THE UNIVERSITY OF TOKYO

# Particle Acceleration in Reconnection

1. Observations of Solar and Earth's reconnections
2. Stochastic reconnection acceleration in many islands
3. Reconnection during MRI in Accretion Disks
4. Relativistic Reconnection

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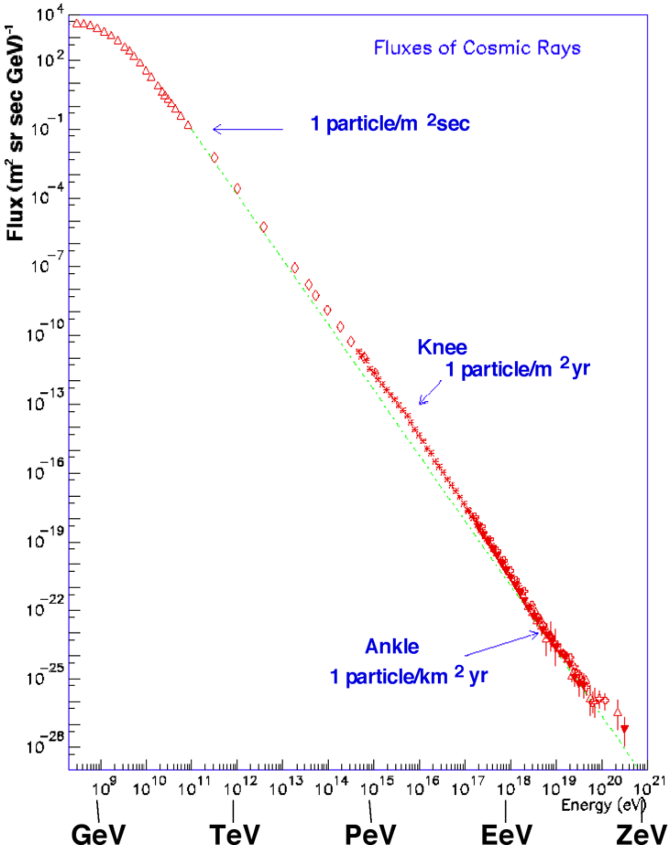
University of Tokyo

Acknowledgments to C. Jaroschek and S. Zenitani

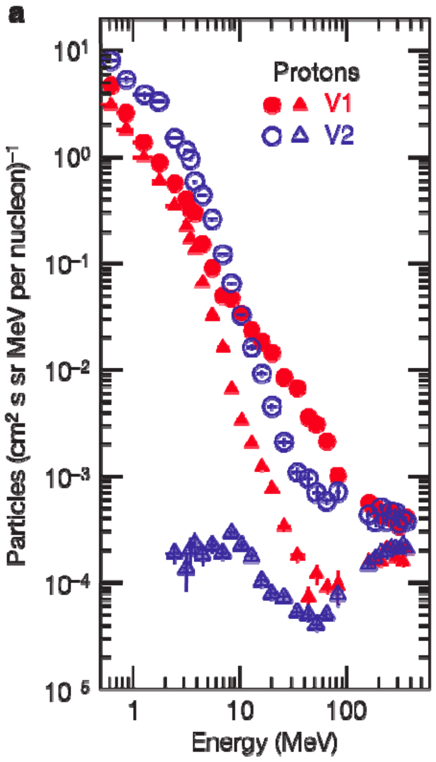
# Nonthermal Universe

## Cosmic Rays



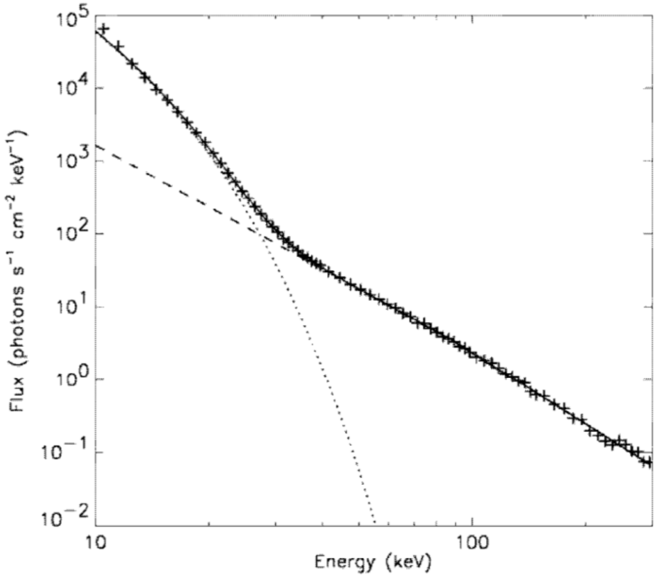
[Nagano & Watson, 2000]

## ACRs



[Stone et al., 2008]

## Solar Flares

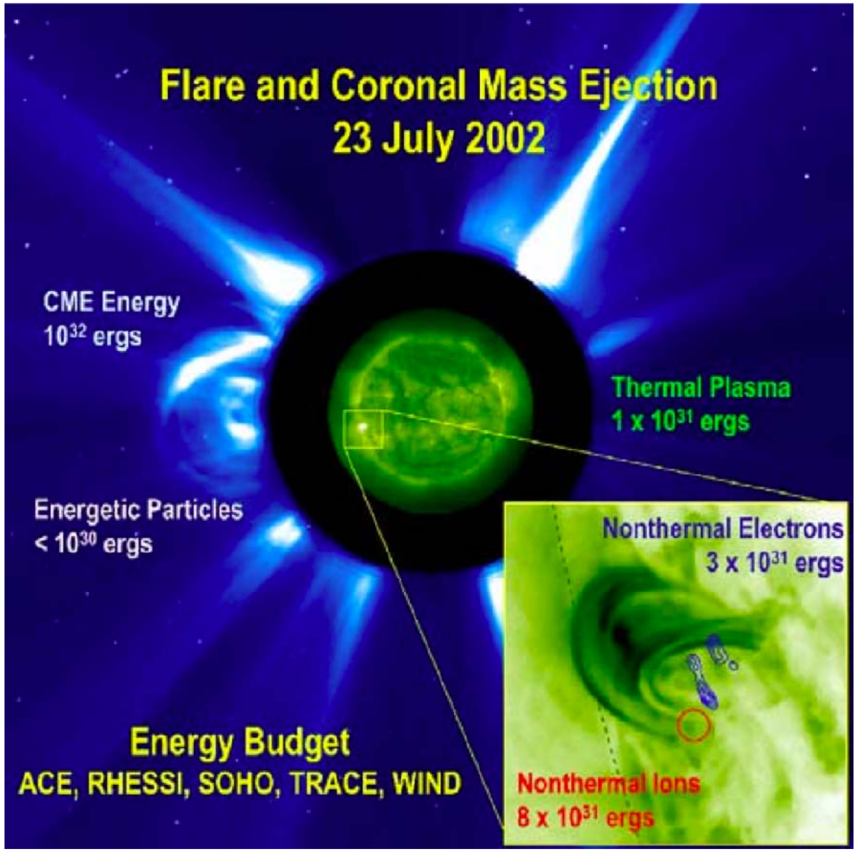


[Lin et al., 2003]

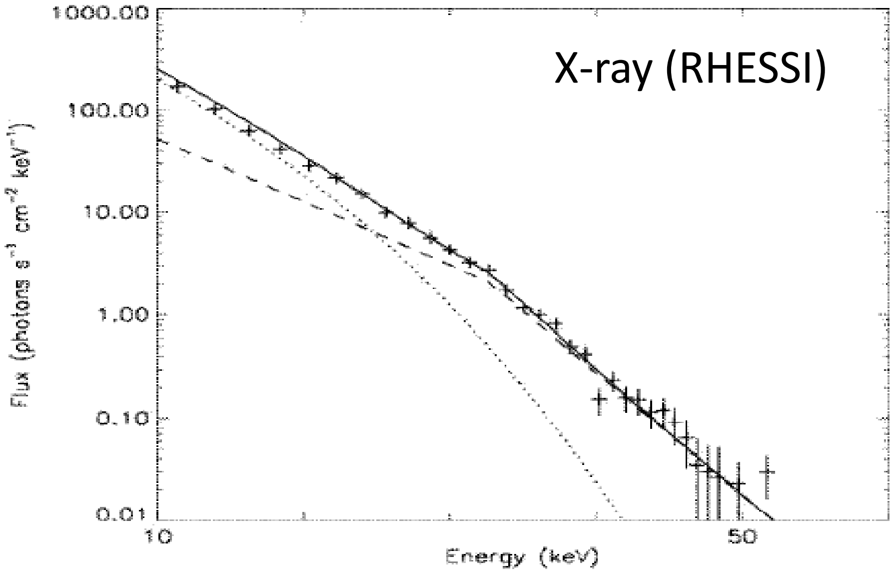
**Can magnetic reconnection produce non-thermal particles?**

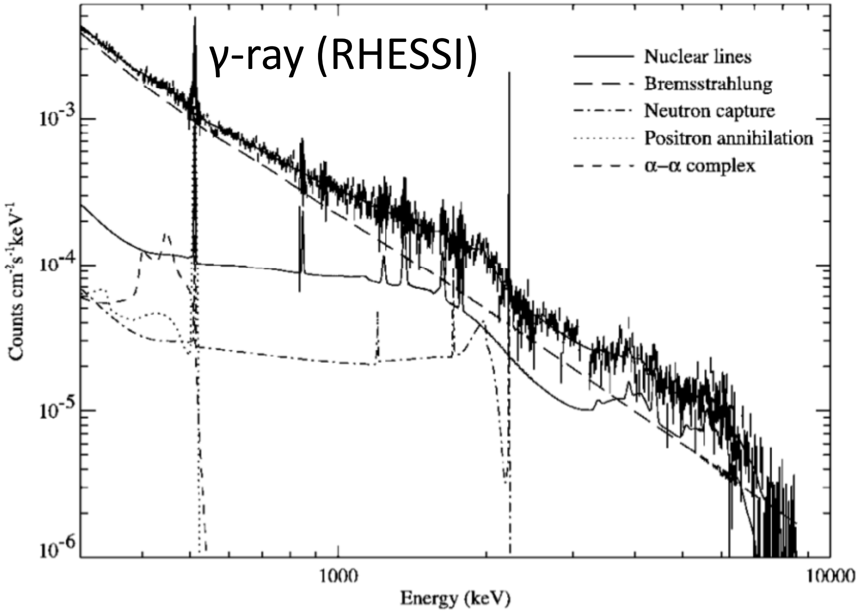
# Energetic ions and electrons in solar flares

(GOES   class X4.8)



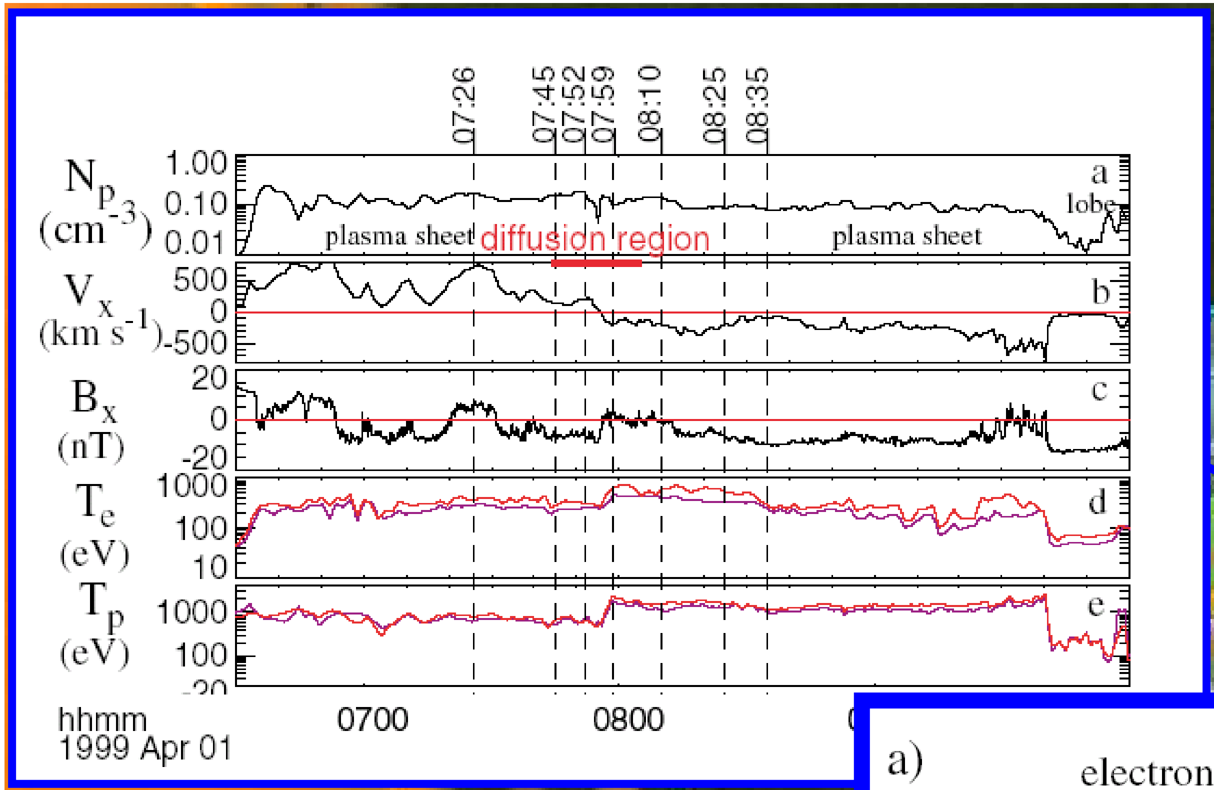
[Emslie et al., 2004]

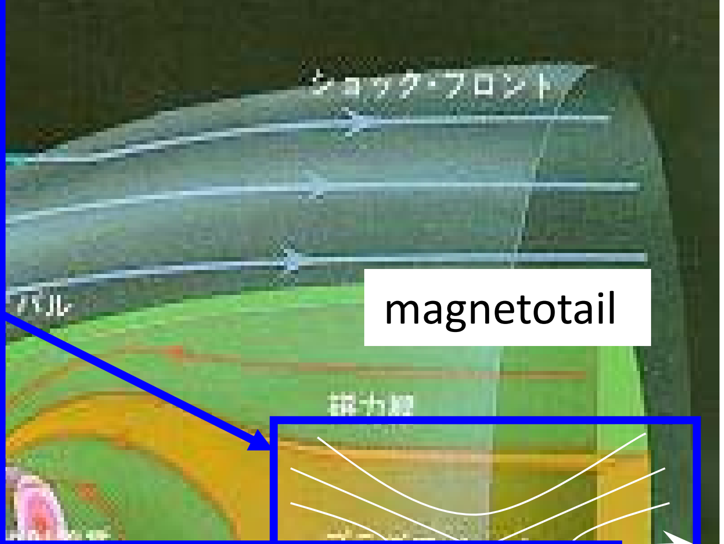




electrons up to tens of MeV,
ions up to tens of GeV
[Lin et al., 2003]

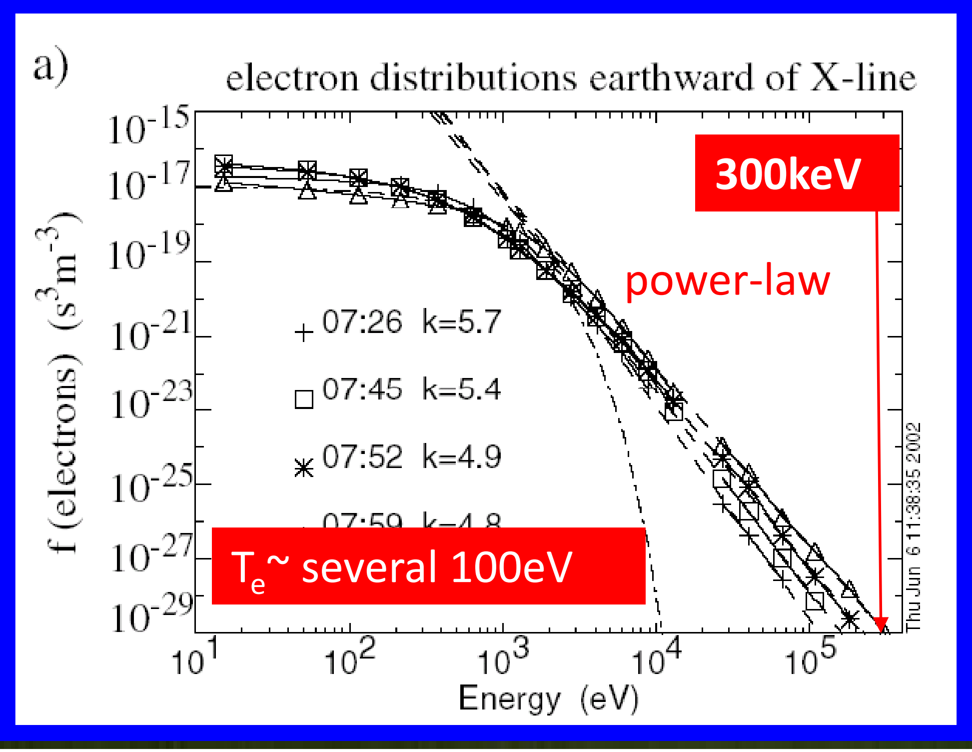
# Wind Observation





Reconnection signatures

- flow reversal (Vx)
- weak magnetic field (Bx)
- hot electron & ion plasmas (Te,Ti)

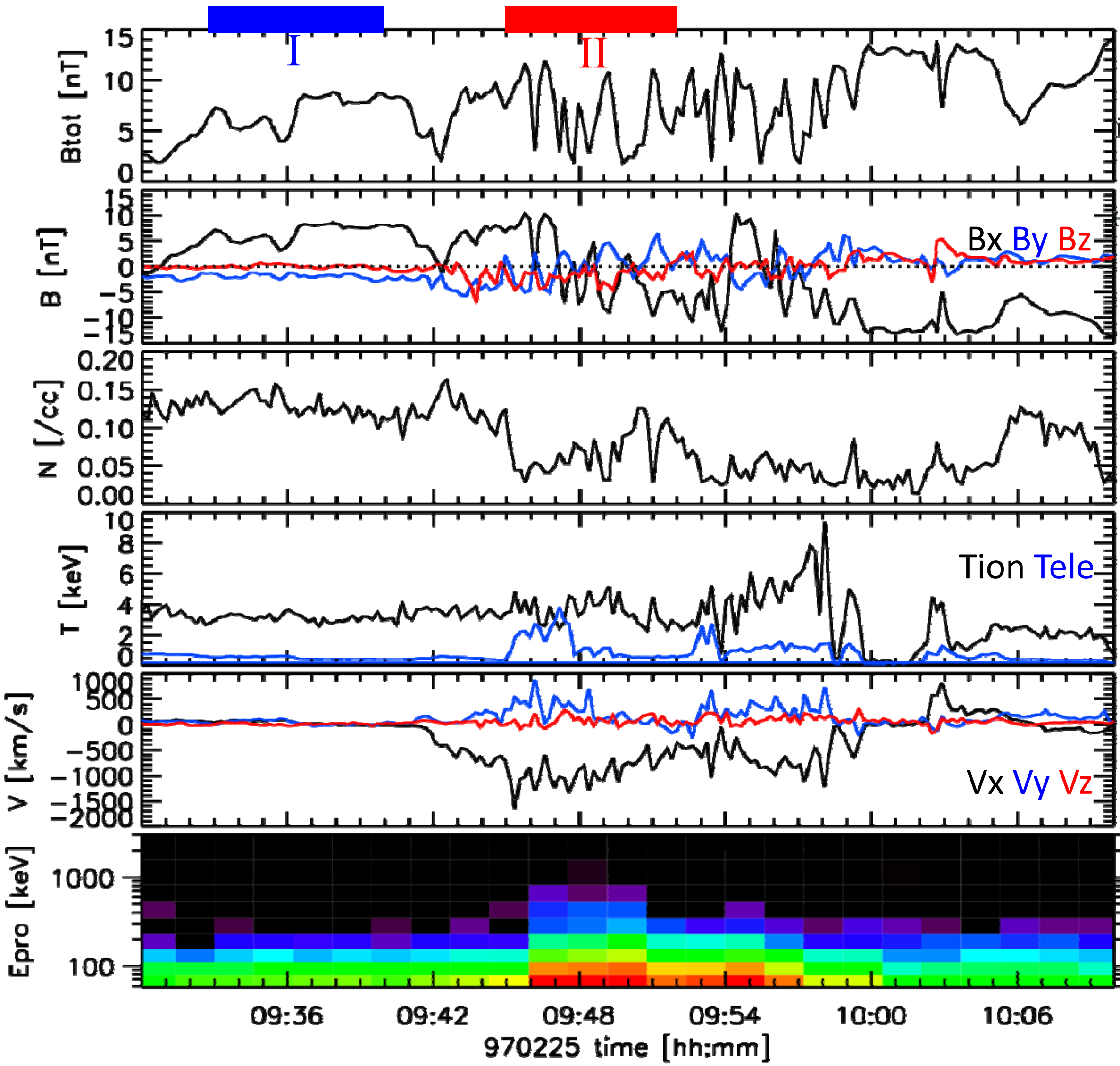


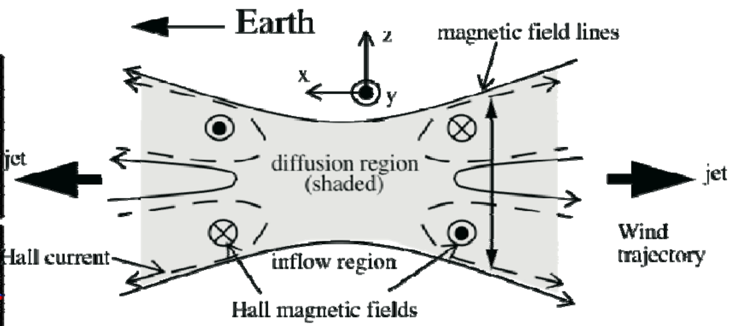
300keV

power-law

$T_e$~ several 100eV

# Reconnection in Earth's magnetotail





Observed MRX signatures

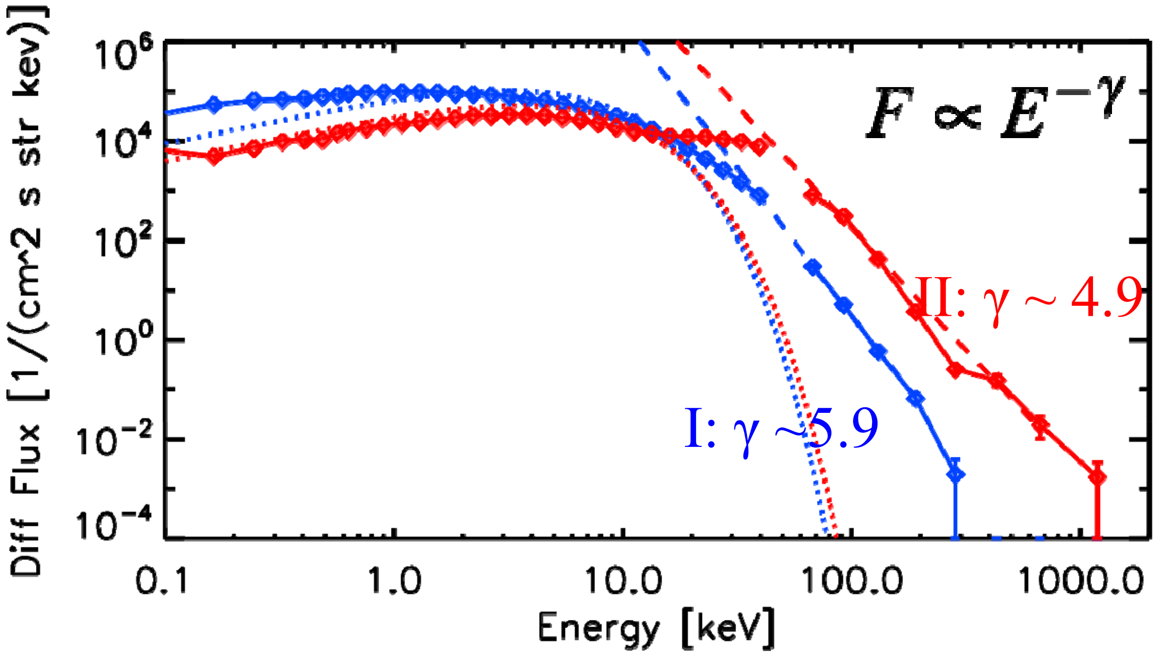
- neutral sheet crossing (Bx)
- fast Alfenic flow (Vx)
- strong ion/electron heating
- Hall magnetic field (By)

[e.g., Nagai et al.1998]

$(X, Y, Z) = (-27, 6, -1)\ R_E$

Hirai , MH et al, 2011

# Energetic ions in Earth's magnetotail

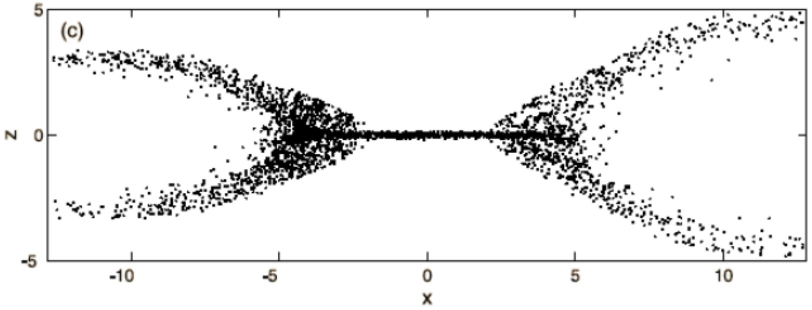


I: Before the onset of reconnection → II: After

| | I: Before | II: After |
|---|---|---|
| $\gamma$ | 5.9±0.8 | 4.9±0.2 |
| $P_{\text{nonthermal}}$(>100keV) [nPa] | $(3.4 \pm 3.2) \times 10^{-3}$ | $(9.2 \pm 2.2) \times 10^{-2}$ |

# Acceleration in MRX simulation

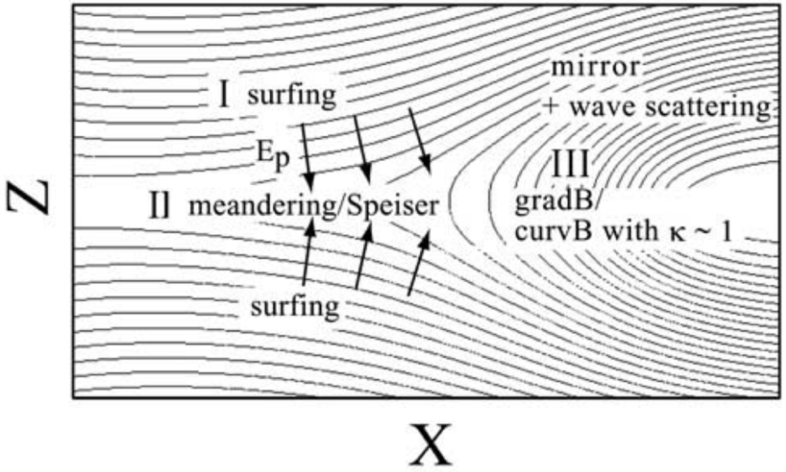
Pritchett, 2005

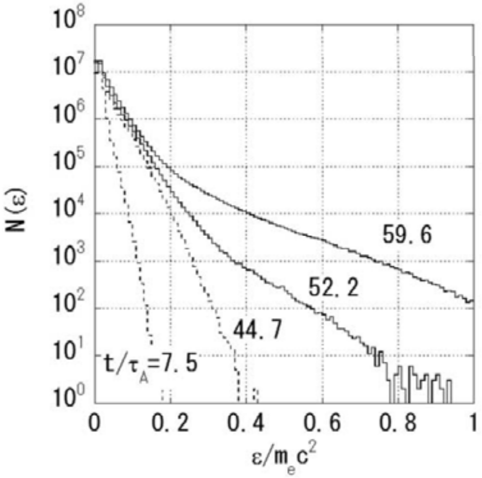


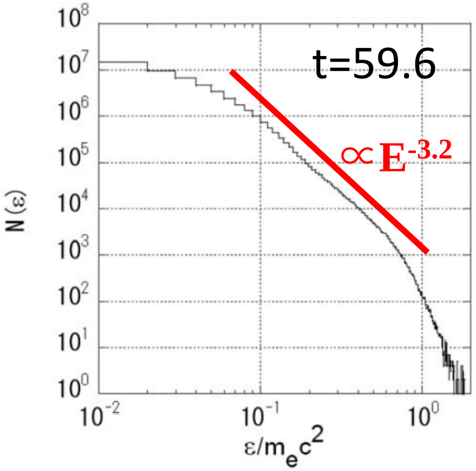
Several Acceleration Mechanisms:

- Linear X-line acceleration (Pritchett, 2005)
- Mulit-step processes including (1) electron “surfing” in the bounday, (2) Speiser/ meandering around X-line, and (3) Betatron acceleration in B pile-up region (MH 2005)

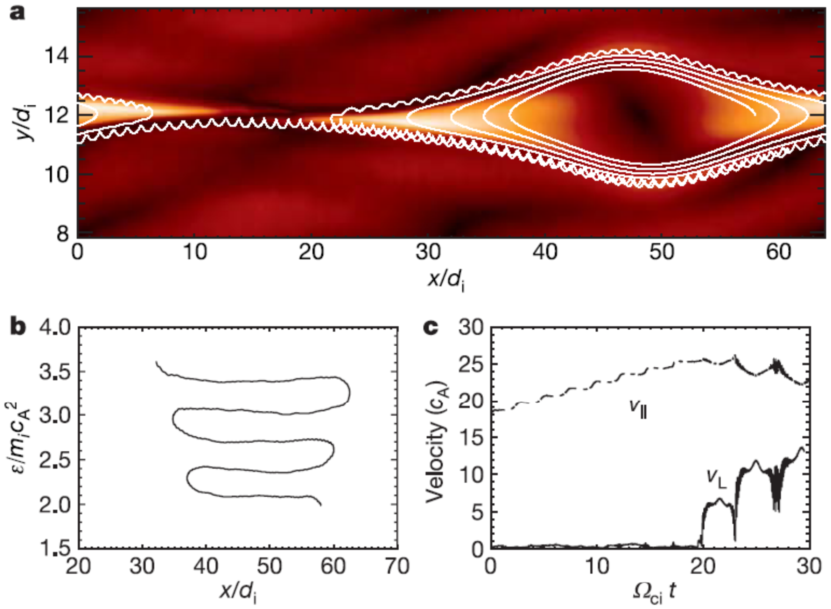
MH 2005



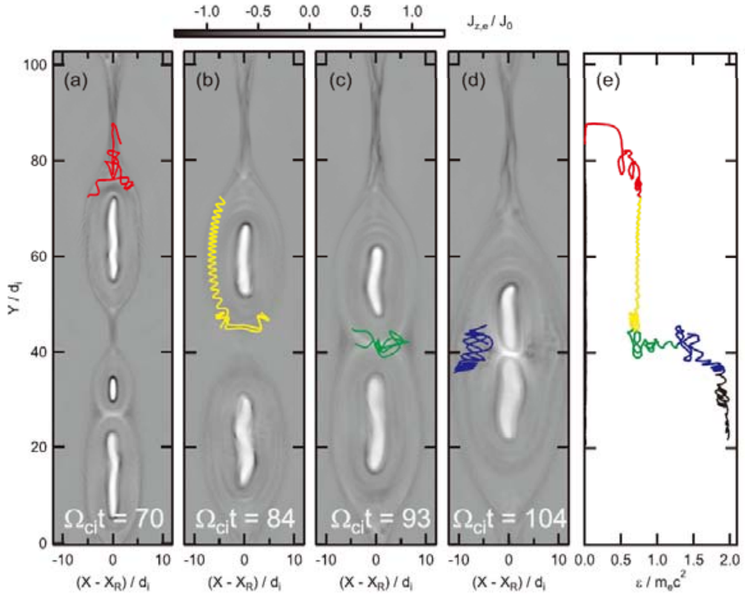




Drake et al. 2006



Oka et al. 2006

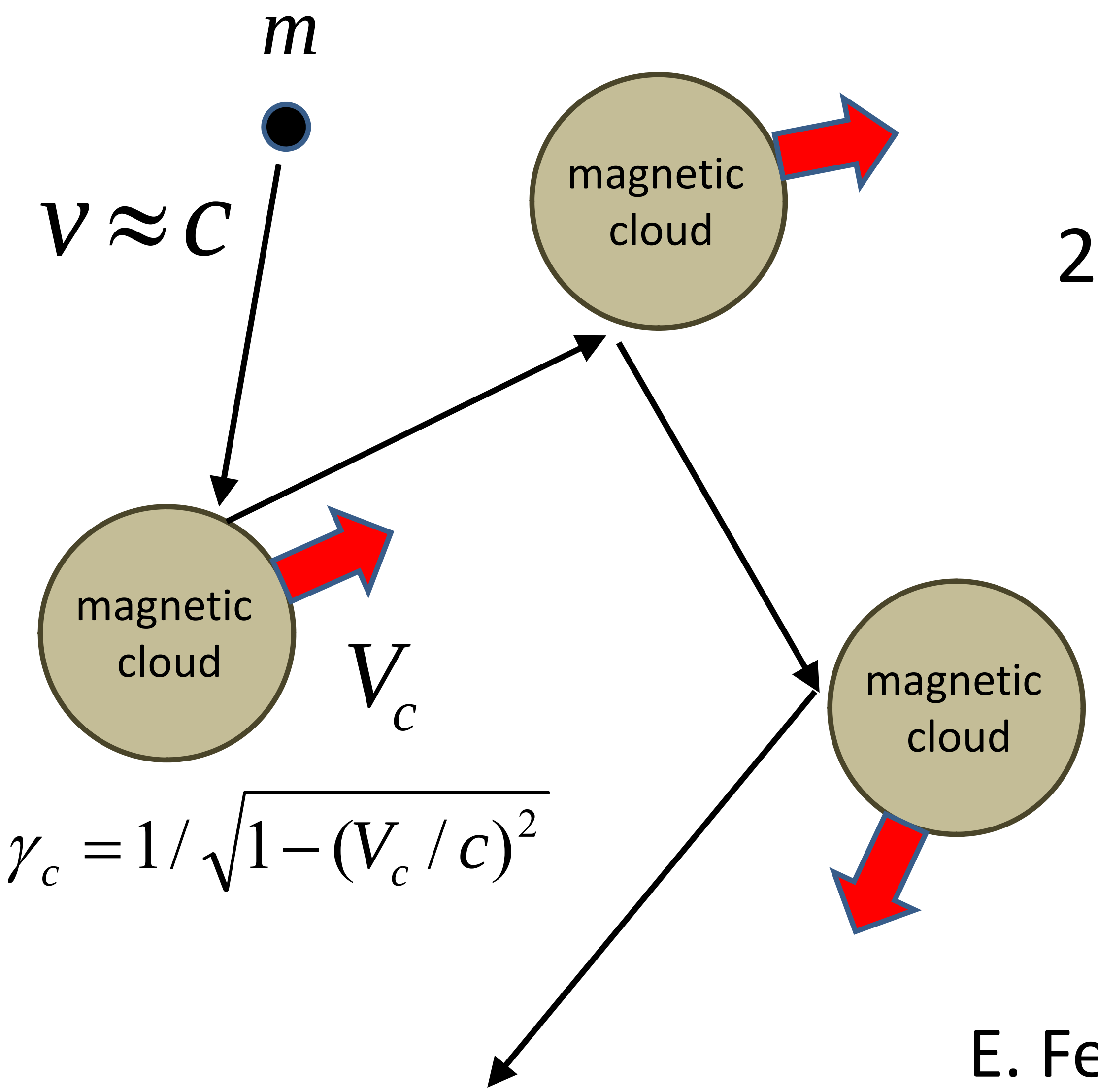


Several Acceleration Mechanisms:

- Fermi acceleration during magnetic island contraction (Drake et al 2005, 2006)

- Acceleration during magnetic island coalescence with surfing process (Oka et al 2010)

# Original Fermi Acceleration



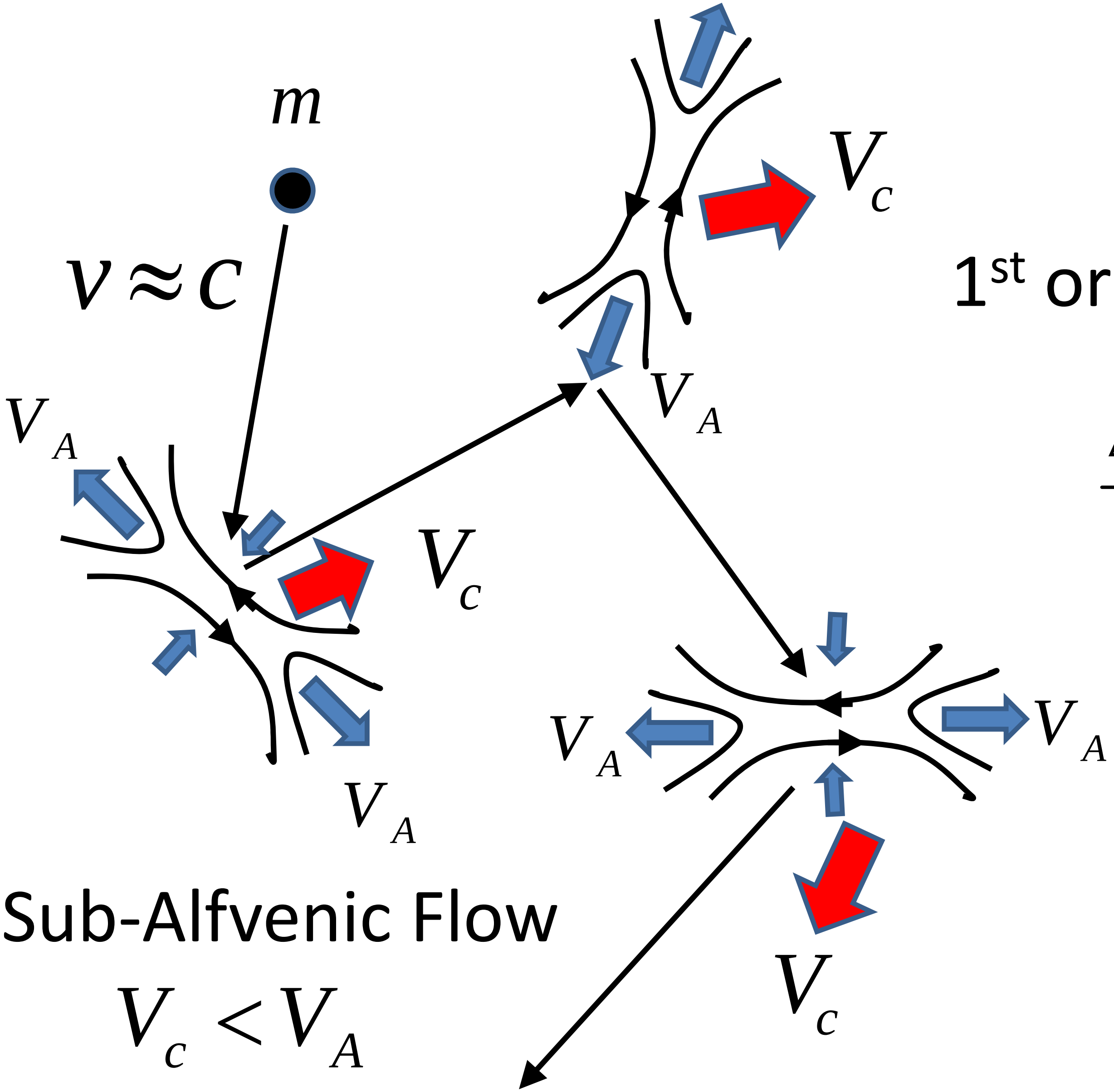
$$\gamma_c = 1/\sqrt{1-(V_c/c)^2}$$

2nd order Acceleration

$$\frac{\Delta\varepsilon}{\varepsilon} = 4\gamma_c^2\left(\frac{V_c}{c}\right)^2$$

E. Fermi, Phys. Rev. (1949)

# Stochastic Acceleration by Reconnection



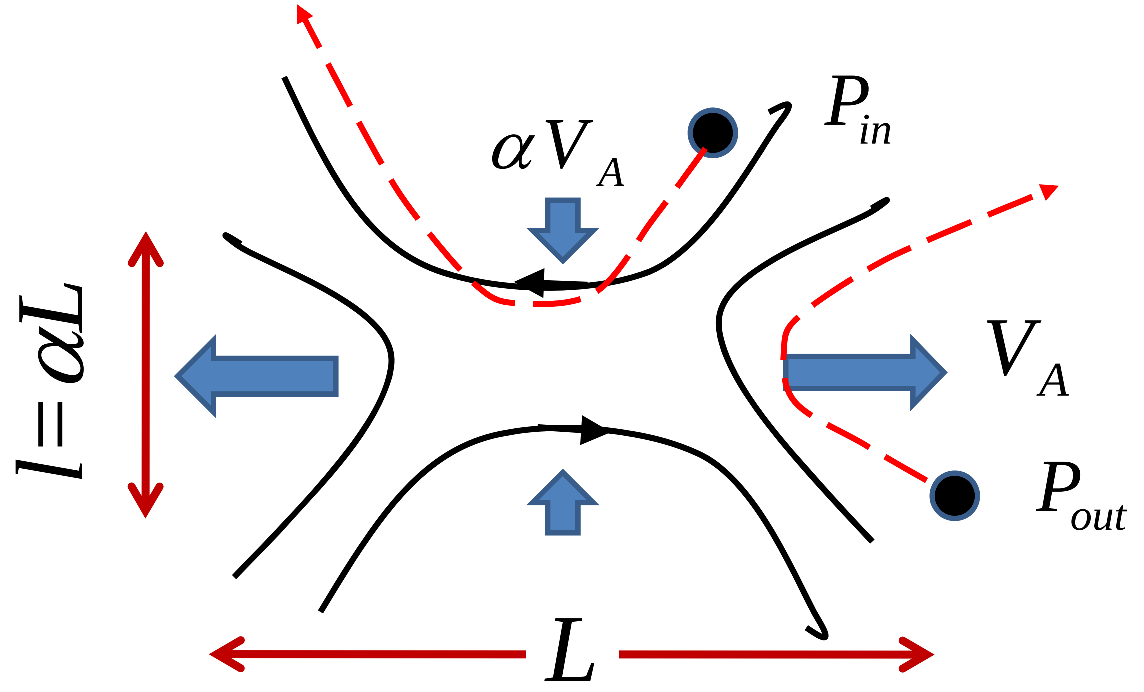
Sub-Alfvenic Flow

$V_c < V_A$

1st order Acceleration

$$\frac{\Delta \varepsilon}{\varepsilon} \approx \left( \frac{V_A}{c} \right)$$

# Probability of Interaction



reconnection rate

$\alpha \approx 0.1$

probability

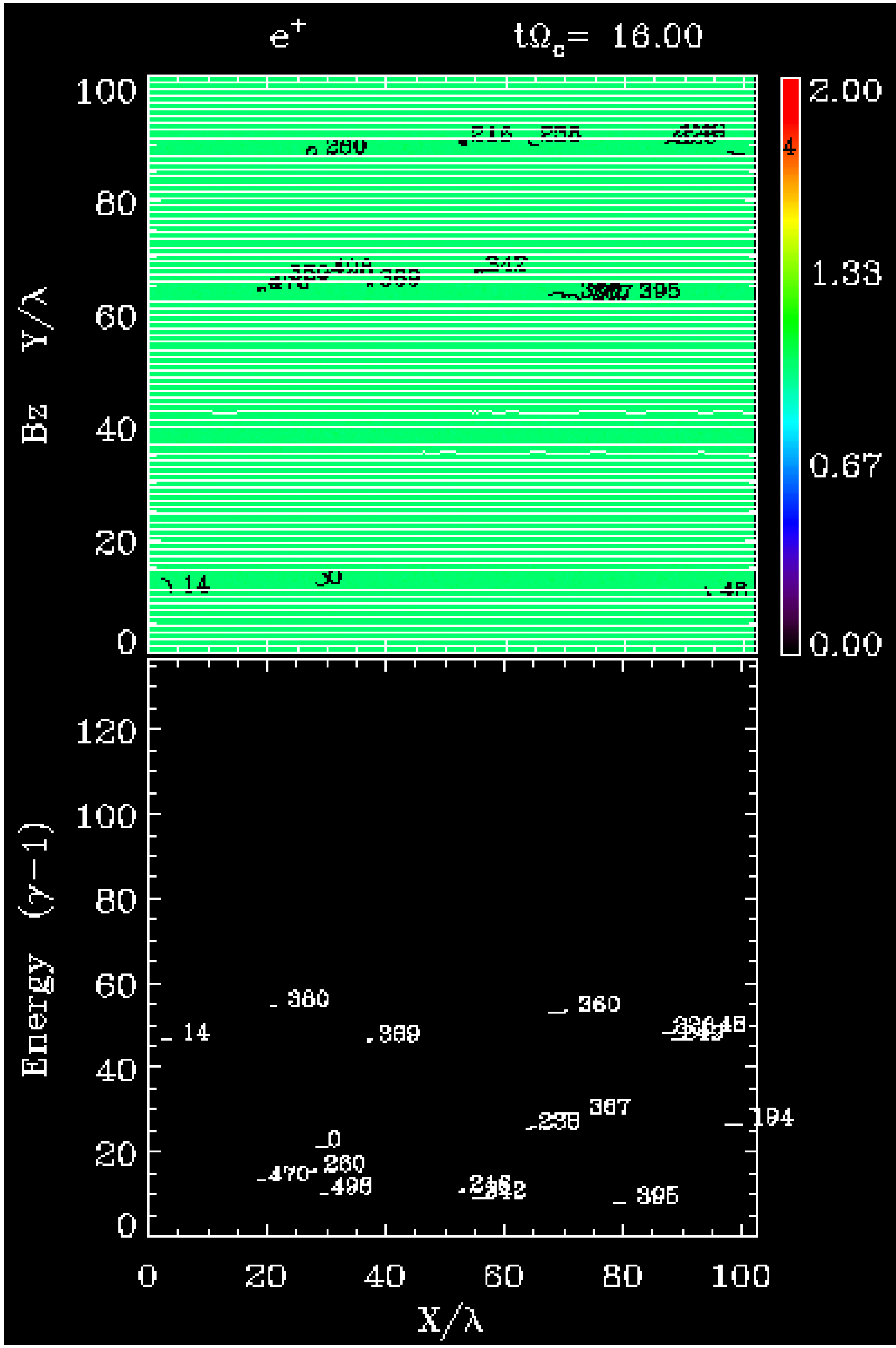
$P_{out} = l/(l+L)$

$P_{in} = L/(l+L)$

If energetic particles were uniformly distributed,

$$\frac{\Delta\varepsilon}{\varepsilon} \approx 2\frac{V_A}{c}P_{out} - 2\alpha\frac{V_A}{c}P_{in} = 0$$

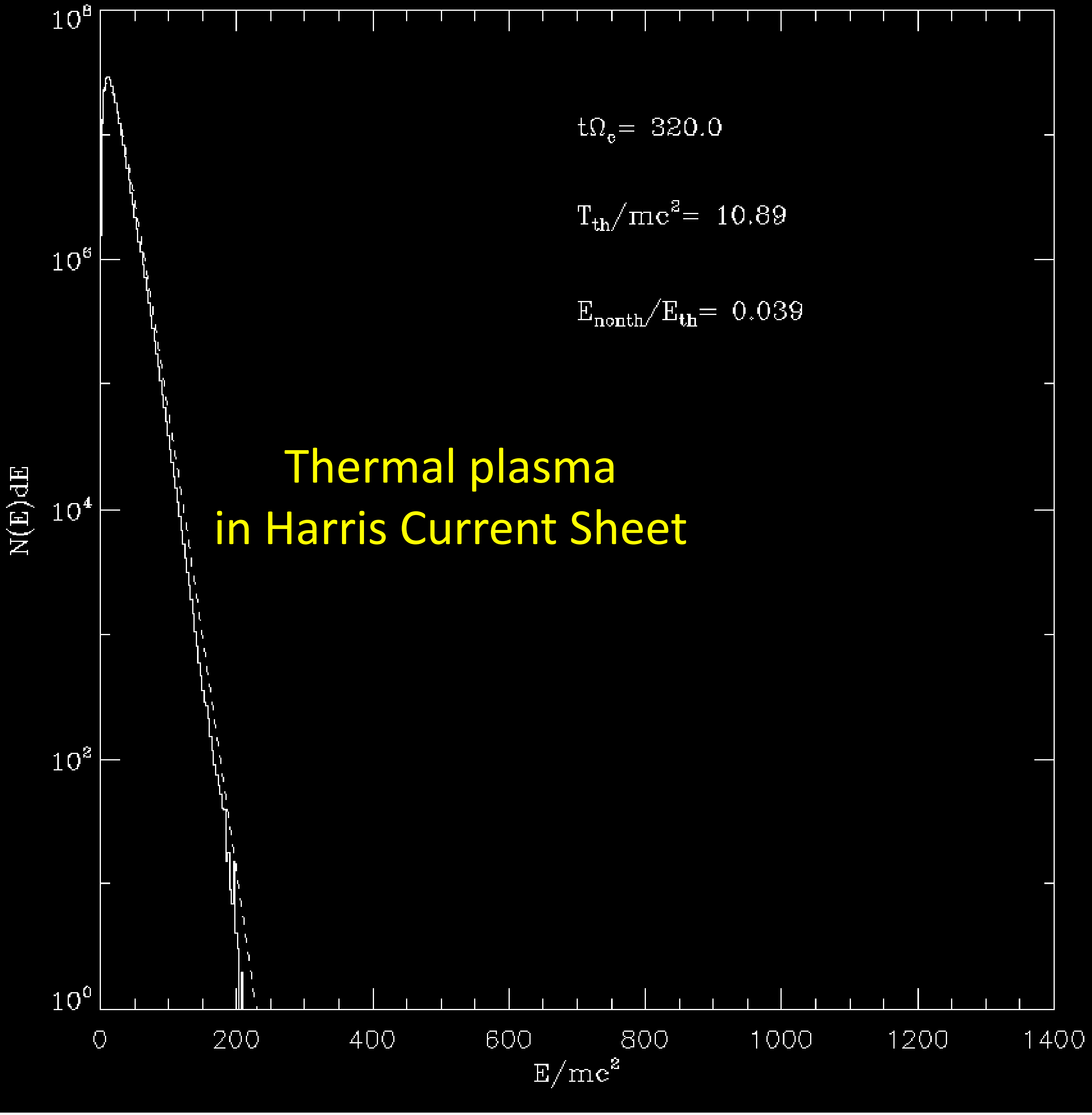
Assumption of “uniformly distributed” is correct ???



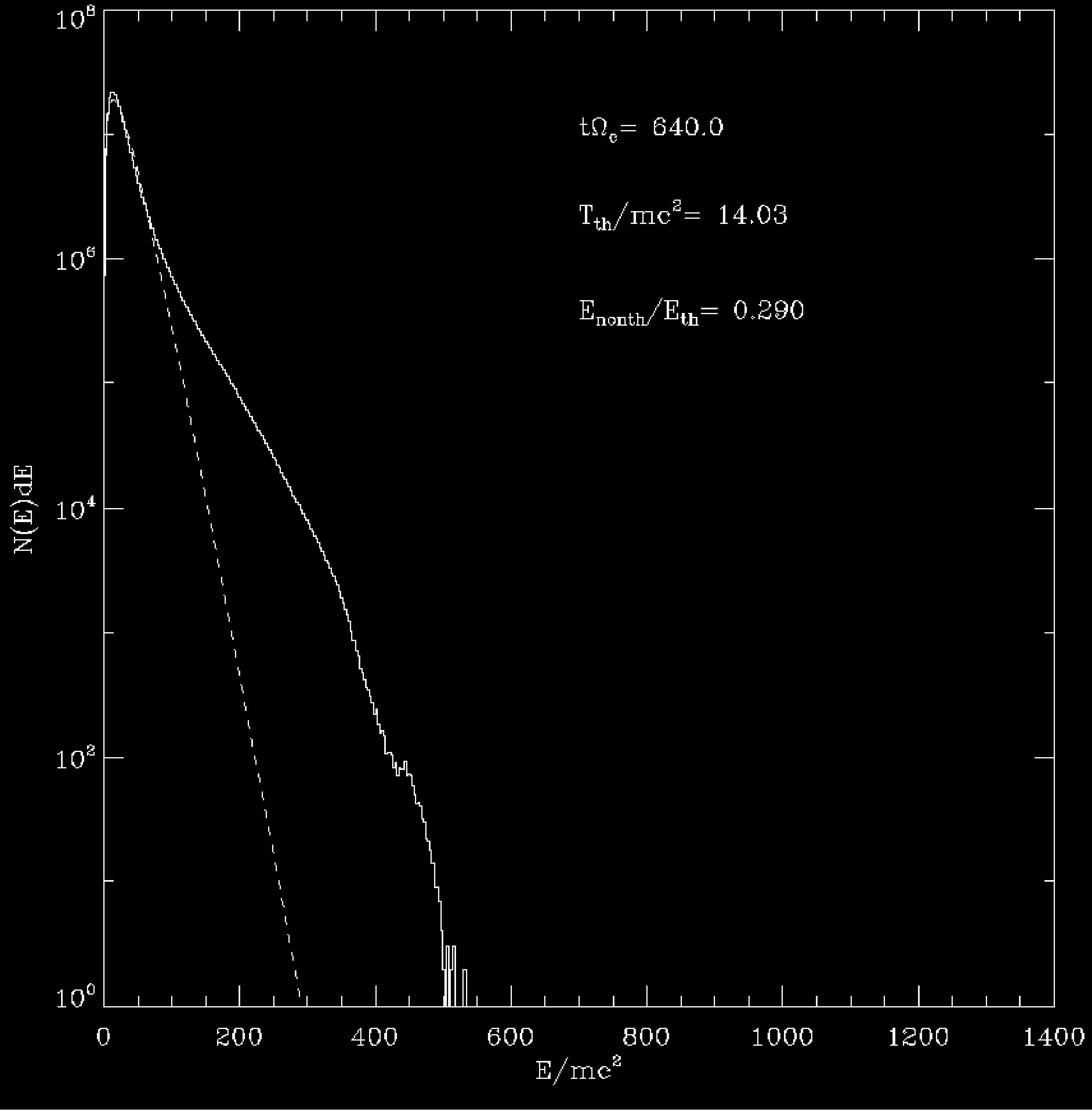
# 2D PIC Simulation

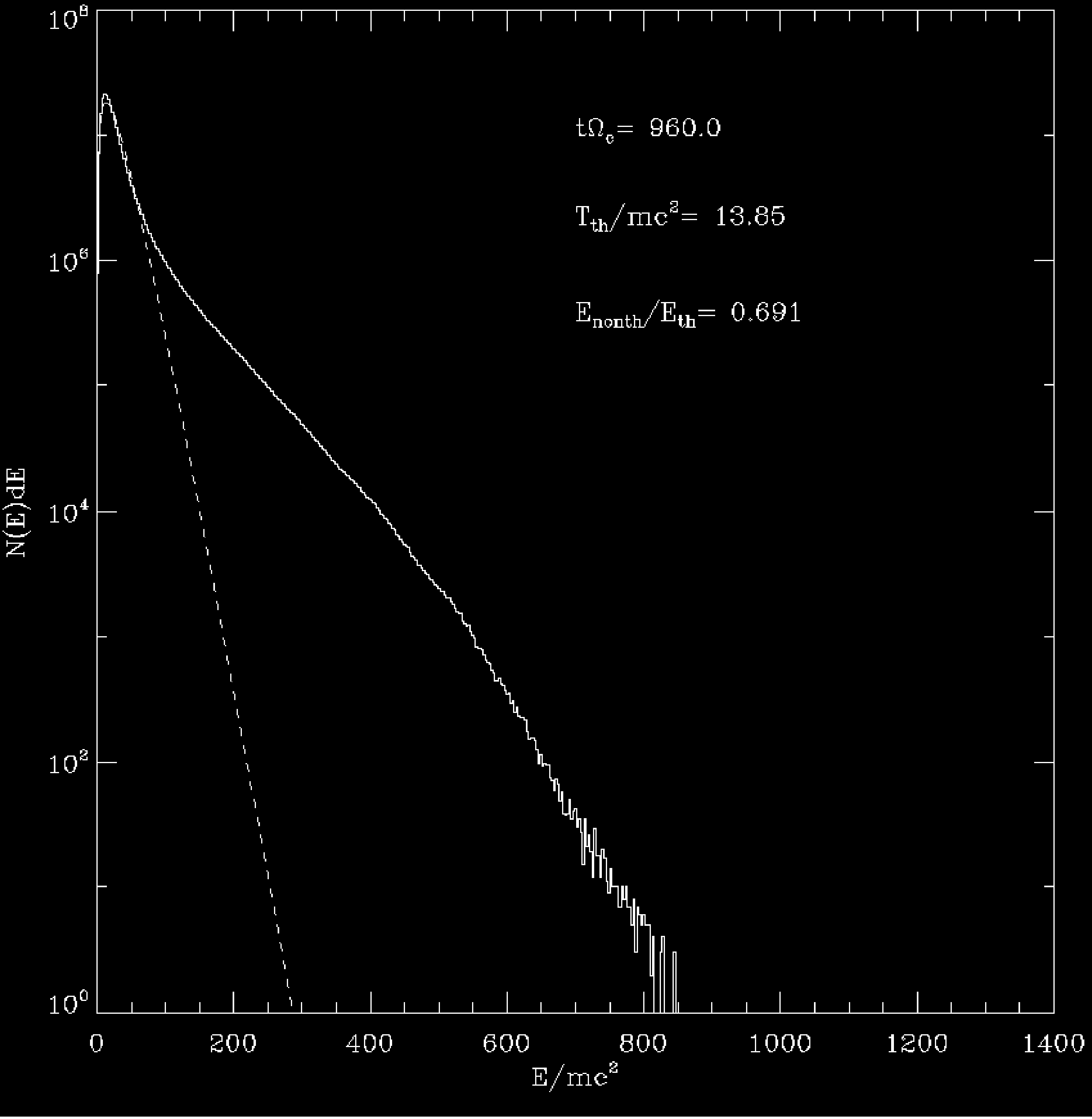
Particle Trajectories,
Magnetic Field Lines

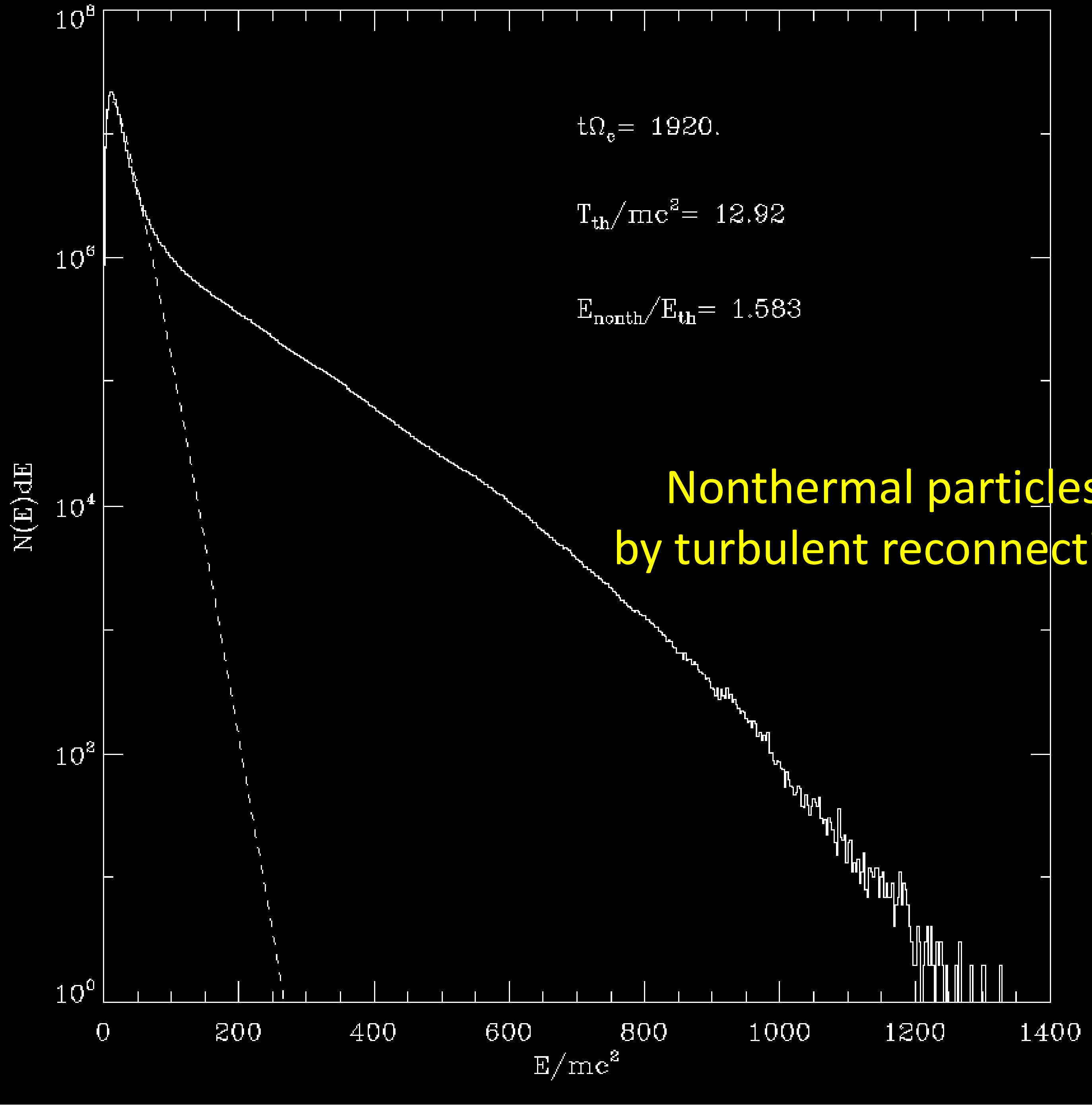
Particle Energies



Thermal plasma
in Harris Current Sheet


$t\Omega_c$= 640.0
$T_{th}/mc^2$= 14.03
$E_{nonth}/E_{th}$= 0.290
N(E)dE
$10^8$
$10^6$
$10^4$
$10^2$
$10^0$
0
200
400
600
800
1000
1200
1400
$E/mc^2$

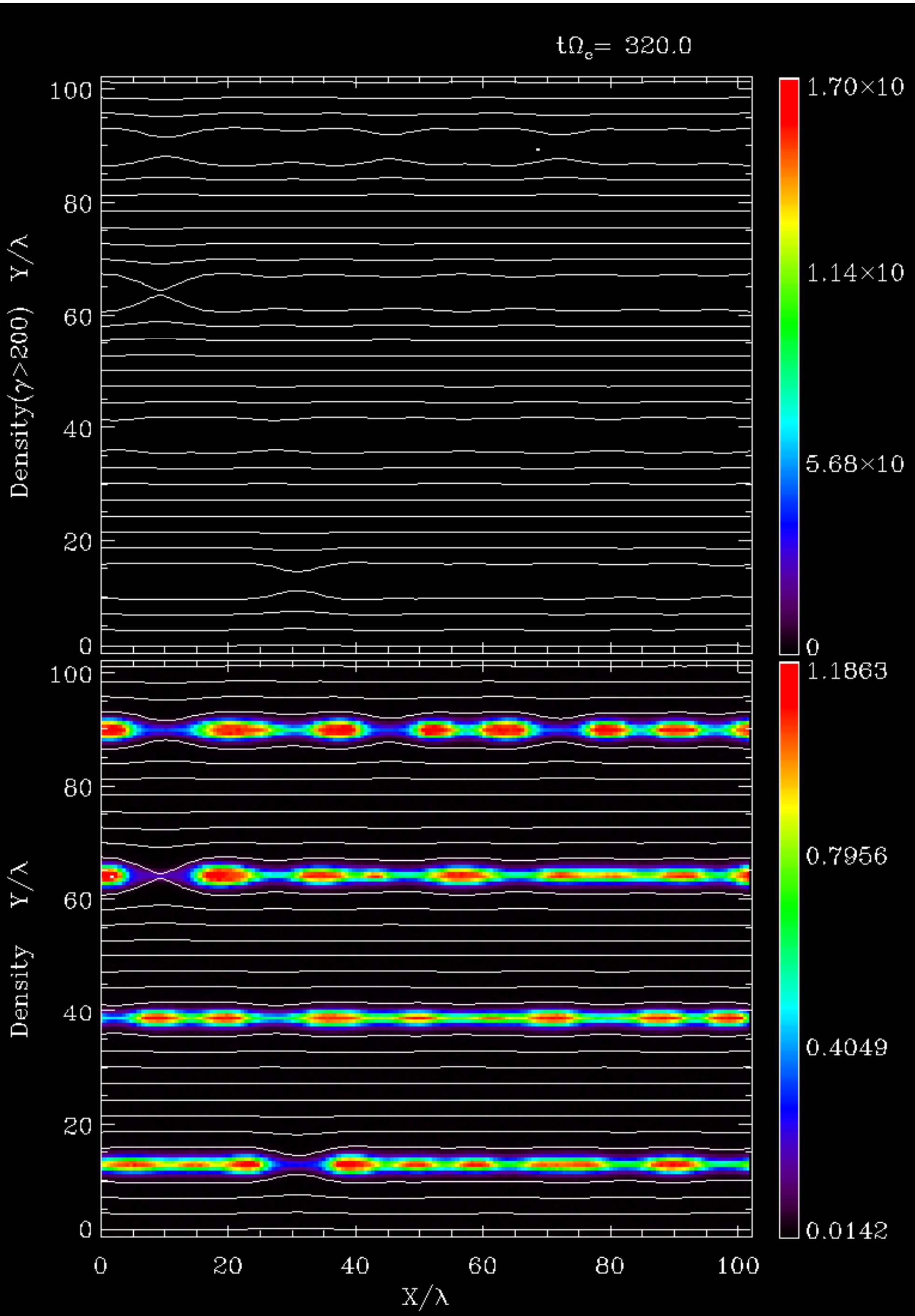

$t\Omega_c$= 960.0
$T_{th}/mc^2$= 13.85
$E_{nonth}/E_{th}$= 0.691
N(E)dE
$10^8$
$10^6$
$10^4$
$10^2$
$10^0$
0
200
400
600
800
1000
1200
1400
$E/mc^2$



Nonthermal particles
by turbulent reconnection

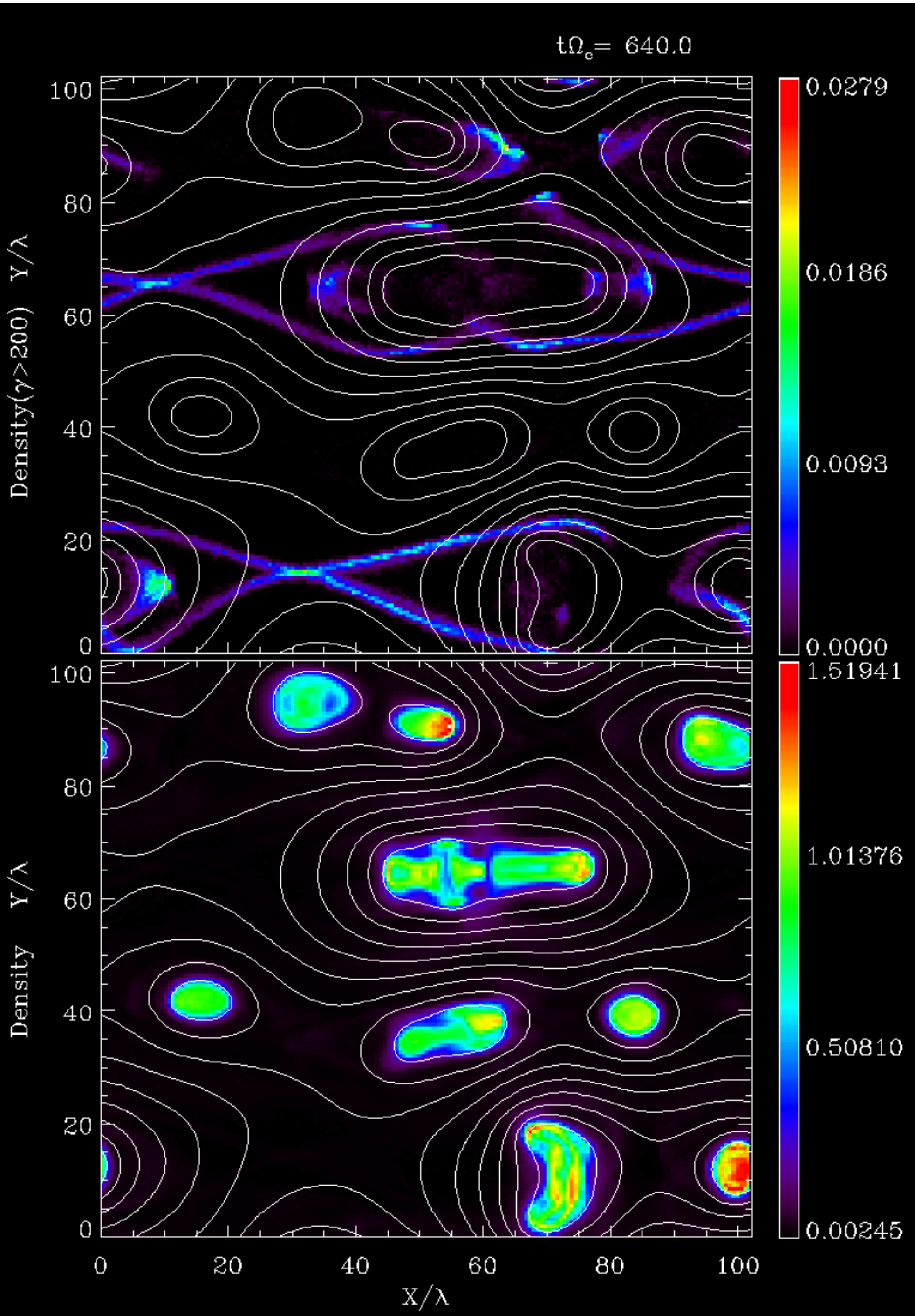
Density for High Energy

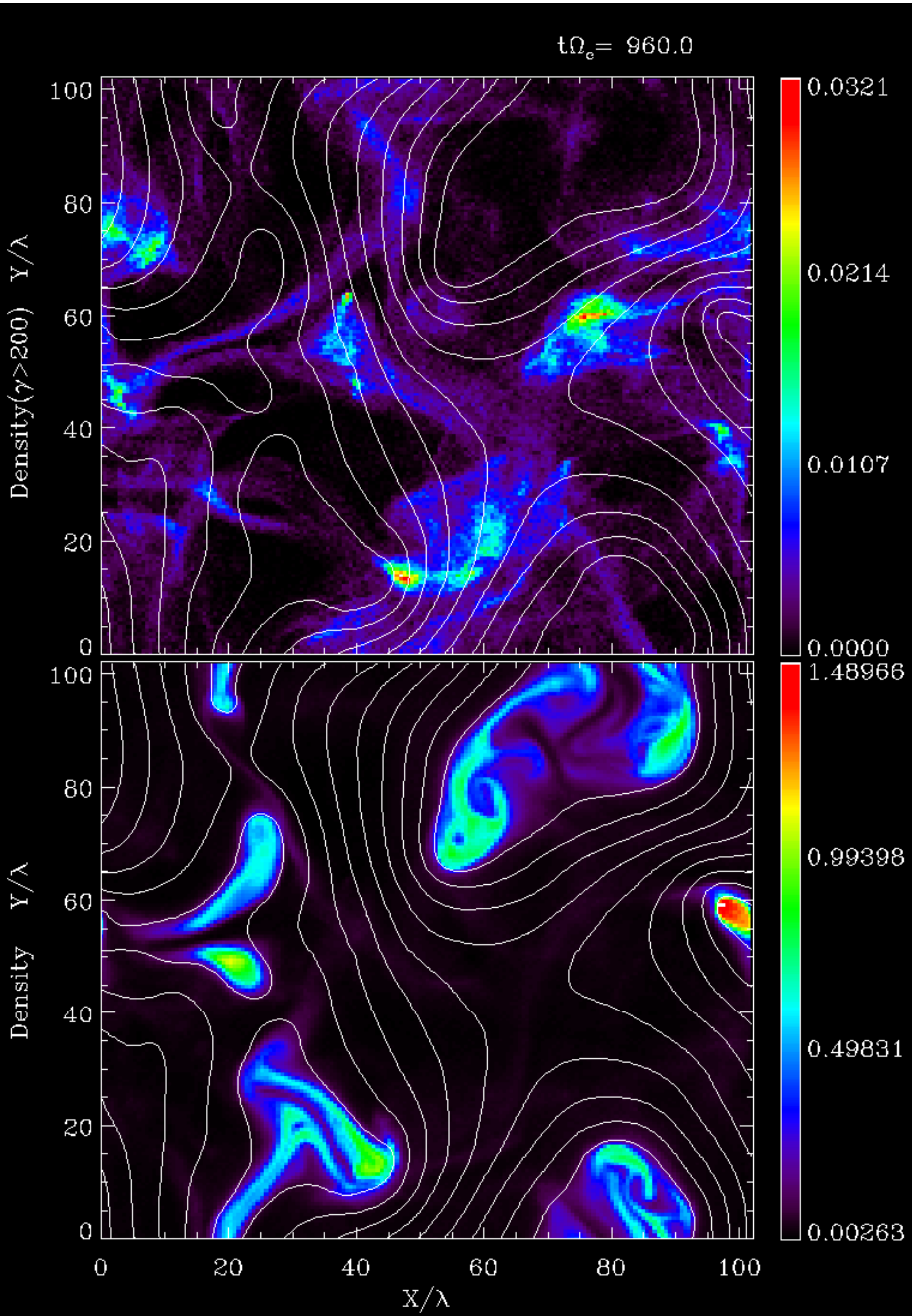
Plasma Density (Thermal)



Density for High Energy

Plasma Density (Thermal)



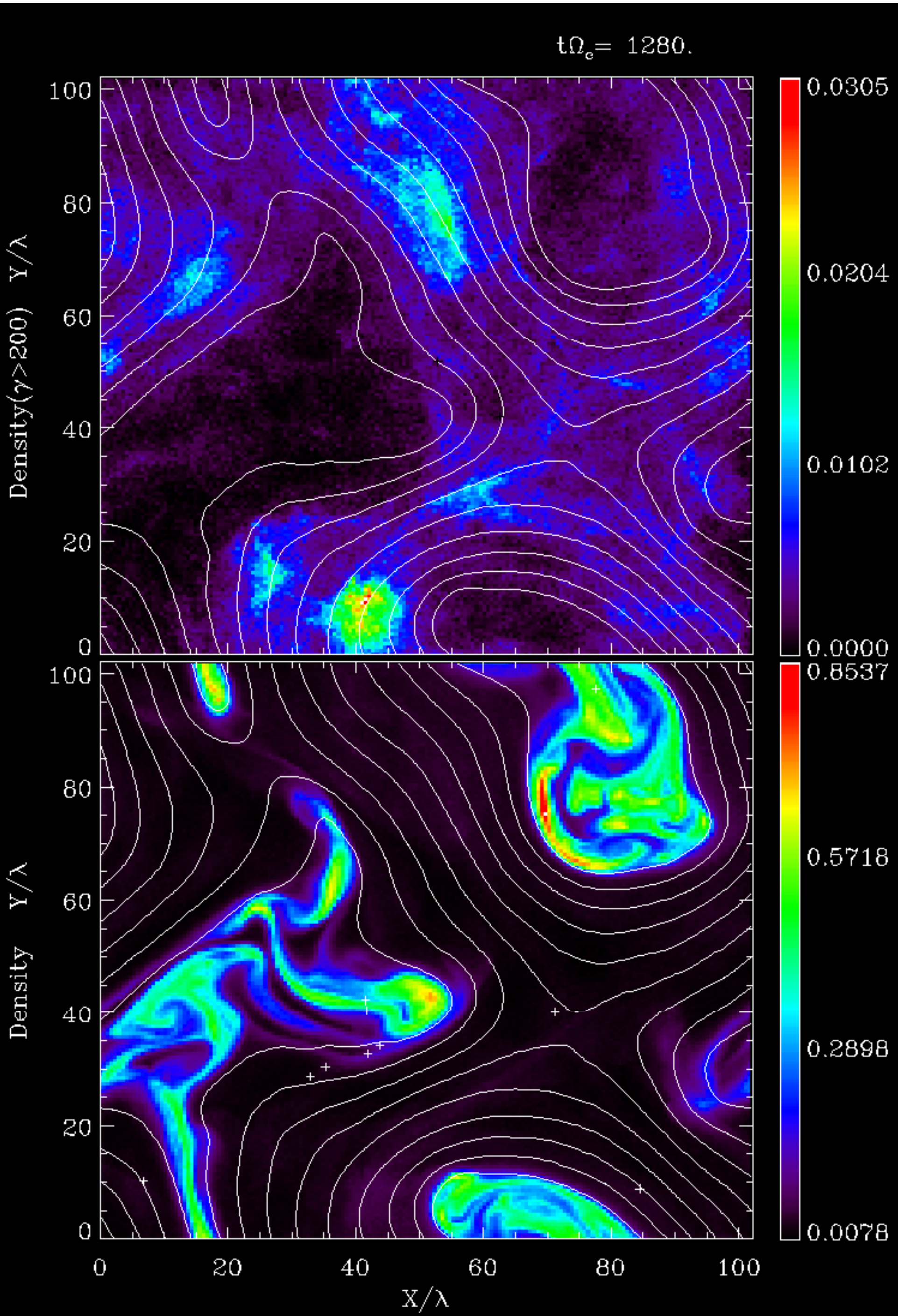


Density for High Energy

Plasma Density (Thermal)

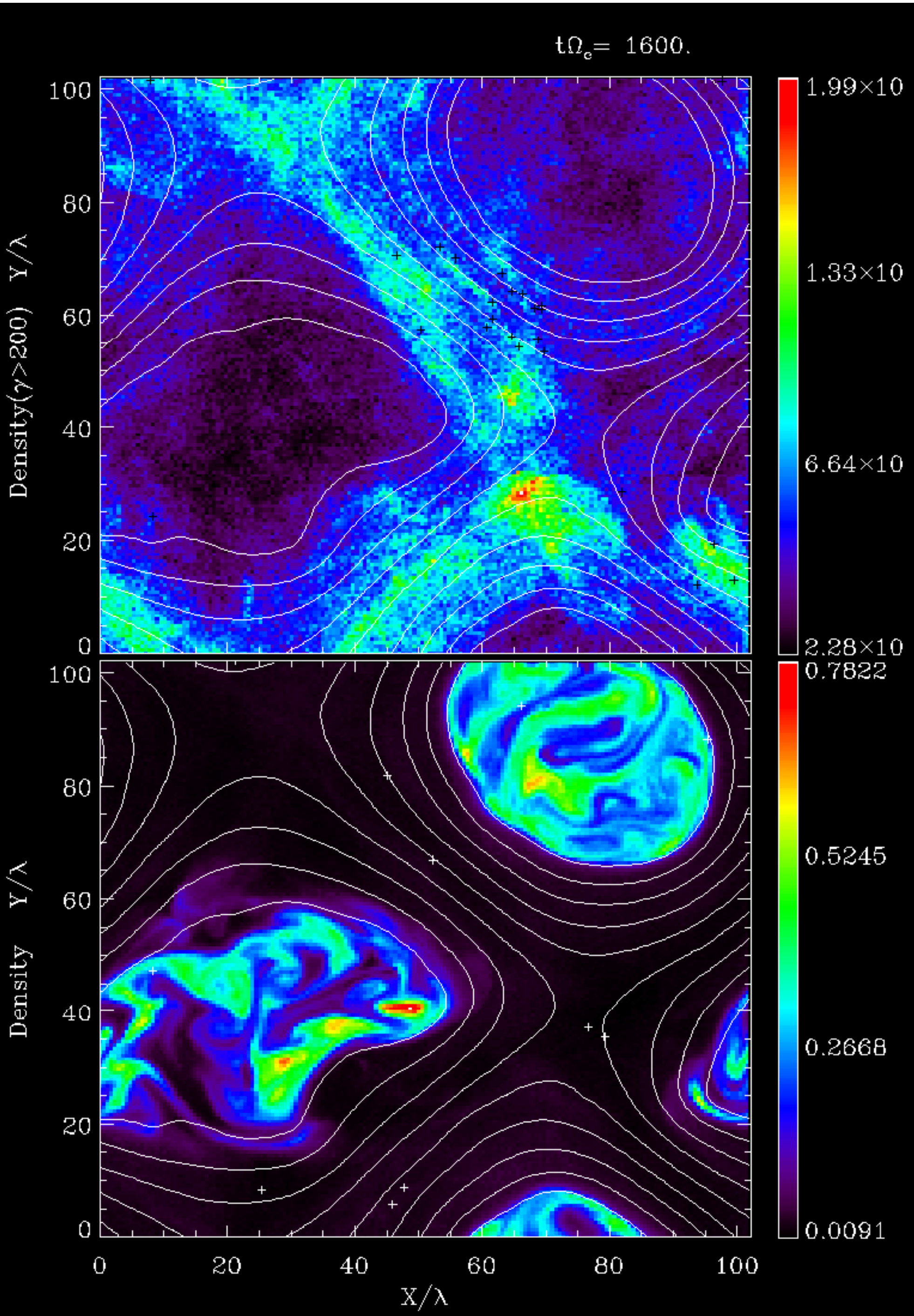
Density for High Energy

Plasma Density (Thermal)



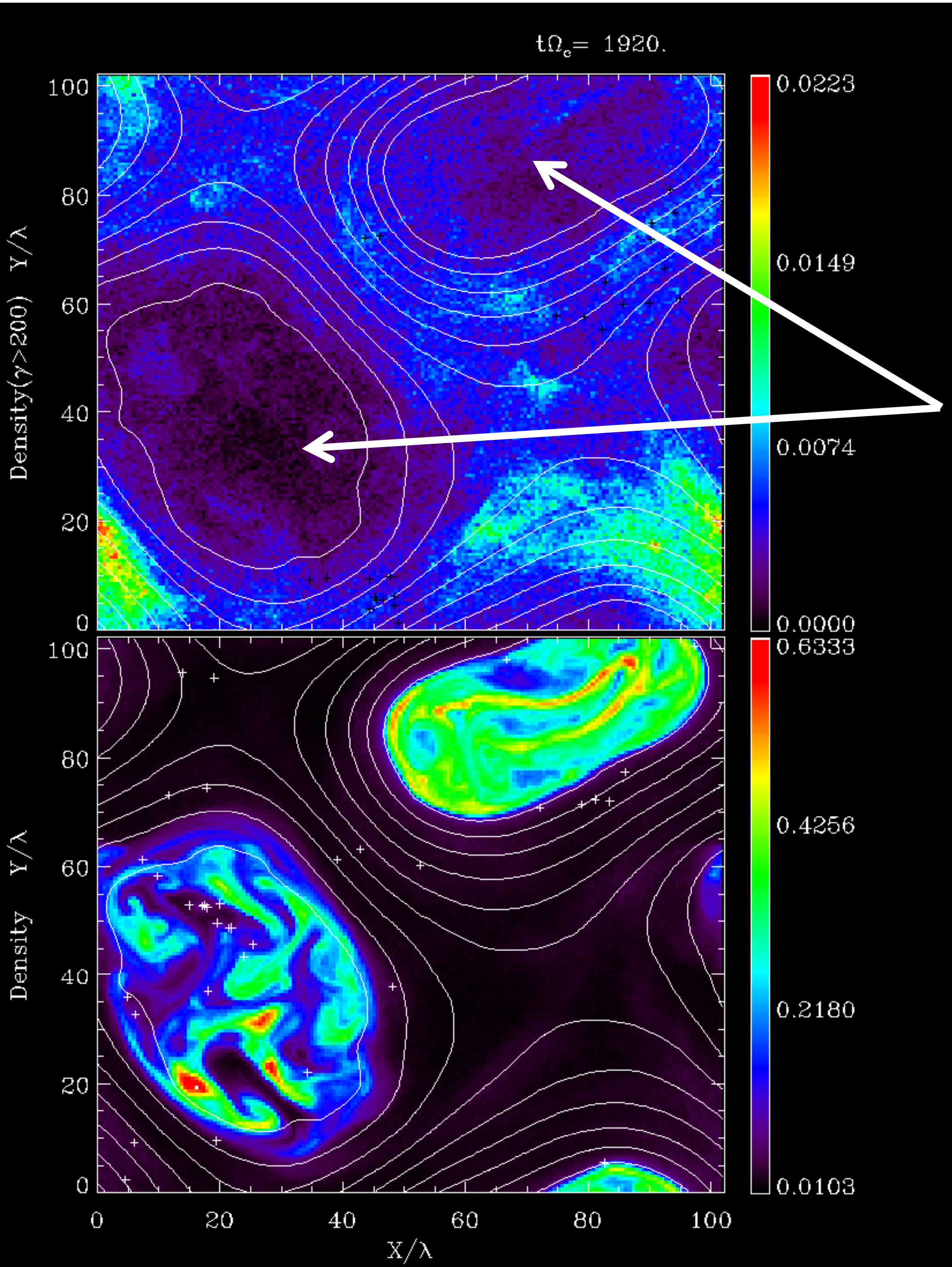
Density for High Energy

Plasma Density (Thermal)



Density for High Energy

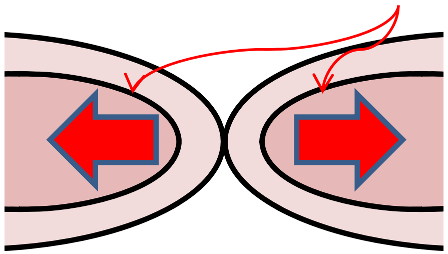
Plasma Density (Thermal)



void

# Injection of Energetic Particles

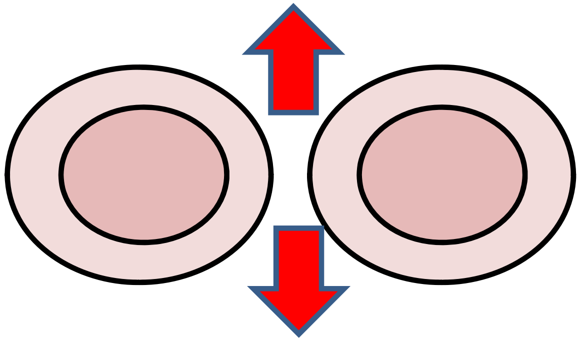
Early Stage
(plasma sheet
Reconnection)



energetic particles are included

Reconnection jet
into plasma sheet

Late Stage
(plasmoid
Reconnection)

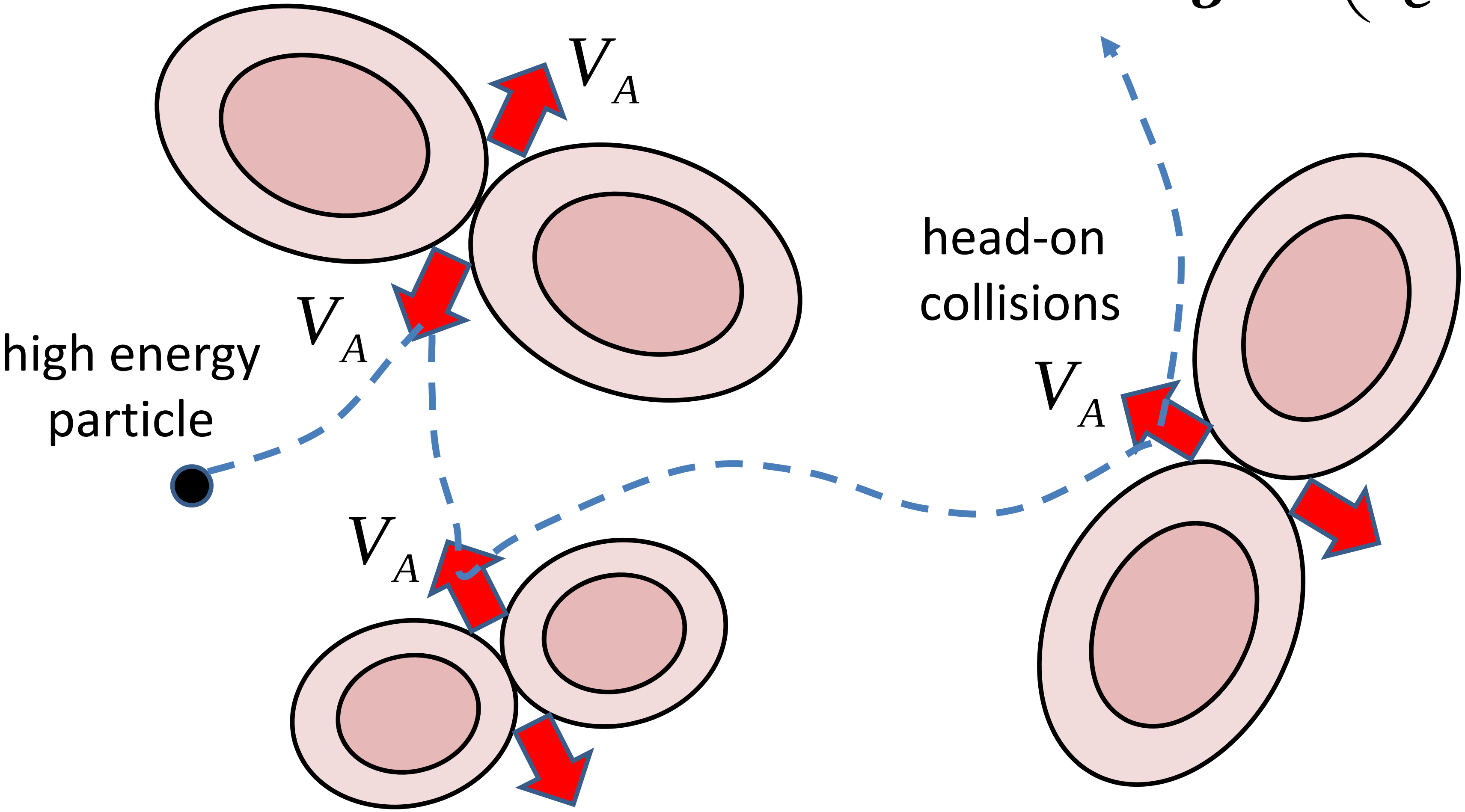


energetic particles

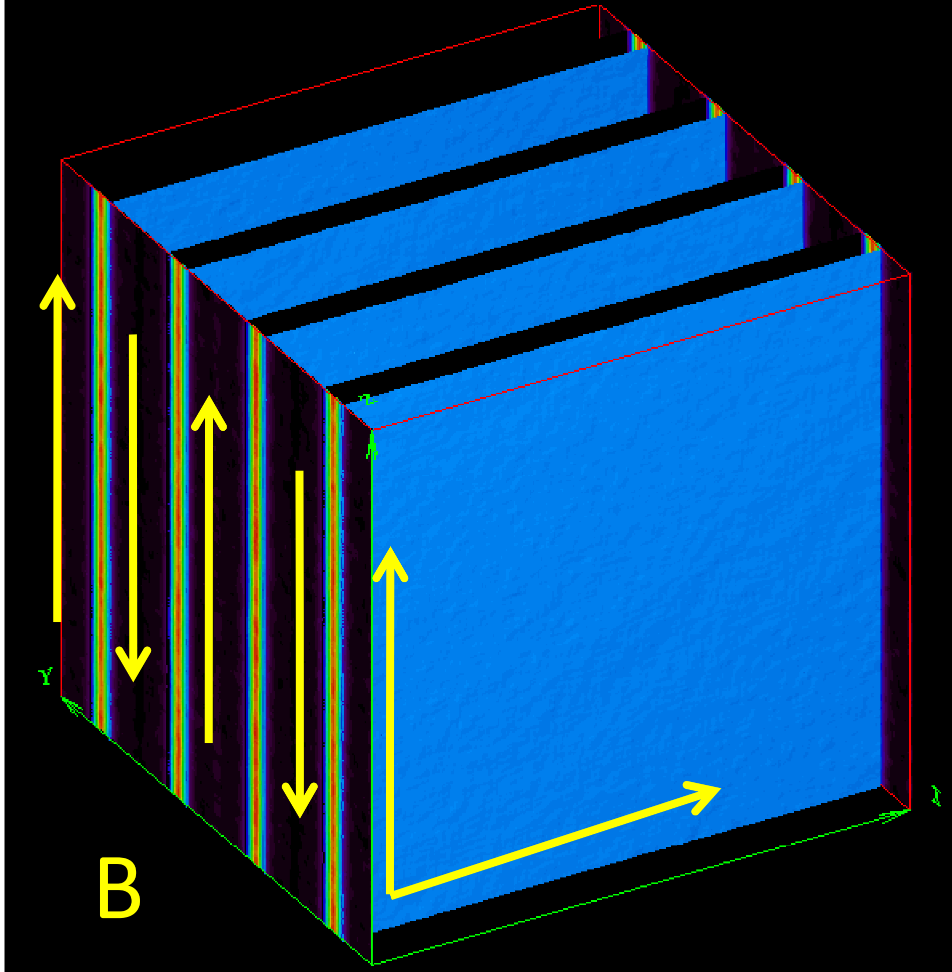
Reconnection jet
toward high B region

# Acceleration in Turbulent MRX

1st order Acceleration $\frac{\Delta\varepsilon}{\varepsilon} \approx \left(\frac{V_A}{c}\right)$

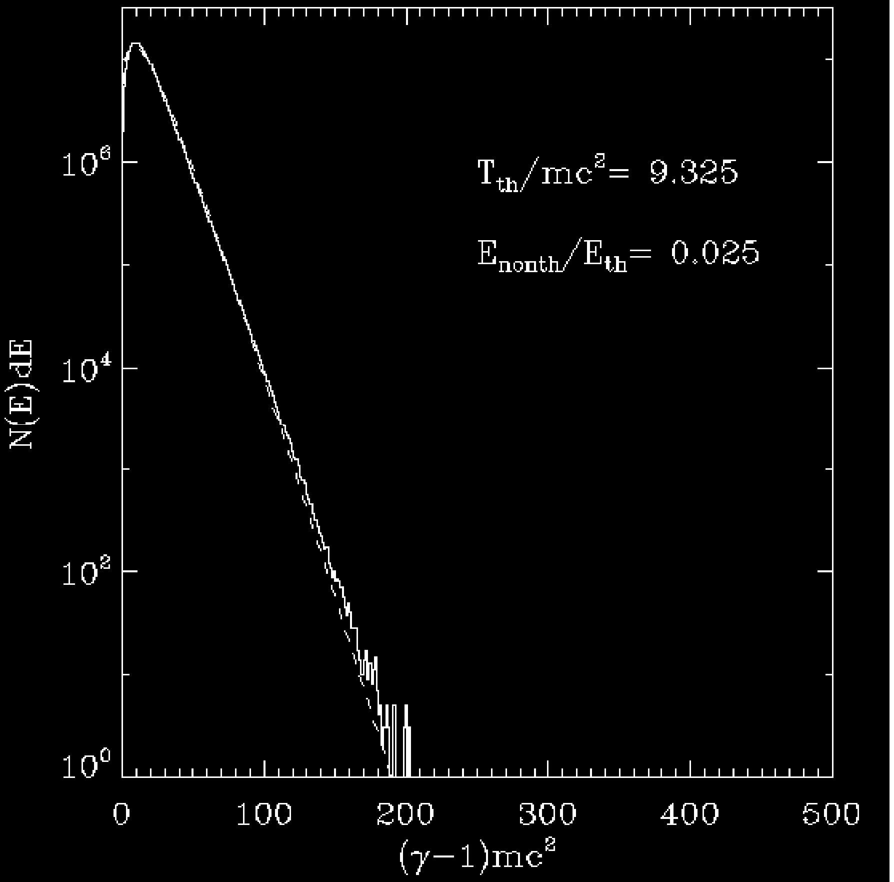


# 3D Reconnection with $B_G/B_0=1$



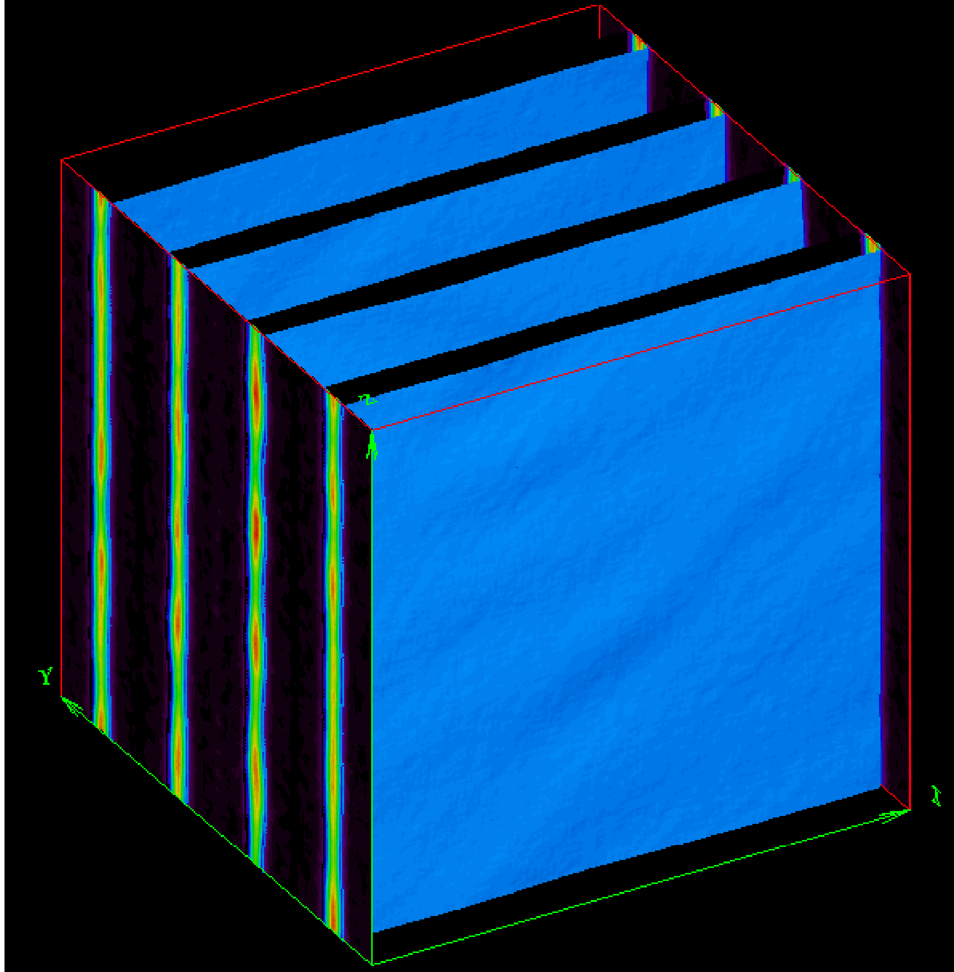
+ Uniform Guide Field

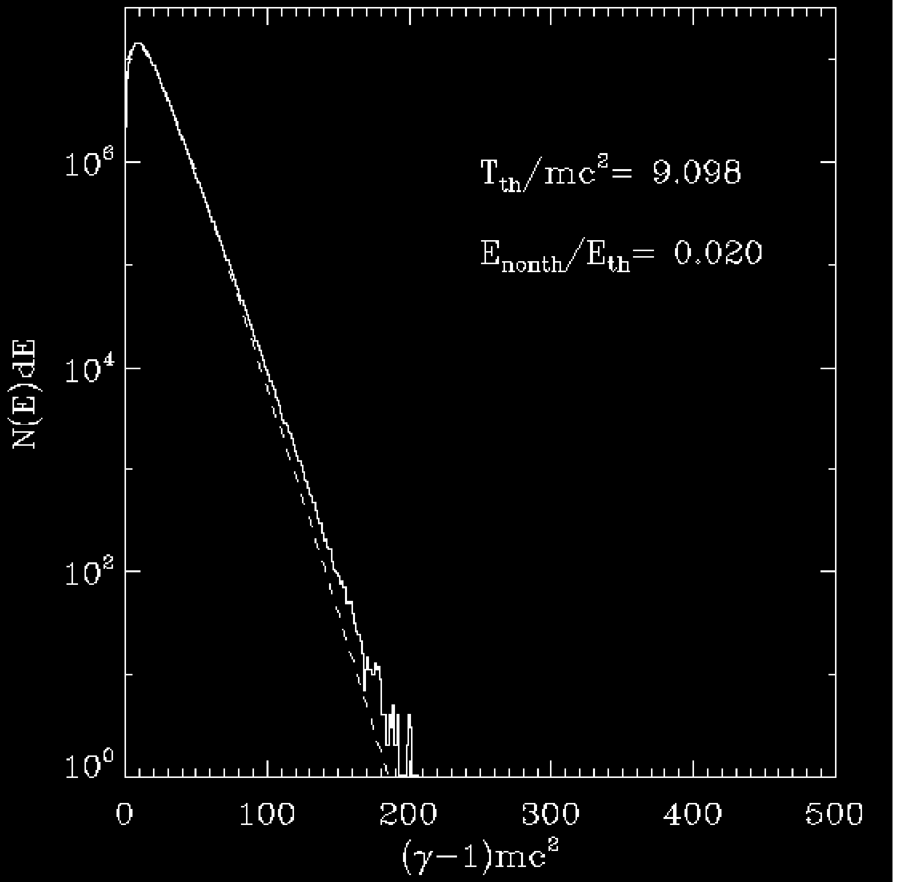
Isosurface of plasma density



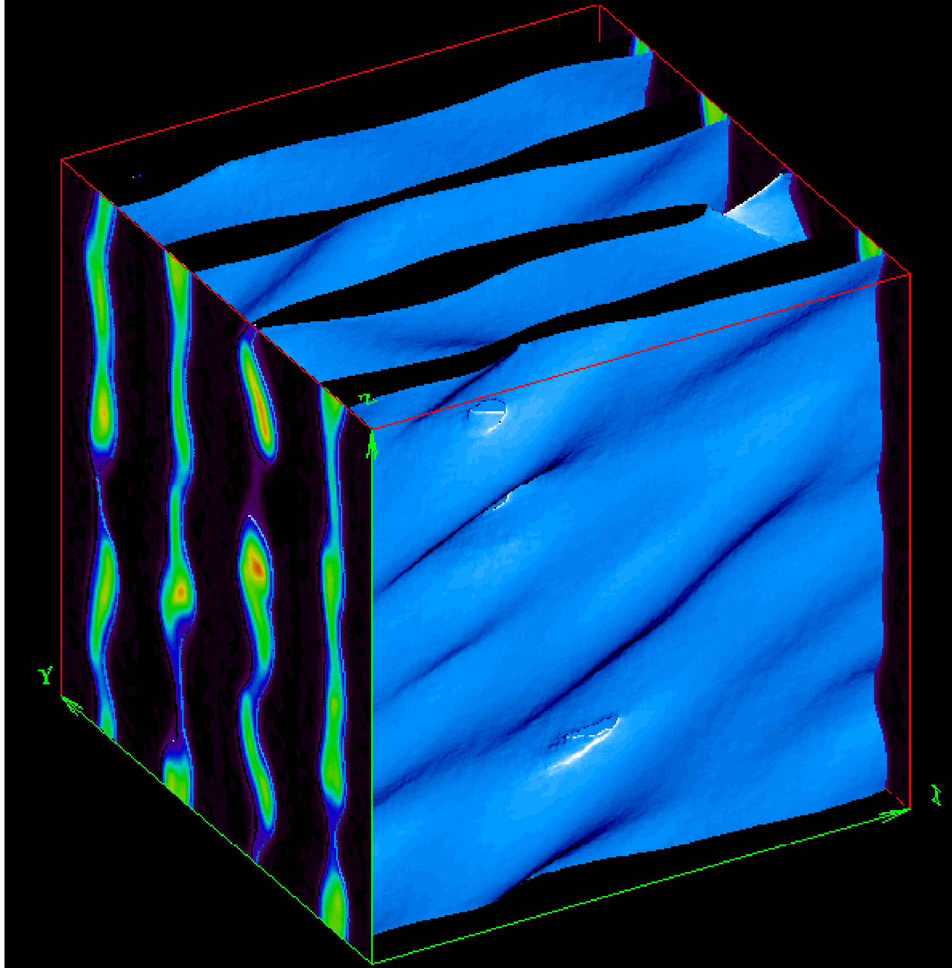
(Nx X Ny X Nz)=(512,512,512)

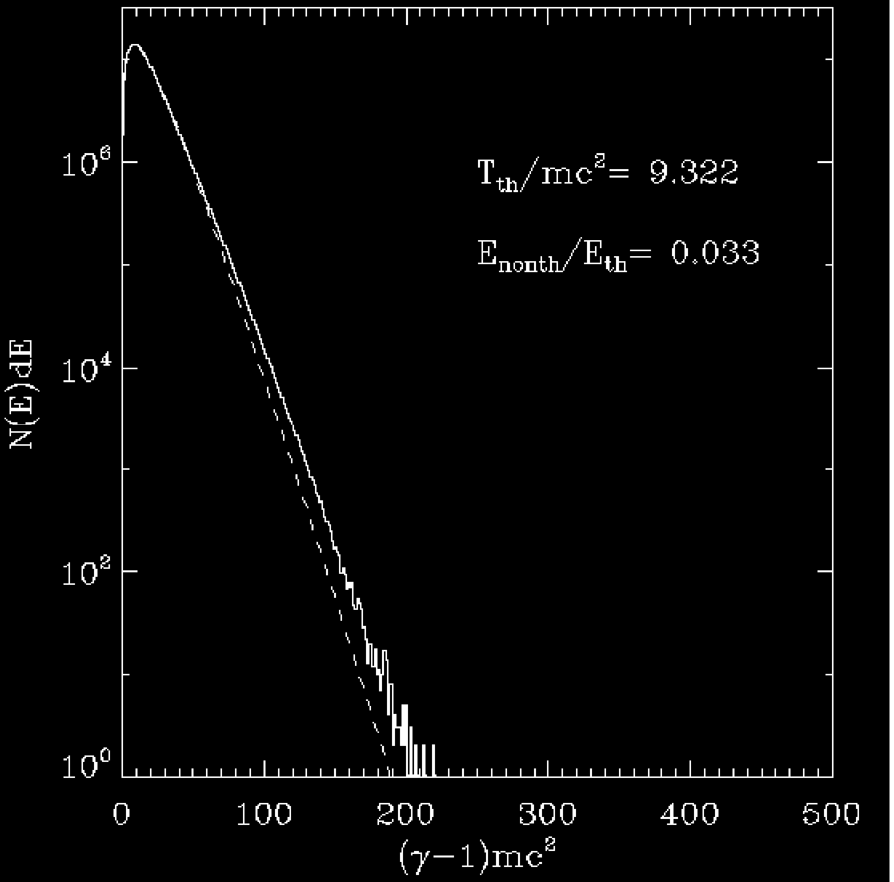
# 3D Reconnection with $B_G/B_0$=1



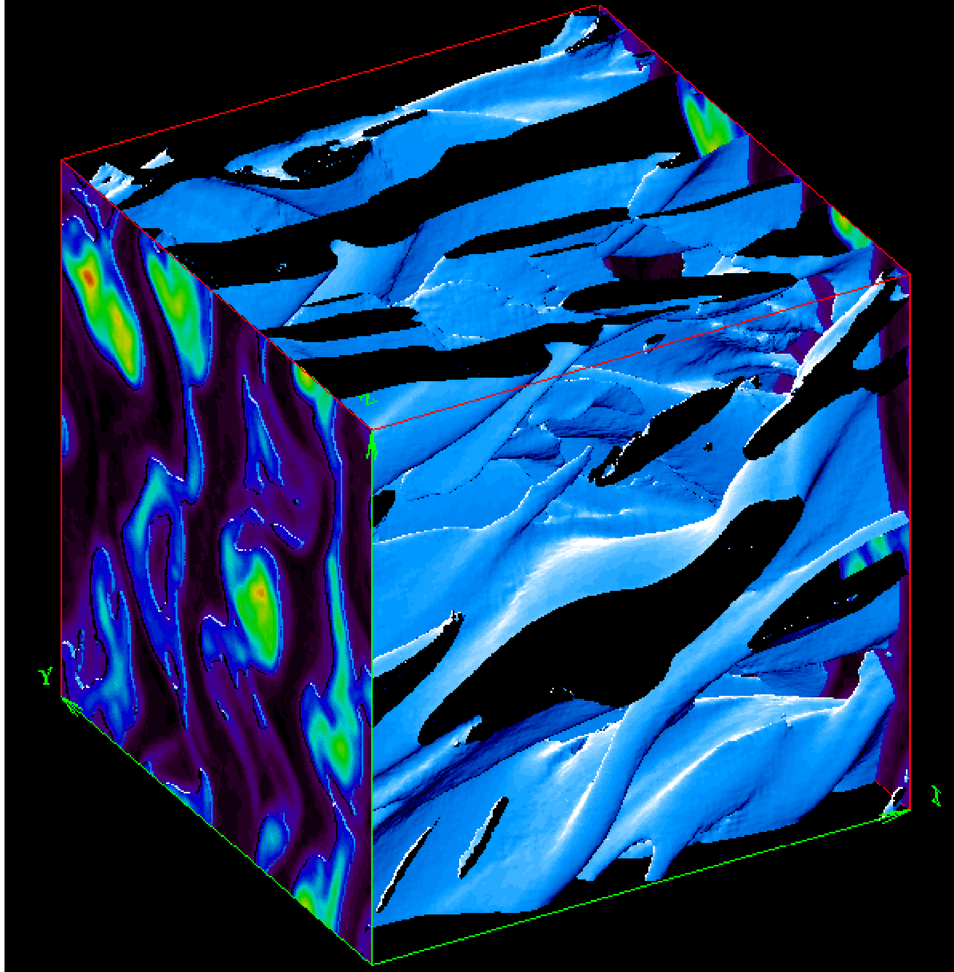


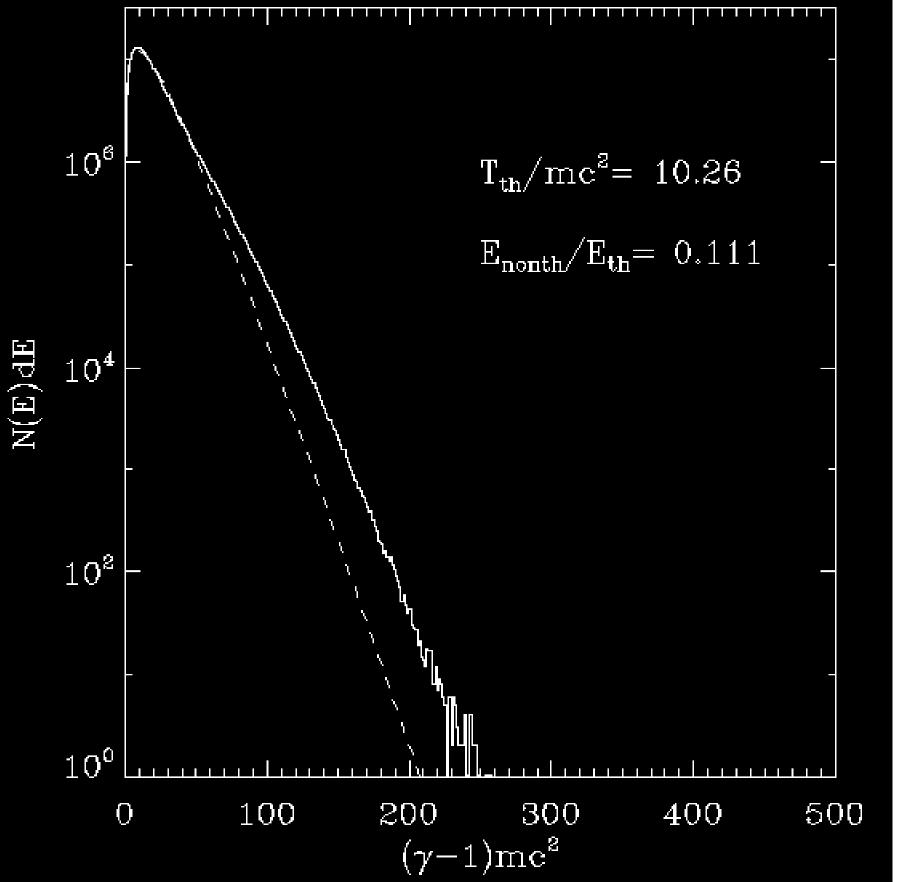
# 3D Reconnection with $B_G/B_0$=1



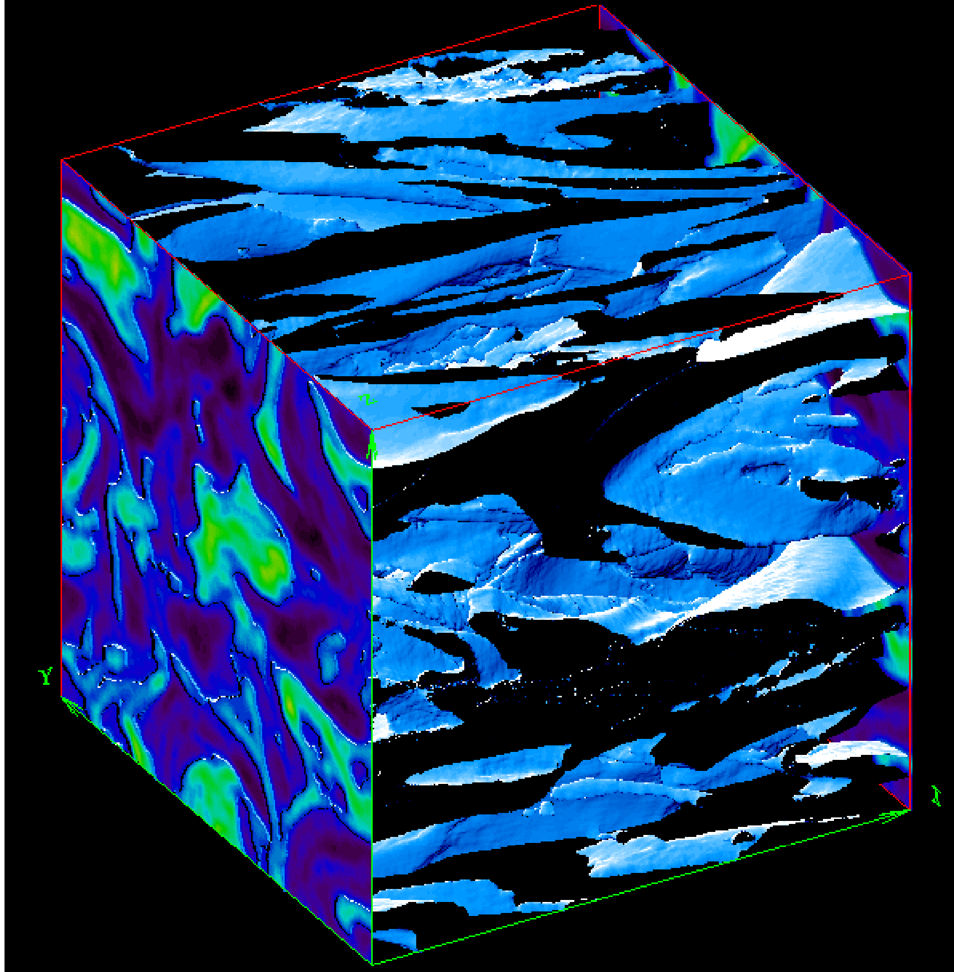


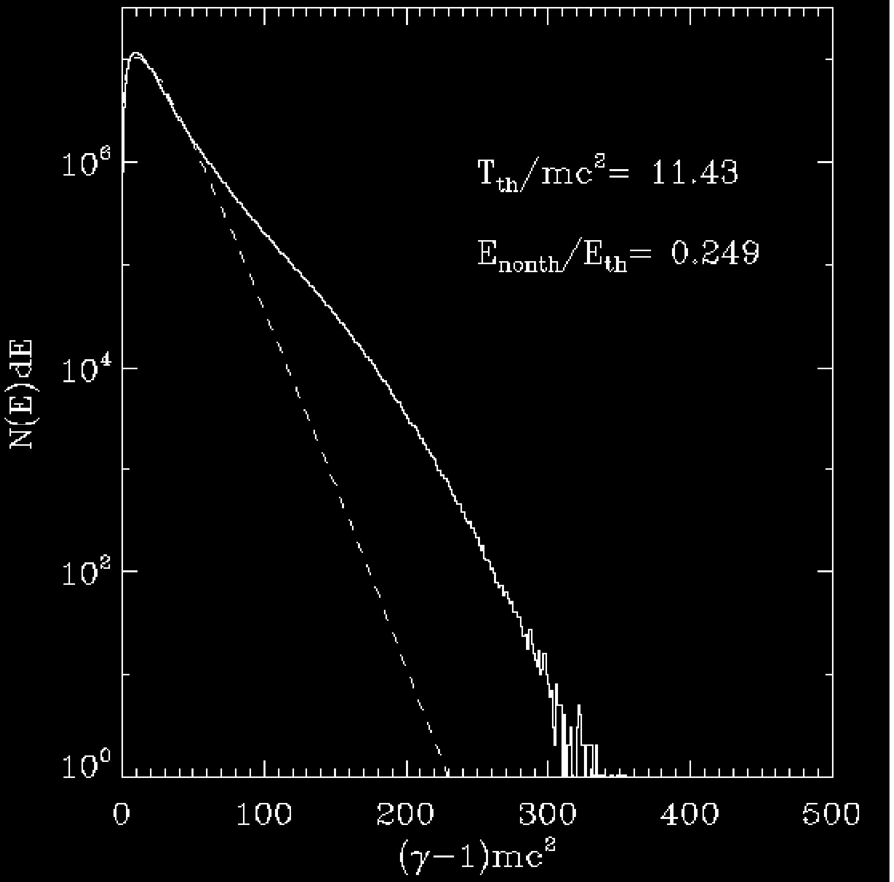
# 3D Reconnection with $B_G/B_0=1$



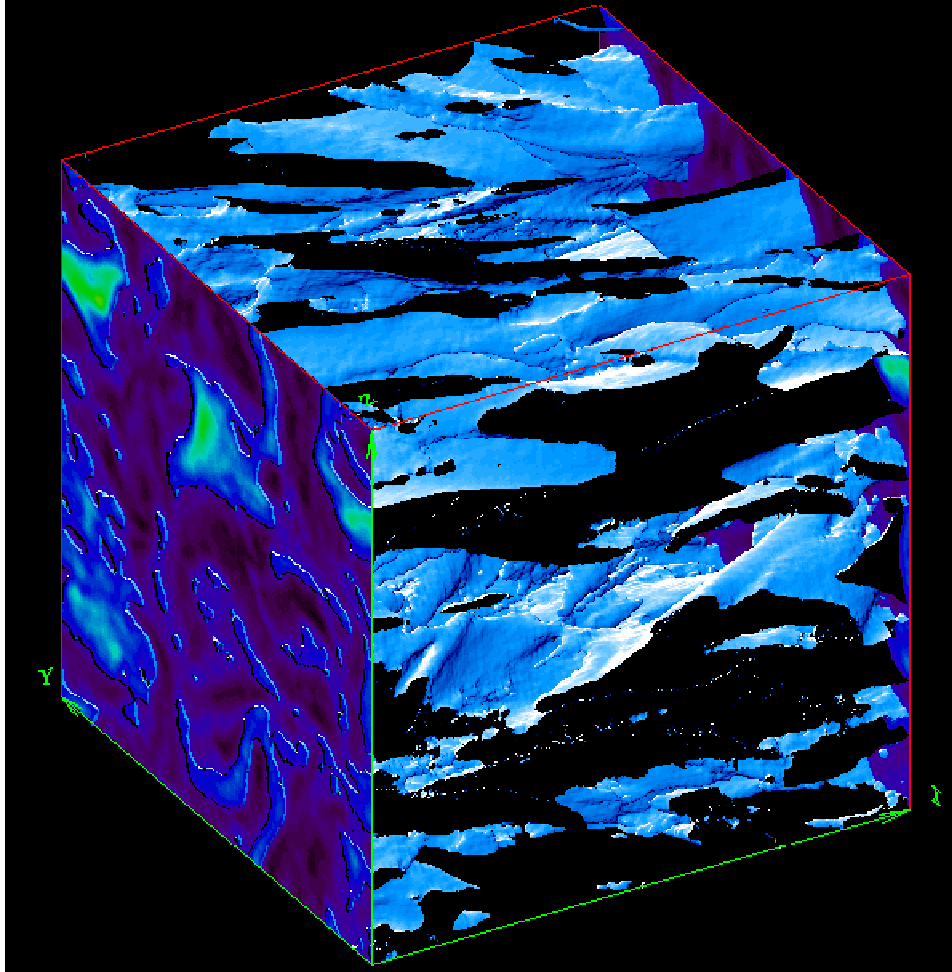


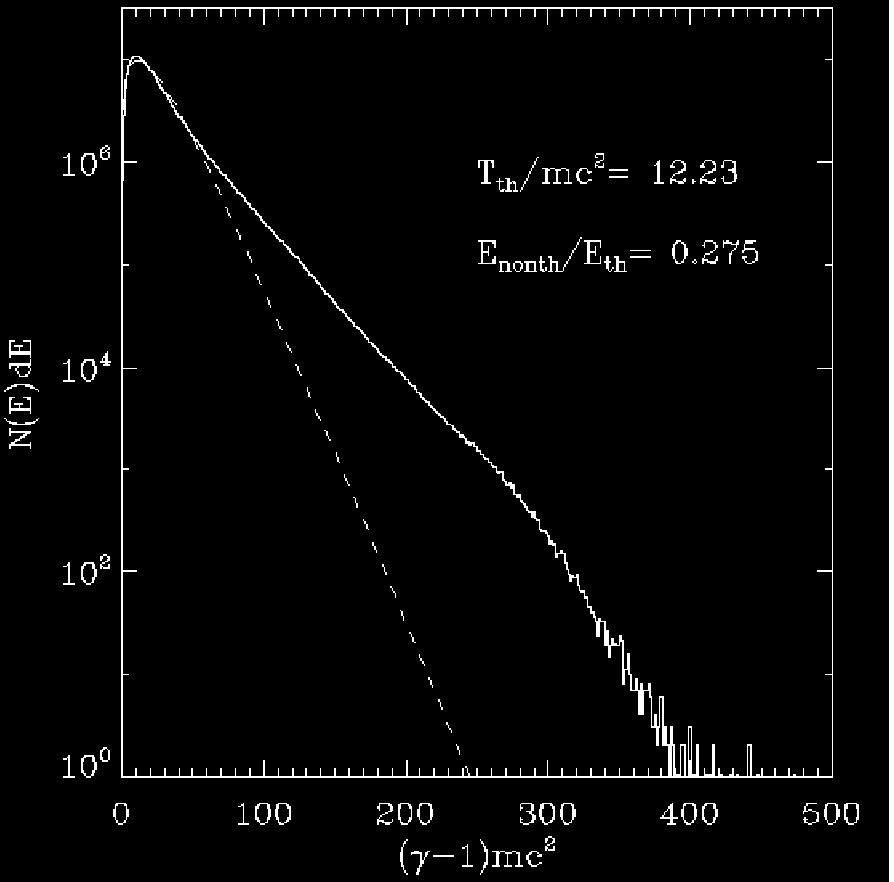
# 3D Reconnection with $B_G/B_0$=1



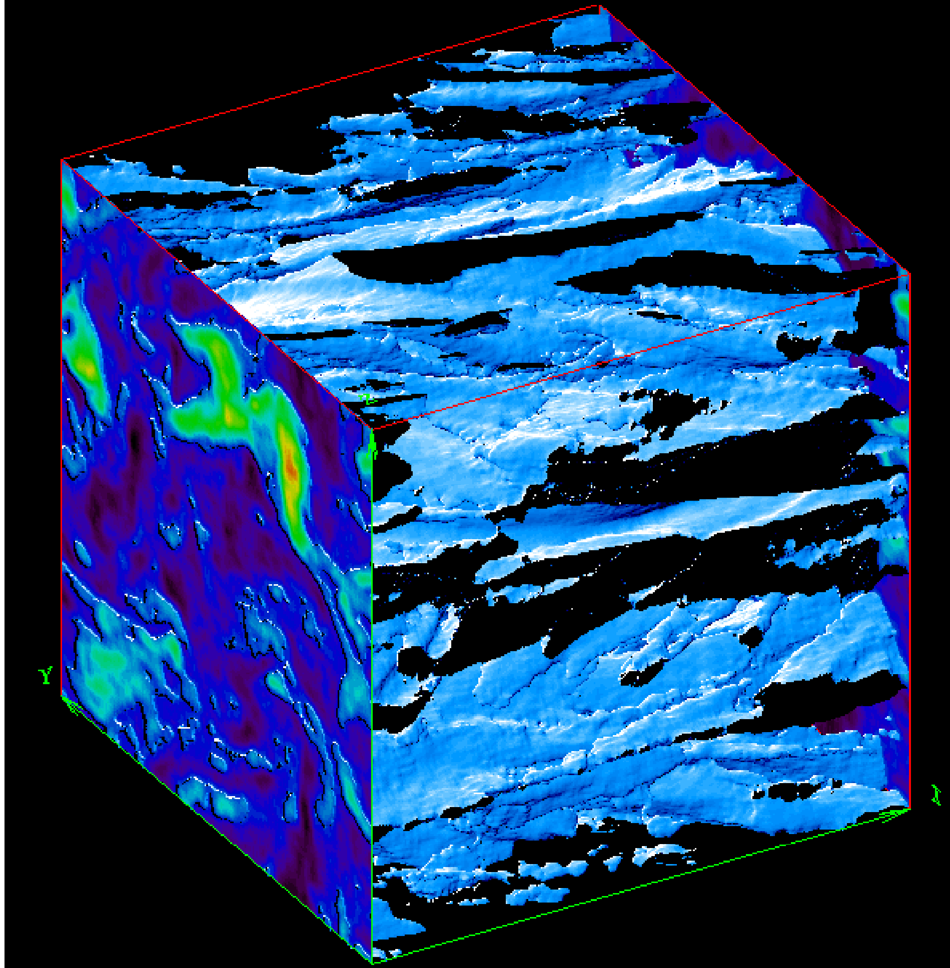


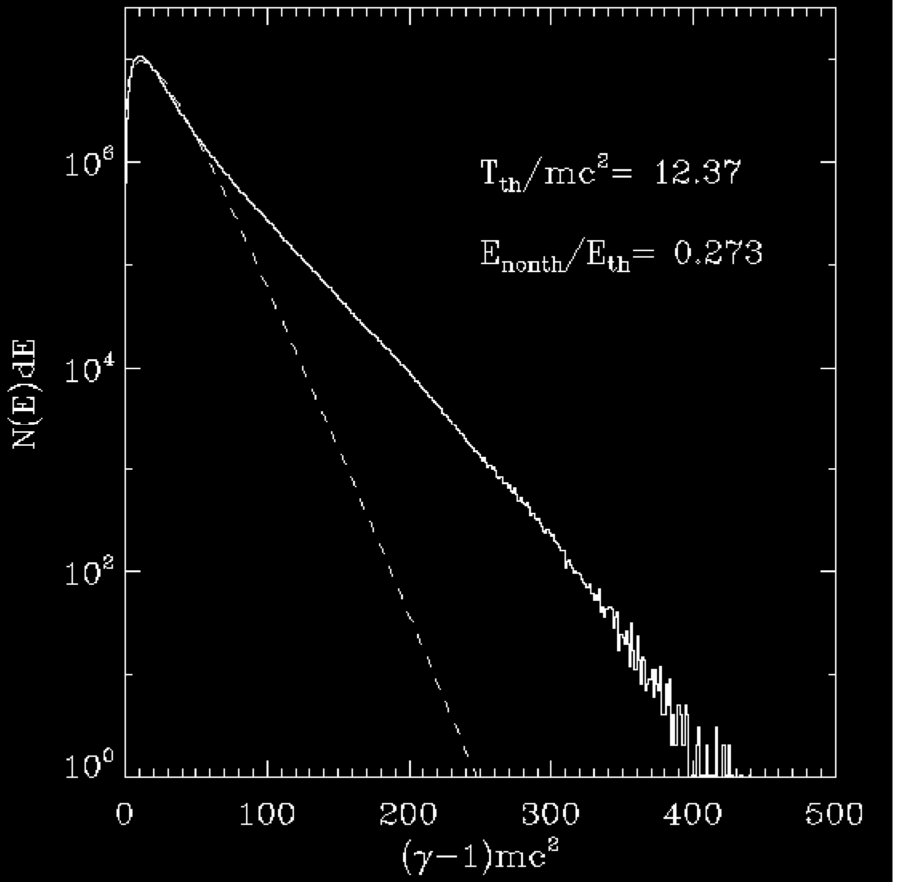
# 3D Reconnection with $B_G/B_0=1$





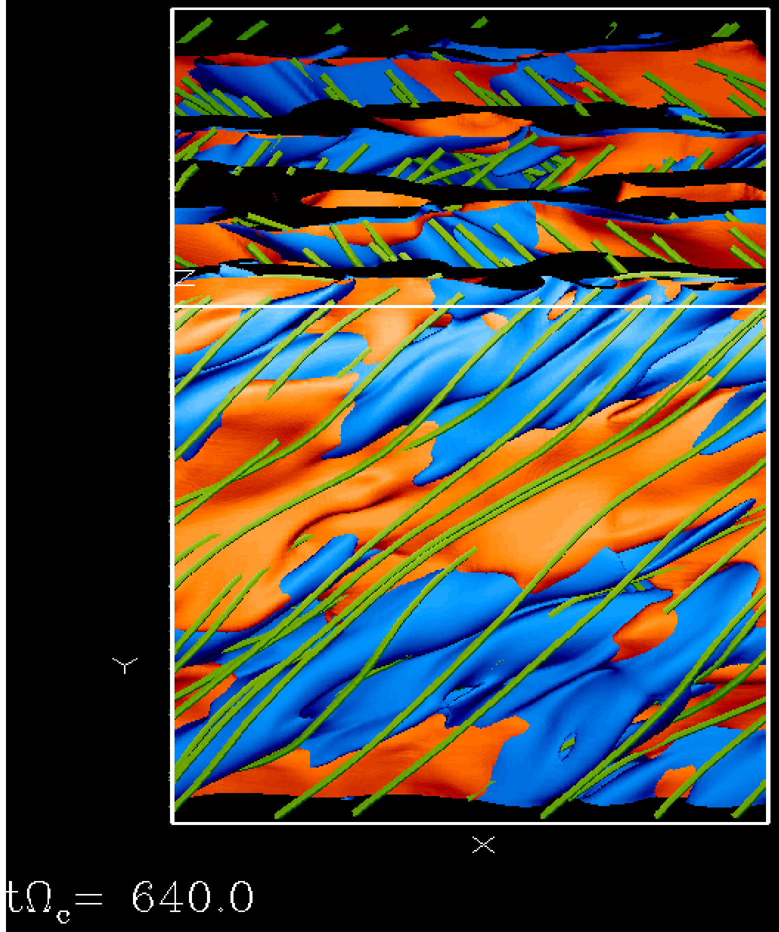
# 3D Reconnection with $B_G/B_0=1$

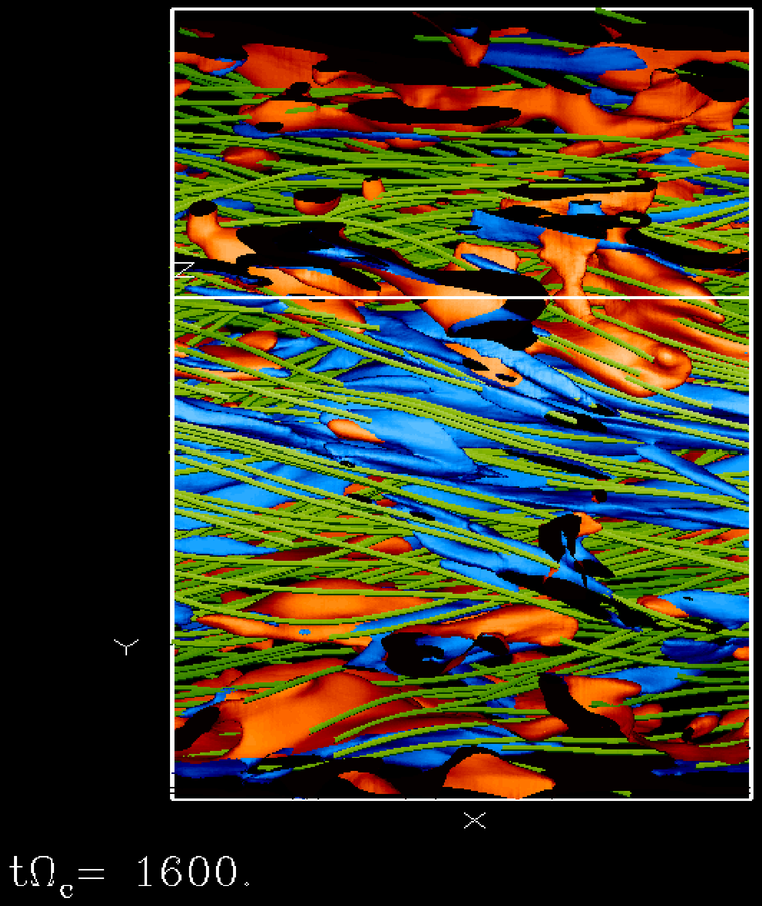




3D simulation result is basically same as 2D

# 3D Reconnection



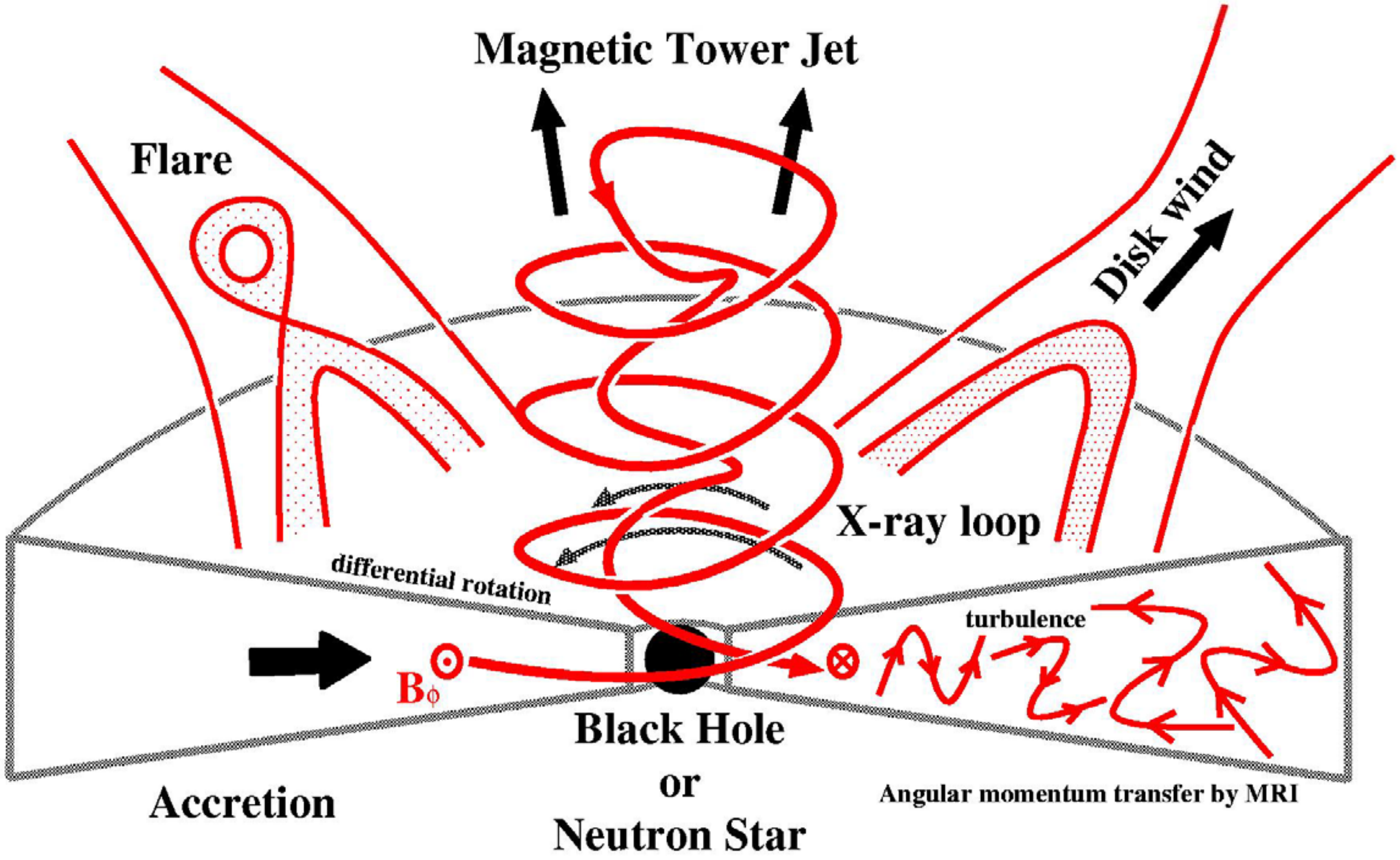


Blue Region:
Thermal Plasma

Red Region :
High Energy Particle

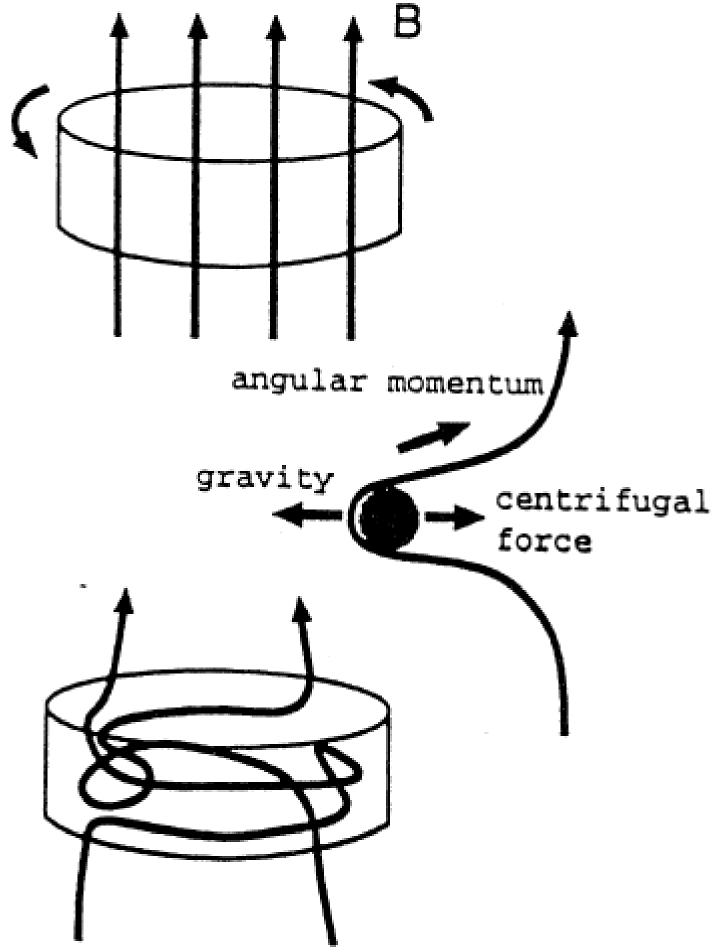
Green :
Magnetic Field Lines

# Reconnection in Accretion Disk

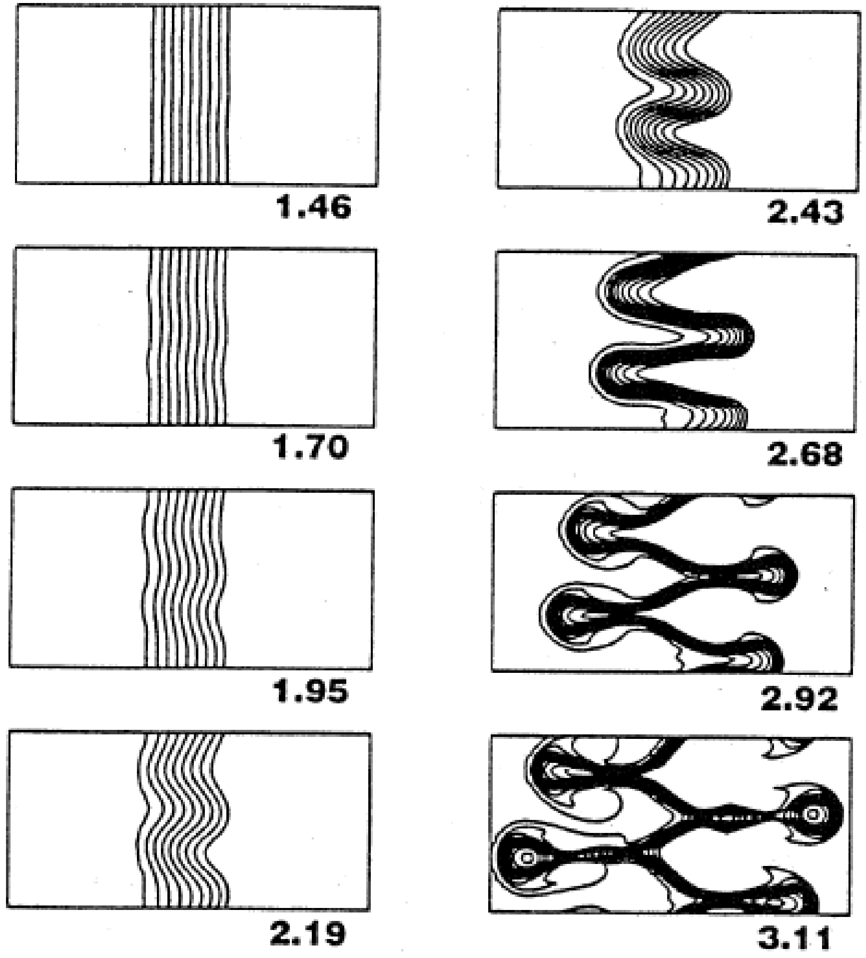


Courtesy of Kato

# Reconnection in Magneto-Rotational Instability (MRI)

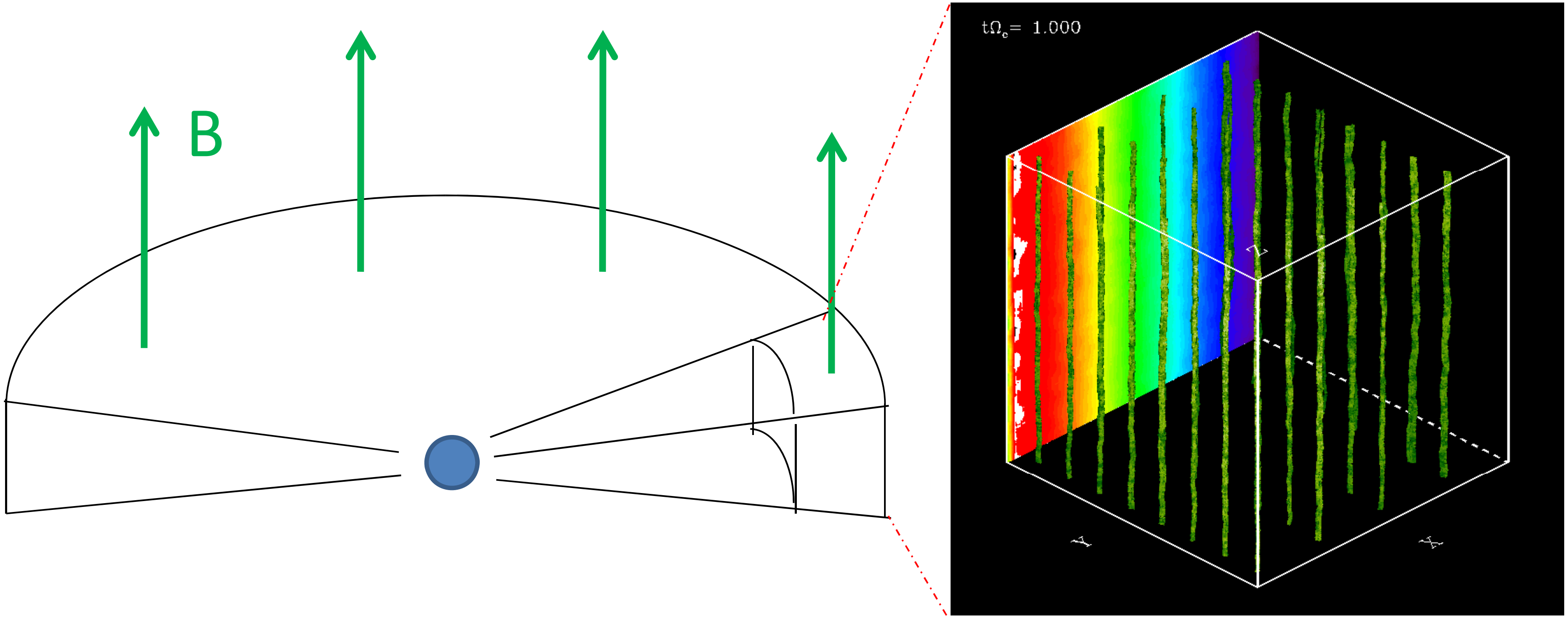


weak magnetic field ($\beta >> 1$) → $\beta = 1\text{-}10$
dynamo process



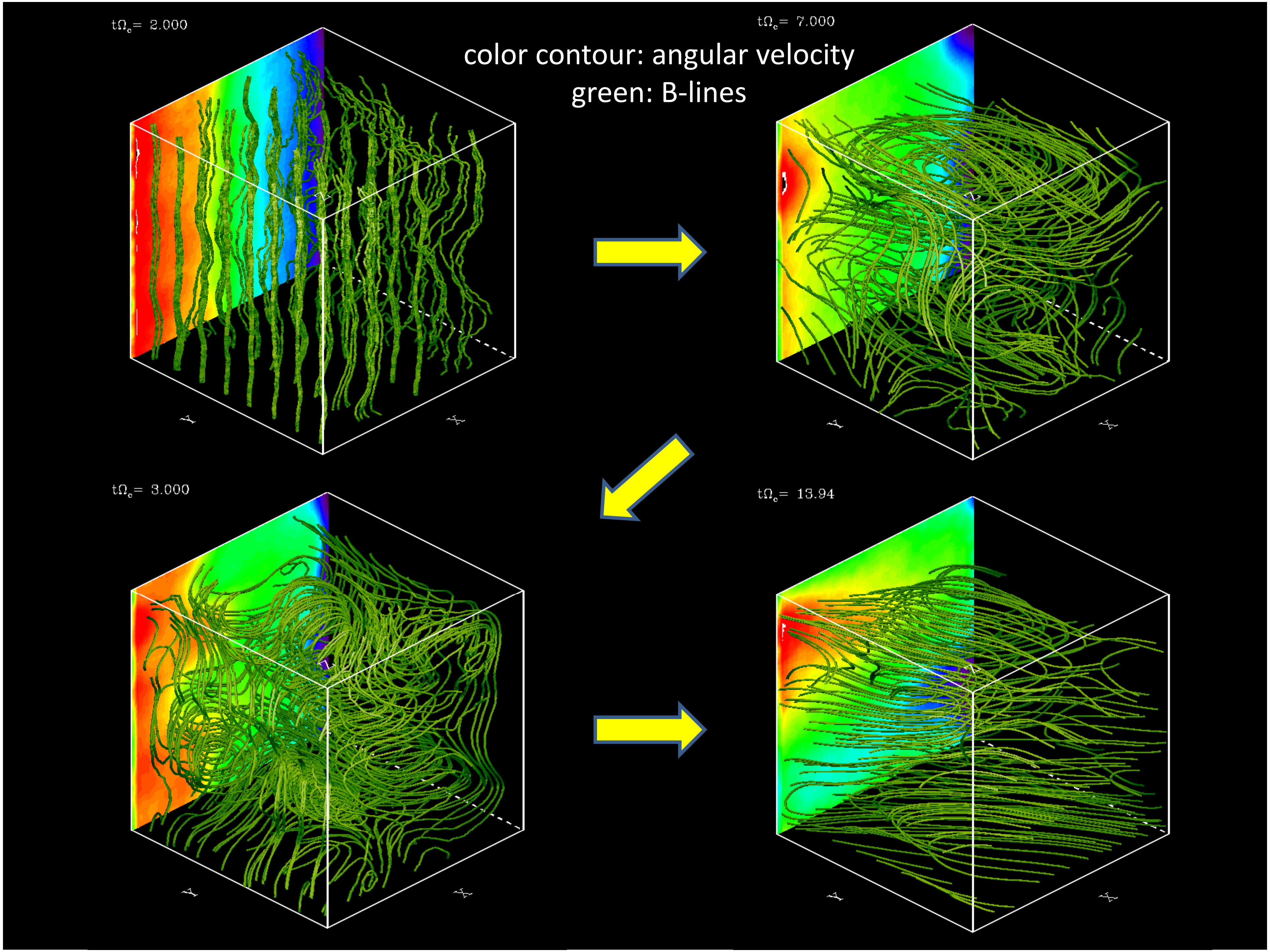
Balbus and Hawley, 1998; Velikov 1959

# MRI and Reconnection in PIC simulation

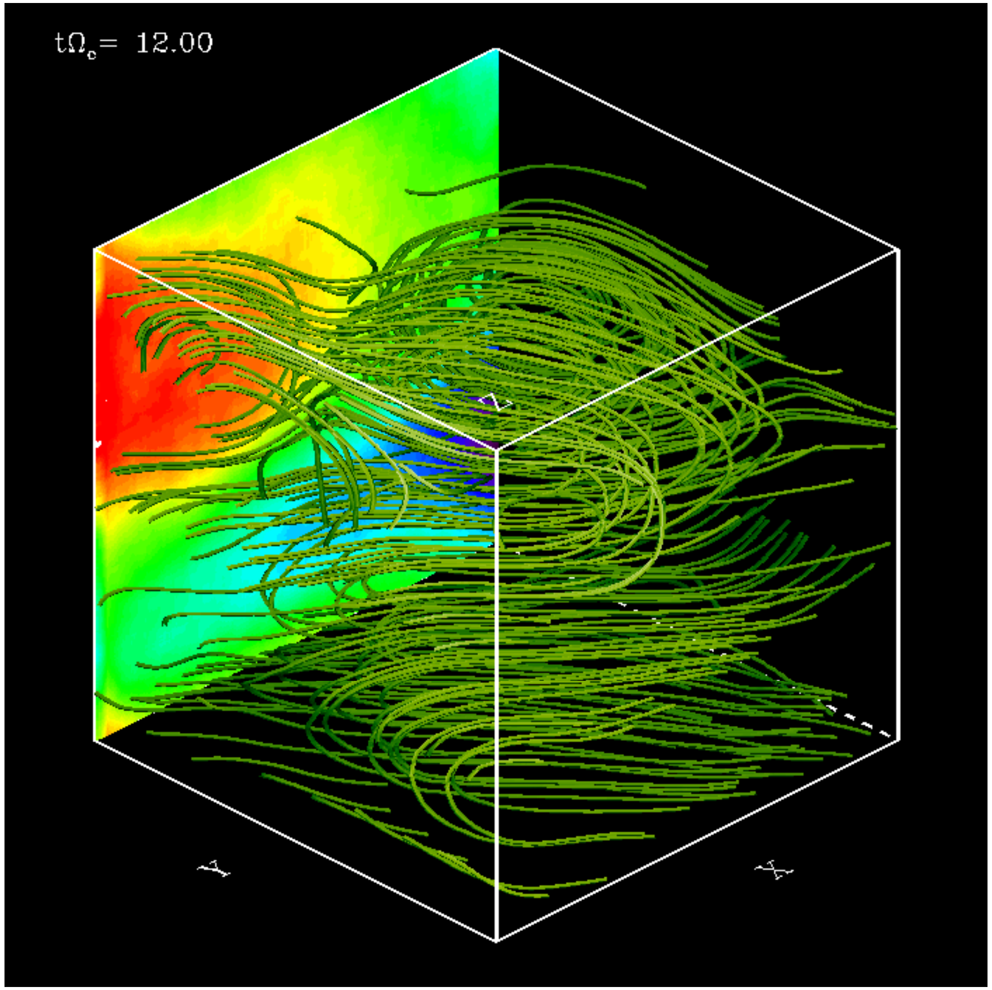


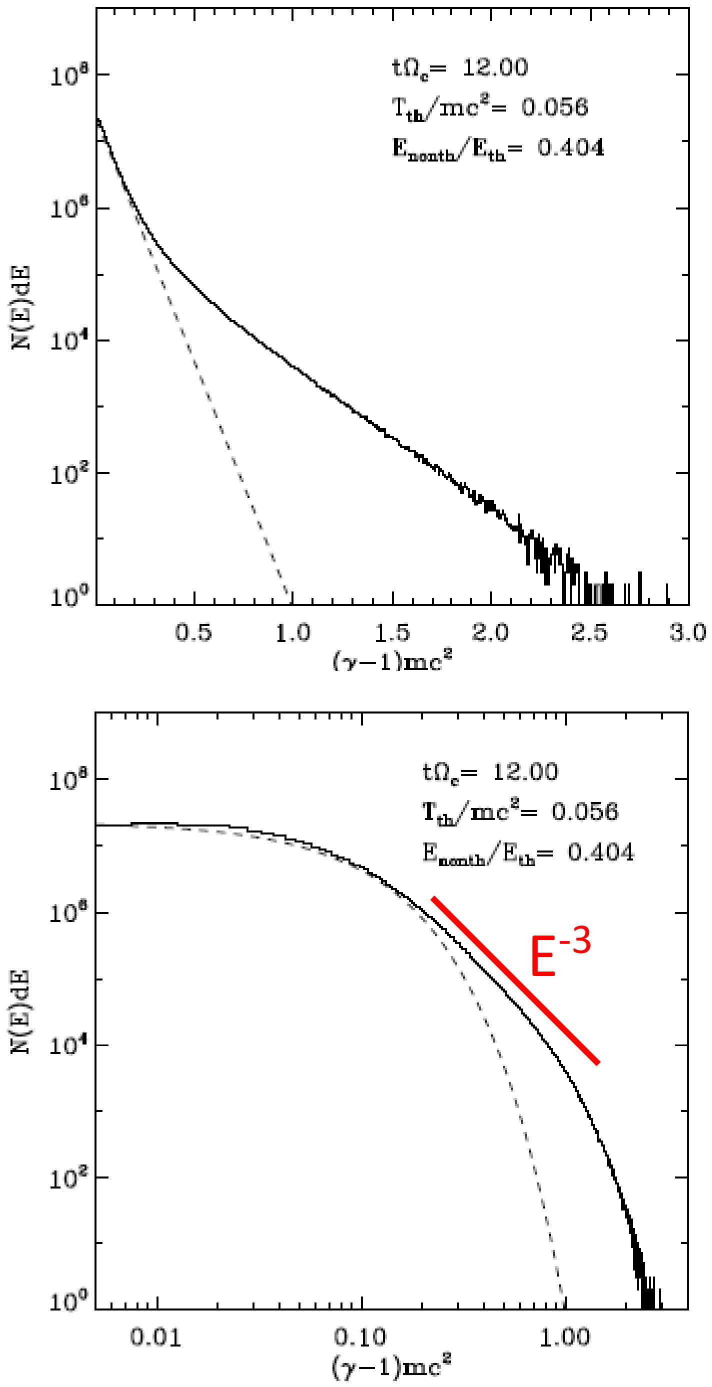
green: magnetic field lines
color contour: angular velocity

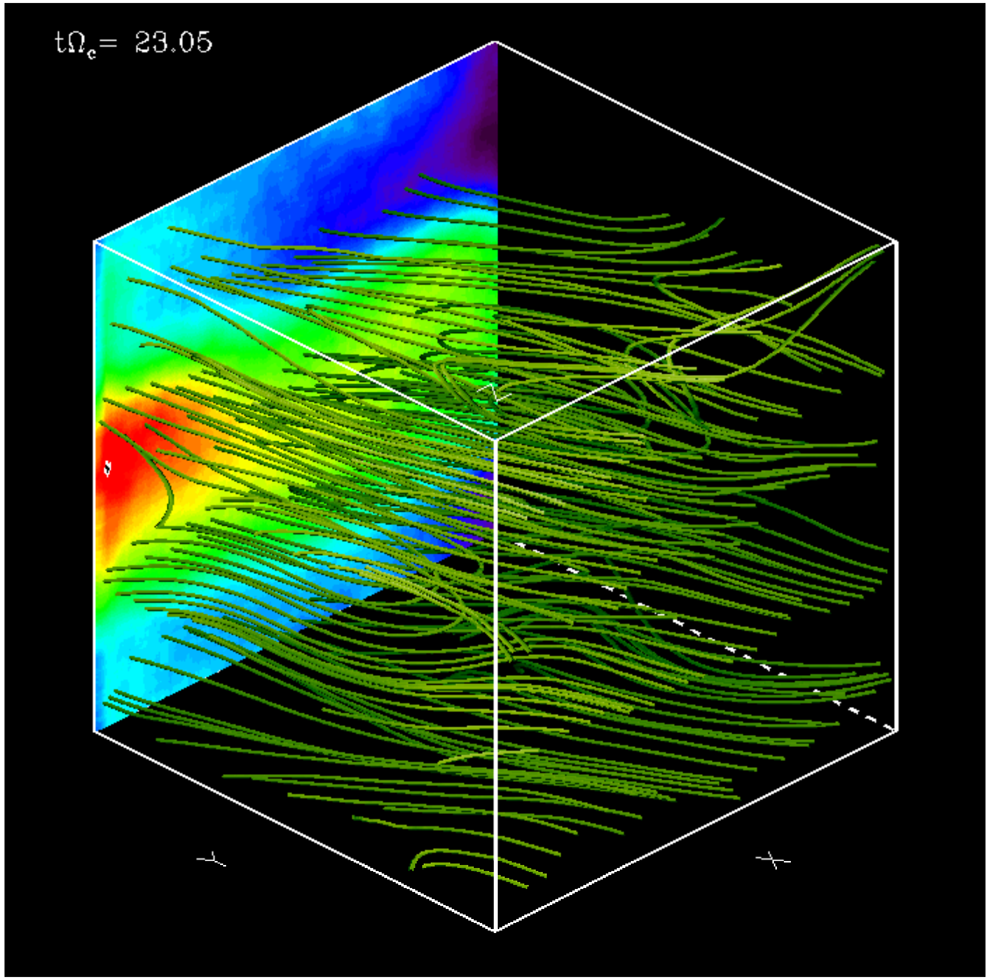
β=100, Kepler rotation Ω
256^3 grids  20 particles/cell,
periodic shearing box, electron-positron plasma

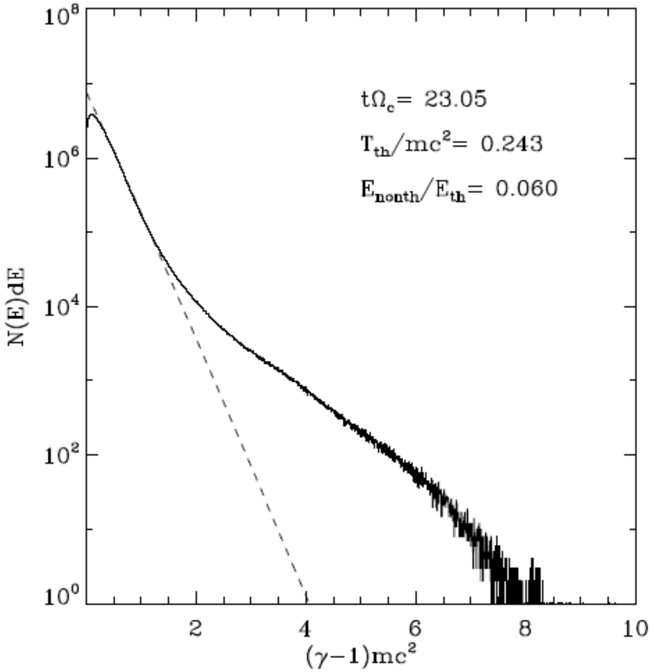


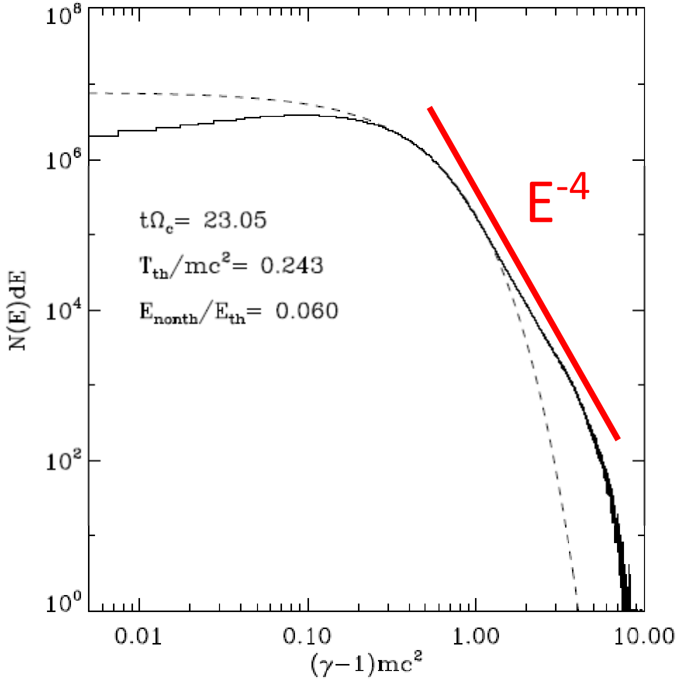
color contour: angular velocity
green: B-lines


tΩc= 12.00
Y
X


tΩc= 12.00
Tth/mc²= 0.056
Enonth/Eth= 0.404
N(E)dE
10⁸
10⁶
10⁴
10²
10⁰
0.5
1.0
1.5
2.0
2.5
3.0
(γ−1)mc²
tΩc= 12.00
Tth/mc²= 0.056
Enonth/Eth= 0.404
E⁻³
N(E)dE
10⁸
10⁶
10⁴
10²
10⁰
0.01
0.10
1.00
(γ−1)mc²

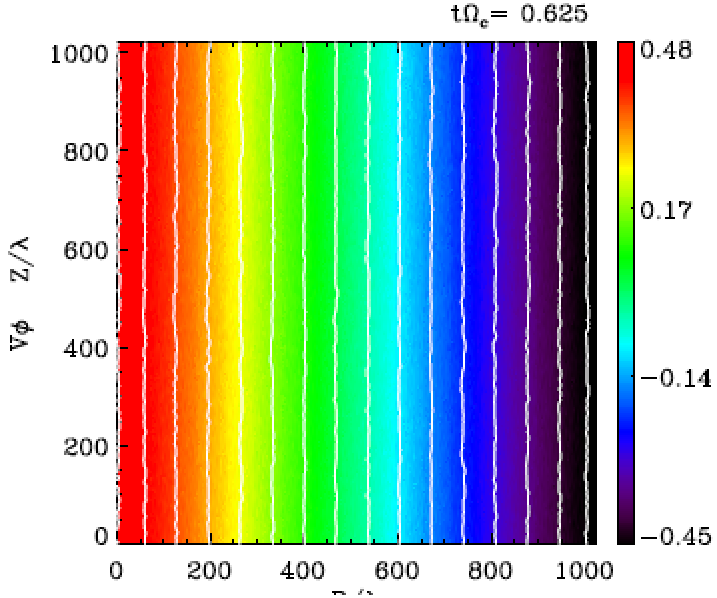

tΩ$_c$= 23.05
Y
X

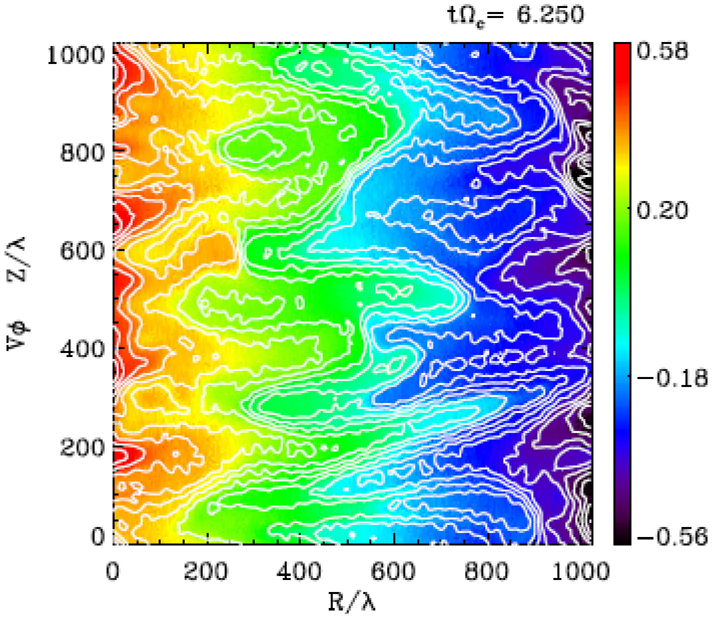

tΩ$_c$= 23.05
T$_{th}$/mc$^2$= 0.243
E$_{nonth}$/E$_{th}$= 0.060
N(E)dE
(γ−1)mc$^2$
10$^8$
10$^6$
10$^4$
10$^2$
10$^0$
2
4
6
8
10

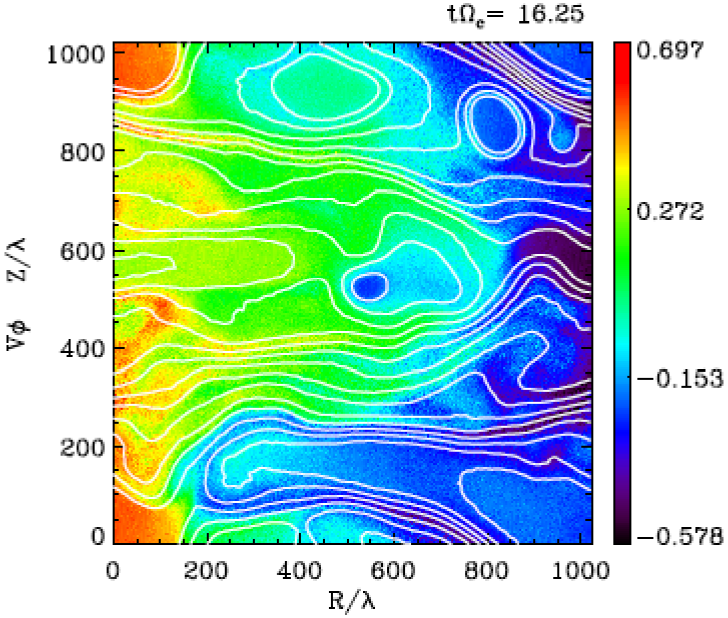

E$^{-4}$
tΩ$_c$= 23.05
T$_{th}$/mc$^2$= 0.243
E$_{nonth}$/E$_{th}$= 0.060
N(E)dE
(γ−1)mc$^2$
10$^8$
10$^6$
10$^4$
10$^2$
10$^0$
0.01
0.10
1.00
10.00

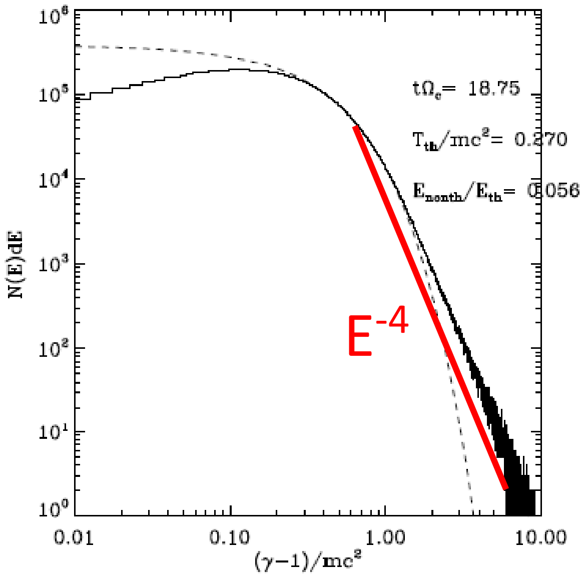
# Reconnection in a large scale 2D MRI

1024x1024 grids, 50 particles/cell

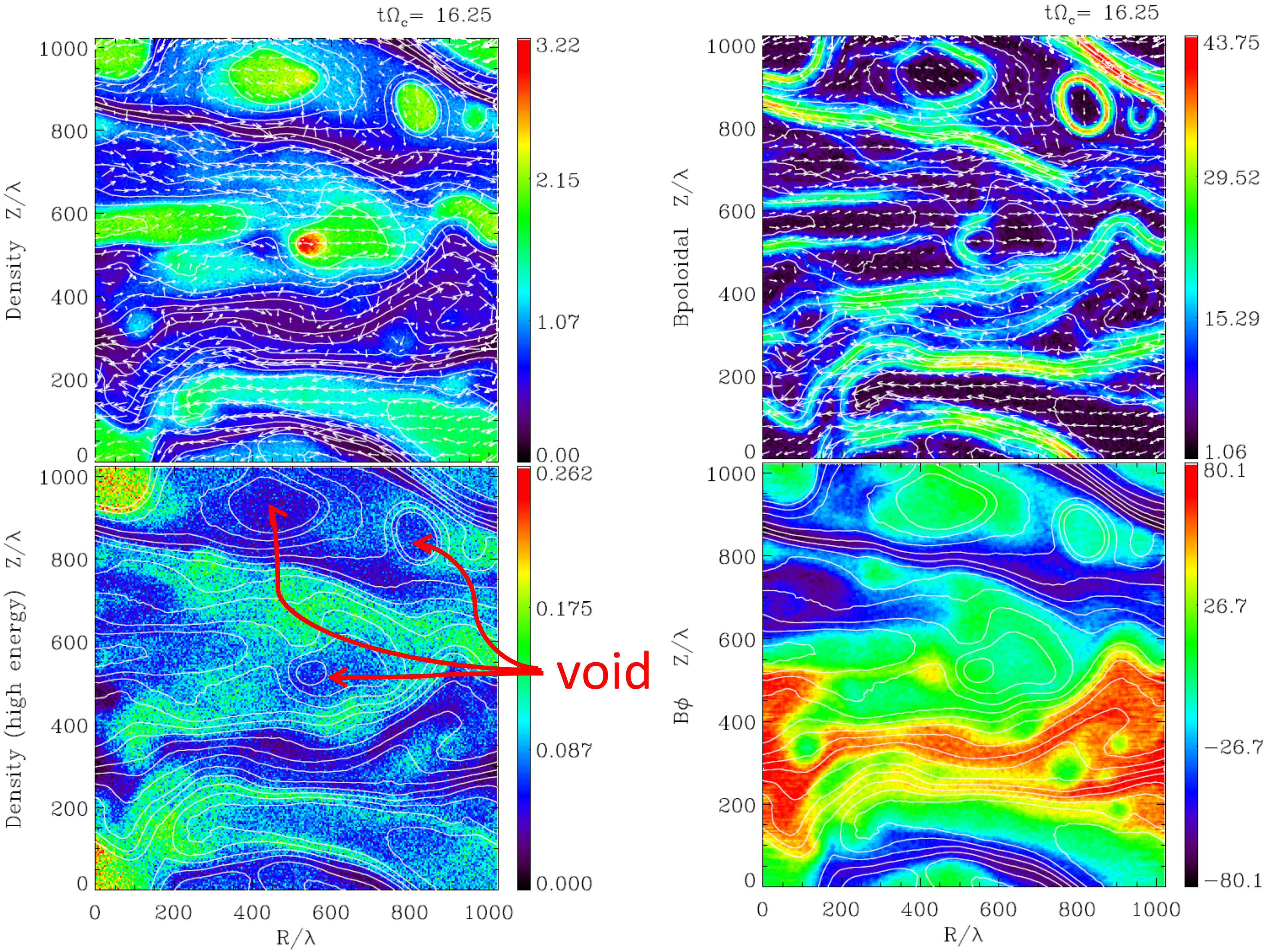






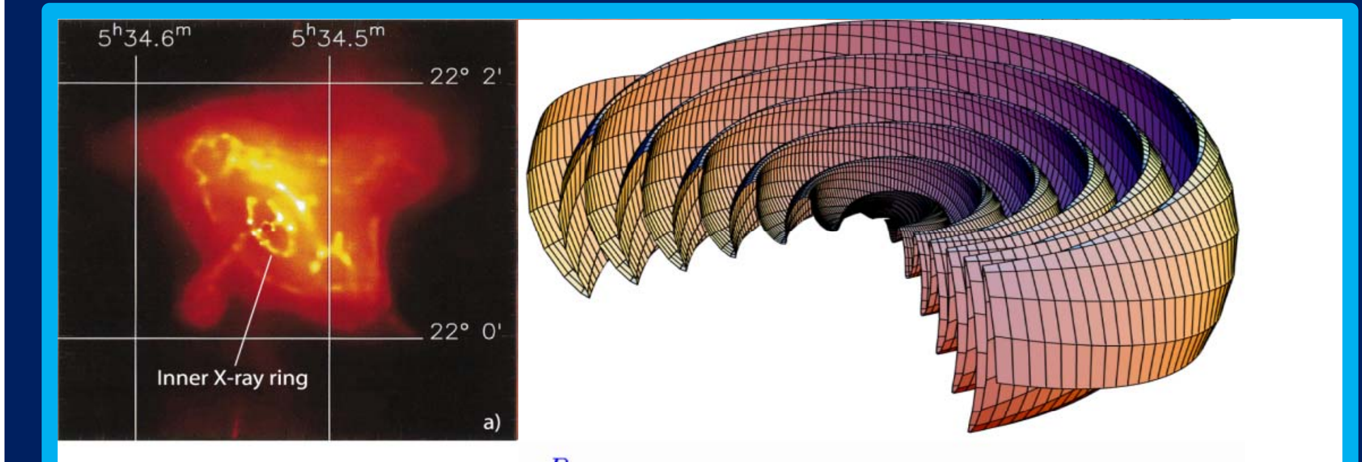


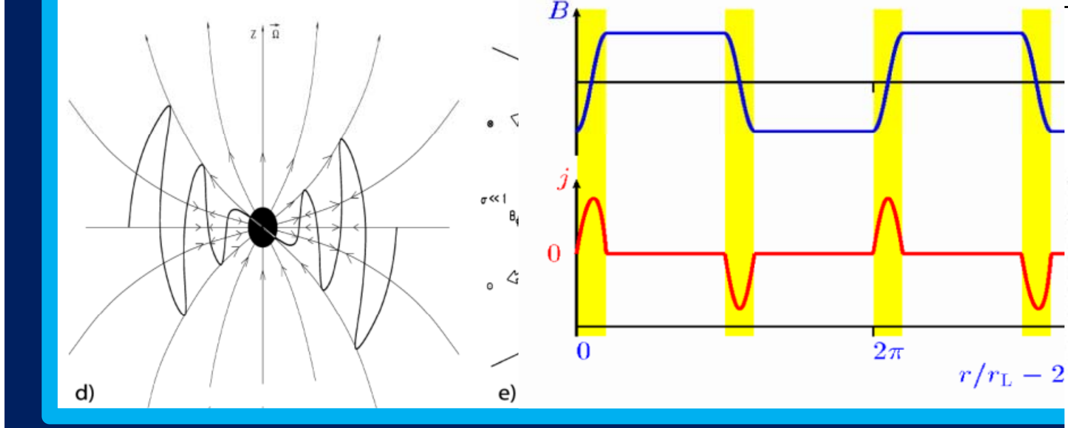
# Turbulent reconnection in MRI



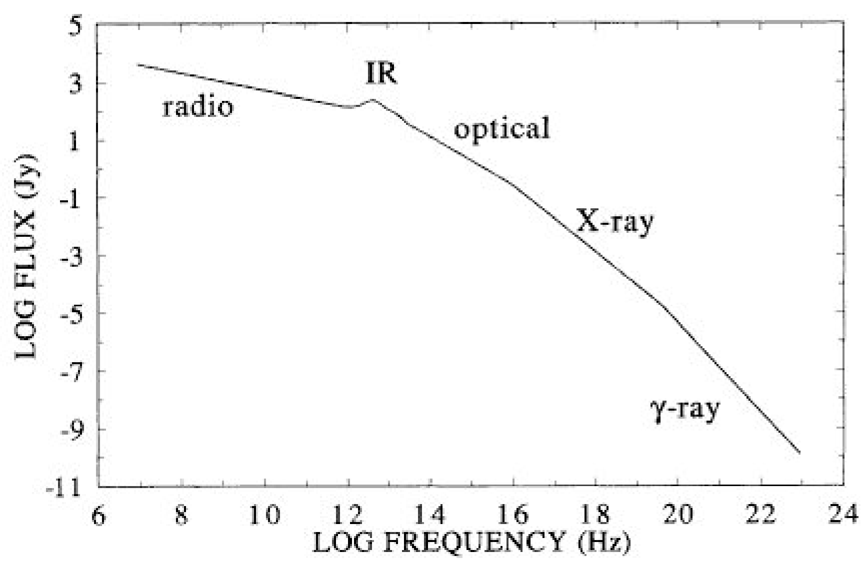
void

# Pulsar Wind & Nebula





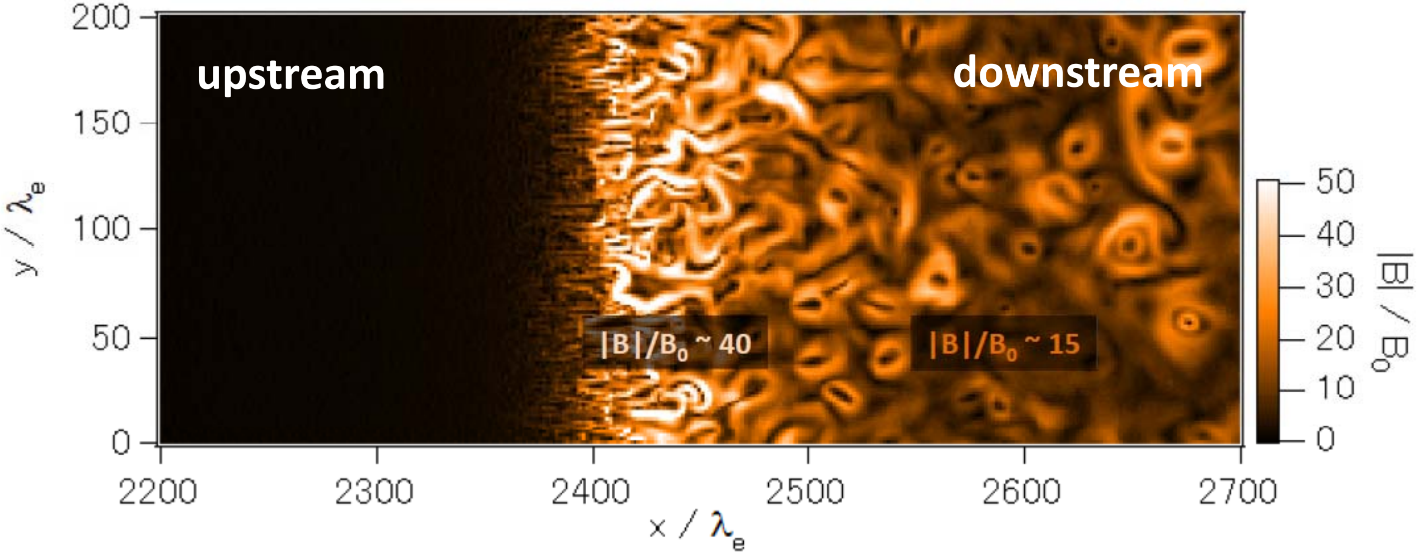
Crab Nebula



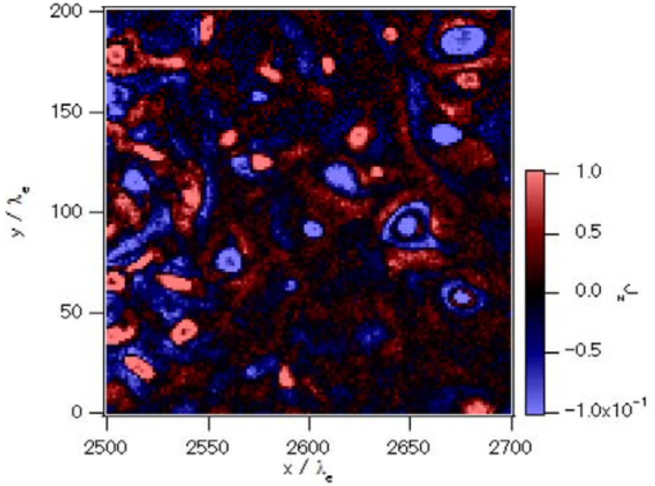
Reconnection Model:
Coroniti ApJ 1990, Kirk+ PRL 2003

# High Mach Number Shocks

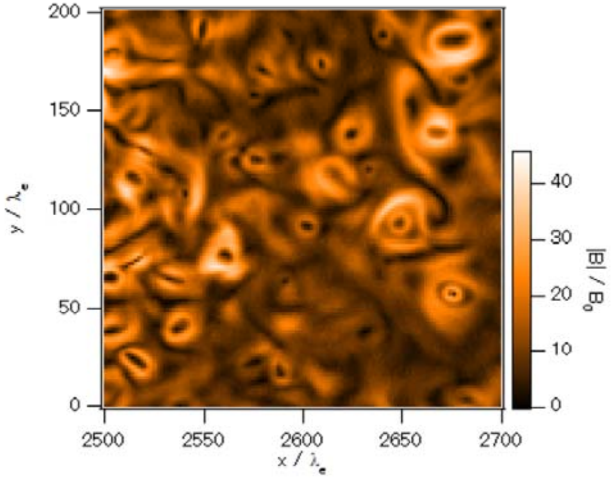
Magnetic field strength normalized to the upstream $B_0$



Current Density $J_z$



Magnetic Field $|B|/B_0$



Kato, 2010

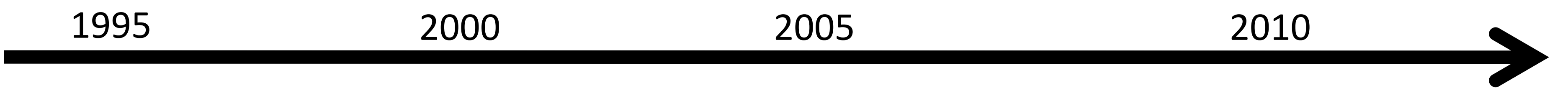
# Summary (Part 1)

1. Observations in Solar corona & Earth's Magnetosphere:
   Particle acceleration and energy release processes are intimately linked.

2. Stochastic reconnection acceleration:
   Possibility of 1st order Fermi acceleration in turbulent magnetic reconnection with many islands.

3. Reconnection during MRI in Accretion Disks:
   Nonthermal particle acceleration during magneto-rotational instability.

# Progress of Relativistic Reconnection



Blackman & Field (1994)
Lyutikov & Uzdensky (2003)
Lyubarsky (2005)
Watanabe & Yokoyama (2006)
Zenitani et al (2009)

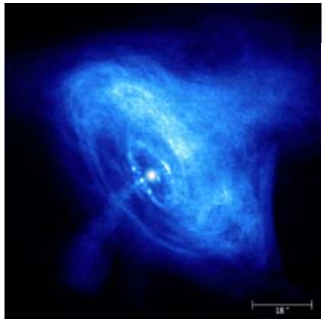
MHD modeling (fast reconnection)

MHH simulation

Zenitani & MH (2001)
Jaroschek et al (2004)
Bessho & Battacharjee (2007)

PIC simulation (particle acceleration & heating)

In astrophysical context

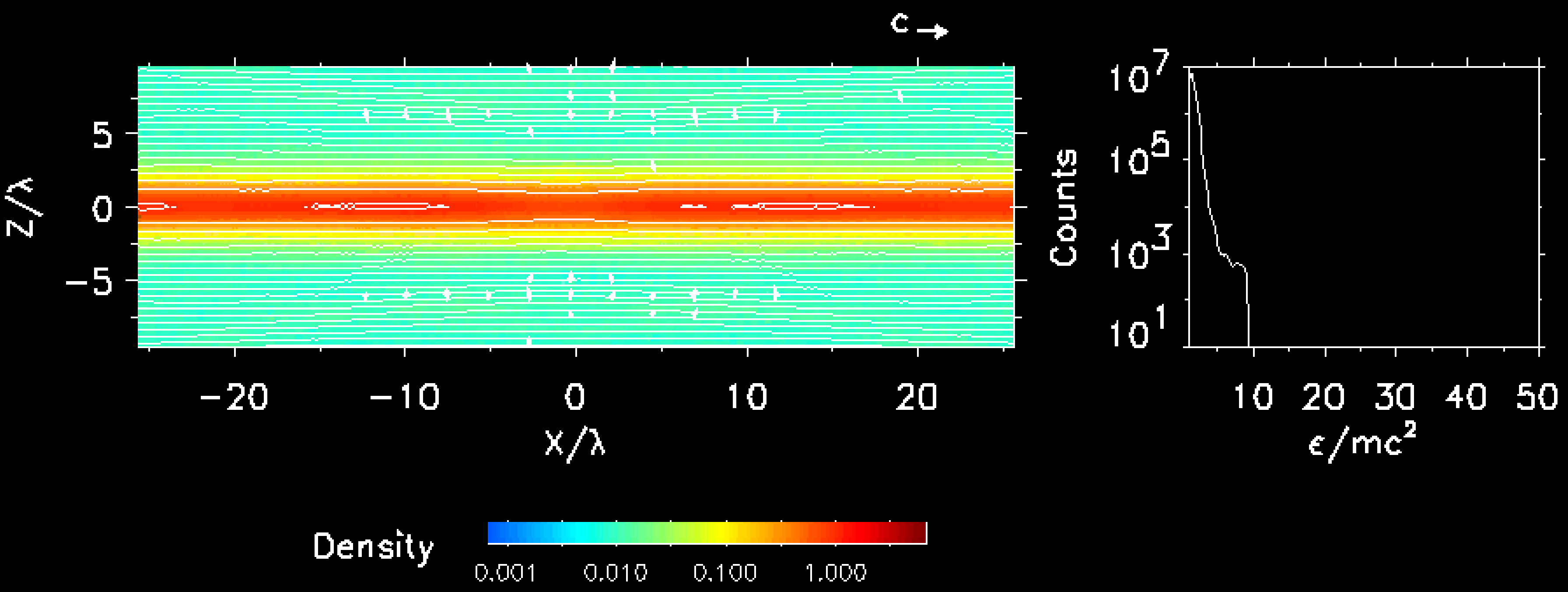


Coroniti (1990), Kirk et al (2003), Giannois et al (2010), Nalewajko et al (2011),….

Jaroschek & MH (2009)
Uzdensky & McKinney (2010)

(radiation cooling)

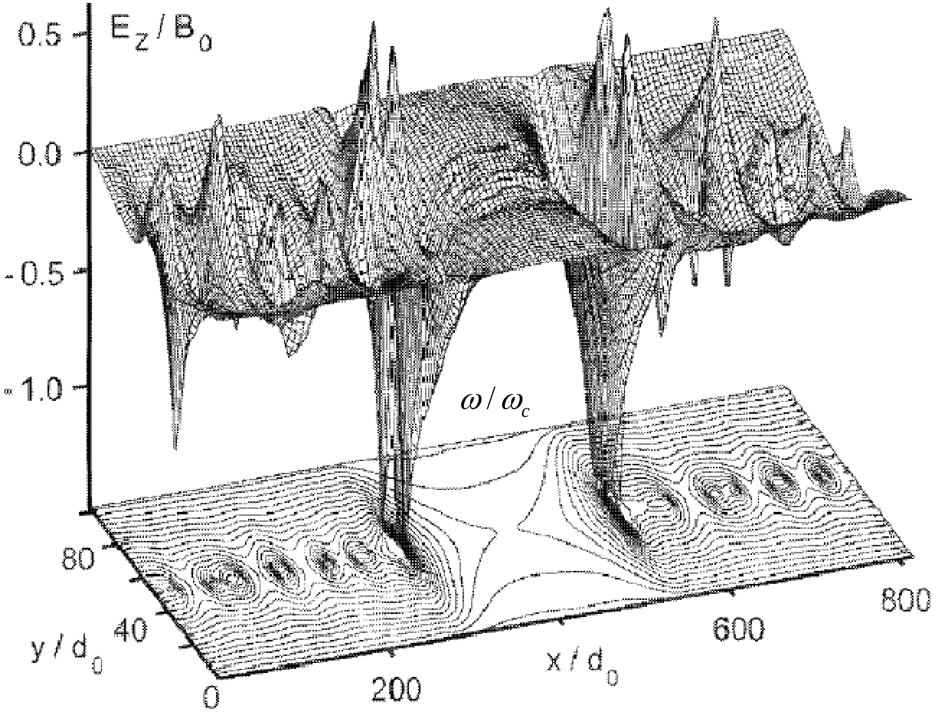
# Relativistic Reconnection
## (Particle-in-Cell simulation)



Non-thermal particle acceleration

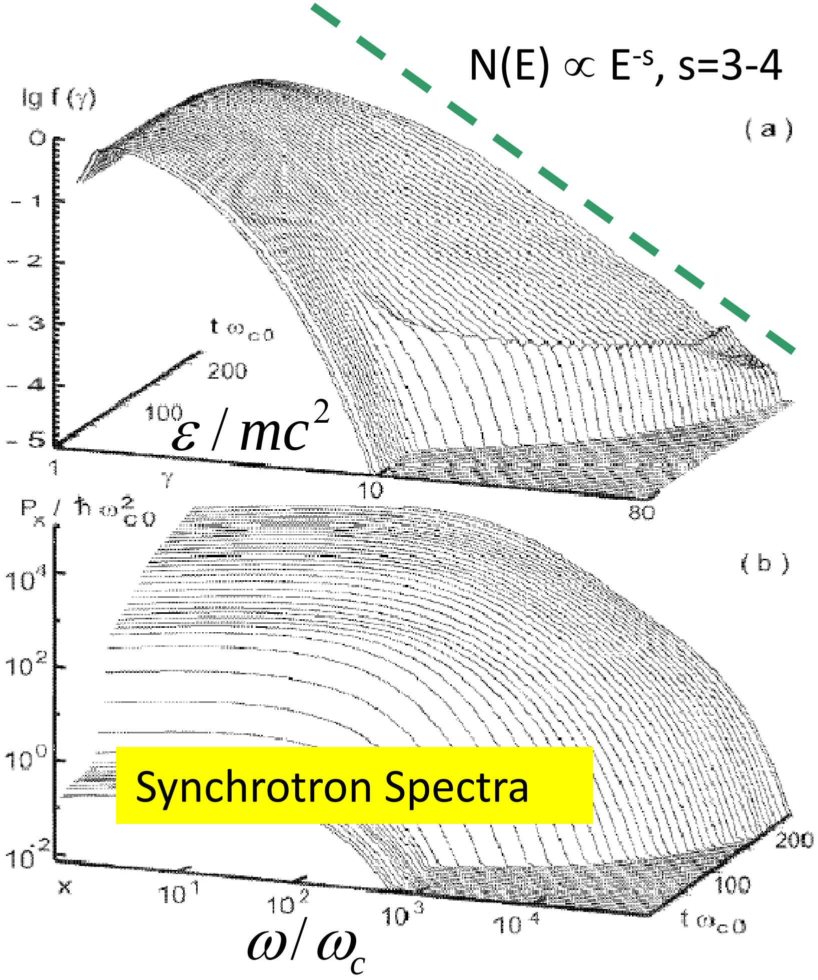
Zenitani & MH, ApJ (2001)

# Large Scale Relativistic Reconnection



Power-law Energy Spectrum

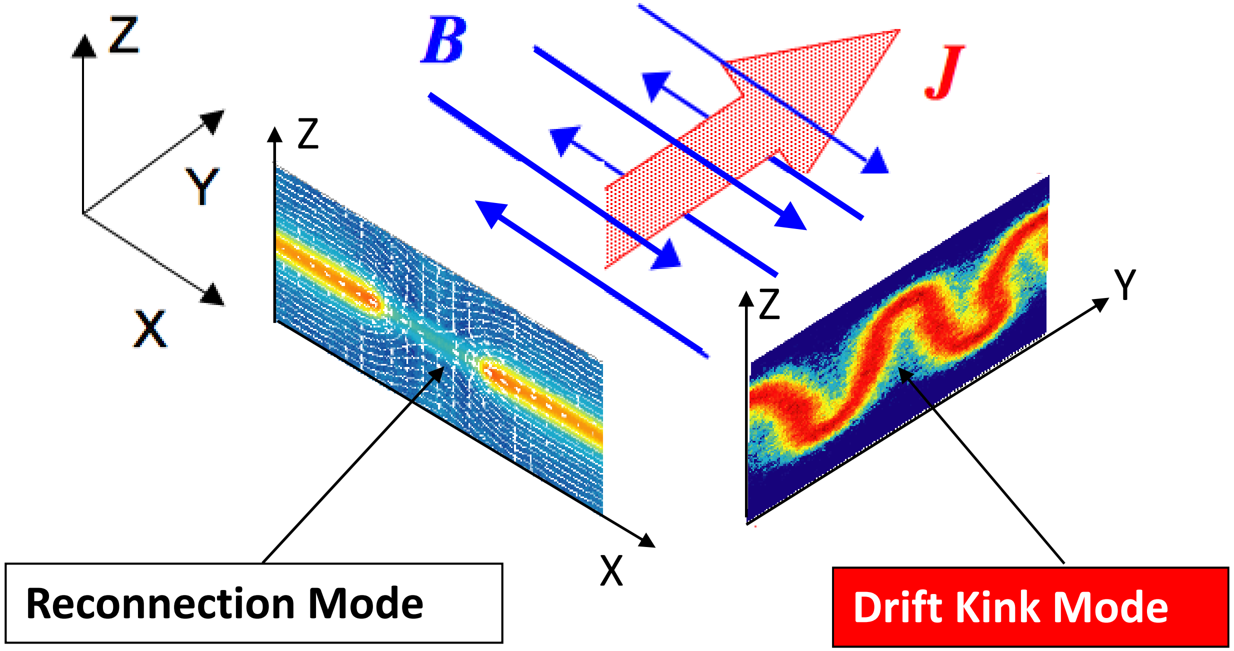
$N(E) \propto E^{-s}$, s=3-4



Synchrotron Spectra

Jaroschek et al. ApJ 2004

# Drift Kink Instability
# (Current Driven Instability)

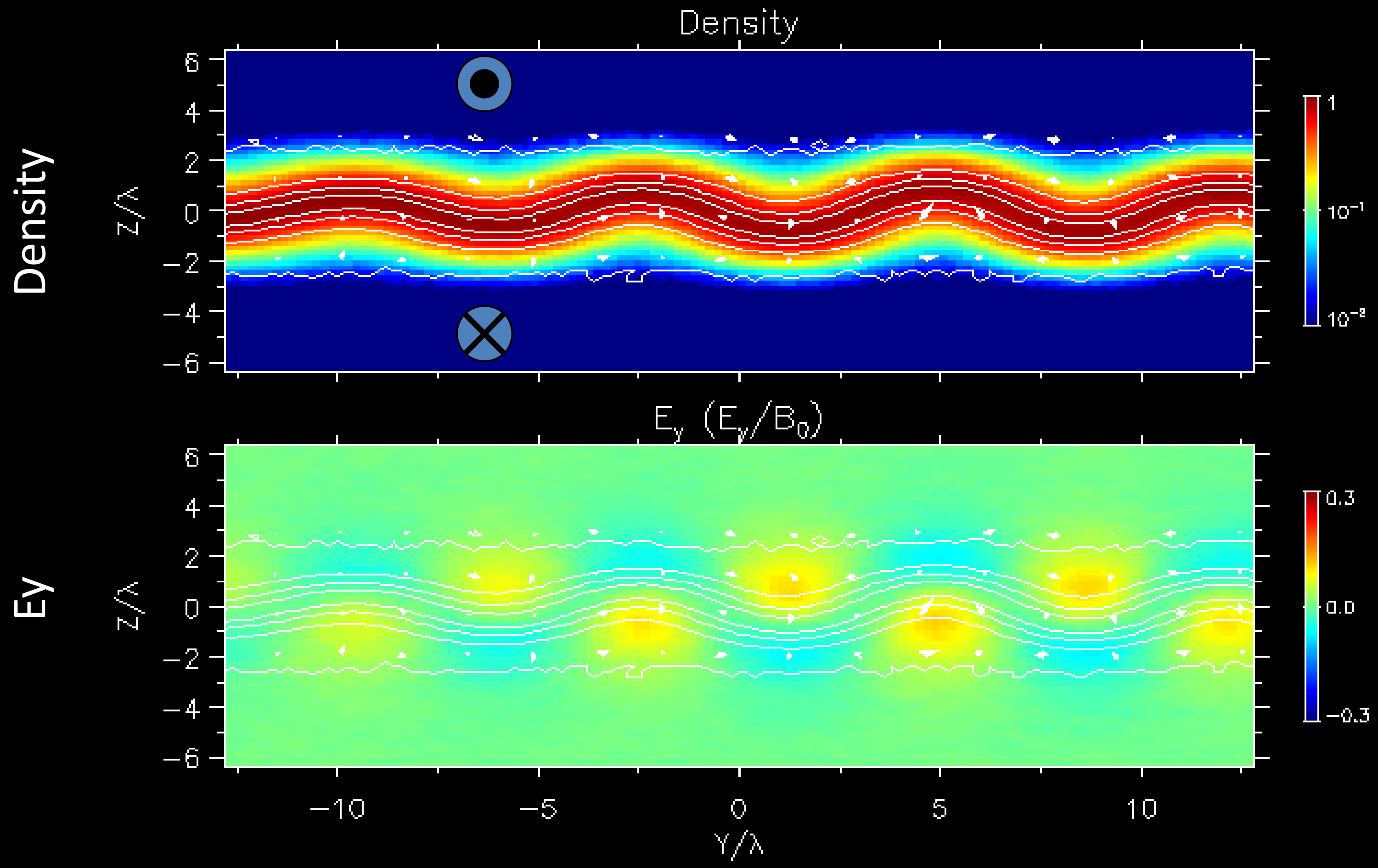


**Reconnection Mode**

**Drift Kink Mode**

Pritchett et al 1996; Daughton 1998

# Drift-Kink Mode (early stage)

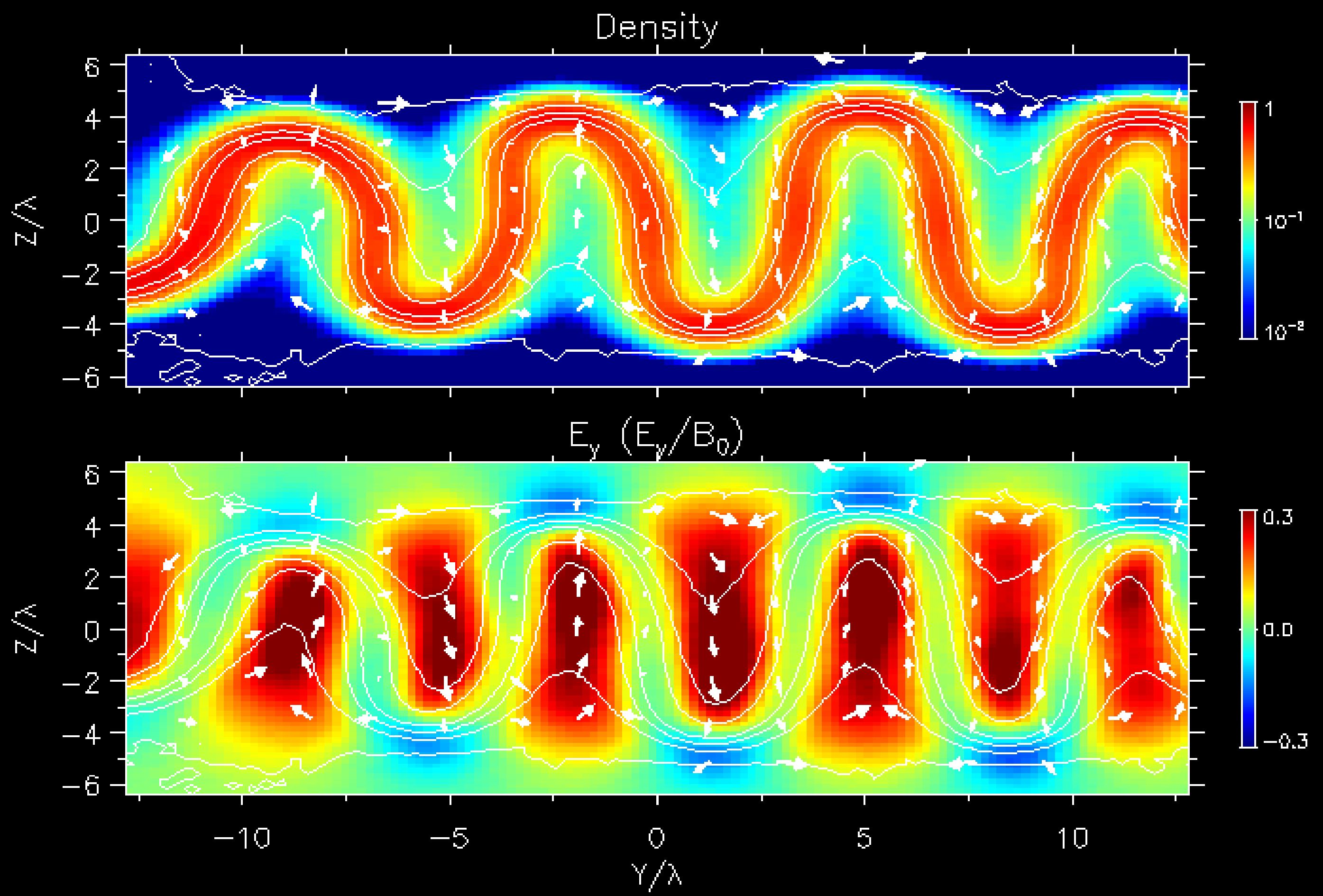


Initial condition: relativistic Harris solution

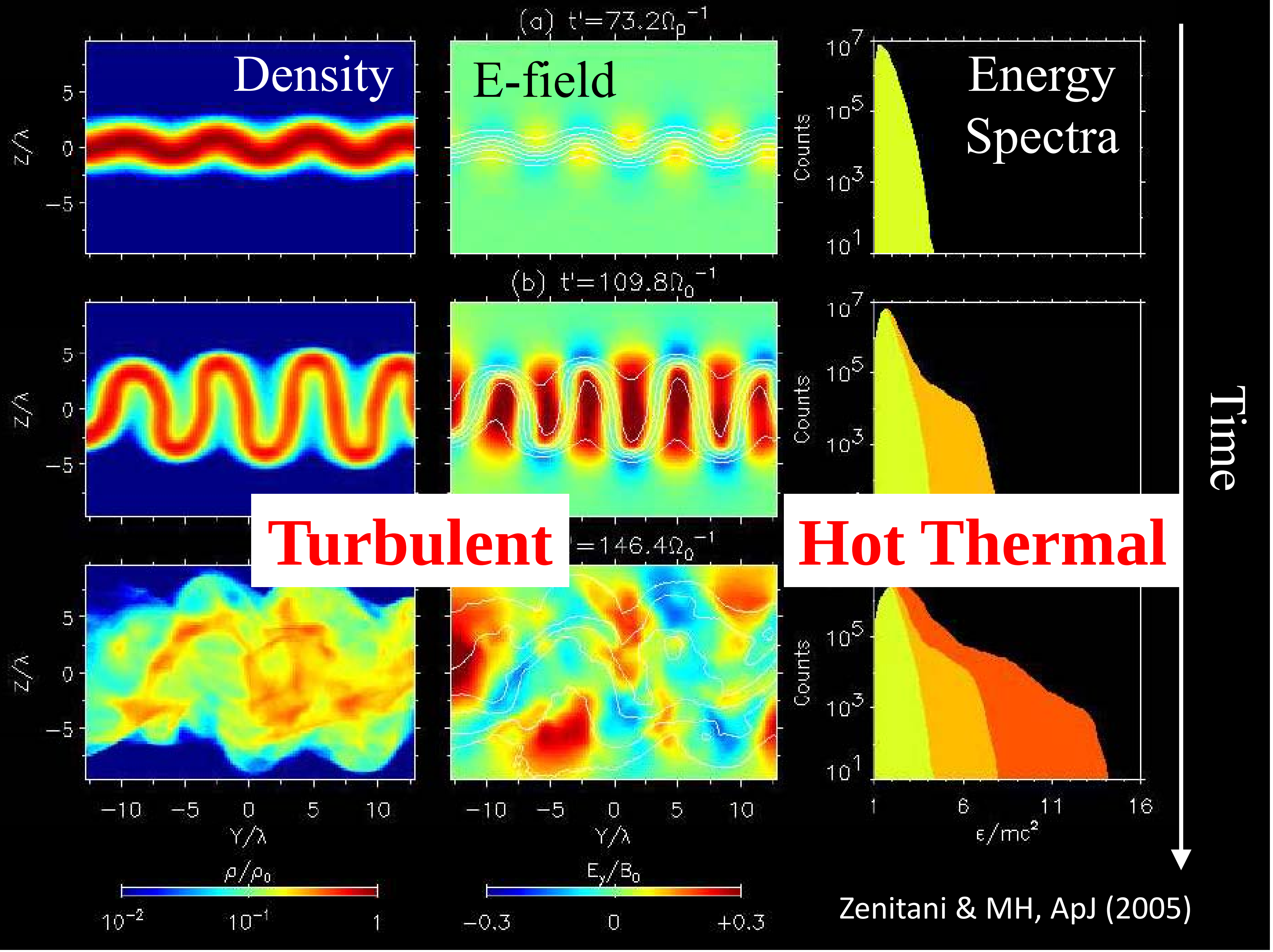
# Drift-Kink Mode (nonlinear stage)

Density

Ey



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

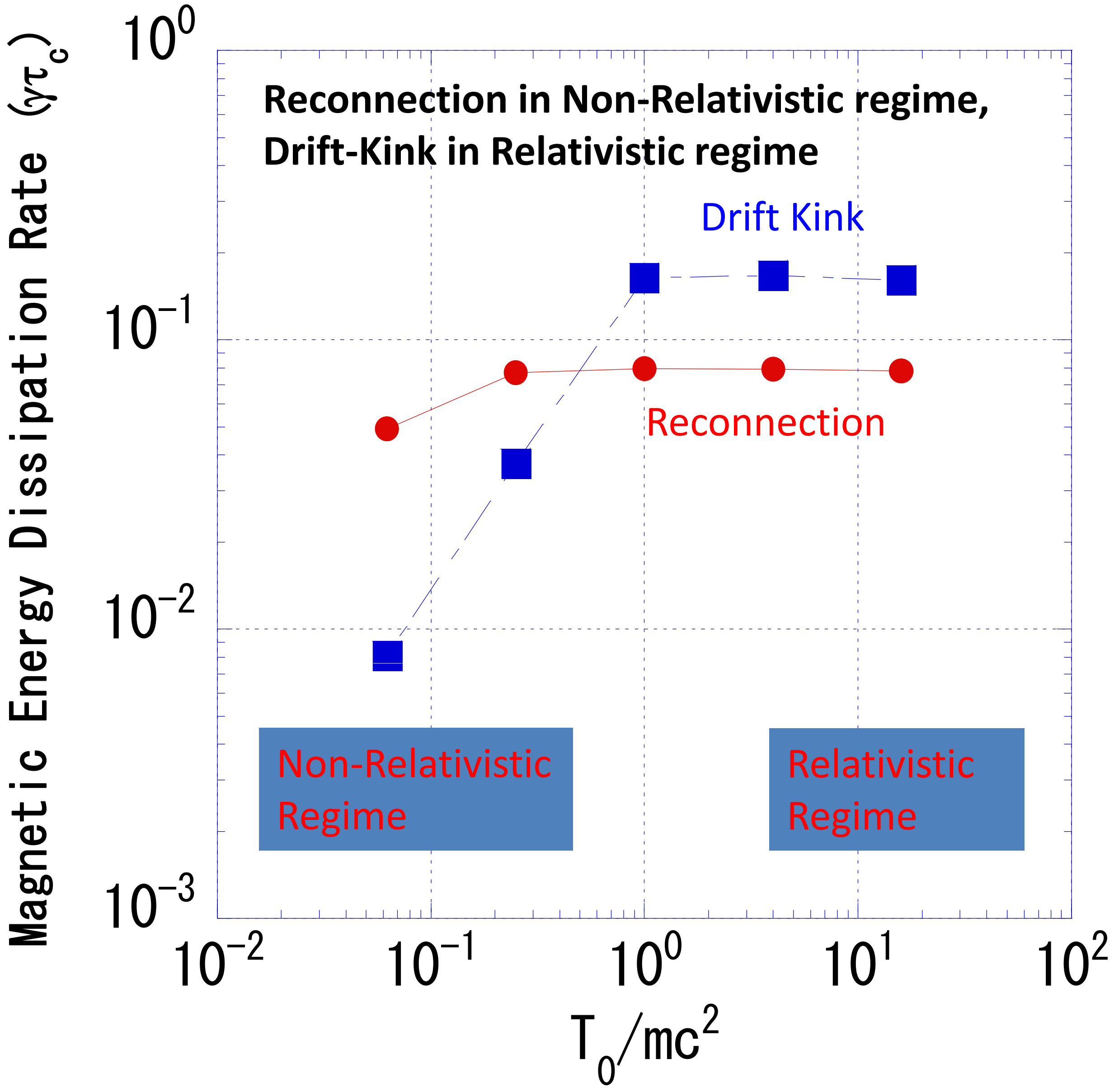


**Turbulent**

**Hot Thermal**

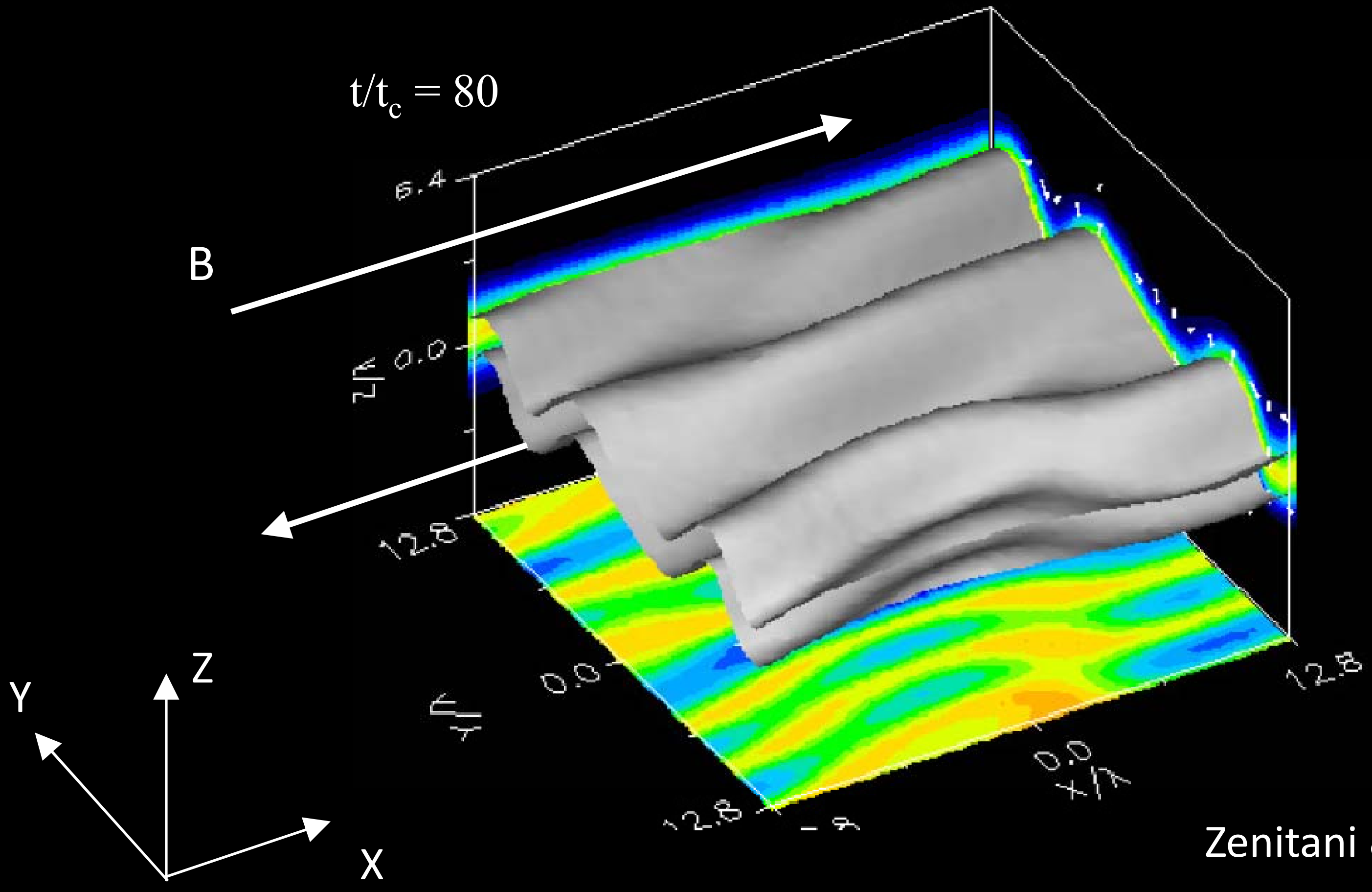
Zenitani & MH, ApJ (2005)

# Energy Dissipation Rate



# 3D Current Sheet Evolution

Isosurface of N,  Color contour of N at neutral sheet

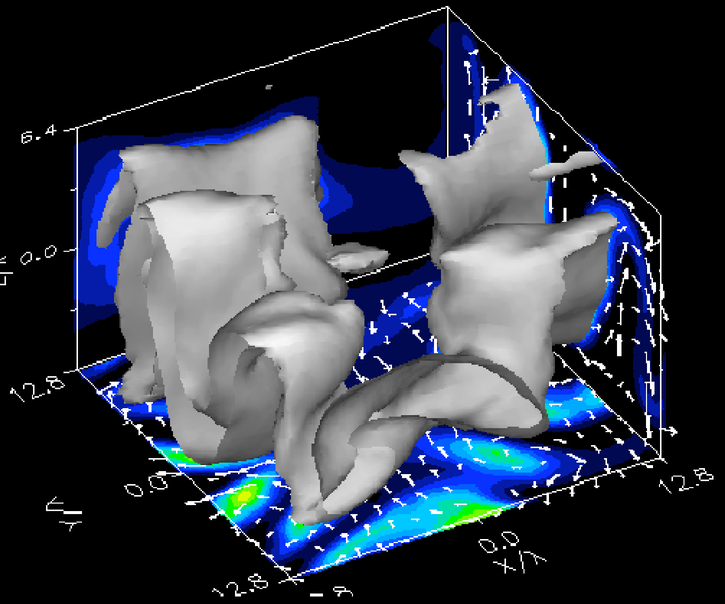


Zenitani & MH, PRL 2005

Drift-Kink grows faster than Reconnection

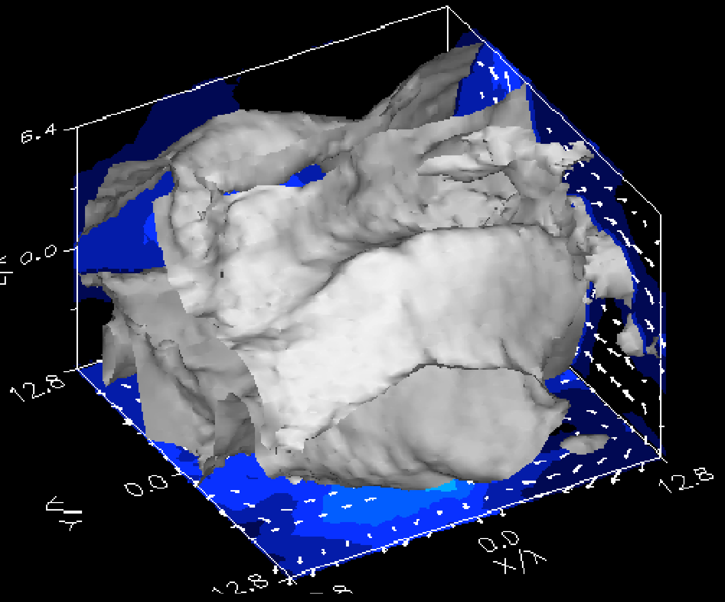
# Nonlinear Stage of 3D Current Sheet

$t/t_c = 110$



Drift-Kind Mode
dominates,
No Reconnection.

$t/t_c = 140$



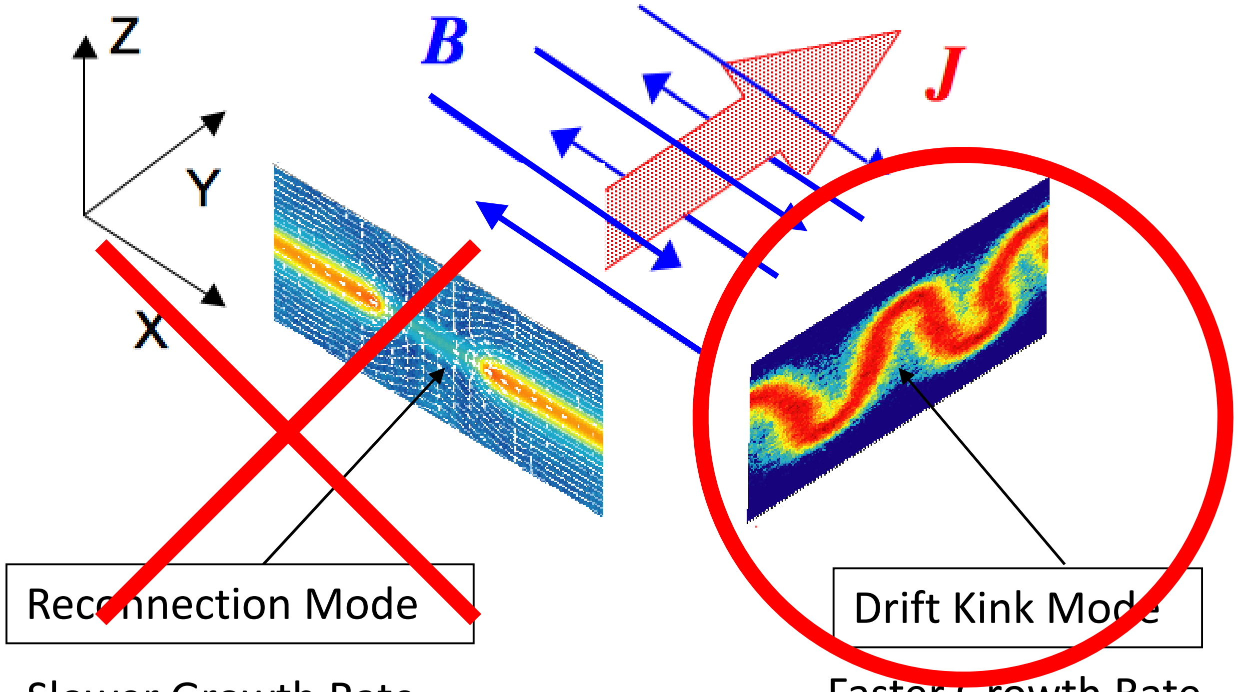
Turbulent Sheet

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

plasma mixing

# Relativistic Current Sheet Instabilities

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



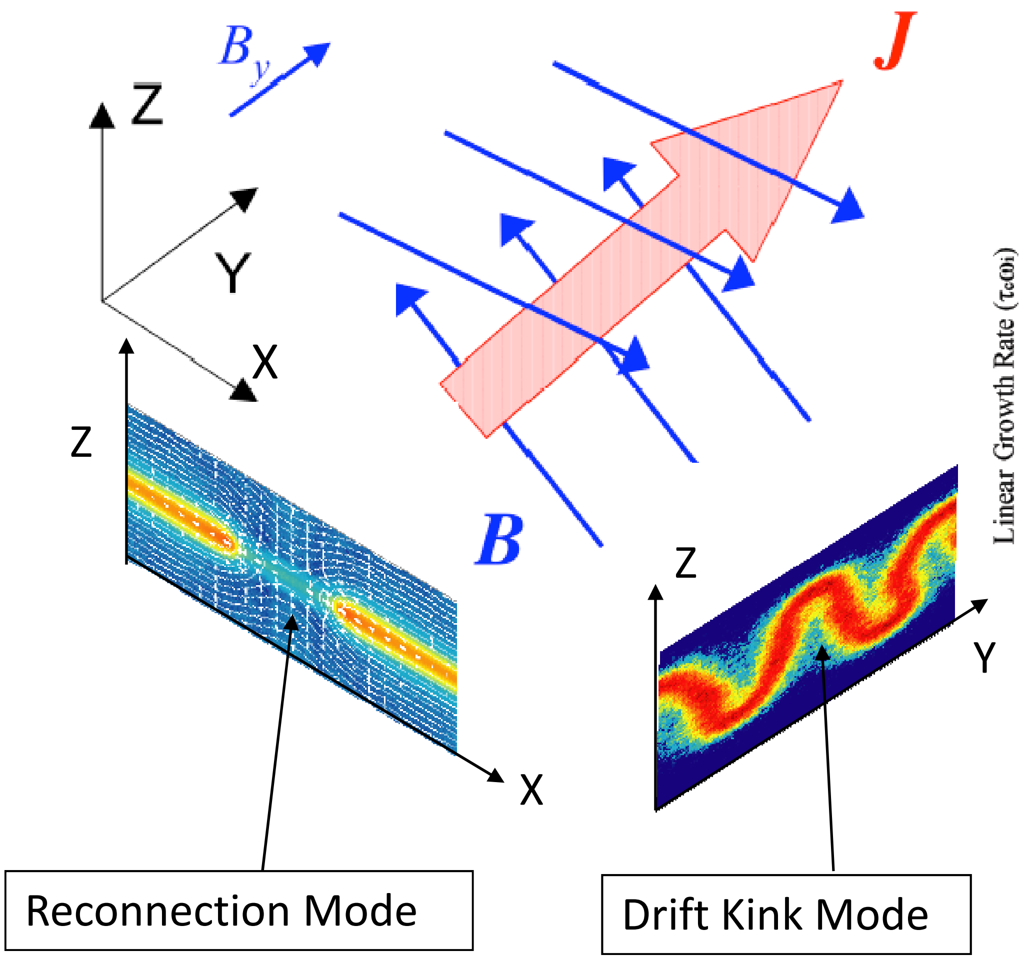
Reconnection Mode

Slower Growth Rate

Drift Kink Mode

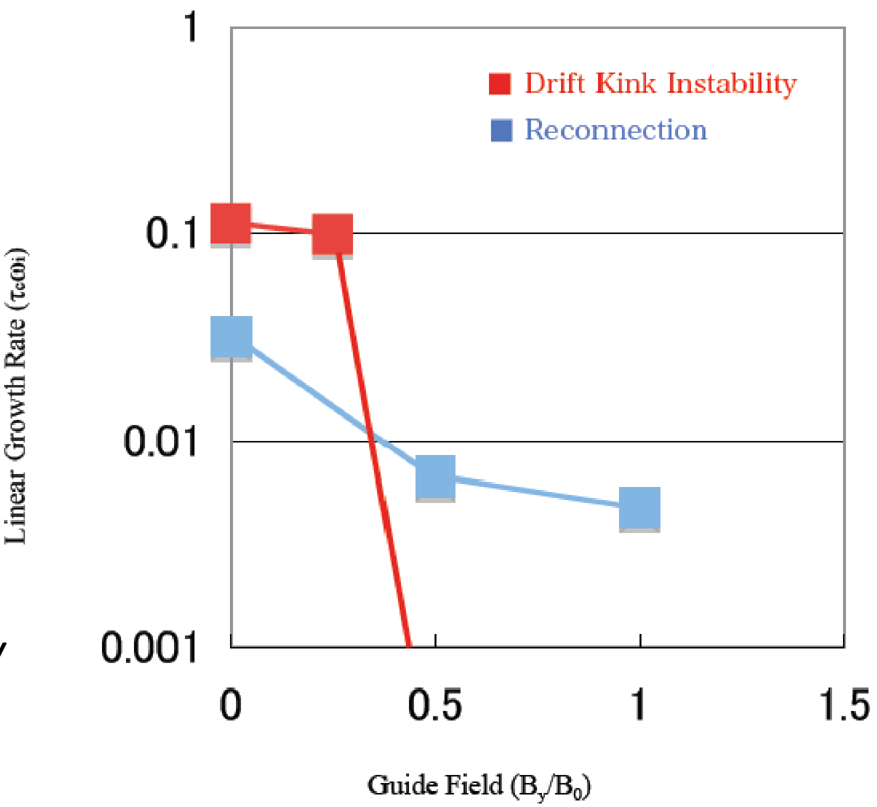
Faster Growth Rate

# 3D Reconnection with Guide Field (By)



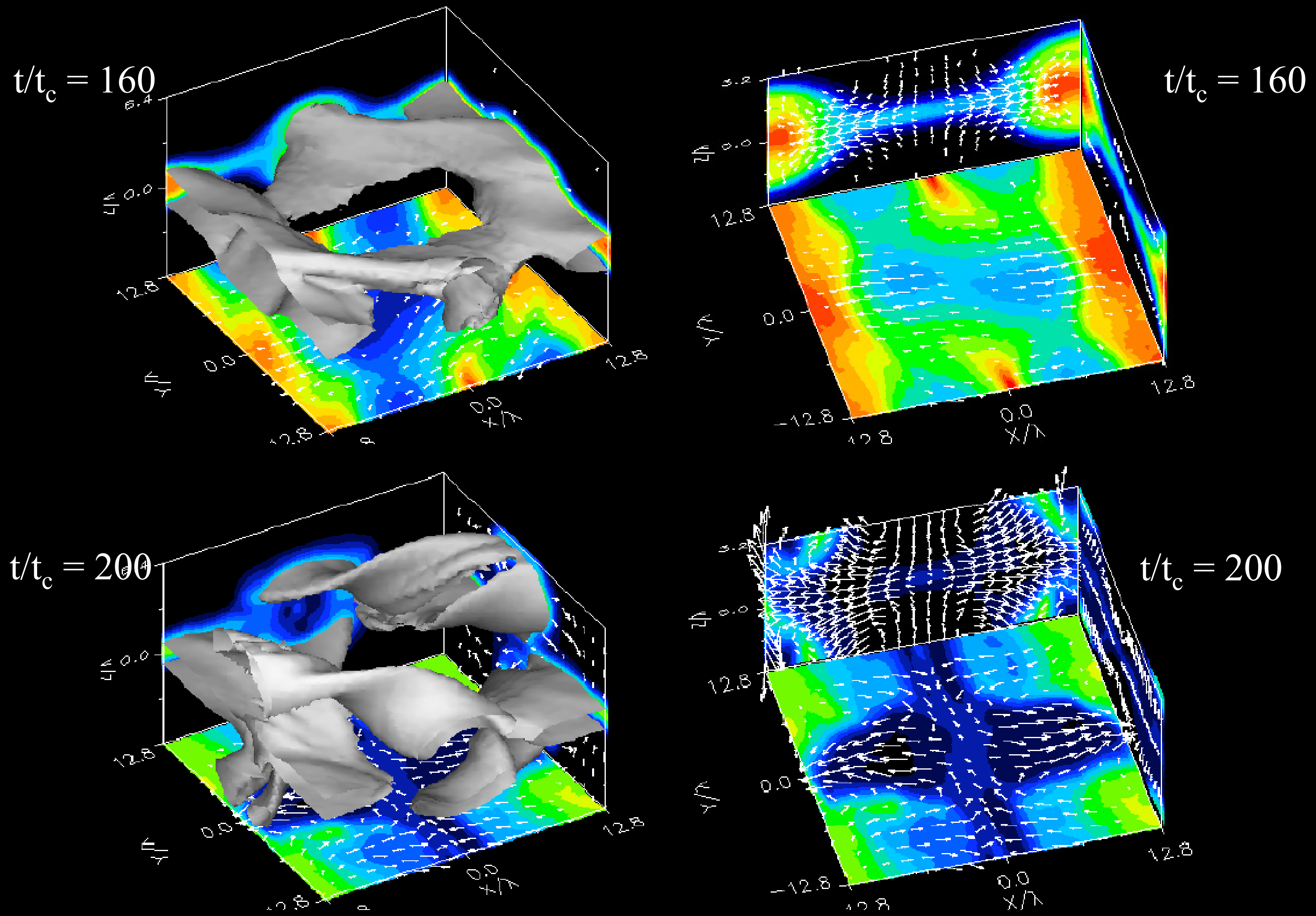
Faster Growth Rate

Slower Growth Rate



Drift-Kink is suppressed due to magnetic tension force

# 3D Reconnection with Guide Field

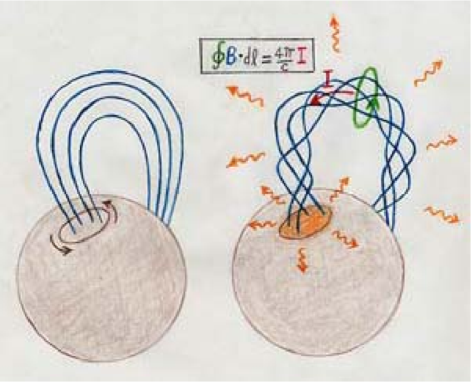


Zenitani & MH, PRL 2005

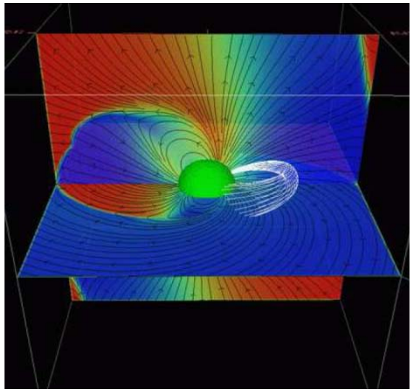
# Radiation-Dominated Relativistic Reconnection

- synchrotron cooling in strong B

$$\frac{\tau_{loss}}{\tau_{dyn}} \approx \left(\frac{10^2}{\tau_{dyn}\Omega_c}\right)\left(\frac{10^{12}\,G}{B}\right)\left(\frac{10}{E/mc^2}\right)^2$$


magnetar

Duncan & Thompson


pulsar

Spitkovsky (2006)

# Radiation Loss Effect in PIC Simulation Code

## Abraham-Lorentz Formula for Radiation Drag Force

$$mc\,\frac{du^i}{ds} = \frac{e}{c}F^{ik}u_k + g^i$$ (Dirac Form)

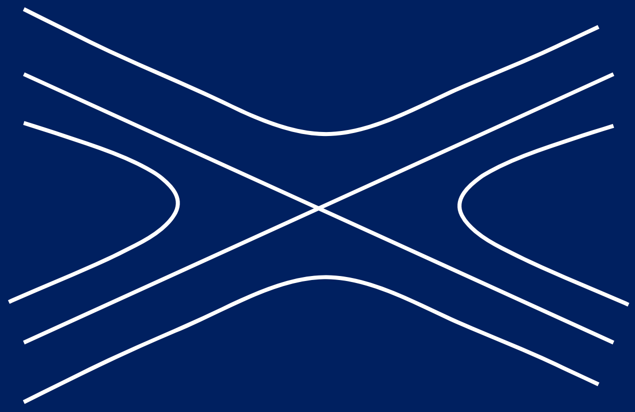
$$\begin{aligned} g^i &= \frac{2e^2}{3c}\left(\frac{d^2\,u^i}{ds^2} + u^i\frac{d\,u^k}{ds}\frac{d\,u_k}{ds}\right) \\ &= \frac{2e^3}{3mc^3}\frac{\partial F^{ik}}{\partial x^l}u_k u^l \quad - \quad \frac{2e^4}{3m^2c^5}F^{ik}F_{lk}u^l \quad + \quad u^i\cdot\frac{2e^4}{3m^2c^5}(F^{kl}u_l)(F_{km}u^m) \end{aligned}$$

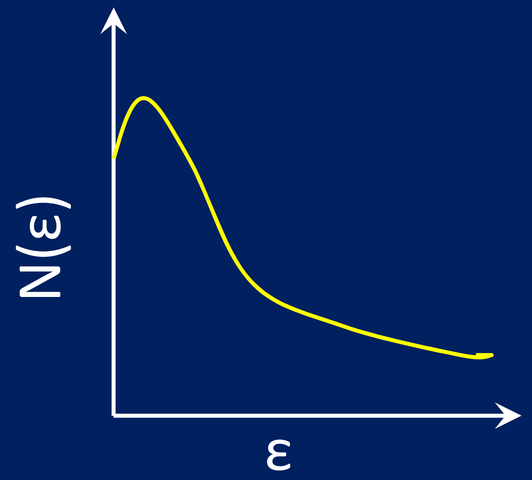
$$\alpha \equiv \omega_c\tau_0 = \frac{eB}{mc}\frac{e^2}{mc^3} << 1$$ $\tau_0$ : Light crossing time over classical electron radius

(cf. Noguchi & Liang 2006; Koga et al. 2007)

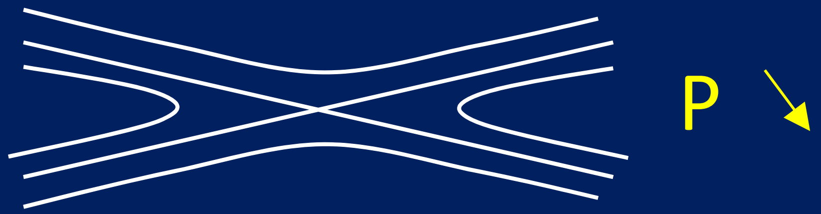
# Synchrotron Radiation Effect

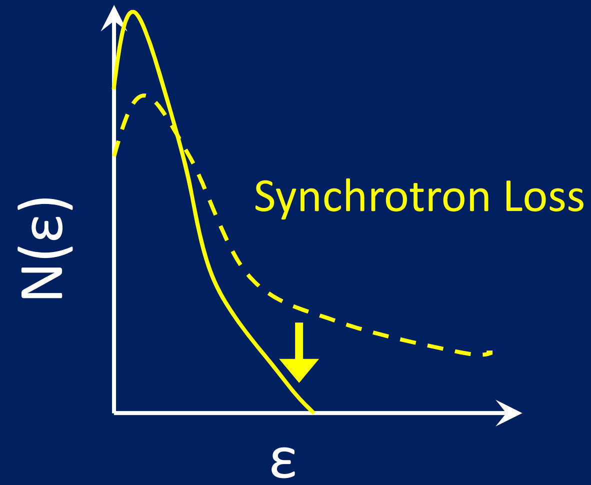
Without radiation loss





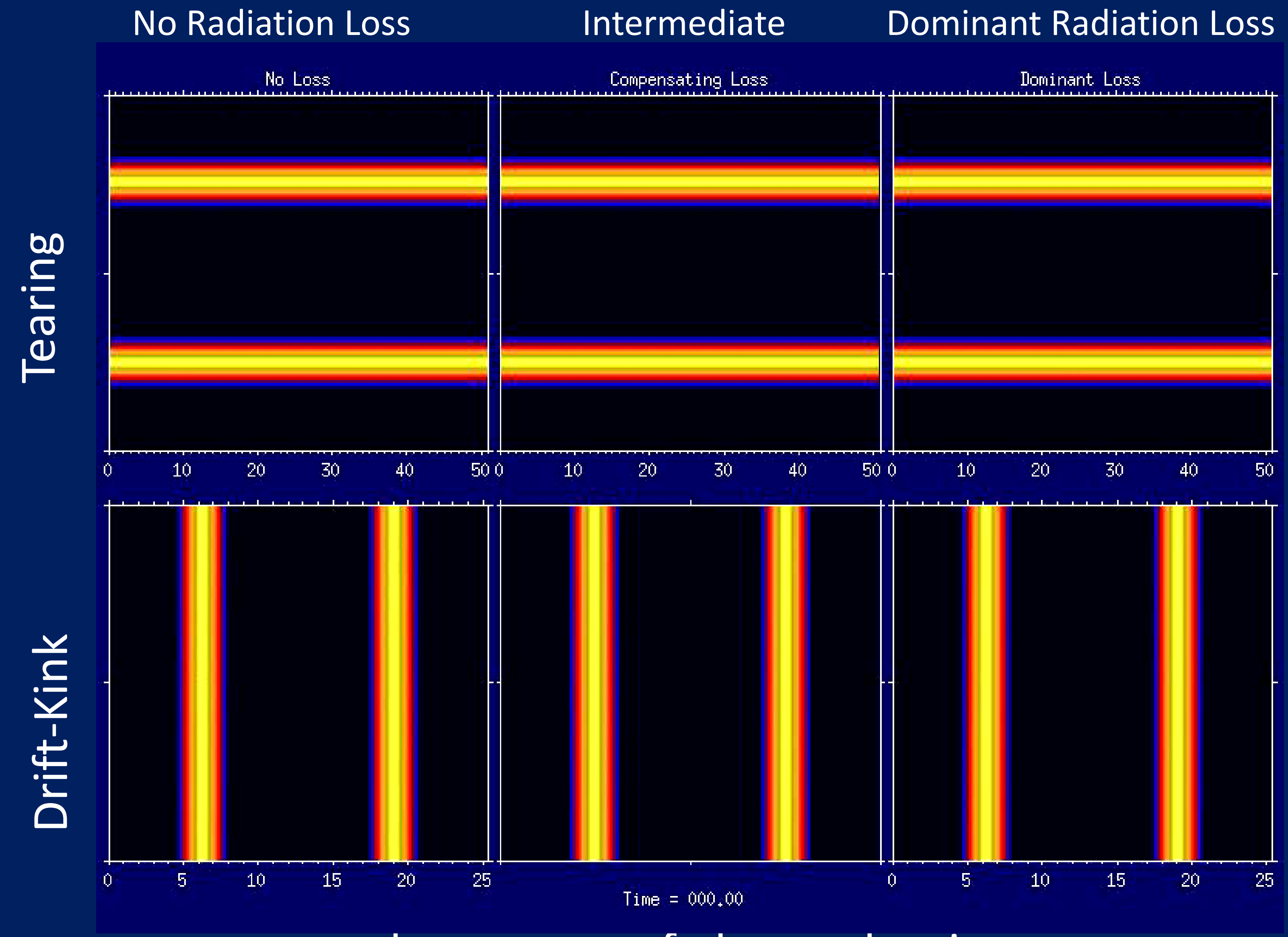
With radiation loss





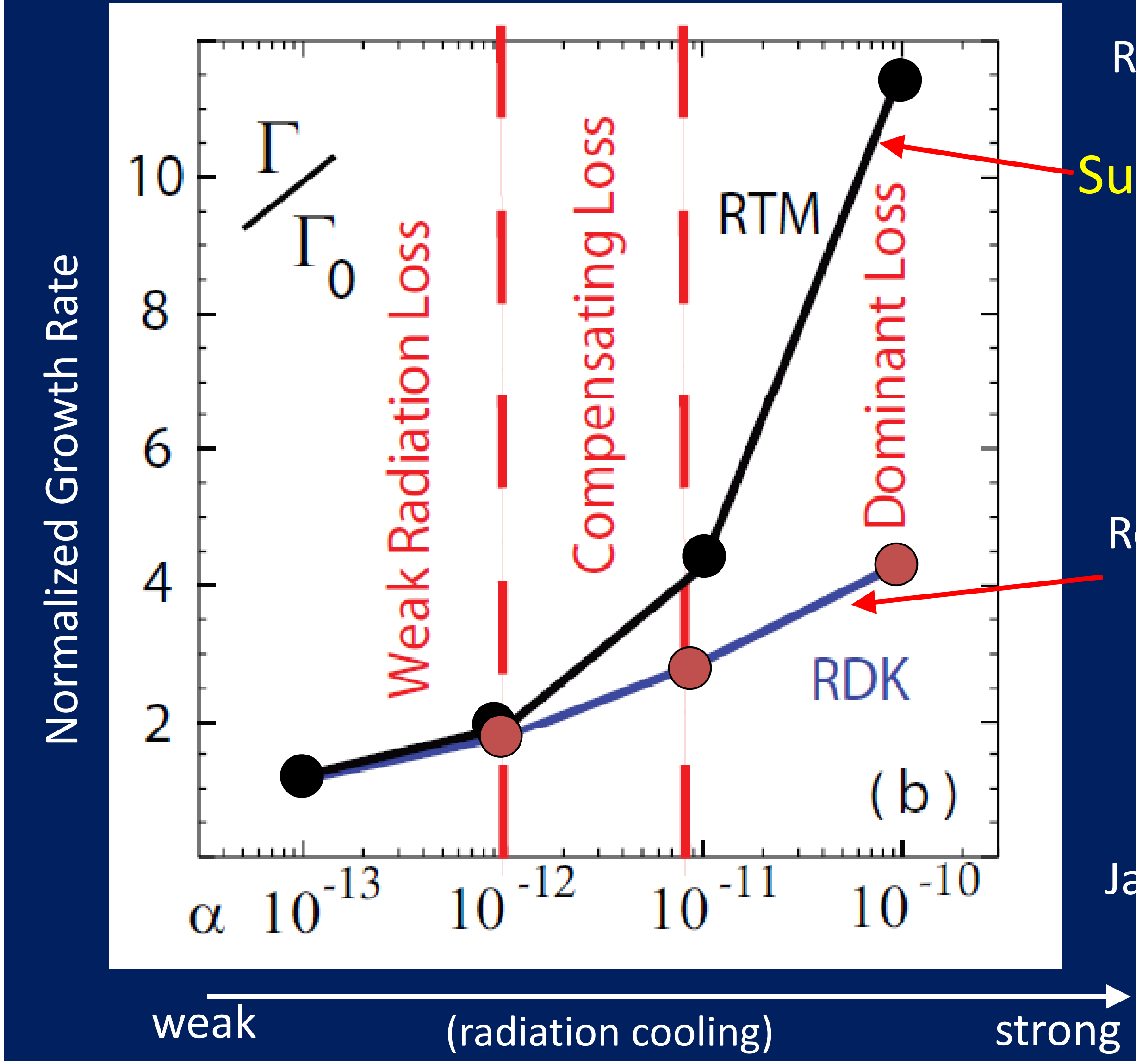
Fast Reconnection

# Time Evolution of MR & DKI



color contour of plasma density

# Comparison of Growth Rate



Relativistic Tearing Mode

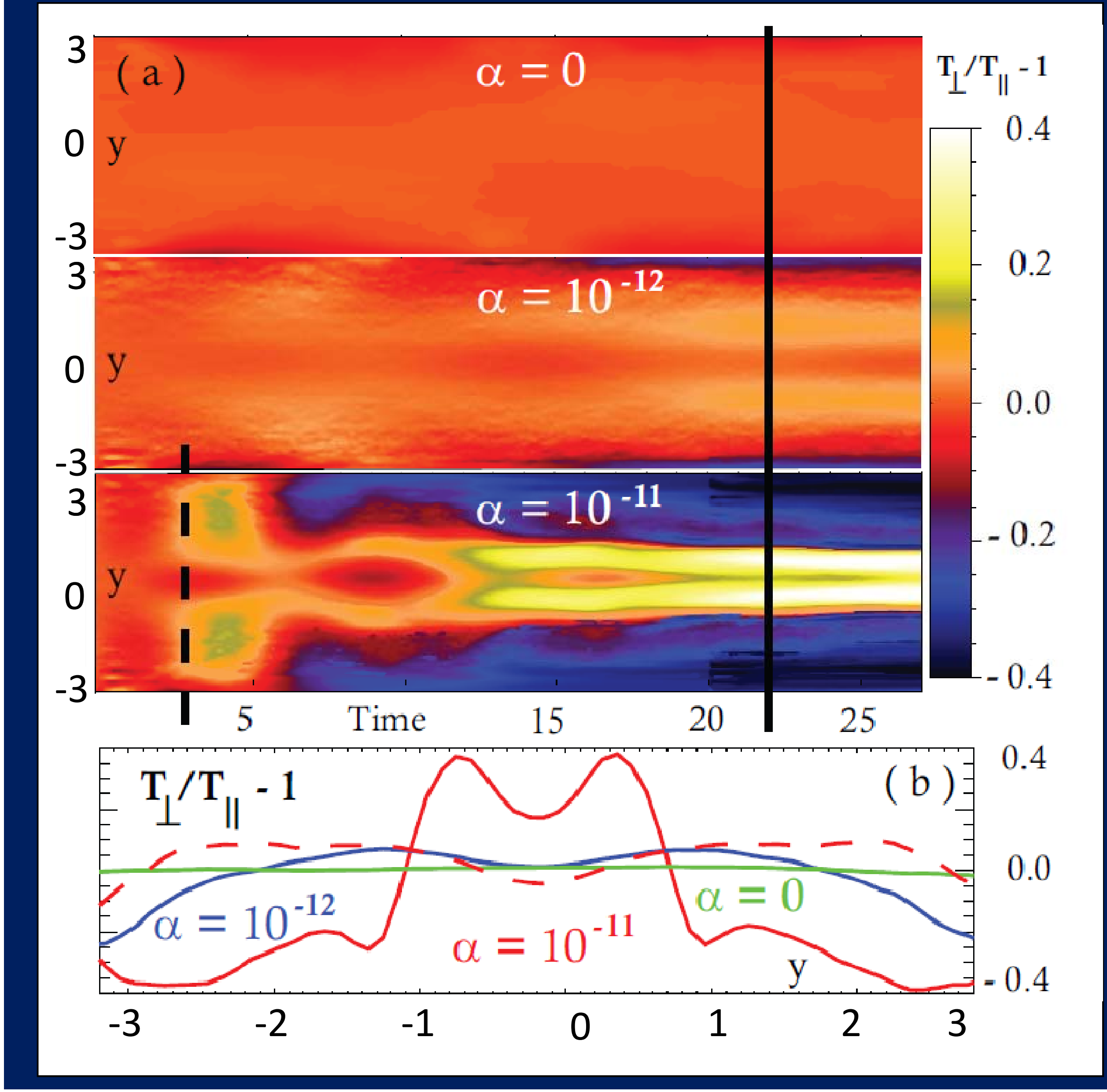
Super-Fast Reconnection

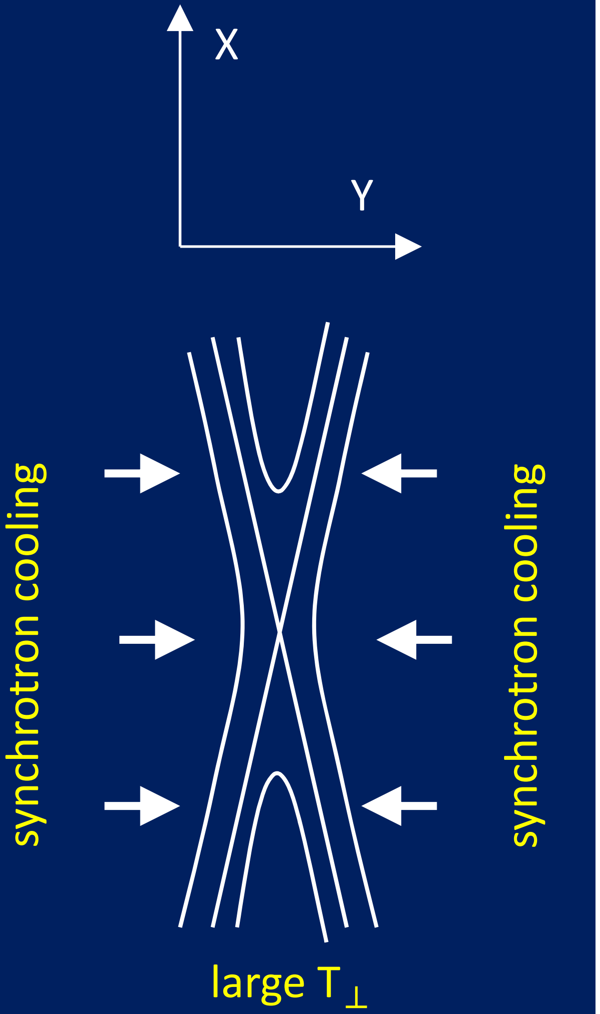
$T_{\perp} > T_{//}$

Relativistic Drift-Kind Mode

Jaroschek & MH, PRL, 2009

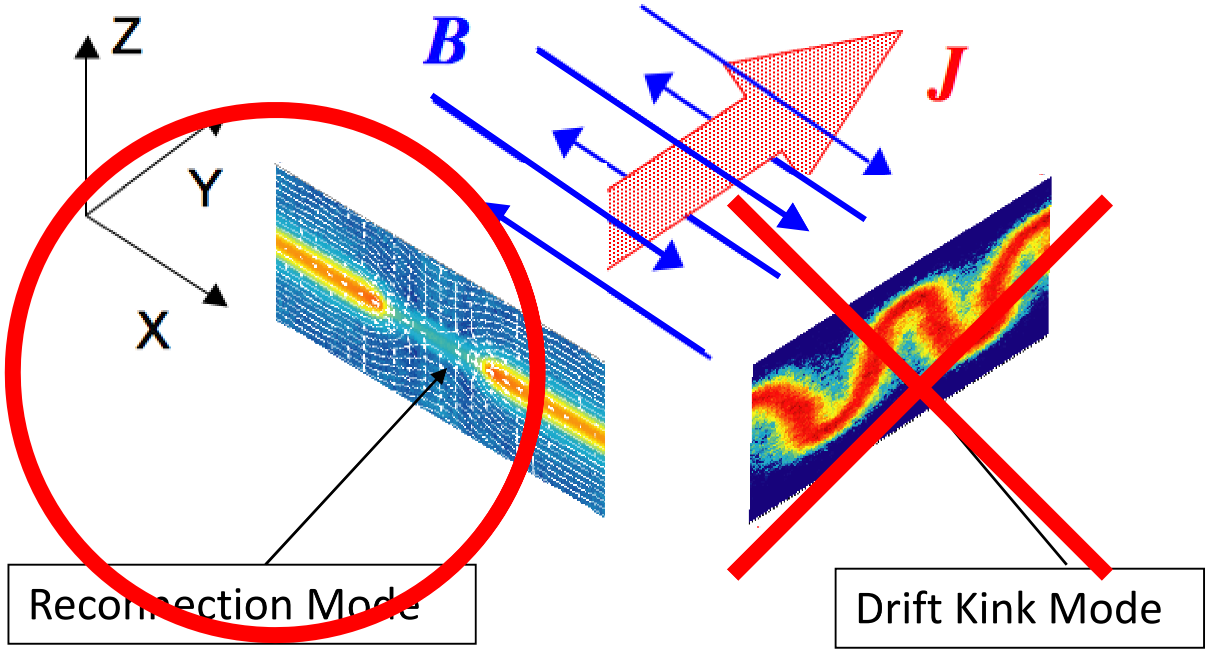
# Temperature Anisotropy (Early Stage)





# Relativistic Current Sheet Instabilities

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



Reconnection Mode

Faster Growth Rate

Drift Kink Mode

Fast Growth Rate

# Summary (Part 2)

1. Relativistic Reconnection vs Drfit-Kink Instability:
   Reconnection (MRX) -> non-thermal particle
   Drift-Kink (DK) -> thermal plasma

2. Guide Magnetic Field:
   growth rate of MRX > DK with guide field
   growth rate of MRX < DK without guide field

3. Radiation-Dominated Reconnection:
   super-fast dissipation,
   growth rate of MRX > DK,
   transition to Sweet-Parker type reconnection