Spectral Variability Signatures of Diffusive Shock Acceleration in Blazars

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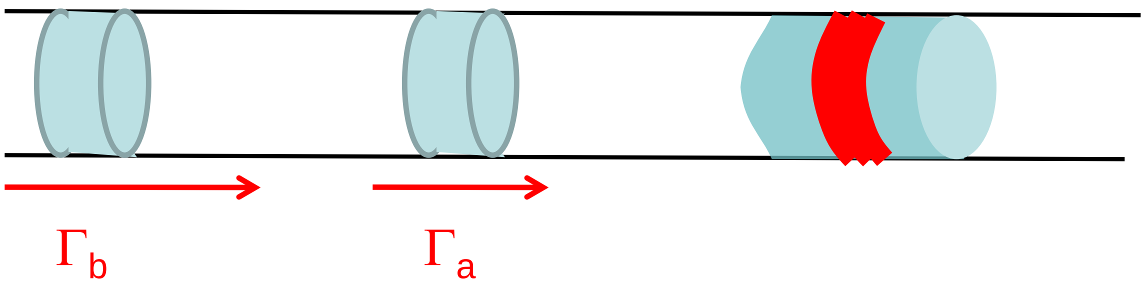
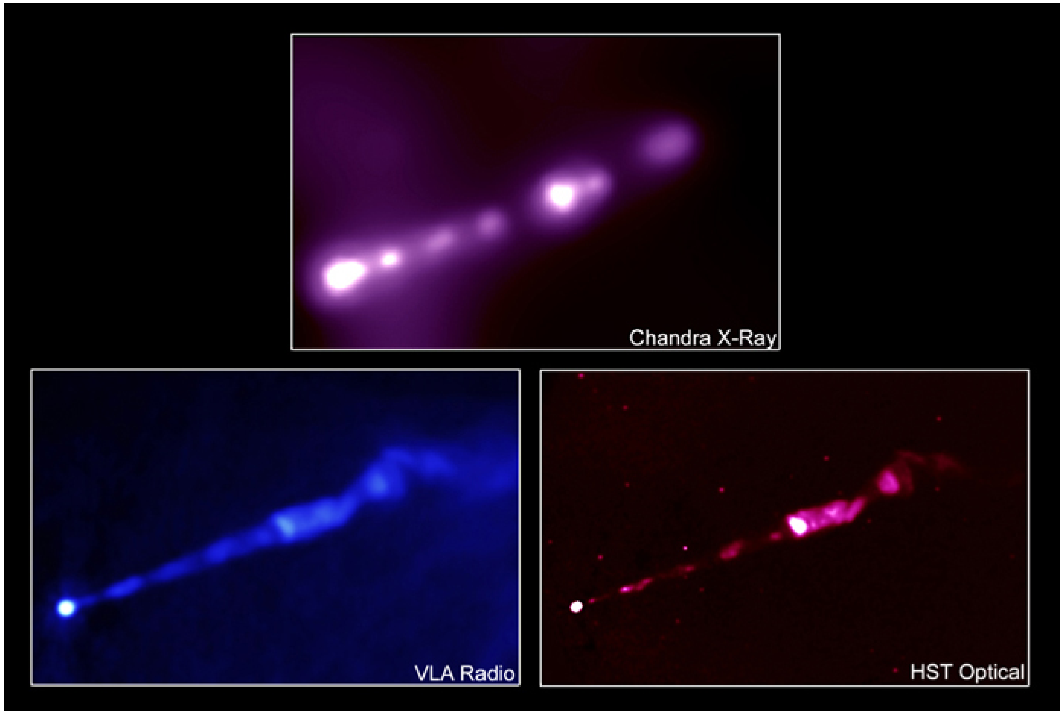
Relativistic Shocks in Jets



- Internal Shocks: likely sites of relativistic particle acceleration.
- Most likely mildly relativistic, $\beta\gamma \sim 1$
- 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".

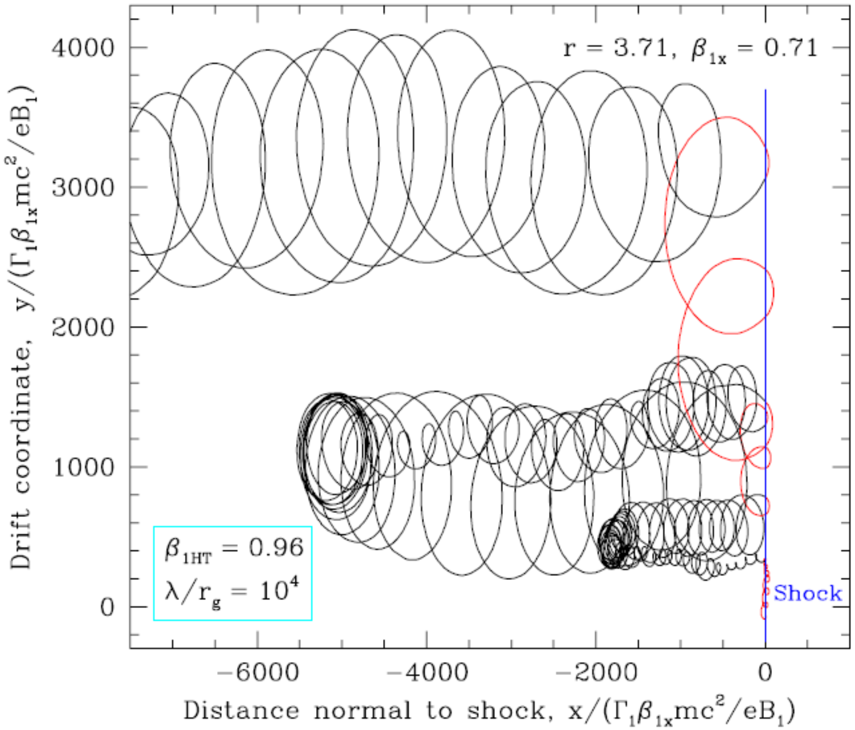


Jet of M87 at different wavelengths

Monte-Carlo Simulations of Diffusive Shock Acceleration (DSA)

- Gyration in B-fields and diffusive transport (pitch-angle diffusion) 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.

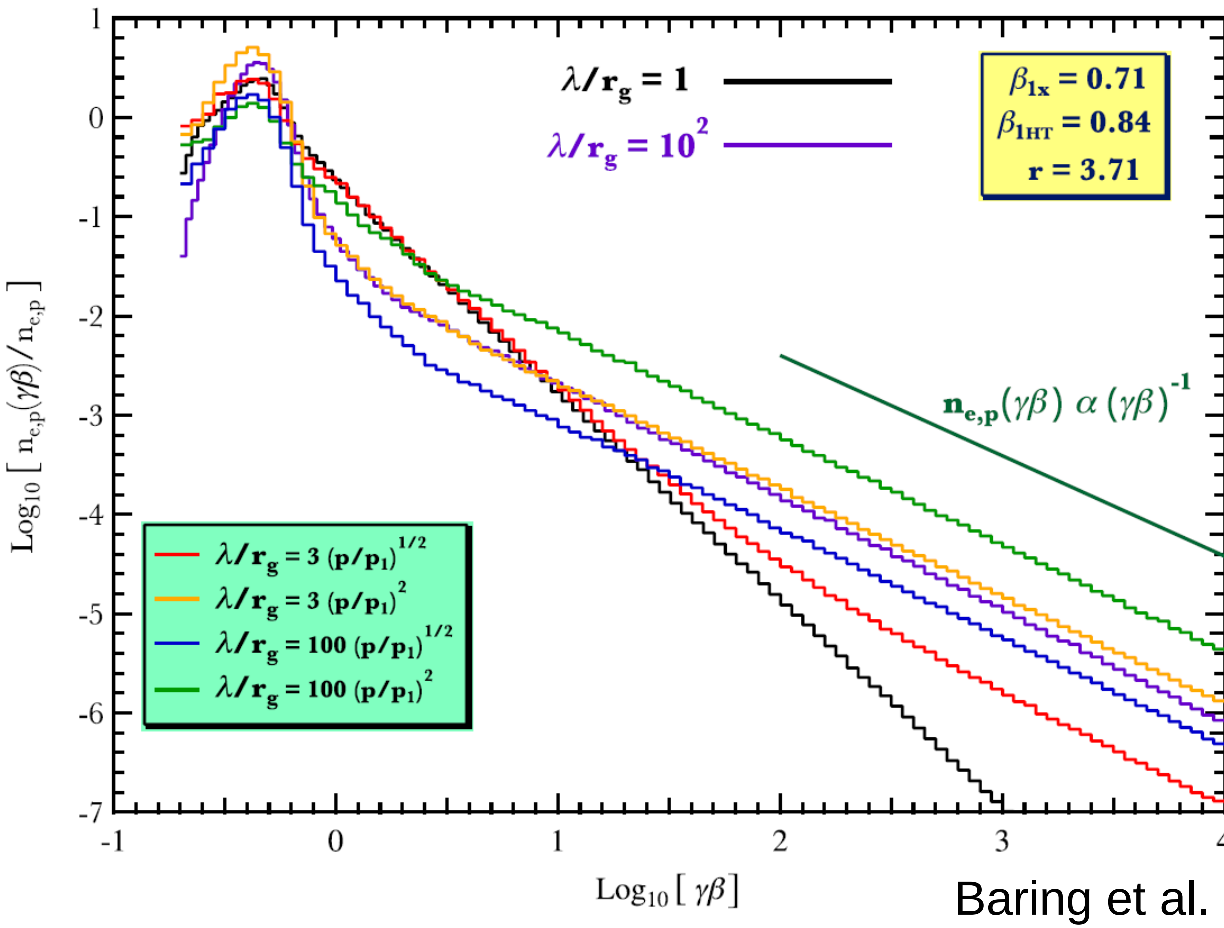


(Summerlin & & Baring 2012)

- Pitch-angle diffusion parameterized through a mean-free-path (λ_{pas}) parameter η (p):

$$\lambda_{pas} = \eta(p)*r_g = \eta_0 \, (p/p_0)^{\alpha} \qquad (\alpha \geq 1)$$

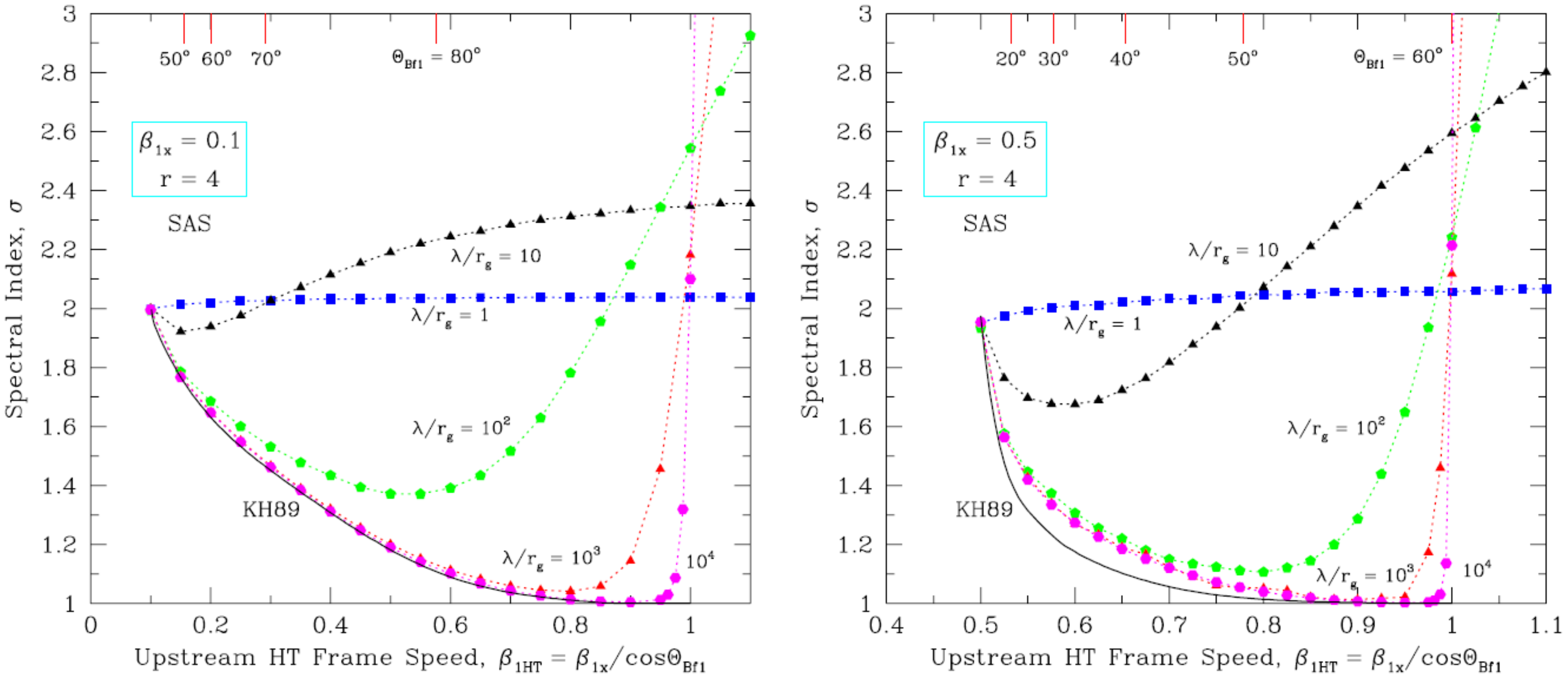
Shock Acceleration Injection Efficiencies



Baring et al. (2017)

- Non-thermal particle spectral index and thermal-to-non-thermal normalization are strongly dependent on η_0, α, and B-field obliquity!

Acceleration Indices for Oblique Shocks



(Summerlin & Baring 2012)

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

Constraints from Blazar SEDs

Synchrotron peak $\leftrightarrow \gamma_{max}$

Balance $t_{acc} \sim \eta(\gamma)\ \omega_{gyr}(\gamma)^{-1}$
with radiative cooling time scale

If synchrotron cooling dominates:

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

$\Rightarrow h\nu_{sy} \sim 100\ \delta\ [\eta(\gamma_{max})]^{-1}$ MeV (independent of B-field!)

Constraints from Blazar SEDs

$h\nu_{sy} \sim 100\ \delta\ [\eta(\gamma_{max})]^{-1}$ MeV (independent of B-field!)

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

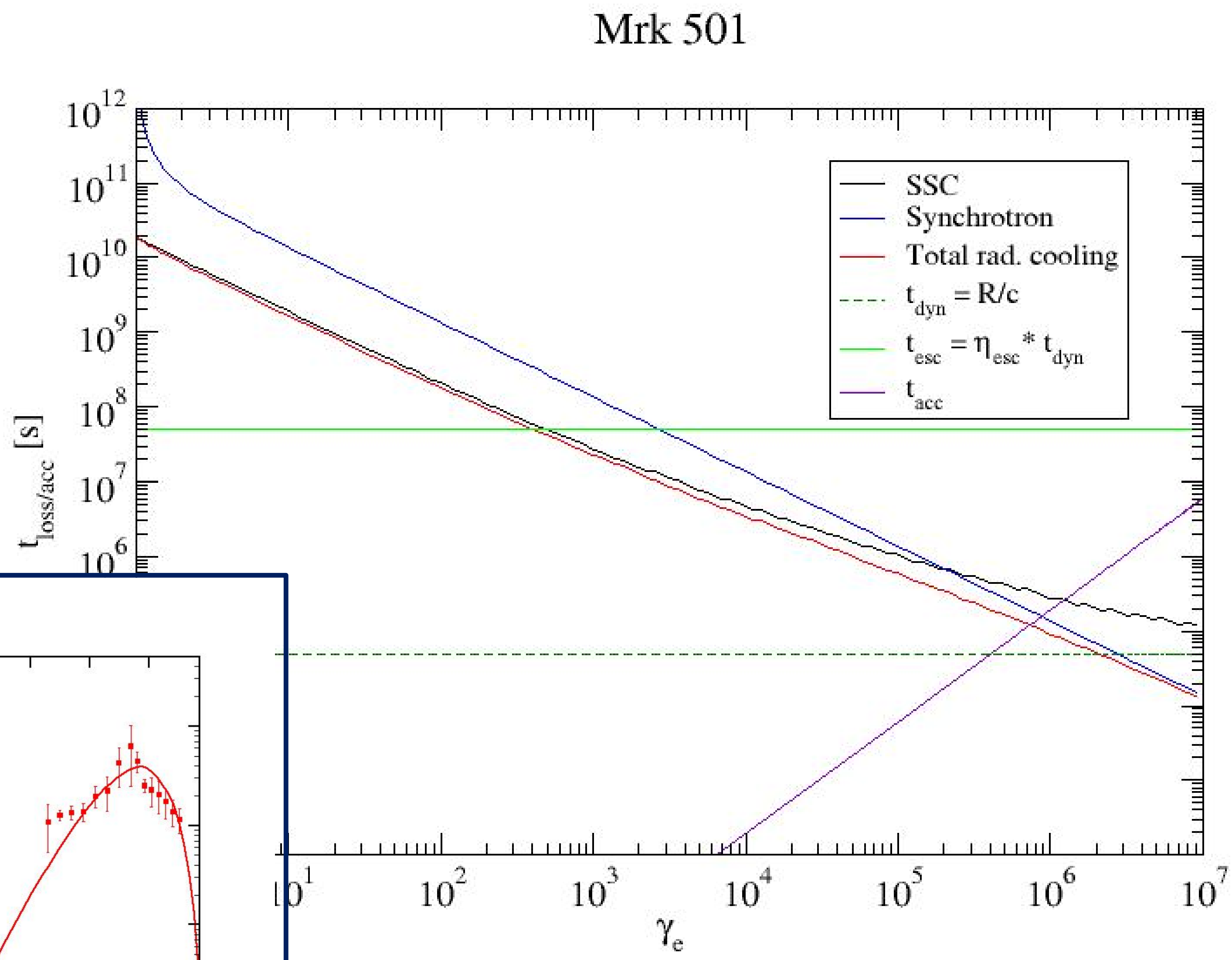
$\Rightarrow$ But: Need moderate $\eta(\gamma \sim 1)$ for efficient injection of particles into the non-thermal accelerations scheme

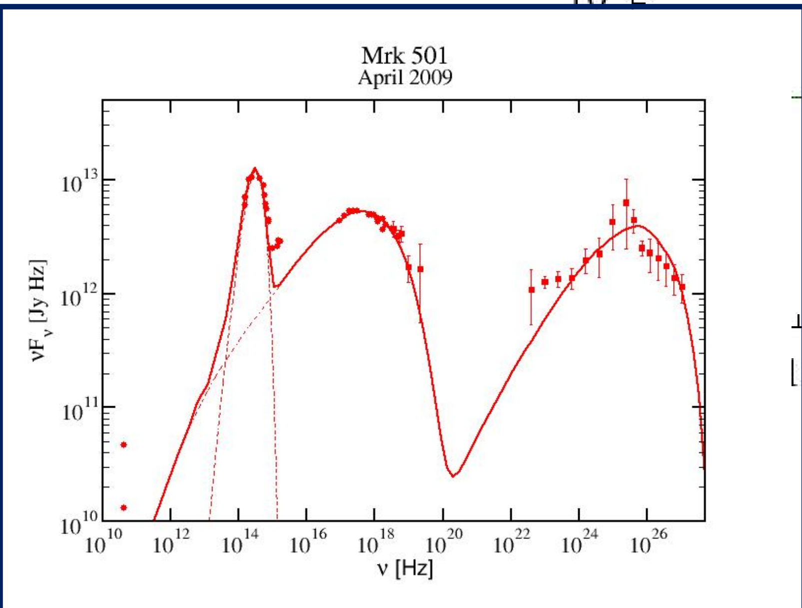
$\Rightarrow$ Need strongly energy dependent pitch-angle scattering m.f.p., with $\alpha > 1$

$\Rightarrow$ For Extreme HBLs: $\eta(\gamma)$ still small at ultra-relativistic energies

$\Rightarrow$ Effective pitch-angle scattering out to ultra-relativistic energies.

Electron Evolution Time Scales





Time-Dependent Electron Evolution with Radiative Energy Losses

Acceleration time scale:

$$t_{acc}(\gamma) = \eta\,(\gamma)\,t_{gyr} = \eta(\gamma)\,\frac{2\pi\,\gamma\,m_e\,c}{eB} \ll t_{cool}, t_{dyn}$$

For almost all electrons

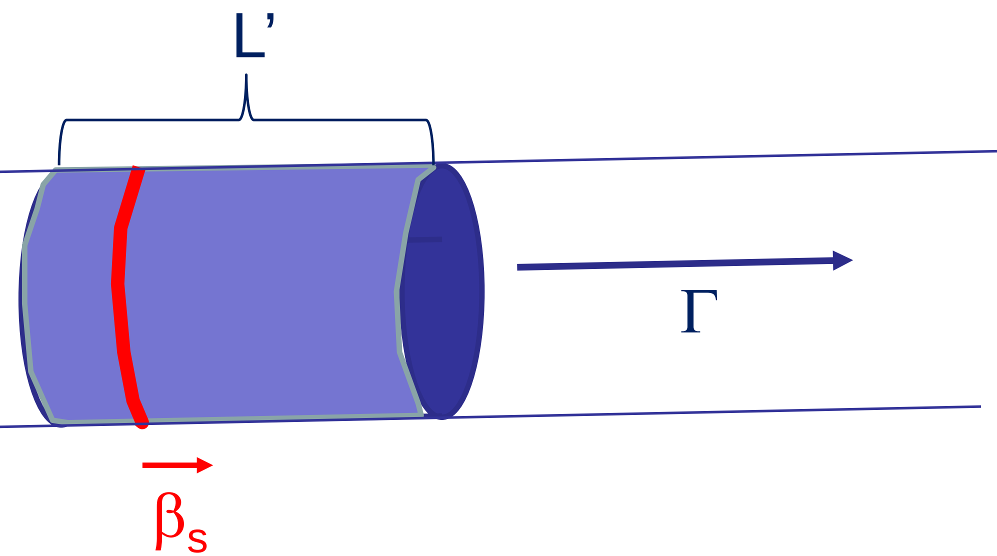
$\Rightarrow$ Use shock-accelerated electron spectrum as instantaneous injection $Q_e(\gamma)$;

$\Rightarrow$ Solve Fokker-Planck Equation for electrons:

$$\frac{\partial n_e\,(\gamma,t)}{\partial t} = - \frac{\partial}{\partial \gamma}\,(\dot{\gamma}\,n_e) + Q_e\,(\gamma,t) - \frac{n_e\,(\gamma,t)}{t_{esc,e}}$$

Numerical Scheme

- Injection spectra from turbulence characteristics + MC simulations of DSA
- Injection from small acceleration zone (shock) into larger radiation zone
- Time-dependent leptonic code based on Böttcher & Chiang (2002),
- Radiative processes:
  - Synchrotron
  - Synchrotron self-Compton (SSC)
  - External Compton (EC: dust torus + BLR + direct accretion disk)



Shock injection "on" for $0 < \Delta t' < L'/v'_s$

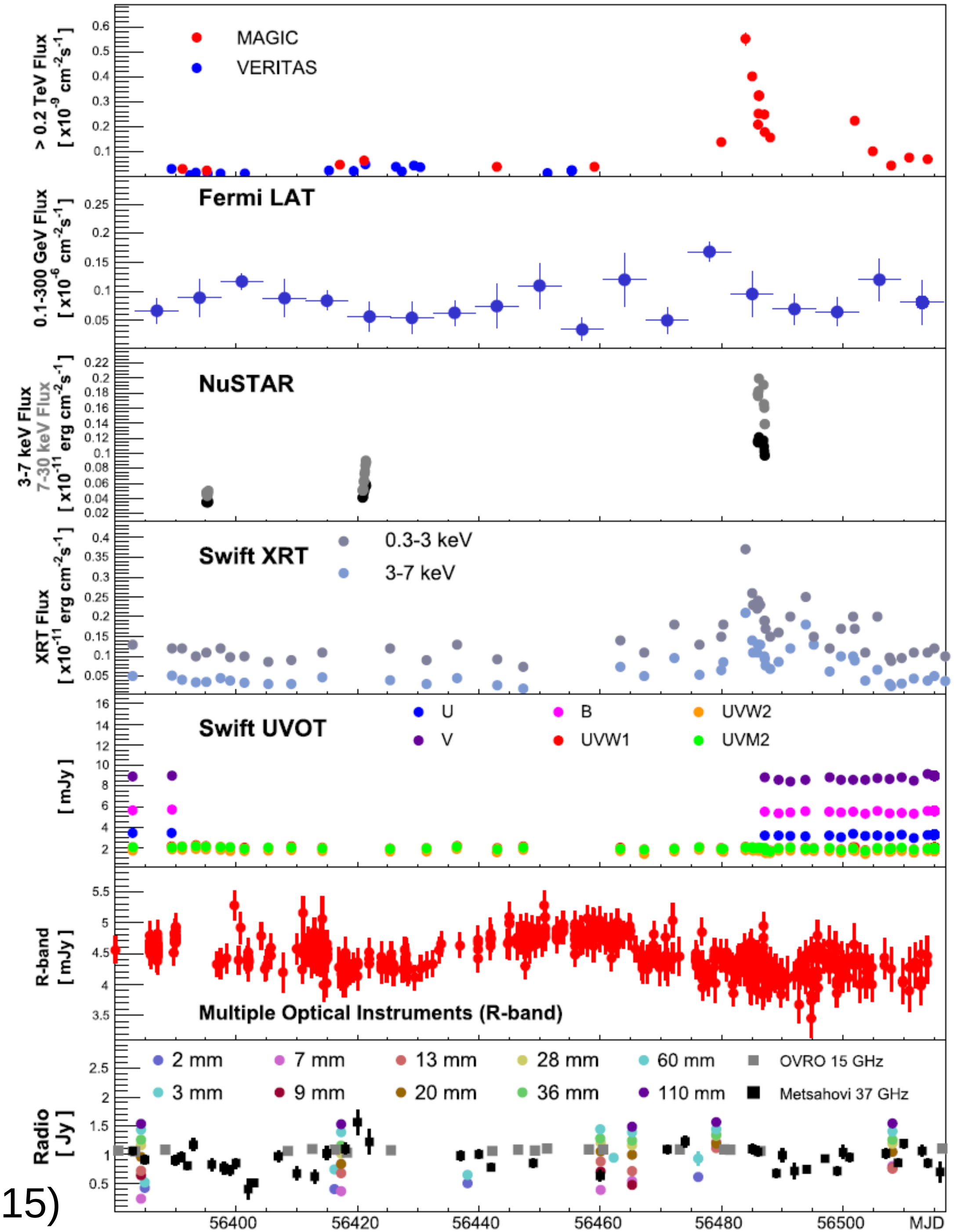
$$Q_{e,s}(\gamma,t') = Q_{e,s}(\gamma)\, H(t';\, 0,\, \Delta t')$$

Example: HBL Mrk 501

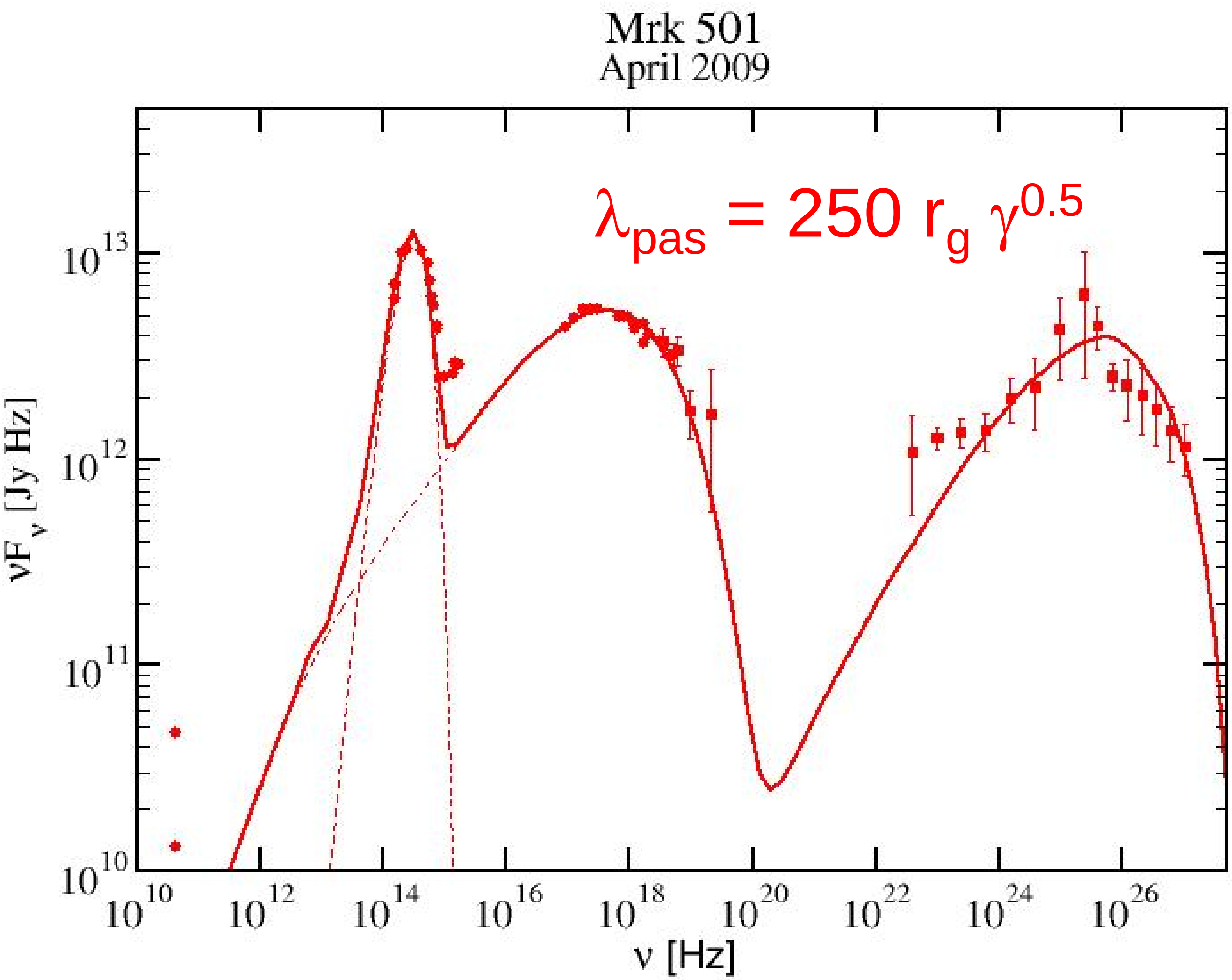
Prototypical TeV BL Lac object (with Mrk 421)

Typical flare durations ~ minutes – a few hours

(Furniss et al. 2015)



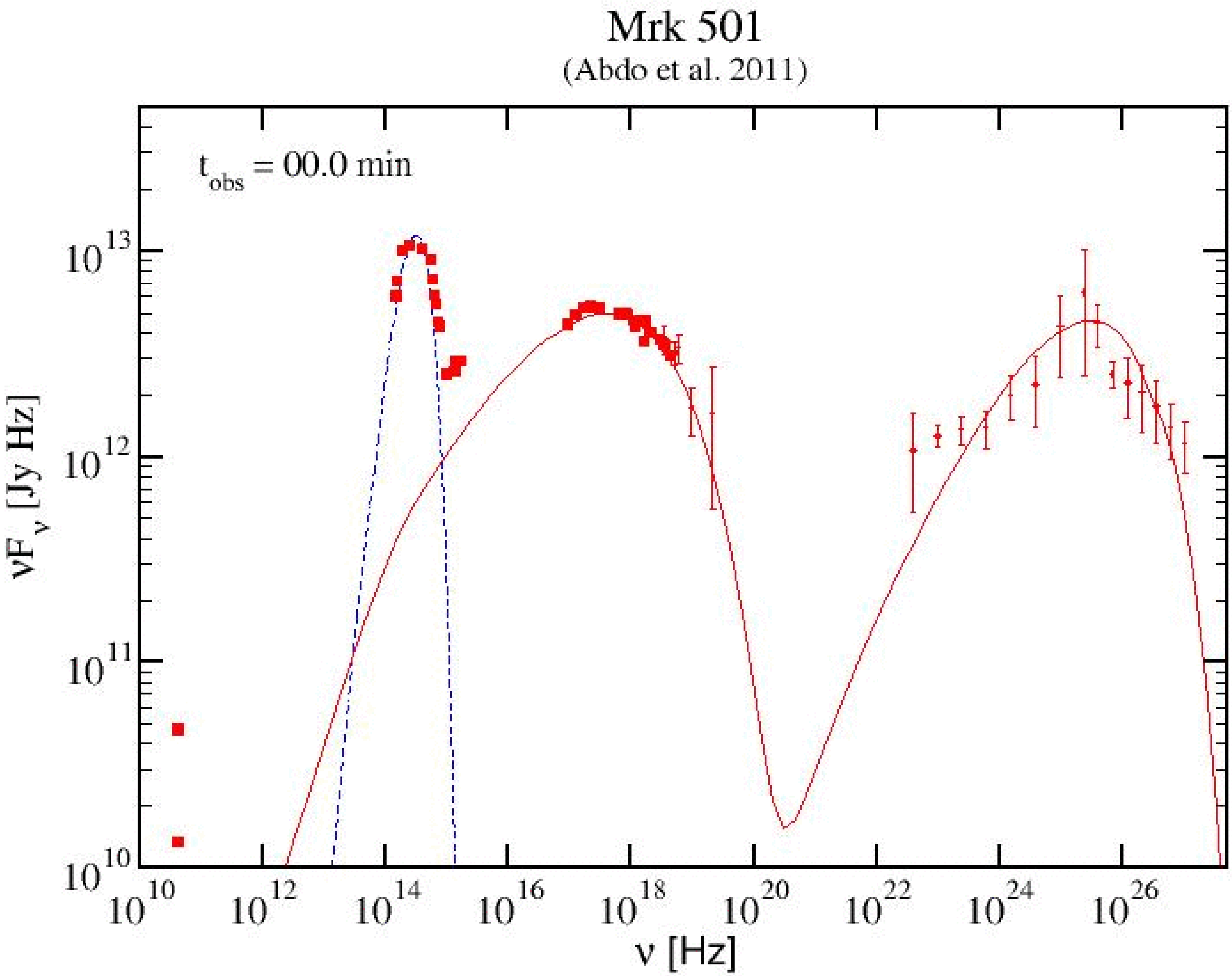
Example: HBL Mrk 501



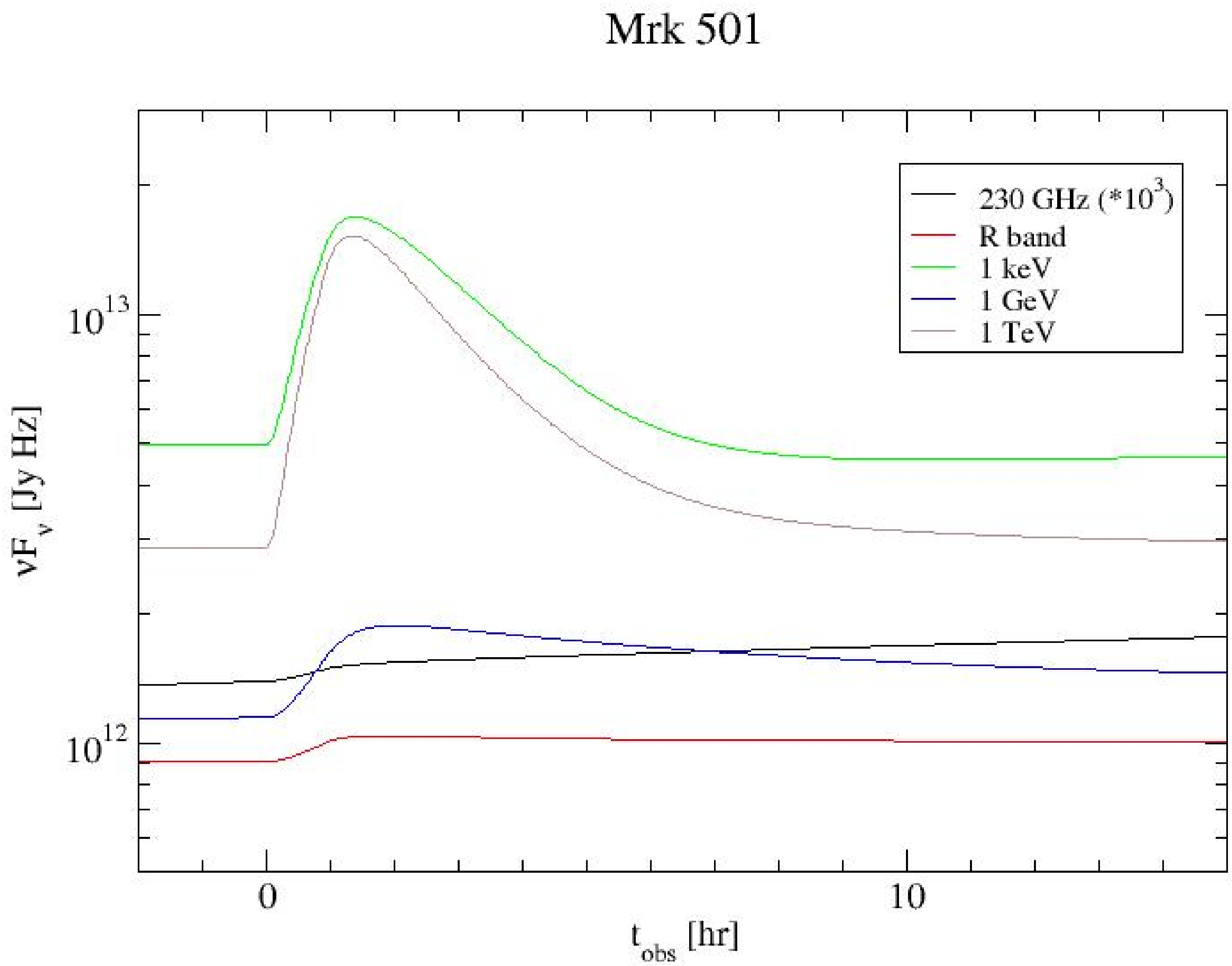
Baring et al. (2017, MNRAS)

B = 0.075 G
δ = 30
R = 1.5×10^{15} cm
-> $\Delta t' \sim 10^5$ s
-> $\Delta t_{obs} \sim 1$ h

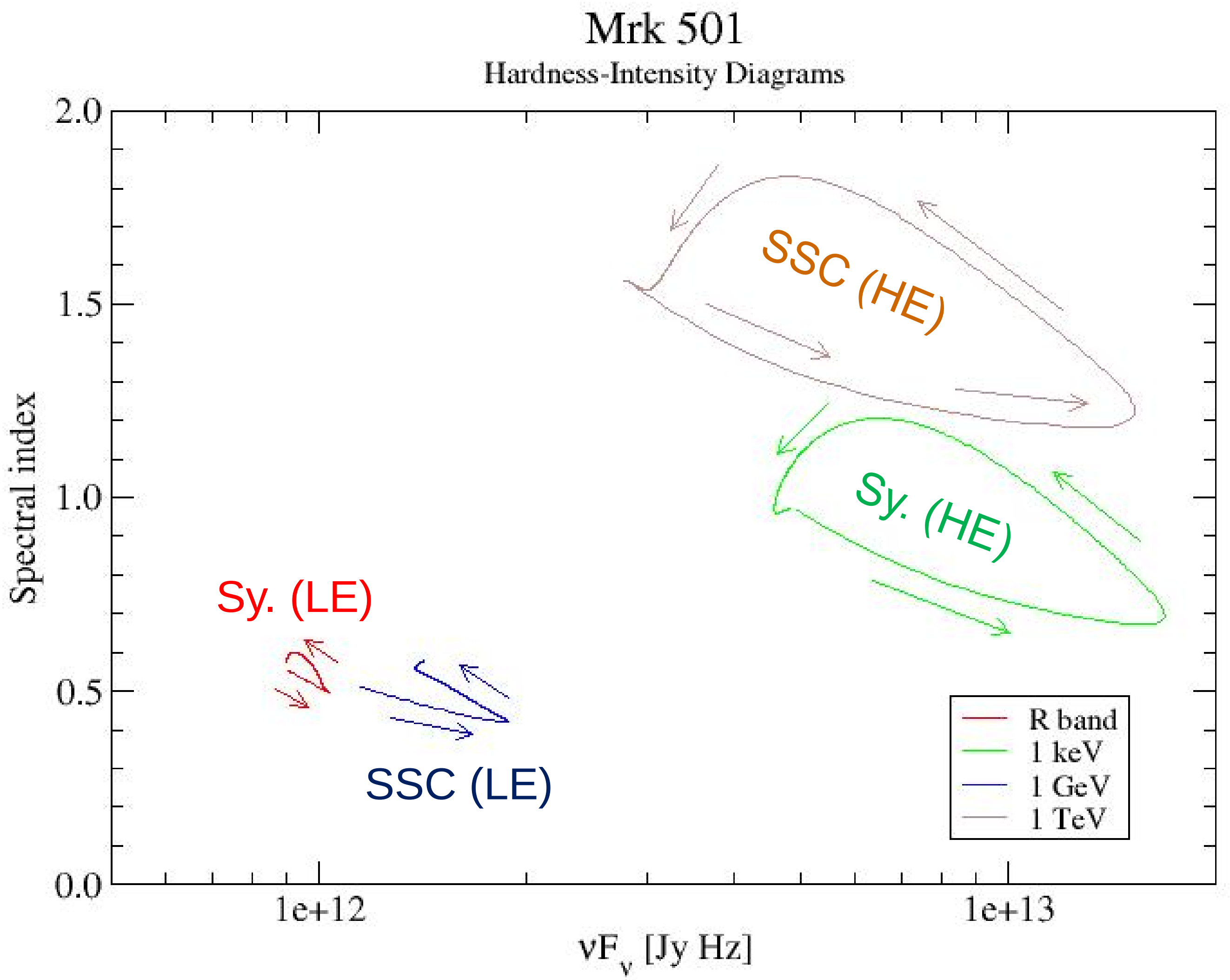
HBL Mrk 501 Flare Spectral Evolution



Model Light Curves

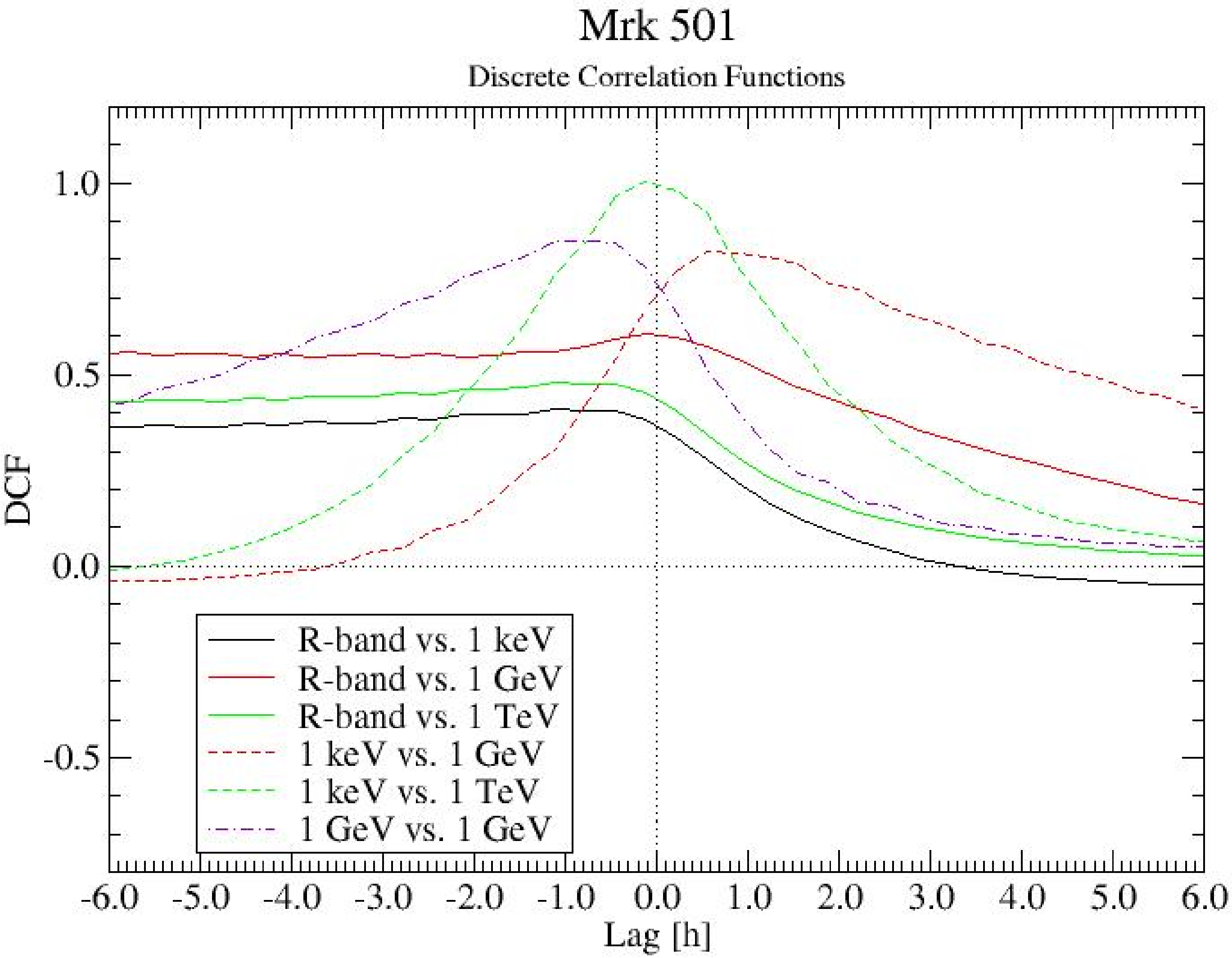


Hardness-Intensity Diagrams



Counter-clockwise spectral hysteresis, as expected if $t_{acc} << t_{cool}, t_{dyn}$

Discrete Correlation Functions



- Optical poorly correlated with other bands
- Strong (~ 0 lag) correlation between X-rays and VHE
- Correlation between X-rays and GeV γ-rays (X-rays lead by ~ 1 hr)
- Correlation between GeV and TeV (TeV leads by ~ 1 hr)

Summary

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

2. Time-dependent simulations of shock-in-jet model with realistic particle injection from diffusive shock acceleration:

3. Characteristic counter-clockwise spectral hysteresis in all spectral bands.

4. Extreme HBLs indicate effective pitch-angle scattering out to ultra-relativistic energies.

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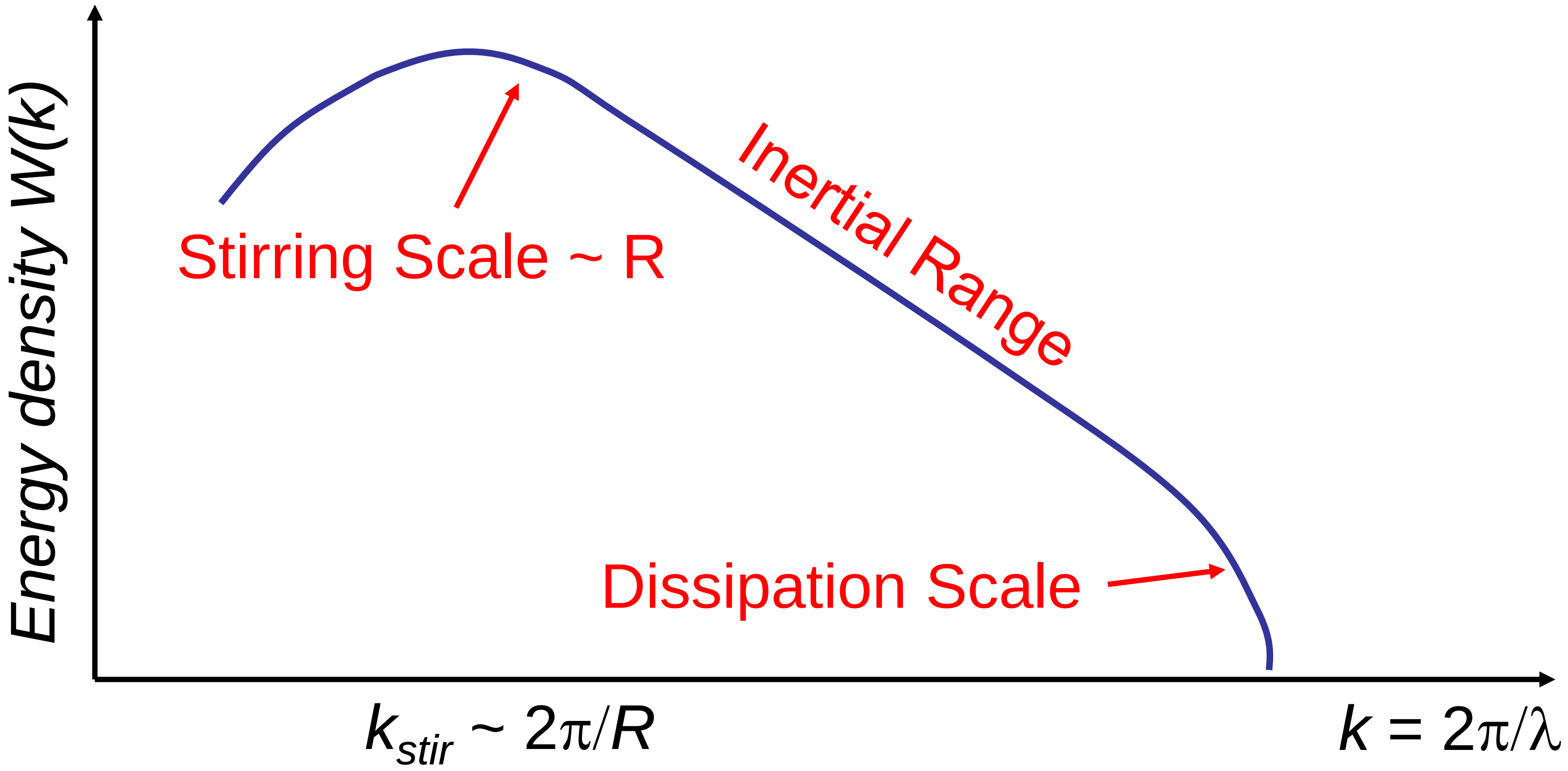
Backup Slides

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

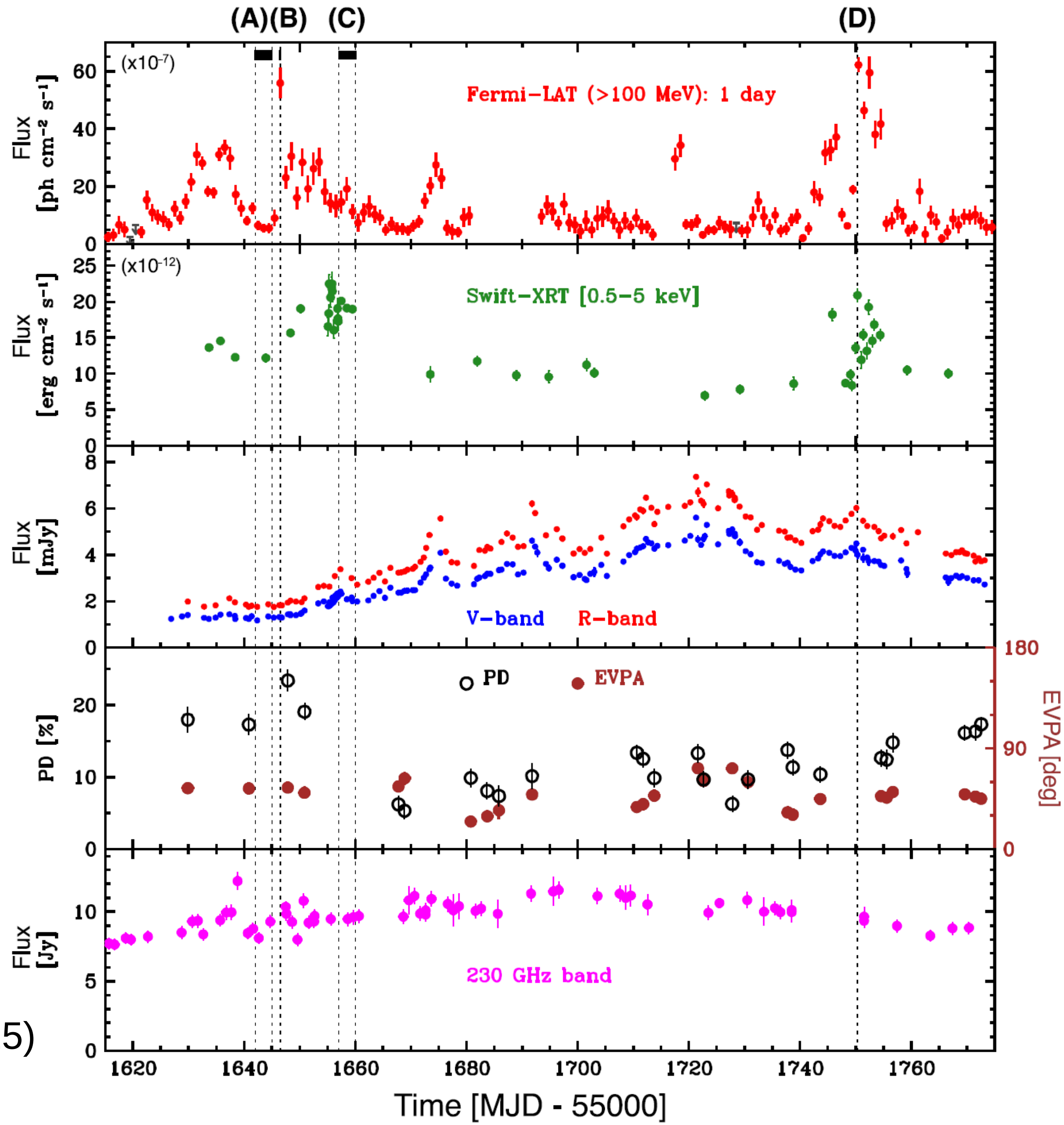
$\Rightarrow$ Large λ_{pas}

Example: FSRQ 3C279

Extended flaring period 2013 – 2014

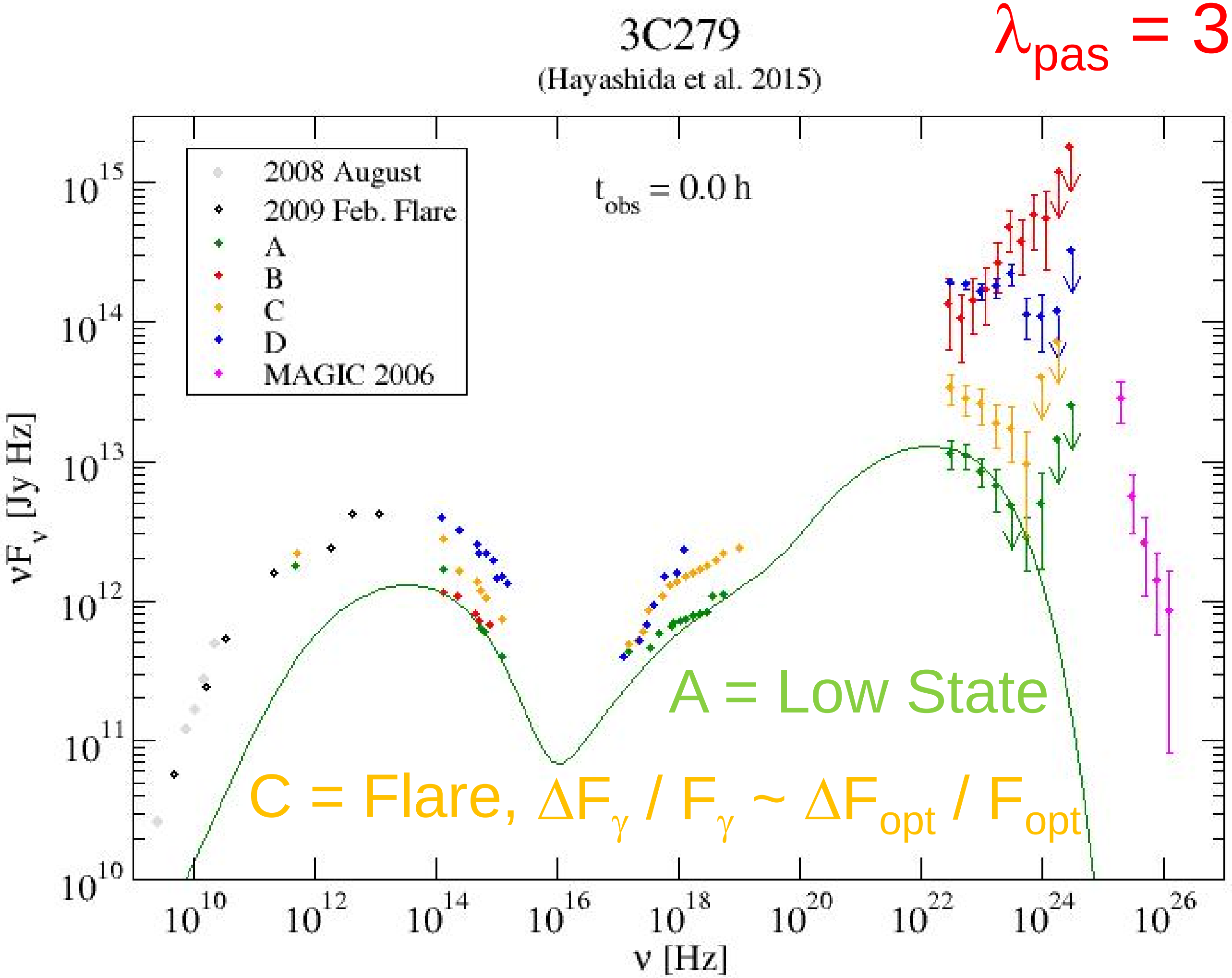
Variability time scale ~ 1 day

(Hayashida et al. 2015)



Example: FSRQ 3C279 (2013 – 2014)

$\lambda_{pas} = 300\ r_g\ \gamma^2$



A = Low State

C = Flare, $\Delta F_\gamma / F_\gamma \sim \Delta F_{opt} / F_{opt}$

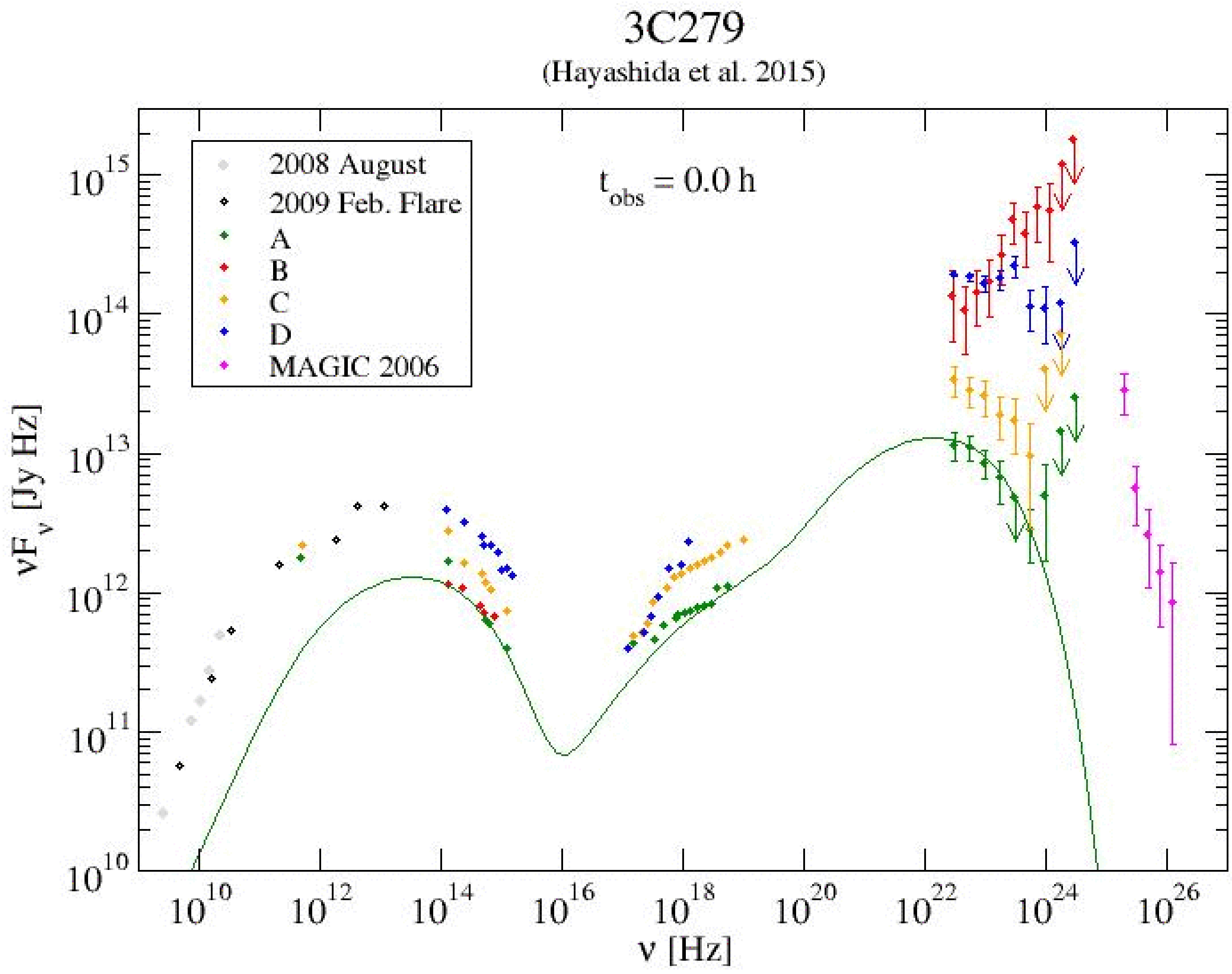
B = 0.65 G
δ = 15
R = 1.8×10^{16} cm
$\rightarrow \Delta t' \sim$ few$\times 10^5$ s
$\rightarrow \Delta t_{obs} \sim$ few hr

γ-rays EC (Dust Torus) dominated:

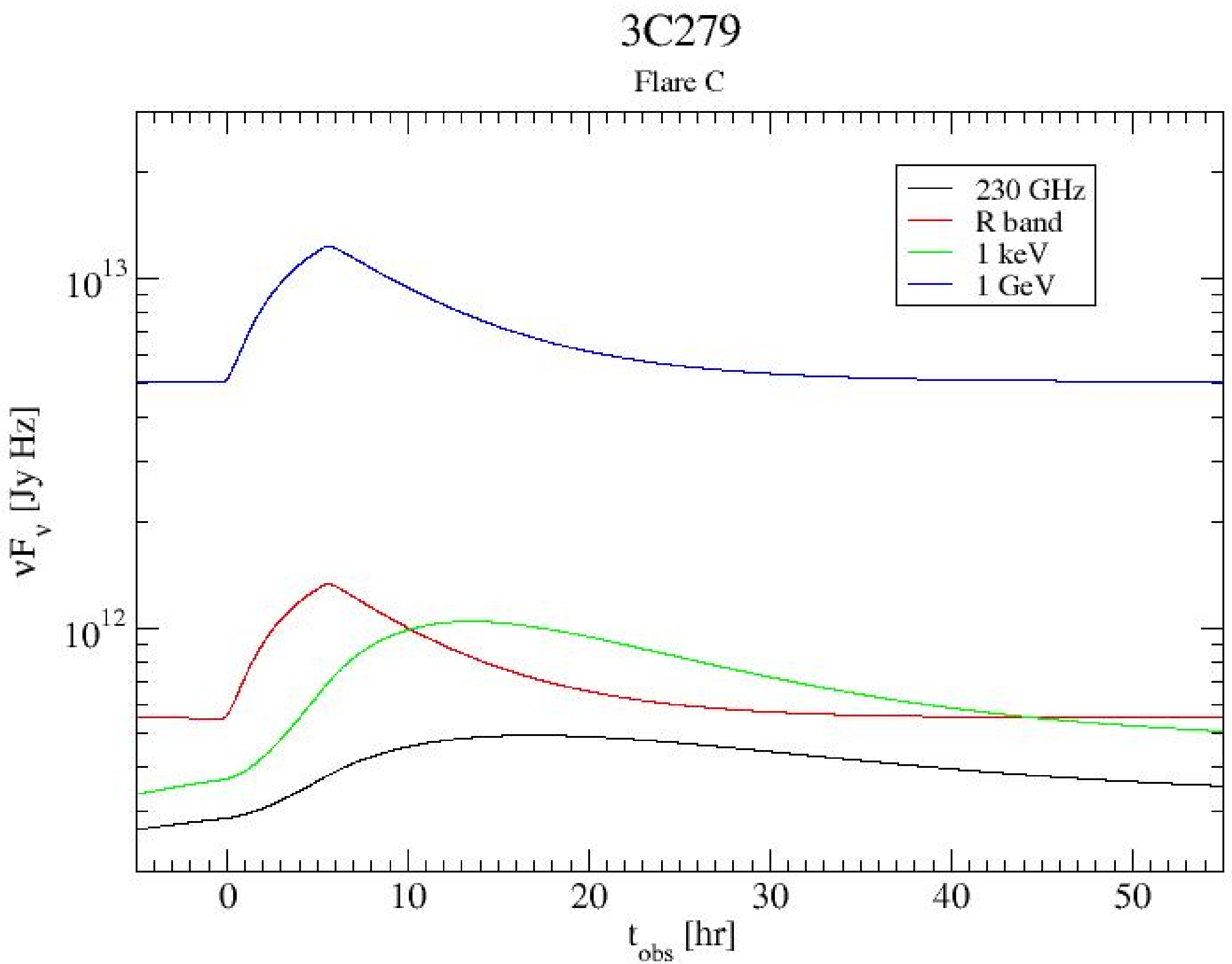
u = 4×10^{-4} erg/cm^3
T_{BB} = 300 K

Note: Flares with strongly increasing Compton dominance would require additional parameter changes.

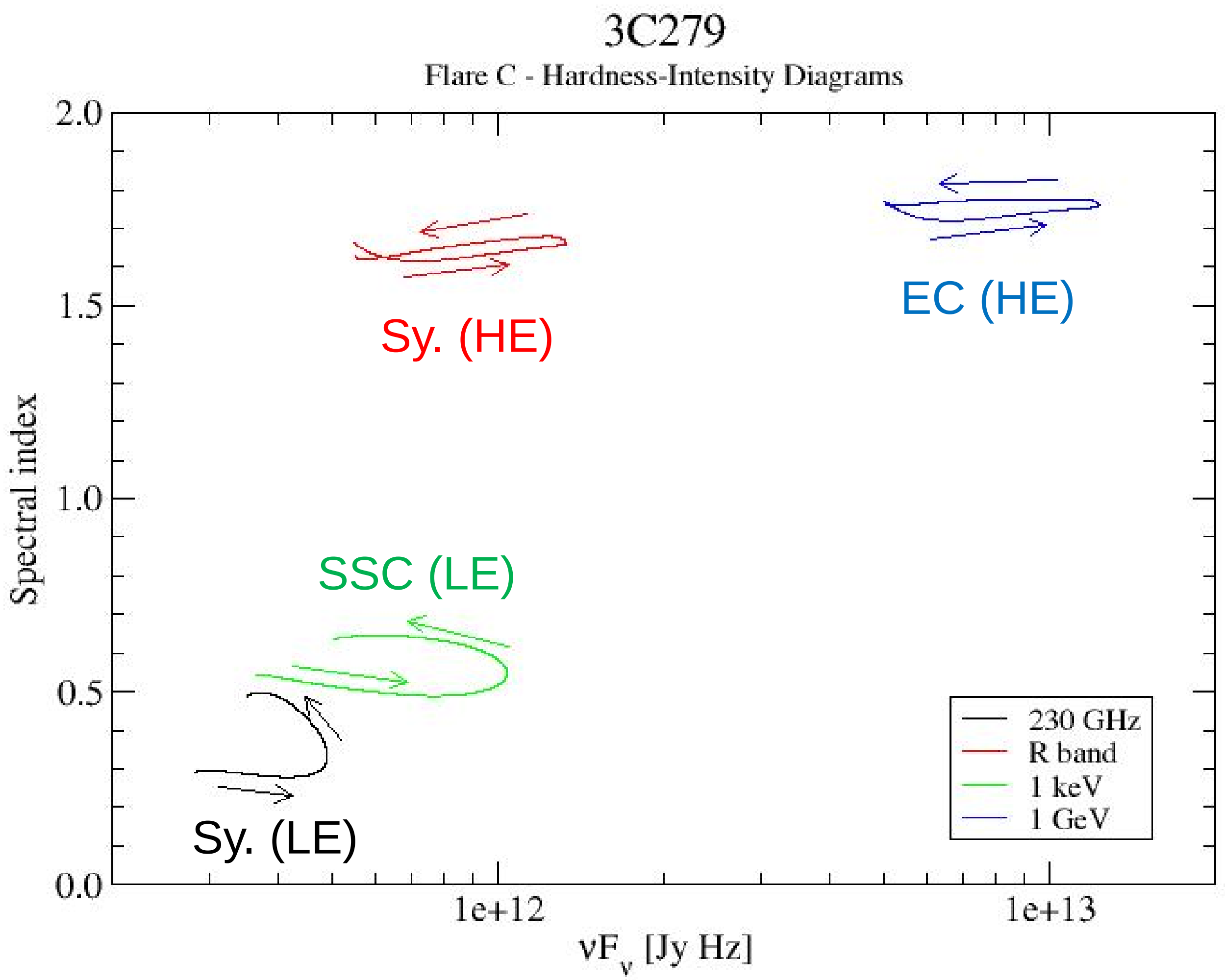
3C279 – Flare C



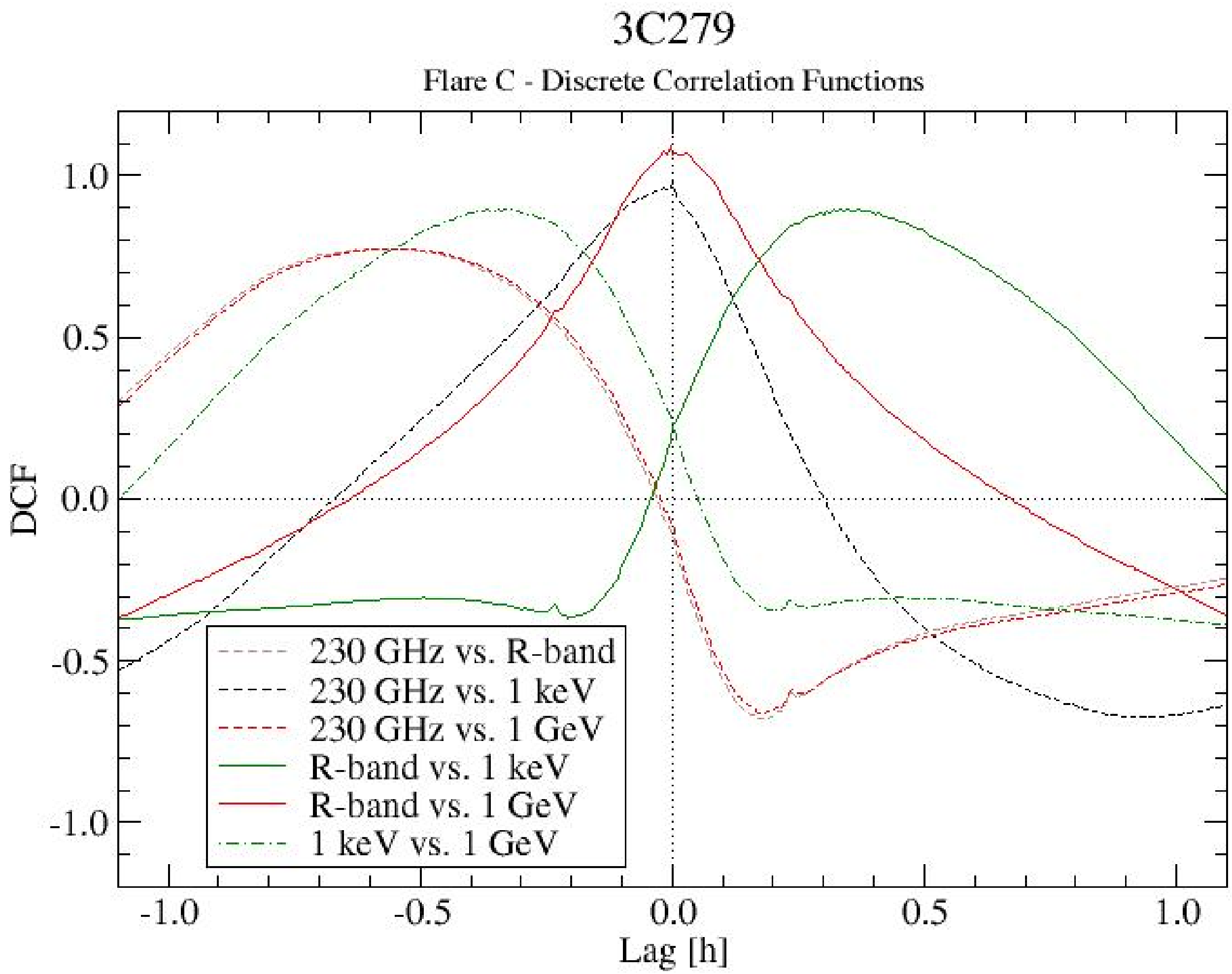
3C279 – Flare C
Model Light Curves



3C279 – Flare C
Hardness-Intensity Diagrams



3C279 – Flare C
Discrete Correlation Functions



- Optical and γ-rays well correlated (0 lag)
- X-rays and radio well correlated (0 lag)
- X-rays and radio lag optical + γ-rays by ~ ½ hr)