Gamma-Ray Flares and Optical Polarization Angle Swings Reveal Magnetic Reconnection in Blazars

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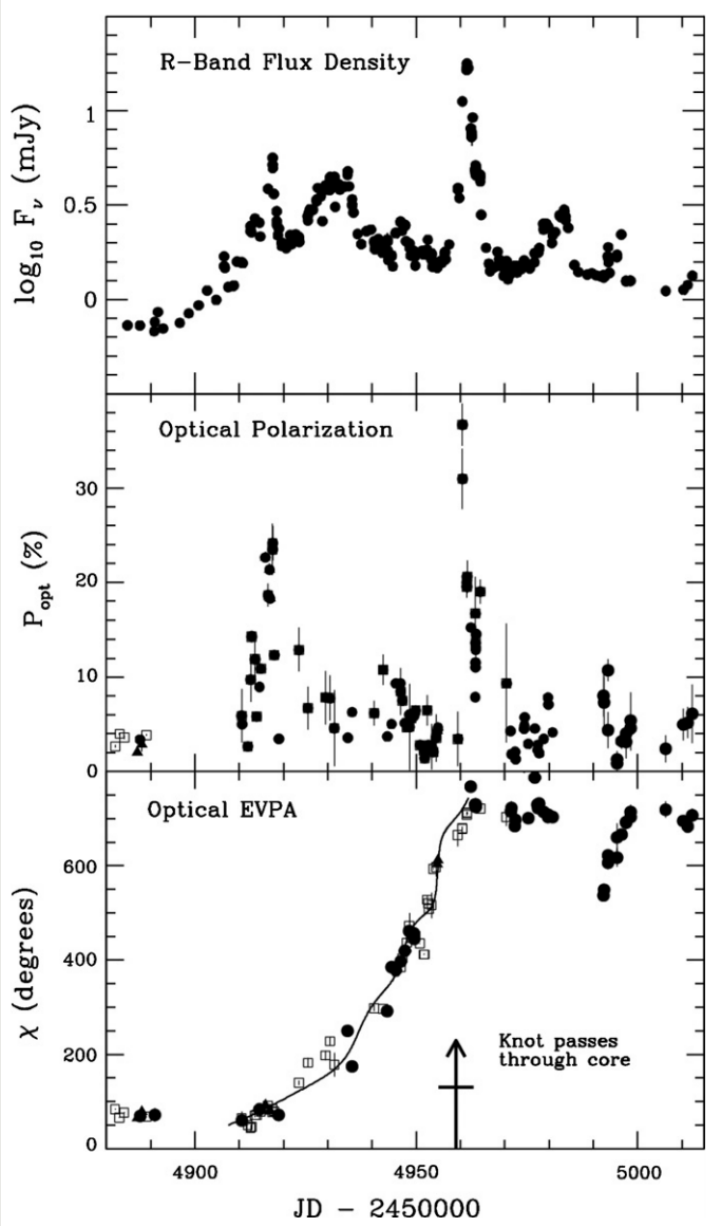
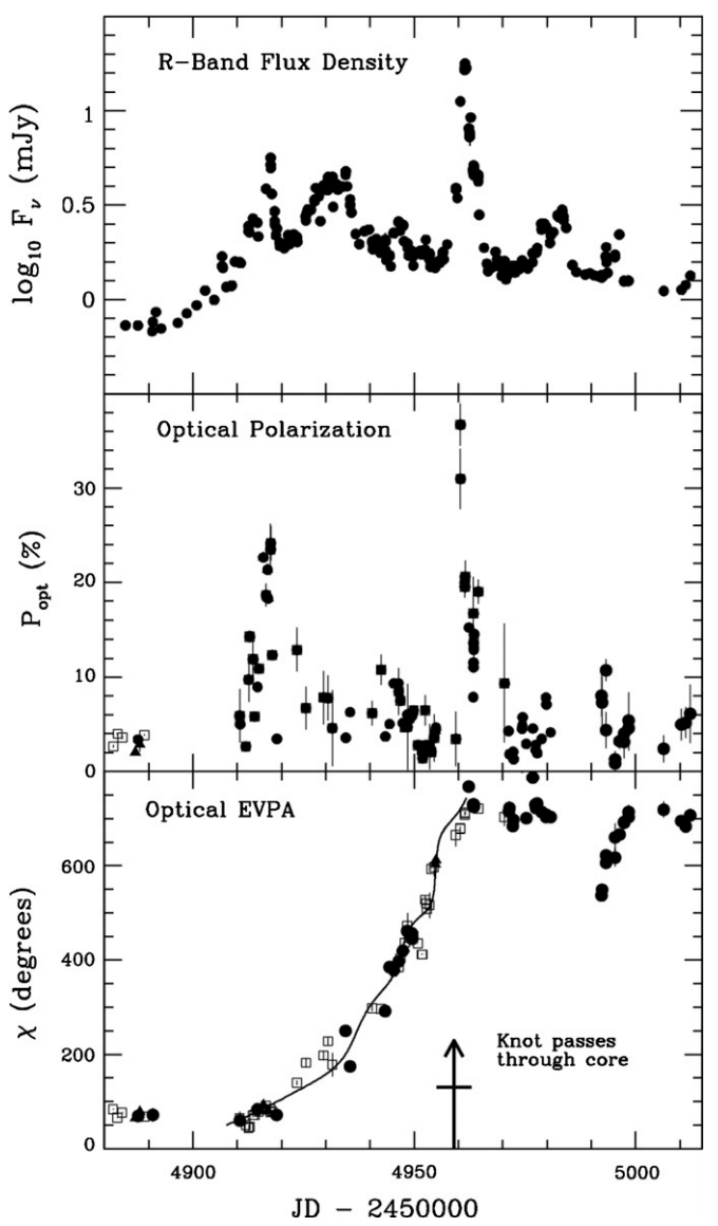
Polarization Contains Key Information



Marscher et al. 2010 ApJL 710, L126

Polarization Contains Key Information



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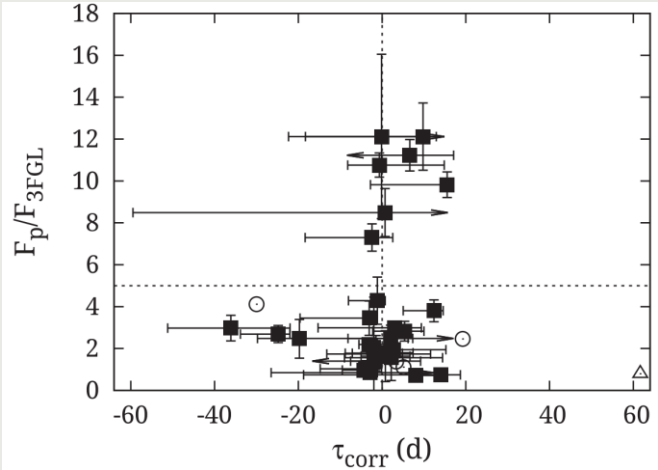
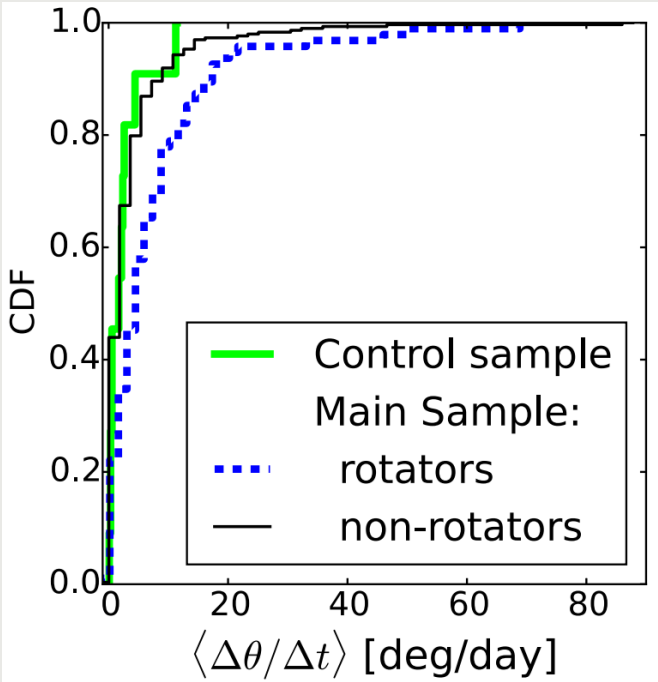


Blinov et al. 2018 MNRAS 474, 1296



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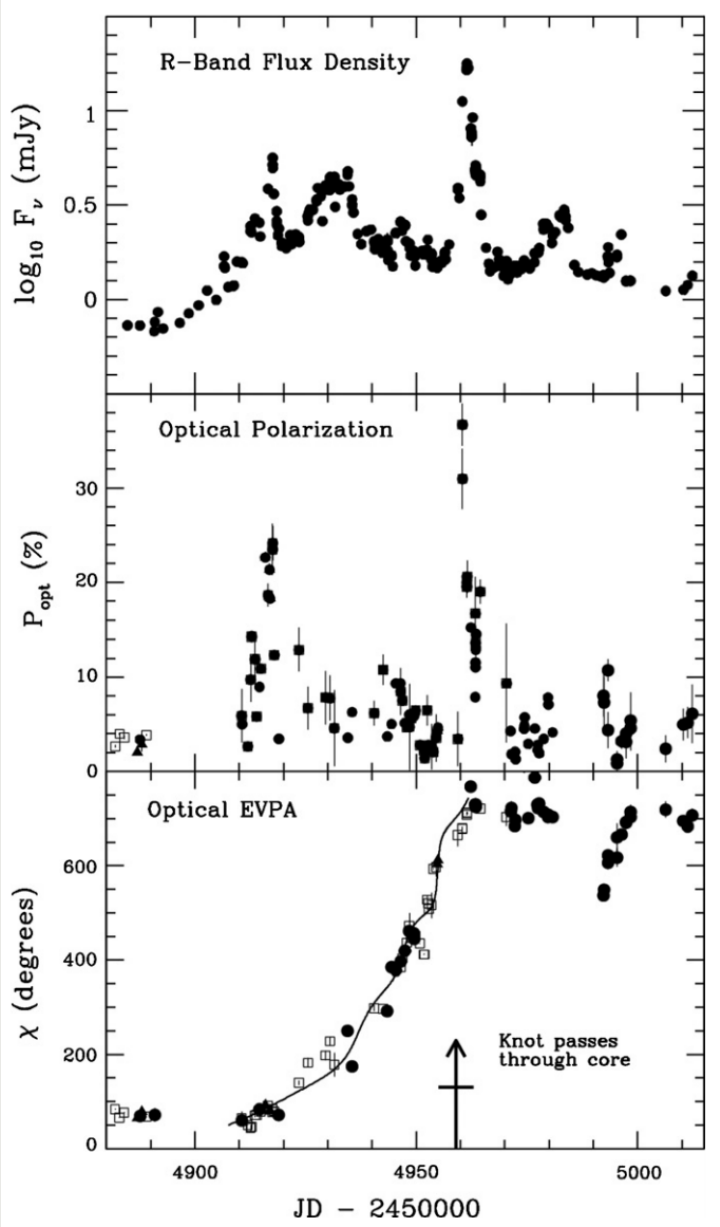

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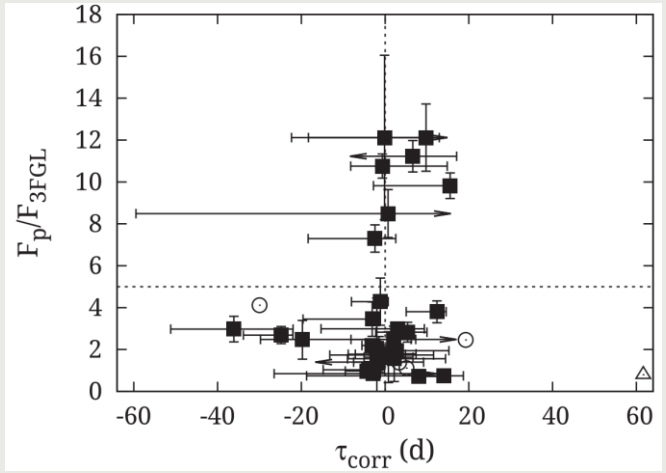

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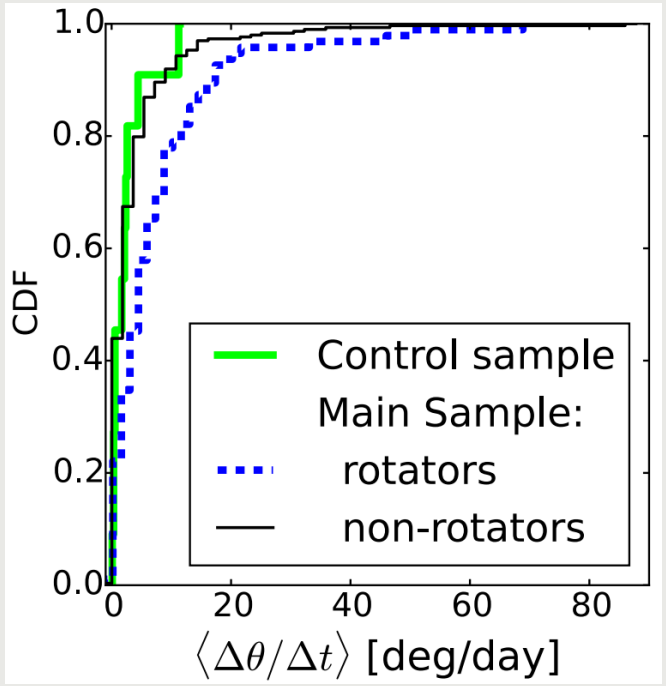

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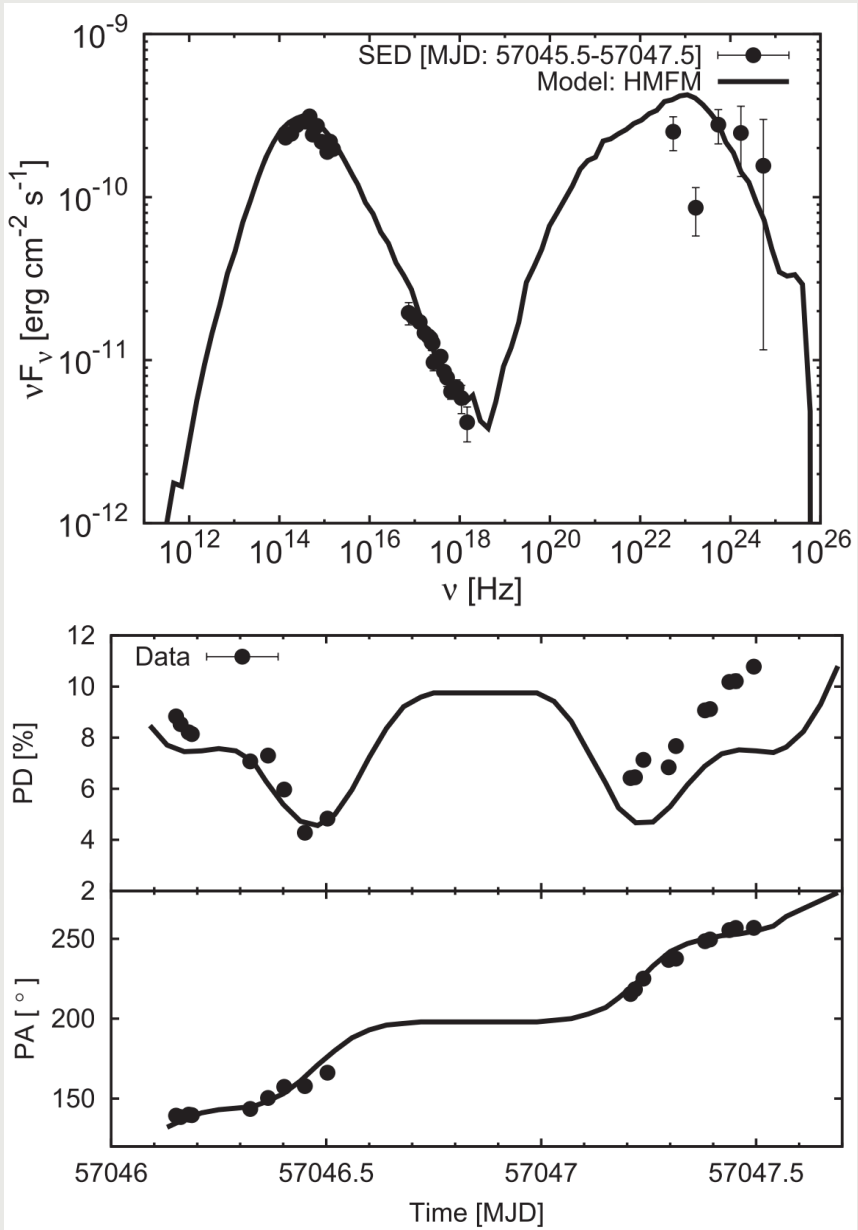
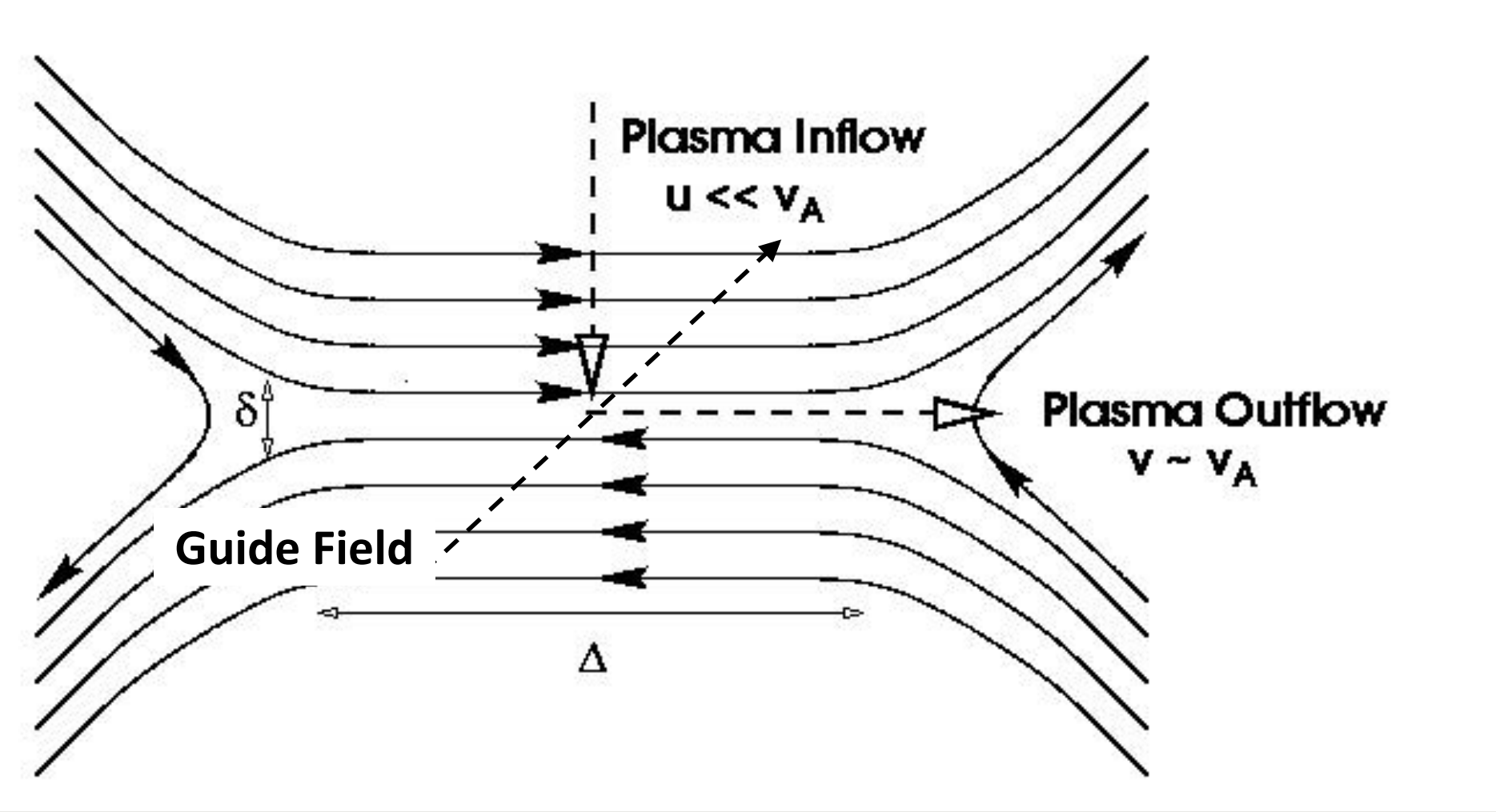


Chandra et al. 2015 ApJ 809, 130

Shock vs Magnetic Reconnection vs Turbulence

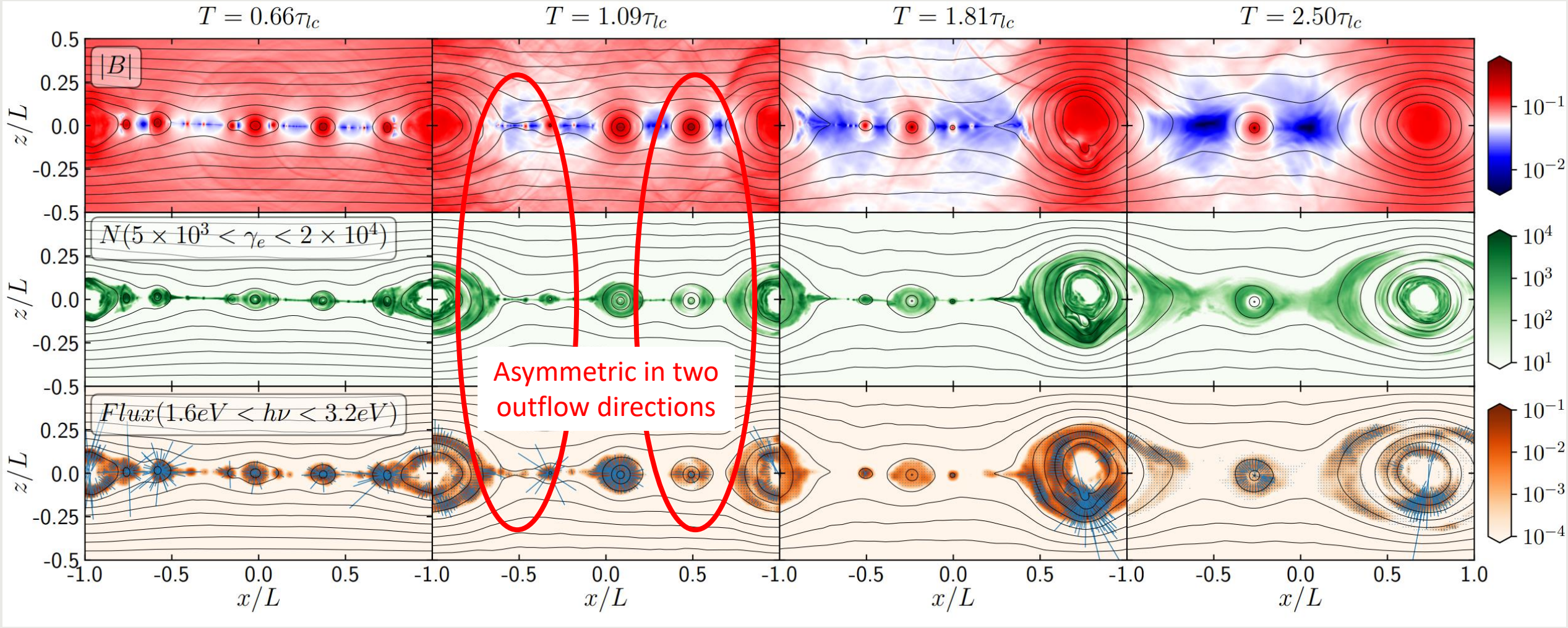
- All three mechanisms can lead to typical blazar flares and power-law spectra.
- However, they require very different physical conditions in the blazar zone, implying distinct jet energy evolution during the jet propagation.
- They involve different magnetic field evolution, which can be examined with polarization.

Magnetic Reconnection



Magnetic reconnection is a plasma physical process where oppositely directed magnetic field lines rearrange the topology and release a large amount of magnetic energy.

Particle-In-Cell with Radiation Transfer Simulation

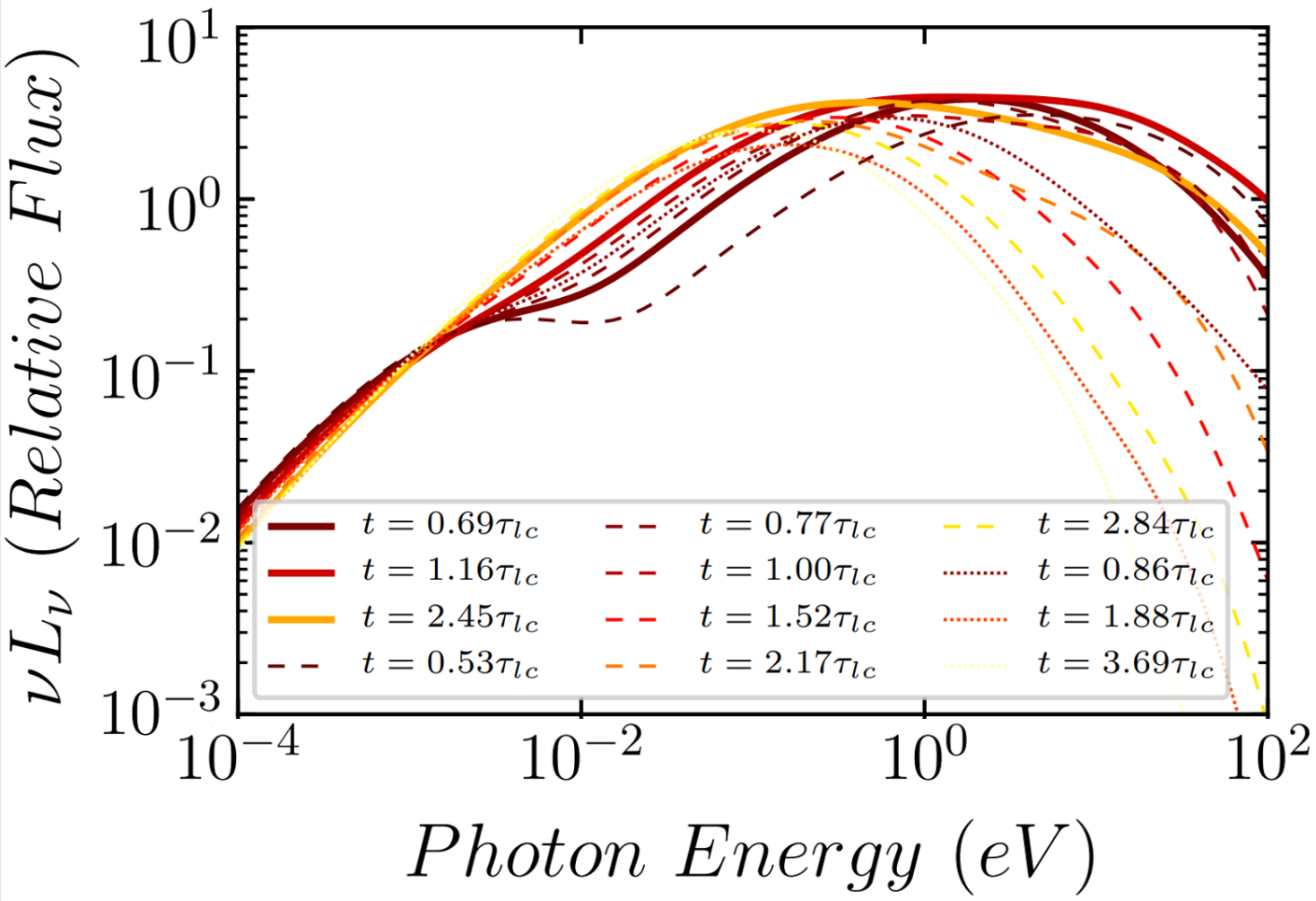


Zhang et al. 2020 ApJ 901, 149

First-principle treatment of all relevant plasma processes including radiative cooling.

Key radiation signatures do not rely on kinetic-scale physics.

Harder-When-Brighter Trend



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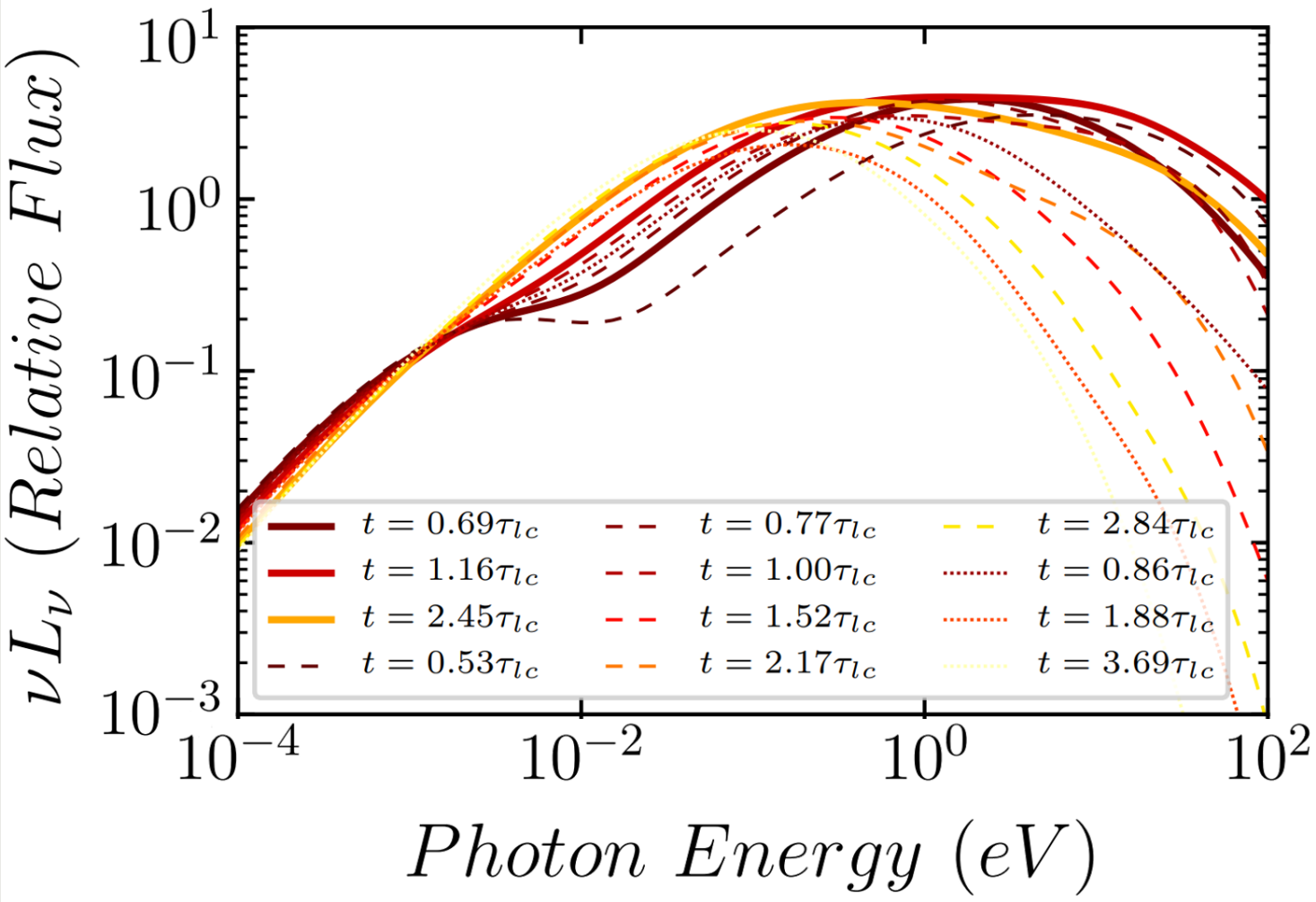
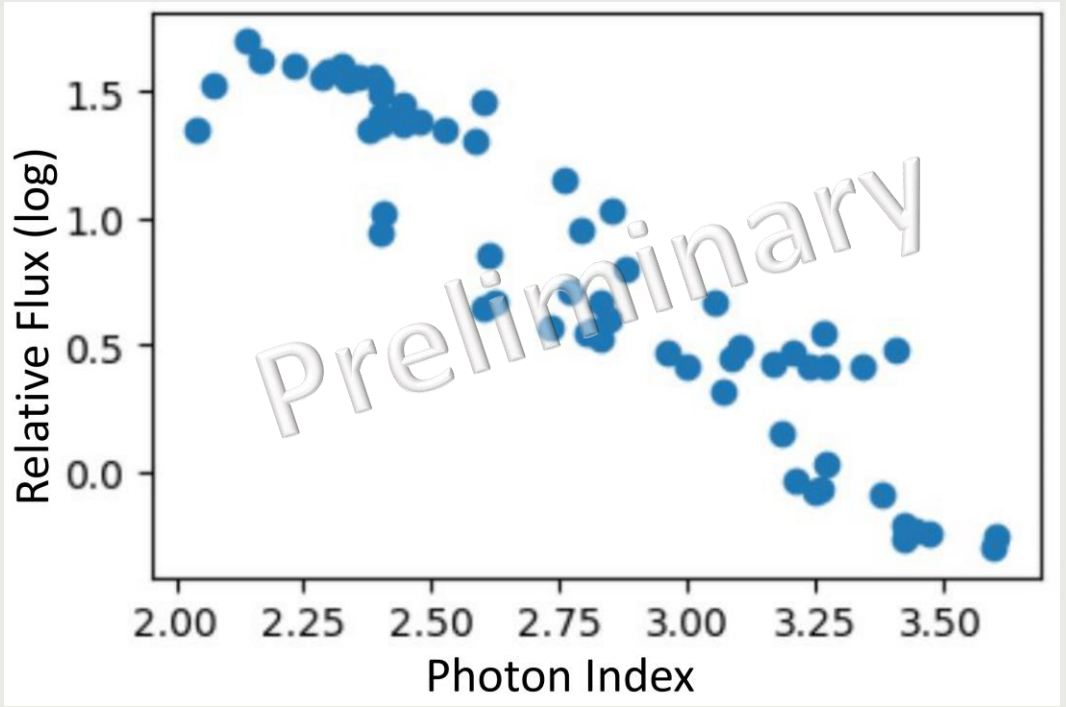
Magnetic reconnection predicts a harder-when-brighter trend near and beyond the cooling break.

Harder-When-Brighter Trend





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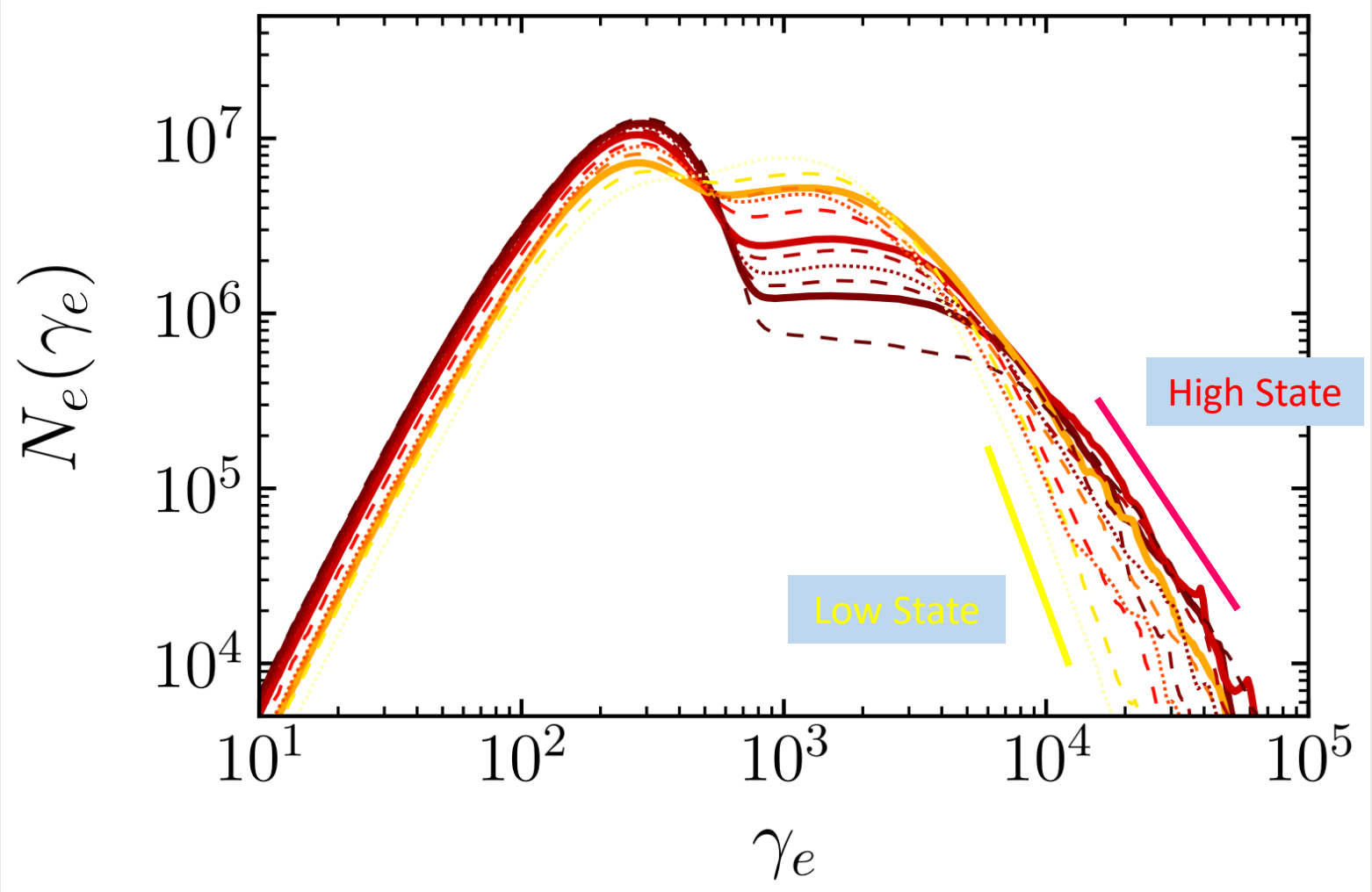
Physical Reason Behind Harder-When-Brighter



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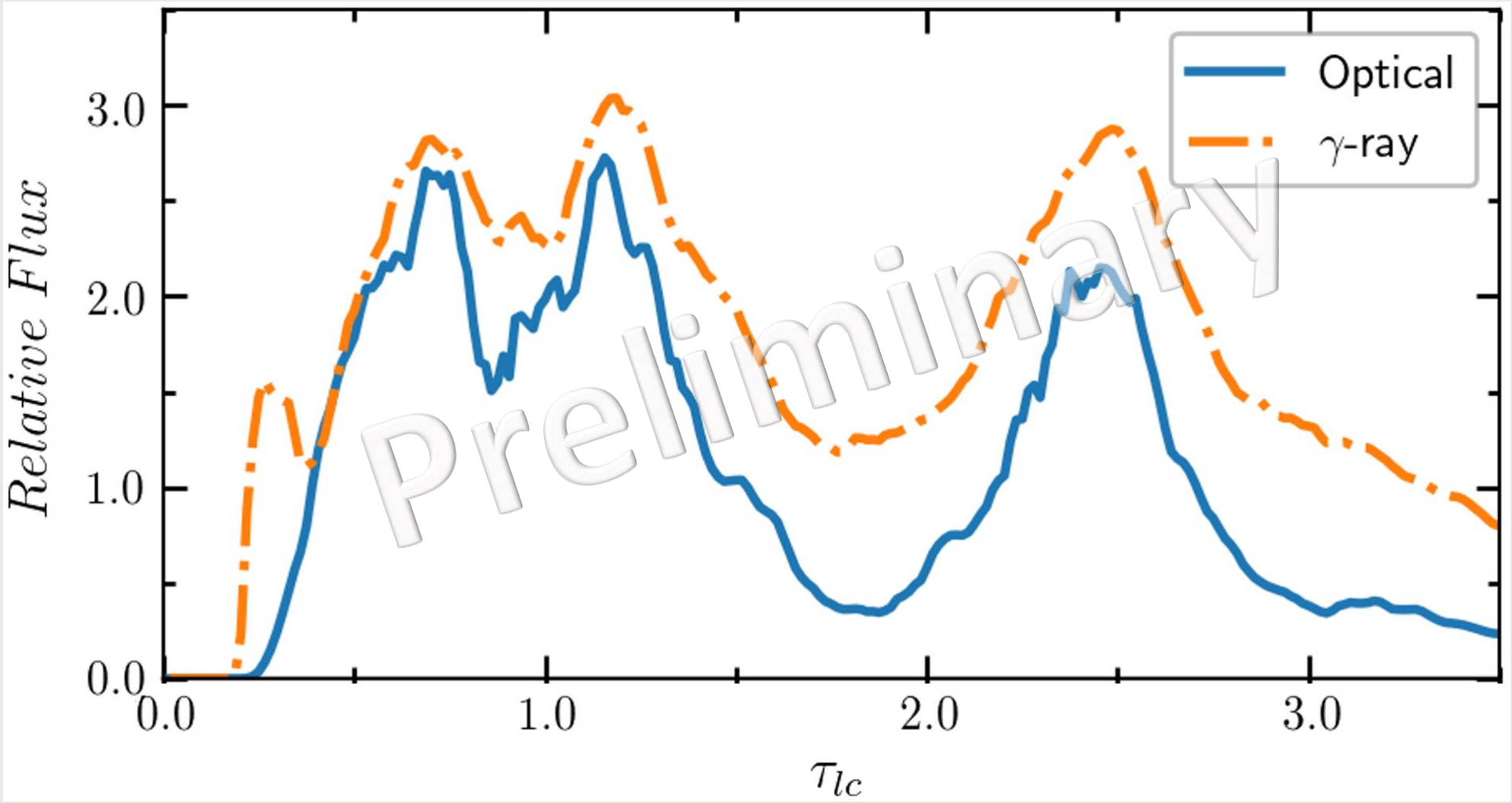
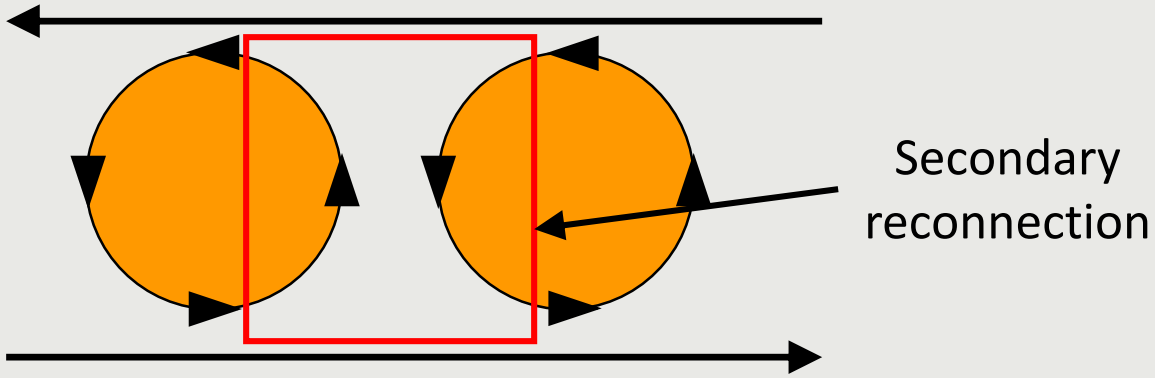
Particle acceleration in magnetic reconnection is very fast. The spectrum tends to accelerate to the peak energy at the maximal efficiency of reconnection, then gradually cool down.

Multi-Wavelength Flares



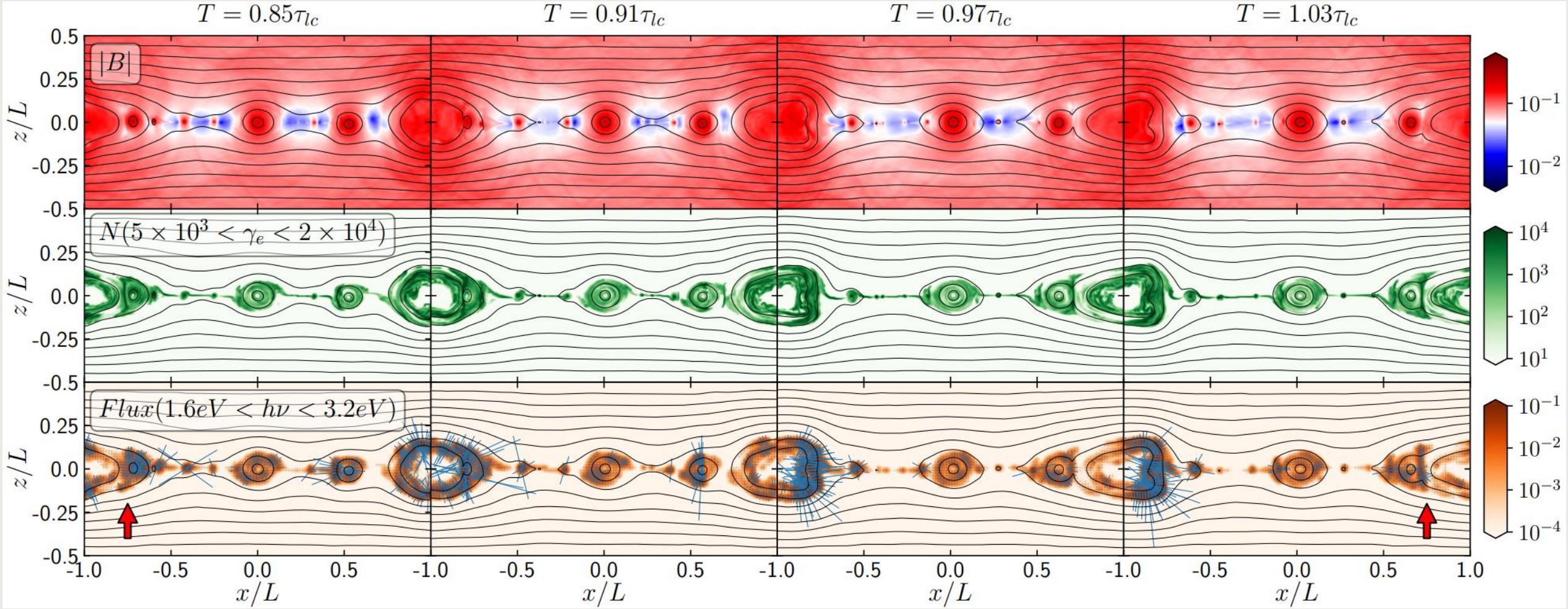
Magnetic reconnection predicts multiple flares in both synchrotron and high-energy components. The duration of some flares can be very short.

Flares from Plasmoid Mergers



Plasmoid mergers lead to secondary reconnection, which results in additional particle acceleration.

Flares from Plasmoid Mergers



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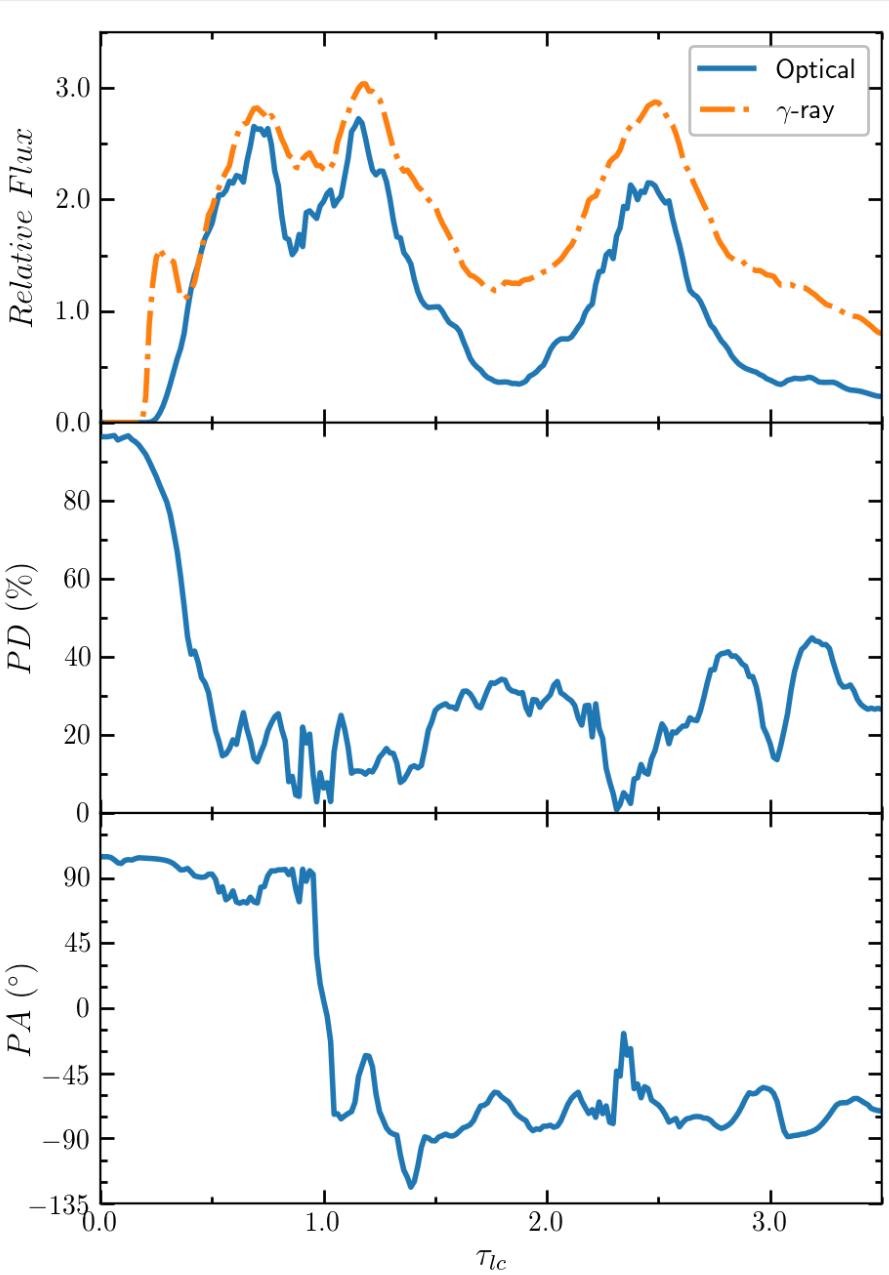
Flares from mergers have a duration correlated to the plasmoid radius.

Polarization Angle Swing



- Polarization angle swings are associated to flares.
- Polarization angle can rotate in both directions.
- Swing amplitude is typically around 180 degrees, but can be smaller (around 90 degrees) or extend beyond 180 degrees (the largest one in our simulations goes to 360 degrees).
- During swings, the polarization degree typically drops.

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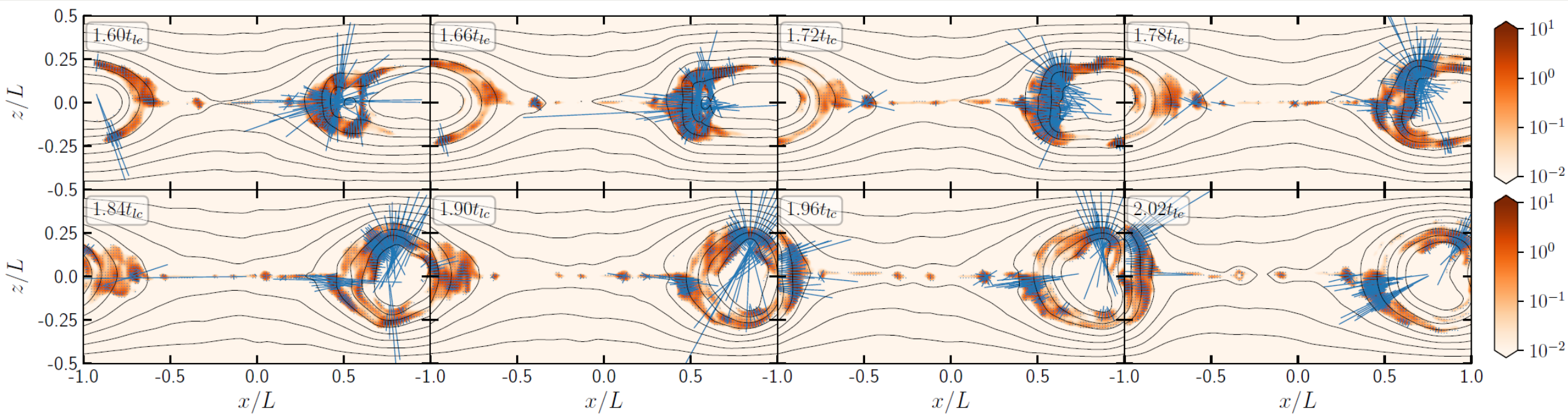
Swings due to Major Plasmoid Mergers

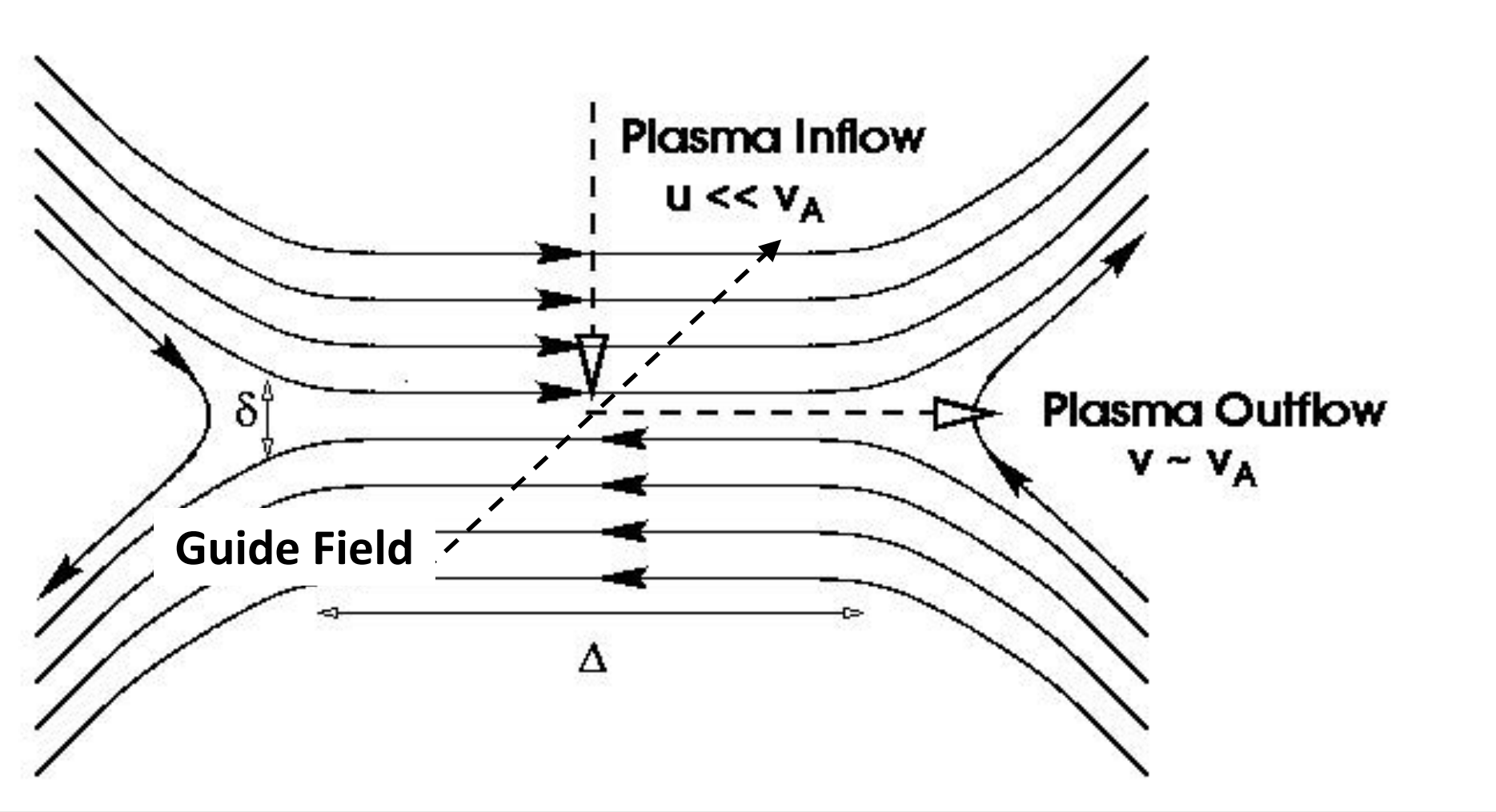


Zhang et al. 2021 arXiv:2103.14914

Angle swings result from large plasmoid mergers, where new particles can stream along the magnetic field lines of the post-merger plasmoid.

Flares and angle swings therefore happen together.

Magnetic Reconnection



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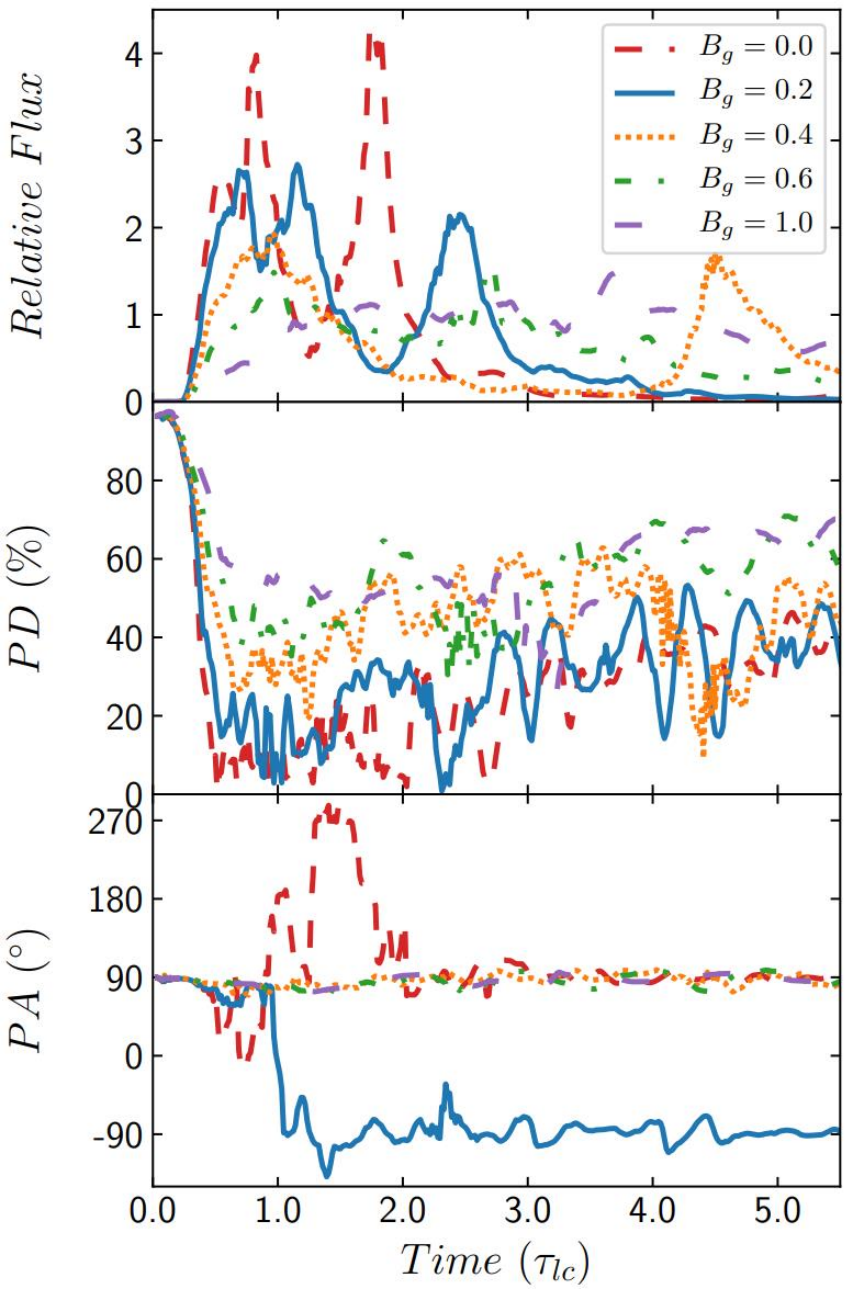
Dependence on Guide Field



- Smaller guide field leads to stronger flares and polarization evolution.
- The average polarization degree during flares is lower for smaller guide field.
- Polarization angle swings only happen with small guide fields.
- Implication: blazars that show angle swings are more active in both flux and polarization than those without angle swings.

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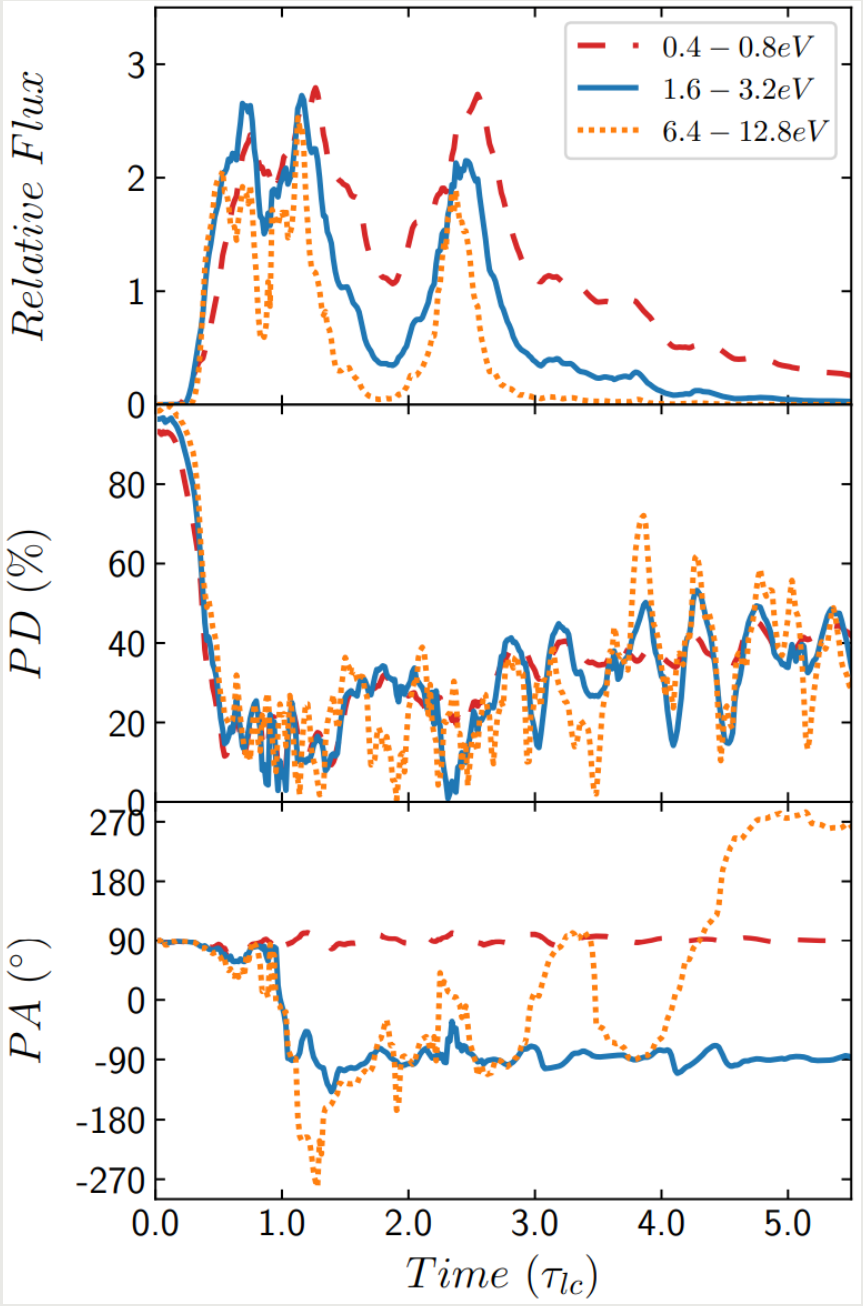
Dependence on Cooling Break



- Observational bands beyond the cooling break show stronger variations in both flux and polarization than those before the cooling break.
- The average polarization degree is comparable between different observational bands.
- Angle swings are likely to happen in observational bands near and beyond the cooling break.
- Implication: high-frequency-peaked BL Lacs can have X-ray polarization angle swings.

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Summary

- Combined first-principle and radiation transfer simulation is ideal for the study of radiation signatures from magnetic reconnection.
- Magnetic reconnection predicts harder-when-brighter trend in the blazar spectra.
- Magnetic reconnection predicts multiple and fast flares, due to plasmoid mergers.
- Large plasmoid mergers can lead to polarization angle swings in the synchrotron components, which are correlated to flares.
- Blazars that have angle swings are likely to experience strong reconnection between nearly anti-parallel magnetic fields, and are more active in both flux and polarization variations compared to those without swings.
- Fast flares and angle swings are likely to happen near and beyond the cooling break.
- Future observations should consider co-analyze multi-wavelength spectra, light curves, and polarization signatures to better constrain the blazar zone physics.