A Shock-in-Jet Synchrotron Mirror Model for Blazars

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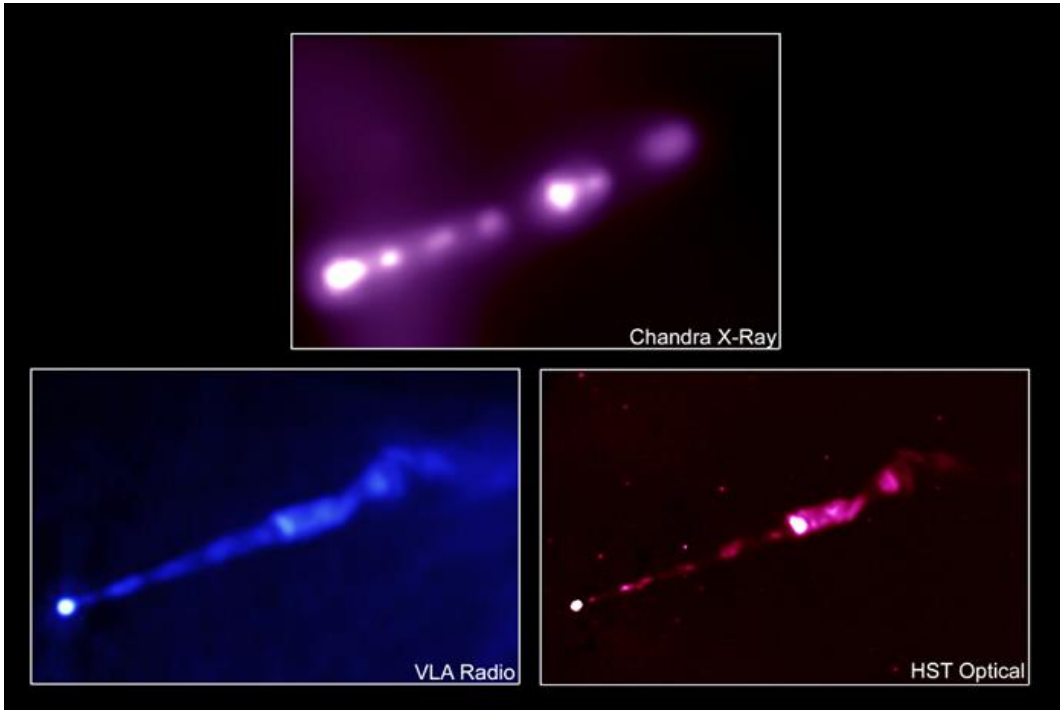
Supported by the South African Research Chairs Initiative (SARChI) of the Department of Science and Technology and the National Research Foundation of South Africa.

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 obliquity and efficiency of pitch-angle scattering.



Jet of M87 at different wavelengths

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

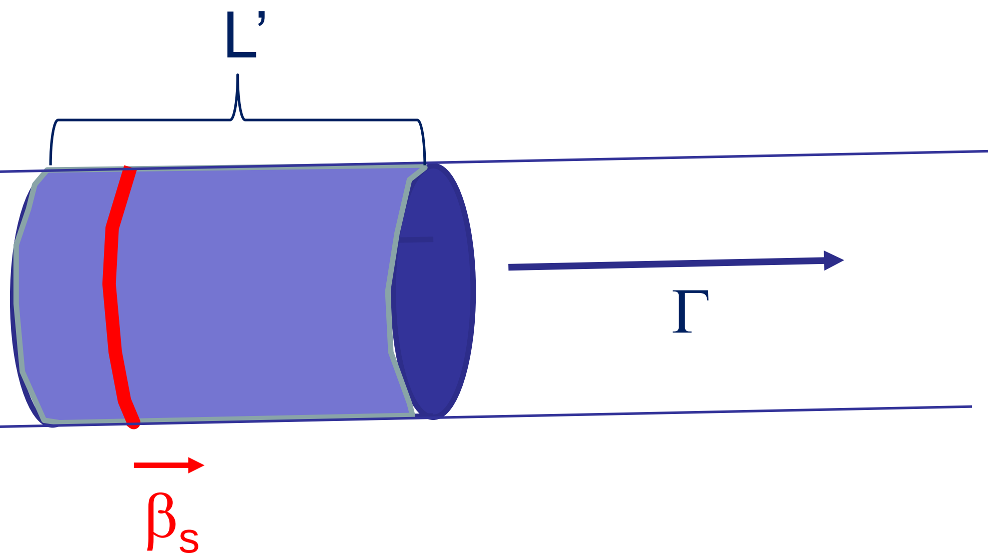
$\Rightarrow$ Use shock-accelerated electron spectrum (MC simulations of DSA by Summerlin & Baring 2012) as instantaneous injection $Q_e(\gamma)$;

$\Rightarrow$ 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)



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

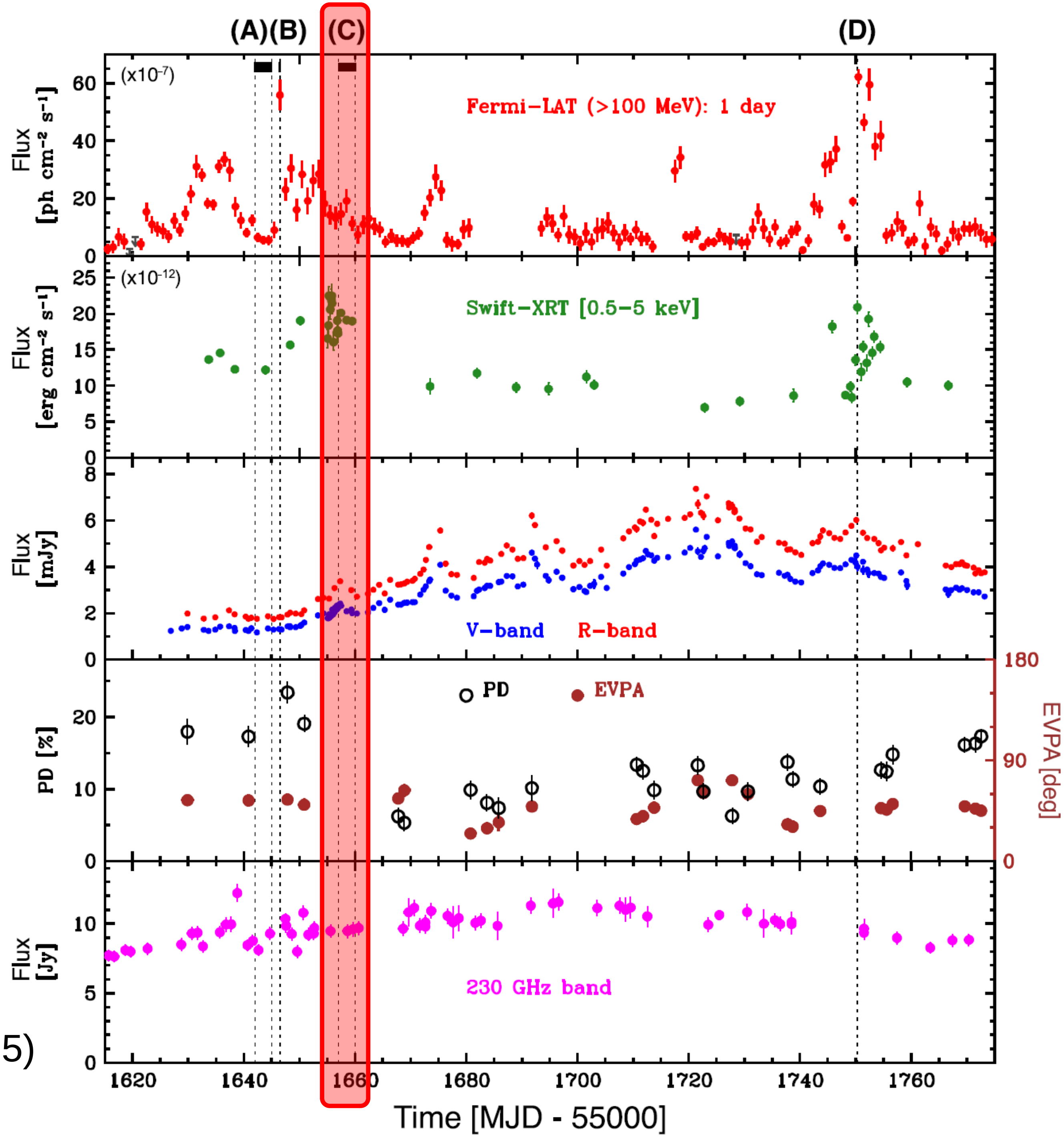
$$Q_{e,s}(\gamma,t') = Q_{e,s}(\gamma)\, H(t';\, 0,\, \Delta t')$$

Example: FSRQ 3C279

Extended flaring period 2013 – 2014

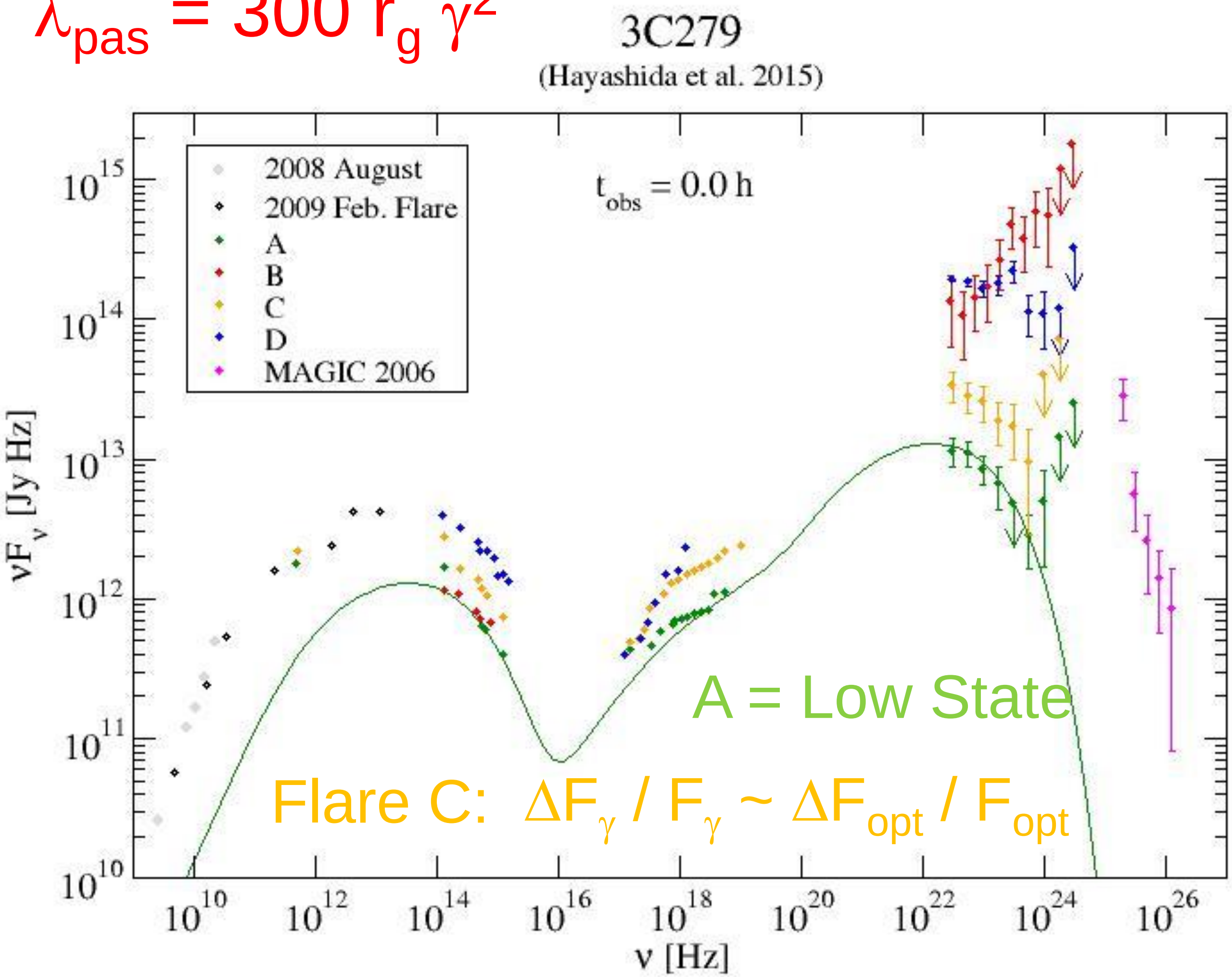
Variability time scale ~ 1 day

(Hayashida et al. 2015)



Example: FSRQ 3C279 (2013 – 2014)

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



(Böttcher & Baring 2019)

$\eta_1 = 300$

$\alpha = 3$

B = 0.65 G

$\delta = 15$

R = 1.8×10^{16} cm

→ $\Delta t' \sim$ few$\times 10^5$ s

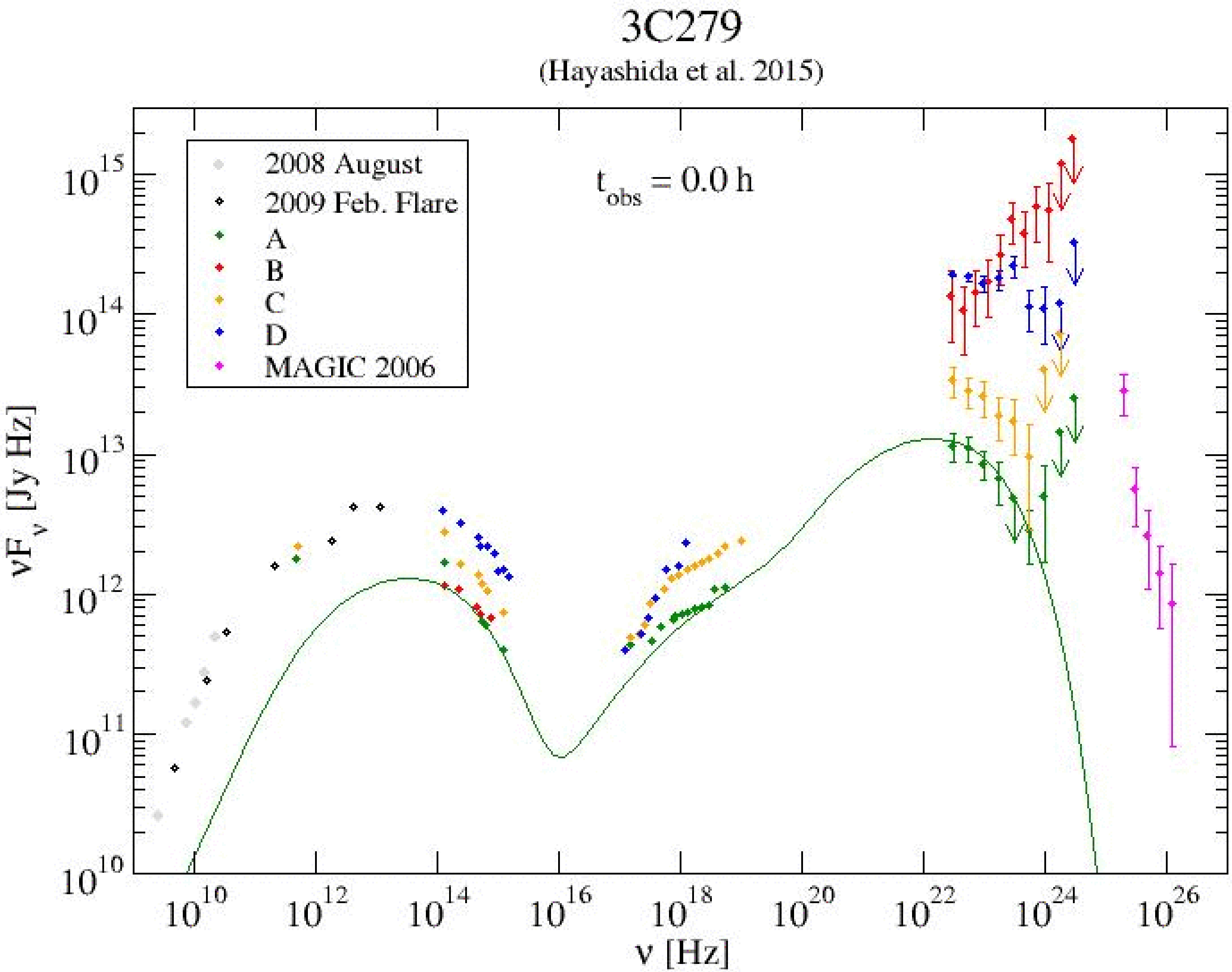
→ $\Delta t_{obs} \sim$ few hr

γ-rays EC (Dust Torus) dominated:

u = 4×10^{-4} erg/cm^3

T_{BB} = 300 K

3C279 – Flare C



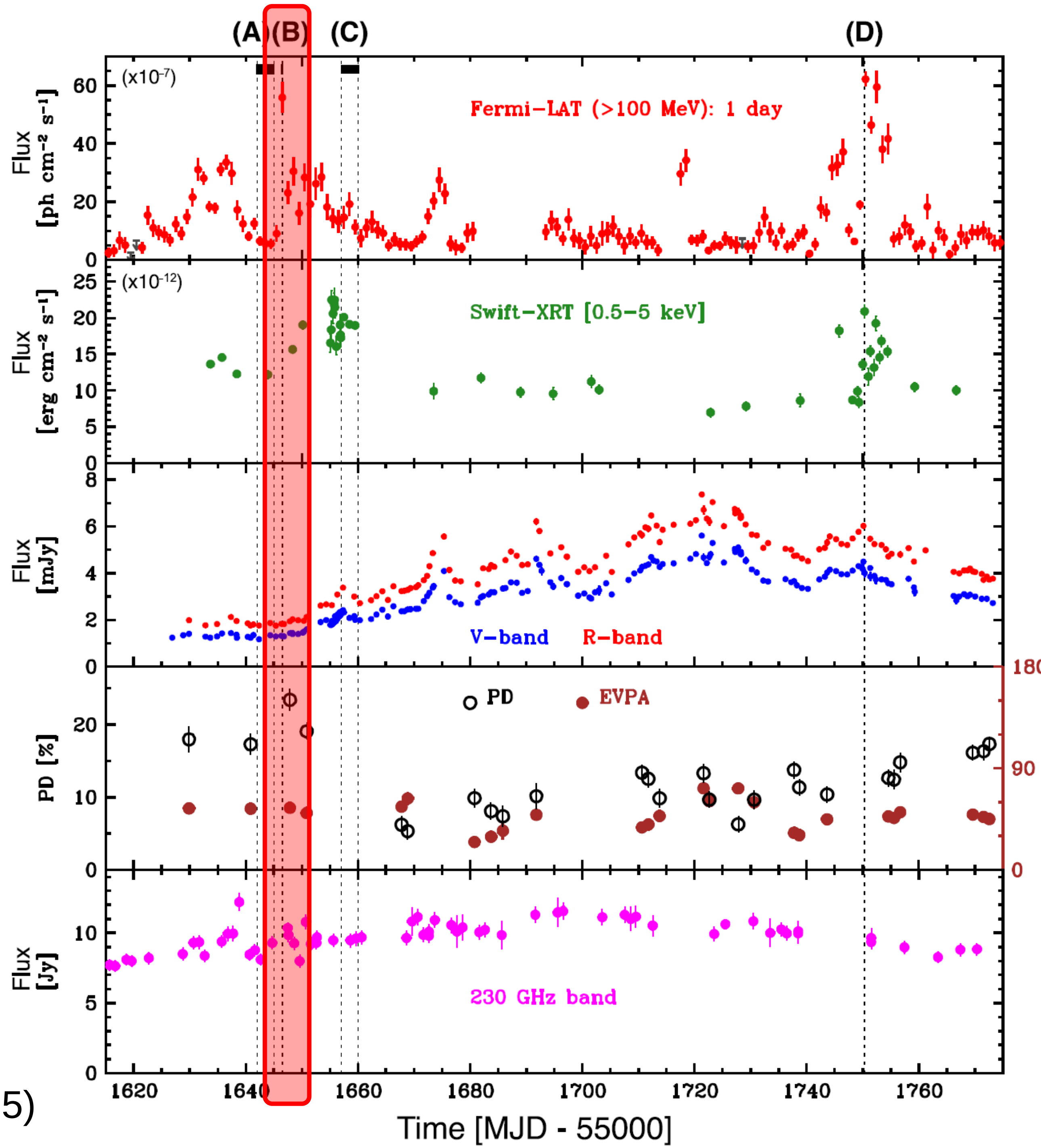
Flare modeled with

$L_{inj} = 1.1 \times 10^{43}$
$\rightarrow 5.0 \times 10^{43}$ 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)

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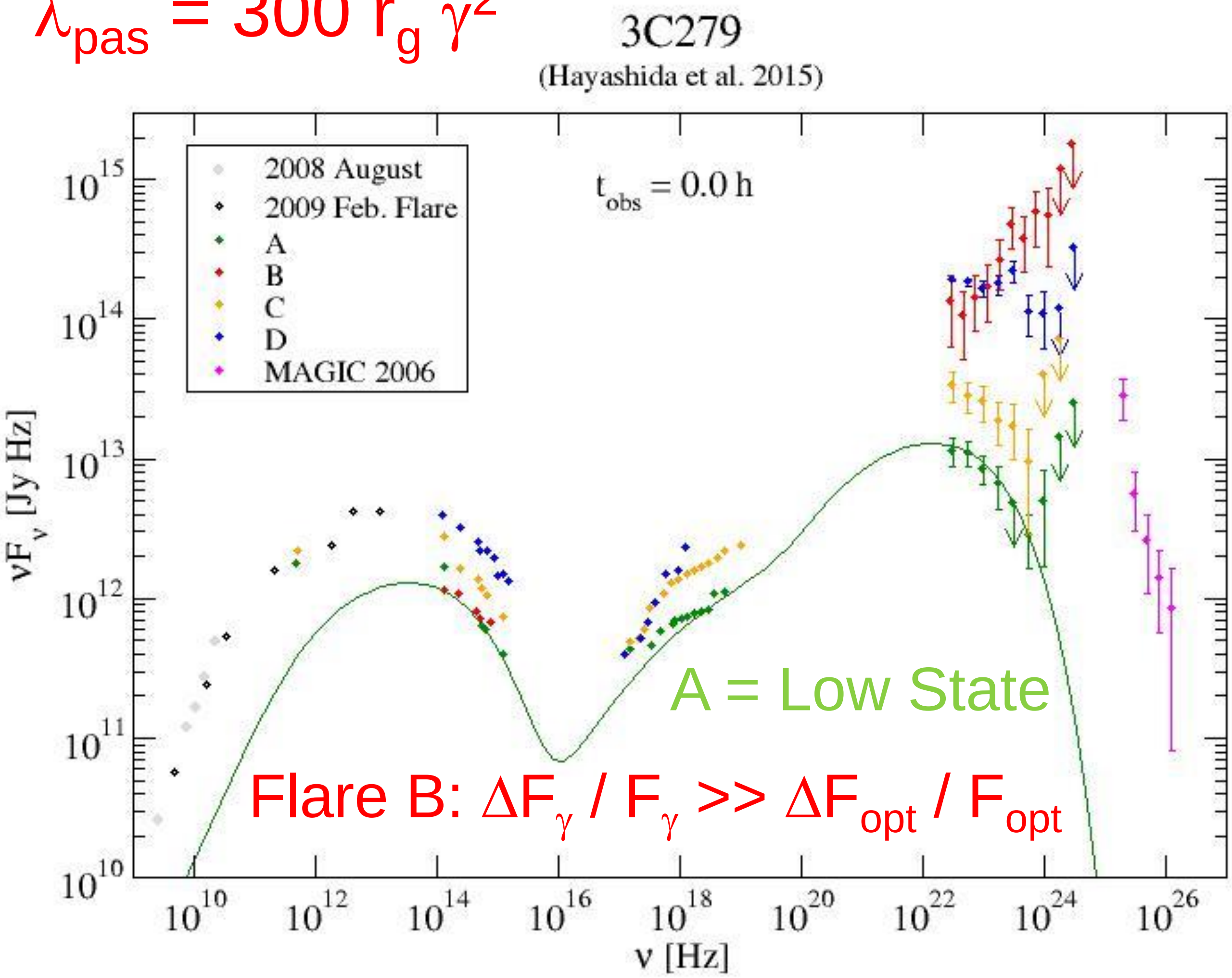

$\eta_1 = 300$
$\alpha = 3$
$B = 0.65$ G
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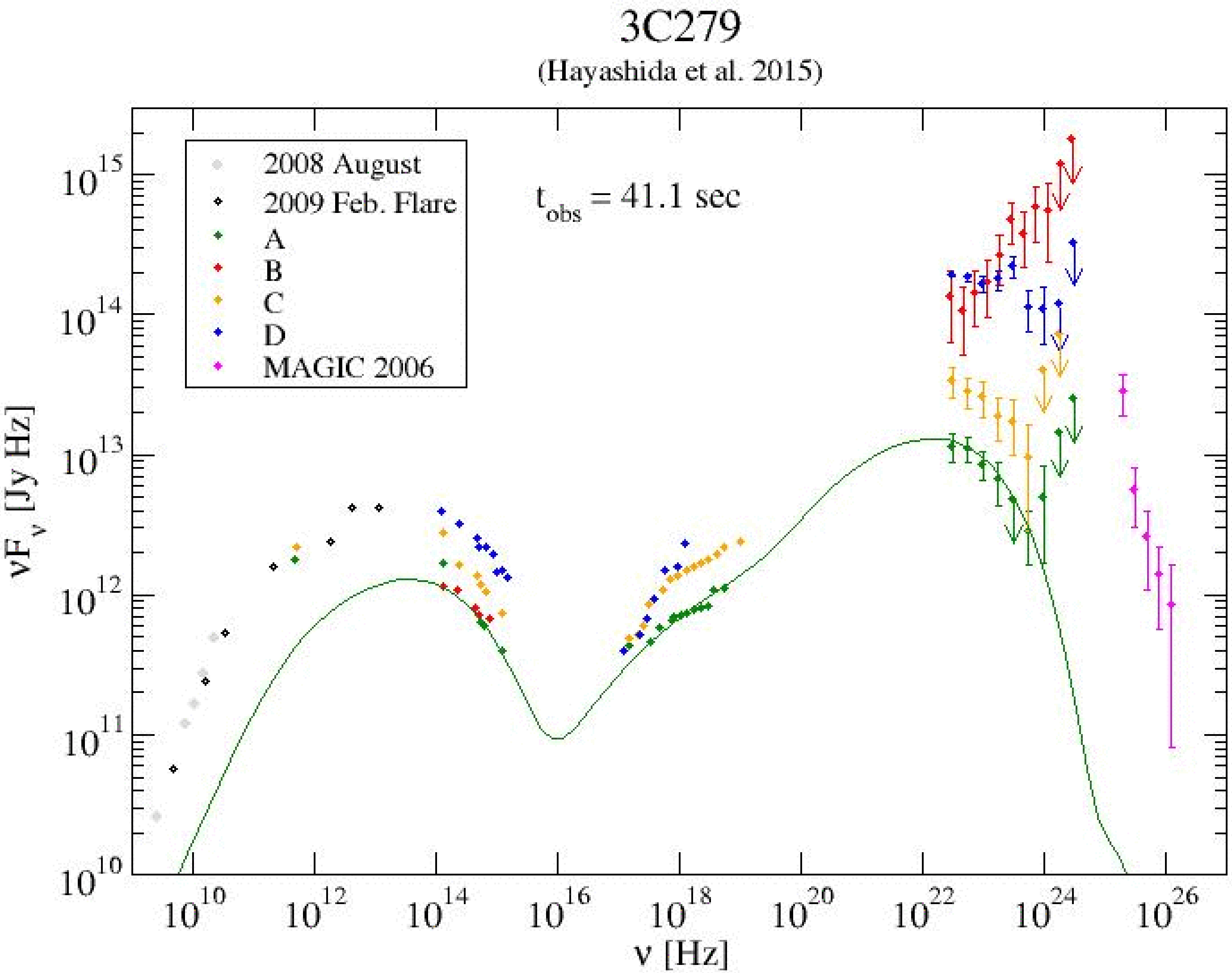
3C279 – Flare B



(Böttcher & Baring 2019)

Flare modeled with

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

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

B = 0.65 → 0.075

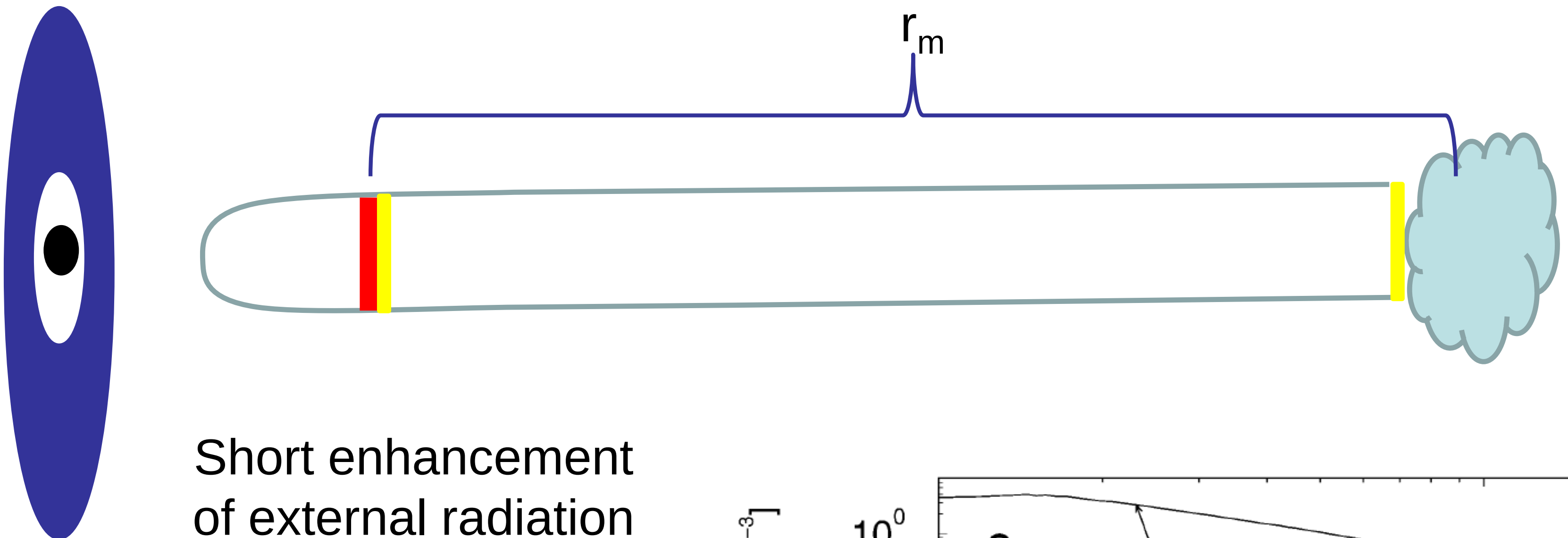
with gradual recovery after shock passage:

$$B(t) = B_q + (B_f - B_q)\, e^{-(t' - t'_{\rm end})/t'_{\rm rec}}, \qquad t' > t'_{\rm end}$$

Alternative Idea: Synchrotron Mirror

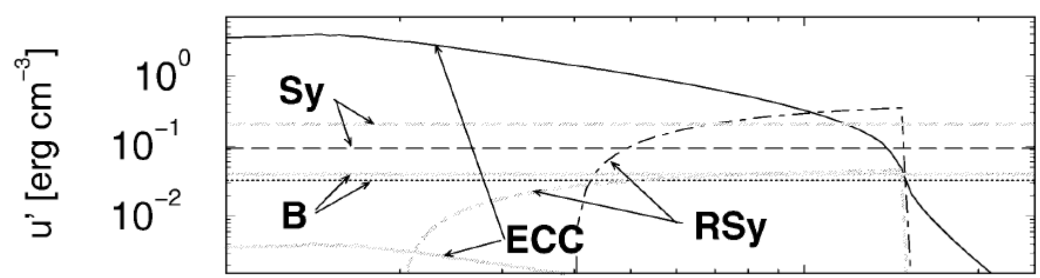
Originally proposed by Ghisellini & Madau (1996); Böttcher & Dermer (1998); Bednarek (1998);

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



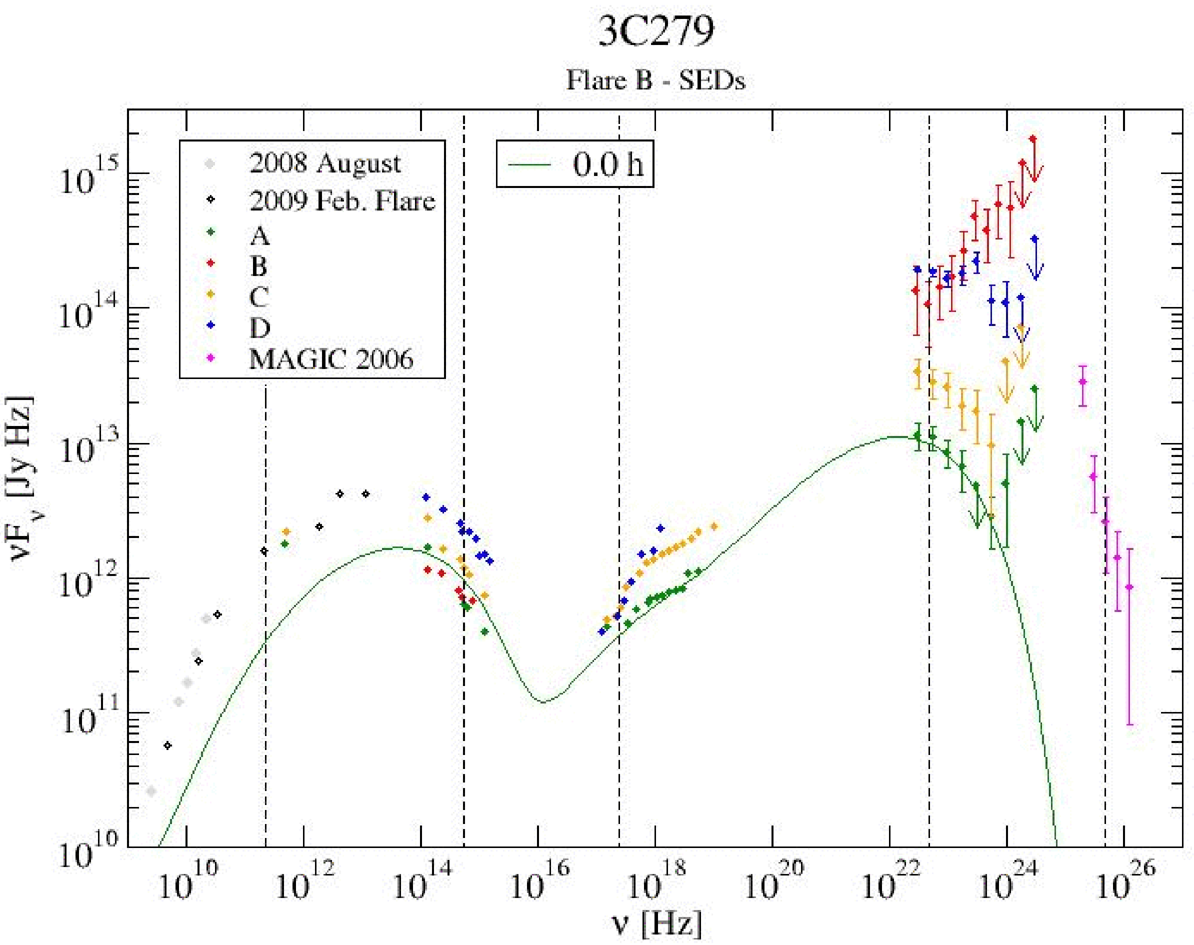
Short enhancement of external radiation field on observed time scale

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



(Böttcher & Dermer 1998)

3C279 Flare B with the Synchrotron Mirror Model?



Keeping all shock parameters constant:

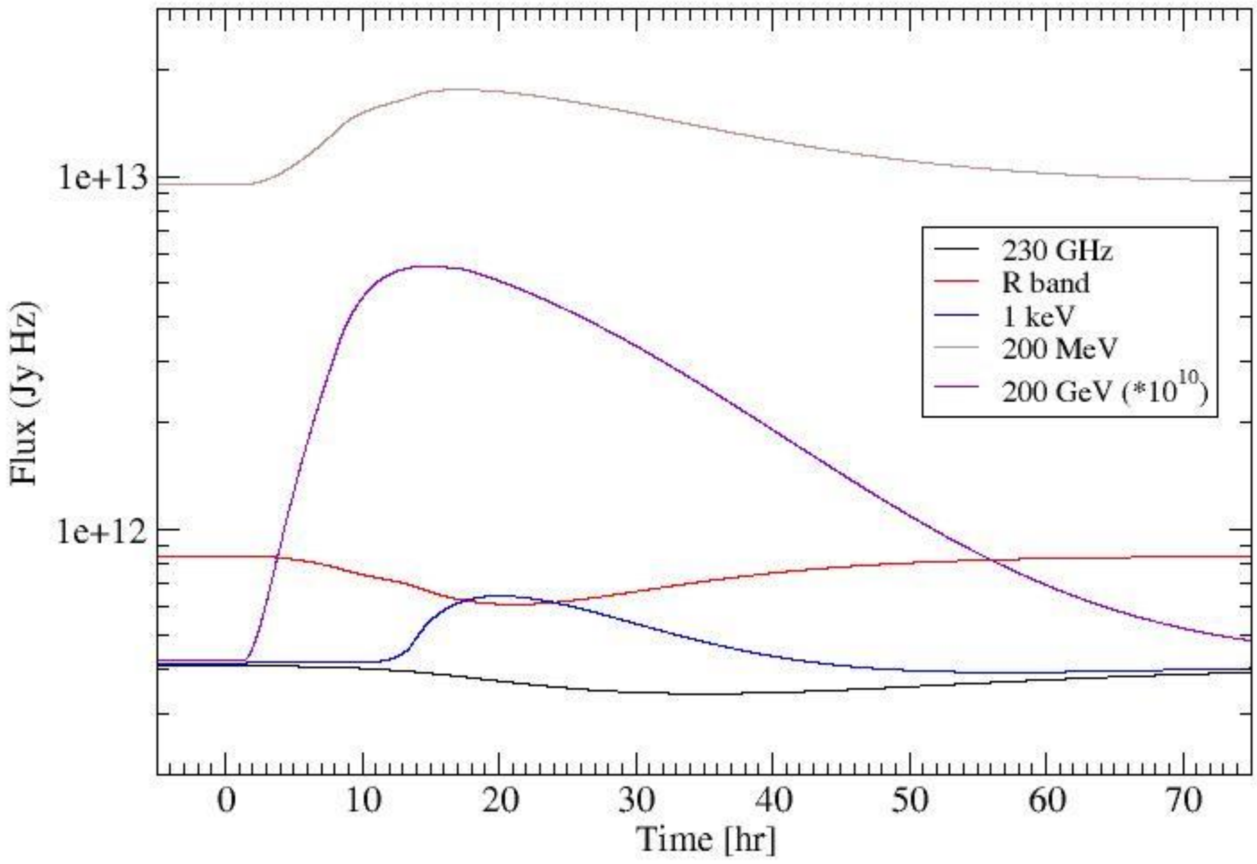
Only moderate orphan flare, irrespective of mirror parameters, due to limited energy budget.

Impossible to reproduce large orphan flare (Flare B)

Suppression of synchrotron emission due to increased radiative cooling.

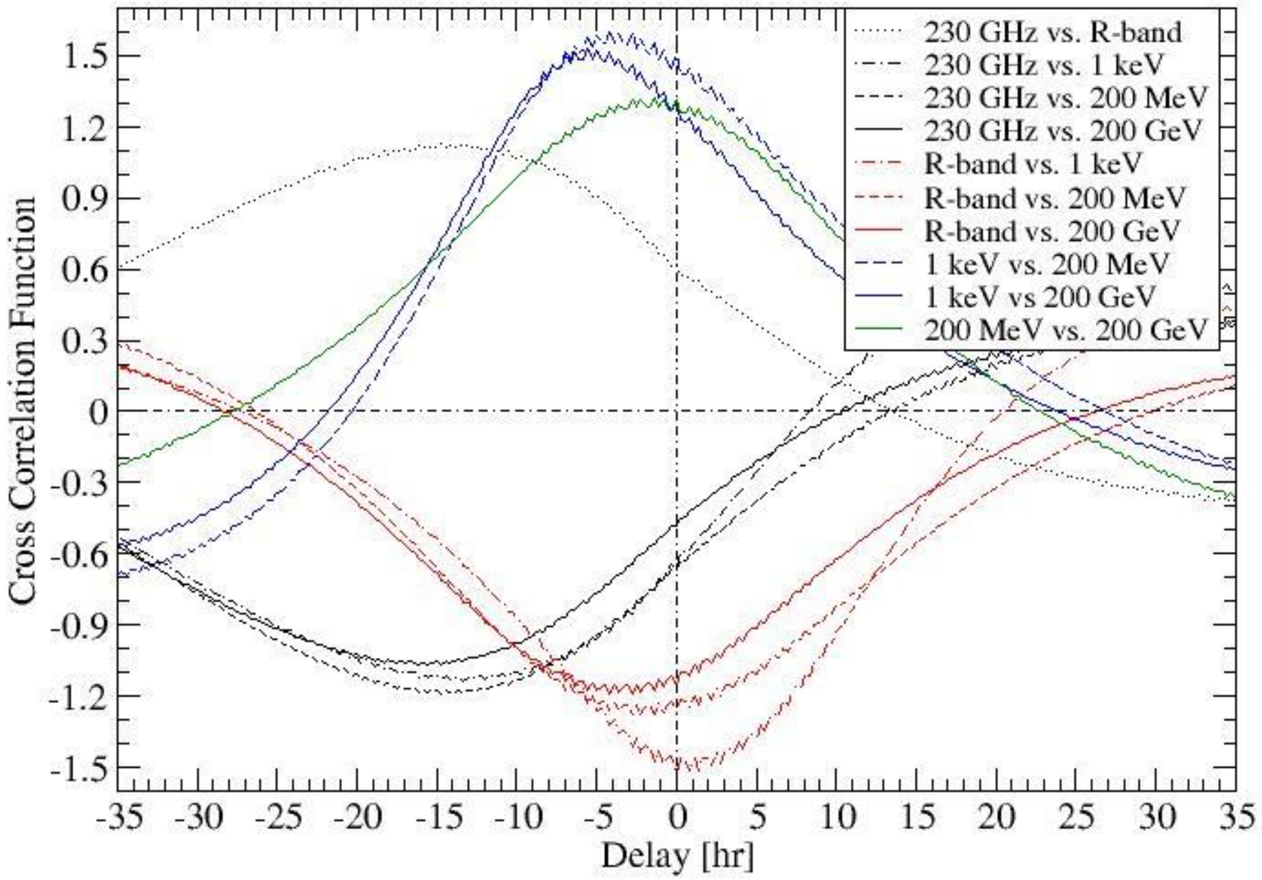
Spectral Variability Features of the Shock-in-Jet Synchrotron Mirror Model

Multi-wavelength lightcurves



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

Cross-Correlations

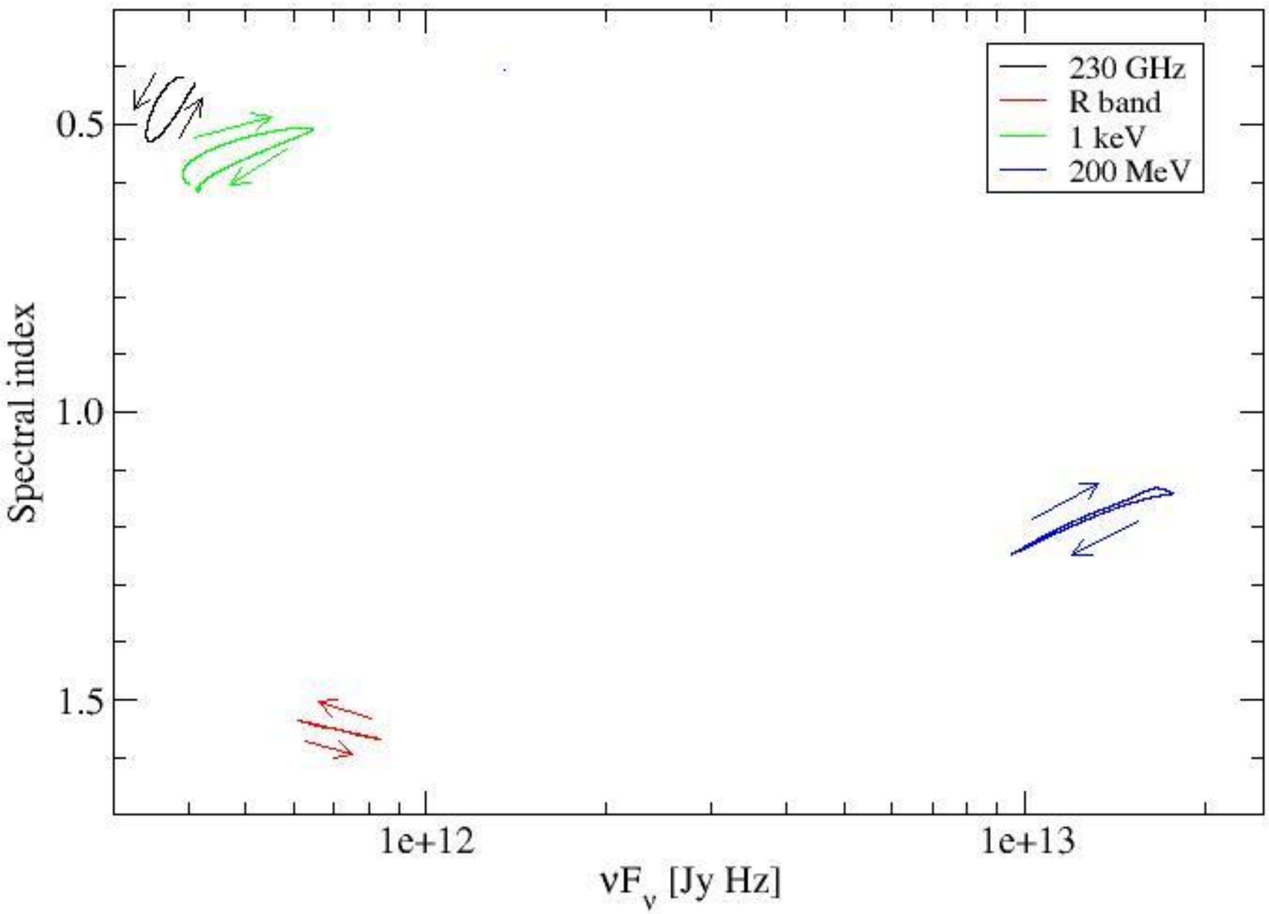


Radio and optical anti-correlated with X-ray and γ-ray emission.

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.

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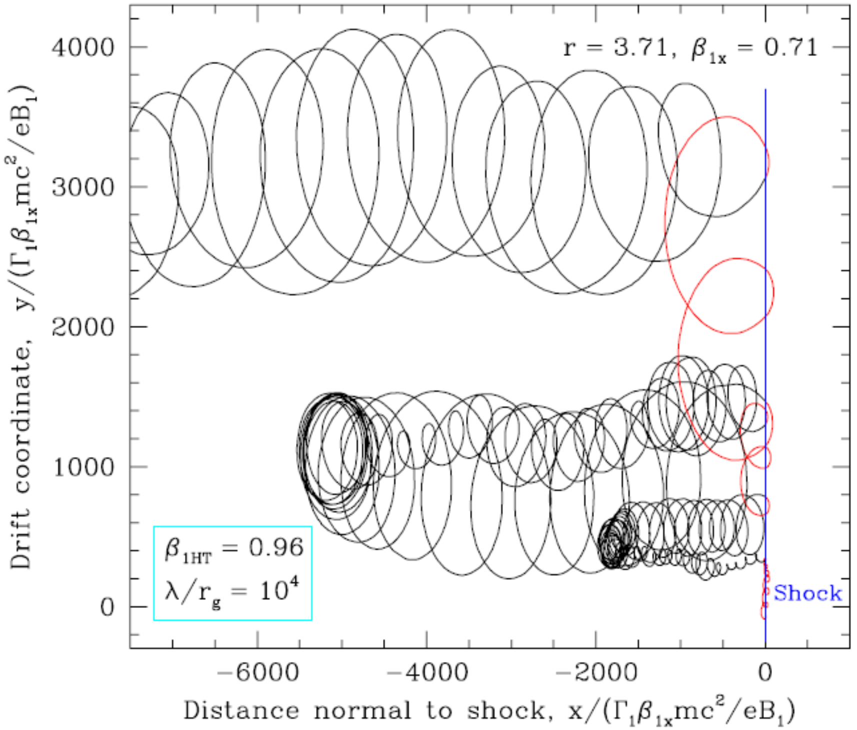
Thank you!

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.

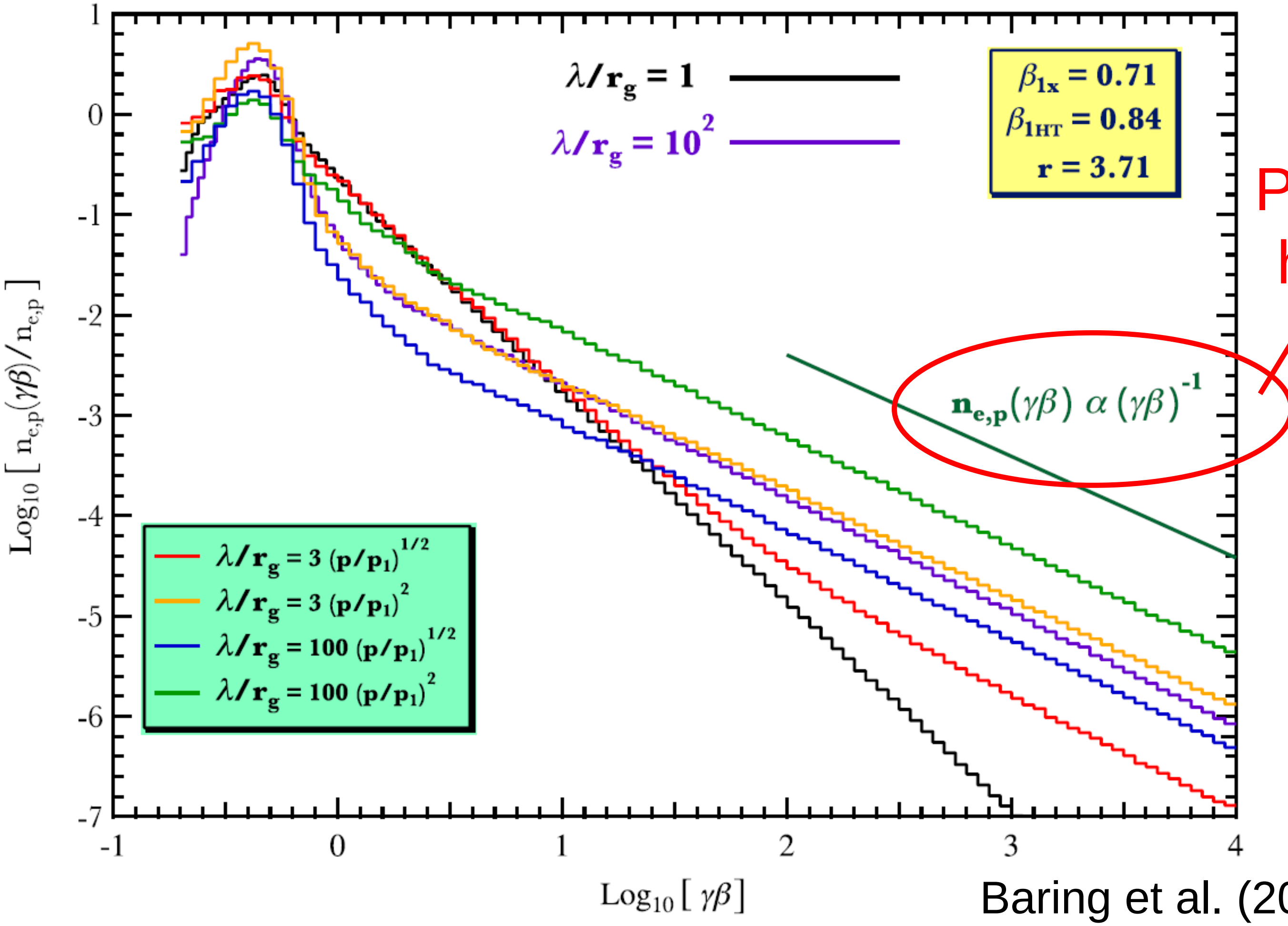


(Summerlin & Baring 2012)

- 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

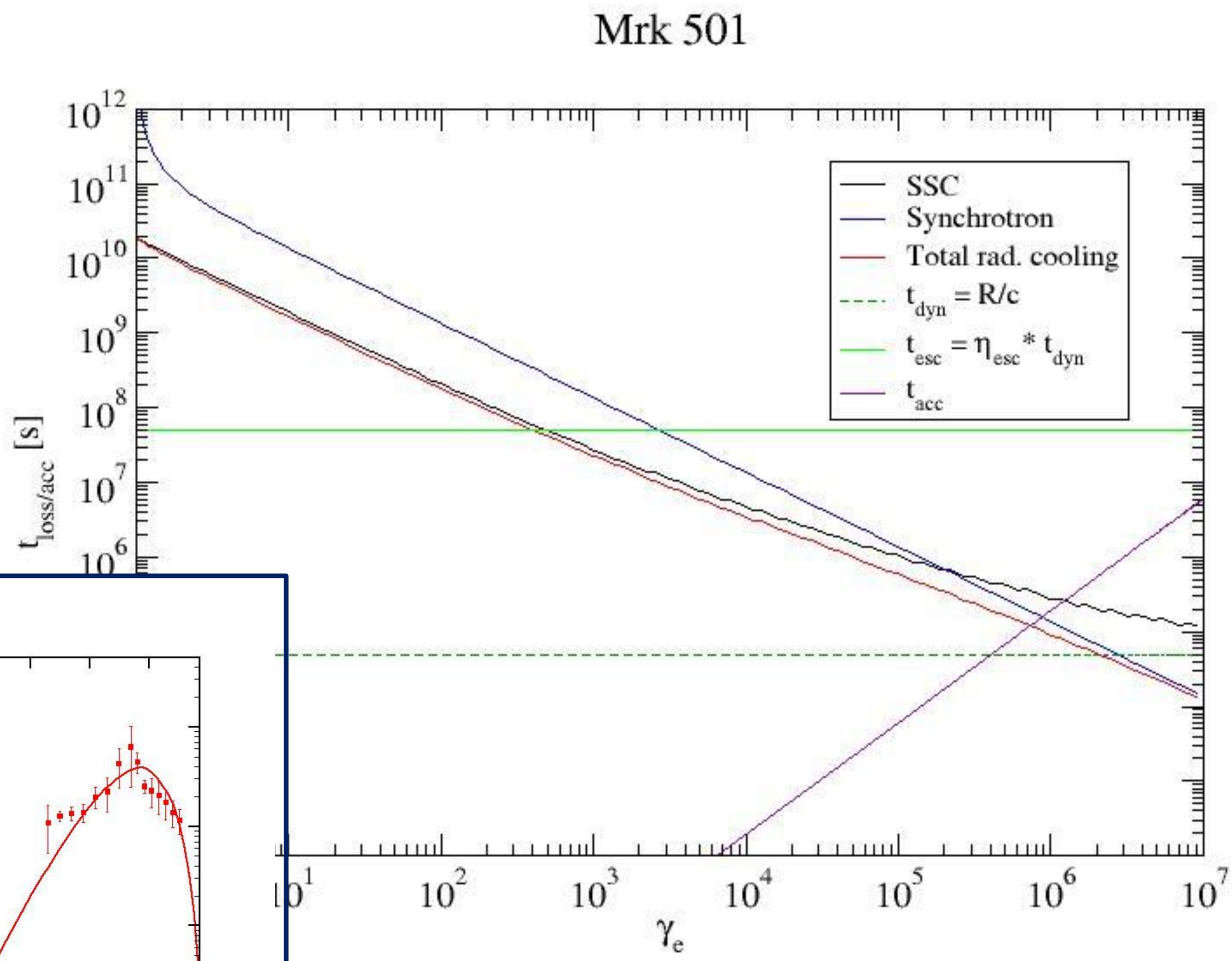


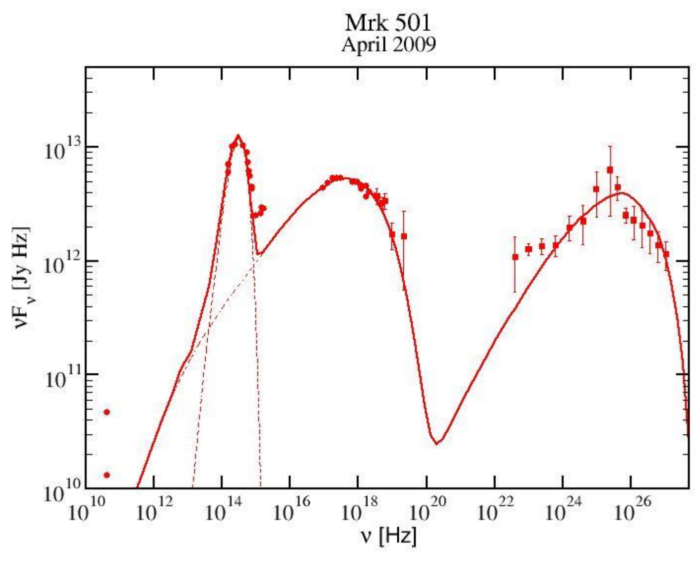
Particle spectra as hard as $n(\gamma) \sim \gamma^{-1}$ possible!

Baring et al. (2017)

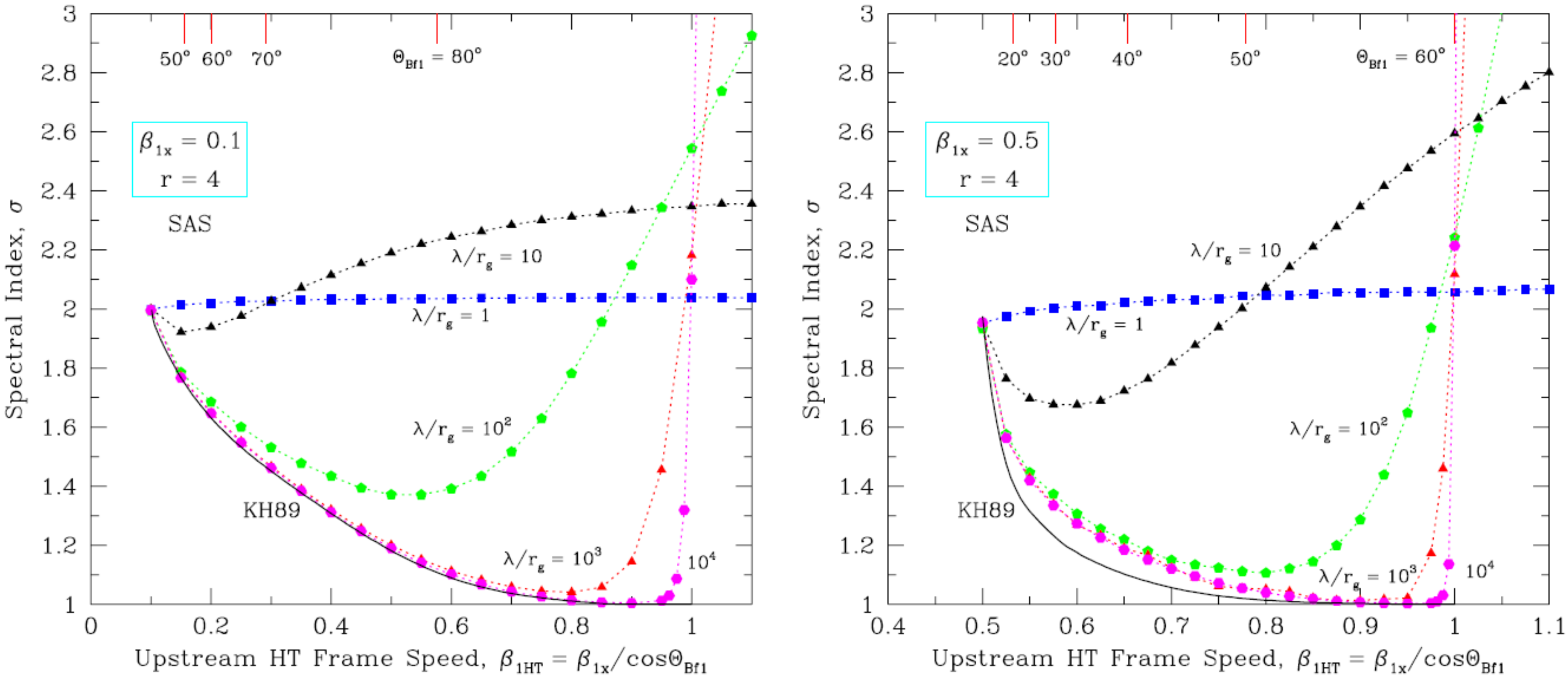
Non-thermal particle spectral index and thermal-to-non-thermal normalization are strongly dependent on η_0, α, and B-field obliquity!

Electron Evolution Time Scales





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

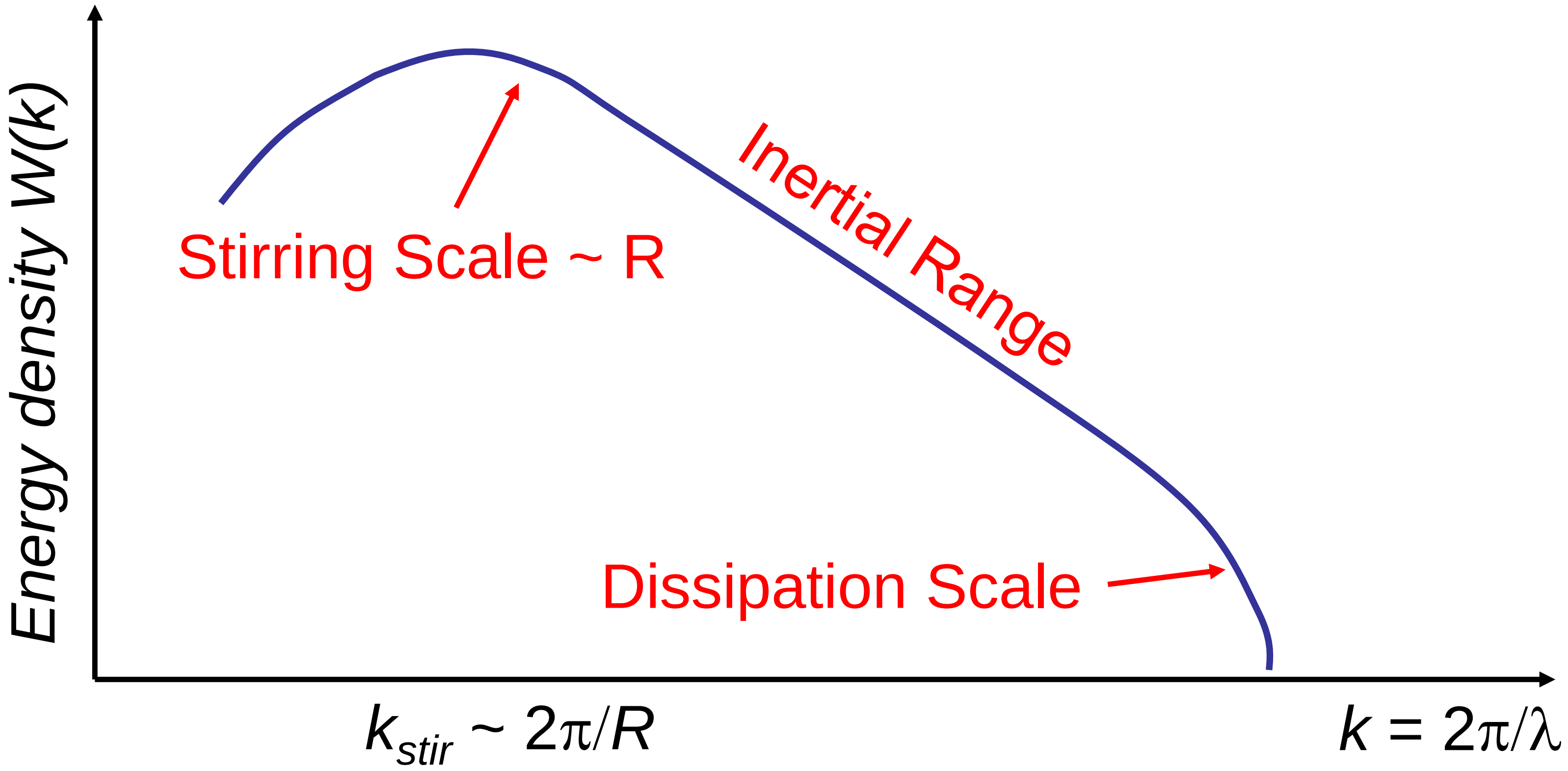
$\Rightarrow$ But: Need moderate $\eta(\gamma \sim 1)$ for efficient injection of particles into the non-thermal accelerations scheme

$\Rightarrow$ Need strongly energy dependent pitch-angle scattering m.f.p., with $\alpha > 1$ (Baring et al. 2017)

Implications for Shock-Induced Turbulence

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

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

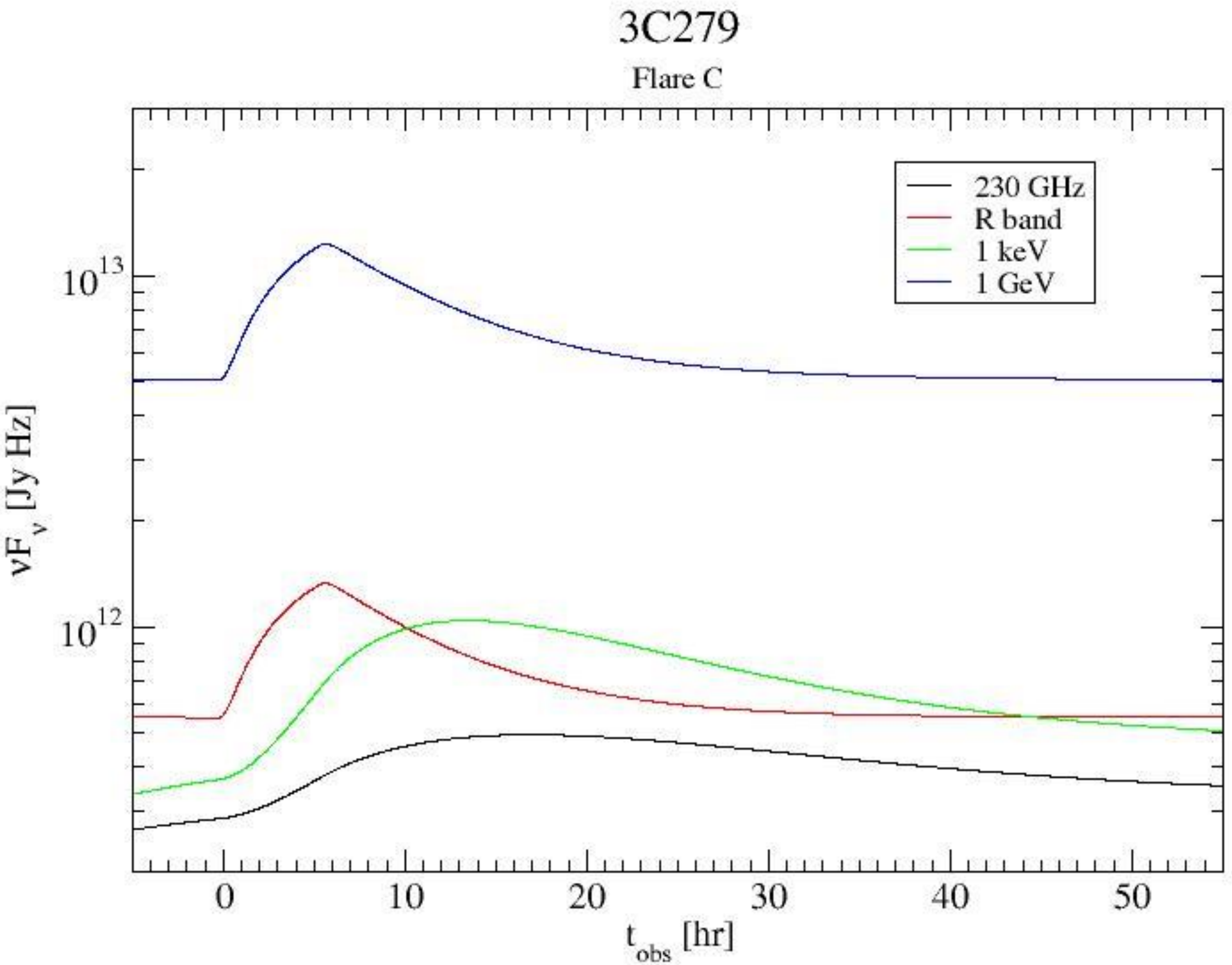


Turbulence level decreasing with increasing distance from the shock

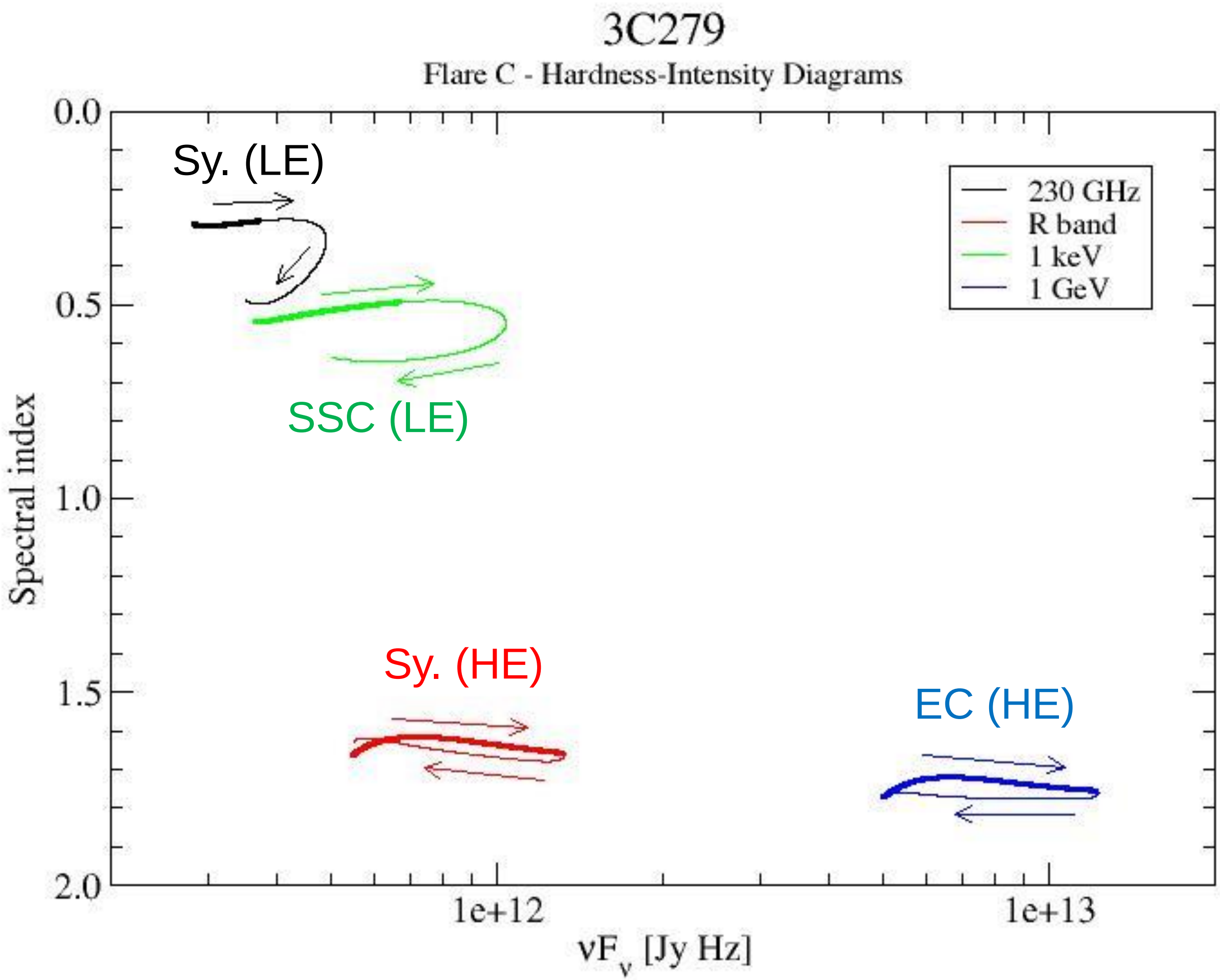
⇒ High-energy (large r_g) particles “see” reduced turbulence

⇒ Large λ_{pas}

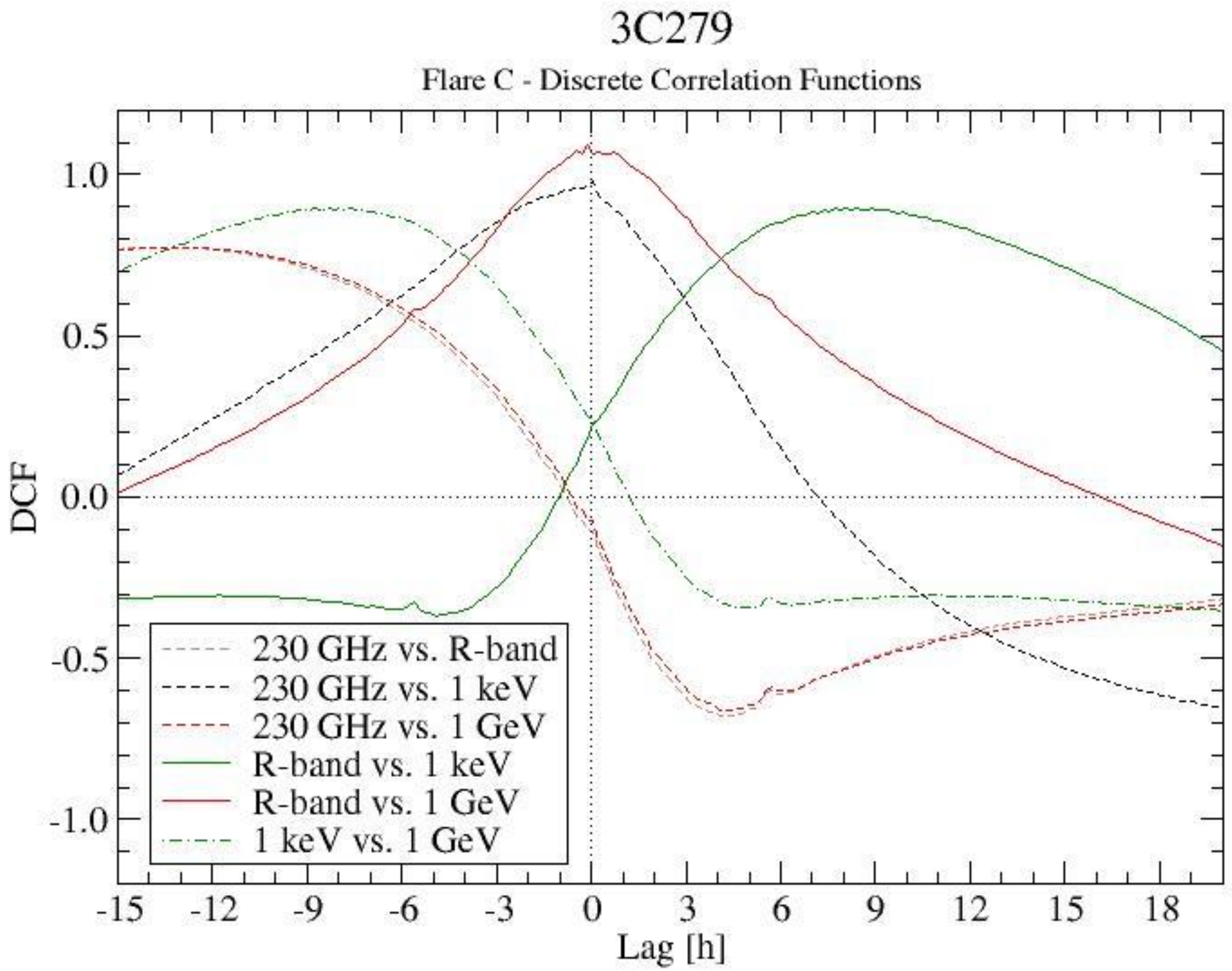
3C279 – Flare C
Model Light Curves



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 ~ 7 - 9 hr)