applying relativistic reconnection to blazar jets

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major questions about blazars

- the origin of the blazar sequence
  is particle acceleration limited by radiative cooling?

- mass loading
  what is the magnetization of jets, how uniform is it?
  what determines the bulk Lorentz factors?

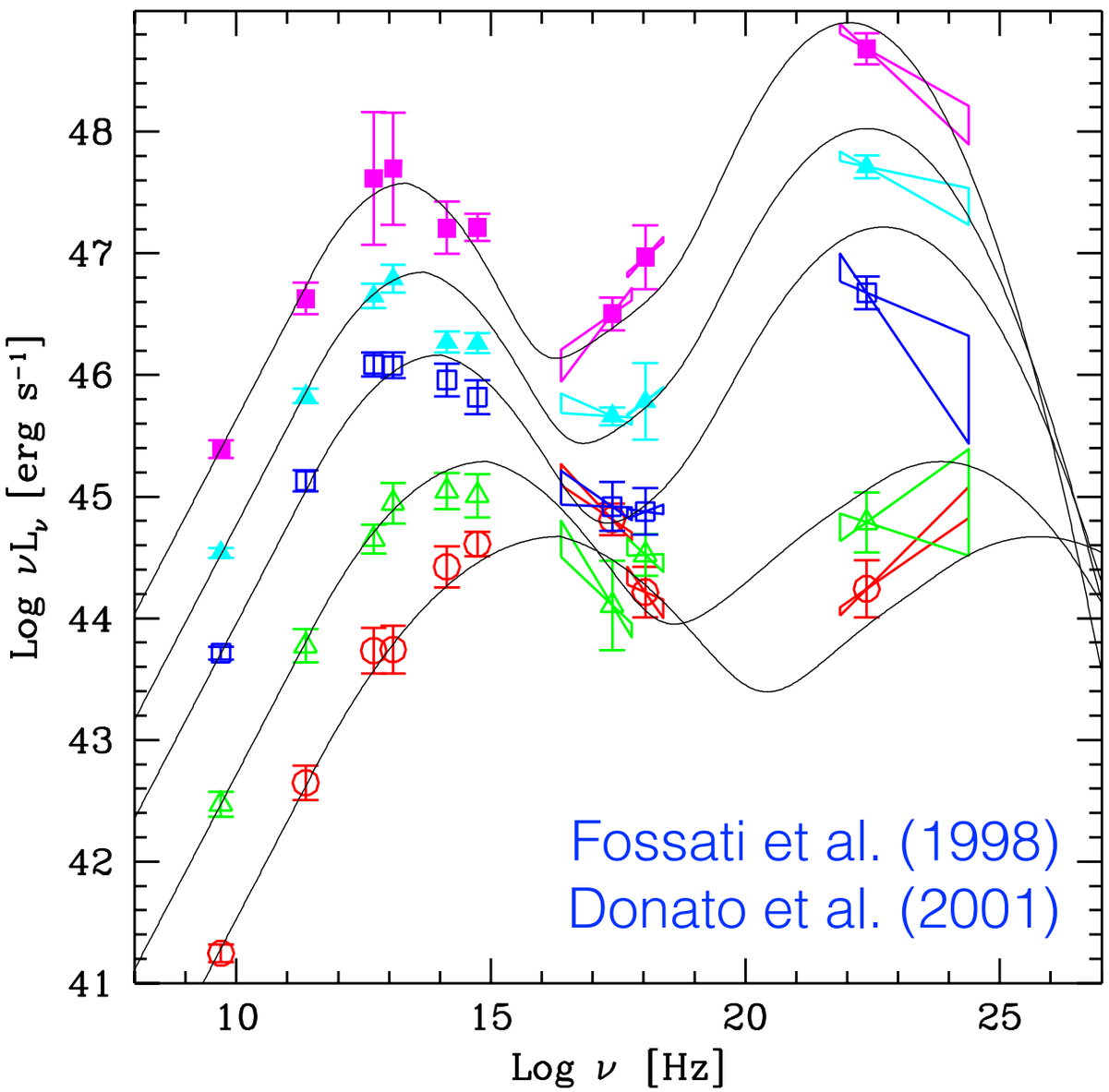
- dissipation mechanism: shocks vs reconnection
  can relativistic reconnection be applied to blazars?

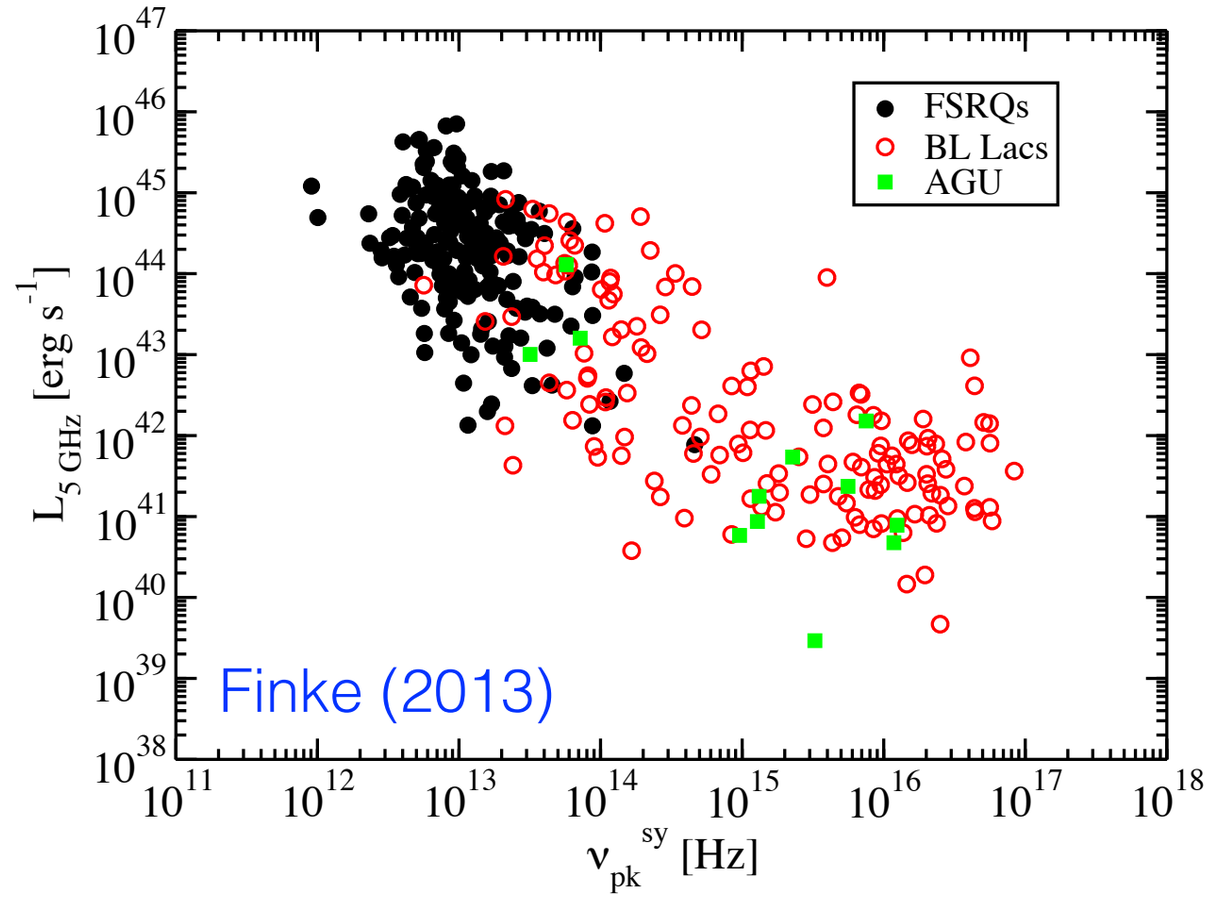
1. selected observations of blazars

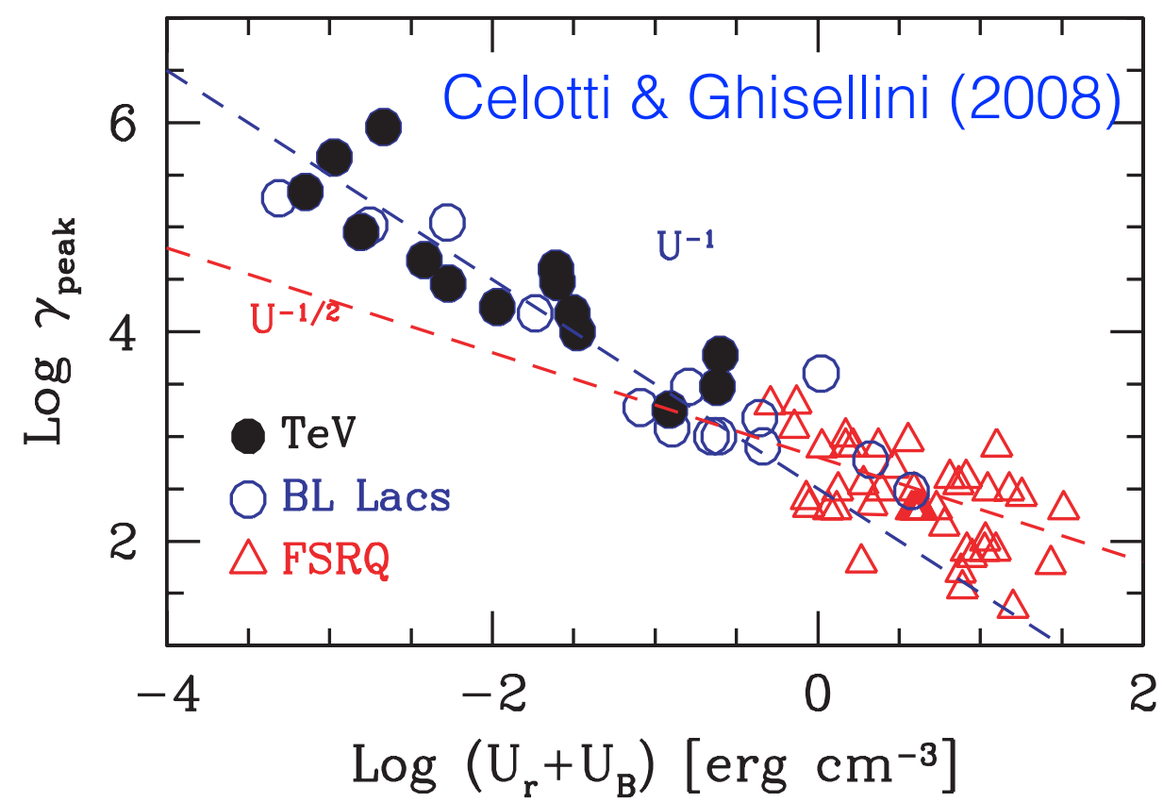
2. kinetic simulations of reconnection

3. applying reconnection to blazar jets

the blazar sequence

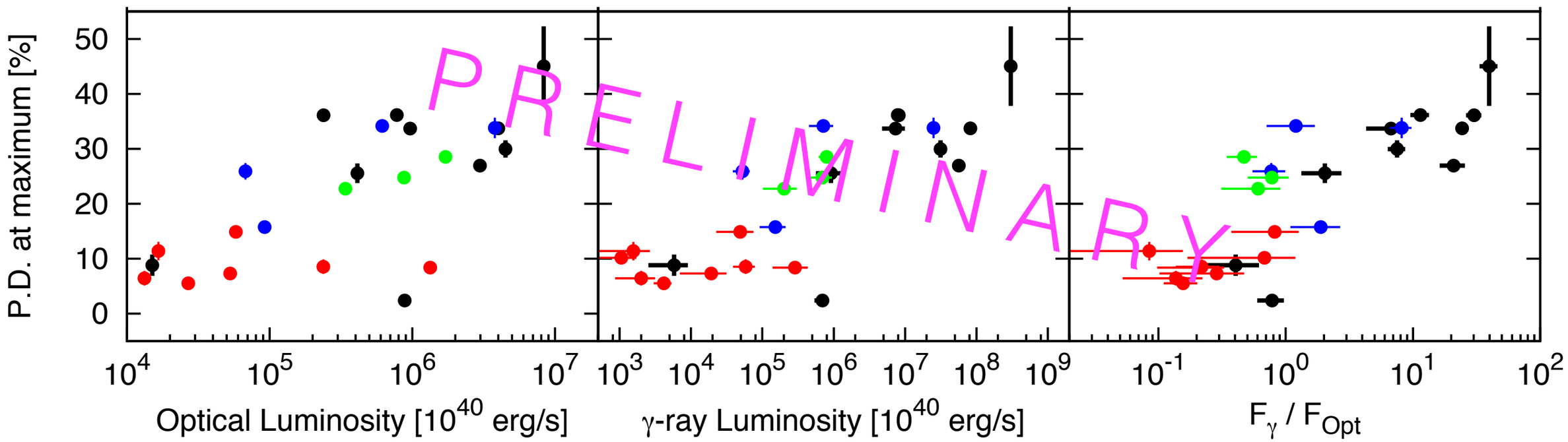






blazar sequence in optical linear polarization?

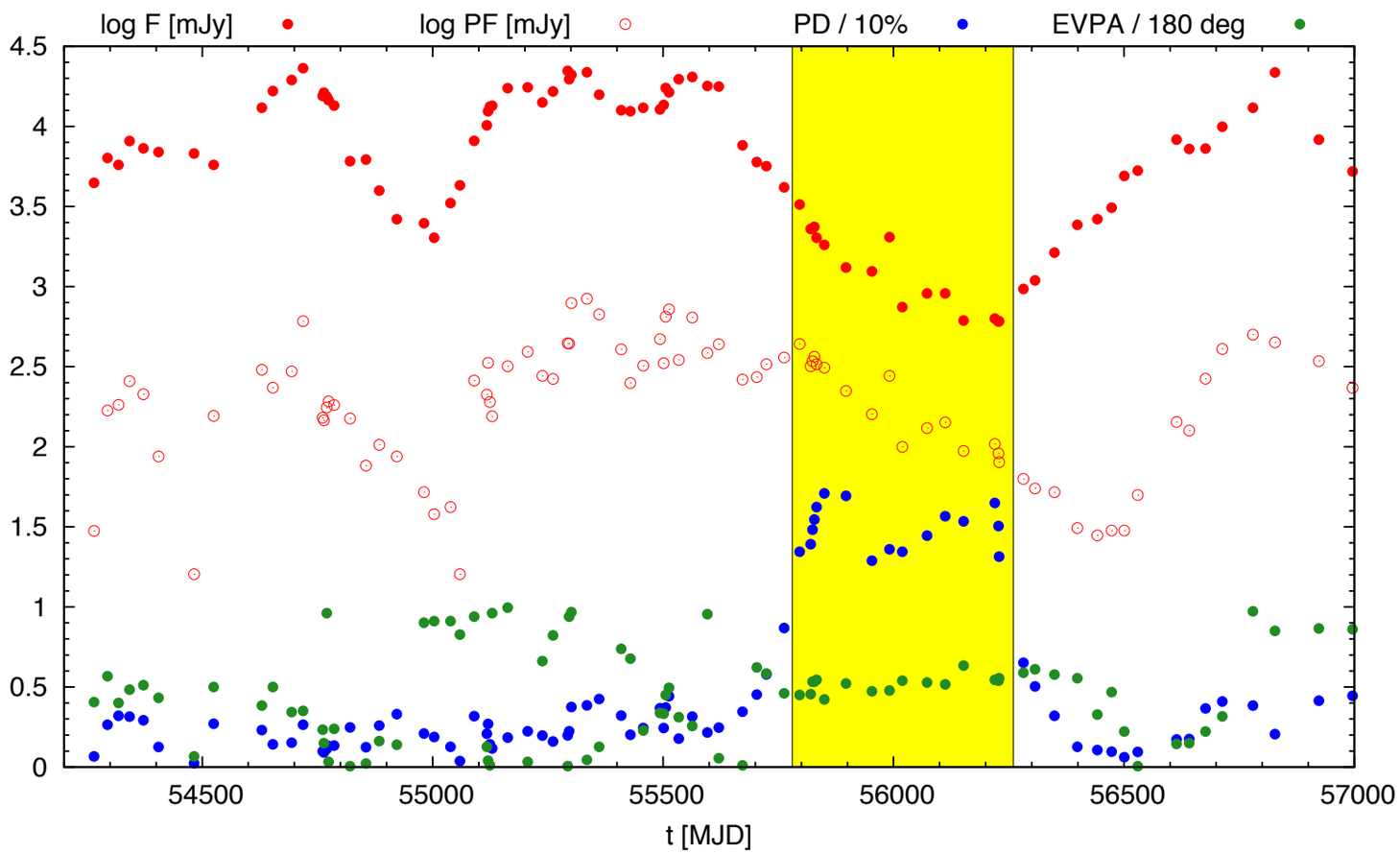
KANATA & Fermi-LAT collaborations

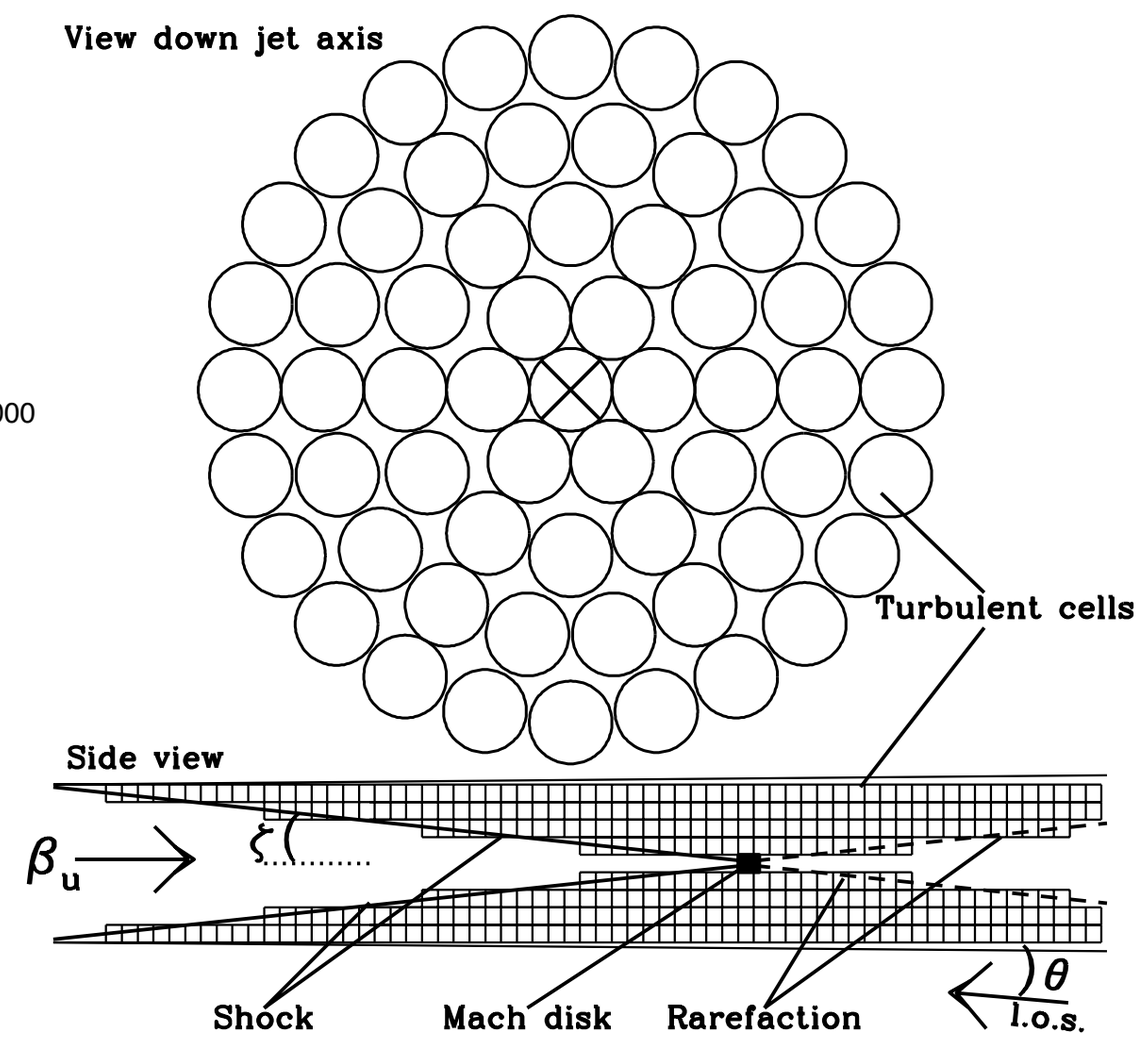


- evidence for systematically stronger depolarization in TeV blazars
- magnetic fields more chaotic in FR I jets?
- or PD scales with (γ_{opt} / γ_{max}) -> high X-ray PD for HBLs

polarization signatures of turbulent jets

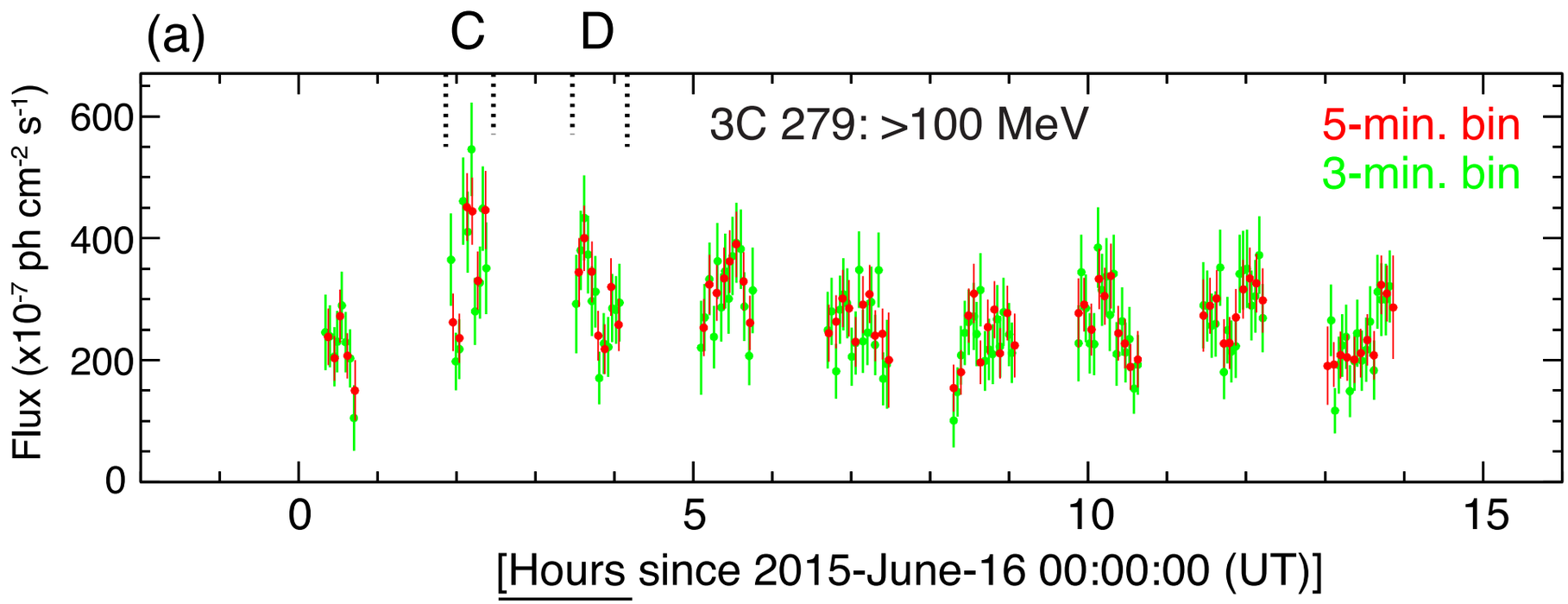
3C 454.3, VLBA (BU)



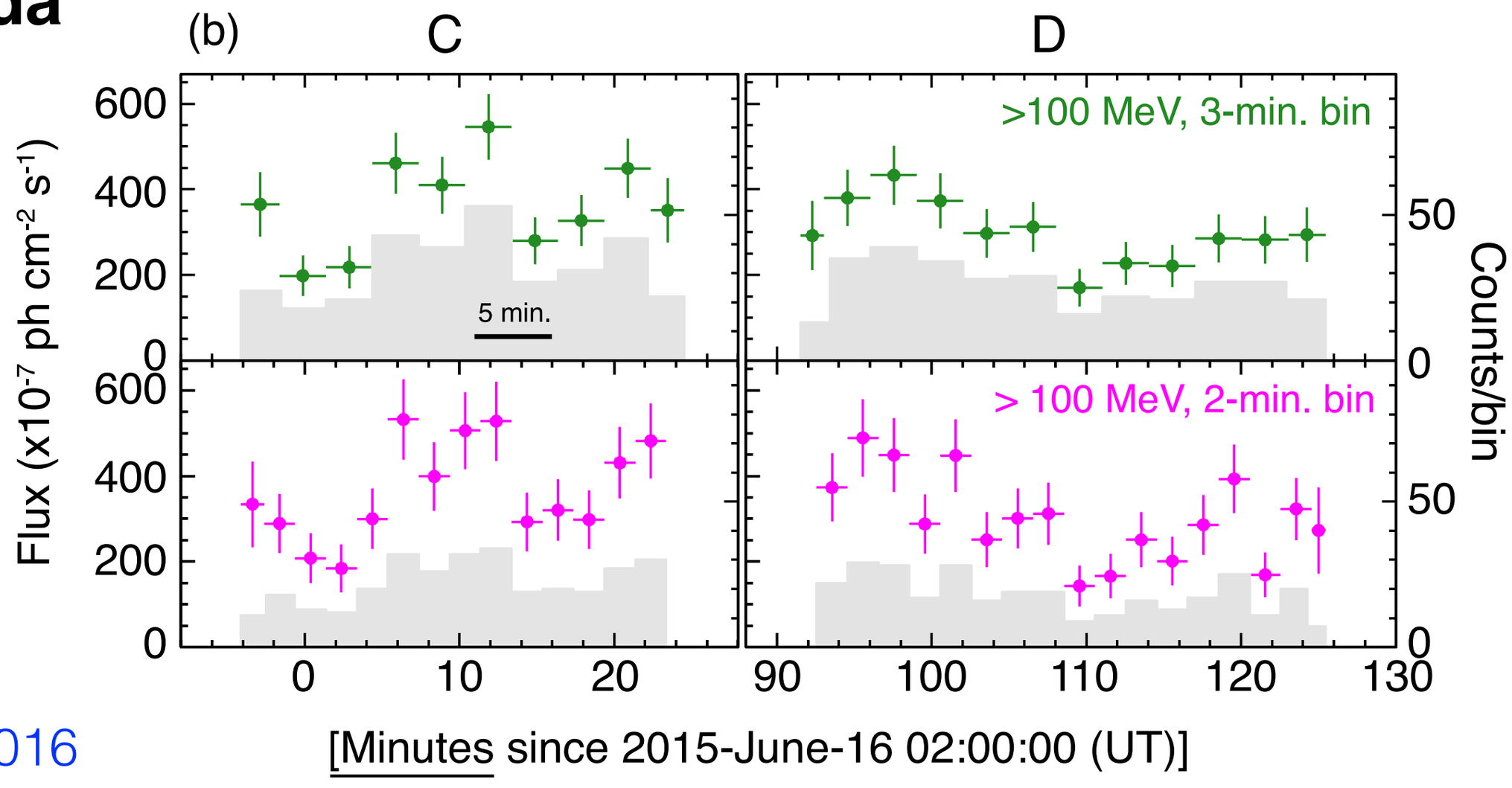


Alan Marscher et al.

MINUTE-TIMESCALE γ-RAY VARIABILITY OF QUASAR 3C 279 IN 2015 JUNE



see talk by M. Hayashida (Tue)



Fermi-LAT Collaboration 2016

rapid GeV variability in 3C 279

- emitting region size 10^{-4} pc
  dissipation region may be larger by factor 10-100
  distance scale as short as 100 M_{bh}
  gamma-ray opacity (15 GeV)

- $\Gamma > 25$ from intrinsic opacity, $\Gamma > 35$ for sub-Eddington jet

- ERC scenario: $\Gamma > 50$ from SSC constraint
  $\Gamma > 120$ from equipartition

- synchrotron scenario: kG B-field, $\gamma \sim 10^6$
  cf Crab flares

- hadronic models: viable at very short distances

Fermi-LAT Collaboration 2016

input from M. Hayashida, G. Madejski, M. Sikora, R. Blandford

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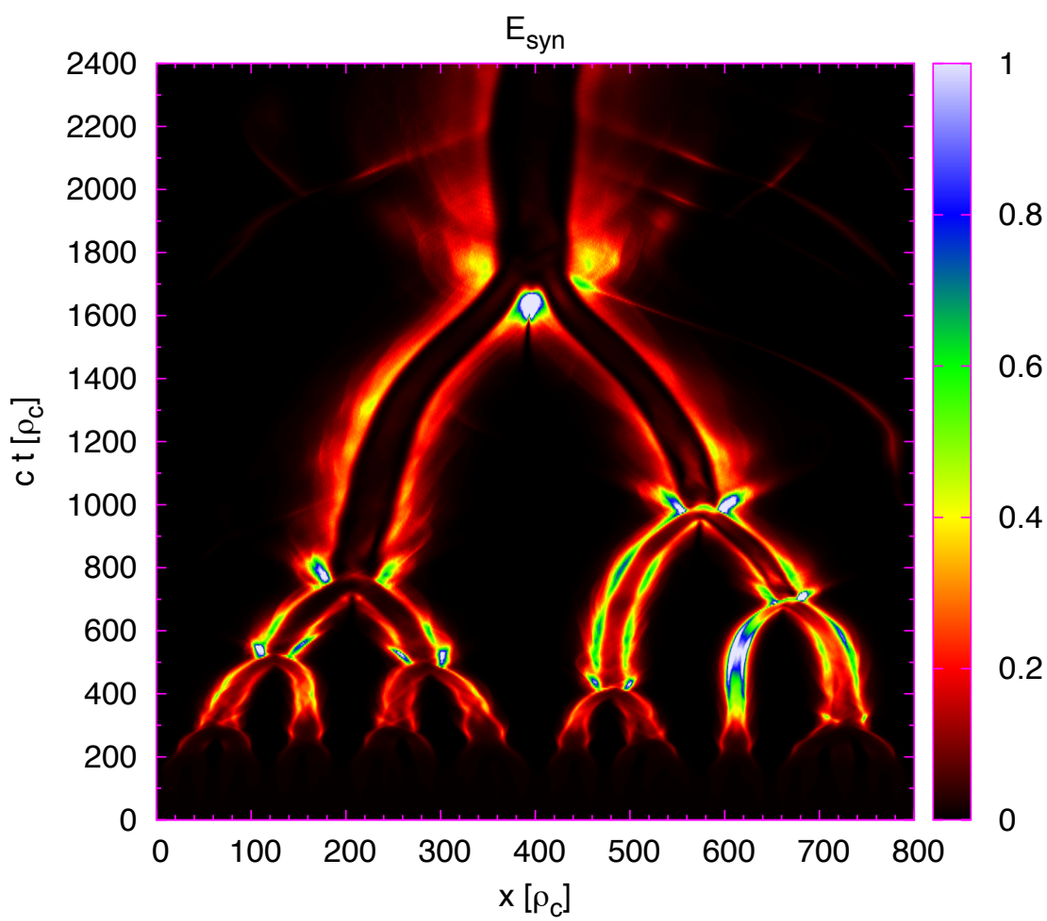
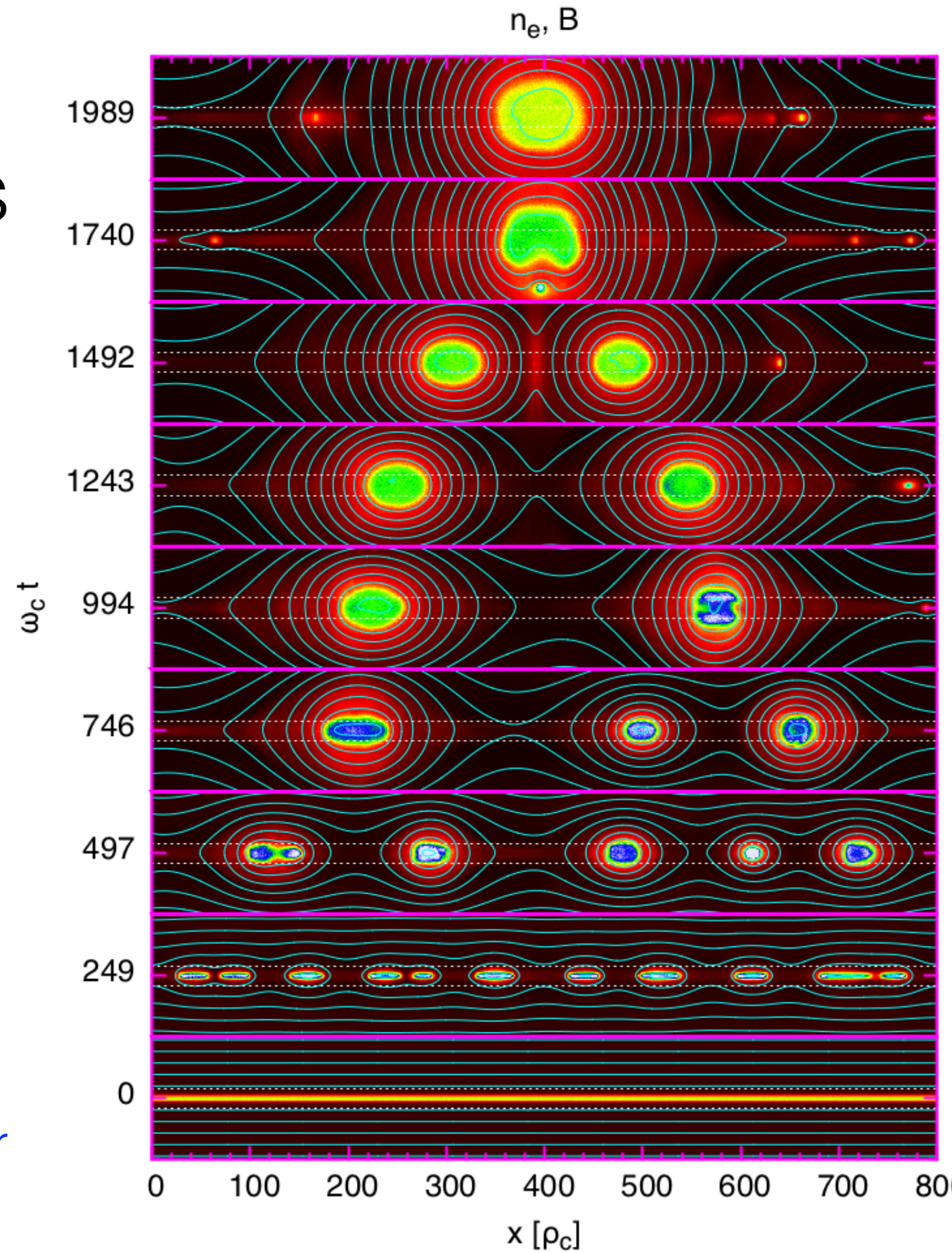
2. kinetic simulations of reconnection

3. applying reconnection to blazar jets

reconnection from Harris layers

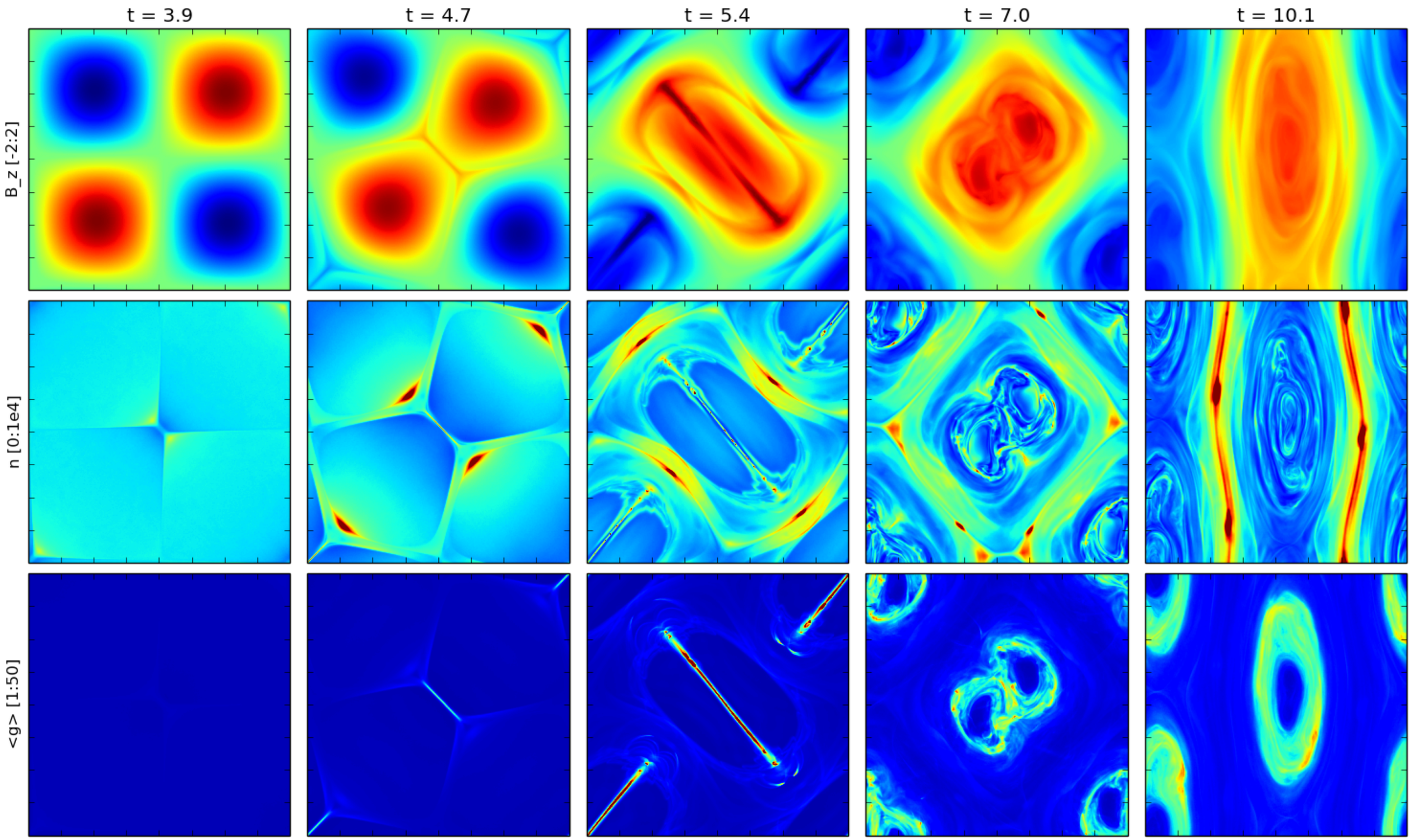
synchrotron power





KN, Uzdensky, Cerutti, Werner & Begelman (2015)

reconnection + current formation from “ABC” fields

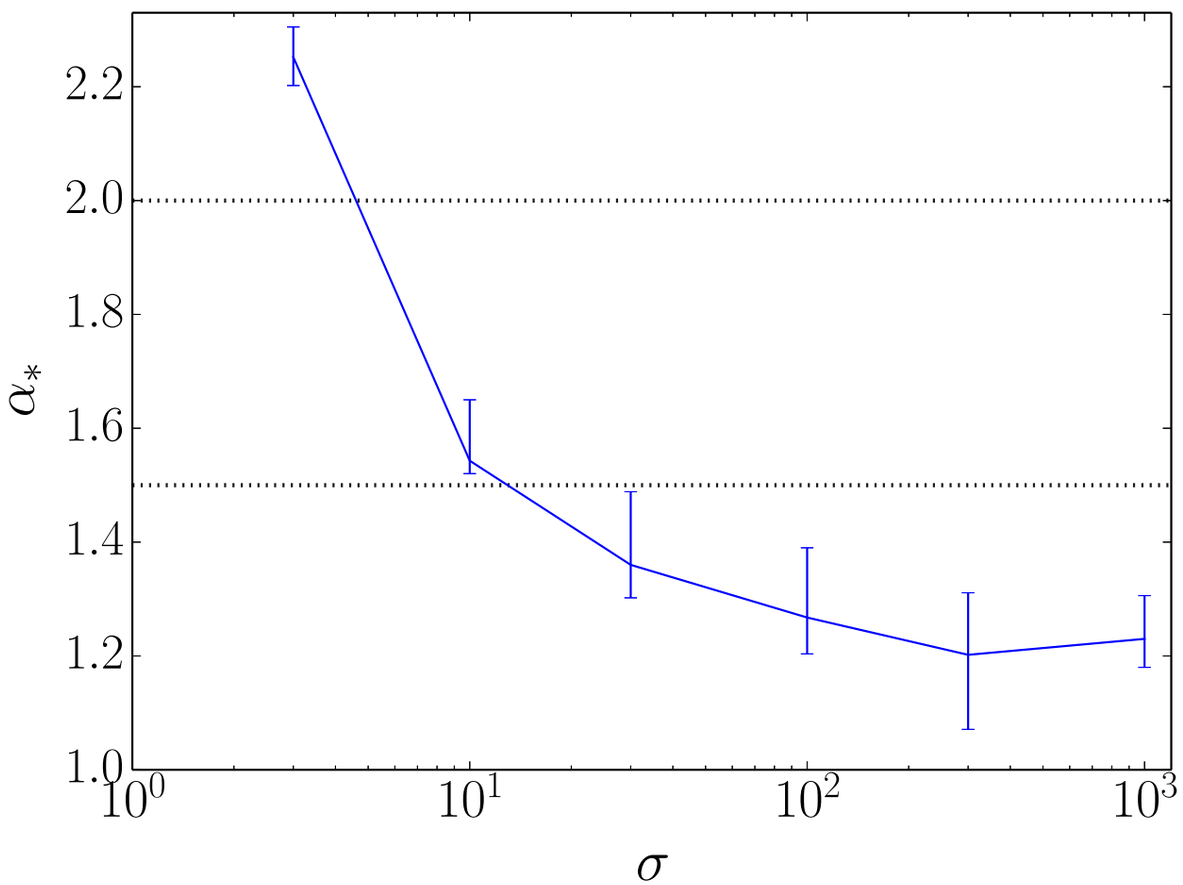


KN, Zrake, Yuan, East & Blandford (2016)

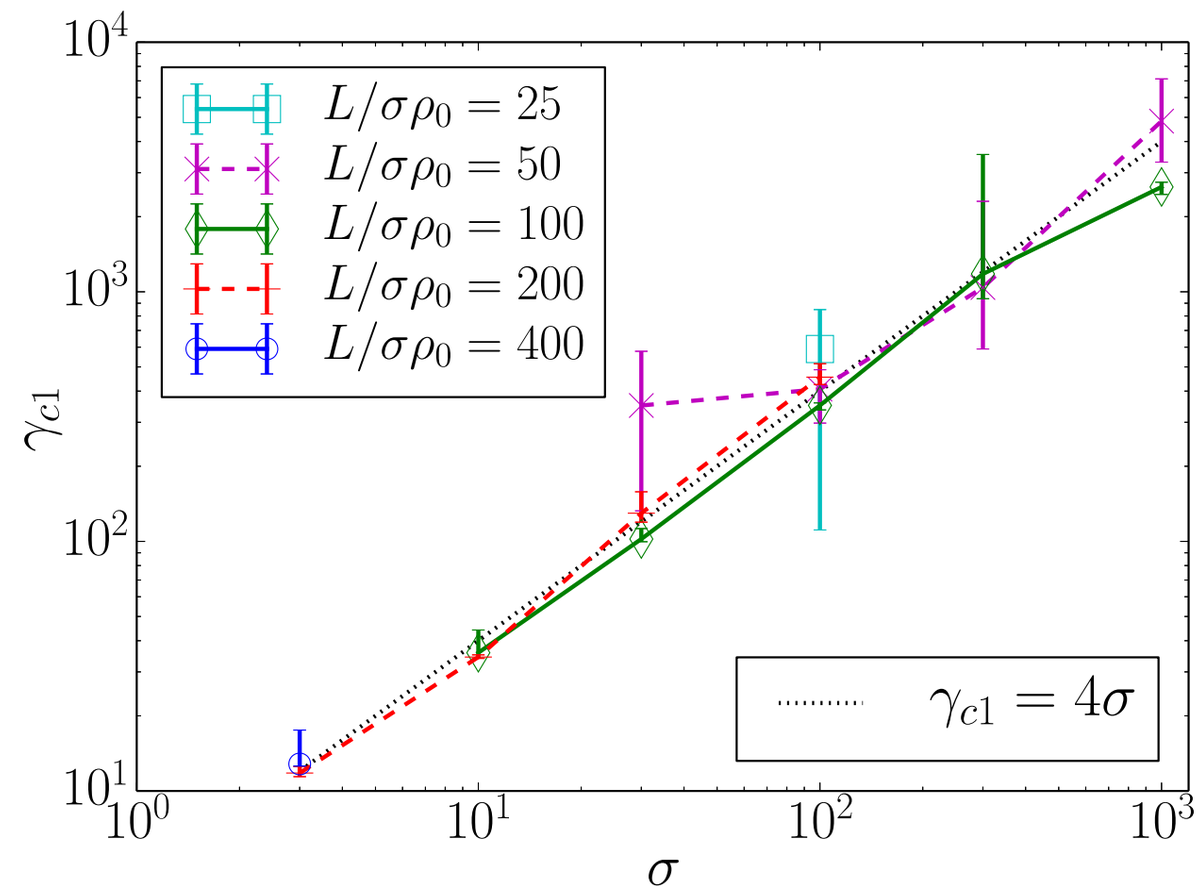
particle acceleration in pair-plasma reconnection

- reconnection produces power-law distributions that are hardening with increasing sigma
  $N(\gamma) \sim \gamma^{-p}$, p -> 1 for $\sigma >> 1$

- high-energy cut-off is exponential with $\gamma_{max} \sim \sigma$



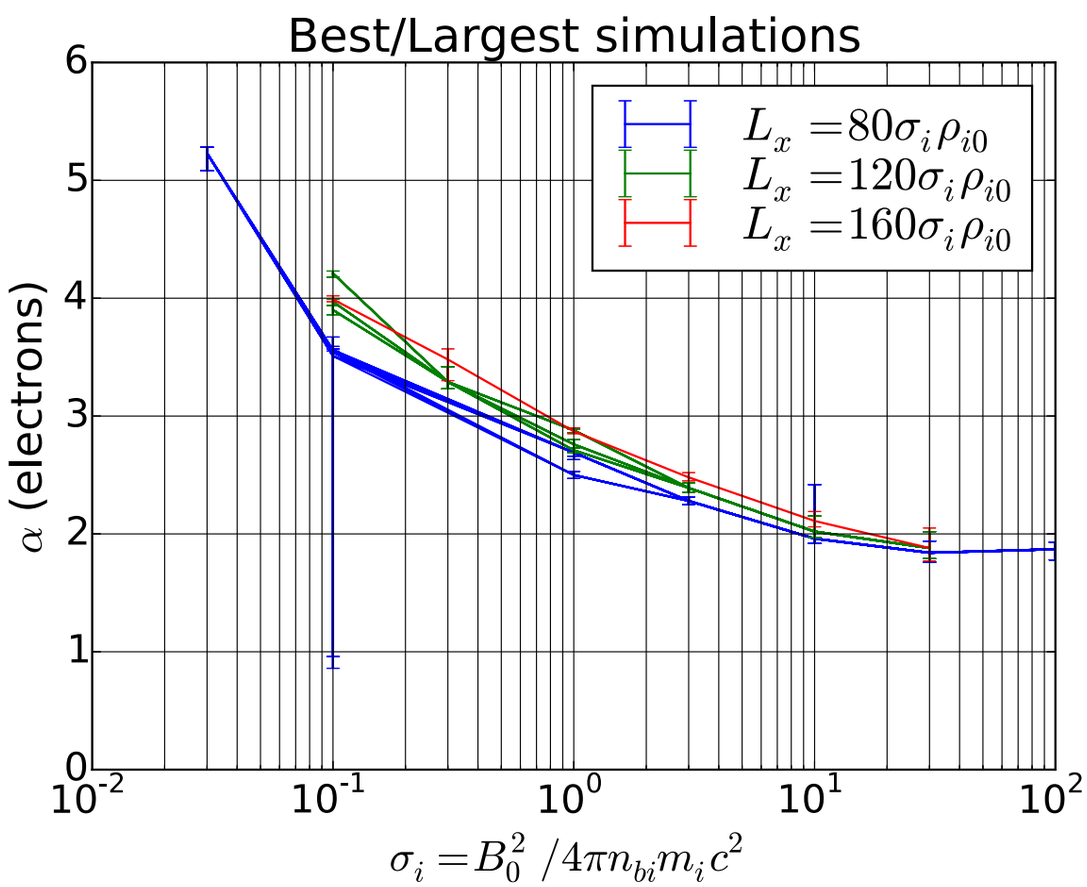
Werner, Uzdensky, Cerutti, KN & Begelman (2016)

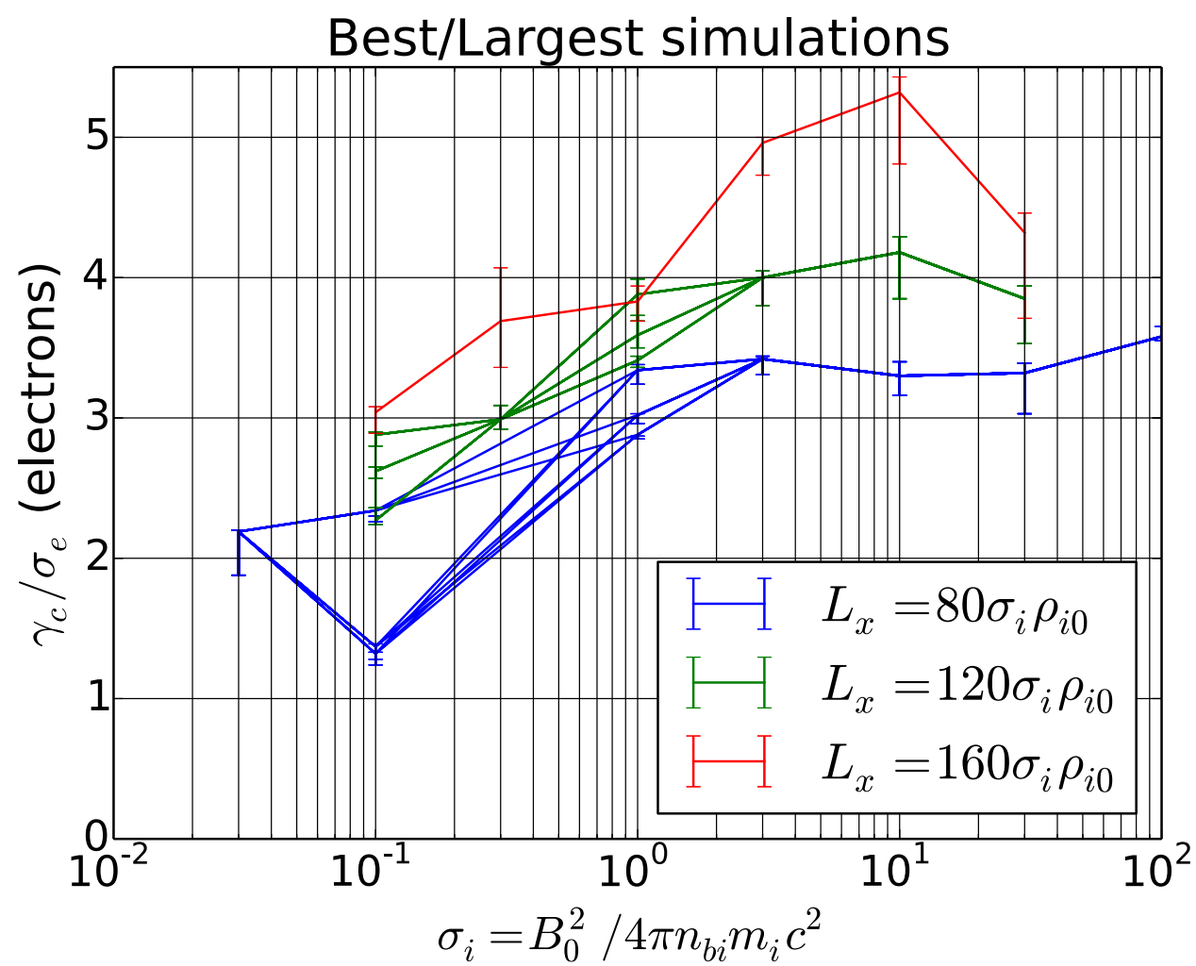


see also Sironi & Spitkovsky (2014)
Guo et al. (2014, 2015)

particle acceleration in electron-proton reconnection

- softer electron spectra, with p ~ 2.5-3 for $\sigma_i \sim 1$
- $\gamma_{max} \sim \sigma_e \sim (m_e/m_i)\, \sigma_i$

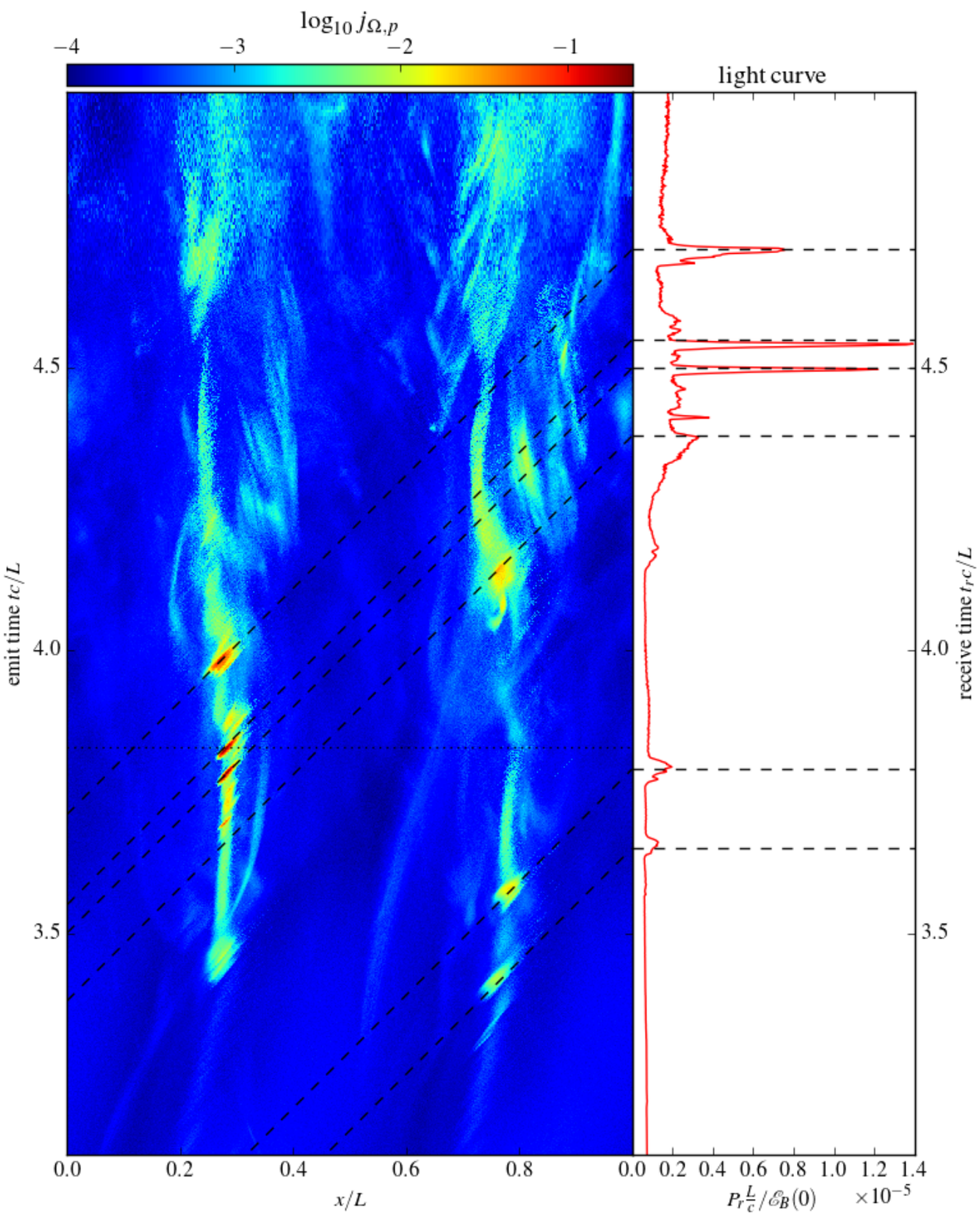


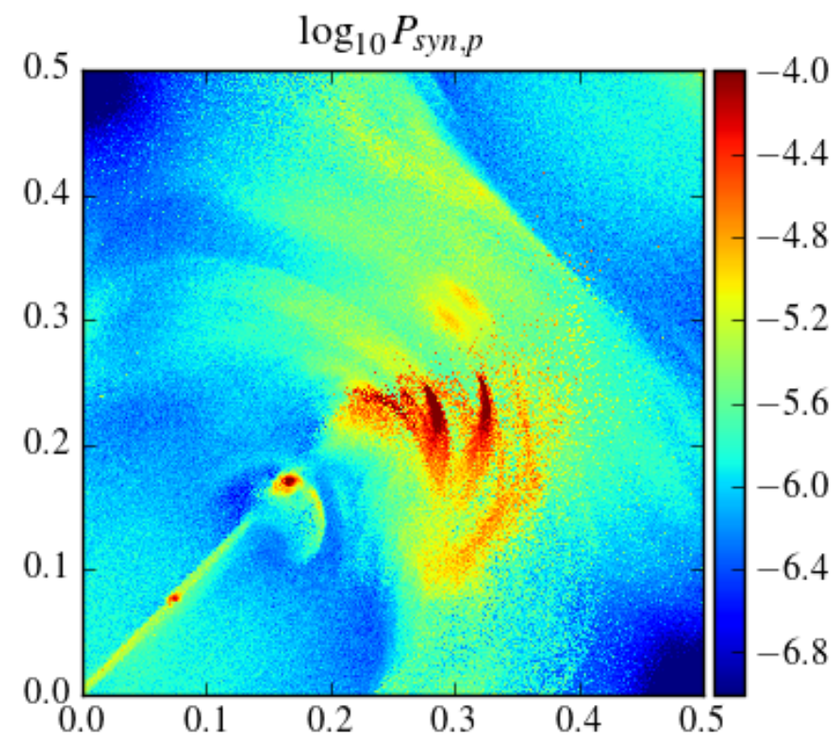


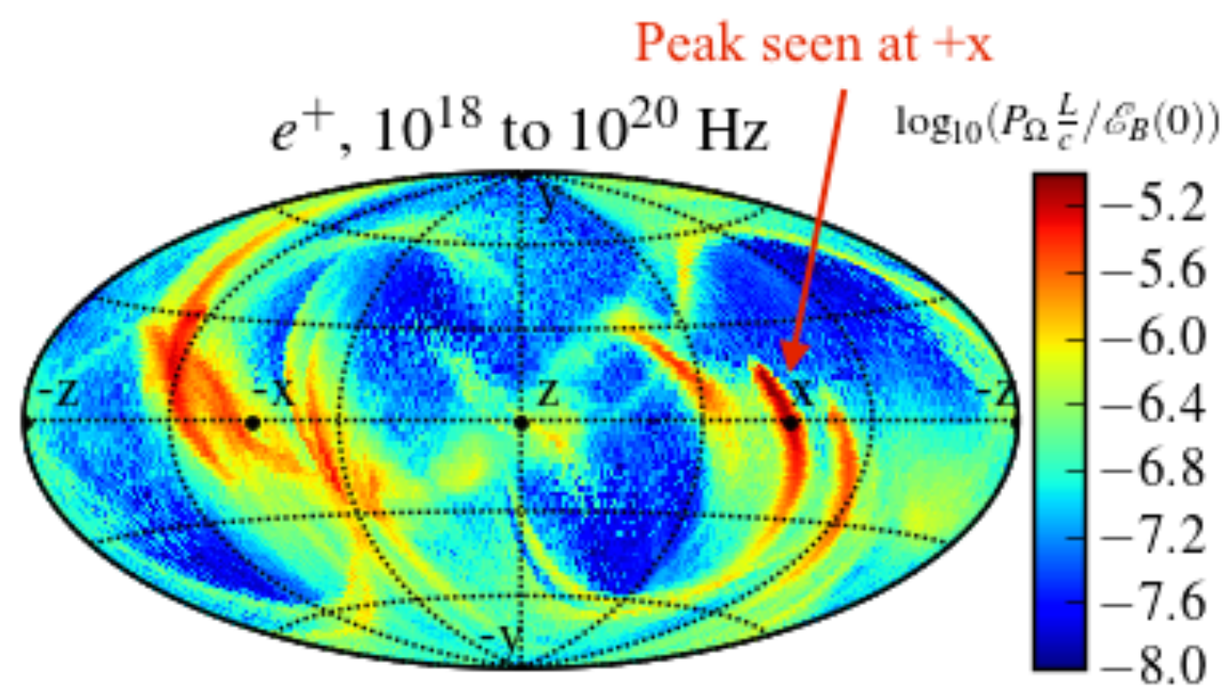
Werner, Uzdensky, Begelman, Cerutti & KN (in prep)

synchrotron signatures of ABC relaxation

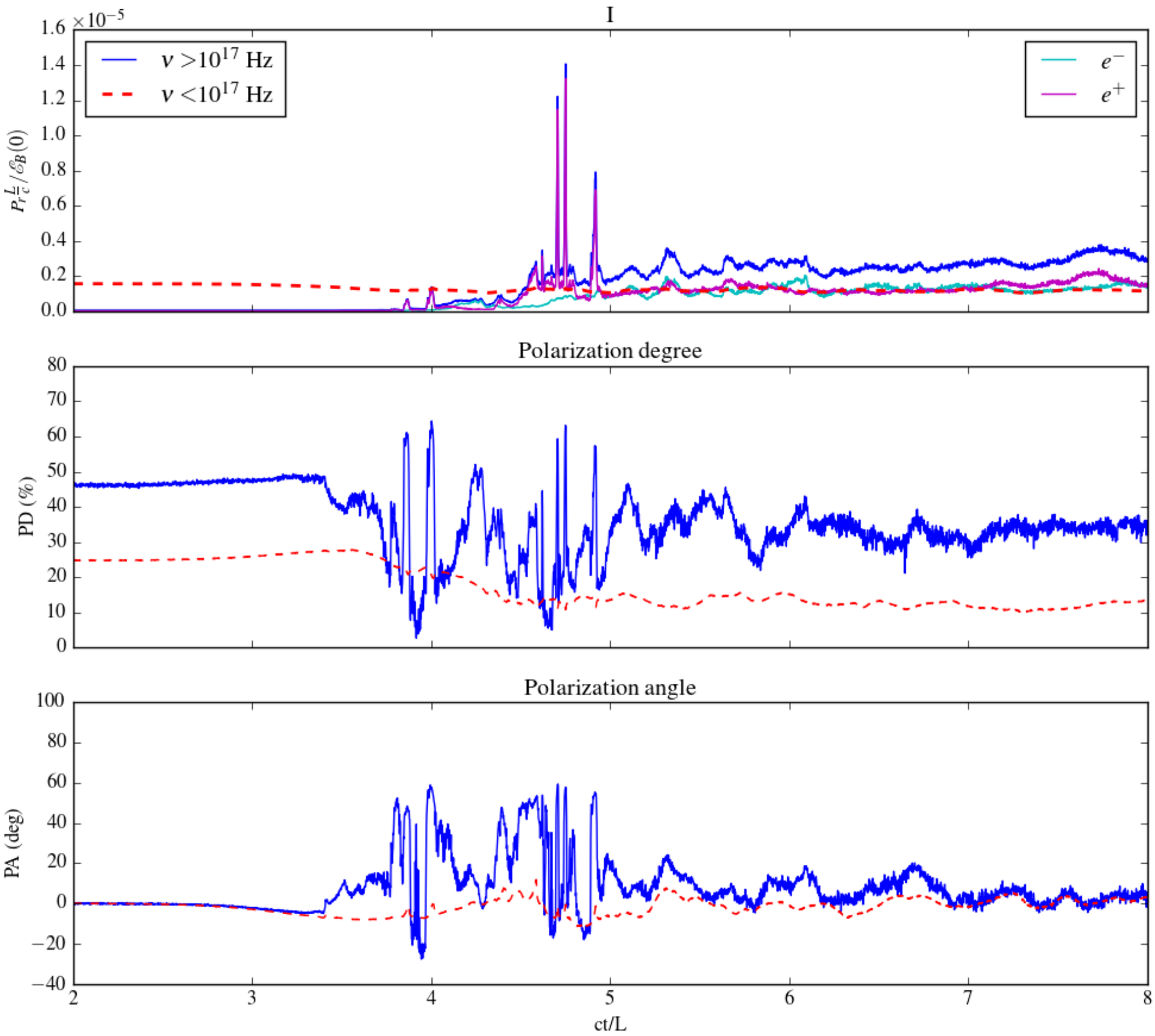
Yuan, KN, Zrake, East & Blandford (2016)







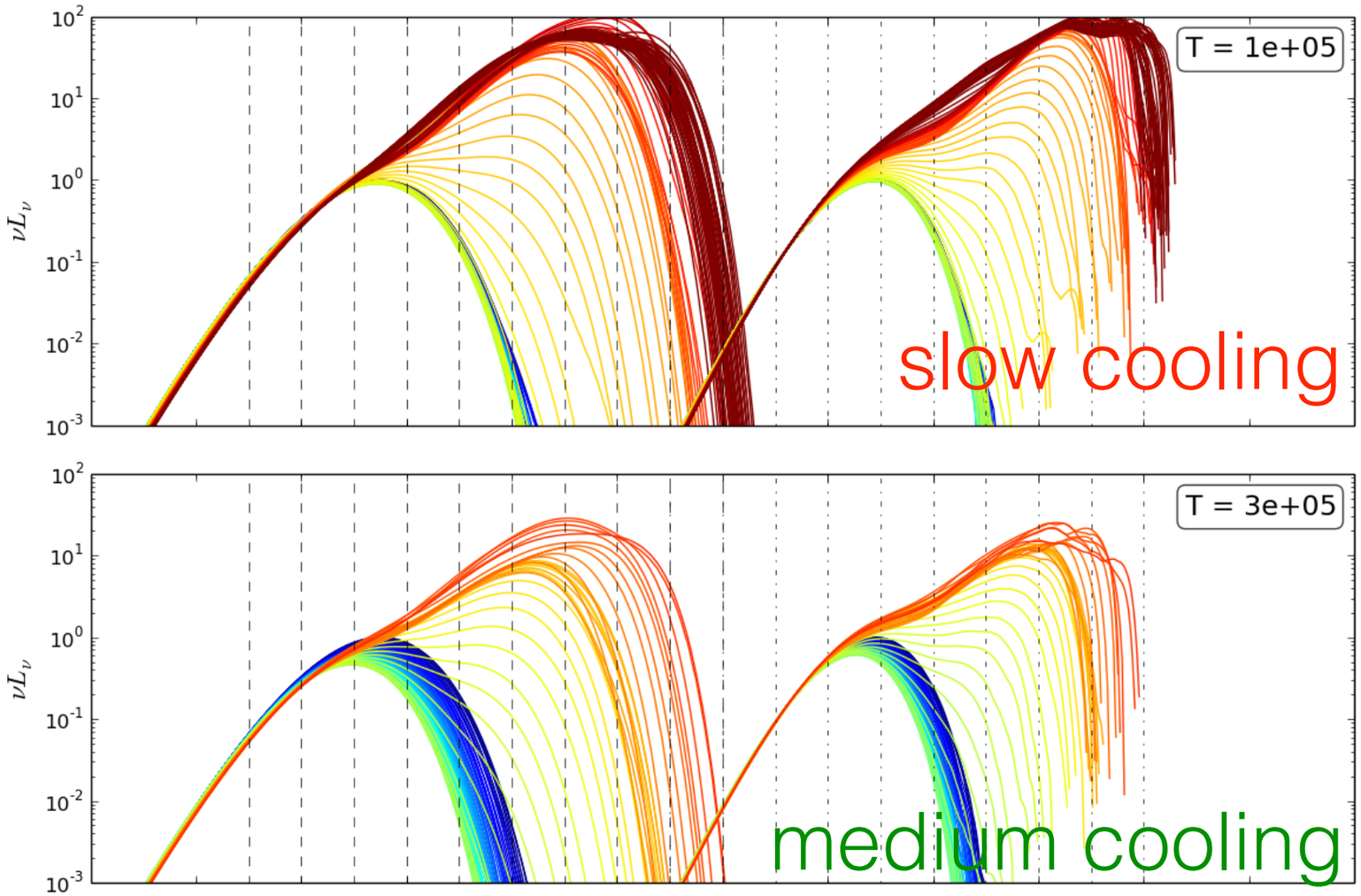
linear polarization (2D symmetry)

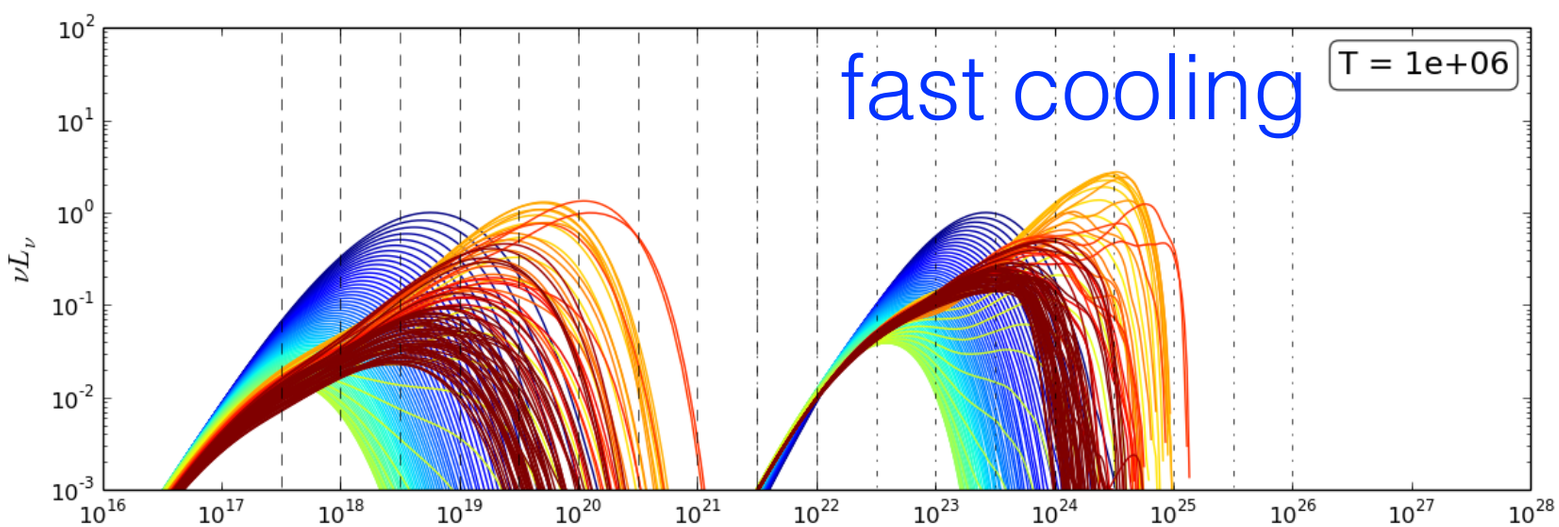


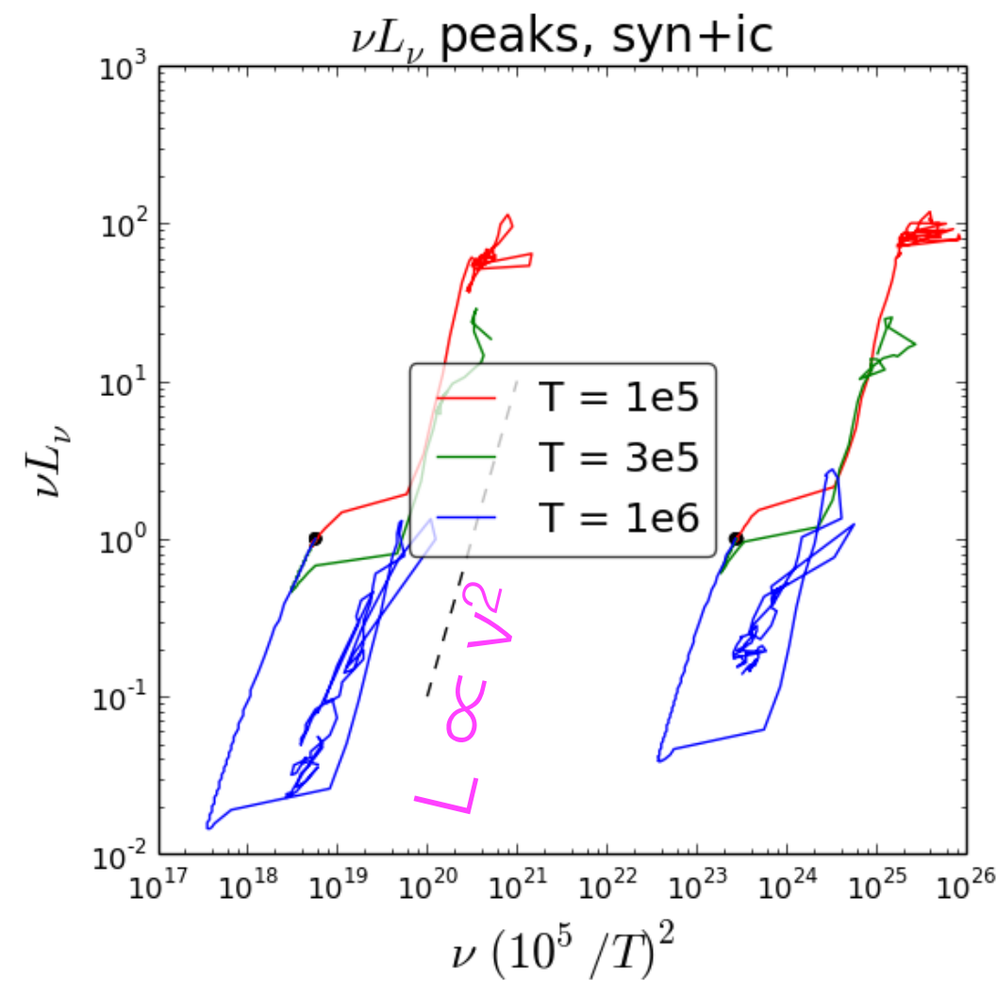
Yuan, KN, Zrake, East & Blandford (2016)

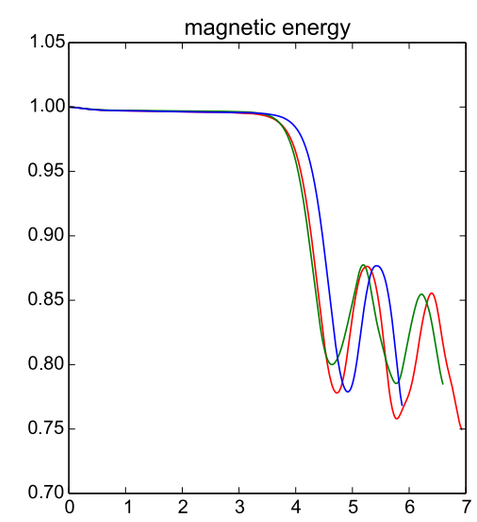
synchrotron and inverse Compton

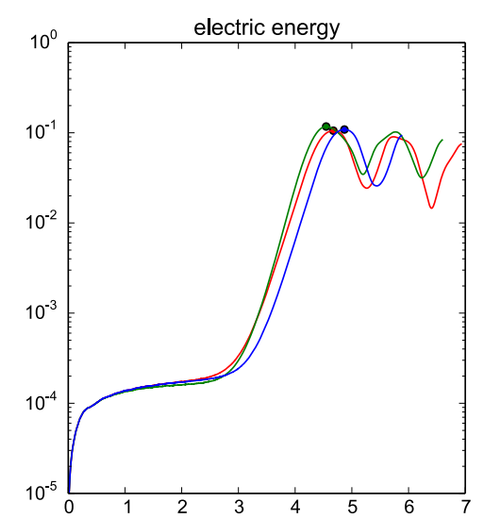
(with Martyna Chruślińska, PRELIMINARY)











what we learned about relativistic magnetic reconnection?

- efficient particle acceleration, hard power-laws with p -> 1 for $\sigma >> 1$
- electron spectra are softer in the presence of protons
- reconnection rate $v_{rec} \sim 0.1 v_A$, reconnection outflows $v_{out} \sim v_A$
- rapid variability due to kinetic beaming (energy-dependent particle anisotropy) and tearing instability (spatial bunching), $t_{var} \sim 0.01$ L/c

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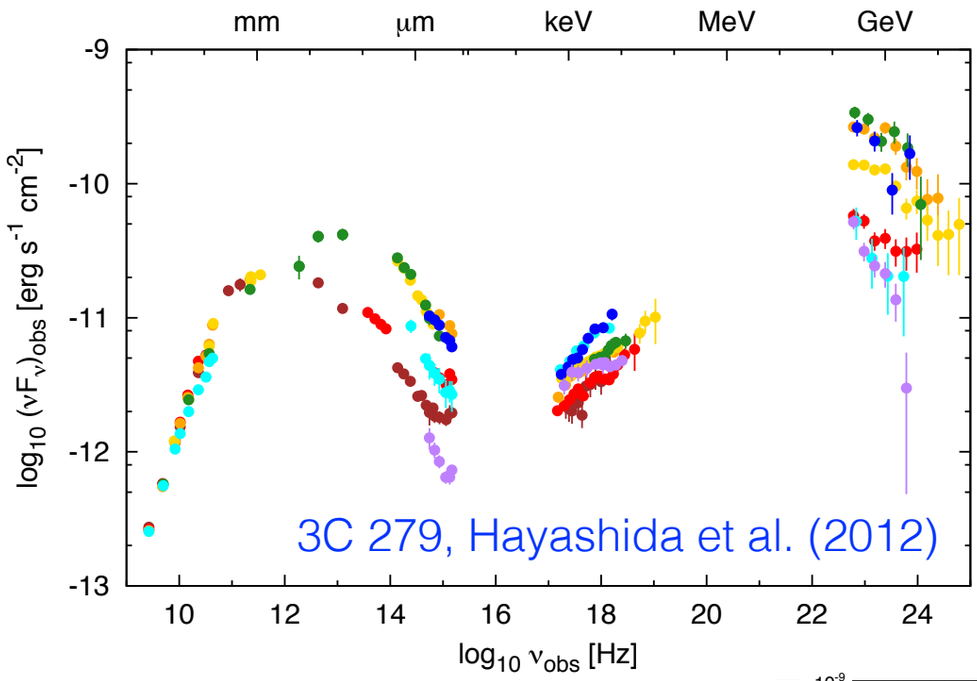
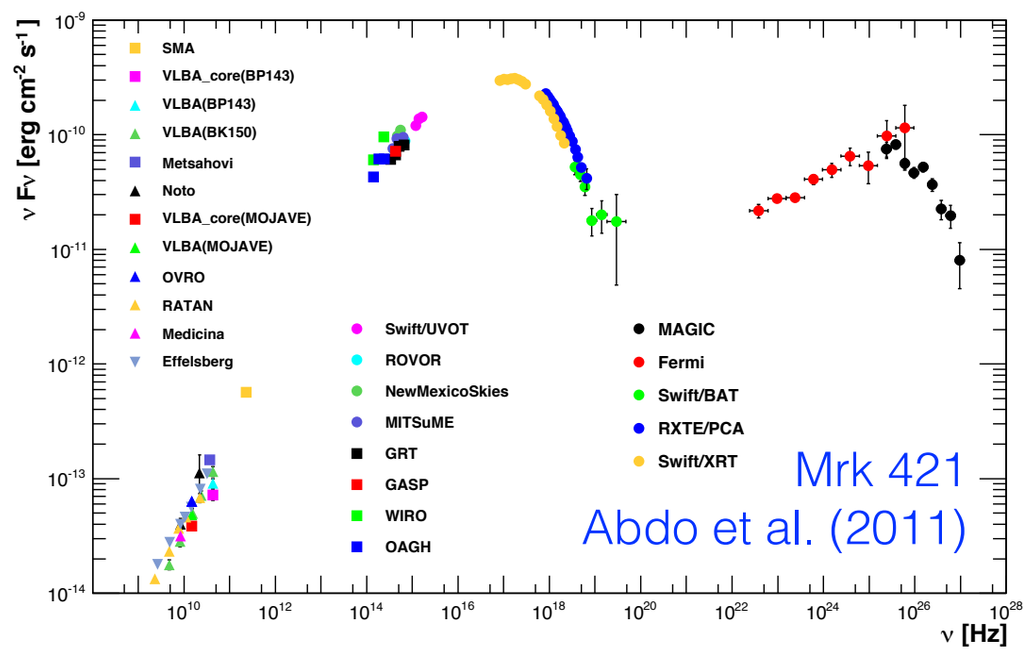
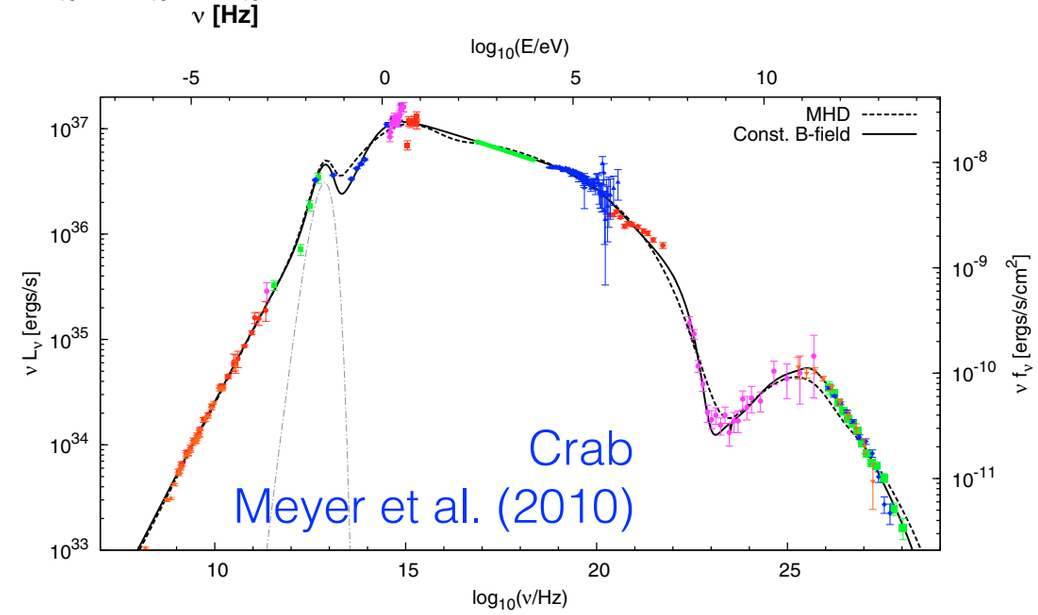
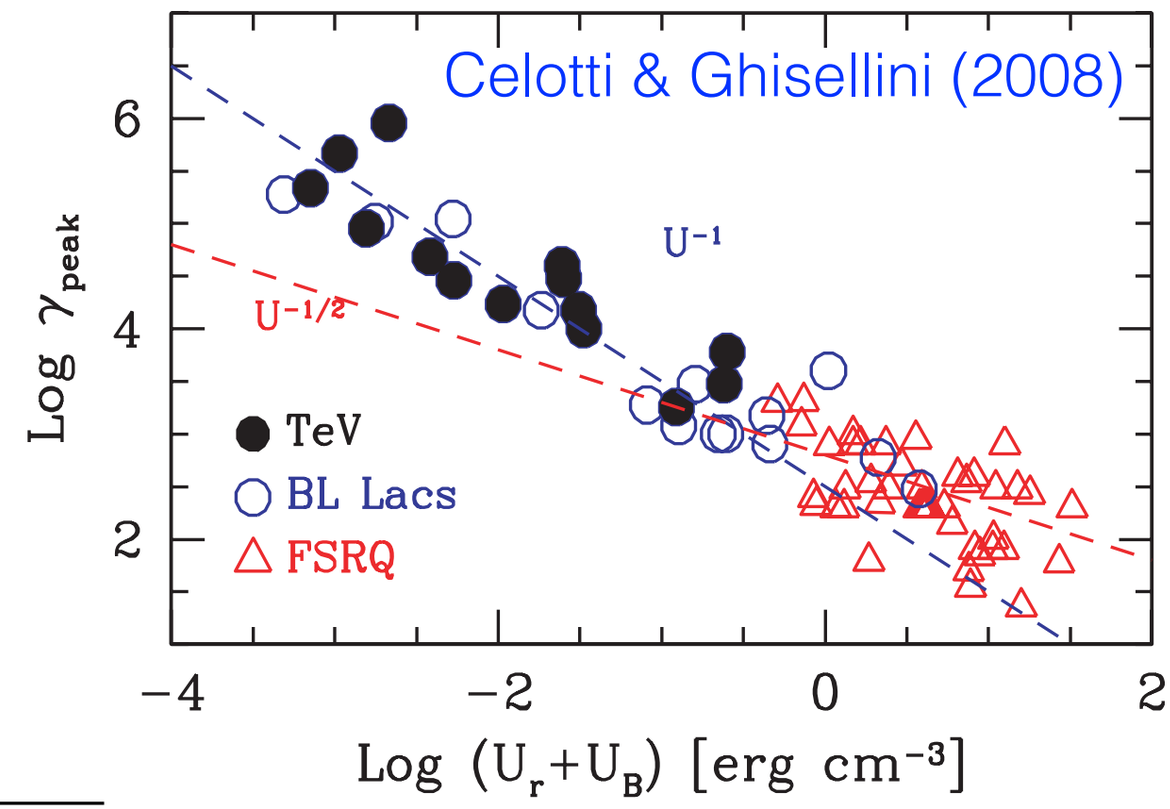
blazars vs Crab







particle acceleration limited by radiative cooling?



- for $E = \beta_{rec} B$, $t_{acc} << t_{cool}$

$$\frac{d\gamma}{dt} = \frac{eE}{mc} - \frac{4\sigma_T u_{cool}\gamma^2}{3mc}$$

$$\gamma_{eq} = \sqrt{\frac{3e\beta_{rec}B}{4\sigma_T u_{cool}}} = 2.3 \times 10^7 \sqrt{\frac{\beta_{rec}B_0}{u_{cool,0}}}$$

- $\beta_{rec} \sim 10^{-9}$ for blazar sequence ($\gamma_{eq} \sim \gamma_{peak}$)

- $\beta_{rec} \sim 0.01$-0.1 for collisionless reconnection
(enhanced by tearing instability or turbulence)

maximum particle energy

- average electron energy limited by magnetization
  $\gamma_{ave} \sim \sigma_e \gamma_0 \sim (m_e/m_i)\, \sigma_i \gamma_0$

- $\sigma >> 1$: hard power-law spectra ($p \sim 1$)
  $\gamma_{max} \sim \gamma_{ave}$
  seems necessary for TeV blazars

- $\sigma \sim 1$: soft power-law spectra ($p \sim 3$)
  $\gamma_{max} > \gamma_{ave}$, but unlikely to be high

- stochastic acceleration in turbulence, can it compete with radiative and adiabatic losses?

magnetization of jets

- unsolved mass loading problem
- leptons seeded quasi-uniformly by pair creation (very model-depenent)
- barions may only be introduced non-uniformly (interchange instability stars)
- diffusion or mixing inefficient?
- blazar zones (post-dissipation regions) roughly in equipartition, whether resulting from shocks or reconnection
  (Sironi, Petropoulou & Giannios 2015)

proposition of highly inhomogeneous jets

- large regions of very high magnetization $\sigma_{max} \sim \gamma_{max}$ from pair loading, no protons
- pair loading regulated by external radiation
  -> blazar sequence
- proton-rich filaments, moderate $\sigma_{mean} \sim \Gamma_{jet}$
  -> bulk acceleration

conclusions

- relativistic magnetic reconnection has been studied extensively by means of kinetic plasma simulations
- particle acceleration in reconnection sites is rapid, maximum energy limited by upstream magnetization
- for particle acceleration to be regulated by radiative cooling in line with the blazar sequence, particle acceleration should be extremely slow
- the sequence could be due to jet magnetization limited by pair creation regulated by external radiation fields