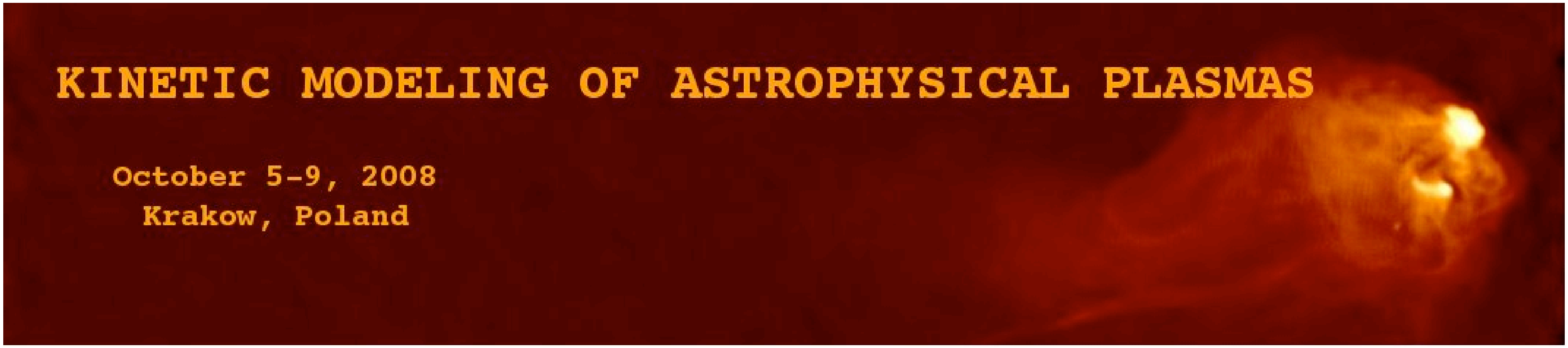

KINETIC MODELING OF ASTROPHYSICAL PLASMAS

October 5-9, 2008
Krakow, Poland

Relativistic Current Sheets in Electron-Positron Plasmas

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Outline

- Introduction

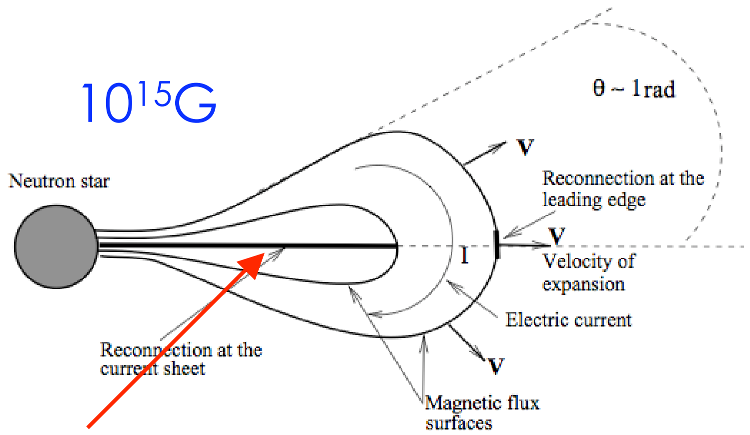
- Basic processes in a relativistic current sheet
  - 2D Reconnection
  - 2D Drift Kink Instability
  - 3D Evolution
  - 3D Guide field effect
  - Weibel instability

- Discussions
- Large-scale MHD problem (option)

- Summary + Open questions

Sites of relativistic current sheets

- <u>Pulsar winds</u>
  - Magnetic dissipation in relativistic outflow of electron positron plasma winds
- <u>Magnetars</u>
  - giant flare models for SGR
- Various potential sites
  - Active galactic nuclei
  - Gamma ray bursts



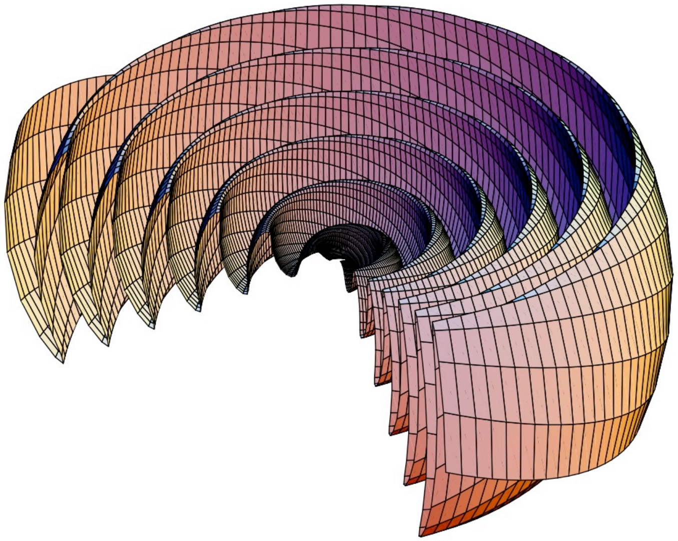
10^{15}G

Reconnection
in the current sheet

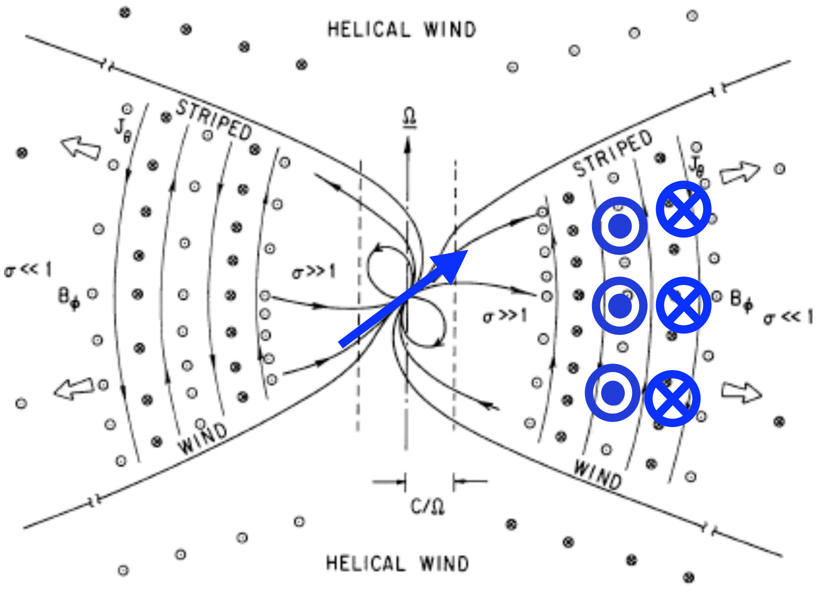
Lyutikov 2006 MNRAS

Striped pulsar wind

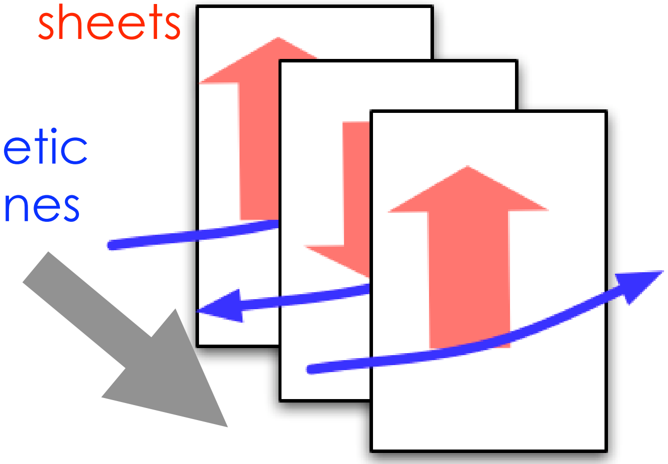
- Magnetic dissipation process is highly demanded in the striped current sheets (Coroniti 1990 ApJ, Lyubarsky & Kirk 2001 ApJ, Kirk & Skjaeraasen 2003 ApJ)



Kirk et al. 2007 astroph/0703116



Coroniti 1990 ApJ



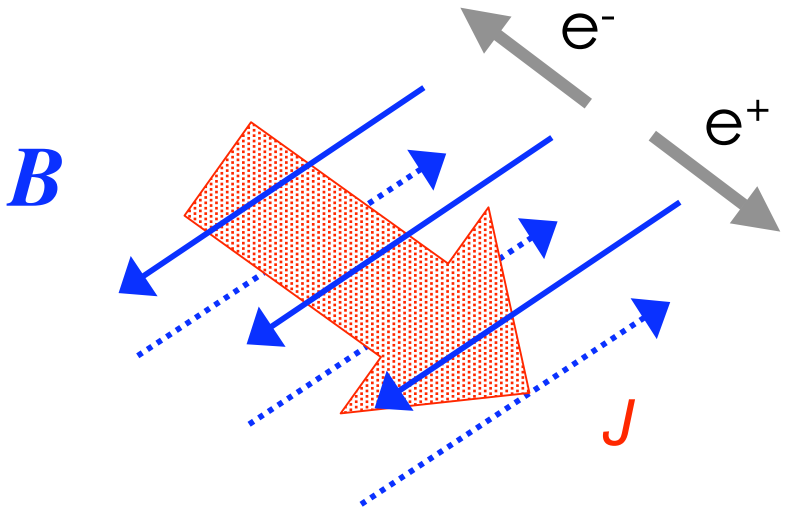
current sheets

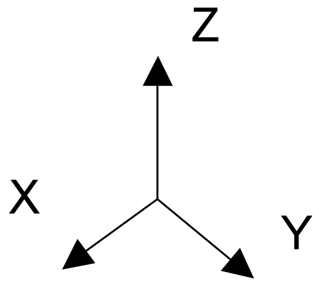
magnetic field lines

e$^+$, e$^-$ flow

Basic processes
in a relativistic current sheet

Relativistic Current Sheet (RCS)



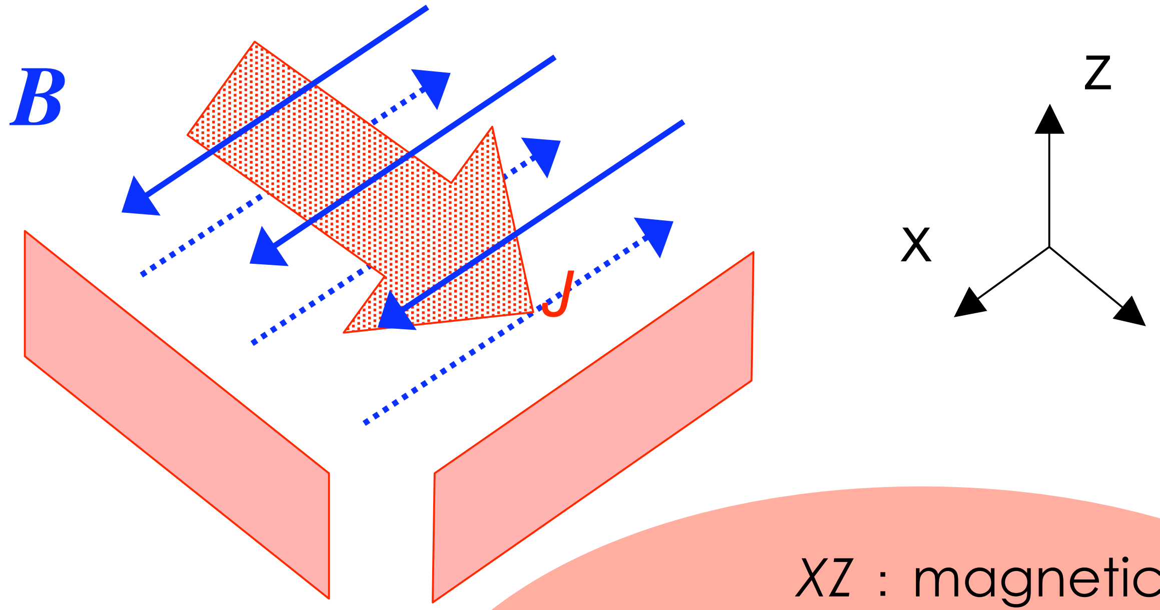


- Antiparallel magnetic field lines
- Dense plasma current sheet at the center
- Current : the counter-streaming of electrons and positrons
- Relativity : T~mc^2, c$_A$ ~ c
- Relativistic Harris model (Hoh 1966, Kirk & Skjaeraasen 2003)

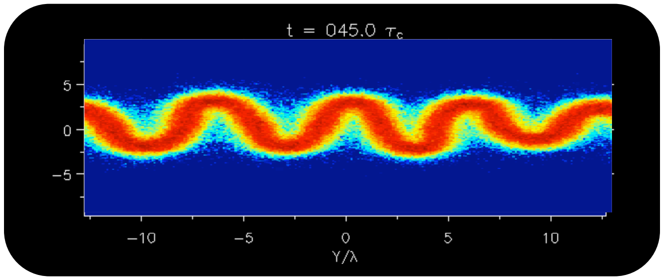
$$B = B_0 \tanh(z/\lambda)\hat{x}$$

$$f_s = \frac{n_0}{4\pi m^2 c T K_2(mc^2/T)} \cosh^{-2}(z/\lambda) \exp\left[- \frac{\gamma_s(\varepsilon - \beta_s m c u_y)}{T} \right]$$

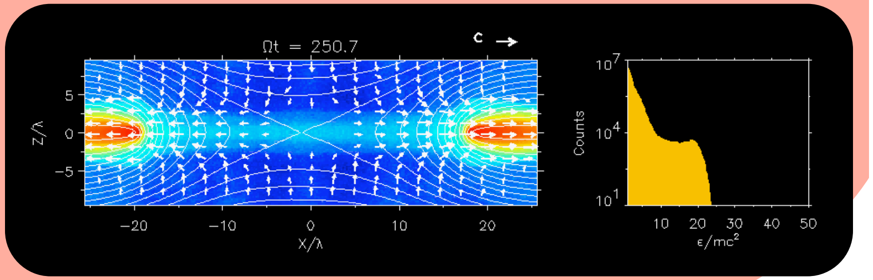
Magnetic Reconnection (RX)



YZ : drift kink instability (DKI)

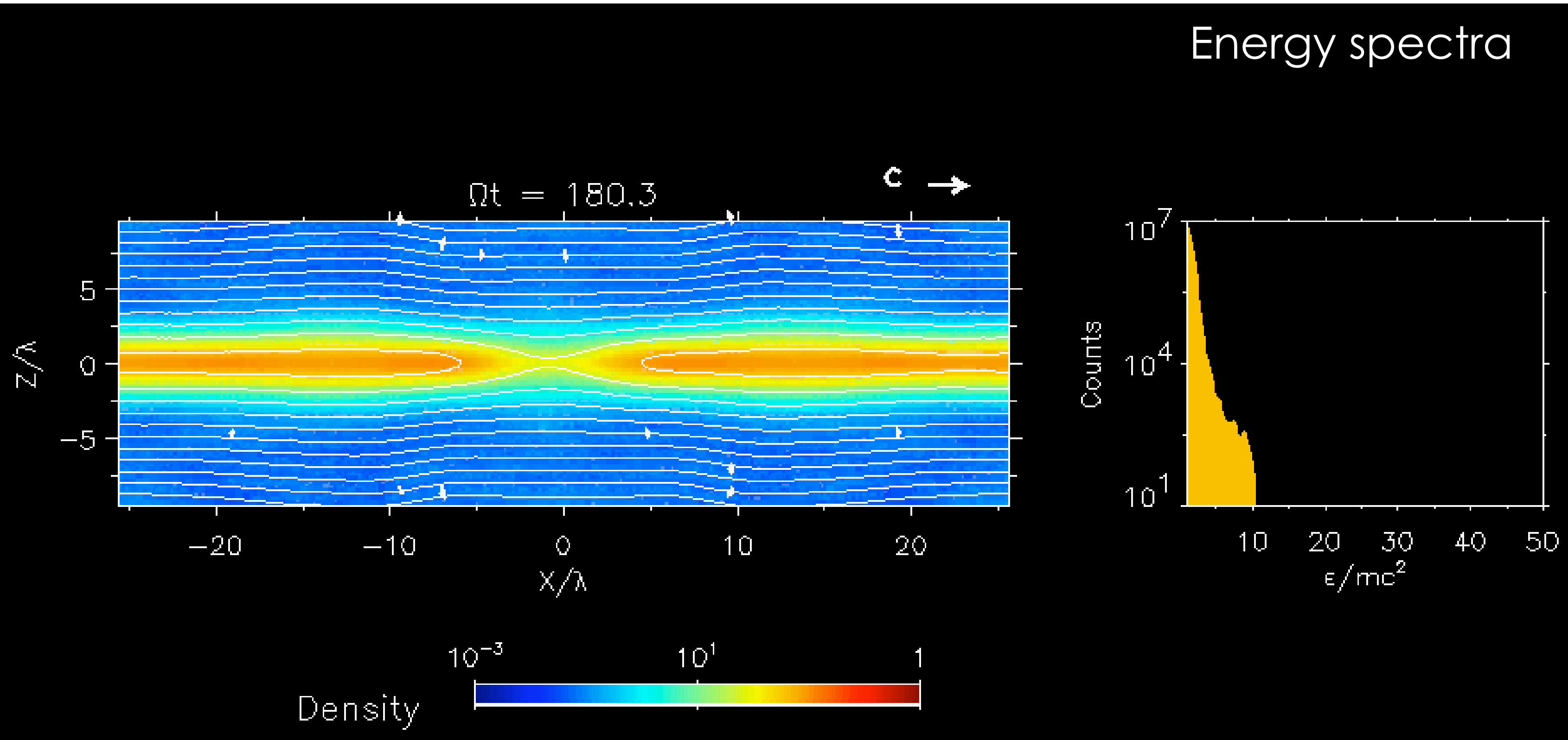


XZ : magnetic reconnection (RX)

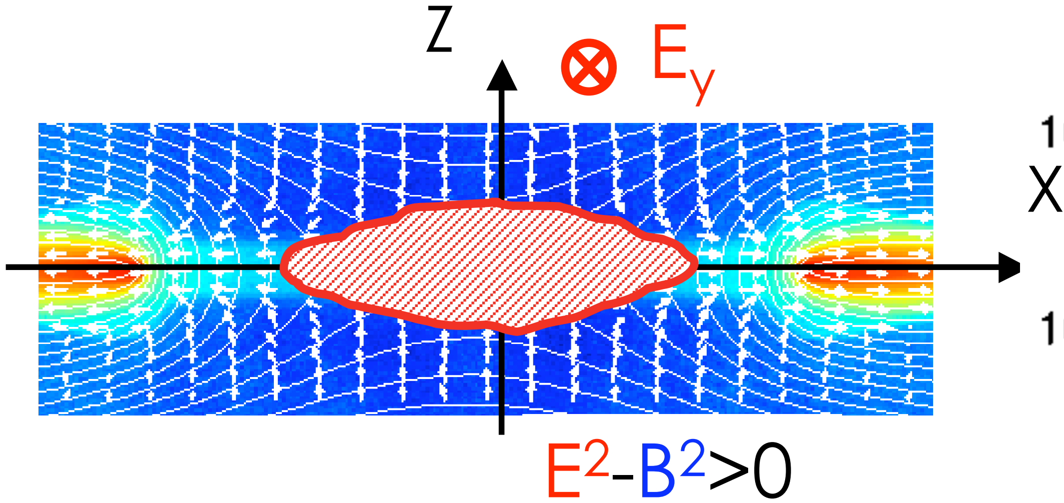


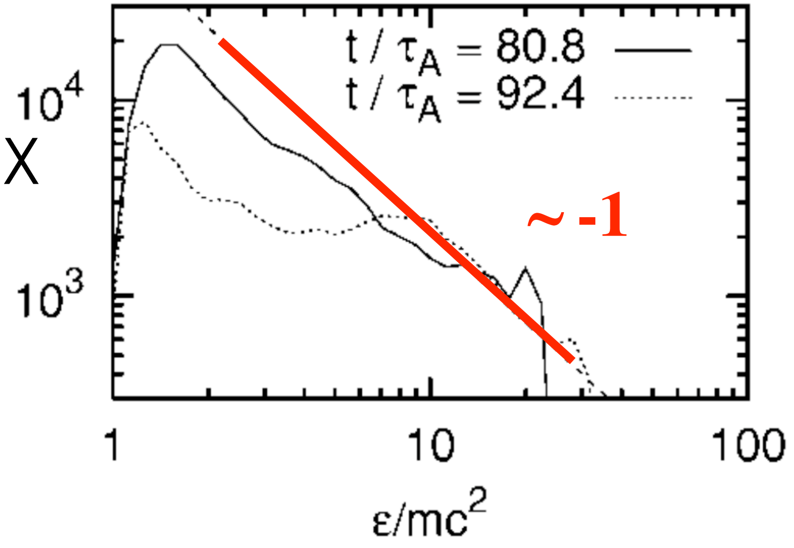
2D PIC simulation

- Fast reconnection occurs
- Particle acceleration around the *X*-region

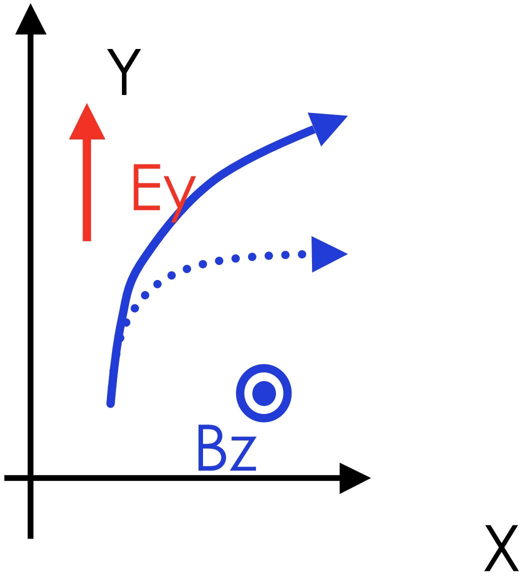


DC particle acceleration





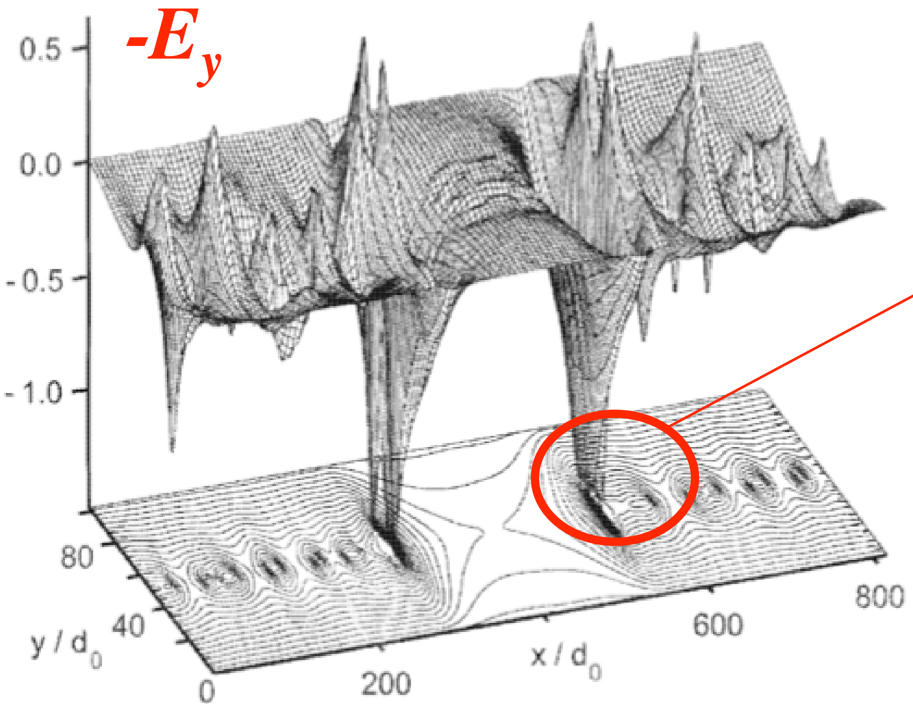
Zenitani & Hoshino 2001 ApJ



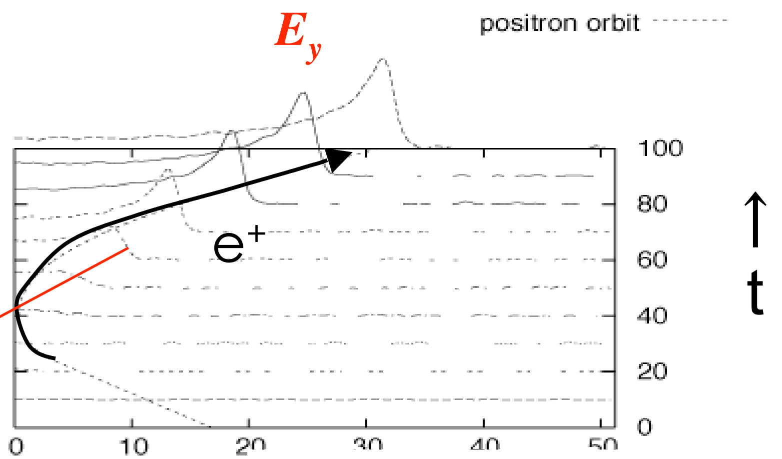
Trapping condition
~ Gyro motion by B_z (Speiser orbit)
==> extended in the *Y* direction

$$r_L \approx \frac{c}{\omega_C} = \frac{\gamma m_0 c^2}{eB_Z} \propto \varepsilon$$

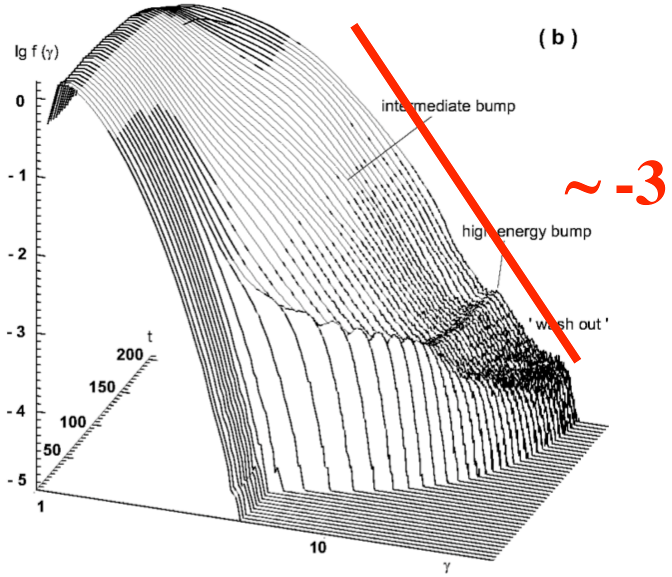
Large-scale dynamic evolution



Jaroschek et al. 2004 ApJ



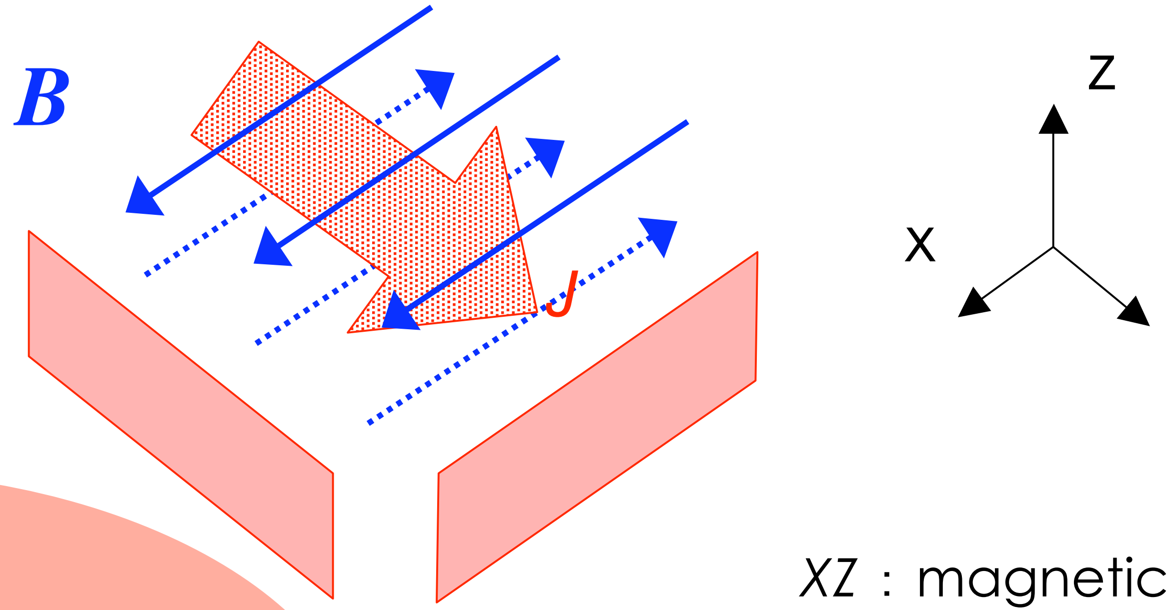
Zenitani & Hoshino 2007 ApJ



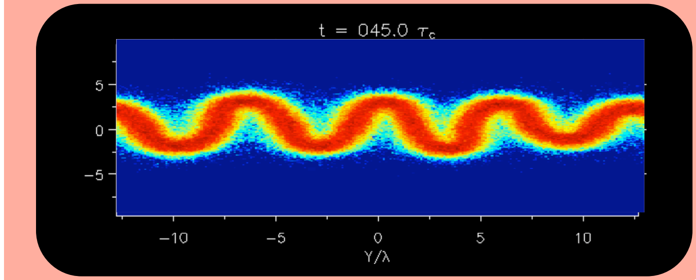
Jaroschek et al. 2004 Phys. Plasmas

- Powerful motional electric fields at multiple magnetic islands
- Entire acceleration mechanism: not yet well understood

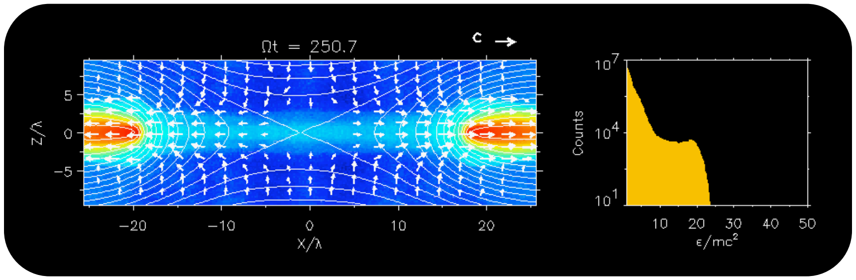
Drift Kink Instability (DKI)



YZ : drift kink instability (DKI)

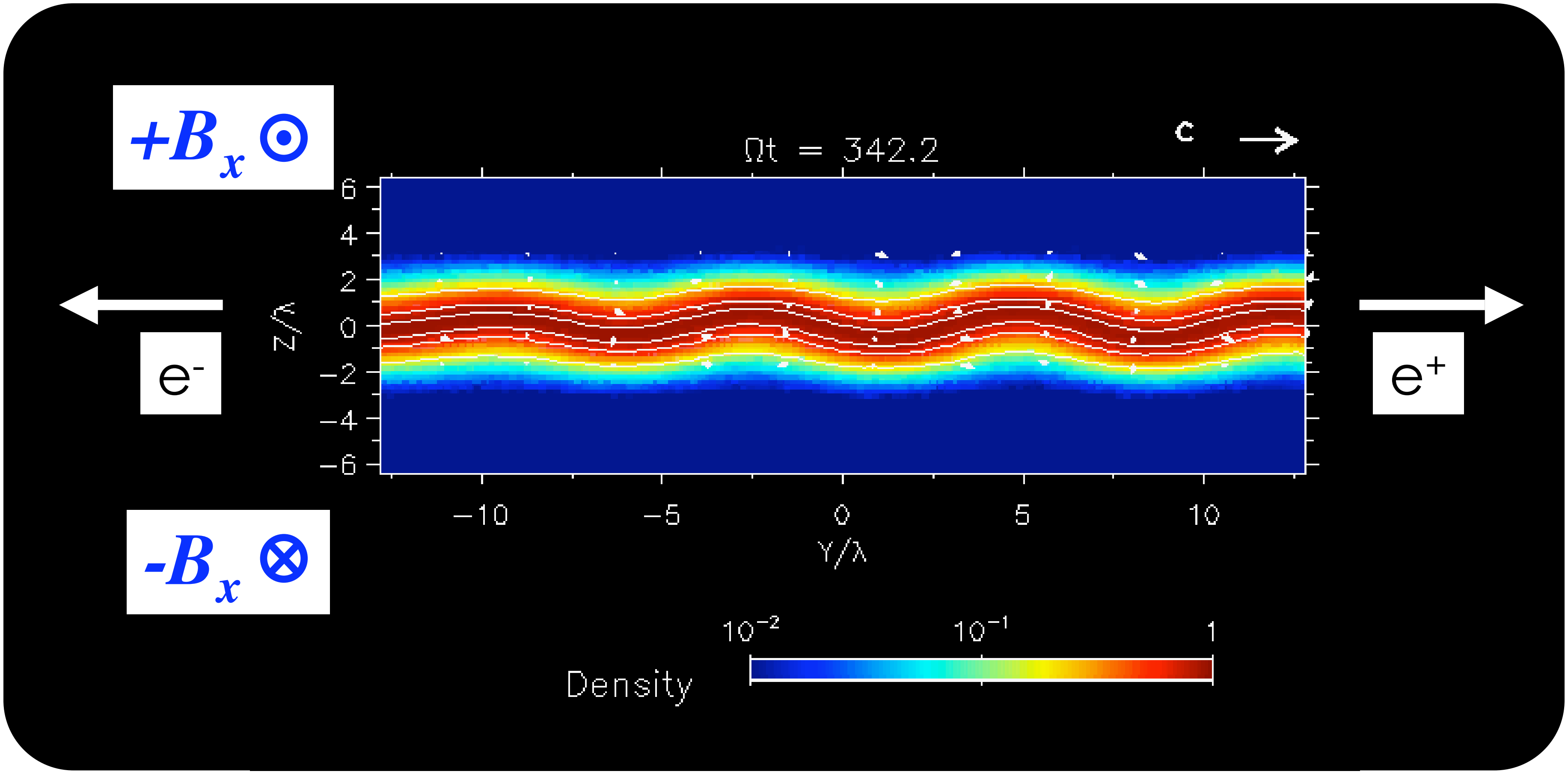


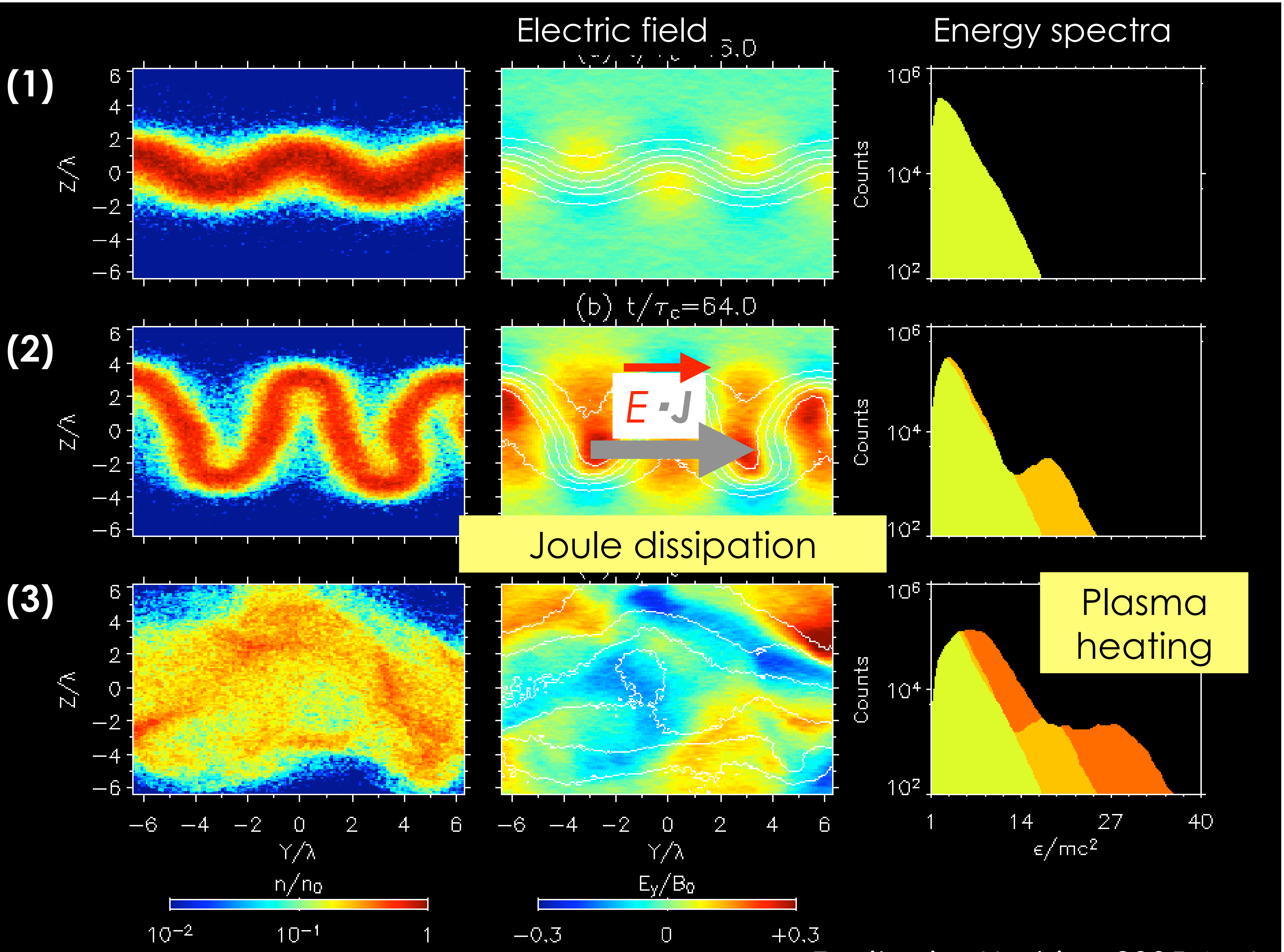
XZ : magnetic reconnection (RX)



2D PIC simulation

- A kink-type instability, driven by the electron-positron counter-streaming (Zhu & Winglee 1996 JGR, Ozaki et al. 1996 Phys. Plasmas, Pritchett et al 1996 JGR, Daughton 1999 Phys. Plasmas)





Electric field

Energy spectra

(1)

(2)

(3)

$E \cdot J$

Joule dissipation

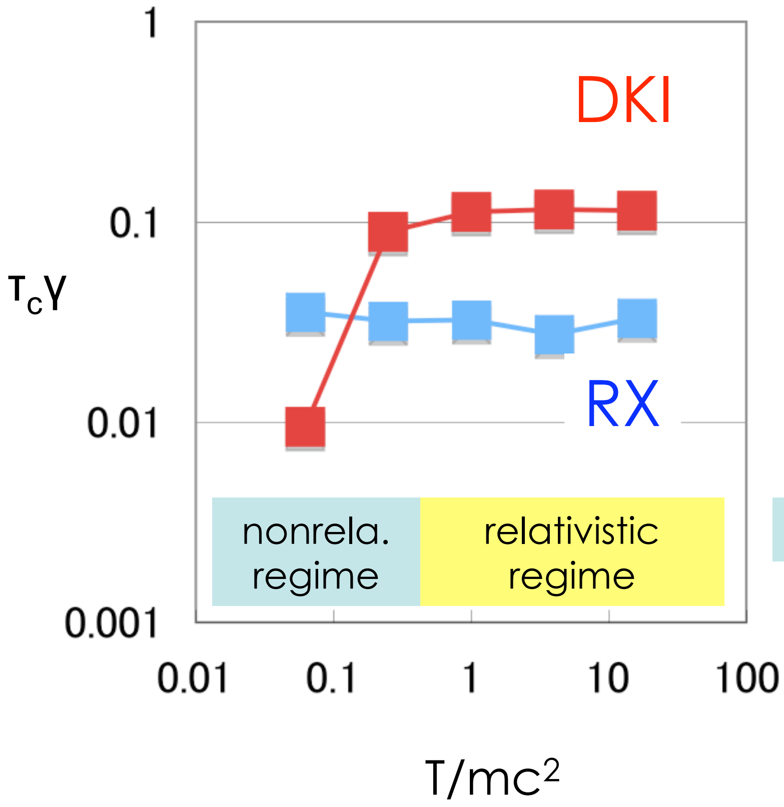
Plasma heating

Zenitani & Hoshino 2005 ApJ

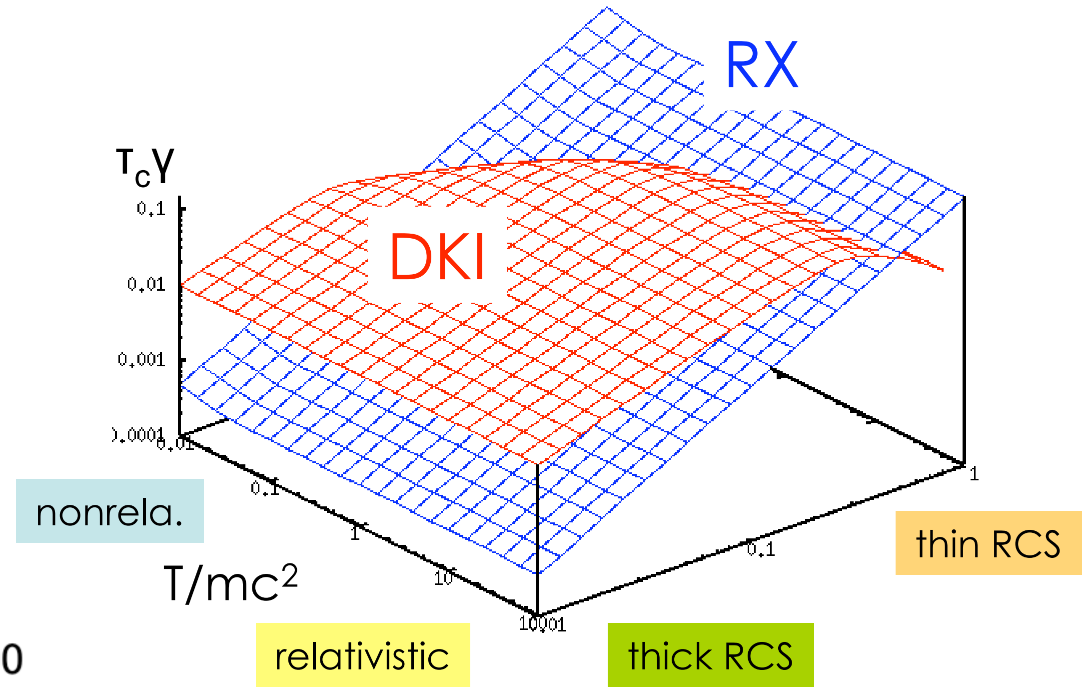
Two competing modes

RX (nonthermal acceleration) vs DKI (plasma heating).
In the relativistic regime, DKI grows faster.

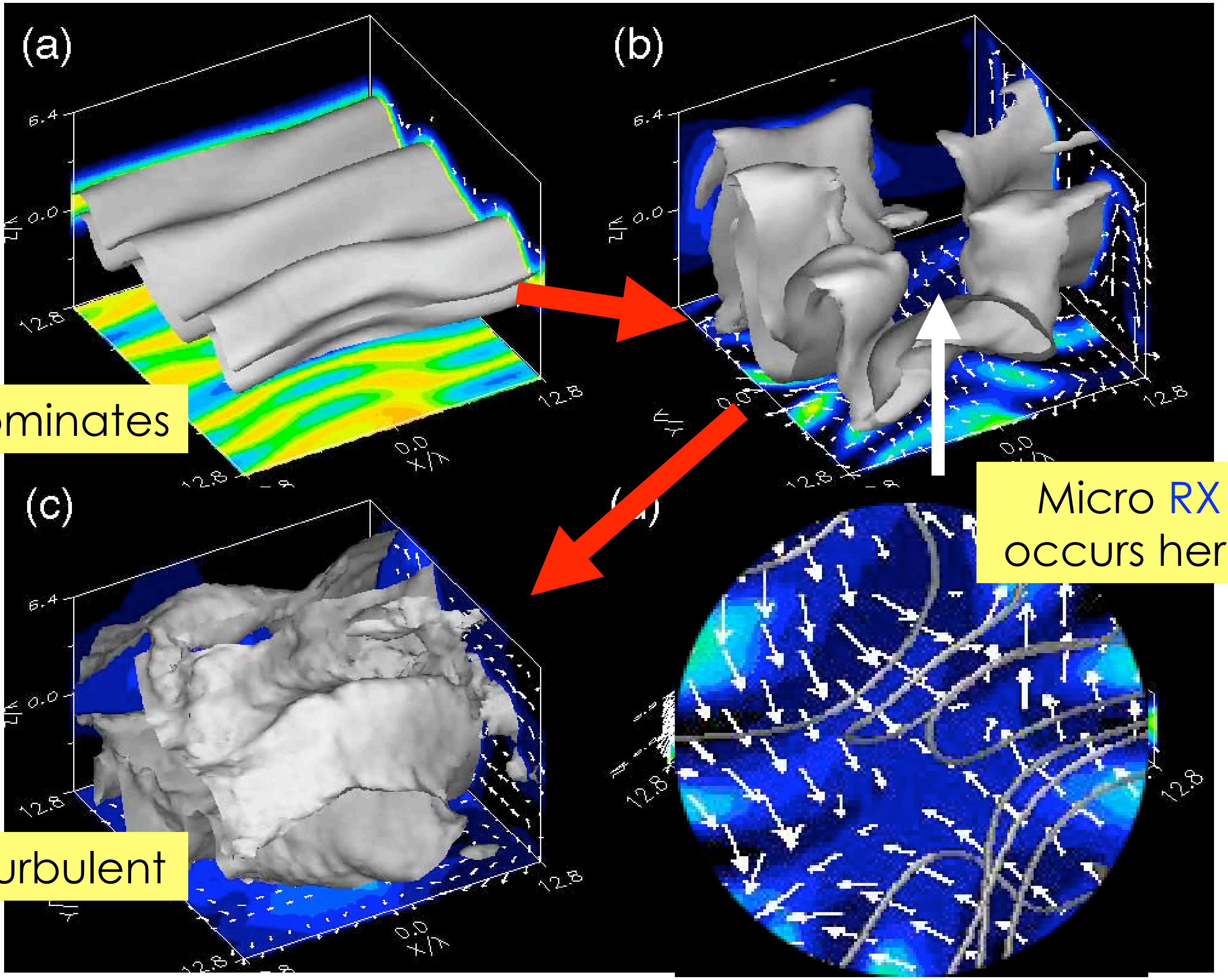
- PIC simulation



- Analytical estimate



3D evolution



DKI dominates

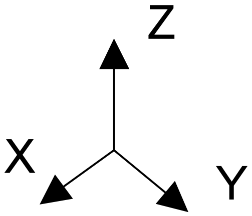
Micro RX occurs here

Turbulent

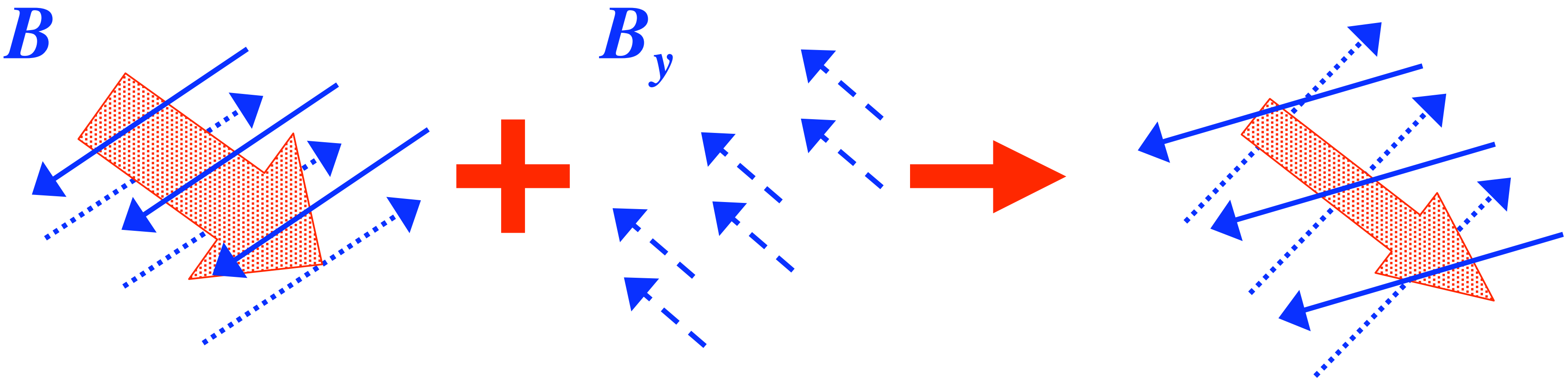
Zenitani & Hoshino 2008 ApJ

Guide field case

The Guide field (B_y)

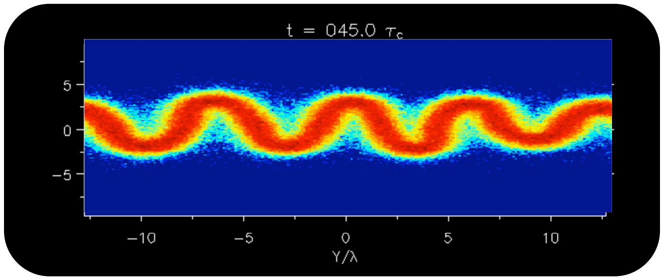


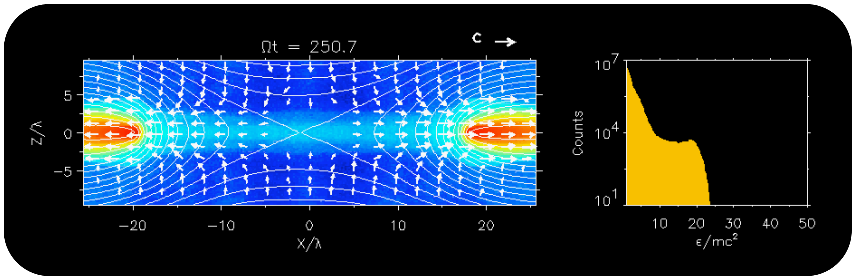
- Harris field + Uniform B_y = Twisted equilibrium



YZ : drift kink instability (DKI)

XZ : magnetic reconnection (RX)



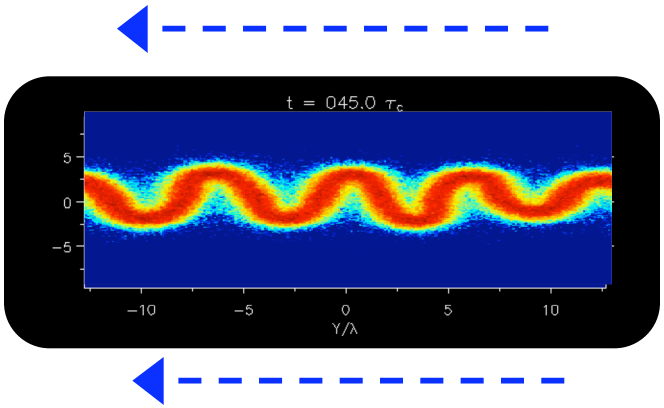


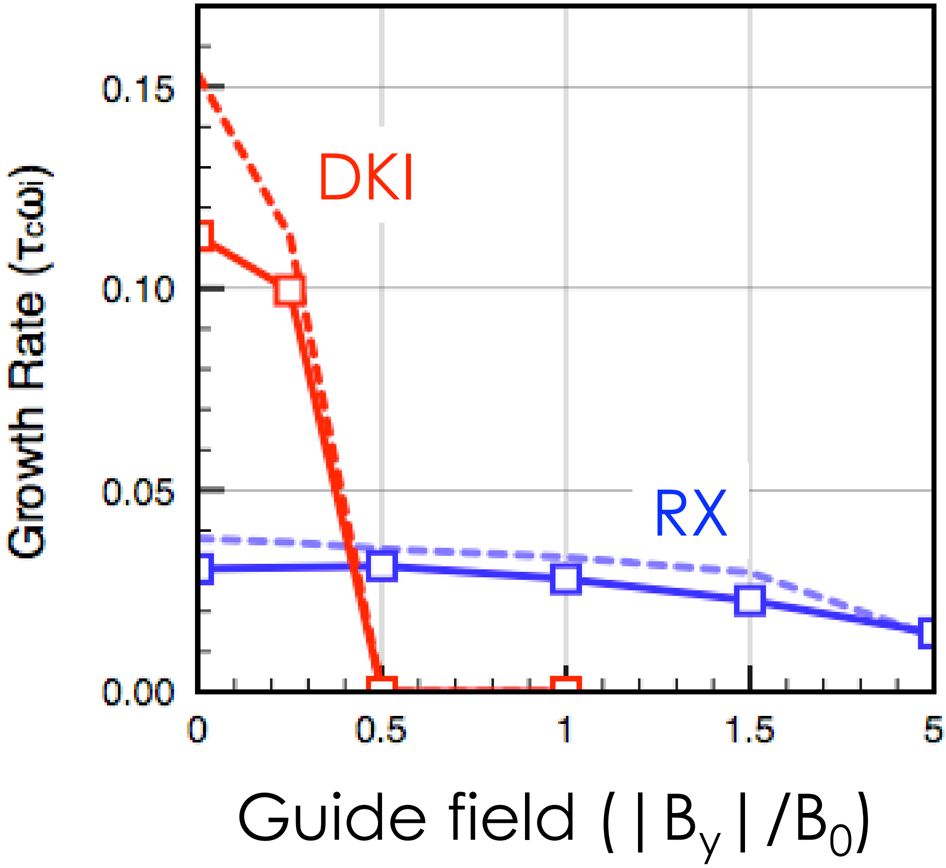
← *B*

B ⊗ ⊗

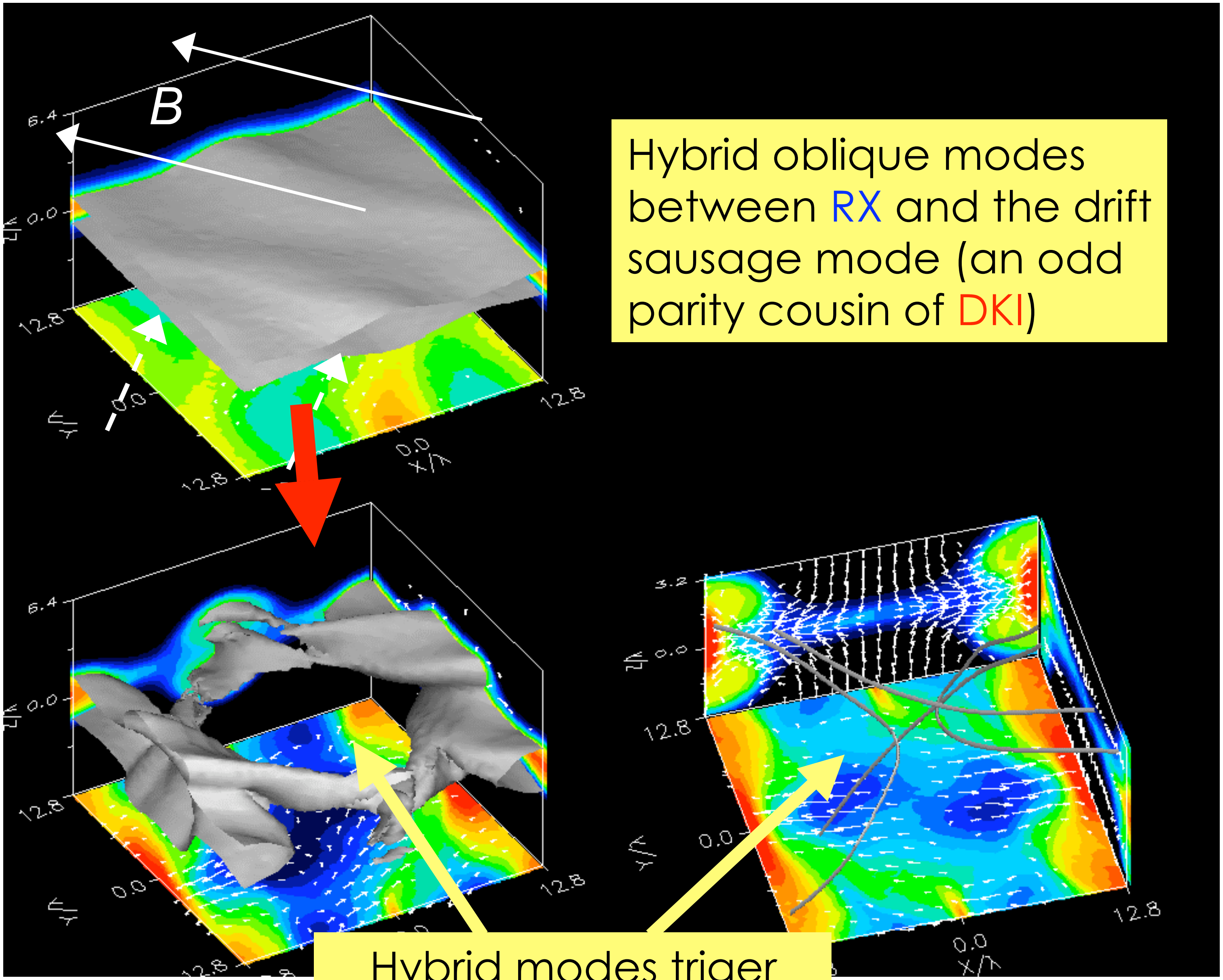
Growth rate: guide field dependency

- RX is insensitive
- DKI is stabilized by the magnetic tension
- We expect that RX dominates in 3D





3D evolution with guide field

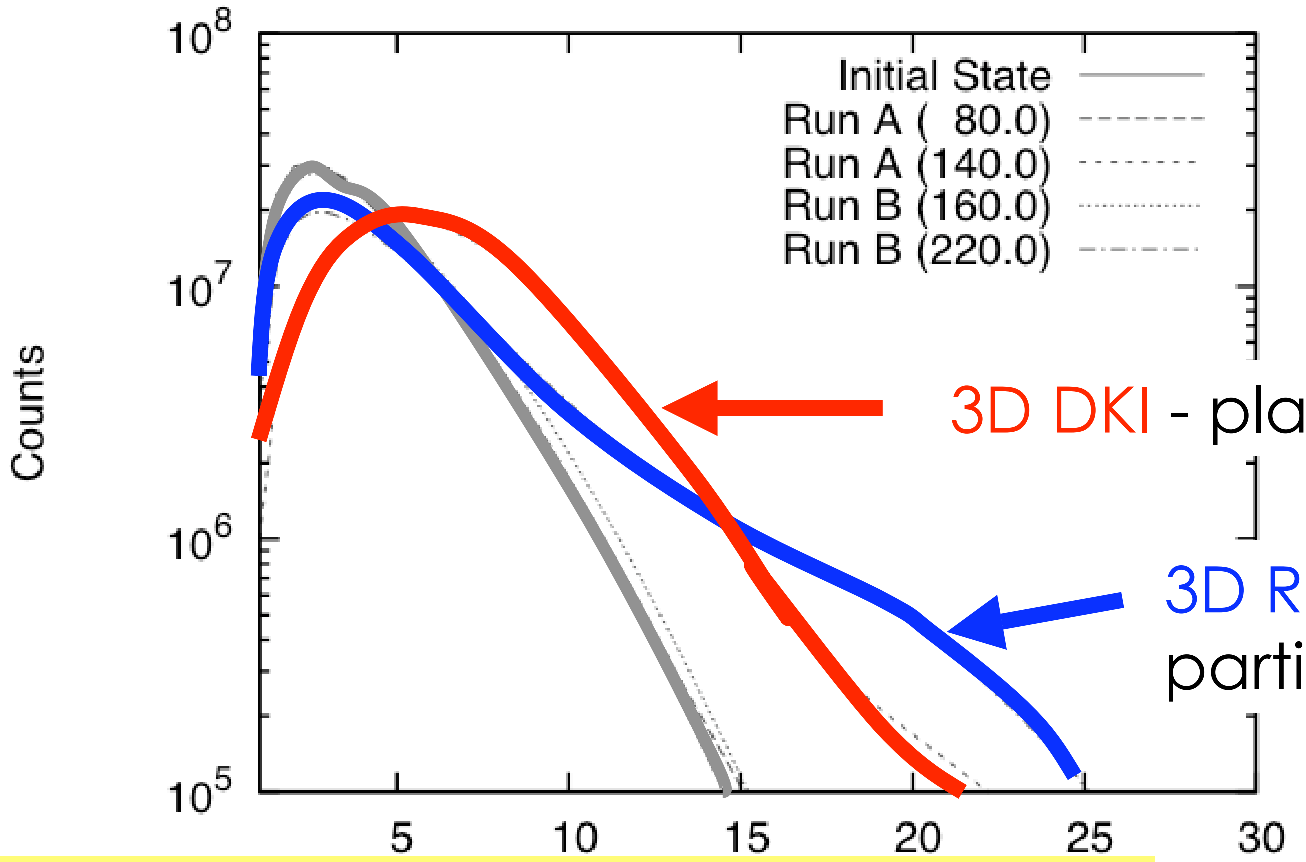


Hybrid oblique modes between RX and the drift sausage mode (an odd parity cousin of DKI)

Hybrid modes triger secondary RX

Zenitani & Hoshino 2005 PRL

Energy distribution



3D DKI - plasma heating

3D RX (guide field)
particle acceleration

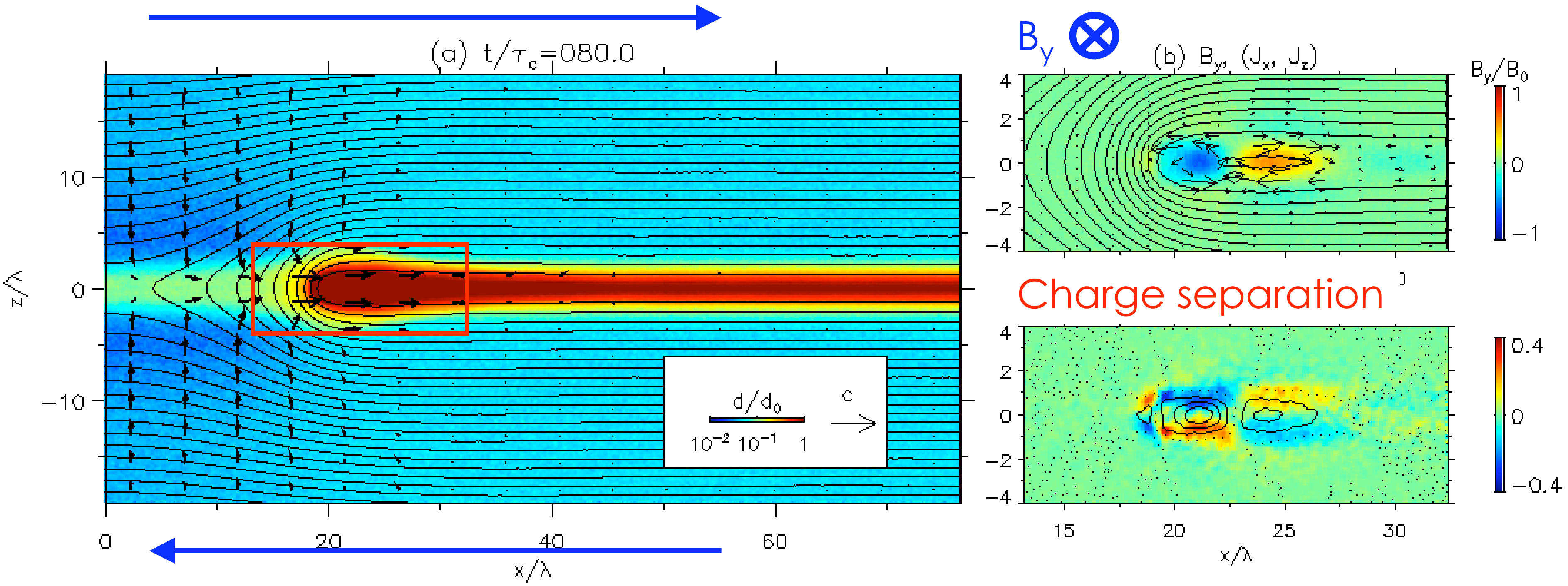
Magnetic topology changes
the destination of released energy;
plasma heat or non-thermal energy.

Zenitani & Hoshino 2005 PRL

Recent discovery:
Weibel instability

Weibel-type instability in reconnection

- Anisotropy-driven Weibel instability (WBI)
  generates out-of-plane magnetic field at the outflow jet front
- Small scale mode of ($L \sim \gamma^{1/2} c/\omega_p$)

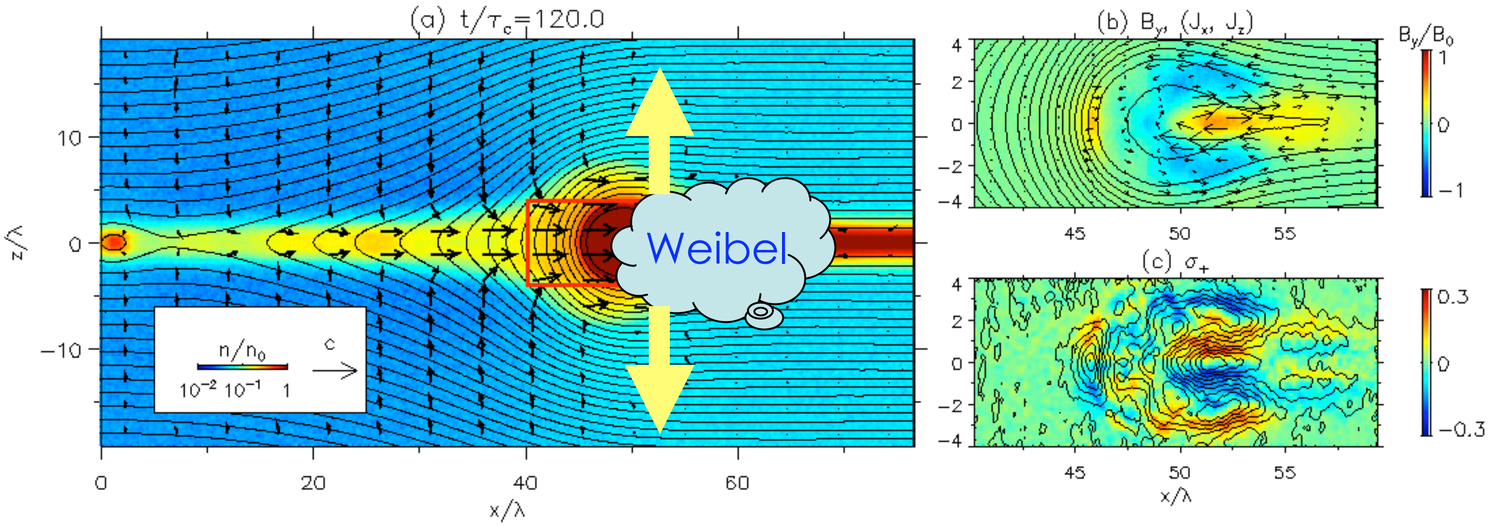


B_y ⊗

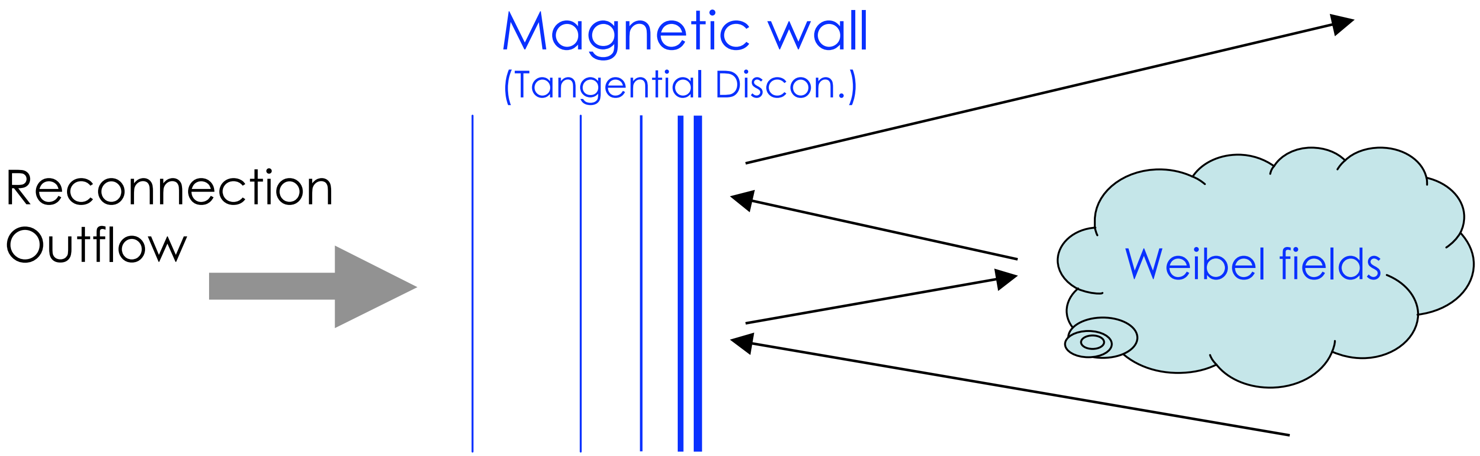
Charge separation

Zenitani & Hesse 2008 Phys. Plasmas

- The WBI quickly widens the magnetic island



- The WBI works as a shock-downstream scatterer



Magnetic wall

(Tangential Discon.)

Reconnection Outflow

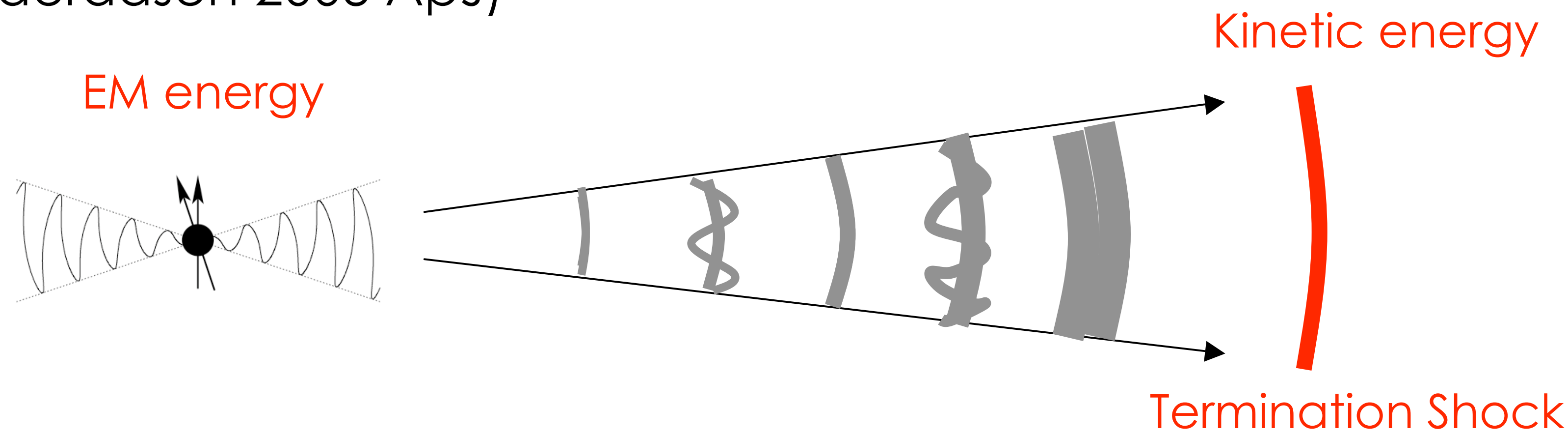
Weibel fields

- The WBI seems to be universal (Nonrelativistic case; Swisdak's Talk)

Discussions

On the dissipation problem

- Radial 1D flow model (Lyubarsky & Kirk 2001 ApJ, Kirk & Skjaeraasen 2003 ApJ)



  - A realistic rate by RX (the collisionless tearing mode; Zelenyi & Krasnosel'skikh 1979)
  - The DKI will give better dissipation

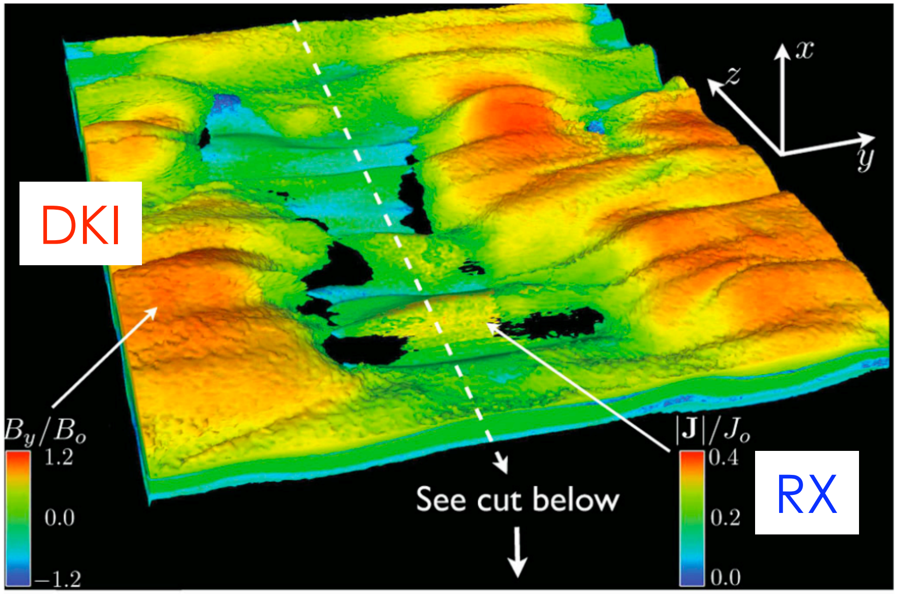
$$\beta_{RTI} = \tau_c \gamma_{RTI} = \beta^{3/2}$$

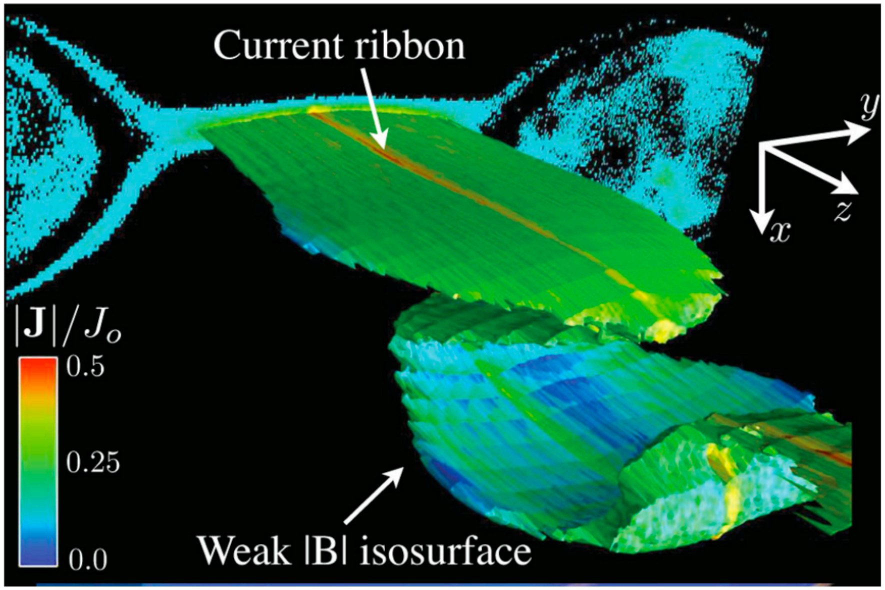
$$\beta_{RDKI} \sim \beta > \beta_{RTI}$$

- Dissipation & particle acceleration at the shock
  - Lyubarsky 2005 MNRAS, Pétri & Lyubarsky 2007 A&A, Nagata et al. 2008 ApJ
  - 2D/3D instabilities would enhance magnetic dissipation - even when $(r_L/L) \sim O(0.1)$, 2D instabilities grows fast in such a thin RCS

Large scale PIC simulation

- 3D evolution in a nonrelativistic pair plasma is more dynamic than expected
- DKI saturates, RX grows, and again kink-like mode in the thin reconnection CS
- At least the linear physics would be similar





Lin et al. 2008 PRL

Large-scale evolution of RCS remains unclear
It should be checked by large-scale PIC simulation

Spectral index

- Magnetic reconnection
  - Acceleration region --- s ~ 1.x
    - Theory: Romanova & Loverace 1992 A&A, Larrabee et al. 2003 ApJ
    - PIC: Zenitani & Hoshino 2001 ApJ
  - Universal index --- s ~ 3 (2.x)
    - PIC: Jaroschek et al. 2004 Phys. Plasmas, Zenitani & Hoshino 2007, 2008 ApJ, Bessho & Battarachargee 2007 Phys. Plasmas, Karlíky 2008 ApJ
    - Moderate guide field may make it harder
  - Further enhanced in pulsar-wind driven configuration
    - Lyubarsky & Liverts 2008 ApJ
- 1D RCS problem
  - Nonadiabatic acceleration in an individual RCS : s=2-4
    - Jaroschek et al. 2008 Adv. Space. Res.
  - Shock - RCSs interaction : s=4
    - Nagata et al. 2008 ApJ

Large-scale MHD evolution of RCS

Beyond the kinetic scale …

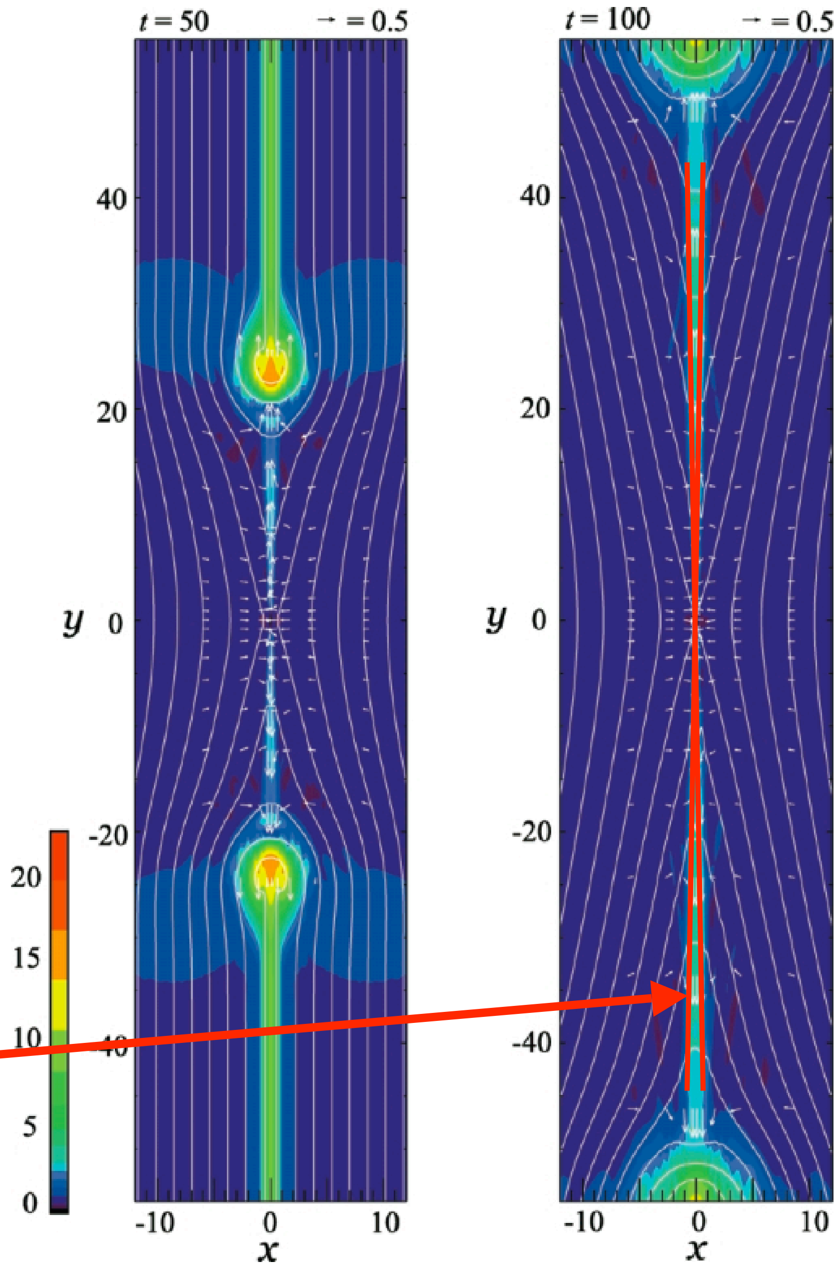
Resistive RMHD reconnection

- RCS processes dissipate magnetic energy
- Limited number of resistive relativistic MHD (RMHD) studies

- Watanabe & Yokoyama 2006 ApJ
  - Relativistic resistive MHD simulation in weakly magnetized regime
  - Ohm's law: localized resistivity at

$$\gamma\left(\boldsymbol{E}+\frac{\boldsymbol{v}}{c}\times\boldsymbol{B}\right)=\eta\left[\boldsymbol{j}+\gamma^{2}\left(\boldsymbol{j}\cdot\frac{\boldsymbol{v}}{c}-\rho_{e}c\right)\frac{\boldsymbol{v}}{c}\right]$$

- Petschek reconnection with a pair of slow shocks



Watanabe & Yokoyama 2006 ApJ

Two-fluid RMHD reconnection (1)

$$\frac{\partial d_p}{\partial t} = \frac{\partial}{\partial t}\gamma_p n_p = -\nabla\cdot(n_p \boldsymbol{u}_p) \quad (1)$$

$$\frac{\partial \boldsymbol{m}_p}{\partial t} = \frac{\partial}{\partial t}\gamma_p w_p \boldsymbol{u}_p = -\nabla\cdot\Big(w_p \boldsymbol{u}_p \boldsymbol{u}_p + \delta_{ij} p_p\Big) + \gamma_p n_p q_p(\boldsymbol{E} + \boldsymbol{v_p}\times\boldsymbol{B}) - \tau_{fr} d_p d_e(\boldsymbol{v}_p - \boldsymbol{v}_e) \quad (2)$$

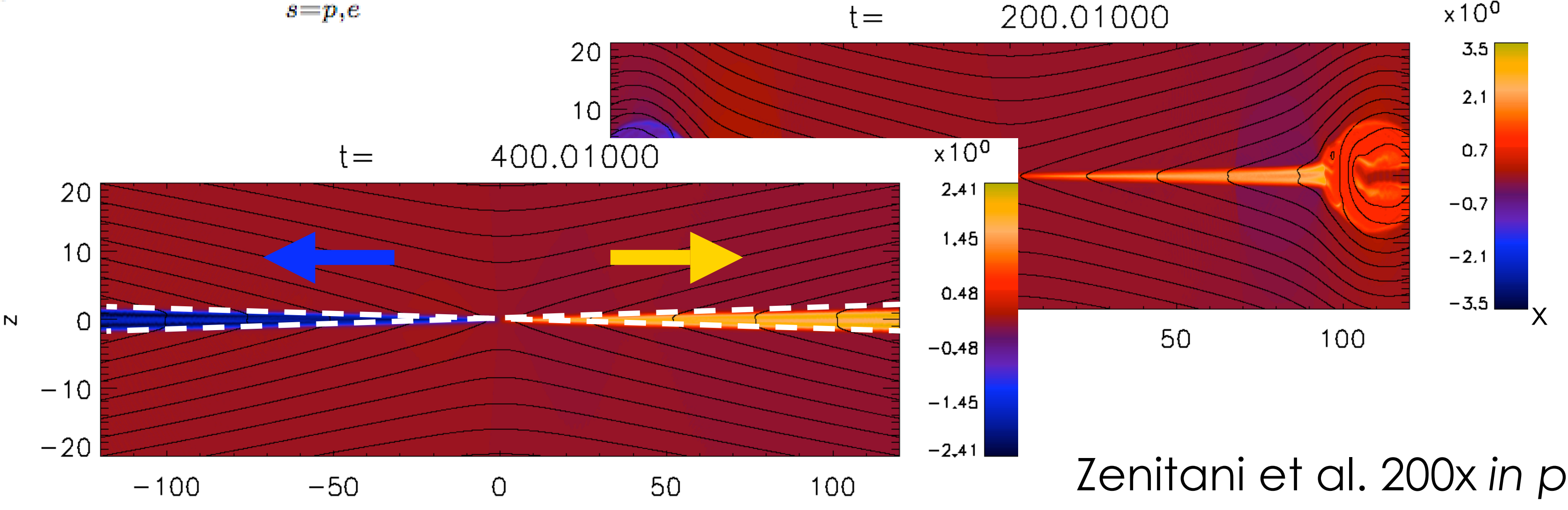
$$\xrightarrow{} \eta_{eff}\,\boldsymbol{j}$$

$$\frac{\partial K_p}{\partial t} = \frac{\partial}{\partial t}\Big(\gamma_p^2 w_p - p_p - d_p m c^2\Big) = -\nabla\cdot(\gamma_p w_p \boldsymbol{u}_p - n_p m c^2 \boldsymbol{u}_p) + \gamma_p n_p q_p(\boldsymbol{v_p}\cdot\boldsymbol{E}) \quad (4)$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -c\nabla\times\boldsymbol{E} \quad (5)$$

$$\frac{\partial \boldsymbol{E}}{\partial t} = c\nabla\times\boldsymbol{B} - 4\pi\sum_{s=p,e} q_s n_s \boldsymbol{u}_s \quad (6)$$

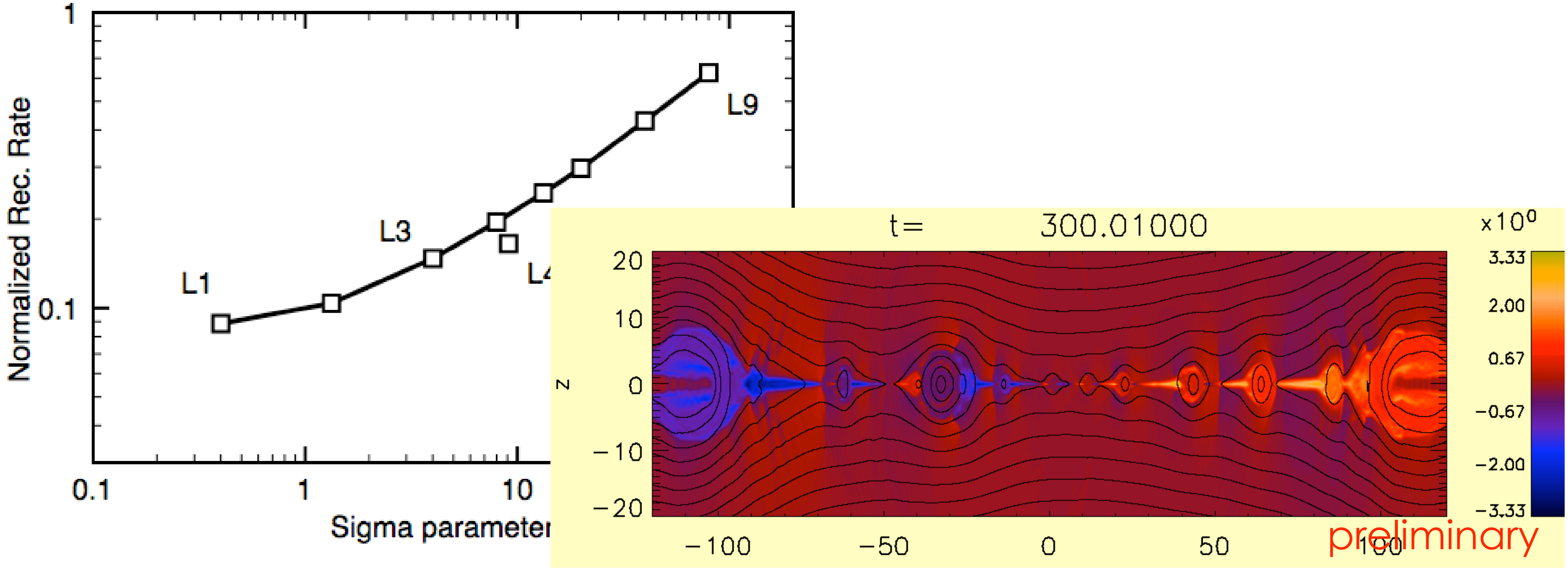
- Independent electron-positron motion
- Resistivity = an inter-species friction force
- Localized resistivity profile



Zenitani et al. 200x *in prep*

Two-fluid RMHD reconnection (2)

- When the inflow is more magnetic-dominated, we observe Sweet-Parker-type fast reconnection of the rate ~1.



- The system evolution highly depends on the resistivity profile, which essentially comes from the small-scale <u>kinetic</u> physics.
- RMHD + kinetic joint study required.

Summary

- Basic instabilities in RCS
  - Magnetic Reconnection (RX; nonthermal acceleration)
  - Relativistic Drift Kink Instability (DKI; plasma heating)
  - Hybrid oblique modes
  - The Weibel Instability (WBI)
- RCS 3D evolution
  - Antiparallel : RX < DKI (?) → Plasma heating
  - Guide field : RX > DKI → Nonthermal acceleration

  - DKI will be the better dissipation mechanism
  - Power Law : universal index of s ~ 3
  - RMHD simulation: important tools to study large-scale astrophysical problems, with PIC

- Open Questions (Next slide)

Open questions

- Large scale kinetic evolution
- Large scale RMHD evolution, and its consistency with kinetic model
- RX
  - Acceleration rate or power-law index
  - Dependence to the upstream σ
  - Origin of the resistivity, and how to scale it?
  - The steady reconnection model and its reconnection rate?
- DKI
  - Saturation mechanism
  - Compressed configuration

- and many more…
  - Radiative effect (→ Jaroschek's Talk)
  - Positron-ion-electron plasma

Dziękuję

(Thank you!)