A Shock-in-Jet Synchrotron Mirror Model for Blazars

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Relativistic Shocks in Jets

- Internal Shocks: likely sites of relativistic particle acceleration.

- Most likely mildly relativistic, $\beta\gamma \sim 1$

- Efficient Diffusive Shock Acceleration at mildly relativistic, oblique shocks produces relativistic, non-thermal electron distributions which can be as hard as $n_e(\gamma) \sim \gamma^{-1}$, depending on B-field obliquity and efficiency of pitch-angle scattering.

- Key parameter: Mean free path for pitch-angle scattering:

$$\lambda_{pas} = \eta_1 \, r_g(p) \, p^{\alpha-1}$$

Jet of M87 at different wavelengths

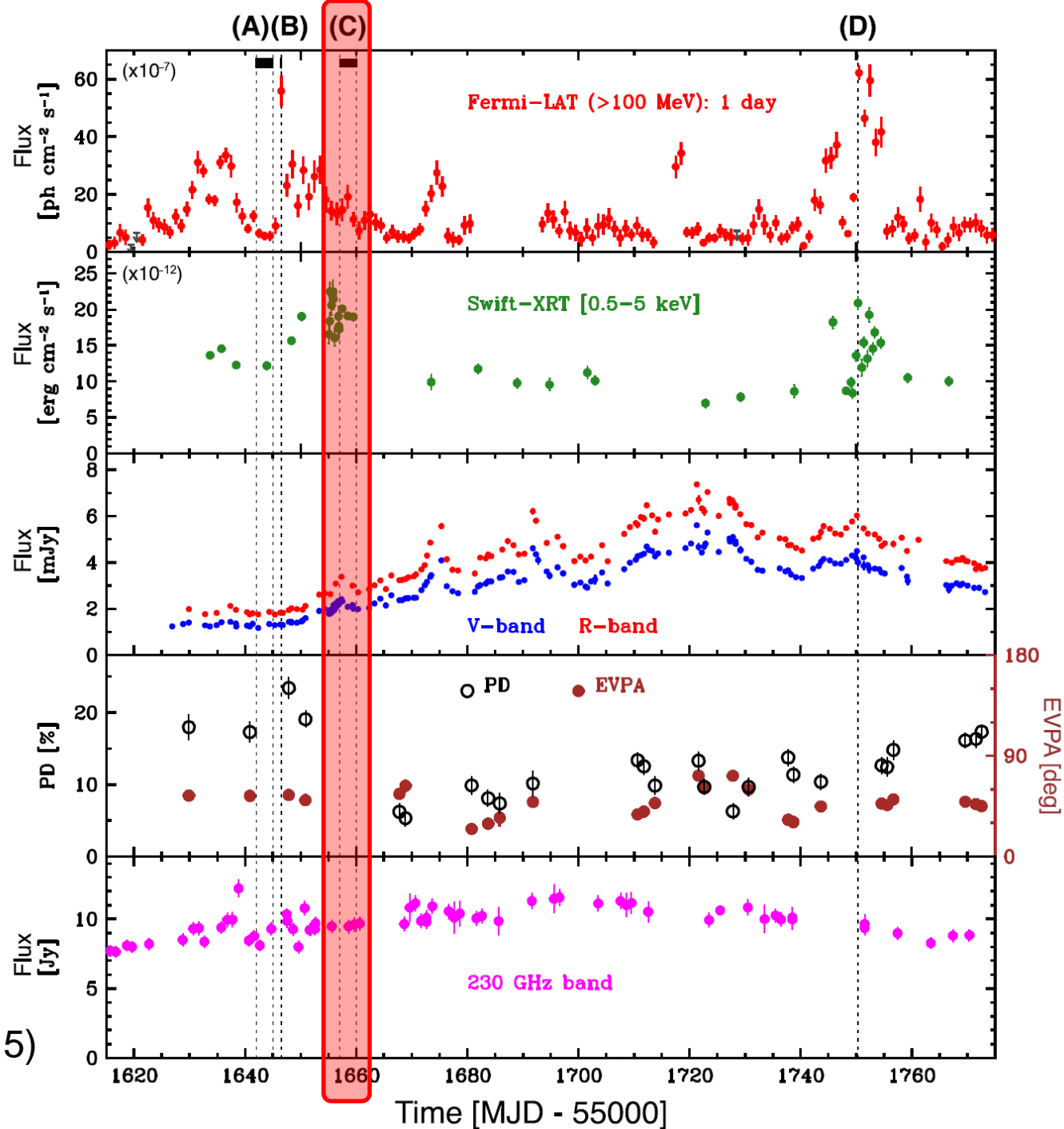Chandra X-Ray

VLA Radio

HST Optical
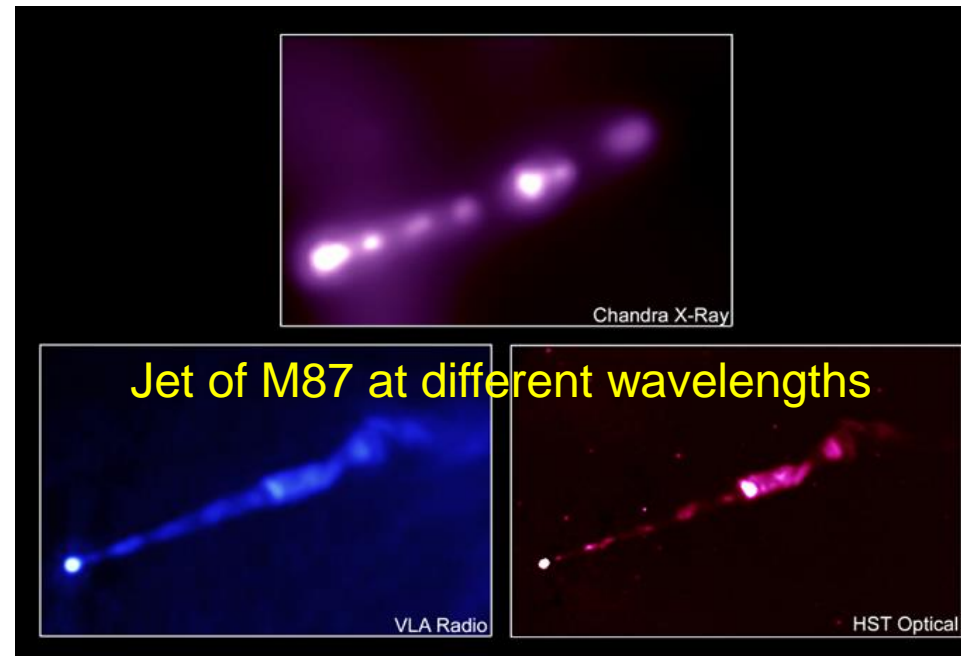
Example: FSRQ 3C279

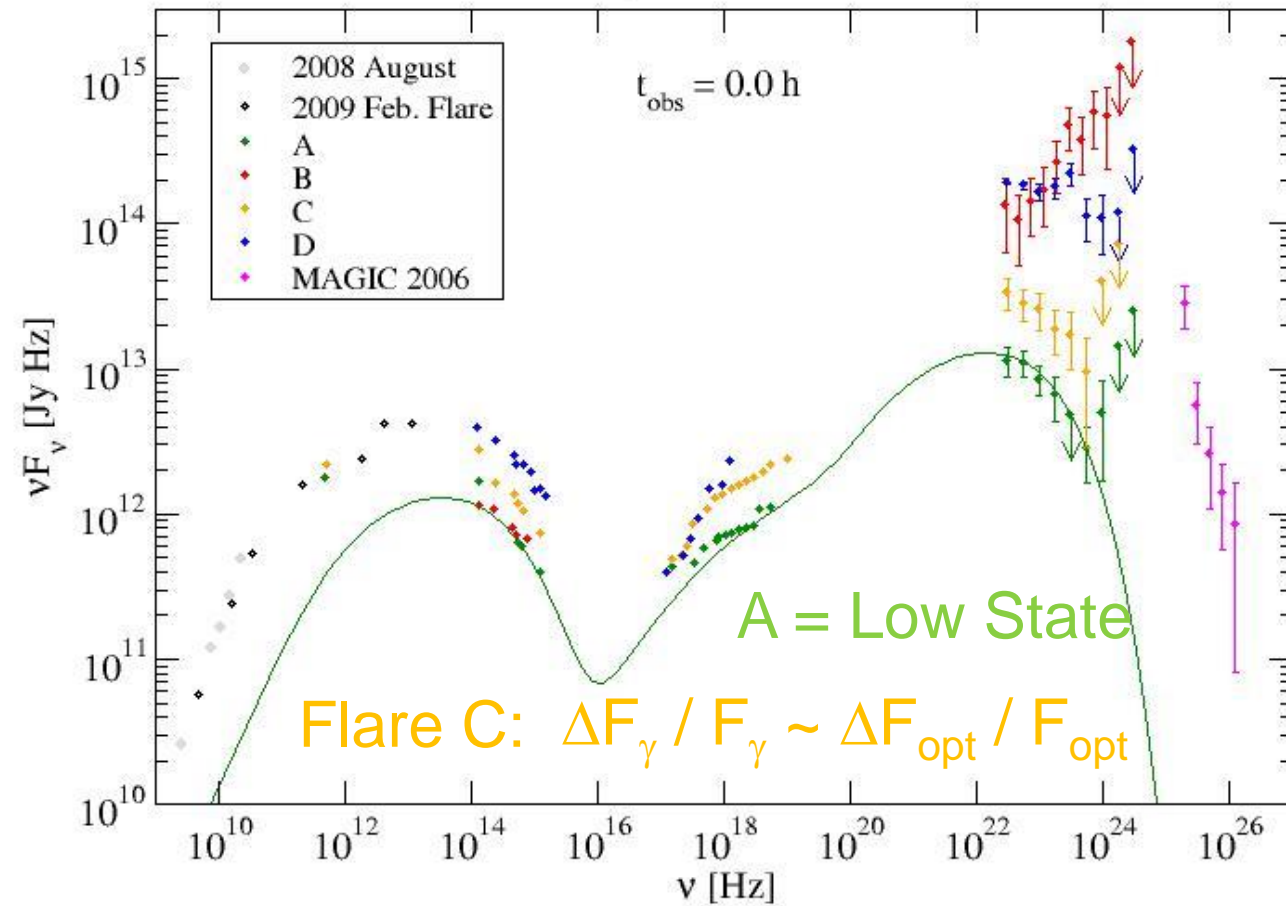Extended flaring period 2013 – 2014

Variability time scale ~ 1 day

(Hayashida et al. 2015)

Example: FSRQ 3C279 (2013 – 2014)

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

3C279
(Hayashida et al. 2015)

$t_{obs} = 0.0$ h

Legend:
- 2008 August
- 2009 Feb. Flare
- A
- B
- C
- D
- MAGIC 2006

A = Low State

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

y-axis: νF_ν [Jy Hz]
x-axis: ν [Hz]

(Böttcher & Baring 2019)

$\eta_1 = 300$
$\alpha = 3$
$B = 0.65$ G
$\delta = 15$
$R = 1.8*10^{16}$ cm
$\rightarrow \Delta t' \sim$ few$*10^5$ 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

3C279 – Flare C

3C279
Flare C - SEDs
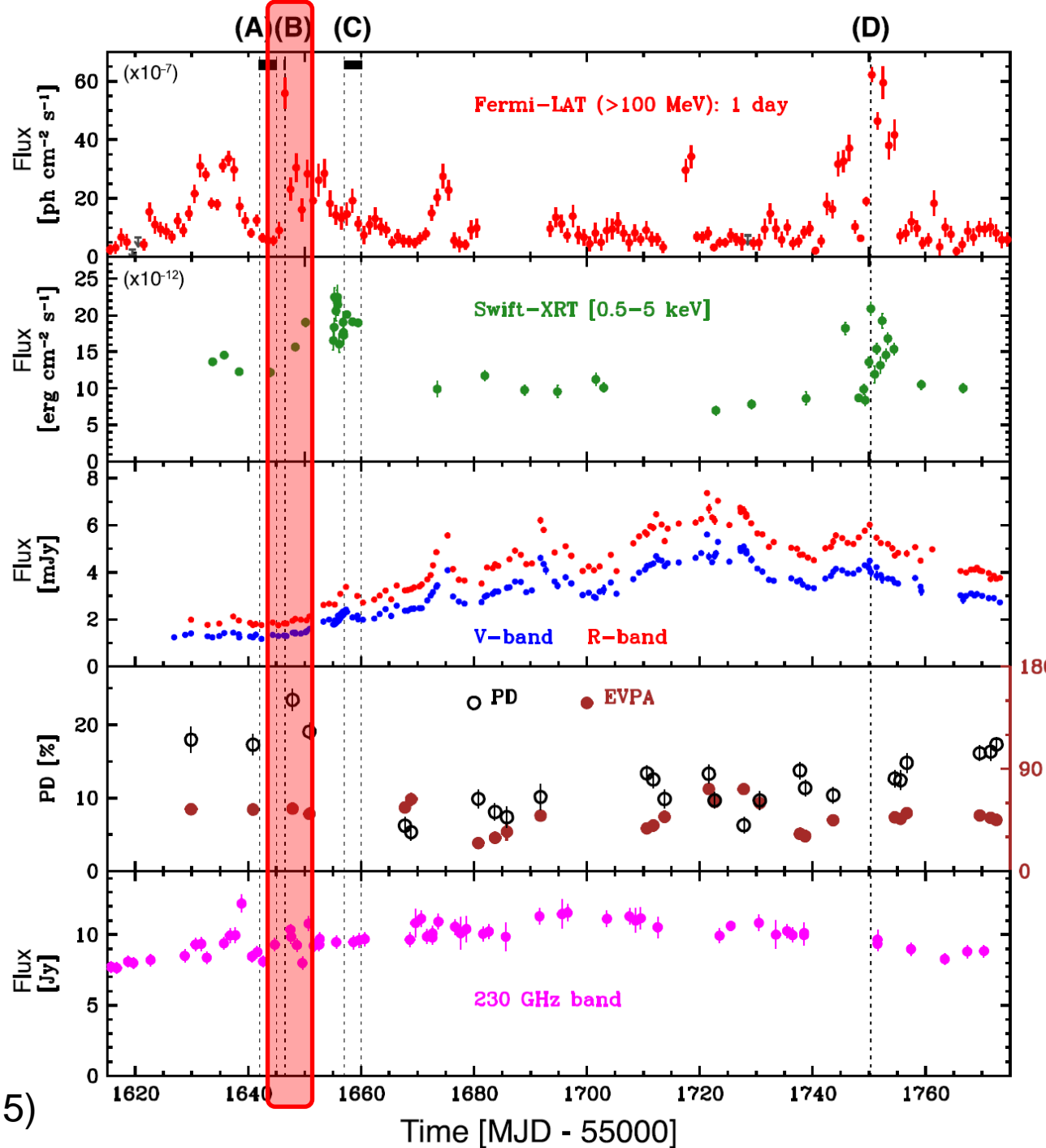
Flare modeled with

$L_{inj} = 1.1 \times 10^{43}$
$\rightarrow 5.0 \times 10^{43}$ erg/s

(Böttcher & Baring 2019)

Example: FSRQ 3C279

Flare B
(December 2013):
Orphan γ-ray flare

(Hayashida et al. 2015)
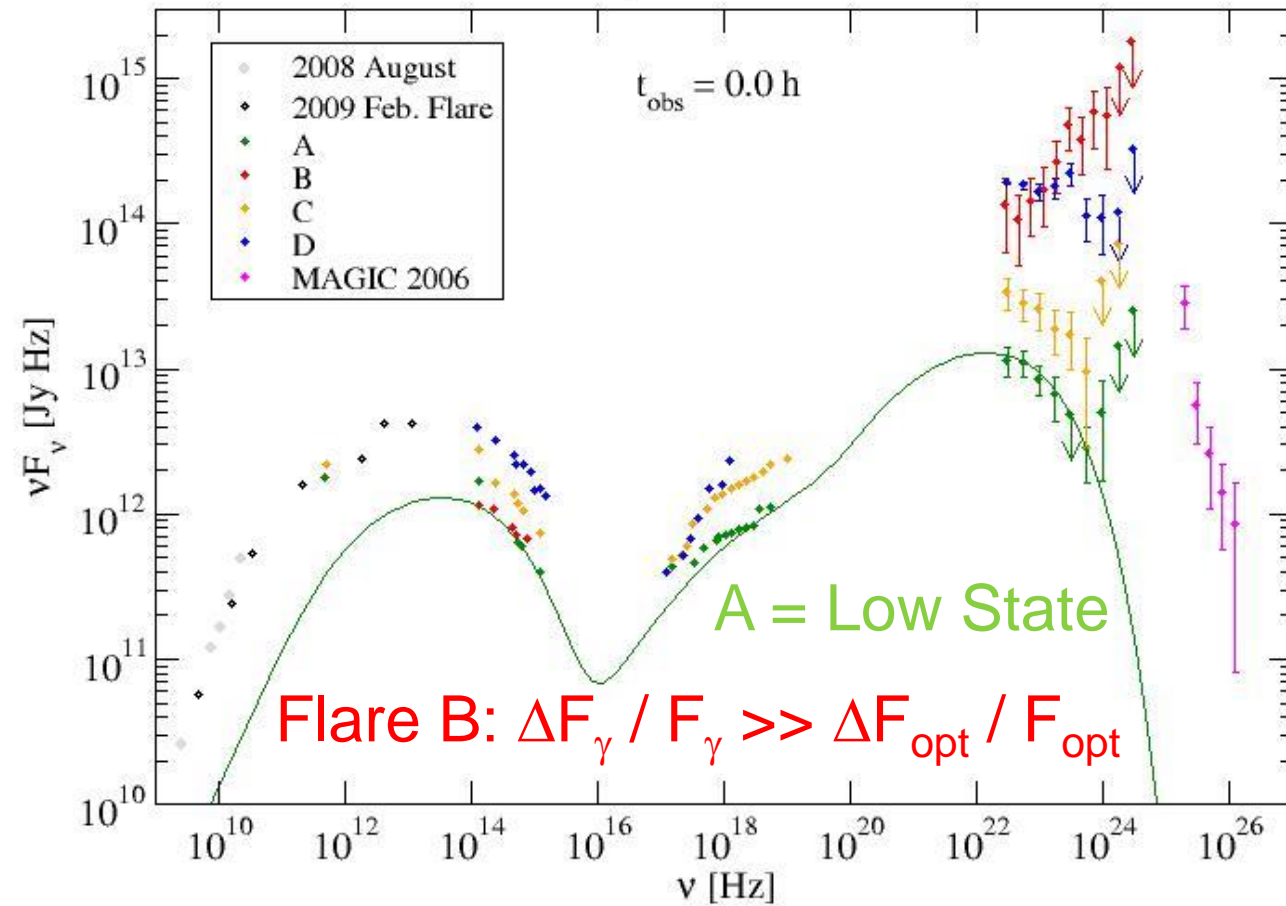
Example: FSRQ 3C279 (2013 – 2014)

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

3C279
(Hayashida et al. 2015)

$t_{obs} = 0.0$ h

A = Low State

Flare B: $\Delta F_\gamma / F_\gamma >> \Delta F_{opt} / F_{opt}$

Legend:
- 2008 August
- 2009 Feb. Flare
- A
- B
- C
- D
- MAGIC 2006

Axis labels: νF_ν [Jy Hz] vs ν [Hz]

$\eta_1 = 300$
$\alpha = 3$
B = 0.65 G
$\delta = 15$
R = $1.8 * 10^{16}$ cm
$\rightarrow \Delta t' \sim$ few$*10^5$ 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

(Böttcher & Baring 2019)

3C279 – Flare B

3C279
Flare B - SEDs

Legend:
- 2008 August
- 2009 Feb. Flare
- A
- B
- C
- D
- MAGIC 2006

- 0.5 h (dotted)
- 1.4 h (dashed)
- 2.8 h (dash-dot)
- 5.2 h (solid)
- 13.5 h (dash-dot)
- 20.2 h (dash-dot)
- 27.6 h (dash-dot-dot)
- 42.7 h (dash-dot)

Axes: νF_ν [Jy Hz] vs ν [Hz]
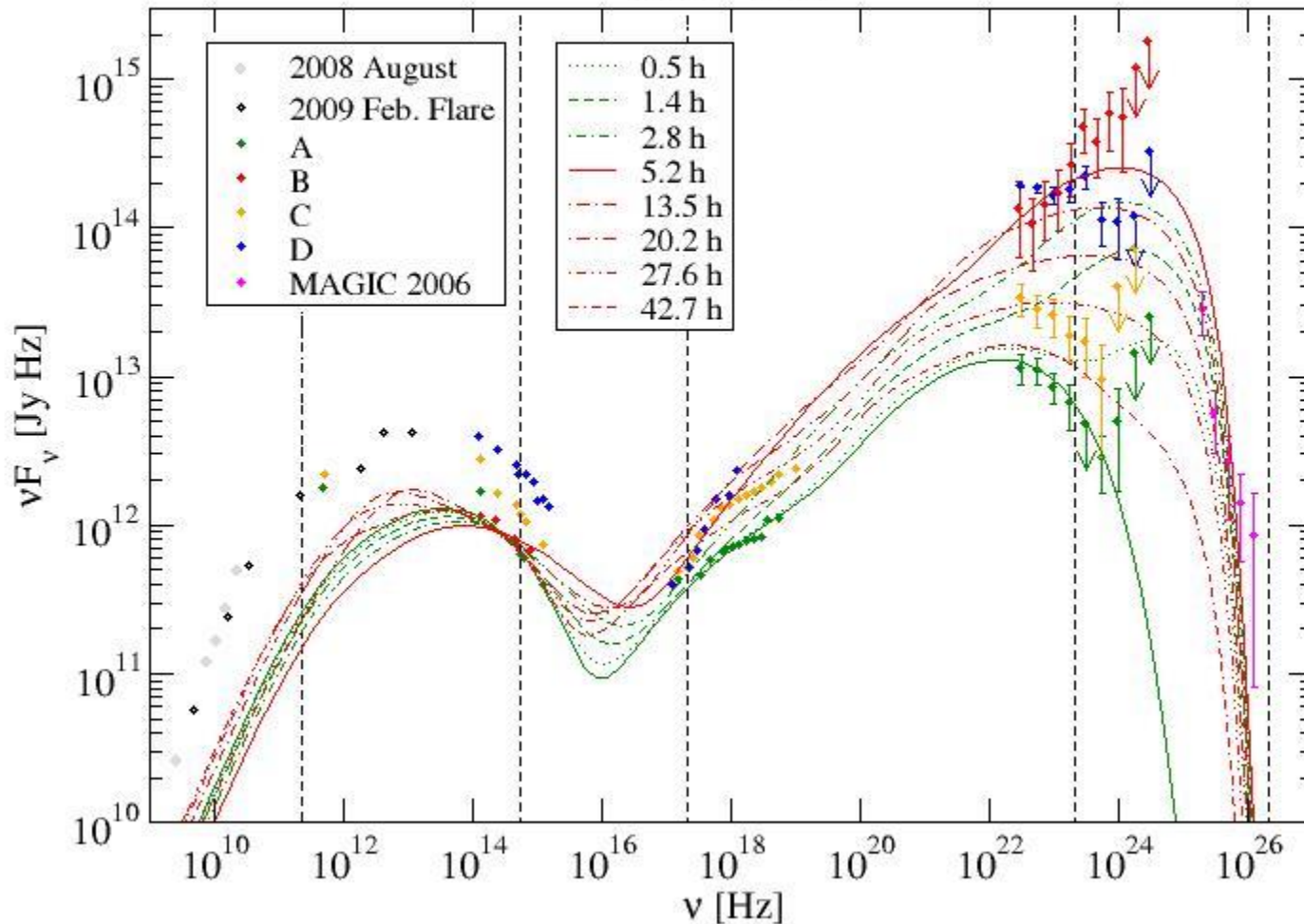
Flare modeled with

$L_{inj} = 1.1 \times 10^{43}$
$\rightarrow 4.0 \times 10^{44}$ erg/s

$\eta_1 = 100 \rightarrow 10$
$\alpha = 3.0 \rightarrow 2.3$
$\Rightarrow$ Harder electron spectrum

$B = 0.65 \rightarrow 0.075$

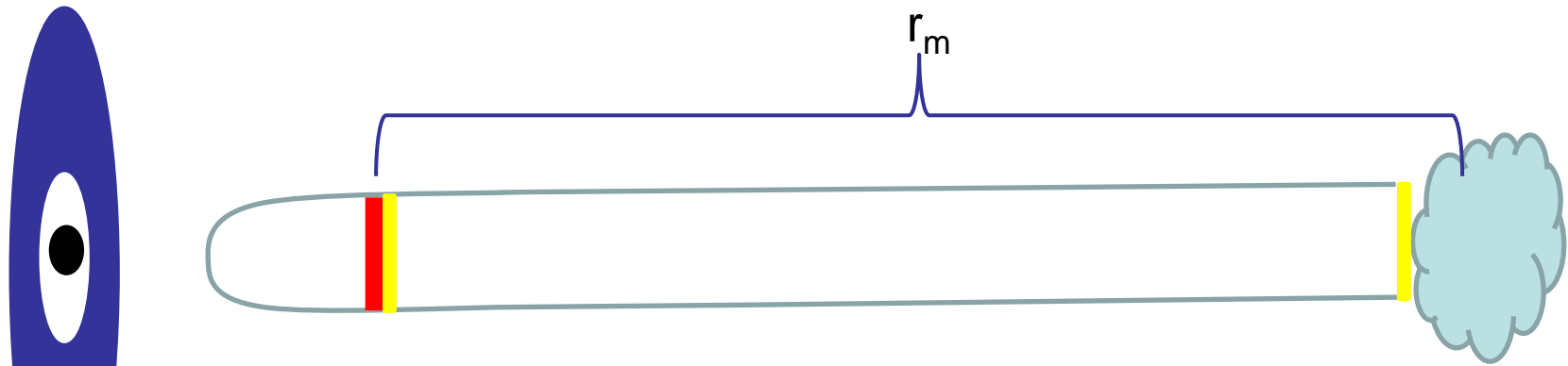with gradual recovery after shock passage:

(Böttcher & Baring 2019)

$$B(t) = B_q + (B_f - B_q)\, e^{-(t' - t'_{end})/t'_{rec}}, \quad t' > t'_{end}$$
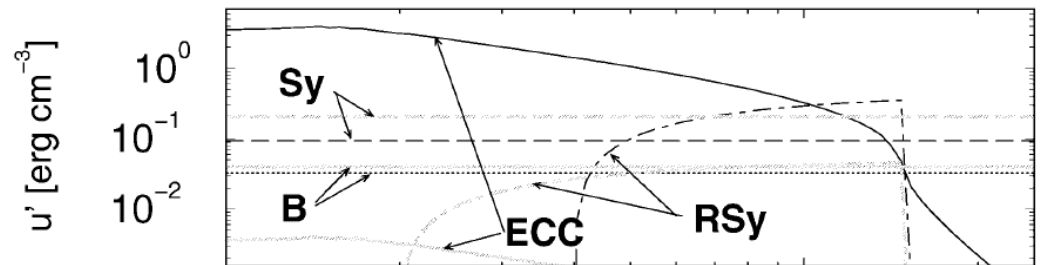
Alternative Idea: Synchrotron Mirror

Originally proposed by Ghisellini & Madau (1996); Böttcher & Dermer (1998); Bednarek (1998);

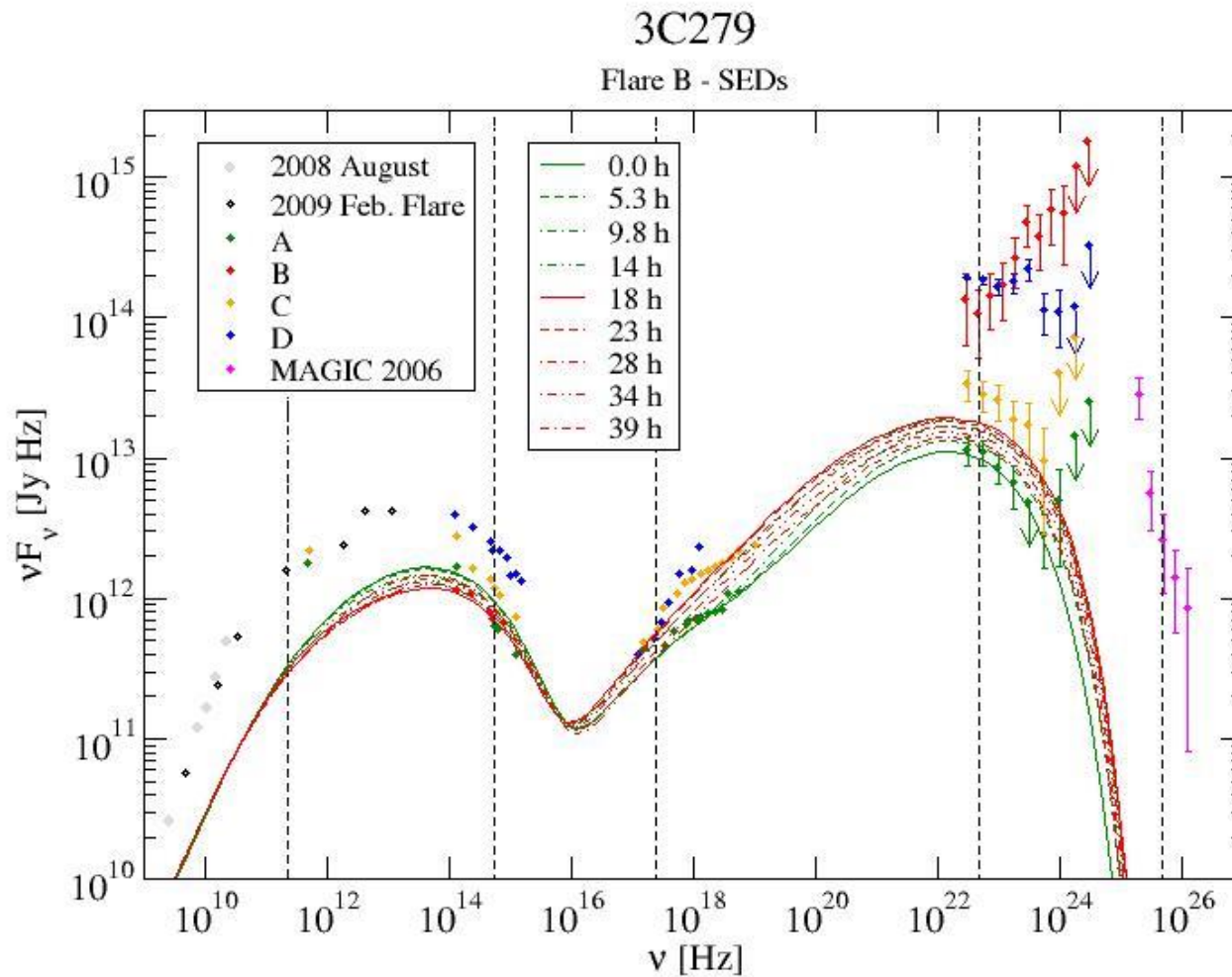further developed by Vittorini et al. (2014); Tavani et al. (2015)

Short enhancement of external radiation field on observed time scale

$$\Delta t_{obs} \sim \frac{r_m}{8\,\Gamma^4\,c}$$

(Böttcher & Dermer 1998)

3C279 Flare B with the Synchrotron Mirror Model?

3C279
Flare B - SEDs

Legend:
- 2008 August
- 2009 Feb. Flare
- A
- B
- C
- D
- MAGIC 2006

- 0.0 h
- 5.3 h
- 9.8 h
- 14 h
- 18 h
- 23 h
- 28 h
- 34 h
- 39 h

Keeping all shock parameters constant:

Only moderate orphan flare, irrespective of mirror parameters, due to limited energy budget.

Impossible to reproduce large orphan flare (Flare B)

Suppression of synchrotron emission due to increased radiative cooling.
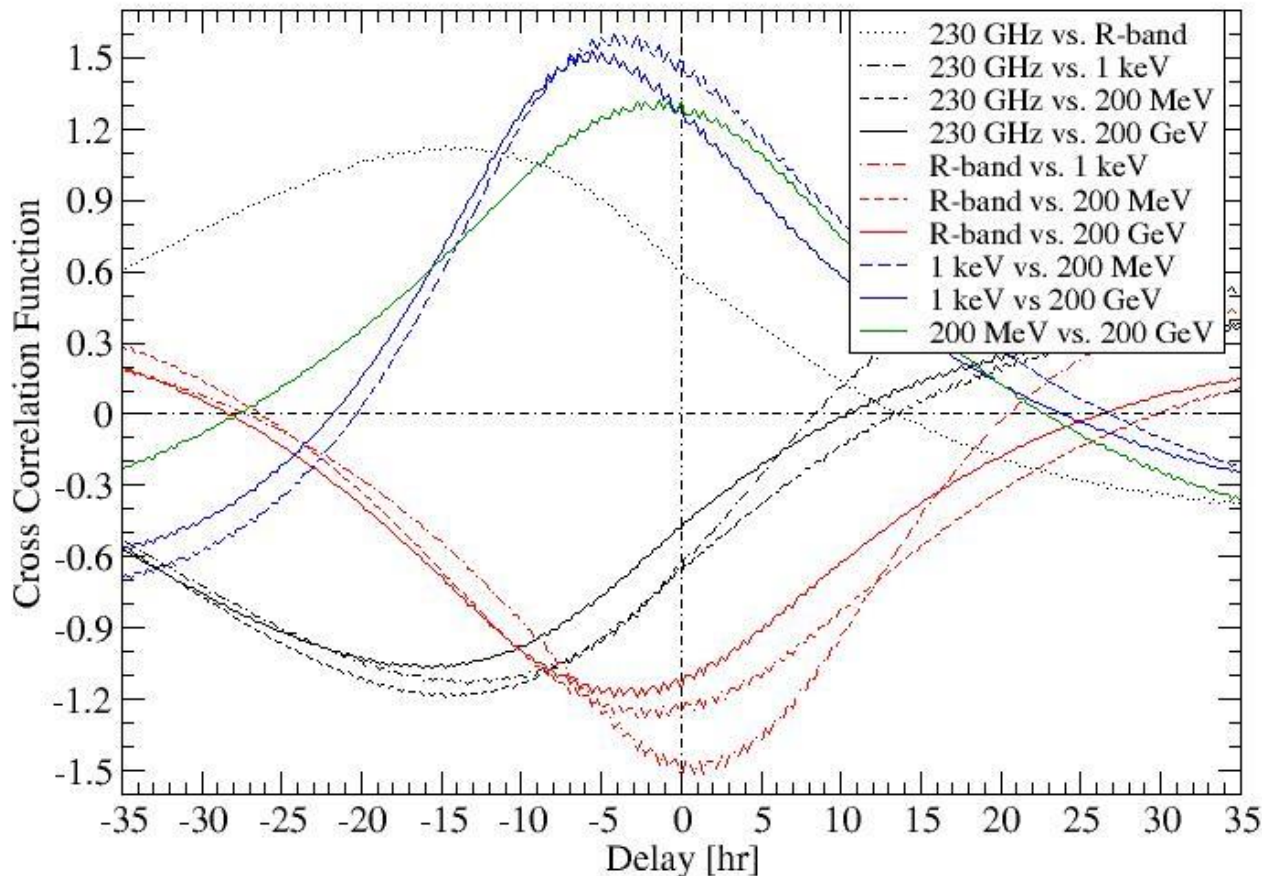
Spectral Variability Features of the Shock-in-Jet Synchrotron Mirror Model

Multi-wavelength lightcurves
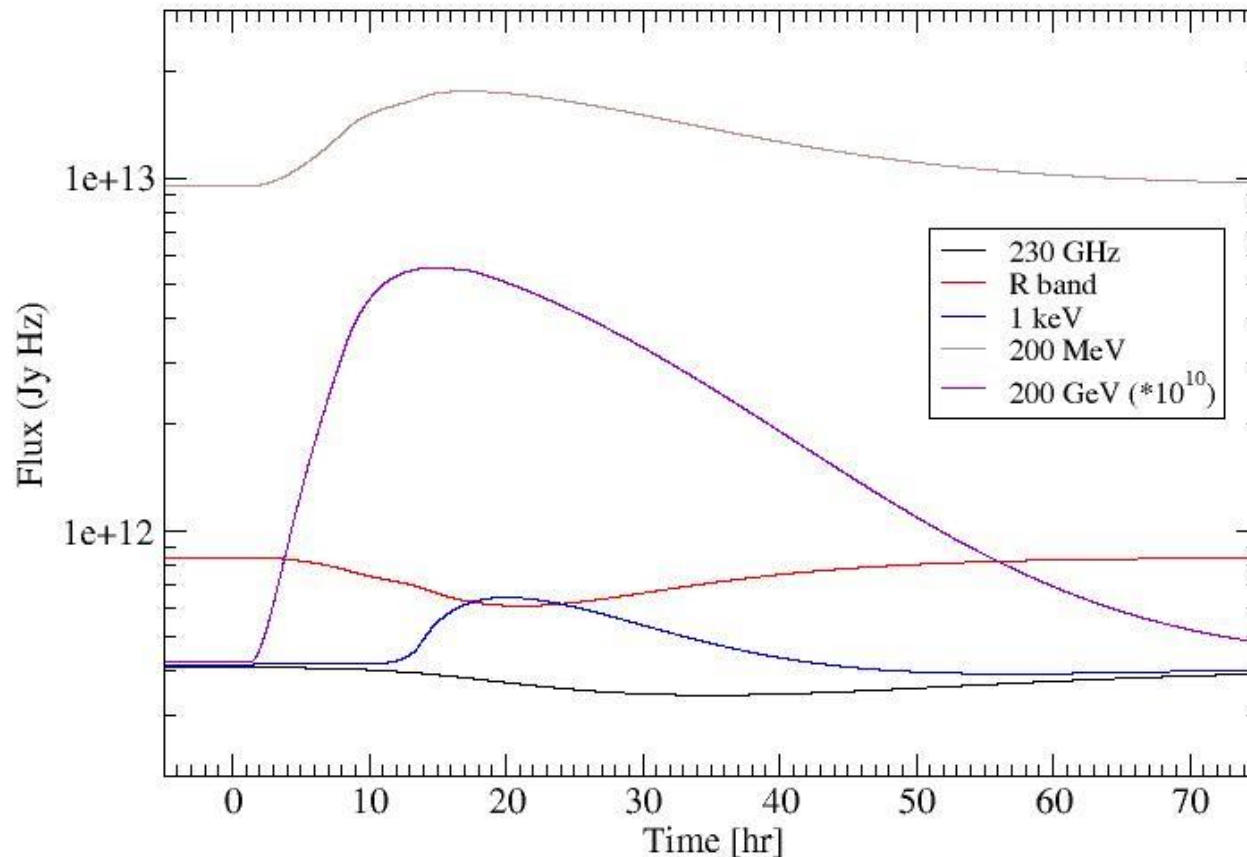
Spectral Variability Features of the Shock-in-Jet Synchrotron Mirror Model
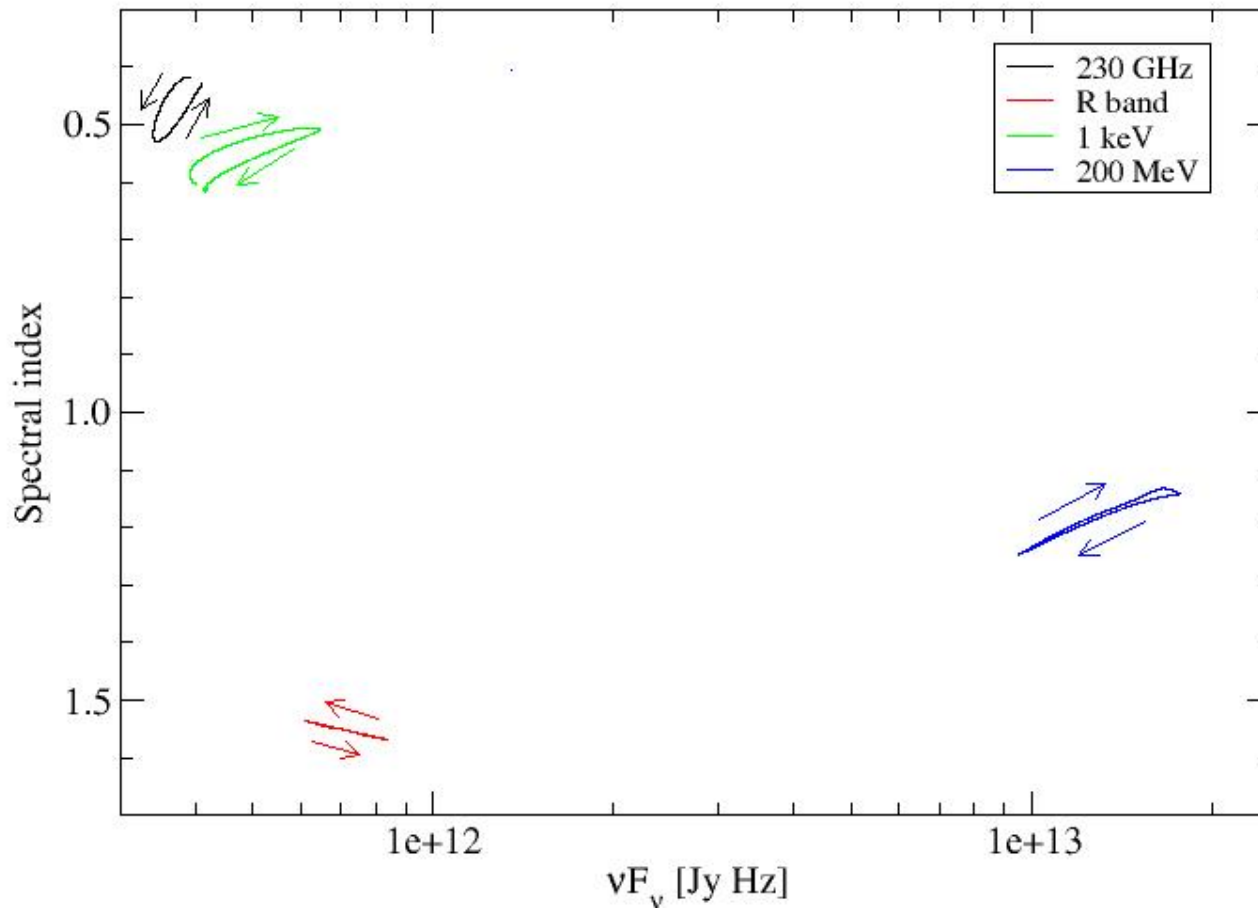
Cross-Correlations

Radio and optical anti-correlated with X-ray and γ-ray emission.

Radio dip delayed by ~ 10 – 20 hr behind flares / dips in other wavebands.

Spectral Variability Features of the Shock-in-Jet Synchrotron Mirror Model

Hardness-Intensity Diagrams

No significant spectral hysteresis in any waveband.

Harder-when-brighter trend in all wavebands, except optical (synchrotron).

Summary

1. Time-dependent, coupled MC Simulations of Diffusive Shock Acceleration and radiation transport: Naturally capable of reproducing MWL flares with roughly equal flare amplitude in synchrotron and Compton SED components (e.g., flare C of 3C279 in 2013).

2. Flares with strongly increased Compton dominance (incl. orphan γ-ray flares, e.g. flare B of 3C279 in 2013) require fine-tuned B-field evolution to avoid simultaneous synchrotron flares.

3. Alternative interpretation through synchrotron mirror scenario plausible, but without increased energy input into electrons, only moderate orphan flares can be produced.

4. Significant anti-correlations between synchrotron (radio – optical) and Compton (X-rays – γ-rays) with radio time lags of ~ 10 – 20 hours.

5. No significant spectral hysteresis, with harder-when brighter trend in most wavebands, except optical.
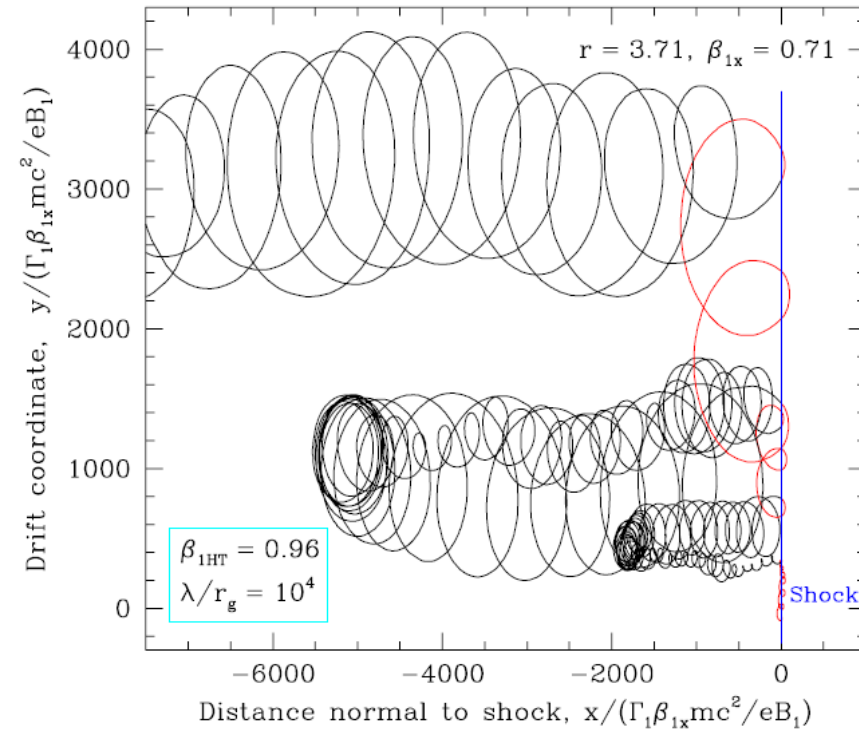
Thank you!

Backup Slides

Monte-Carlo Simulations of Diffusive Shock Acceleration (DSA)

- Gyration in B-fields and diffusive transport (pitch-angle diffusion) modeled by a Monte Carlo technique.

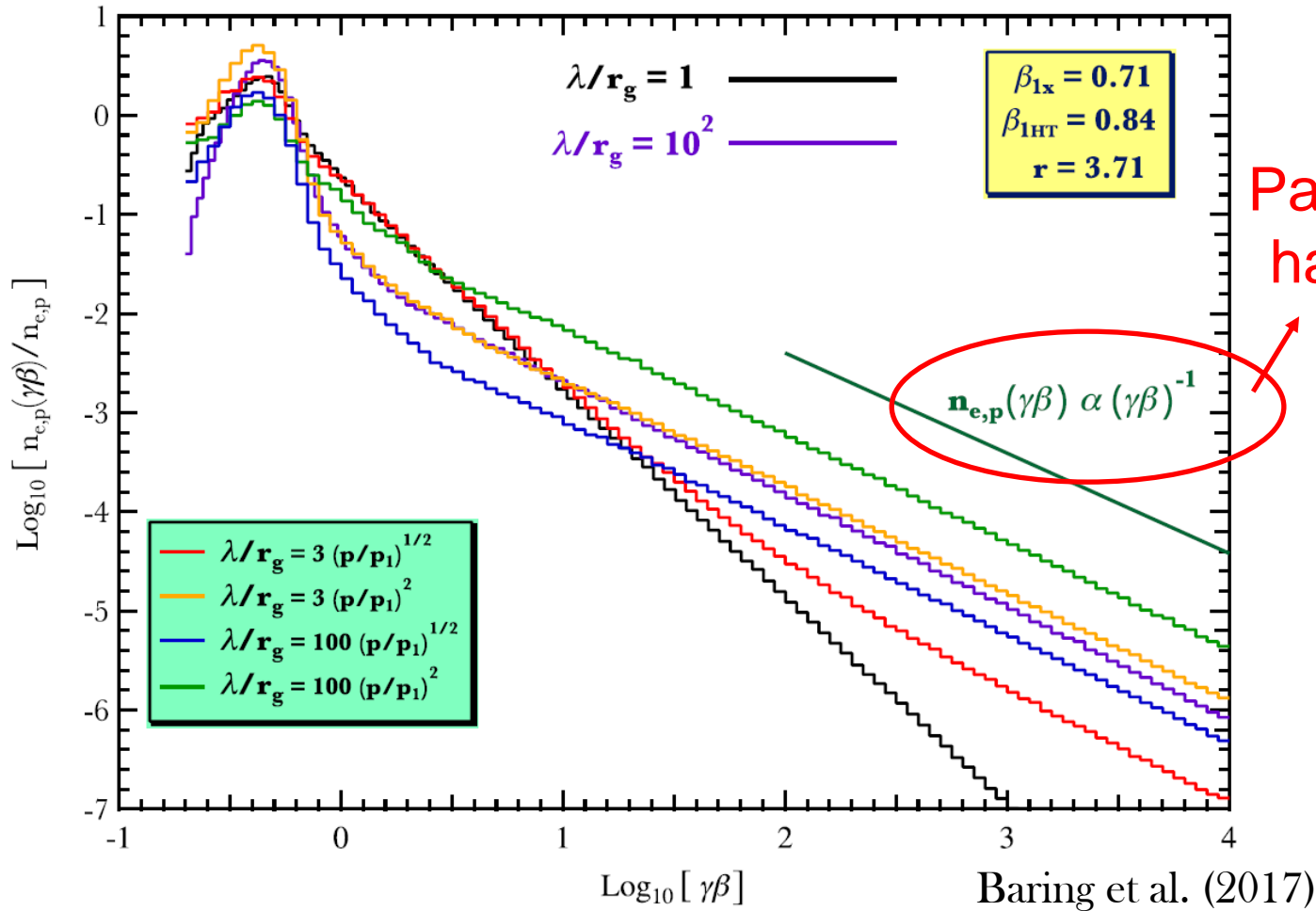- Shock crossings produce net energy gains → first-order Fermi.

(Summerlin & Baring 2012)

- 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 Spectra

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!

Time-Dependent Electron Evolution with Radiative Energy Losses

Acceleration time scale:

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

for almost all electrons

$\Rightarrow$ Use shock-accelerated electron spectrum (MC simulations of DSA by Summerlin & Baring 2012) 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)
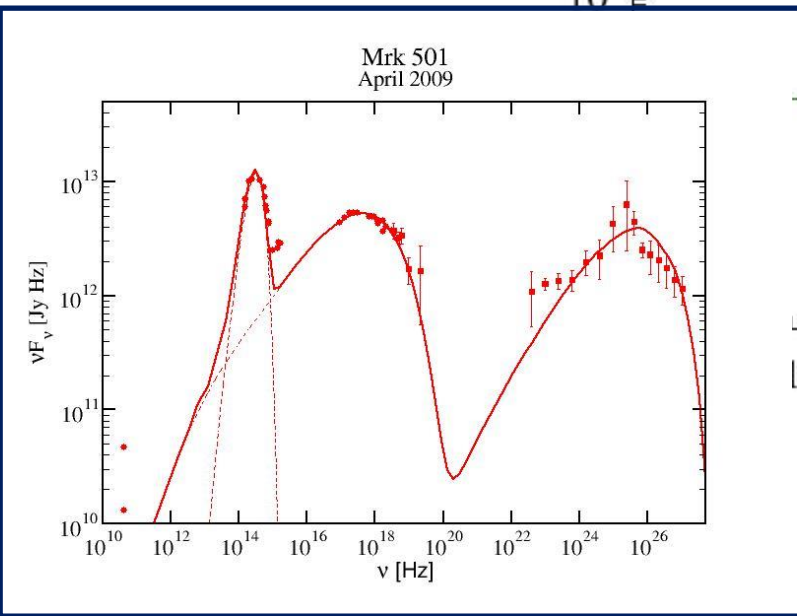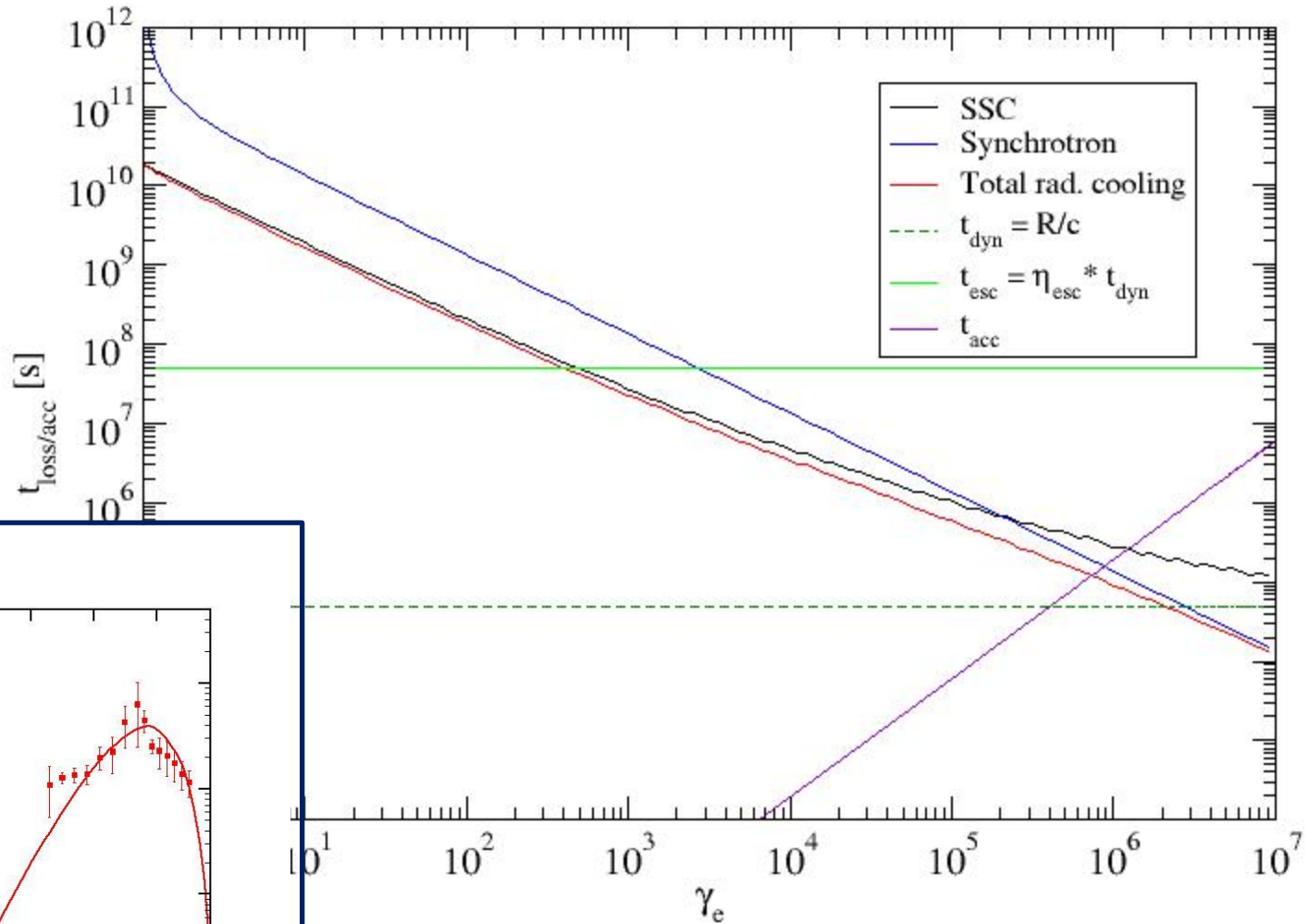 - External Compton (EC: dust torus + BLR + direct accretion disk)

L'

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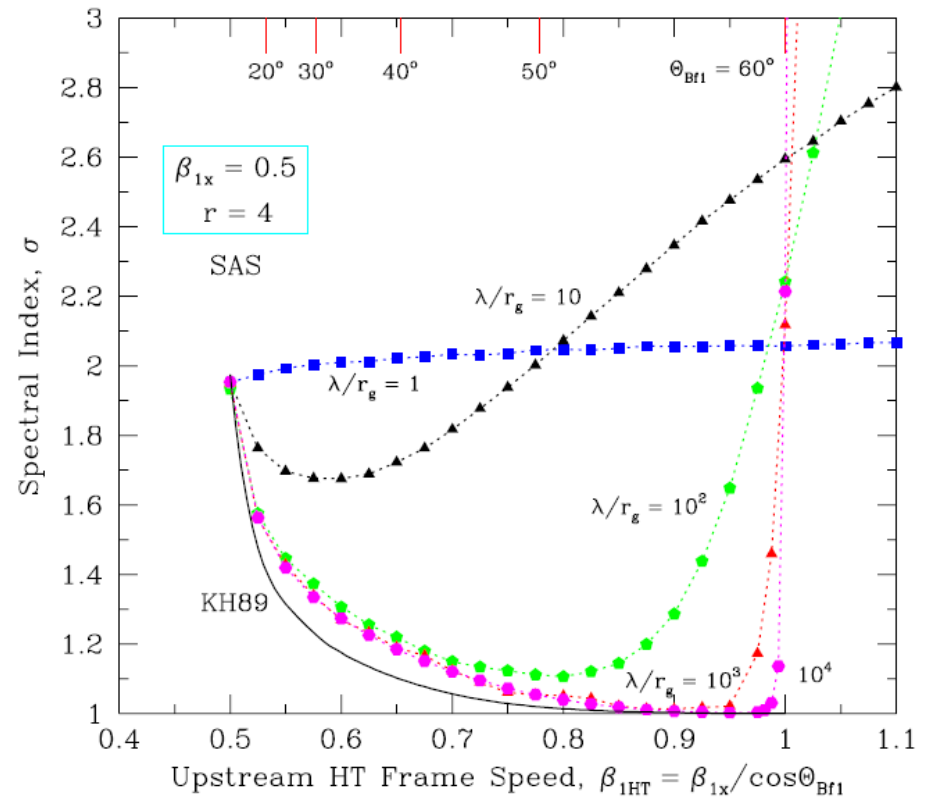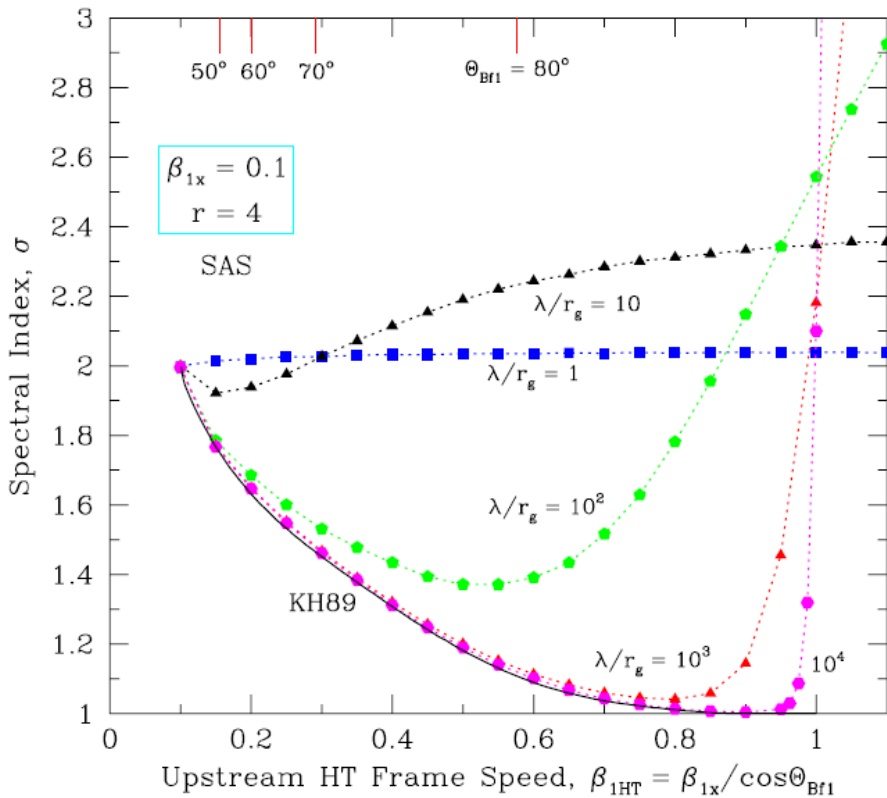$$0 < \Delta t' < L'/v'_s$$

Γ

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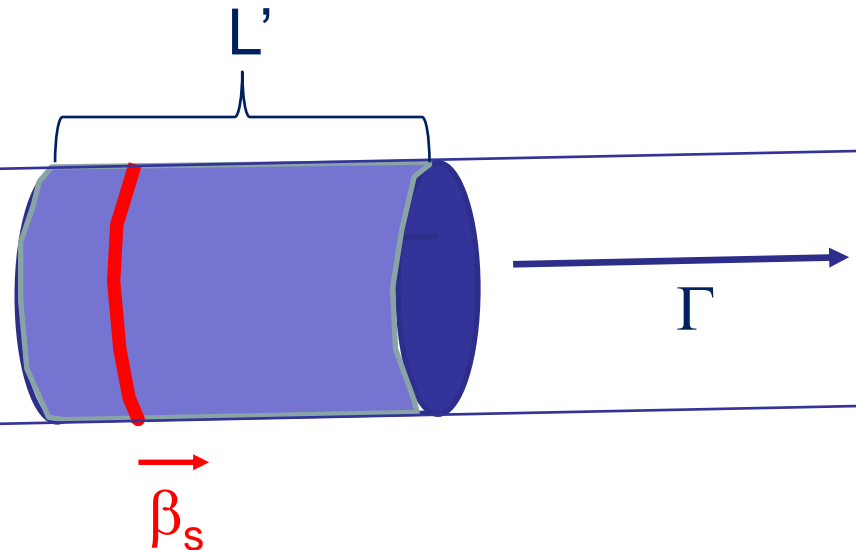
$$Q_{e,s}(\gamma,t') = Q_{e,s}(\gamma)\, H(t'; 0, \Delta t')$$

Electron Evolution Time Scales

Mrk 501

Acceleration Indices for Oblique Shocks

(Summerlin & Baring 2012)

- Non-thermal spectra as hard as n(p) ~ 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!)
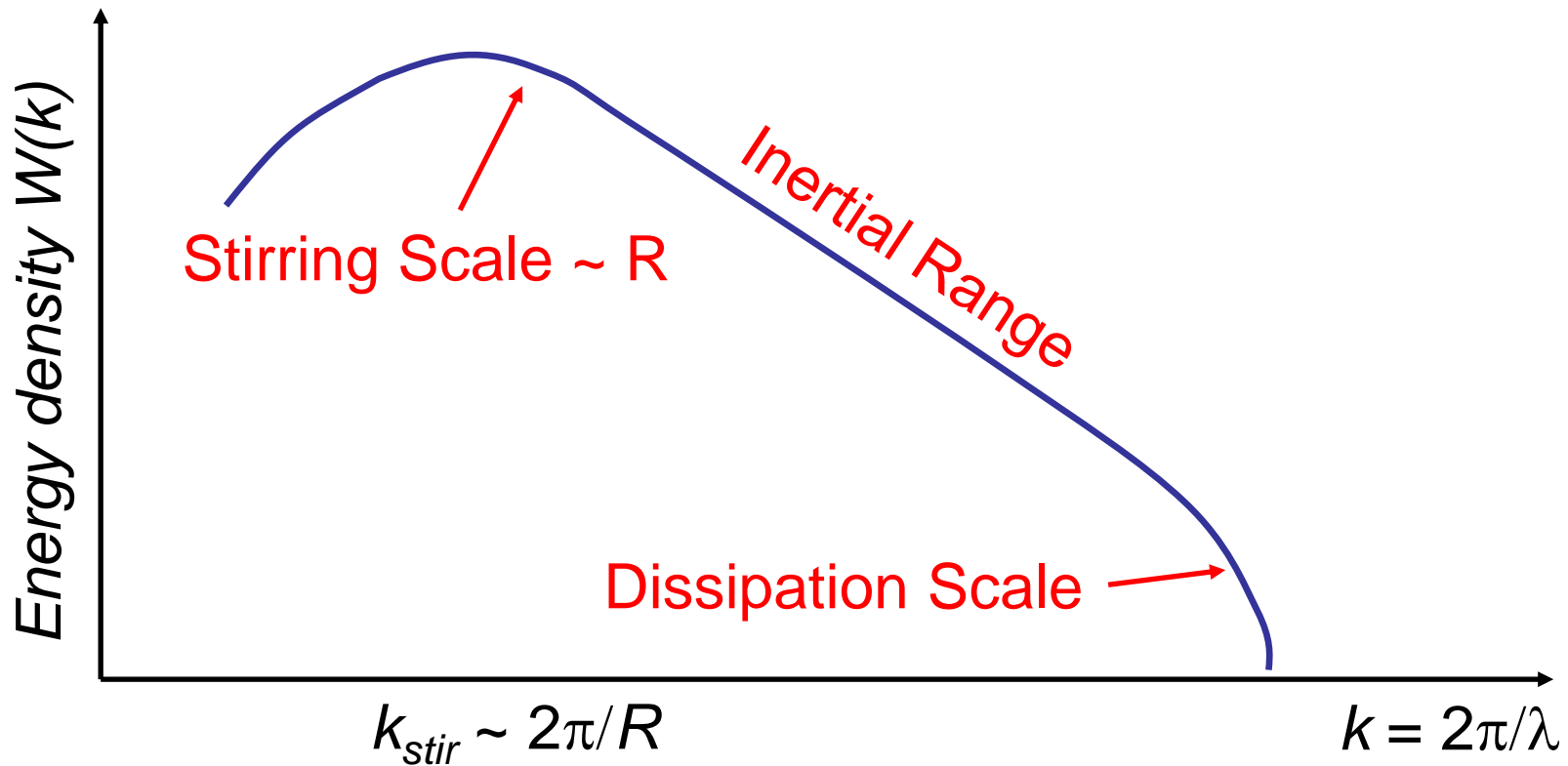
$\Rightarrow$ Need large $\eta(\gamma_{max})$ to obtain synchrotron peak in optical/UV/X-rays

$\Rightarrow$ 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 $\alpha > 1$ (Baring et al. 2017)

Implications for Shock-Induced Turbulence
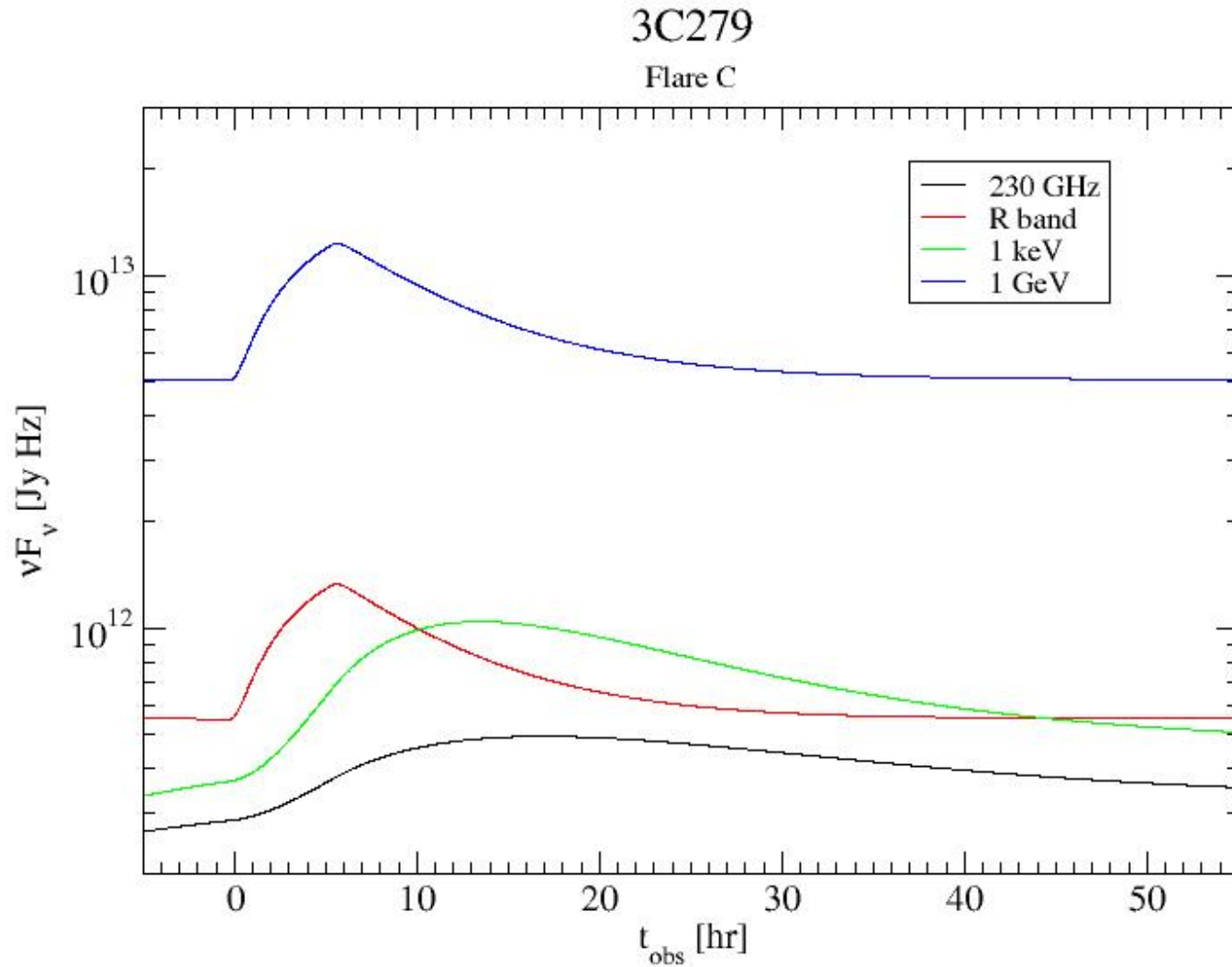
Gyro-resonance condition: $\lambda_{res} \propto p$

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

Stirring Scale ~ R

Inertial Range

Dissipation Scale

Energy density $W(k)$

$k_{stir} \sim 2\pi/R$

$k = 2\pi/\lambda$

Turbulence level decreasing with increasing distance from the shock
$\Rightarrow$ High-energy (large r_g) particles "see" reduced turbulence
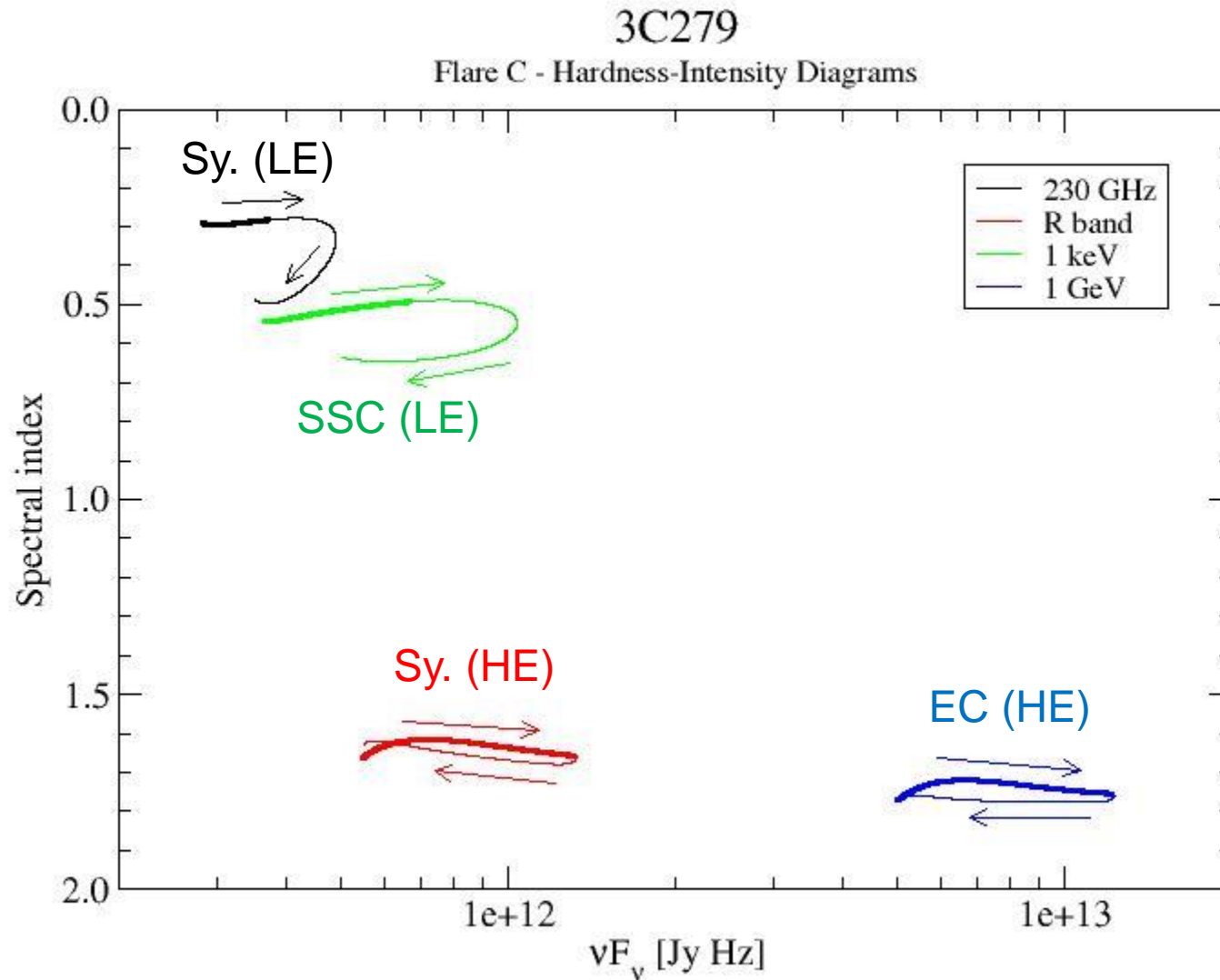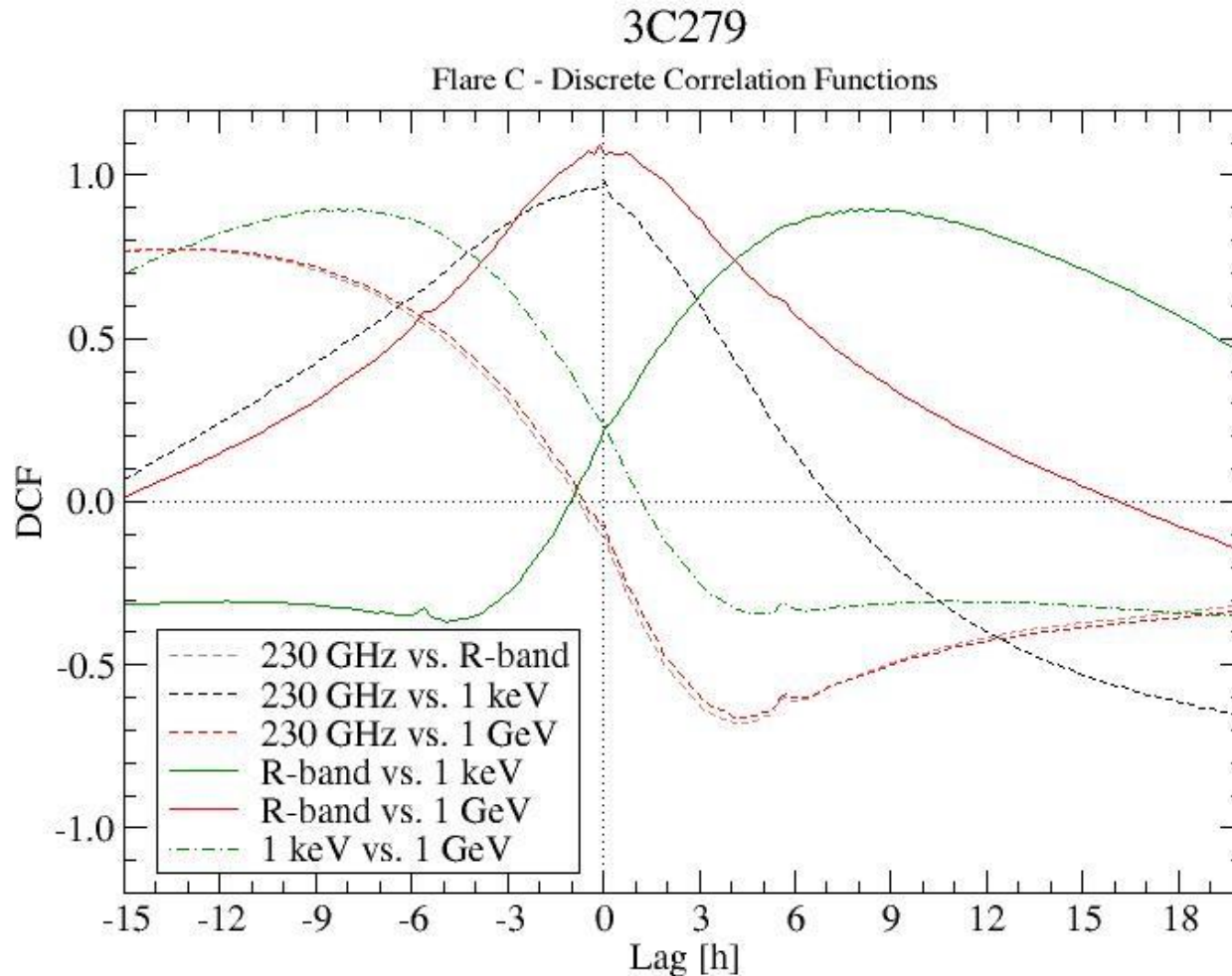$\Rightarrow$ Large λ_{pas}

3C279 – Flare C
Model Light Curves

3C279

Flare C

3C279

Flare C - Hardness-Intensity Diagrams

3C279 – Flare C
Discrete Correlation Functions

3C279

Flare C - Discrete Correlation Functions

Legend:
- 230 GHz vs. R-band
- 230 GHz vs. 1 keV
- 230 GHz vs. 1 GeV
- R-band vs. 1 keV
- R-band vs. 1 GeV
- 1 keV vs. 1 GeV

- 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 ~ 7 - 9 hr)