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Particle Acceleration in Turbulent Magnetic Reconnection

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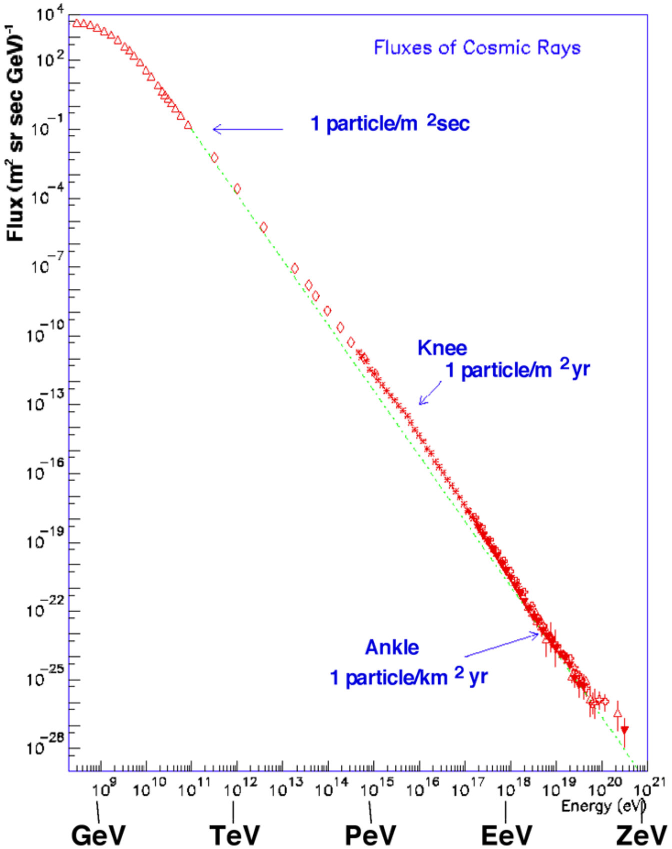
University of Tokyo

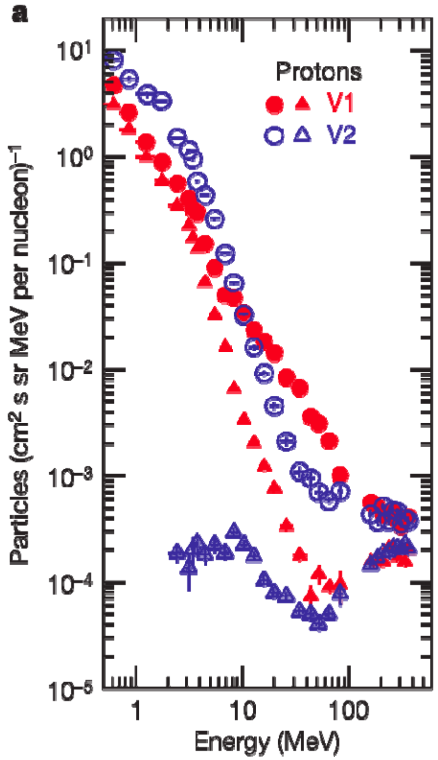
Nonthermal Universe

Cosmic Rays



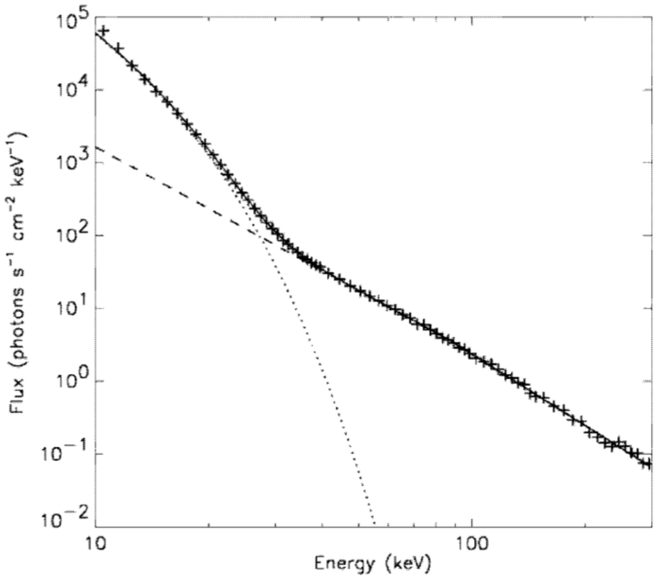
[Nagano & Watson, 2000]

ACRs



[Stone et al., 2008]

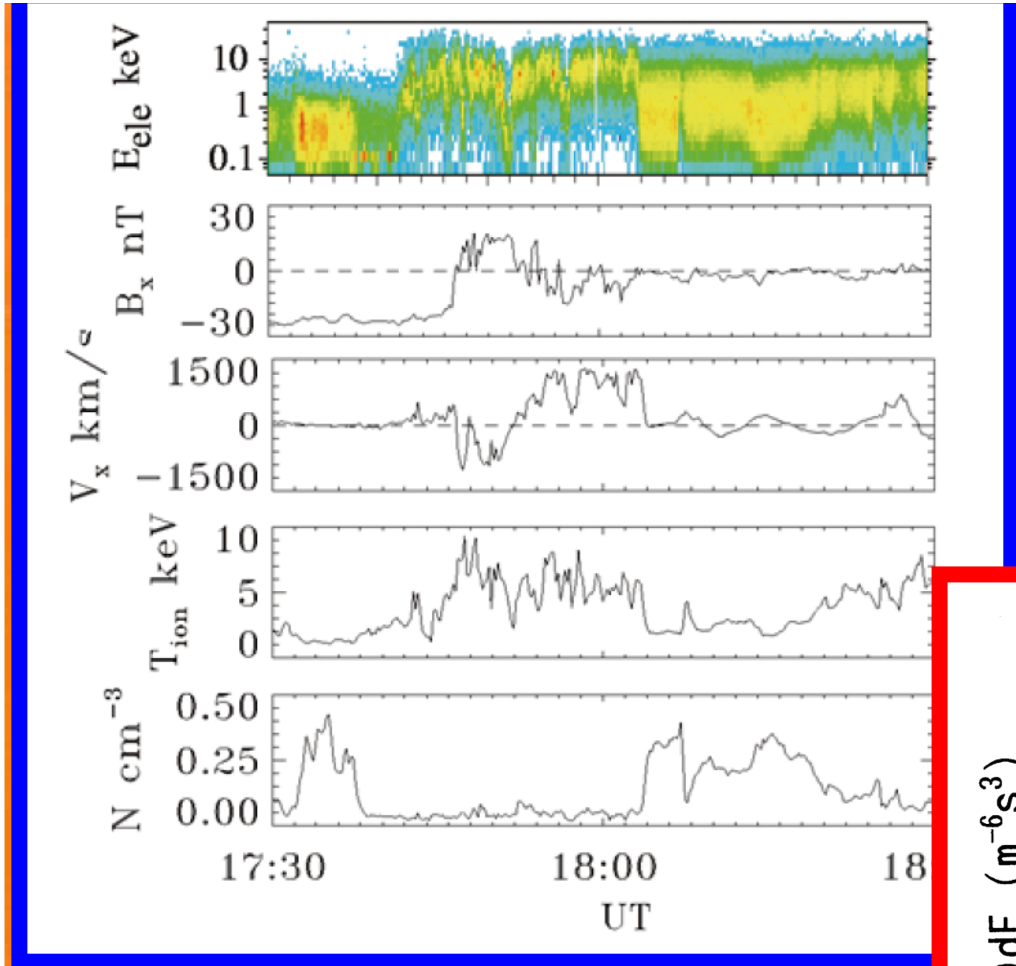
Solar Flares

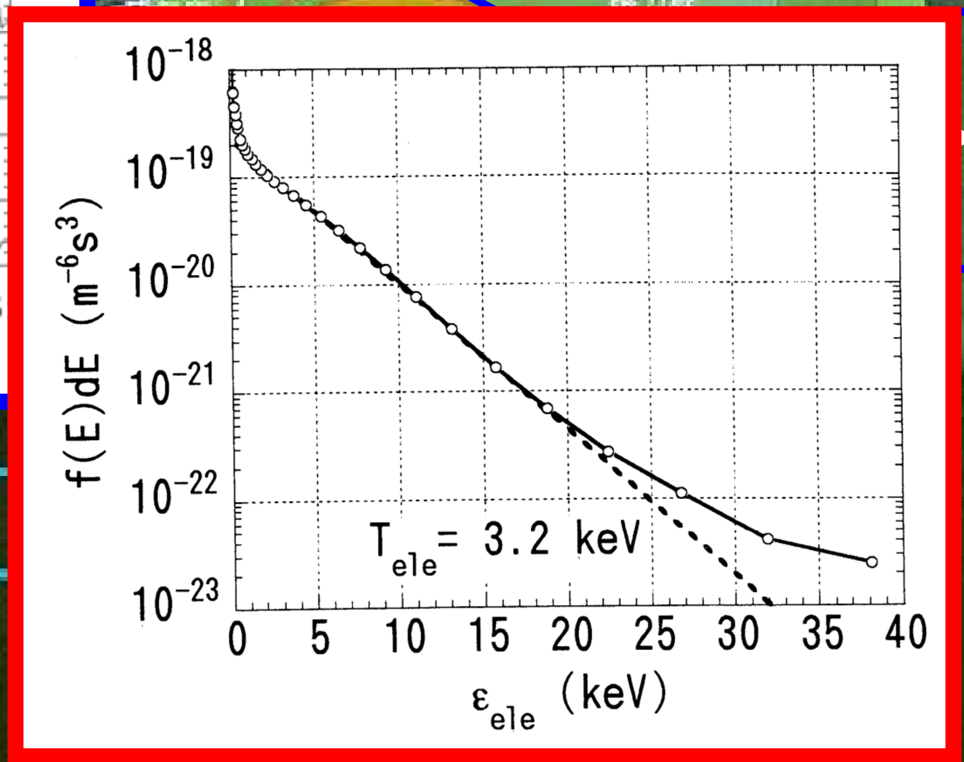


[Lin et al., 2003]

Magnetic reconnection plays an important role on particle acceleration in our universe?

Geotail Observation

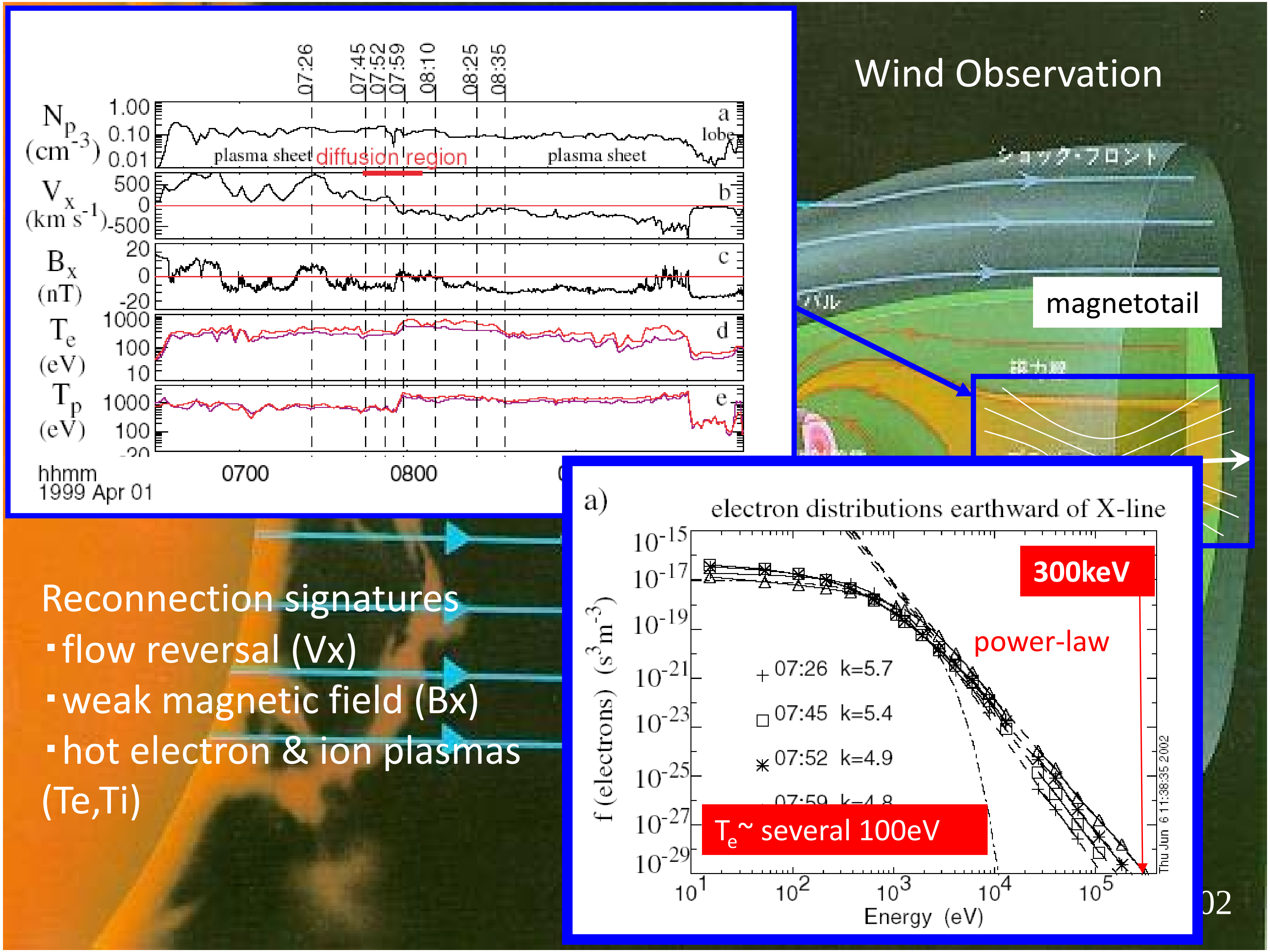




Reconnection signatures

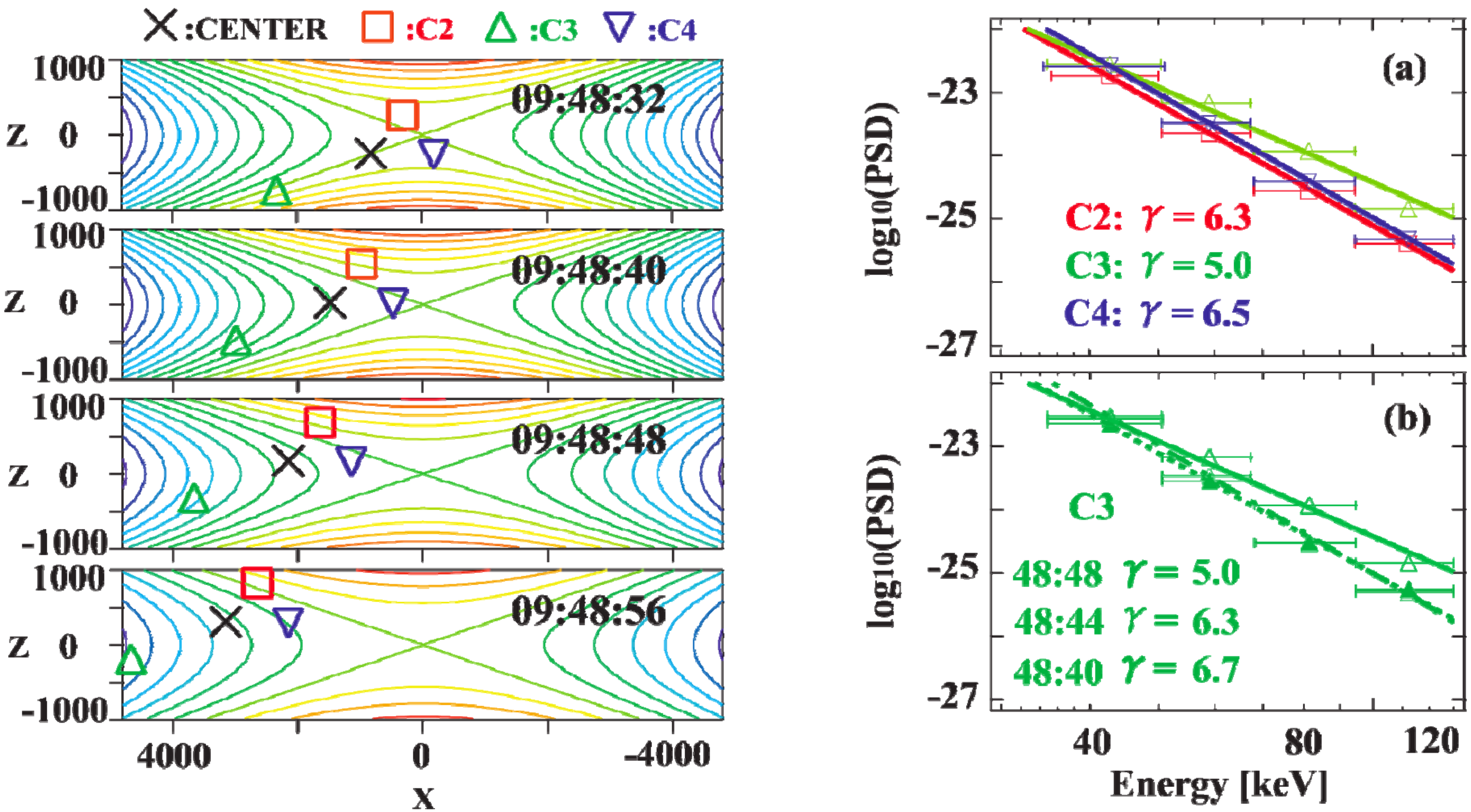
- flow reversal (Vx)
- weak magnetic field (Bx)
- hot & high speed plasma

MH+ 2001



Wind Observation
07:26
07:45
07:52
07:59
08:10
08:25
08:35
N_p (cm^{-3})
1.00
0.10
0.01
a
lobe
plasma sheet
diffusion region
plasma sheet
V_x ($km\ s^{-1}$)
500
0
-500
b
B_x (nT)
20
0
-20
c
T_e (eV)
1000
100
10
d
T_p (eV)
1000
100
e
hhmm
1999 Apr 01
0700
0800
ショック・フロント
magnetotail
Reconnection signatures
・flow reversal (Vx)
・weak magnetic field (Bx)
・hot electron & ion plasmas (Te,Ti)
a)
electron distributions earthward of X-line
f (electrons) ($s^3 m^{-3}$)
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-23}
10^{-25}
10^{-27}
10^{-29}
300keV
power-law
07:26 k=5.7
07:45 k=5.4
07:52 k=4.9
07:59 k=4.8
T_e~ several 100eV
10^1
10^2
10^3
10^4
10^5
Energy (eV)
Thu Jun 6 11:38:35 2002

Energetic electrons in reconnection (Cluster observation with 4 satellites)

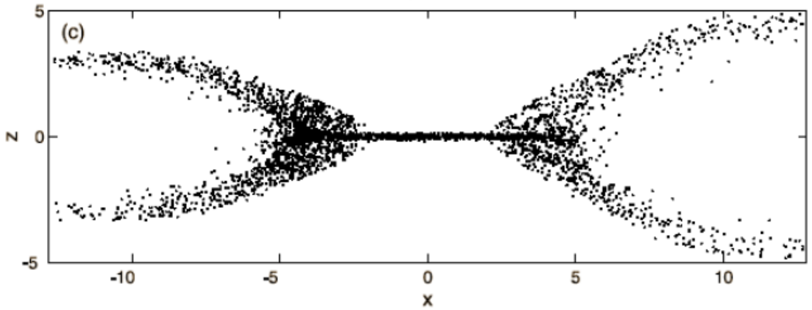


Four Cluster satellites found that energetic electrons are accelerated in the magnetic field pile-up region

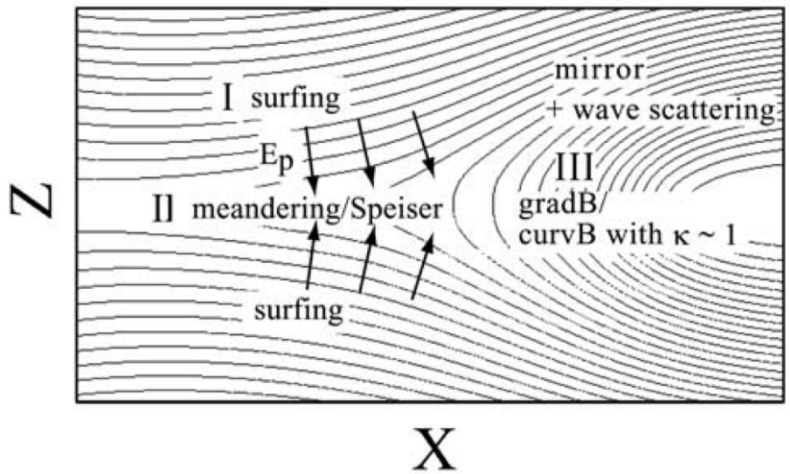
Imada et al. 2007

Particle Acceleration in PIC Simulations

Pritchett, 2005

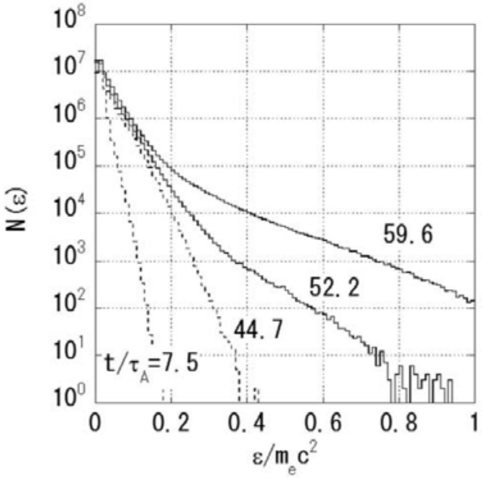


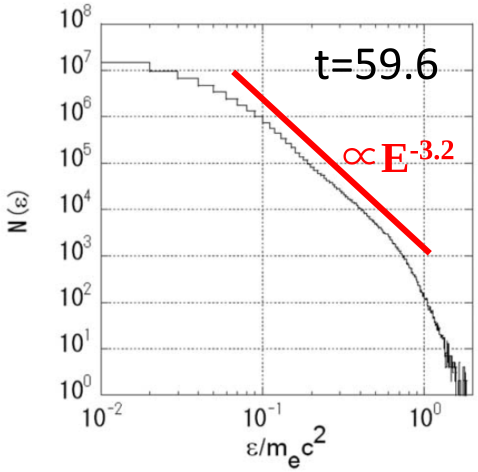
MH 2005



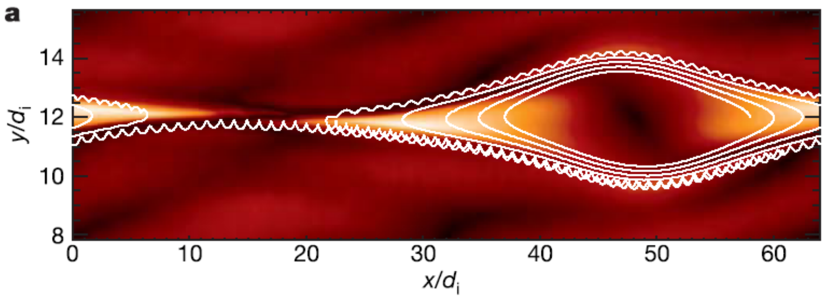
- Linear X-line acceleration
  - Direct resonance of particle with dawn-dusk electric field
  - Energetic particle flux is low because of the limited size of X-line

- Multistep Acceleration/B-file pileup region
  - In addition to X-line acceleration, gradB & curvB drift acceleration around the magnetic field pileup region
  - Energetic particle flux is high

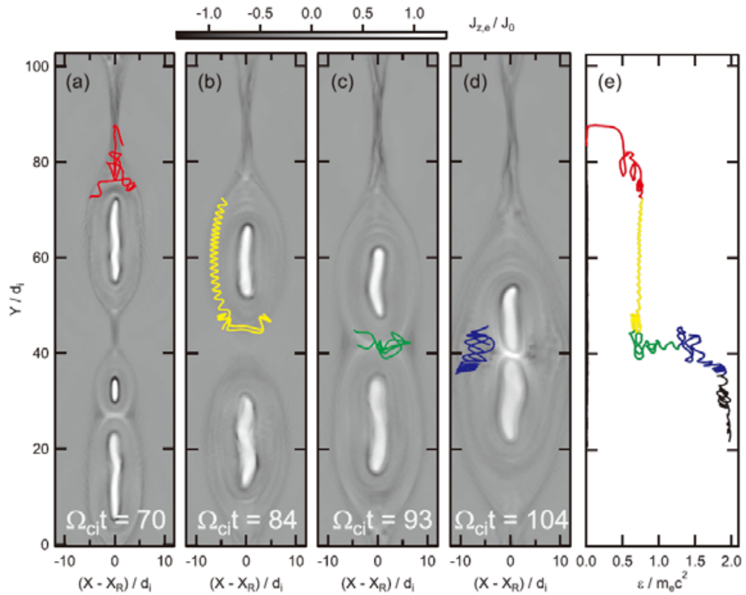




Drake et al. 2006



Oka et al. 2006

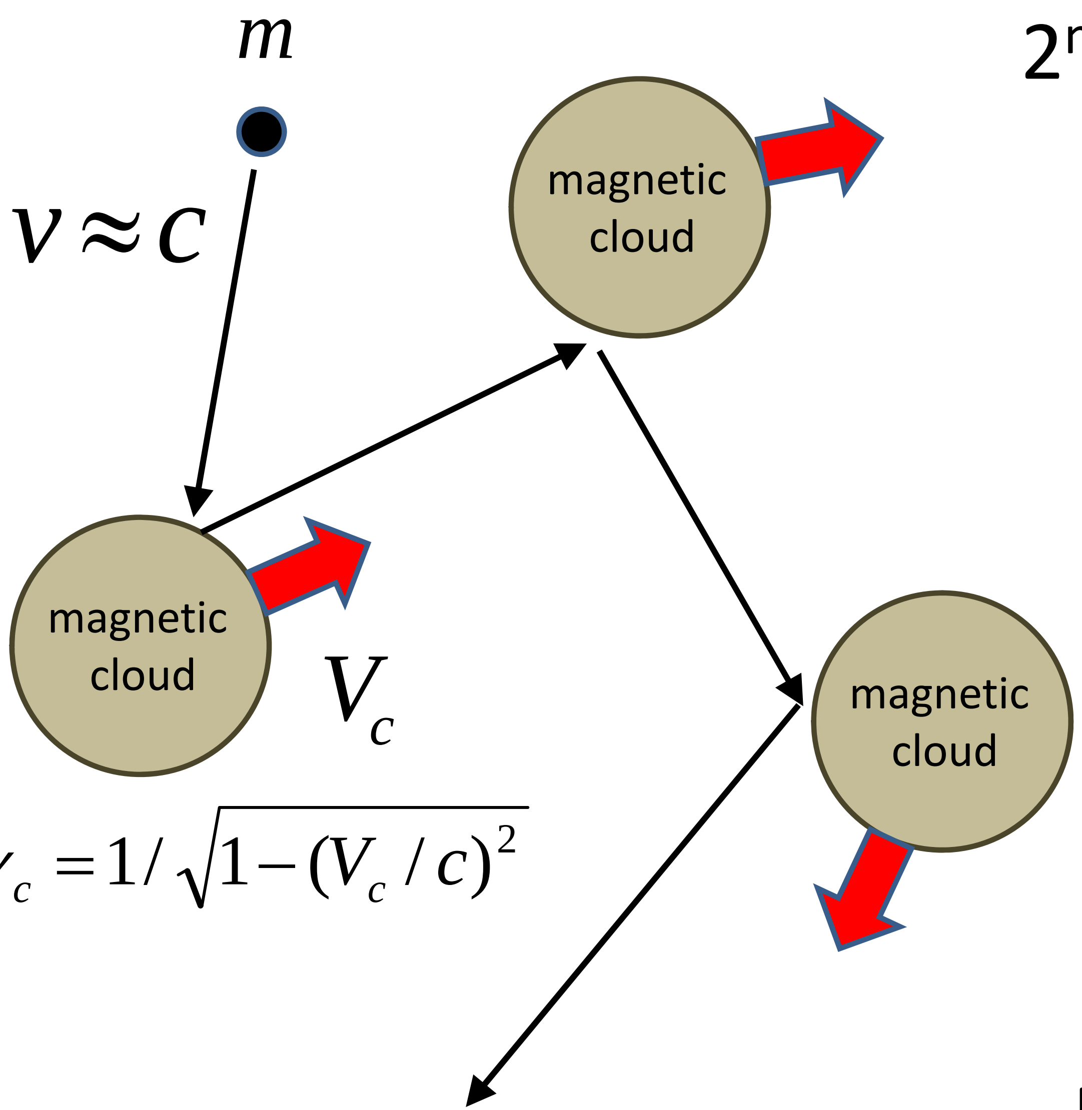


- Shrinking Island Acceleration
  - Acceleration for the trapped particles inside the magnetic island
- Coalescence Island
  - Similar to X-line acceleration
  - Acceleration efficiency is better than the X-line acceleration
  - Energetic particle flux is small because of the limited size of the coalescence region

Maximum attainable energy $E_{max} = eEL$

For higher energetic particles, larger acceleration region is required

Original Fermi Acceleration



$$V_c$$

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

2nd order Acceleration

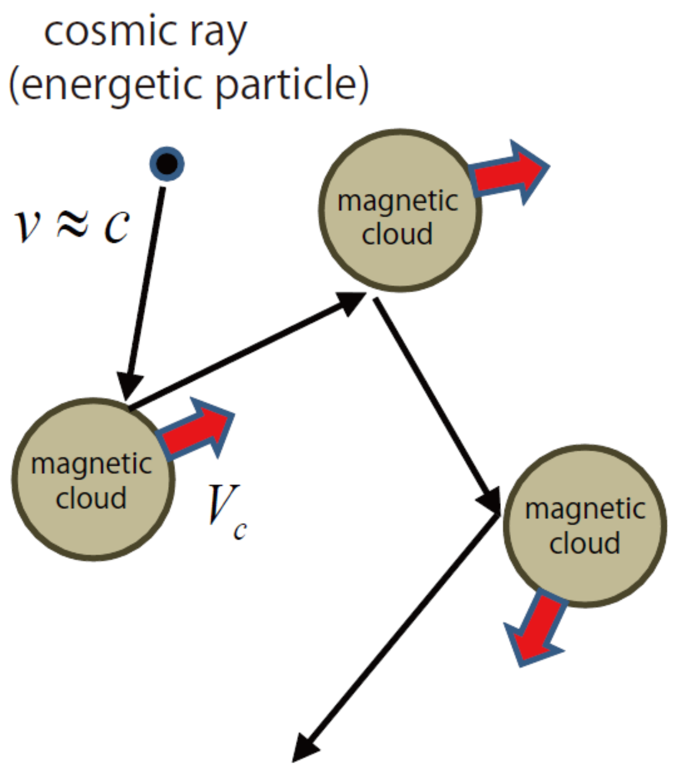
$$\frac{\Delta\varepsilon}{\varepsilon} = 4\gamma_c^2\left(\frac{V_c}{c}\right)^2$$

"Slow Acceleration"

Fermi, Phys. Rev. (1949)

Fermi-Reconnection Acceleration in Many Magnetic Islands

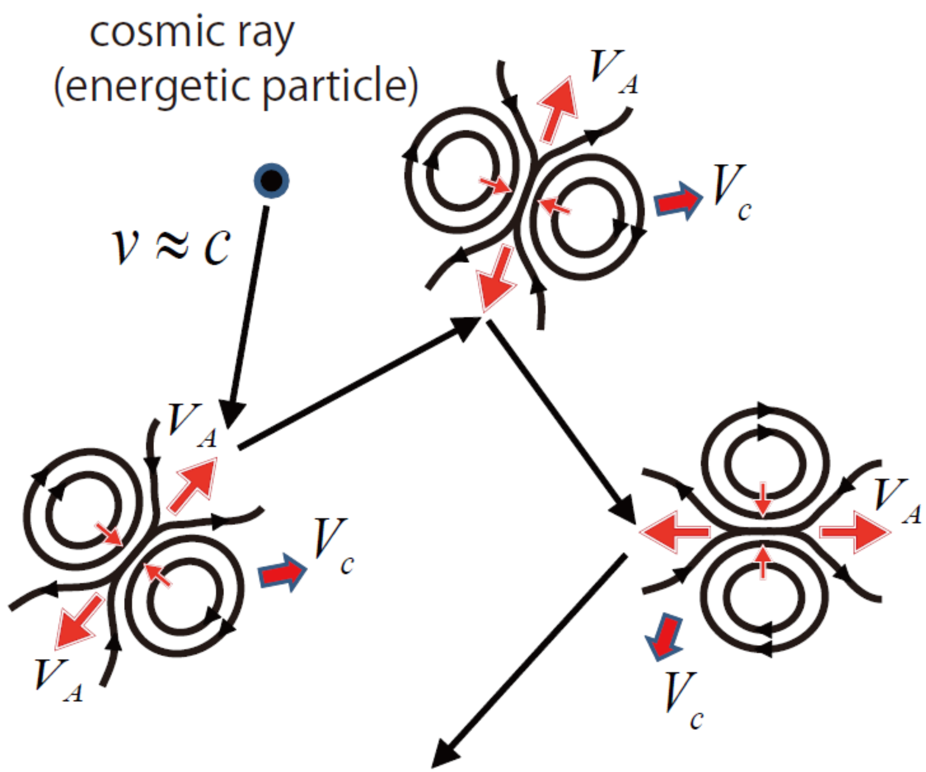
2nd order Acceleration



$$\frac{\Delta\varepsilon}{\varepsilon} \approx \left(\frac{V_c}{c}\right)^2$$

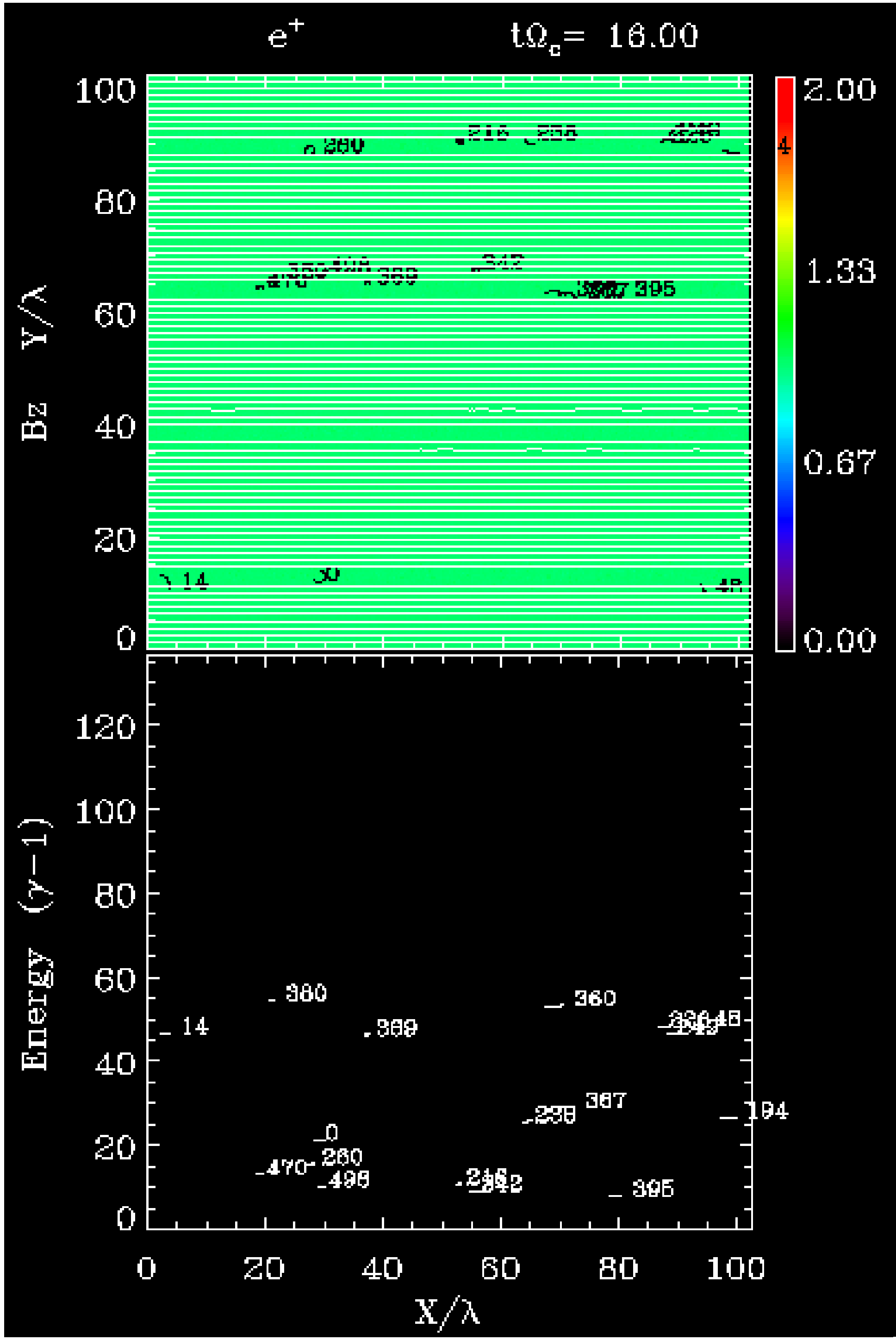
Fermi, Phys. Rev. (1949)

1st order Acceleration



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

MH PRL (2012)



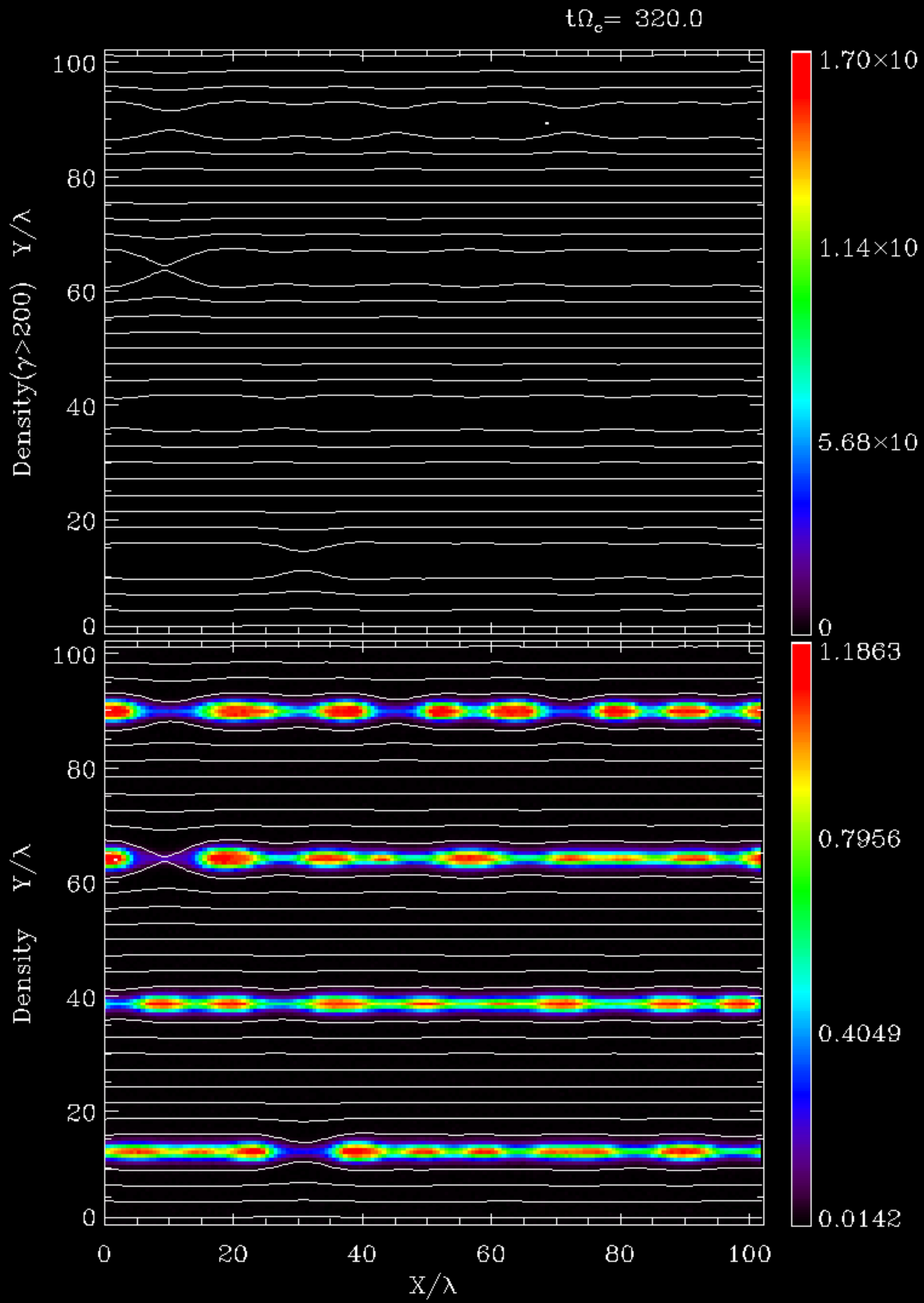
2D PIC Simulation

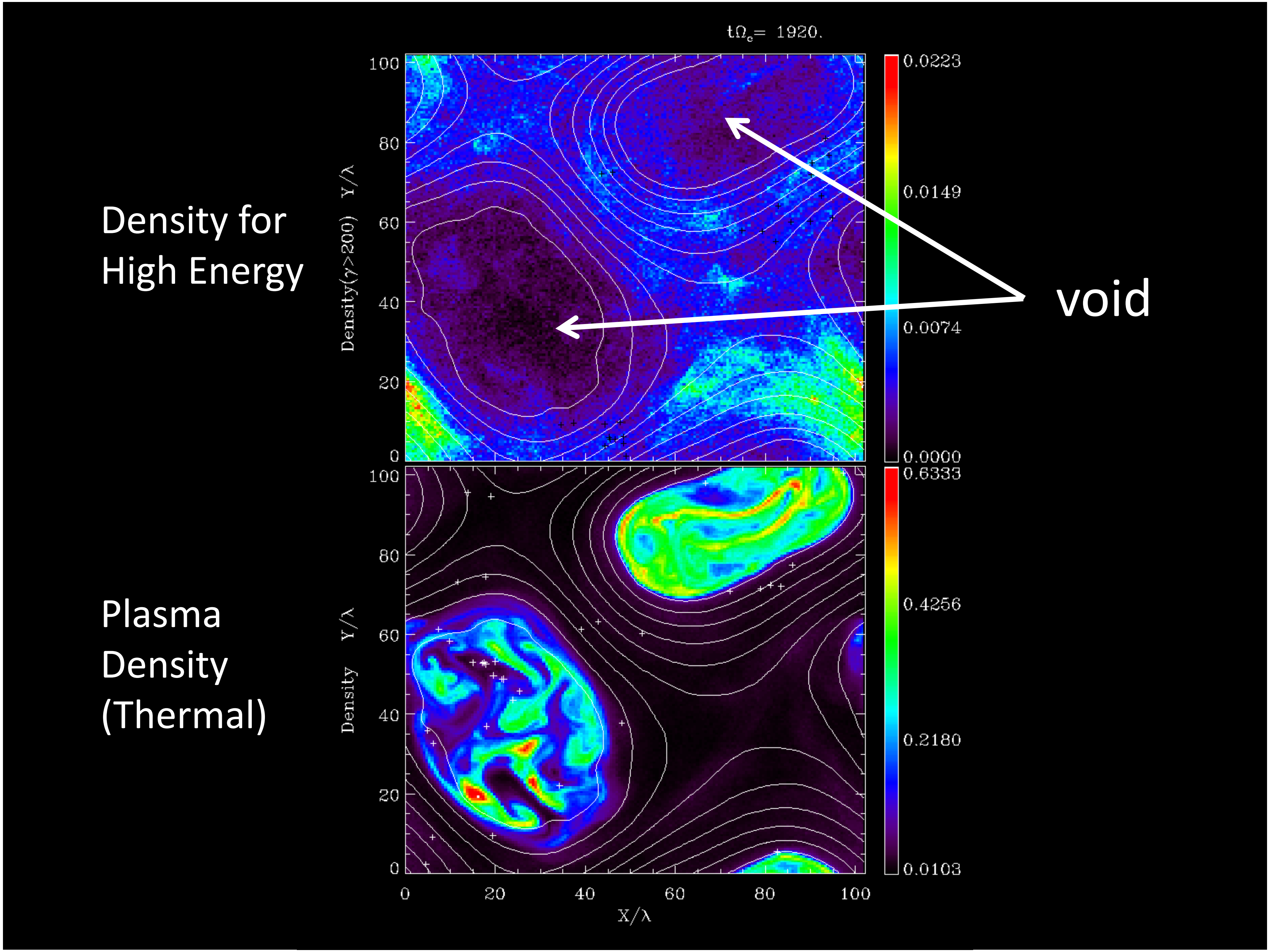
Particle Trajectories,
Magnetic Field Lines

Particle Energies

Density for High Energy

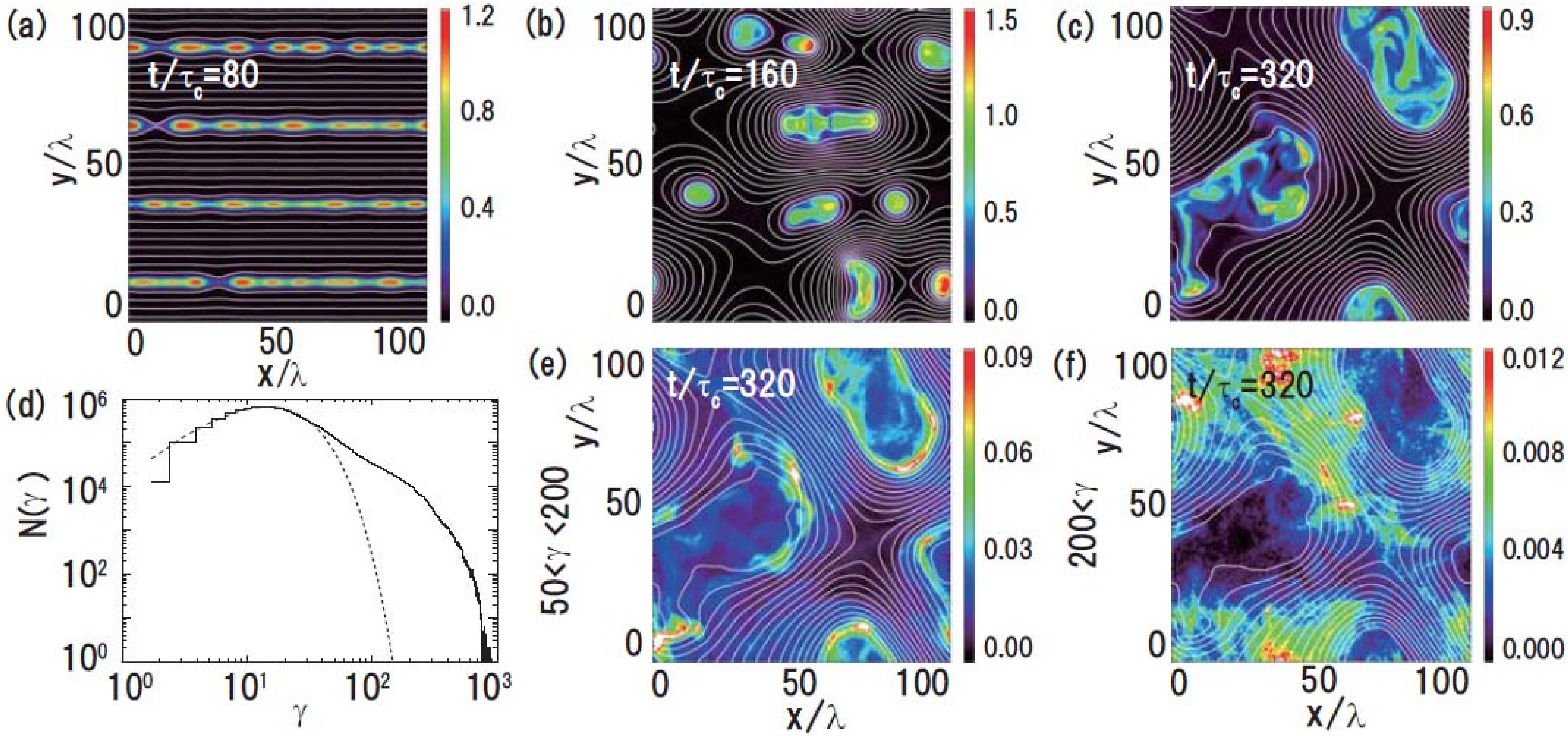
Plasma Density (Thermal)





Density for High Energy
Plasma Density (Thermal)
void
tΩc= 1920.
Density(γ>200) Y/λ
Density Y/λ
X/λ
0.0223
0.0149
0.0074
0.0000
0.6333
0.4256
0.2180
0.0103

Stochastic particle acceleration in multiple magnetic islands during reconnection

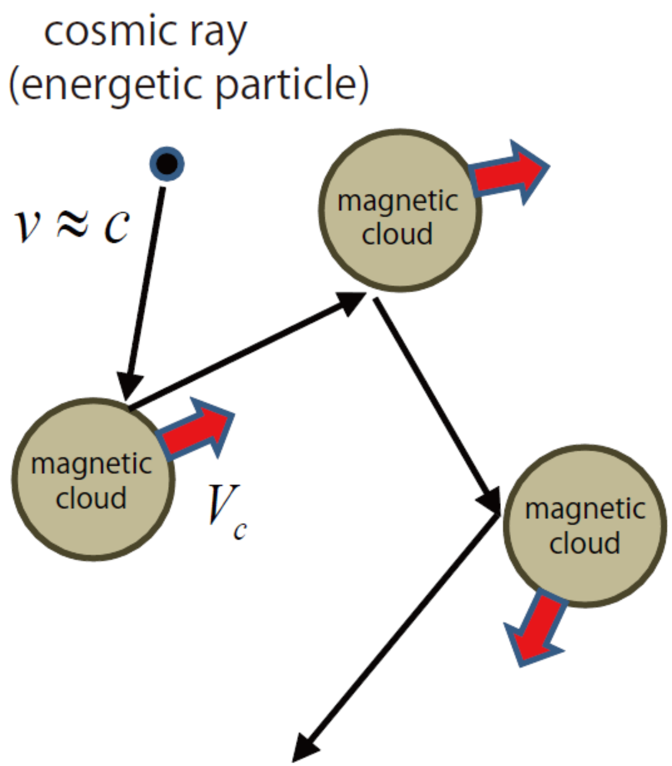


$$\frac{\gamma c}{\Omega_c \lambda} = 10 \text{ for } \gamma = 200$$

MH, PRL 2012

Fermi-Reconnection Acceleration in Many Magnetic Islands

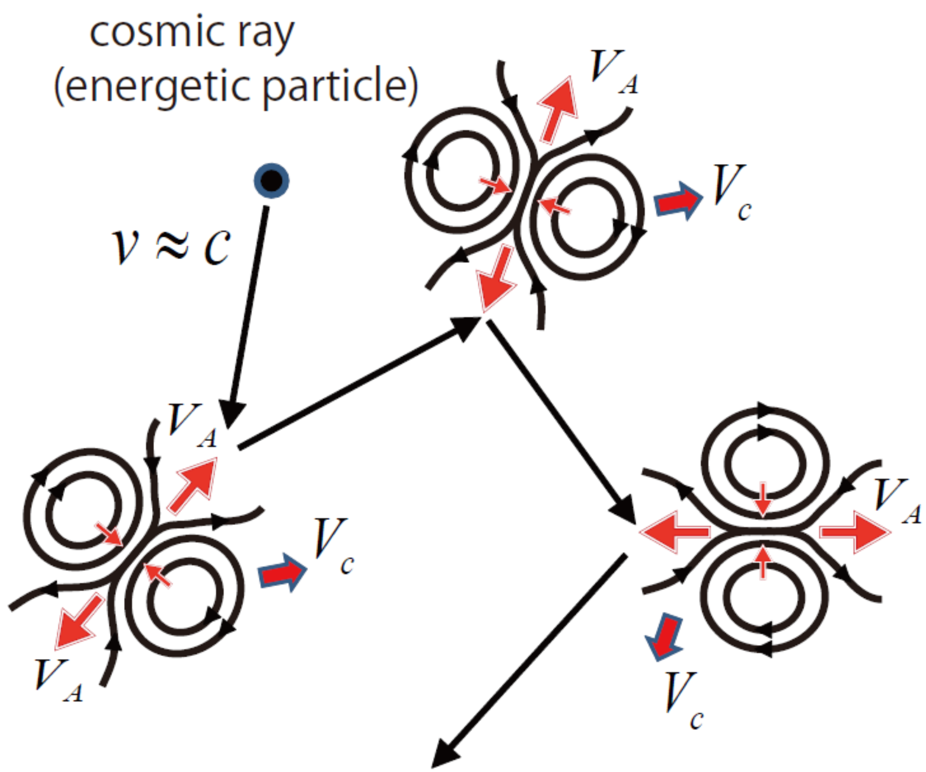
2nd order Acceleration



$$\frac{\Delta\varepsilon}{\varepsilon} \approx \left(\frac{V_c}{c}\right)^2$$

Fermi, Phys. Rev. (1949)

1st order Acceleration



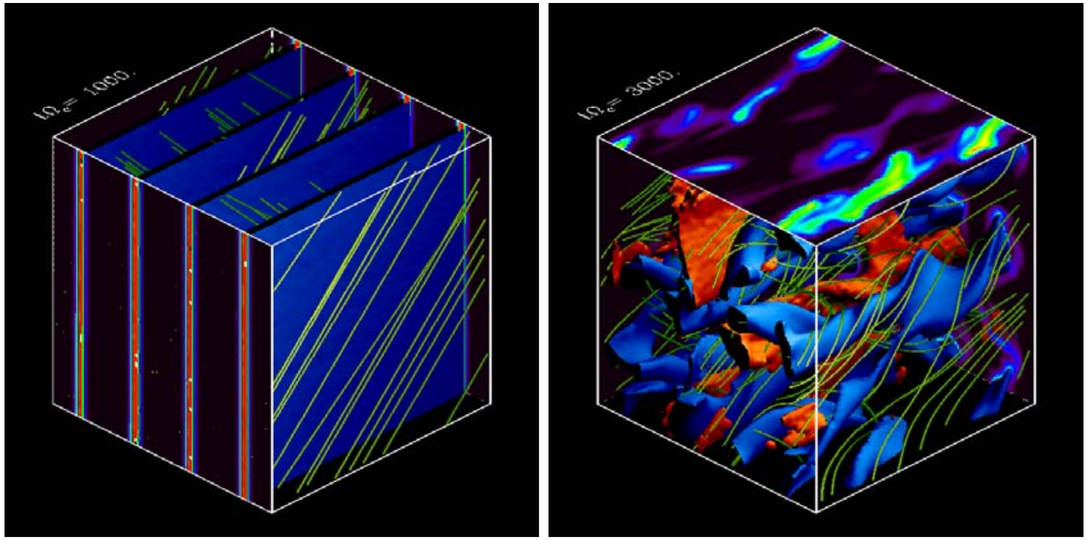
$$\frac{\Delta\varepsilon}{\varepsilon} \approx \left(\frac{V_A}{c}\right)$$

MH PRL (2012), MH & Lyubarsky SSR (2013)

3d multi-island acceleration

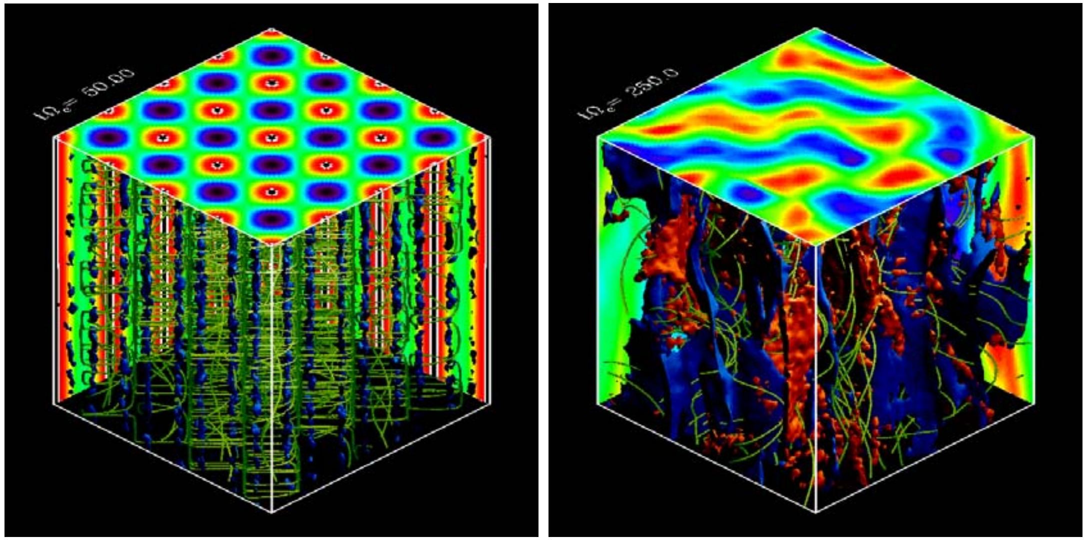
Model (A)
Harris Current Sheet
with guide field

$$\vec{B} \propto (1, 0, \tanh y)$$

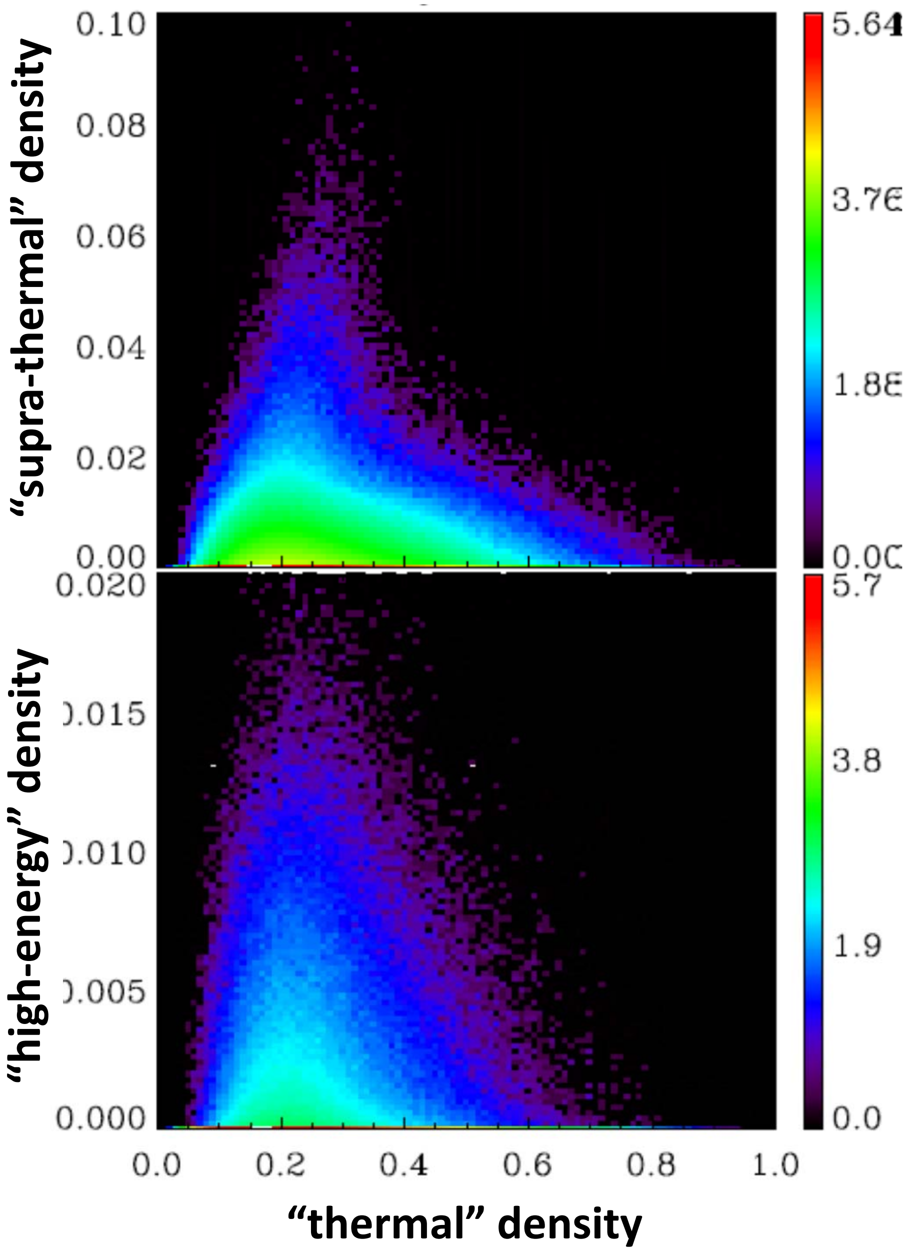


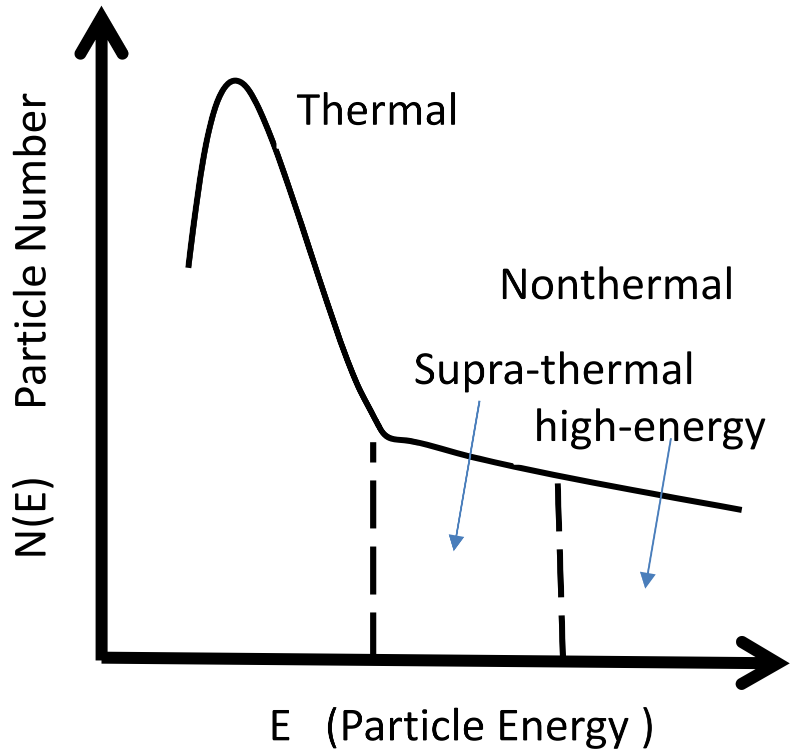
Model (B)
Force Free ABC-Type
Current Sheets

$$\vec{B} = (\sin y\,, -\sin x\,, \cos x + \cos y)$$

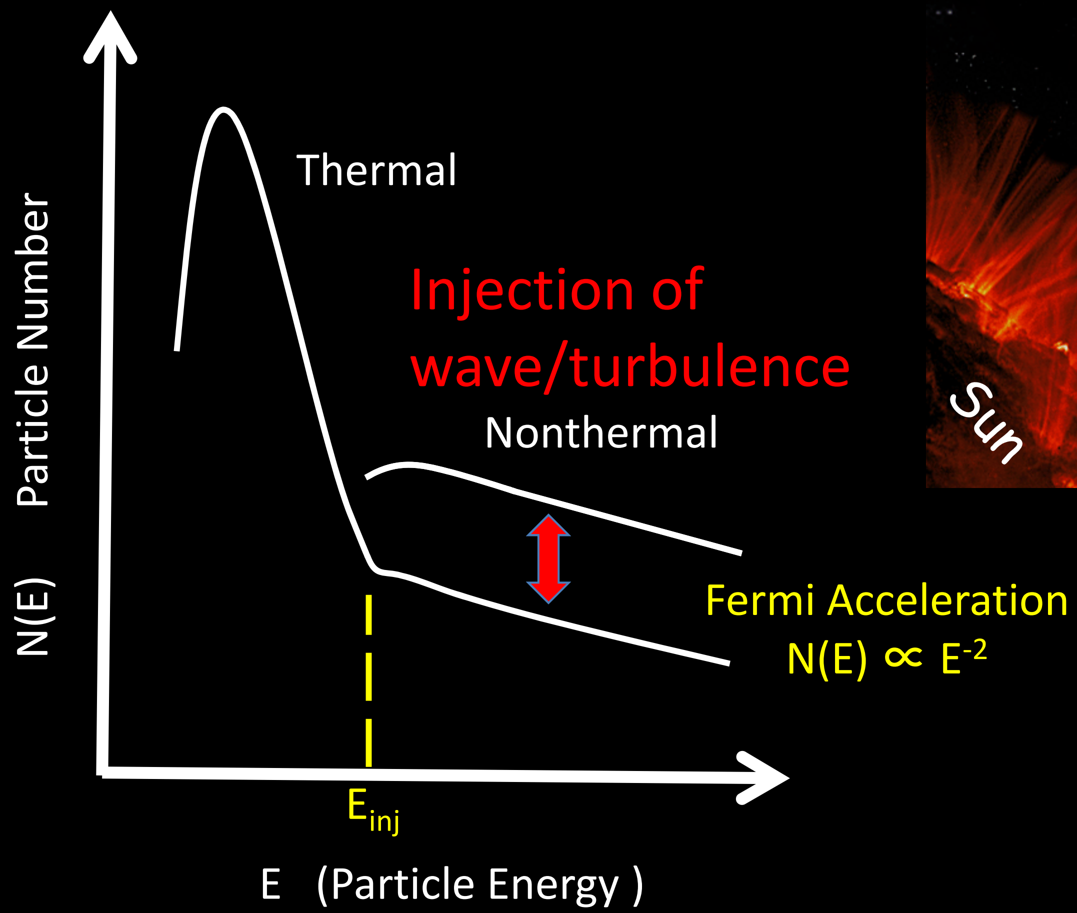


Energetic particles are distributed in low density region

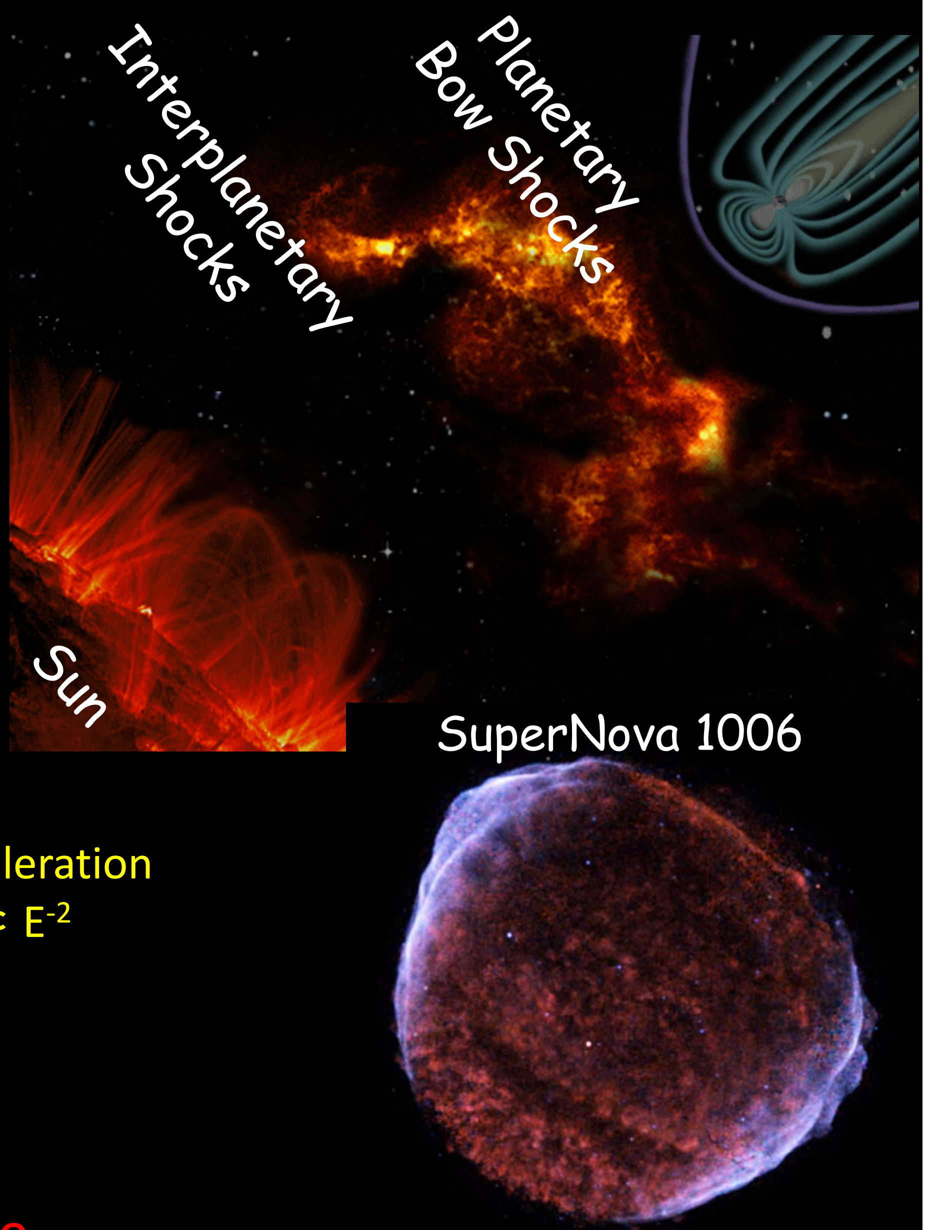




Reconnection in Shock Waves



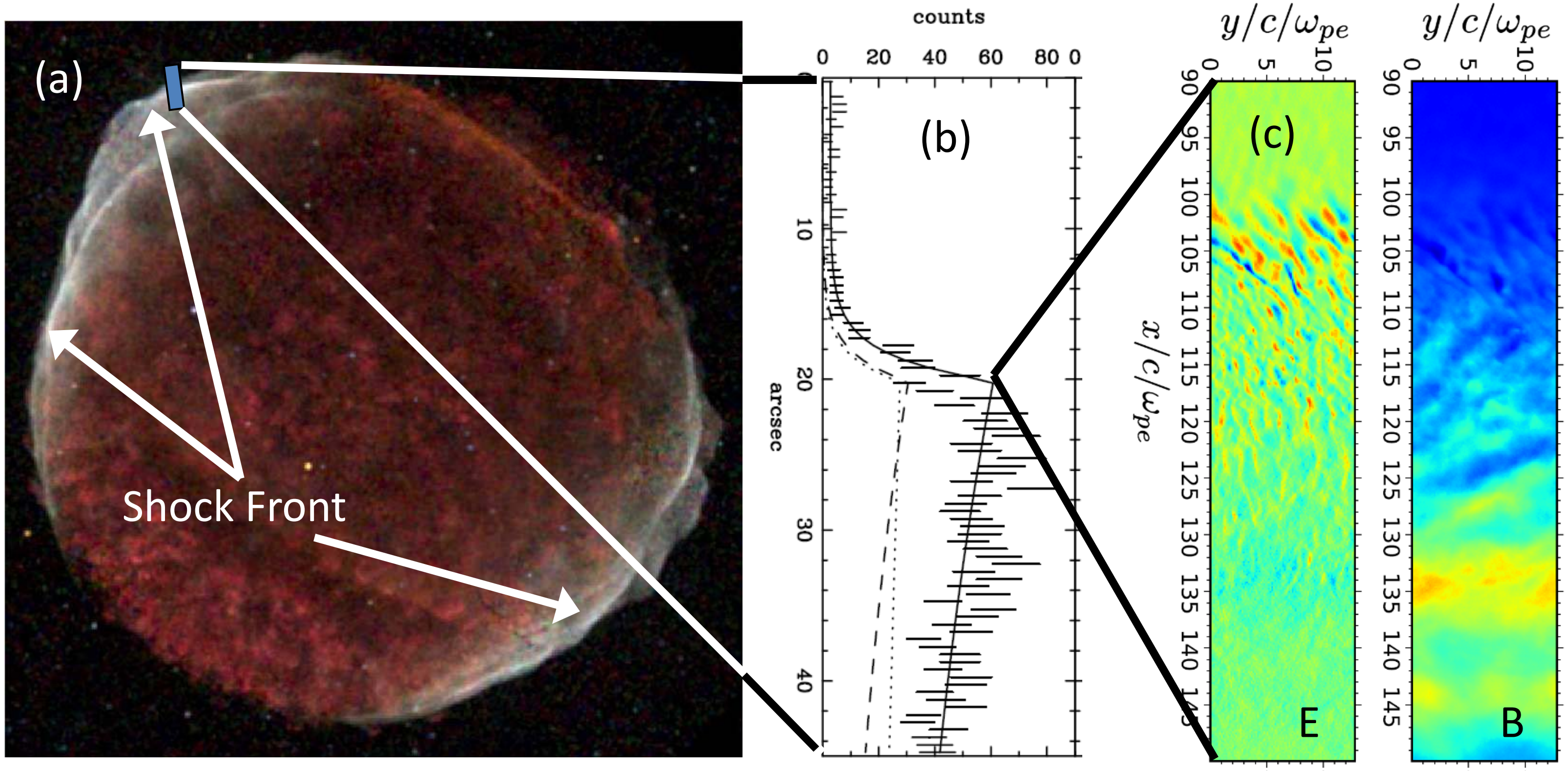
Injection of supra-thermal particle



Origin of Cosmic Rays

Multi-Scale Couplings in Supernova Shock

X-ray observations PIC simulation

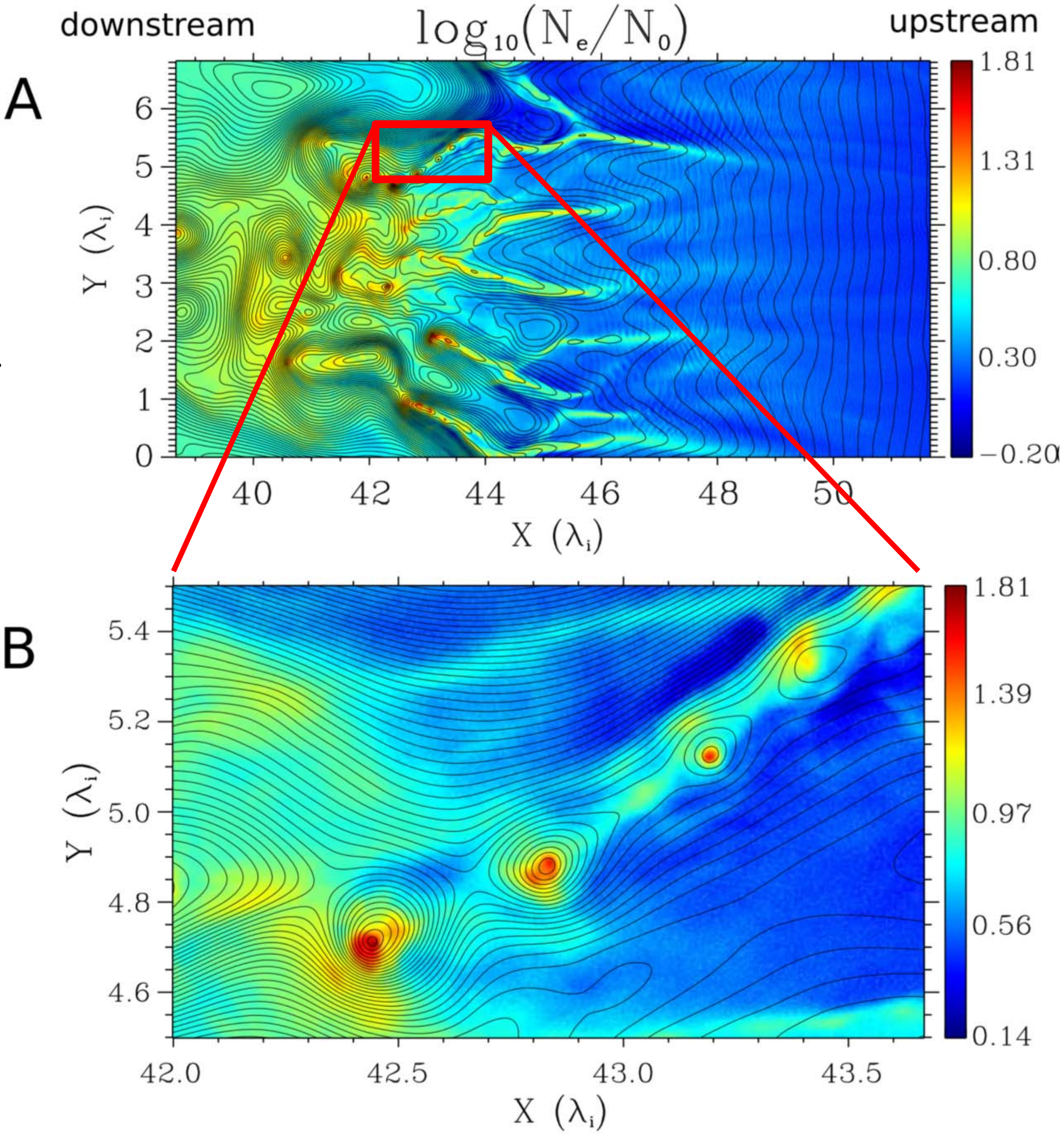


(a) SN1006, Supernova remnant and shock front region observed by X-ray satellite "Chandra", (b) photon count of X-ray near shock front/filament, (c) Turbulent structure near high Mach number shock studied by Particle-in-Cell simulation

e.g. Amano & MH, ApJ 2007

Magnetic Islands in Shock

M_A=42, m_i/m_e=225, ω_{pe}/ω_{ce}=10



fast flow

Ion reflection from shock front

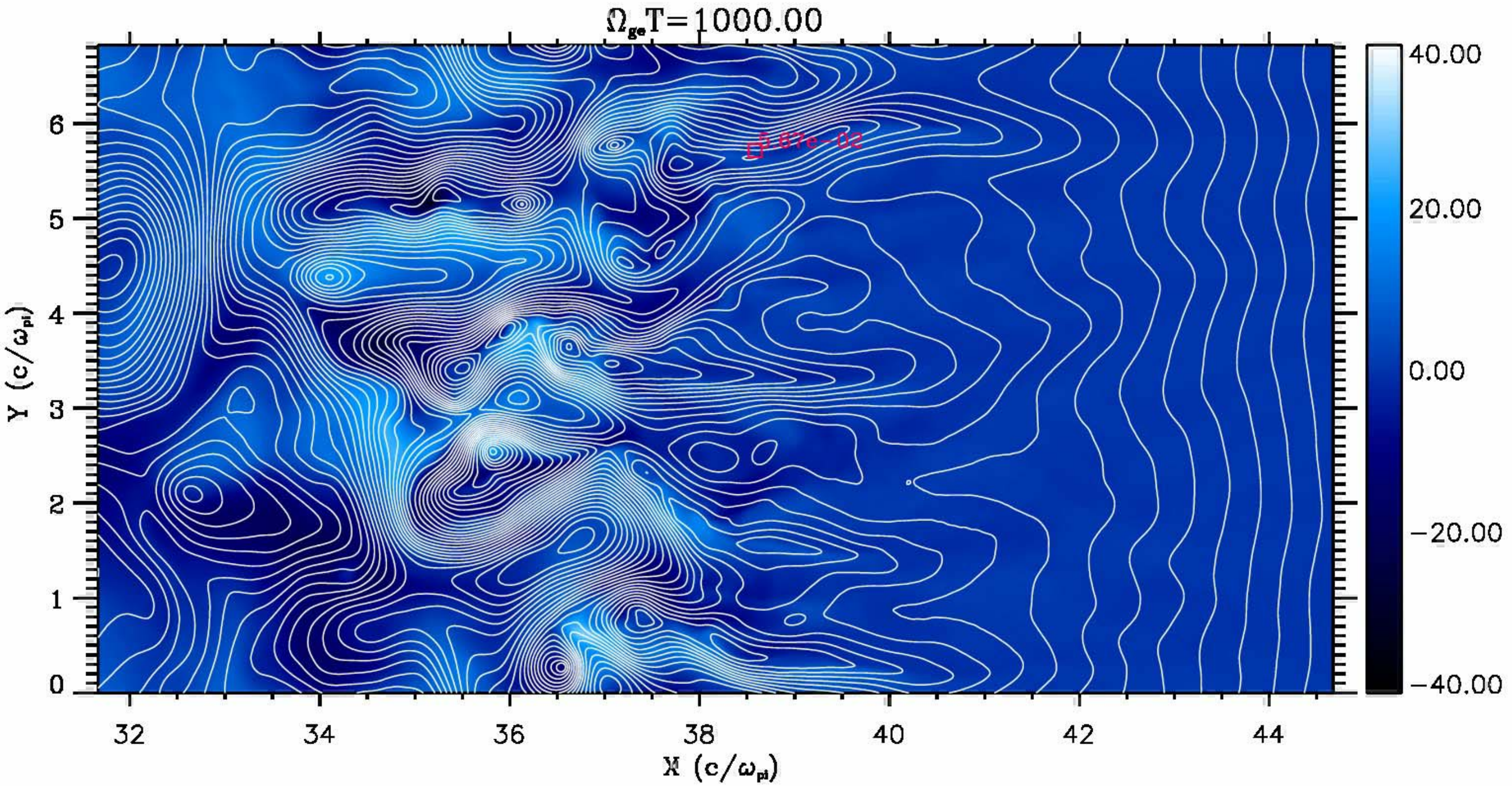
Tpara > Tperp

Weibel Instability & B filed generation

magnetic reconnection

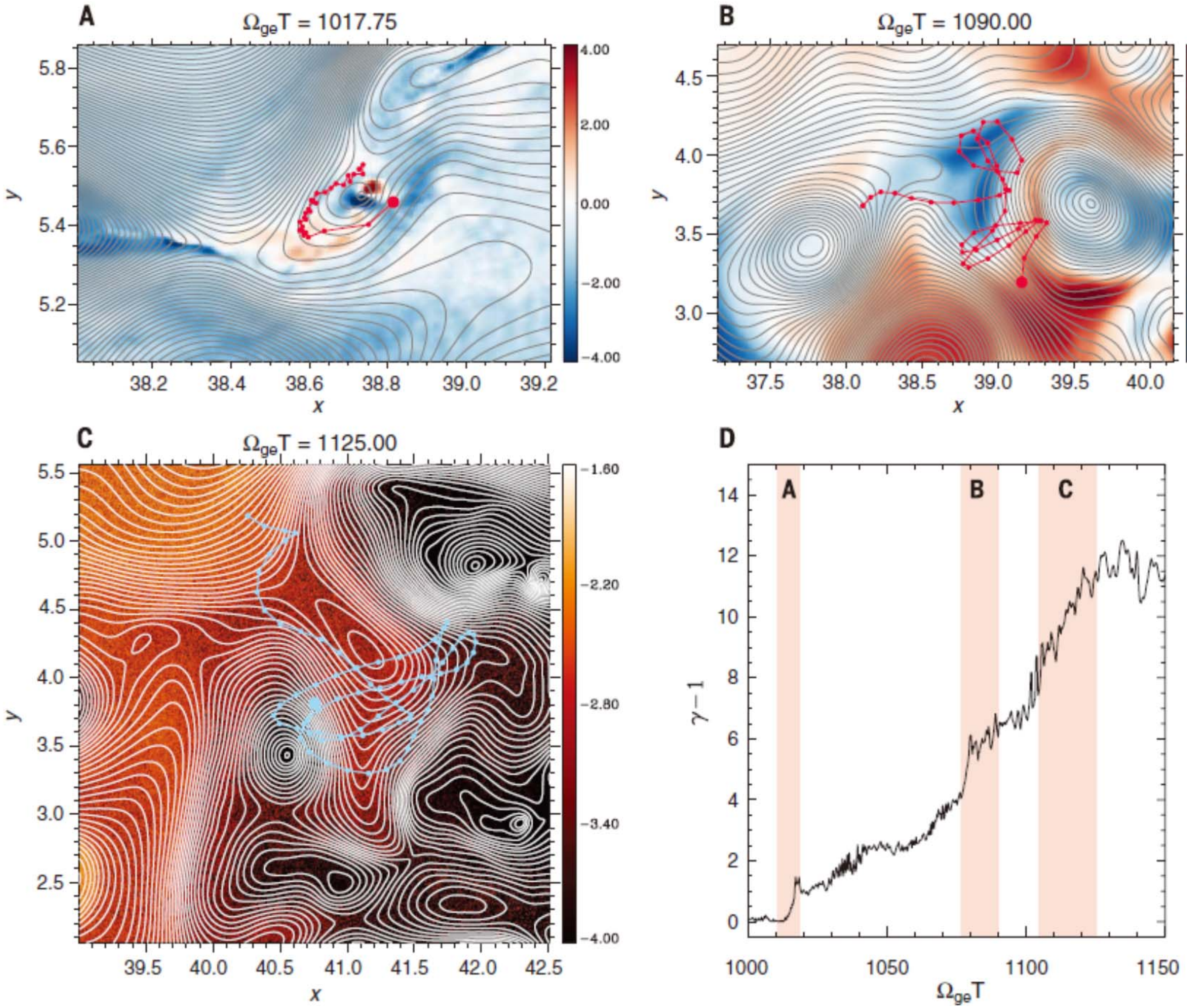
Matsumoto+, Science (2015)

Acceleration by Reconnection

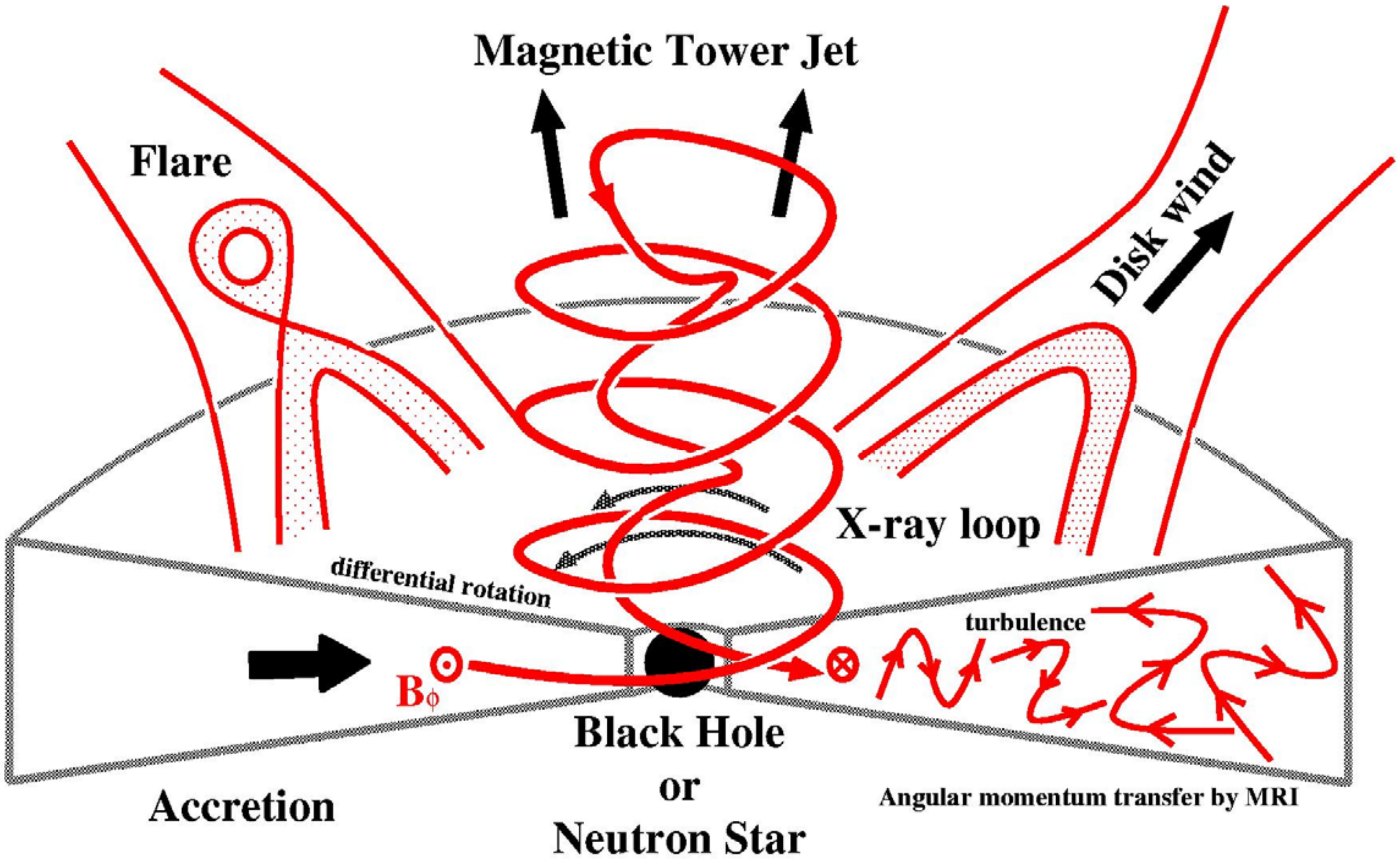


Matsumoto, Amano, Kato & MH, Science 2015

Stochastic Acceleration in Reconnection

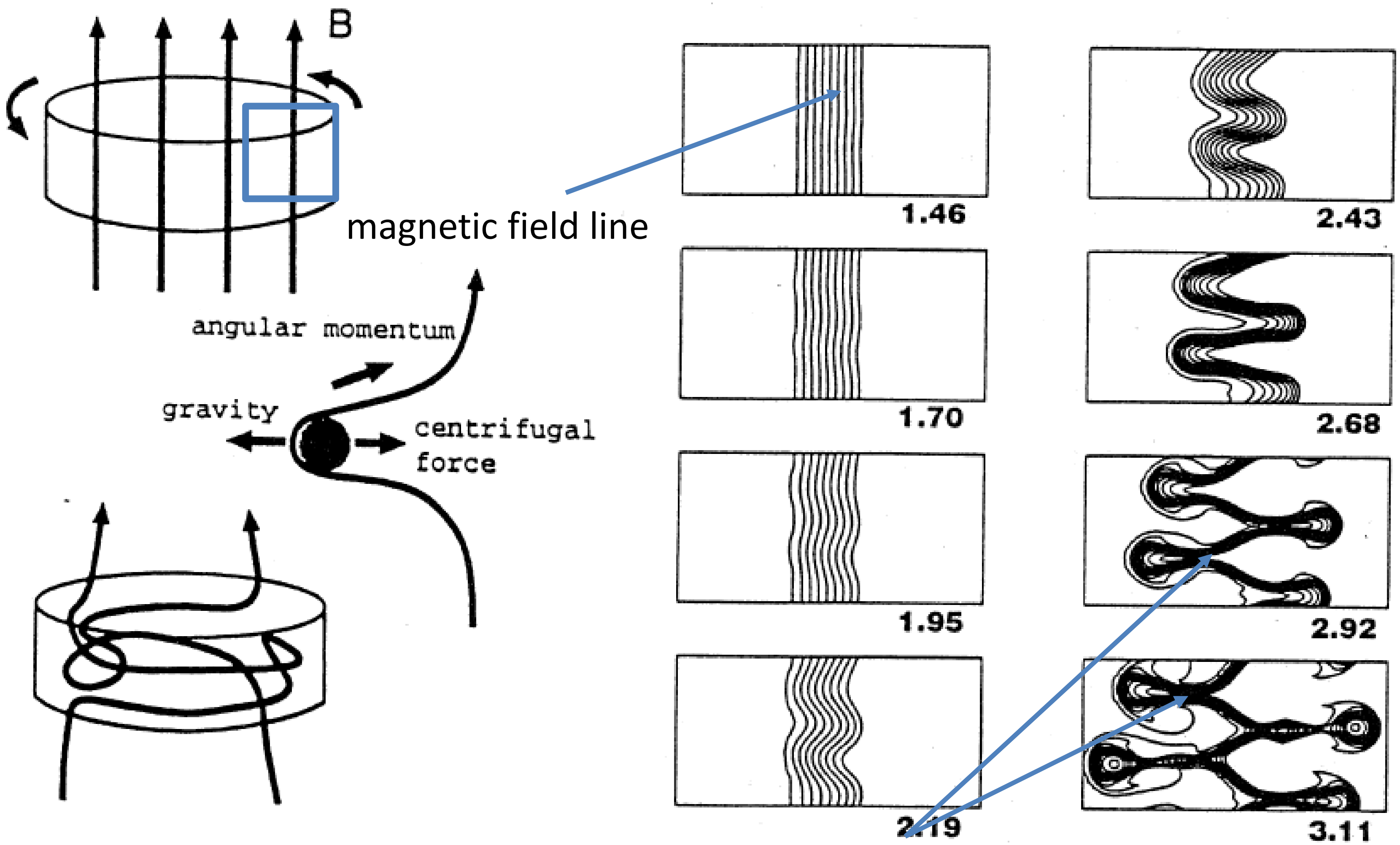


Reconnection in Accretion Disk



Courtesy of Kato

Magneto-Rotational Instability (MRI)

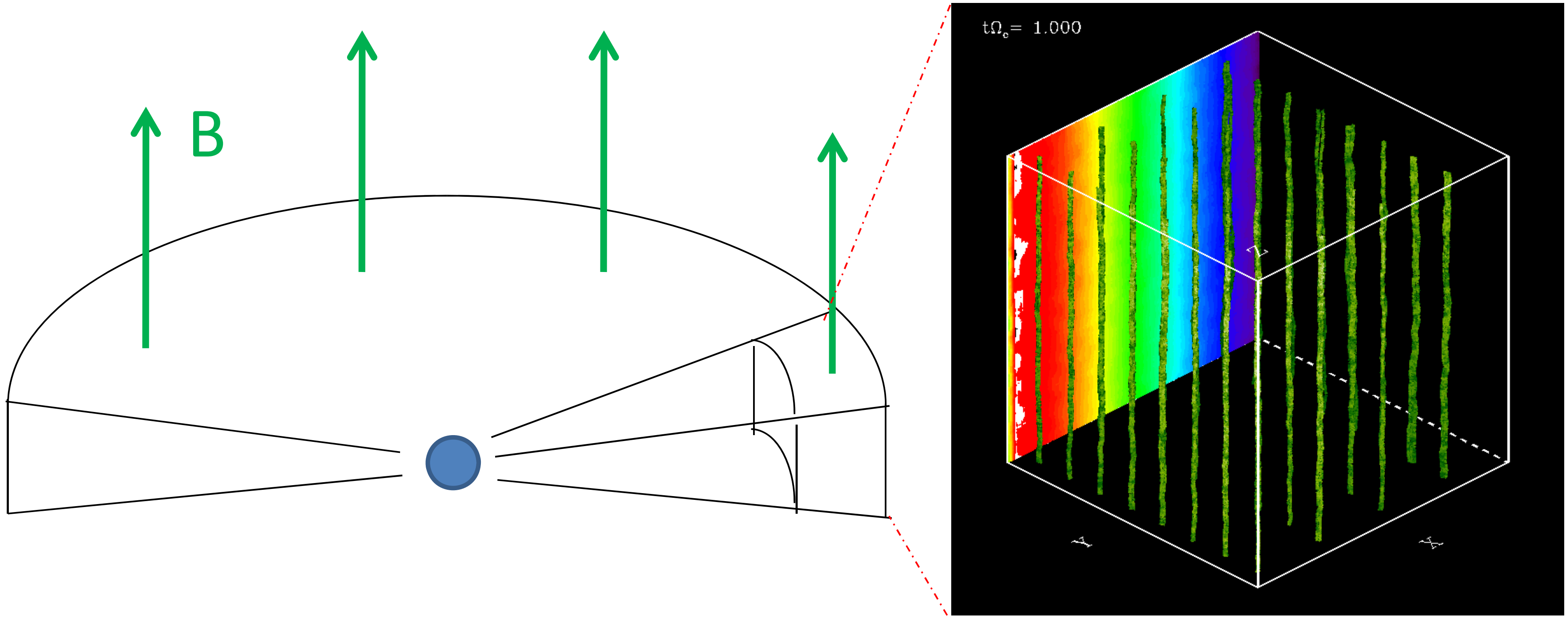


initial weak B-field (β>>1) → β ~ 10
dynamo process

magnetic reconnection

Balbus and Hawley, 1998

MRI and Reconnection in PIC simulation



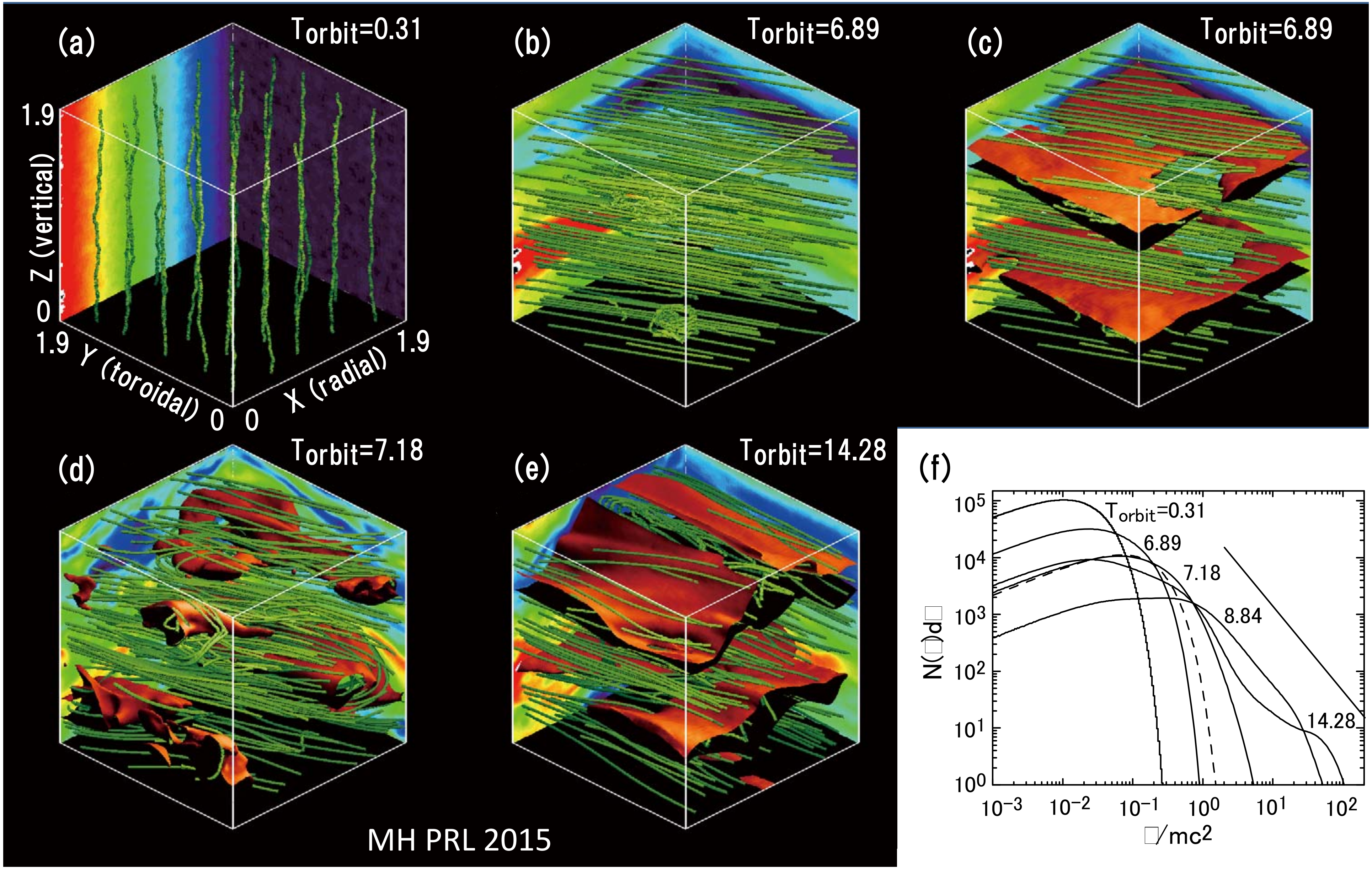
β=1536, Kepler rotation Ω

300^3 grids 40 particles/cell,

periodic shearing box, electron-positron plasma

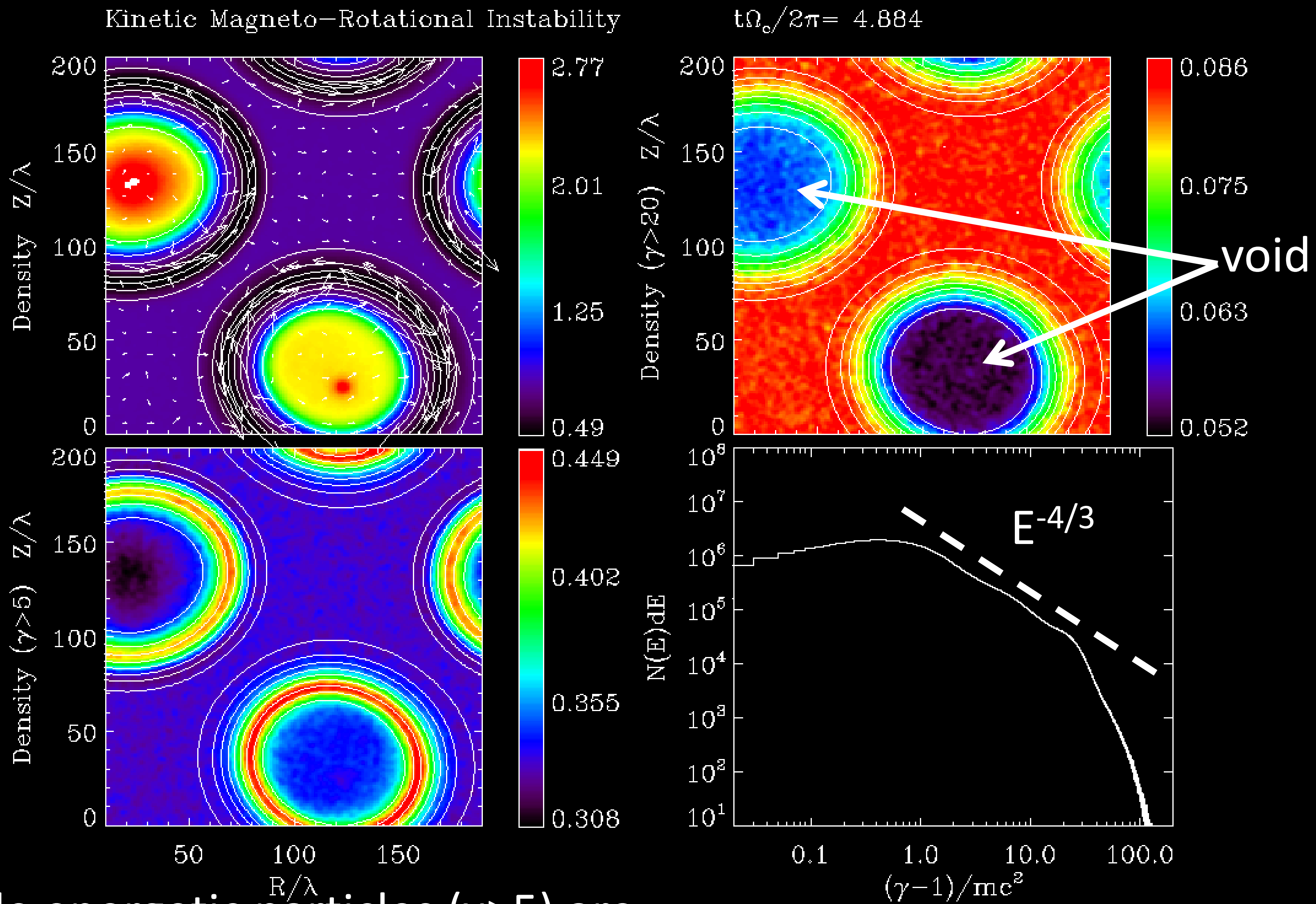
MH ApJ 2013, Shirakawa & MH 2014, MH PRL 2015

Particle Acceleration in Accreation Disks



thermal plasma is confined inside magnetic islands

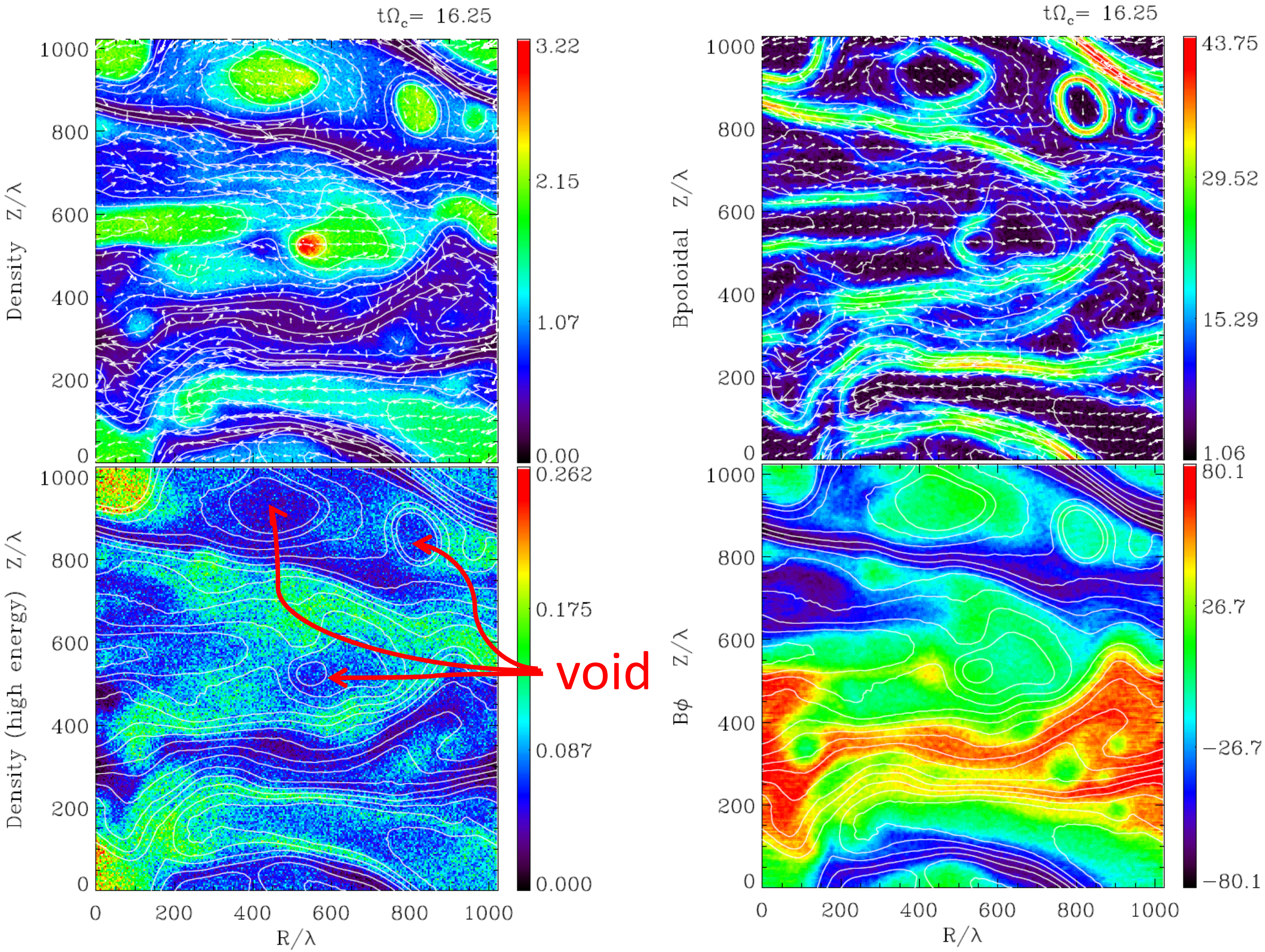
high energetic particles (γ>20) are located outside magnetic islands



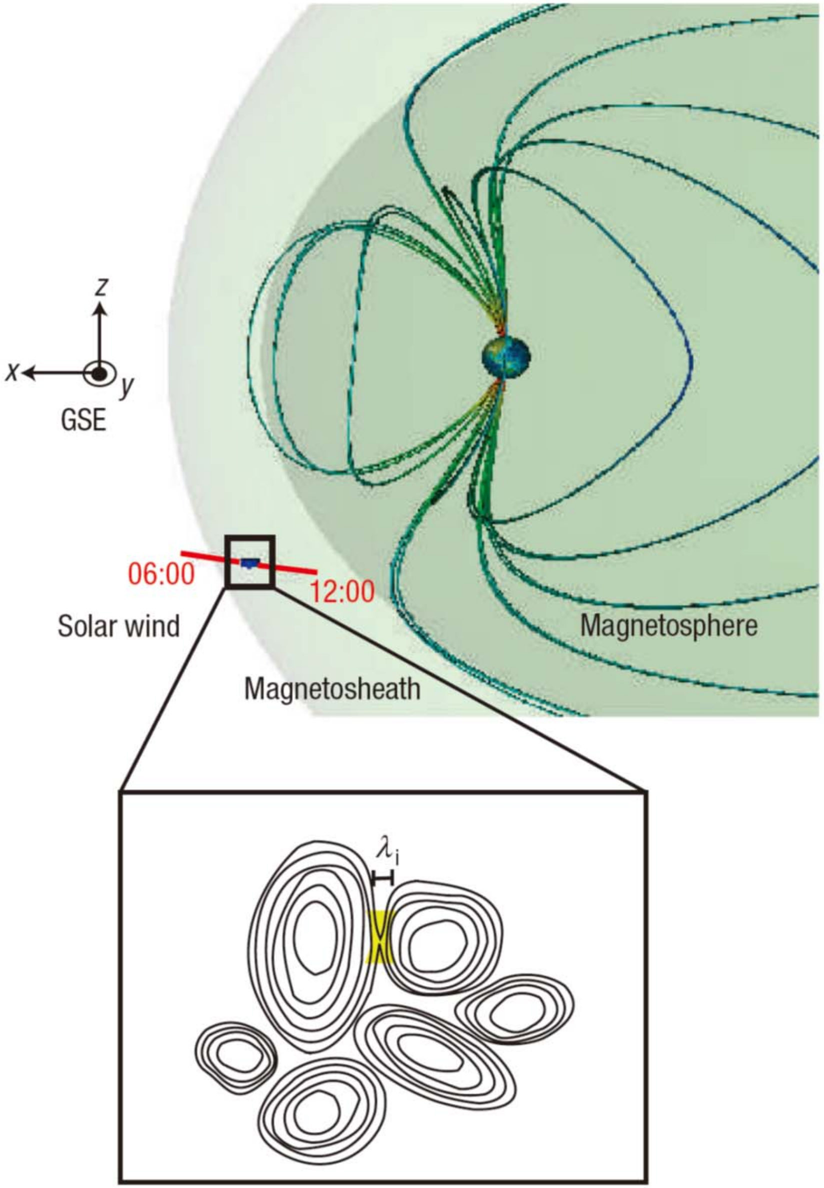
middle energetic particles (γ>5) are located at outer edge of islands

MH ApJ 2013

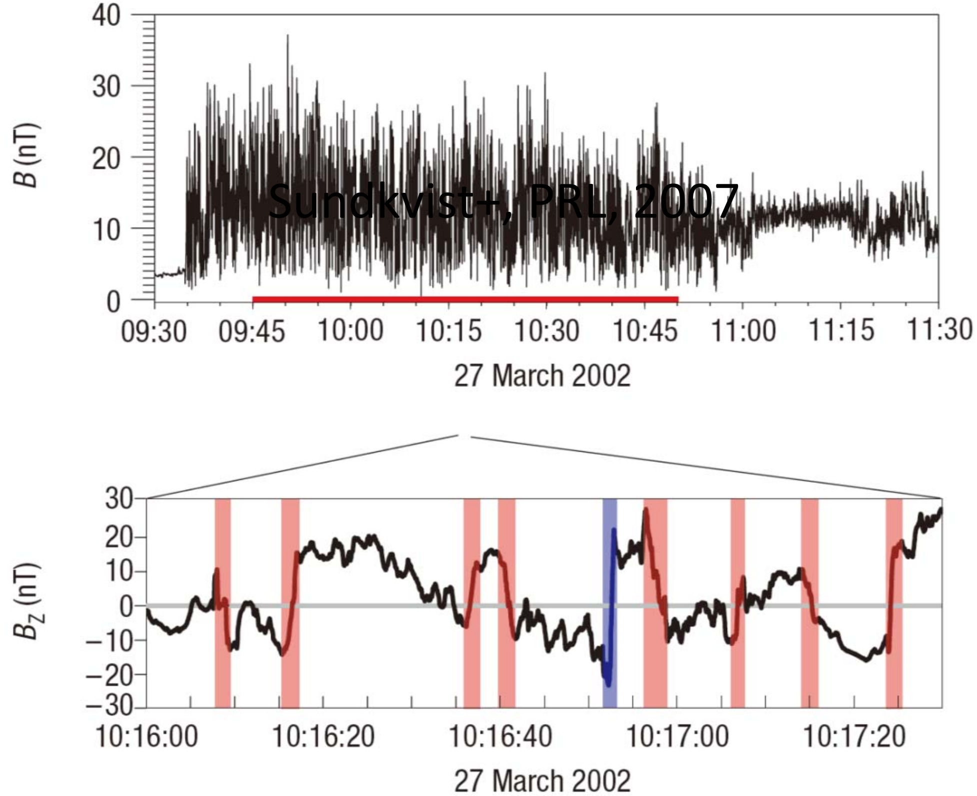
Turbulent reconnection in MRI



Turbulent Reconnection in Magnetosheath



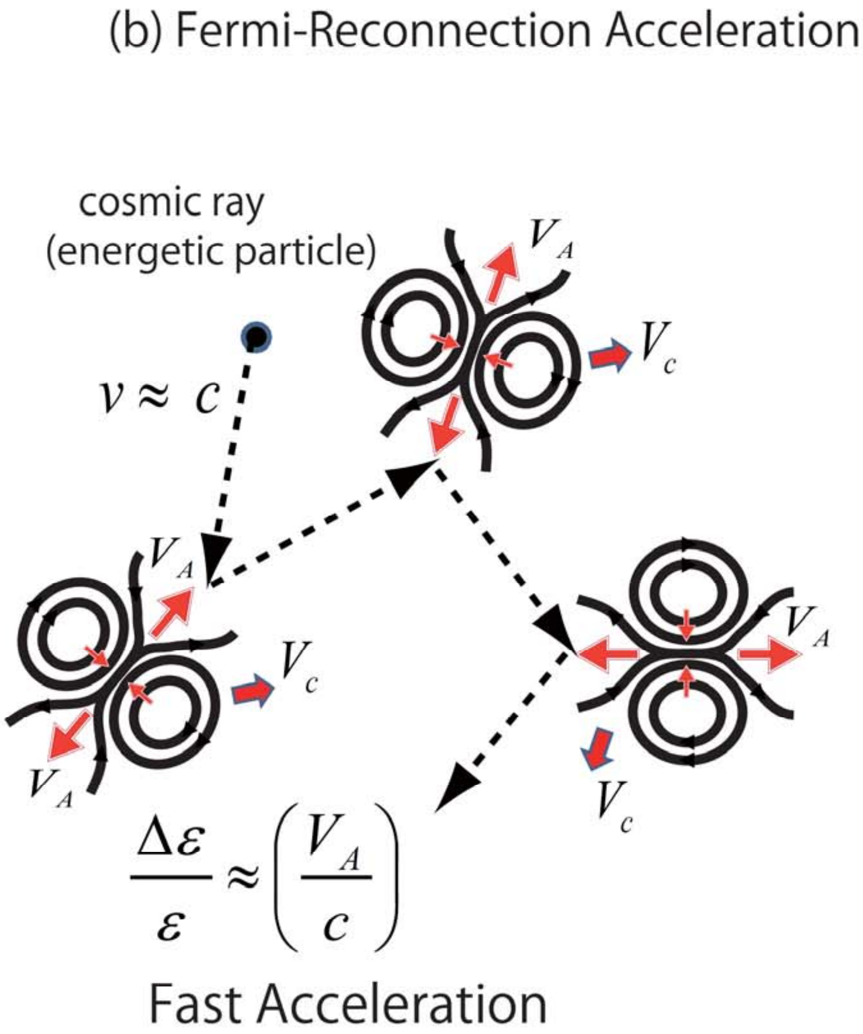
Cluster Observation

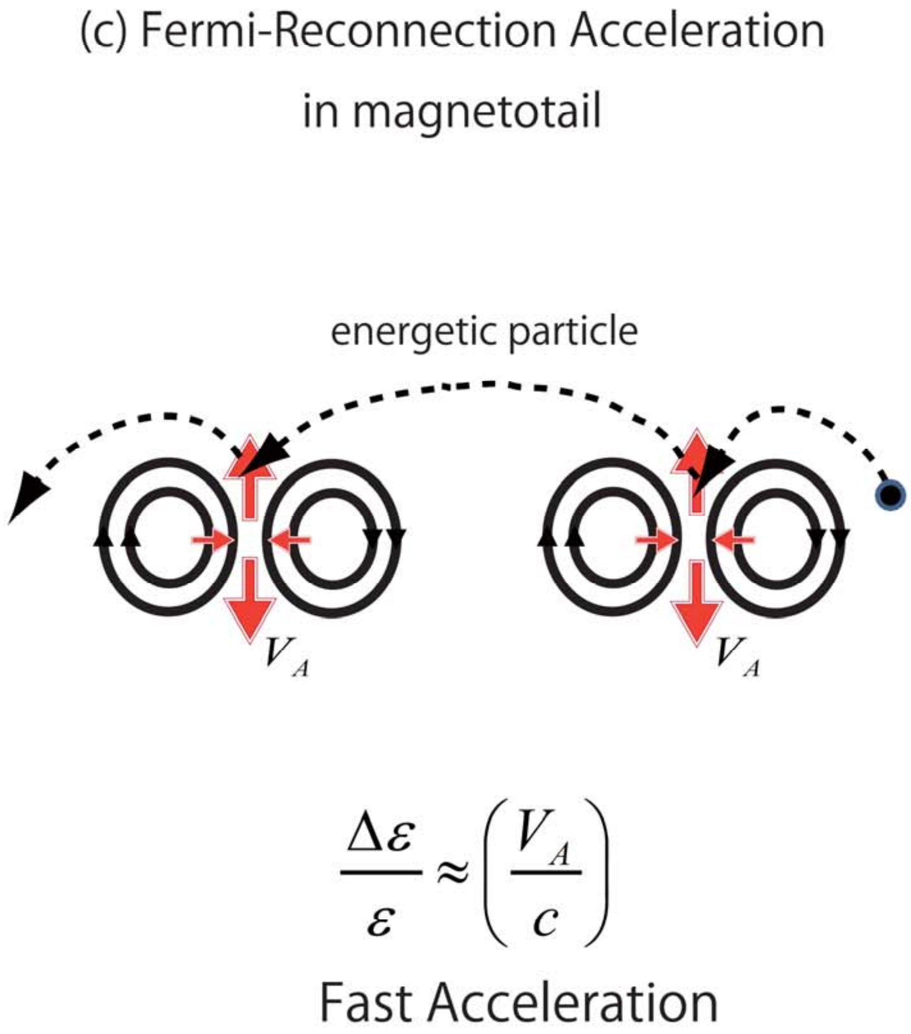


many magnetic islands with energetic ions of 20 keV

Retino+ Nature Physics 2007; Sundkvist+ PRL 2007

Multiple Acceleration in Magnetotail





MH & Lyubarsky SSR (2013)

Summary

1. Observations and simulations in the Earth's Magnetosphere:
   Magnetic reconnection can generate nonthermal particles

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

3. Reconnections in shock waves and in accretion disks:
   Energy dissipation by reconnection playa an important role in many astrophysical settings

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