TIME-DEPENDENT RADIATIVE SIGNATURES OF RELATIVISTIC MAGNETIC RECONNECTION

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NATIONAL SCIENCE CENTRE
POLAND

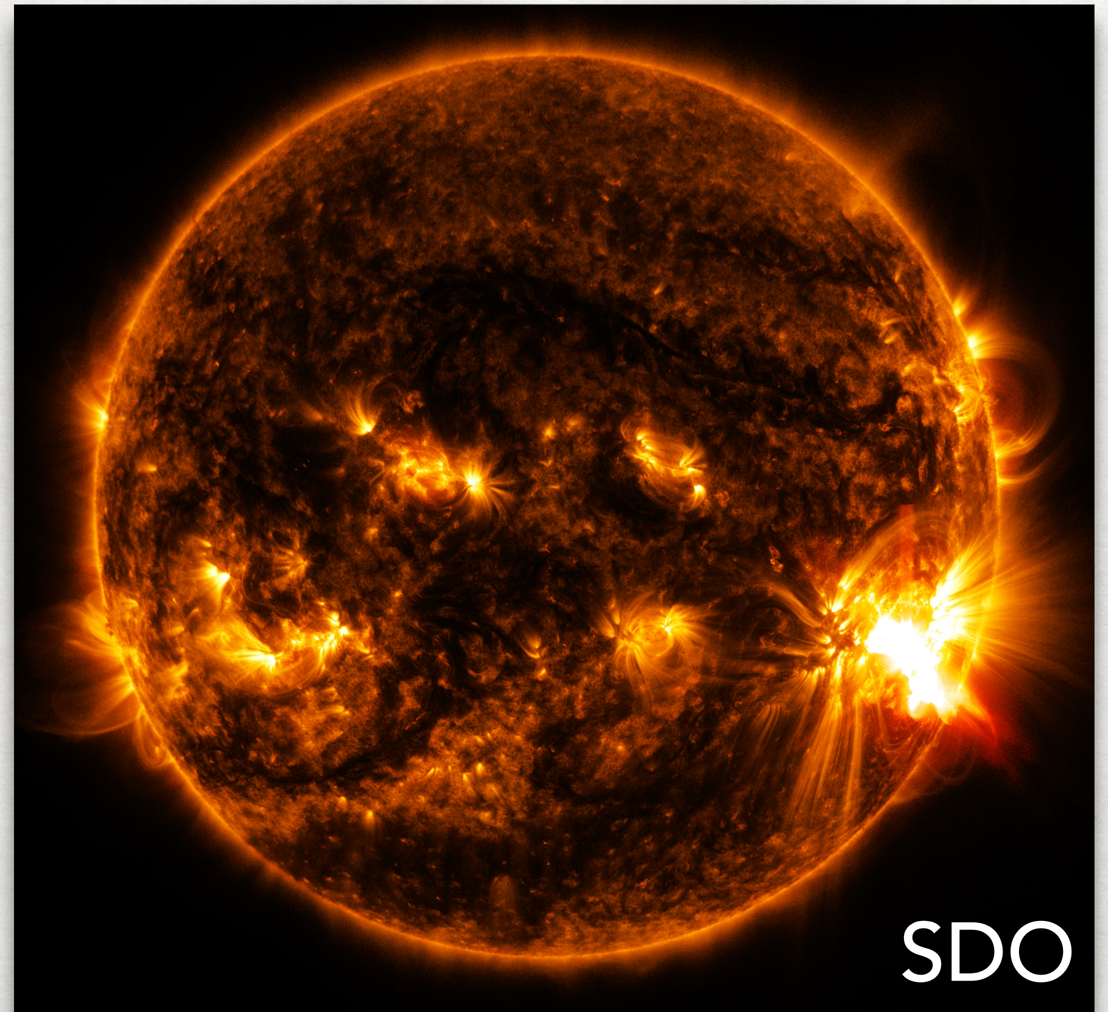
1. ASTROPHYSICAL MOTIVATION

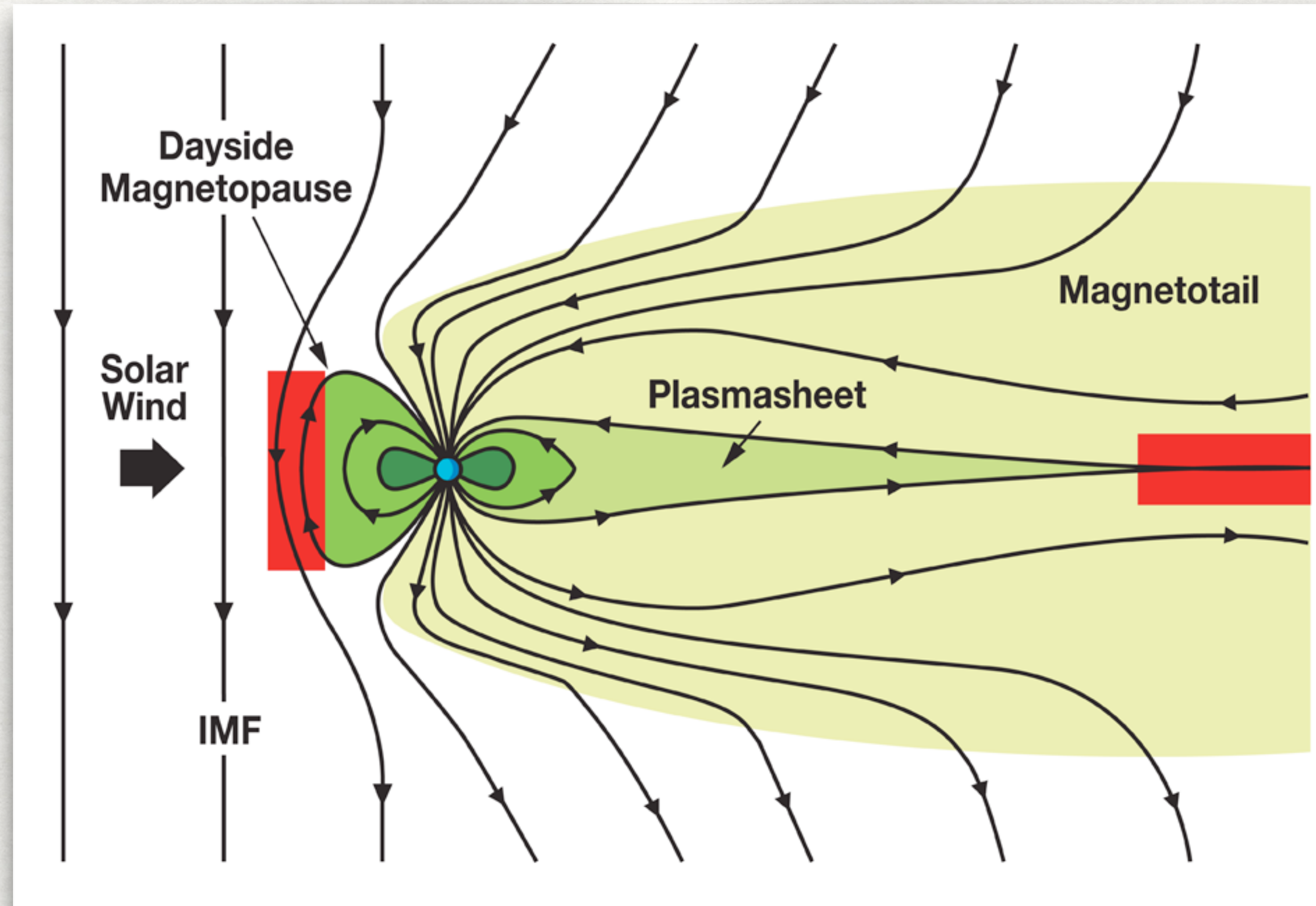
2. KINETIC SIMULATIONS OF RELATIVISTIC MAGNETIC RECONNECTION:

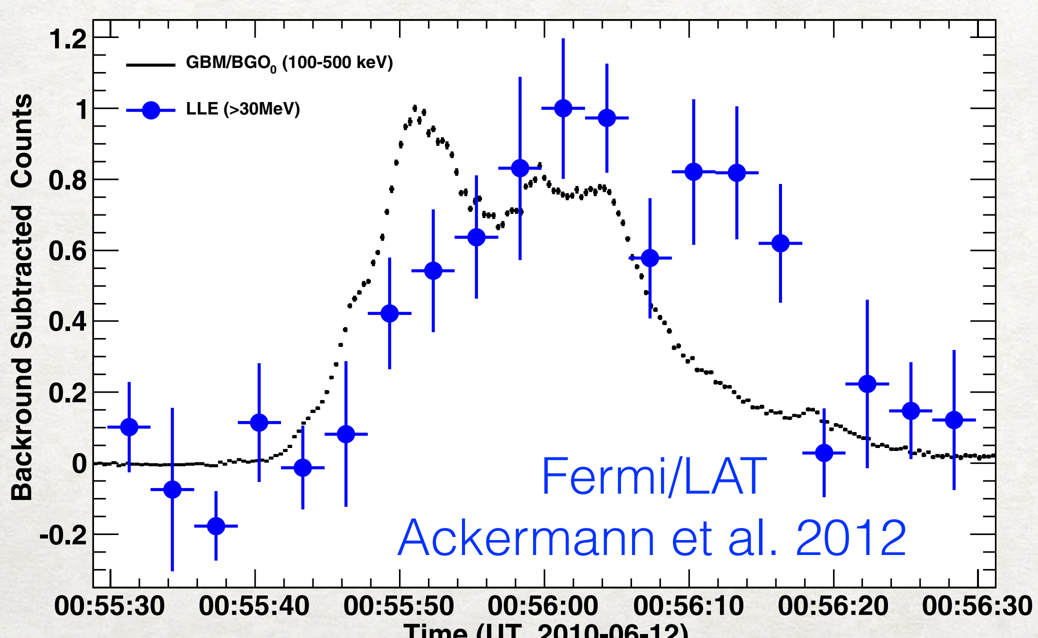
A) PARTICLE ACCELERATION

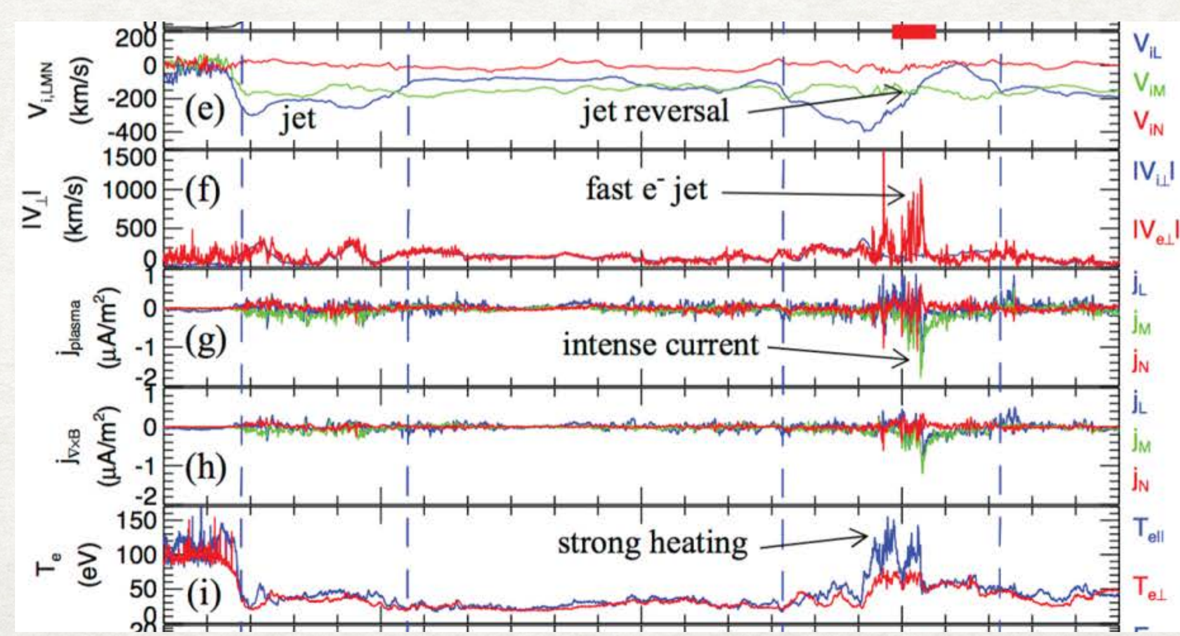
B) RADIATIVE SIGNATURES

RECONNECTION IN THE SOLAR SYSTEM









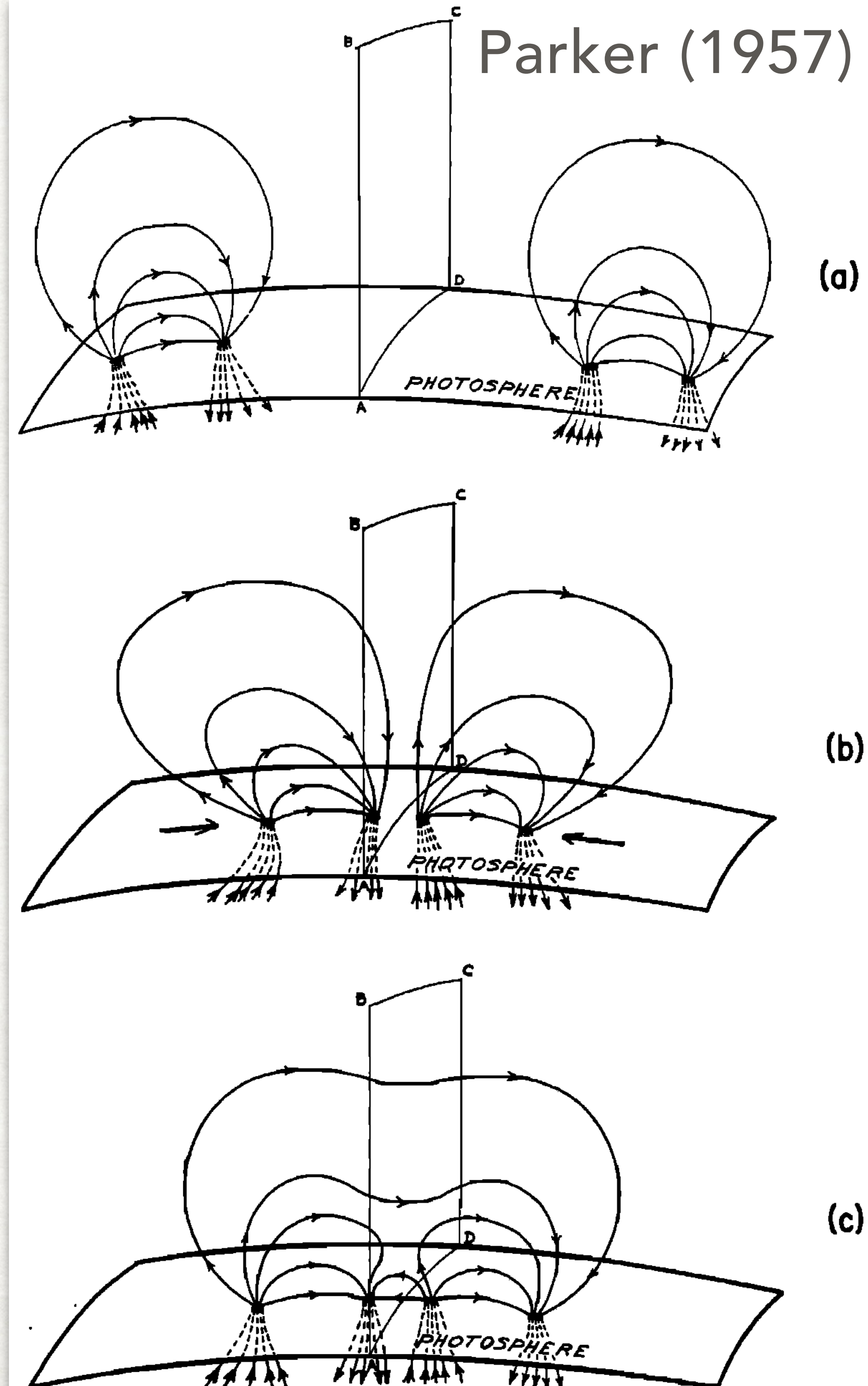
MMS
Burch+
(2016)

PROPOSITION OF MAGNETIC RECONNECTION

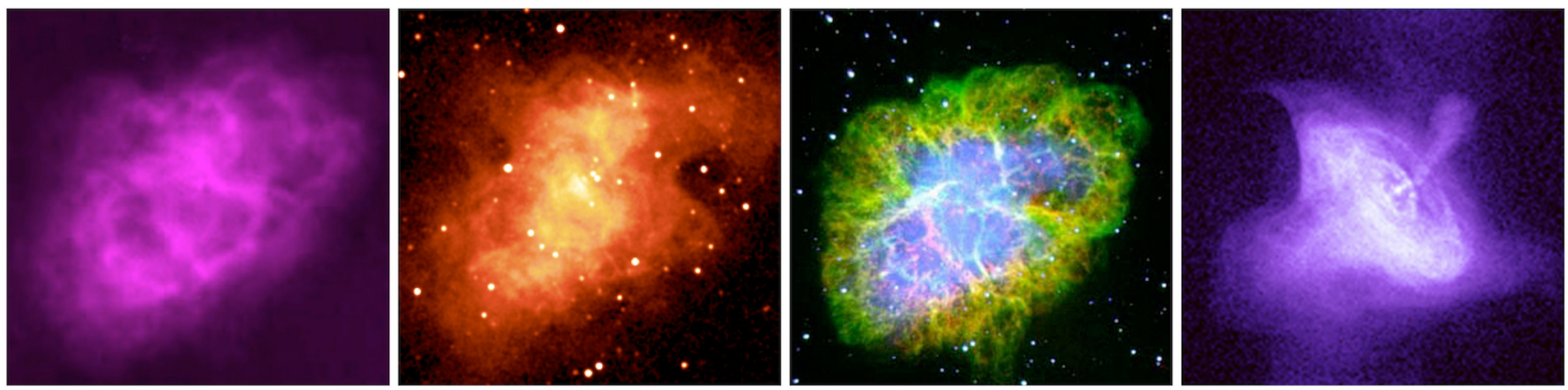
A mechanism is proposed here for the production of these flares based on the energies acquired by charged particles moving in induced electric fields associated with sunspots.

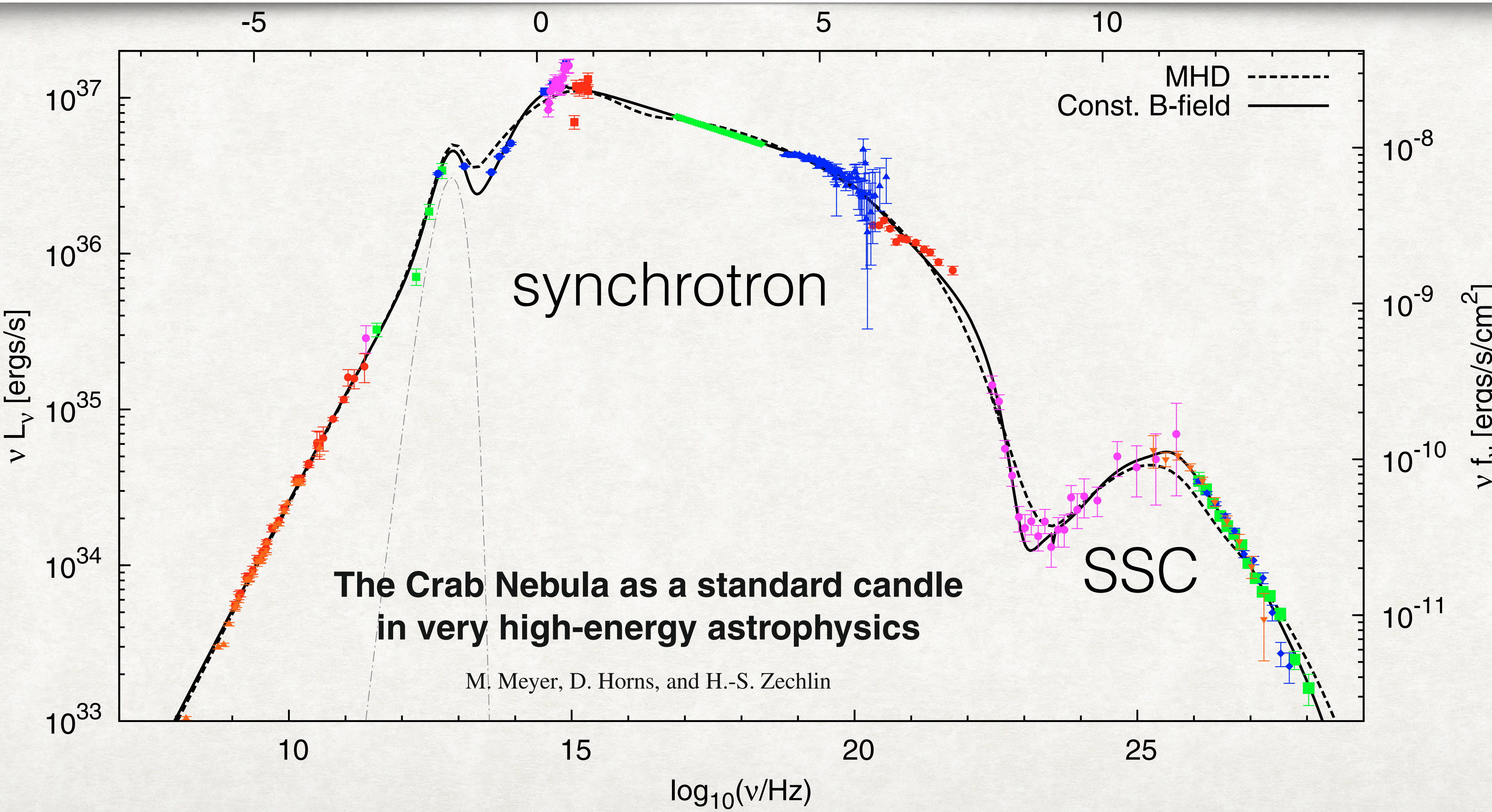
Apart from a general magnetic field, fields from other sunspots may still be of appreciable size in the neighbourhood of the spot under consideration. It is thus to be expected that there will be places where actual neutral points exist and where conditions are thus suitable for the excitation of atoms by collision.

Giovanelli (1946)

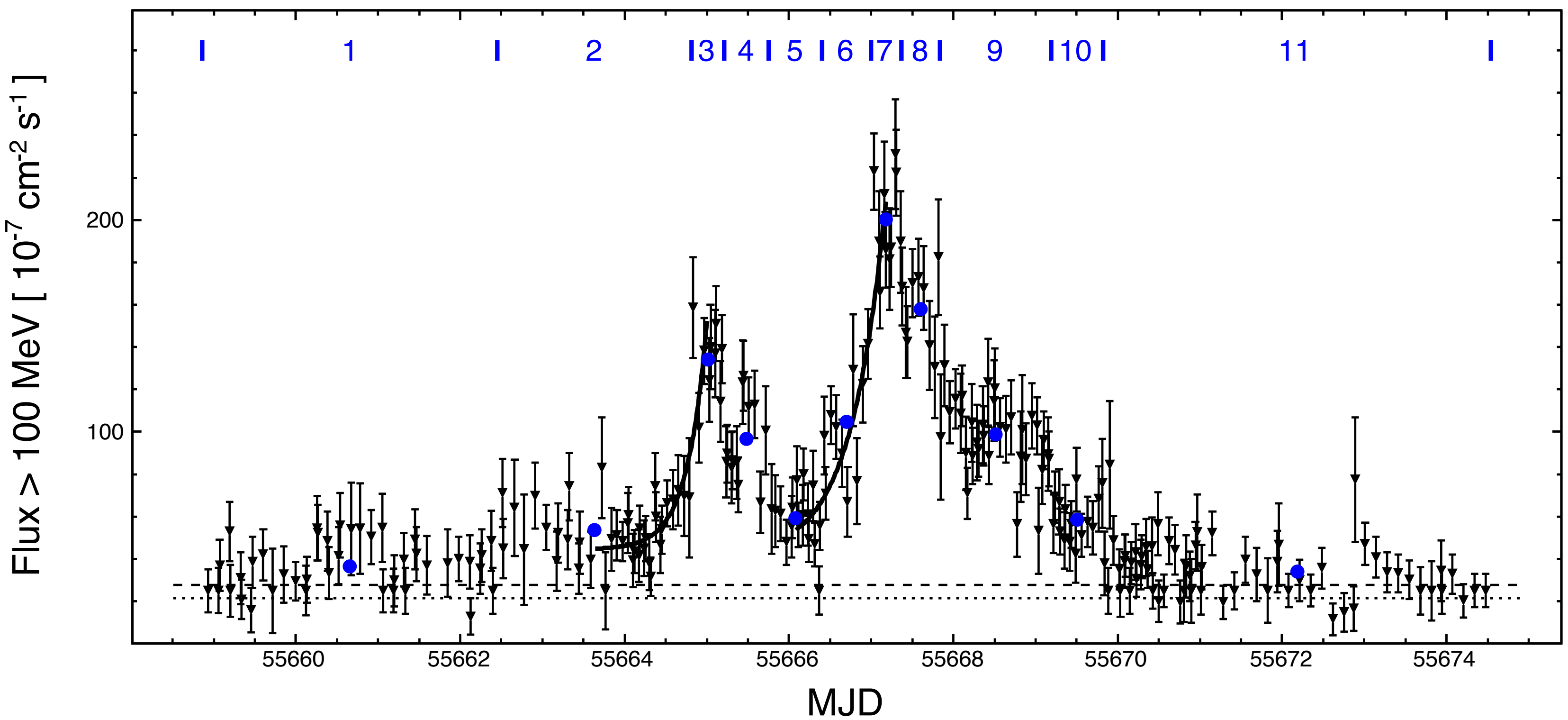


Parker (1957)

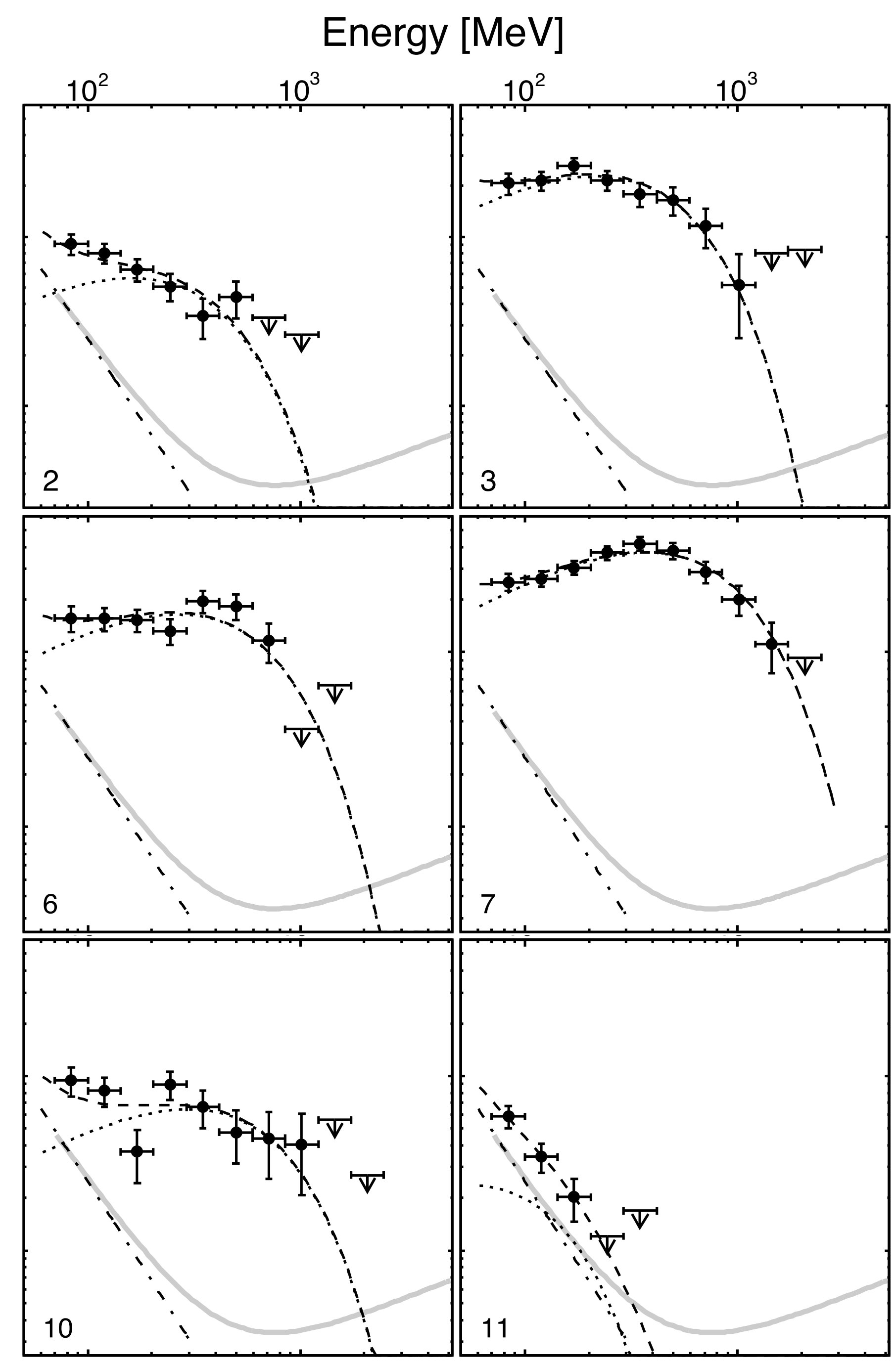



-5
0
5
10
MHD
Const. B-field
10^{37}
10^{36}
10^{35}
10^{34}
10^{33}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
νL_ν [ergs/s]
νf_ν [ergs/s/cm^2]
synchrotron
SSC
The Crab Nebula as a standard candle
in very high-energy astrophysics
M. Meyer, D. Horns, and H.-S. Zechlin
10
15
20
25
$\log_{10}(\nu/\text{Hz})$

gamma-ray flares from the Crab Nebula



Science
Tavani et al. (2011)
Abdo et al. (2011)

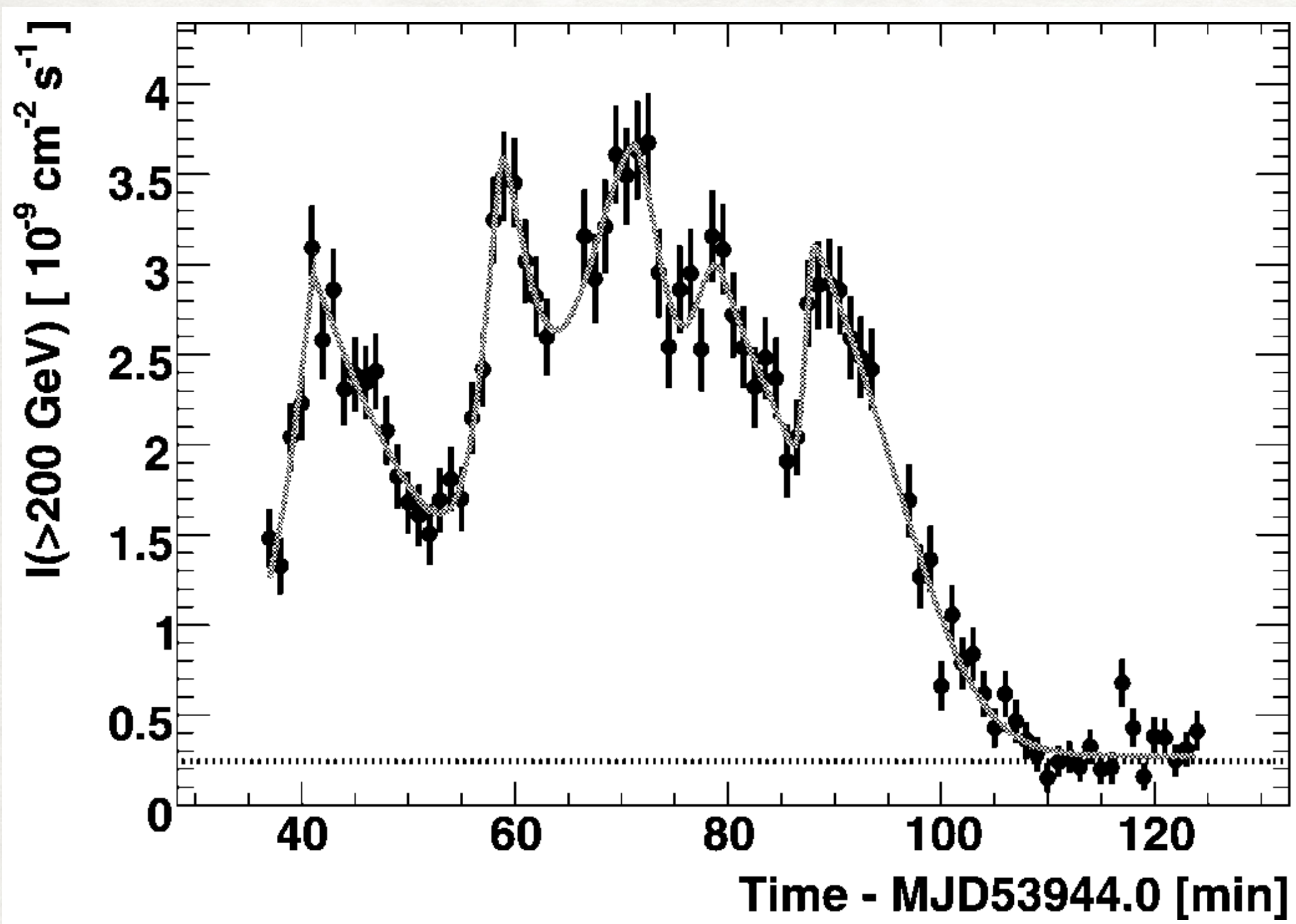


- emission peak at ~400 MeV
- variability time scale of a few hr
- must be synchrotron radiation from PeV electrons
- exceeds the synchrotron limit $m_e c^2/\alpha$ ~100 MeV

Uzdensky et al. (2011), Bednarek & Idec (2011)

Buehler et al. (2011)

GAMMA-RAY VARIABILITY OF BLAZARS AND MISALIGNED AGNS



PKS 2155-304

H.E.S.S. Collaboration (2007)

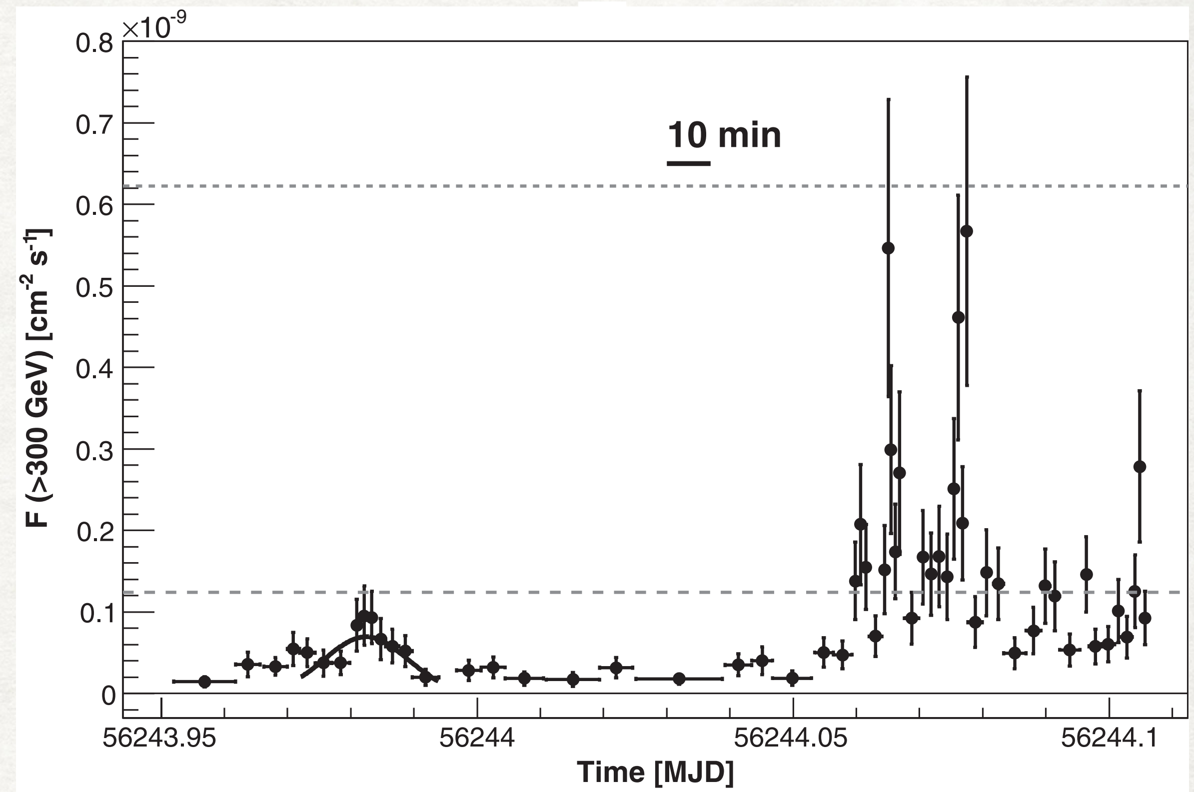
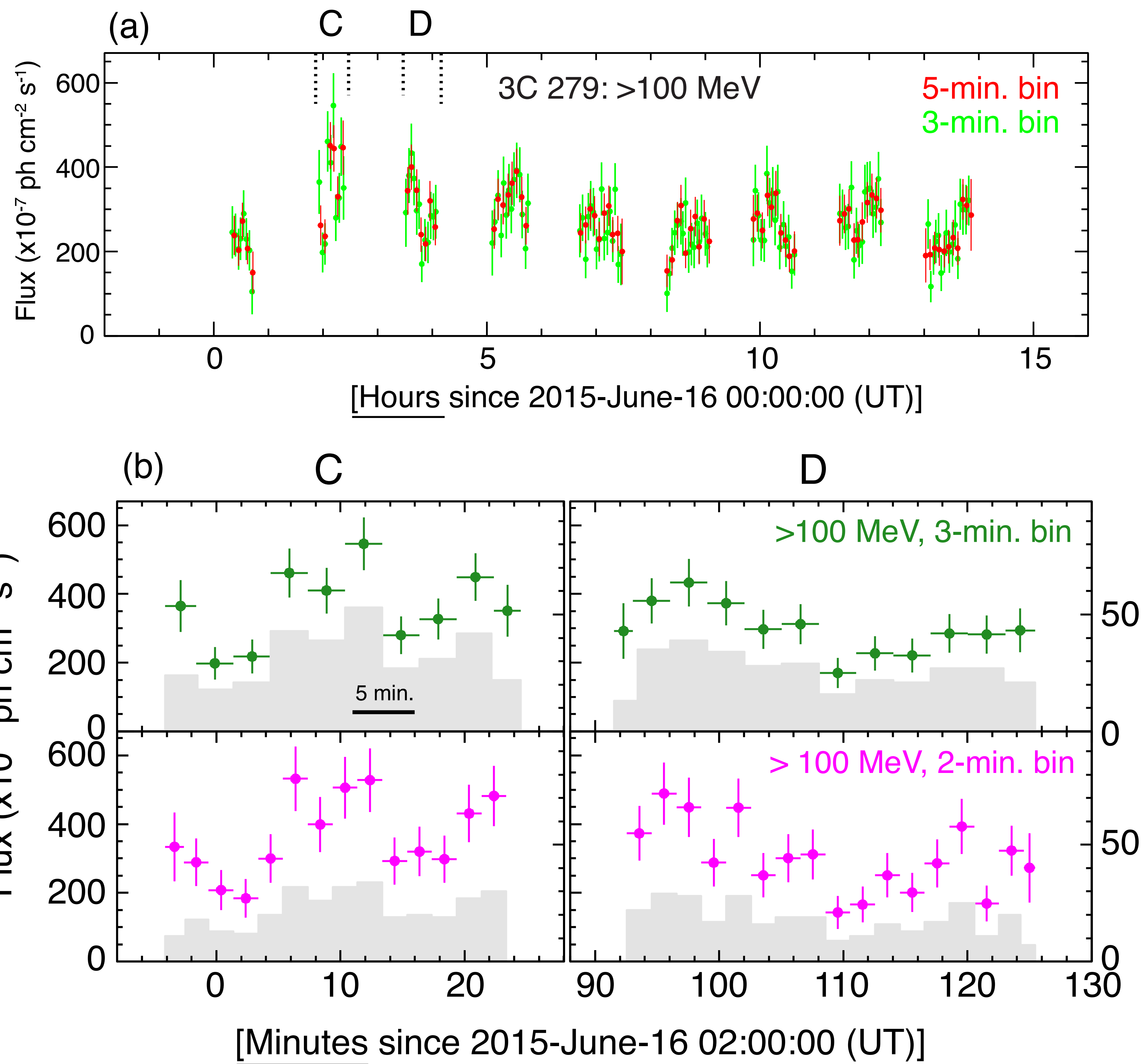


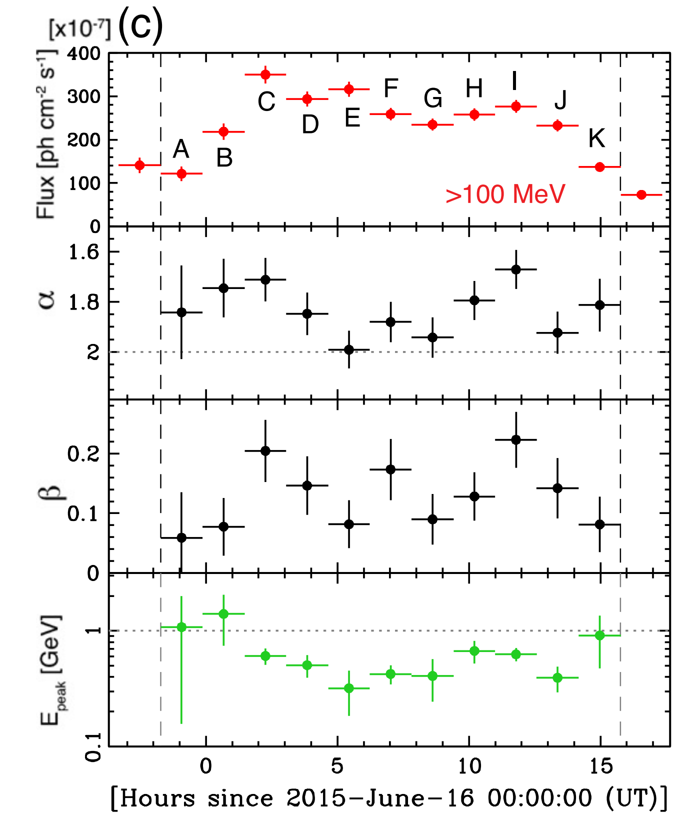
Fig. 4. Light curve of IC 310 observed with the MAGIC telescopes on the night of 12/13 November 2012, above 300 GeV. As a flux reference, the two gray lines indicate levels of 1 and 5 times the flux level of the Crab Nebula, respectively. The precursor flare (MJD 56243.972-56243.994) has been fitted with a Gaussian distribution. Vertical error bars show 1 SD statistical uncertainity. Horizontal error bars show the bin widths.

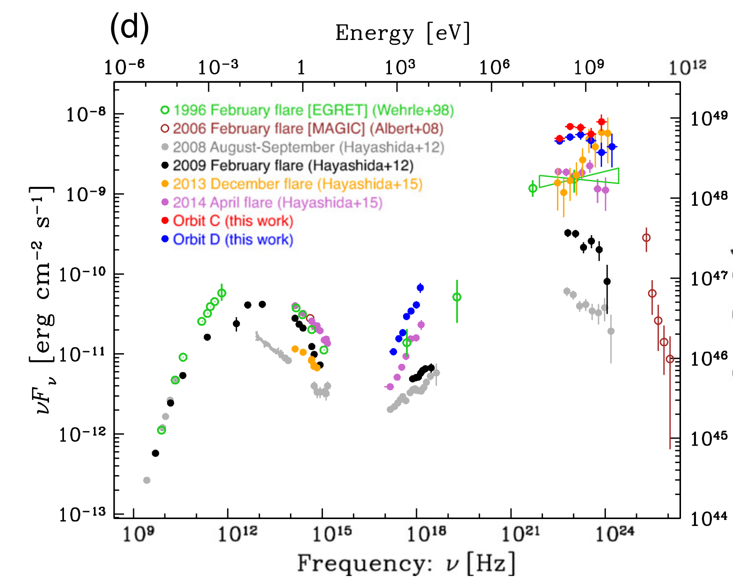
IC 310

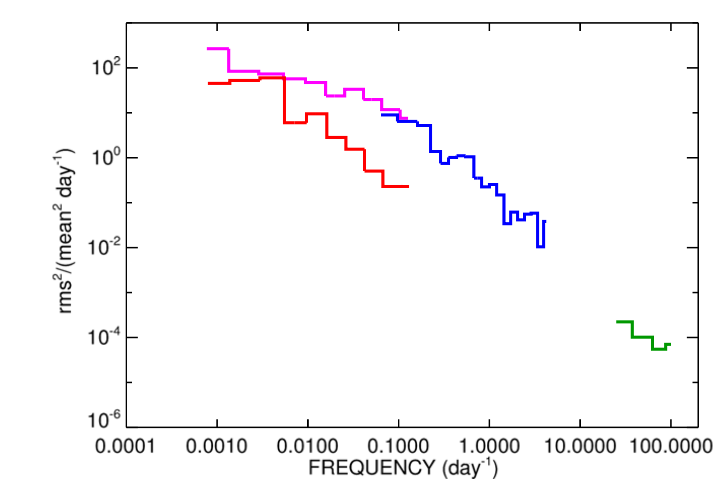
MAGIC Collaboration (2014)

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









Ackermann et al. (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
  (Ackermann et al. 2016)
  input from M. Hayashida, G. Madejski, M. Sikora, R. Blandford

- hadronic models: disfavoured
  (Petropoulou, KN, Hayashida & Mastichiadis, submitted)

1. ASTROPHYSICAL MOTIVATION

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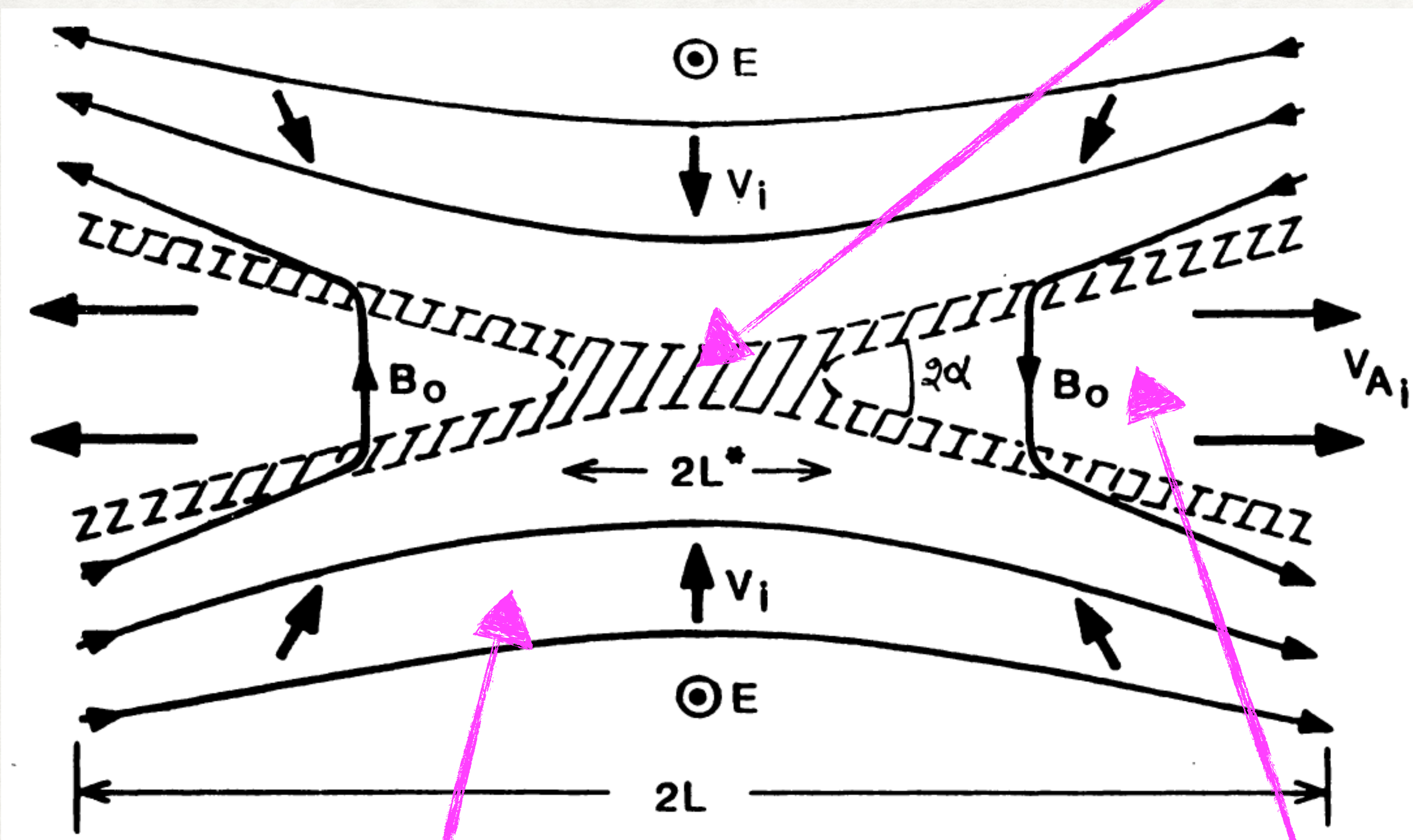
MAGNETIC RECONNECTION

magnetic diffusion region (X-point)



$E \sim (v_{in}/c)\, B_0$

$v_{in} \sim 0.1\, v_A$
reconnection rate
(Liu et al.)

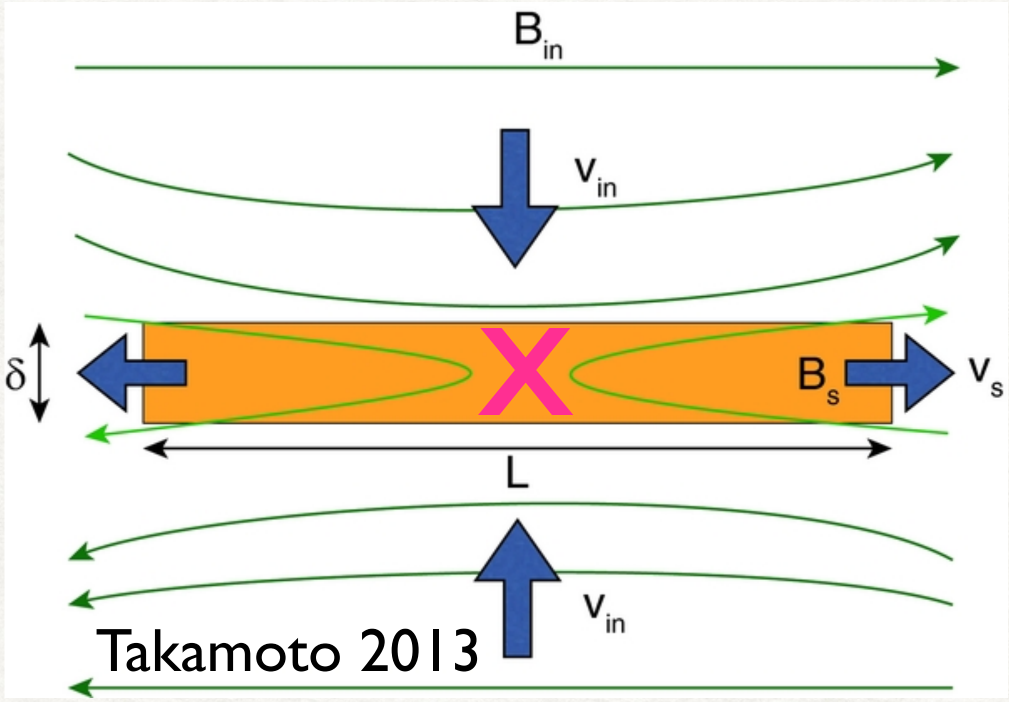
Vlasov
momentum
equation
$\partial_t u^i + \partial_j P^{ij} =$
$qn[E + (v/c) x B]^i$

reconnecting magnetic field
(background, upstream)

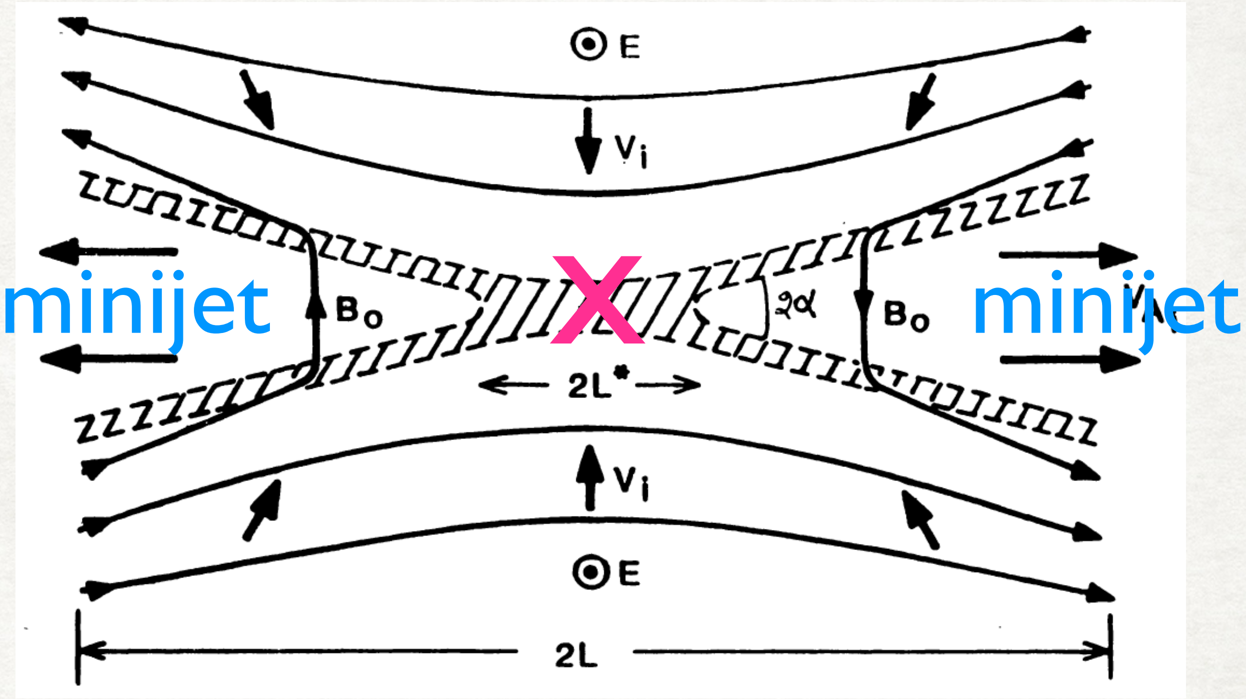
reconnection outflow
(downstream)

RECONNECTION MODELS

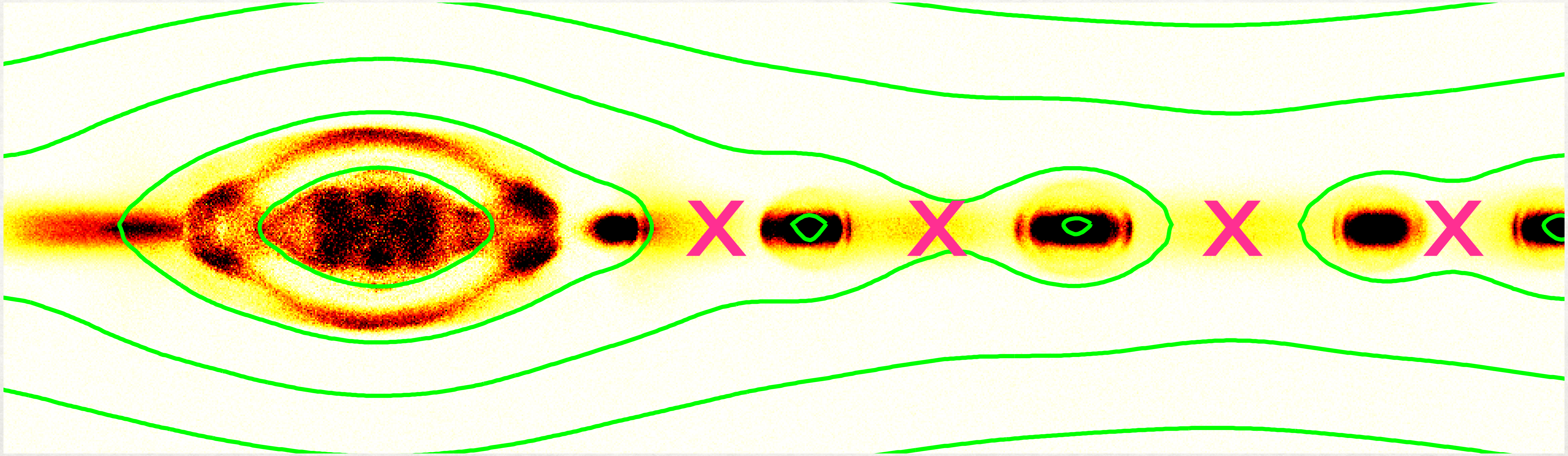
Sweet-Parker



Petschek



plasmoid-dominated



relativistic magnetic reconnection from Harris-type layers

The Astrophysical Journal Letters, 783:L21 (6pp), 2014 March 1 doi:10.1088/2041-8205/783/1/L21

RELATIVISTIC RECONNECTION: AN EFFICIENT SOURCE OF NON-THERMAL PARTICLES

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[2] Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544-1001, USA; anatoly@astro.princeton.edu
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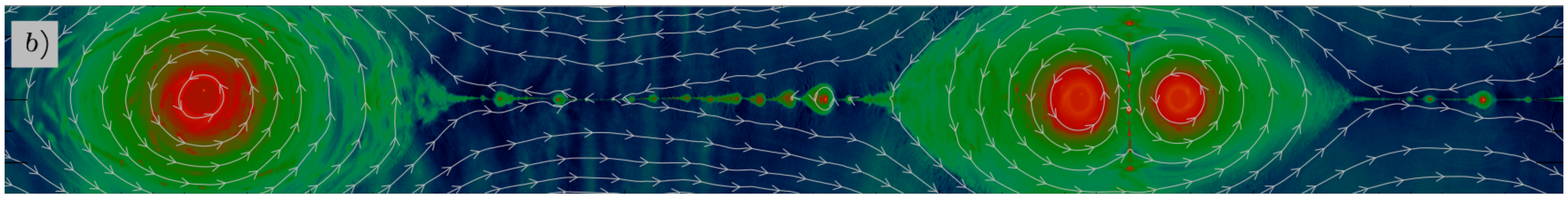
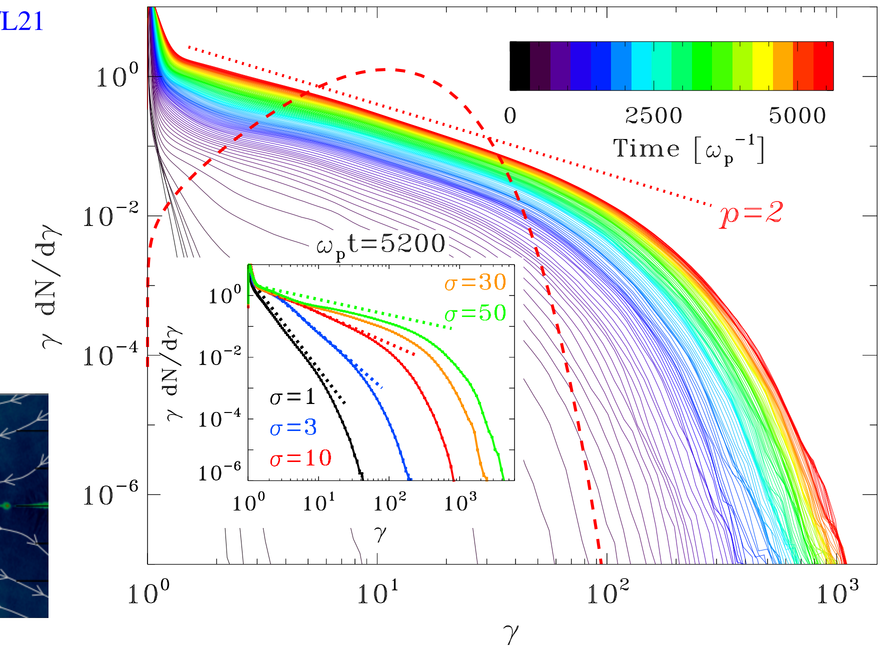
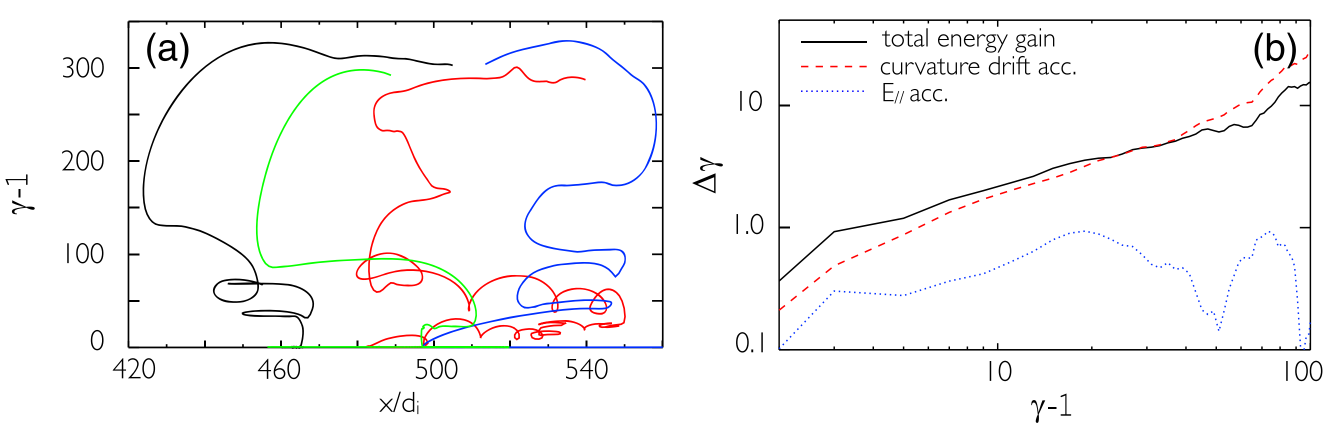


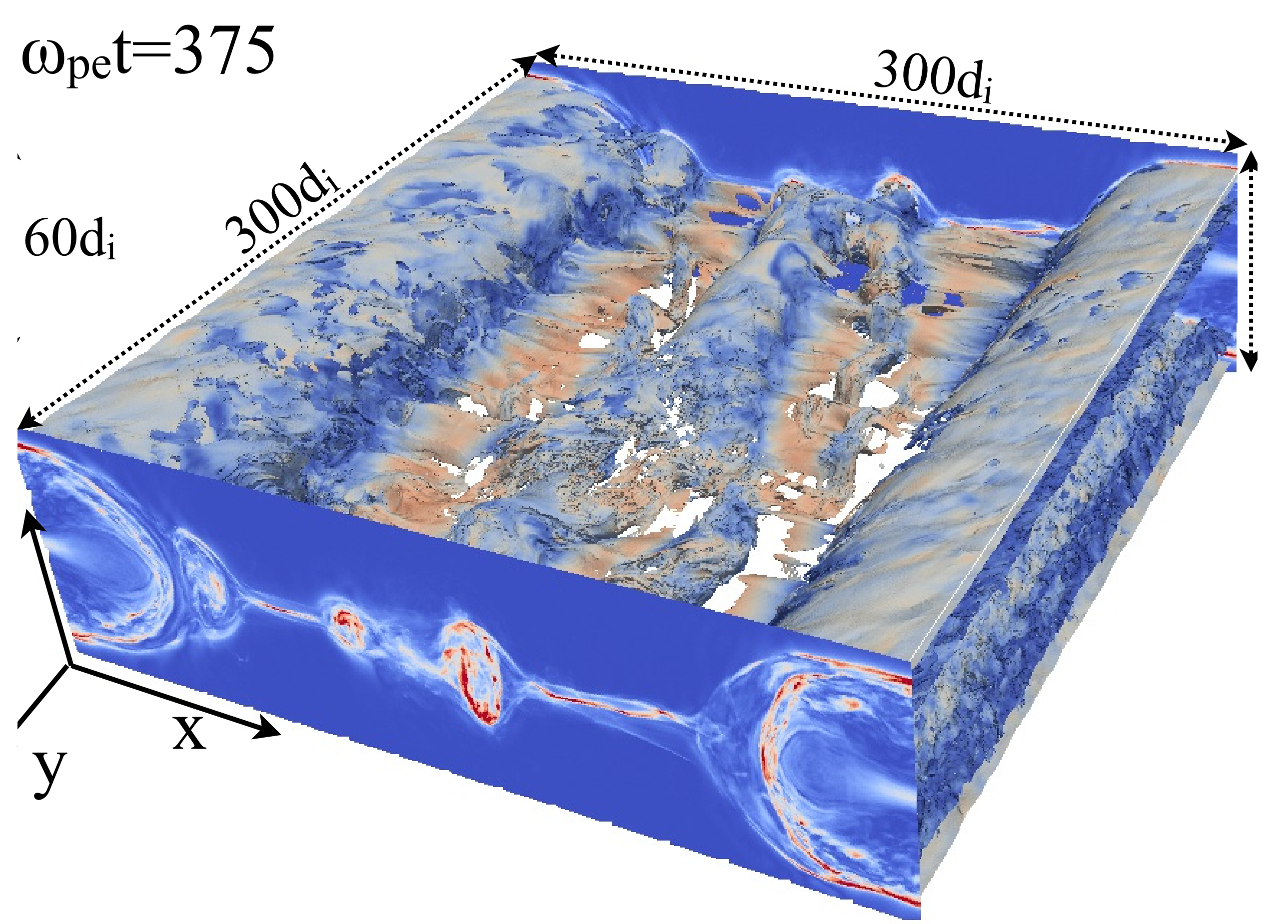


PRL 113, 155005 (2014) PHYSICAL REVIEW LETTERS week ending 10 OCTOBER 2014

Formation of Hard Power Laws in the Energetic Particle Spectra Resulting from Relativistic Magnetic Reconnection

Fan Guo, Hui Li, William Daughton, and Yi-Hsin Liu
Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, New Mexico 87545, USA
(Received 15 May 2014; published 8 October 2014)

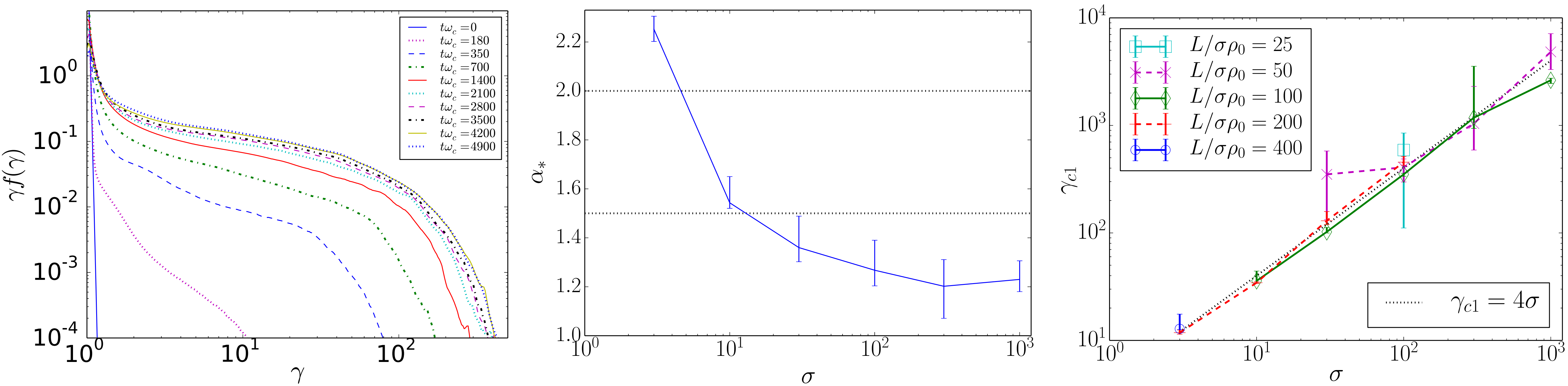




particle acceleration in pair-plasma reconnection

- 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)

RECONNECTION IN ELECTRON-PROTON PLASMA

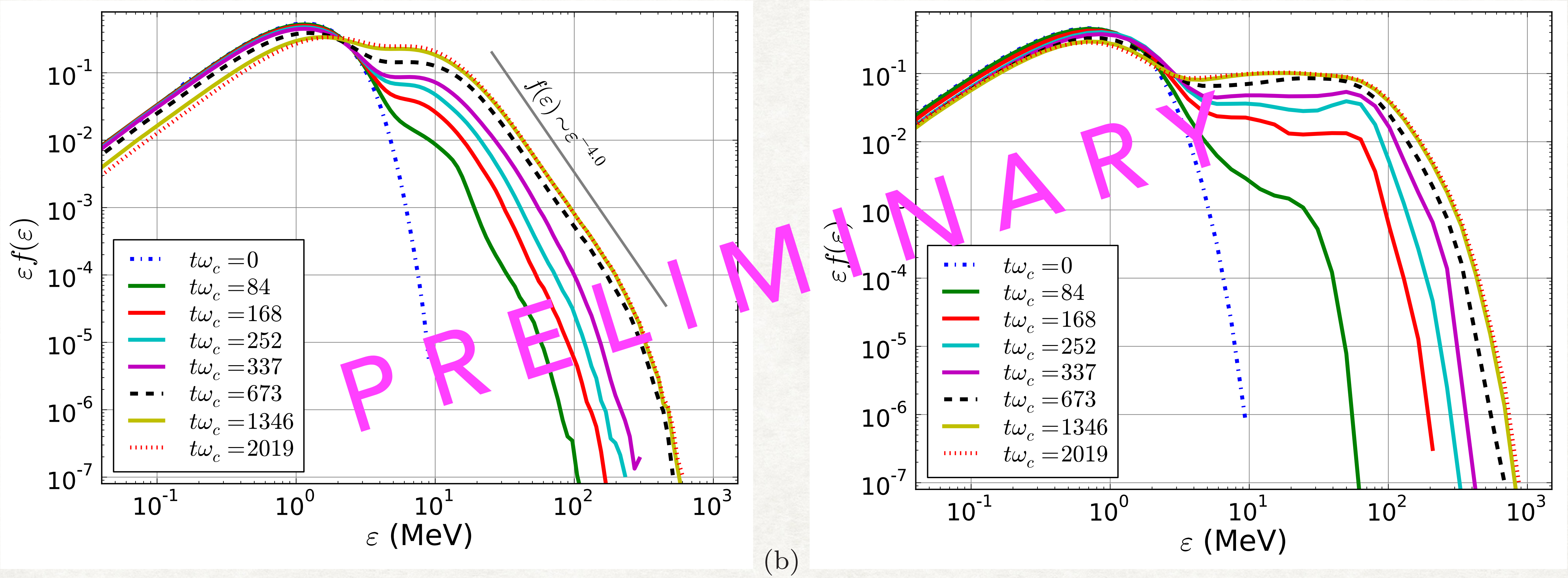
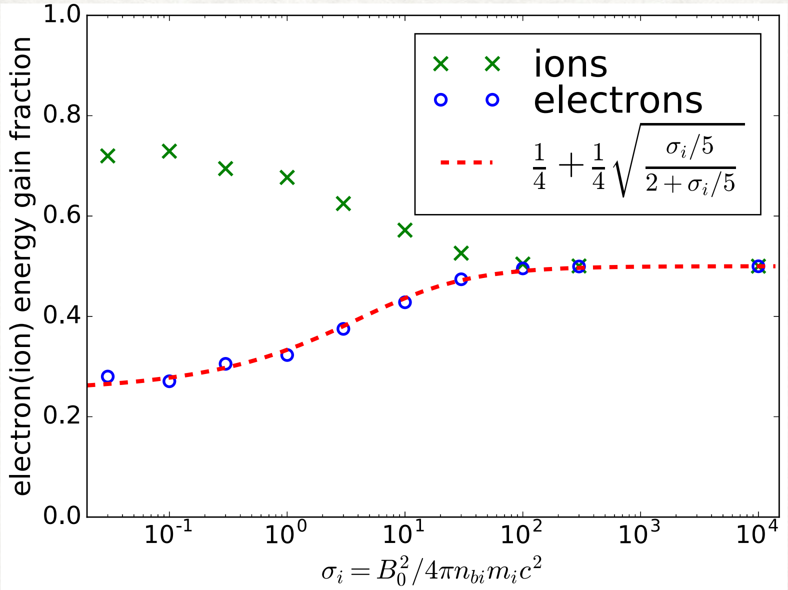


Figure 20. Time evolution of the (a) electron and (b) ion energy distributions, $f(\varepsilon)$ (compensated by ε) for $\sigma_i = 0.1$.



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

see also Melzani et al. (2014)
Guo et al. (2016)

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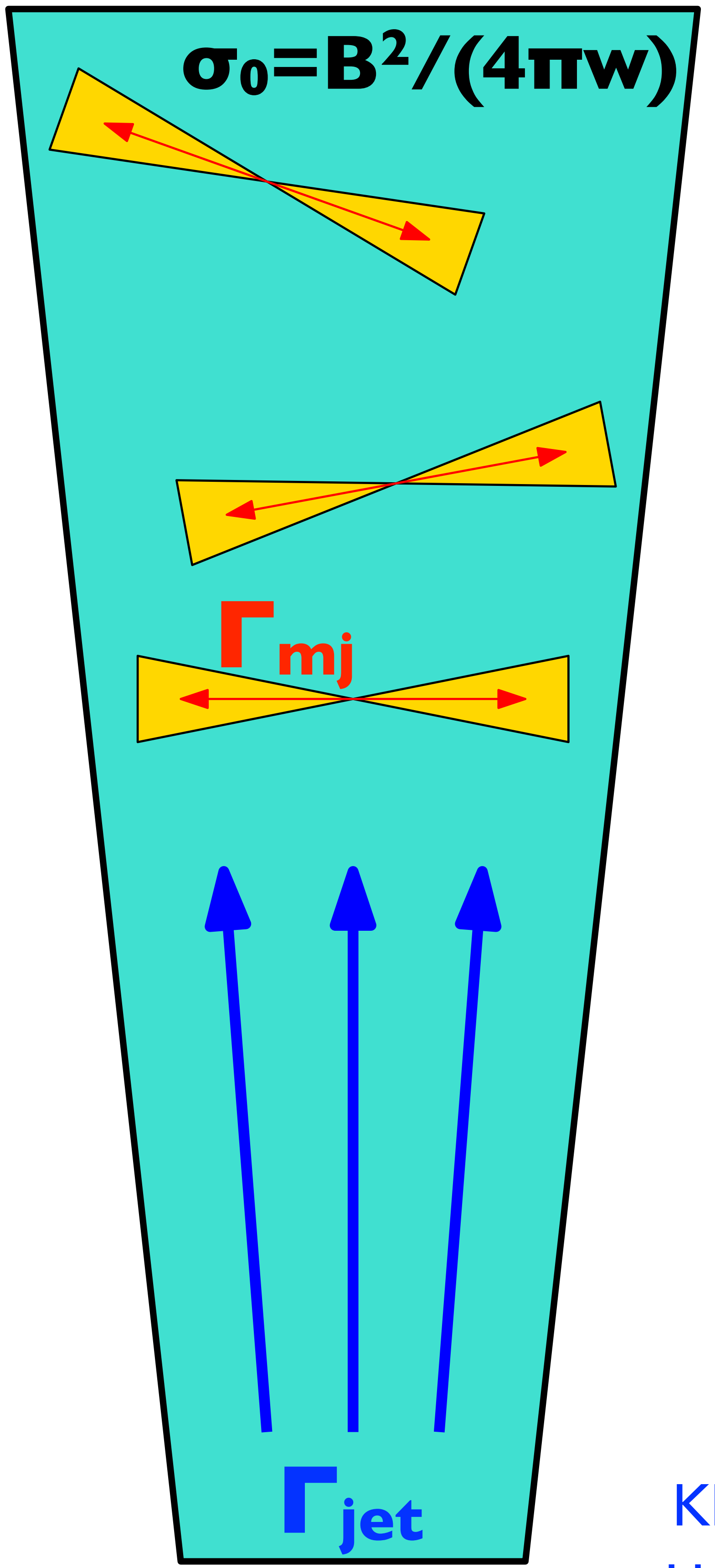
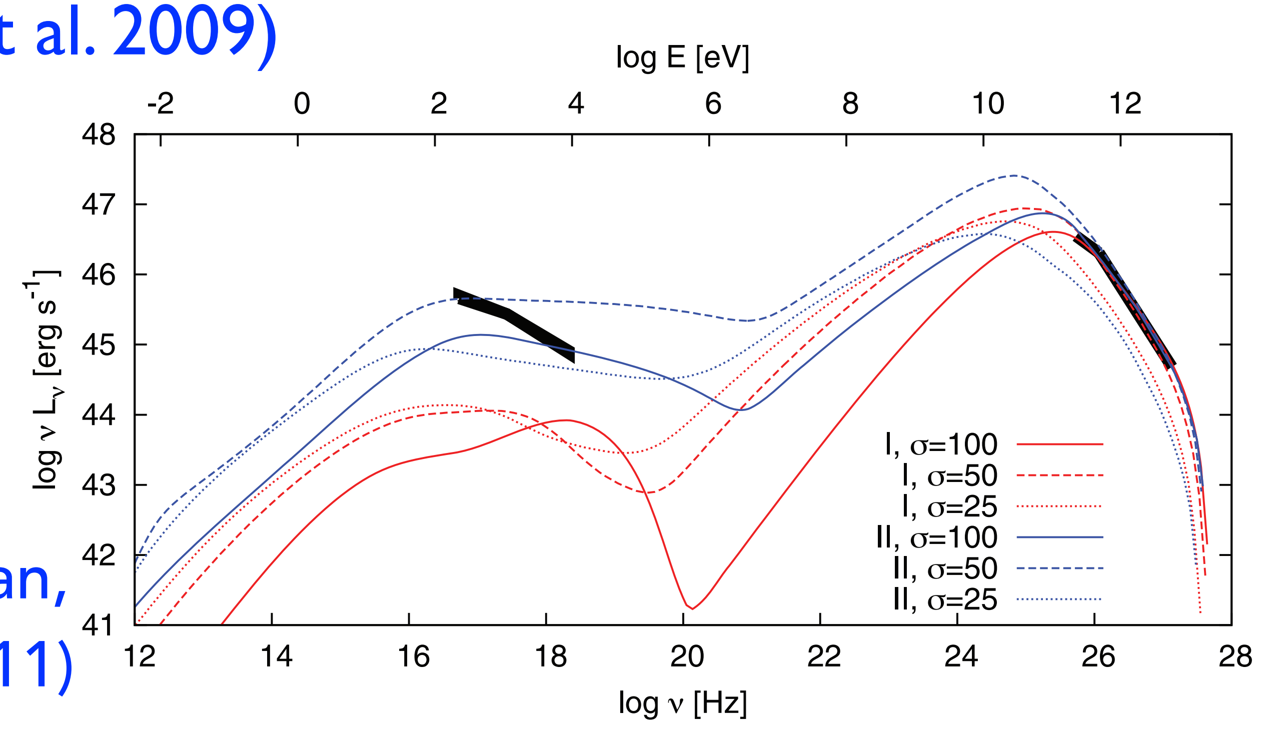
minijets model



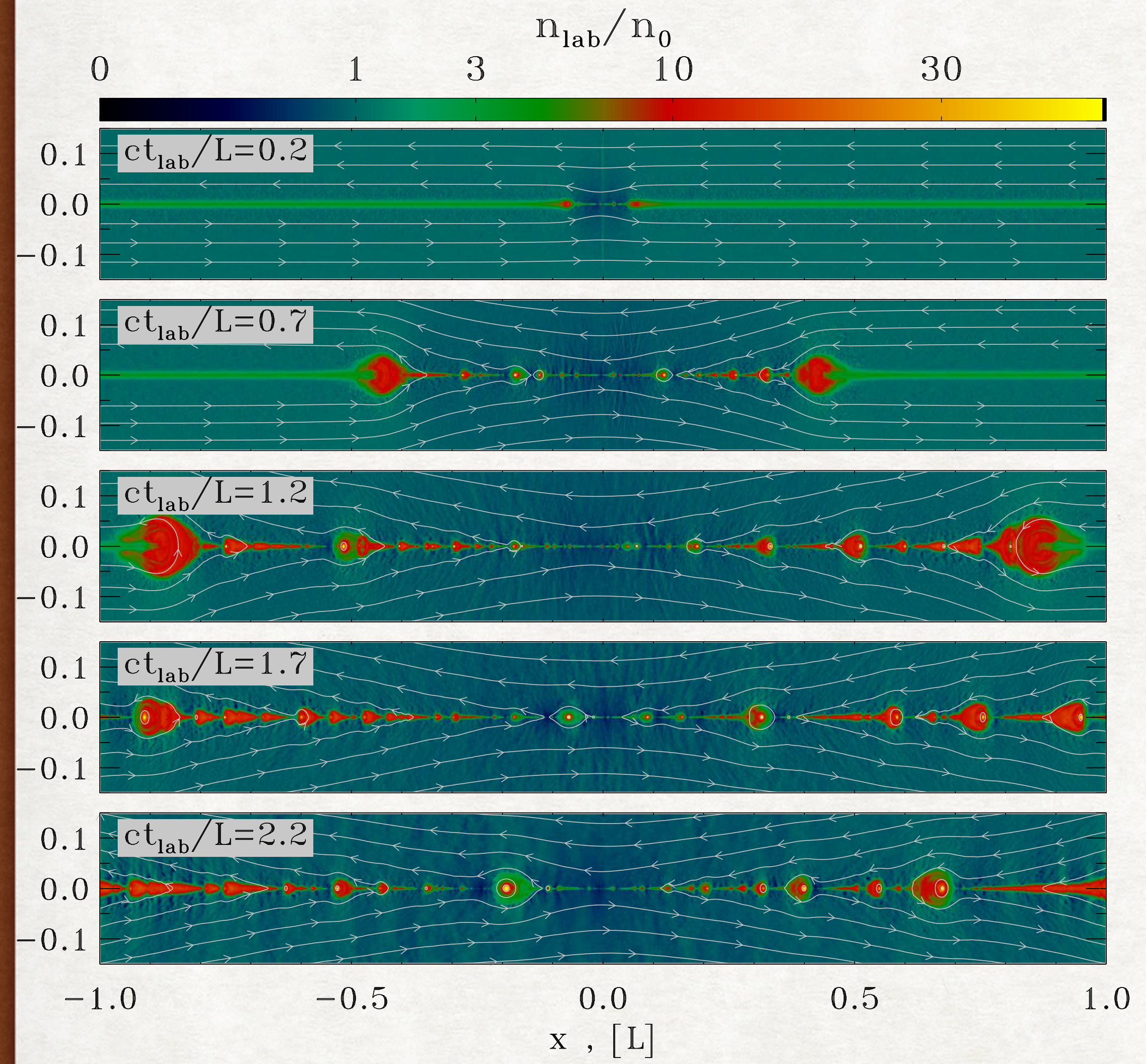
- reconnection produces localized relativistic outflows (minijets) with Γ_{mj} within a larger relativistic jet
- explains additional relativistic Lorentz boost ($\Gamma_{fl} \sim \Gamma_{jet}\Gamma_{mj}$) and local dissipation
- based on relativistic Petschek reconnection model (Lyubarsky 2005)
- depends on the scaling of minijet Lorentz factor with jet magnetization $\Gamma_{mj} \propto \sigma_0^{1/2}$ in relativistic regime (Giannios et al. 2009)

KN, Giannios, Begelman, Uzdensky & Sikora (2011)

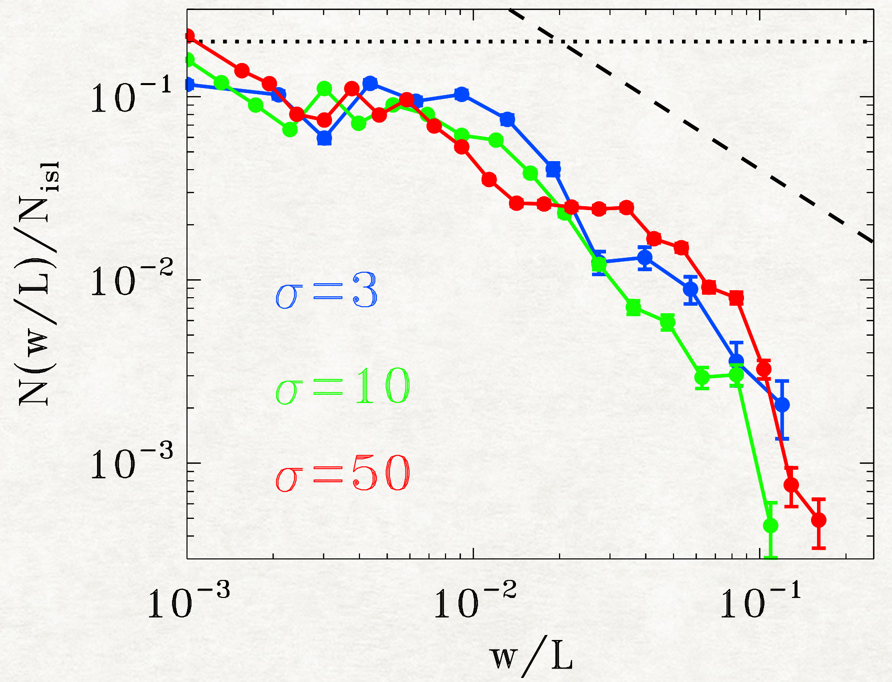


MINIJETS UPDATED

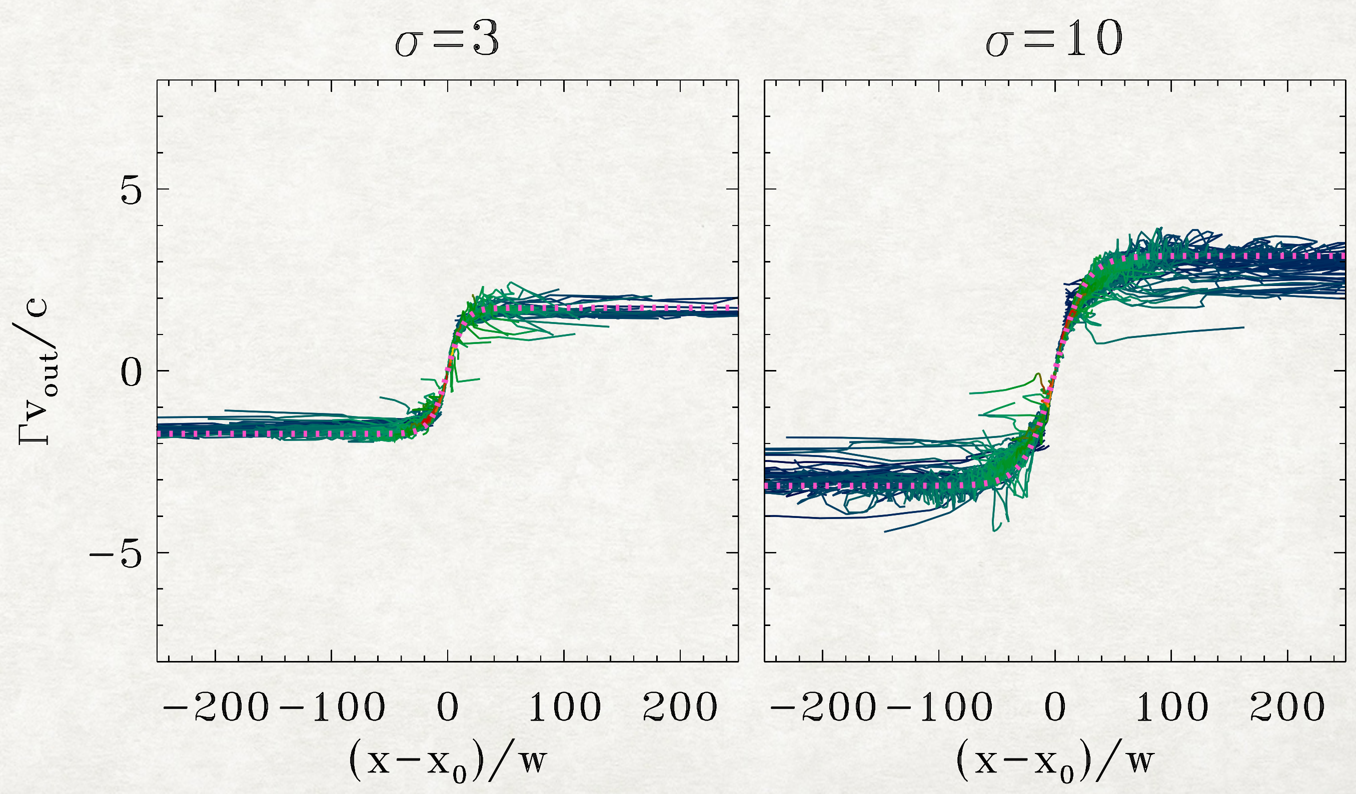
plasmoids are roughly in equipartition regardless of $\boldsymbol{\sigma}_0$ (Sironi et al. 2015)



plasmoid size distribution

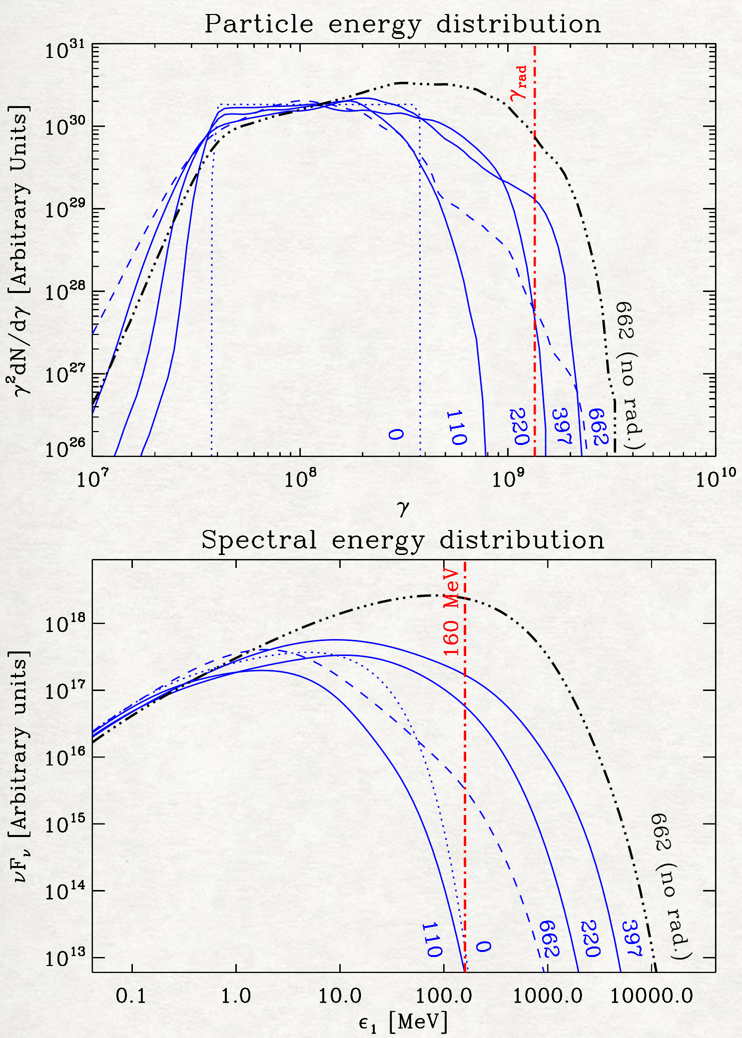


plasmoid acceleration profile



Sironi, Petropoulou & Giannios (2016)
Petropoulou, Giannios & Sironi (2016)

SYNCHROTRON SIGNATURES APPLIED TO CRAB FLARES (CERUTTI ET AL. 2013)



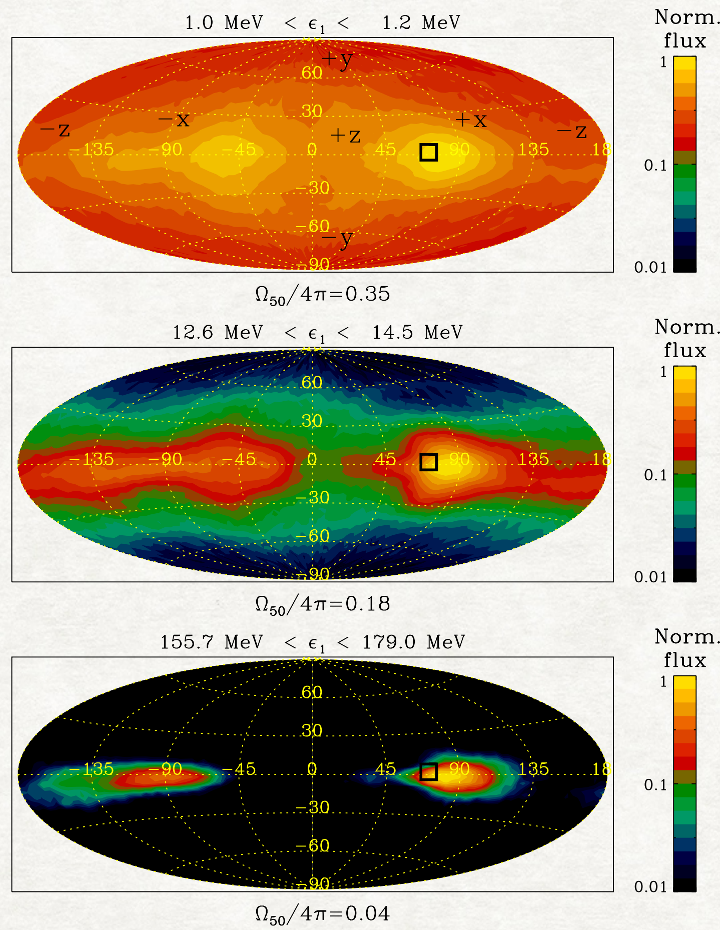
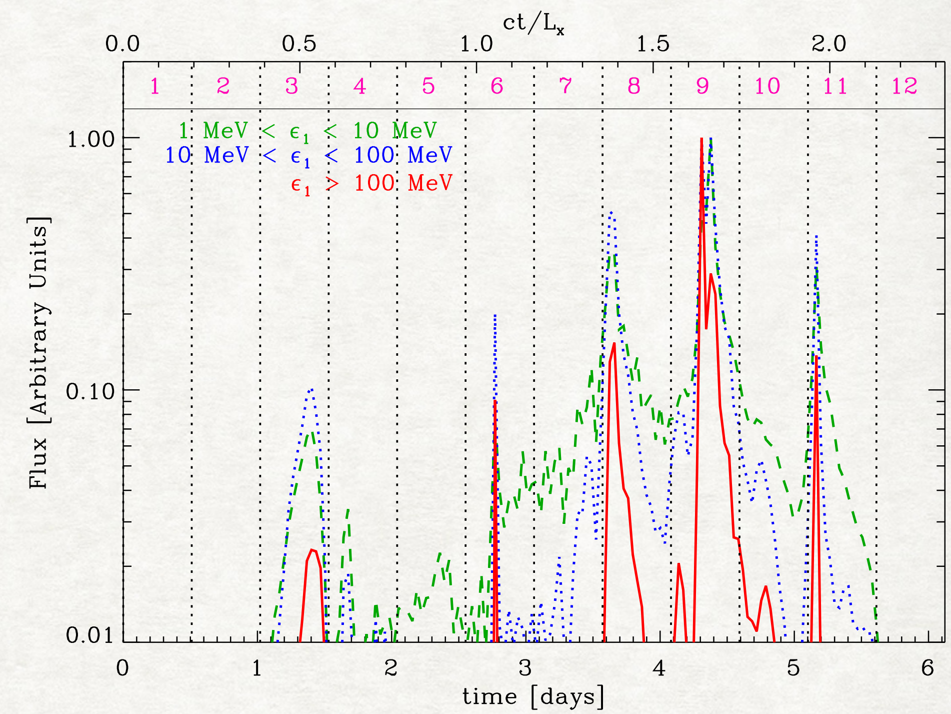
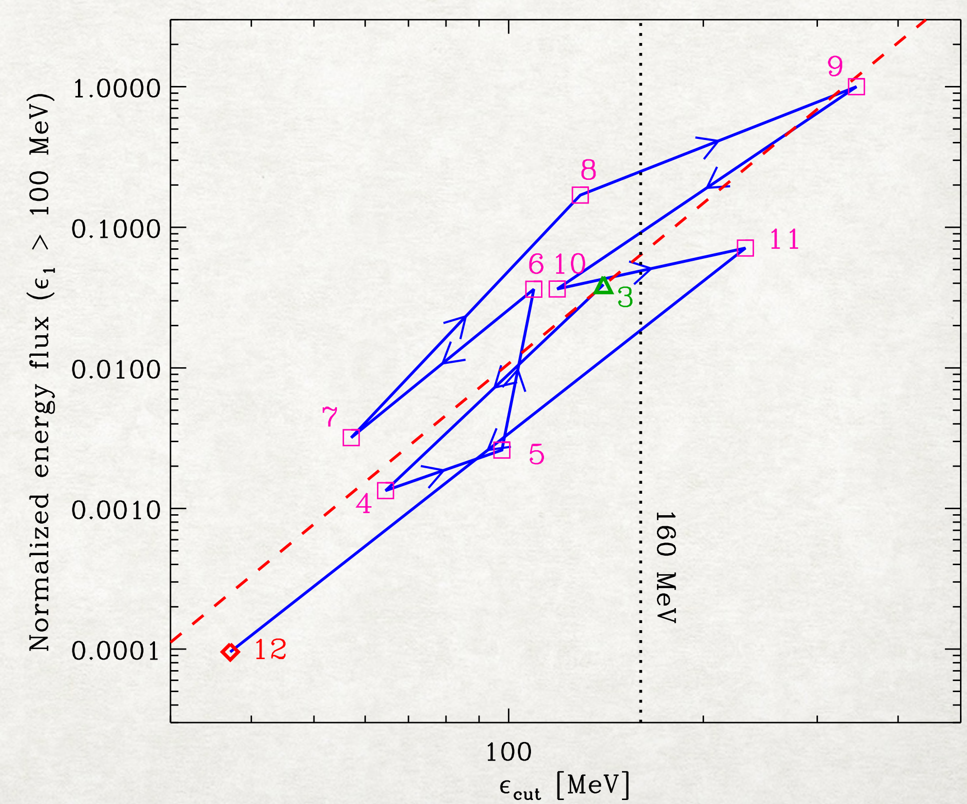
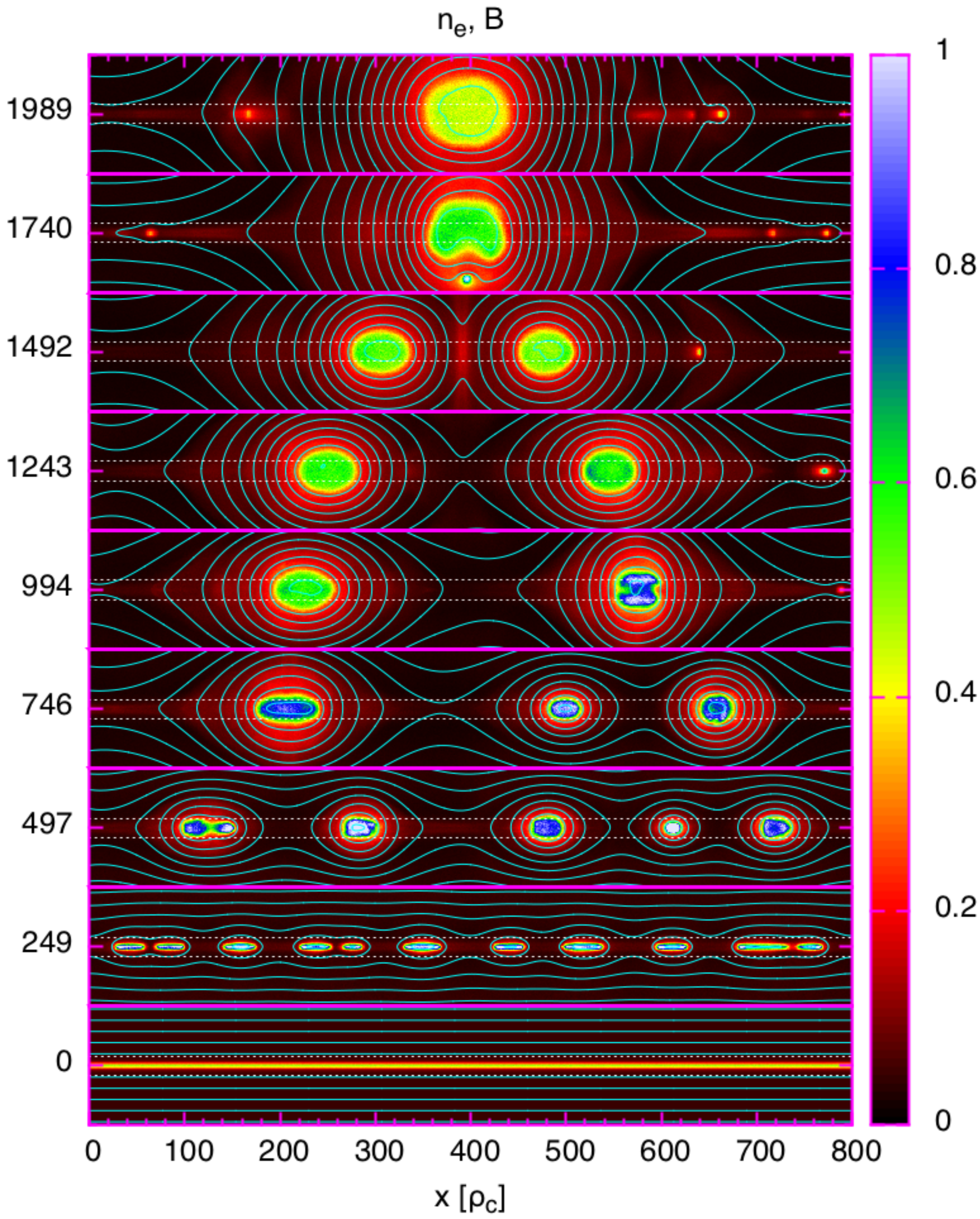
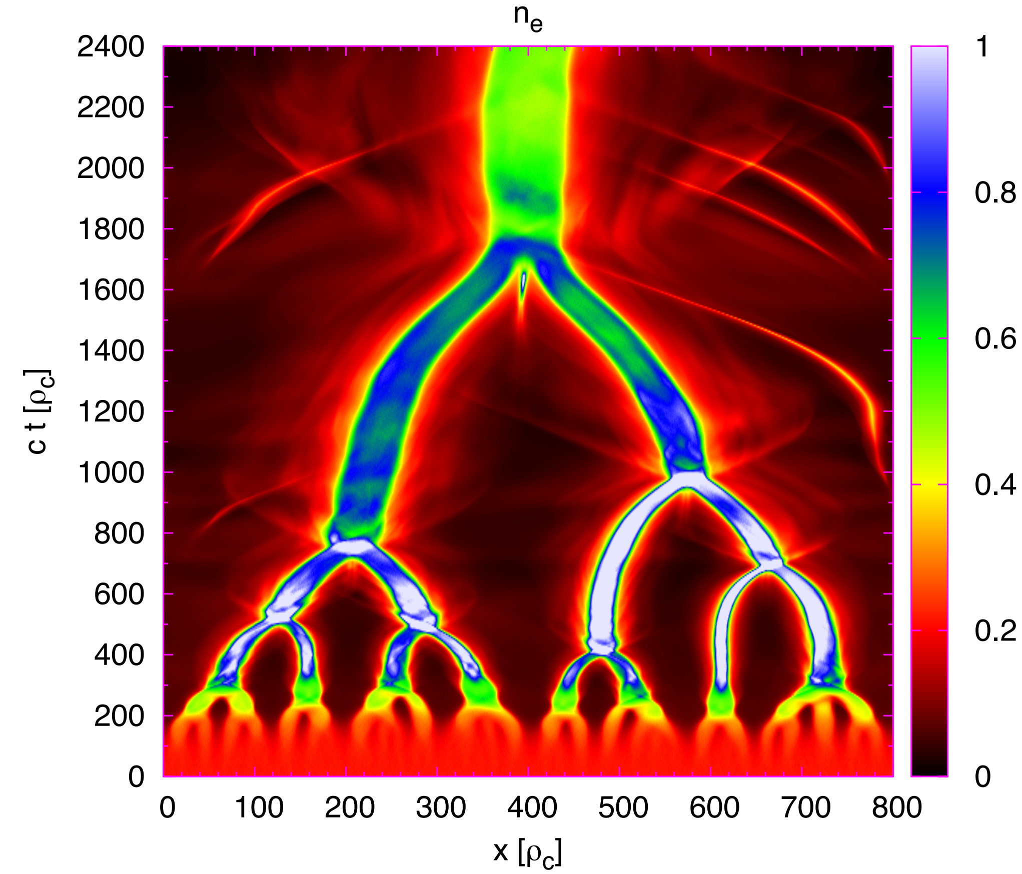


FIG. 5.— Energy-resolved angular distribution of the synchrot radiation flux $d(\nu F_\nu)/d\Omega/d\epsilon_1$ emitted at $t\omega_1$ = 397, using Aitoff projection. Each panel shows the angular distribution of



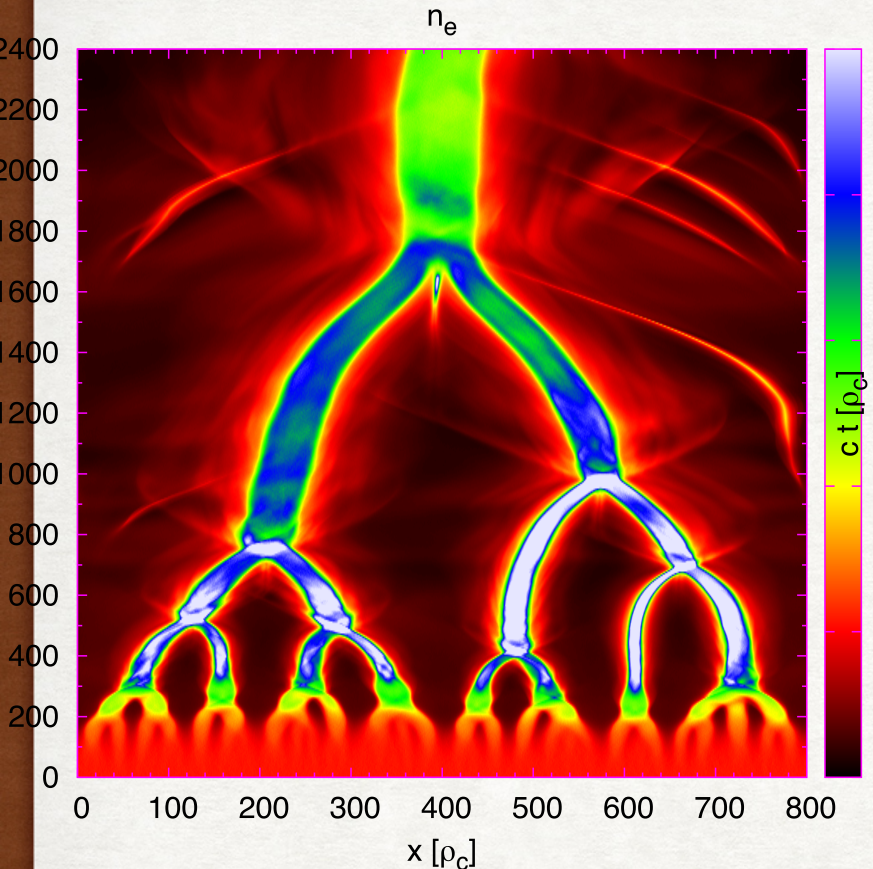




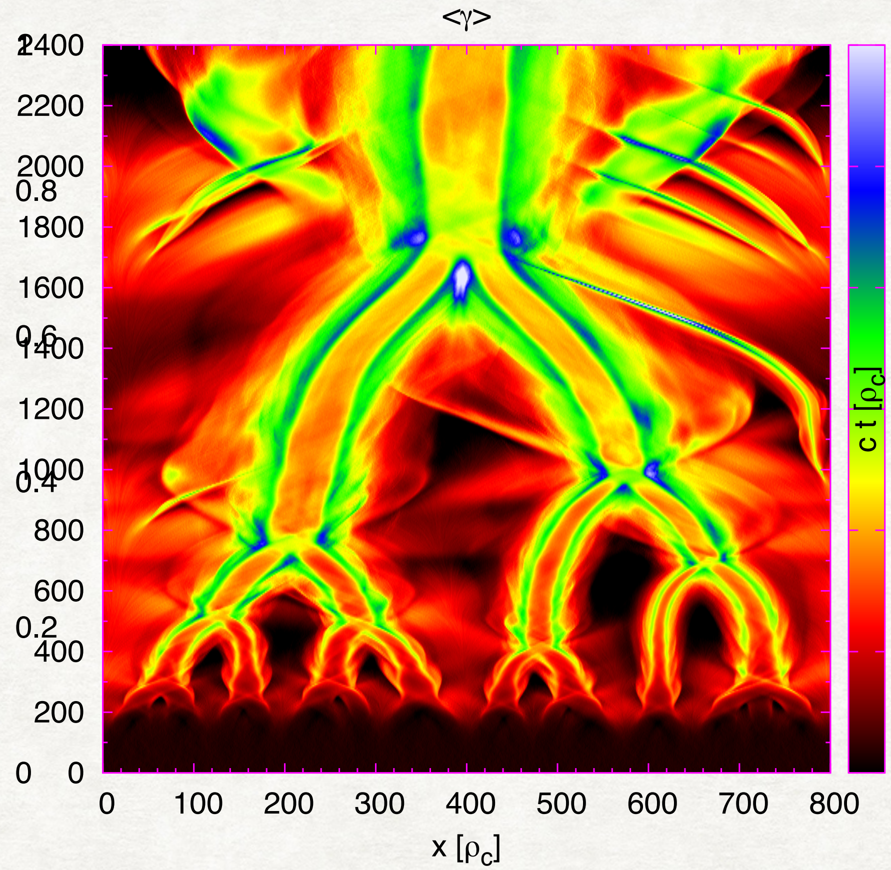


KN, Uzdensky, Cerutti, Werner & Begelman (2015)

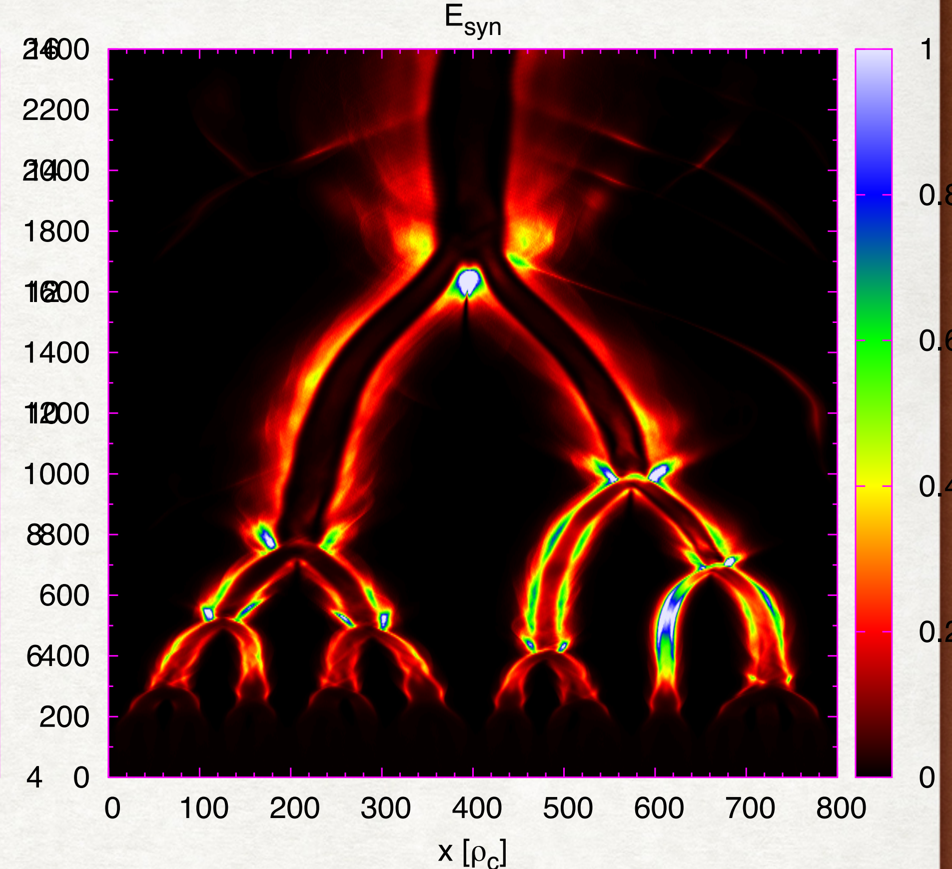
density



average energy

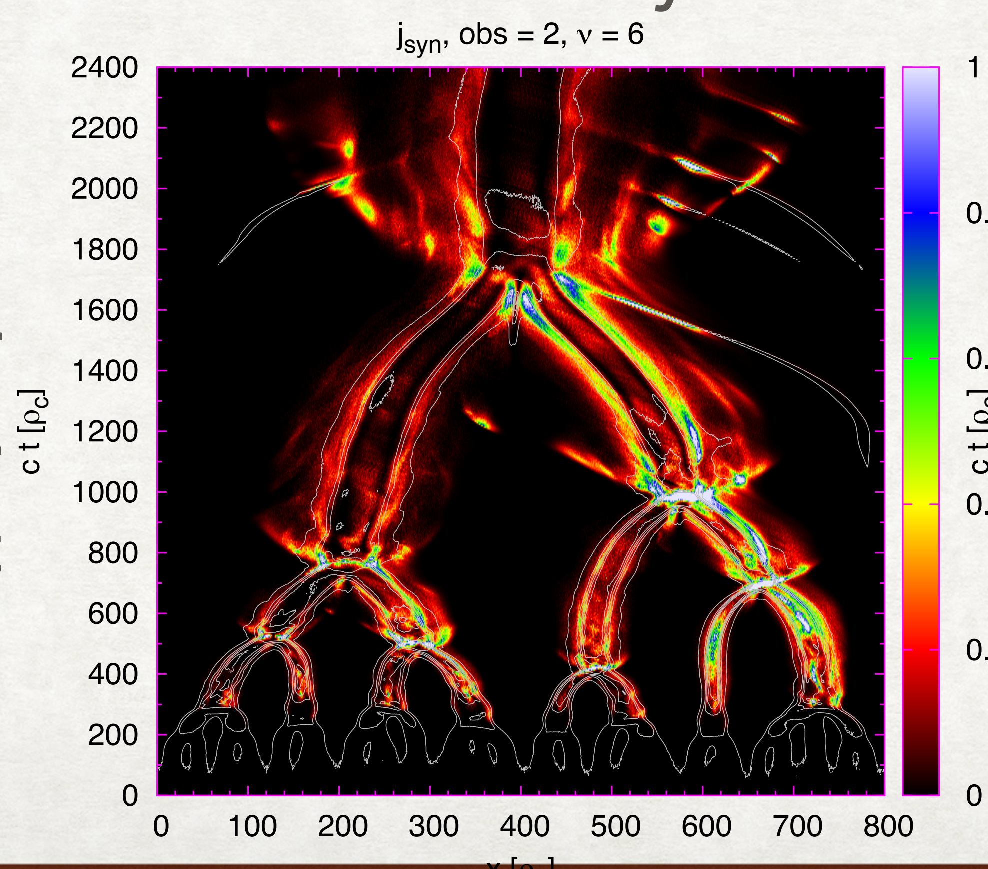


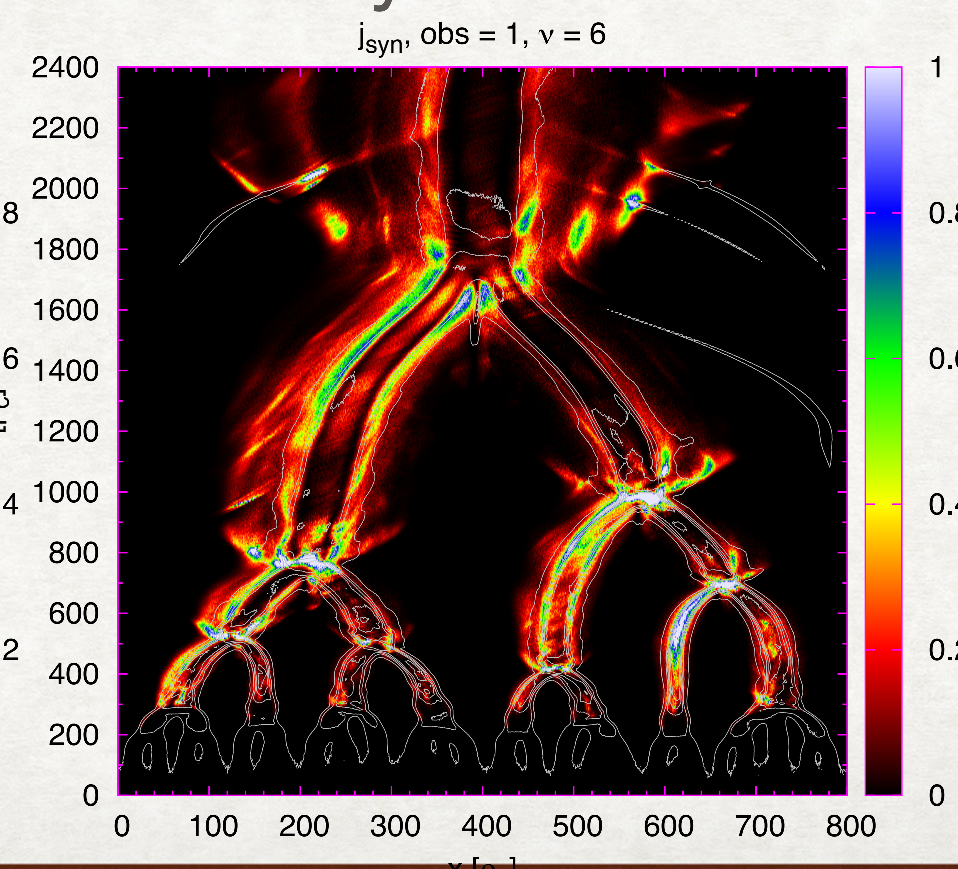
synchrotron power



synchrotron emissivity

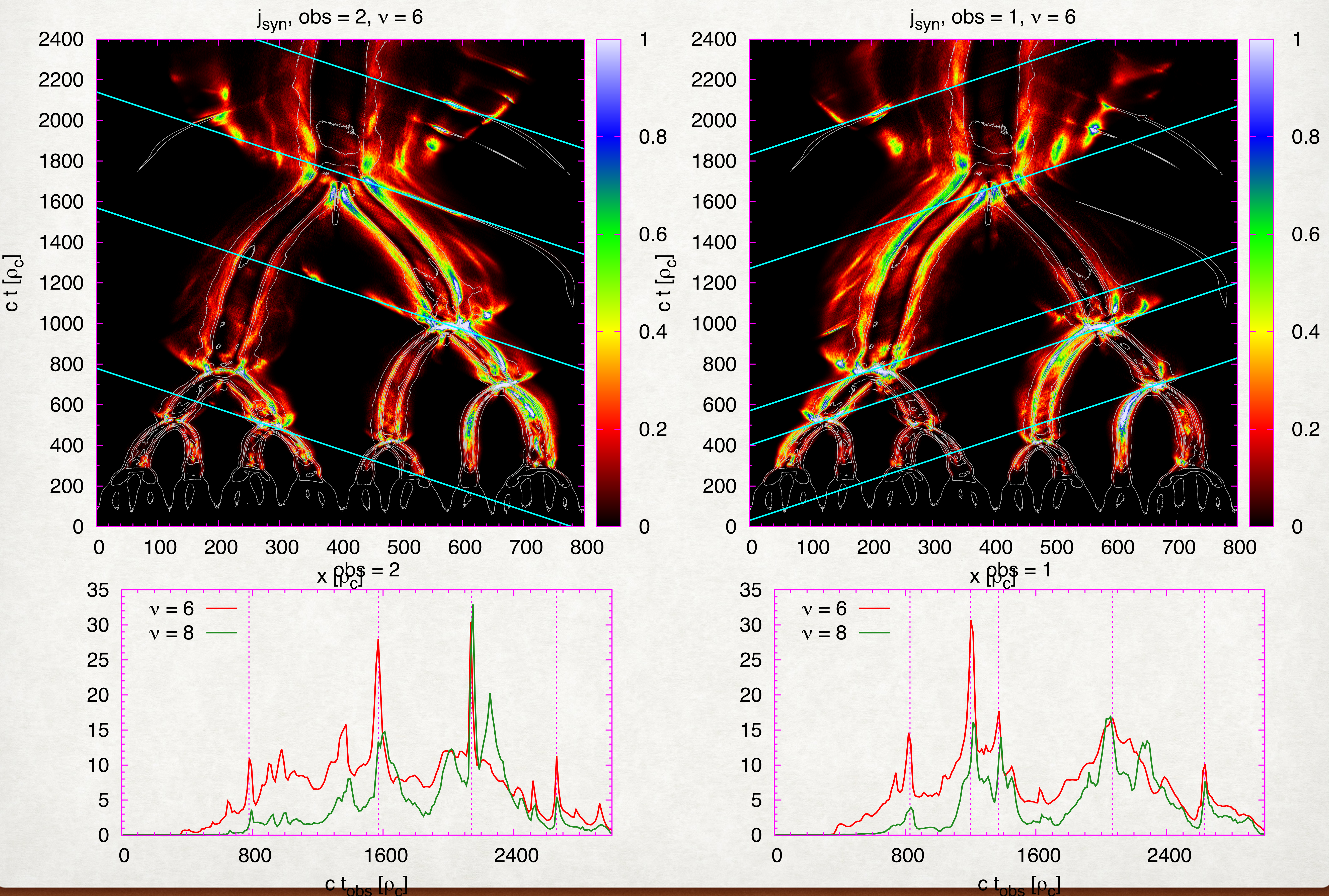
observer to the left



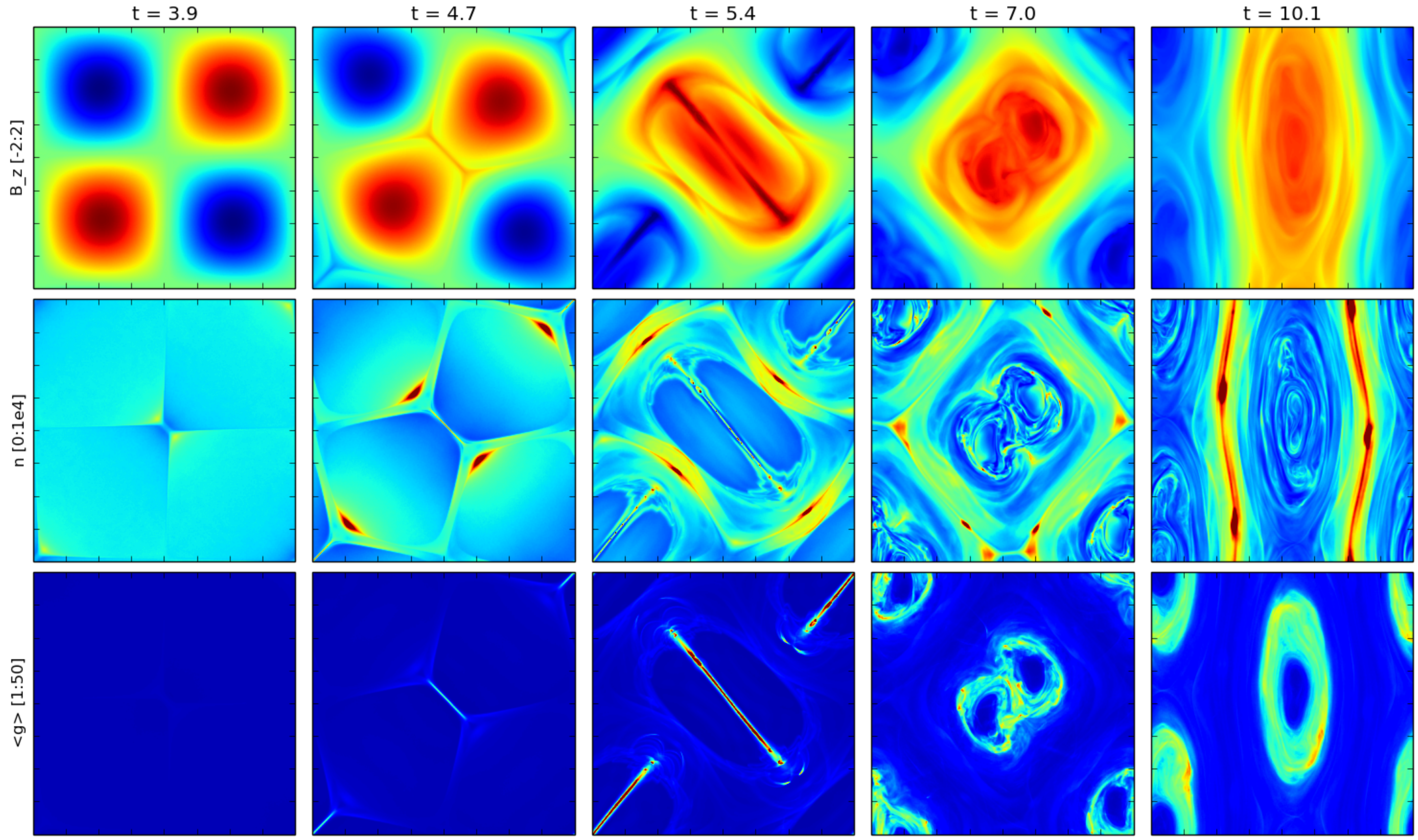


observer to the right

OBSERVED LIGHT CURVES



“ABC” MAGNETIC FIELDS

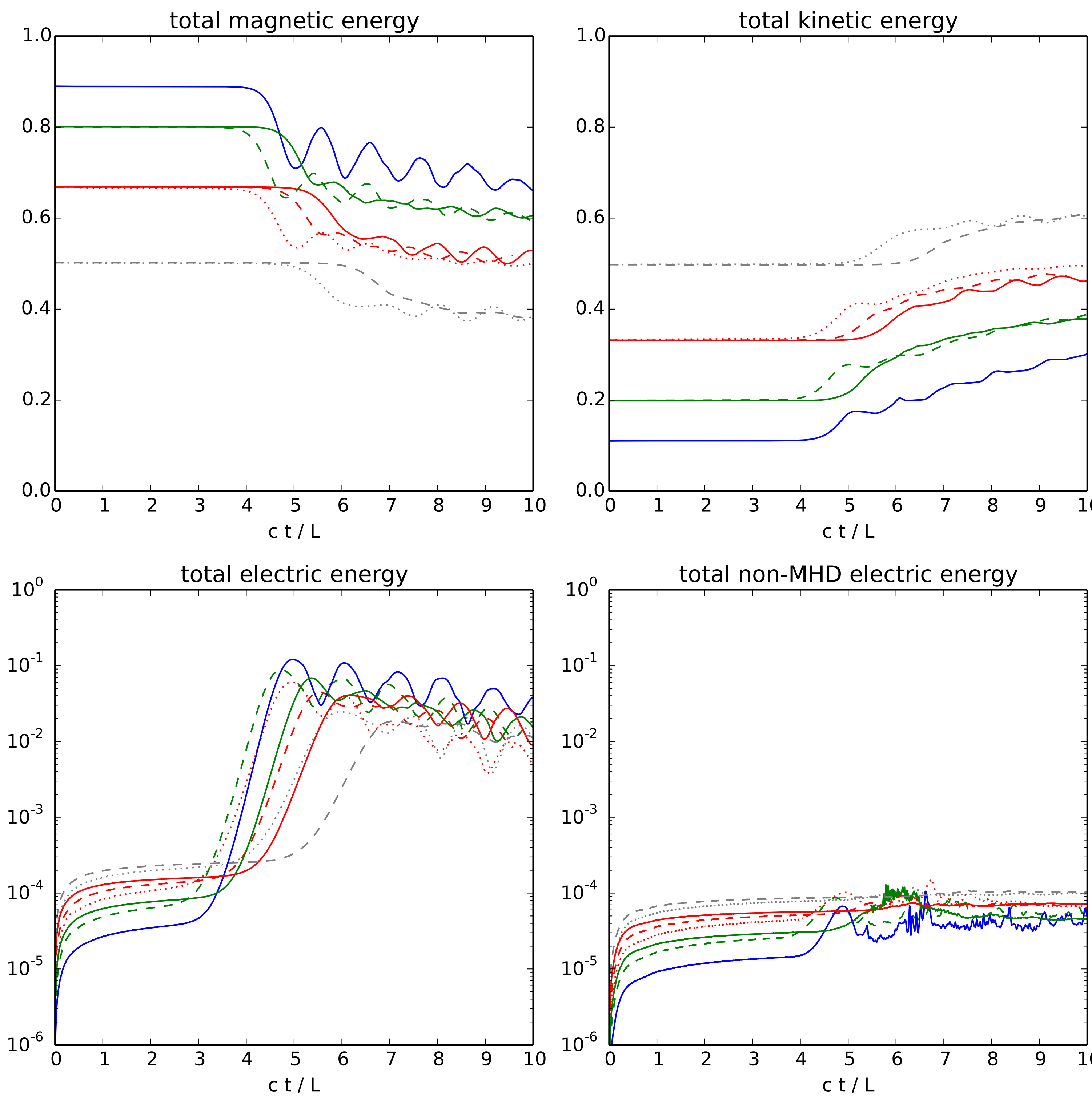


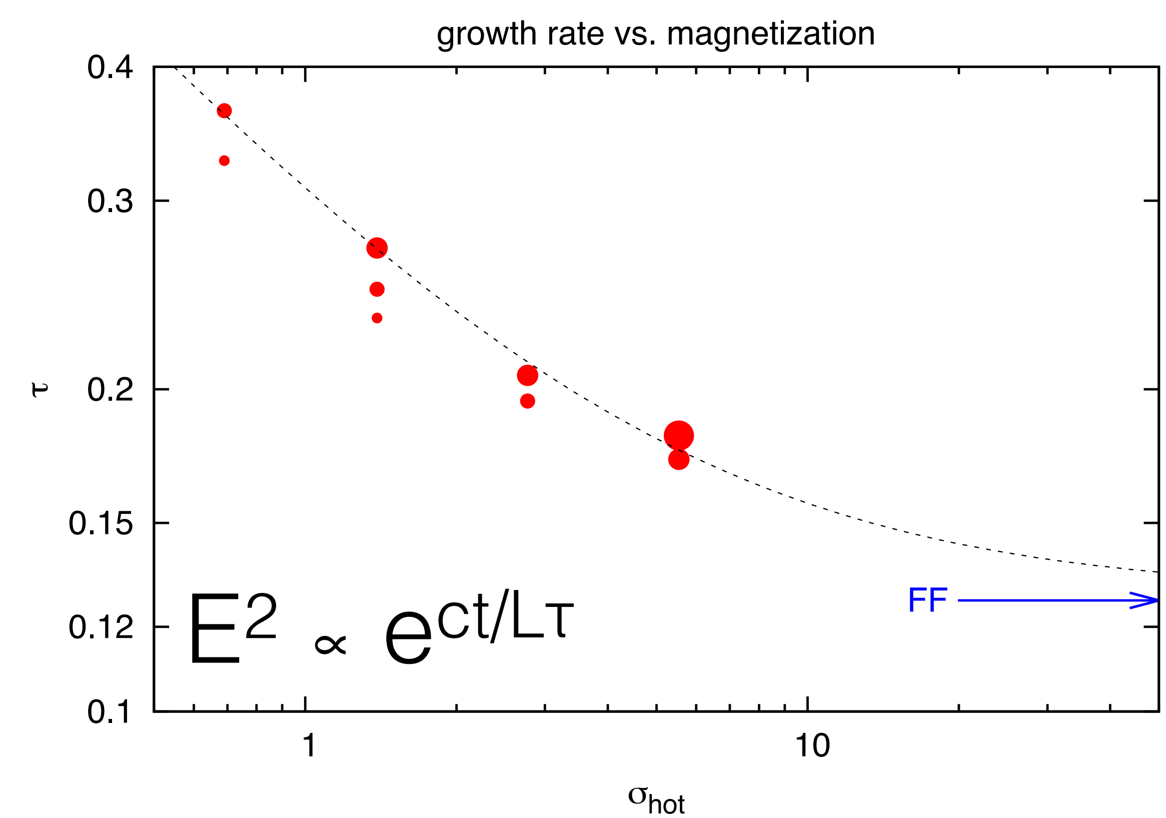
KN, Zrake, Yuan, East & Blandford (2016)

see also Lyutikov, Sironi, Komissarov & Porth (2016)

total energy

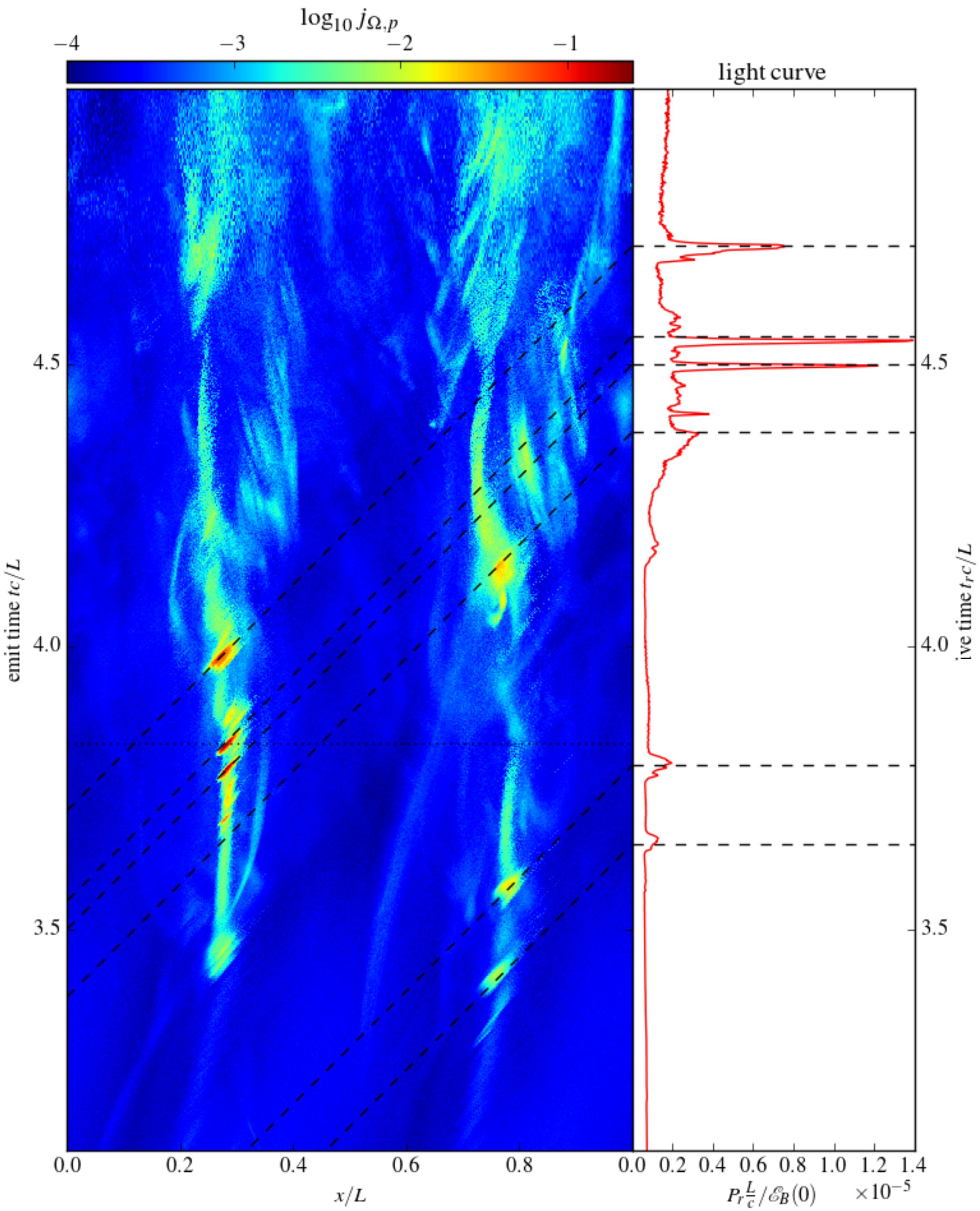
- linear instability seen in total electric energy
- non-ideal electric energy appears insignificant
- relative magnetic dissipation efficiency is constant

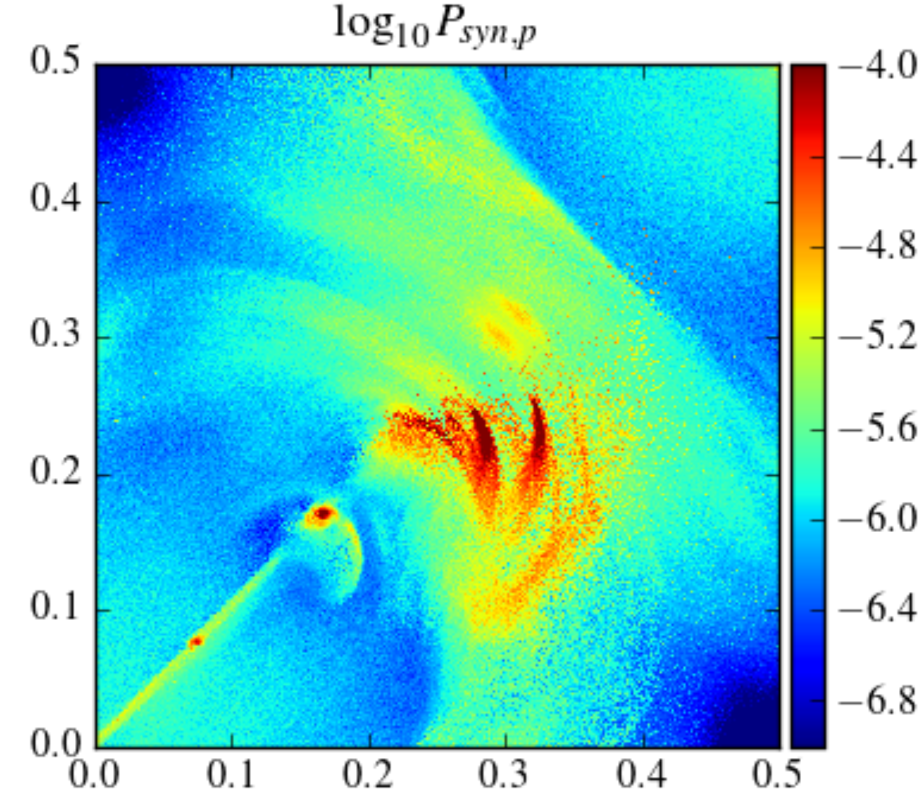


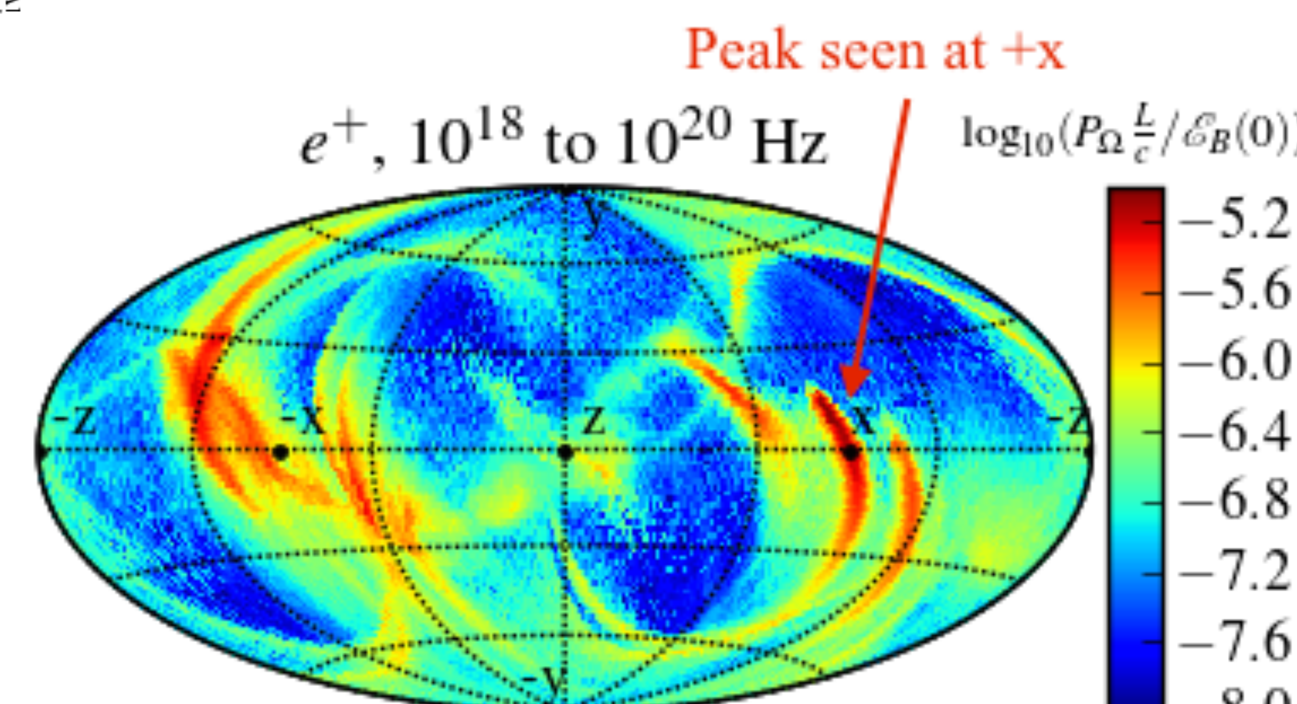


synchrotron signatures of ABC reconnection

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

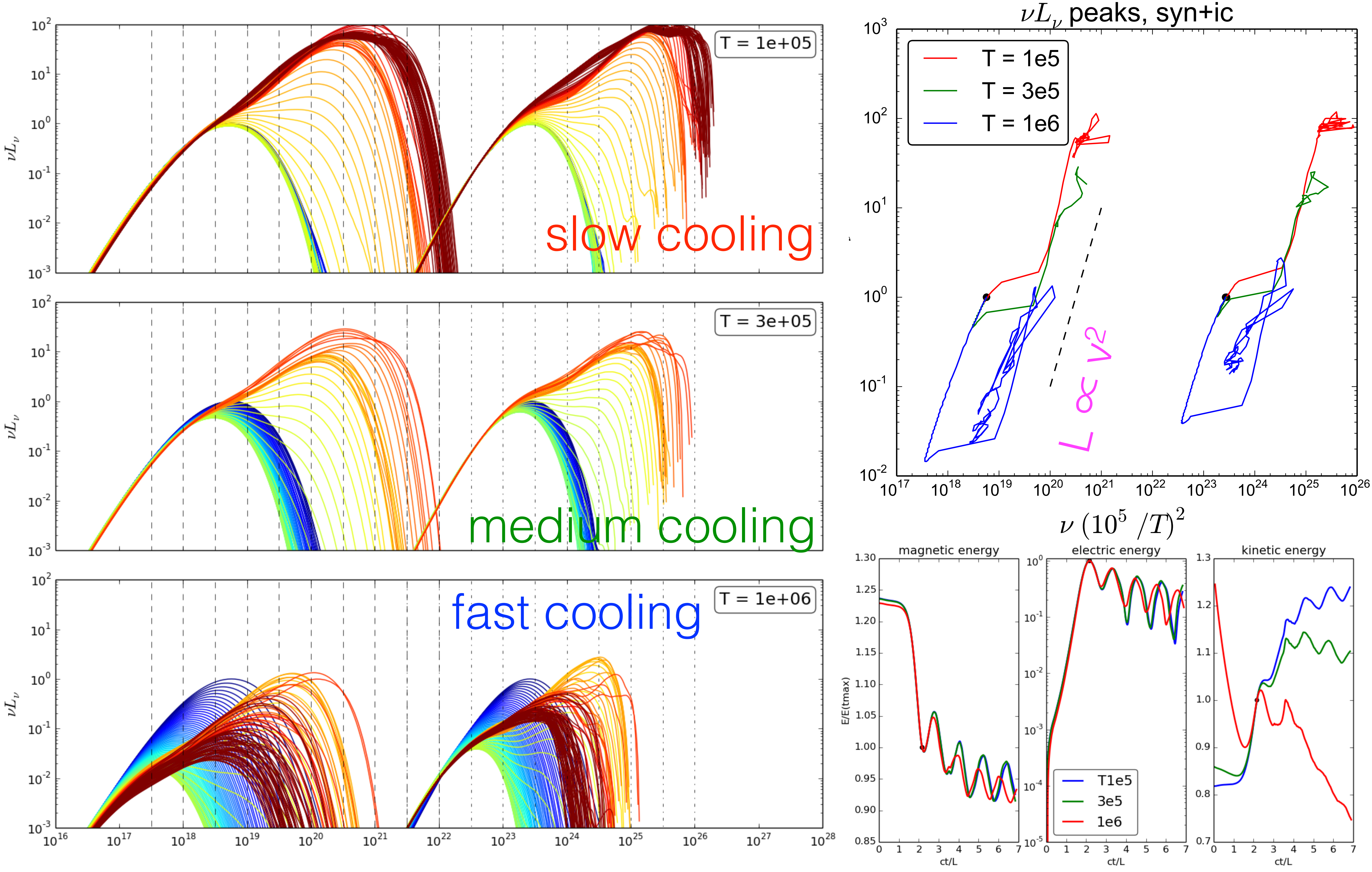




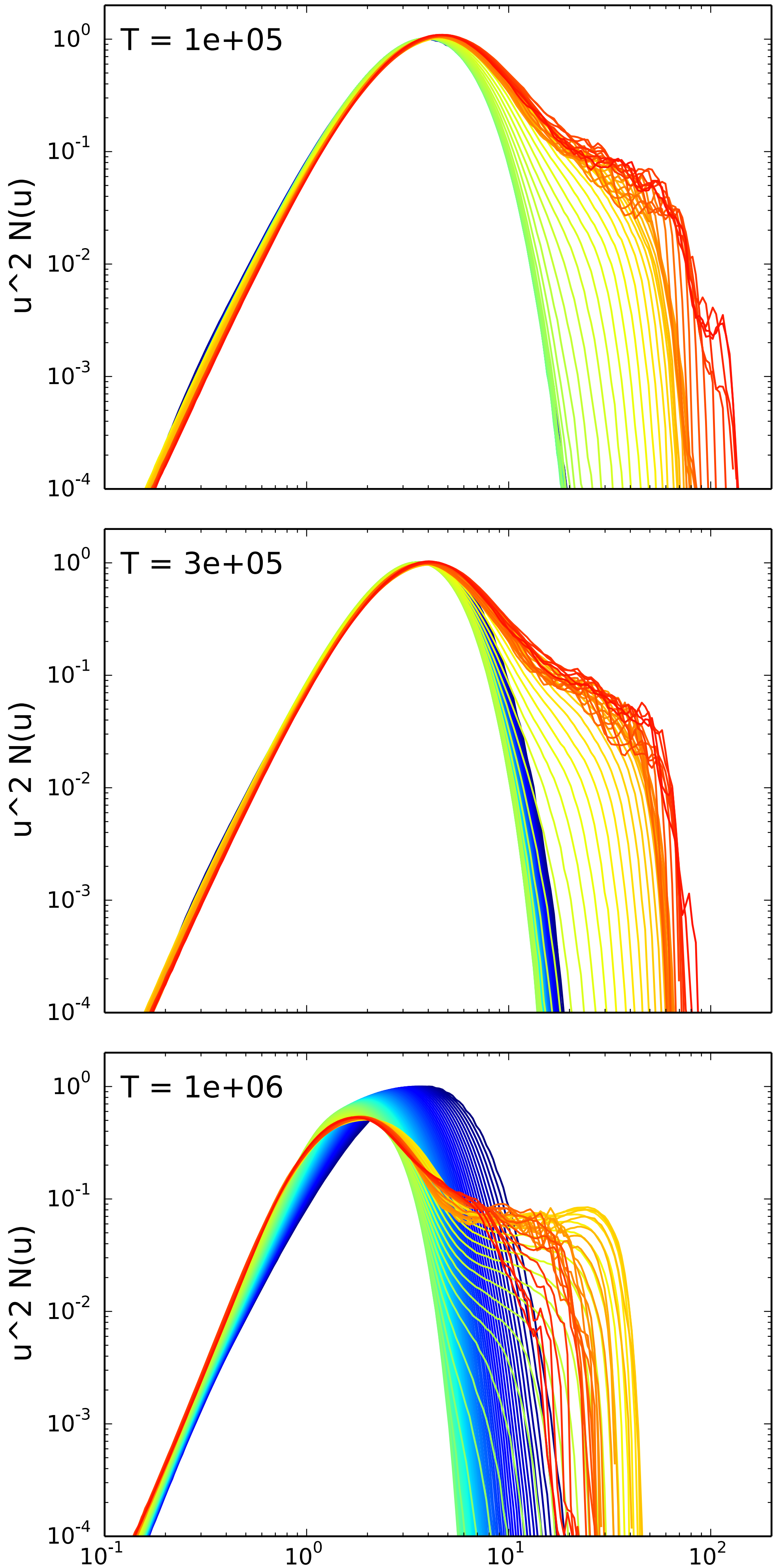


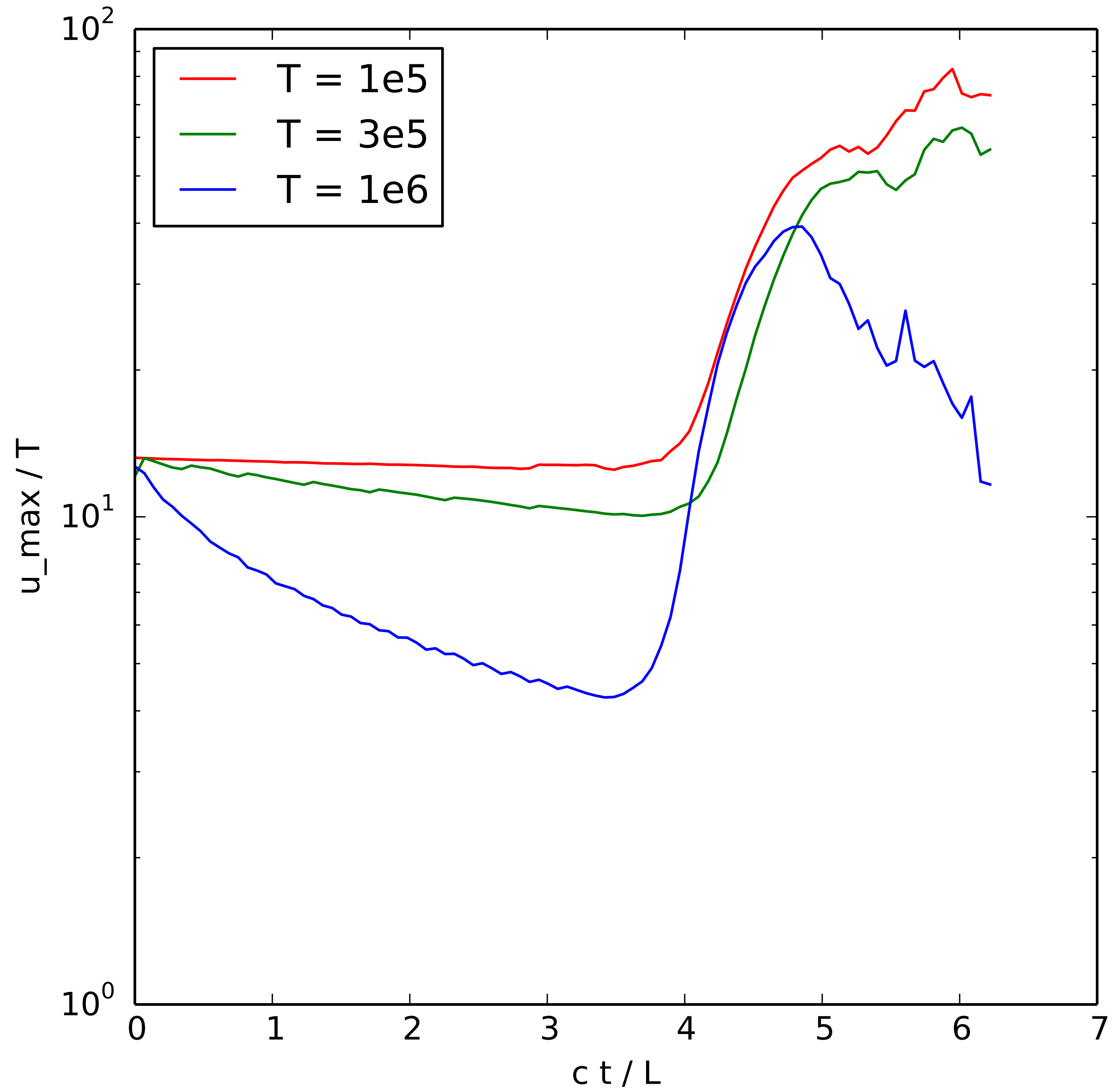
synchrotron and inverse Compton

(with Martyna Chruślińska, PRELIMINARY)

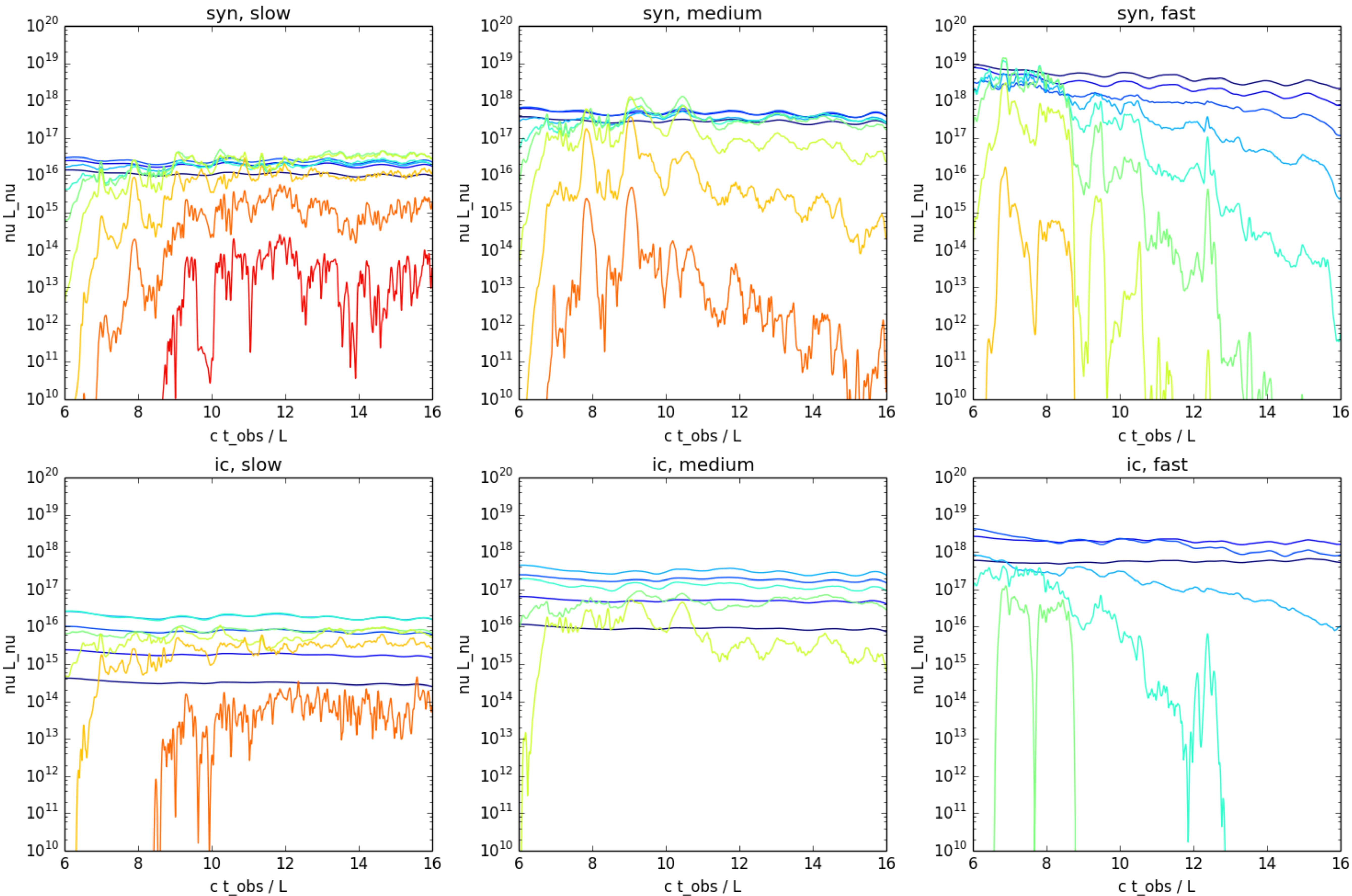


particle energy distributions





syn+ic light curves (PRELIMINARY)



SUMMARY

- Relativistic magnetic reconnection is a promising dissipation mechanism in exotic astrophysical plasmas
- Rapid progress in understanding relativistic reconnection has been made in recent years, primarily due to kinetic numerical simulations
- Relativistic reconnection has been proved to be a very efficient mechanism for particle acceleration with the particle distribution index $p \sim 1$ for $\sigma >> 1$
- Radiation produced in reconnection sites is characterized by rapid variability time scale, potentially explaining even the most extreme gamma-ray flares observed in relativistic jets and pulsar winds
- This project is supported by NCN grant SONATA BIS. PhD scholarships and post-doctoral position will be offered next year.