Small-scale B-field & Reconnection Application in TeV Astrophysics

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Celestial Targets of LHAASO

- Supernova (SN) & Supernova Remnant:
  non-relativistic mostly
  massive stellar collapse at final evolution stage
  radio, optical & X-ray, GeV, particle
- Gamma-ray burst (GRB): 10^51-54 erg
  relativistic jet (bulk Lorentz factor>100)
  massive stellar collapse/BH merger, strongest energy
  radio, optical, X-ray, & gamma-ray (GeV), particle,
- BLAZAR: 10^46 erg/s
  relativistic jet of active galactic nuclear (AGN)
  bulk Lorentz factor>10, central massive BH
  radio, optical, X-ray, GeV & TeV, particle
- Gravitational wave (GW), neutrino

Physical Scenario

- Huge energy release: energy dissipation
- Radiation mechanisms
- Electrons/ions are relativistic: acceleration
- B-field structure & generation
- Magnetized outflow of BLAZAR & GRB

Observations

- Multi-wavelength observation radiation: BURST

  radio, optical, X-ray, GeV, TeV, …

  telescope/detector position & accuracy

  optical: arcsecond in field-of-view of arcmin-deg

  high-energy: deg in field-of-view of deg

- Cosmic-ray: source of high-energy particle?
- LINK: radiation + particle

  (1) radiation: particle energy loss

  (2) celestial burst: high energy radiation & particle

  simultaneous production

Physics Unsolved

- Huge energy release: energy dissipation

  (1) dynamic or magnetic energy release ?
- Radiation mechanisms

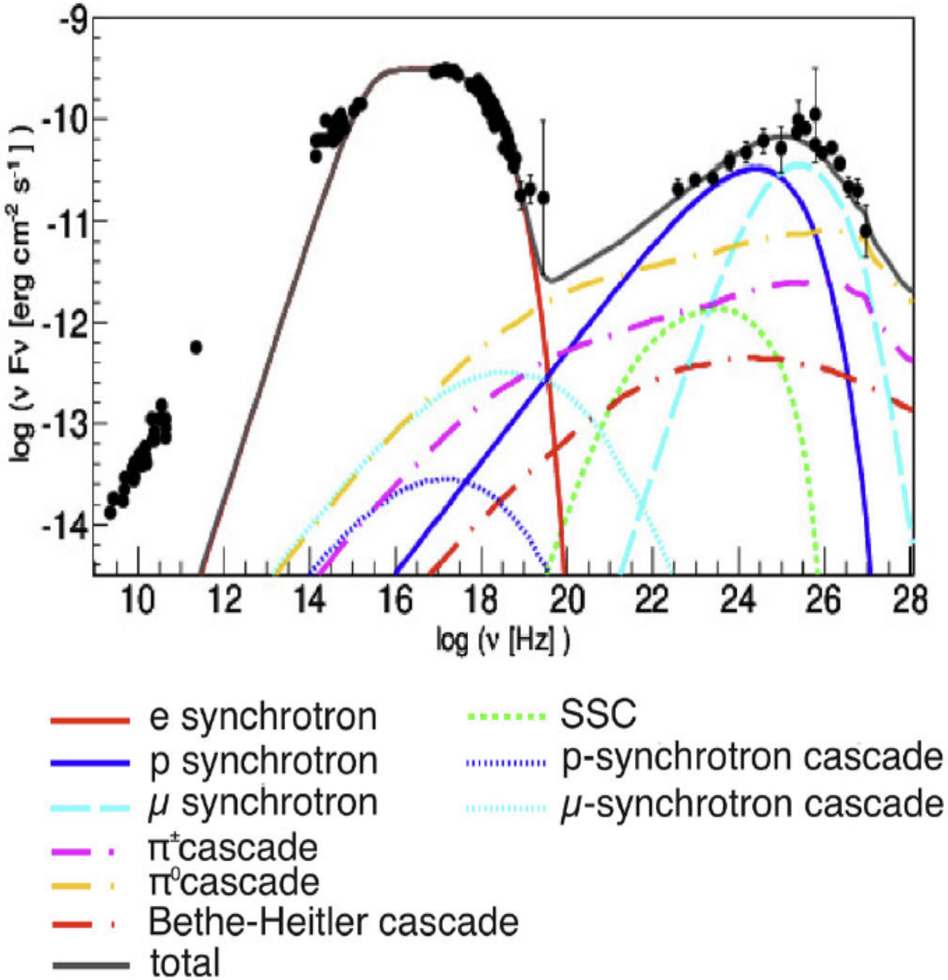
  synchrotron, Compton scattering(EC, SSC)

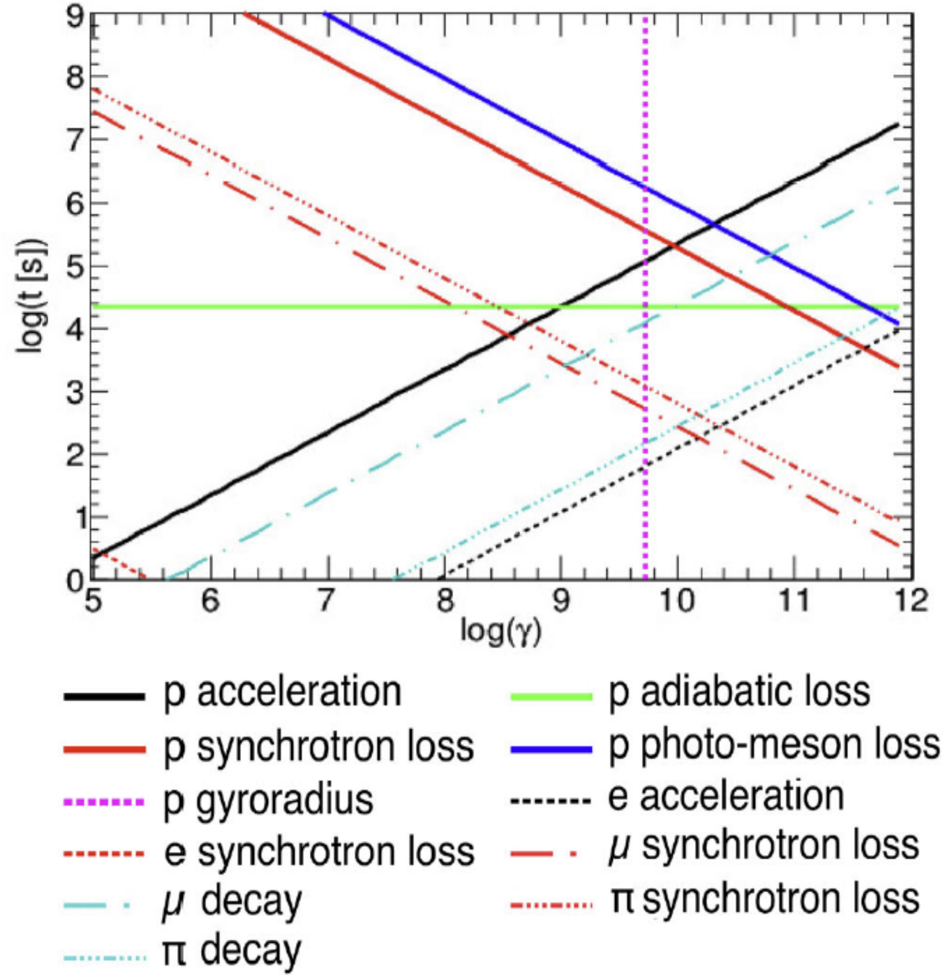
  (2) lepton, hadronic or others ? B-field
- Electrons/ions acceleration

  (3) shock, turbulence or others? B-field

- Magnetized outflow of BLAZAR & GRB

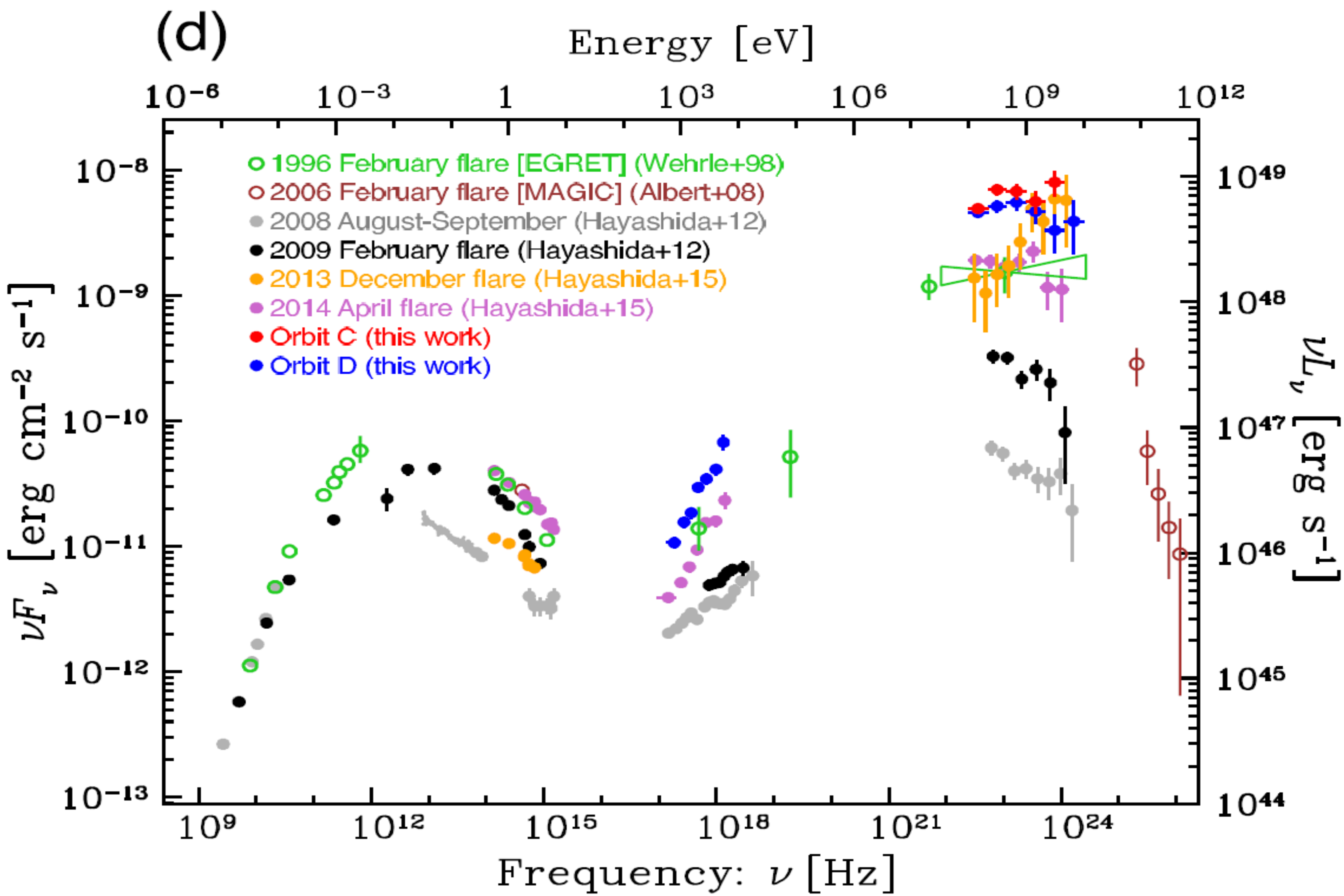
BLAZAR Mrk 421: hadronic





Cerruti et al. 2015

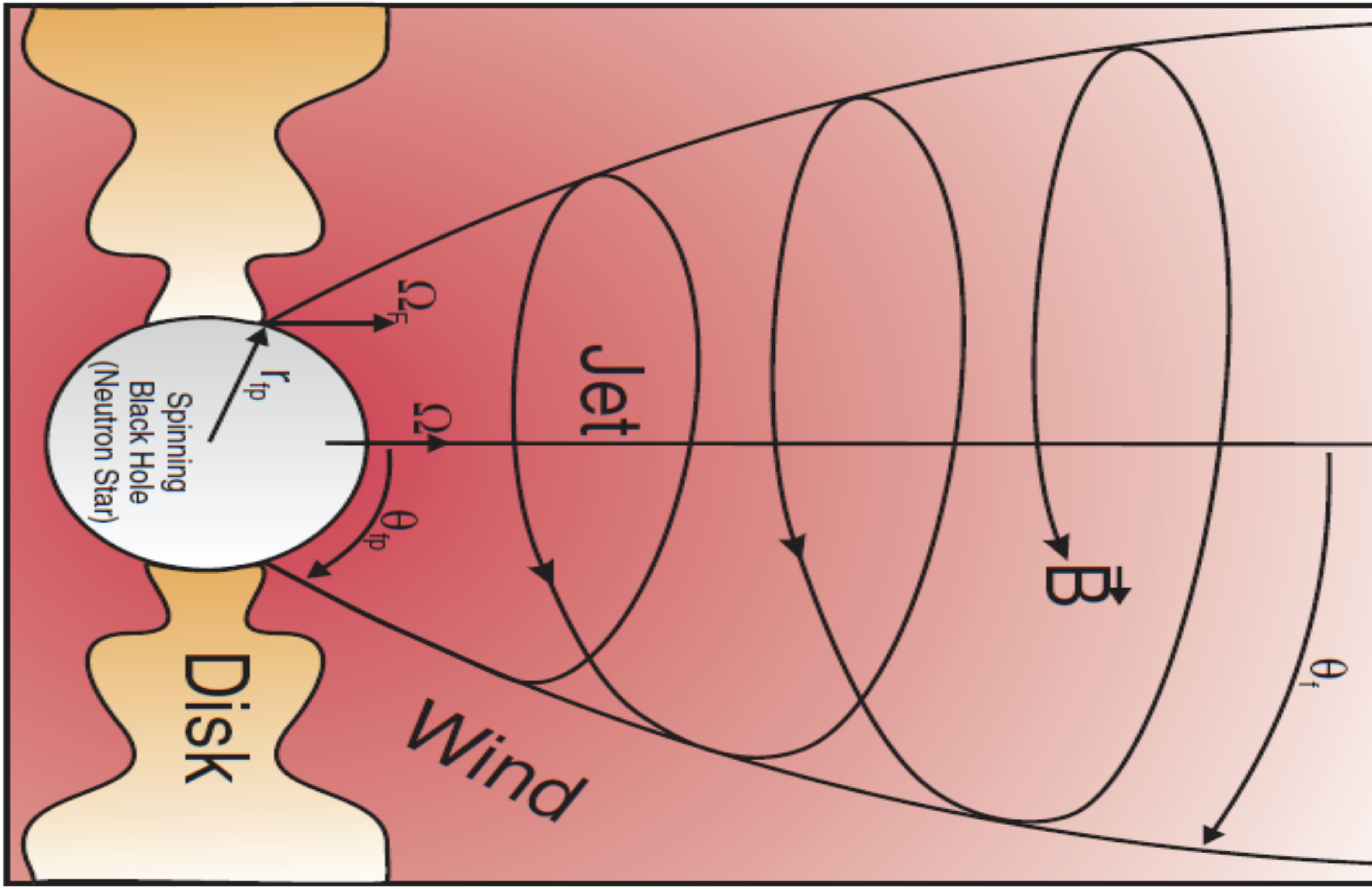
BLAZAR 3C279 TeV-Flare: minutes-hours
Lepton & Hadronic models invalid



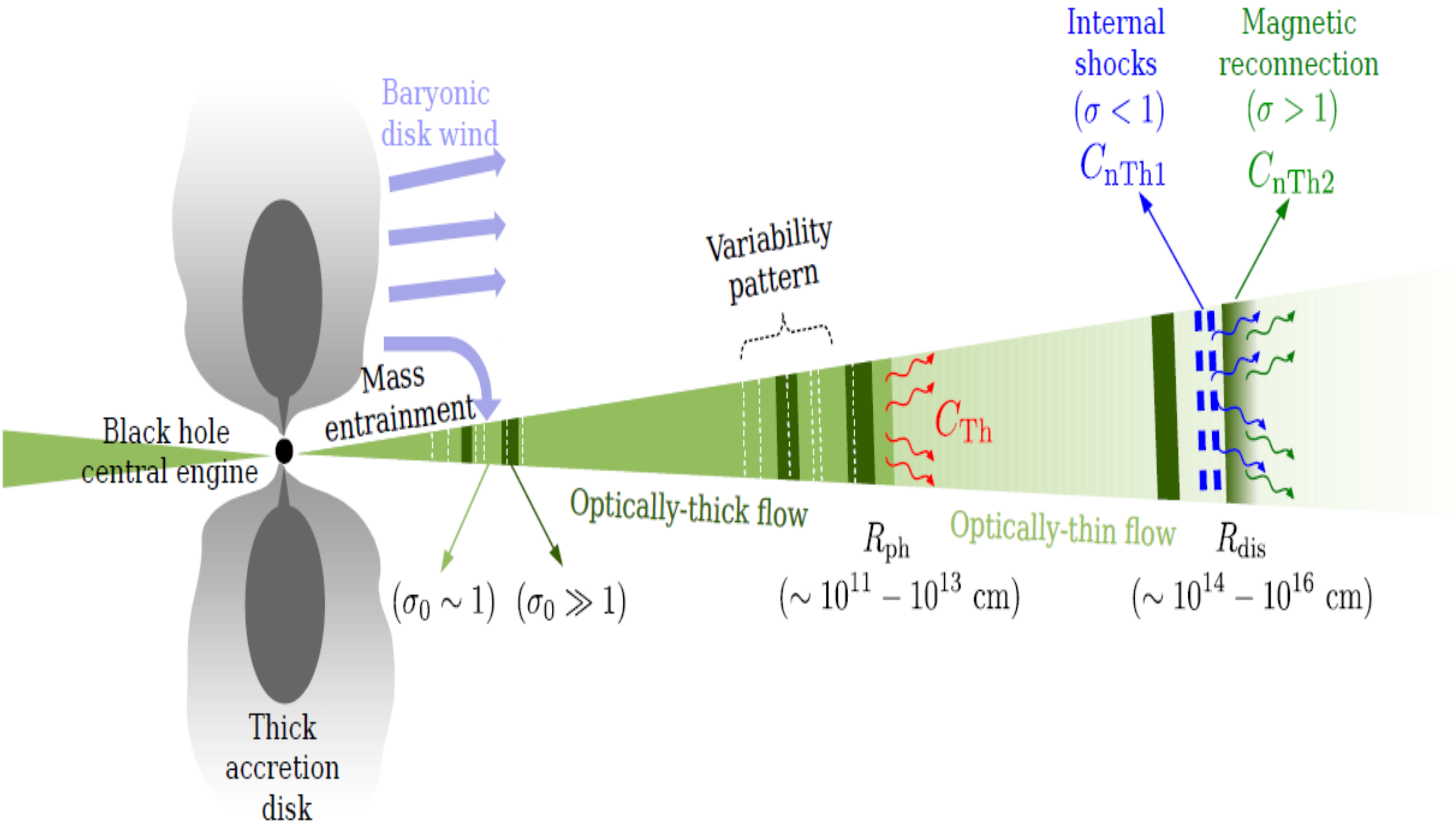
Theoretical Tools for LHAASO

- Length scale and corresponding physical condition
- Small-scale dynamo for small-scale B-field and relation to large-scale B-field
- Plasma instabilities
- Turbulence: trigger reconnection/enhance B-field
- Collisionless magnetic reconnection
- Particle acceleration
- Radiation

Large-Scale B-field



Small-scale B-field



Outline

（A） Length scale and physical condition

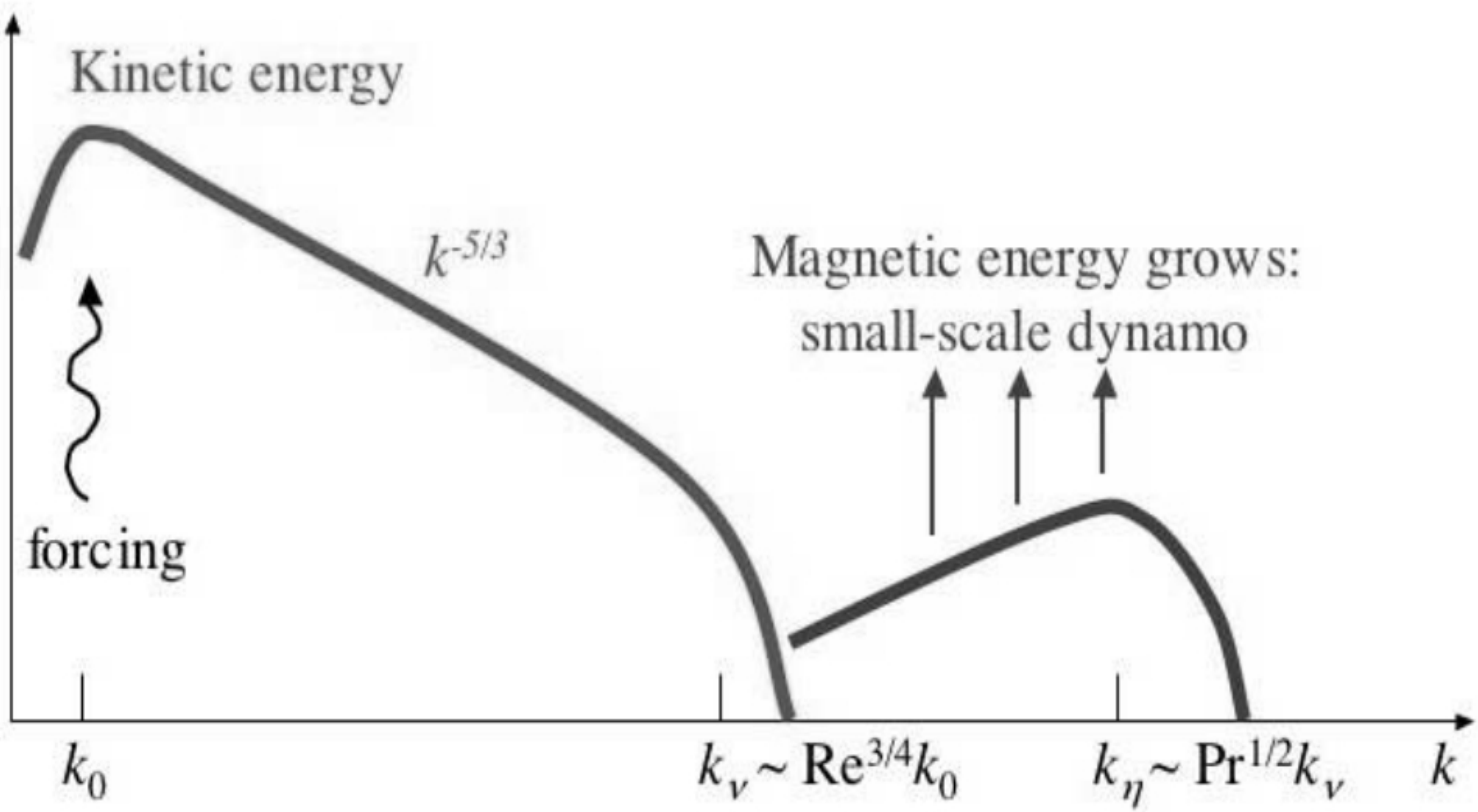
（B） Recent development

1. small-scale B-field from small-scale turbulence
2. B-filed from plasma instability
3. plasma kinetic turbulence
4. collisionless shock
5. two-fluid model
6. reconnection
7. radiation

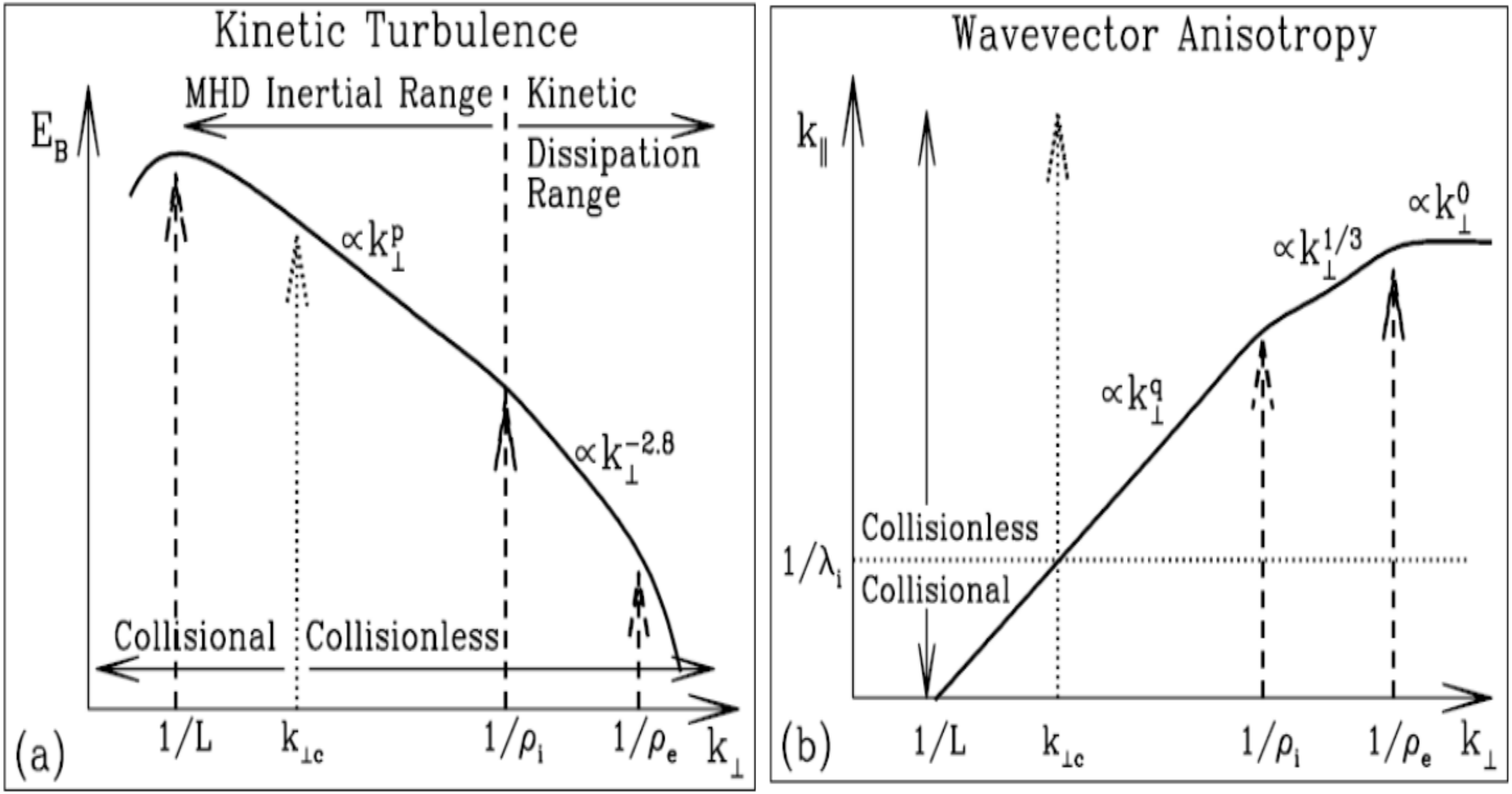
Small-Scale Definition & MHD/Kinetic Method

- Far less than the system length
- Length: comparable to ion gyro-radius
- Length: comparable to skin length
- MHD or kinetic?
- Approximation: kinetic MHD

Small-scale (Schekochihin et al. 2007)

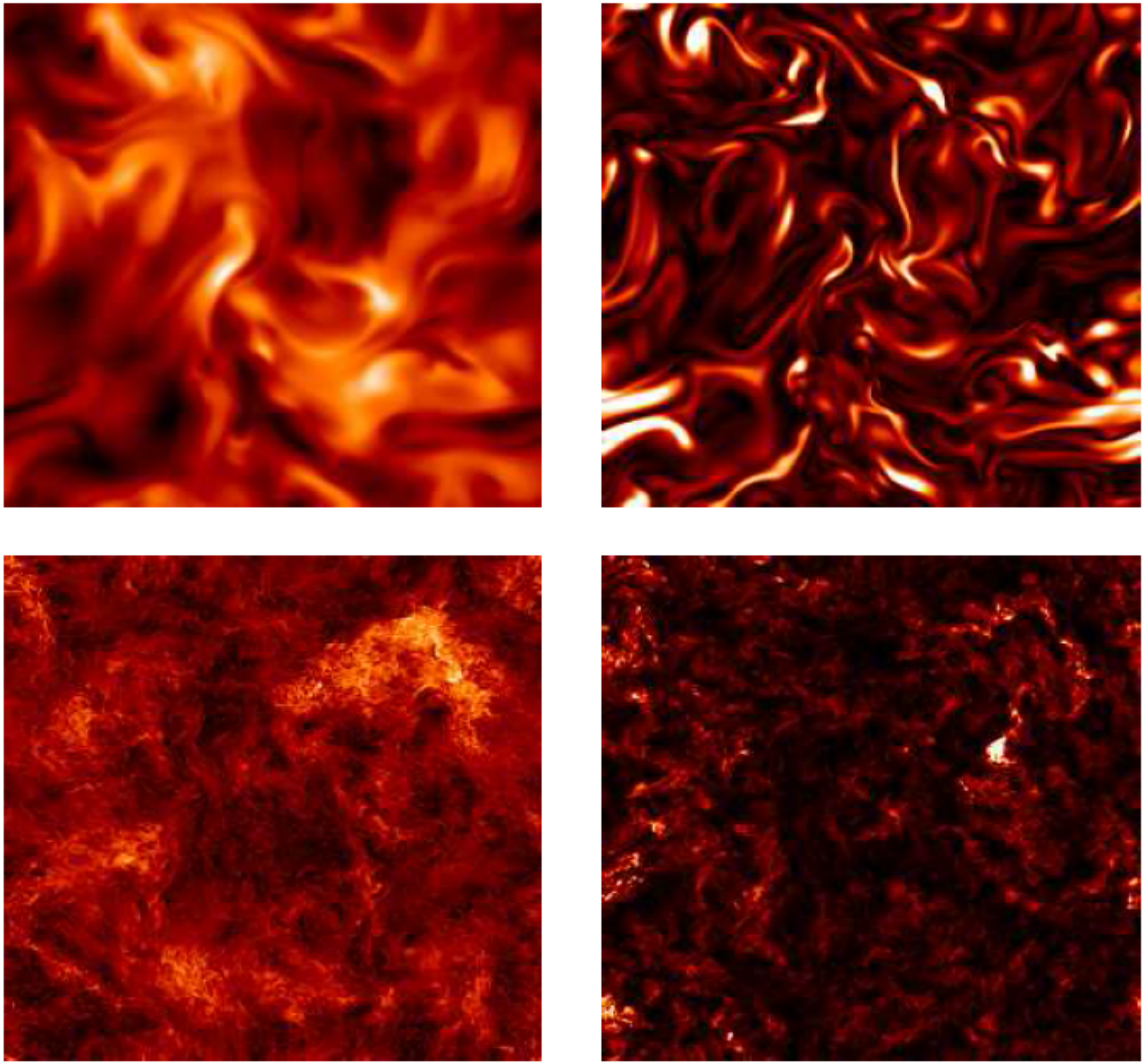


Kinetic Turbulence (Howes 2015)



1. B-field generation by small-scale turbulence

- B-field generation by small-scale turbulence
  Schekochihin et al.（2007, 2009）
- Small-scale system, B-field by dynamo
  large-scale system, B-field by Weibel instability
  （PIC, Schoeffler et al. 2016）
- Large scale B-field can be generated by dynamo, not suppressed by small-scale B-field
  （Squire & Bhattacharjee 2015）



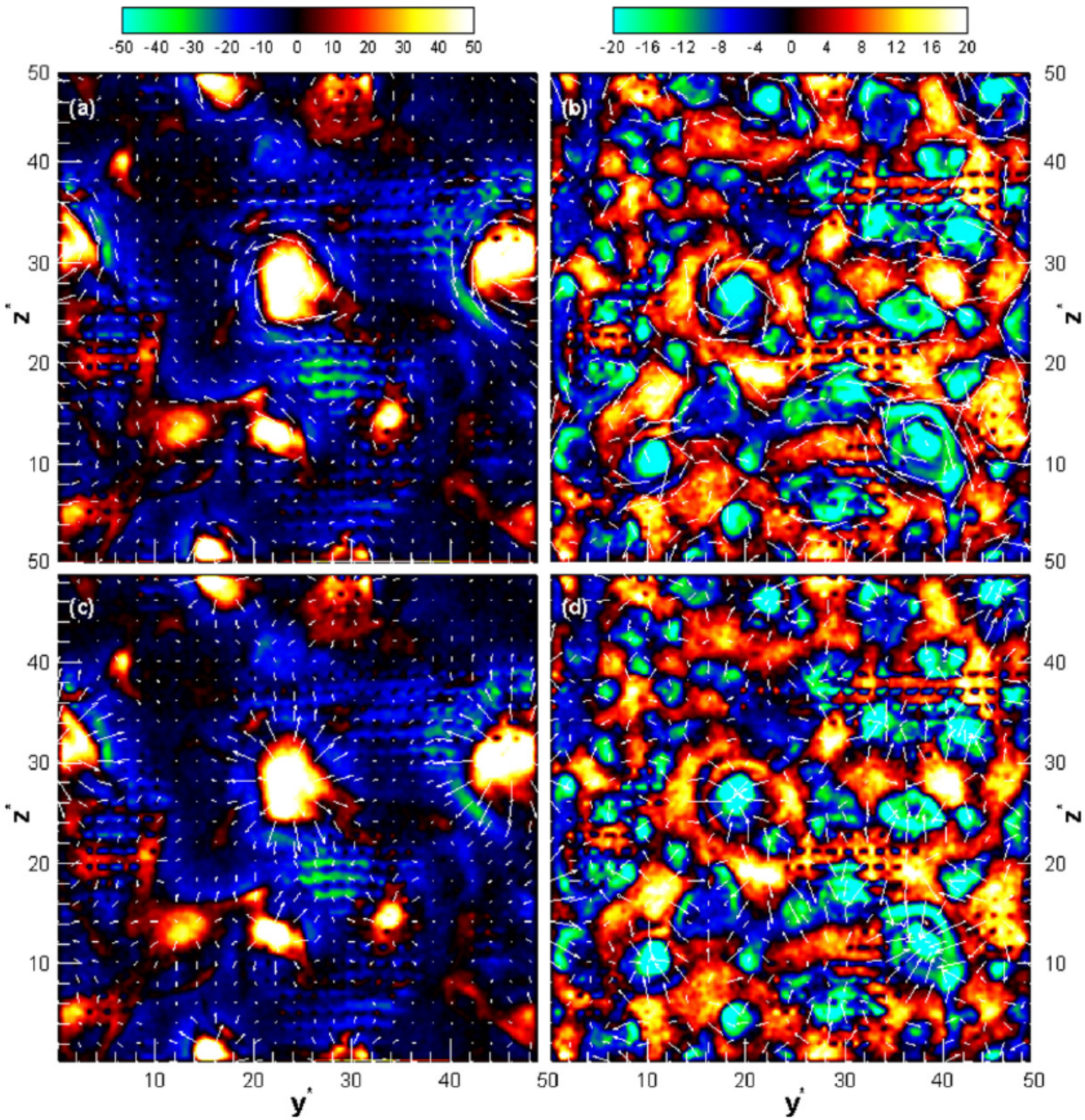
Schekochihin et al. 2007

2. B-field generation by plasma instabilities

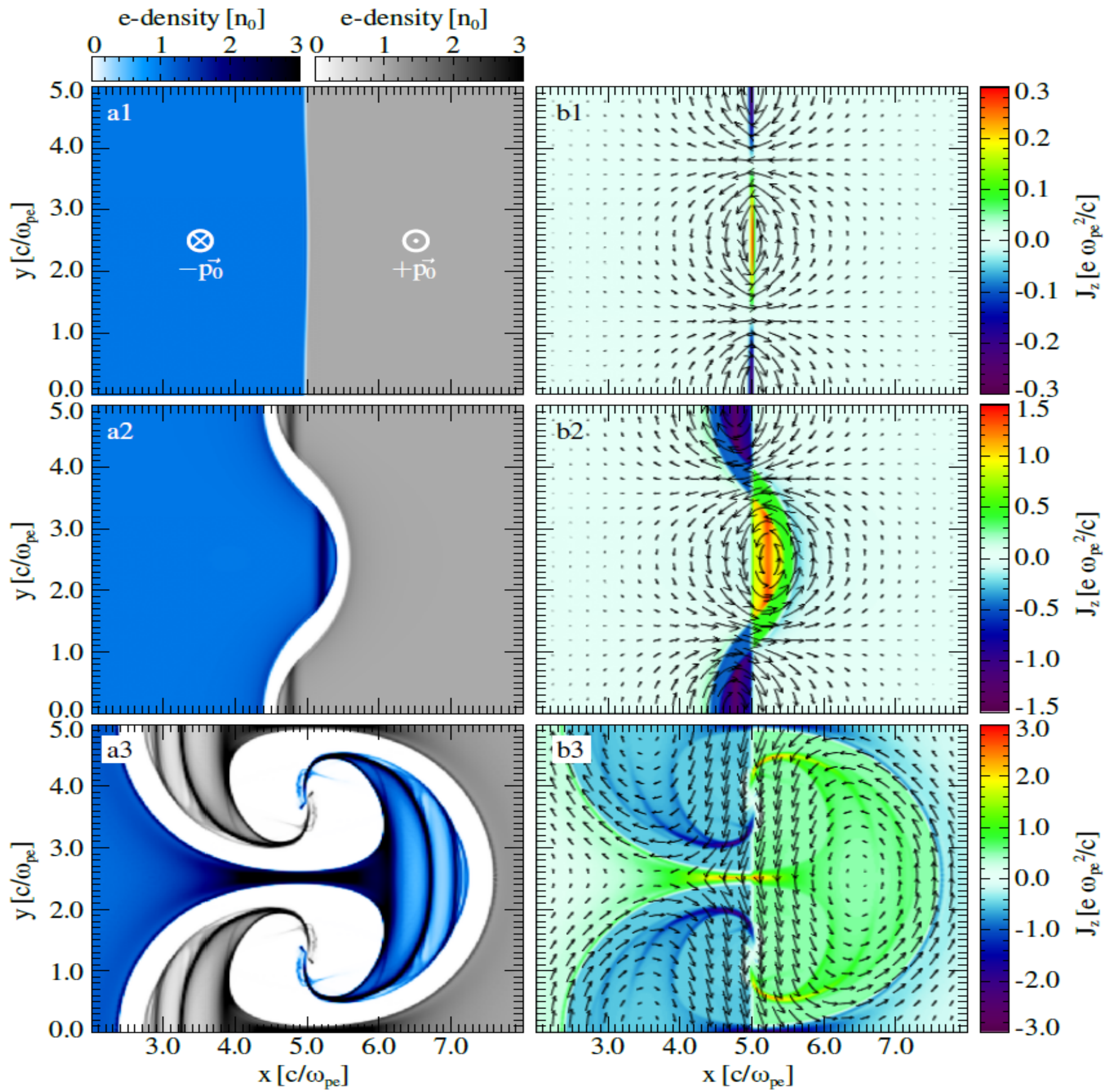
- Relativistic shear flow into cold gas: K-H instability generation in the electron scale, B-field generation
  (PIC, Alves et al. 2015)

- Relativistic shock interaction with surrounding medium
  electron filaments, Weibel instability, B-field generation and saturation, B-field and ion interaction, inverse shock, electron acceleration
  (PIC, Ardaneh et al. 2015)

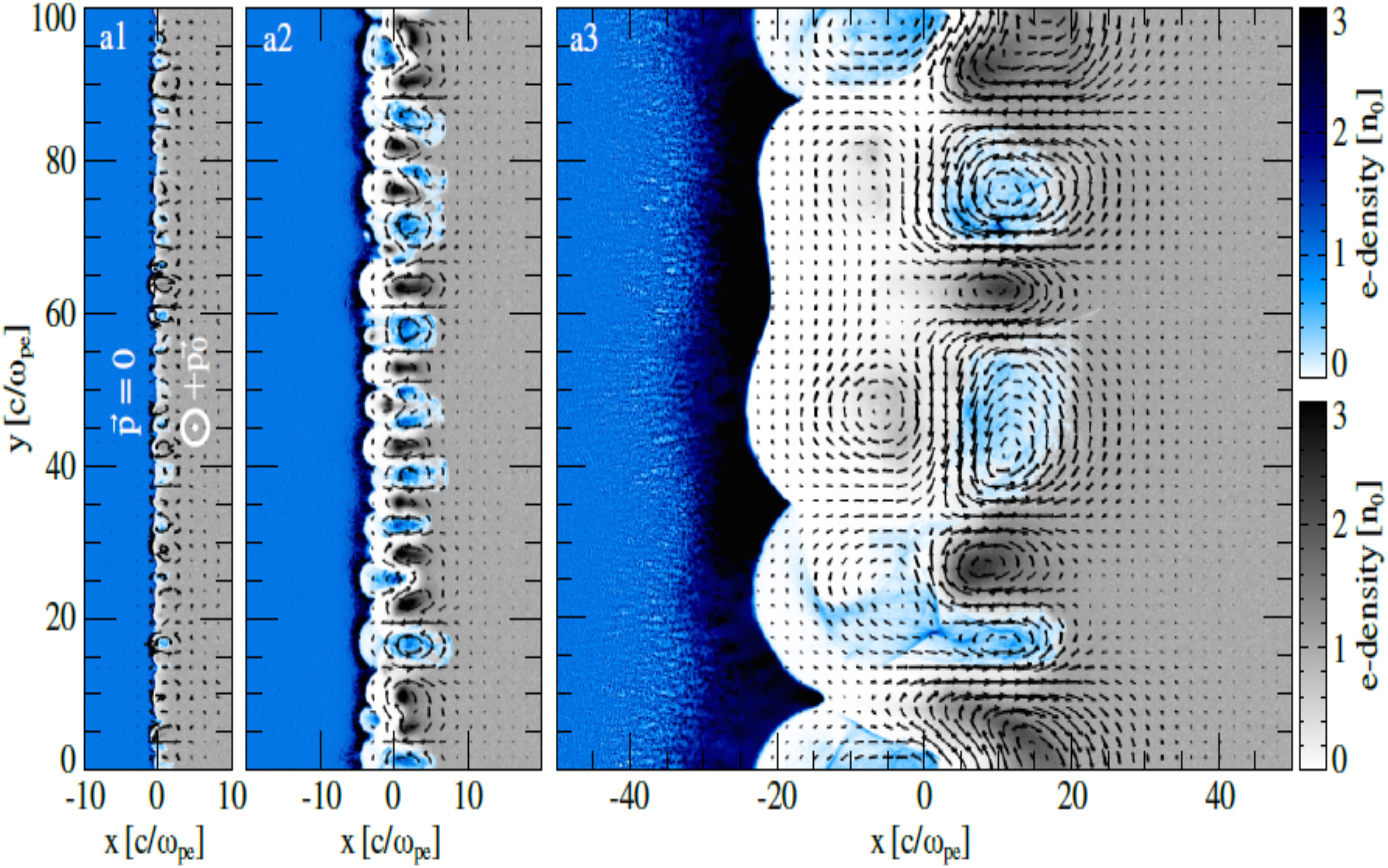
- application： relativistic jet propagation



Ardaneh et al. （2015）



Alves et al. (2015)



Alves et al. (2015)

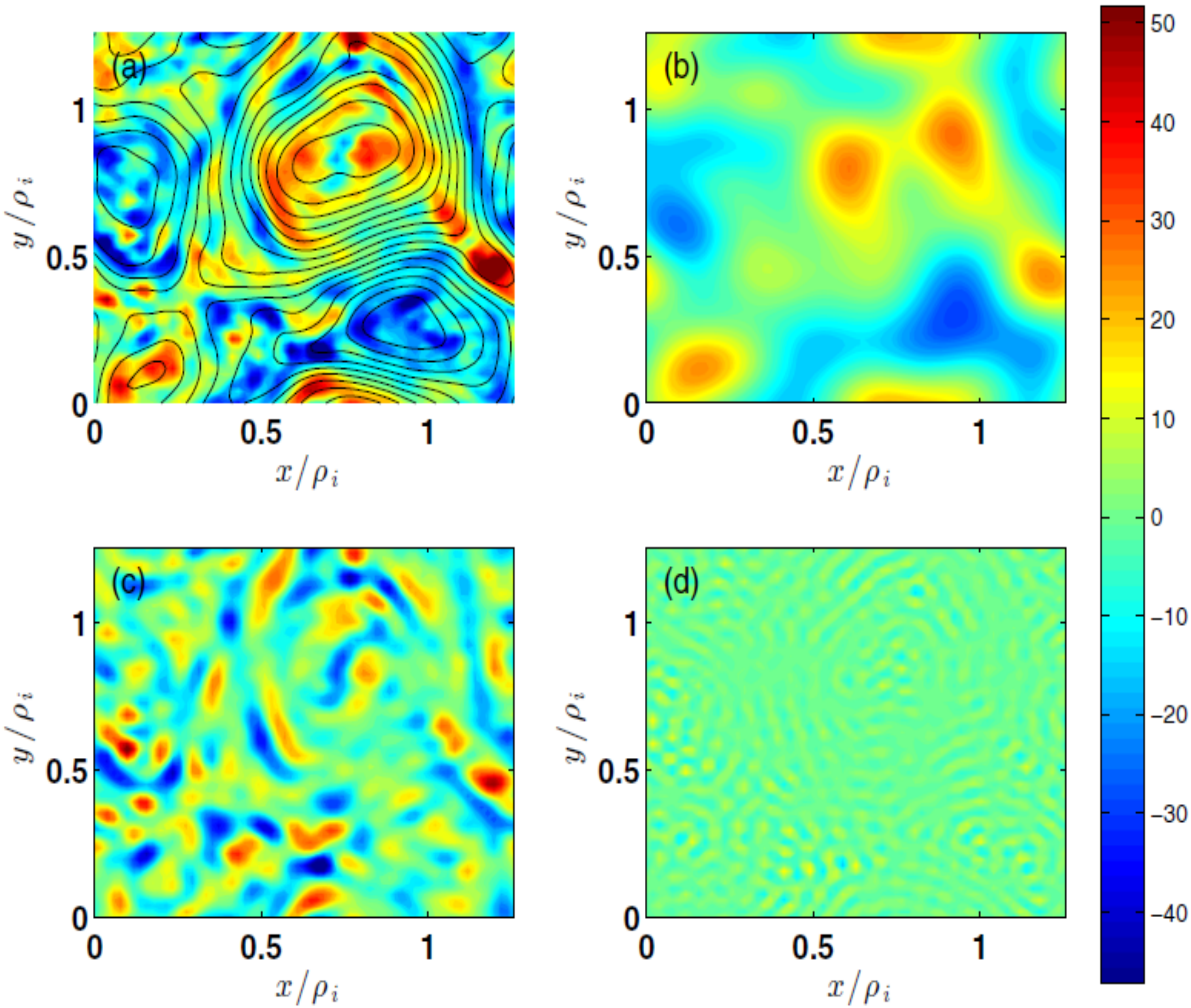
3. Plasma kinetic turbulence

- Hybrid： electron fluid, ion kinetic

  reconnection through Vlasov turbulence

  (Servidio et al. 2015)
- Kinetic Alfven wave (Vasconez et al. 2015)
- 2D and 3D Landau Damping (Li et al. 2015)
- Current sheet on electron scale generated by kinetic turbulence

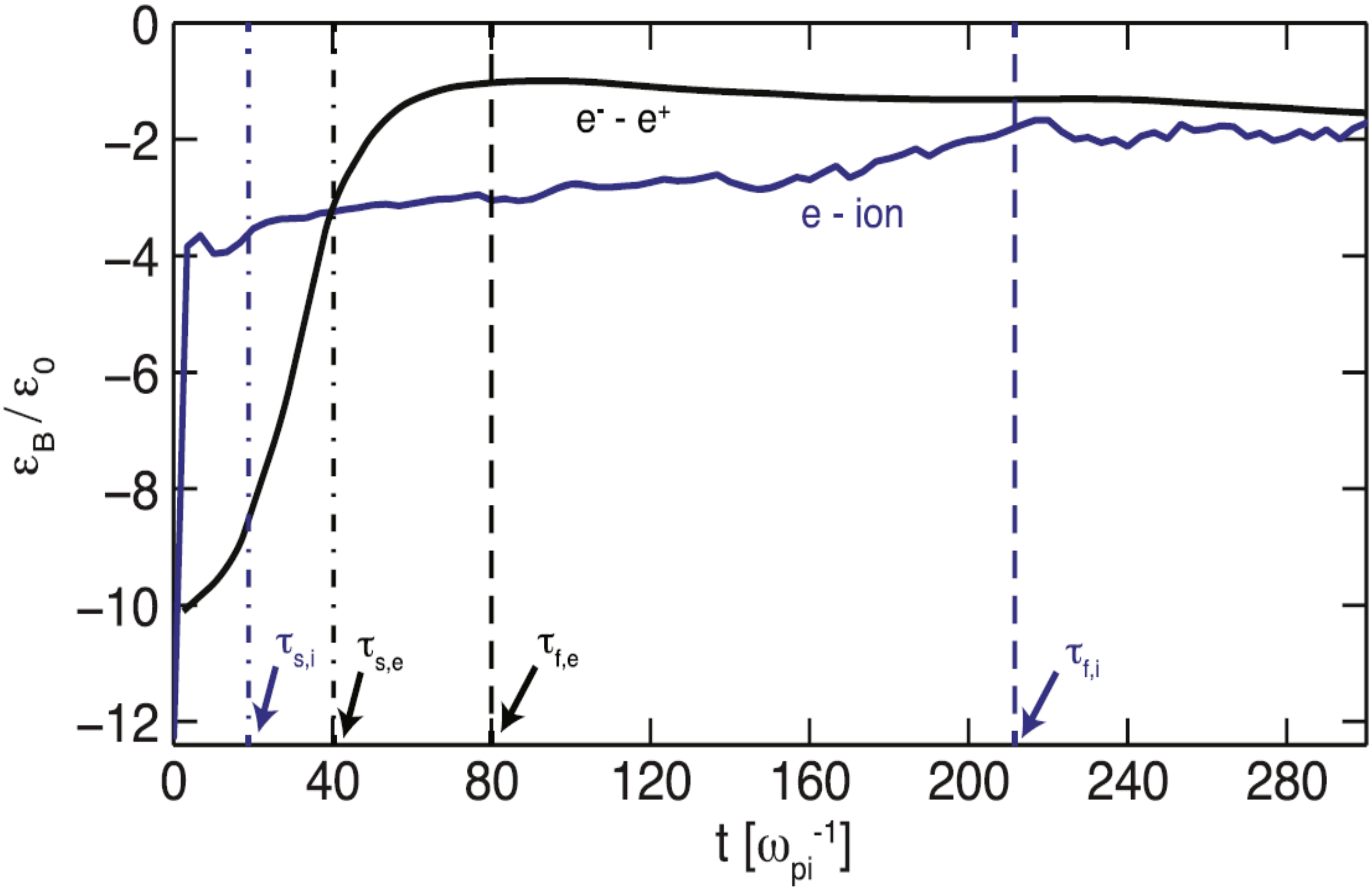
  (Tenbarge & Howes 2013)



Tenbarge & Howes (2013)

4. Collisionless shock

- Weibel instability due to Collisionless shock (Bret et al. 2014, Stockem Novo 2015)
- Acceleration at Weibel instability region, related to B-field formation, electrons scatted by turbulence, no electrons gyration (Lloyd-Ronning & Fryer 2016)
- B-field due to Weibel instability decay at shock front no way to acceleration
- Solve it: turbulence and/or particle injection

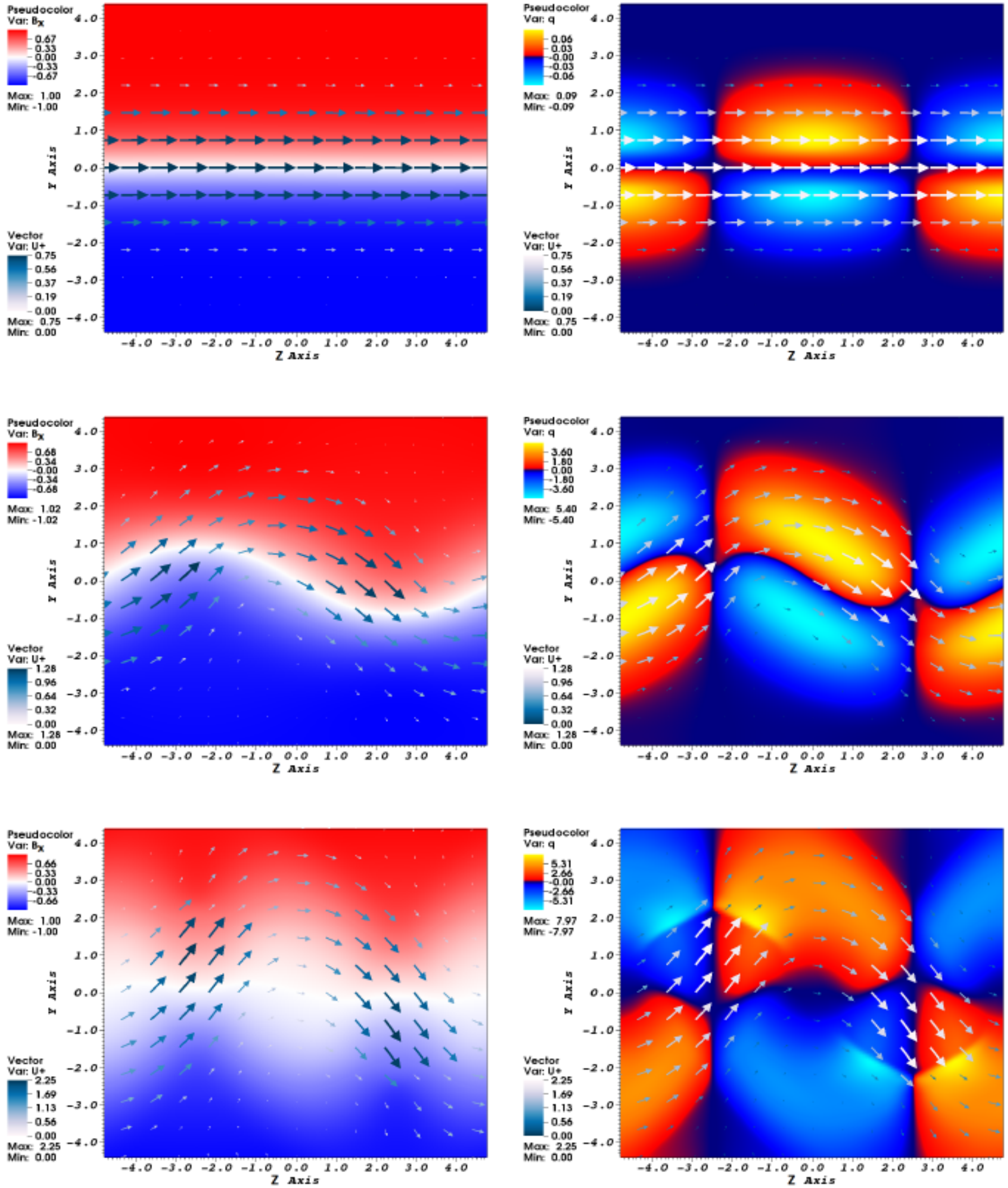


Alves et al. (2015)

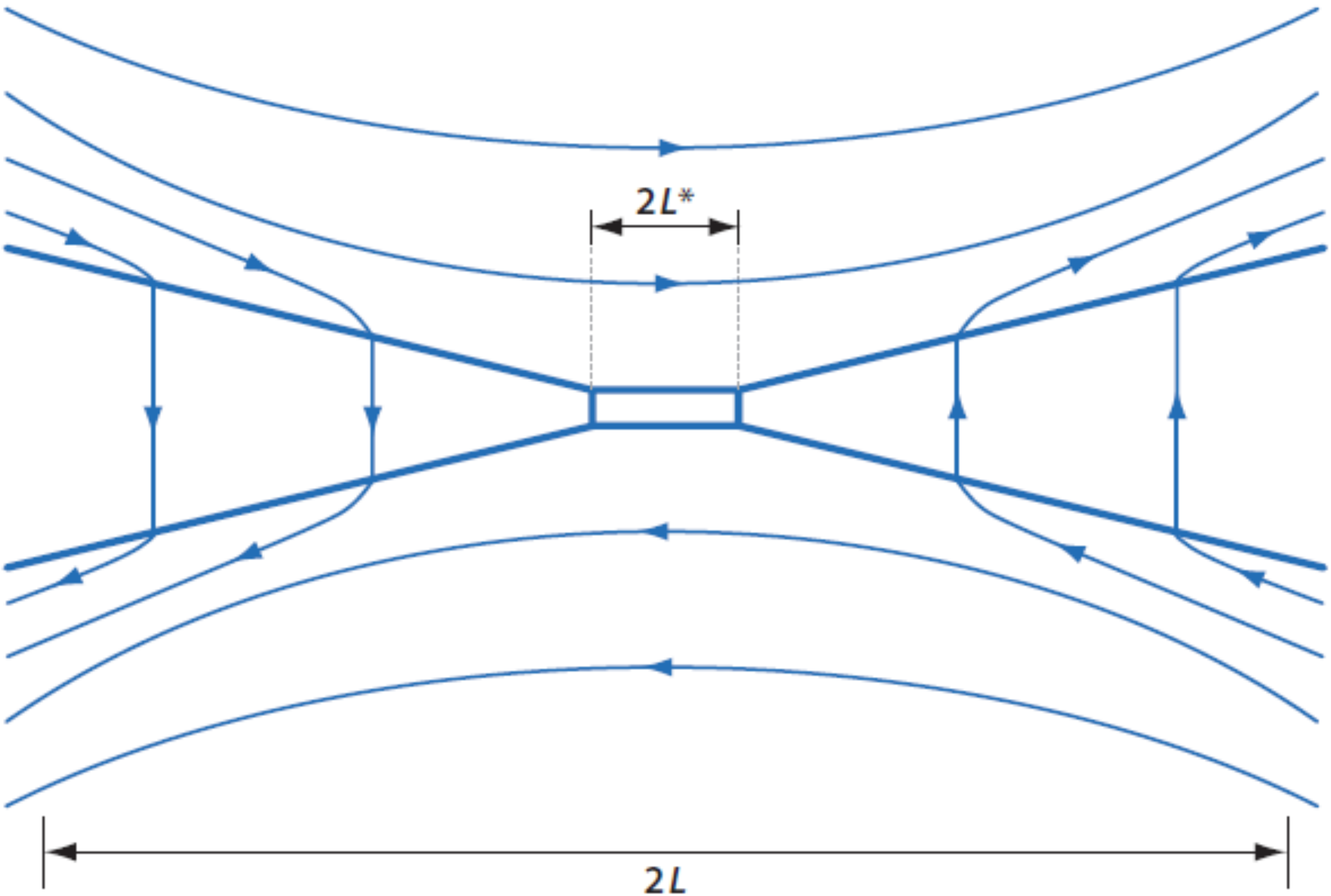
5. Two-fluid

- Relativistic two-fluid magnetic reconnection (Zentitani 2007)
- Initially set on the thickness of current sheet as electron skin depth (Barkov et al. 2014)
- Tear instability and kink instability,

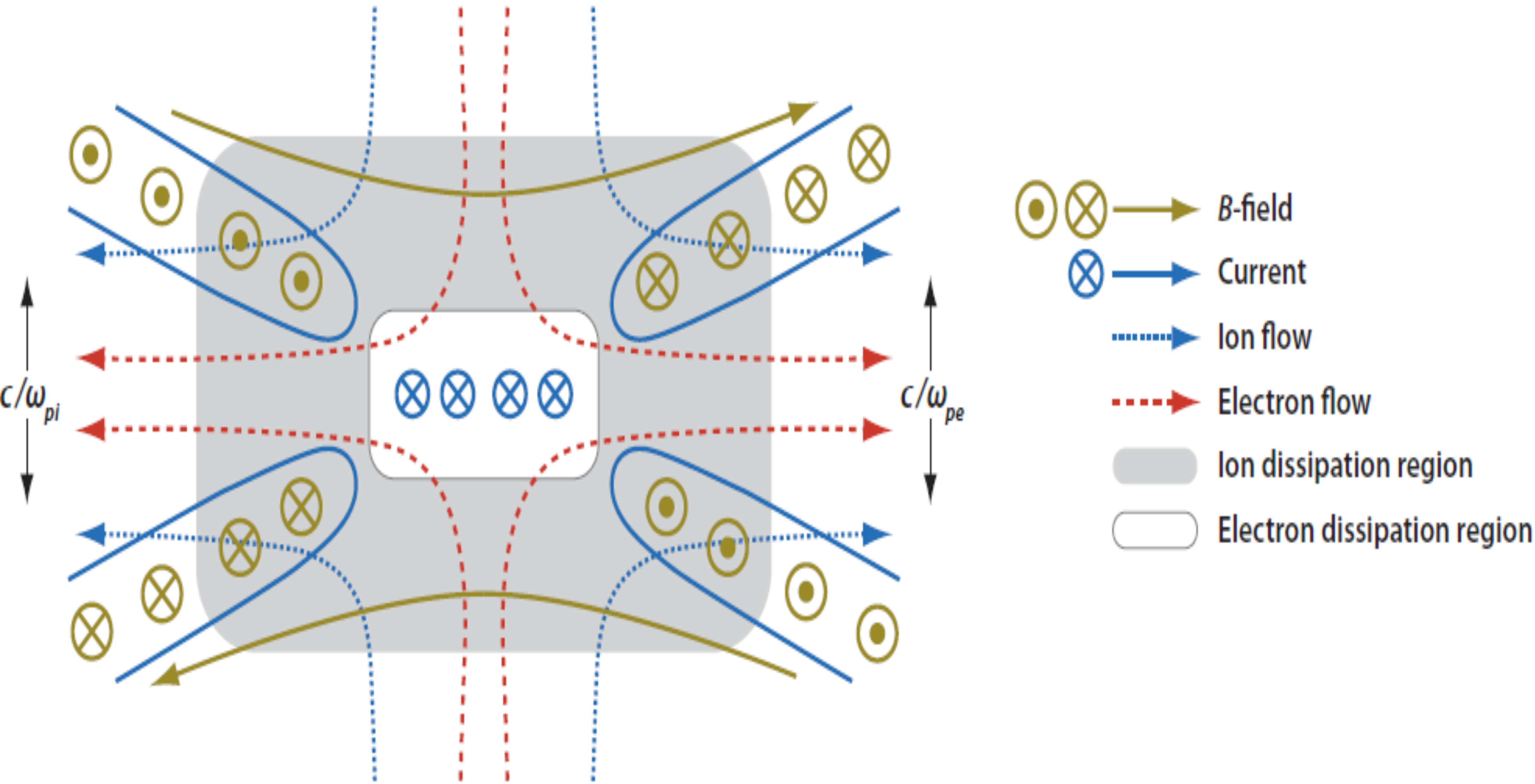
  shock formation (Barkov & Komissarov 2016)



Barkov & Komissarov (2016)



Zweibel & Yamada (2009)



Zweibel & Yamada (2009)

6.1 Collisionless reconnection

- 3D PIC magnetic tube and tear instability

  Turbulence accompanied with reconnection

  (Guo et al. 2015)

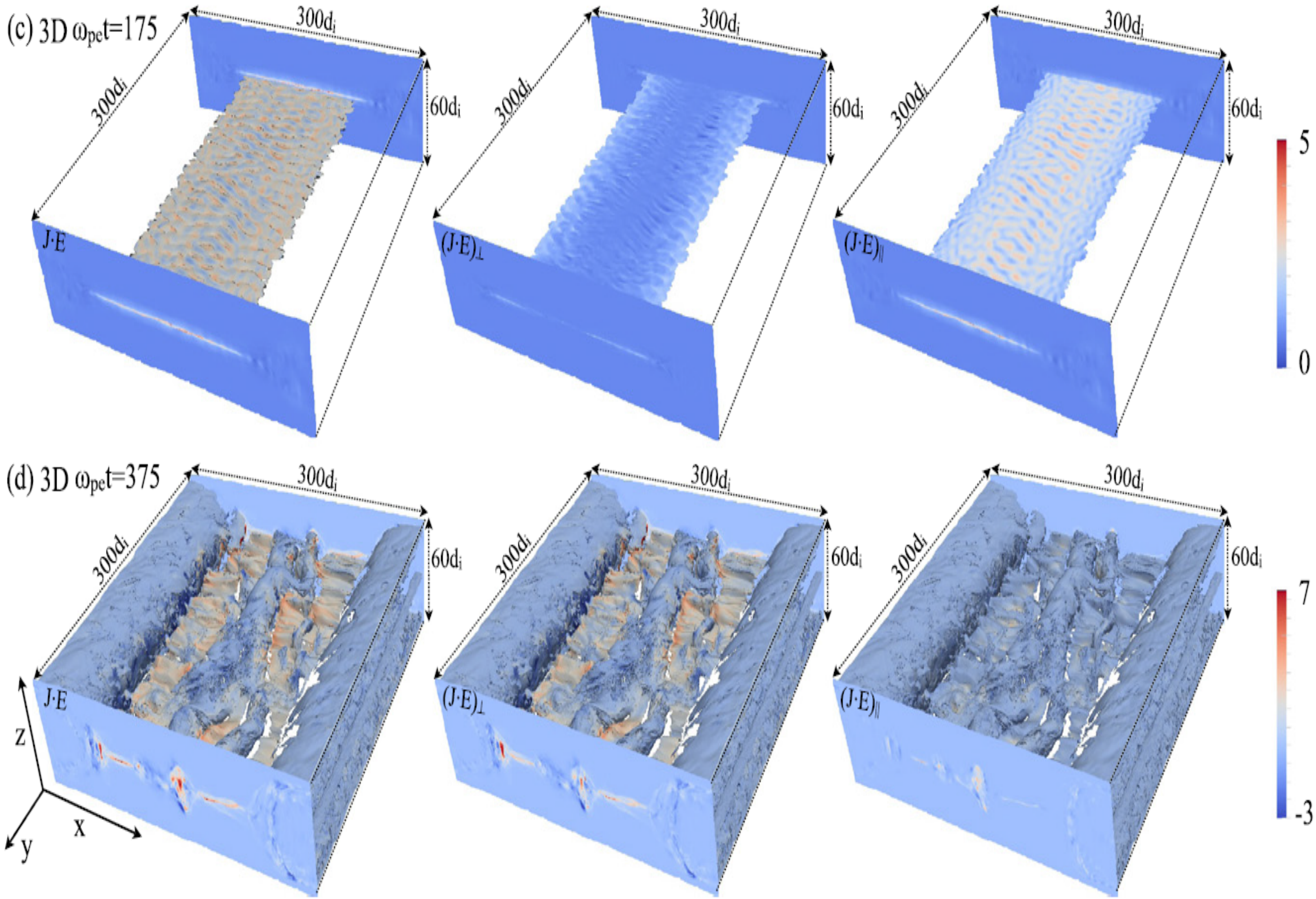
- island by tear instability， particle acceleration inside islands

  (nonrelativistic Li et al. 2015; relativistic Guo et al. 2014)

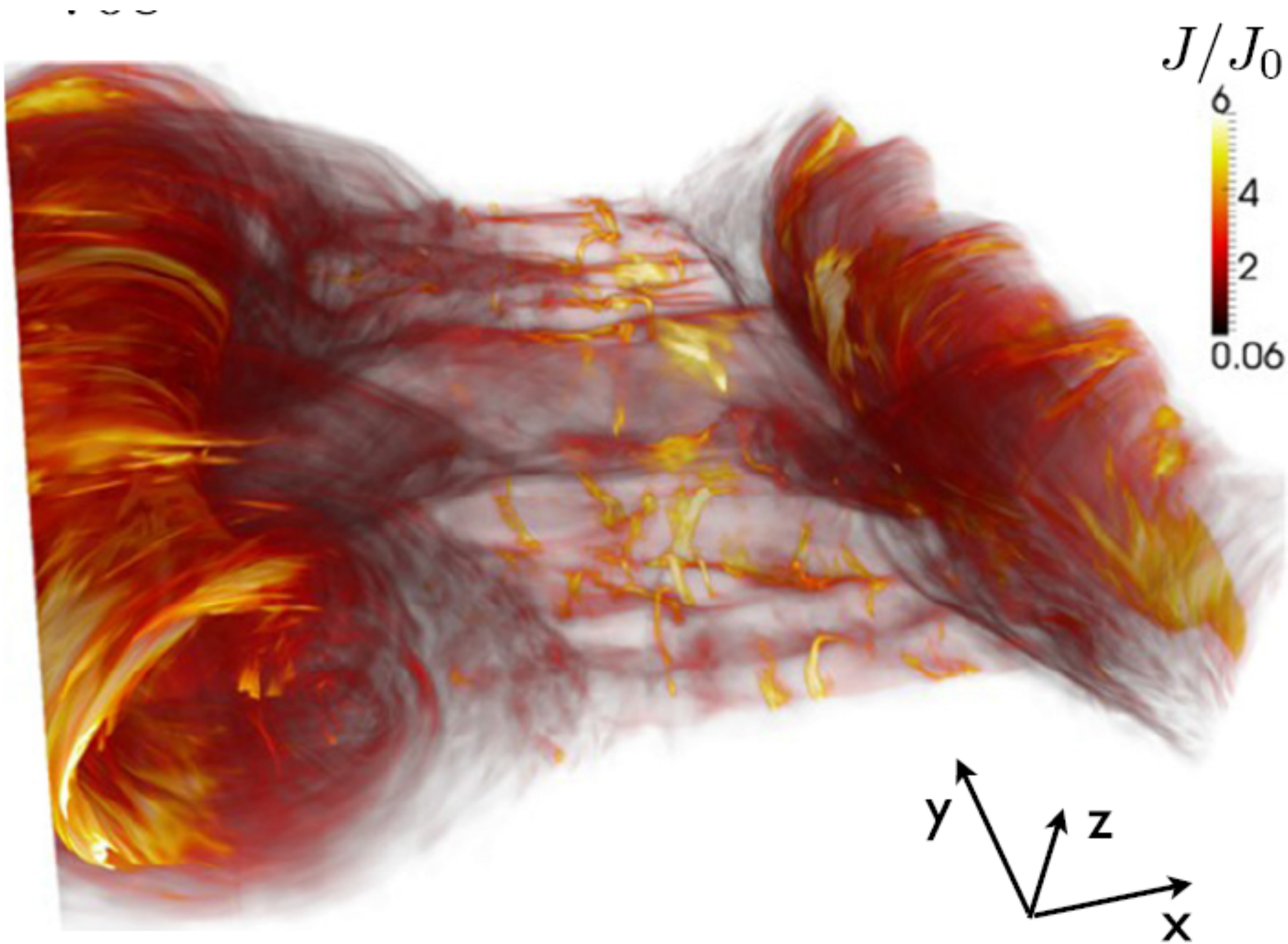
- larger lengthscale longer timescale (Sironi et al. 2016)

  particle distribution isotropic/anisotropic

  disruption of particle acceleration



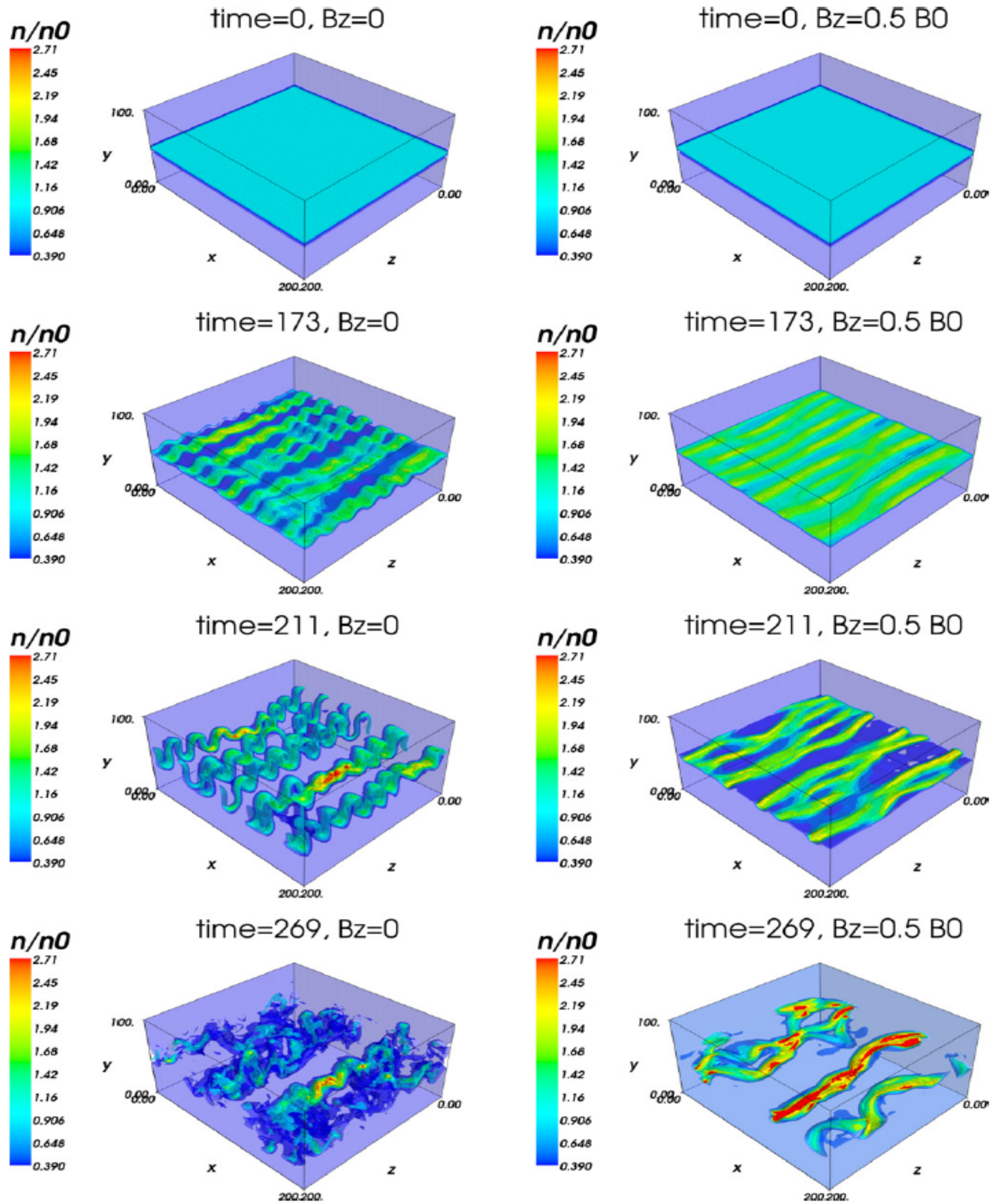
Guo et al. (2015)



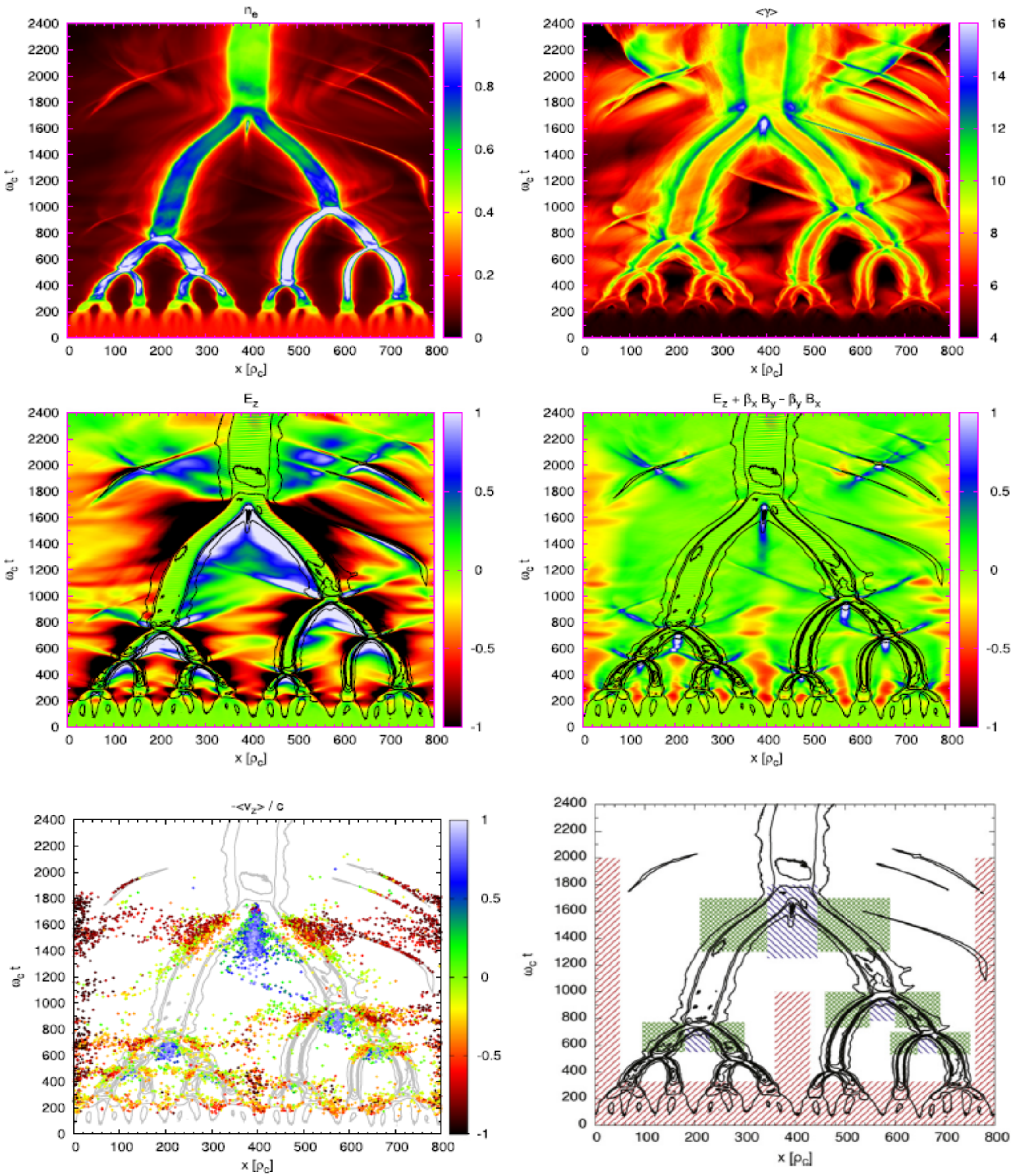
Guo et al. (2015)

6.2 Radiative collisionless reconnection

- Synchrotron cooling in magnetic reconnection (Cerutti et al. 2014)
  guild field: tear instability & acceleration are effective
  no guild field: kink instability depresses tear instability
  heating electrons, destroy acceleration
- Plasmoid dominated reconnection： tear instability makes plasmoids, merger, acceleration in merging region, power-law index 1.6 (Nalewajko et al. 2015)
- particle energy spectrum related to B-filed and radiation scale (Werner et al. 2016)



Cerutti et al. (2014)



Cerutti et al. (2014)

6.3 Particle orbit in collisionless magnetic reconnection

- A simple case: Speiser Orbit in radiative magnetic reconnection (Cerutti et al. 2013)
- Electron sheet inner region：

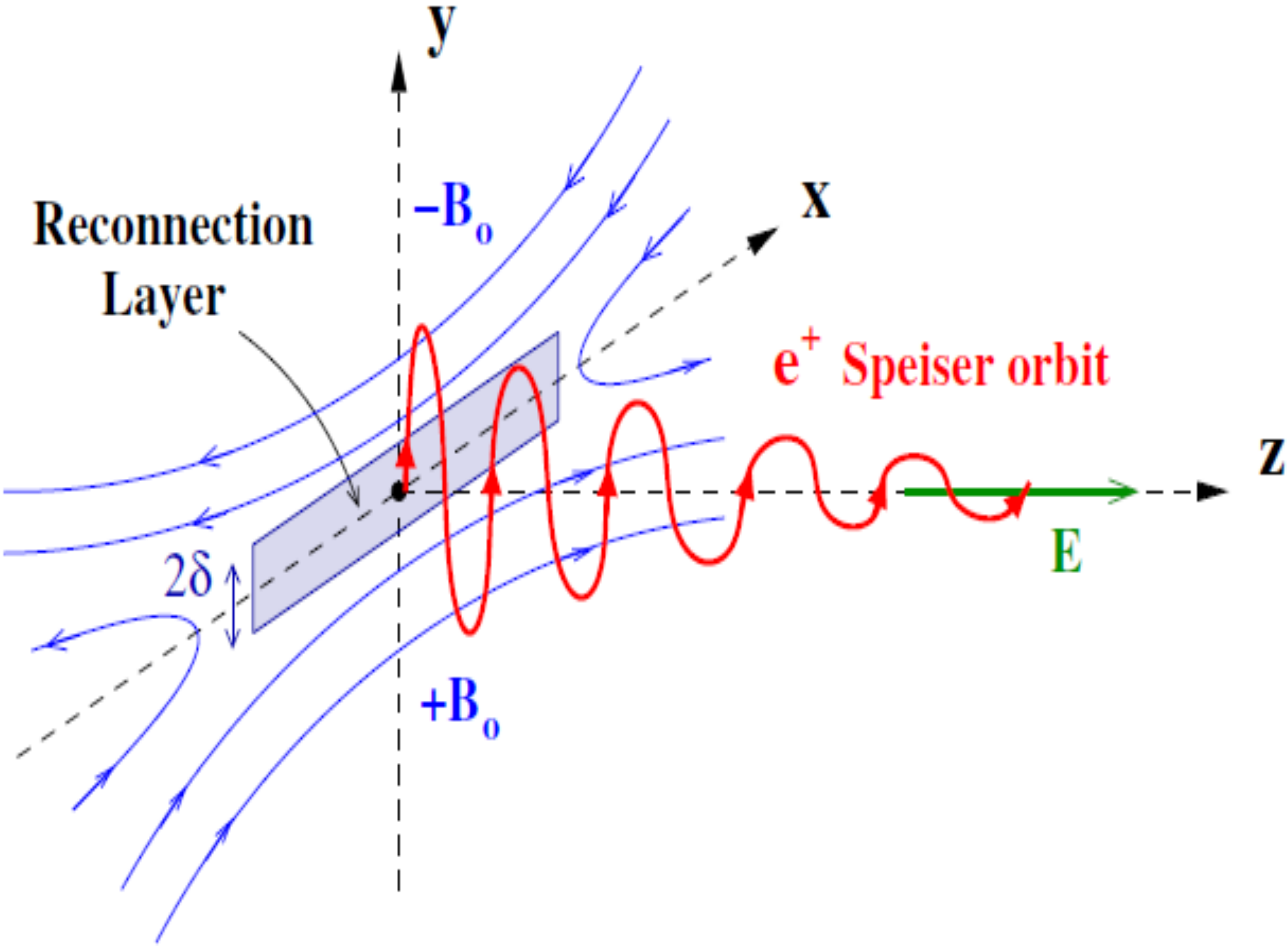
electron nongyrotropy behavior:

electron outflow region: figure-eight-shaped orbit

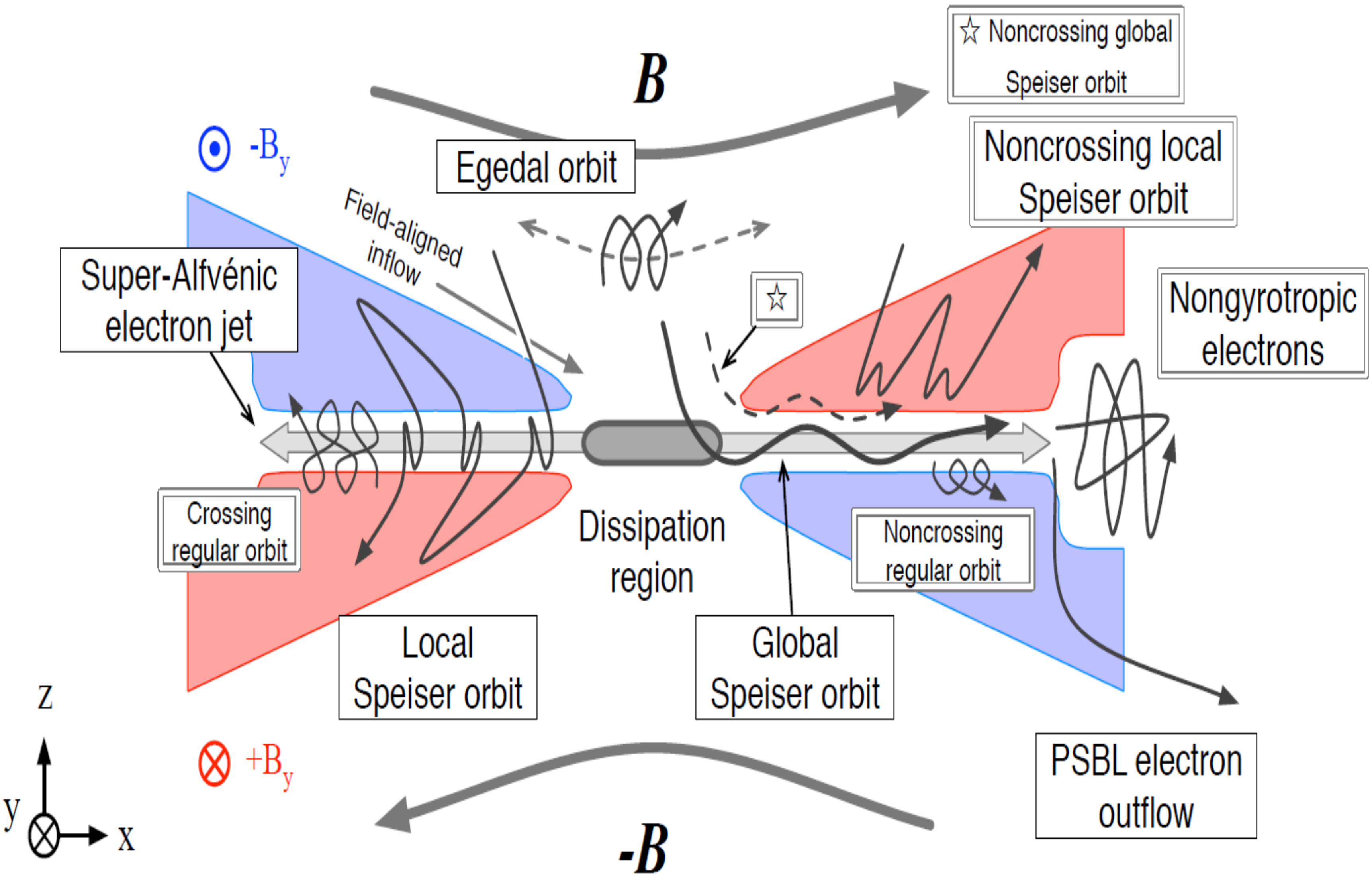
electron outflow edge: noncrossing regular orbit

noncrossing Speiser orbit

(Zenitani 2016)



Cerutti et al. (2013)



Zenitani et al. (2016)

7.1 Small-scale acceleration and radiation

- Long current sheet tear plasmoid merger

  energy spectrum: first, peak forms

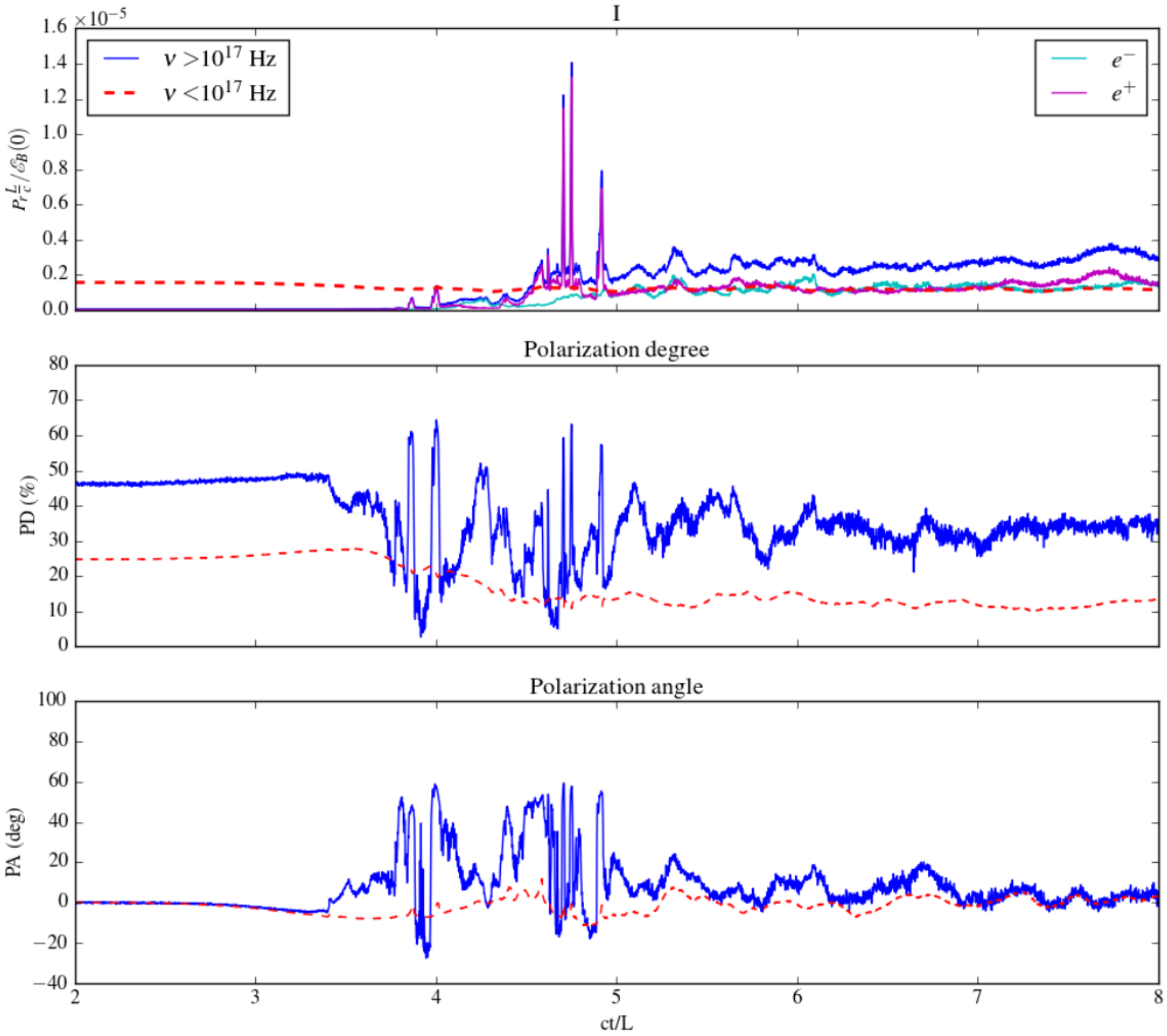
  high-energy tail power-law due to turbulence

  Radiation: short timescale variability and polarization

  radiation instantaneous

  radiation region: 10-20 gyro-radius

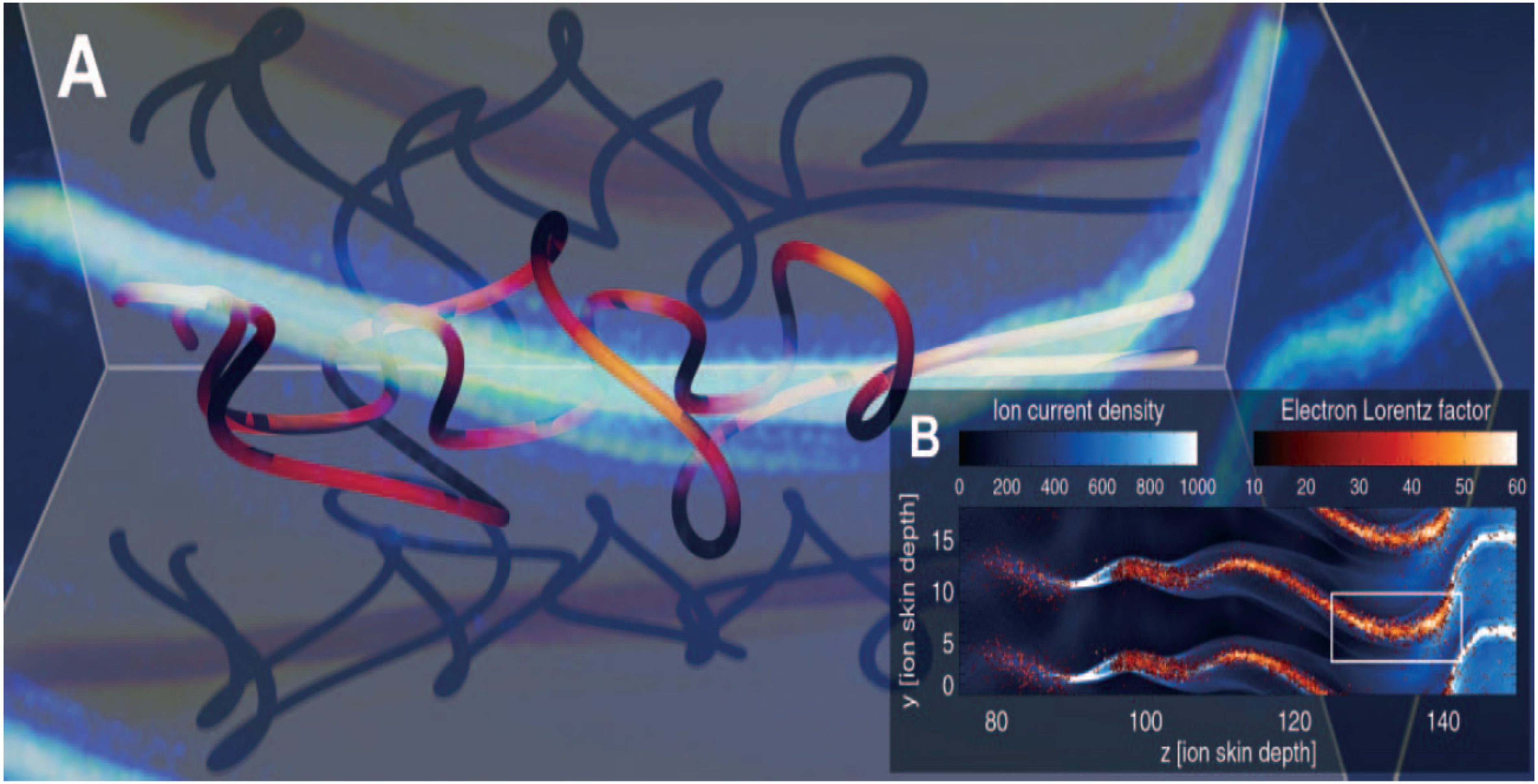
  (Yuan et al. 2016)



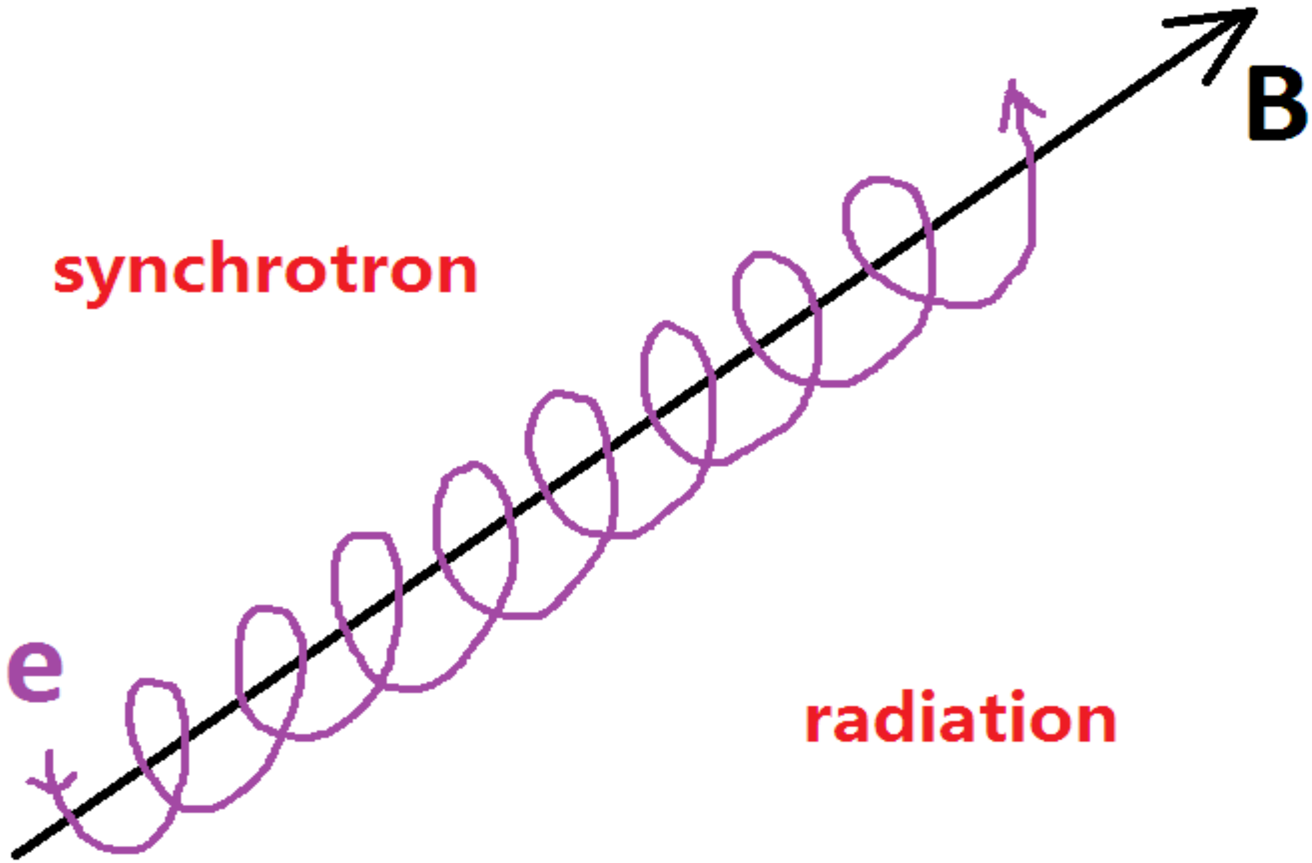
Yuan et al. (2016)

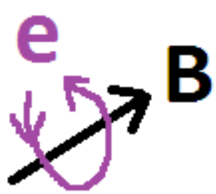
7.2 Radiation mechanism

- Relativistic electrons radiation in random and small-scale B-fields
- 3D PIC electron orbit
  (Hededal et al. 2004)
- Monte-Carlo simulation (Teraki & Takahara 2014)
- Deep research … …



Hededal et al. (2004)


synchrotron
radiation
e
B



still cyclotron/synchrotron moving?

electron random walk inside
random & small-scale fields

special case: electron "collision"
with magnetic elements keeping
same velocity direction
---- jitter radiation

Jitter radiation (Mao & Wang ApJ, 2007, 2011, 2012, 2013)

The Astrophysical Journal, 669: L13–L16, 2007 November 1

KNOT IN CENTAURUS A: A STOCHASTIC MAGNETIC FIELD FOR DIFFUSIVE SYNCHROTRON RADIATION?

Jirong Mao and Jiancheng Wang

The Astrophysical Journal, 731:26 (6pp), 2011 April 10 doi:10.1088/0004-637X/731/1/26

GAMMA-RAY BURST PROMPT EMISSION: JITTER RADIATION IN STOCHASTIC MAGNETIC FIELD REVISITED

Jirong Mao[1,2,3,4] and Jiancheng Wang[3,4]

The Astrophysical Journal, 748:135 (6pp), 2012 April 1 doi:10.1088/0004-637X/748/2/135

JITTER SELF-COMPTON PROCESS: GeV EMISSION OF GRB 100728A

Jirong Mao[1,2,3] and Jiancheng Wang[2,3]

The Astrophysical Journal, 776:17 (9pp), 2013 October 10 doi:10.1088/0004-637X/776/1/17

APPLICATION OF JITTER RADIATION: GAMMA-RAY BURST PROMPT POLARIZATION

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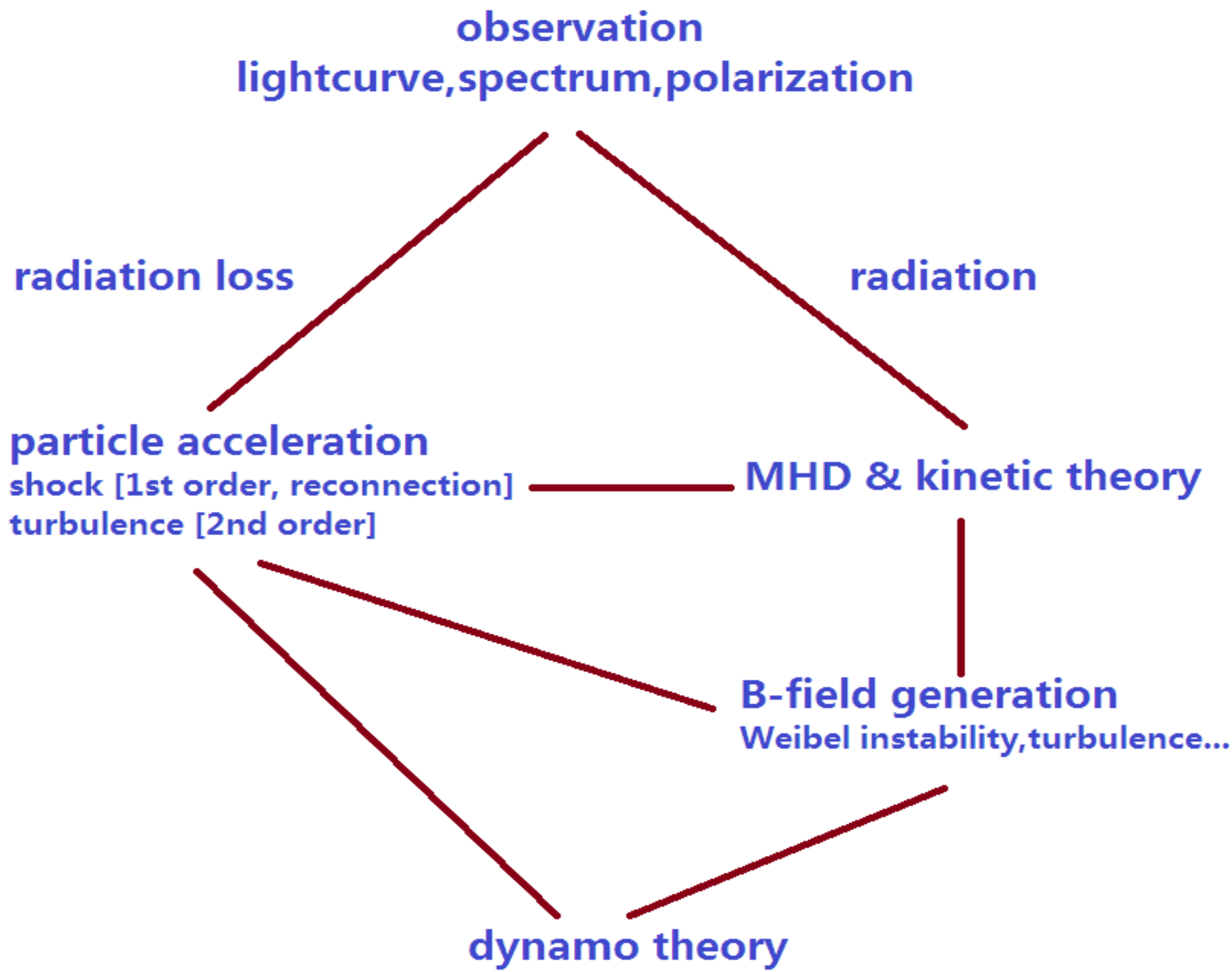
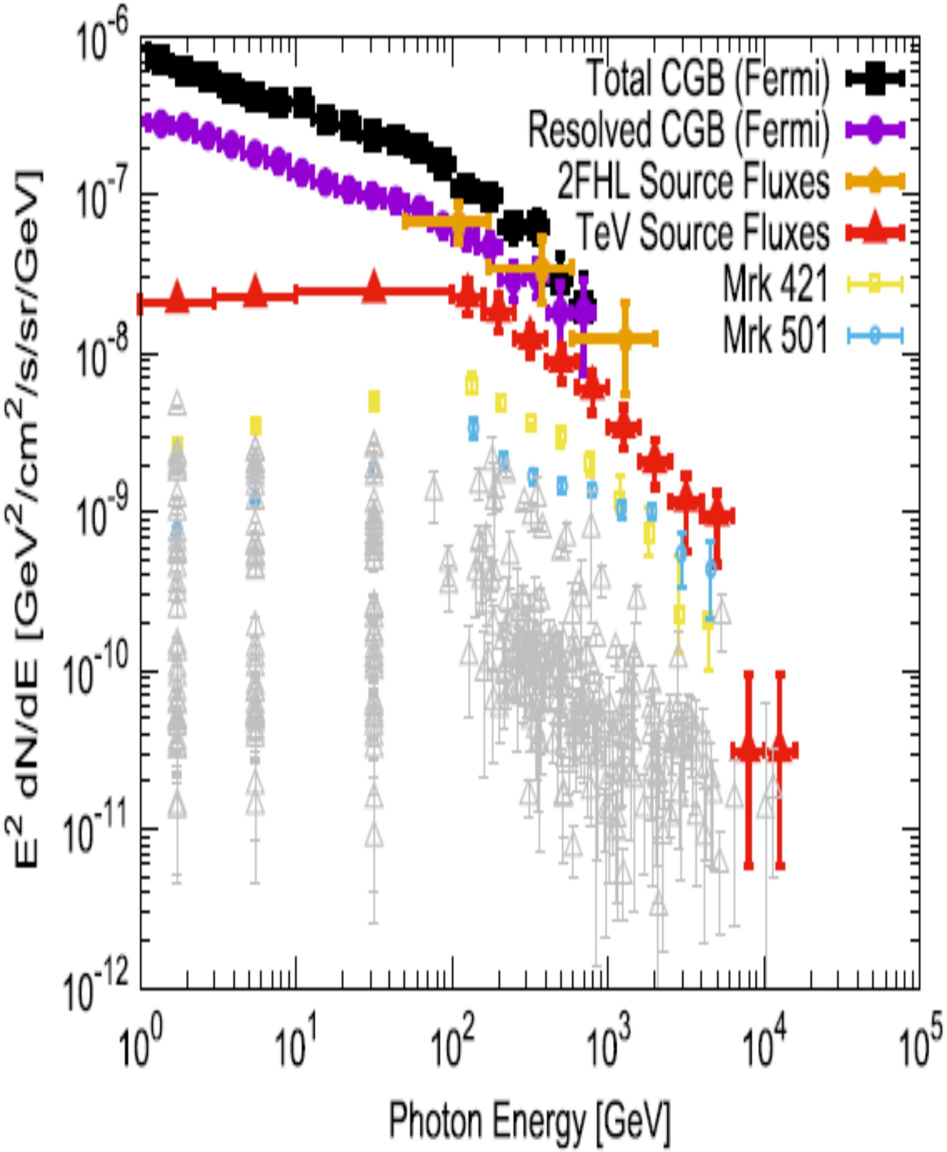

observation
lightcurve,spectrum,polarization
radiation loss
radiation
particle acceleration
shock [1st order, reconnection]
turbulence [2nd order]
MHD & kinetic theory
B-field generation
Weibel instability,turbulence...
dynamo theory

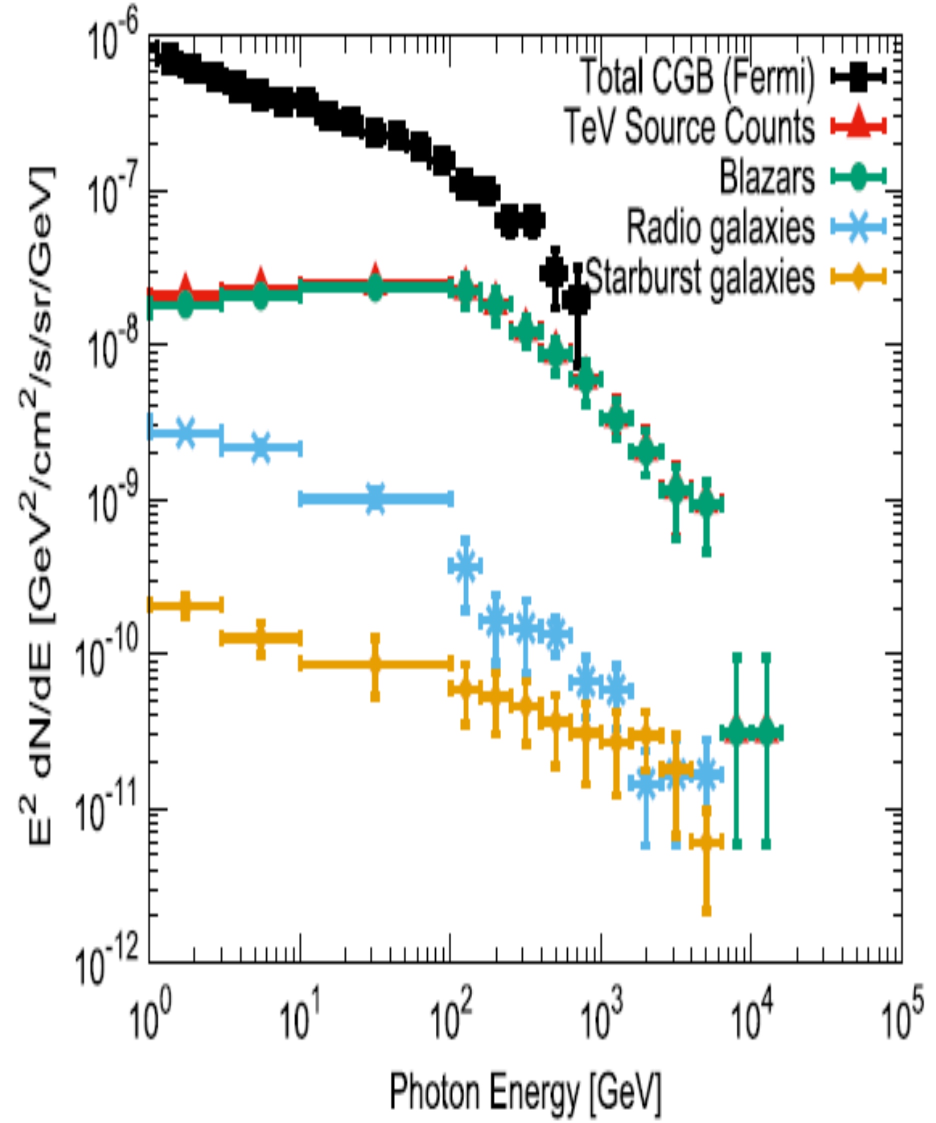
LHAASO Detection

- All high-energy sources to background

- Possibility of single source detection

TeV Background: LHAASO ?





Inoue & Tanaka 2016

LHAASO Single Source Detection

- Difficulty: original position of particles
  large angle in sky, interaction with cosmic B-field
- GRB, AGN flare, SN explosion:
  almost simultaneously photons + particle
- Multi-wavelength detection of an event
  TeV + (GeV, X-ray, optical, radio)+(GW, neutrino)

Solving Problems with LHAASO

- How many sources contributed to LHAASO detection? Monte-Carlo simulation
- Theoretical model: B-field dominated physics
  (1) radiation mechanism
  (2) generation: reconnection-particle energy released?
  (3) propagation: cascade process or particle-induced turbulence?
- Observation: cooperation with LHAASO
  optical & radio telescopes @YNAO
- Data analysis of LHAASO

New Detections + New Models
Astrophysics + High-energy Physics