theory of acceleration of particles

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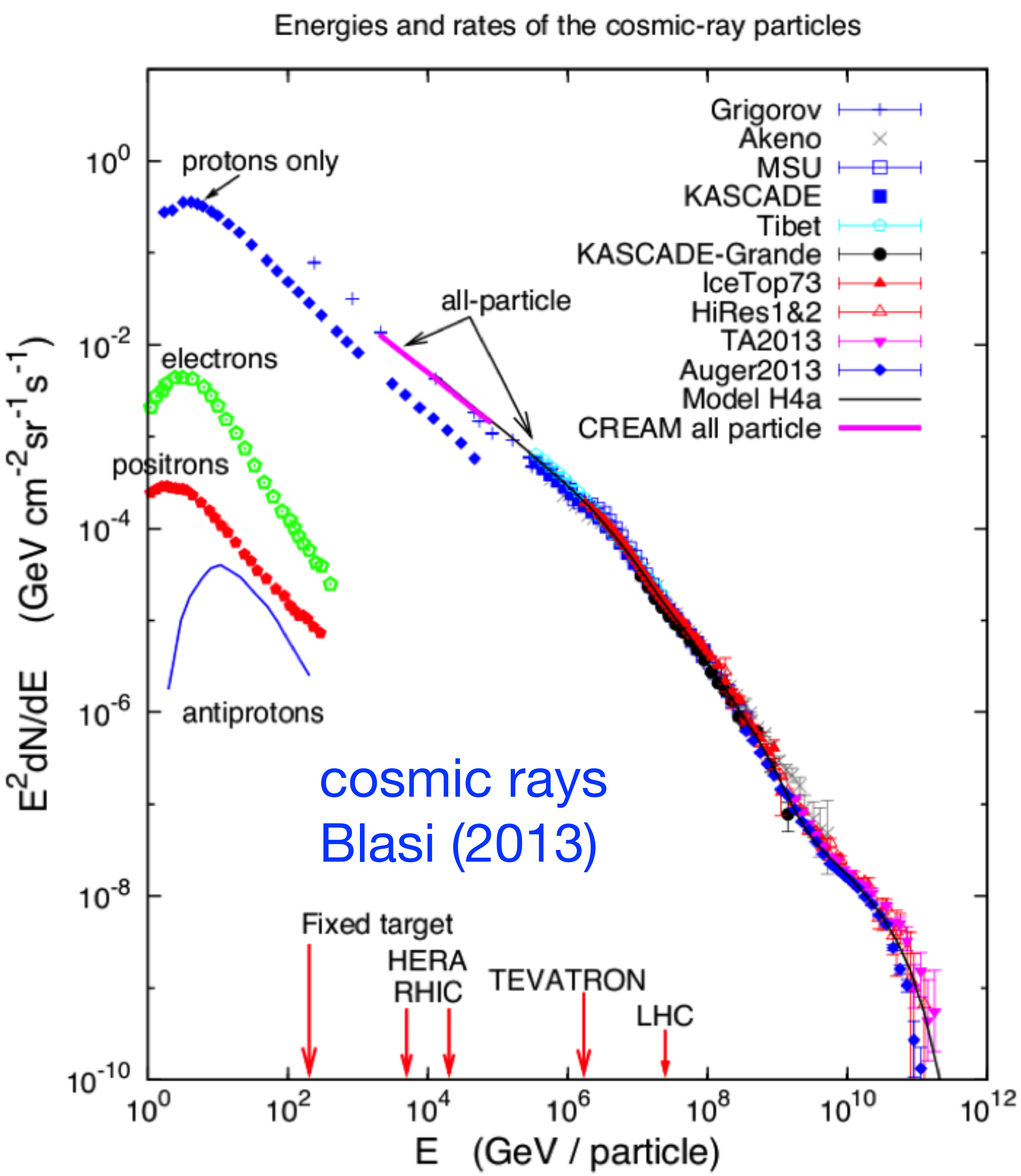
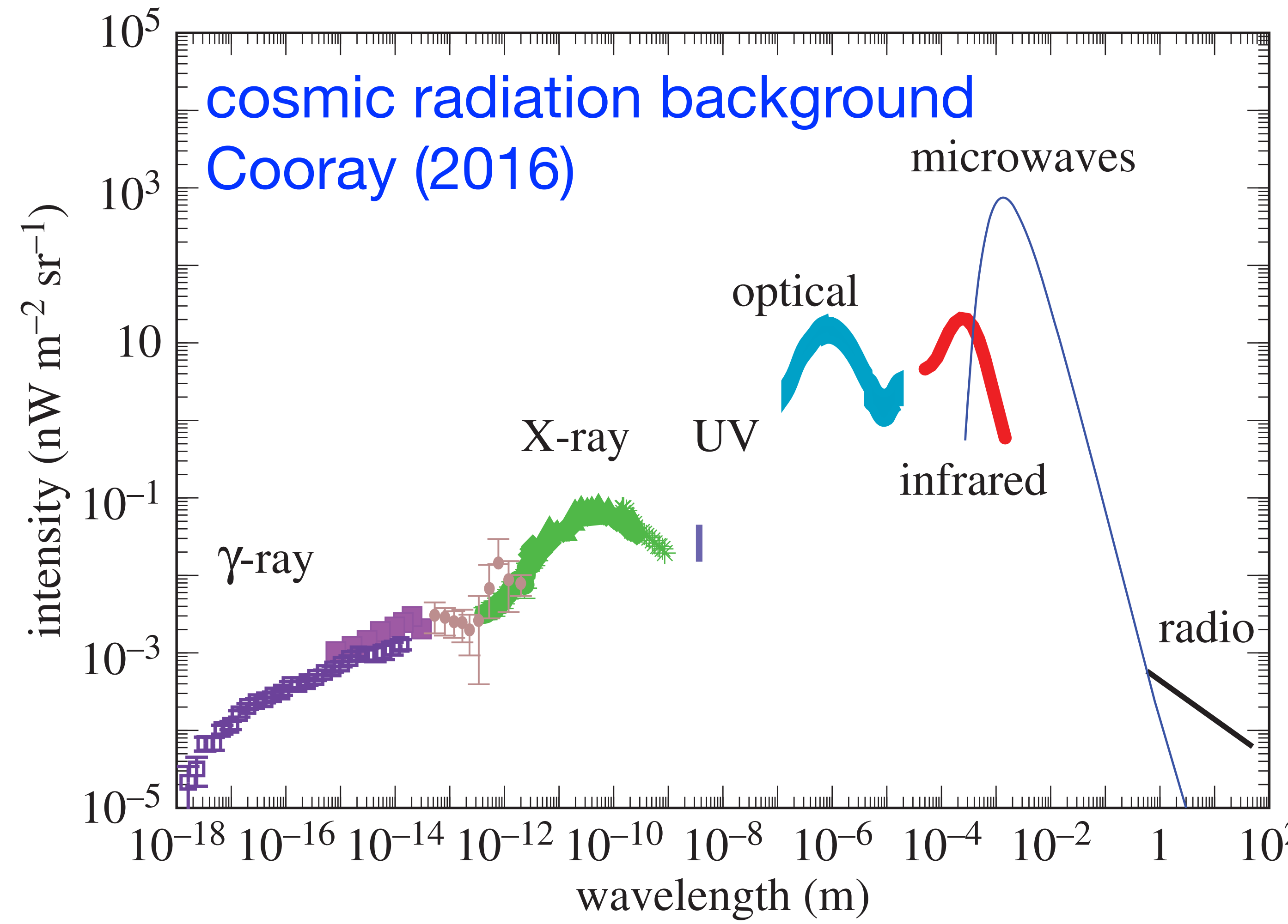
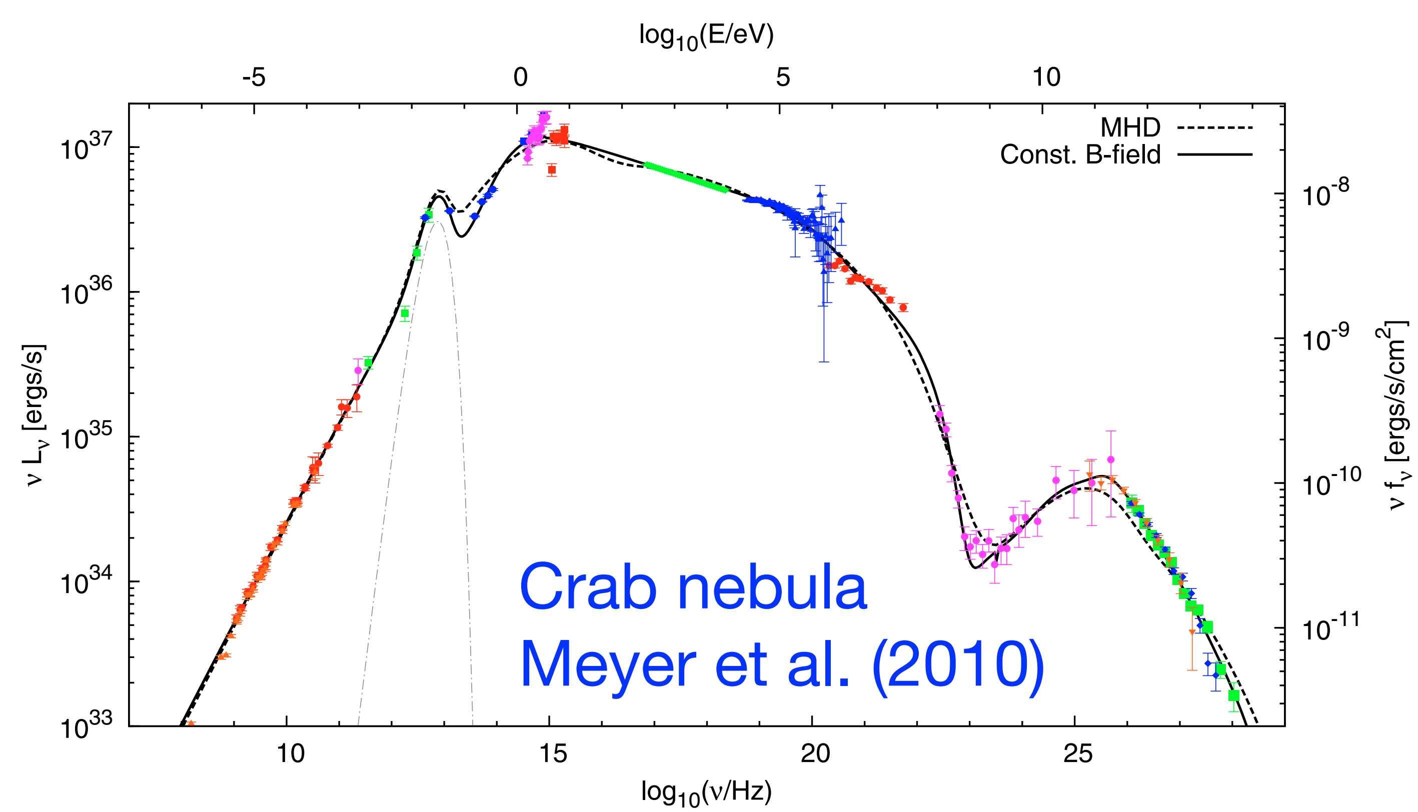
astrophysical motivation

cosmic rays, solar flares, planetary magnetospheres, supernova remnants, pulsars, X-ray binaries, gamma-ray bursts (GRB), active galaxies (AGN), inter-stellar/galactic medium, etc







non-thermal particle acceleration: general remarks

- power-law energy distributions -> severe departure from thermal equilibrium -> very long mean free paths -> collisionless gas (Coulomb collisions negligible)

- charged particles gain energy from electric fields -> (completely) ionized gas

- large-scale electric fields very rare (pulsars) -> convergent magnetized flows; departure from ideal MHD

- electron-ion gas in most cases; electron-positron pairs expected in most extreme environments (pulsars, AGN)

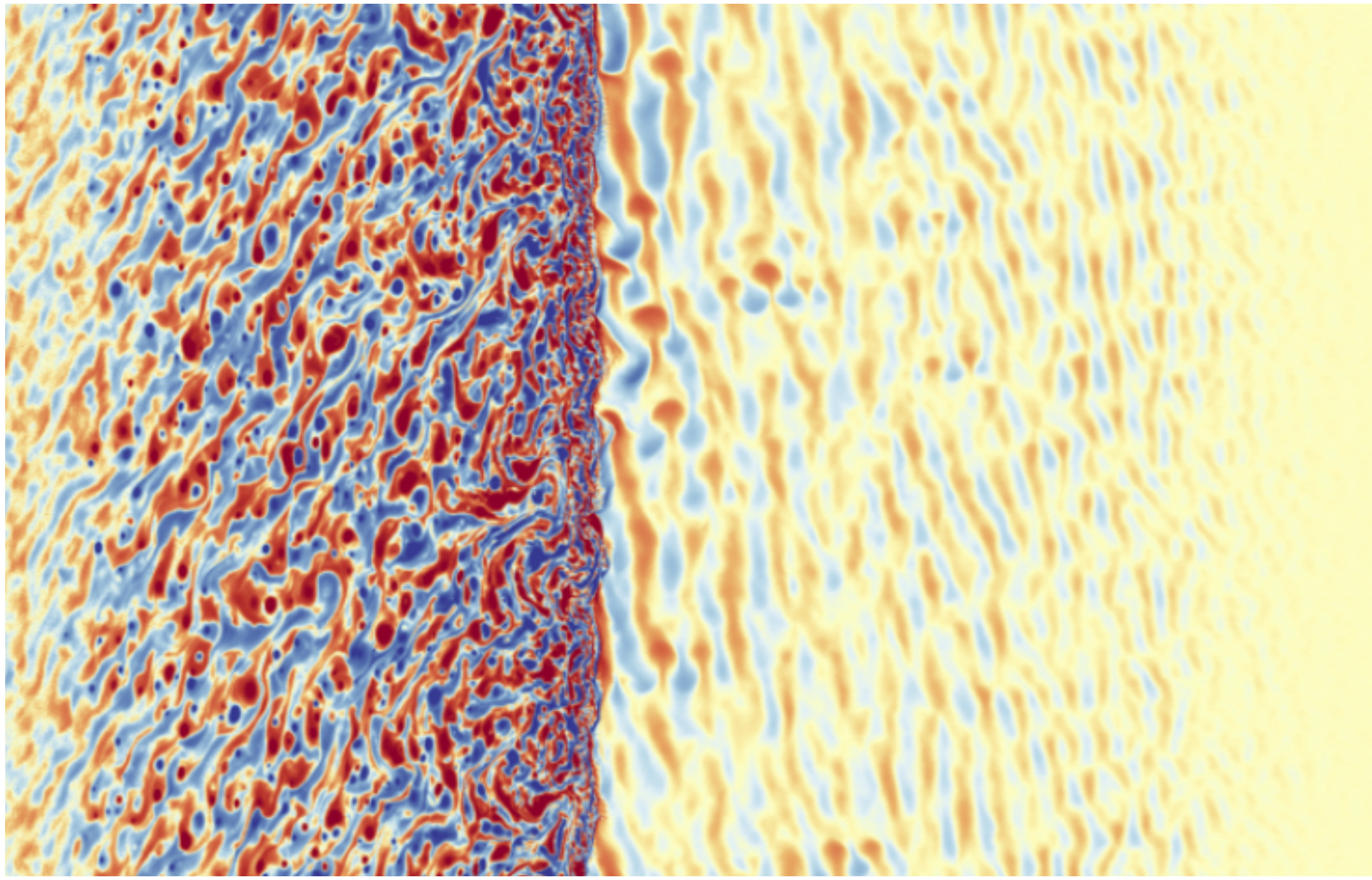
- particle-in-cell (PIC) algorithm for kinetic numerical simulations

particle acceleration in (relativistic) collisionless plasmas

1. **shock waves**

2. magnetic reconnection

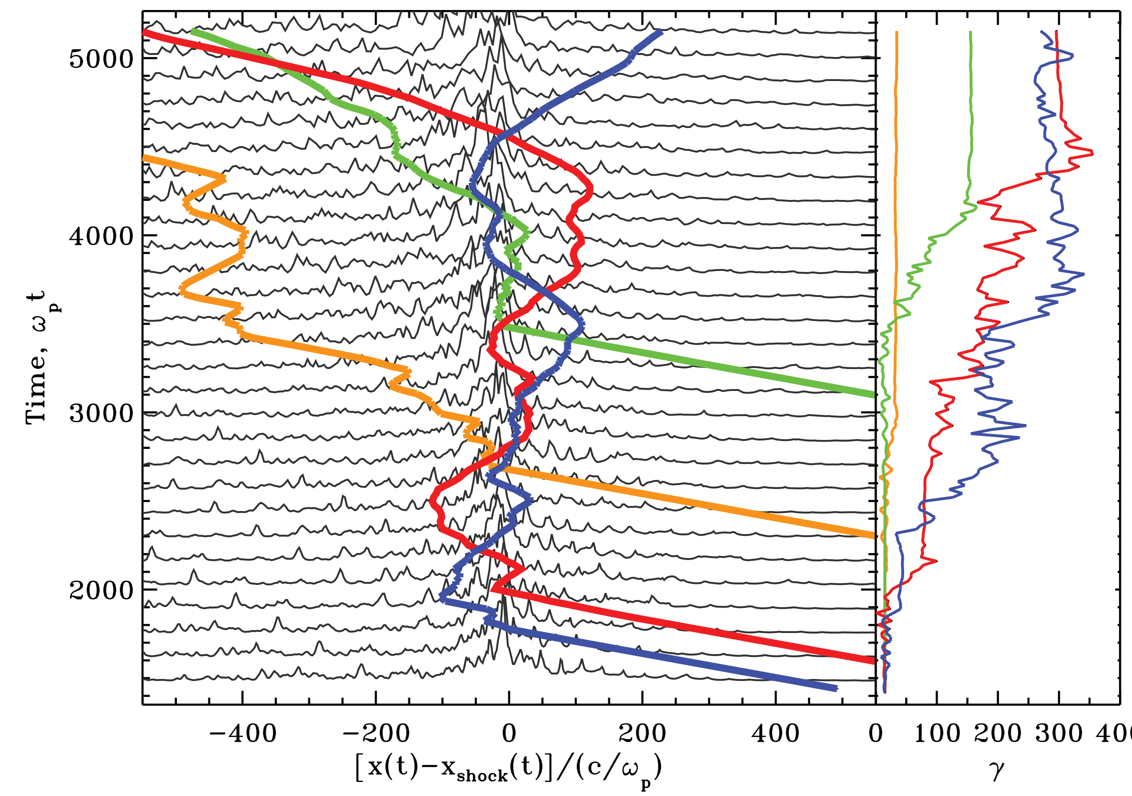
3. turbulence



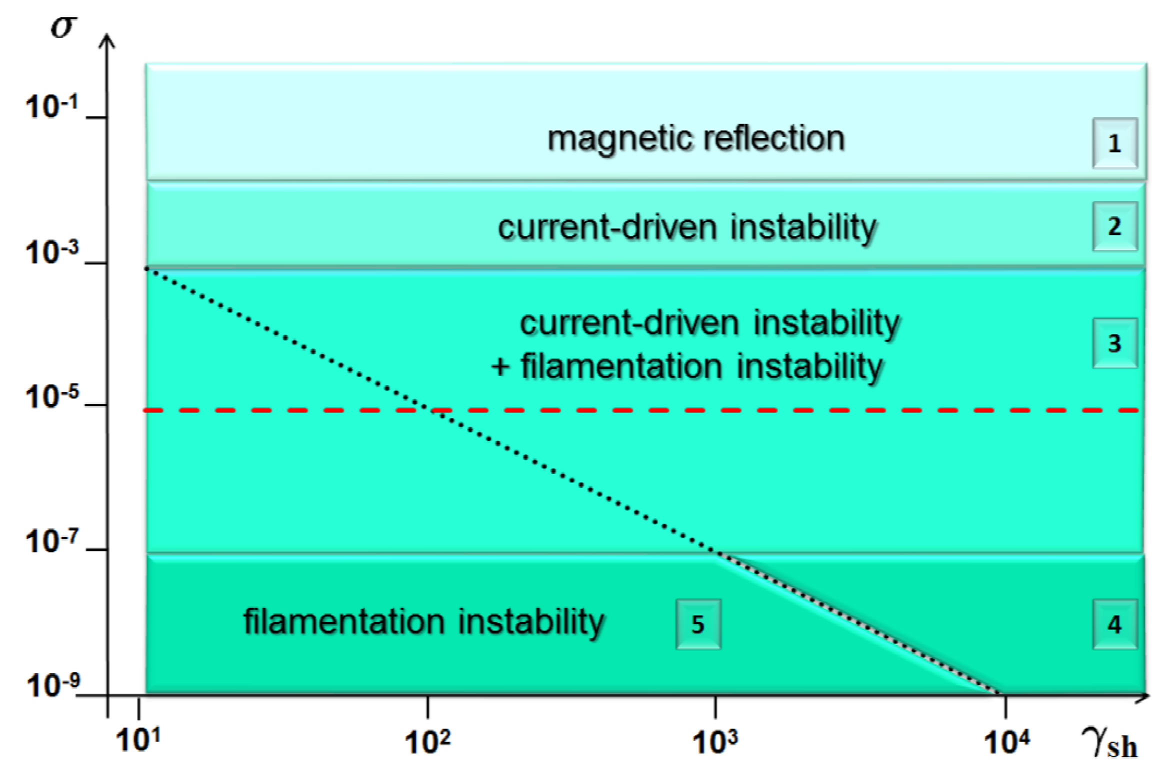
Crumley, Caprioli, Markoff & Spitkovsky (2019)

particle acceleration in (relativistic) shock waves

Spitkovsky (2008)



- mechanisms:
  - diffusive shock acceleration (DSA; 1st order Fermi)
  - pre-acceleration of electrons:
    - shock drift acceleration (SDA)
    - shock surfing acceleration (SSA)
    - magnetic reconnection
    - whistler waves



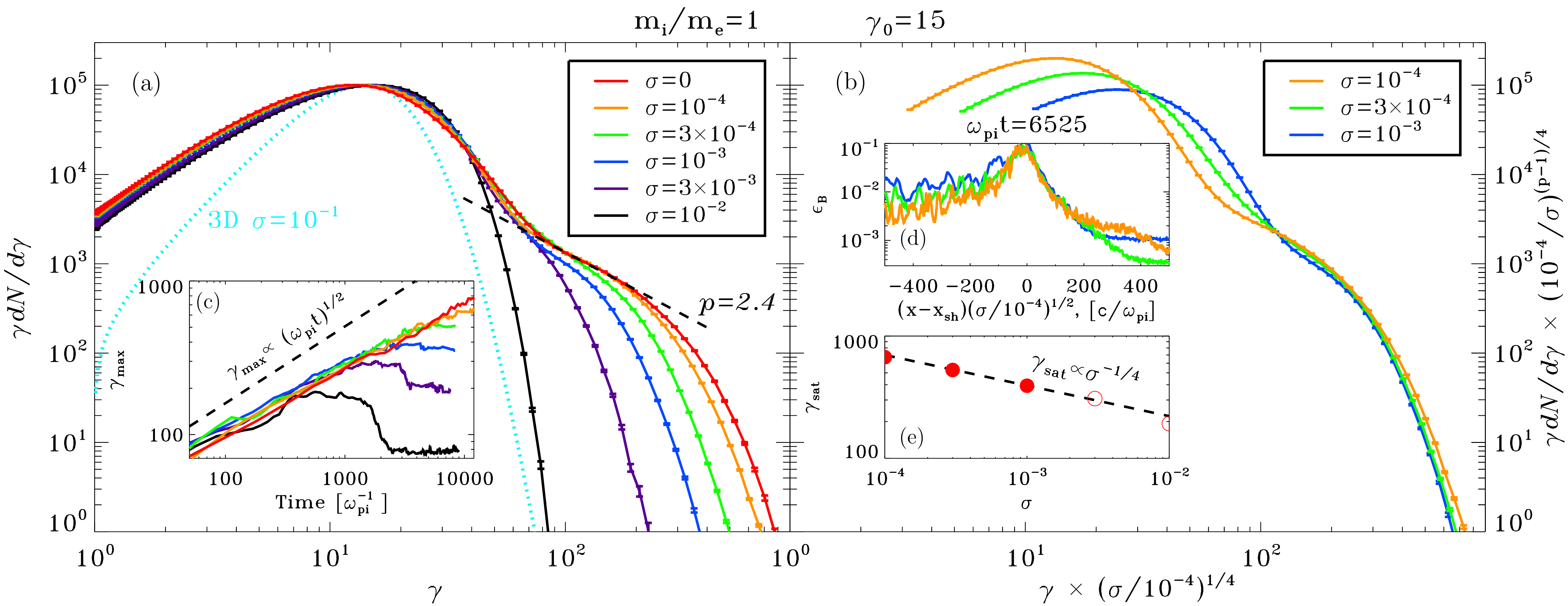
- plasma instabilities triggered by particles reflected from the shock front:
  - counter-streaming instabilities (Weibel/filamentation, Buneman)
  - current-driven instabilities (Bell)

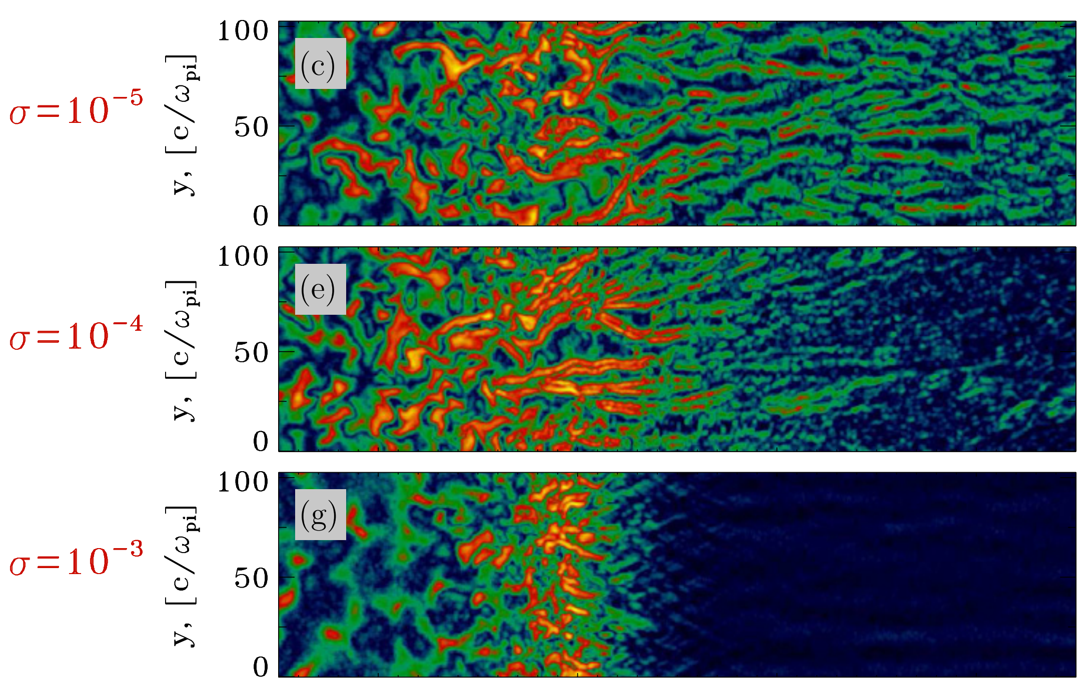
Pelletier et al. (2017)

PIC simulations of relativistic shocks

- Spitkovsky (2008) - unmagnetized pair plasma - efficient DSA ($p = 2.4$) acceleration mediated by Weibel instability
- Sironi & Spitkovsky (2009) - magnetized pair plasma - efficient DSA or SDA acceleration ($p = 2.3 - 2.8$) for subluminal shocks
- Sironi & Spitkovsky (2011) - magnetized electron-ion plasma - efficient acceleration of ions ($p = 2.1$) for subluminal shocks, inefficient acceleration of electrons ($p = 3.5$)
- Sironi, Spitkovsky & Arons (2013) - weakly magnetized perpendicular shocks in electron-ion plasma - limits for maximum particle energy

PIC simulations of weakly magnetized relativistic perpendicular shocks





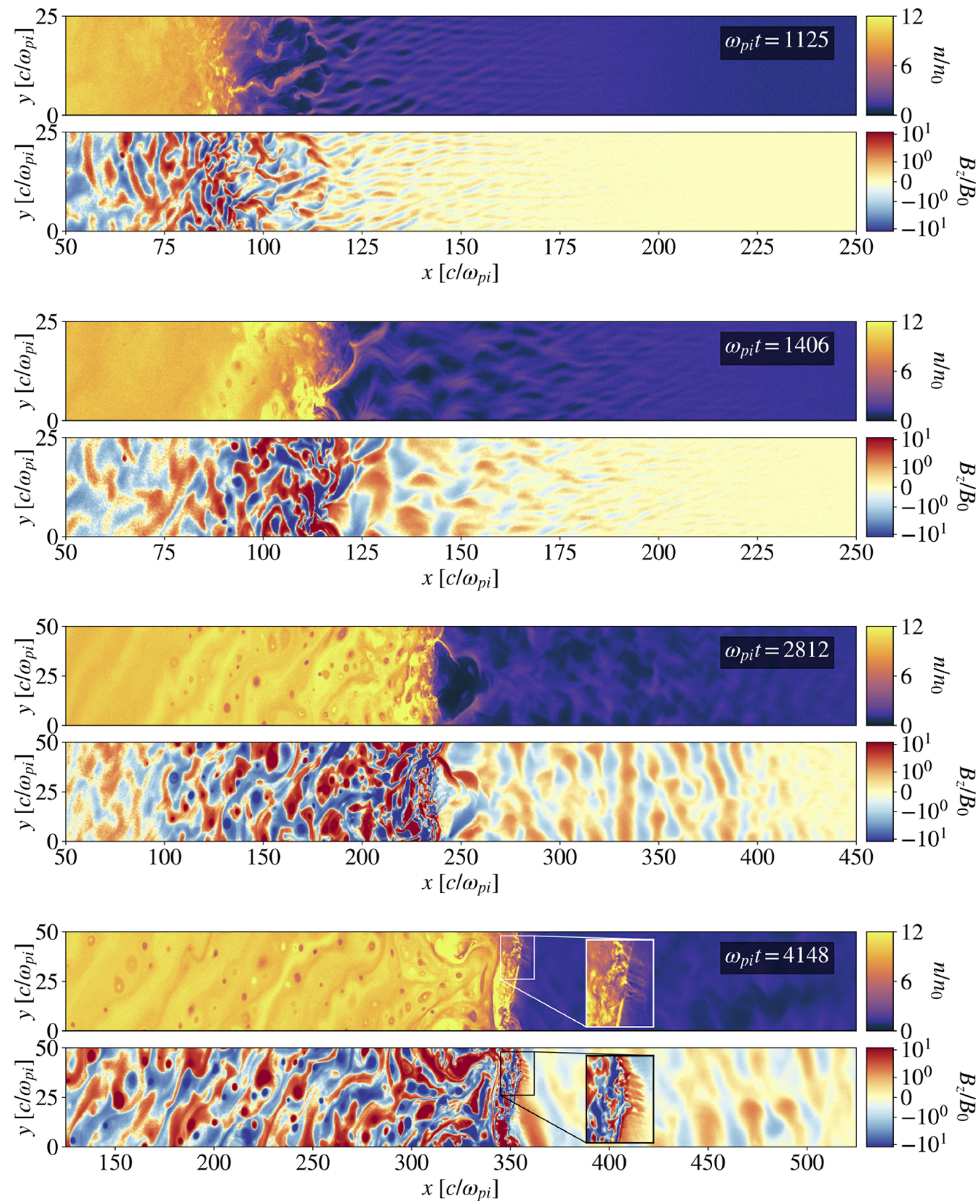
- maximum energy ~ $t^{1/2}$
- saturation energy ~ $\sigma^{-1/4}$
- magnetization limits the range of Weibel filaments

Sironi, Spitkovsky & Arons (2013)

PIC simulations of mildly relativistic shocks

- increasing transverse size and simulation length enable more physical details

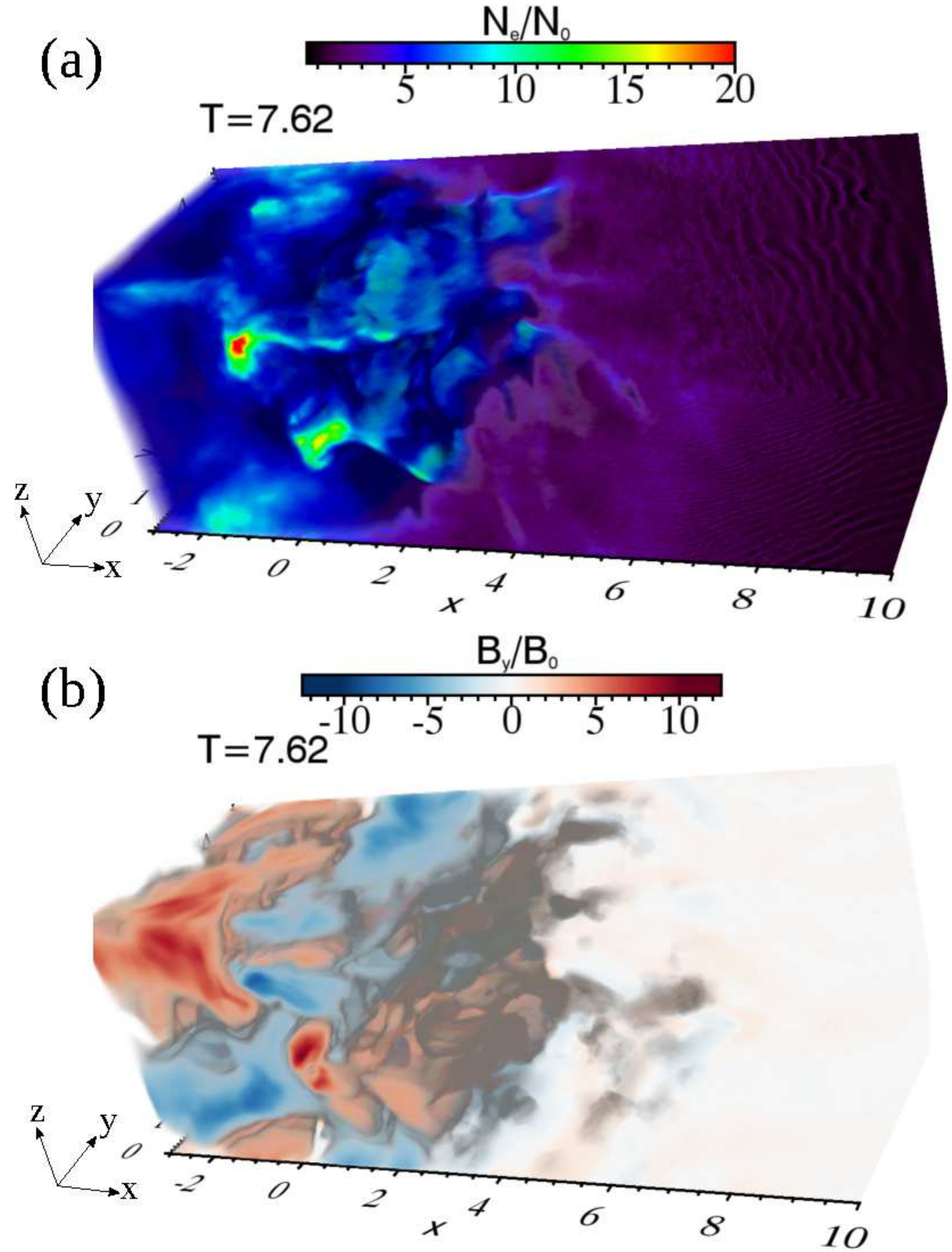
- here, evolution of Weibel-mediated shock into Bell-mediated shock



Crumley, Caprioli, Markoff & Spitkovsky (2019)

non-relativistic weakly magnetized electron-ion shocks

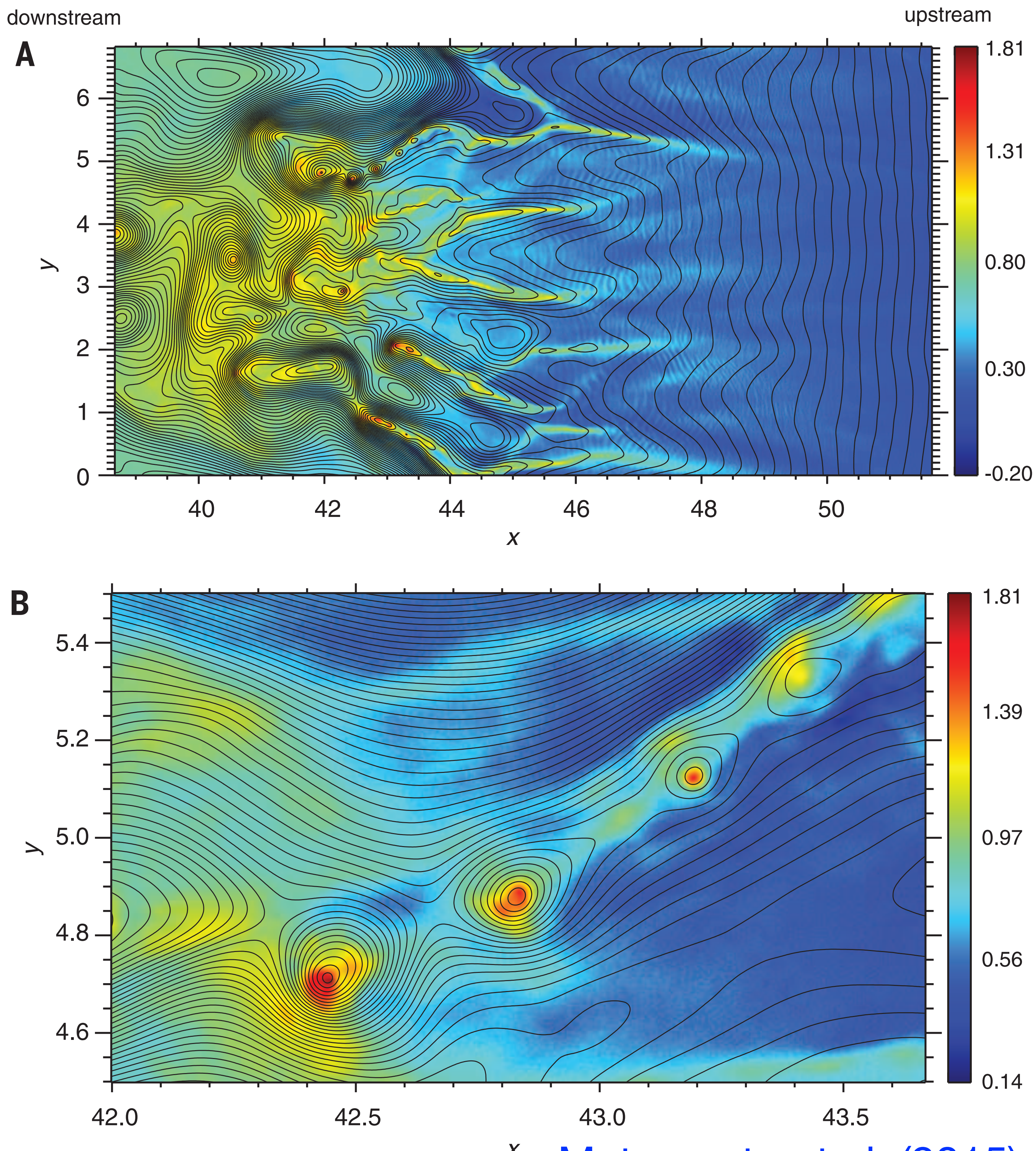
- electron injection problem in quasi-perpendicular shocks with high Alfven Mach number ($M_A \sim 30$)
- co-existence of Weibel (ion-scale) and Buneman (electron-scale) modes in 3D
- pre-acceleration of electrons by both shock surfing (SSA) and shock drift (SDA)
- in 2D, SSA is more efficient for out-of-plane fields (Bohdan et al. 2017, 2019), SDA is more efficient for in-plane fields



Matsumoto et al. (2017)

magnetic reconnection in Weibel filaments

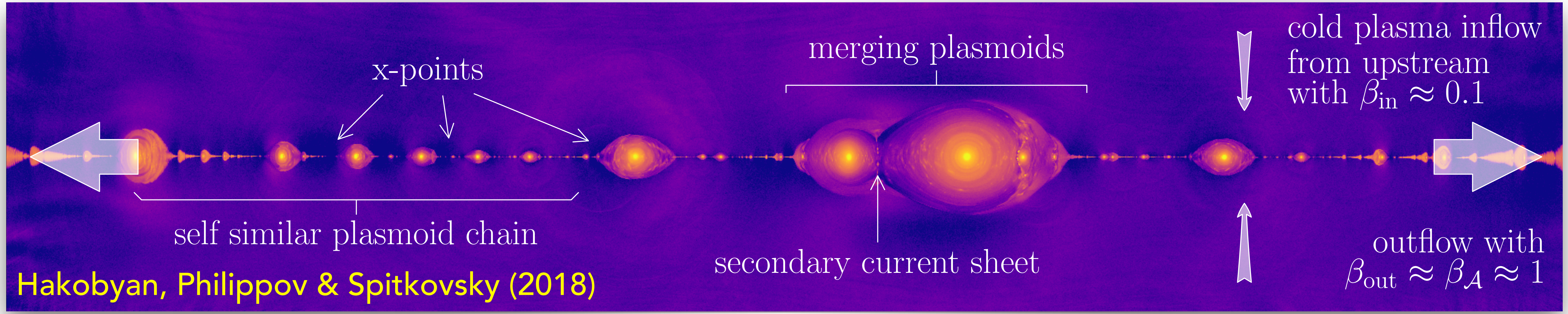
- ion-Weibel filaments form current layers separating regions of reversed magnetic field lines
- plasmoid instability triggers localized magnetic reconnection that energizes electrons and ions



Matsumoto et al. (2015)

particle acceleration in collisionless plasmas

1. shock waves
2. **magnetic reconnection**
3. turbulence



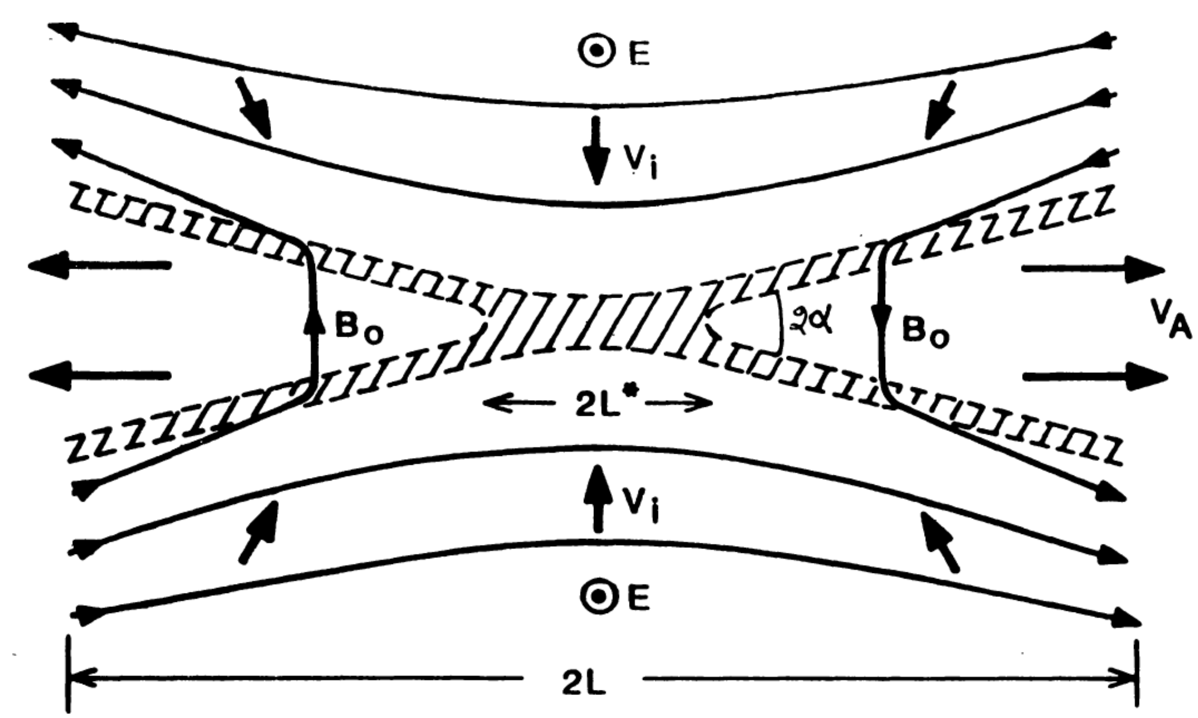
particle acceleration in relativistic magnetic reconnection

- power-law spectra:
  - hardening with increasing magnetization σ
  - p = 1; γ_{max} limited by σ (Guo+14; Werner+16)
  - p = 2; γ_{max} unlimited (Petropoulou+Sironi18)

- acceleration sites:
  - magnetic X-points (Zenitani+Hoshino01)
  - plasmoids (Drake+06)
  - plasmoid mergers (KN+15)

- nature of electric fields:
  - non-ideal
  - ideal (Guo+19)

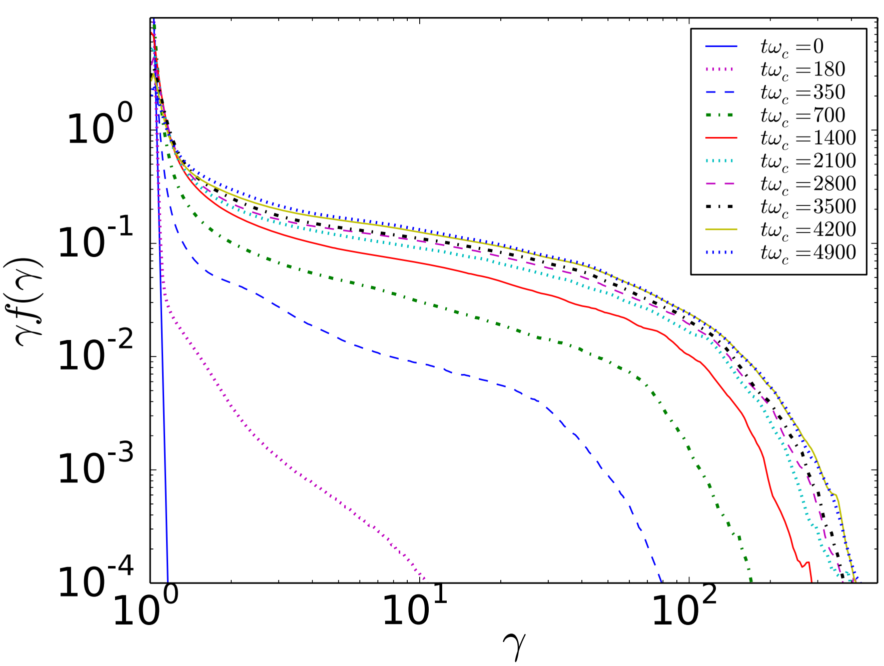
- configuration:
  - Harris layer
  - collapsing X-point / “ABC” fields (KN+16,18; Lyutikov+17)
  - merging flux tubes

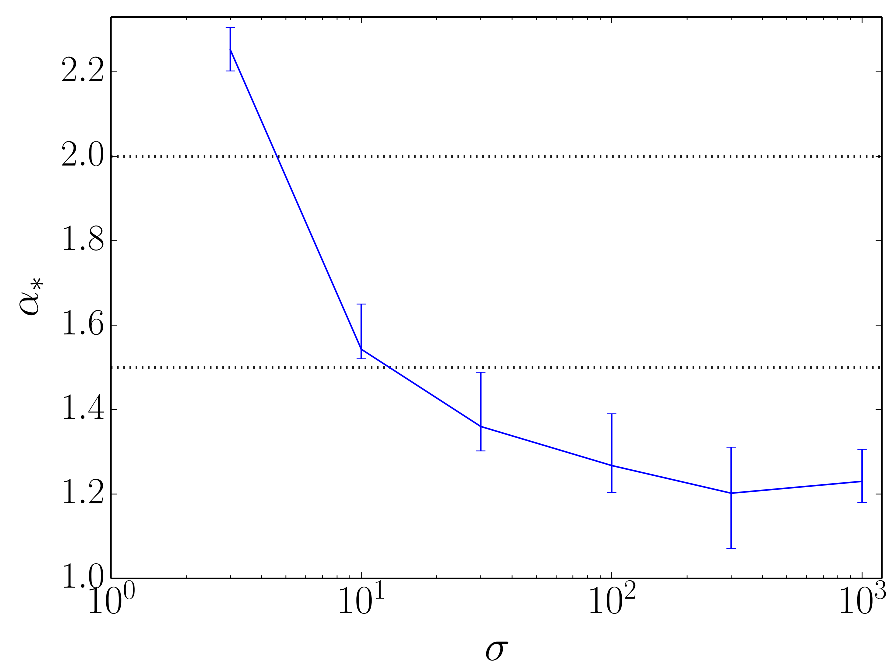


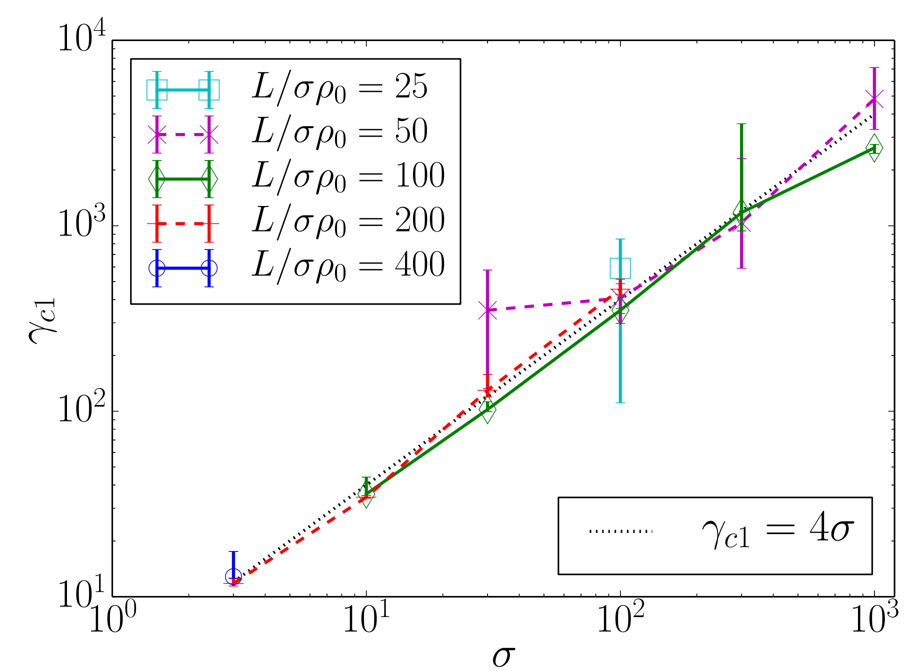
particle acceleration in pair-plasma reconnection

- 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 (ApJL 2016)

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

relativistic magnetic reconnection from Harris-type layers

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RELATIVISTIC RECONNECTION: AN EFFICIENT SOURCE OF NON-THERMAL PARTICLES

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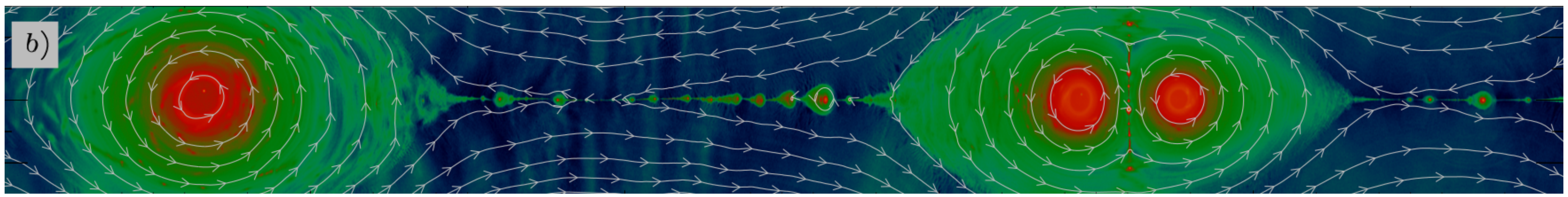

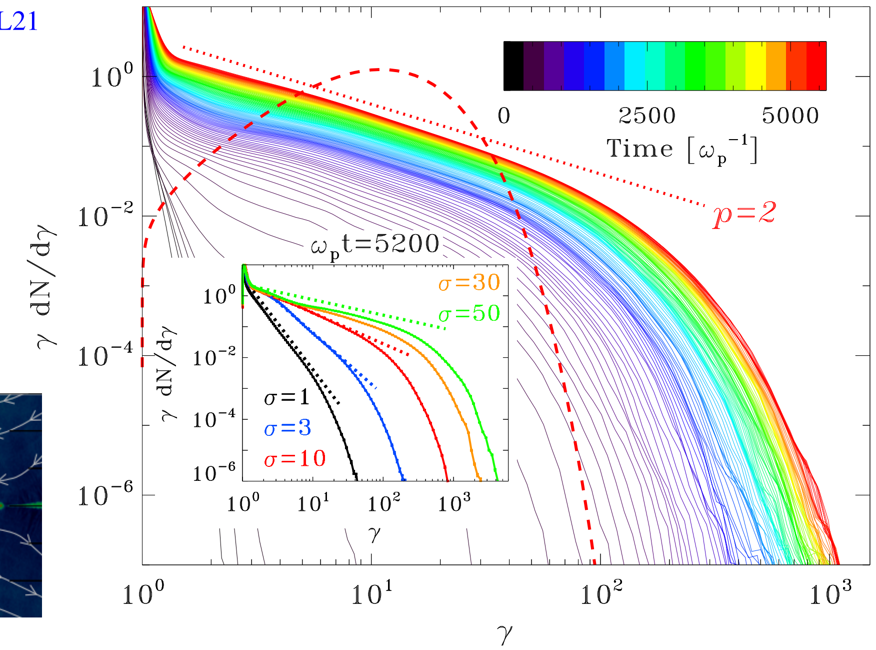

PRL 113, 155005 (2014) PHYSICAL REVIEW LETTERS week ending 10 OCTOBER 2014

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

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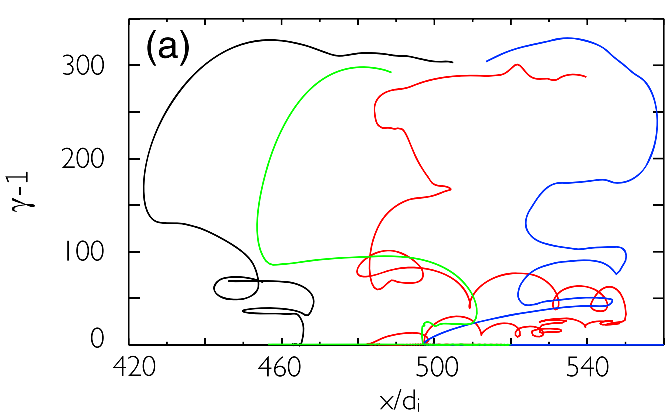
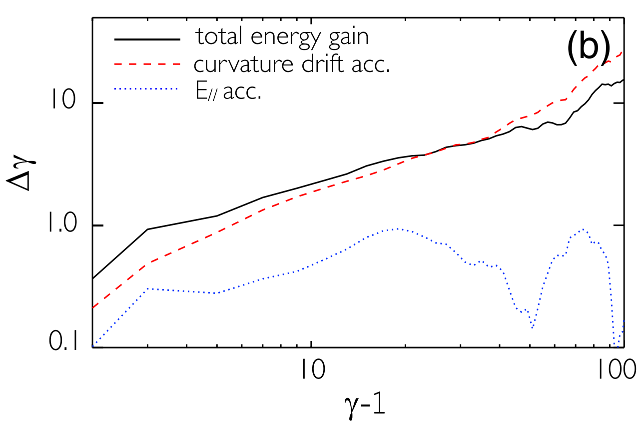
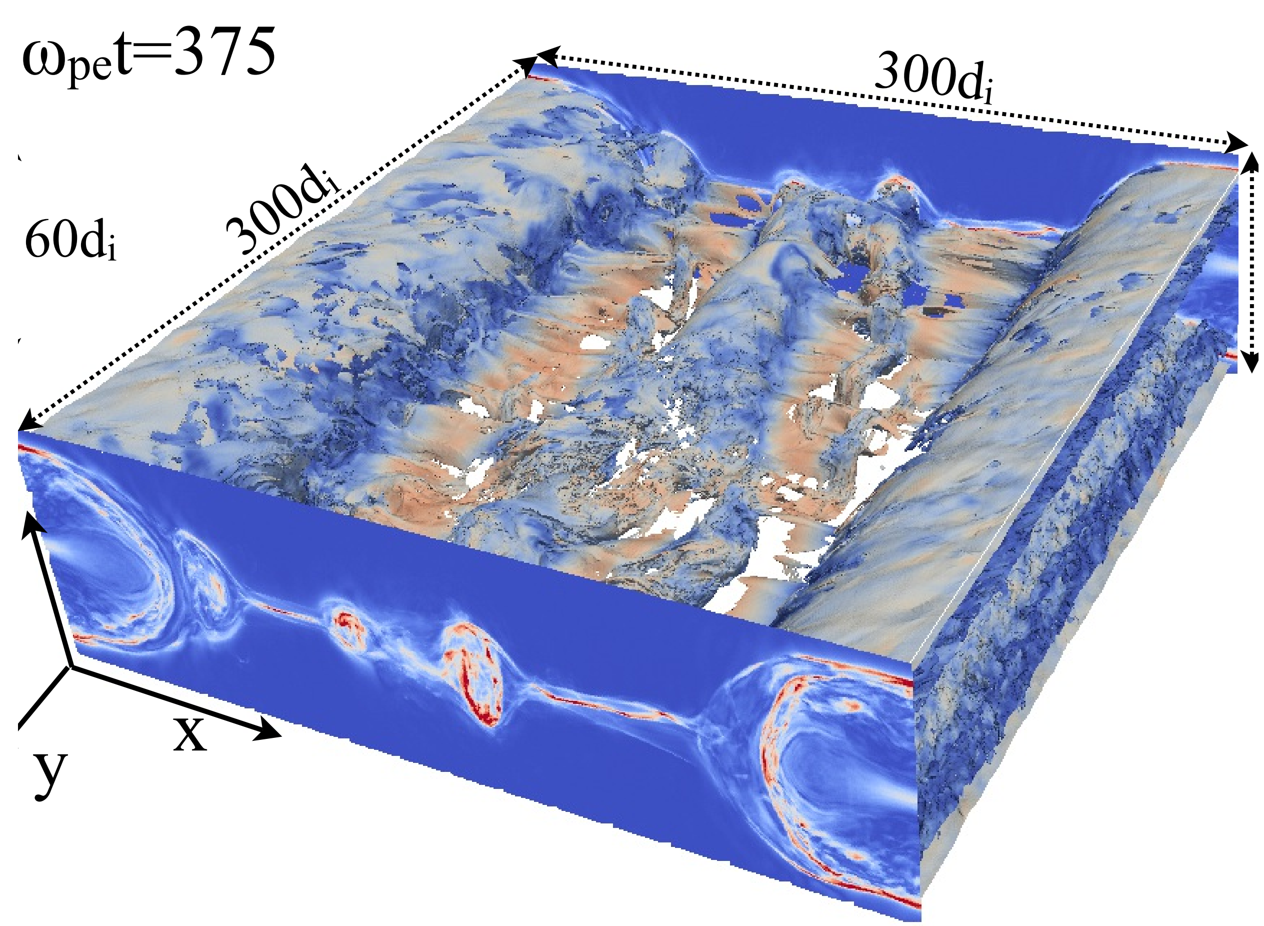
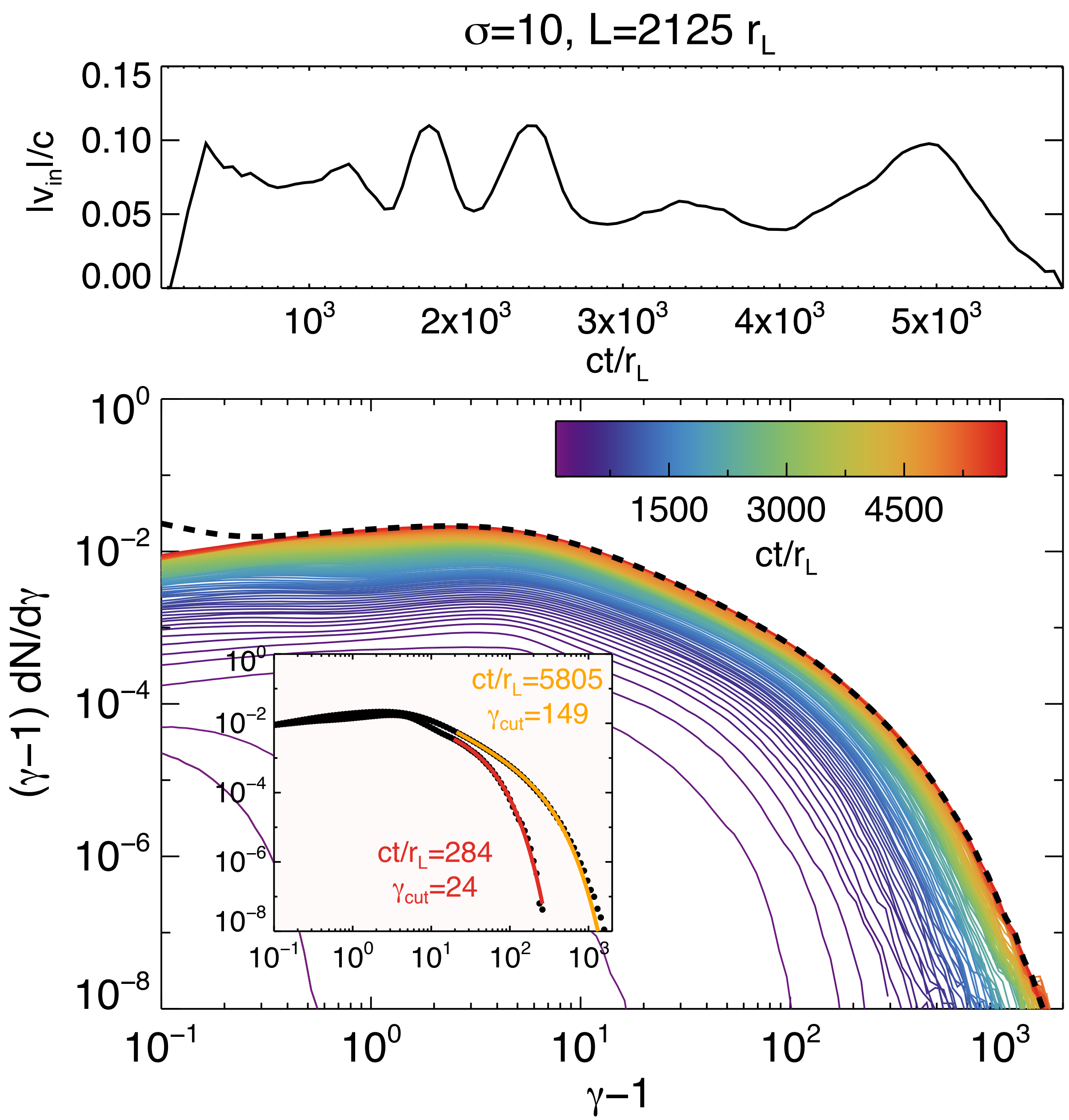
(Received 15 May 2014; published 8 October 2014)

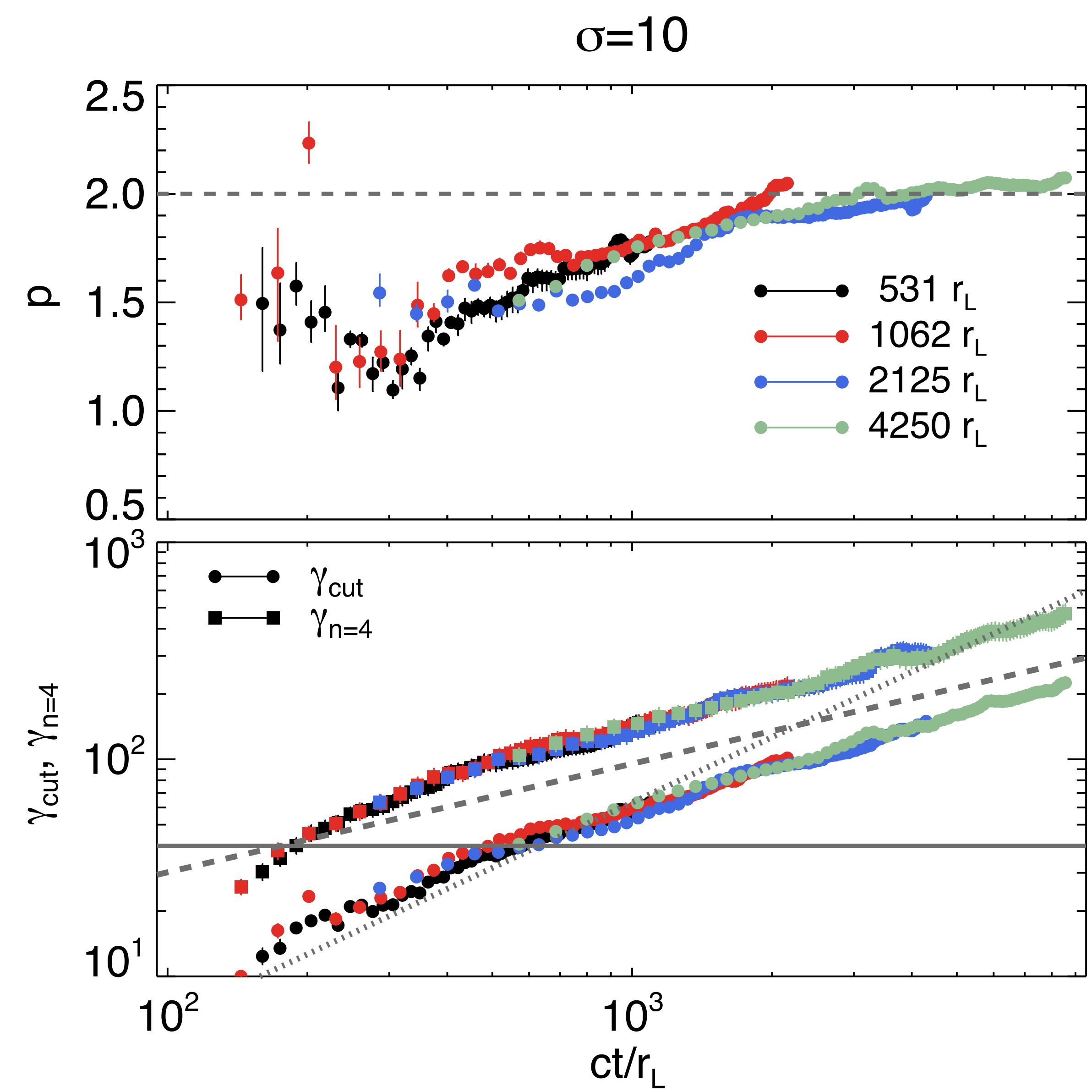






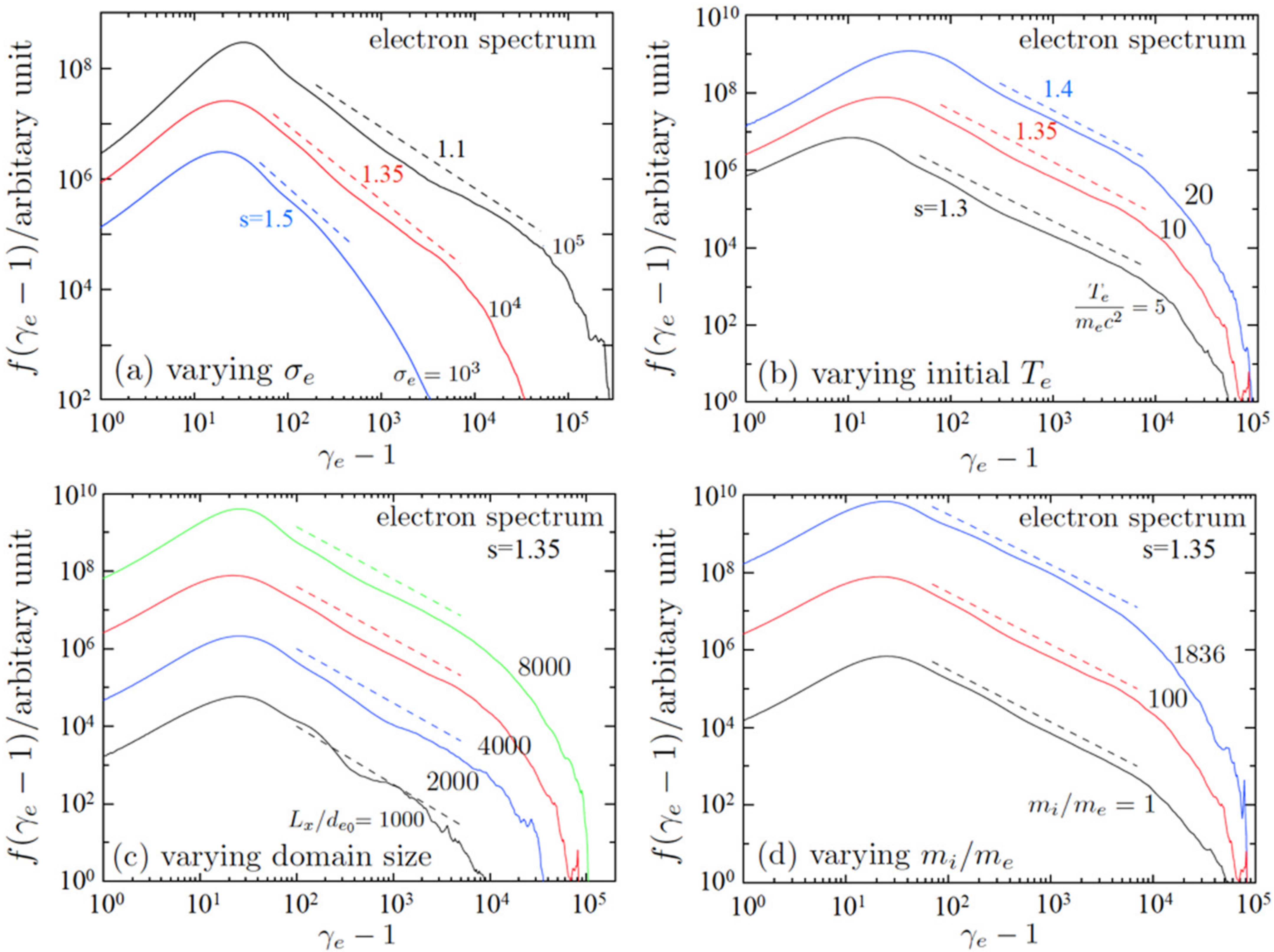
reconnection spectra saturating at p=2





Petropoulou & Sironi (2018)

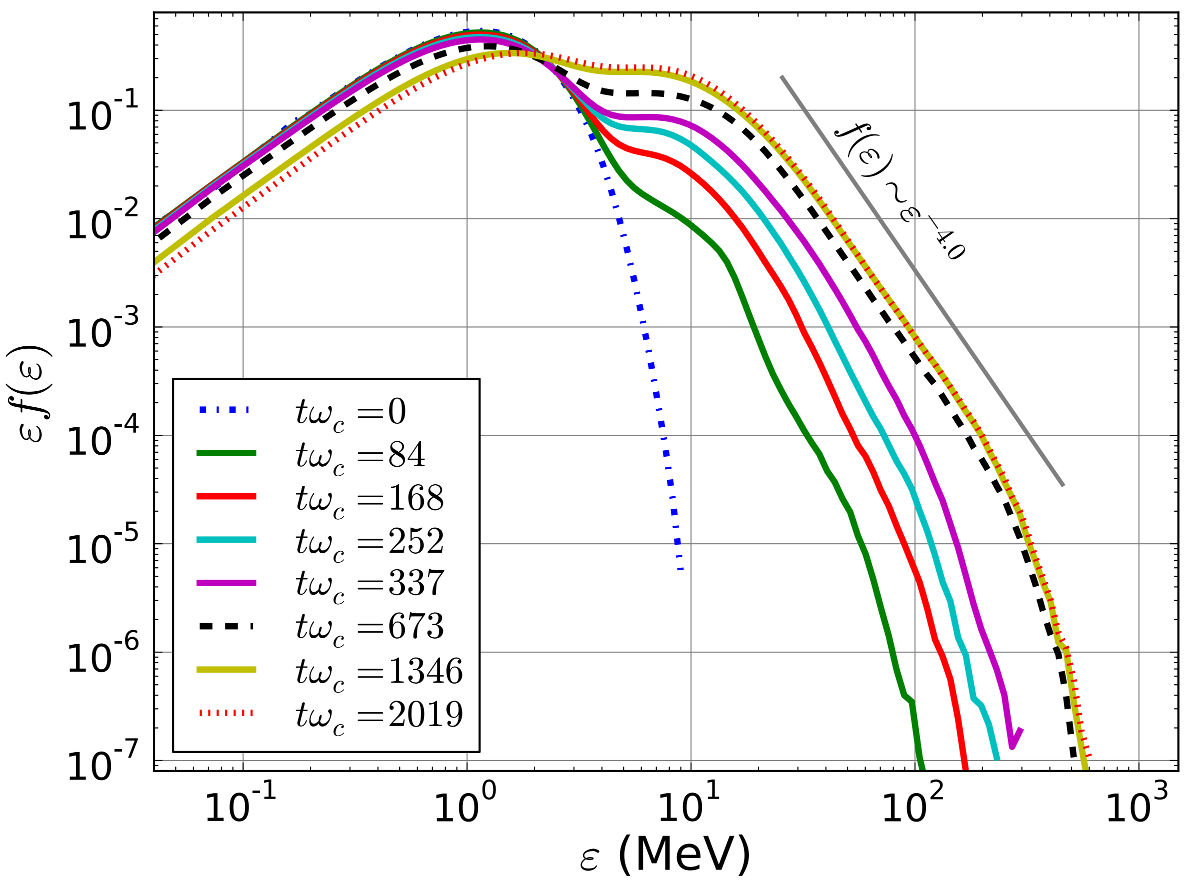
reconnection in electron-proton plasma

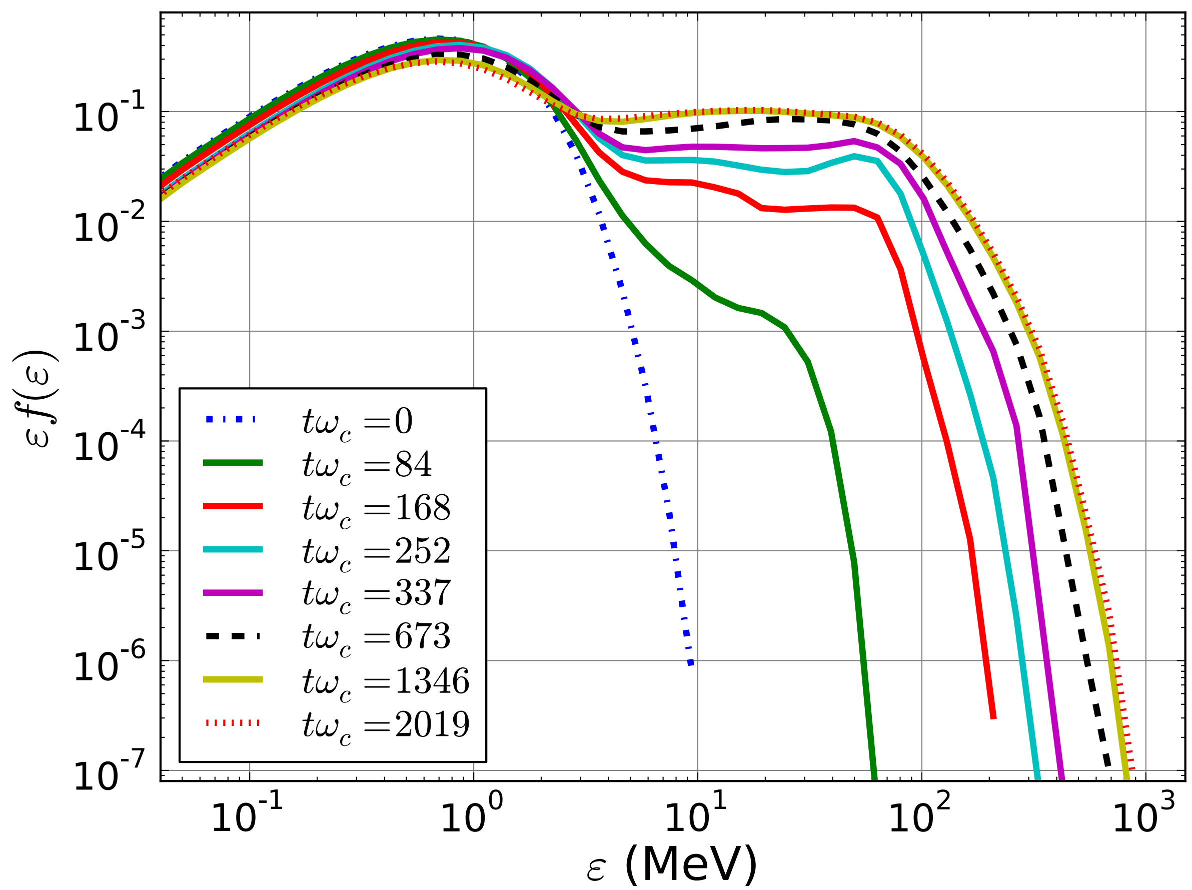


Guo et al. (2016)

see also Melzani et al. (2014)

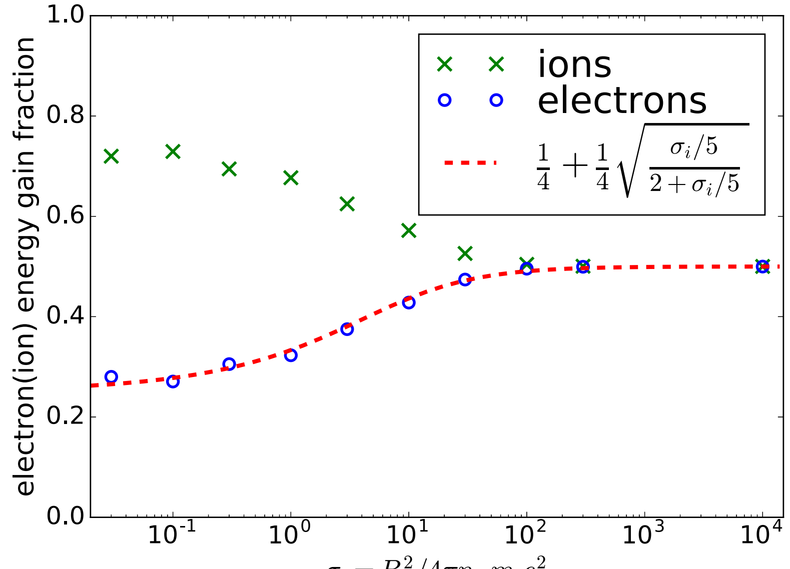
reconnection in electron-proton plasma





(b)

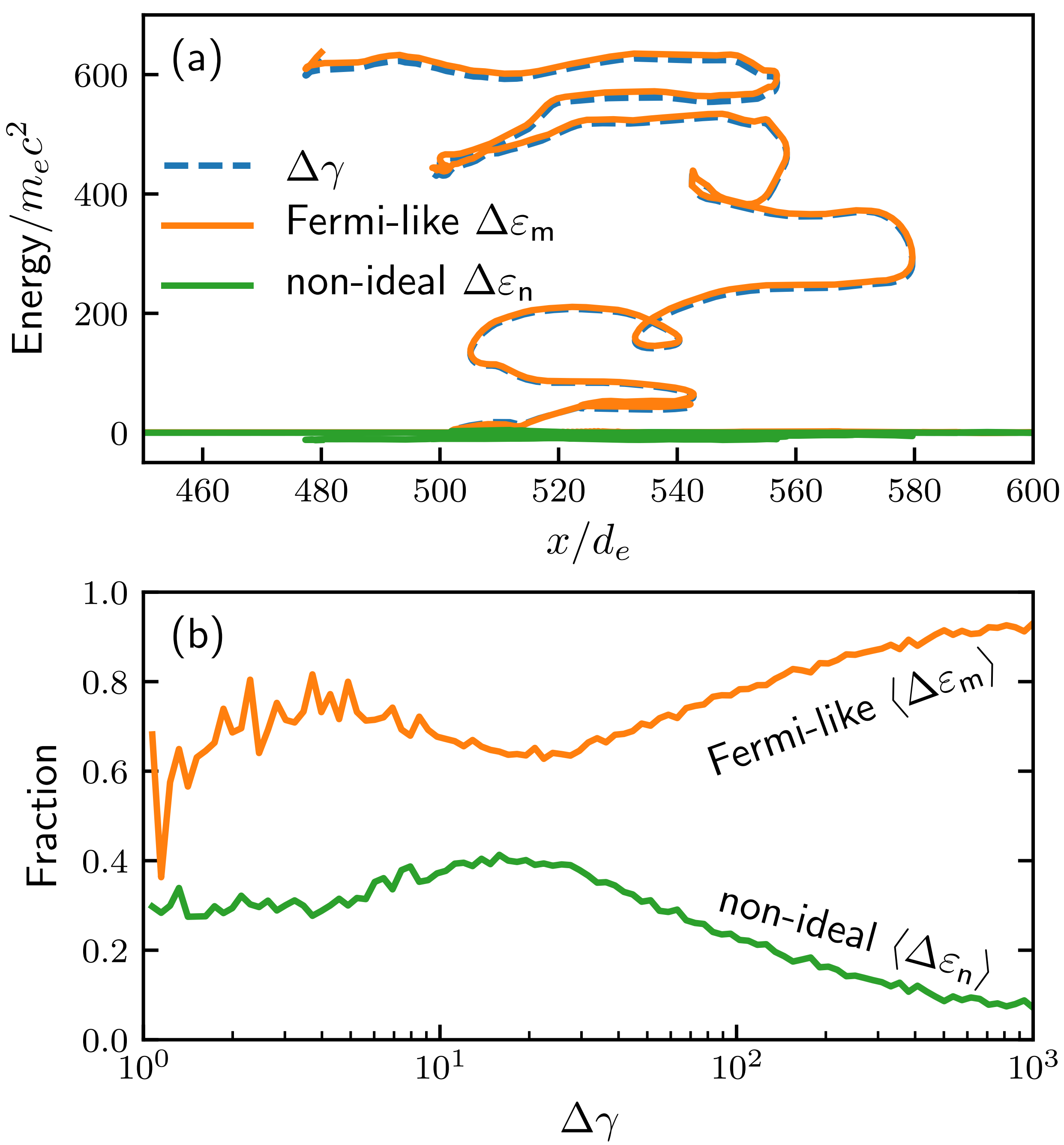
Figure 20. Time evolution of the (a) electron and (b) ion energy distributions, $f(\varepsilon)$ (compensated by ε) for $\sigma_i = 0.1$.

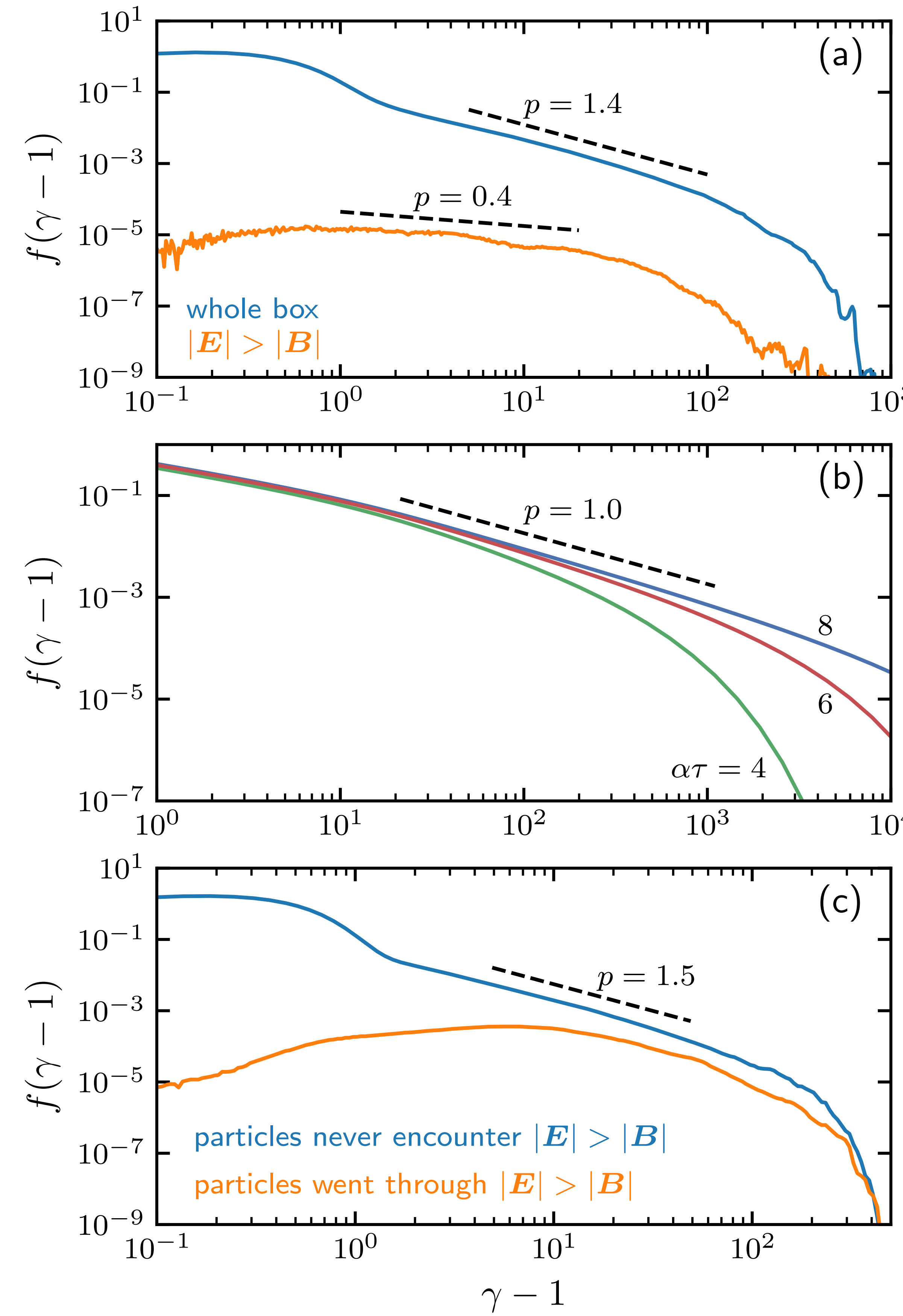


Werner, Uzdensky, Begelman, Cerutti, KN (MNRAS 2018)

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

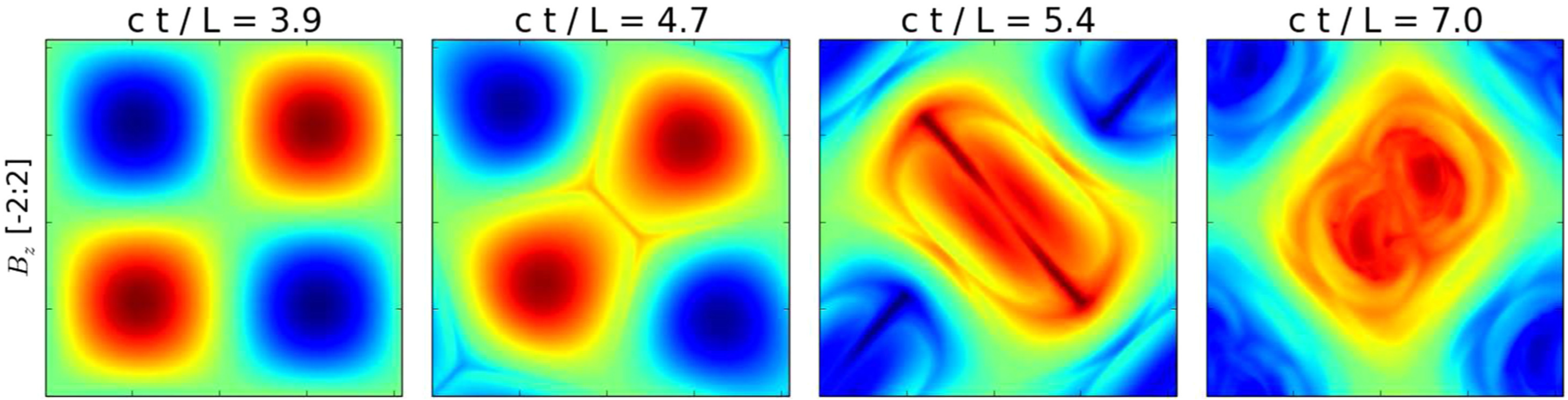
acceleration dominated by ideal electric fields

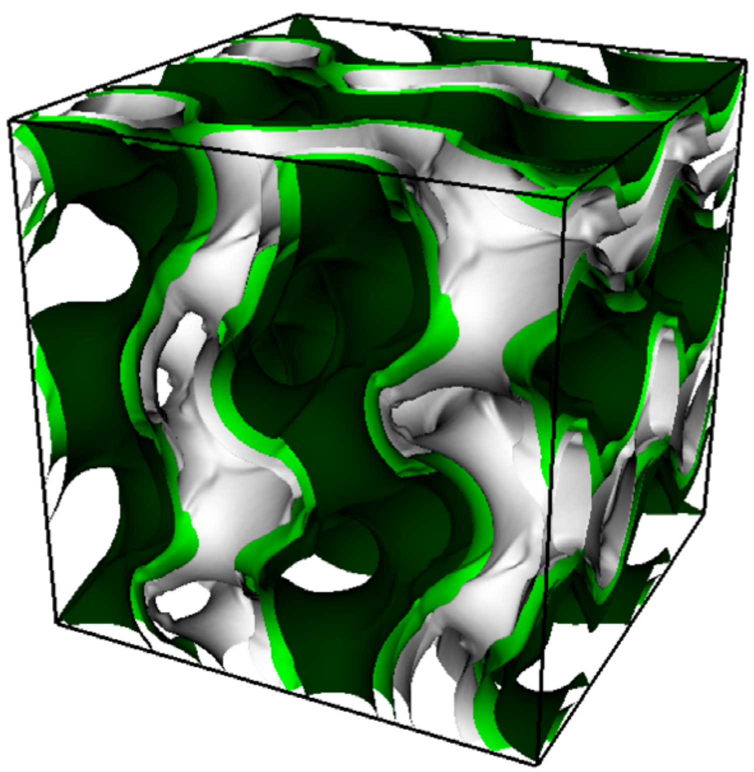


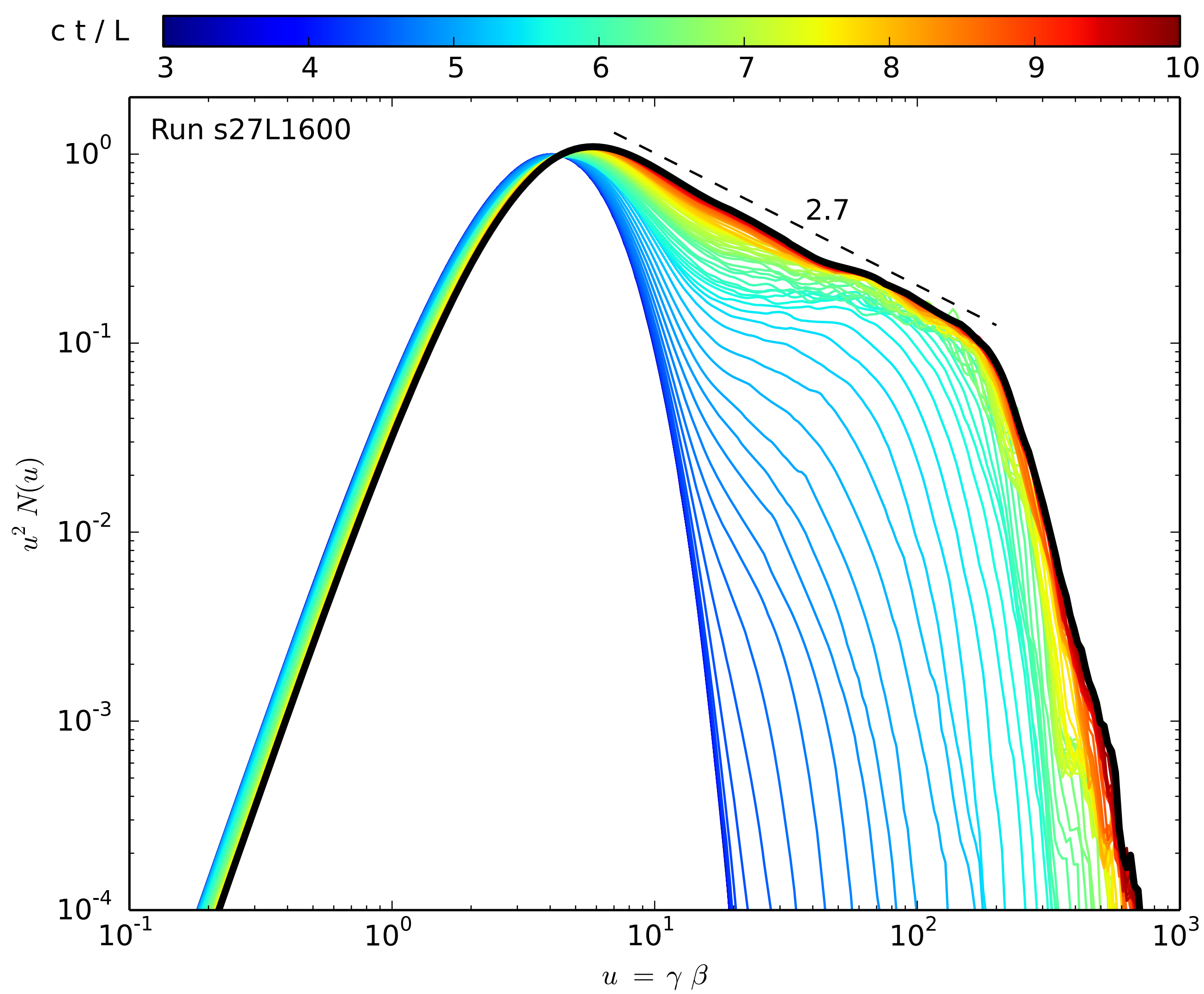


Guo et al. (2019)

magnetic dissipation in “ABC fields”







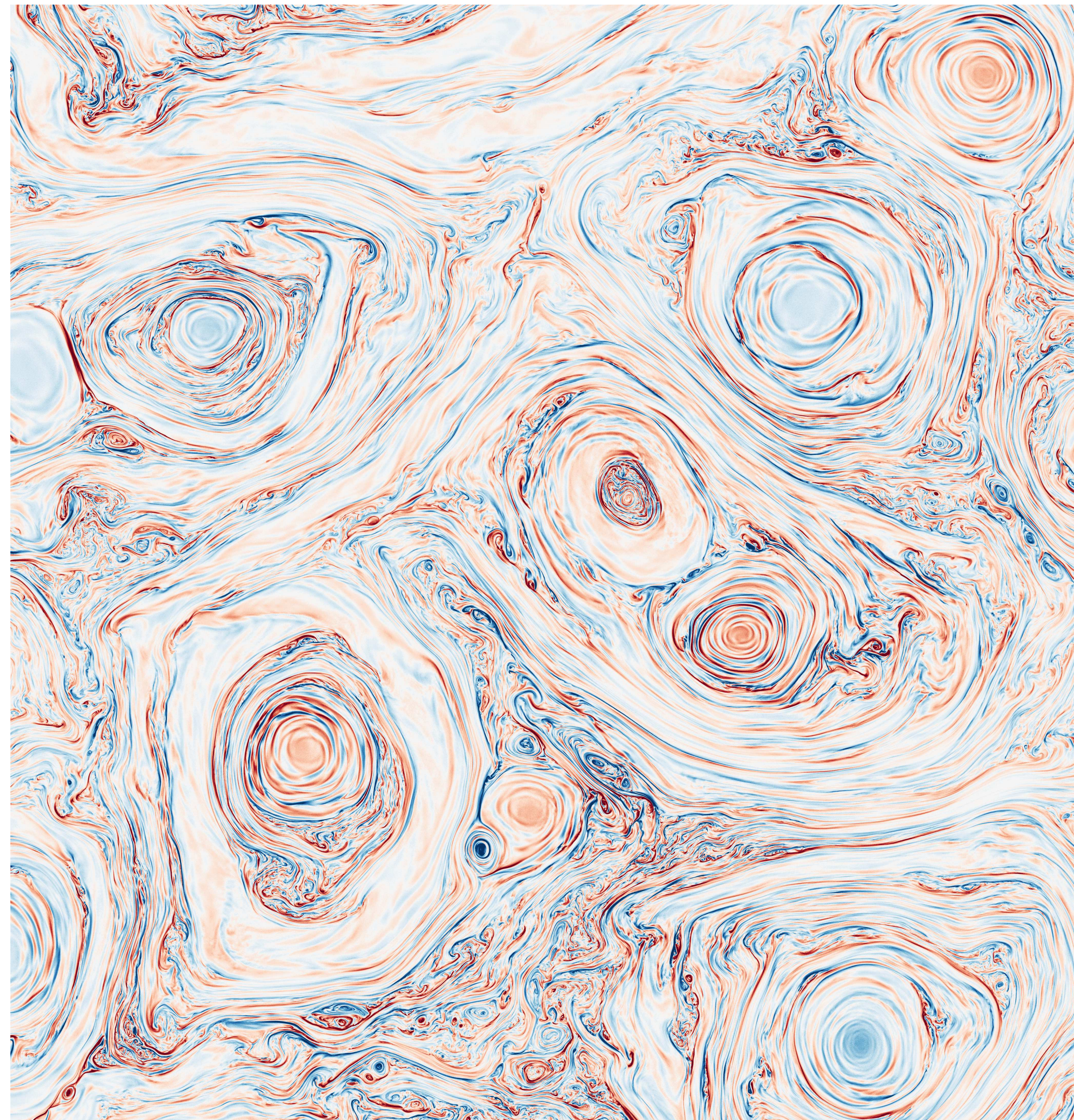
KN, Zrake, Yuan, East & Blandford (2016)
Yuan, KN, Zrake, East & Blandford (2016)
Lyutikov, Sironi, Komissarov & Porth (2017)
KN (2018)

particle acceleration in collisionless plasmas

1. shock waves

2. magnetic reconnection

3. turbulence

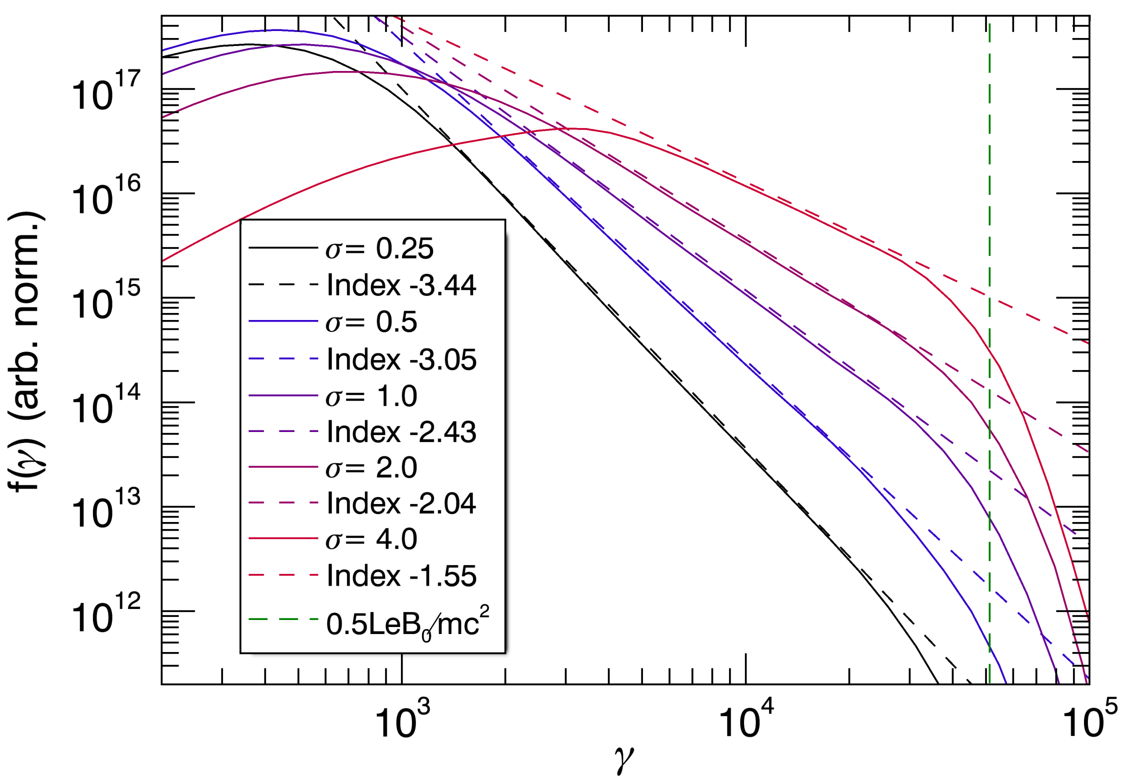


Comisso & Sironi (2018)

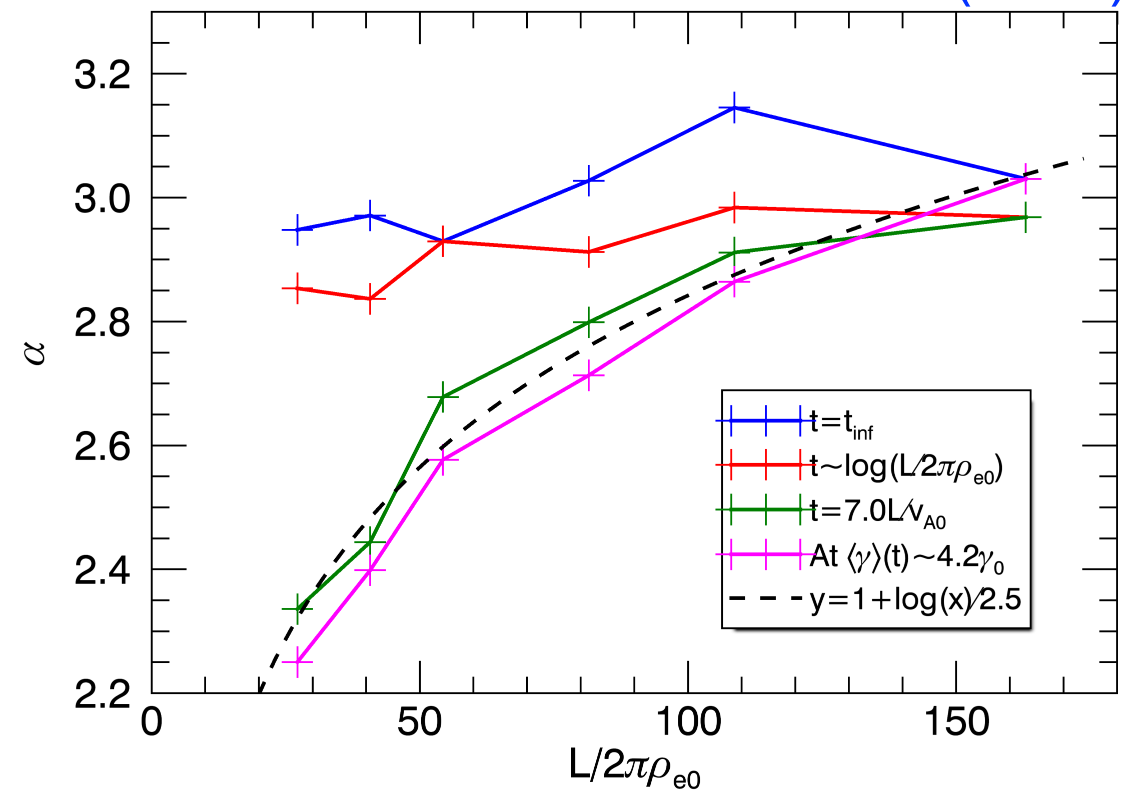
particle acceleration in relativistic turbulence

- power-law spectra:
  - hardening with increasing magnetization σ
  - $p = 2.9$ (Comisso+Sironi18)
- acceleration sites:
  - current layers
- configuration:
  - freely decaying
  - driven

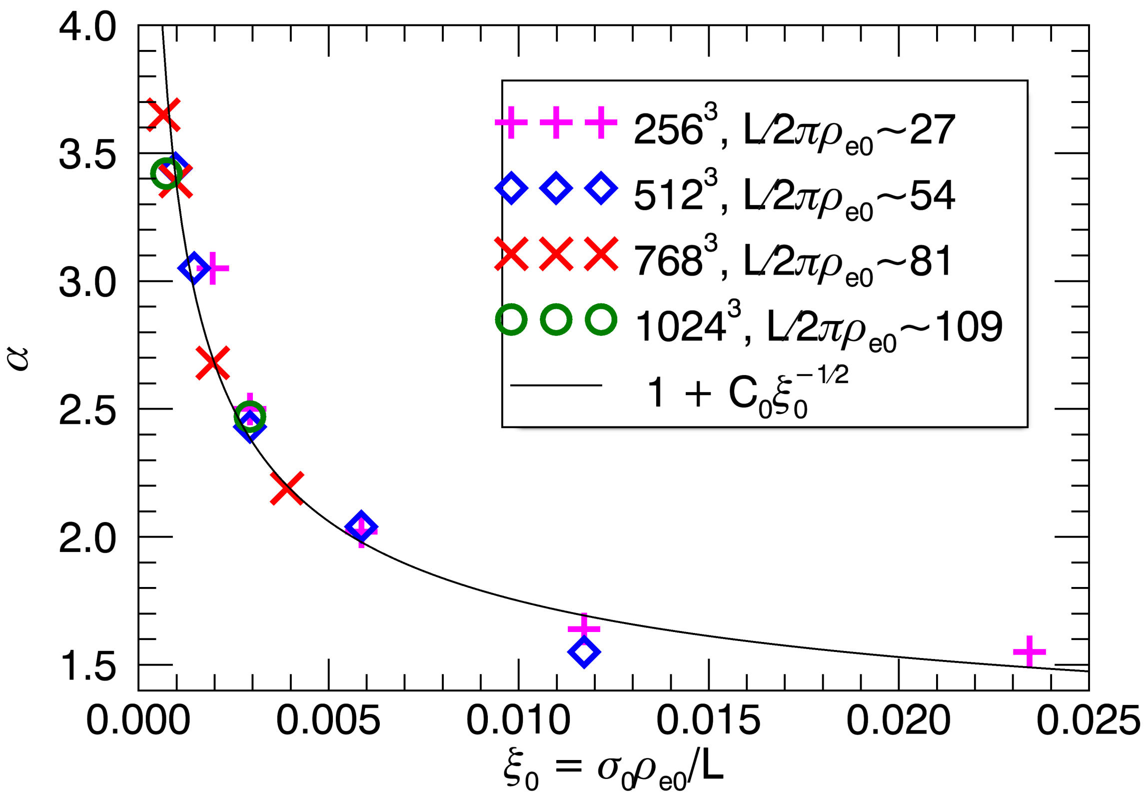
PIC simulations of driven relativistic turbulence



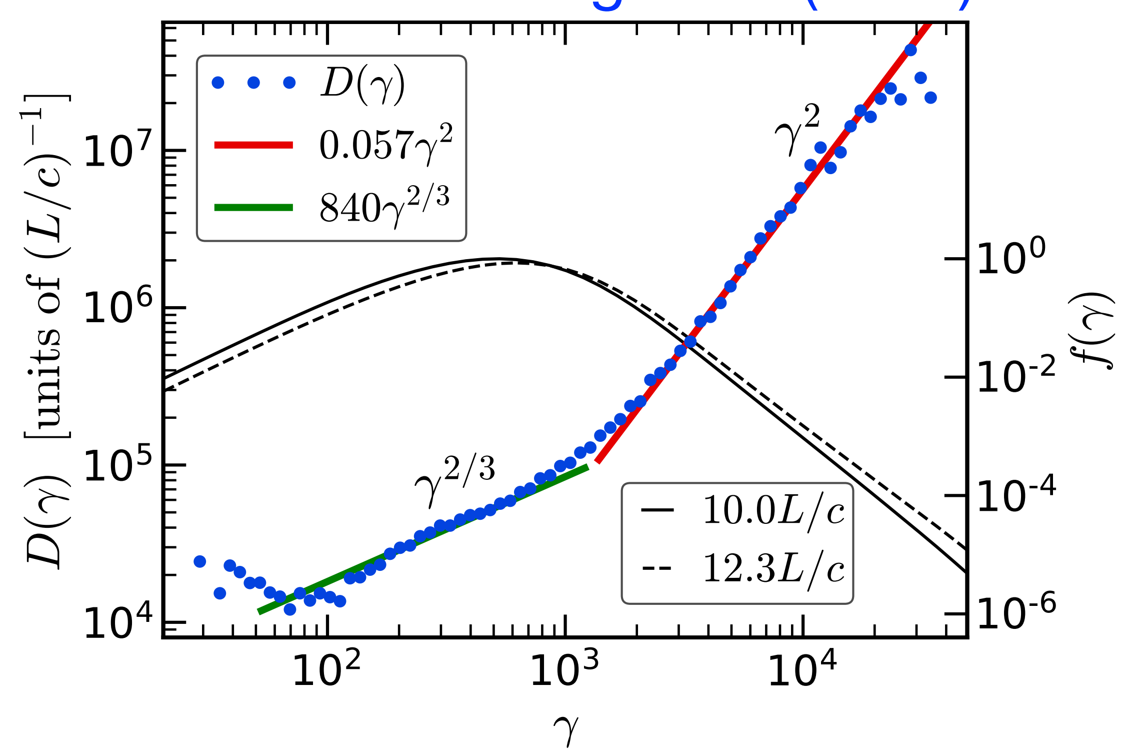
Zhdankin et al. (2018)



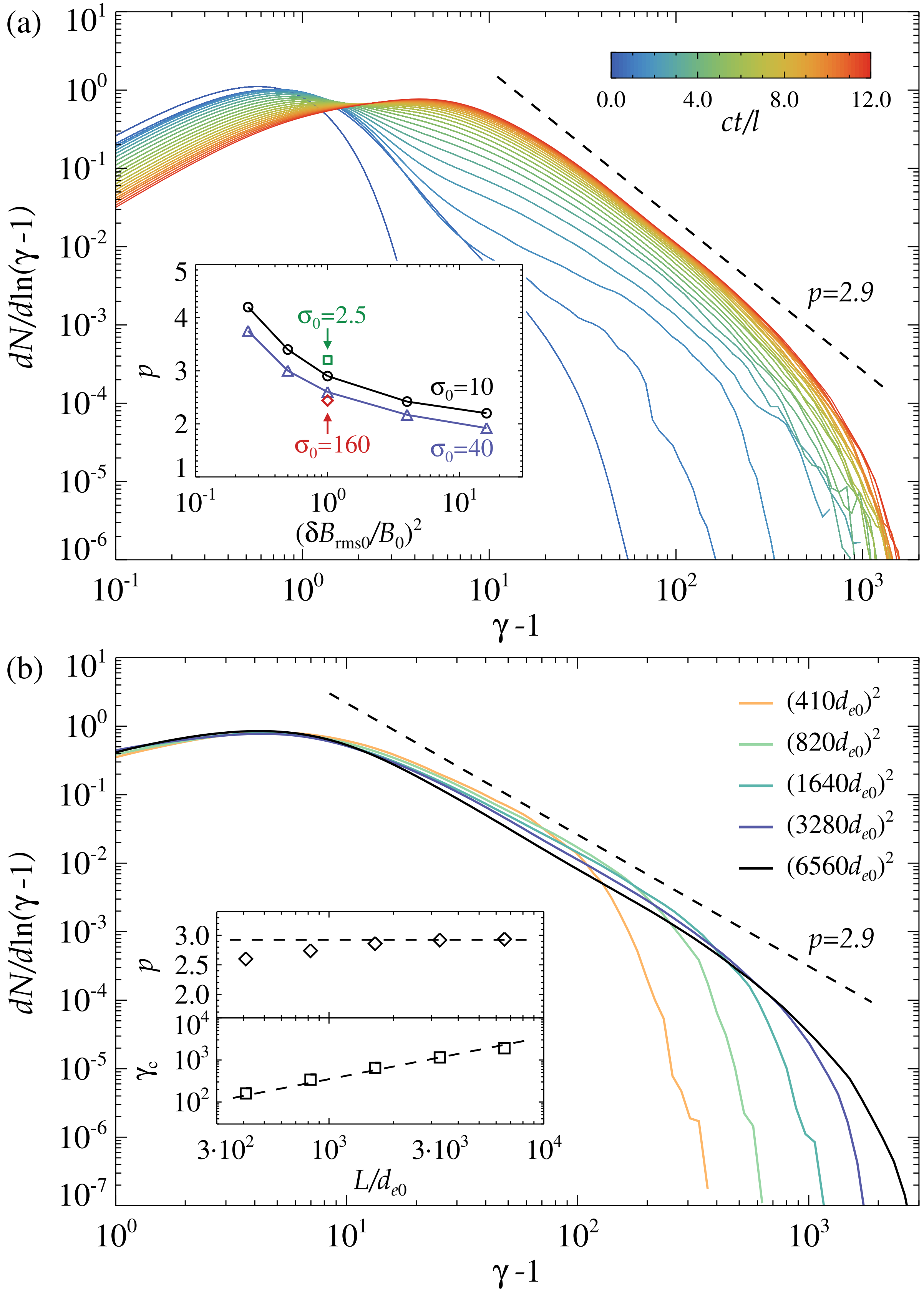
Zhdankin et al. (2017)

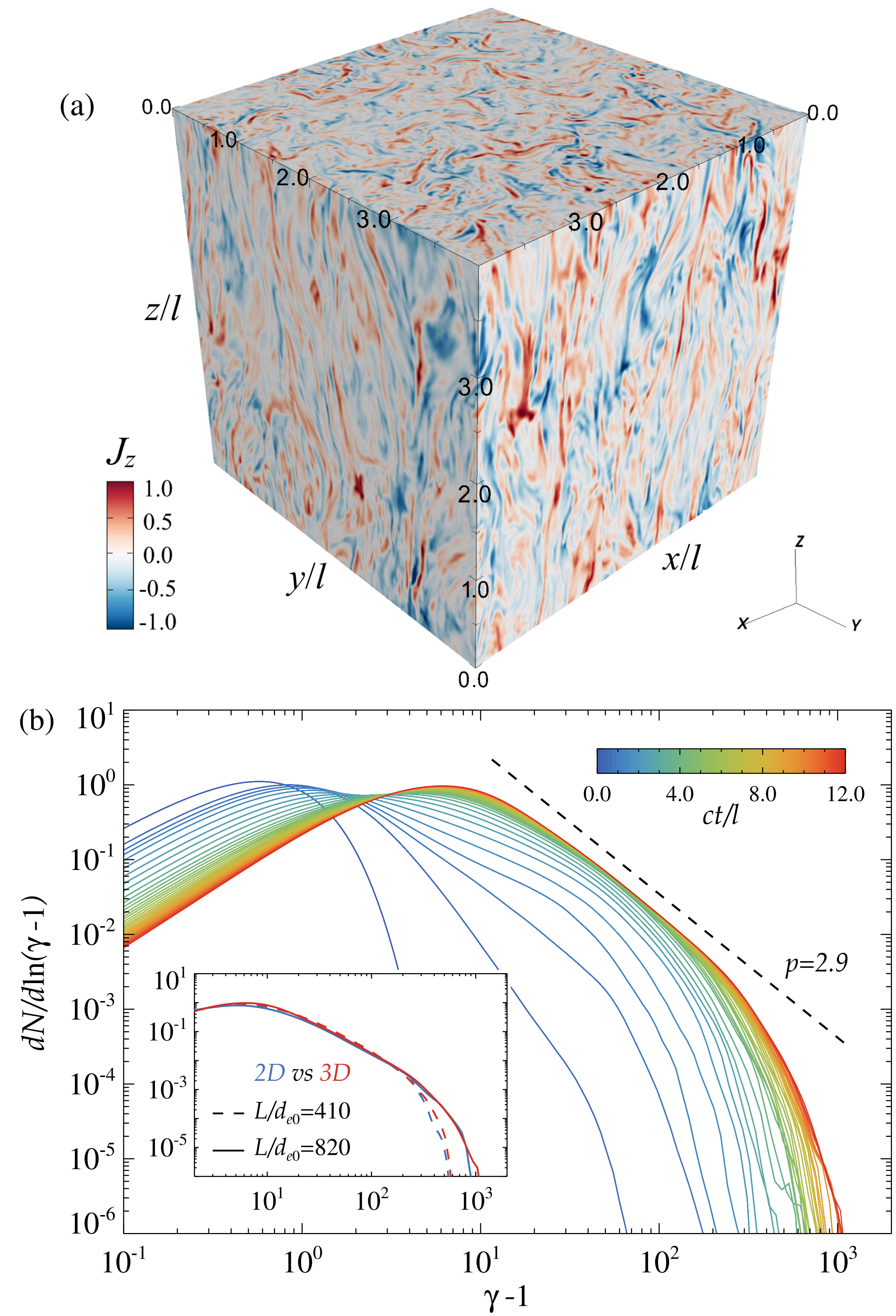


Wong et al. (2019)



PIC simulations of decaying relativistic turbulence





Comisso & Sironi (2018)

summary

- Numerous models for non-thermal particle acceleration (NTPA) in collisionless (relativistic) plasmas
- Shock waves efficient in weakly magnetized plasmas
- Reconnection and turbulence efficient in highly magnetized plasmas
- Stochastic Fermi-type acceleration with power-law slopes $p \sim 2$ demonstrated in all cases