Spectral and Polarization Signatures of Relativistic Shocks in Blazars

Markus Böttcher

North-West University

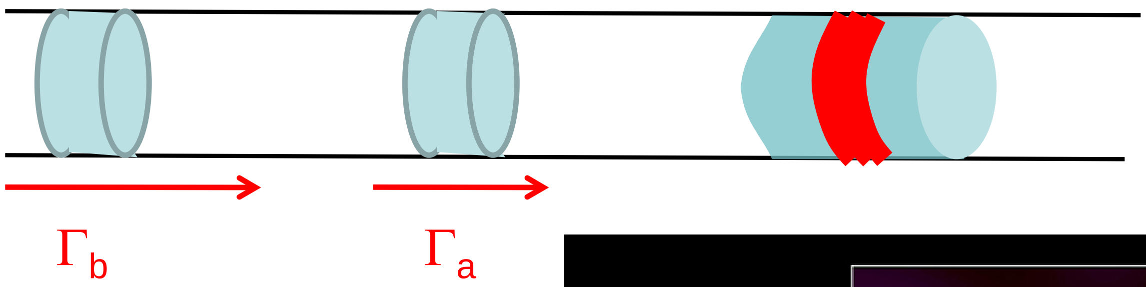
Potchefstroom

South Africa

Collaborators: Haocheng Zhang (UNM / LANL),
Chris Diltz (Ohio University), Matthew Baring (Rice Univ.),
Errol J. Summerlin (GSFC)

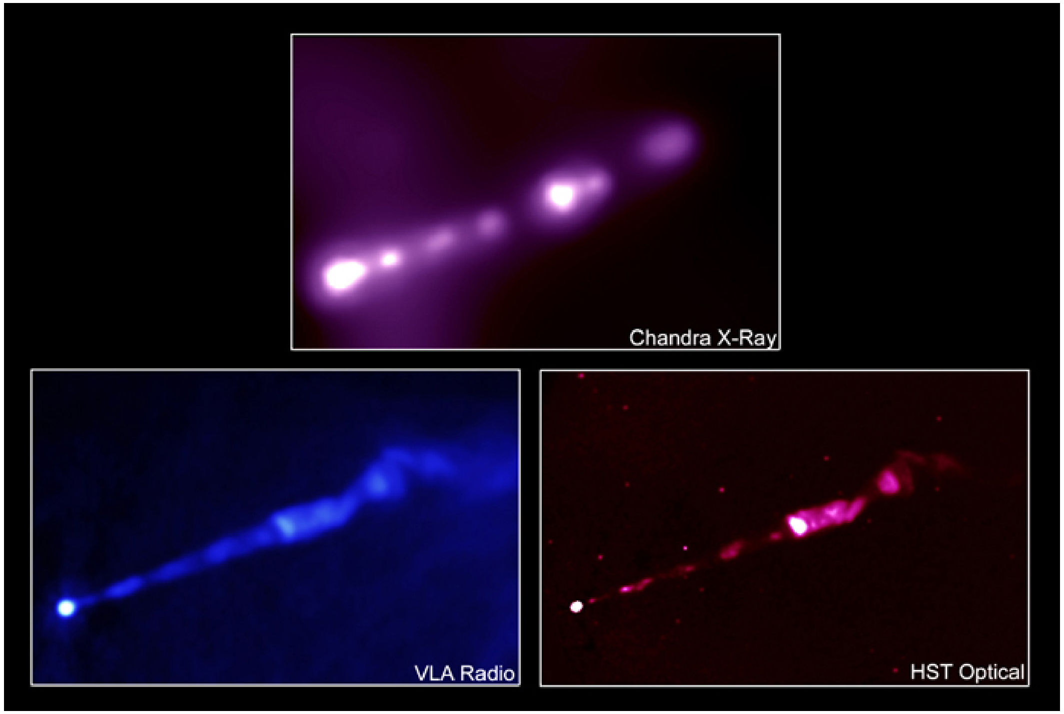
NORTH-WEST UNIVERSITY ®
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT

Relativistic Shocks in Jets



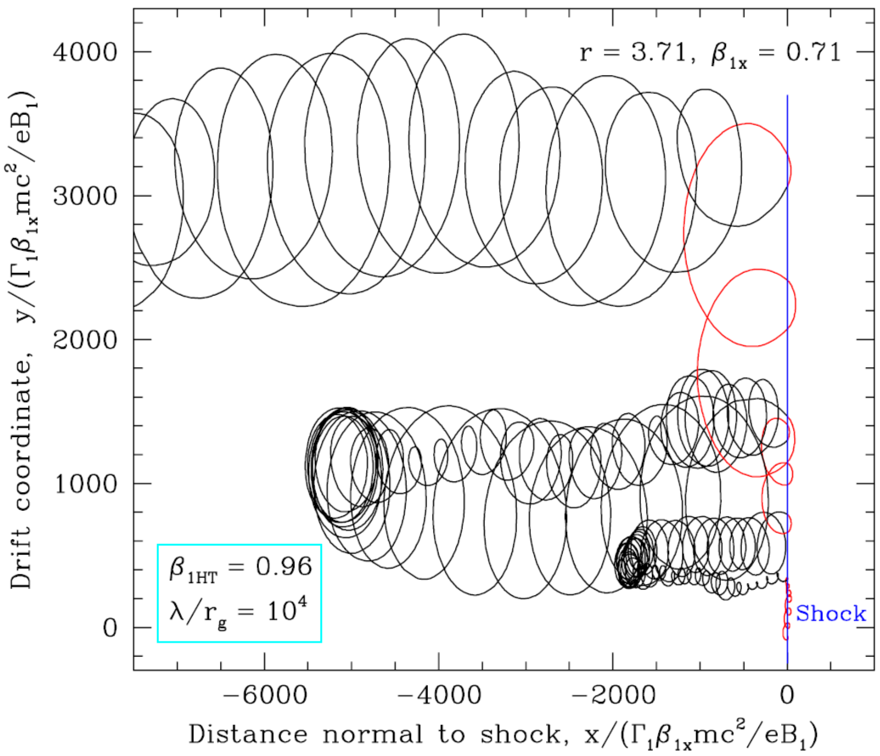
- Internal Shocks: Most likely mildly relativistic, oblique.

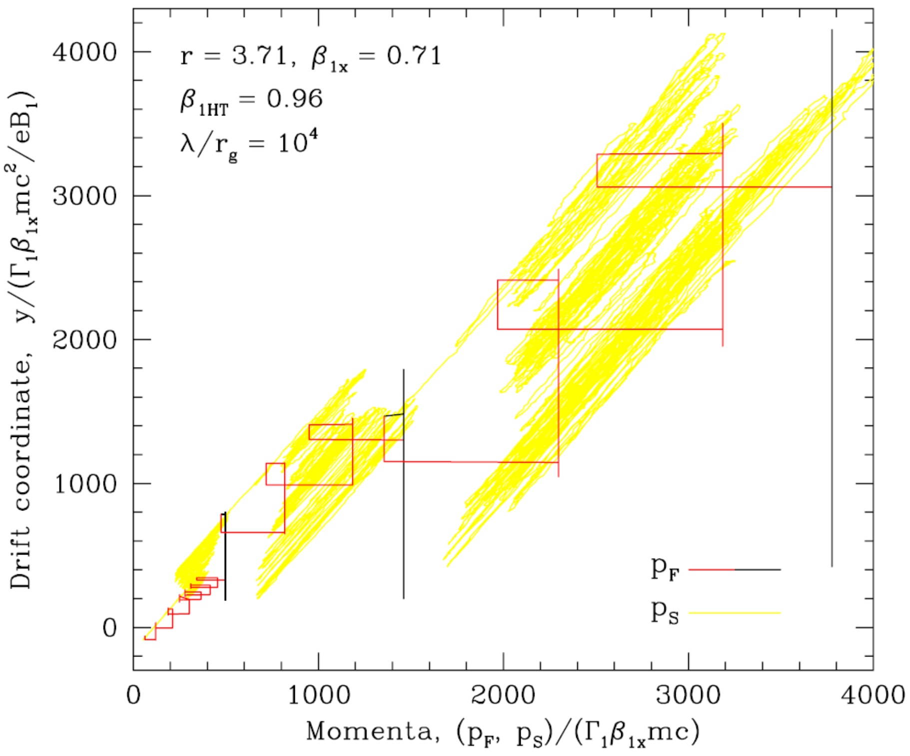
- In most works: Simple power-law or log-parabola electron spectra (from Fermi I / II acceleration) assumed with spectral index (~ 2) put in "by hand".



Marscher & Gear (1985), Spada et al.(2001), Sokolov et al. (2004), Mimica et al. (2004), Sokolov & Marscher (2005), Graff et al. (2008), Böttcher & Dermer (2010), Joshi & Böttcher (2011), Chen et al. (2011, 2012)

Diffusive Shock Acceleration (DSA)



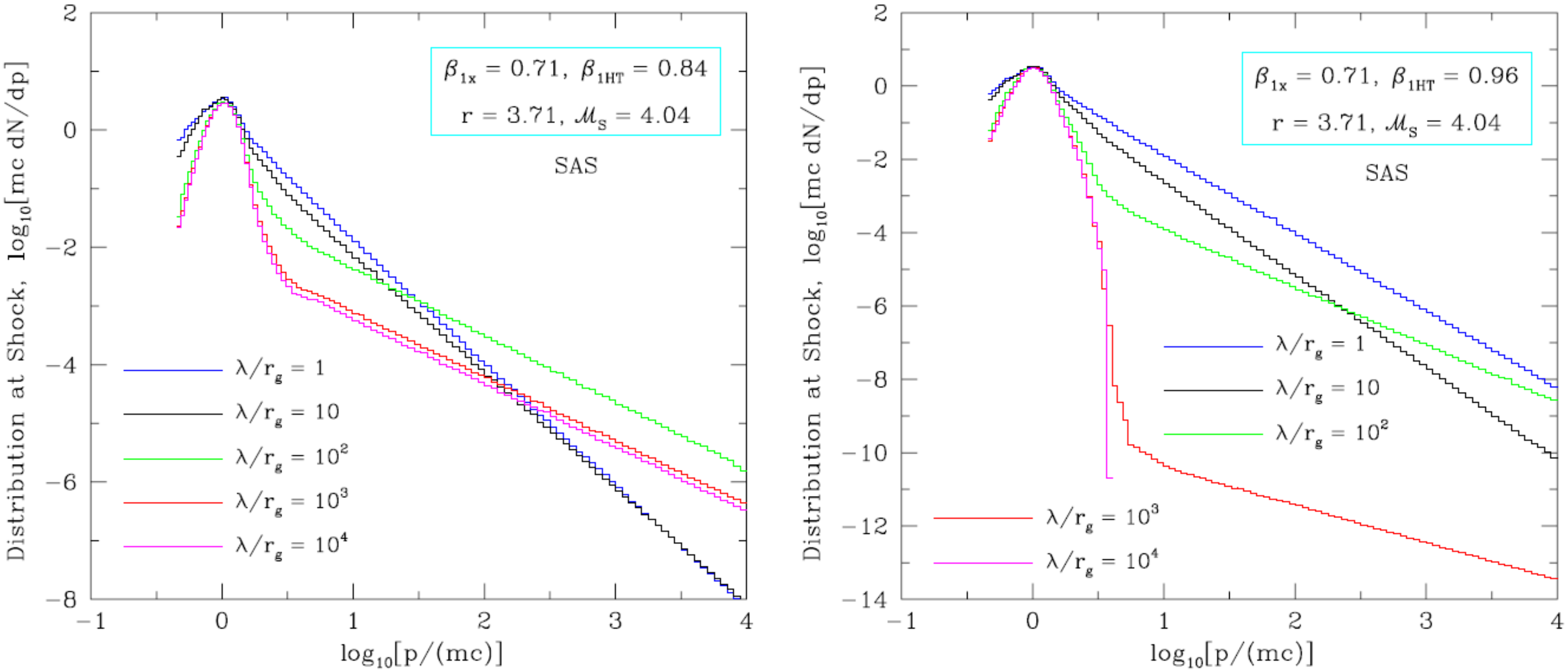


(Summerlin & & Baring 2012)

- Gyration in B-fields and diffusive transport modeled by a Monte Carlo technique.
- Shock crossings produce net energy gains (evident in the increase of gyroradii) according to principle of first-order Fermi mechanism.
- Pitch-angle diffusion parameterized through a mean-free-path (λ_{pas}) parameter η (p):

$$\lambda_{pas} = \eta(p)*r_g \sim p^\alpha \qquad (\alpha \geq 1)$$

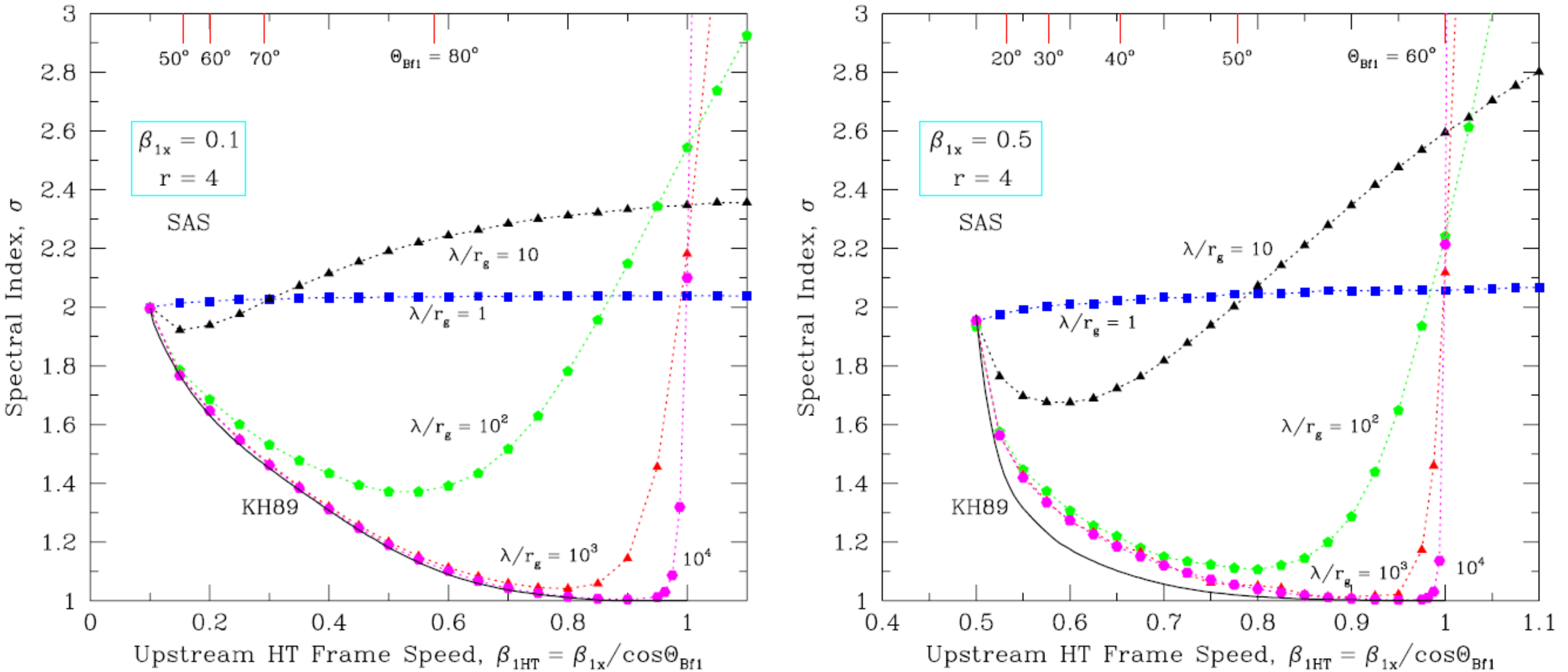
Shock Acceleration Injection Efficiencies



Summerlin & Baring (ApJ, 2012)

- Non-thermal particle spectral index and thermal-to-non-thermal normalization are strongly dependent on η and B-field obliquity!

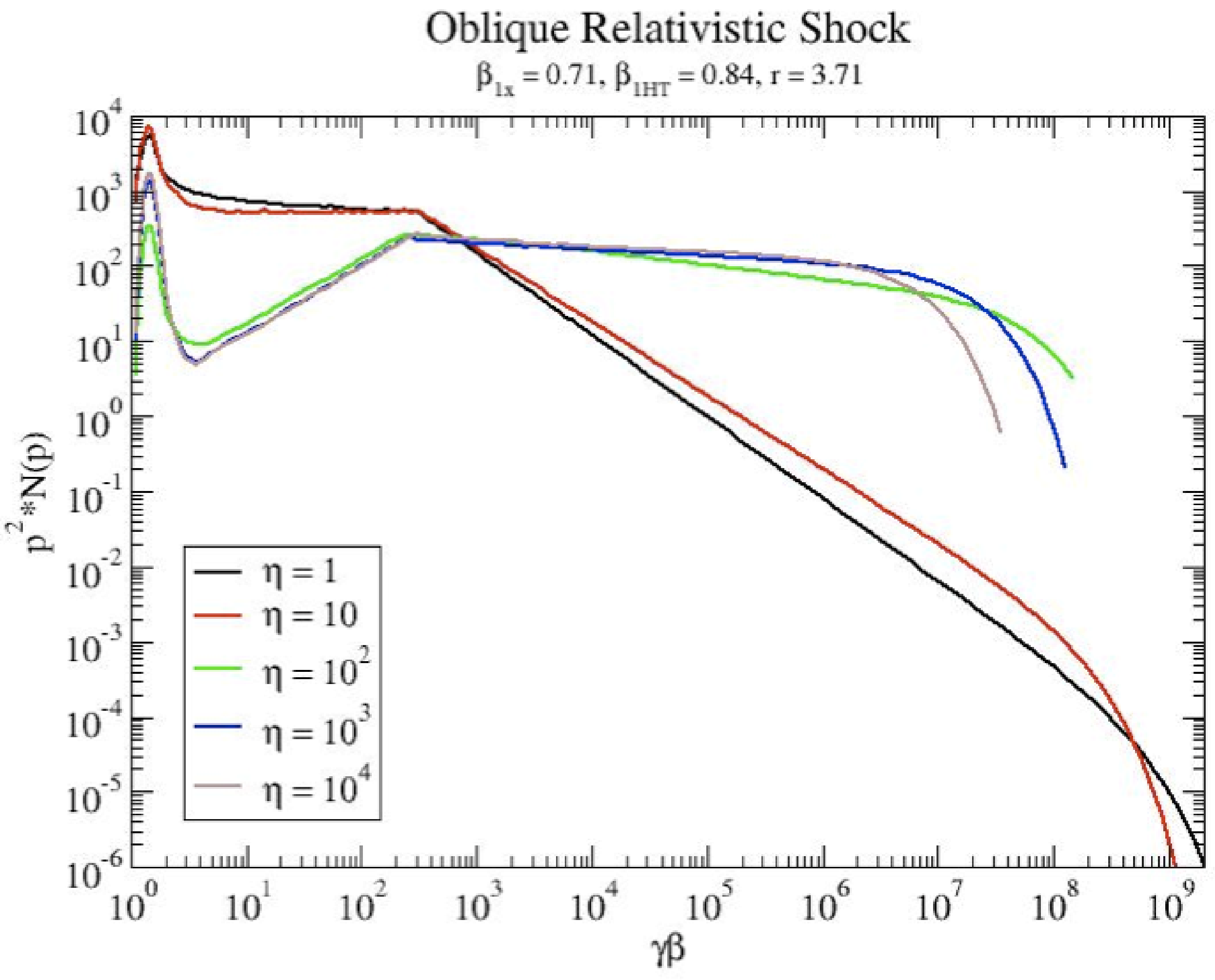
Acceleration Indices: Oblique Shocks



(Summerlin & Baring 2012)

- Non-thermal spectra as hard as $n(p) \sim p^{-1}$ achievable for moderately sub-luminal shocks.

Coupling with Radiative Energy Losses



- High-energy cutoff from balance between acceleration rate (DSA) and radiative (synchrotron + SSC + EC) cooling rate
- Cooling break from balance between radiative cooling and escape time scales.

Constraints from Blazar SEDs

If Synchrotron cooling dominates:

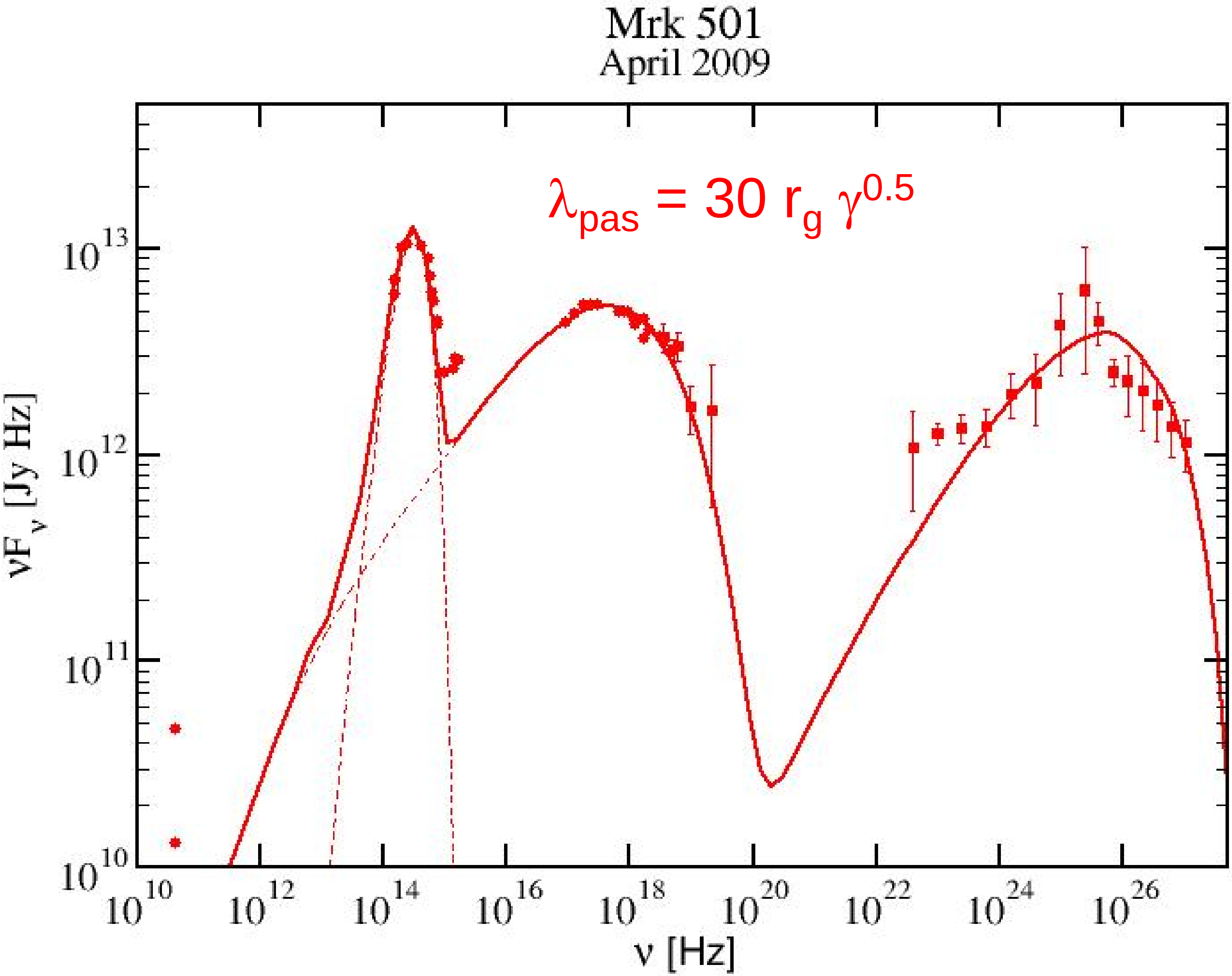
$$\gamma_{max} \sim B^{-1/2}\, \eta(\gamma_{max})^{-1/2}$$

$\Rightarrow \nu_{sy} \sim \eta(\gamma_{max})^{-1}$ (independent of B-field!)

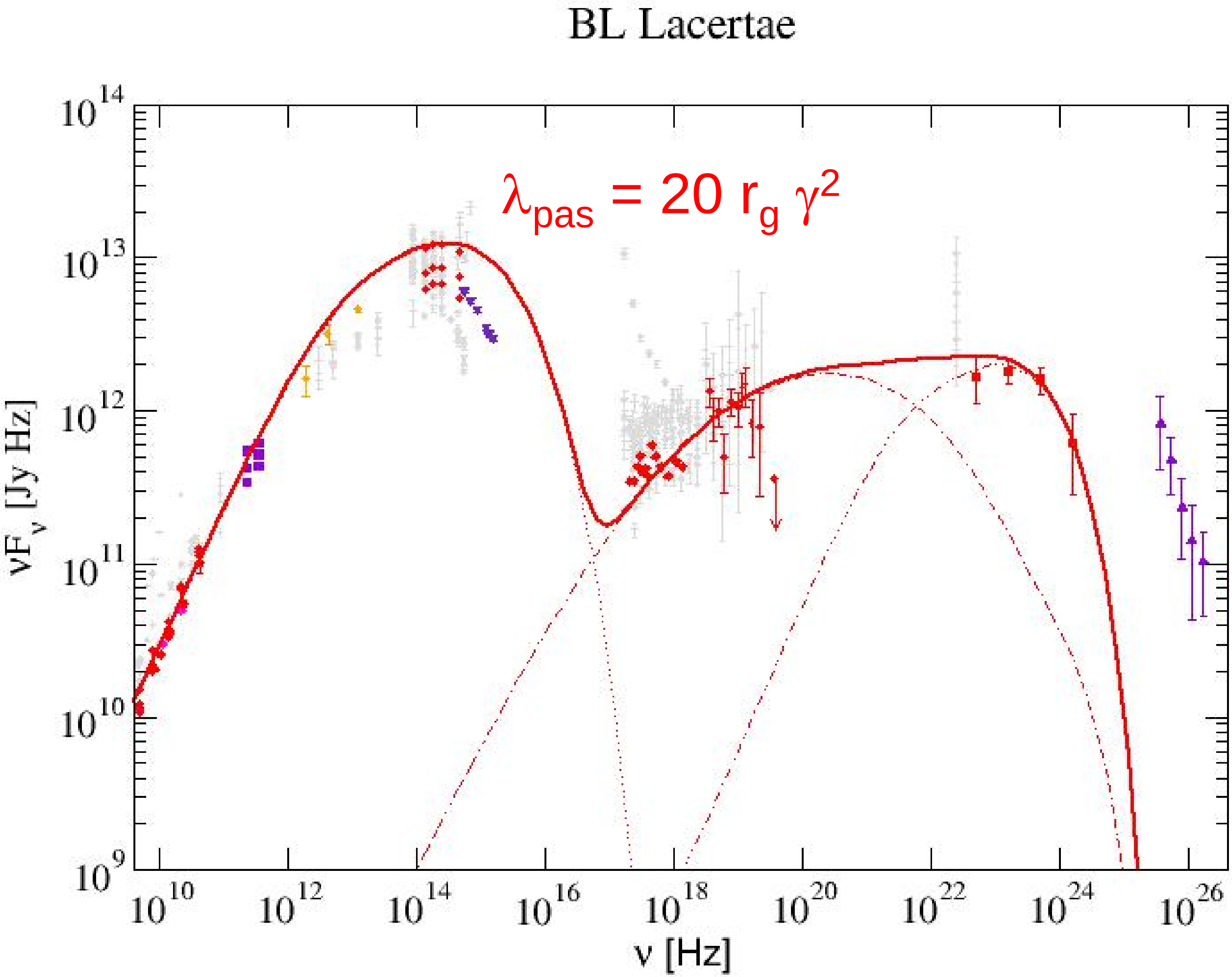
$\Rightarrow$ Need large $\eta(\gamma_{max})$ to obtain synchrotron peak in optical/UV/X-rays

$\Rightarrow$ But: Need moderate $\eta(\gamma \sim 1)$ for efficient injection of particles into the non-thermal accelerations scheme

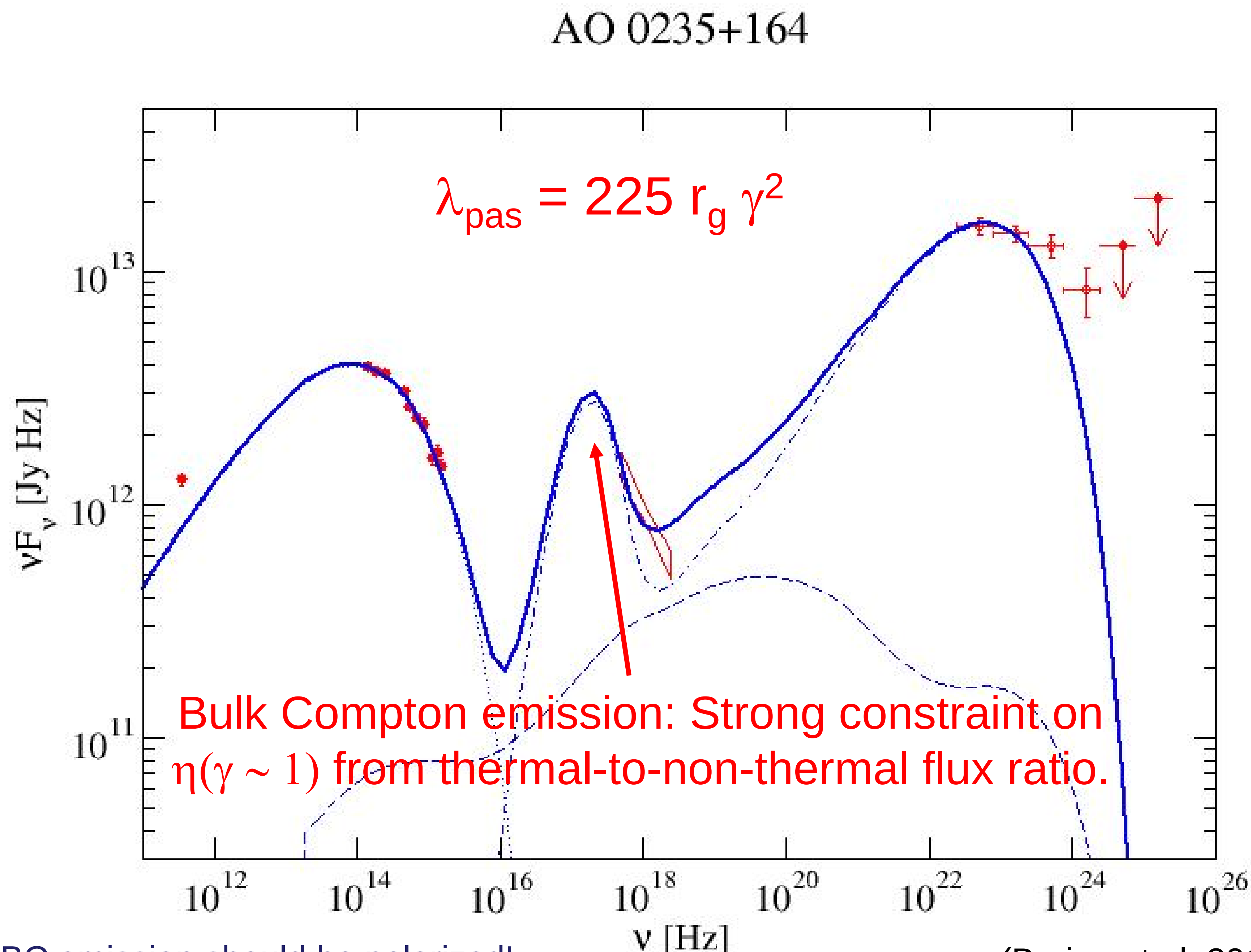
$\Rightarrow$ Need strongly energy dependent pitch-angle scattering m.f.p.



(Baring et al. 2016)



(Baring et al. 2016)



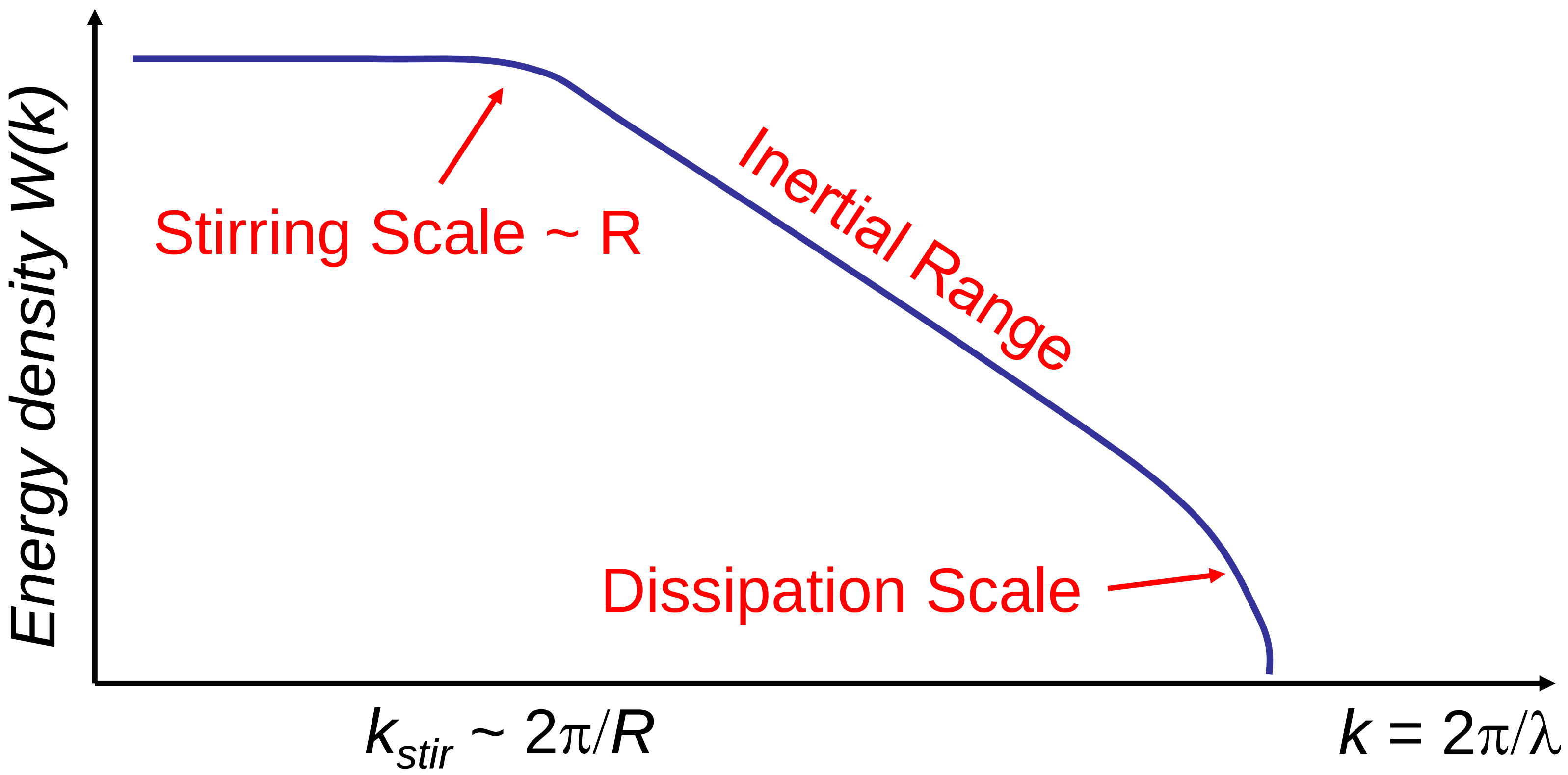
BC emission should be polarized!
→ Poster by T. Garrigoux

(Baring et al. 2016)

Implications for Shock-Induced Turbulence

Gyro-resonance condition: $\lambda_{res} \sim p$

=> Higher-energy particles interact with longer-wavelength turbulence

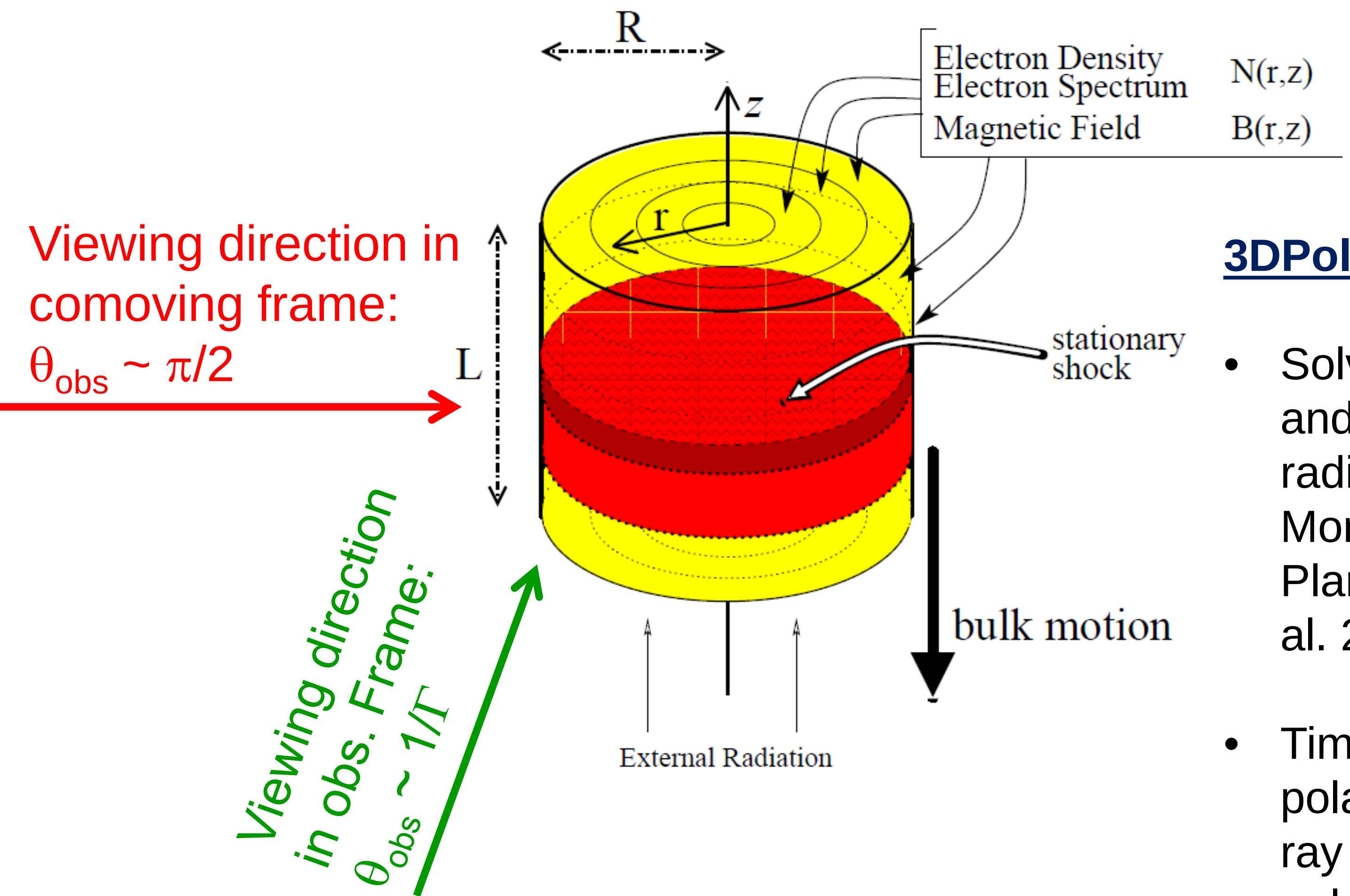


Turbulence level decreasing with increasing distance from the shock

$\Rightarrow$ High-energy (large r_g) particles "see" reduced turbulence

$\Rightarrow$ Large λ_{pas}

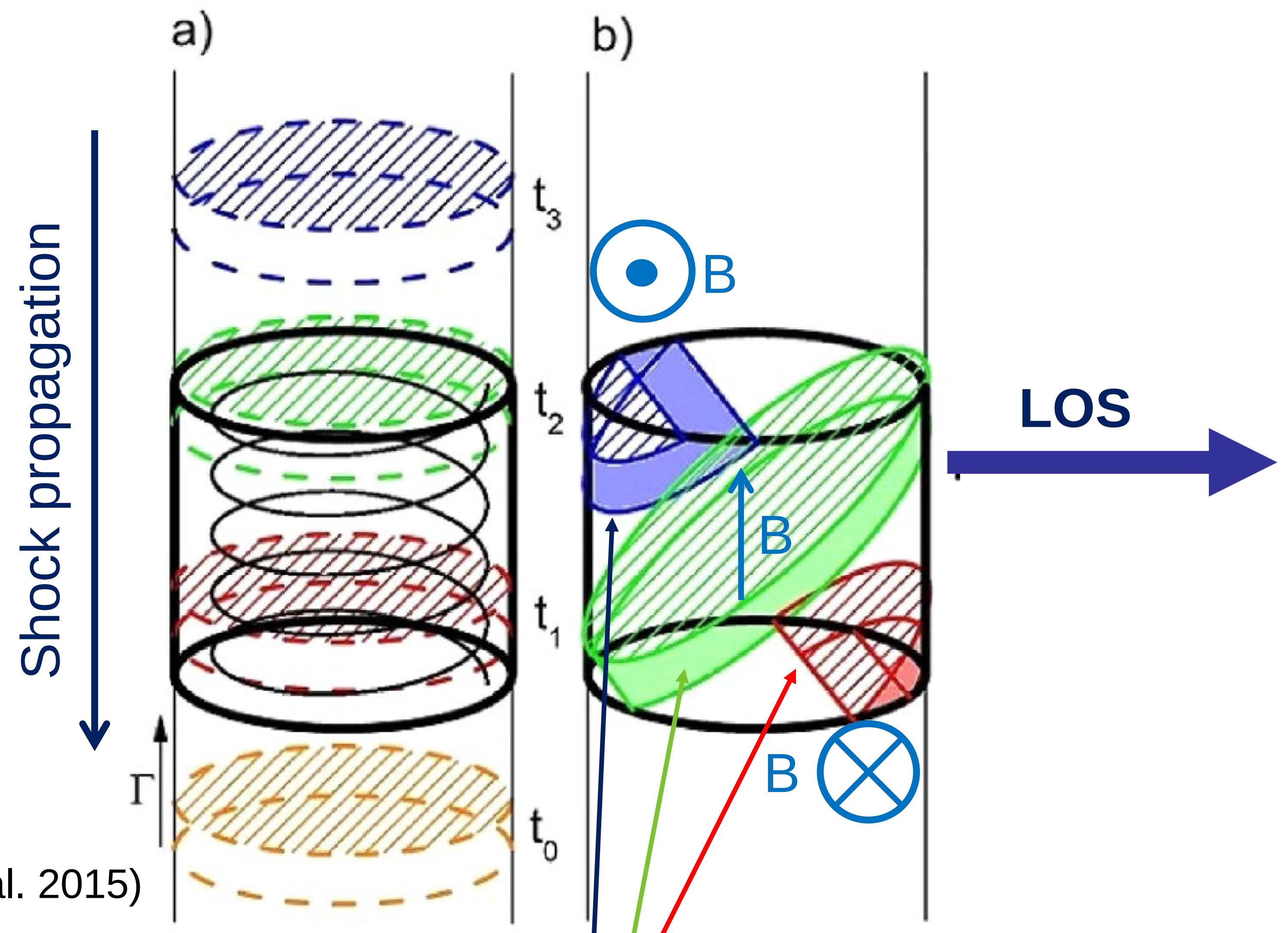
Tracing Synchrotron Polarization in the Internal Shock Model



3DPol (Zhang et al. 2014)

- Solve electron dynamics and (unpolarized) radiation transfer with Monte-Carlo / Fokker-Planck scheme (Chen et al. 2011, 2012)
- Time-dependent, polarization-dependent ray tracing for polarization signatures

Light Travel Time Effects



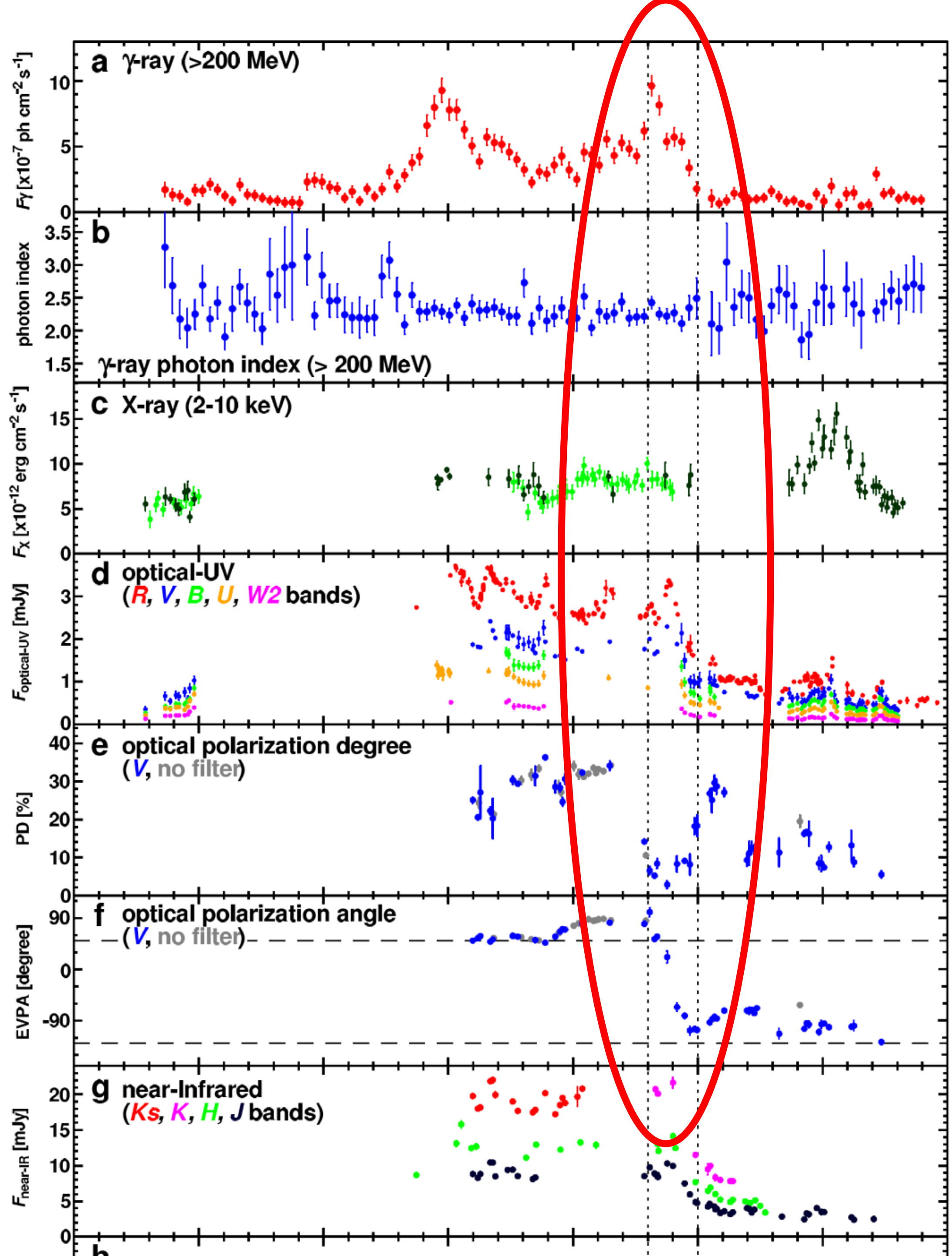
(Zhang et al. 2015)

Shock positions at equal photon-arrival times at the observer

Application to the FSRQ 3C279

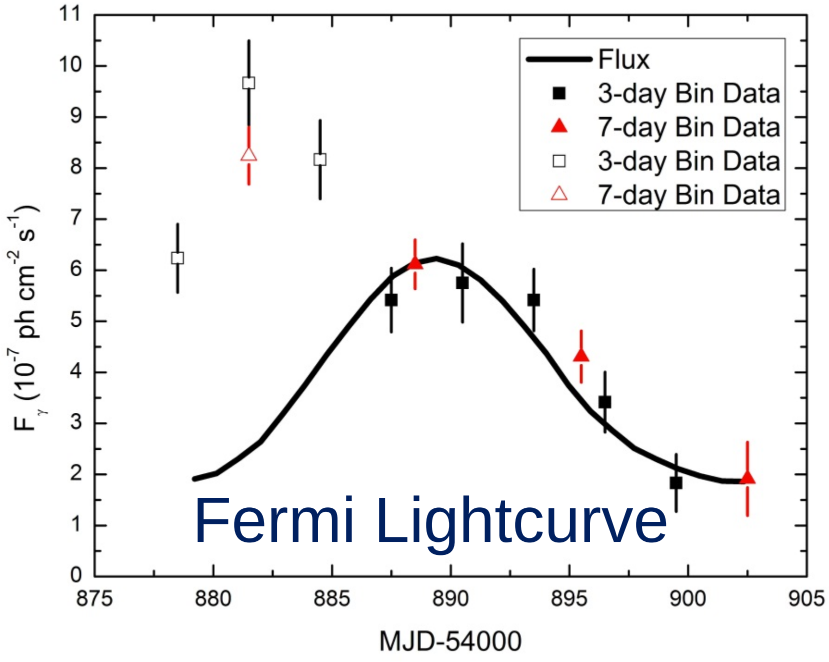
Simultaneous optical + γ-ray flare, correlated with a 180º polarization-angle rotation .

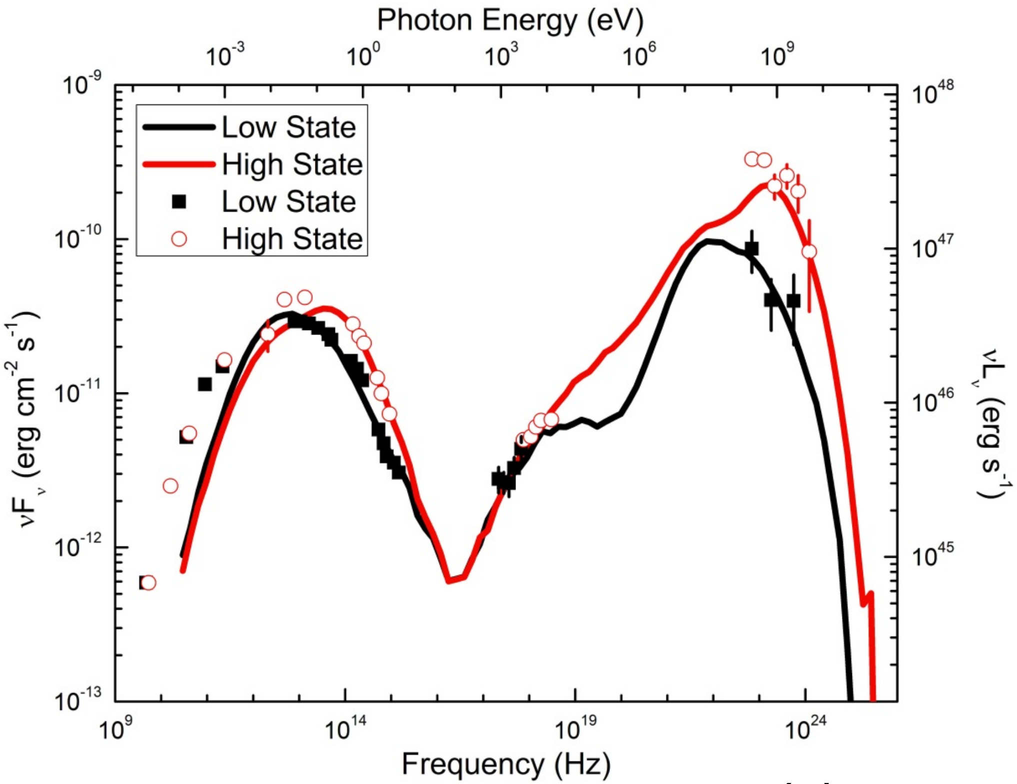
(Abdo et al. 2009)

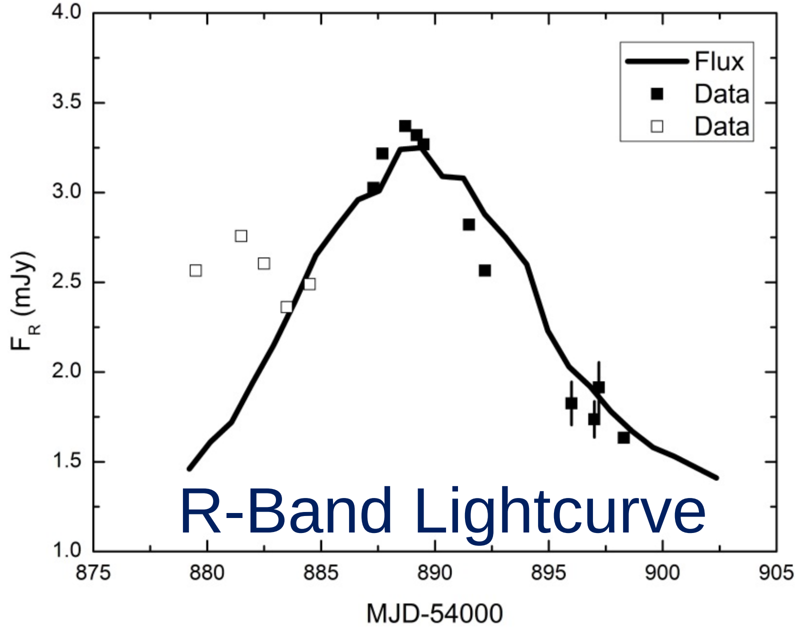


Application to 3C279

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



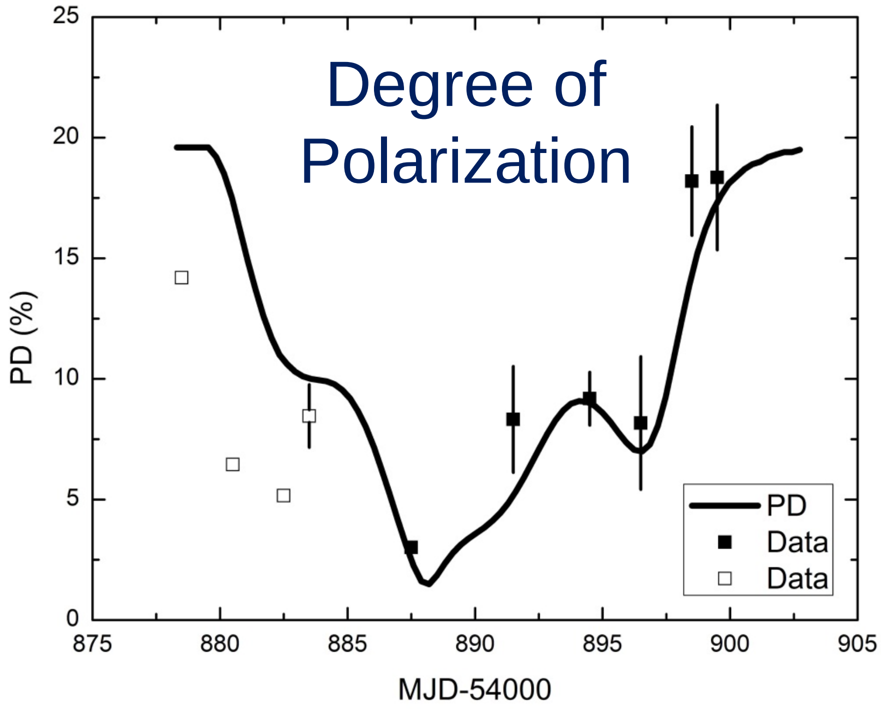


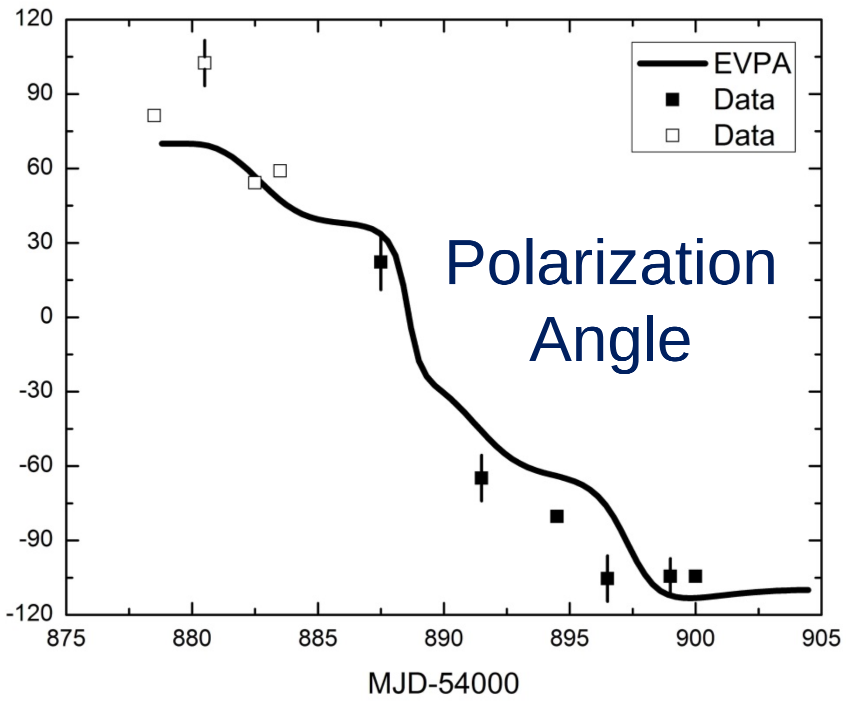


(Zhang et al. 2015)

Application to 3C279

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

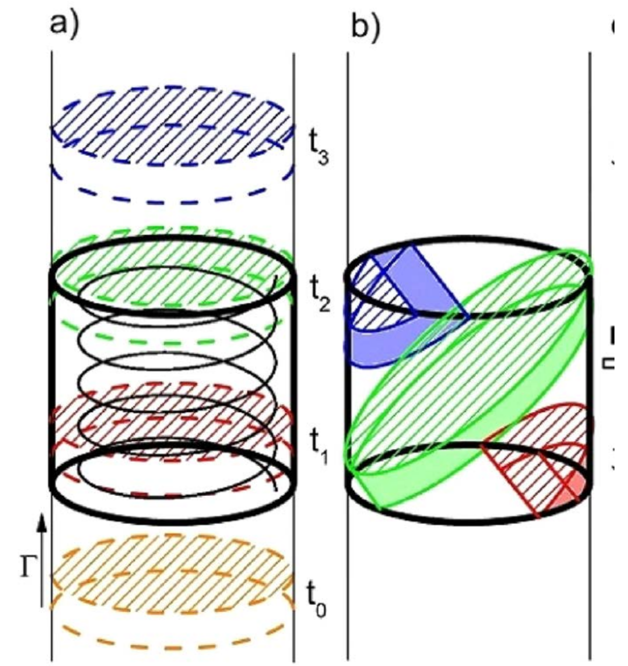




(Zhang et al. 2015)

The Lepto-Hadronic Version

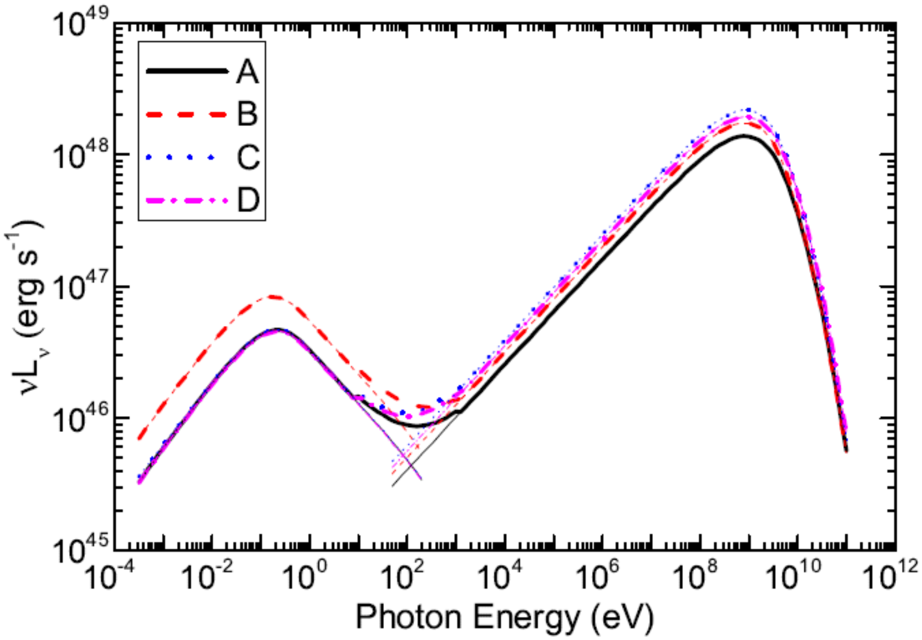
- Lepto-hadronic (p-synchrotron dominated) 3D time- and polarization-dependent internal shock model (Zhang, Diltz & Böttcher 2016, in preparation)
- Model setup as for leptonic (3DPol) model, but include injection of ultrarelativistic protons
- Electron + proton evolution with locally isotropic Fokker-Planck equation
- Fully time- and polarization-dependent ray tracing

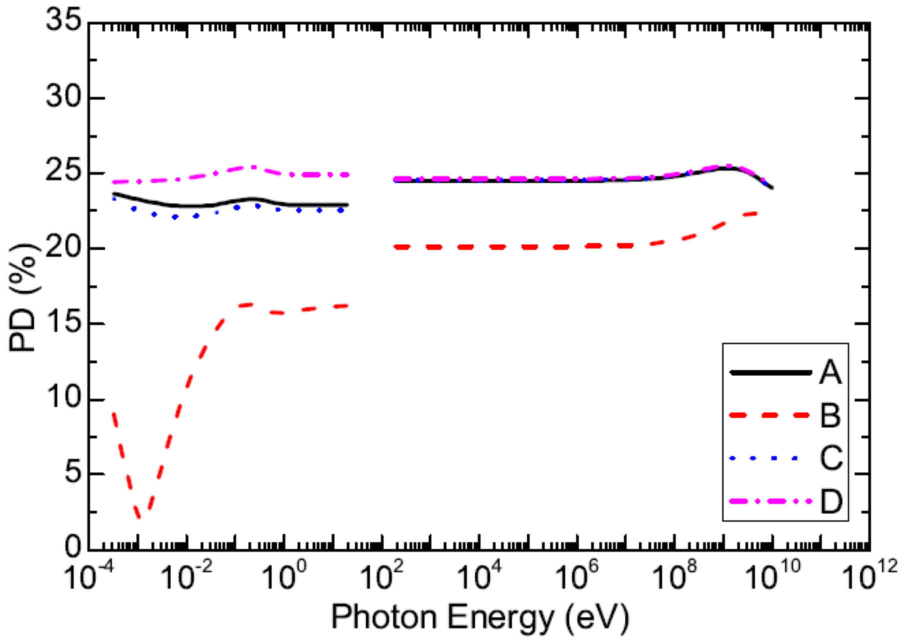


3D Lepto-Hadronic Internal Shock model

Example case: Magnetic energy dissipation (reducing B-field, additional e and p injection)

(Zhang et al. 2016, in prep.)

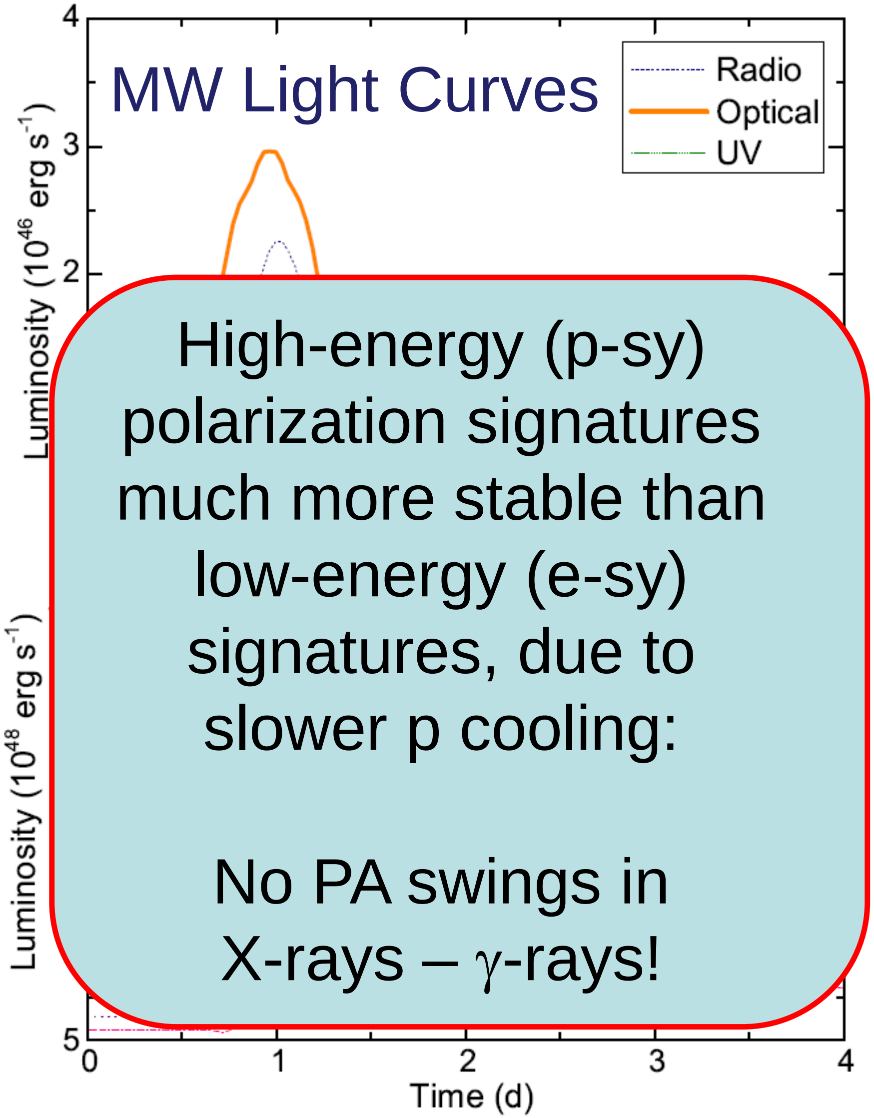




Snap-Shot SEDs

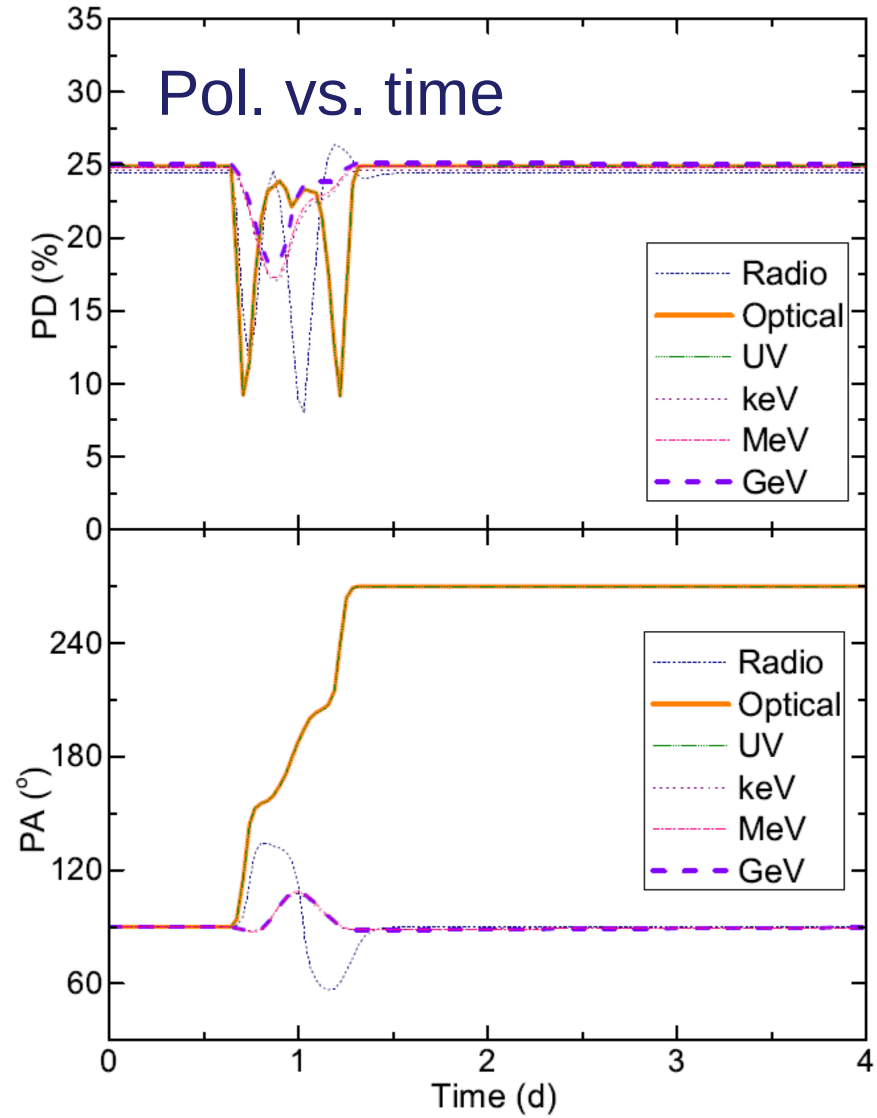
Pol. Deg. vs. Photon Energy

3D Lepto-Hadronic Internal Shock model



High-energy (p-sy) polarization signatures much more stable than low-energy (e-sy) signatures, due to slower p cooling:

No PA swings in X-rays – γ-rays!



(Zhang et al. 2016, in prep.)

Summary

1. Coupled MC Simulations of Diffusive Shock Acceleration and radiation transport reveal strongly energy-dependent mean-free-path to pitch-angle scattering.

2. Polarization-angle swings correlated with MW flares are possible with a straight jet, pervaded by a helical B field. Fit to 3C279 event suggests magnetic energy dissipation as driver of flaring activity.

3. 3D time- and polarization-dependent radiation transfer simulations for a proton-synchrotron dominated lepto-hadronic model: High-energy (X-ray/gamma-ray) polarization signatures are expected to be less variable than low-energy (e-synchrotron) ones. PA swings in X-rays / γ-rays are unlikely if high-energy emission has hadronic origin.

NORTH-WEST UNIVERSITY ®
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT

Astronomers Say the Darnest Things

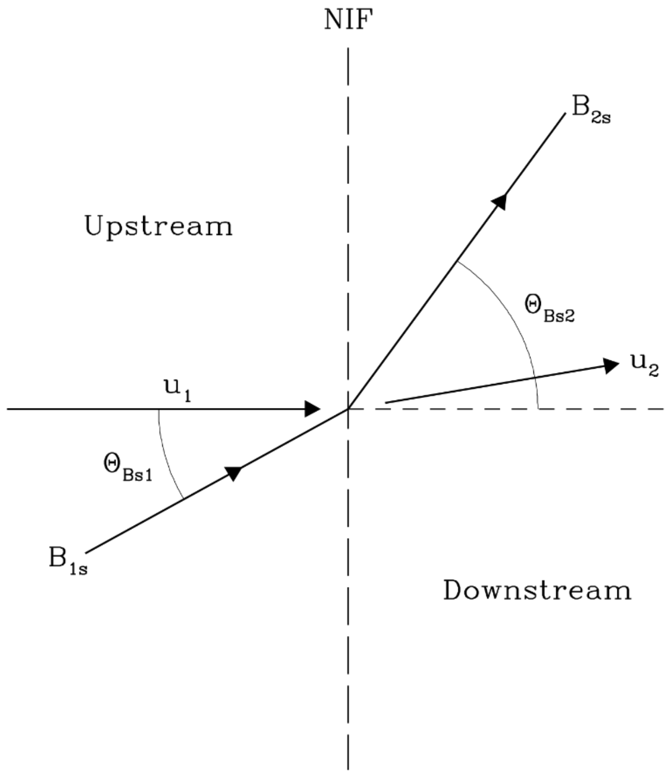
Dear Markus,

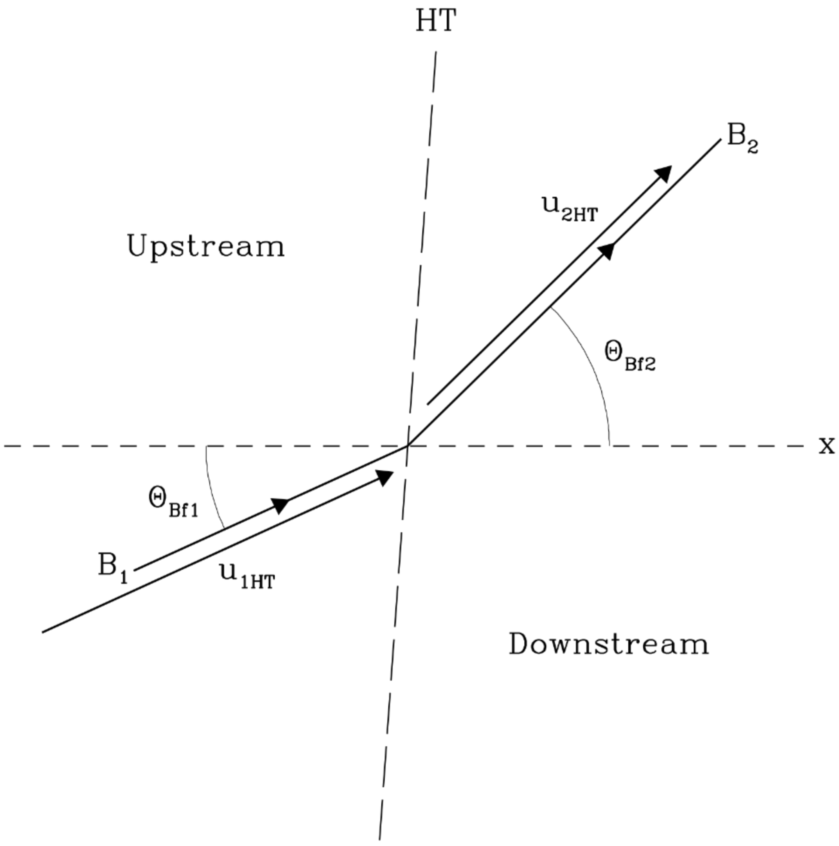
… We know that the BLR in radio quiet AGNs are observed to show clumsiness and substructures…

E-mail from a colleague [name undisclosed]

Oblique Relativistic MHD Shock Geometry

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)

Distinguishing Diagnostic: Variability

In homogeneous, single-zone (spherical-cow) models:

- Time-dependent evolution of particle spectra:

$$\frac{\partial n_i(\gamma,t)}{\partial t} = \boxed{\frac{\partial}{\partial \gamma}\left[\frac{\gamma^2}{(a+2)t_{\rm acc}}\frac{\partial n_i(\gamma,t)}{\partial \gamma}\right]} - \boxed{\frac{\partial}{\partial \gamma}(\dot{\gamma}\cdot n_i(\gamma,t))} + \boxed{Q_i(\gamma,t)} - \boxed{\frac{n_i(\gamma,t)}{t_{\rm esc}}} - \boxed{\frac{n_i(\gamma,t)}{\gamma t_{\rm decay}}}$$

Diffusion in momentum space (stochastic acceleration)

Systematic energy gain/loss (radiative losses)

"Injection" (pick-up, rapid acceleration, parent particle decay

Escape

Decay (for unstable particles: n, $\pi^{\pm}$, $\mu^{\pm}$)

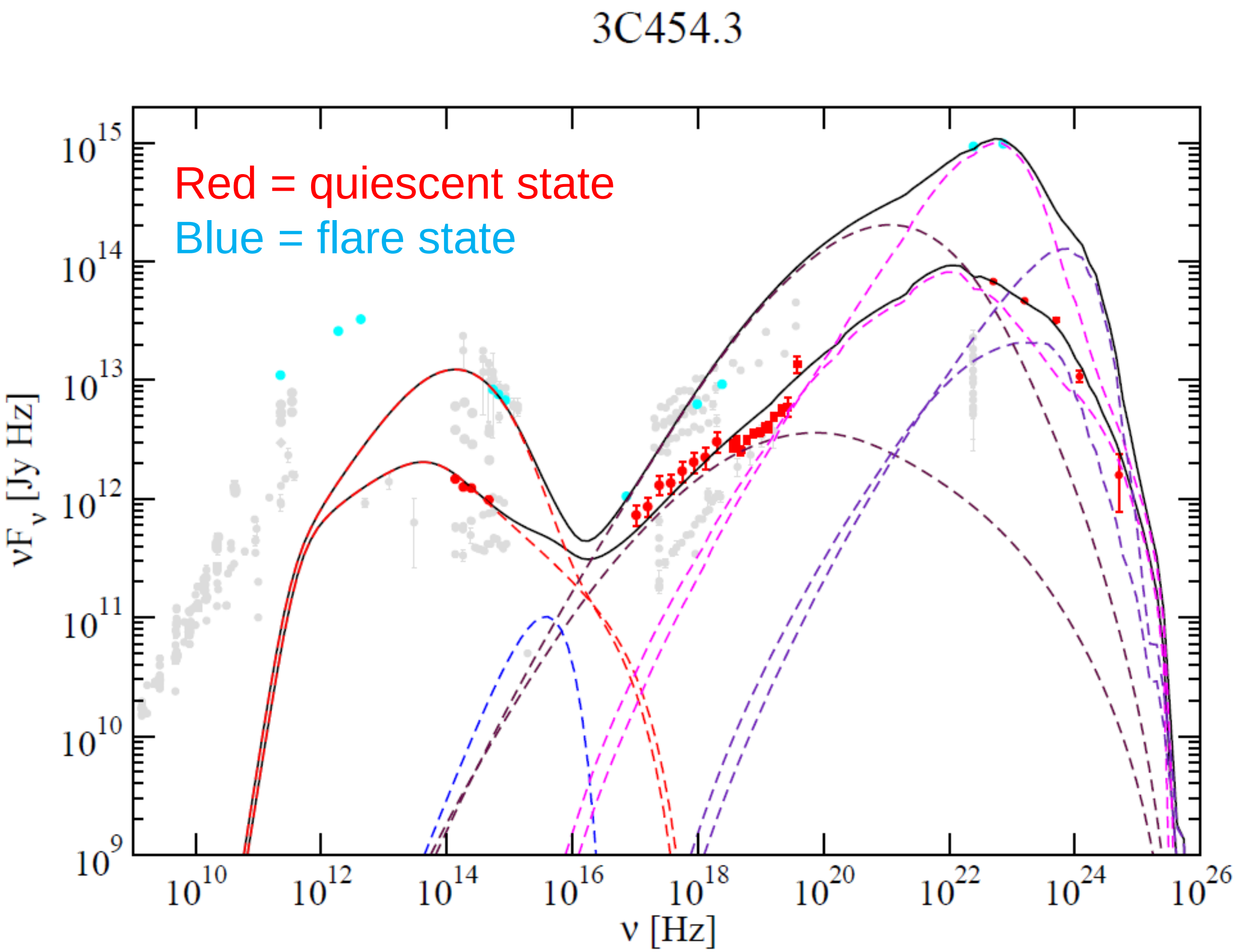
- And corresponding radiation transfer

- Variations of input parameters to model variability

(e.g., Mastichiadis & Kirk 1997; Li & Kusunose 2000; Böttcher & Chiang 2002; Chen et al. 2011; Diltz & Böttcher 2014; Diltz et al. 2015; …)

Distinguishing Diagnostic: Variability

3C454.3 Flare of November 2010



(Diltz & Böttcher 2016)

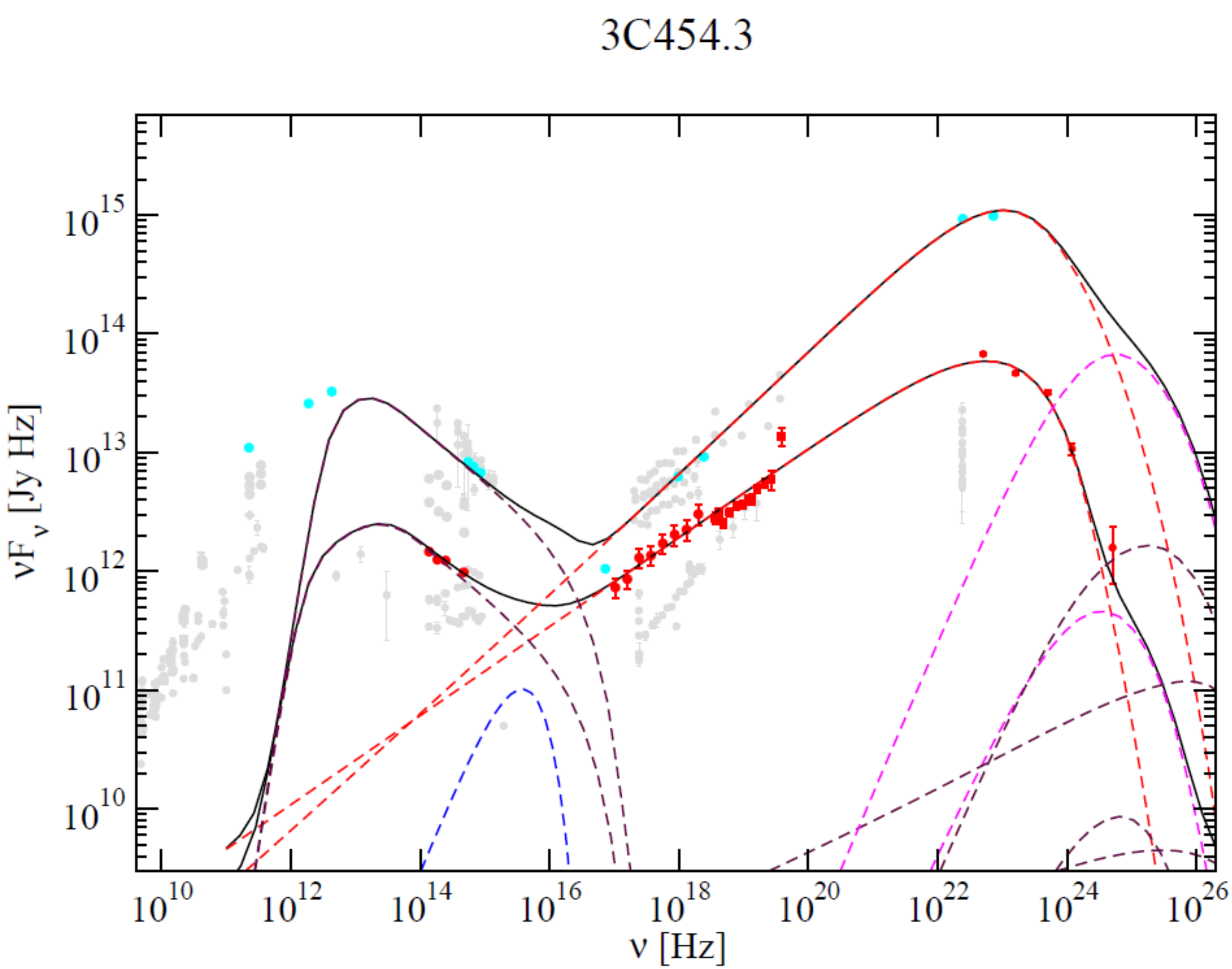
Time-dependent leptonic model

Best-fit variation of

- electron injection power
- B-field
- Stochastic acceleration time-scale

Poor fit to flare-state X-ray spectrum!

3C454.3 Flare of November 2010



(Diltz & Böttcher 2016)

Time-dependent lepto-hadronic model

Best-fit variation of

- electron injection power
- B-field
- Stochastic acceleration time-scale
- Proton injection spectral index

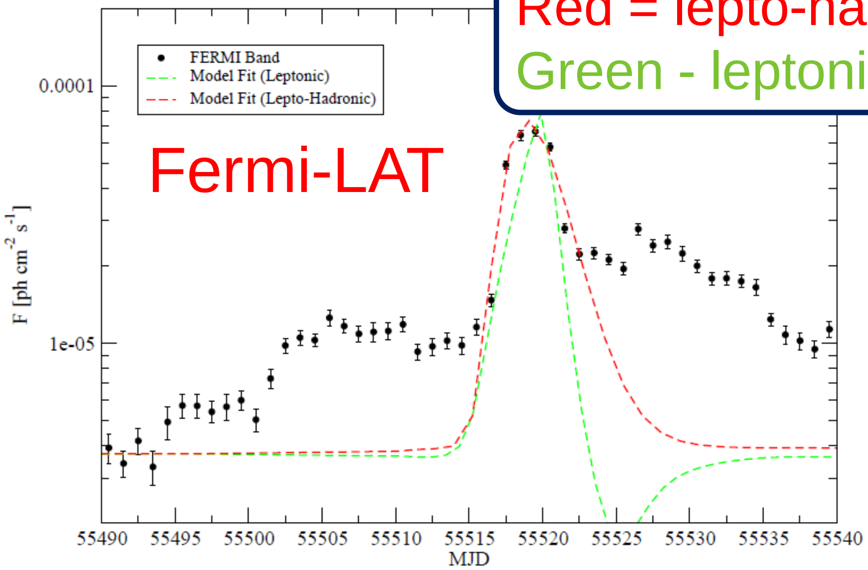
Both quiescent and flare state well represented!

Light Curve Fits

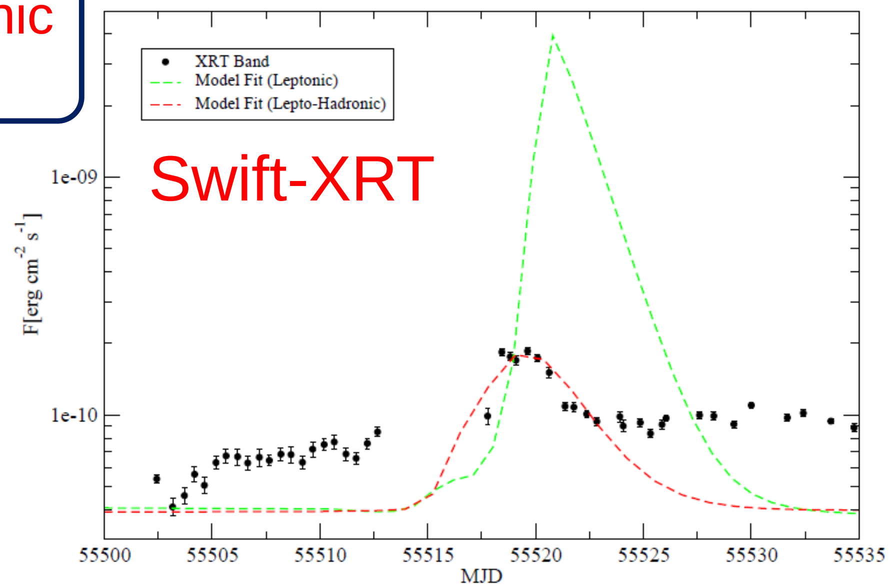
3C454.3 Flare of November 2010

Red = lepto-hadronic
Green - leptonic

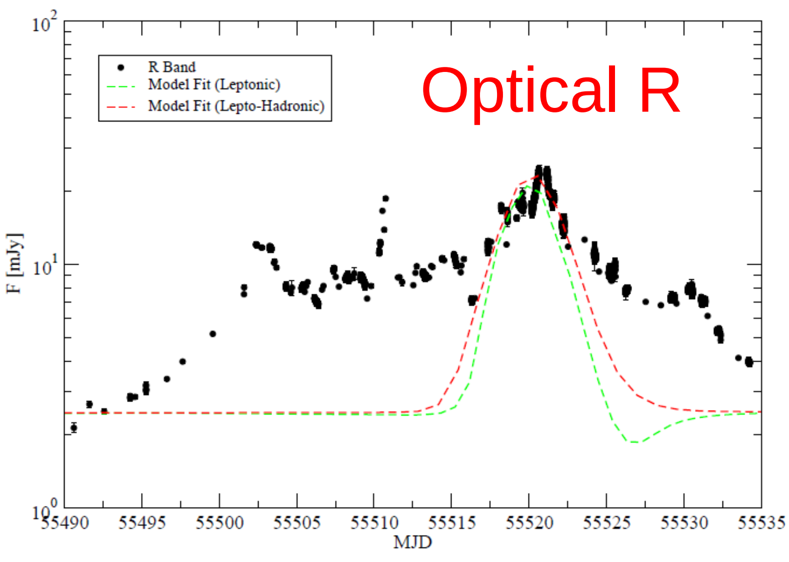
Fermi-LAT



Swift-XRT



Optical R



Good simultaneous fits to snap-shot SEDs **and** multiwavelength light curves with lepto-hadronic model (but requiring $L_p \sim L_{Edd}$!)

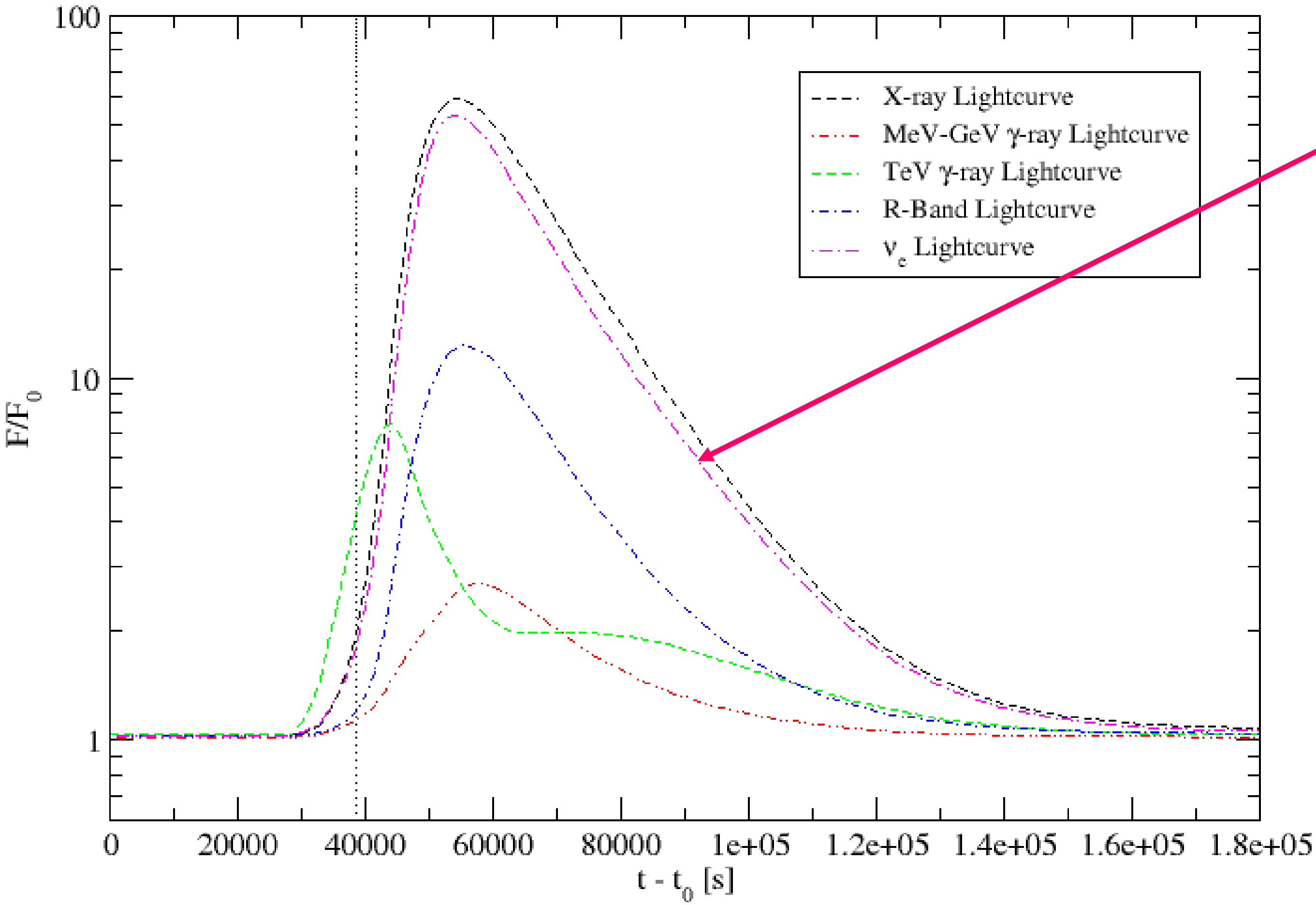
Poor fits to flaring-state X-ray spectrum **and** X-ray light curve with leptonic model.

(Diltz & Böttcher 2016)

Neutrino Emission

Most hadronic / lepto-hadronic models of blazars are proton-synchrotron dominated => Very low expected neutrino flux

Normalized Lightcurves (t_{acc} Perturbation) :



Neutrino flares generally co-incident with X-ray through GeV γ-ray flares:

IceCube detection rates:

- ~ 0.3 yr^{-1} (quiesc.)
- ~ 3 yr^{-1} (flares)

(Diltz et al. 2015)

Coupling to Realistic MHD Simulations

- Ideal RMHD Simualtions (LA-COMPASS [LANL]) of relativistic shocks

- Jets initially pervaded by purely helical B-fields with magnetization parameter

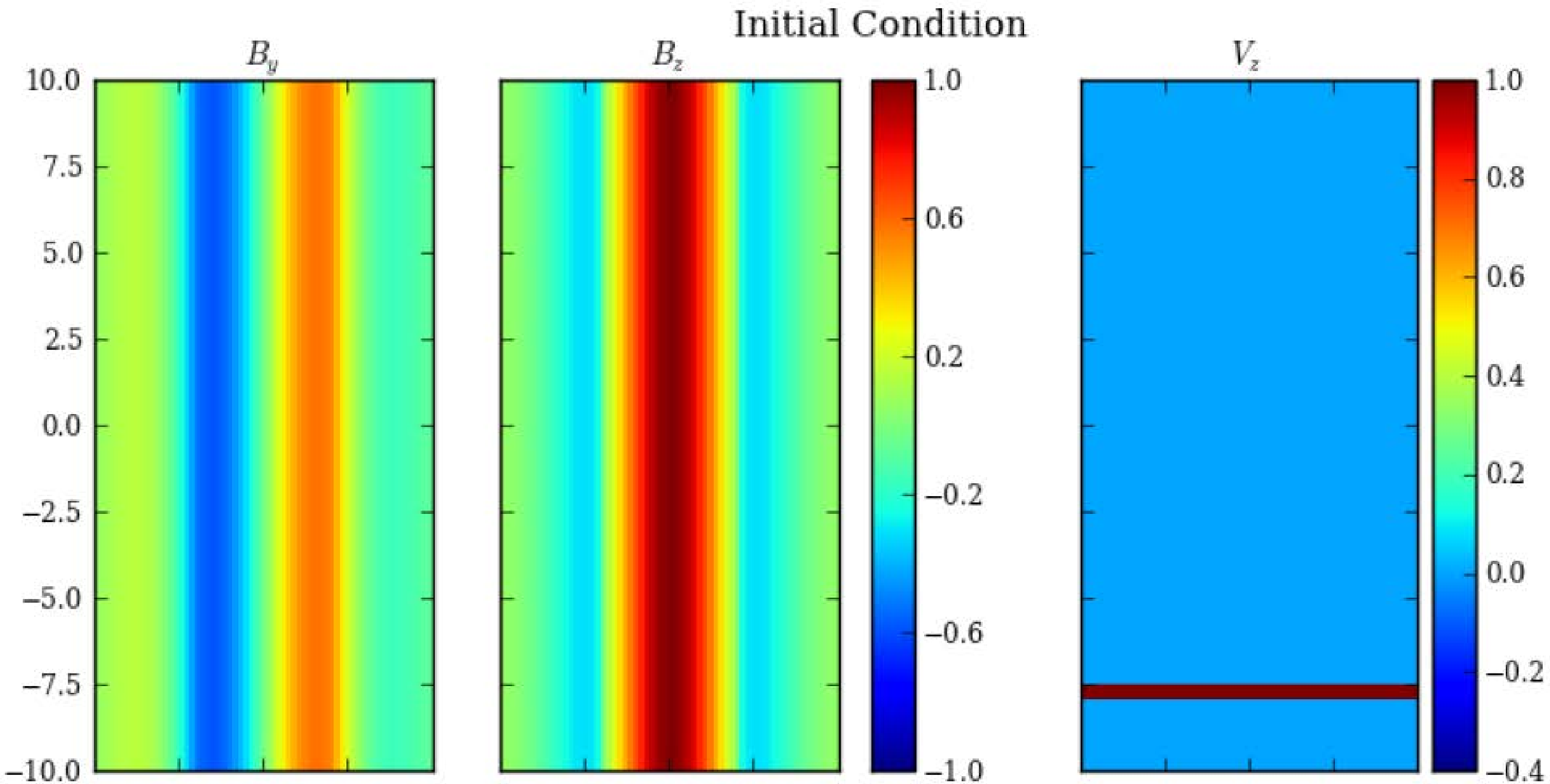
$$\sigma = \frac{E_{em}}{h} \qquad E_{em} = \frac{E^2+B^2}{8\pi} \qquad h = \rho c^2 + \frac{\gamma p}{\gamma - 1}$$

- Fixed fraction of liberated energy converted to the injection of power-law non-thermal electrons

- Follow particle evolution, radiation, and time-dependent polarization signatures using 3DPol.

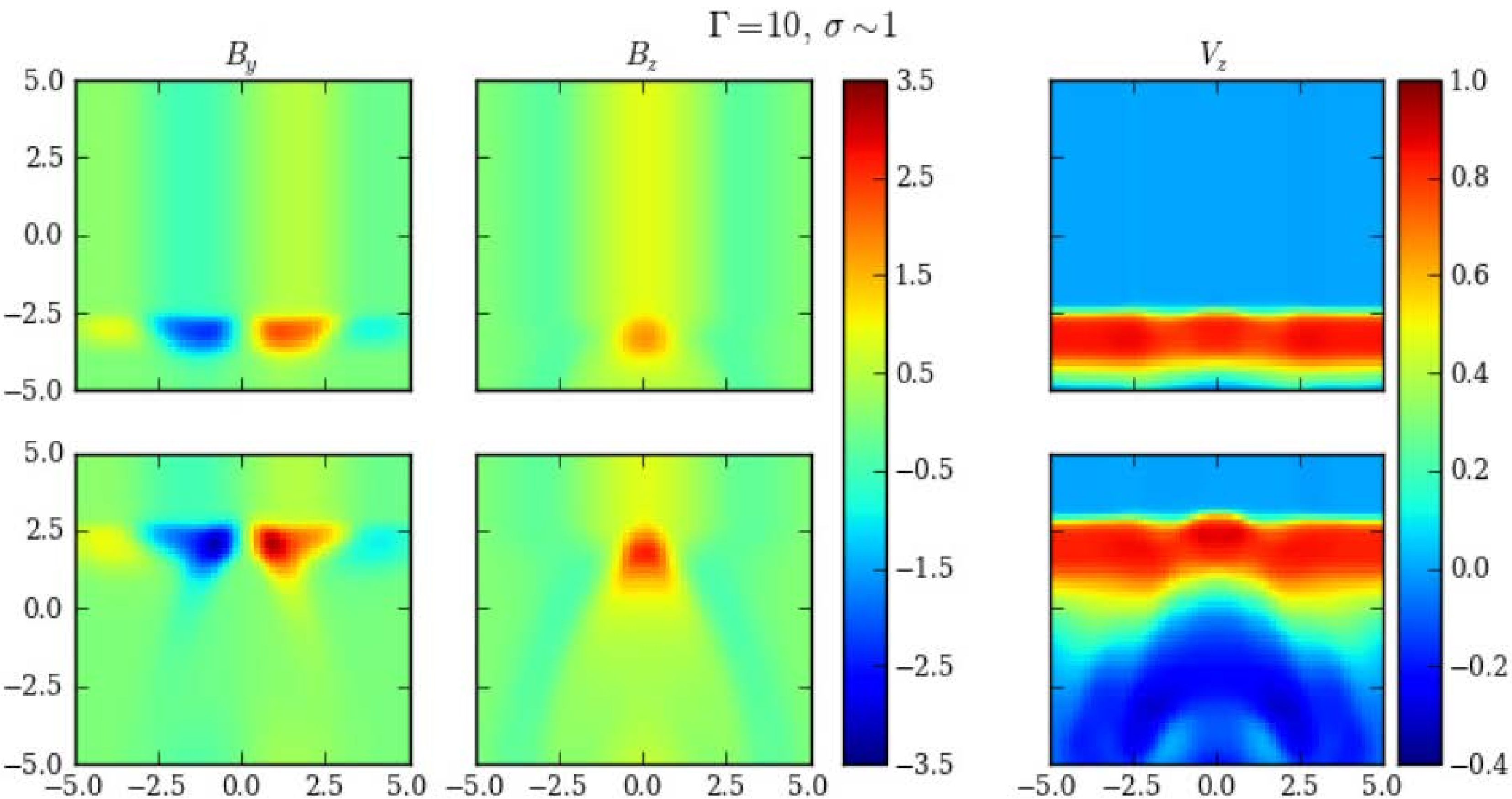
(Zhang et al. 2016)

Simulation Setup



(Zhang et al. 2016)

B-Field Evolution

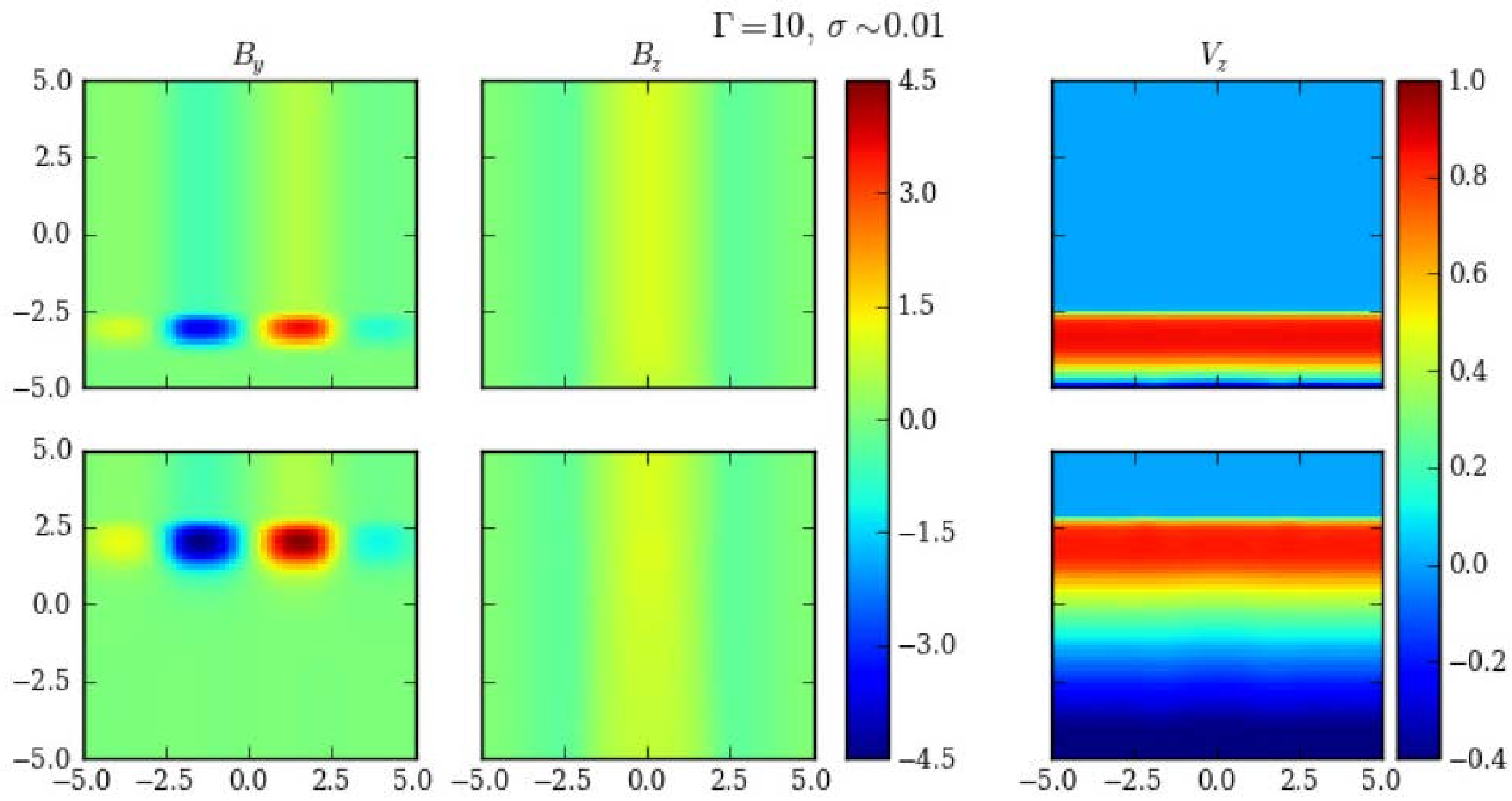


(Zhang et al. 2016)

<u>High / moderate magnetization</u>

- Weak shock
- velocity field strongly disturbed
- B-field restored to its original topology after passage of the shock

B-Field Evolution

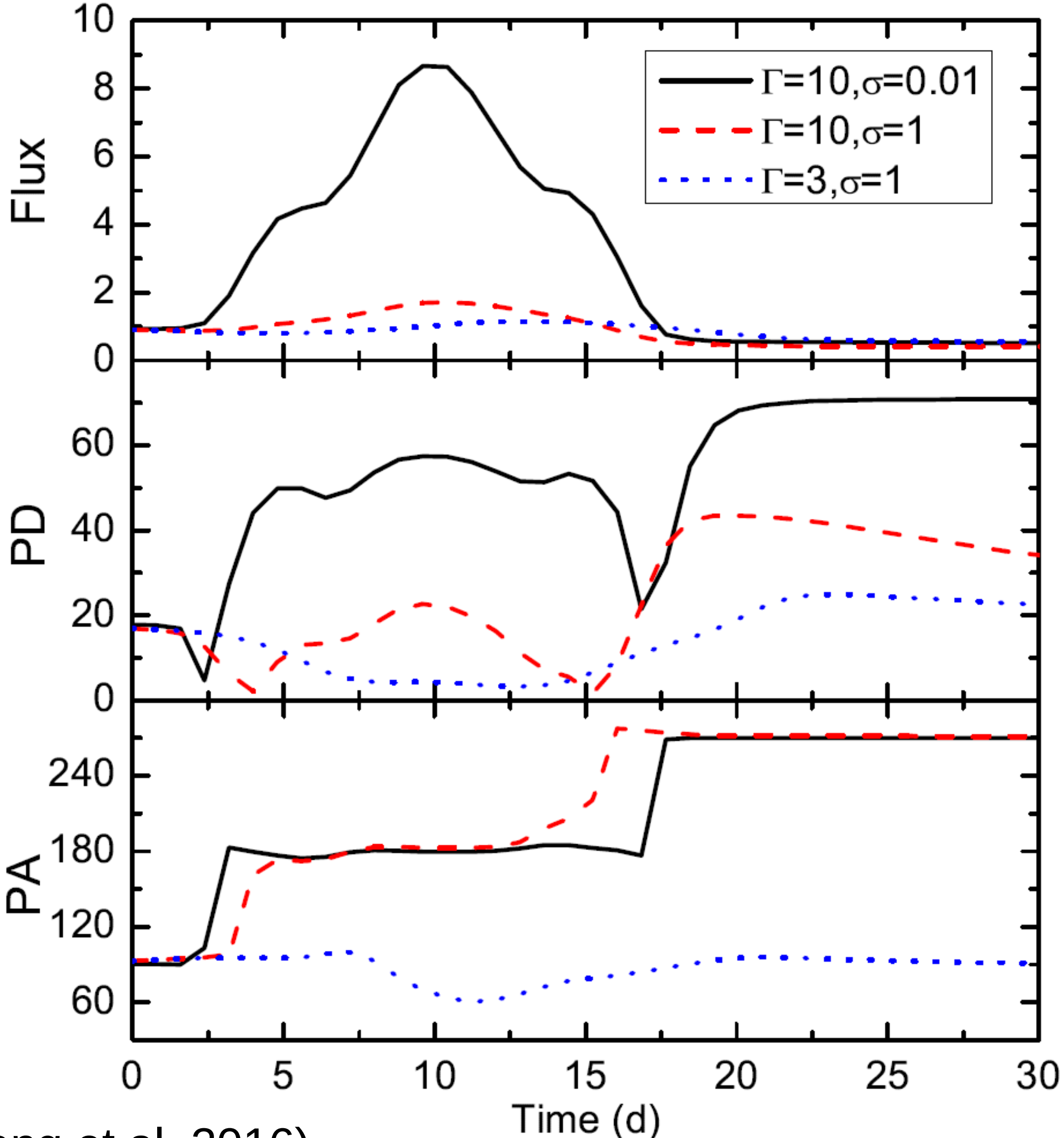


(Zhang et al. 2016)

Low magnetization

- Strong shock
- velocity field almost undisturbed
- B-field topology significantly altered after passage of the shock

Polarization Signatures

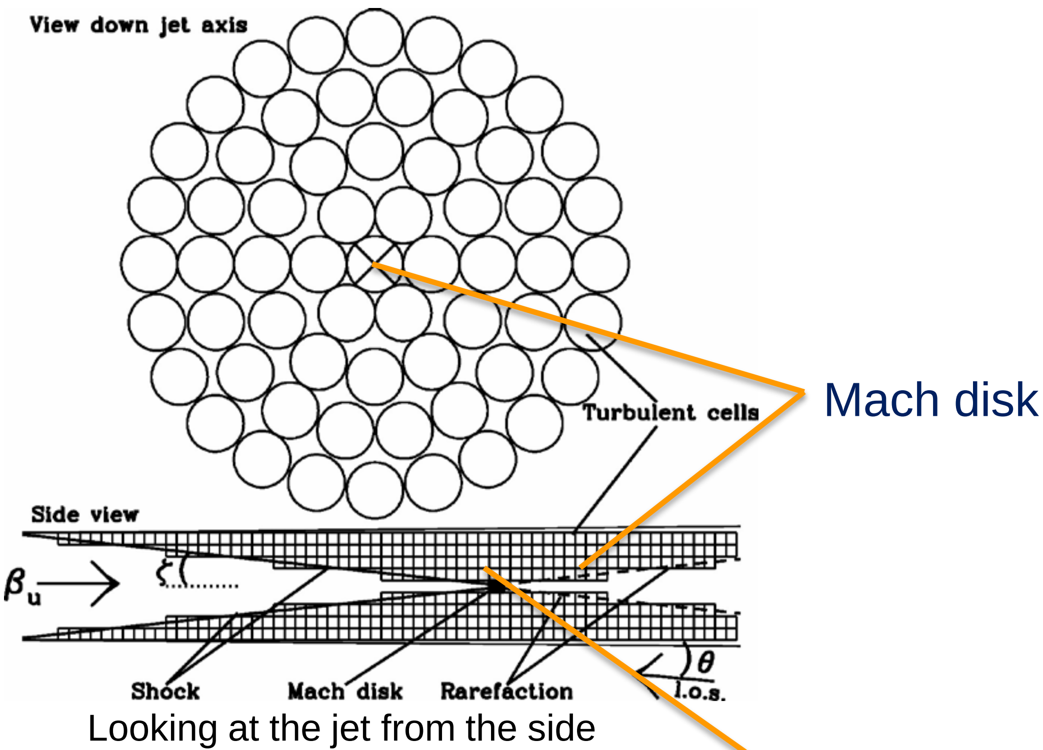


(Zhang et al. 2016)

- PA swings with PD recovering to its pre-flare level require high / moderate magnetization ($\sigma \geq 1$) - otherwise B-field is not restored to its original topology
- Significant flares require strong shocks, i.e., moderate / high shock speed and moderate / low magnetization

Proposed Alternatives

- Helical magnetic fields in a bent jet
- Helical streamlines, guided by a helical magnetic field
- Turbulent Extreme Multi-Zone Model (Marscher 2014)



Looking at the jet from the side