kinetic simulations of relativistic magnetic reconnection

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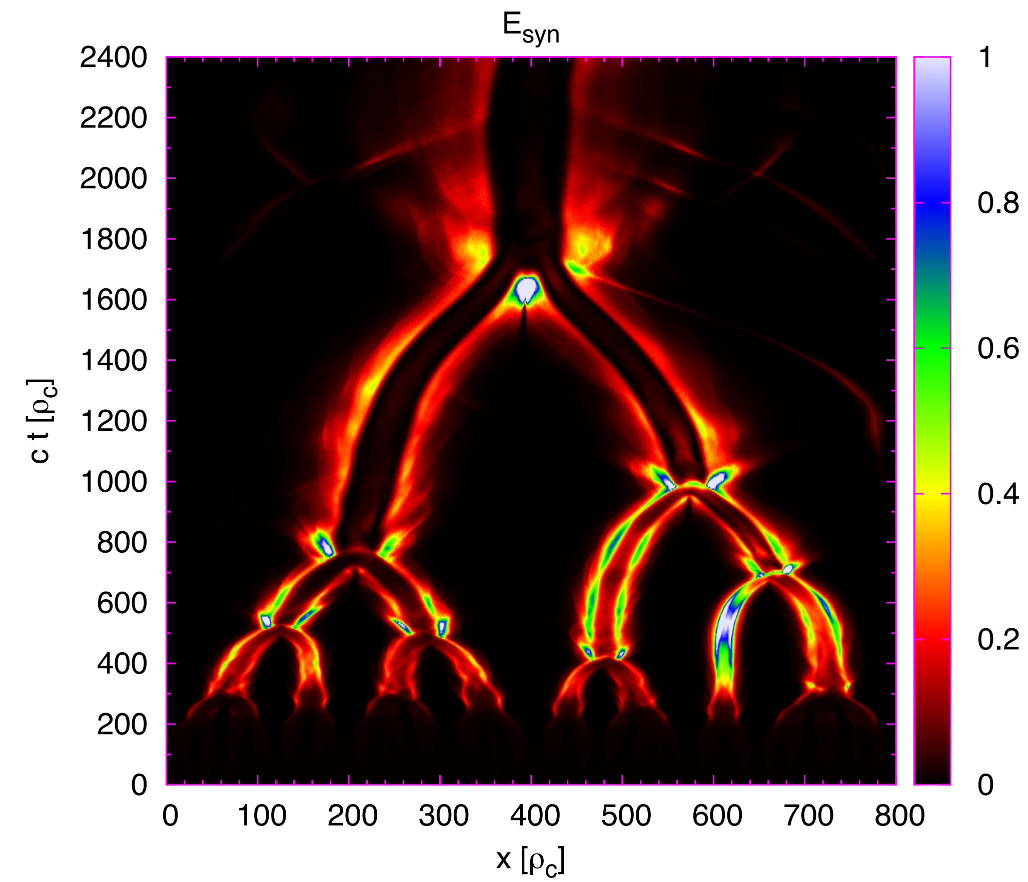
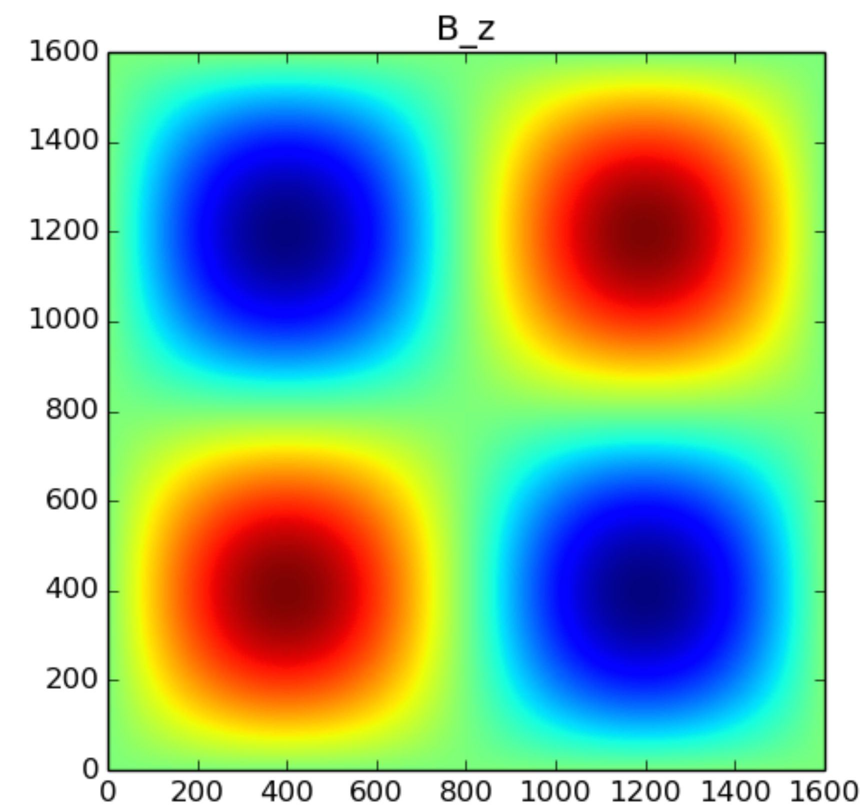
Martyna Chruślińska (University of Warsaw)

content of this talk

- astrophysical motivation
- reconnection in Harris-type layers
  (Werner+16, KN+15)
  (see also Greg's talk)
- reconnection in ABC fields
  (KN+16)
- radiative signatures
  (Yuan+16)
  (see also Yajie's talk)

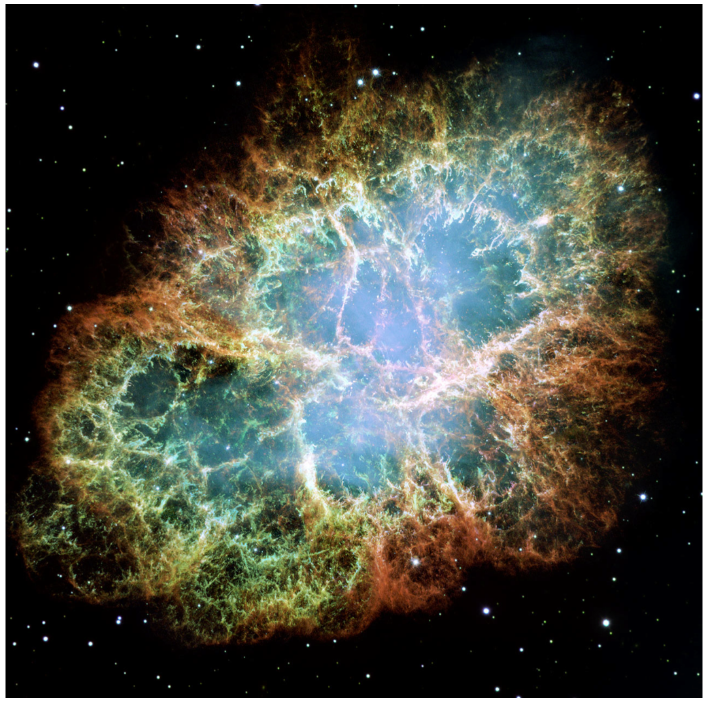


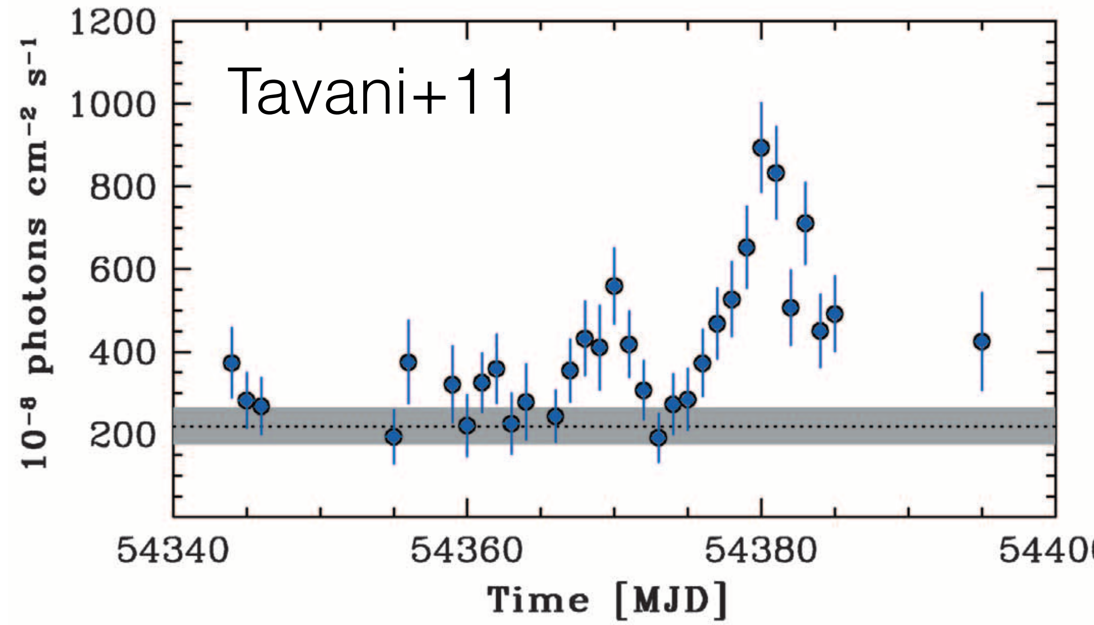


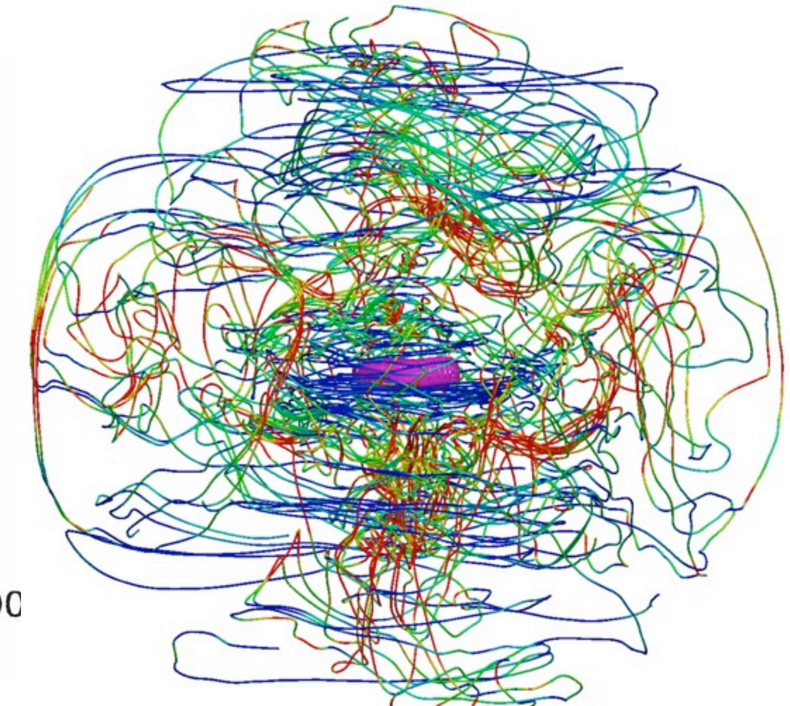
astrophysical motivation

motivation

Crab Nebula

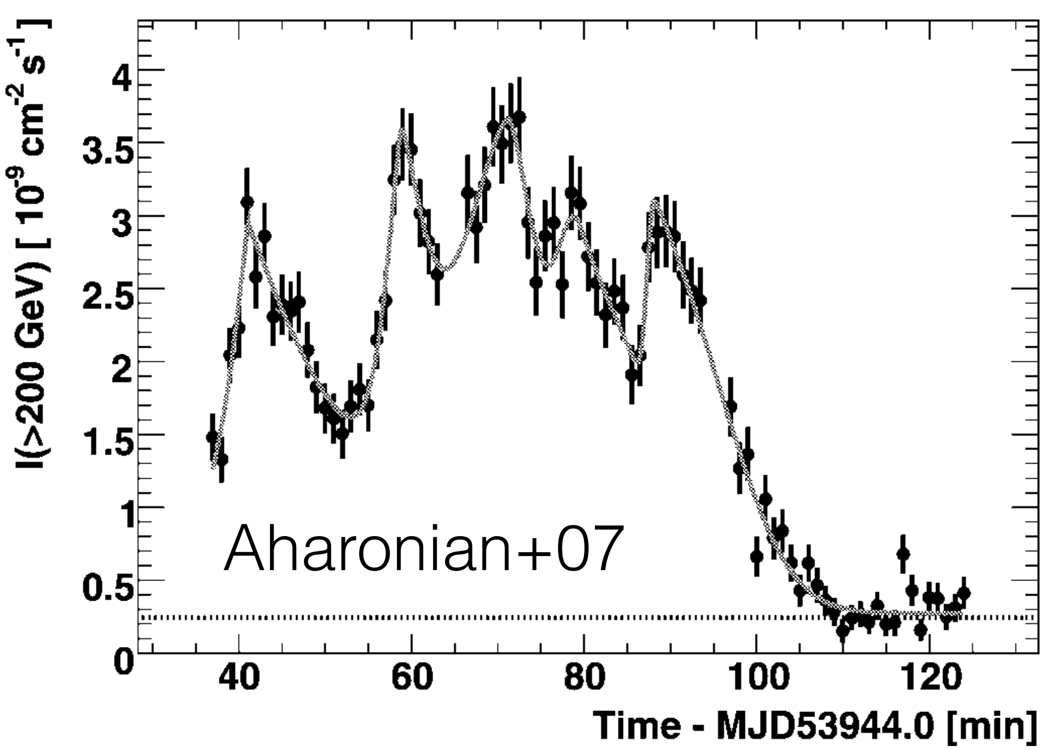


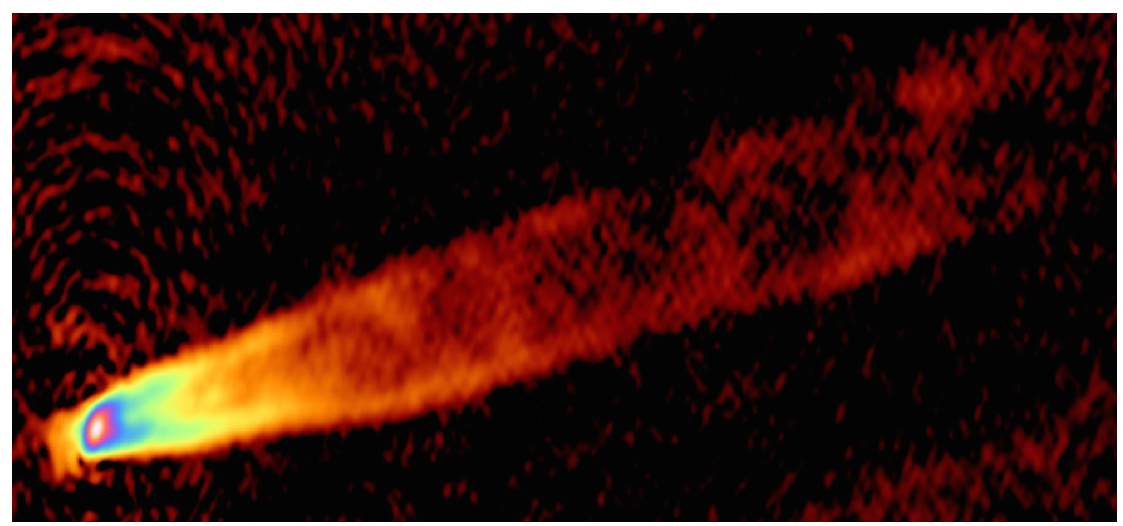




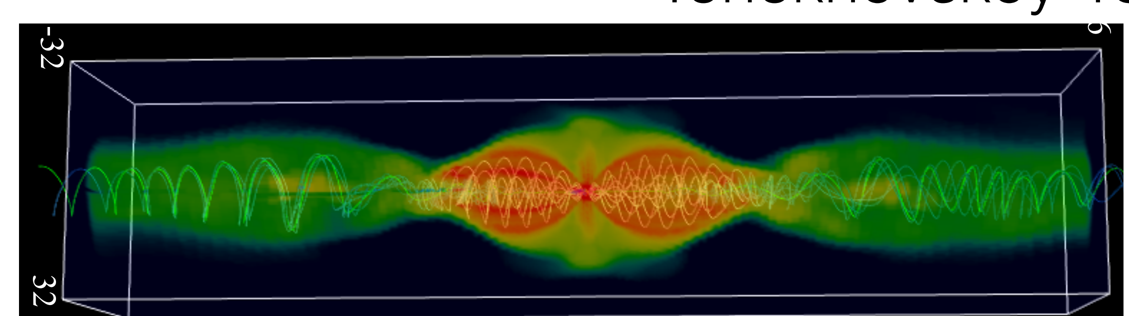
Porth+14

relativistic jets





Bromberg & Tchekhovskoy 15



minute-scale γ-ray variability in AGNs

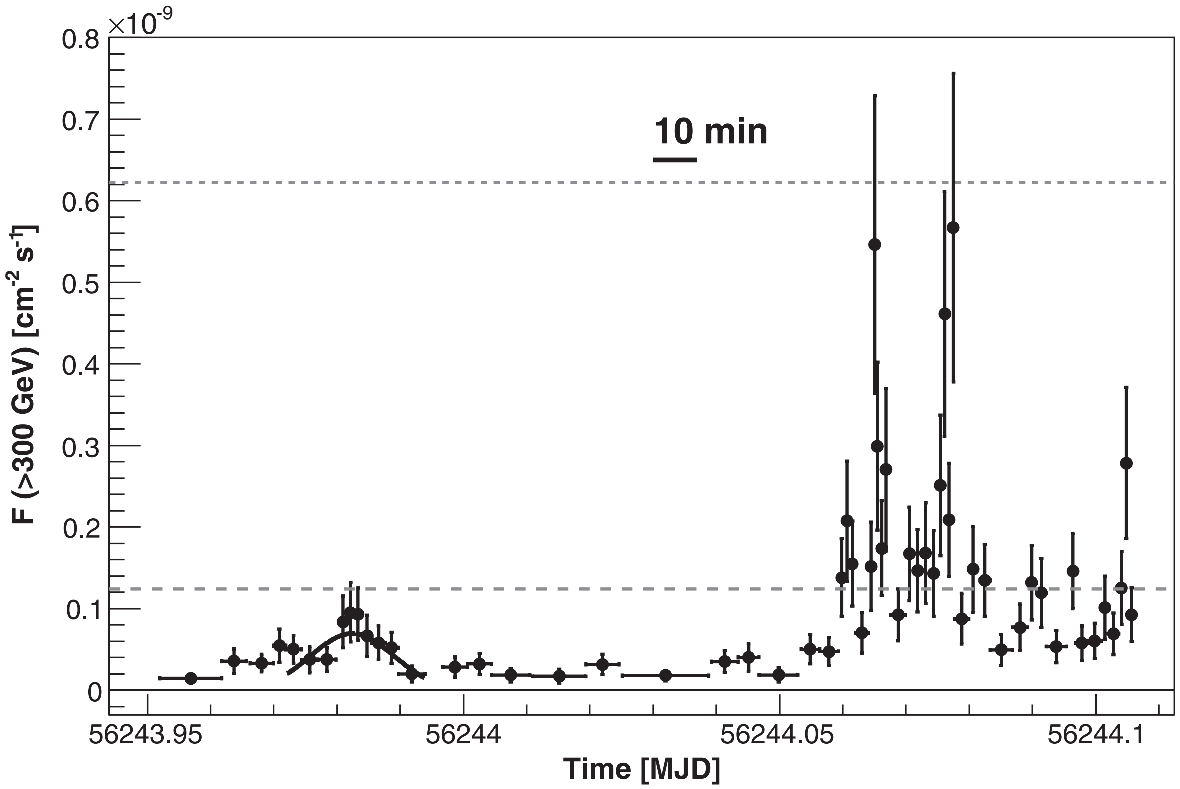
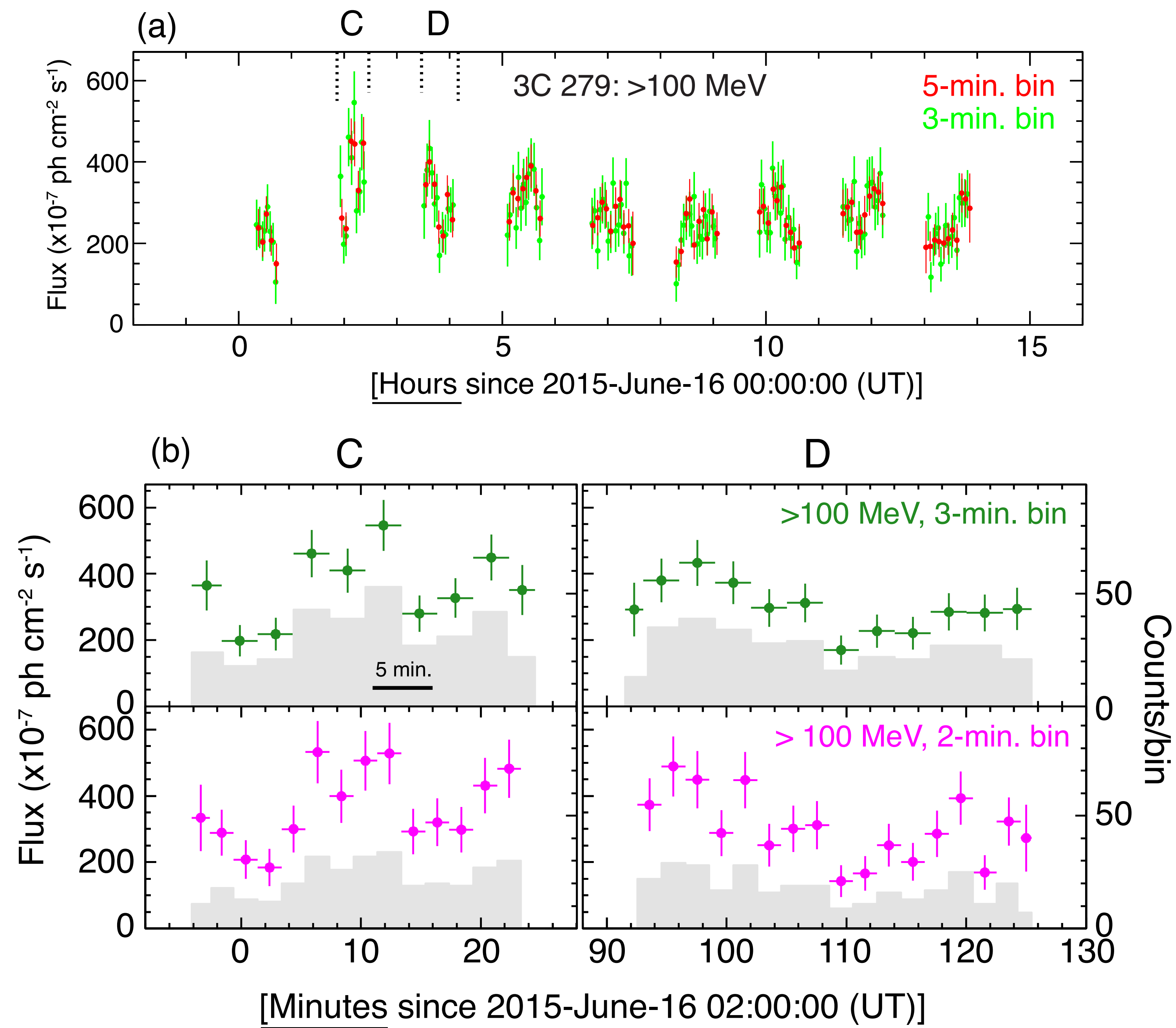


Fig. 4. Light curve of IC 310 observed with the MAGIC telescopes on the night of 12/13 November 2012, above 300 GeV. As a flux reference, the two gray lines indicate levels of 1 and 5 times the flux level of the Crab Nebula, respectively. The precursor flare (MJD 56243.972-56243.994) has been fitted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

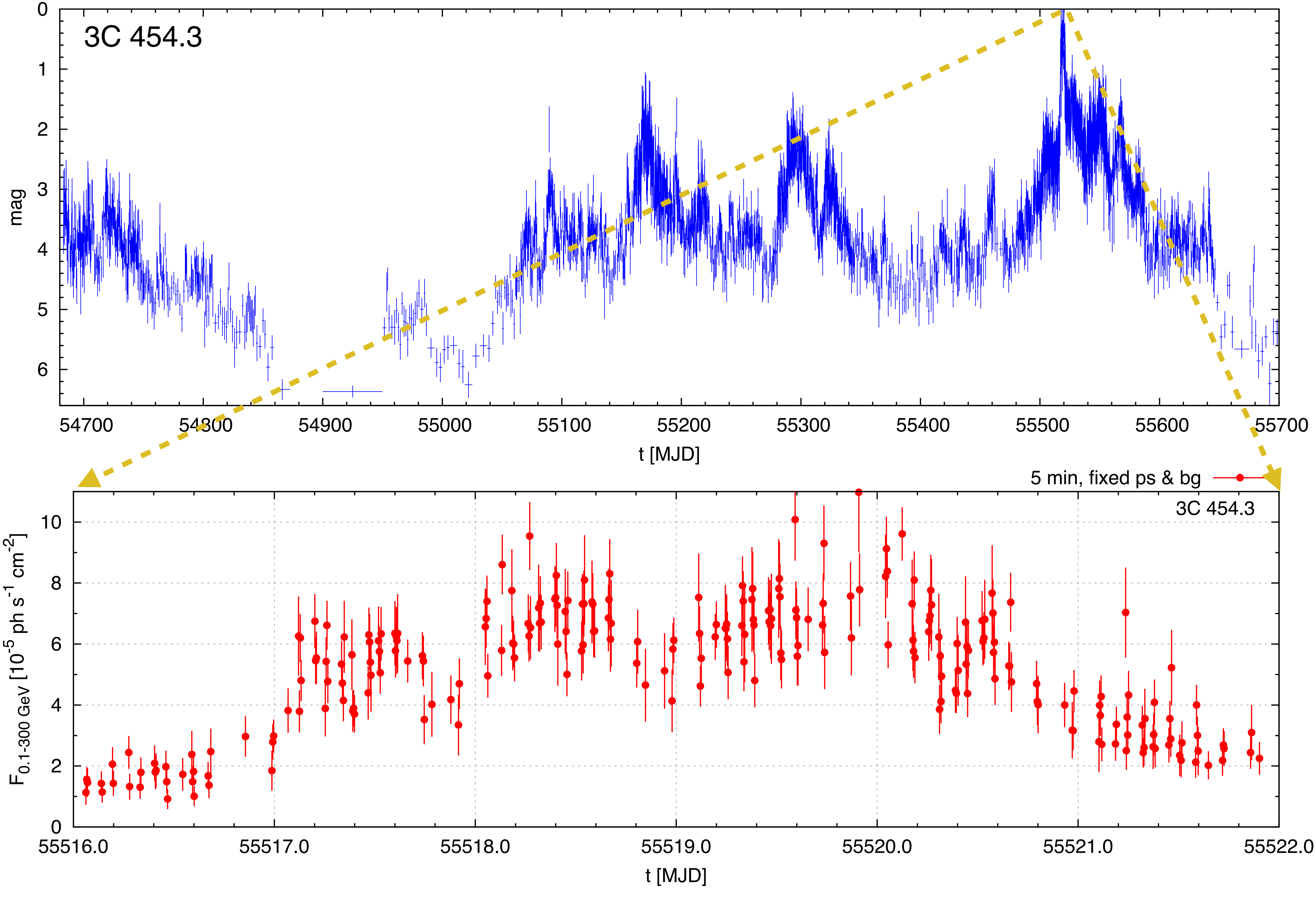
IC 310
MAGIC Collaboration (2014)

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



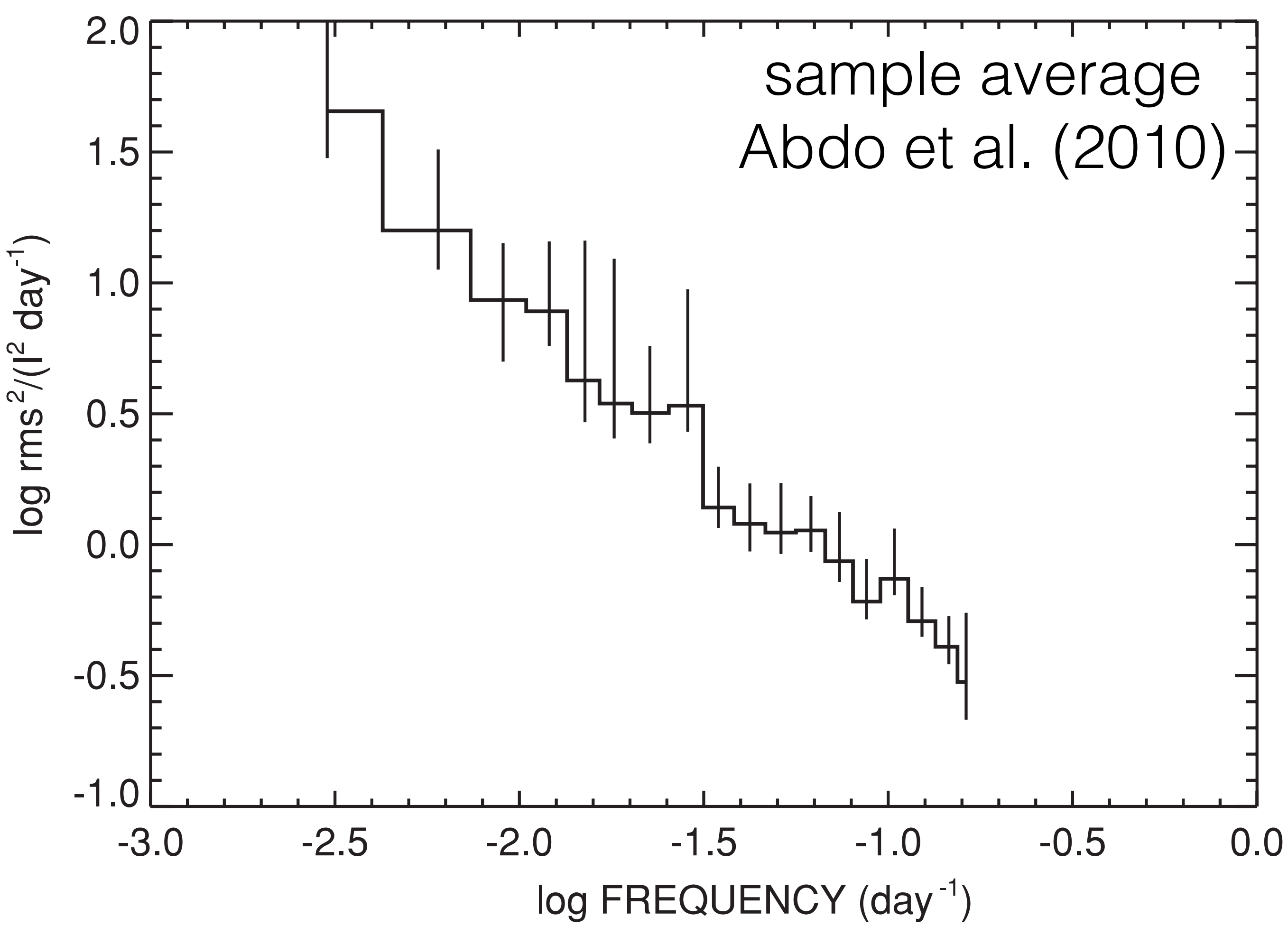
Fermi-LAT Collaboration (submitted)

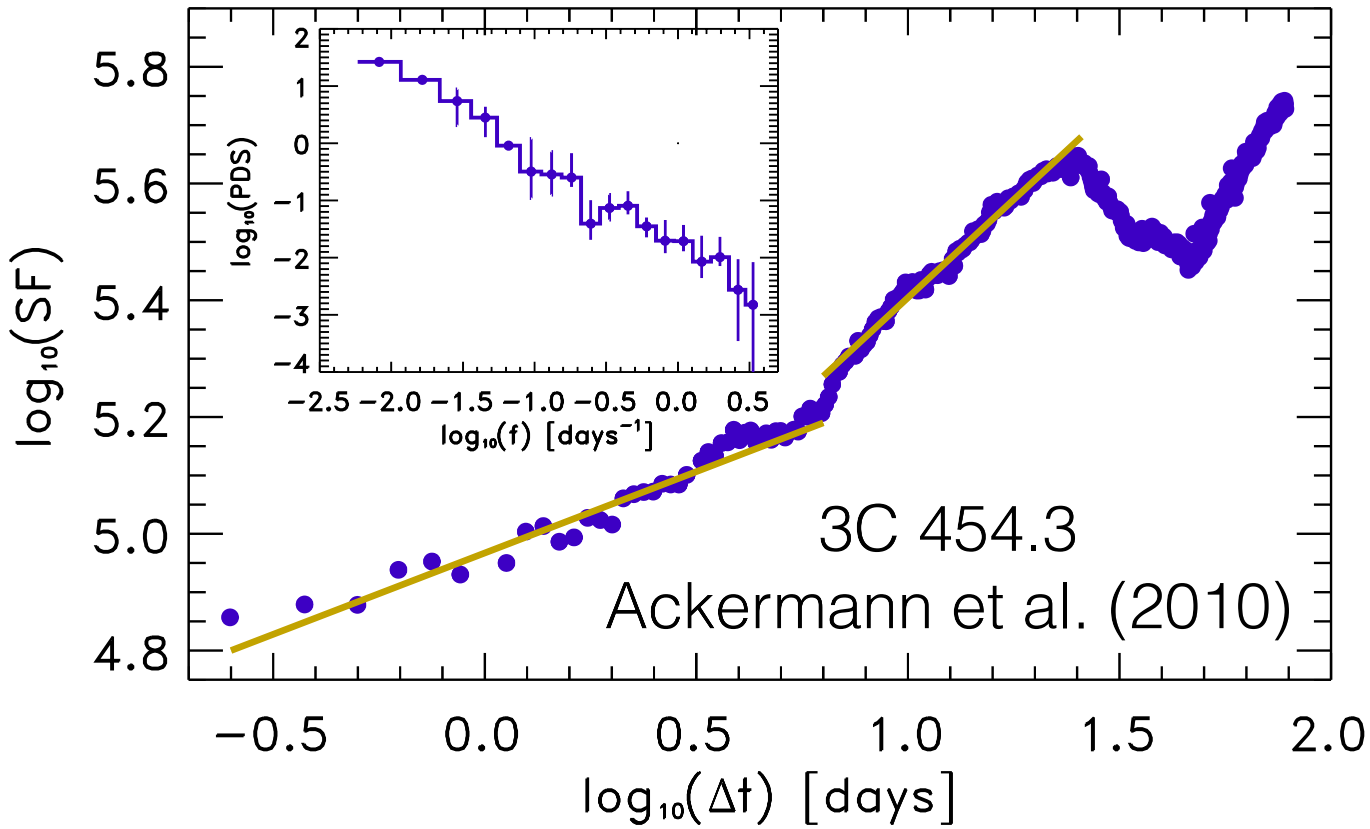
γ-ray variability of blazars



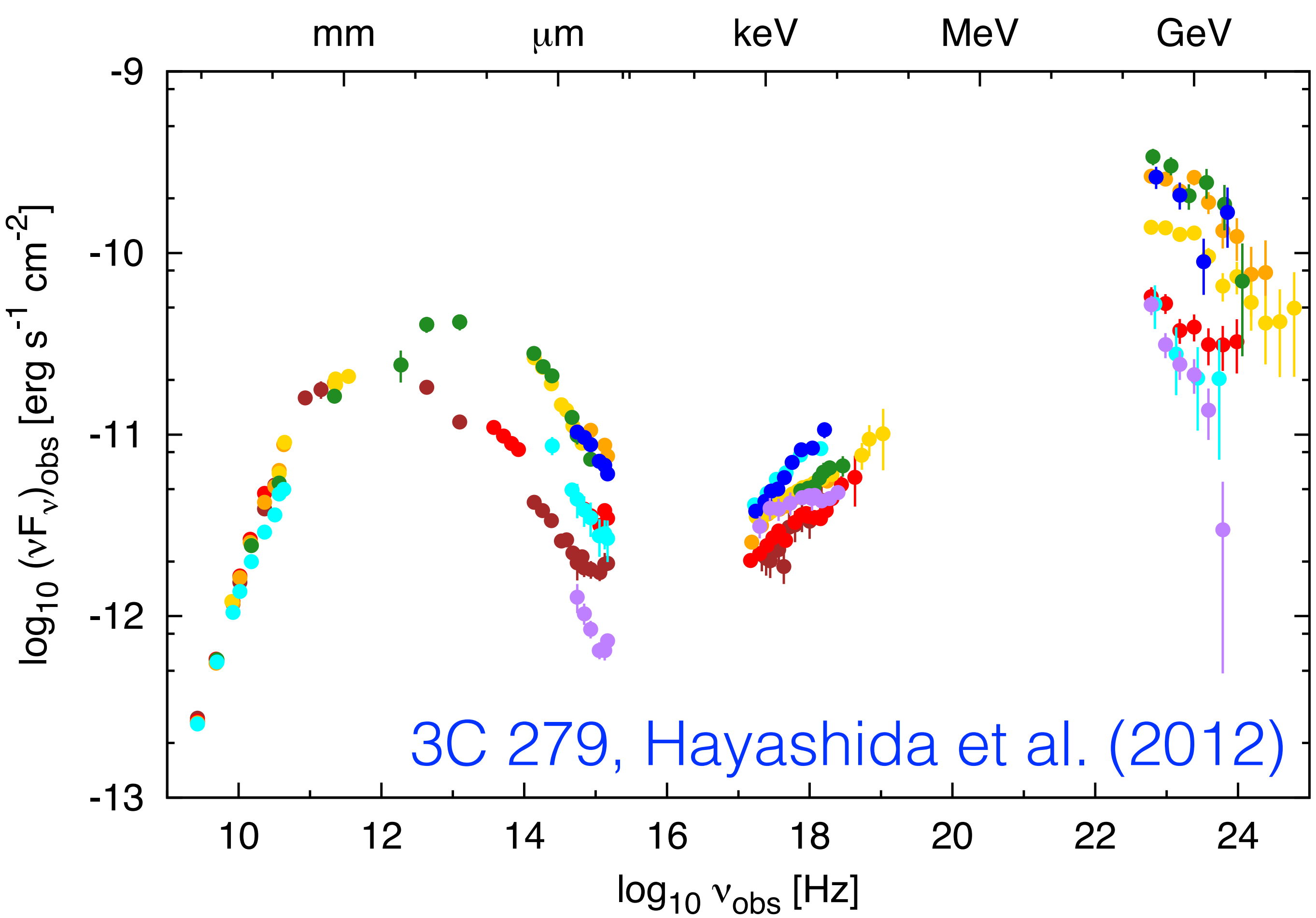
gamma-ray variability of blazars

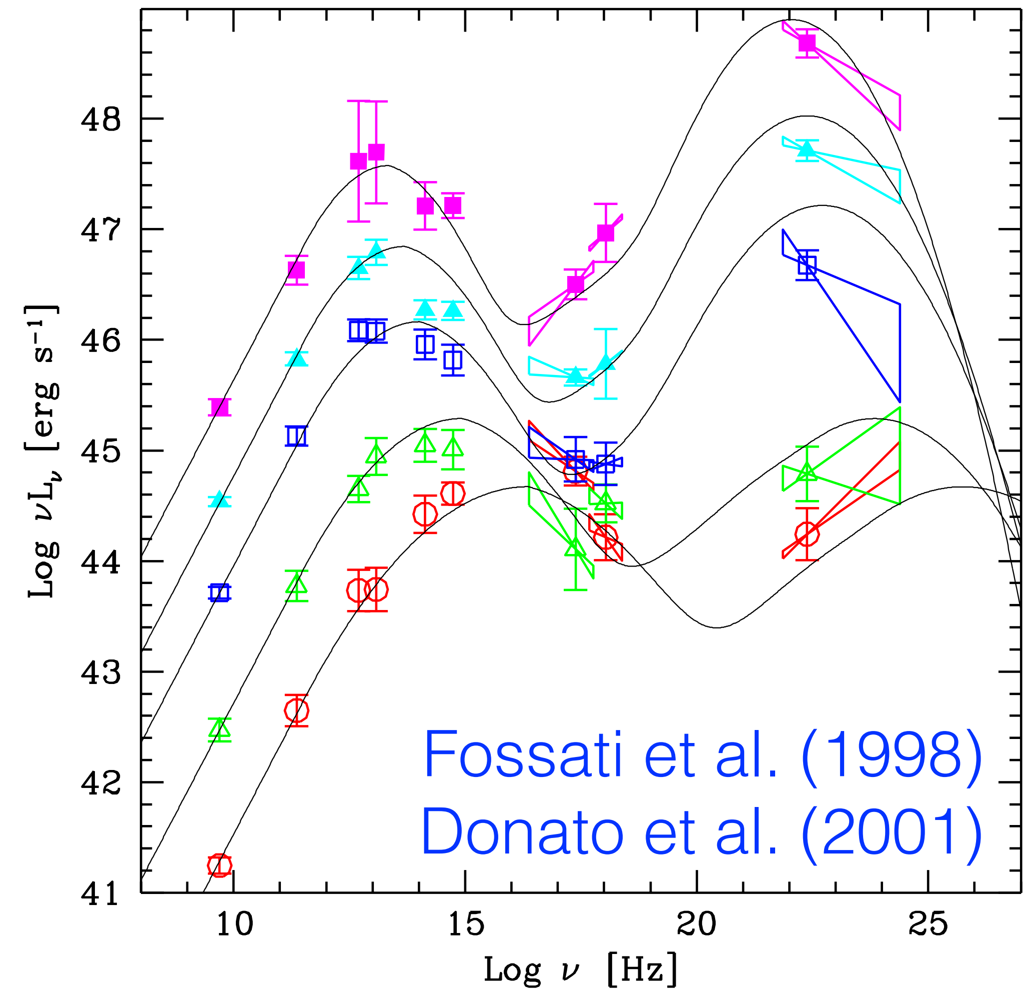
- stochastic
- power-law PDS
- index ~1.5
- no QPOs
- no minimum timescale

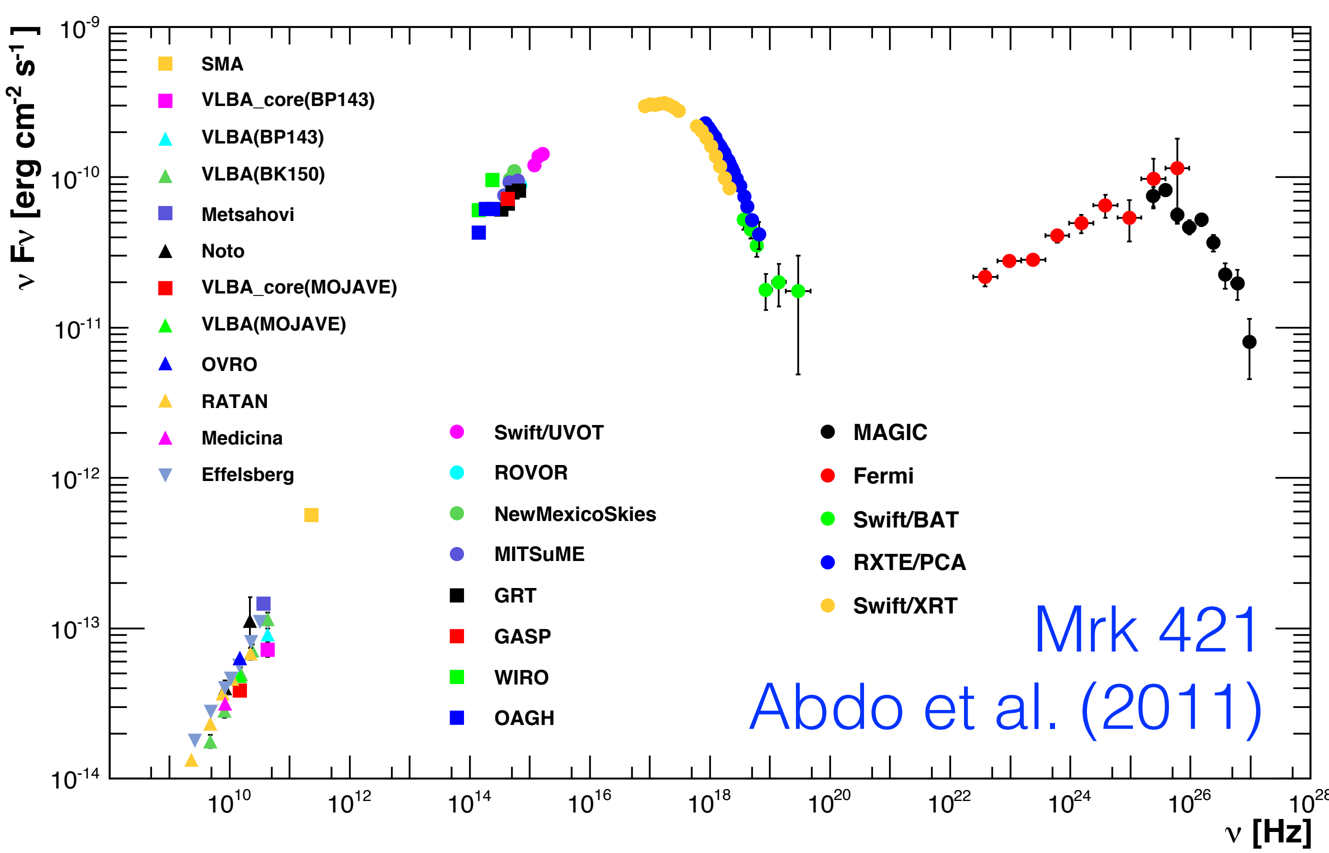


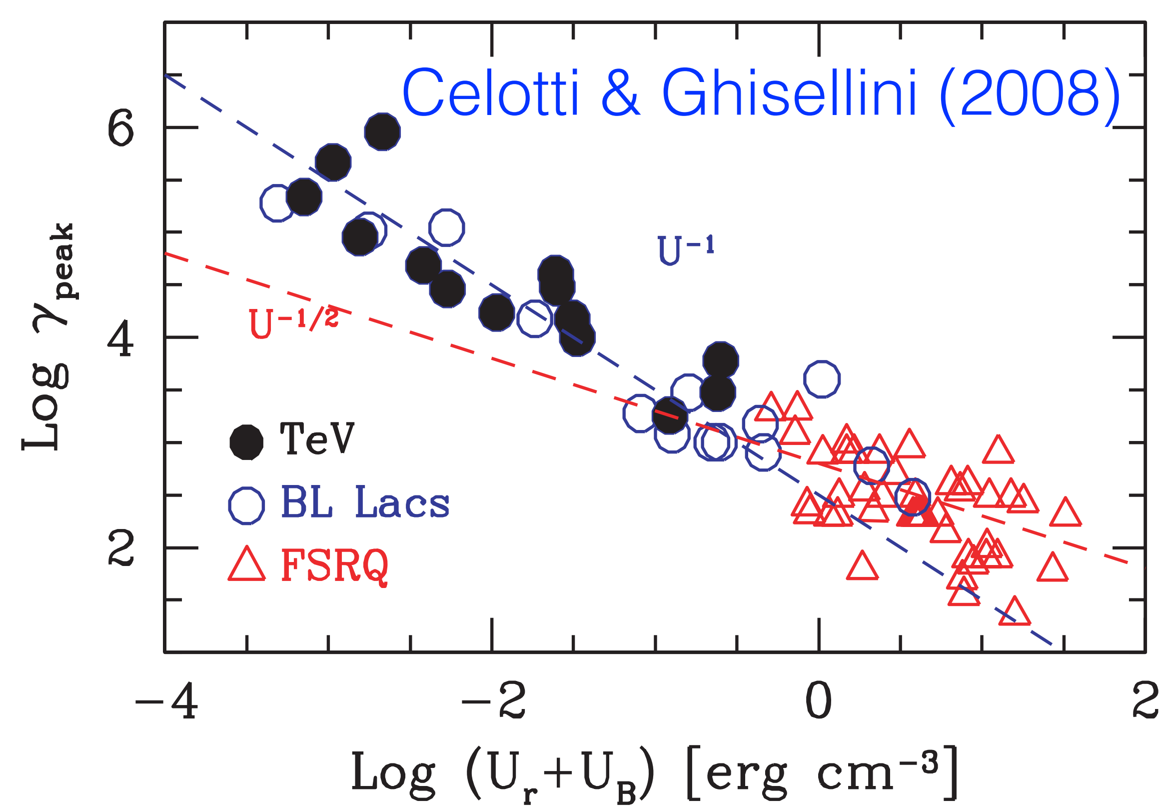


spectral energy distributions of blazars



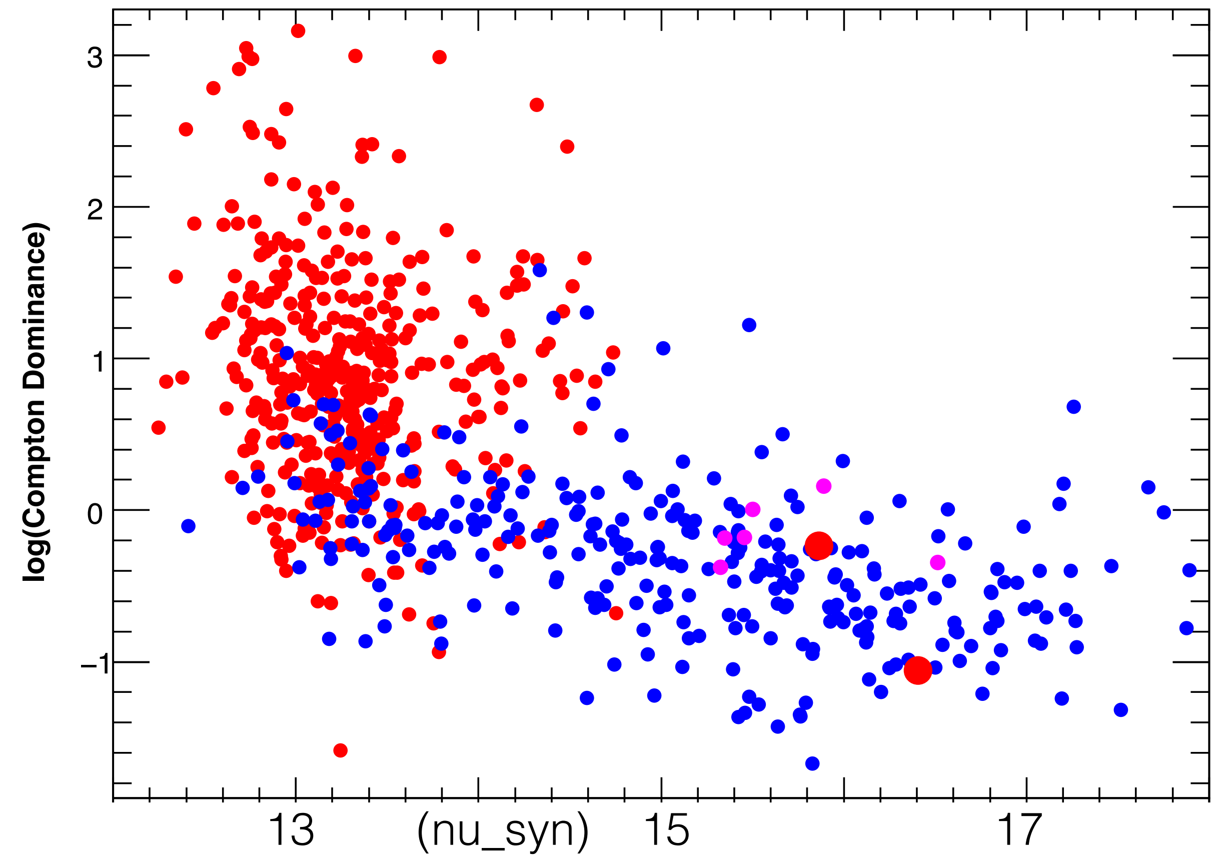


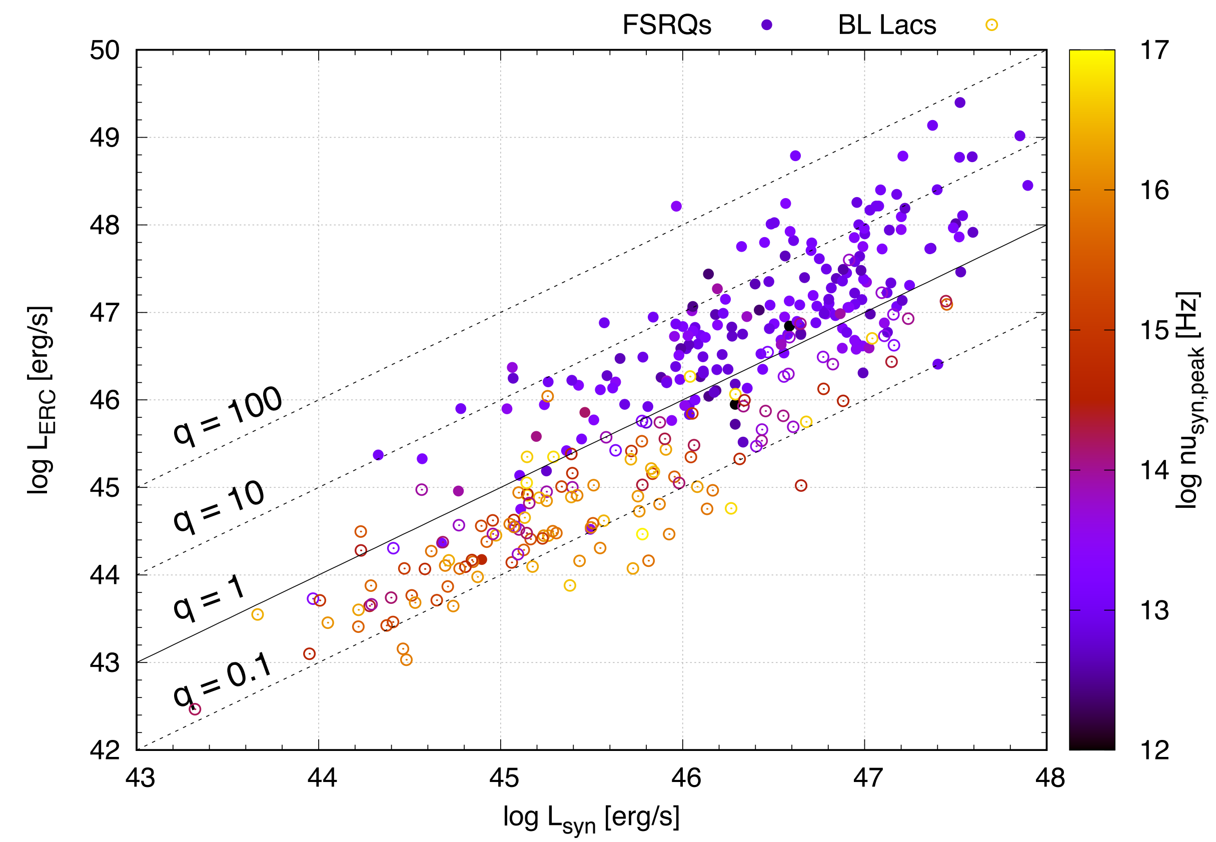




magnetization of jets

- Compton dominance
  $q = L_{IC} / L_{syn} = u_{rad}' / u_B'$
- $u_{rad}' \sim u_e'$, hence $q\,\sigma \sim 1$
- observations indicate that
  $q \sim 0.5\text{-}100$, hence $\sigma < 1$
- equipartition expected for emitting region in relativistic reconnection
  (Sironi, Petropoulou & Giannios 2015)





summary: astrophysical motivation

- **rapid γ-ray and X-ray variability:**
  blazars (PKS 2155-304, 3C 279)
  misaligned AGNs (IC 310)
  Galactic Center (Sgr A*)
  pulsar wind nebulae (Crab)

- **theoretical challenges:**
  sub-horizon time scales
  γ-ray opacity
  in situ particle acceleration
  acceleration limited by radiative cooling

reconnection in Harris-type current layers

Werner, Uzdensky, Cerutti, KN & Begelman (2016, ApJ, 816, L5)
KN, Uzdensky, Cerutti, Werner & Begelman (2015, ApJ, 815, 101)

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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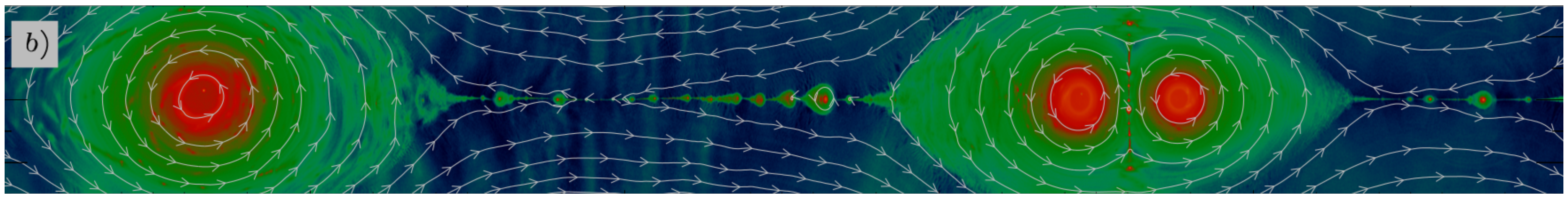
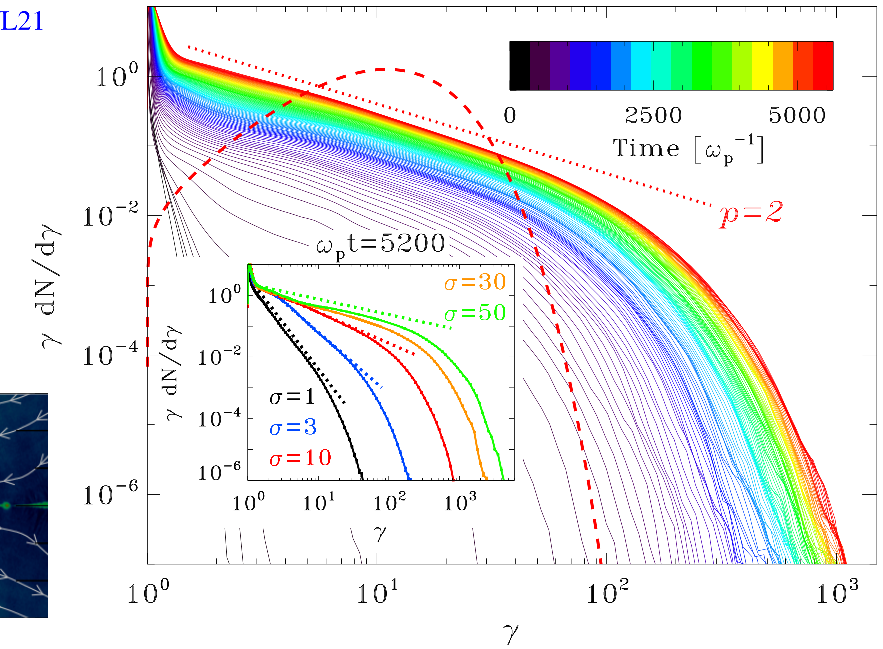
Received 2013 December 23; accepted 2014 January 21; published 2014 February 18

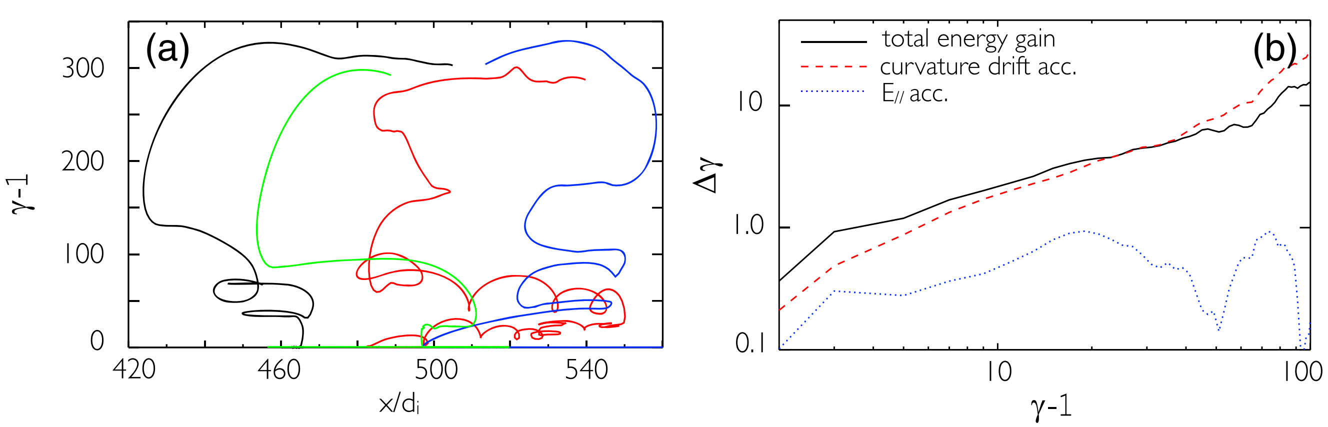


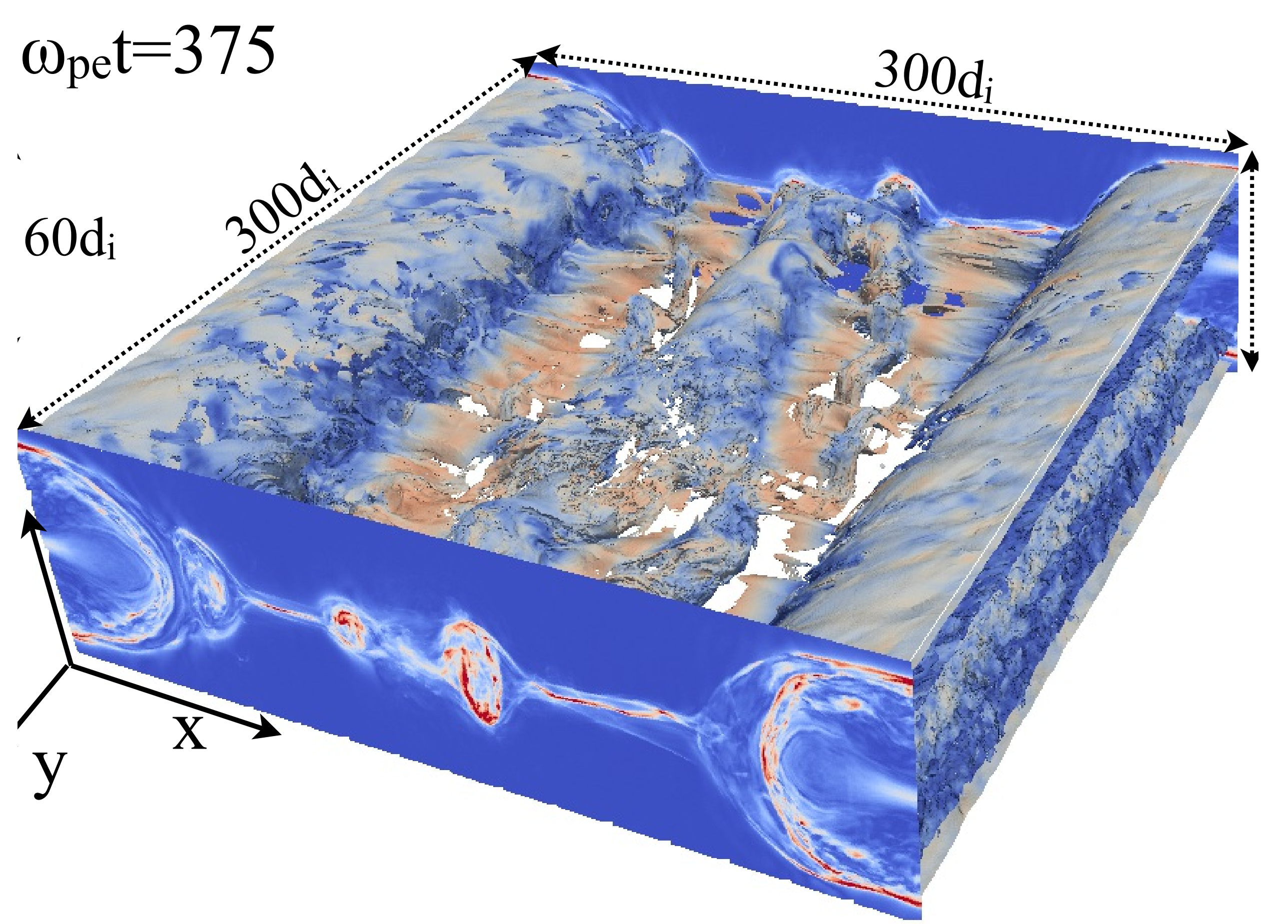


PRL 113, 155005 (2014) PHYSICAL REVIEW LETTERS week ending 10 OCTOBER 2014

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)





The Astrophysical Journal Letters, 816:L8 (5pp), 2016 January 1 doi:10.3847/2041-8205/816/1/L8

THE EXTENT OF POWER-LAW ENERGY SPECTRA IN COLLISIONLESS RELATIVISTIC MAGNETIC RECONNECTION IN PAIR PLASMAS

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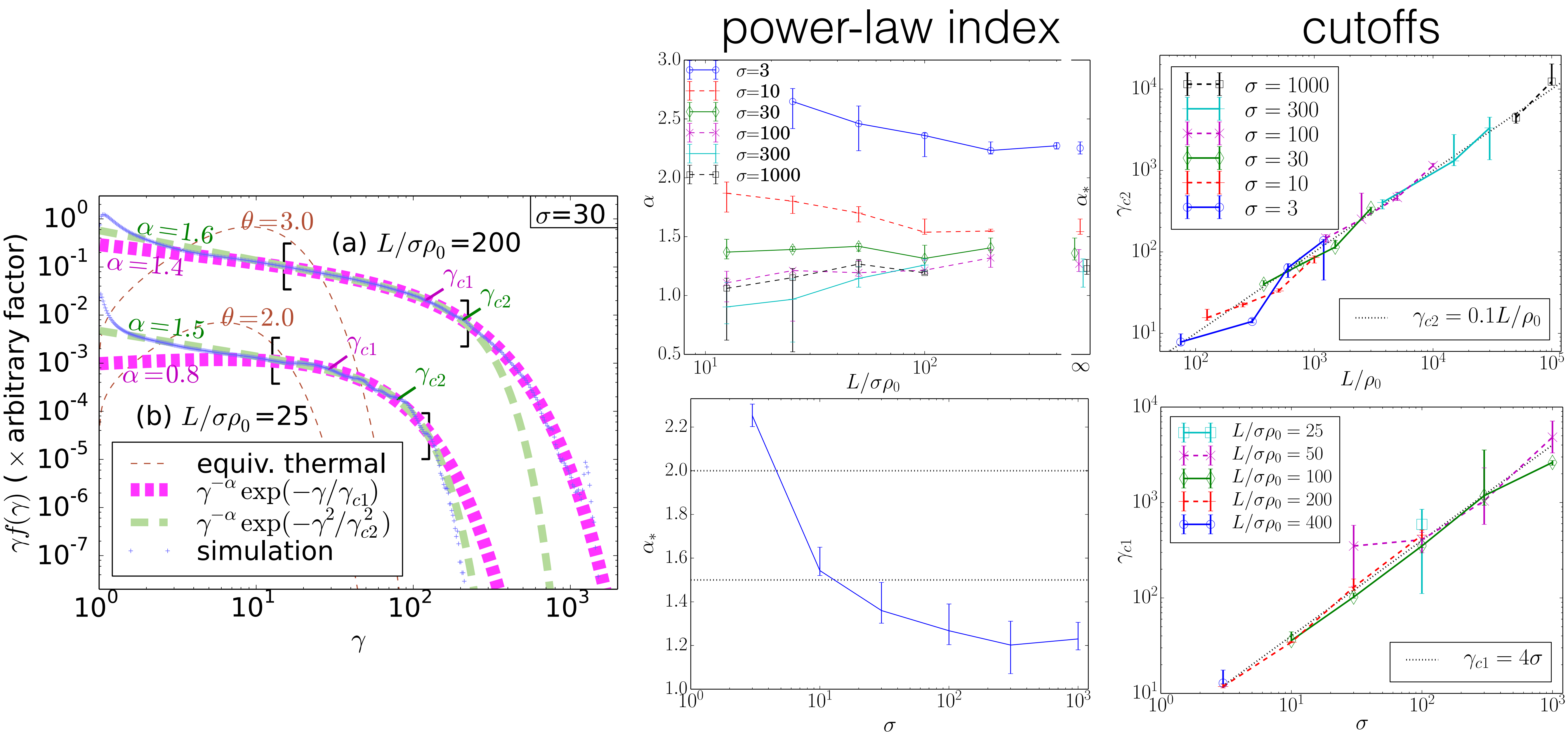
Received 2015 August 16; accepted 2015 December 11; published 2015 December 30

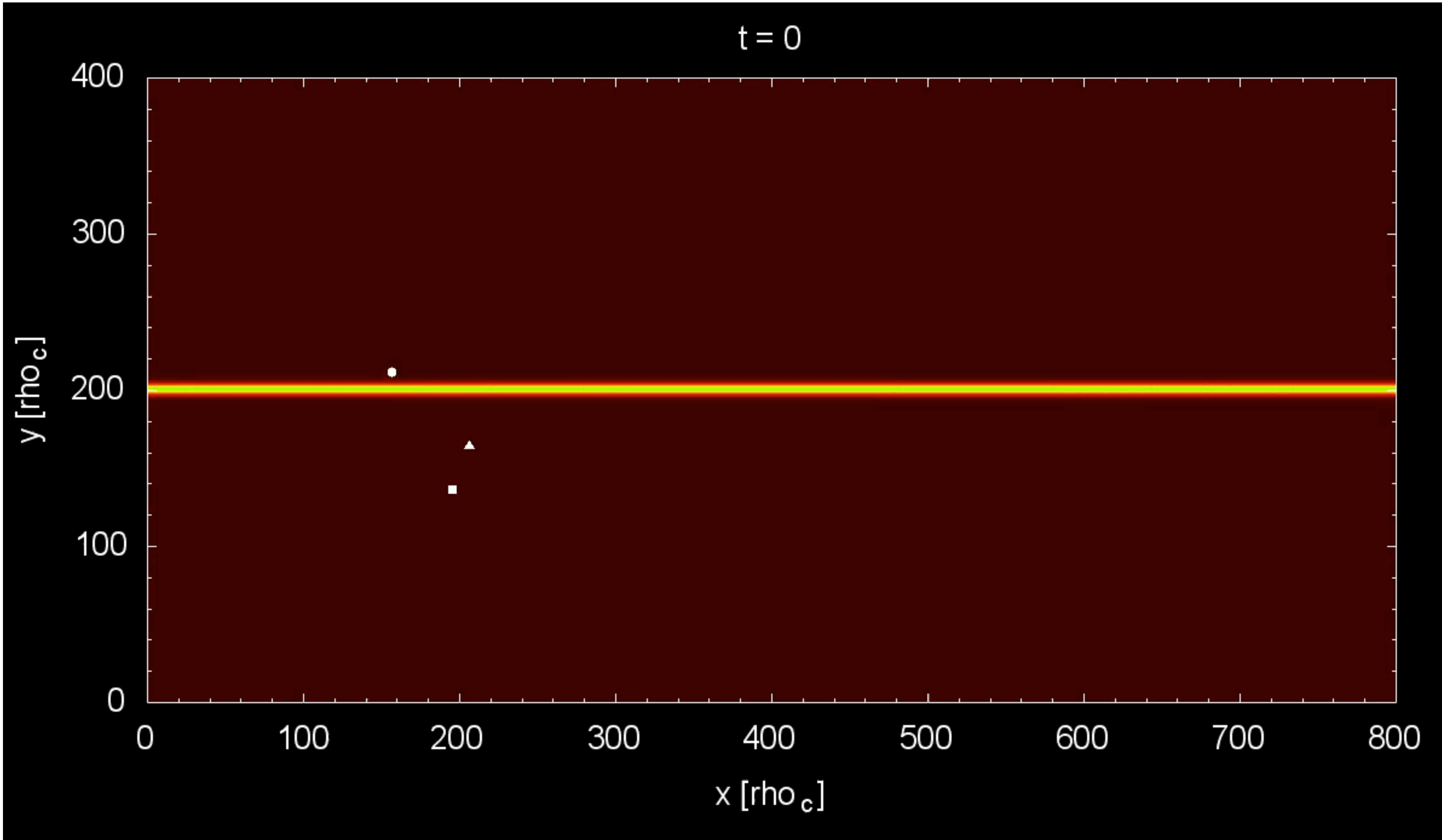
ABSTRACT

Using two-dimensional particle-in-cell simulations, we characterize the energy spectra of particles accelerated by relativistic magnetic reconnection (without guide field) in collisionless electron–positron plasmas, for a wide range of upstream magnetizations σ and system sizes L. The particle spectra are well-represented by a power law $\gamma^{-\alpha}$, with a combination of exponential and super-exponential high-energy cutoffs, proportional to σ and L, respectively. For large L and σ, the power-law index α approaches about 1.2.



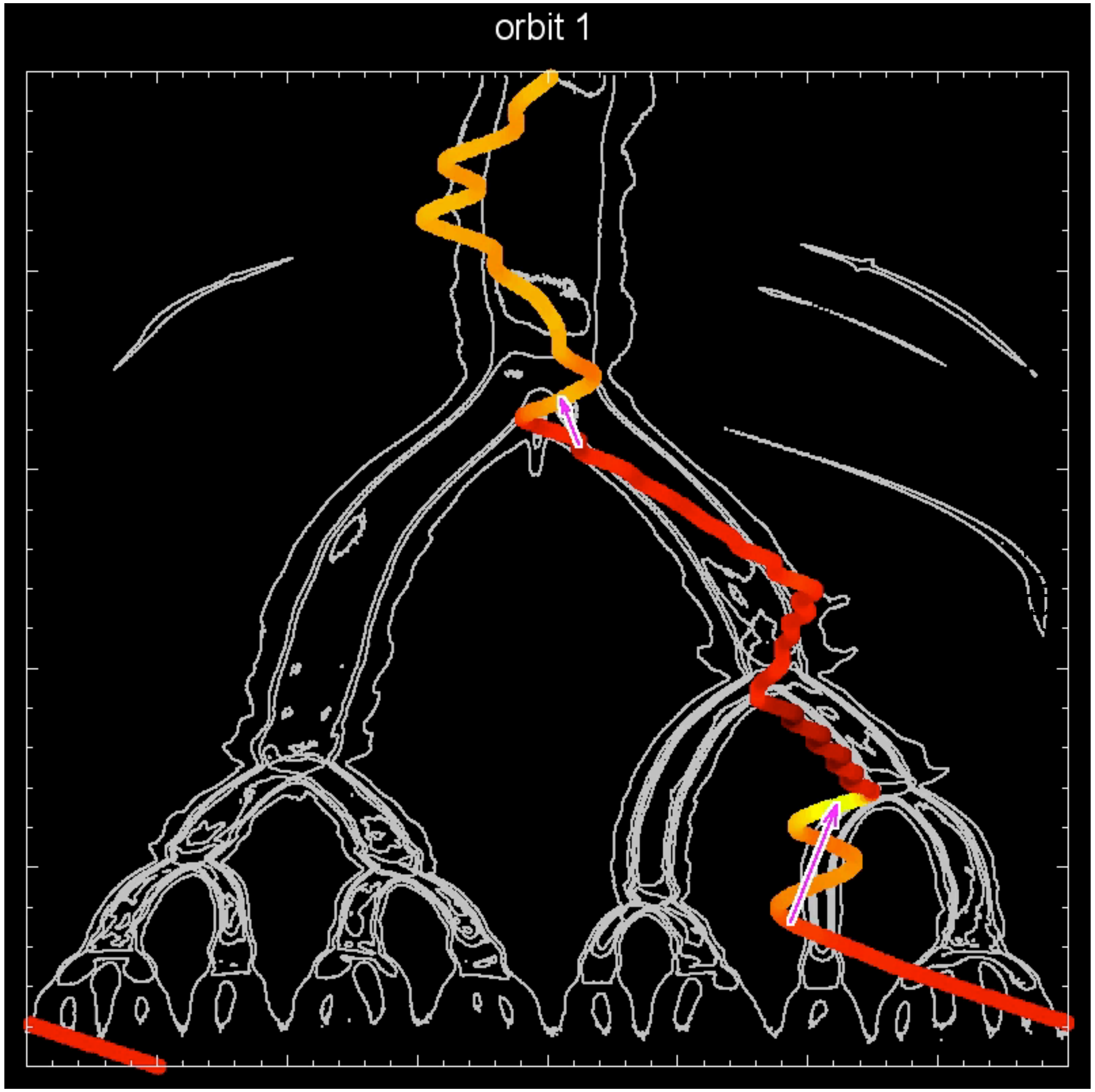
particle acceleration sites

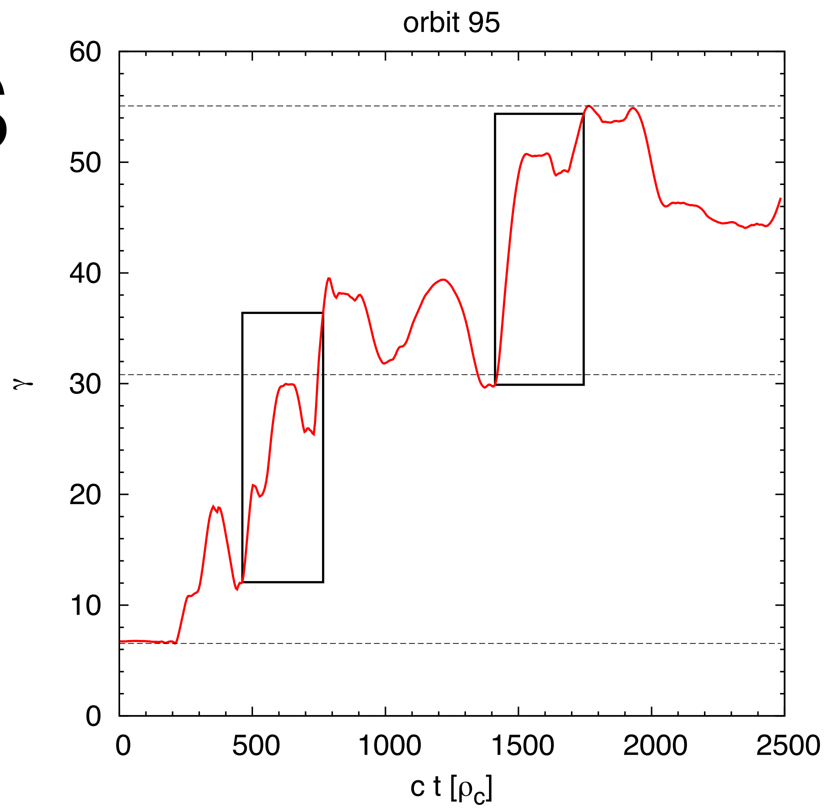
KN+15

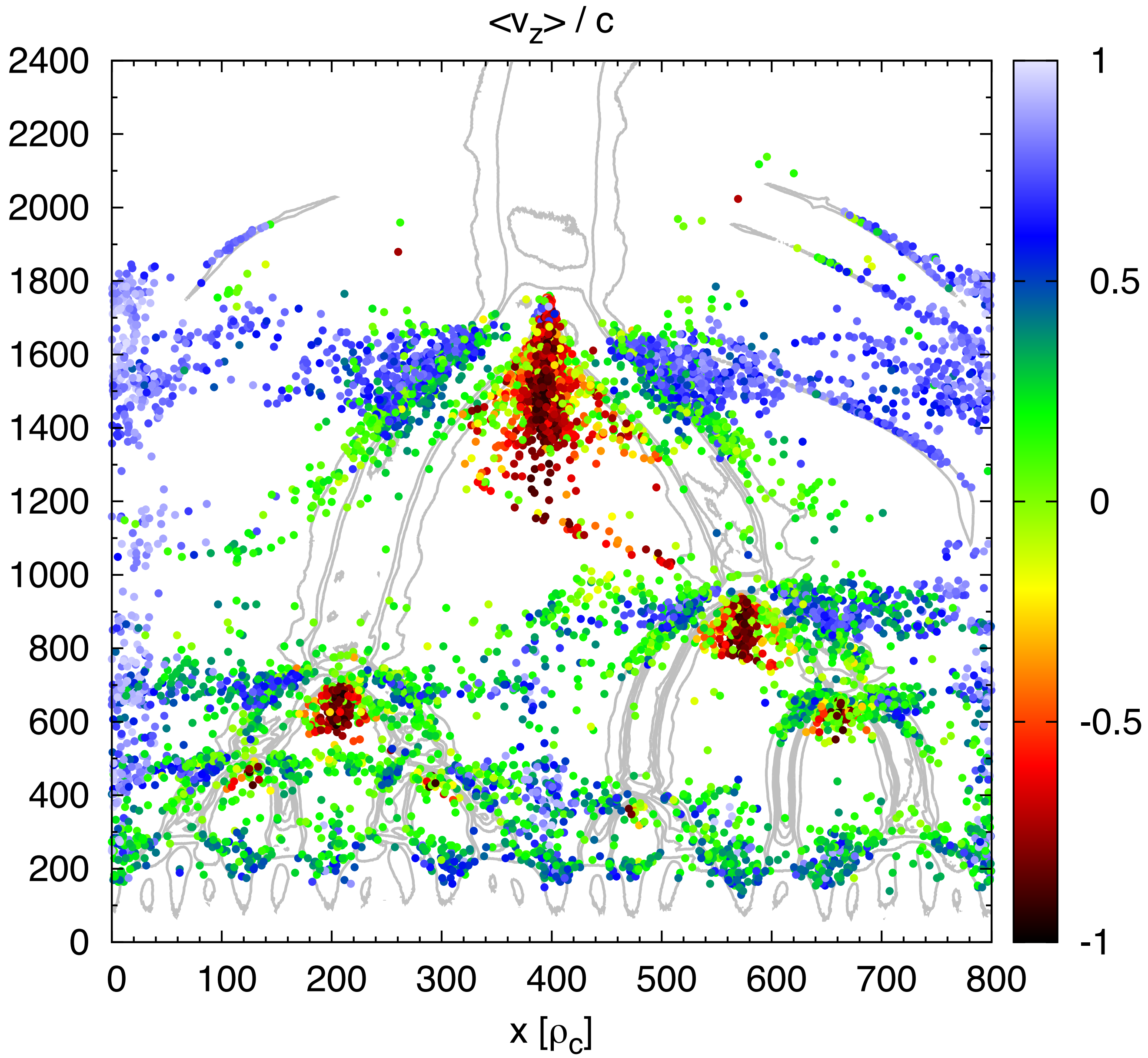


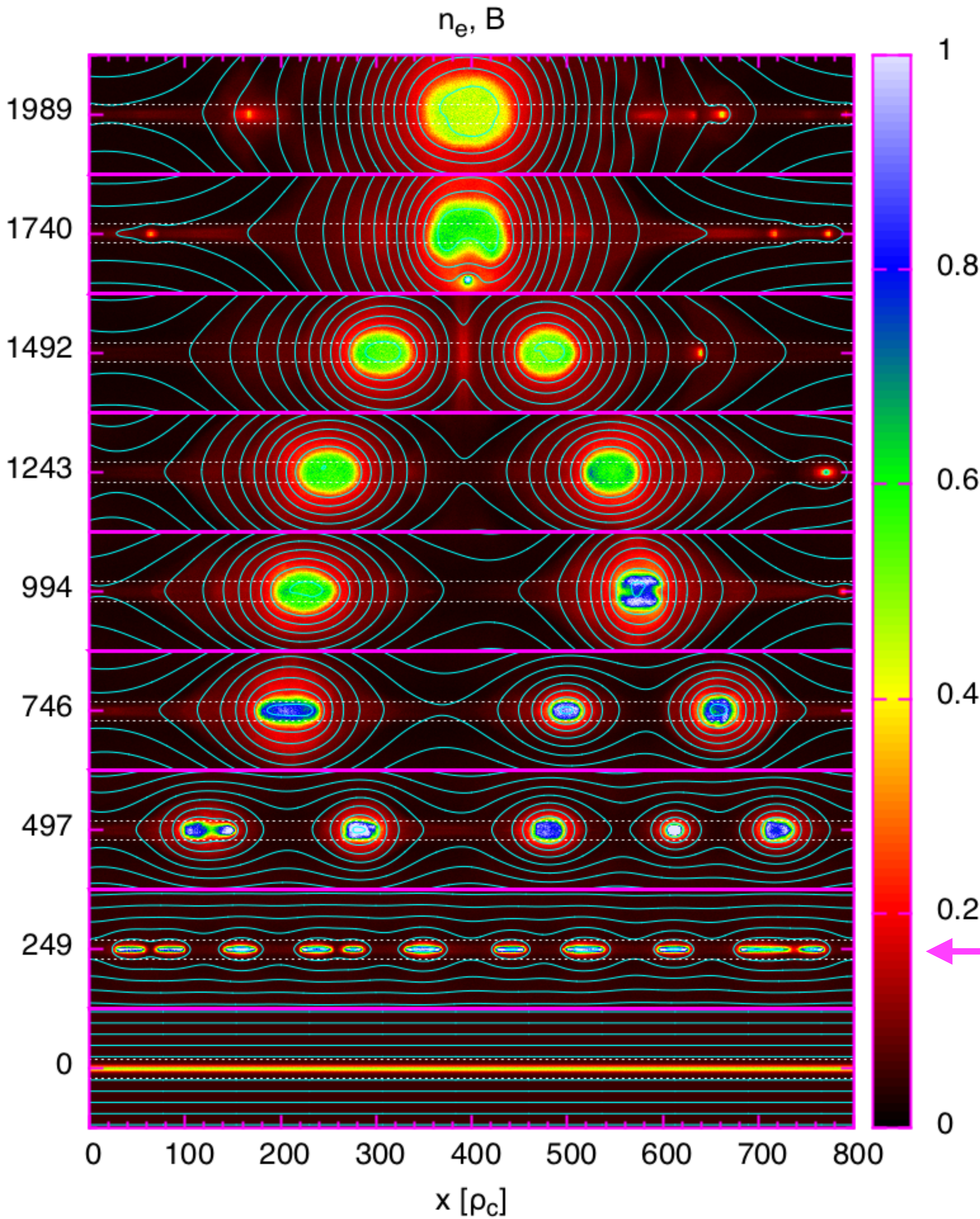
main acceleration episodes

KN+15

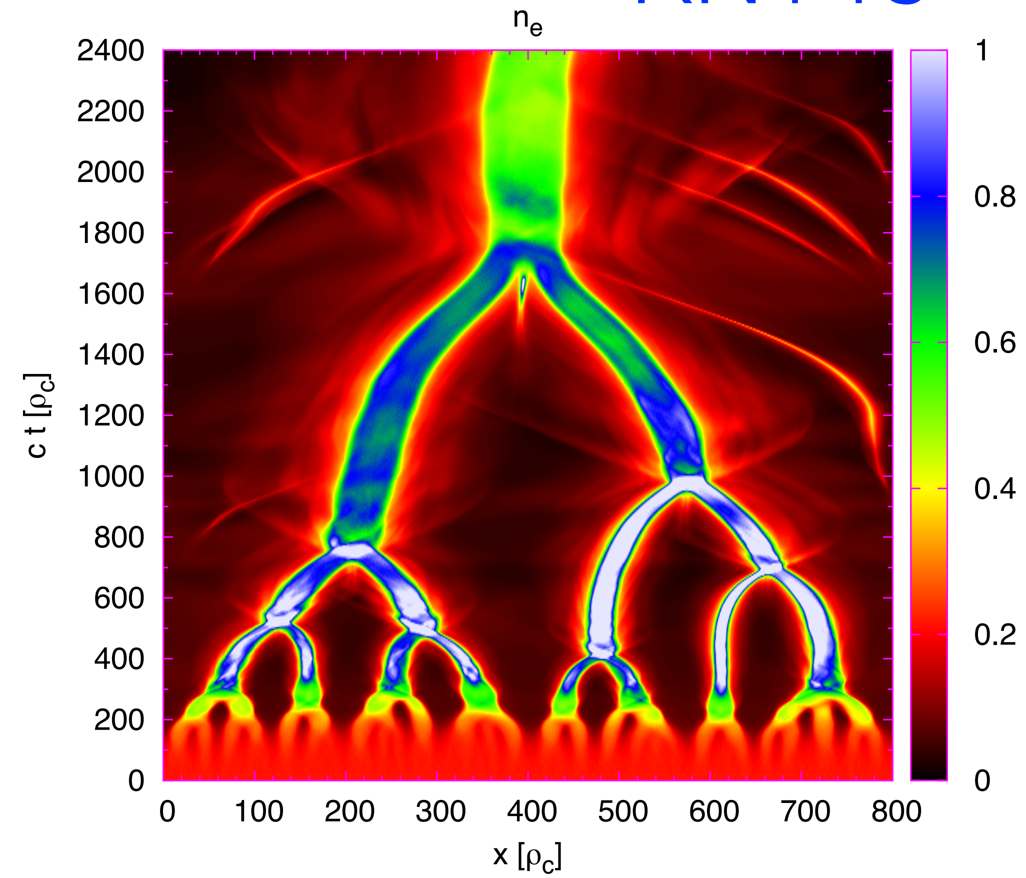






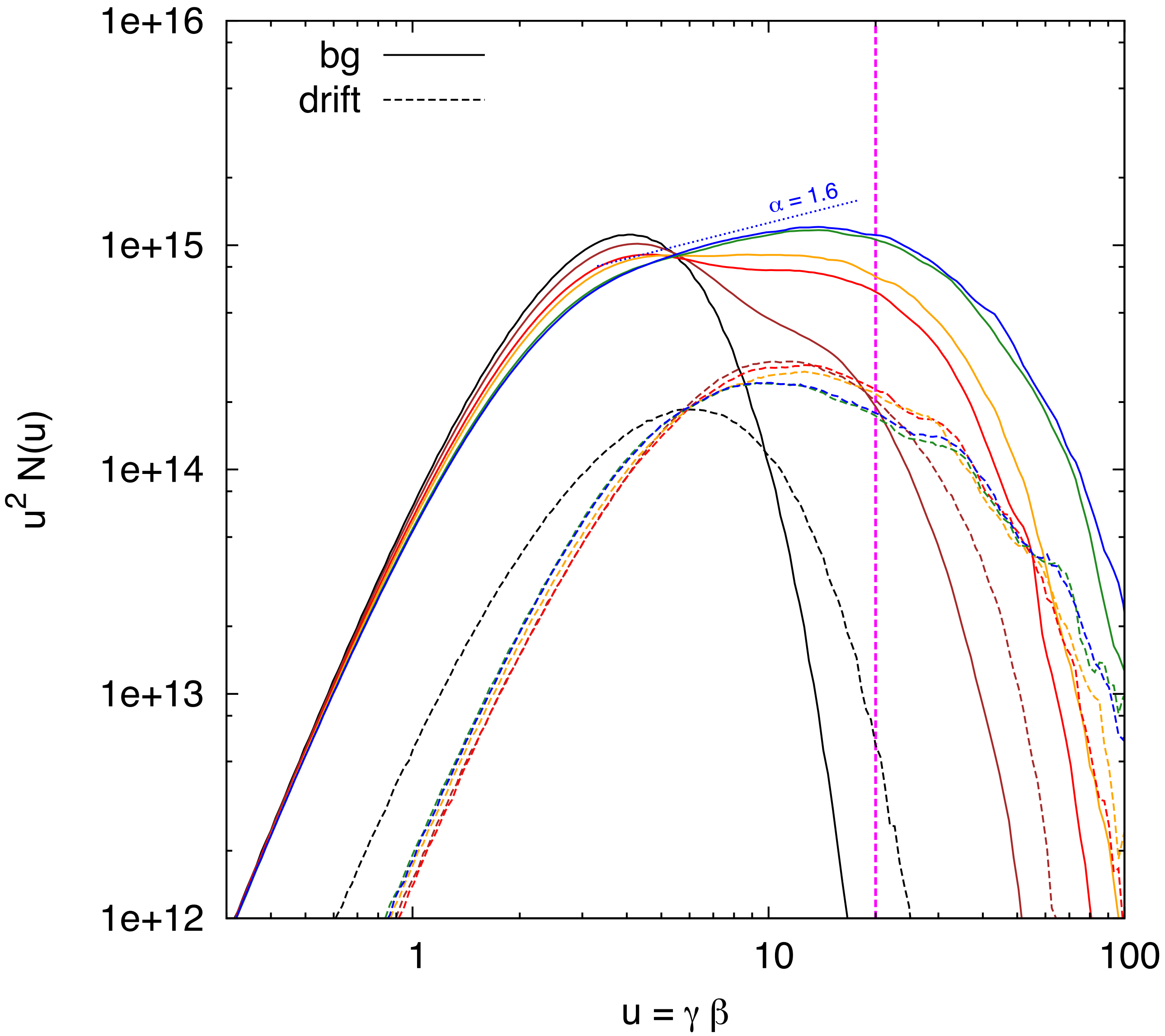


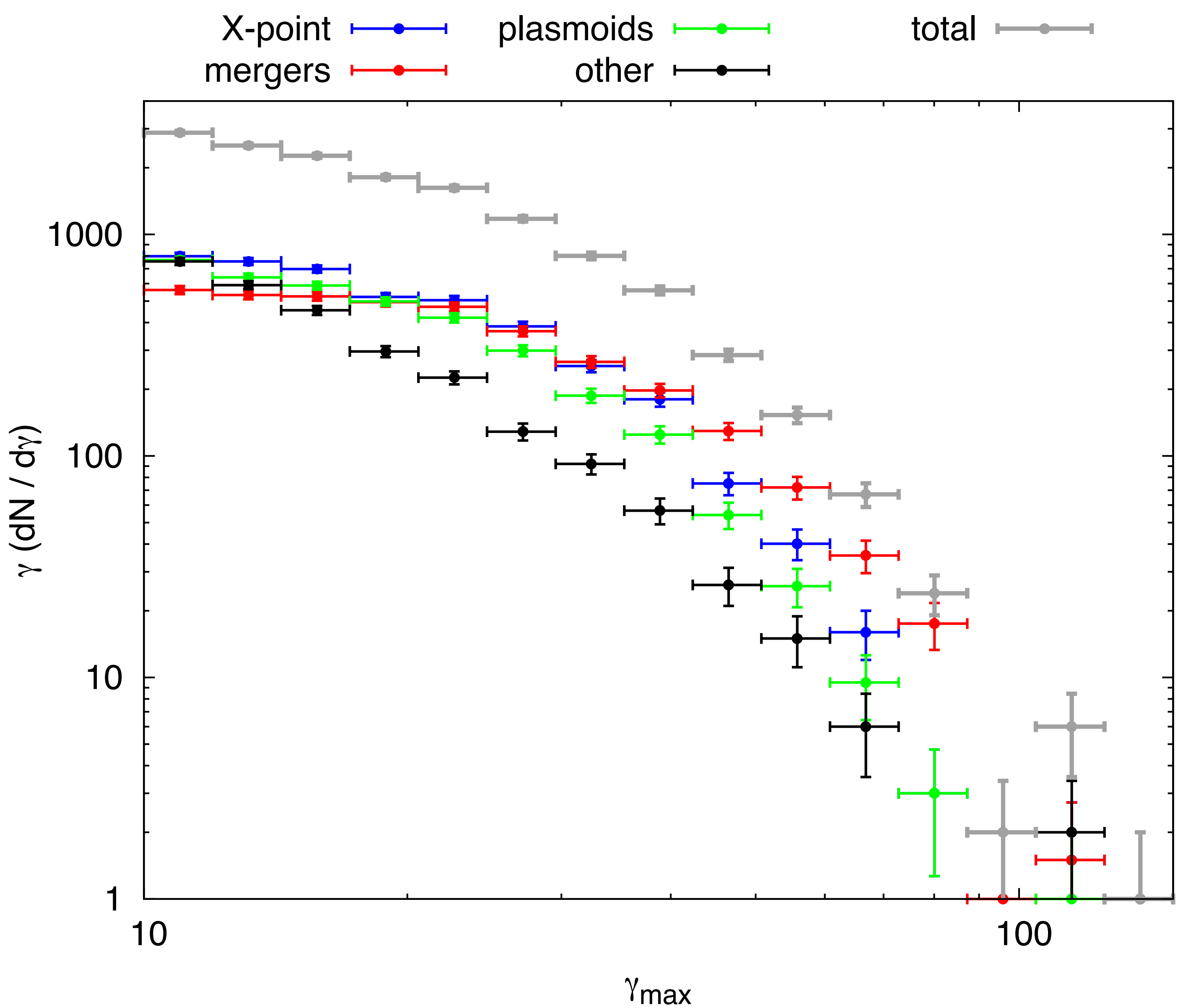
KN+15



elongated plasmoids
(subject to contraction)

particle energy distribution





KN+15

summary: Harris-layer reconnection

- **particle acceleration**
  hard power laws p -> 1 for $\sigma >> 1$
  $\gamma_{max} \sim \sigma$, exponential cut-offs, no soft tails
  X-points vs. curvature drift
  first-order Fermi process

- **problem setup**
  artificial synchronization
  exaggerated tearing

reconnection in “ABC fields”

KN, Zrake, Yuan, East & Blandford (2016, arXiv:1603.04850)

magnetoluminescence

a process of extracting magnetic energy by means of dynamical instability (implosion) leading to transient current layers enabling efficient particle acceleration, and consequently a transient gamma-ray emission

Methods:

- analytical stability analysis (Y. Yuan)
- relativistic MHD (J. Zrake)
- relativistic force-free (W. East)
- particle-in-cell (this talk)
- radiative PIC (Y. Yuan)

SOVIET ASTRONOMY—AJ VOL. 10, NO. 2 SEPTEMBER-OCTOBER, 1966

DYNAMIC DISSIPATION OF A MAGNETIC FIELD AND PARTICLE ACCELERATION

S. I. Syrovat-skii

P. N. Lebedev Physics Institute, Academy of Sciences of the USSR

Translated from Astronomicheskii Zhurnal, Vol. 43, No. 2, pp. 340-355, March-April, 1966
Original article submitted November 20, 1965

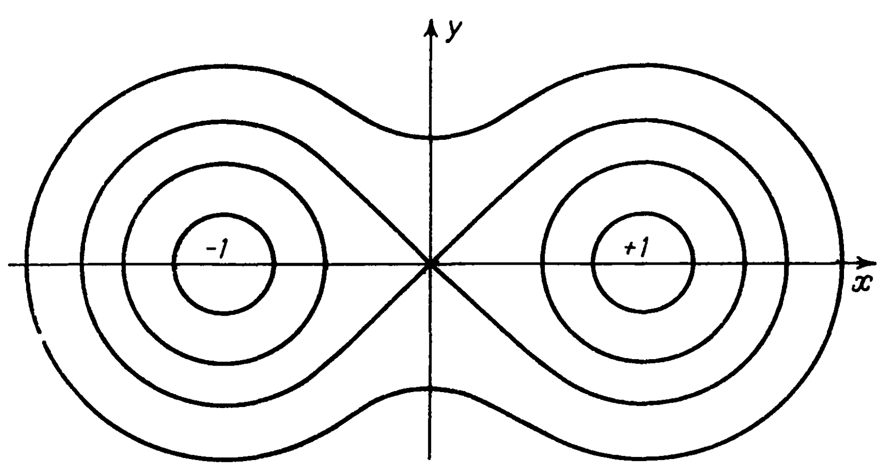


Fig. 1

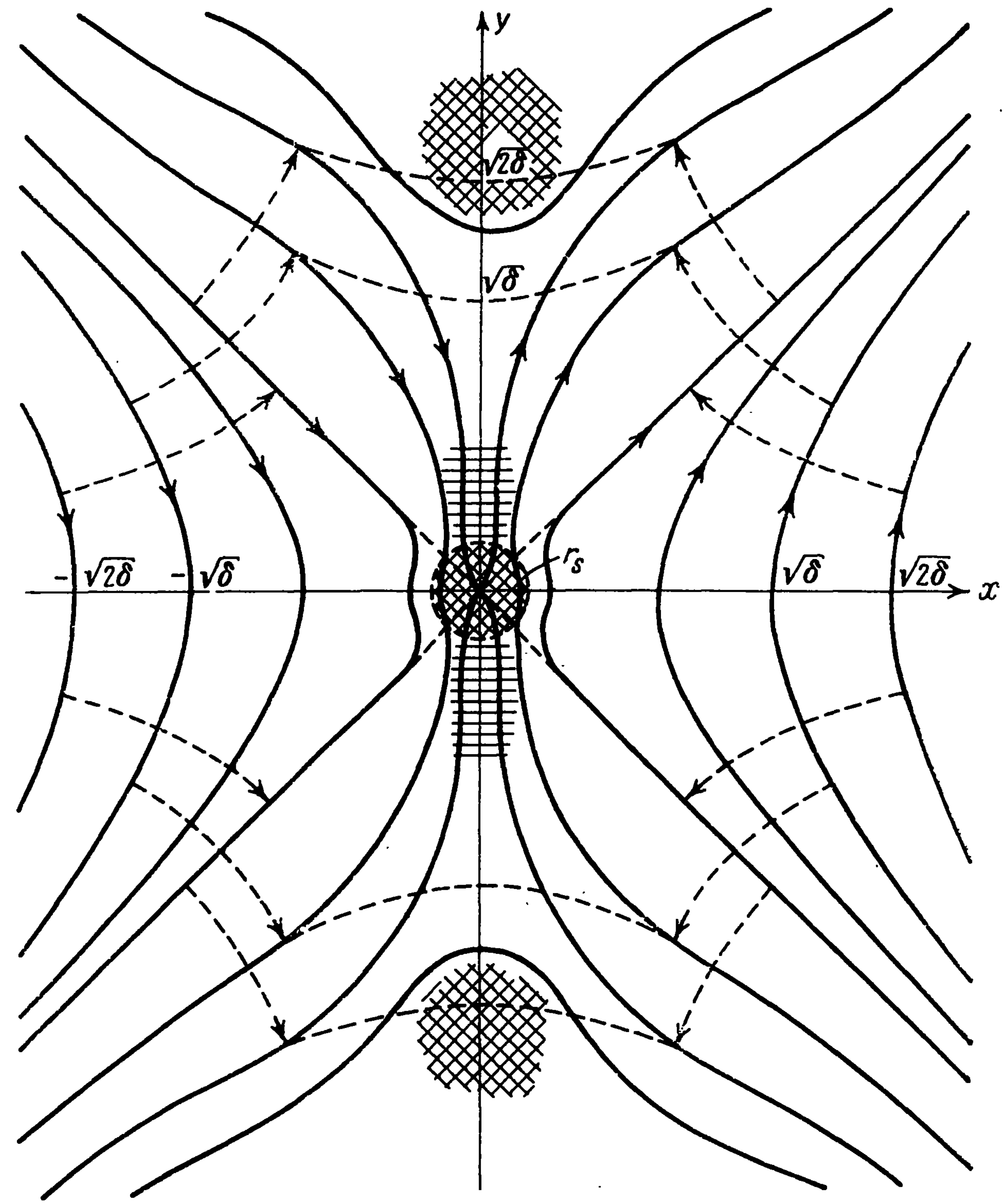


Fig. 2

harmonic magnetic equilibria

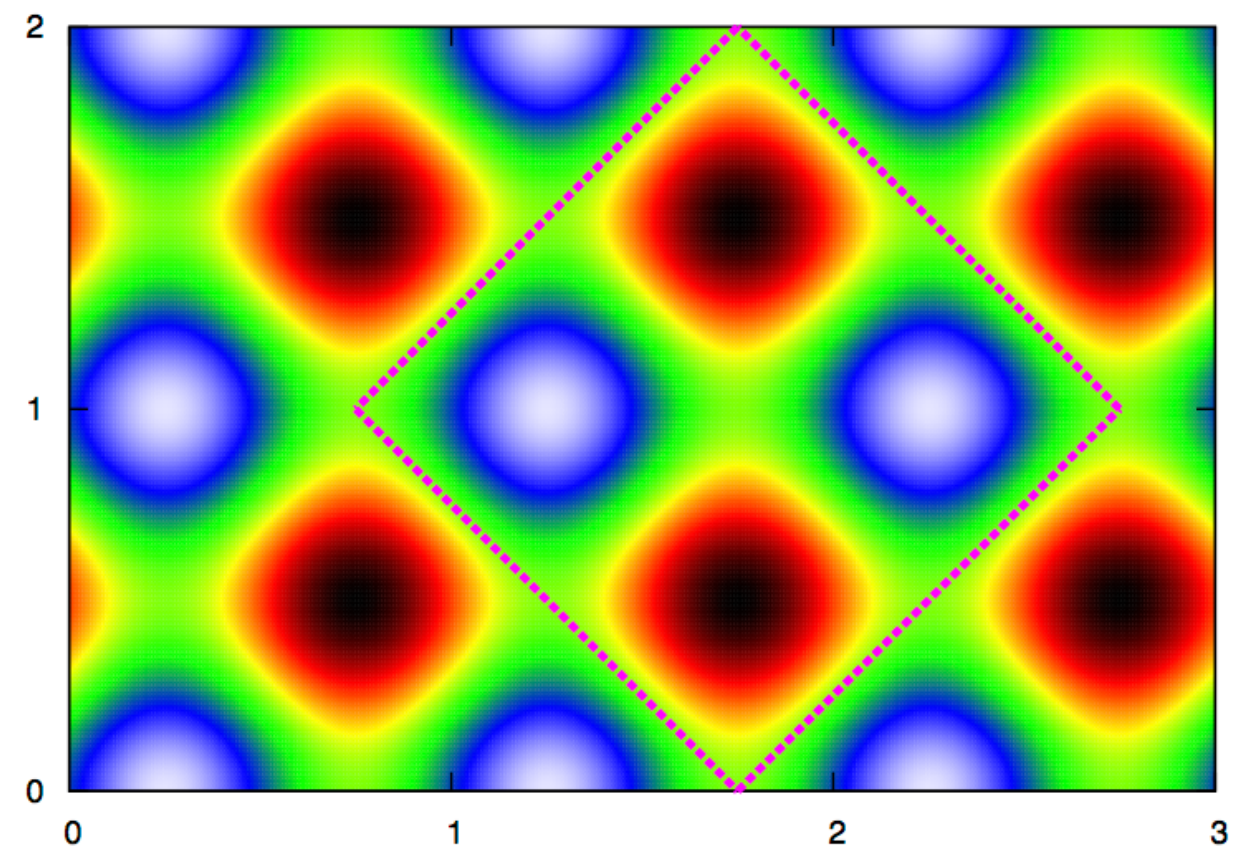
- Beltrami condition:
  $\nabla \times B = \alpha B$
  $B = \alpha A$, $j = -(\alpha c/4\pi)B$

- ABC field:
  $B_x = B_3 \sin(\alpha z) + B_2 \cos(\alpha y)$
  $B_y = B_1 \sin(\alpha x) + B_3 \cos(\alpha z)$
  $B_z = B_2 \sin(\alpha y) + B_1 \cos(\alpha x)$

- 2D: $B_1 = B_2 = 1$, $B_3 = 0$

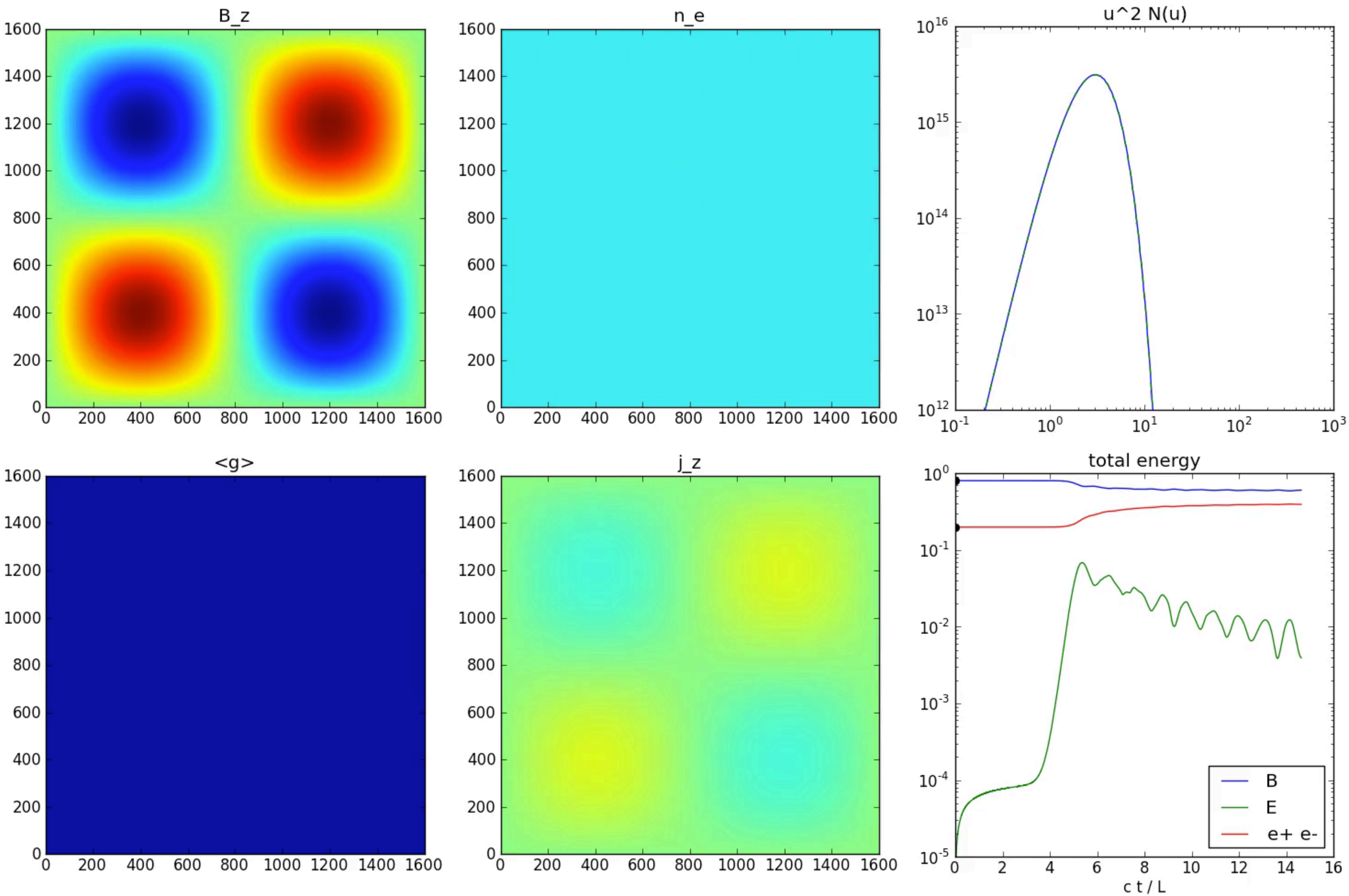
- fundamental unstable mode:
  2 maxima and 2 minima of A_z

- no kinetic-scale initial structure

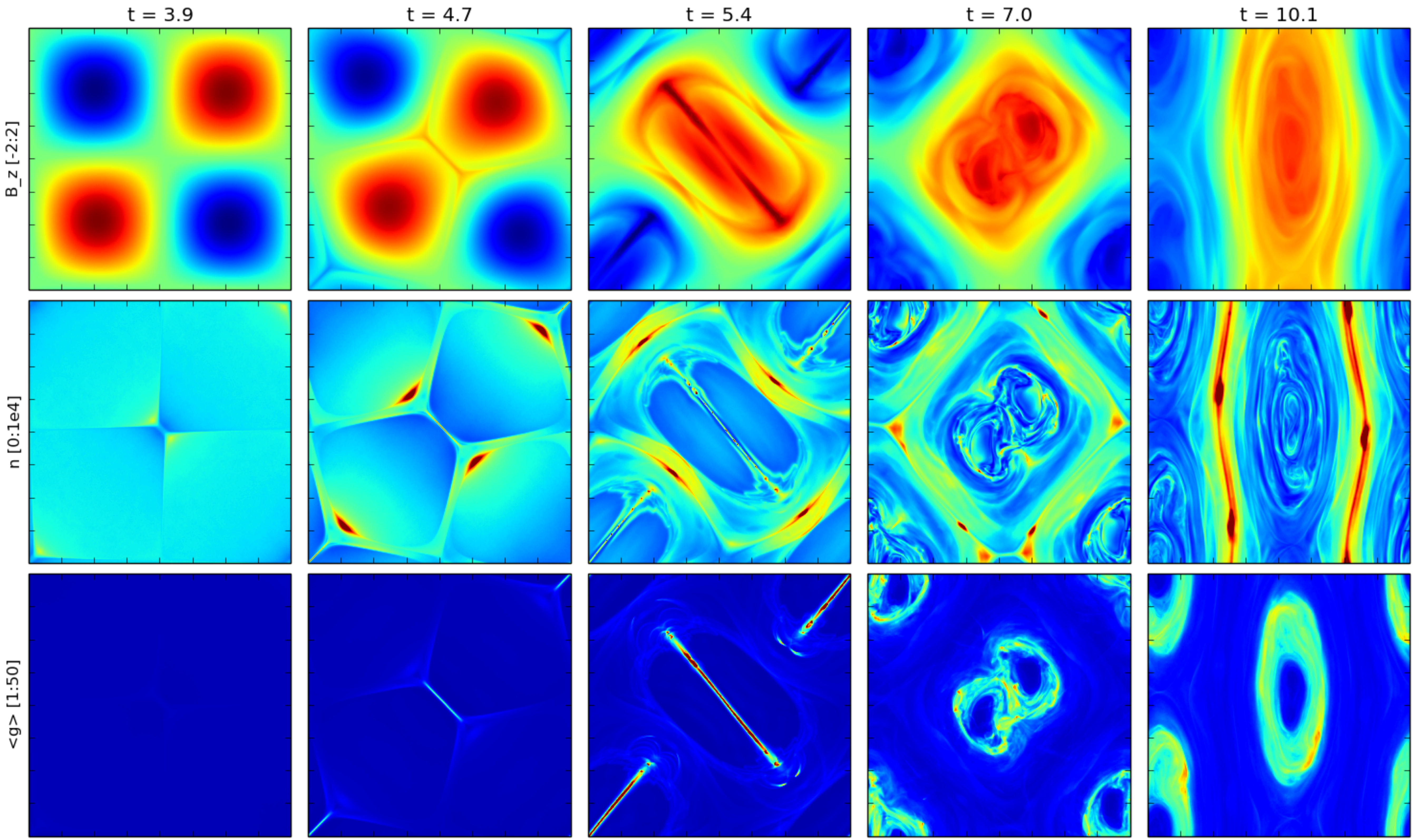


- current density from dipole moment a_1 in particle momentum distribution

- mean magnetization
  $\sigma \propto a_1(L/\rho_0)$

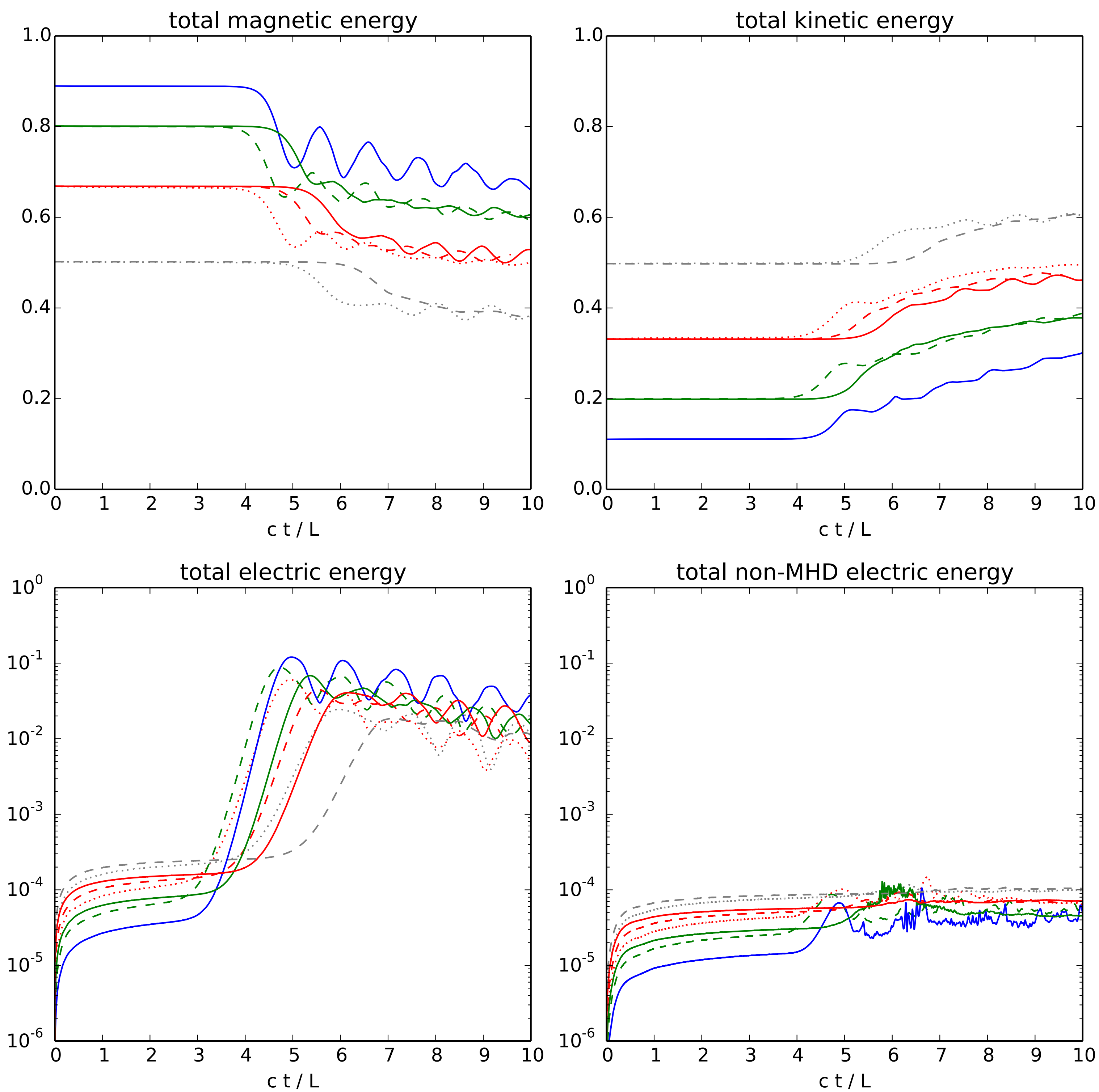


B_z
n_e
u^2 N(u)
<g>
j_z
total energy
B
E
e+ e-
c t / L

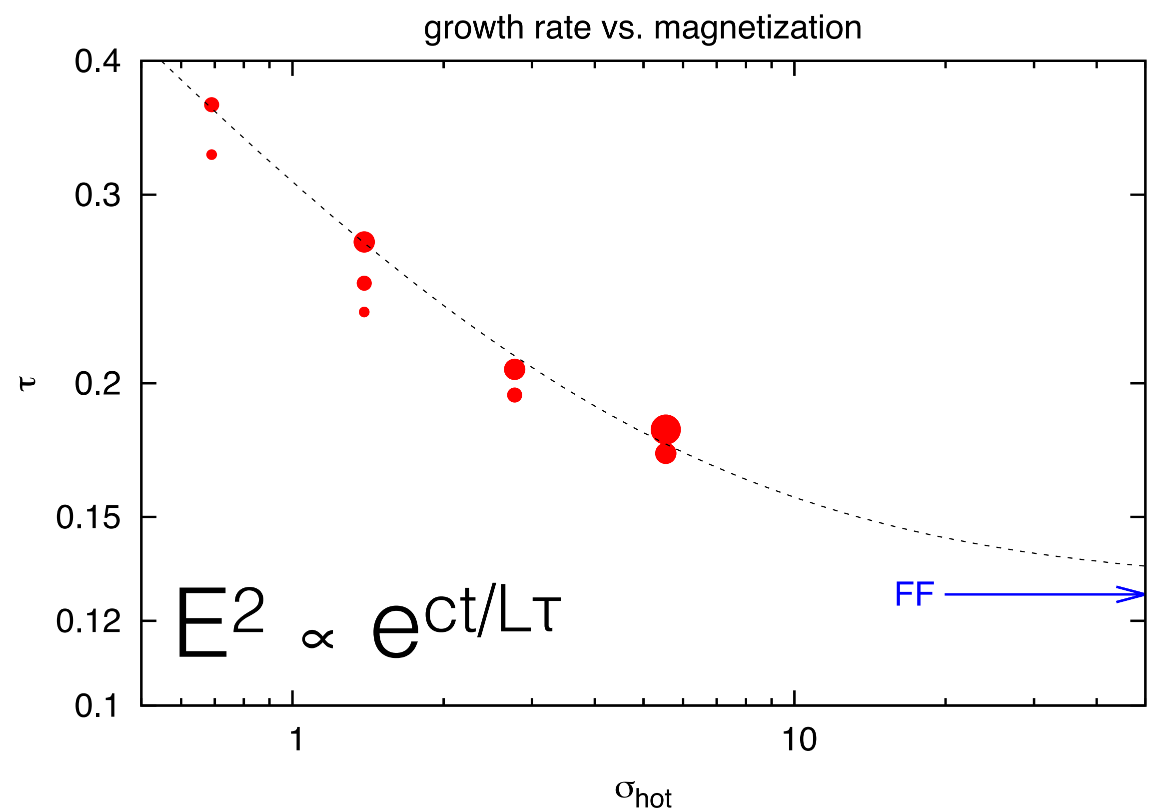


t = 3.9
t = 4.7
t = 5.4
t = 7.0
t = 10.1
B_z [-2:2]
n [0:1e4]
<g> [1:50]

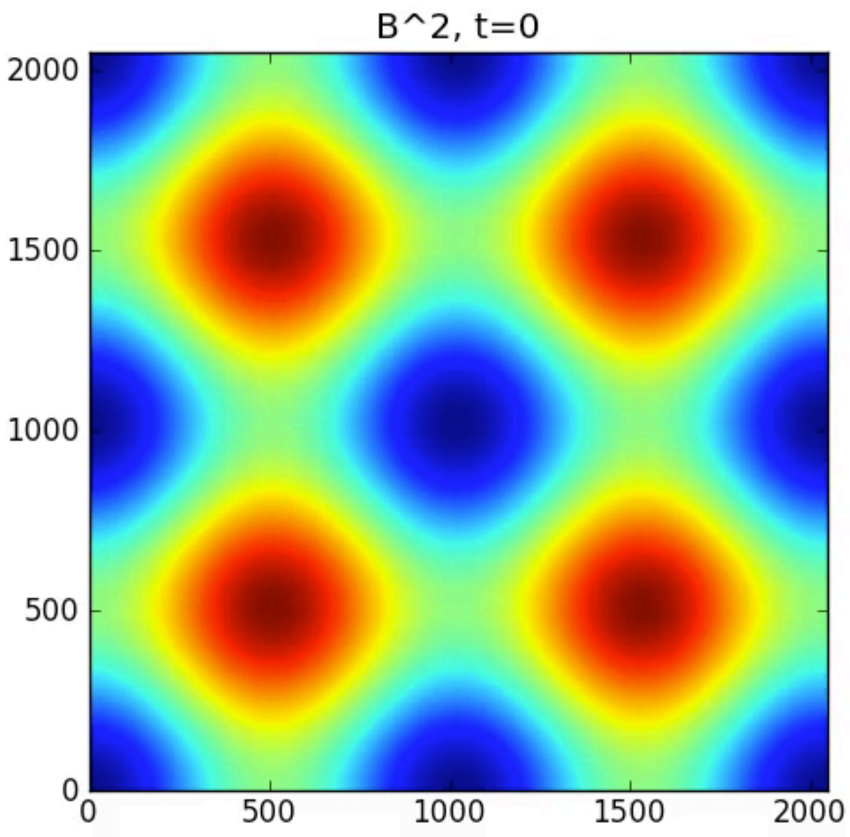
total energy



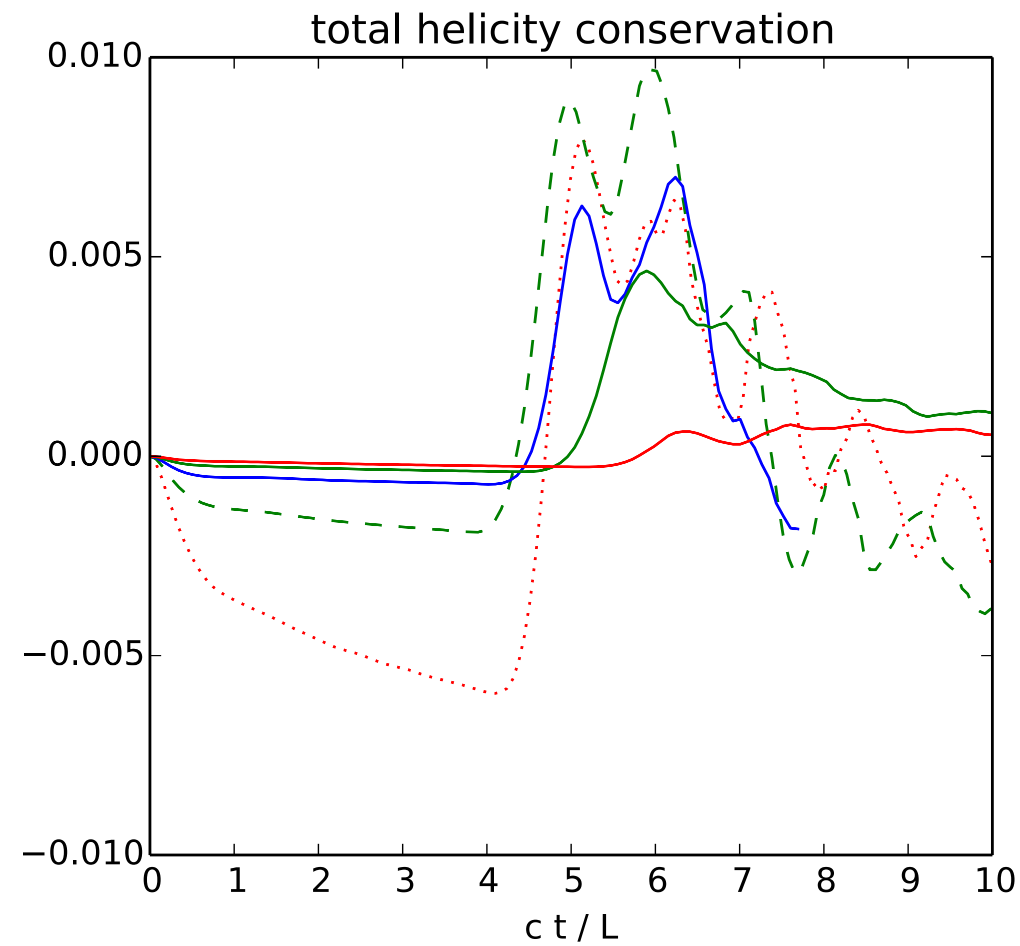
- linear instability seen in total electric energy
- non-ideal electric energy appears insignificant
- relative magnetic dissipation efficiency is constant

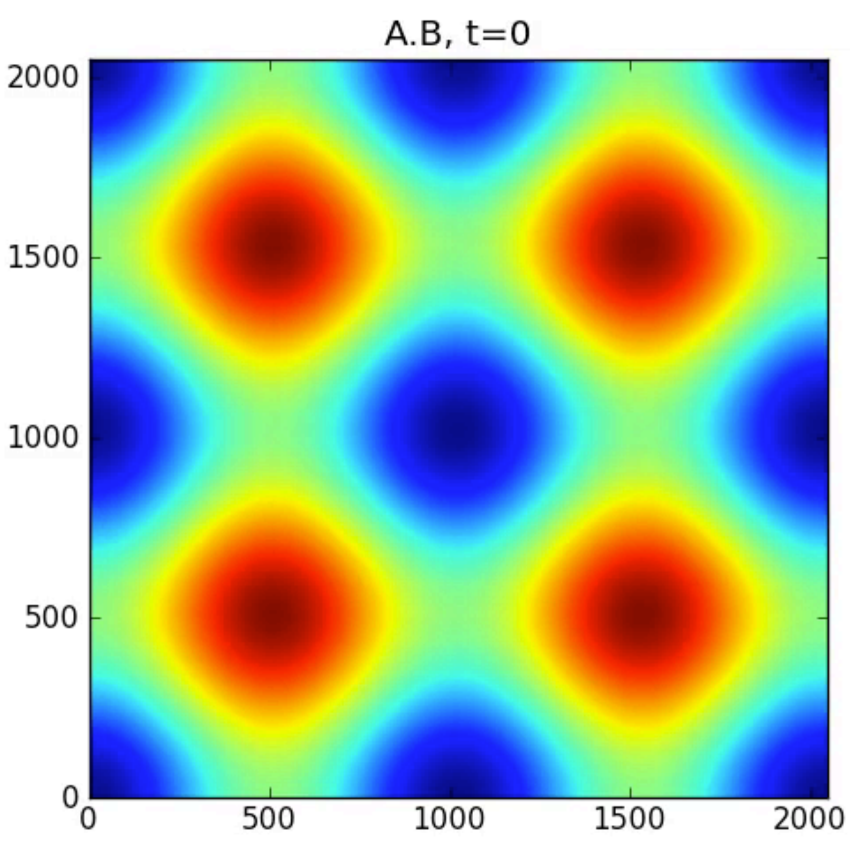


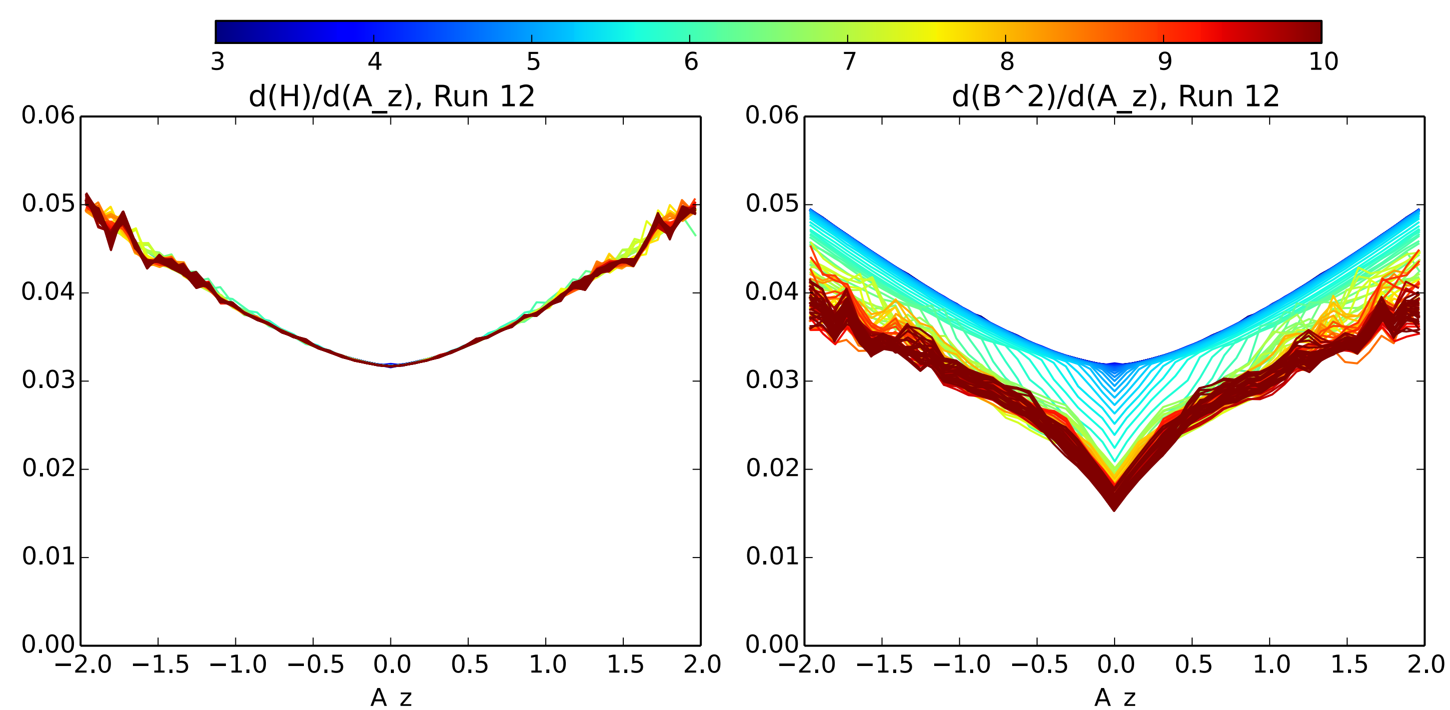
magnetic helicity



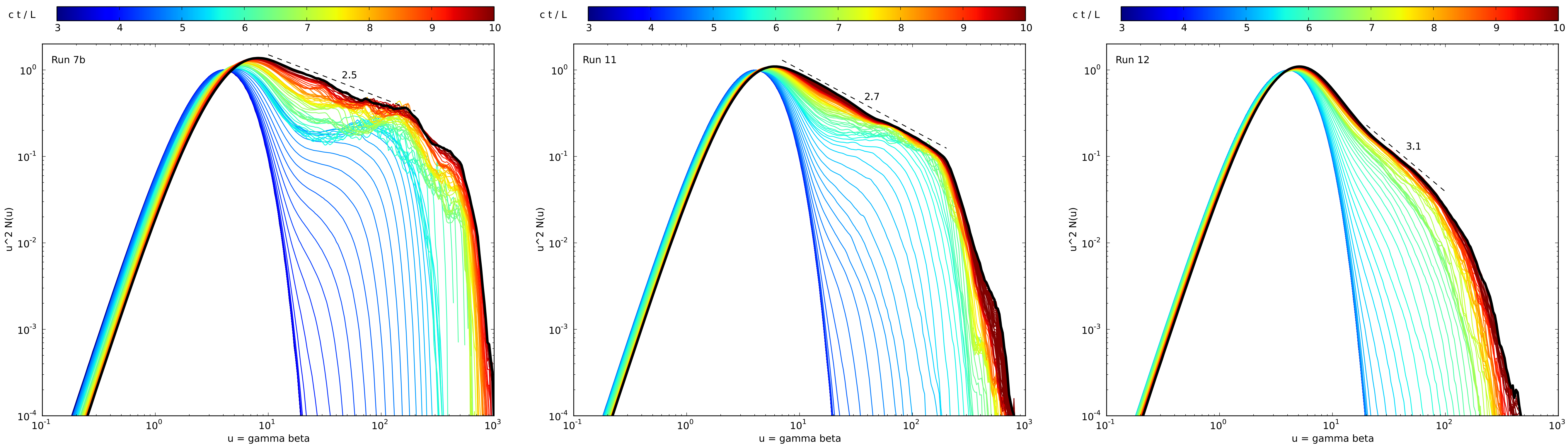
- H = ∫(A.B)dV
- conserved quantity in ideal MHD
- conservation in PIC simulations better than 1%, especially for small dipole moment a_1



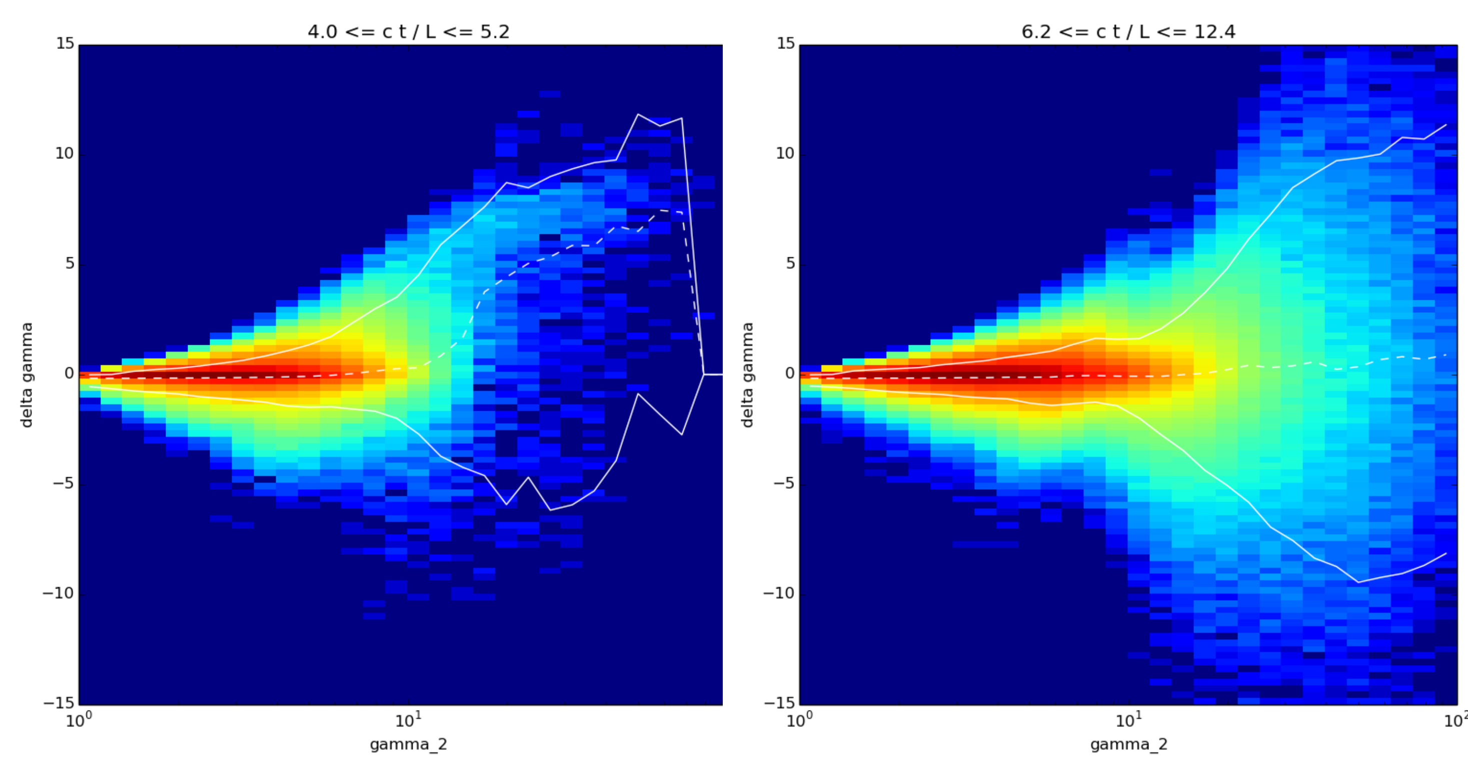




particle energy distribution

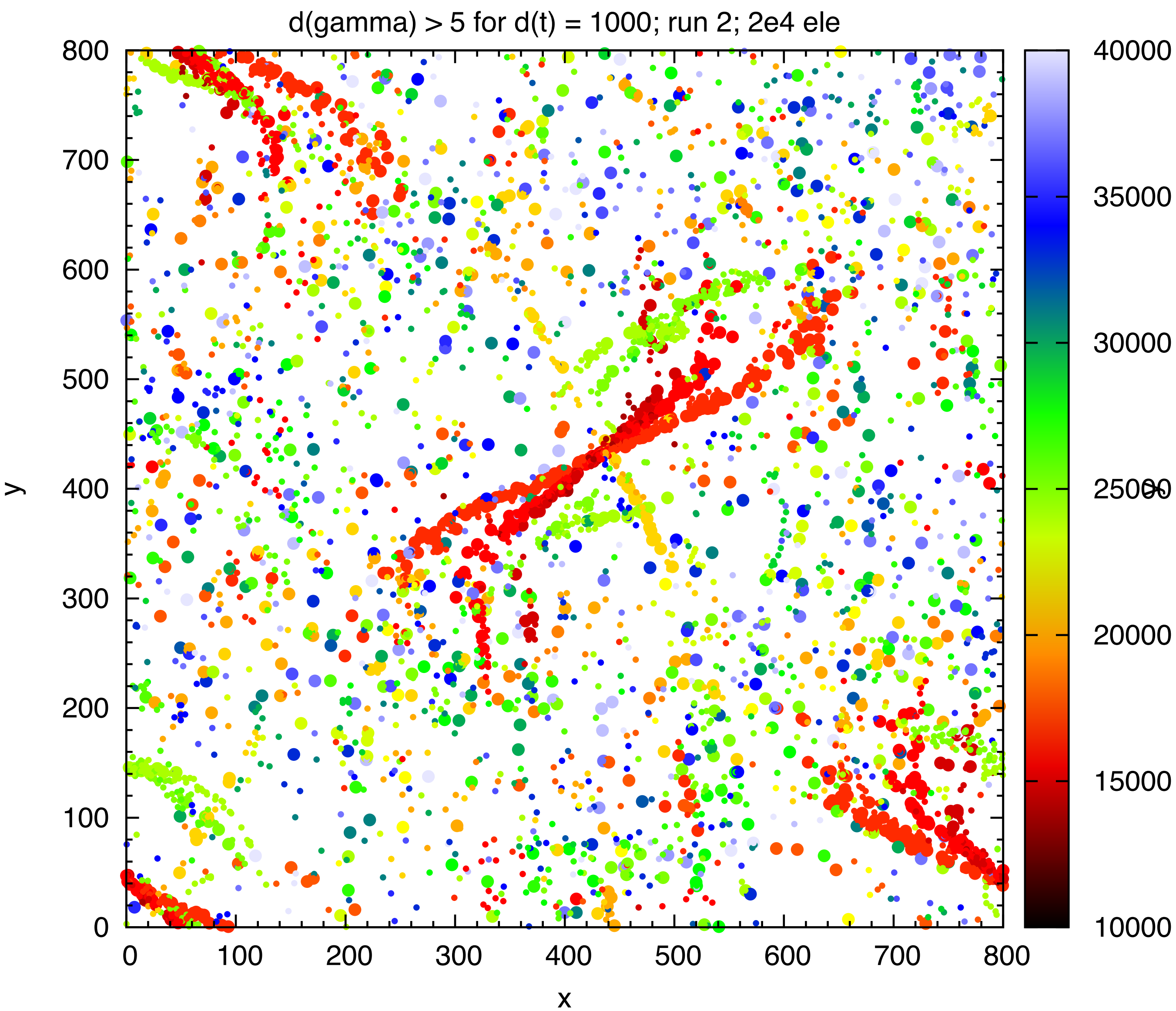


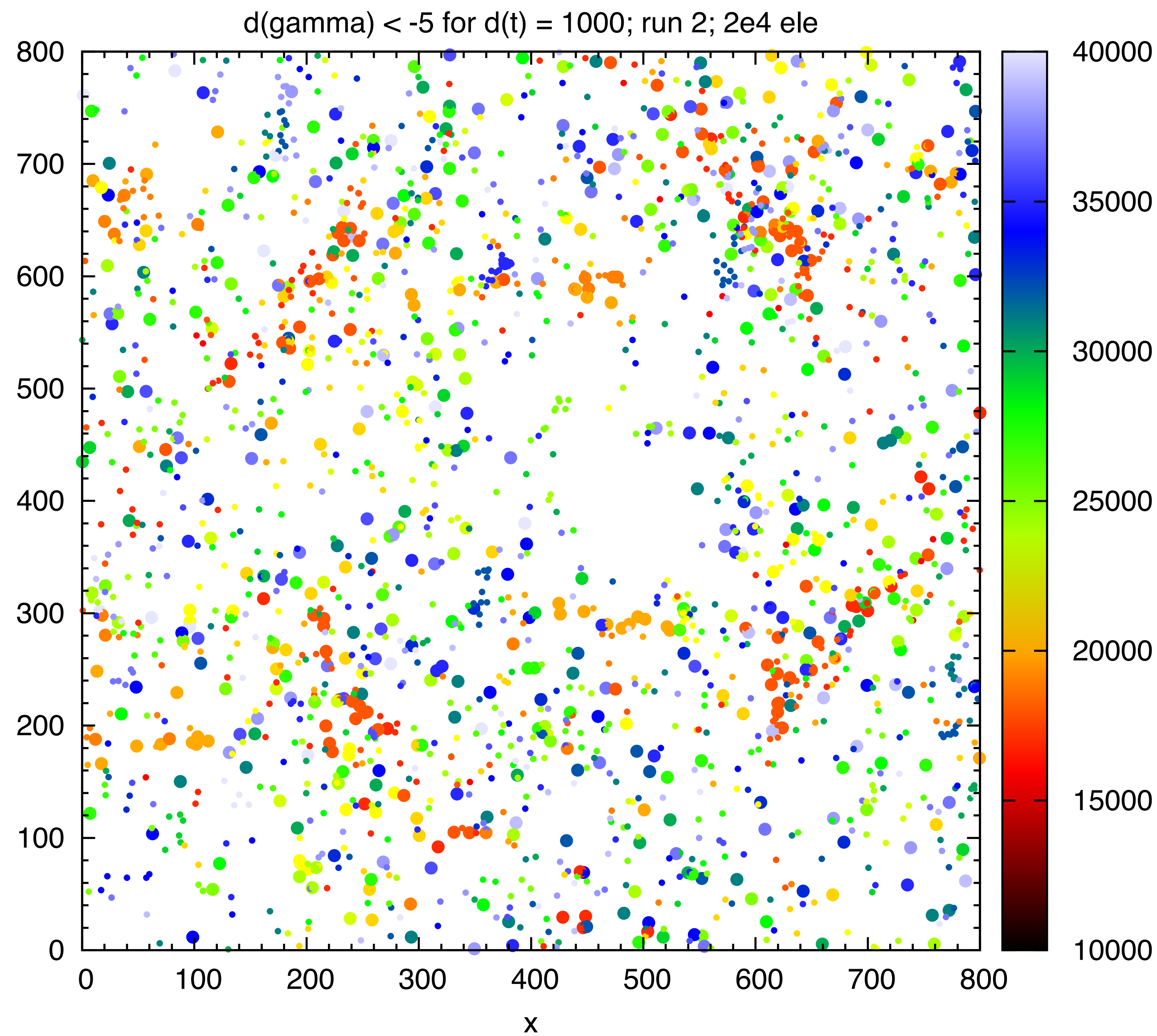
- steady direct acceleration in the linear phase
- stochastic acceleration in the non-linear phase produces a power-law



strong accelerations
$\Delta\gamma > 5$

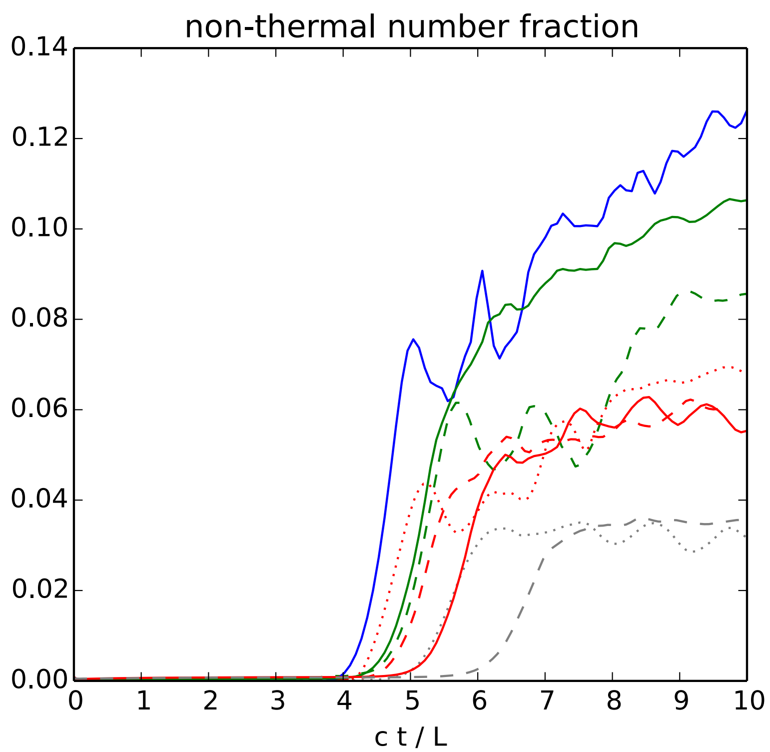
strong decelerations
$\Delta\gamma < -5$

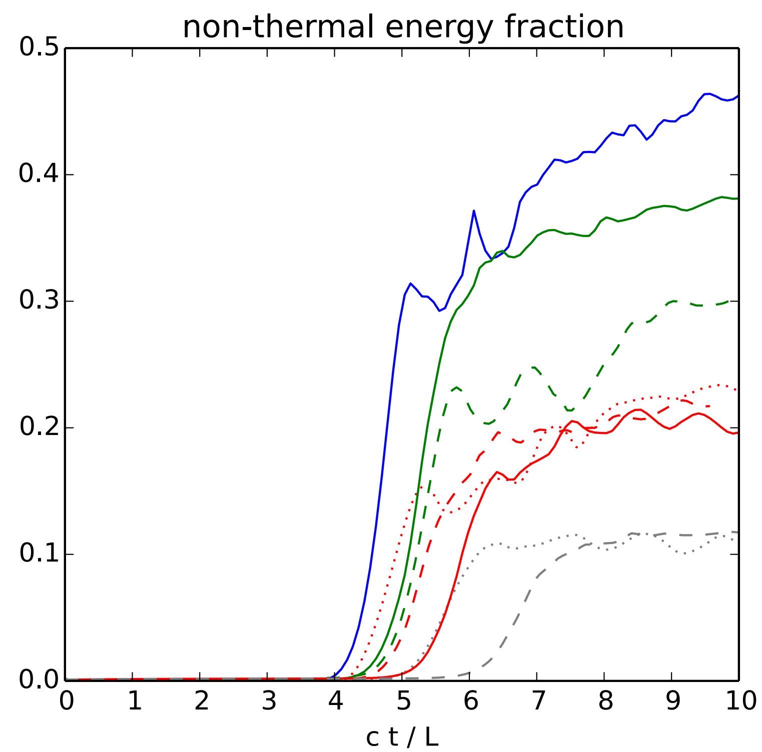


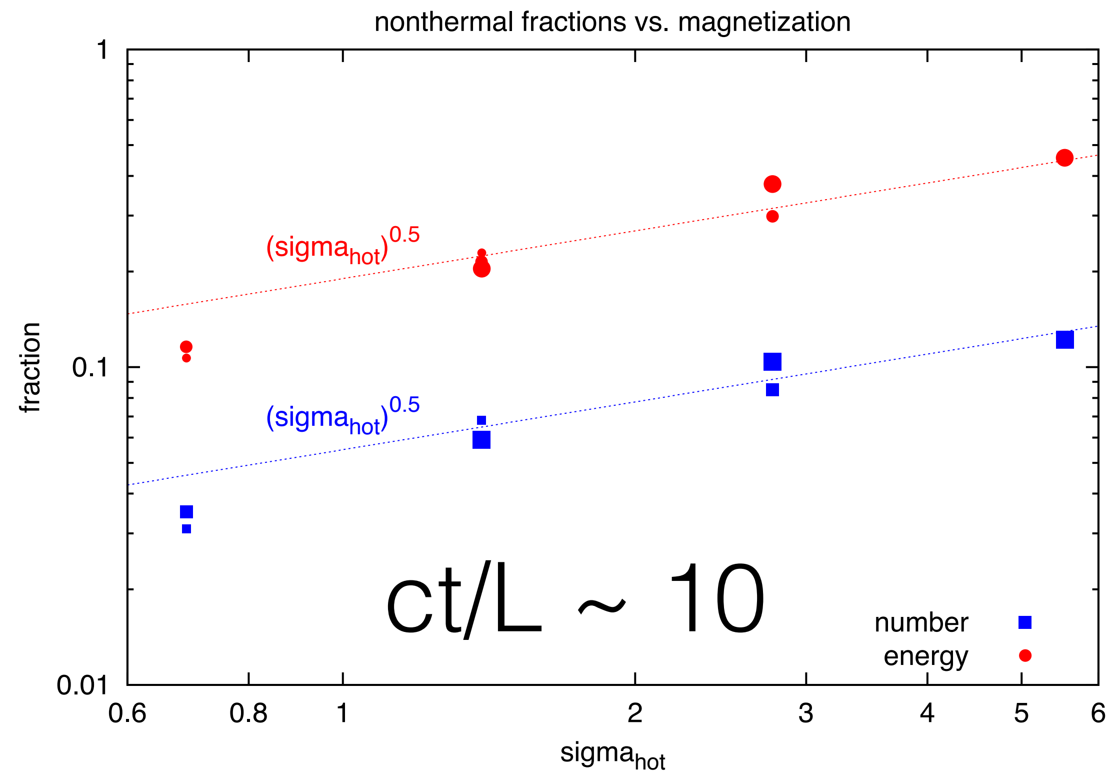


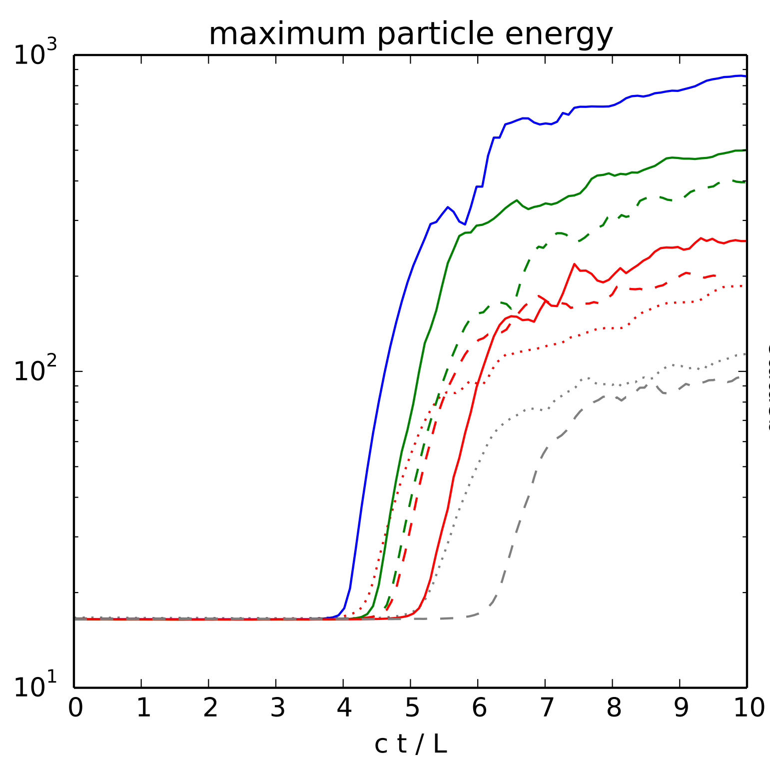
high-energy bump

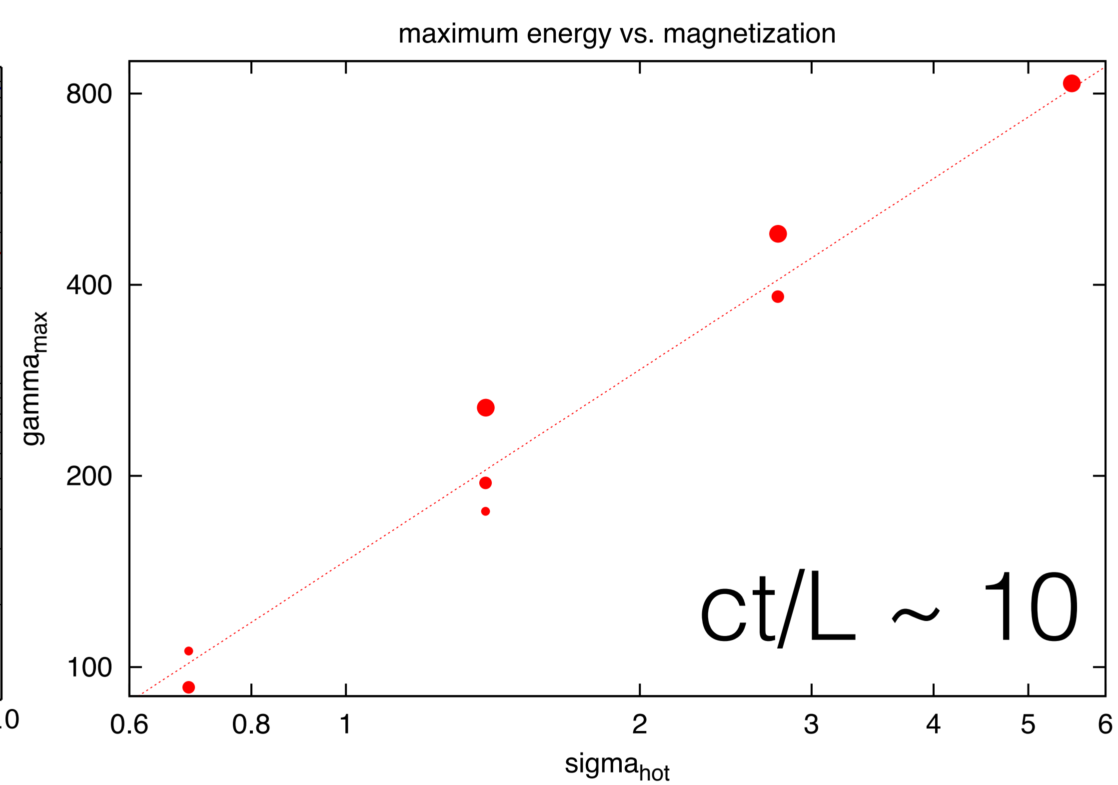
- particle number and energy fraction beyond the Maxwellian component
- both fractions systematically increase with the magnetization





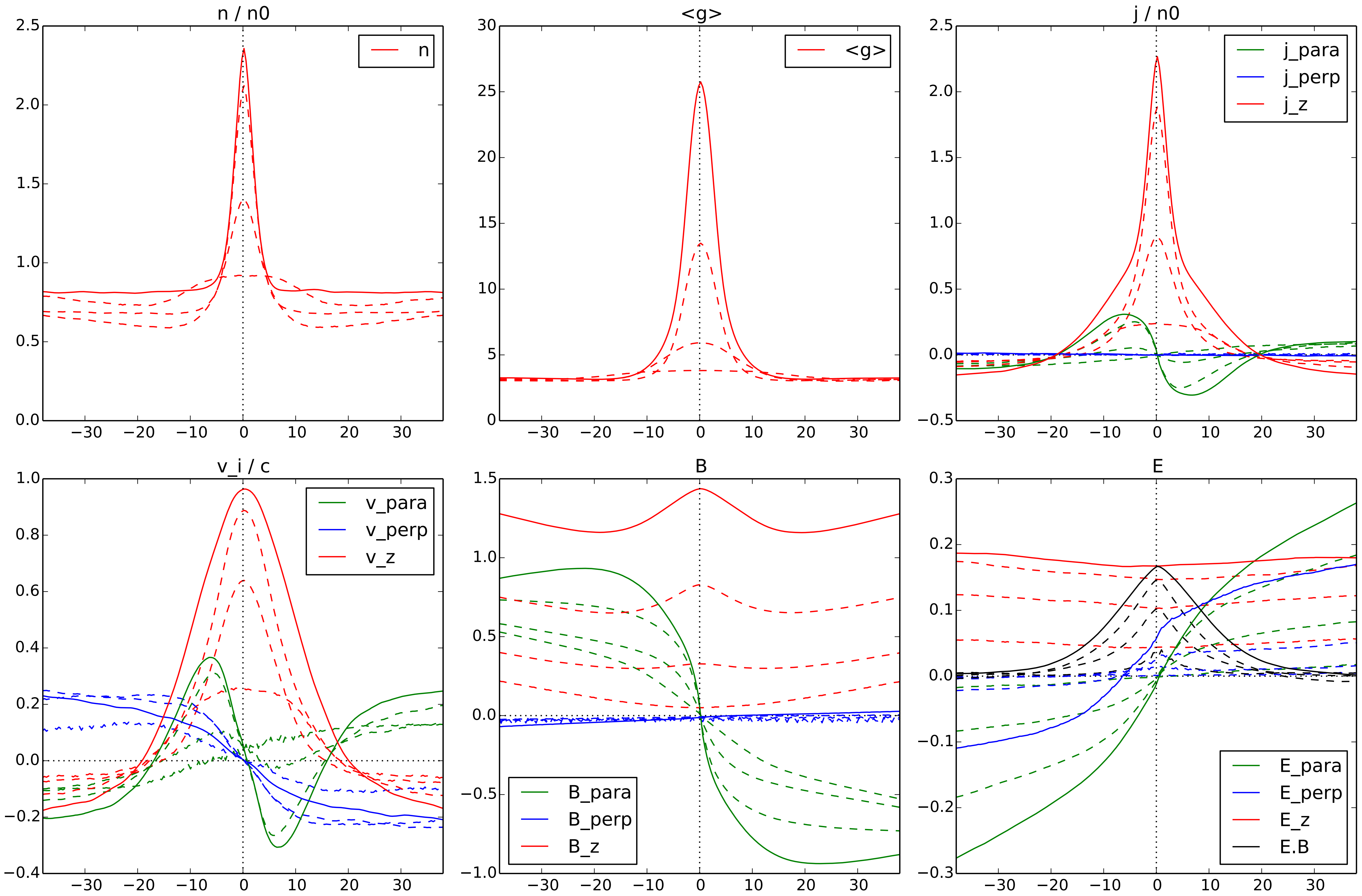






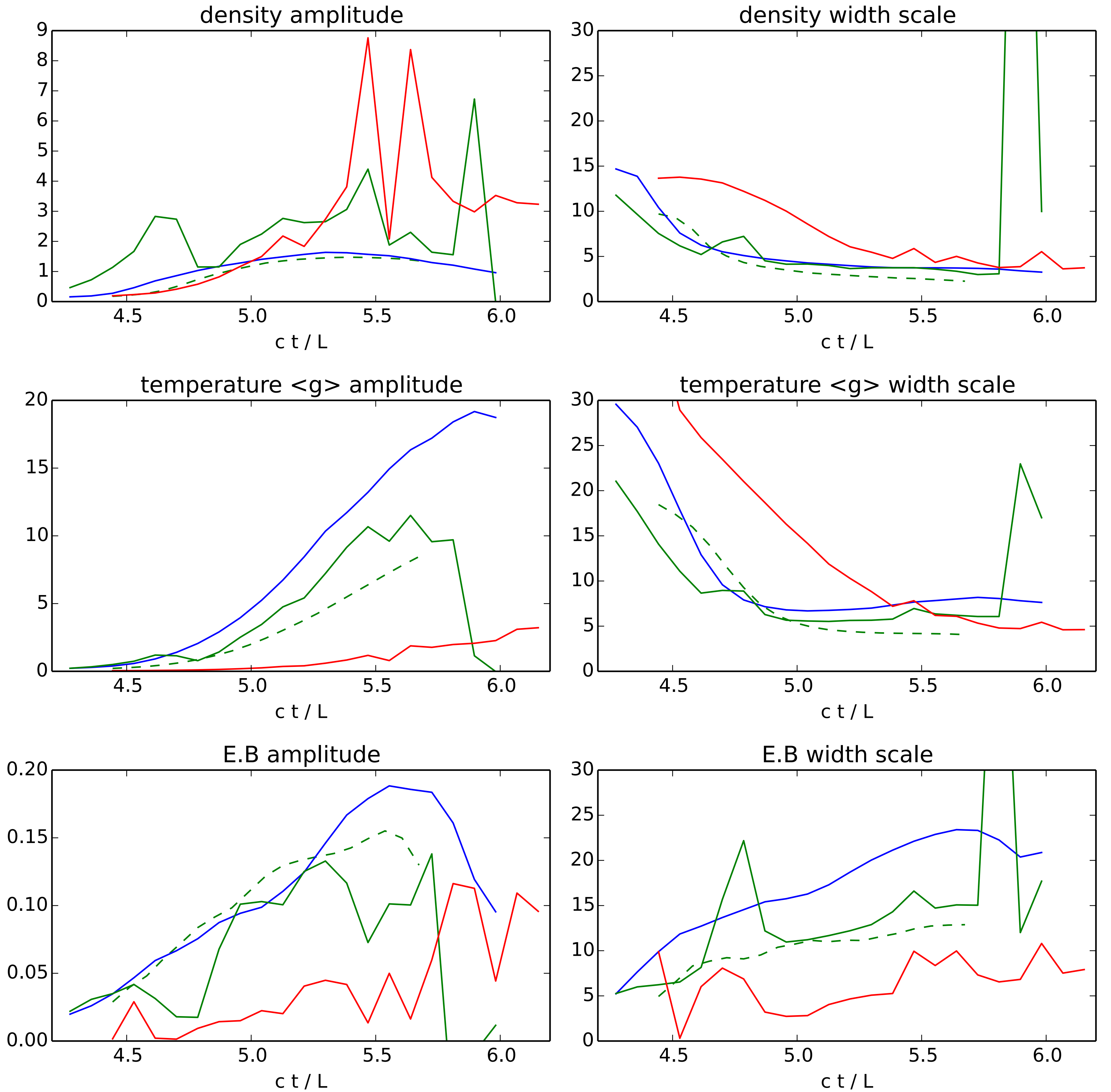
- maximum particle energy measured at $u^2 N(u) = 10^{-3}$

structure of current layers



evolution of current layers

- density width scale consistent with the skin-depth
- E.B width scale consistent with the gyro radius
- E.B volume increasing with the magnetization



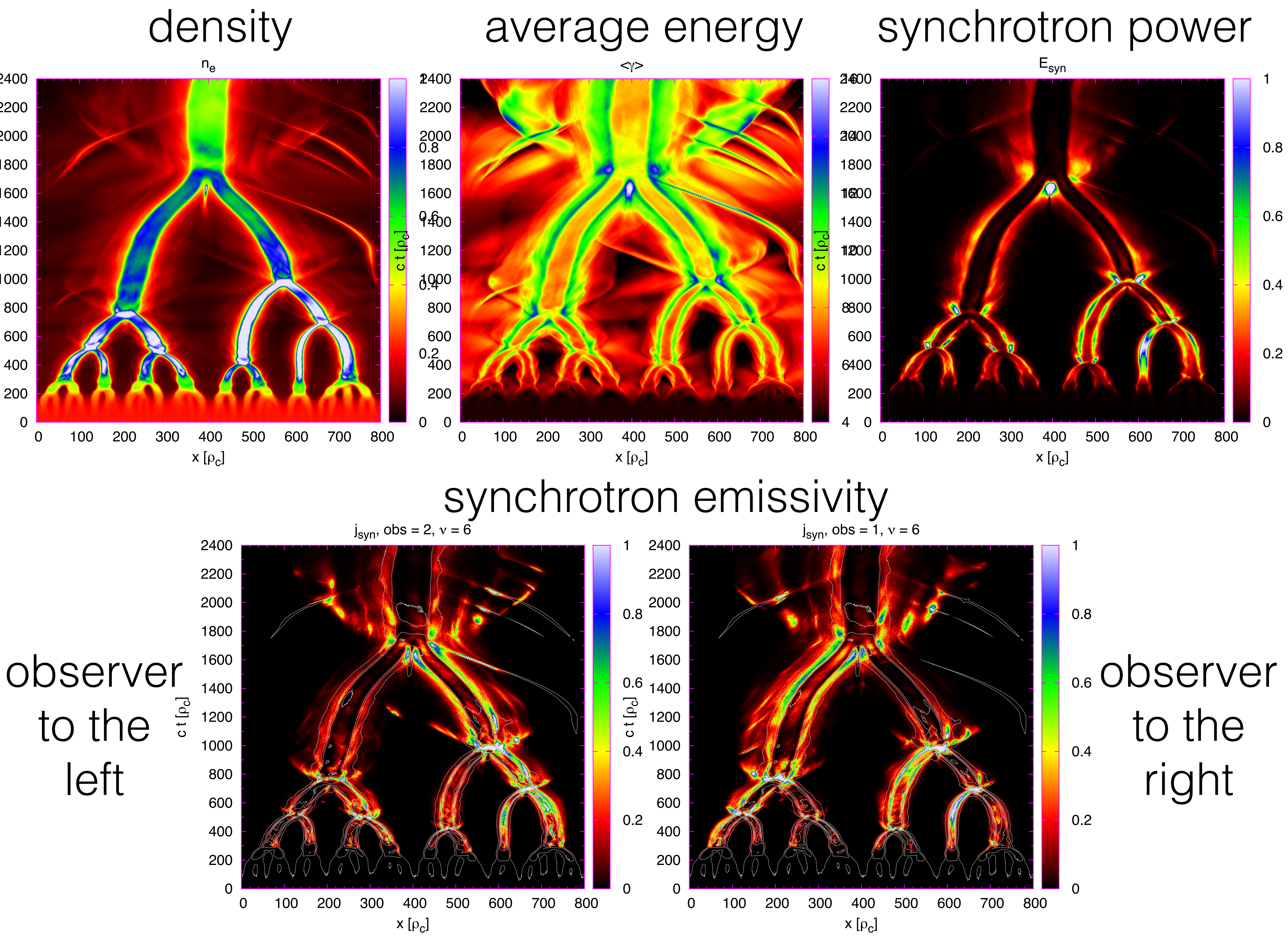
summary: “ABC” reconnection

- **particle acceleration**
  softer power laws for given σ
  direct acceleration by reconnection E-field

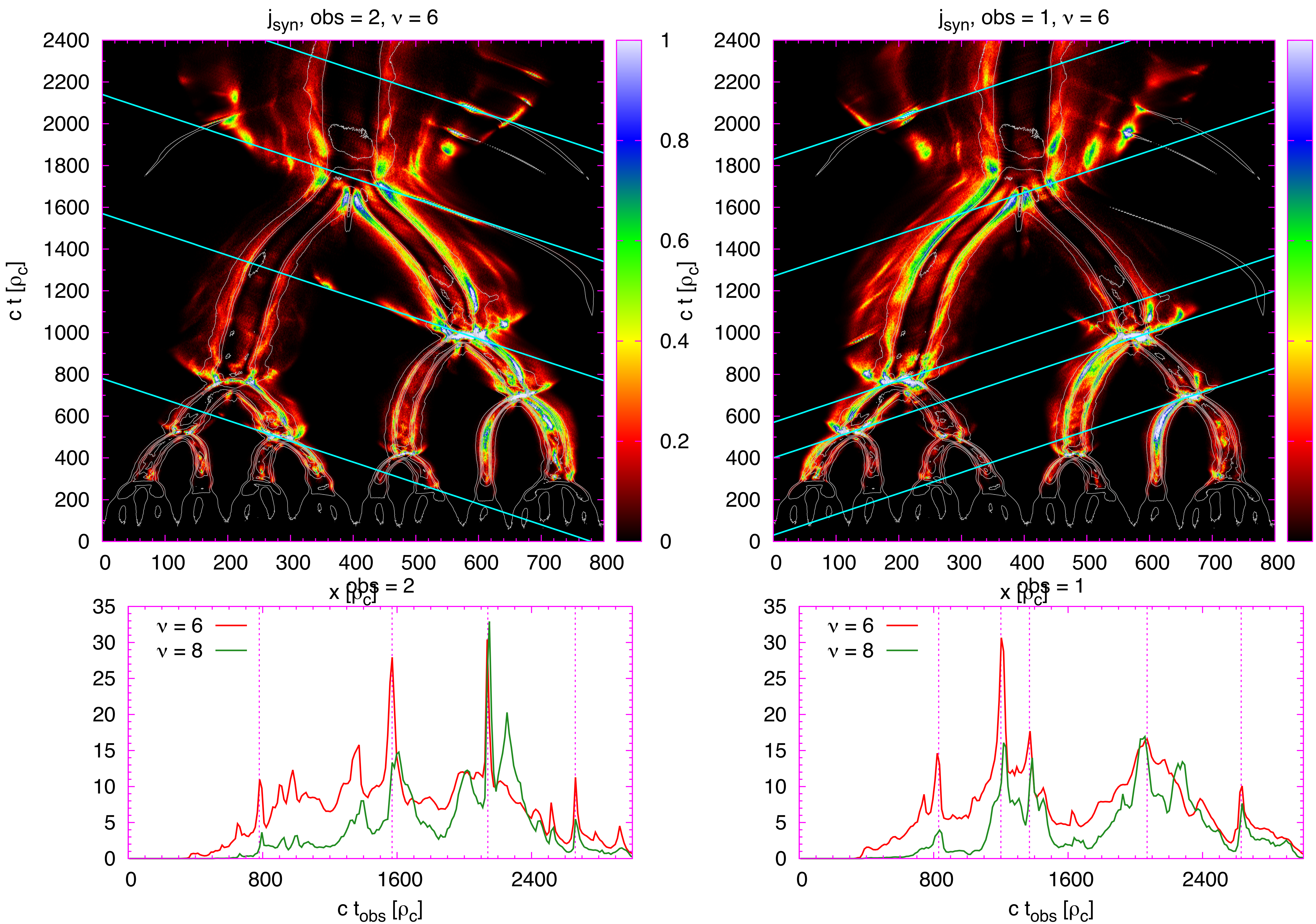
- **problem setup**
  dynamically evolving current layer
  mild tearing
  σ limited by L/ρ_0 (volumetric currents)

radiative signatures of relativistic reconnection

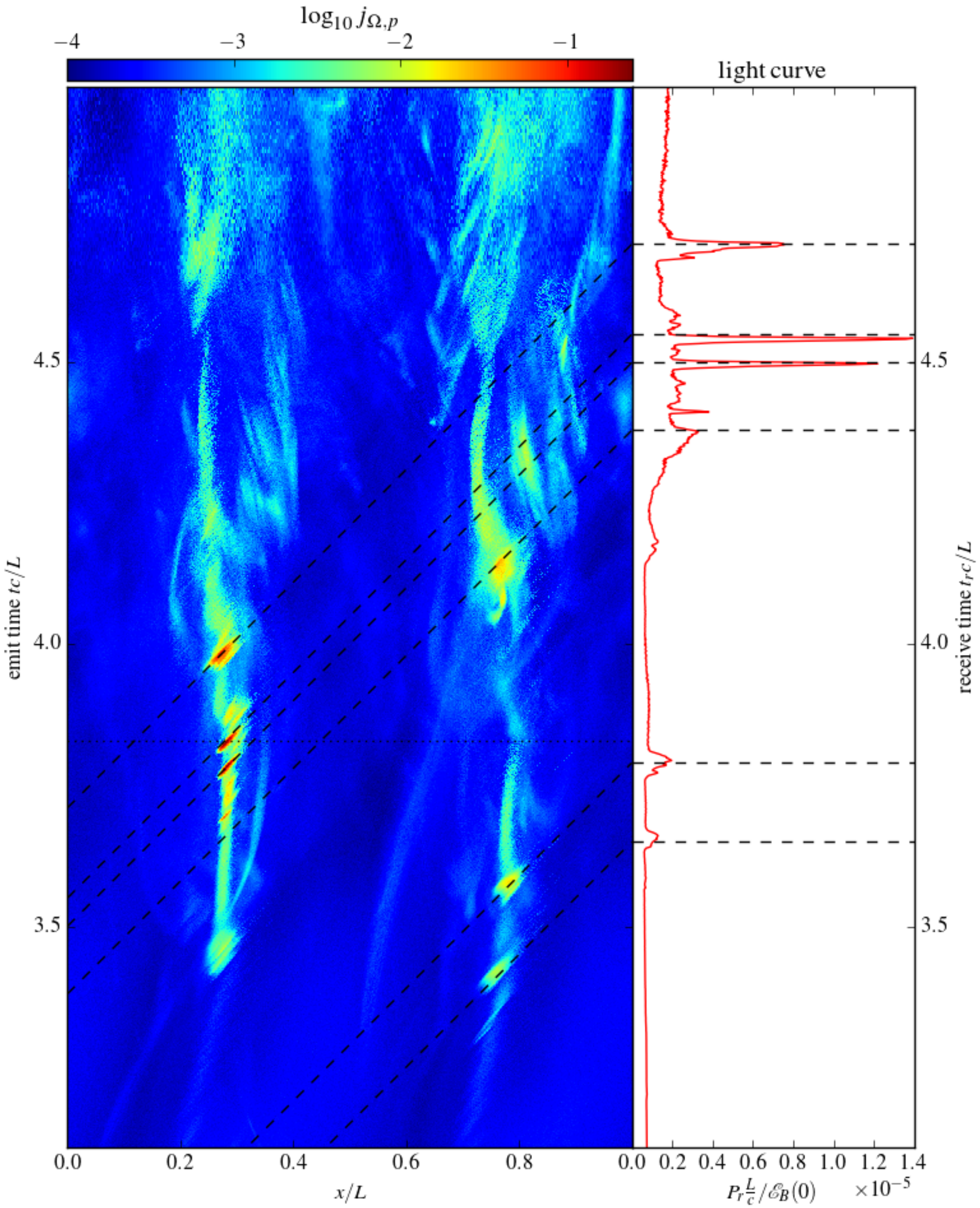
Yuan, KN, Zrake, East & Blandford (2016, arXiv:1604.03179)

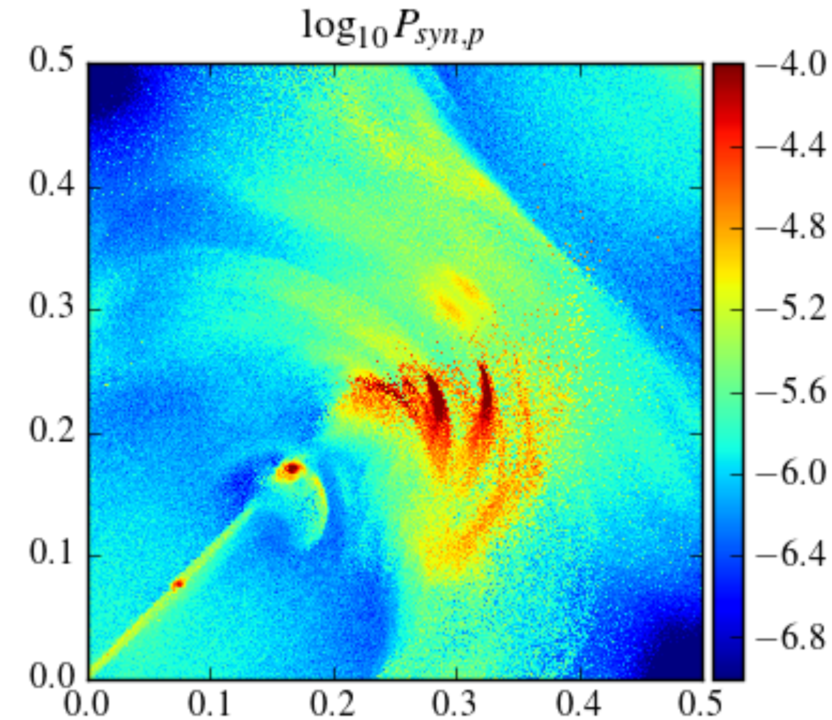

density
average energy
synchrotron power
n_e
<γ>
E_syn
c t [ρ_c]
x [ρ_c]
synchrotron emissivity
j_syn, obs = 2, ν = 6
j_syn, obs = 1, ν = 6
observer to the left
observer to the right

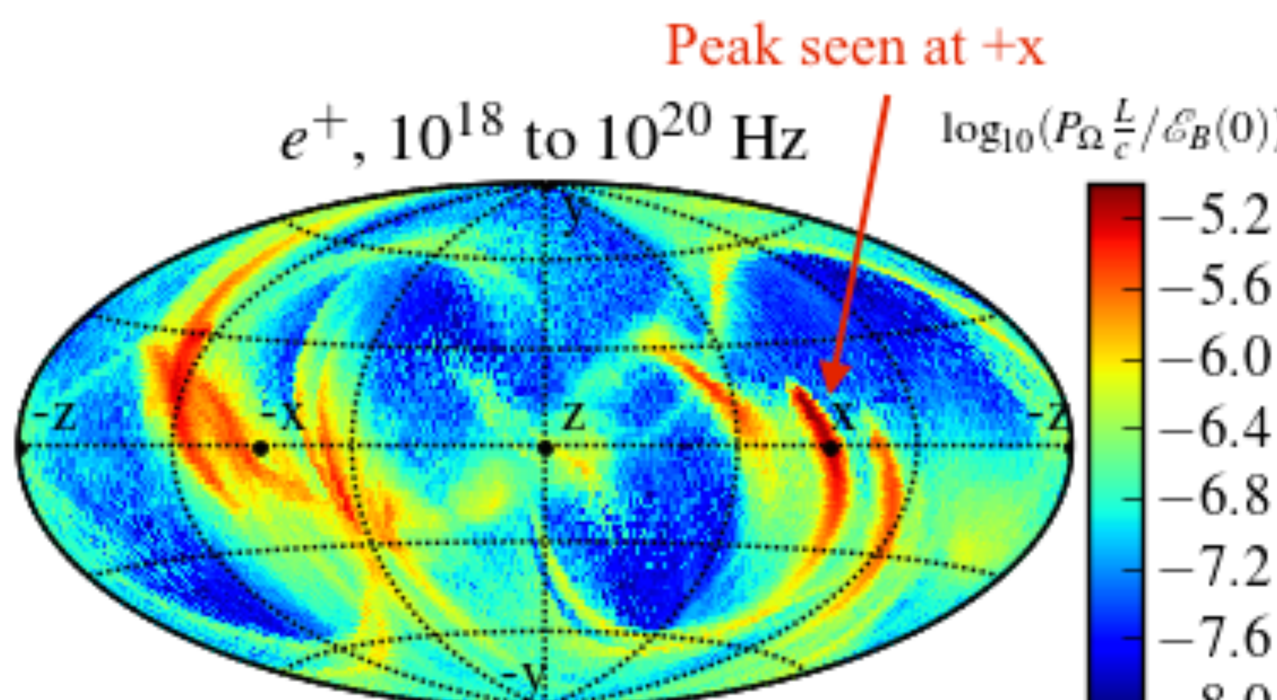
observed light curves



synchrotron signatures of ABC reconnection (Yuan et al.)

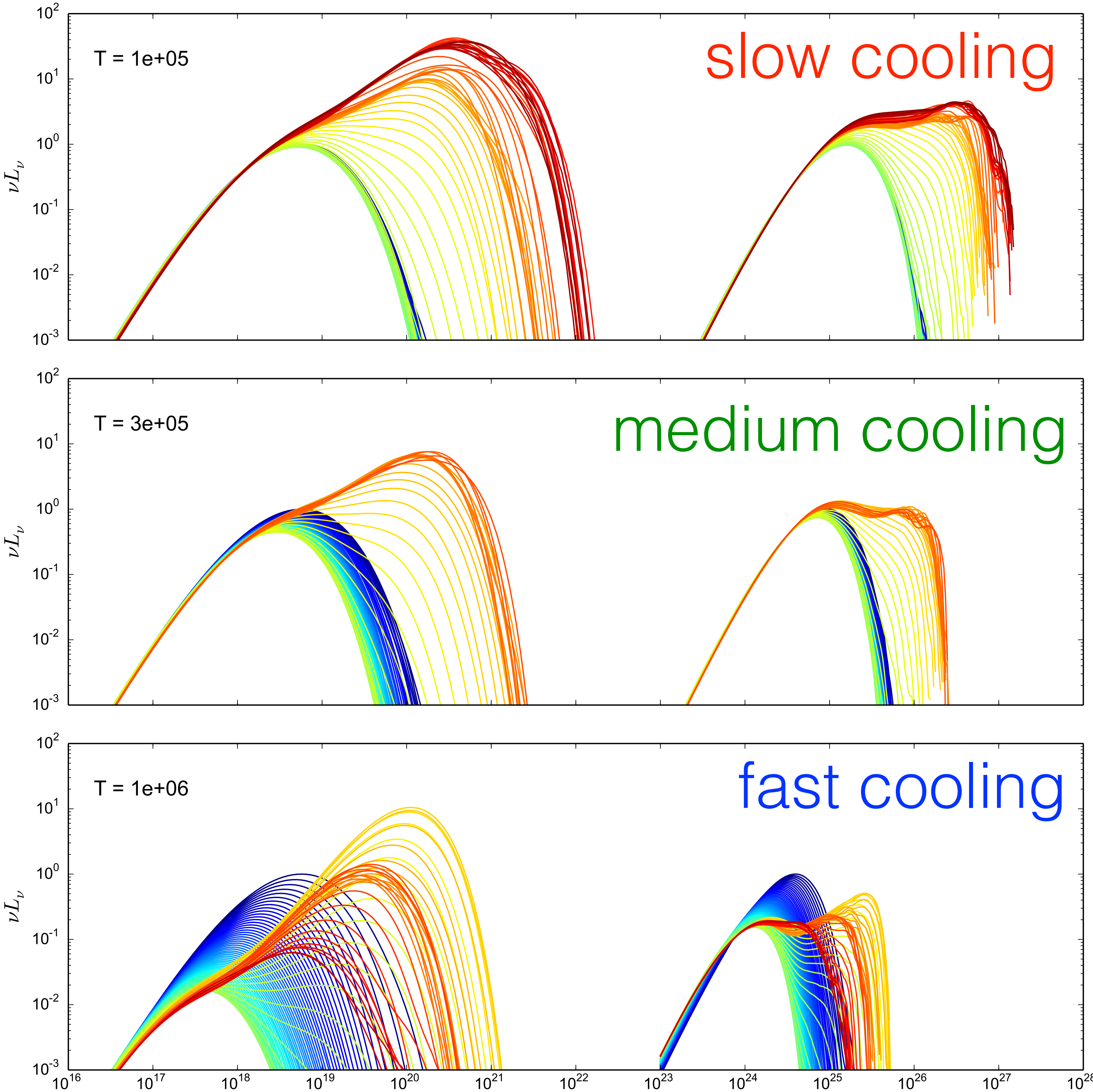


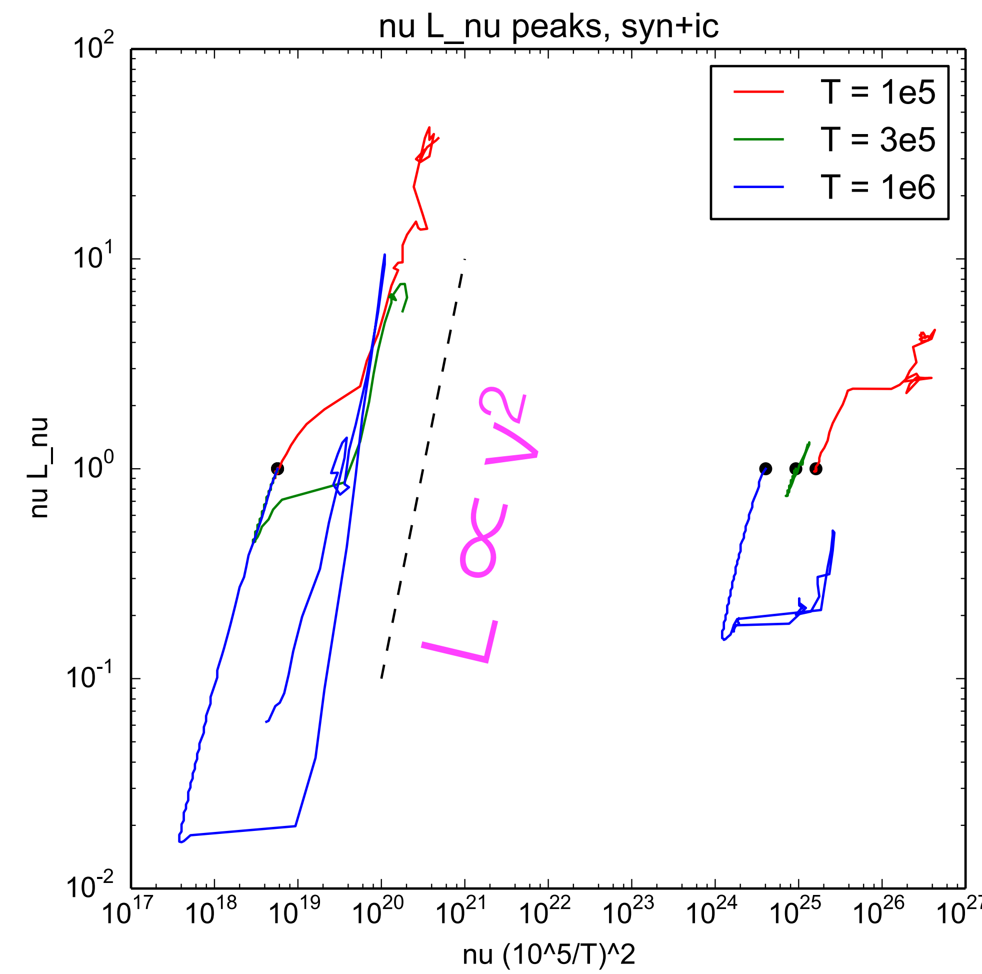


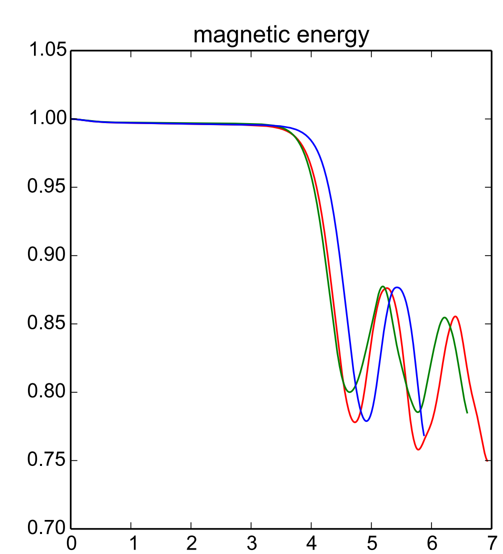


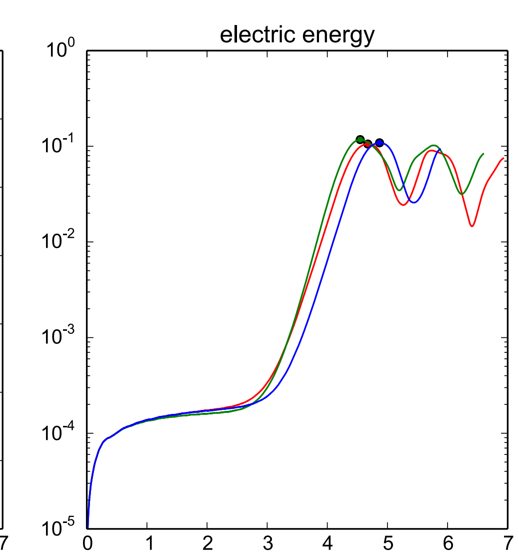
synchrotron and inverse Compton

(with M. Chruślińska, PRELIMINARY)

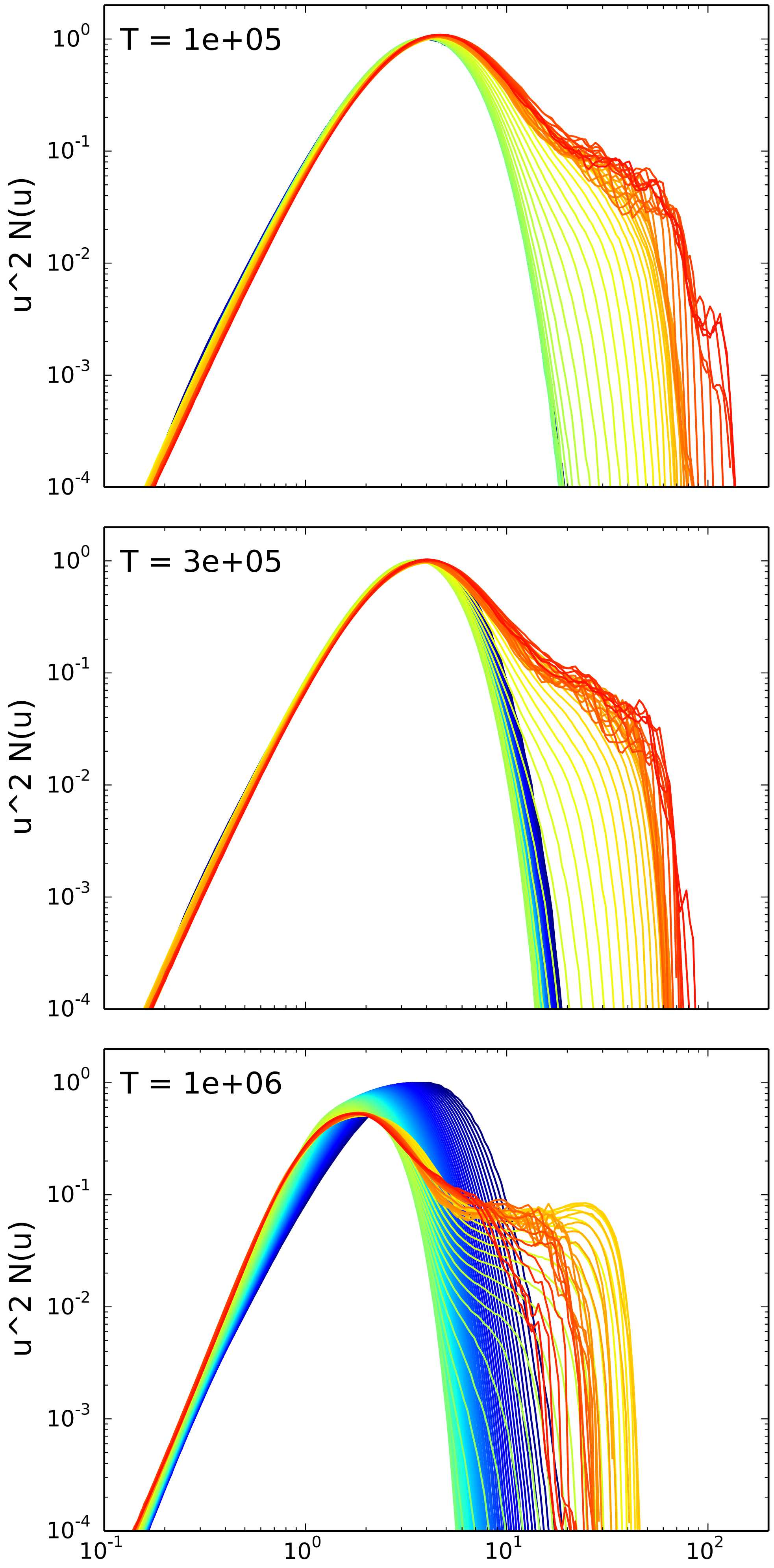


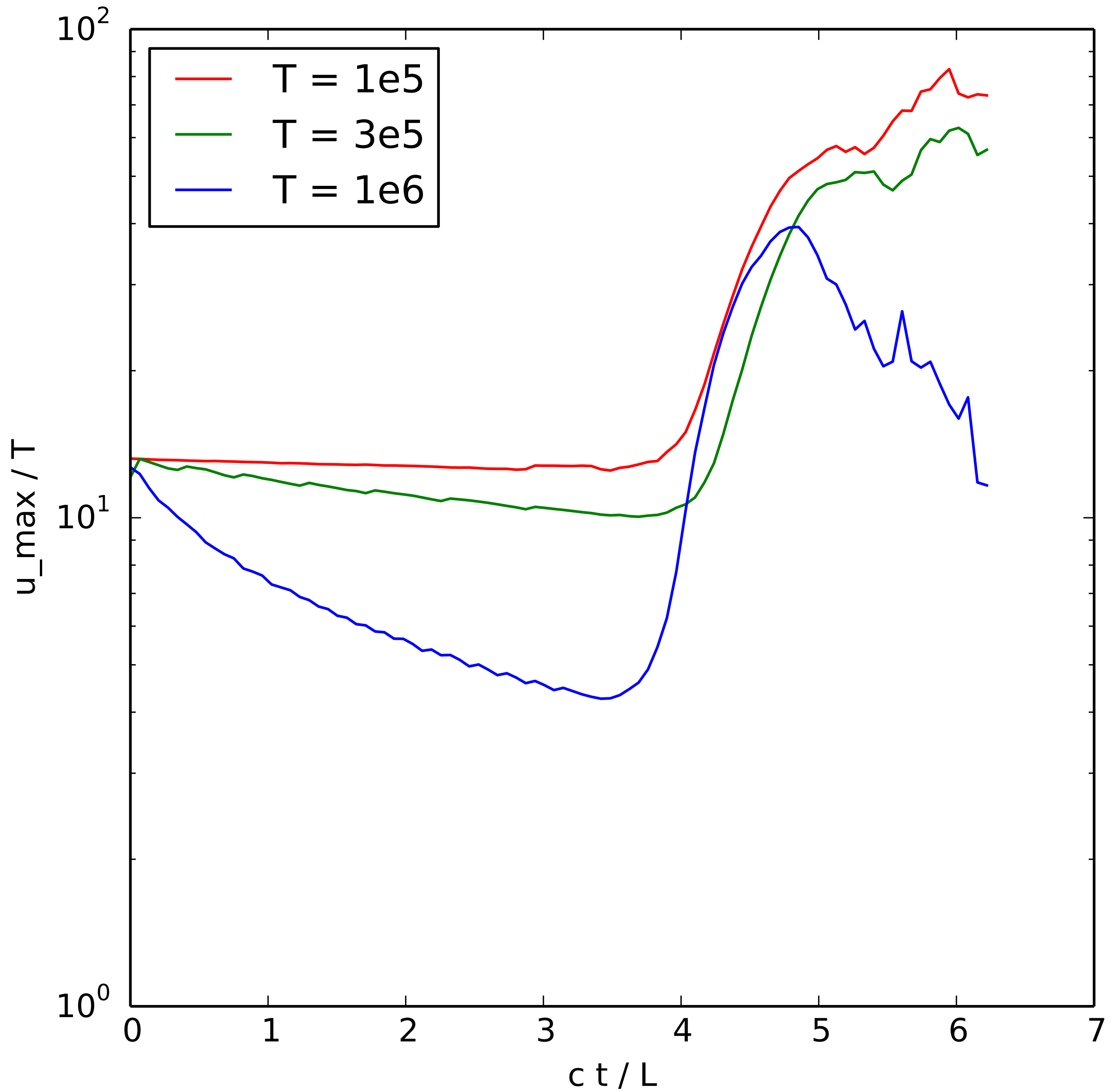






particle energy distributions

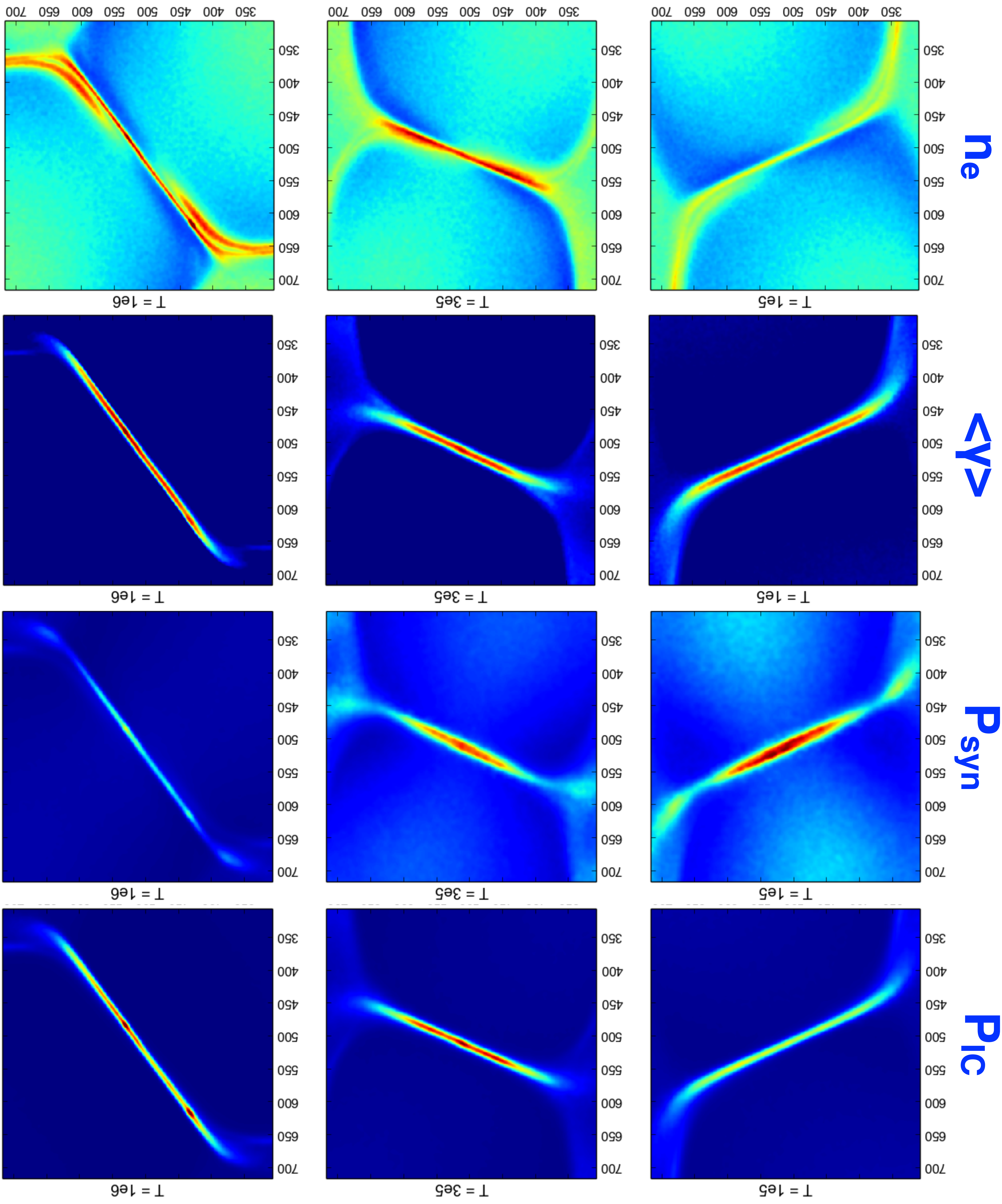




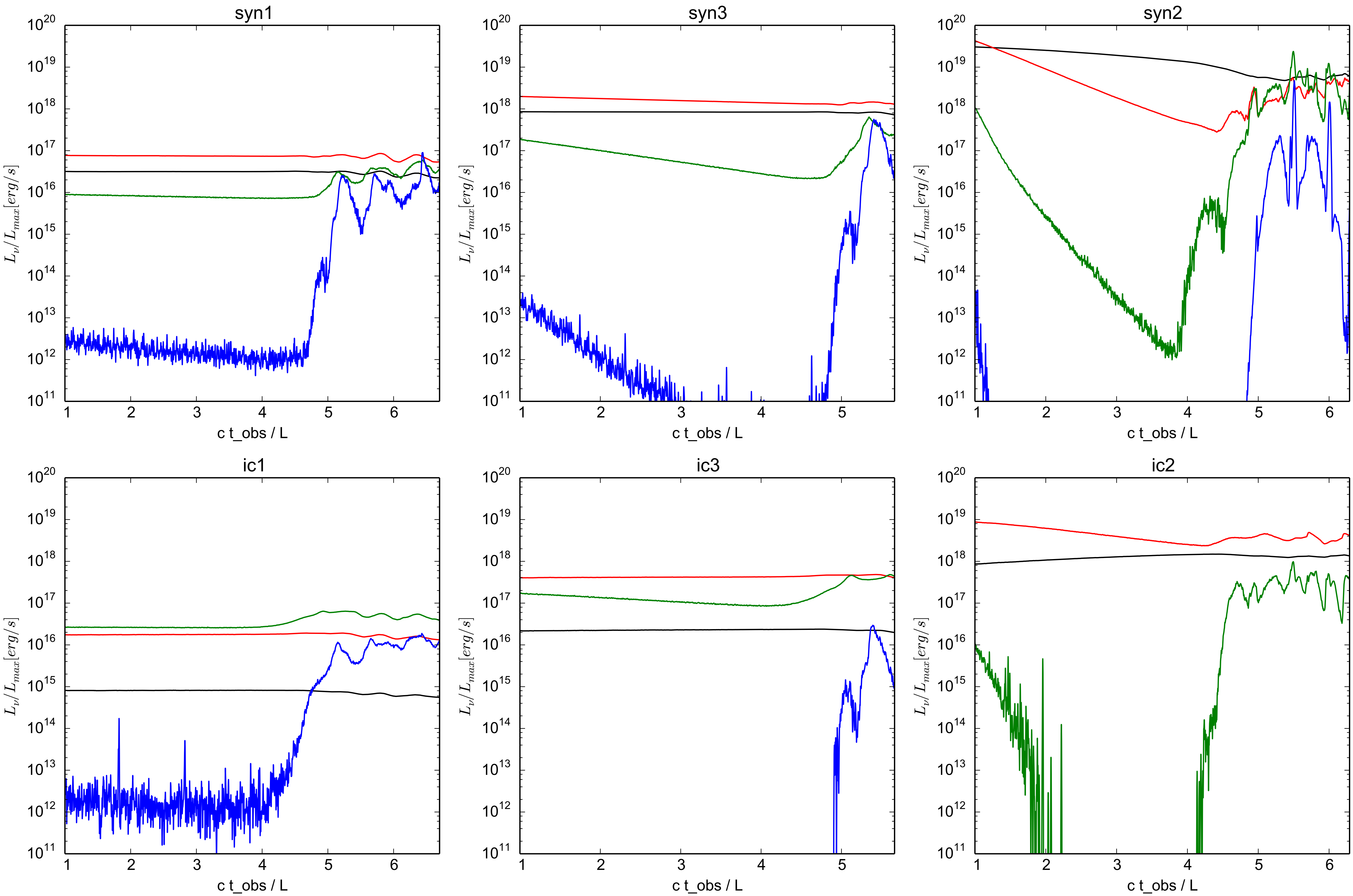
linear instability
saturation moment

cooling

PRELIMINARY



syn+ic light curves (PRELIMINARY)



summary: radiative signatures

- **rapid variability**
  t_{obs} ~ (0.01-0.1) L/c
  allows to relax causality constraints
  both kinetic beaming (sweeping anisotropic beams) and spatial bunching are important
  Doppler beaming insignificant
  mild tearing important for modulating radiation

- **radiative efficiency?**

- **dynamical effects**
  radiation reaction affects only high-energy particles
  current layer compression

conclusions

- exciting times for studying relativistic collisionless reconnection
- reconnection is efficient particle accelerator, however, hard power laws are not optimal for astrophysical applications
- reconnection naturally produces rapid variability of synchrotron radiation
- details depend on the setup (Harris, ABC, etc), which is the most realistic initial configuration?