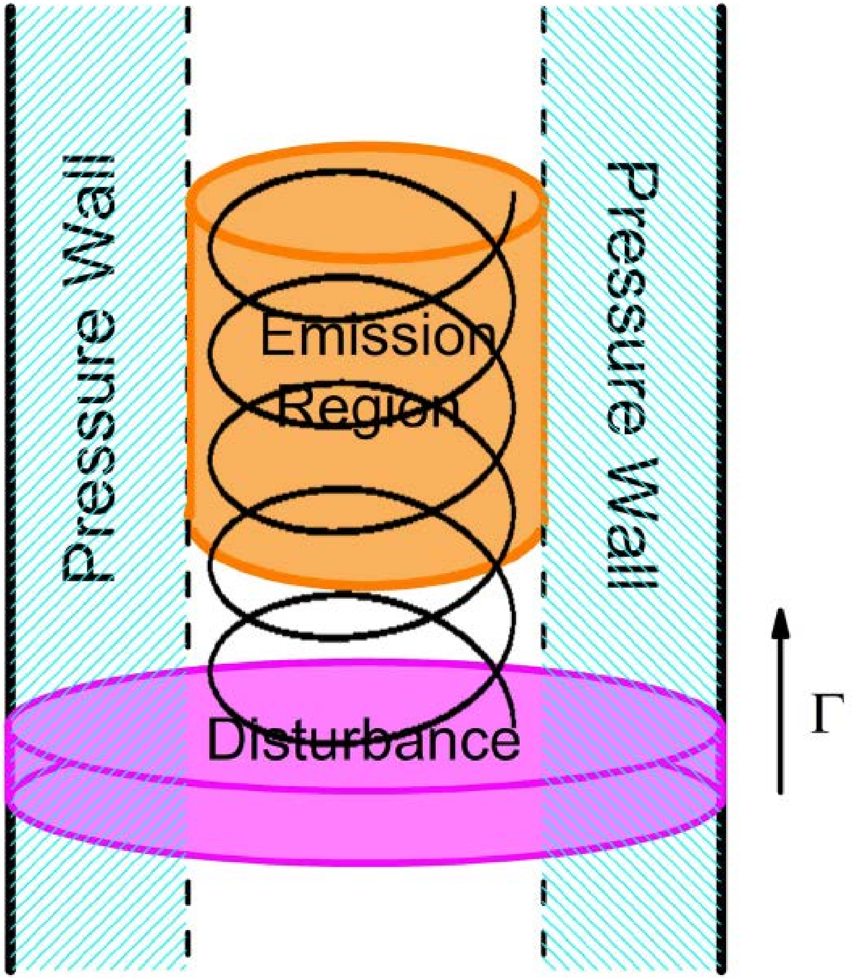
Requires particle acceleration
and reduction of magnetic field,
as expected in magnetic reconnection!



(Zhang et al. 2015)

Coupling to MHD Simulations

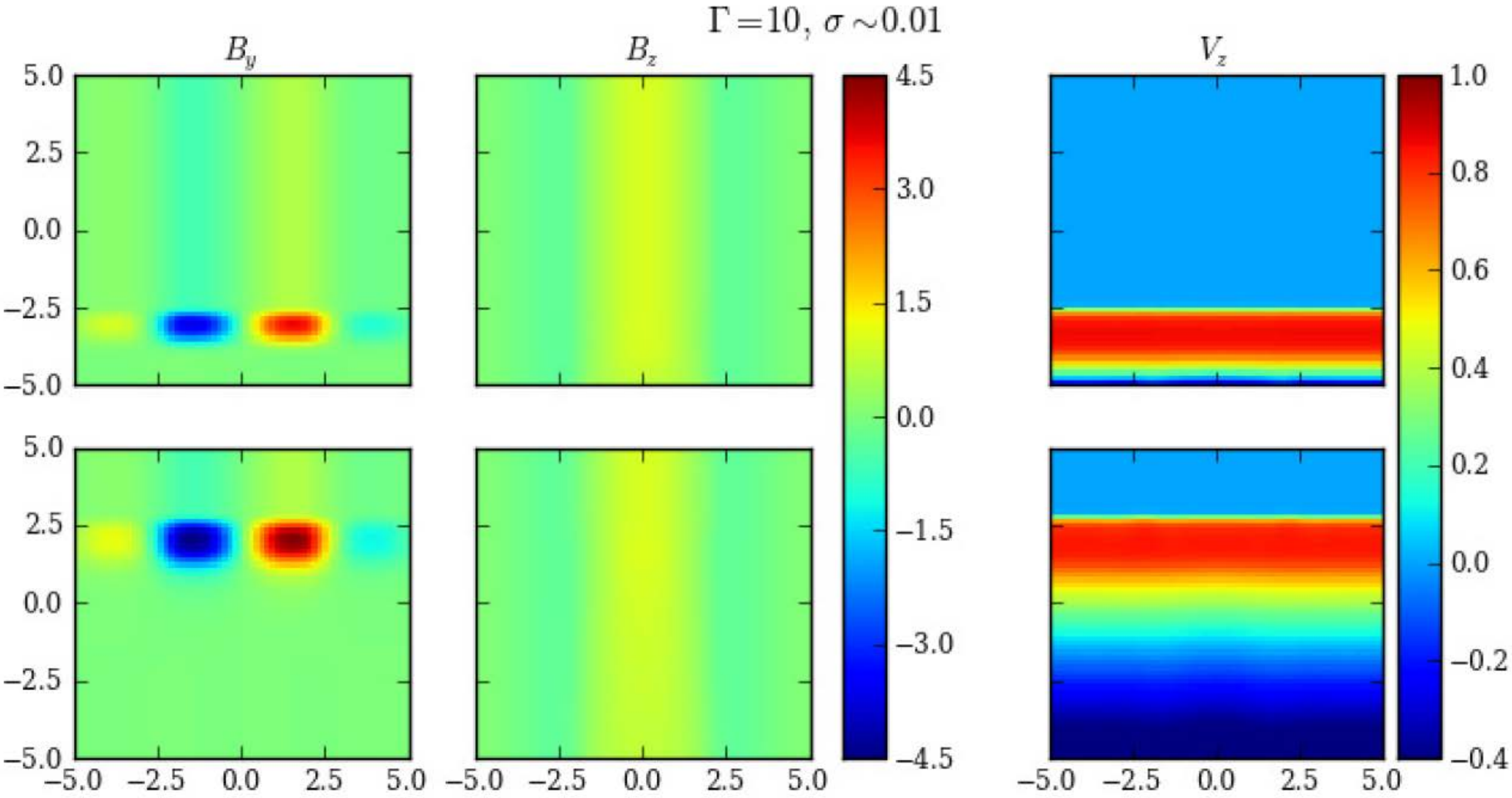
- 3D RMHD Simulations (LA-COMPASS)
- Force-Free helical B-field
- Relativistic disturbance (shock) propagating through the jet
- Non-thermal particle injection at shock front
- B-field from RMHD simulations
- 3DPol to trace time-dependent synchrotron polarization signature



(Zhang et al. 2015)

RMHD Simulations

Highly Relativistic disturbance; low magnetization



Very strong enhancement of B_ϕ;
complete re-structuring of B-field

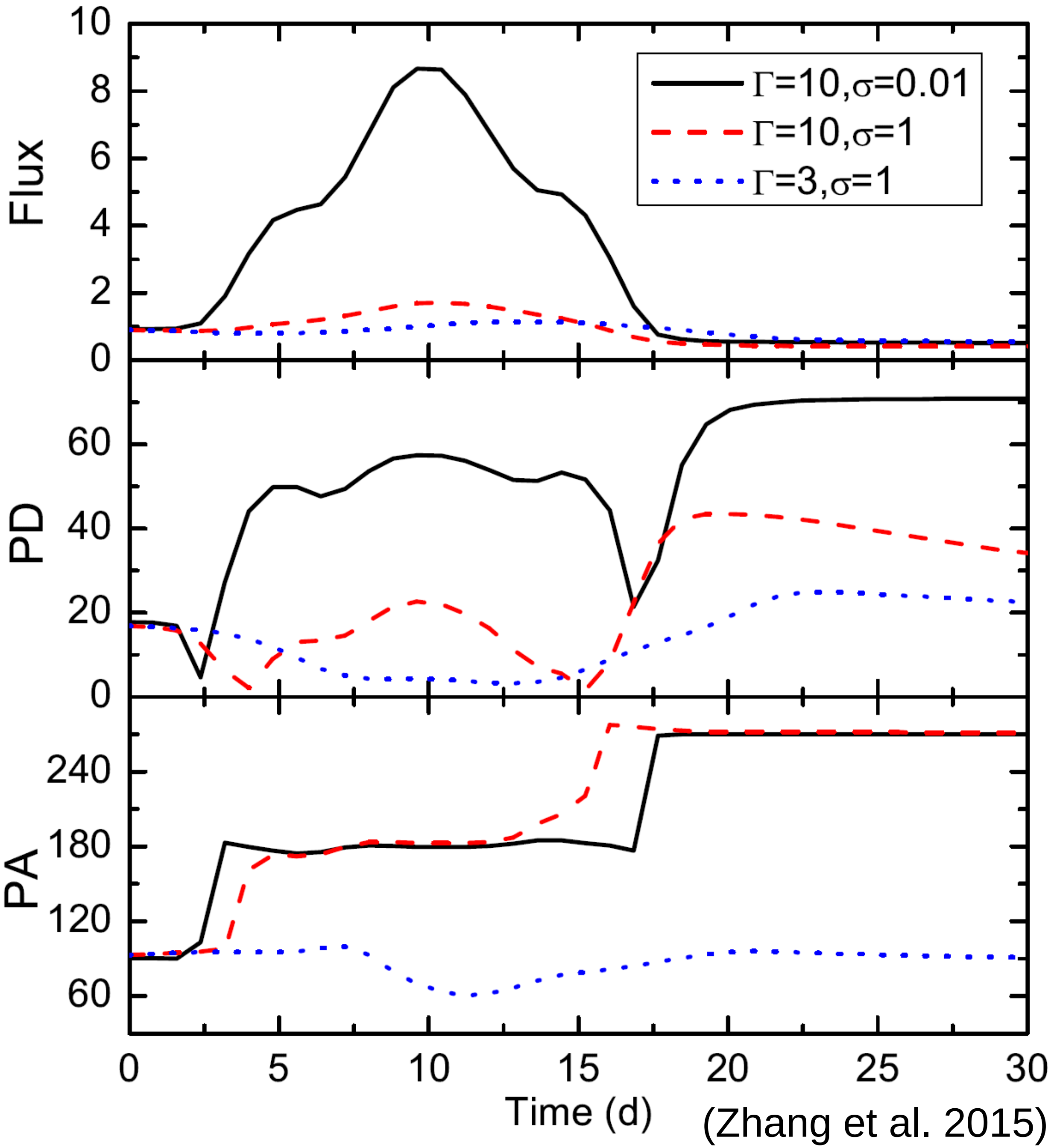
(Zhang et al. 2015)

Parameter Study

- Need moderate magnetization ($\sigma \sim 0.1 - 1$) to produce coherent, but significant changes in polarization signatures

- Slow ($\Gamma \sim 3$) shocks may produce erratic polarization fluctuations

- Fast ($\Gamma \sim 10$) shocks may produce large-angle PA rotations.



(Zhang et al. 2015)

Summary

1. Relativistic Shock Acceleration requires strongly momentum-dependent pitch-angle-scattering mean-free-path parameter η to be consistent with blazar SEDs ($\eta \sim \gamma^2$).

2. Polarization Angle Swings associated with γ-ray flares can be reproduced naturally by a shock-in-jet model with a helical magnetic field structure, without the need for any non-symmetric jet features or motions!

3. RMHD simulations indicate that small-scale polarization changes require moderate magnetization ($0.1 < \sigma < 1$) where slow shocks produce erratic PA variations; fast shocks produce large-angle PA swings.

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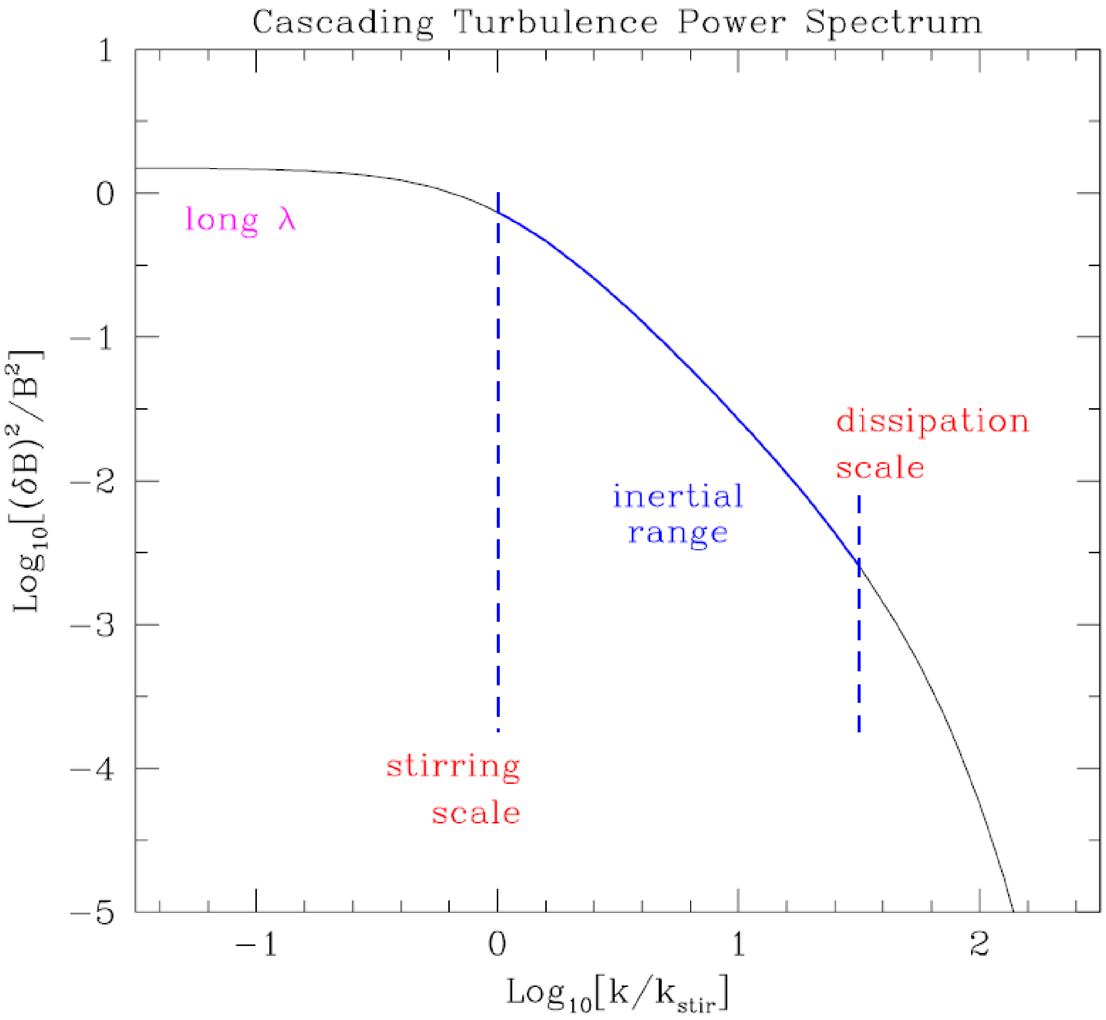
Canonical Turbulence Power Spectrum

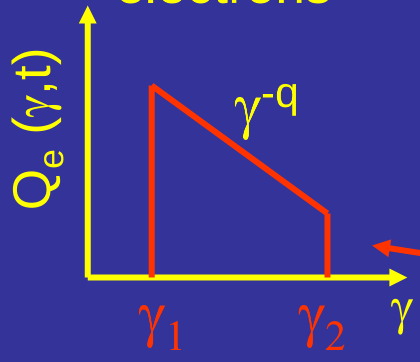
- Inertial range can span 1-5 orders of magnitude.
- Doppler resonance condition $\omega=\Omega/\gamma$ may not be satisfied by charges with large gyroradii;
- => increase of diffusive mean free path parameter $\eta=\lambda/r_g$ at large momenta.
- Expect $\lambda \propto p^2$ at long wavelengths, below stirring scale (QLT).



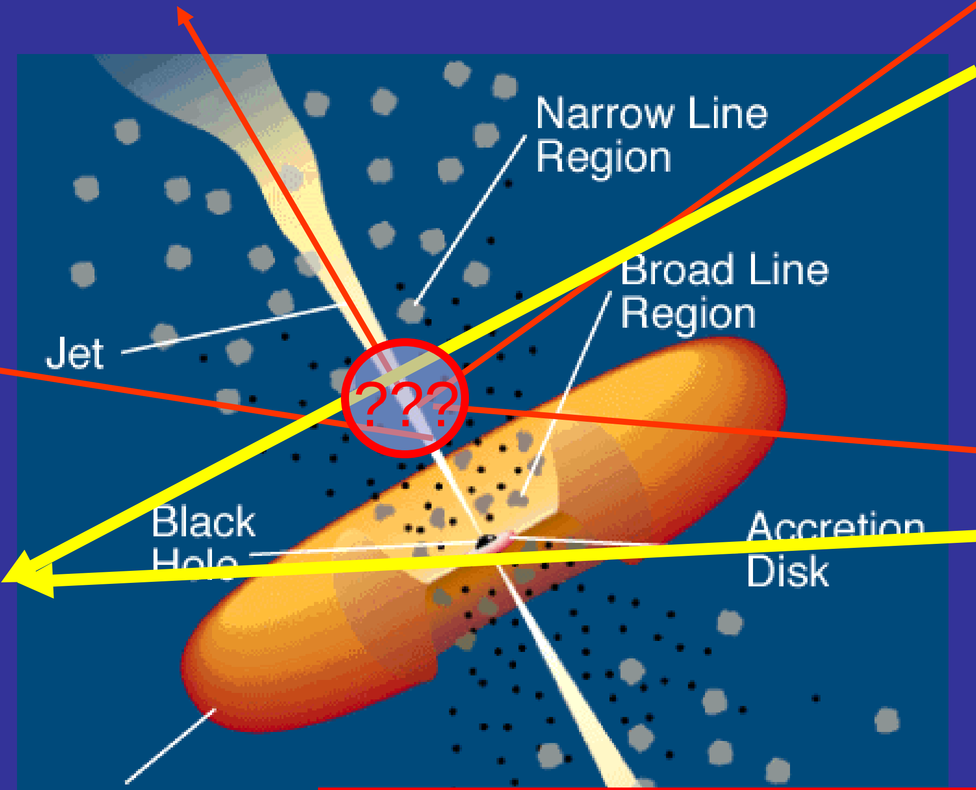
(M. Baring)

Leptonic Blazar Model

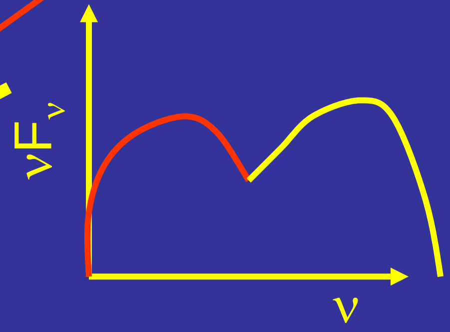
Injection, acceleration of ultrarelativistic electrons



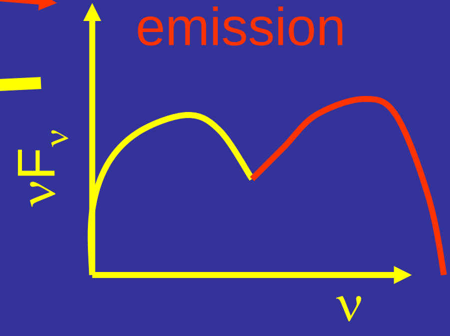
Relativistic jet outflow with $\Gamma \approx 10$



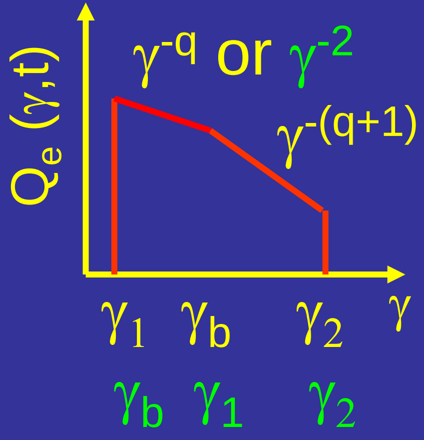
Synchrotron emission



Compton emission



Radiative cooling ↔ escape =>



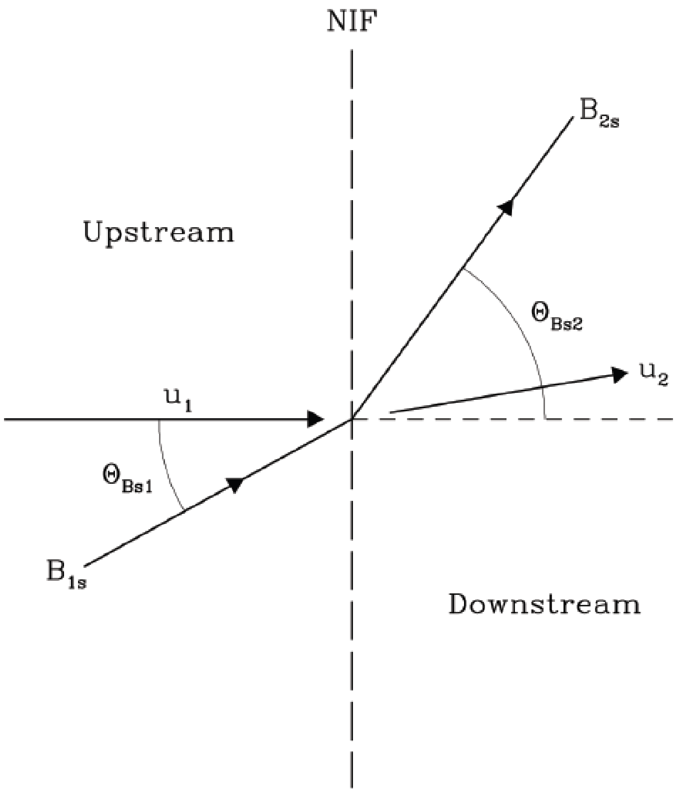
γ_b:
$\tau_{cool}(\gamma_b) = \tau_{esc}$

Seed photons:

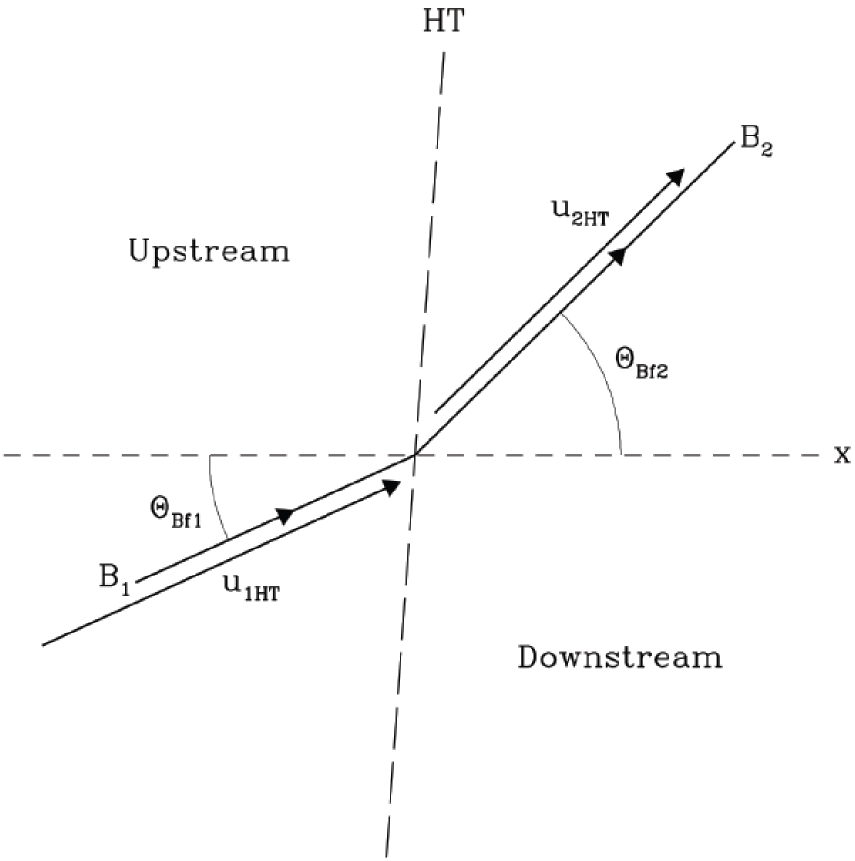
Synchrotron (within same region [SSC] or slower/faster earlier/later emission regions [decel. jet]), Accr. Disk, BLR, dust torus (EC)

Diffusive Shock Acceleration

Particle retention in the shock layer is extremely sensitive to the magnetic field angle w.r.t. the shock normal in relativistic shocks.



Normal Incidence Frame (NIF)



de Hoffmann-Teller frame (HT)