Particle Acceleration and Magnetic Dissipation in Relativistic Reconnection

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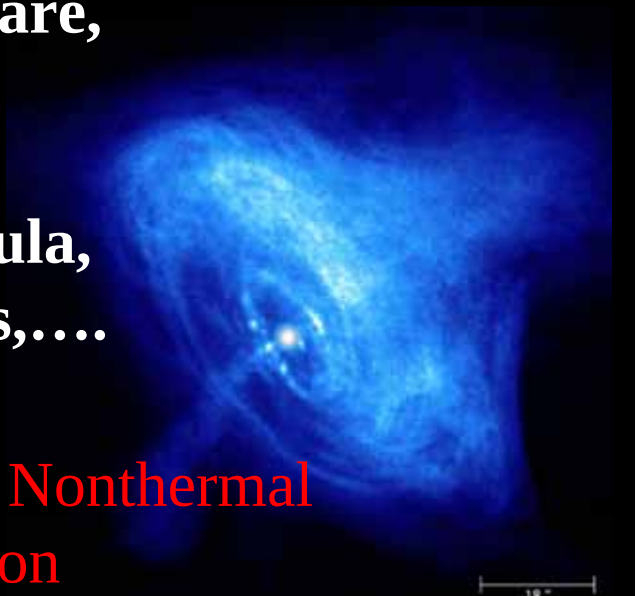
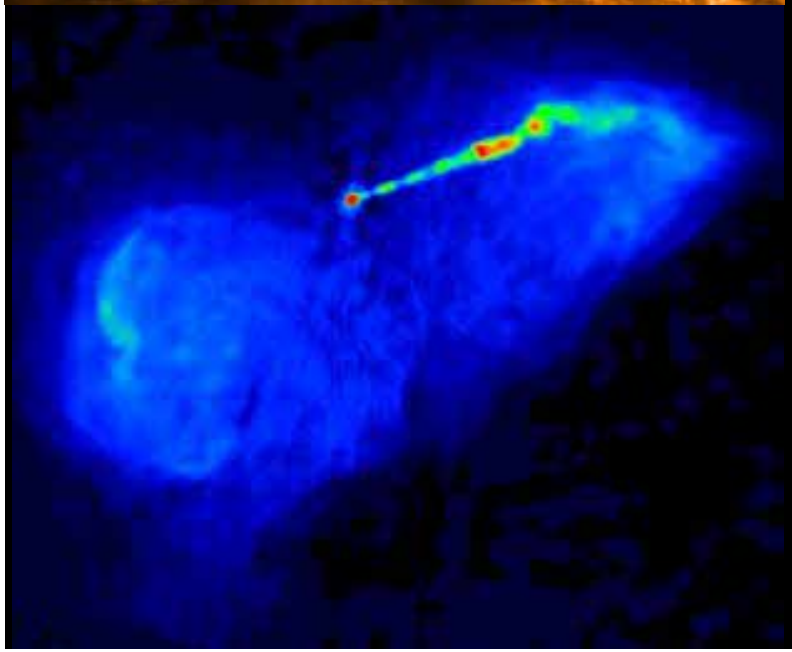
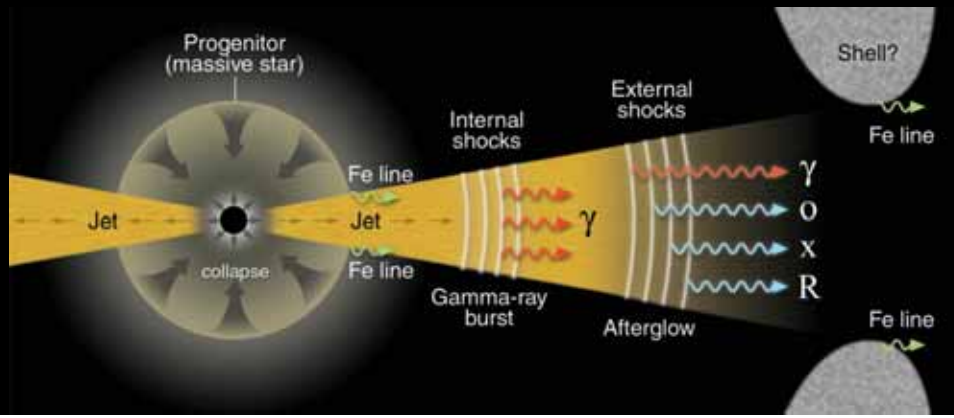
Magnetic Reconnection

Solar & Stellar Flare,
Magnetosphere,
Accretion Disks,
Pulsar Wind-Nebula,
Astrophysical Jets,….



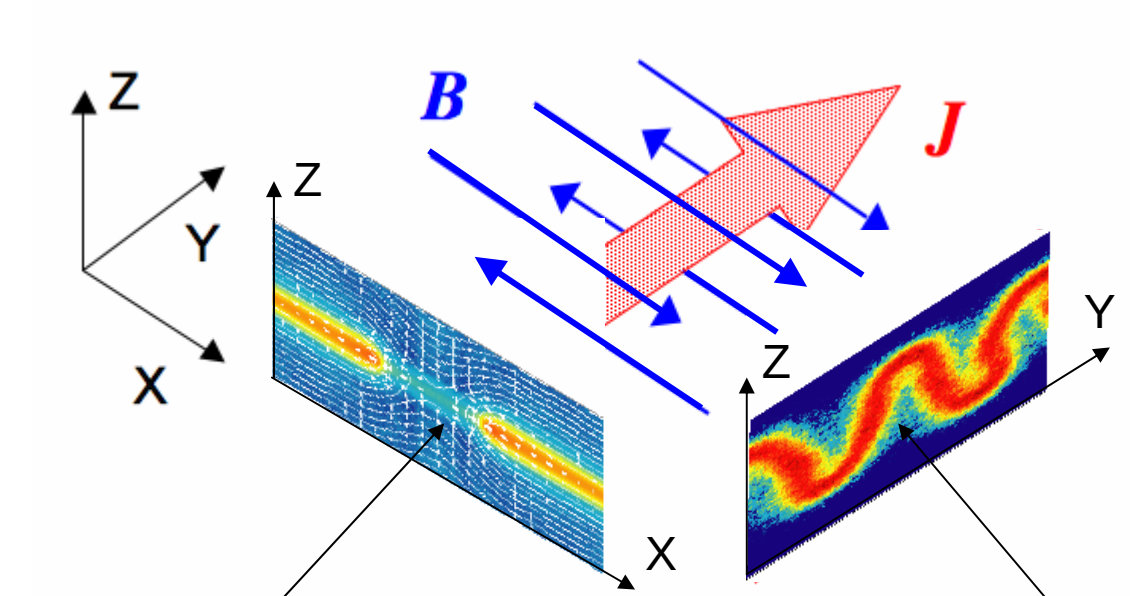


Plasma Heating & Nonthermal
Particle Acceleration



Relativistic Current Sheet Instability

$V_A/c \sim O(1)$, $T/mc^2 \sim O(1)$,
Electron and Positron Plasmas



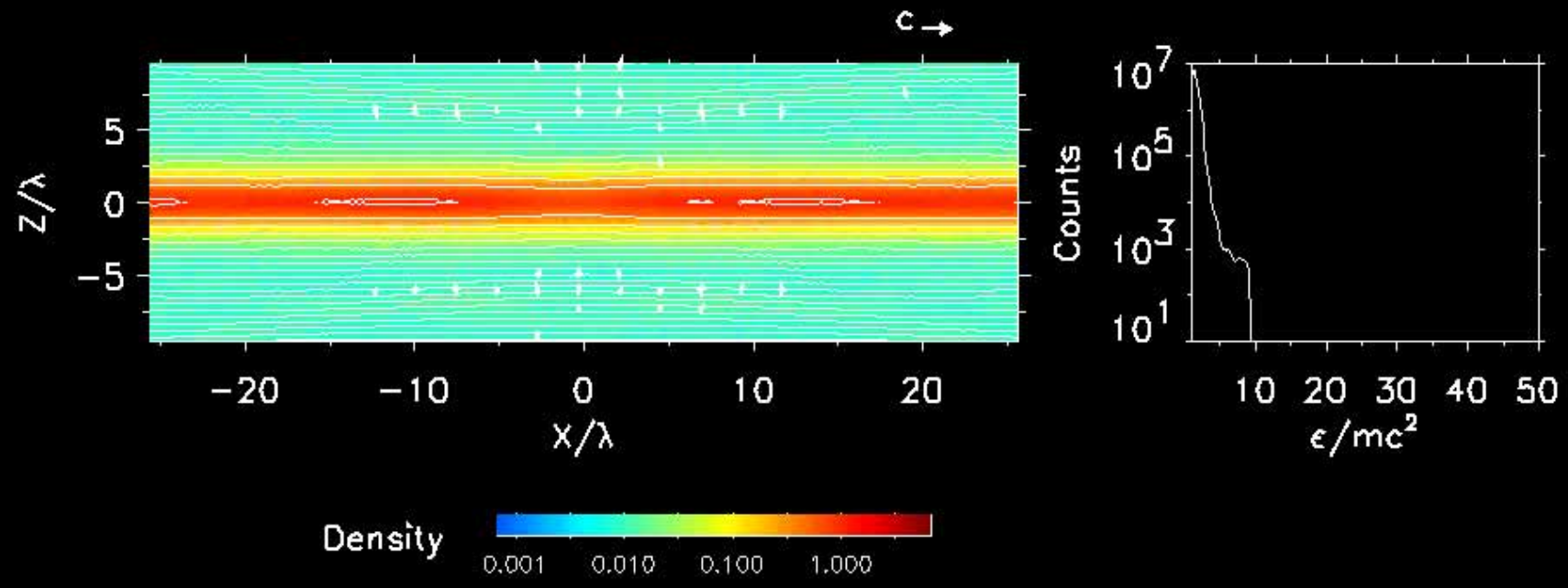
Reconnection Mode

Slower Growth Rate

Drift Kink Mode

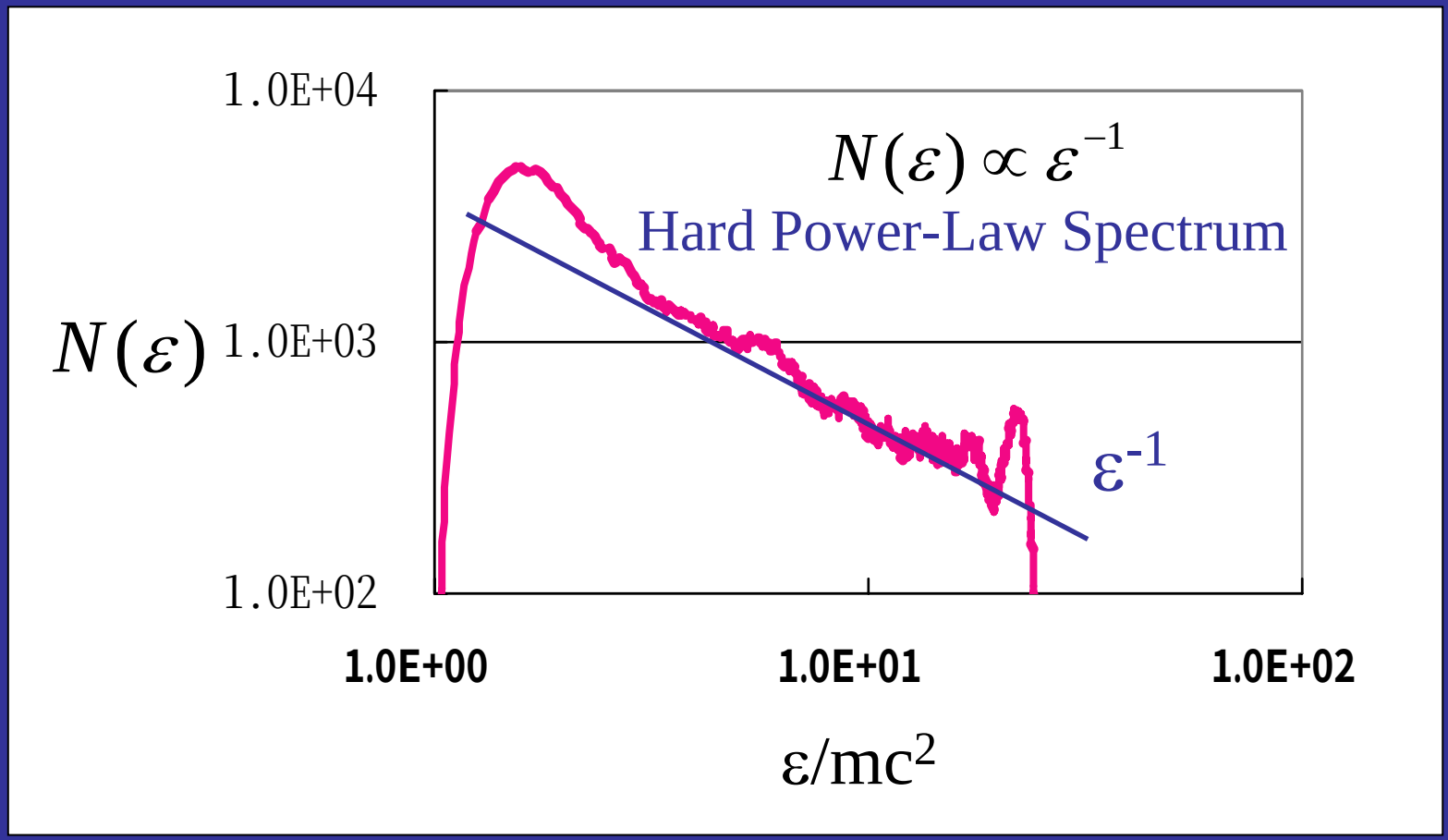
Faster Growth Rate

Relativistic Reconnection
(Particle-in-Cell simulation)



Zenitani & MH, ApJ (2001)

Energy Spectrum
(near the X-type region)



Power-Law Spectrum in Reconnection

- Acceleration rate

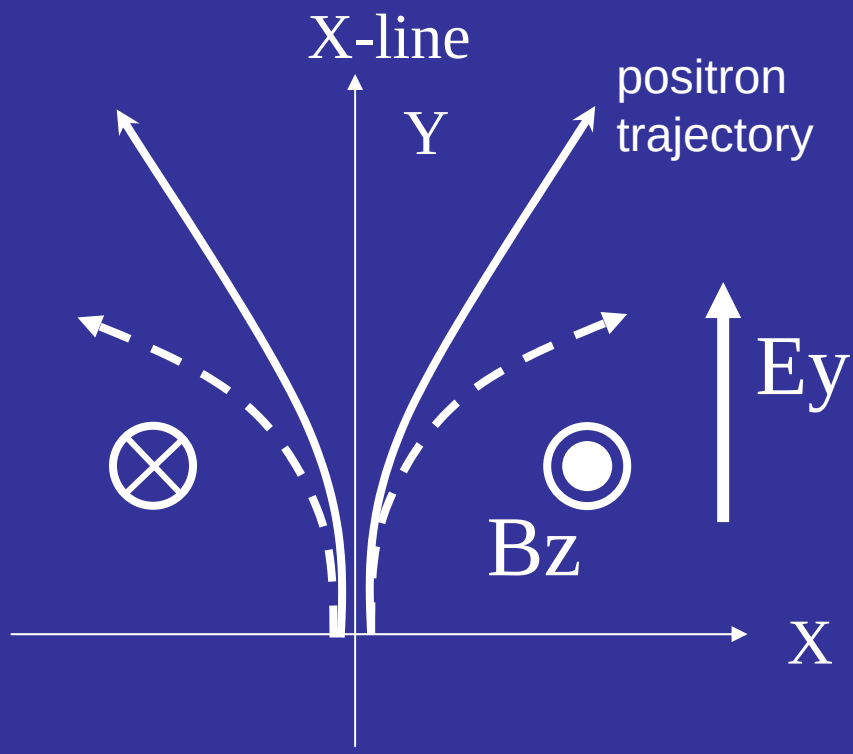
$$\frac{d\varepsilon}{dt} \approx eEc$$

- Loss rate

$$\frac{1}{N}\frac{dN}{dt} \approx -\frac{1}{\tau(\varepsilon)} \approx -\frac{m_0c^2}{\varepsilon}\frac{eB}{m_0c}$$

- Energy Spectrum

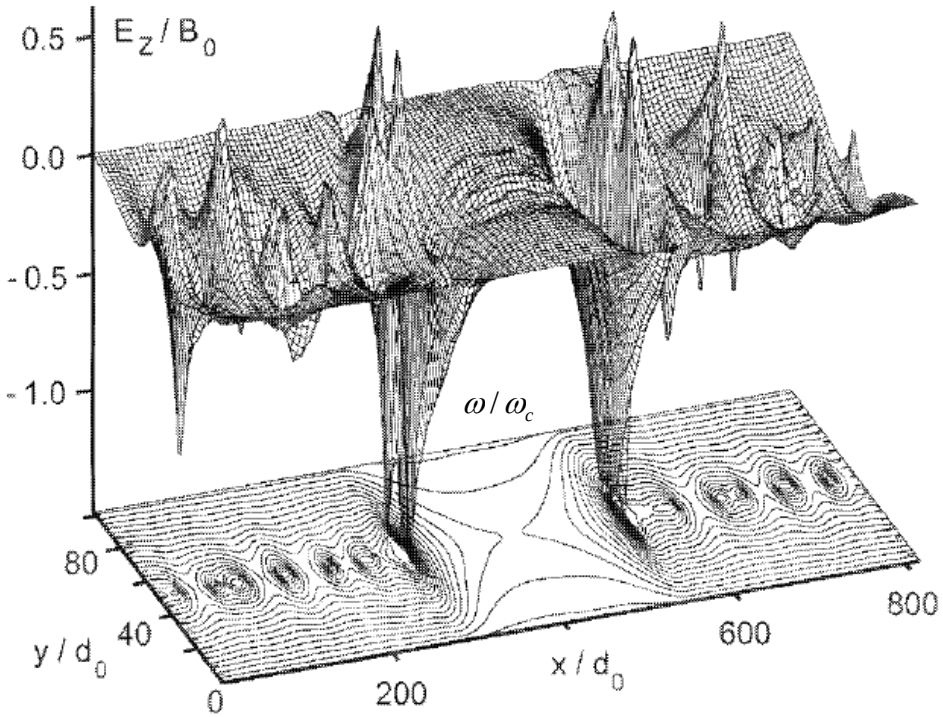
$$N \propto \varepsilon^{-s} \qquad s \approx E/B \approx 1$$

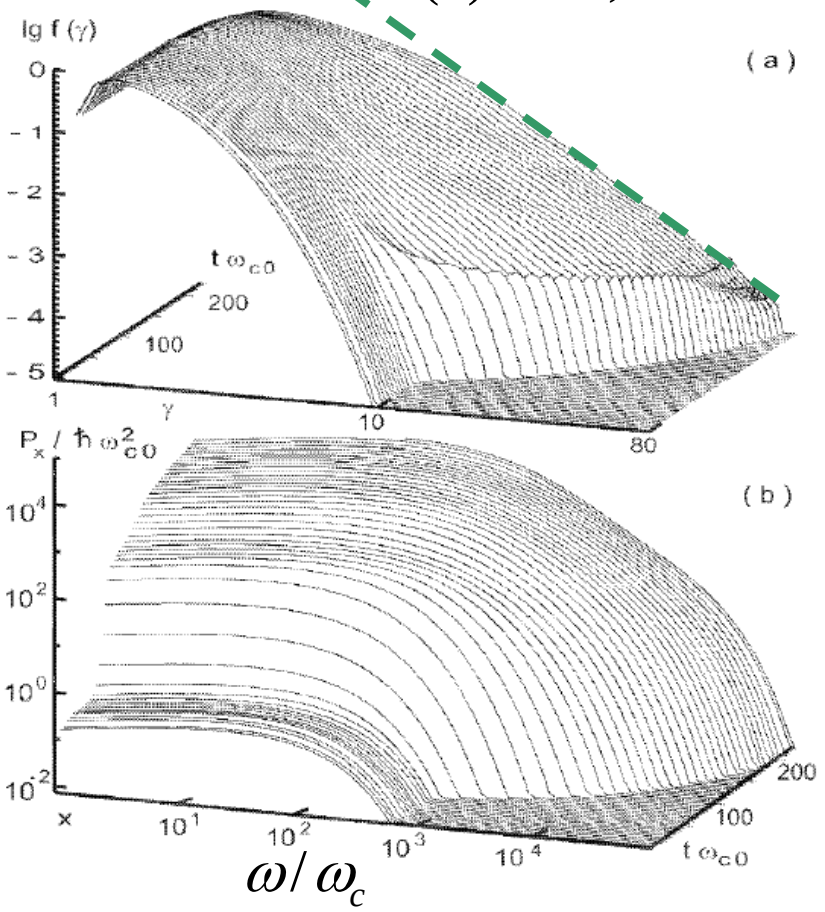


Large-Scale Evolution of MRX

Power-law Energy Spectrum

$N(\varepsilon) \propto \varepsilon^{-s}, \quad s = 1 \sim 3$

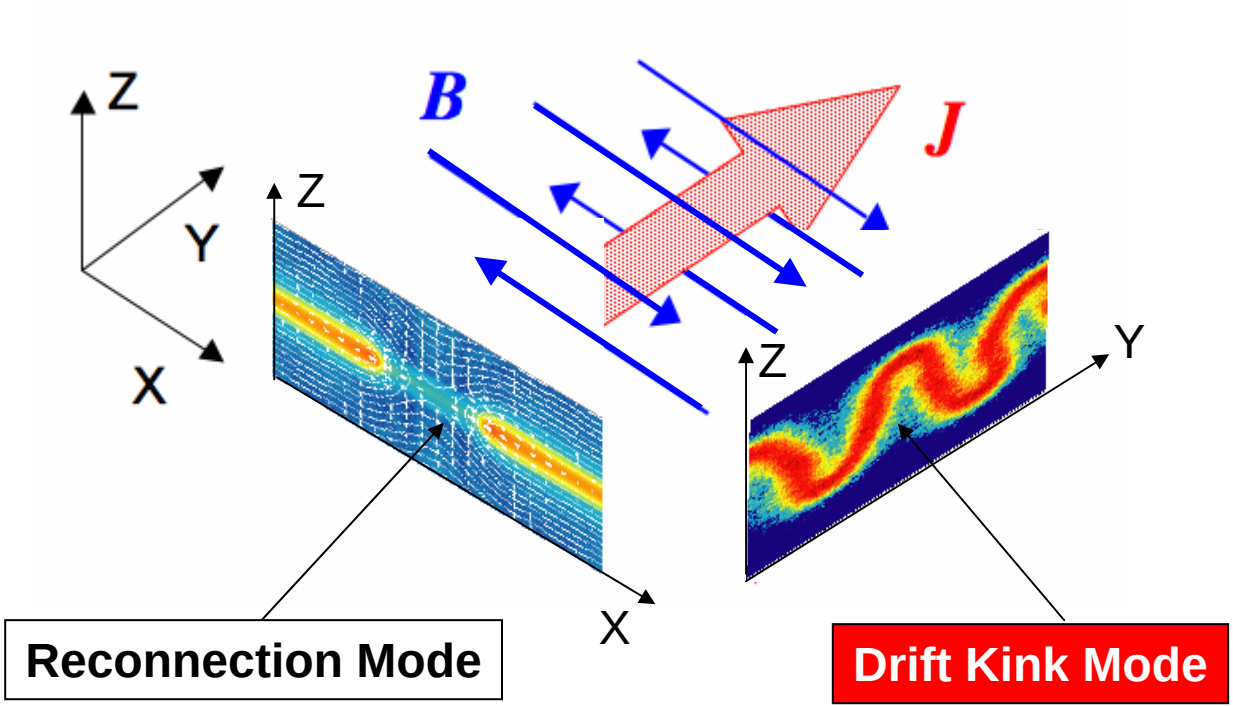




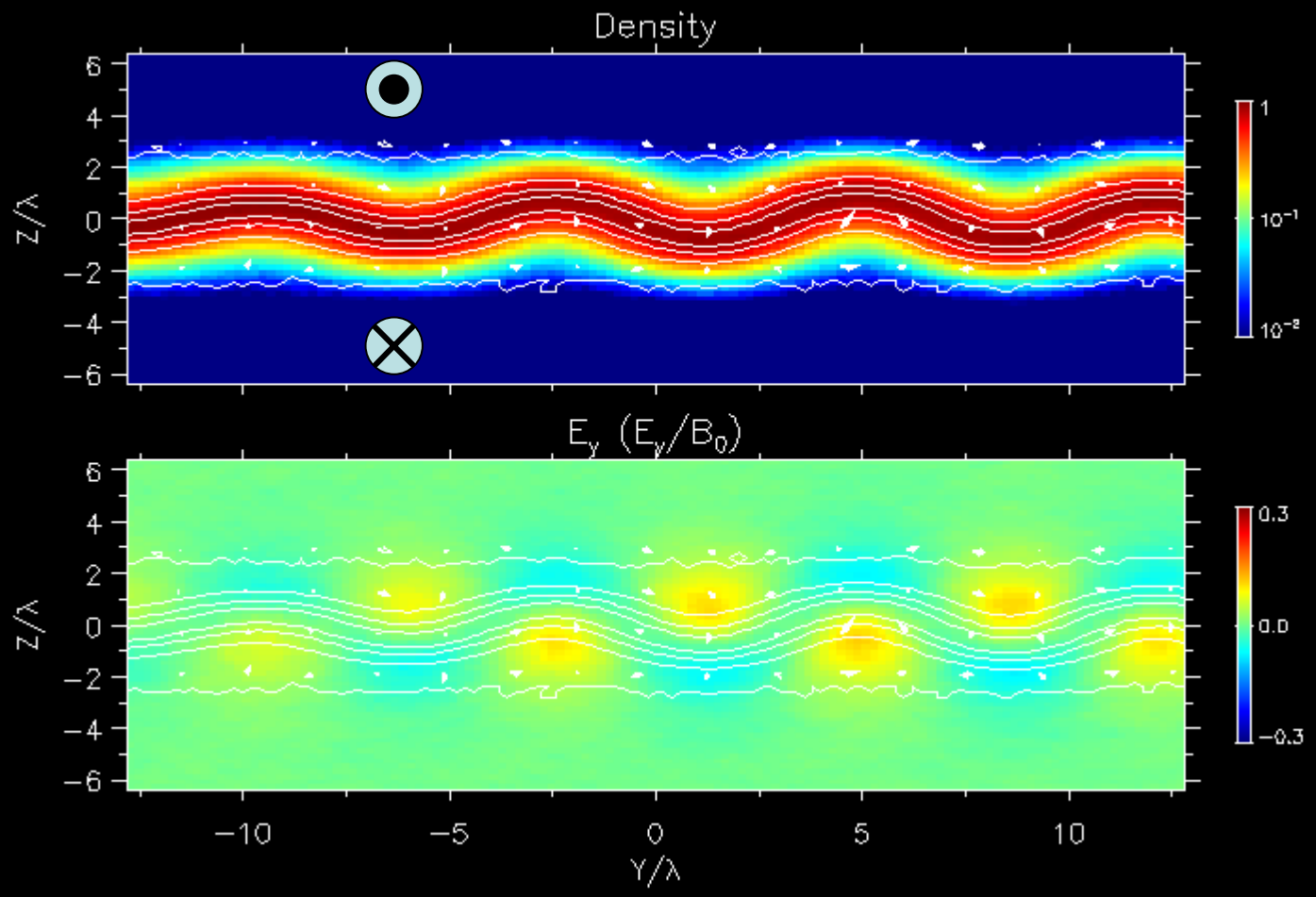
Synchrotron Spectrum

Jaroschek et al. ApJ 2004

Drift Kink Instability
(Current Driven Instability)

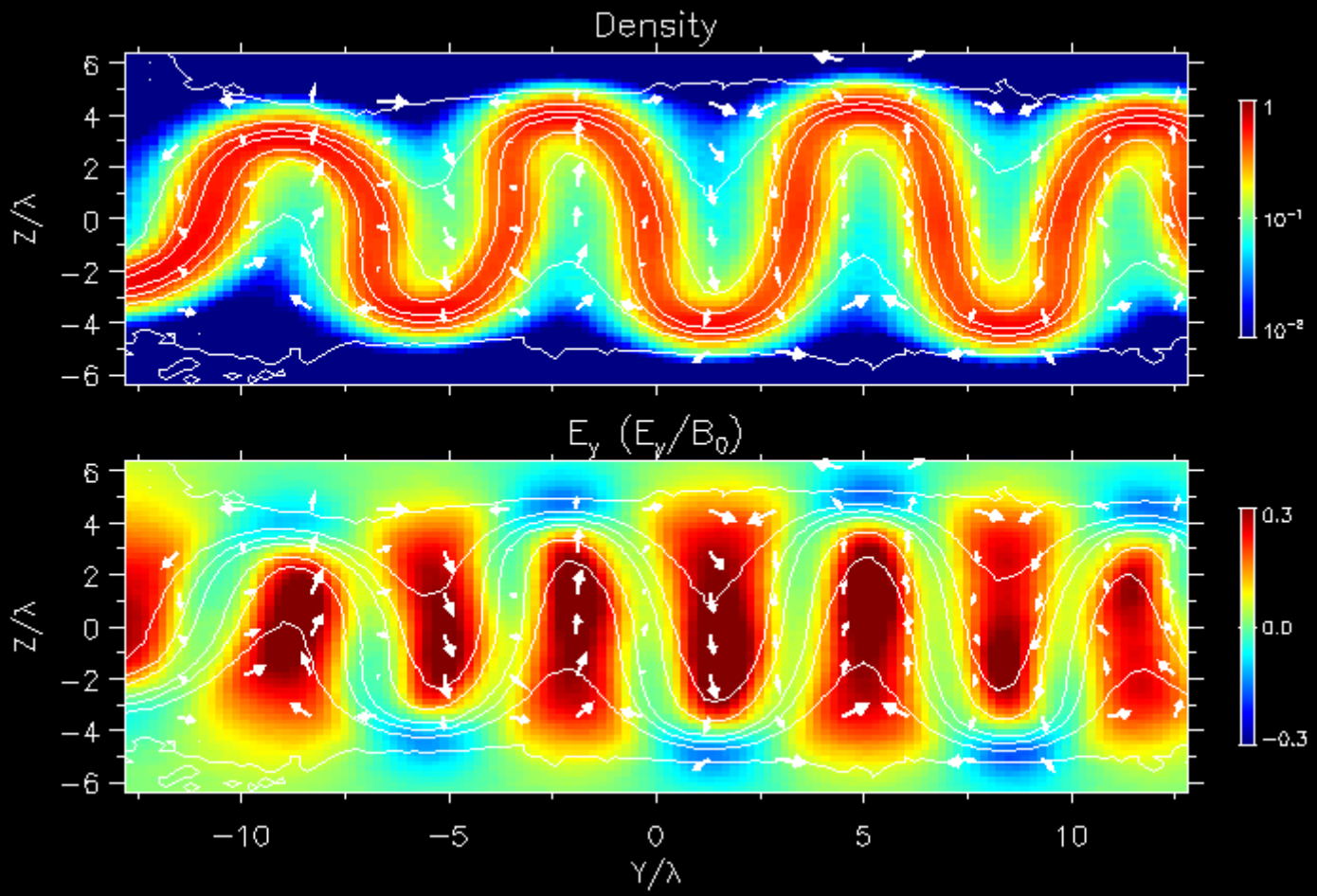


Drift-Kink Mode (early stage)

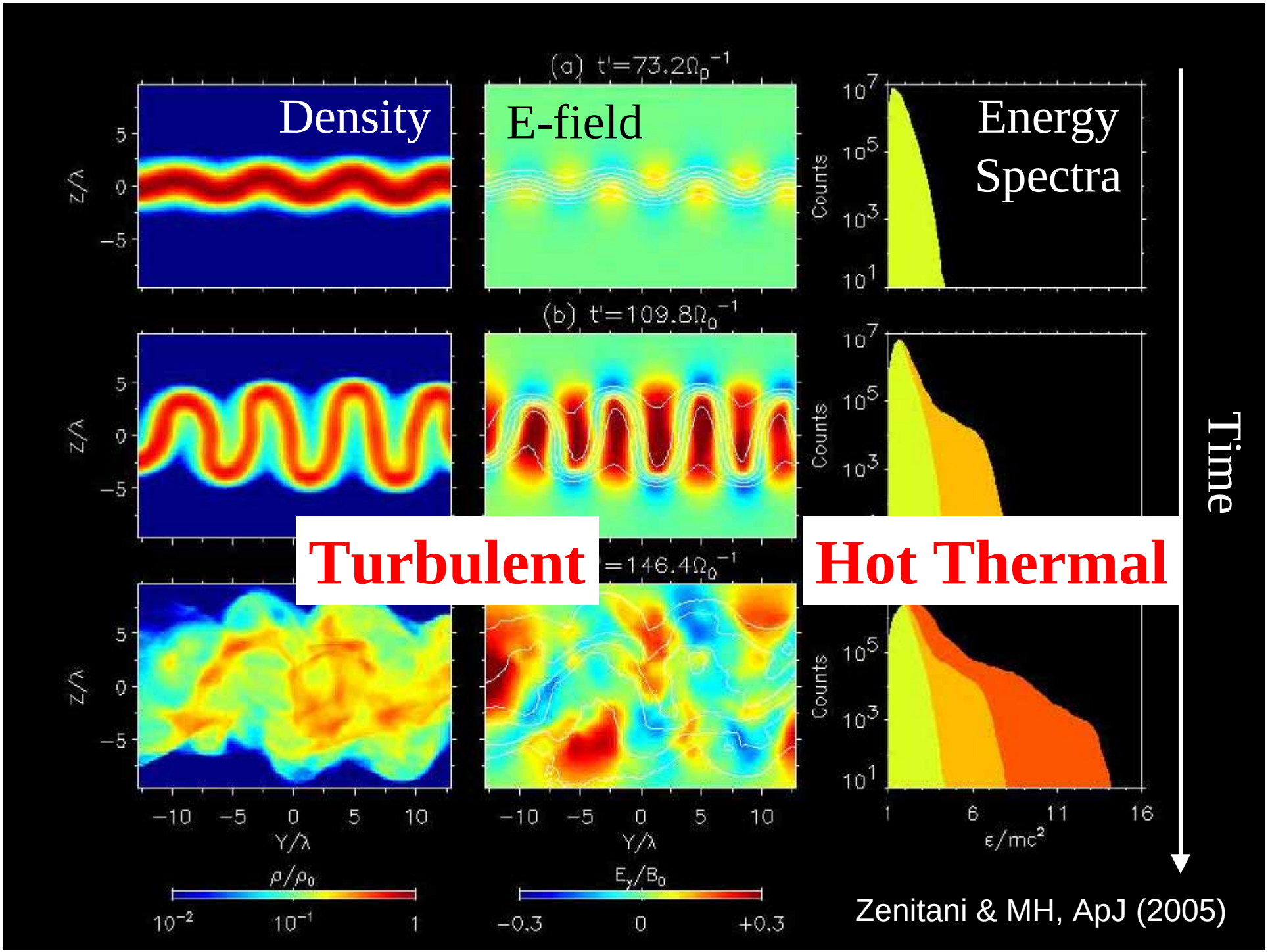


Initial condition: relativistic Harris solution

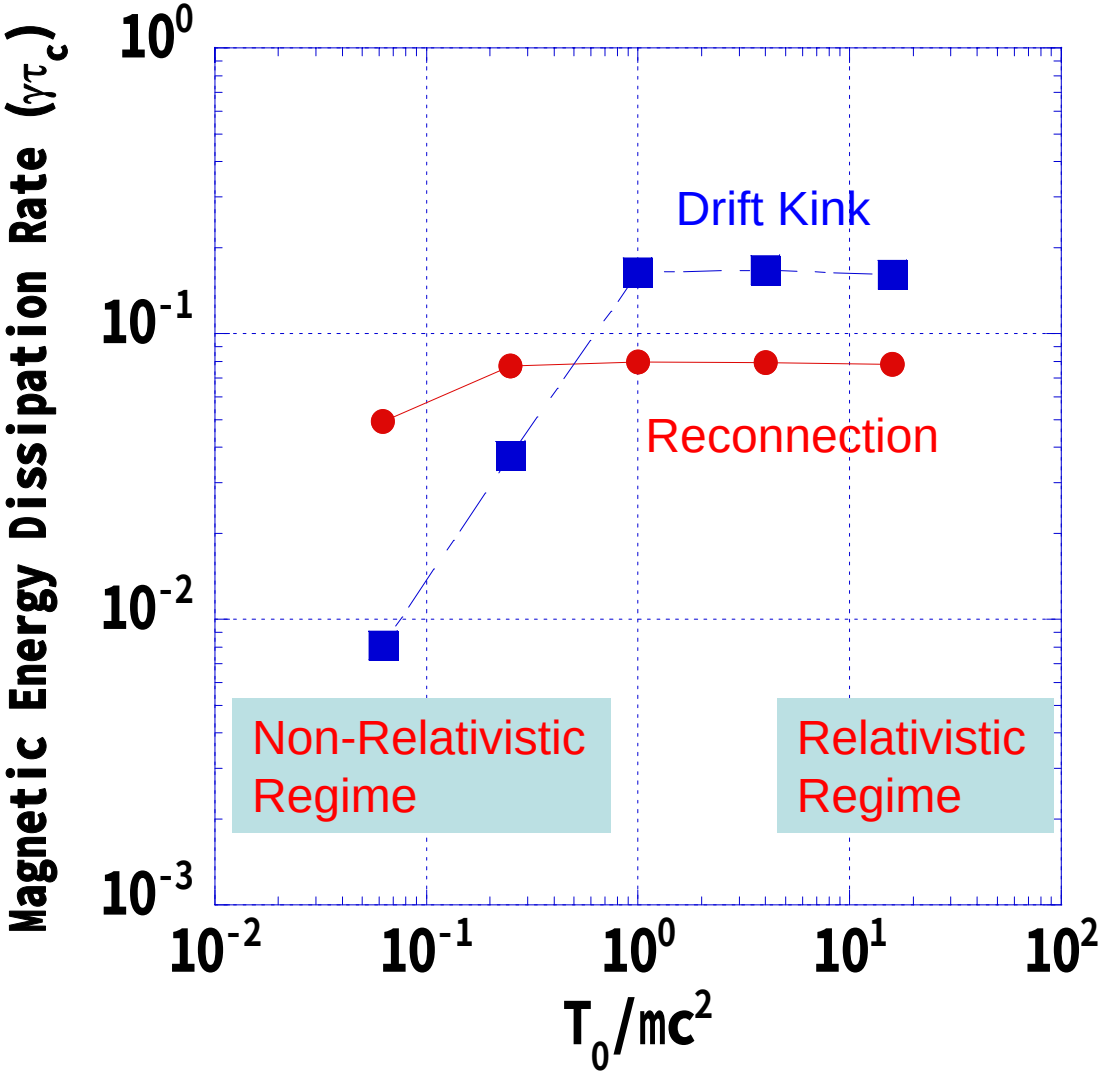
Drift-Kink Mode (nonlinear stage)



$E \cdot J > 0$ strong magnetic energy dissipation


Density
E-field
Energy Spectra
(a) t'=73.2Ω_p^-1
(b) t'=109.8Ω_0^-1
=146.4Ω_0^-1
Turbulent
Hot Thermal
Time
Z/λ
Y/λ
Counts
ε/mc²
ρ/ρ_0
E_y/B_0
Zenitani & MH, ApJ (2005)

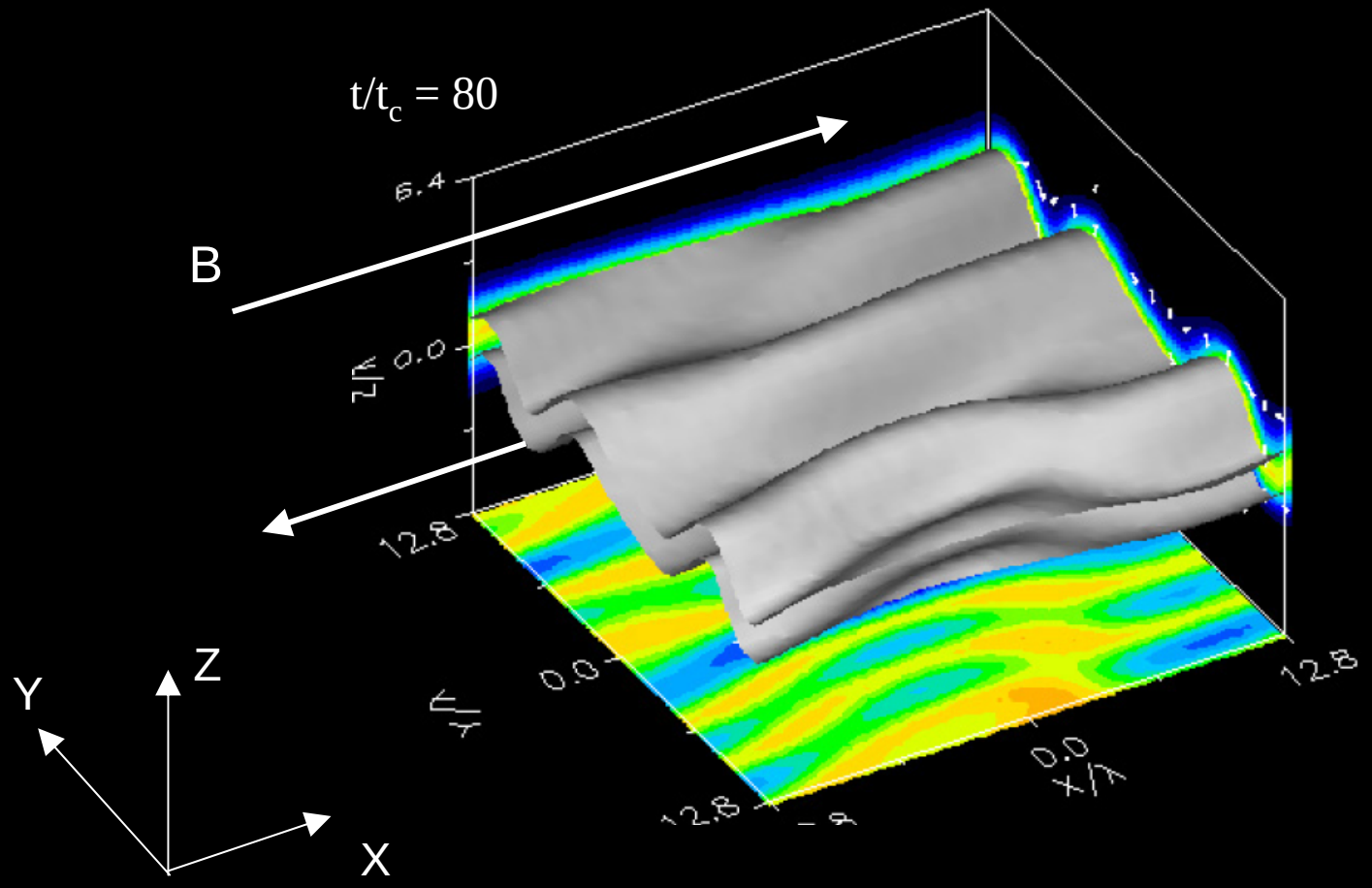
Energy Dissipation Rate



$$\text{Dissipation Rate}(\gamma) = \frac{d}{dt}\ln\left(\int (B(x,0)^2 - B(x,t)^2)dx \,/\, 4\pi \int P(x,0)dx\right)$$

3D Current Sheet Evolution

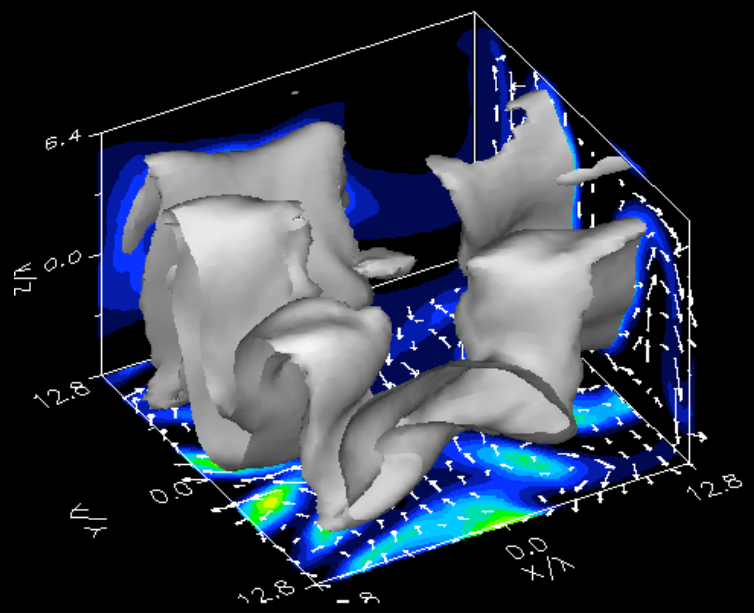
Isosurface of N, Color contour of N at neutral sheet



As we expected, Drift-Kink grows faster than Reconnection

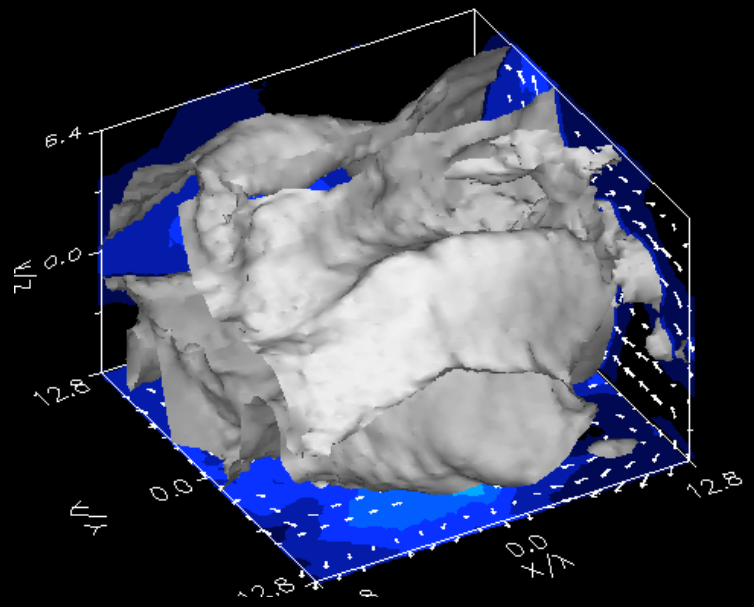
Nonlinear Stage of 3D Current Sheet

$t/t_c = 110$



Transition to Turbulence is fast in 3D than in 2D

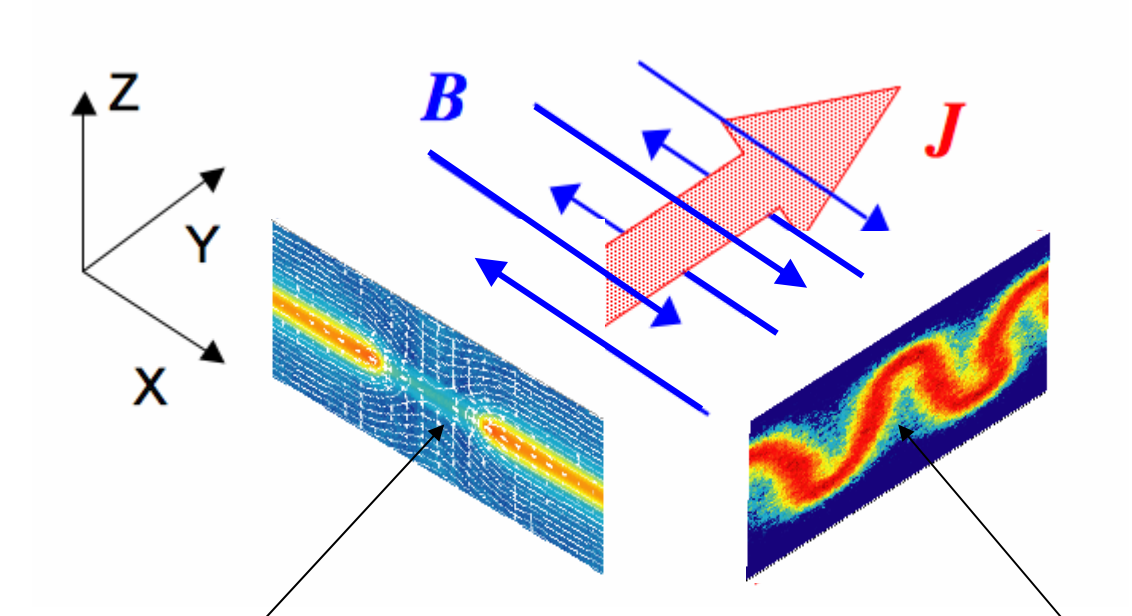
$t/t_c = 140$



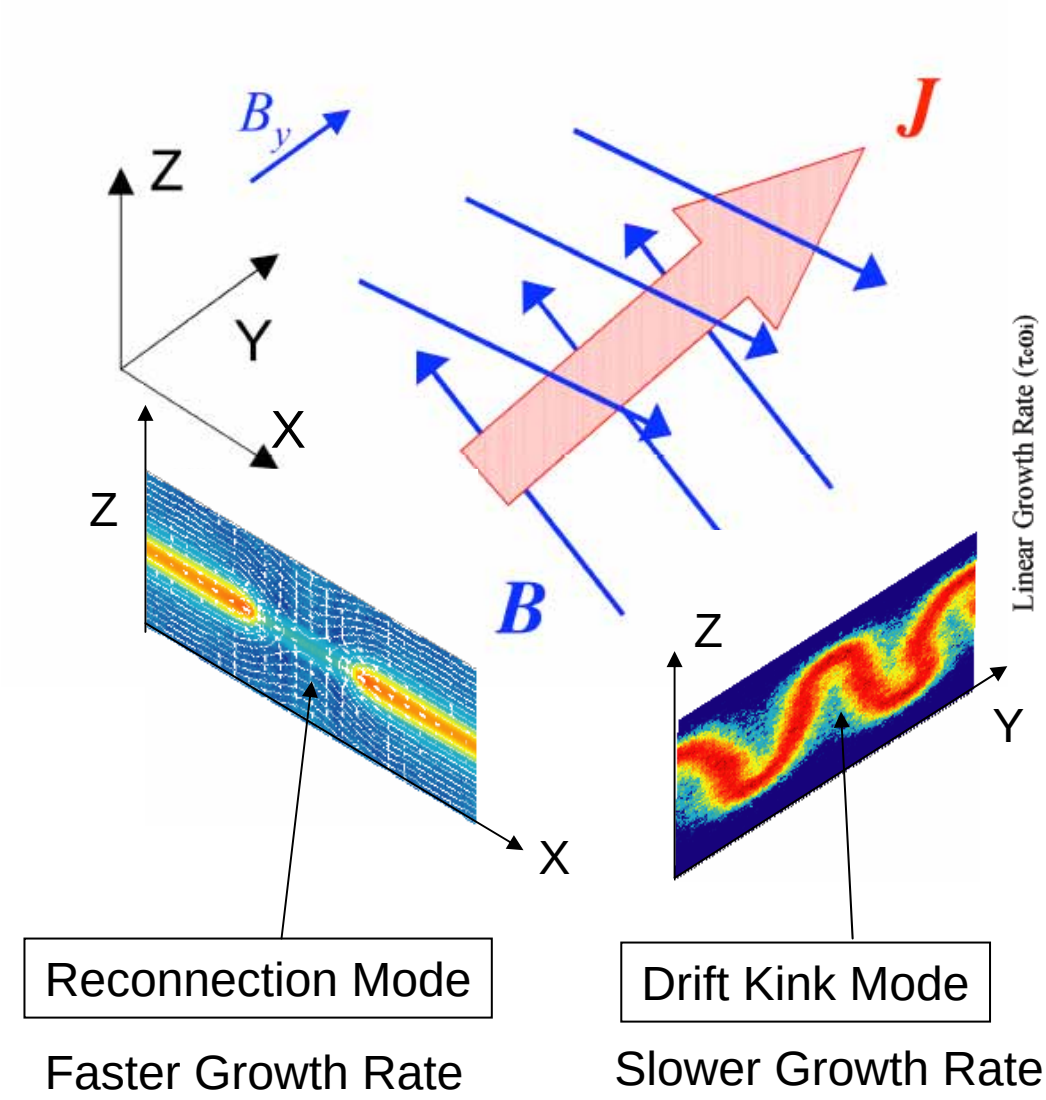
No Reconnection Mode and Relativistic Thermal Plasma

Relativistic Current Sheet Instability

$V_A/c \sim O(1)$, $T/mc^2 \sim O(1)$,
Electron and Positron Plasmas



3D Reconnection with Guide Field (By)

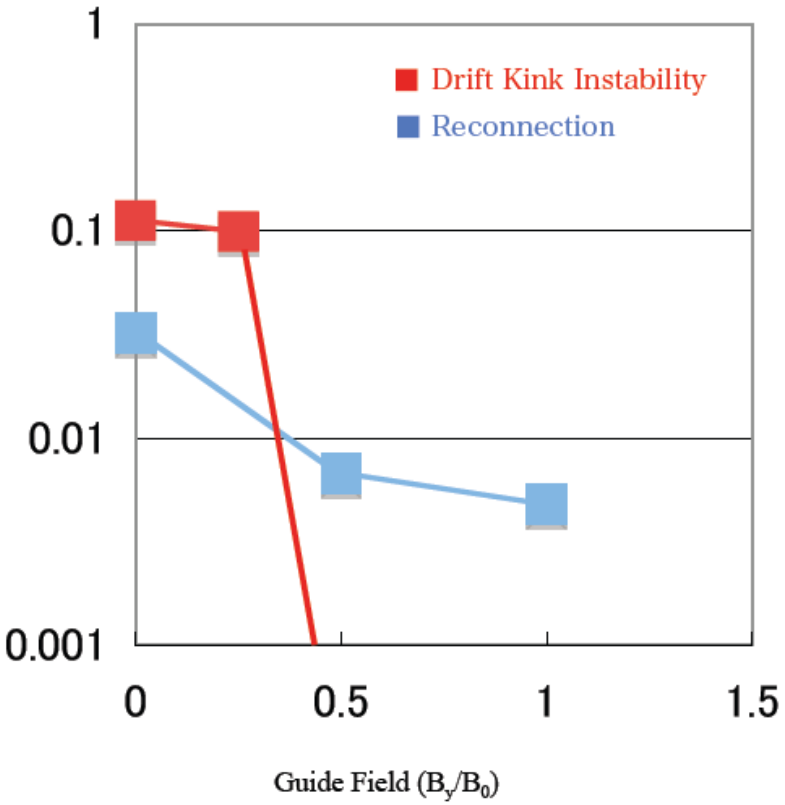


Reconnection Mode

Faster Growth Rate

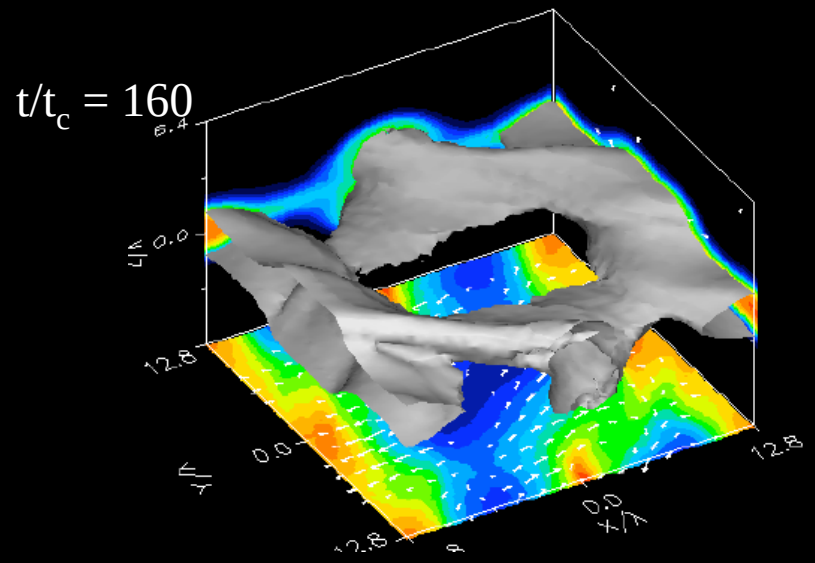
Drift Kink Mode

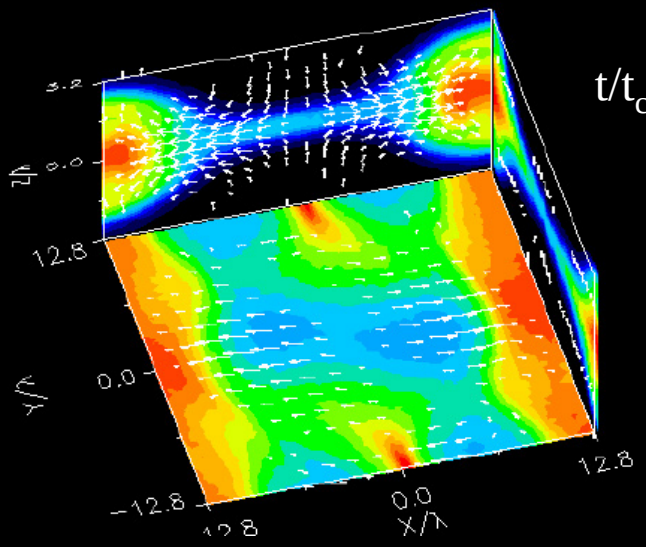
Slower Growth Rate

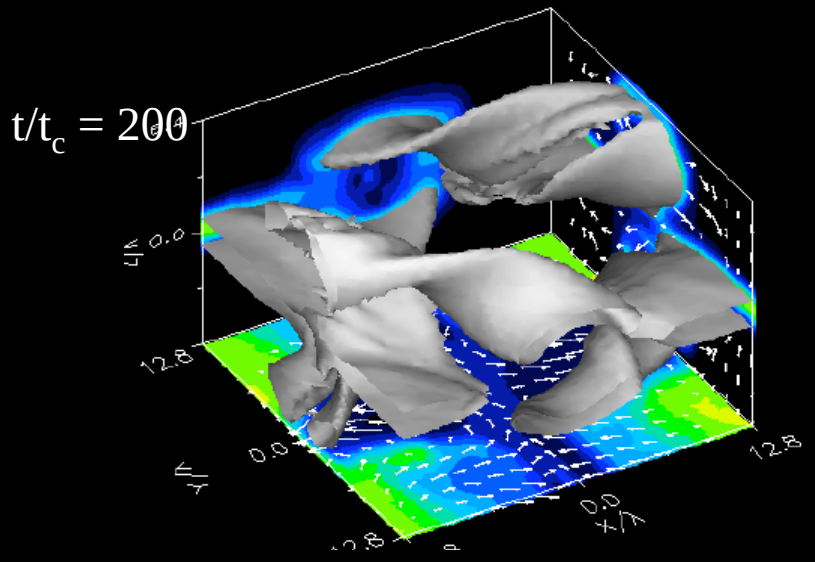


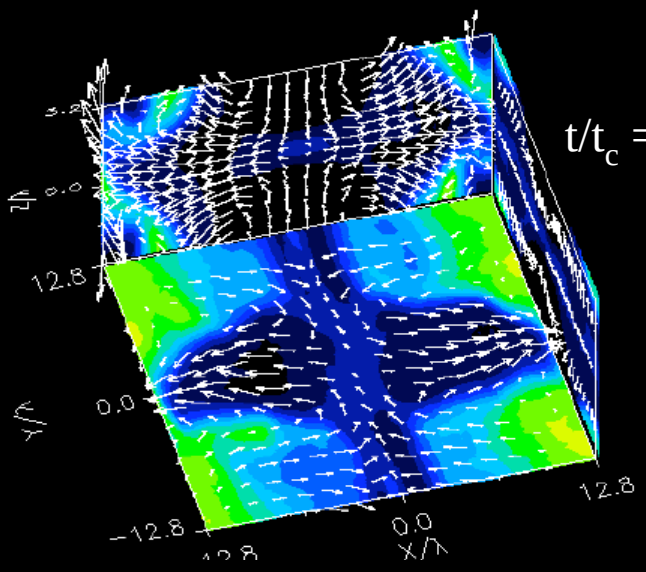
Drift-Kink is suppressed
due to magnetic tension force

3D Reconnection with Guide Field





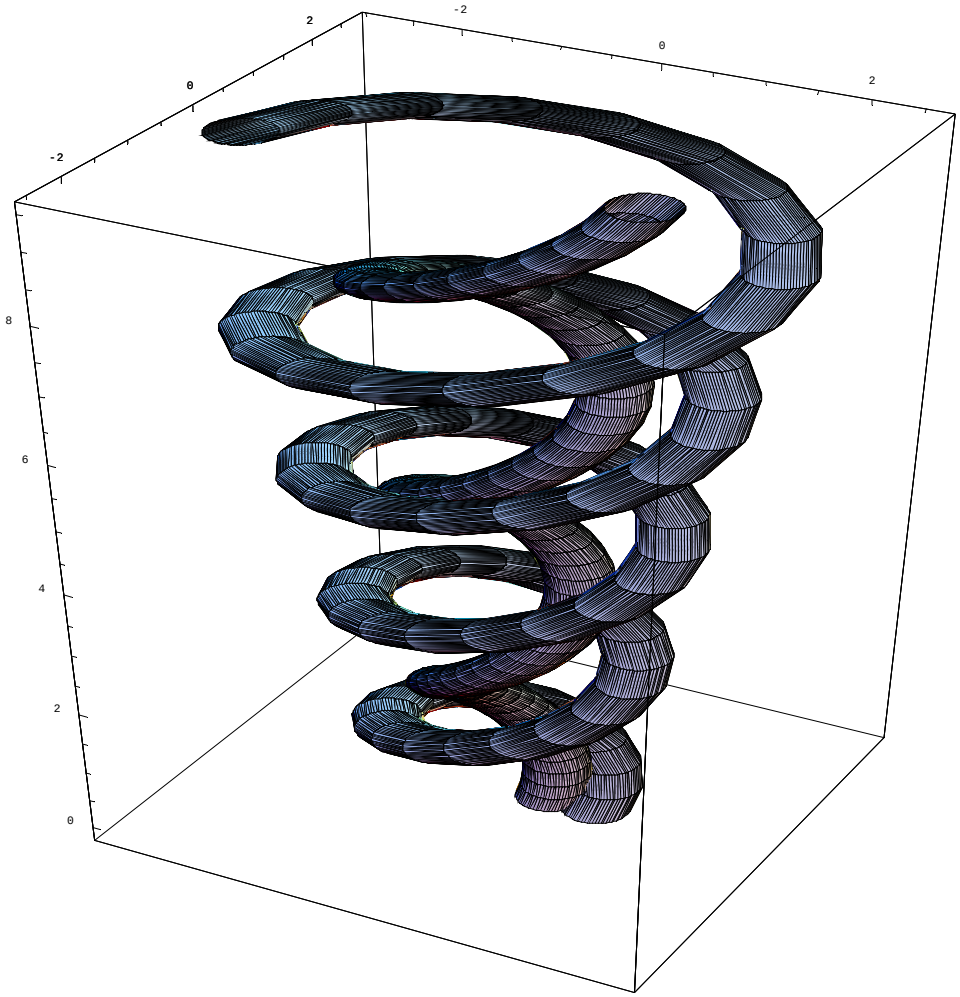




Zenitani & MH, PRL 2005

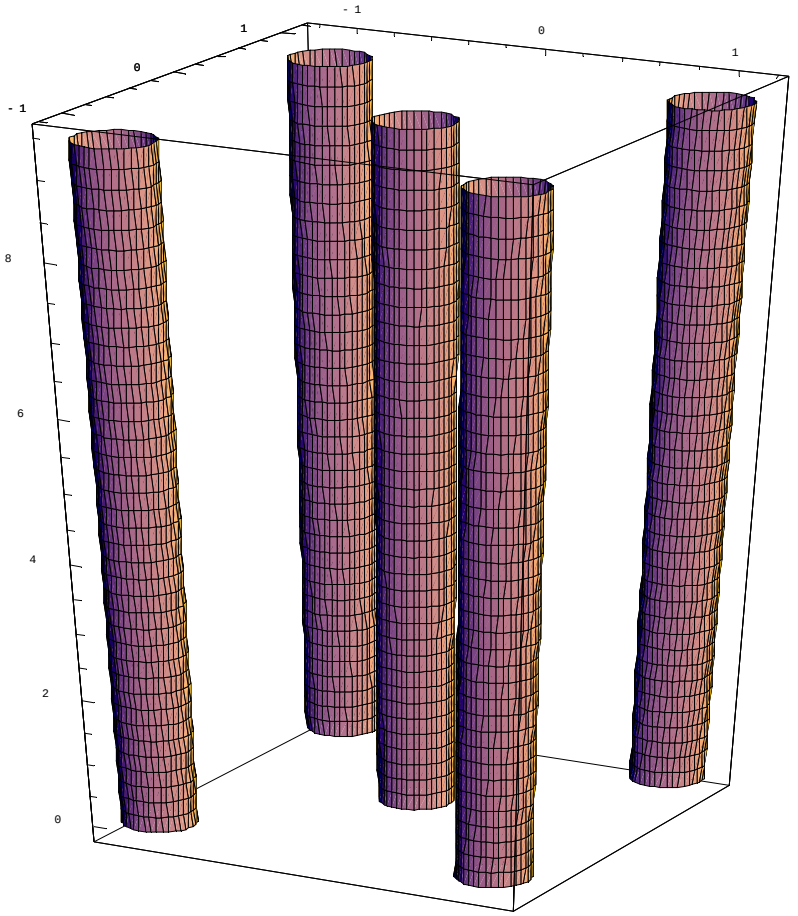
Reconnection

Nonthermal Particle with a Hard Spectrum



Drift Kink

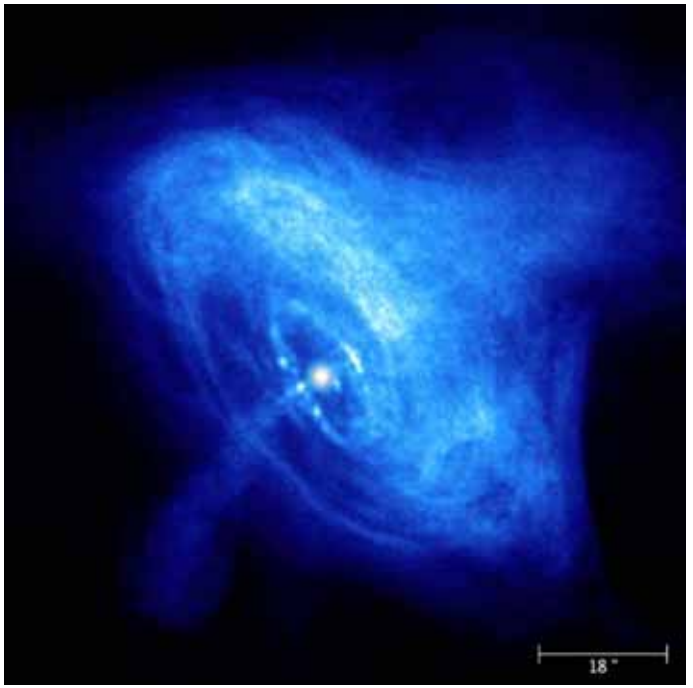
Thermal Plasma

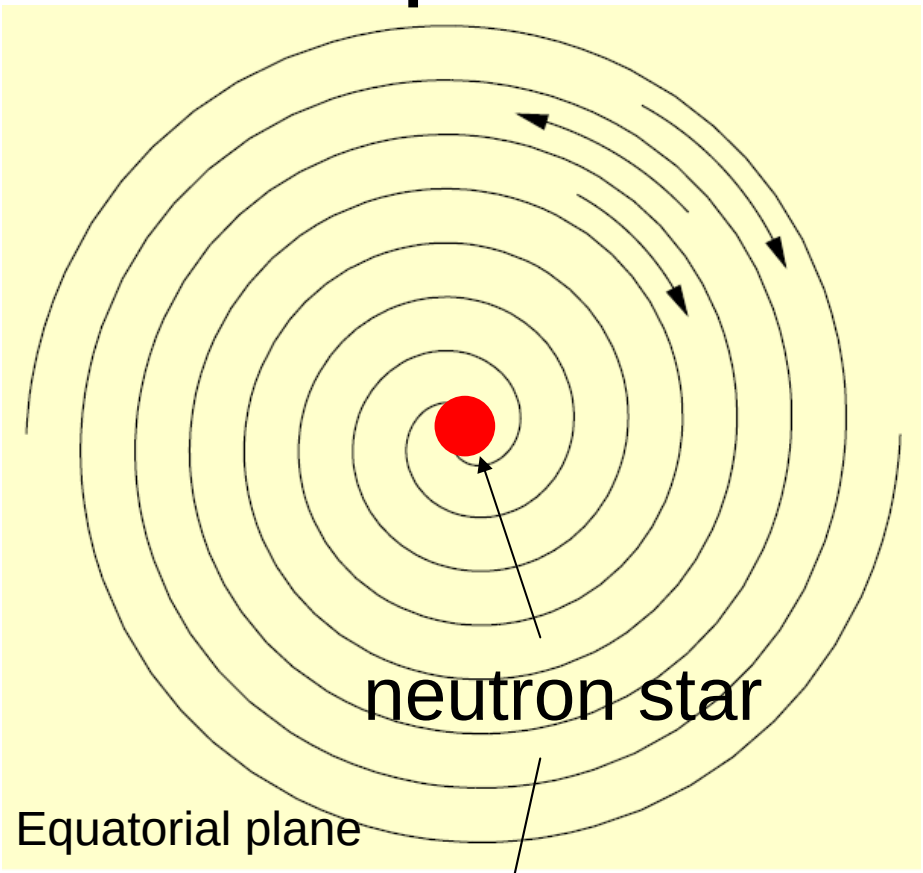


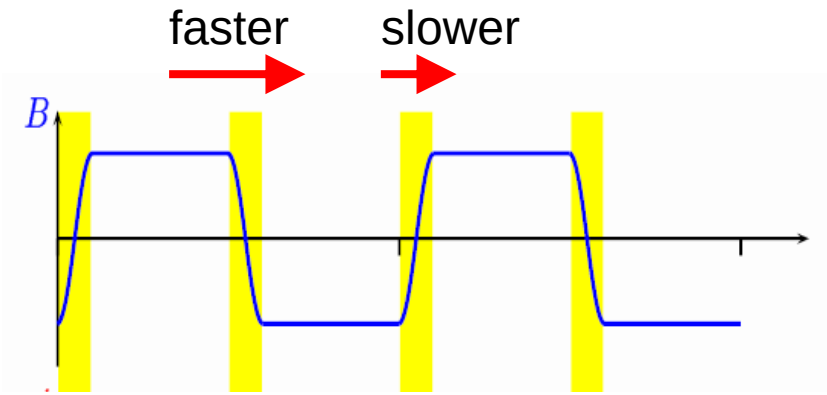
Application of Relativistic Current Sheet

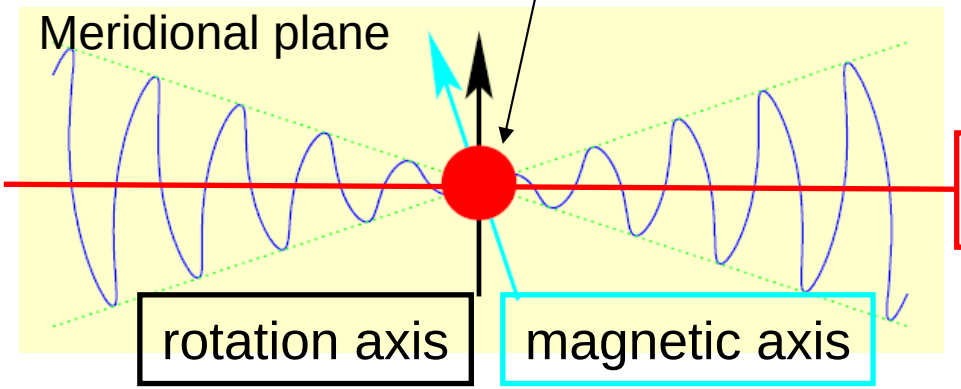
- Interaction between Shock Wave and Current Sheet
  - Fast Shock-Tangential Discontinuity (TD)
- Interaction between CurrentSheet & Current Sheet
  - TD-TD Interaction

Striped Wind





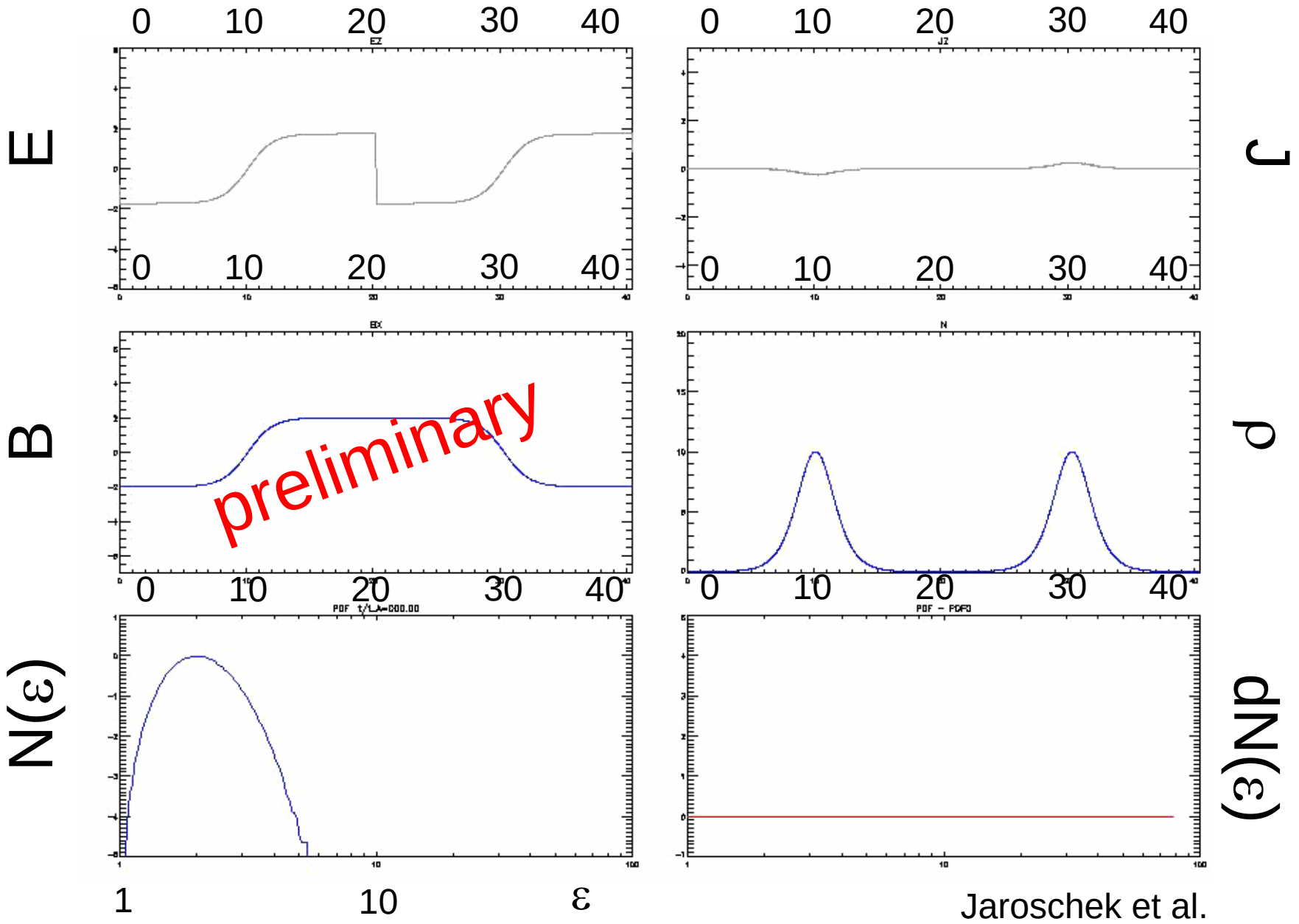




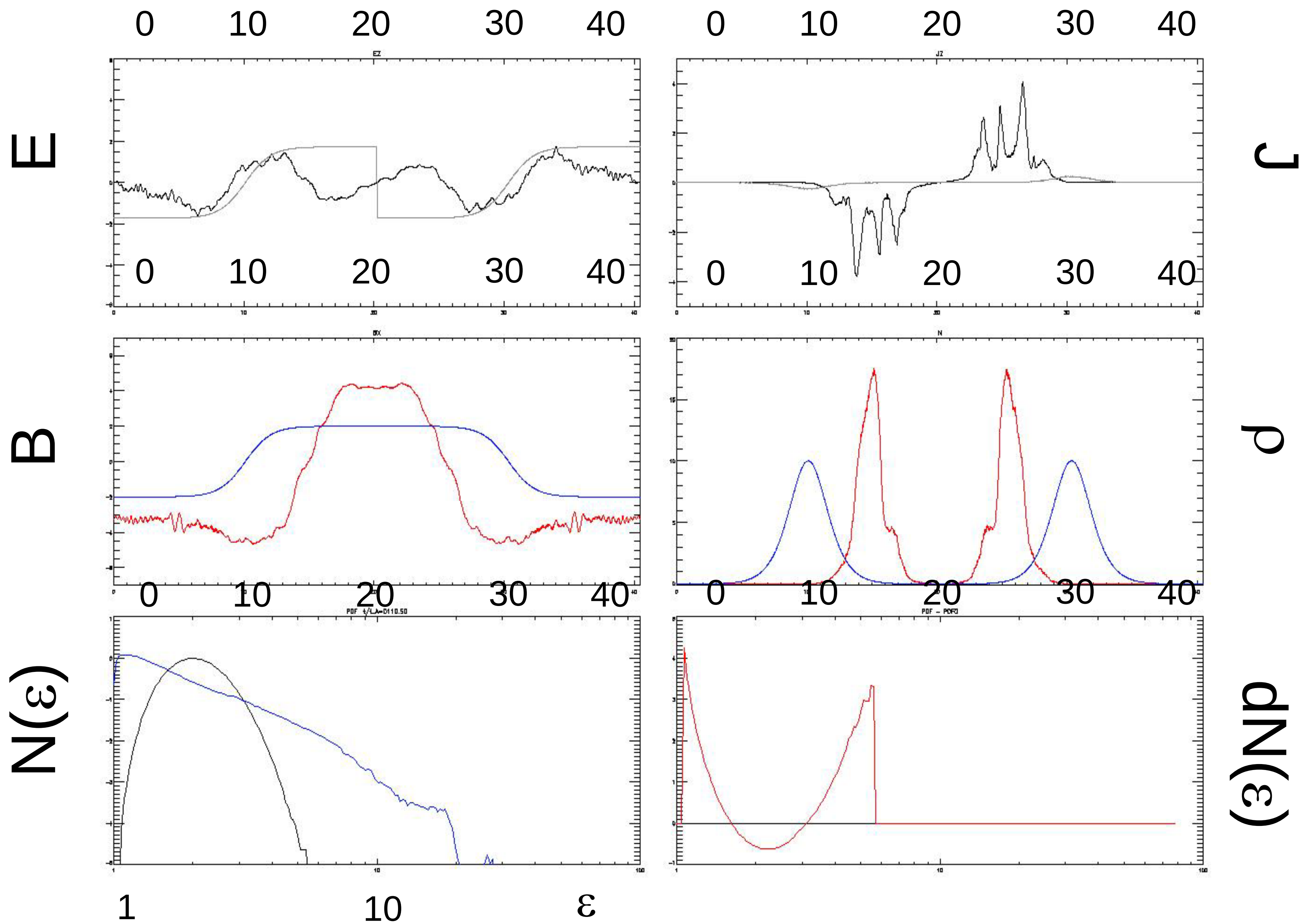
equator

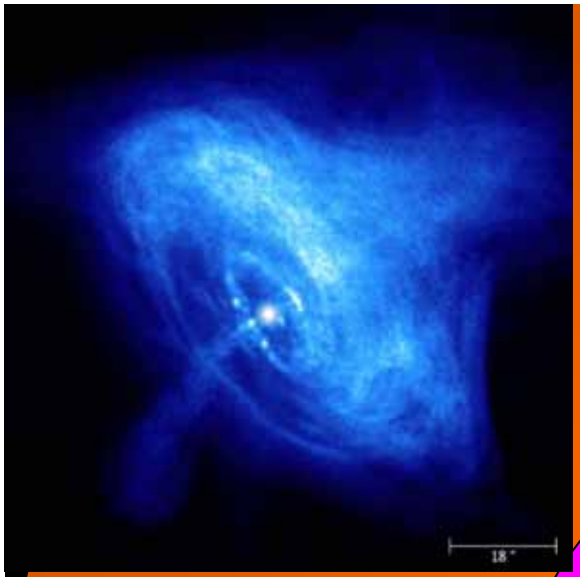
Coroniti, ApJ 1990,
Lyubarsky & Kirk 2001,
Kirk et al. PRL 2003

CurrentSheet-CurrentSheet Interaction



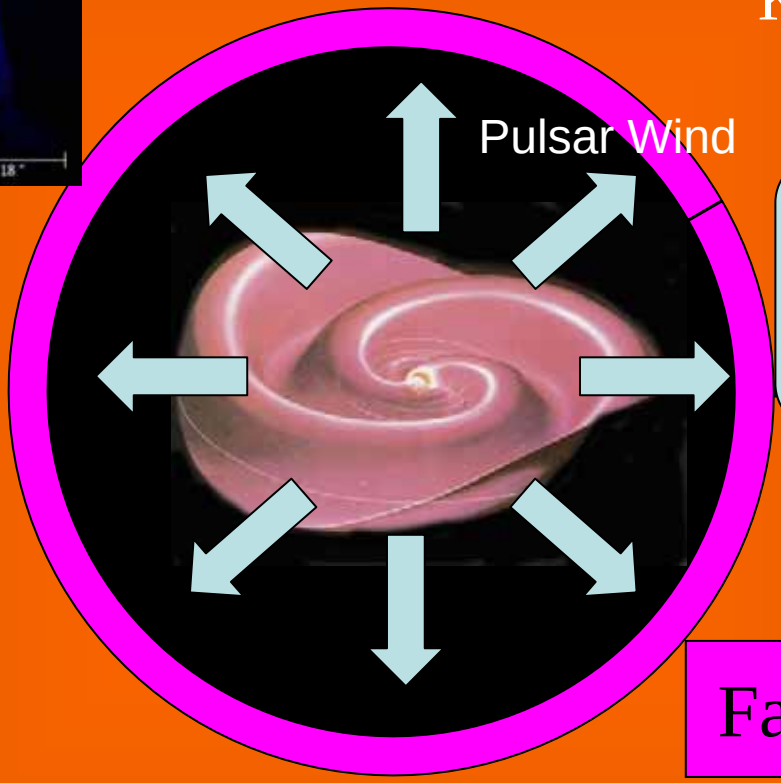
Jaroschek et al.


E
J
B
ρ
N(ε)
dN(ε)
0
10
20
30
40
1
10
ε



Shock Model

Rees & Gunn (’74)
Kennel & Coroniti (’84)



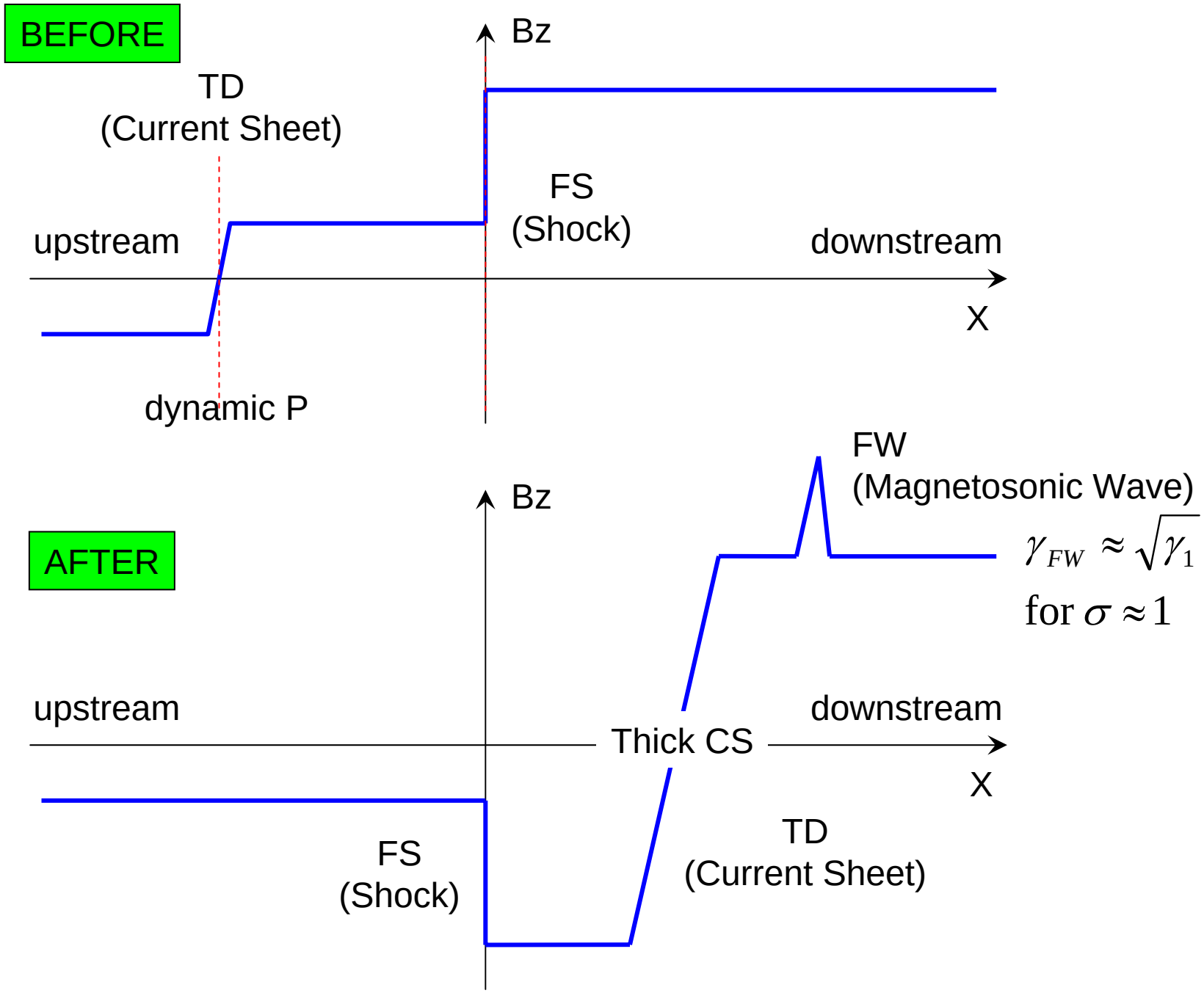
$\gamma = 10^6$

$\sigma = 10^{-3} = EM / KE$

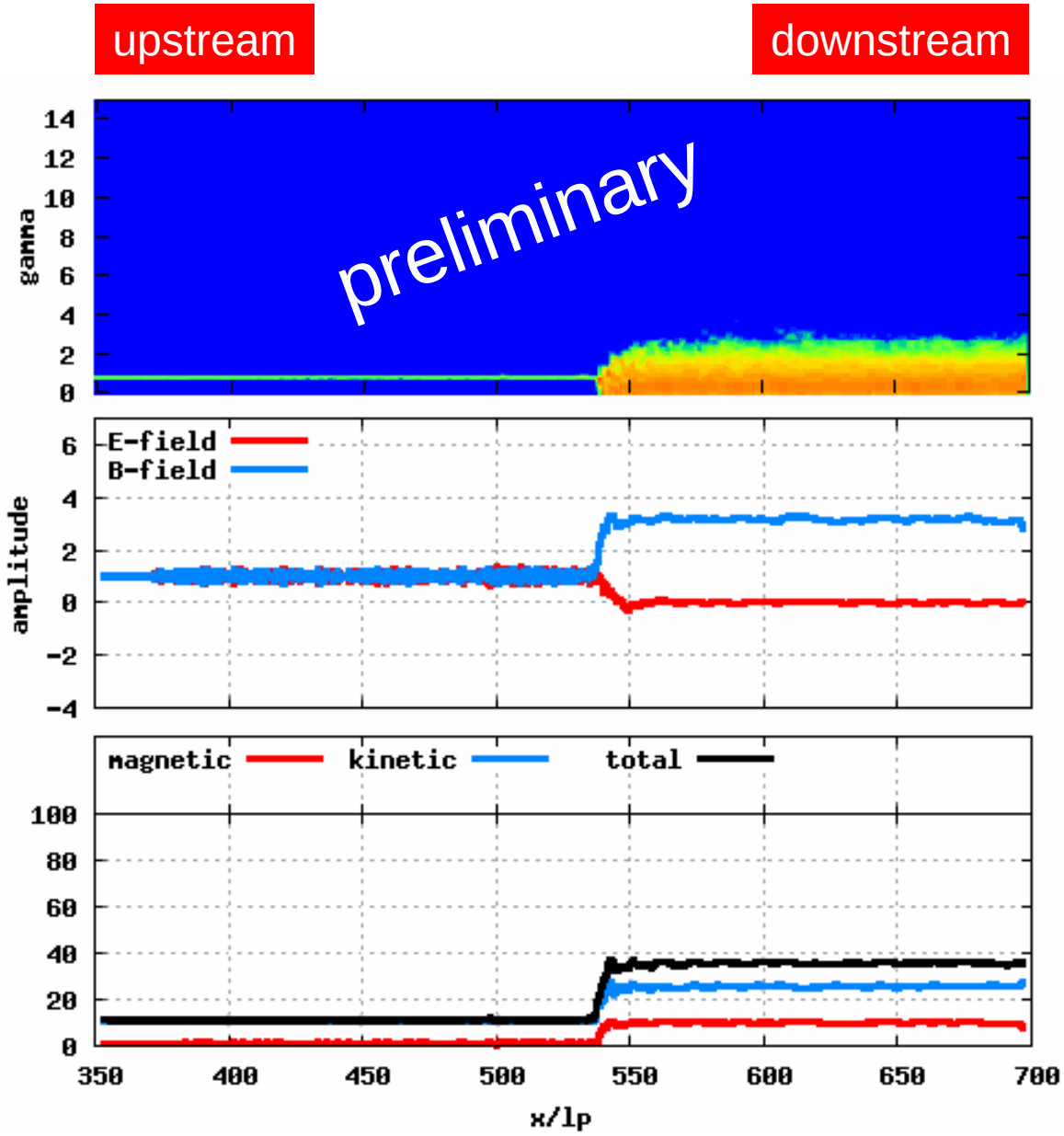
$= B^2 / (4\pi nu\, \gamma mc^2)$

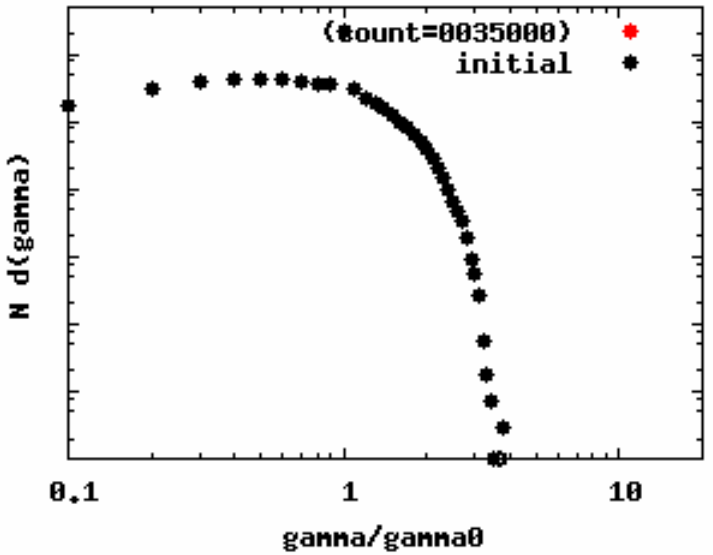
Fast Shock

Nonthermal Particle
→ Synchrotron emission


BEFORE
Bz
TD
(Current Sheet)
FS
(Shock)
upstream
downstream
X
dynamic P
FW
(Magnetosonic Wave)
Bz
AFTER
$\gamma_{FW} \approx \sqrt{\gamma_1}$
for $\sigma \approx 1$
upstream
downstream
Thick CS
X
FS
(Shock)
TD
(Current Sheet)

Shock-CurrentSheet Interaction

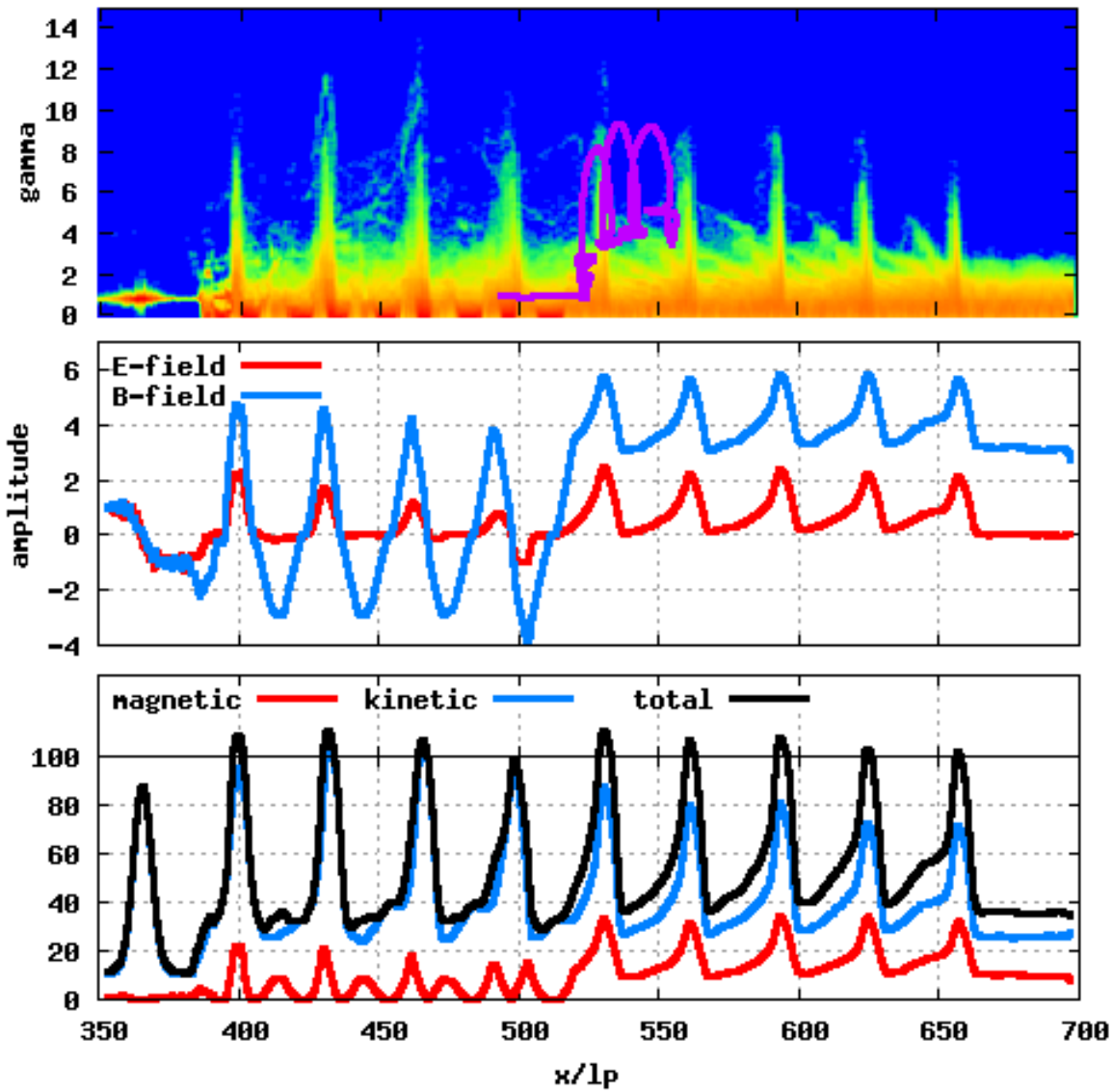


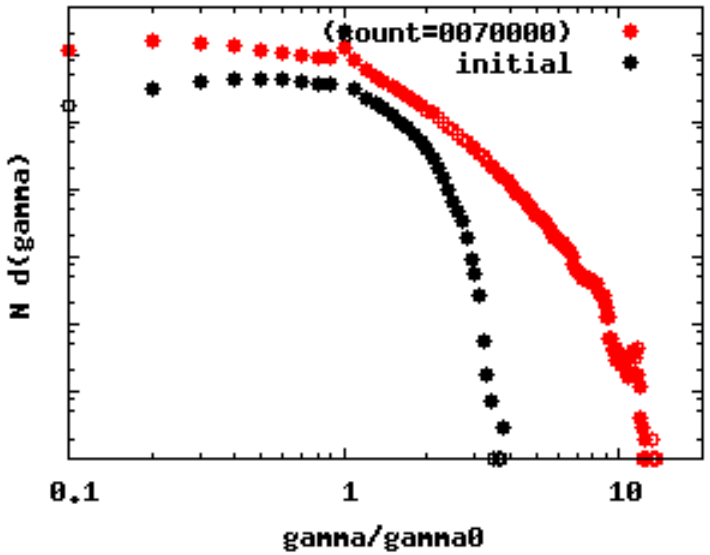


Nagata et al.

upstream

downstream





Summary

- Current Sheet Instabilities (Magnetic Reconnection, Drift-Kink Inst.)
  - MRX (non-thermal acceleration with a hard spectrum)
  - DKI (thermal heating)
  - Growth rate of DKI > MR in relativistic current sheet without guide B field,
  - but MR > DKI for the case with guide B field
- Shock-CurretSheet Acceleration
- CurrentSheet-CurrentSheet Acceleration