Modeling Blazar SEDs and Spectral Variability with Time-Dependent Diffusive Shock Acceleration:

Application to 1ES 1959+650 Observed with AstroSAT

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Based on Böttcher & Baring (2019): ApJ, 887, 133 (arXiv:1911.02834)
+ Chandra et al. (2021): ApJ, submitted

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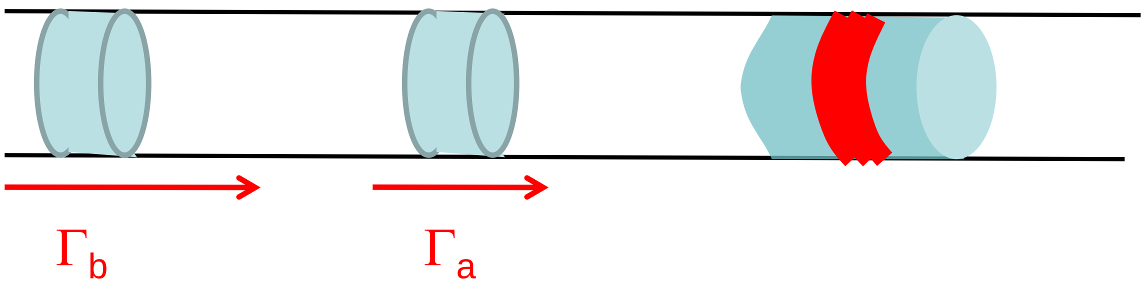
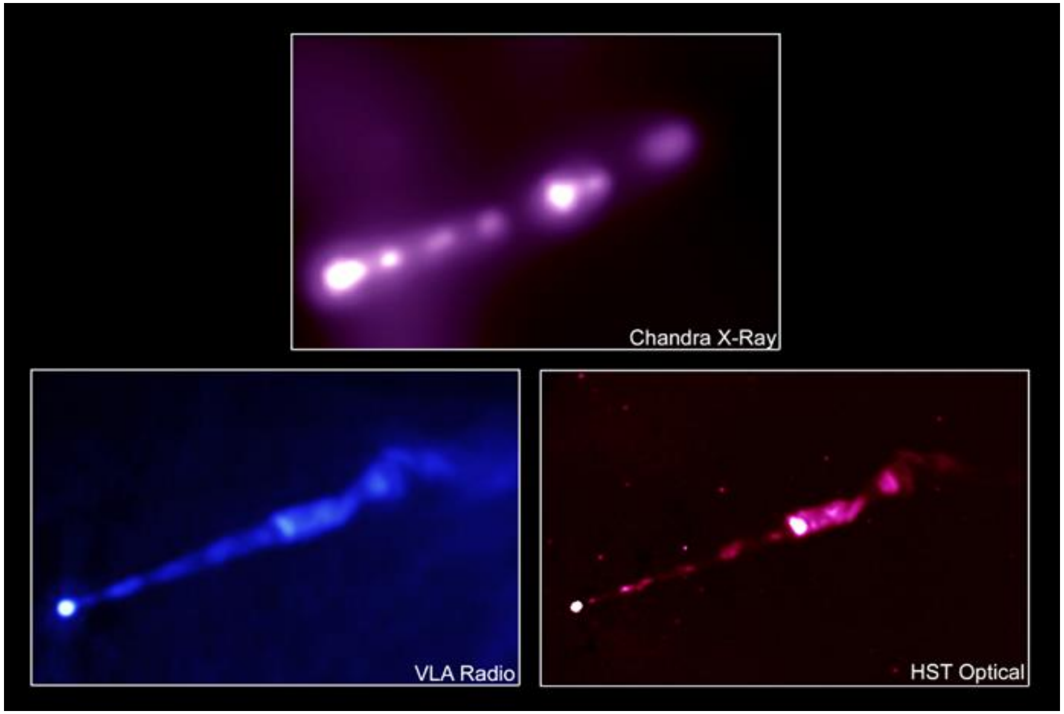
Relativistic Shocks in Jets



- 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".

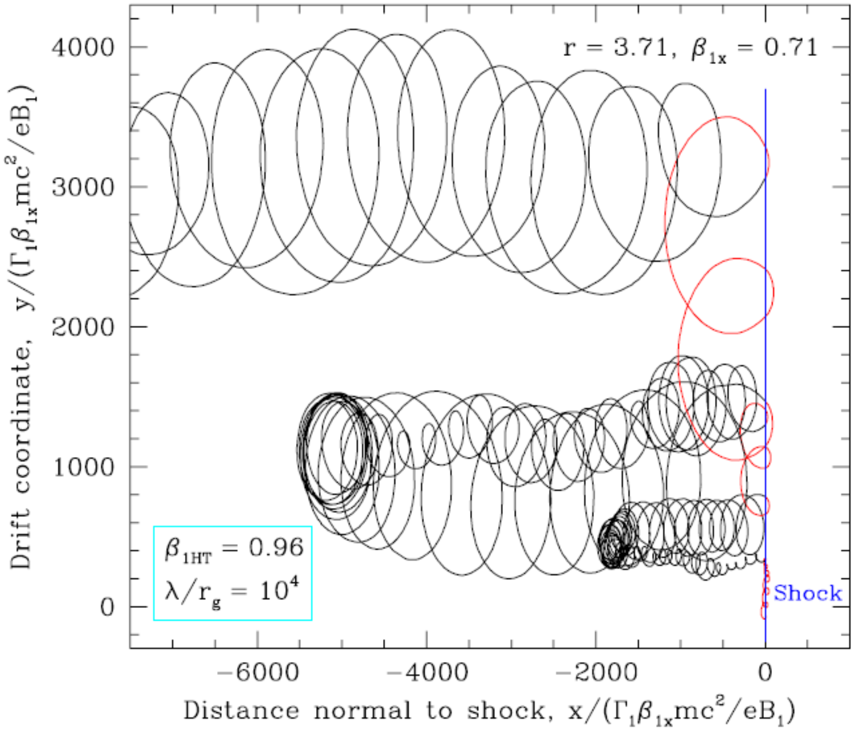


Jet of M87 at different wavelengths

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 → first-order Fermi.

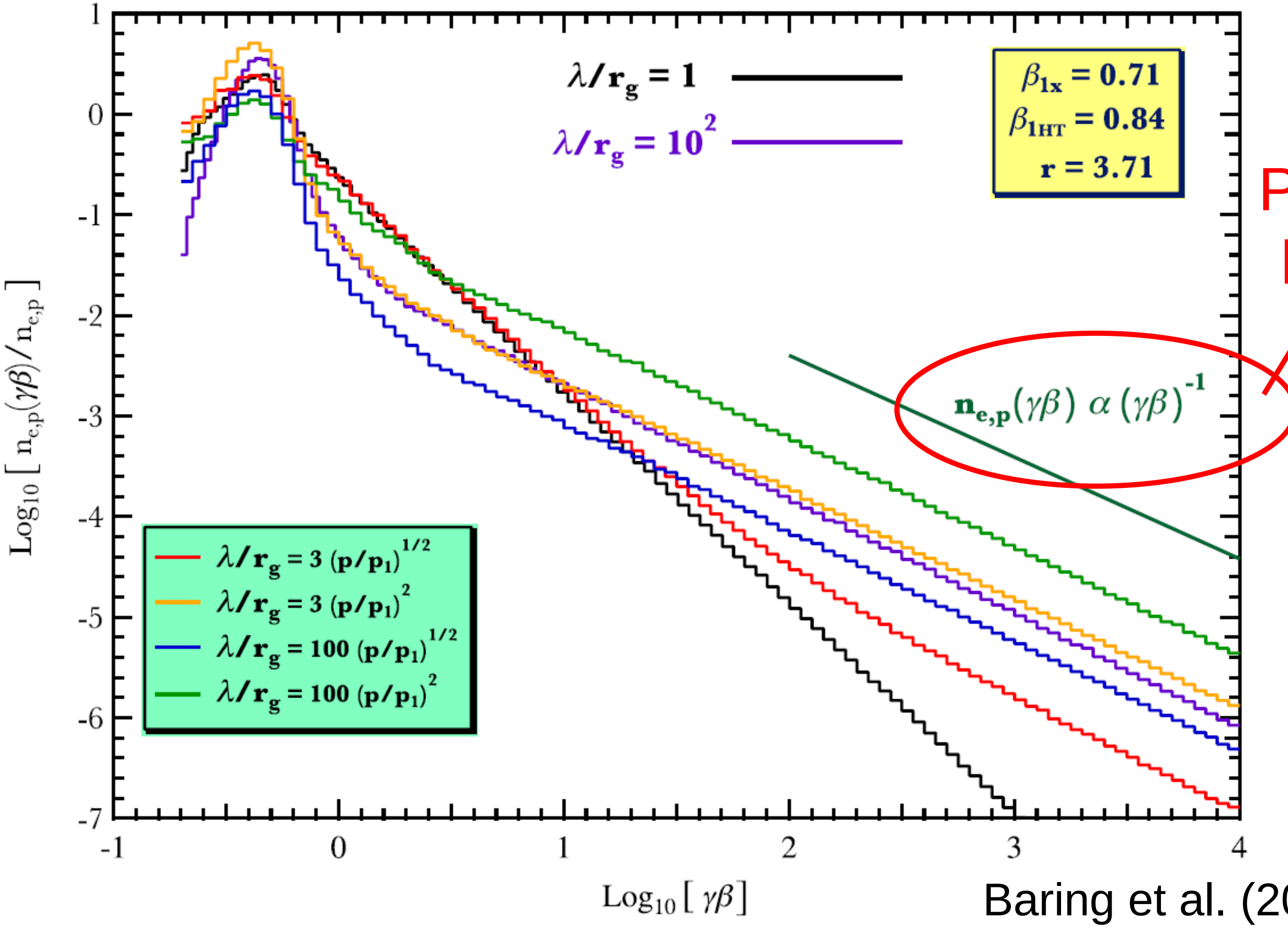


(Summerlin & Baring 2012)

- 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!

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

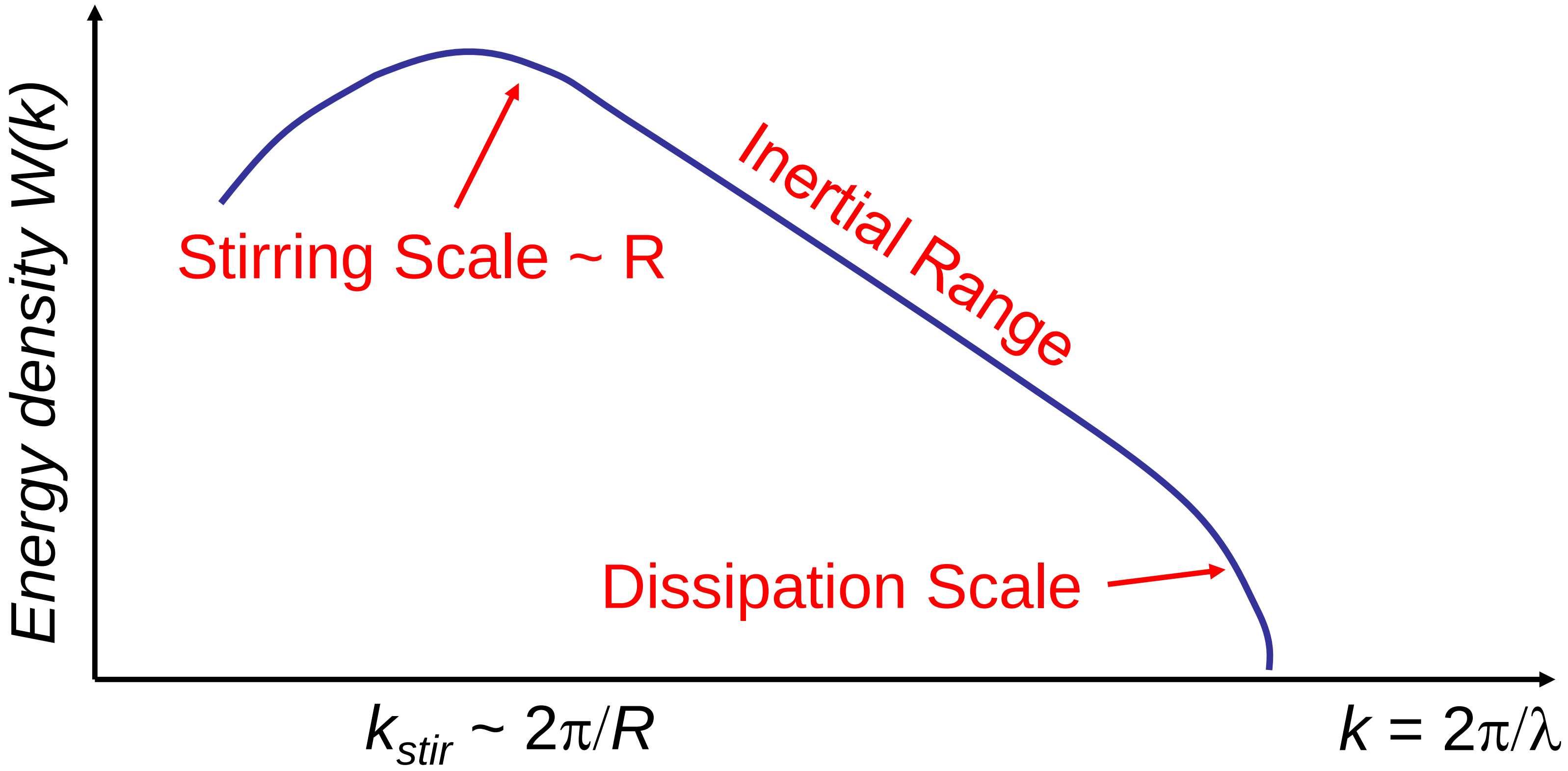
$\Rightarrow$ But: Need moderate $\eta(\gamma \sim 1)$ for efficient injection of particles into the non-thermal accelerations scheme

$\Rightarrow$ 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

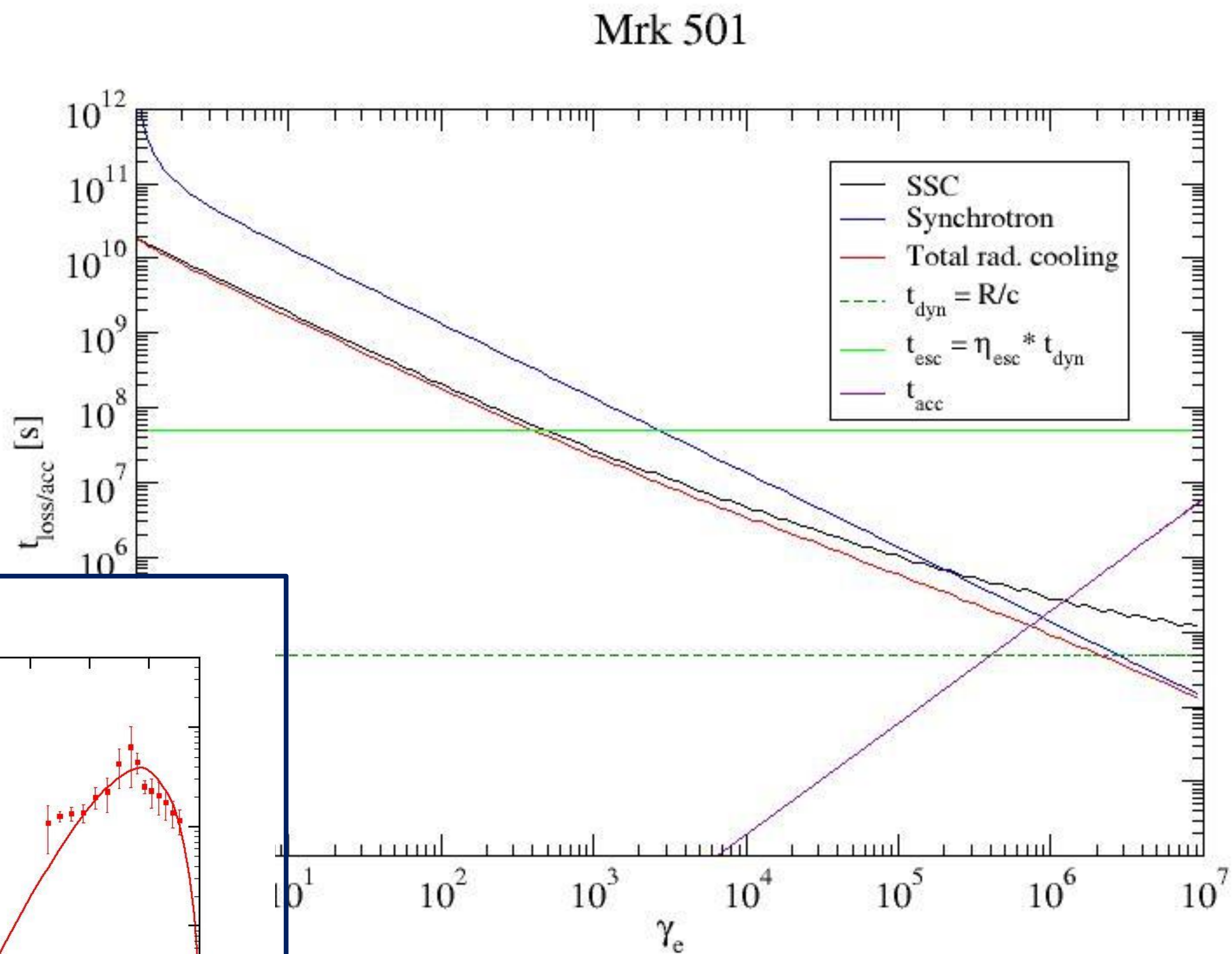


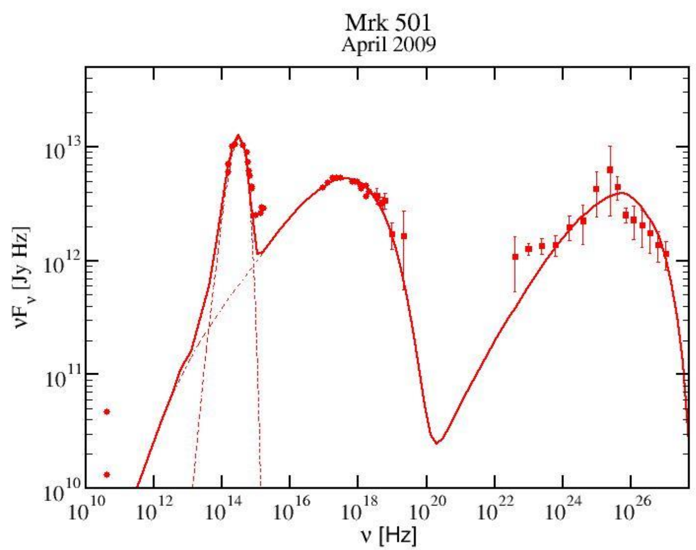
Turbulence level decreasing with increasing distance from the shock

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

⇒ Large λ_{pas}

Electron Evolution Time Scales





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

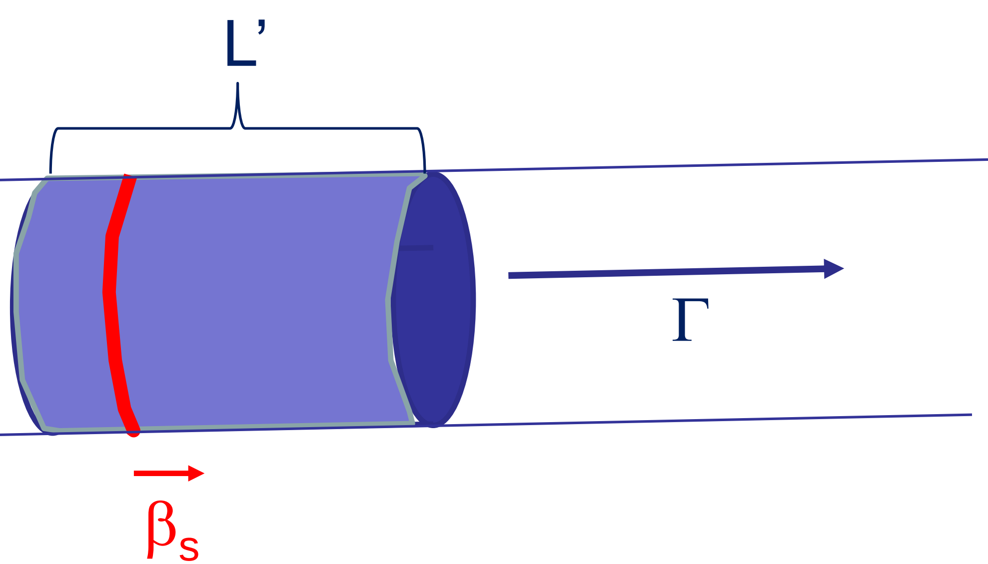
$\Rightarrow$ Use shock-accelerated electron spectrum as instantaneous injection $Q_e(\gamma)$;

$\Rightarrow$ 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)



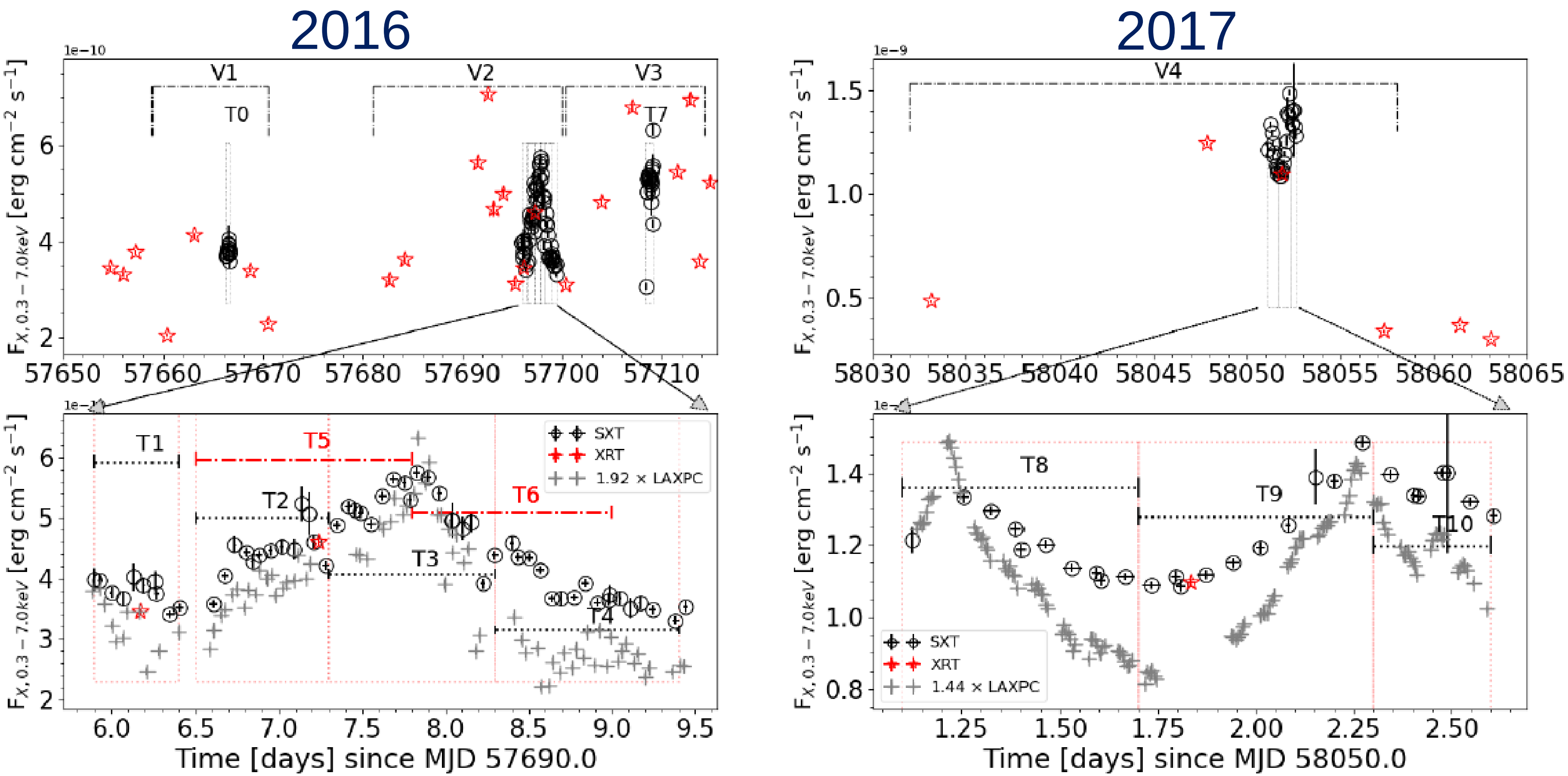
Shock injection "on" for

$0 < \Delta t' < L'/v'_s$

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

Example: HBL 1ES 1959+650

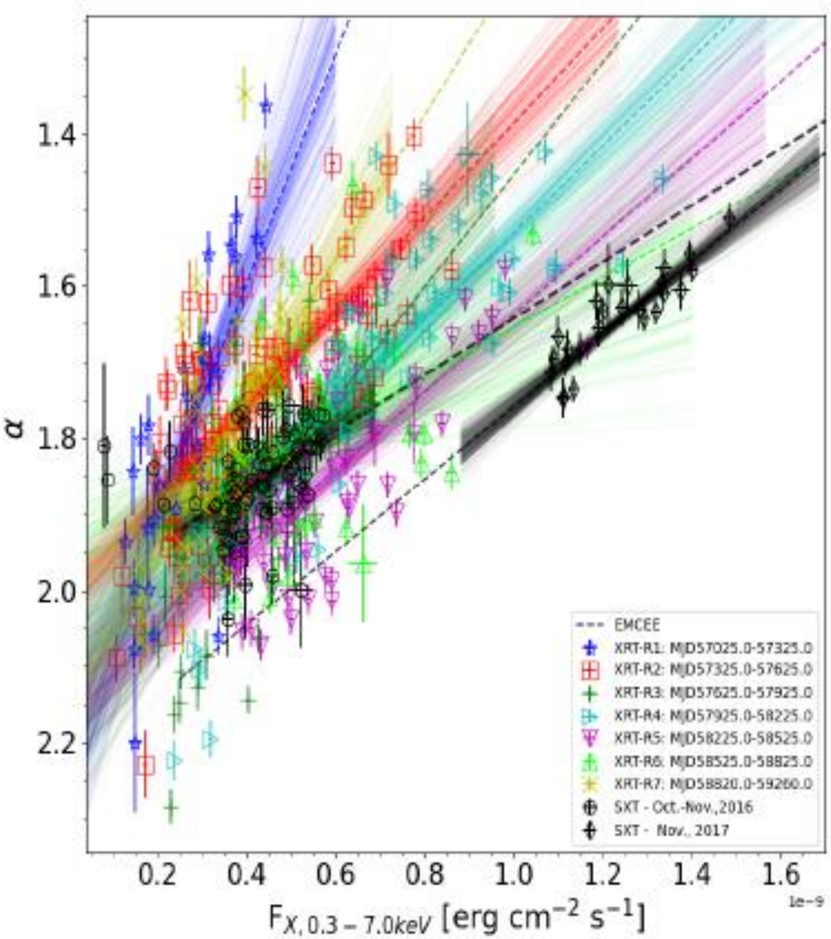
- Prototypical HSP BL Lac object at z = 0.048
- Observed with AstroSAT during flaring states in 2 long (144 ksec) observations in 2016 and 2017

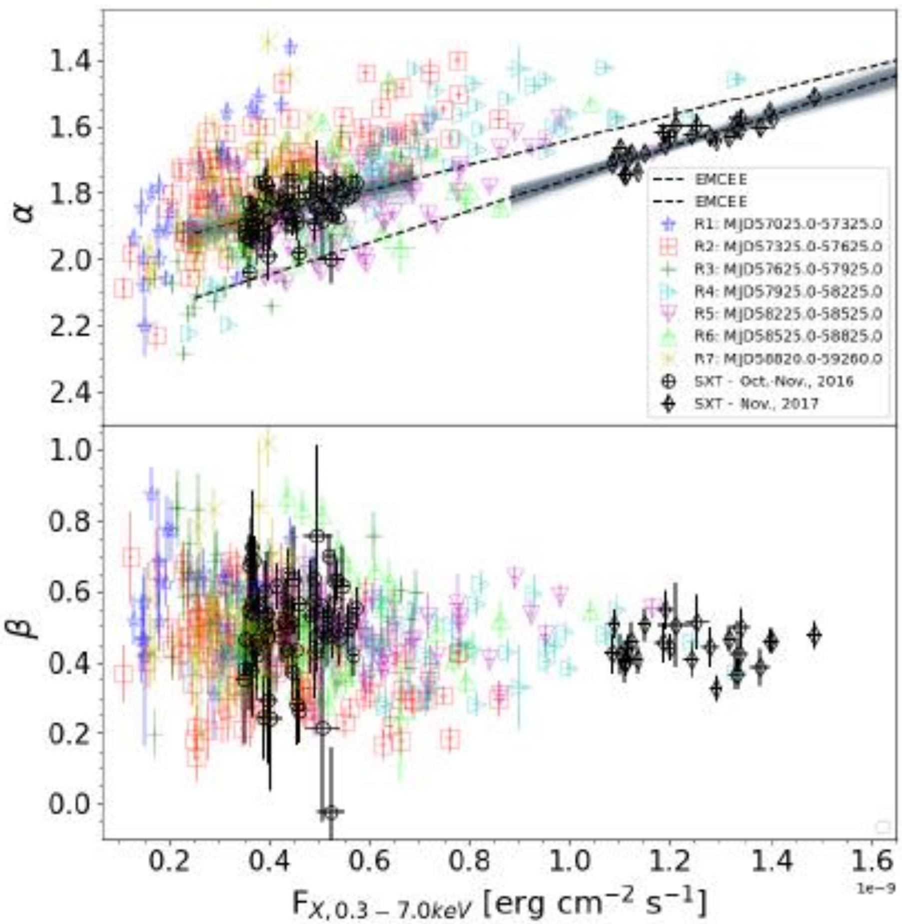


(Chandra et al. 2021)

Example: HBL 1ES 1959+650

- Pronounced spectral variability (harder when brighter)
- Log-parabolic spectral fits: $F_E \sim E^{-(\alpha + \beta \log[E/E0])}$

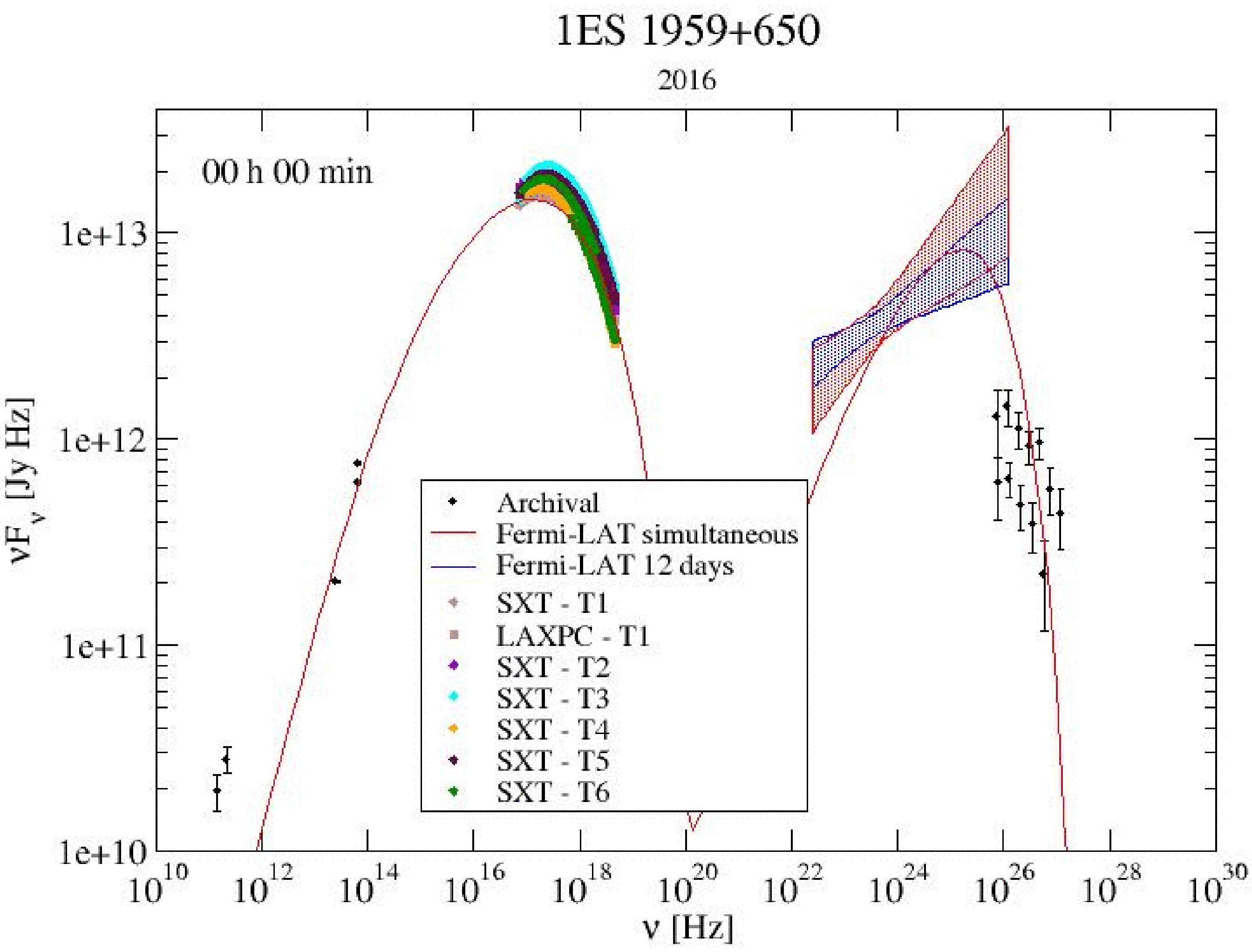




(Chandra et al. 2021)

1ES 1959+650 in 2016

Complex variability patterns require passage of multiple shocks.



(Chandra et al. 2021)

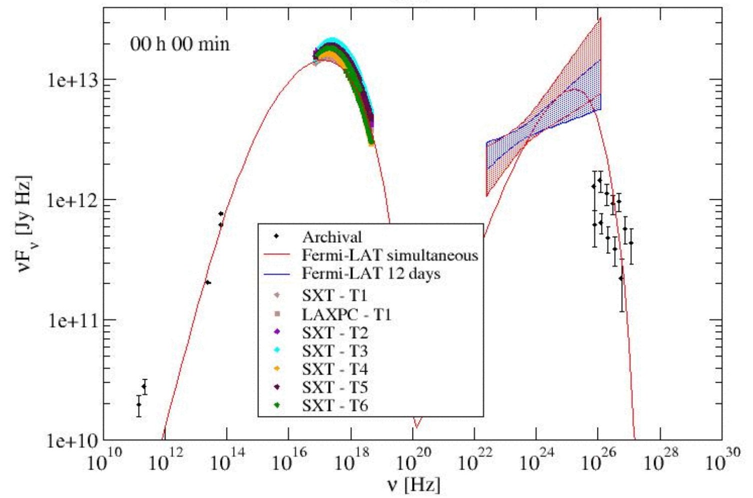
$\lambda_{pas} = 60\ r_g\ \gamma^{0.9}$

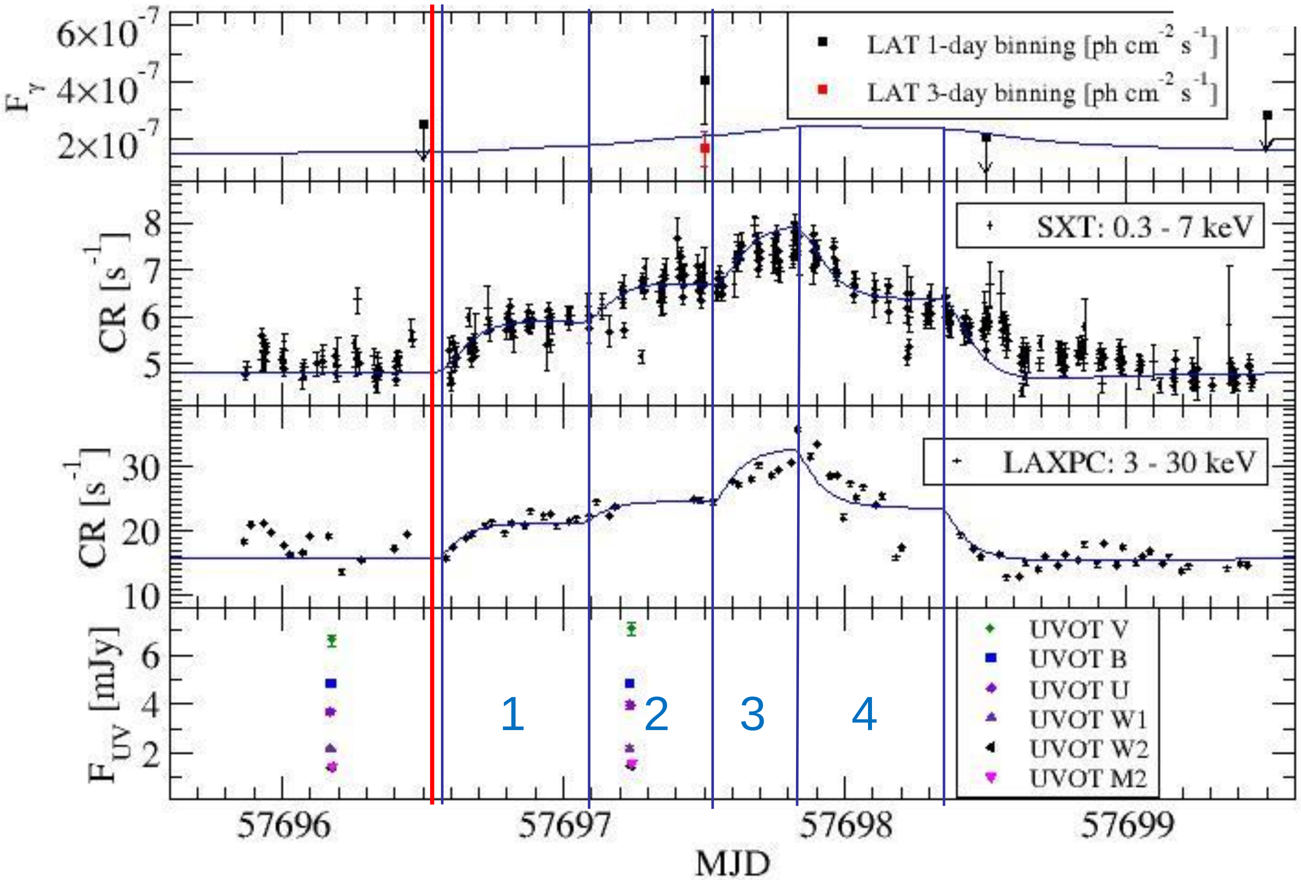
$\eta_1 = 60$
$\alpha = 1.9$
B = 0.15 G
$\delta = 20$
R = $6*10^{15}$ cm
-> $\Delta t' \sim 2*10^5$ s
-> $\Delta t_{obs} \sim 2.8$ h

Flaring caused by
- increasing L_{inj}
- decreasing η_0

2016: MWL Light Curves

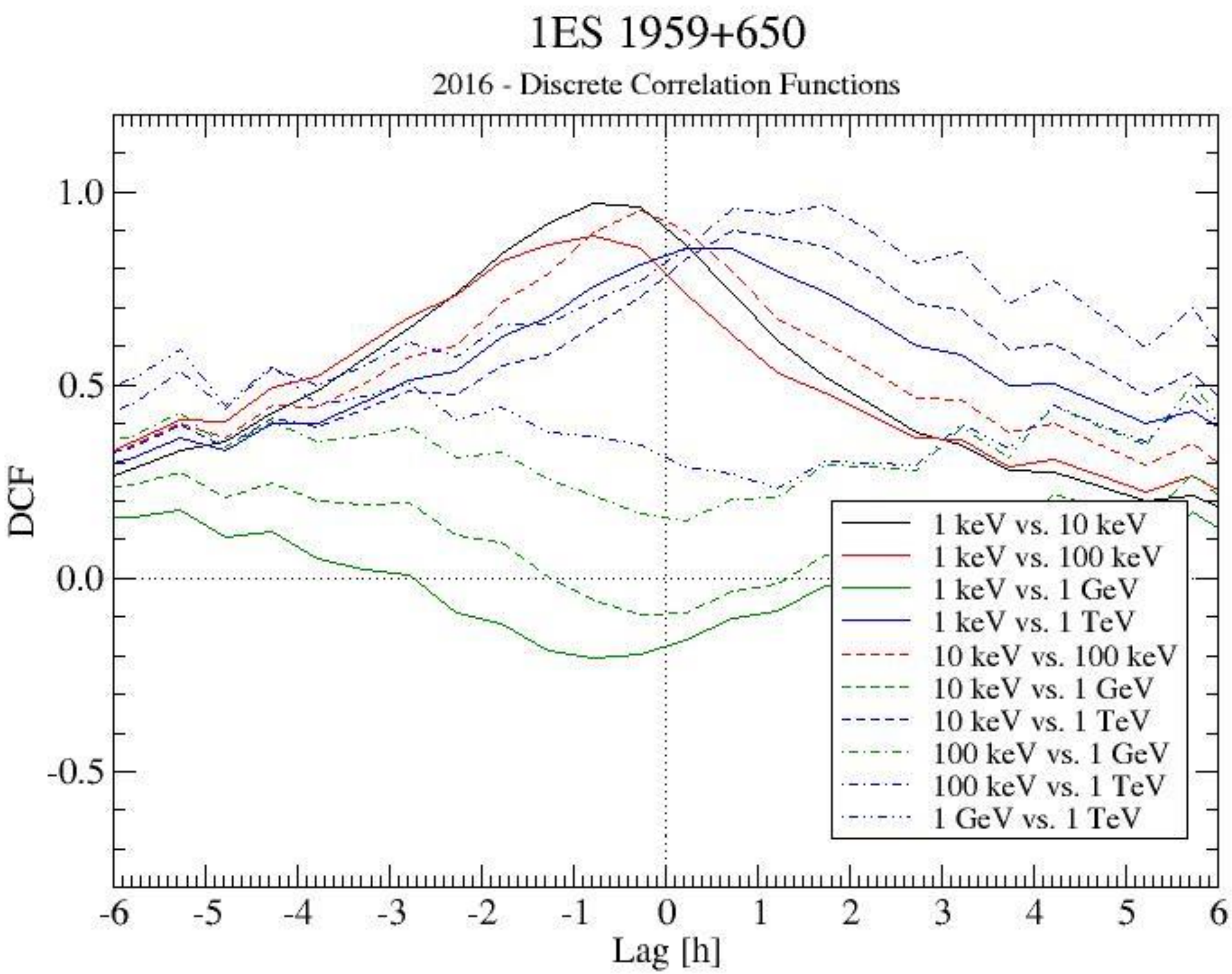
Parameter [units]	$L_{\rm inj}$ [erg/s]	η_0	α
Quiescence	2.5×10^{40}	60	1.9
Shock 1	3.0×10^{40}	50	1.9
Shock 2	3.5×10^{40}	50	1.9
Shock 3	4.1×10^{40}	40	1.9
Shock 4	3.4×10^{40}	50	1.9





(Chandra et al. 2021)

2016: Discrete Correlation Functions

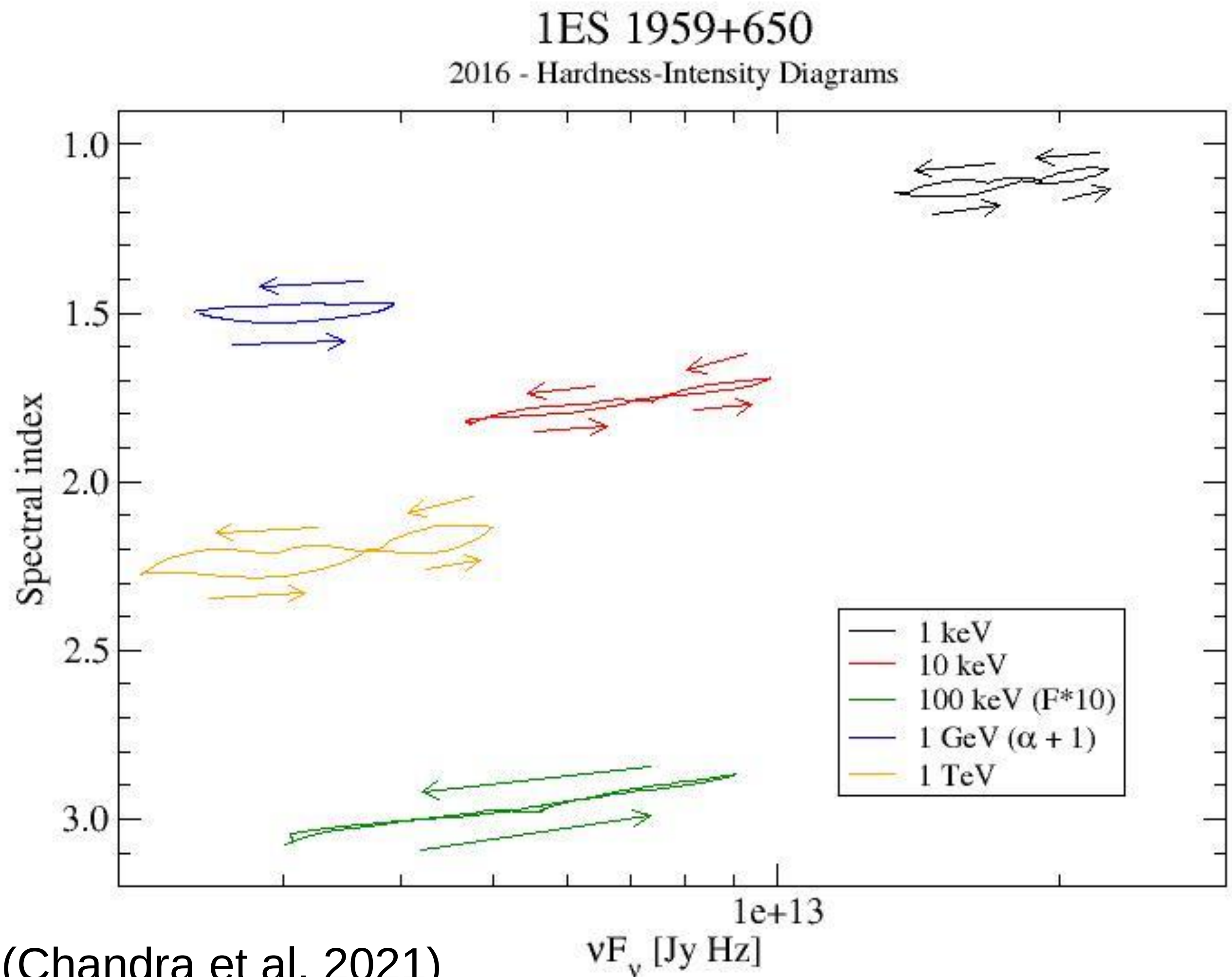


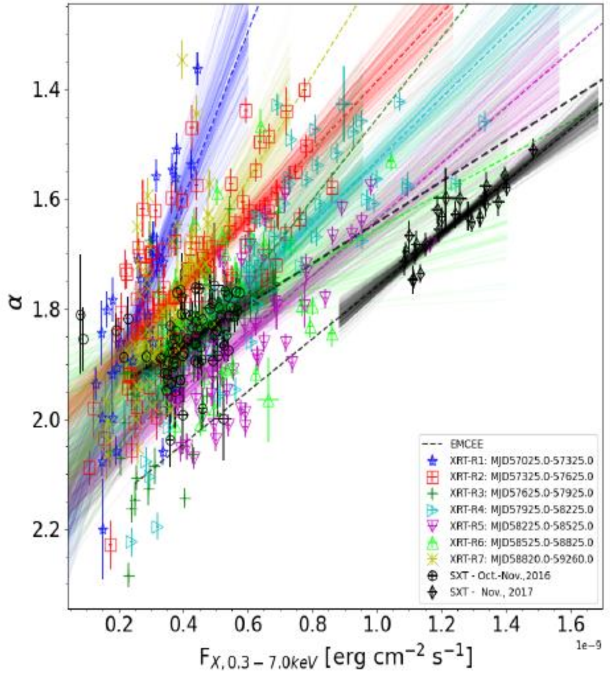
(Chandra et al. 2021)

Strong correlations between X-rays and VHE γ-rays

Soft X-ray lags of ~ 1 hour behind hard X-rays and VHE γ-rays.

2016: Hardness-Intensity Diagrams





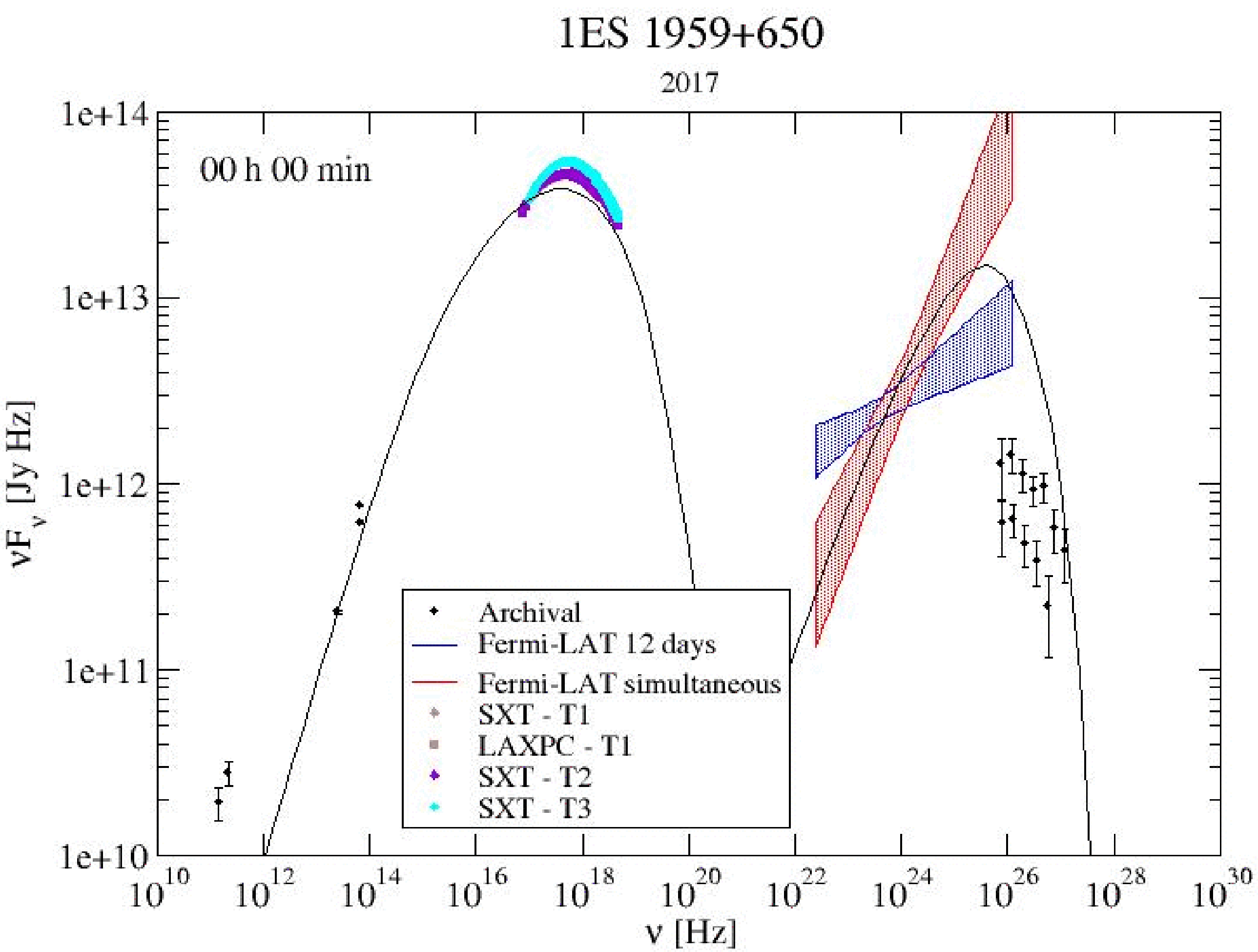
Harder-when-brighter trend without significant spectral hysteresis is well reproduced.

(Chandra et al. 2021)

1ES 1959+650 in 2017

Higher flux state well reproduced by changing Doppler factor (smaller viewing angle θ_{obs}: 2.87° → 2.34°)

$\lambda_{pas} = 40\ r_g\ \gamma^{0.8}$



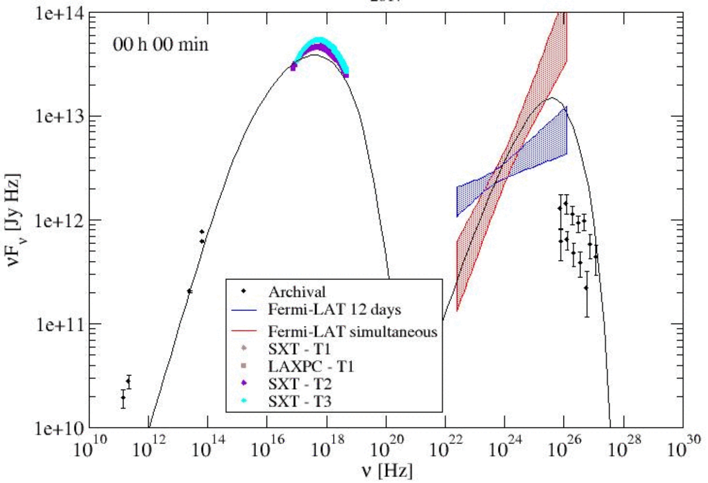
(Chandra et al. 2021)

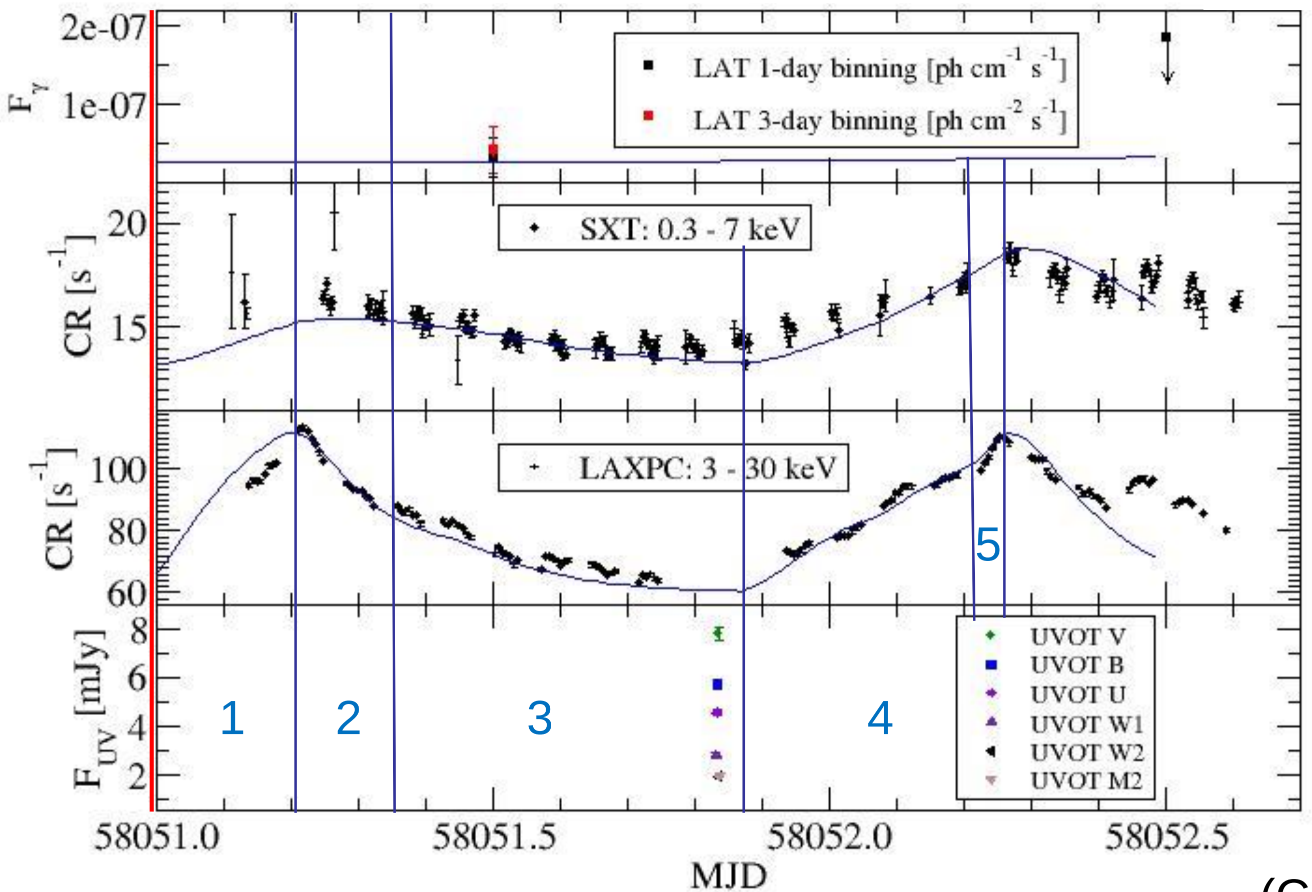
- $\eta_1 = 40$
- $\alpha = 1.8$
- B = 0.08 G
- $\delta = 24$
- R = 10^{16} cm
- -> $\Delta t' \sim 3 \times 10^5$ s
- -> $\Delta t_{obs} \sim 3.9$ h

Flaring caused by
- increasing L_{inj}
- decreasing η_0
- decreasing α

2017: MWL Light Curves

Parameter [units]	L_{inj} [erg/s]	η_0	α
Quiescence	2.8×10^{40}	40	1.8
Shock 1	3.5×10^{40}	30	1.7
Shock 2	3.0×10^{40}	30	1.8
Shock 3	3.6×10^{40}	25	1.8
Shock 4	4.3×10^{40}	25	1.8
Shock 5	5.1×10^{40}	15	1.8





(Chandra et al. 2021)

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, applied to long AstroSAT + MWL observations of 1ES 1959+650 in 2016 and 2017:

3. Flares with harder-when-brighter trend (no significant spectral hysteresis) well reproduced by decreasing pitch-angle-scattering mean-free path → increased turbulence levels induced by shock passage.

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Thank you!

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