THE UNIVERSITY OF TOKYO

Plasma Heating & Acceleration in Collisionless Magnetic Reconnection

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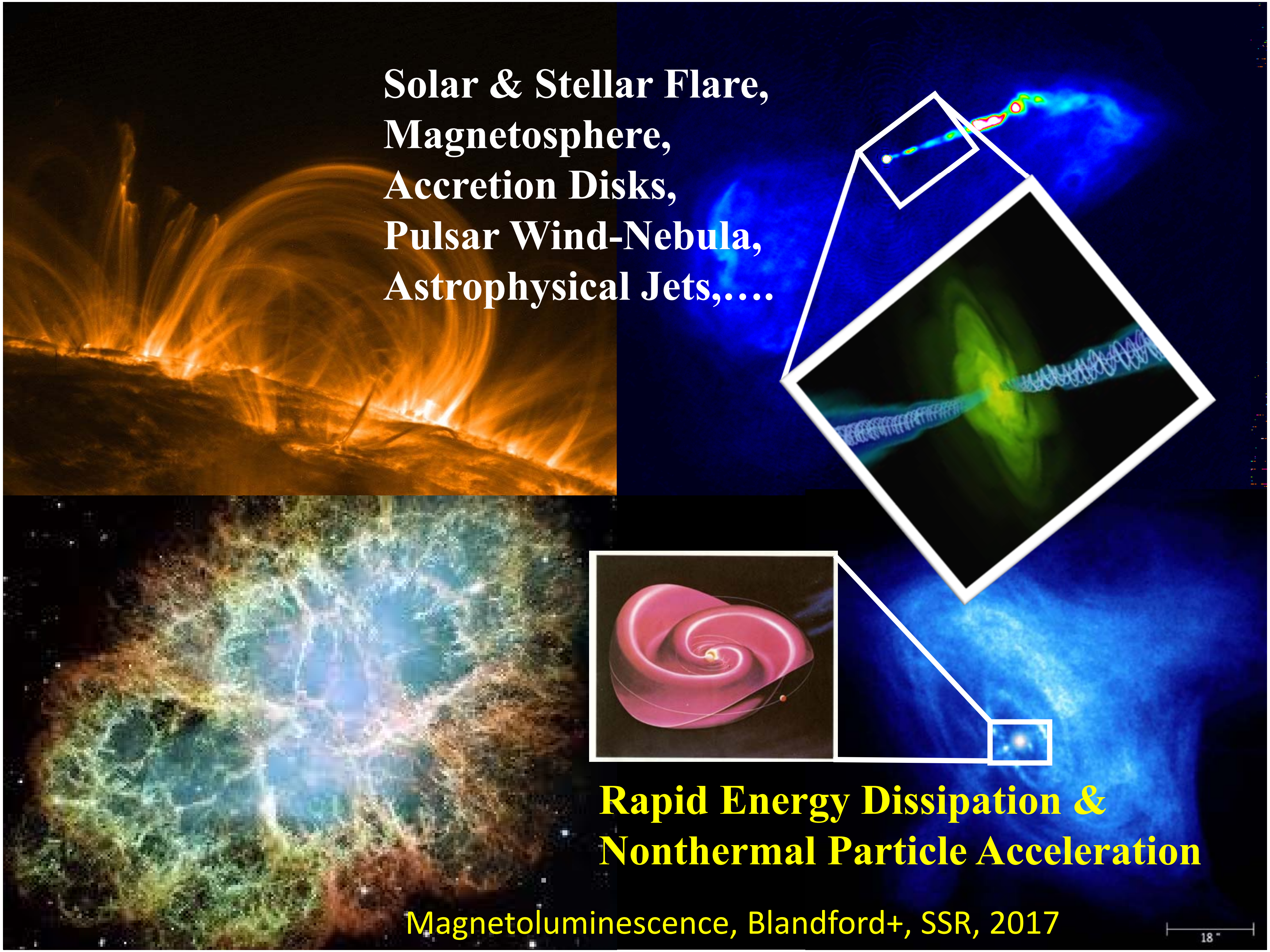
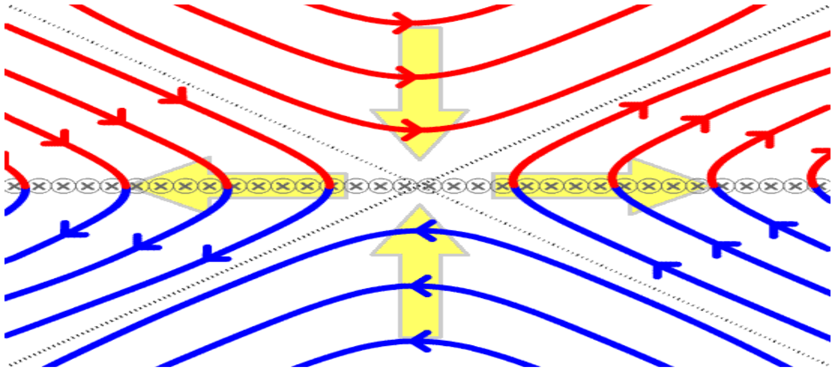
University of Tokyo


Solar & Stellar Flare,
Magnetosphere,
Accretion Disks,
Pulsar Wind-Nebula,
Astrophysical Jets,….
Rapid Energy Dissipation &
Nonthermal Particle Acceleration
Magnetoluminescence, Blandford+, SSR, 2017
18"

Magnetic Reconnection



Giovaneli, Nature, 1949;
Sweet 1958; Parker 1957;
Petschek 1964;
Furth, Killeen & Rosenbluth (FKR)1964;…

magnetic field energy (B)

Inflow and outflow around X-type region, associated with inductive electric field (E)

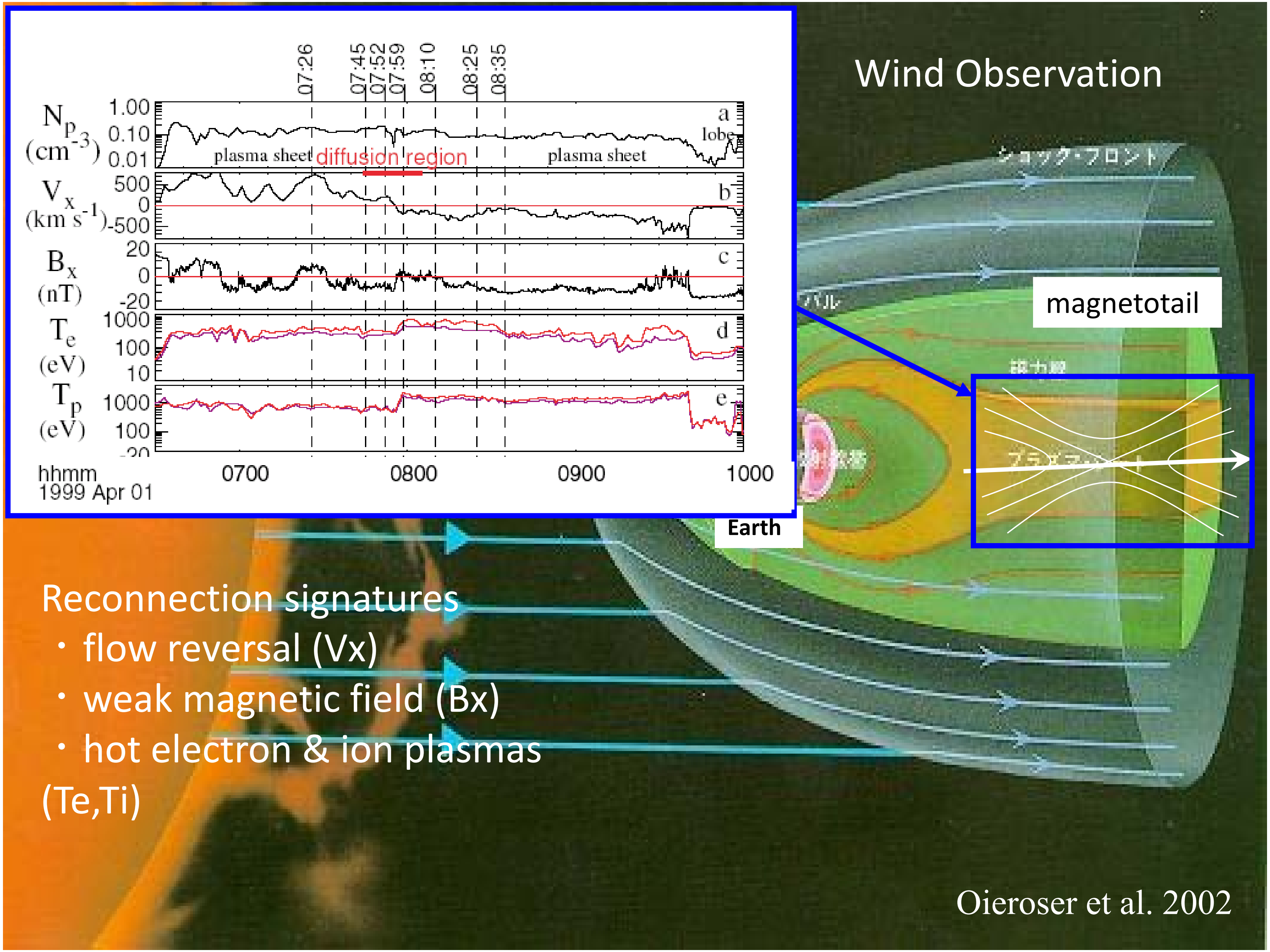
$$E = B \times \frac{V_{in,out}}{c}$$

Alfvénic outflow jet (V_A)

$$V_{out} = V_A$$

magnetic energy dissipation at X-type region

$$E = \eta J$$



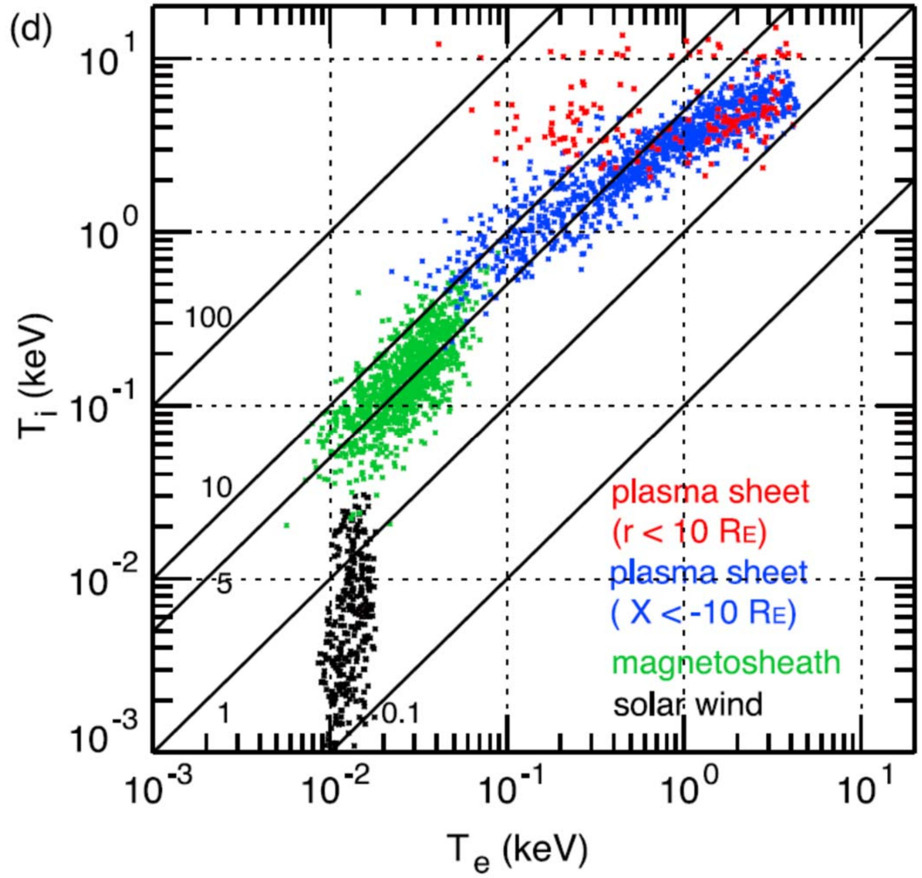
Wind Observation
07:26
07:45
07:52
07:59
08:10
08:25
08:35
N_p (cm^{-3})
1.00
0.10
0.01
a
lobe
plasma sheet
diffusion region
plasma sheet
V_x ($km\ s^{-1}$)
500
0
-500
b
B_x (nT)
20
0
-20
c
T_e (eV)
1000
100
10
d
T_p (eV)
1000
100
e
hhmm
1999 Apr 01
0700
0800
0900
1000
ショック・フロント
magnetotail
Earth
Reconnection signatures
・flow reversal (Vx)
・weak magnetic field (Bx)
・hot electron & ion plasmas (Te,Ti)
Oieroser et al. 2002

Observations of Ti/Te

magnetosphere

$$T_i/T_e = 5 \sim 10$$

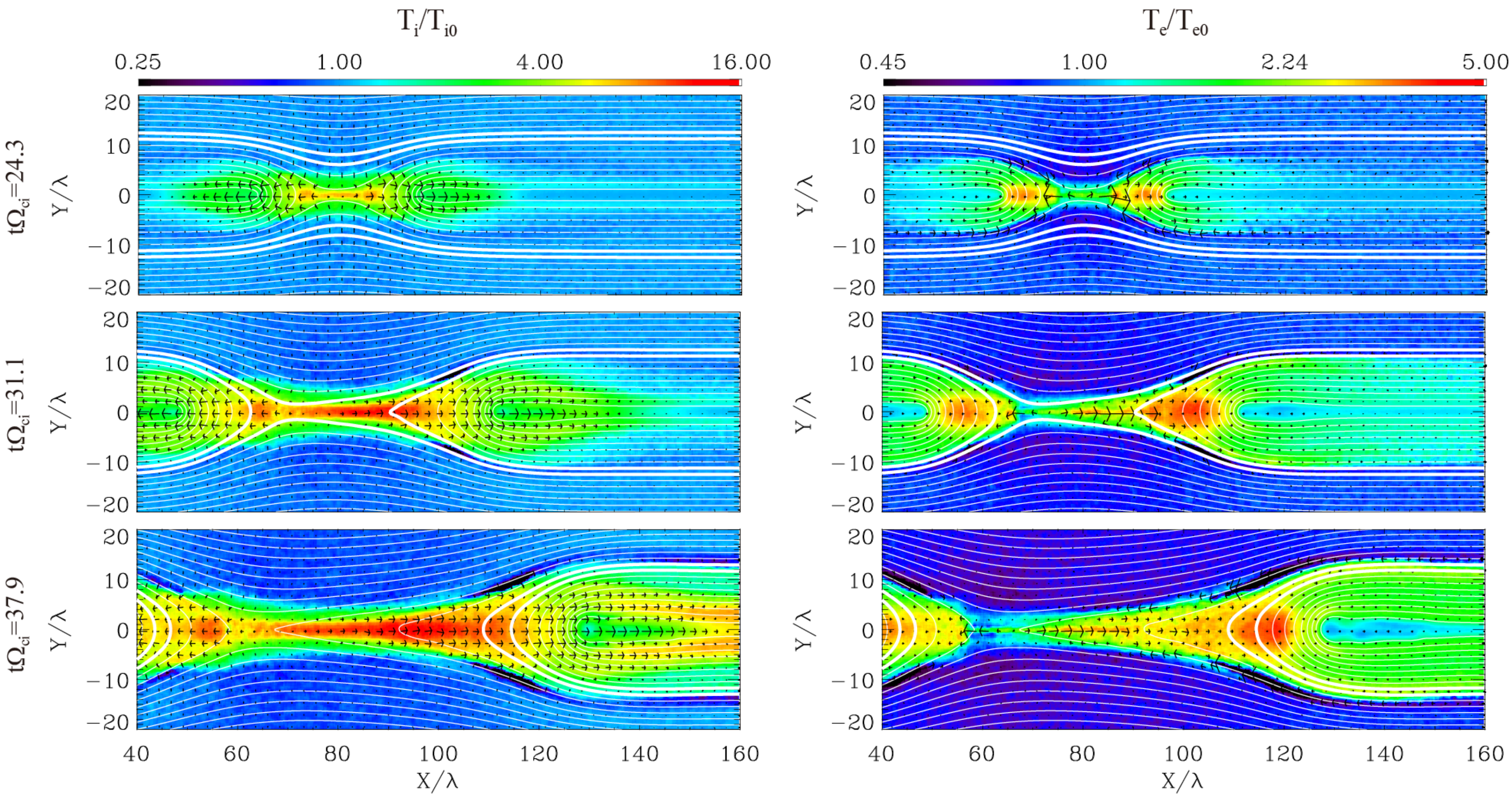
Hot ions are believed to be generated during magnetic reconnection…



(cf. Baumjohann+ JGR 1989; Eastwood+ PRL 2013; Phan+ GRL 2013)

Wang+ JGR 2012

T_i & T_e Heating in PIC simulation



Motion of flux tube in 2D

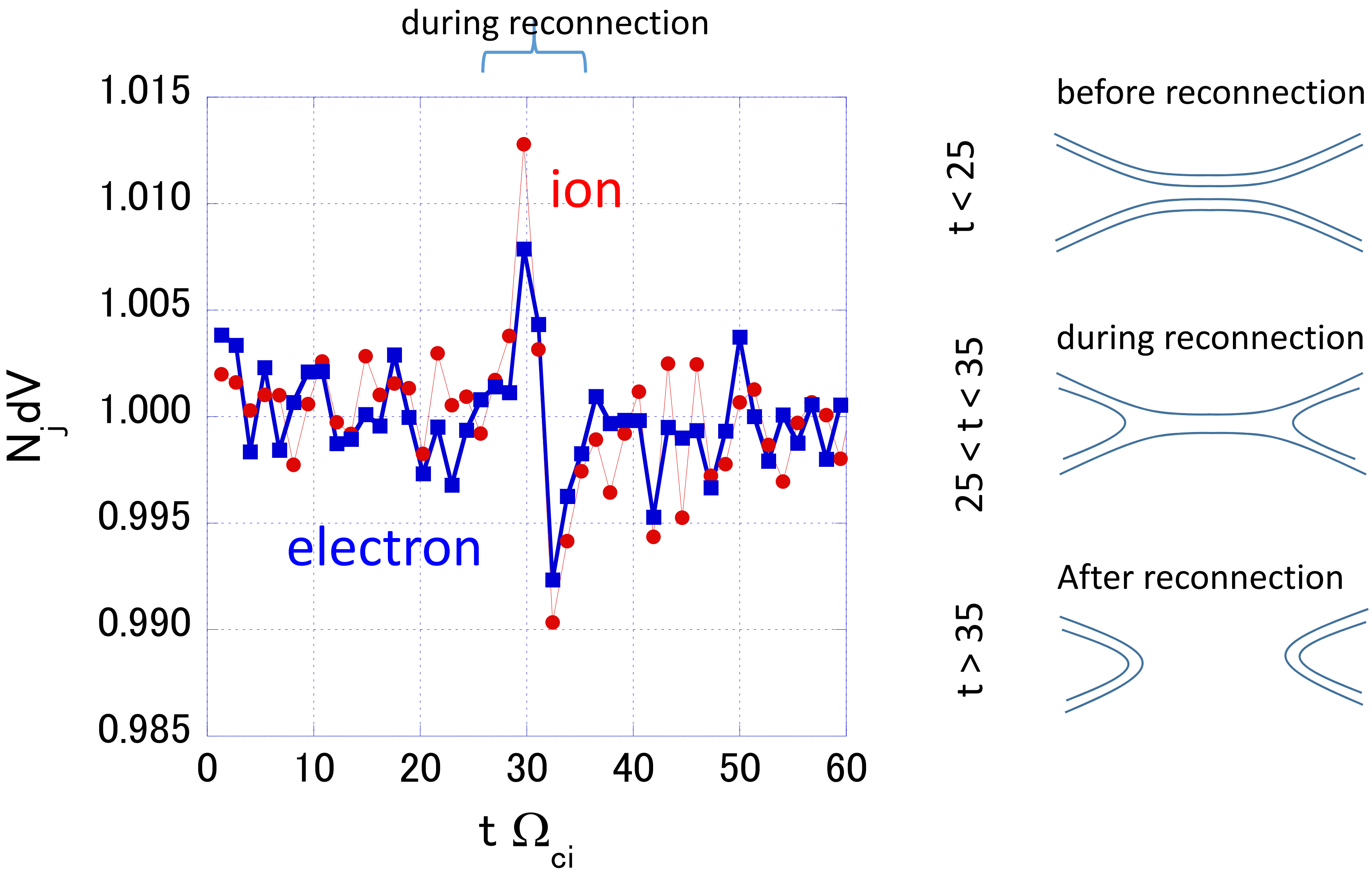
$$\vec{B}(x,y) = \nabla \times A_z(x,y)\vec{e}_z + B_z(x,y)\vec{e}_z$$

$$\frac{dx}{B_x(x,y)} = \frac{dy}{B_y(x,y)} \Leftrightarrow dA_z(x,y) = 0$$

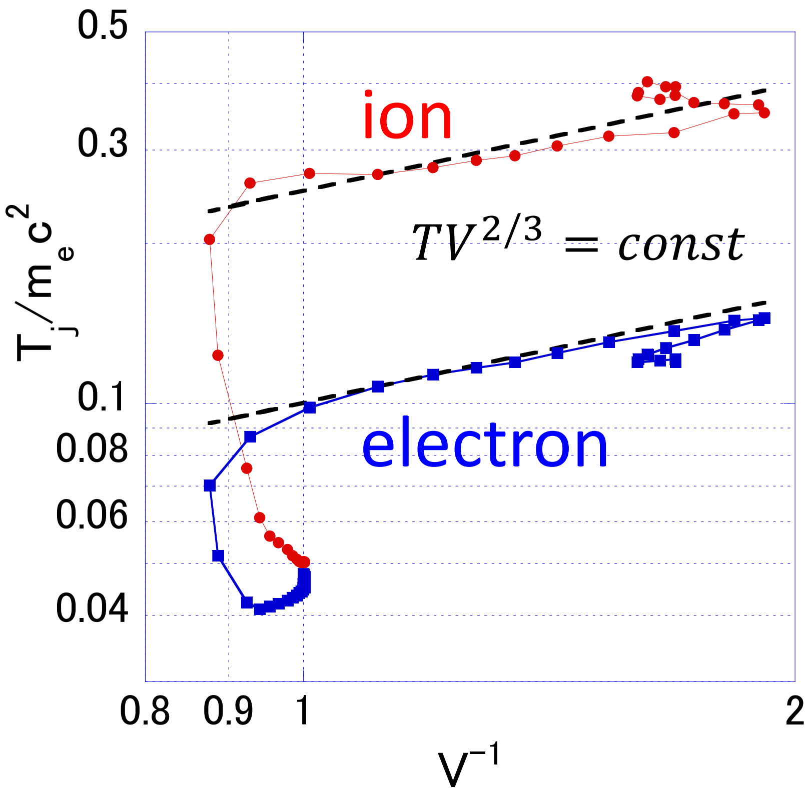
If $\vec{E} + \frac{1}{c}\vec{v} \times \vec{B} = 0,$

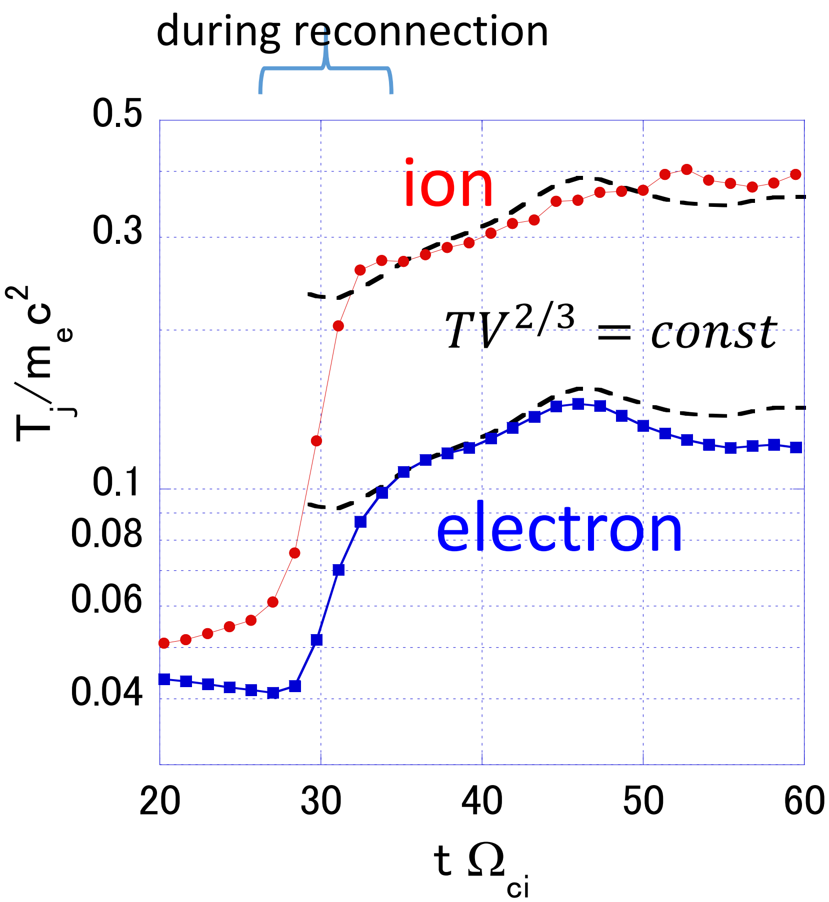
then $\left(\frac{\partial}{\partial t} + \vec{v} \cdot \nabla\right) A_z(x,y,t) = 0.$

Time History of N in Flux Tube



T-V Relations





(V : Volume of Flux Tube)

Plasma Heating (Equation of State)

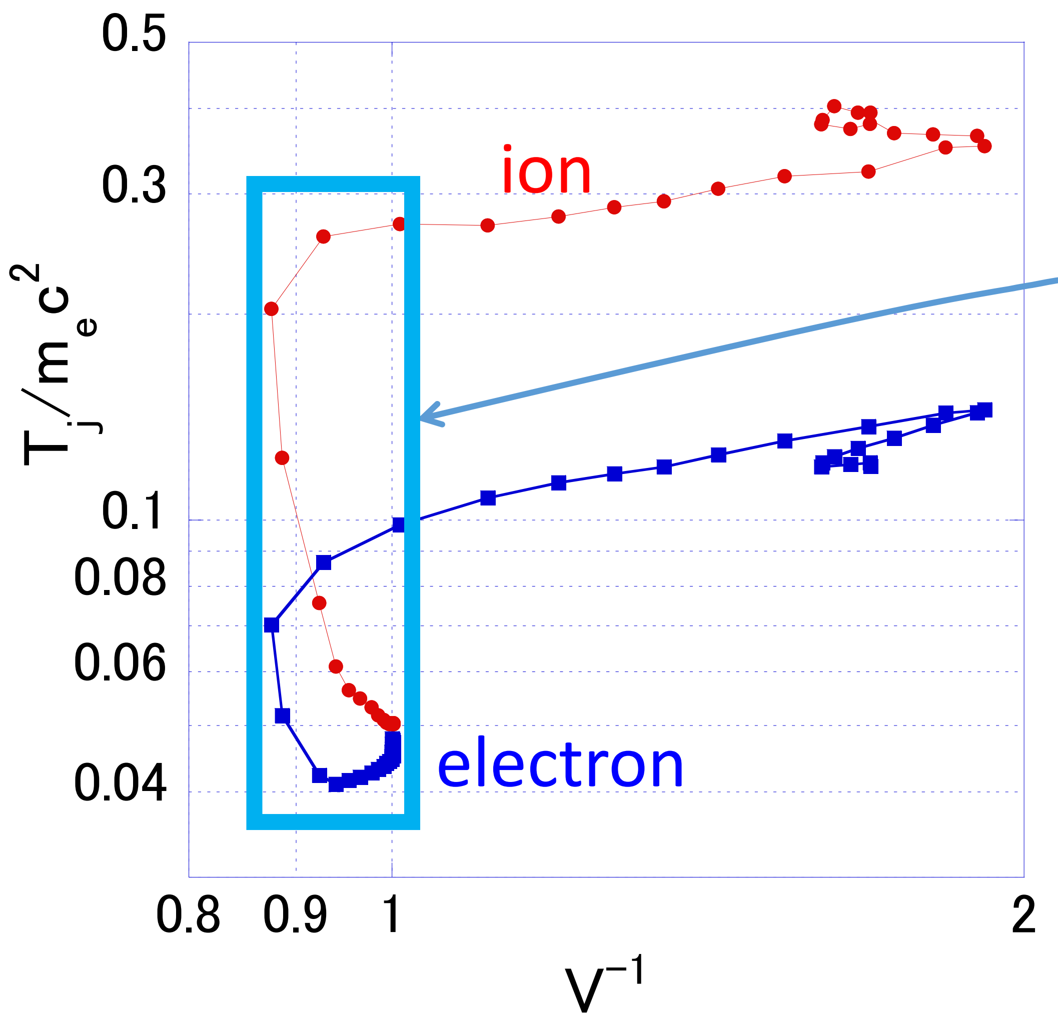
$$\frac{D}{Dt}\left(\frac{p}{\gamma - 1}\right) = \left(\frac{p}{\gamma - 1}\right)\frac{\gamma}{\varrho}\frac{D\varrho}{Dt} + Q_{heat}$$

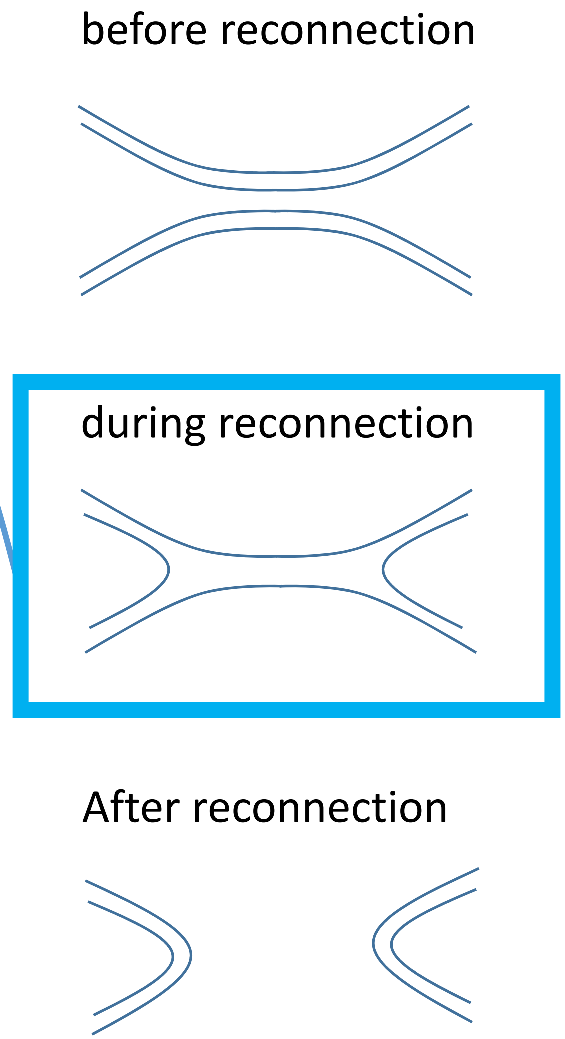
Adiabatic Non-Adiabatic

$$Q_{heat} = \eta J^2 \quad + \quad \text{others}$$

Ohmic Heating Slow Shock, Turbulence etc.

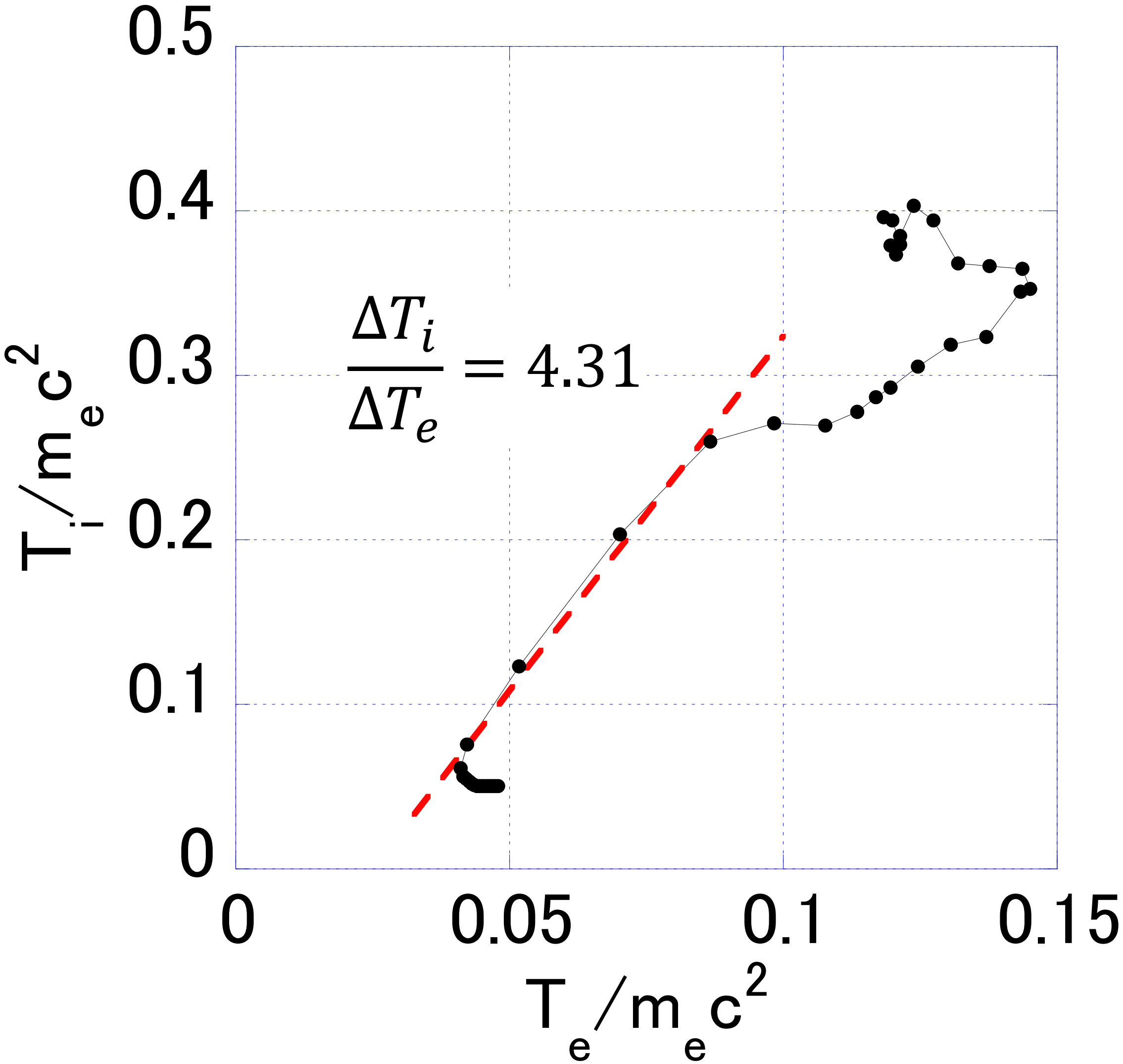
T - V relation





(V : Volume of Flux Tube)

Time history of Ti and Te

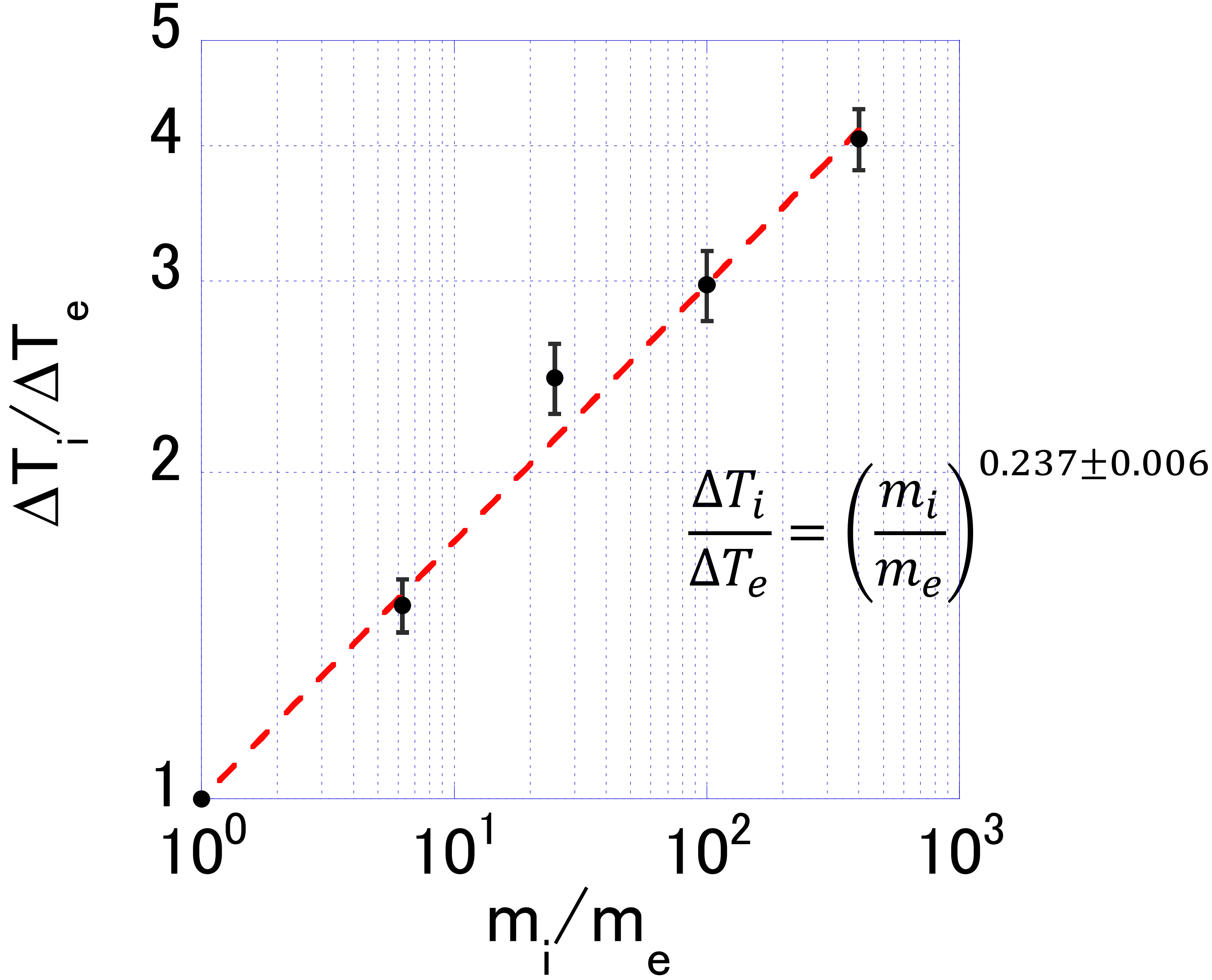


$$\frac{m_i}{m_e} = 400$$

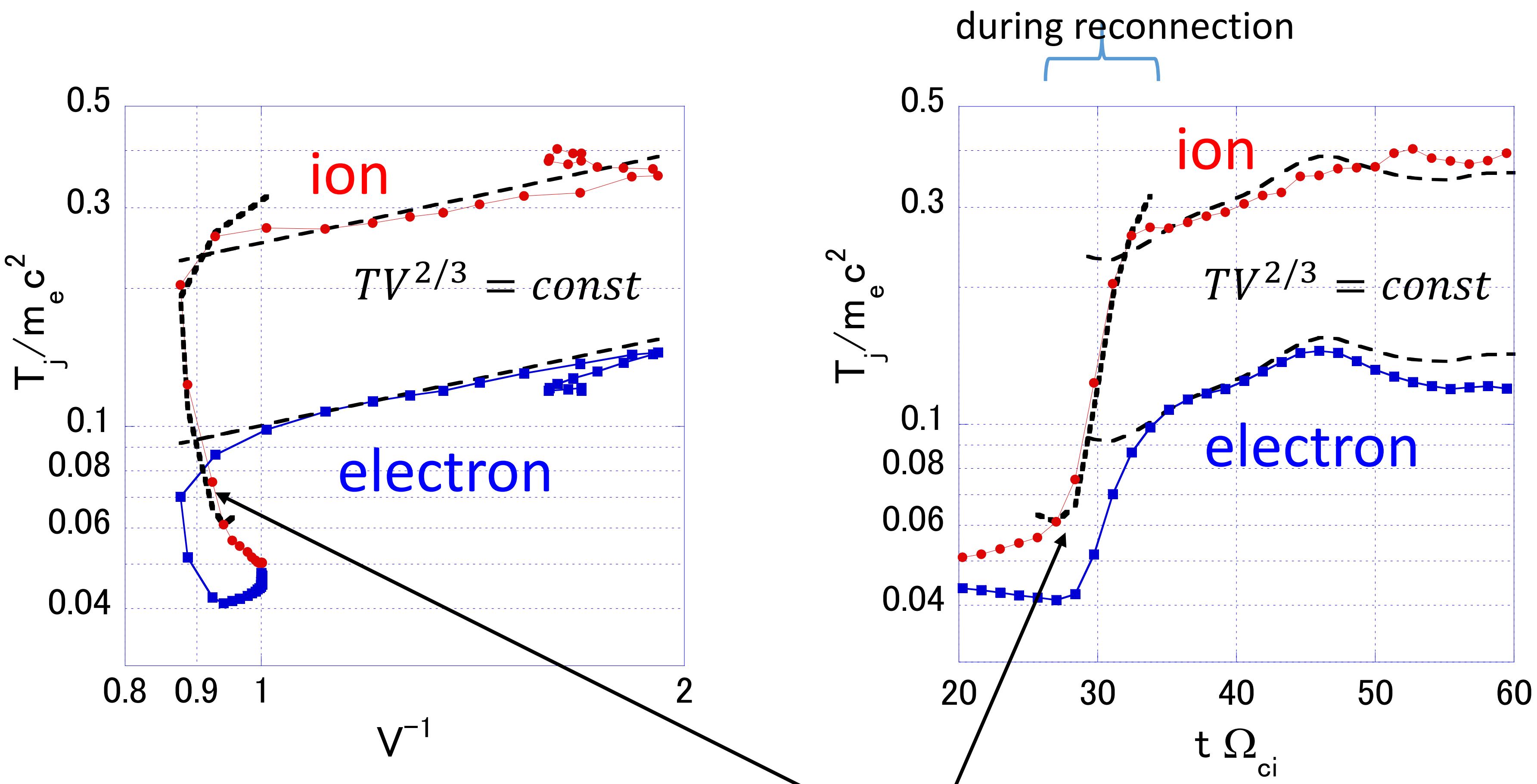
Average for Flux Tubes

$$\frac{\Delta T_i}{\Delta T_e} = 4.06 \pm 0.26$$

Mass dependence



Thermodynamics of Reconnection

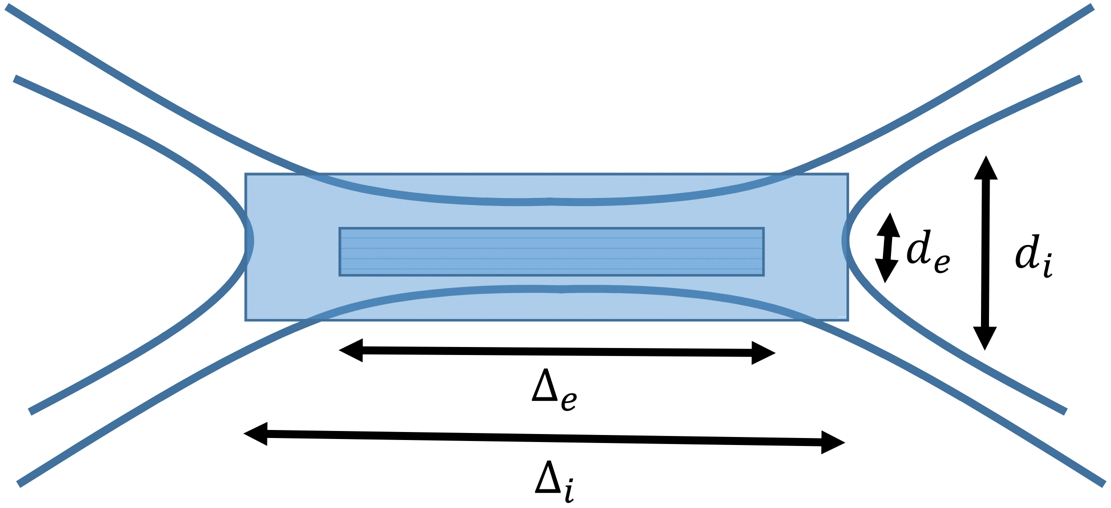


(V : Volume of Flux Tube)

Heating during Reconnection

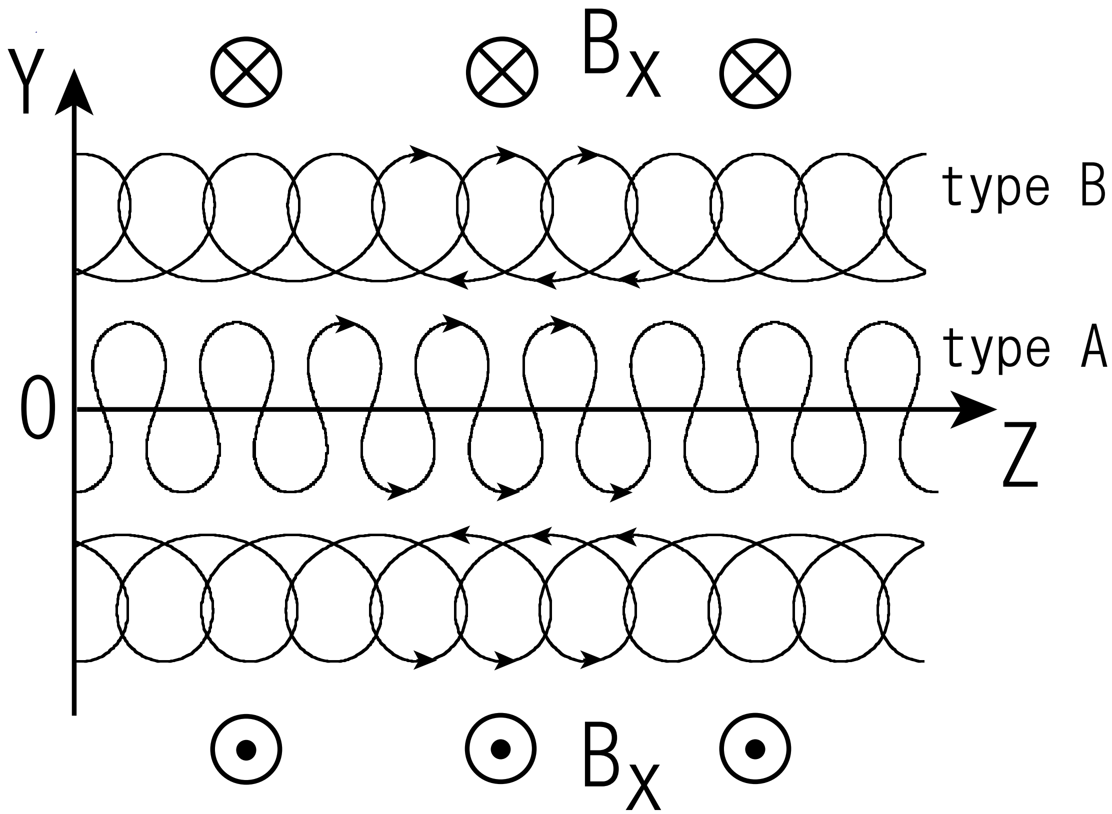
$$\frac{\Delta T_i}{\Delta T_e} = \left(\frac{m_i}{m_e}\right)^{1/4}$$

Effective Ohmic heating model



$$\frac{\Delta T_i}{\Delta T_e} = \frac{Ion\ Heating}{Electron\ Heating} = \frac{E \cdot J_i \Delta_i d_i}{E \cdot J_e \Delta_e d_e}$$

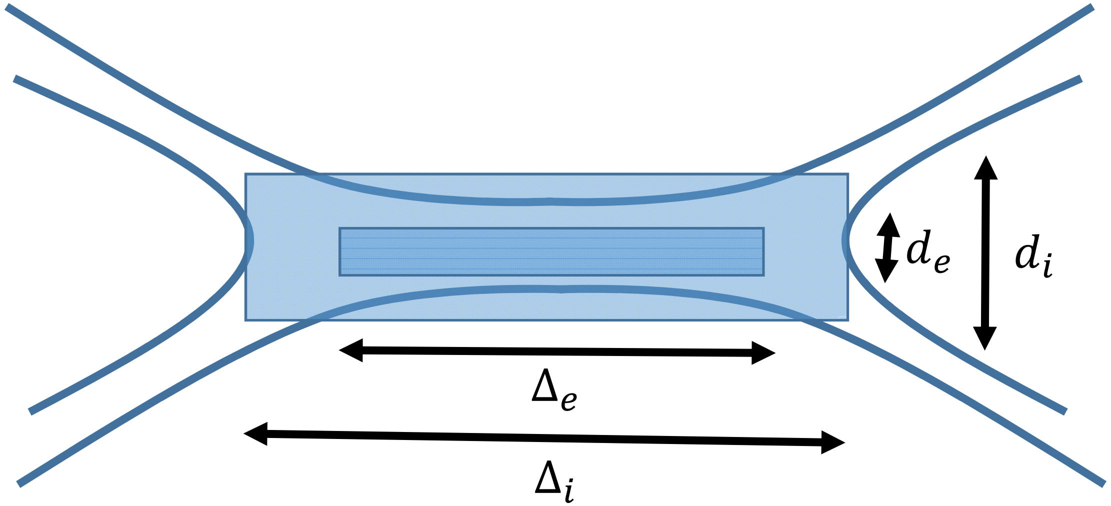
meandering motion in diffusion region



meandering width

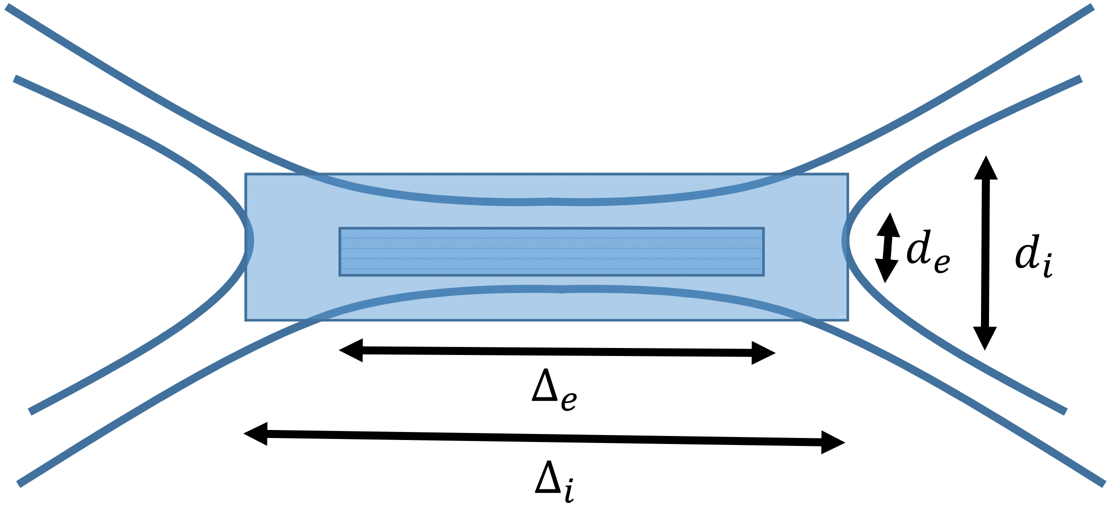
$$d_e = \sqrt{\frac{v_{th,e}\lambda}{\Omega_{ce}}} \propto (m_e T_e)^{1/4}$$

Joule heating model (I)



$$\frac{\Delta T_i}{\Delta T_e} = \frac{Ion\ Heating}{Electron\ Heating} = \frac{E \cdot J_i \Delta_i d_i}{E \cdot J_e \Delta_e d_e} = \frac{J_i \Delta_i}{J_e \Delta_e} \left(\frac{m_i}{m_e} \frac{T_{i0}}{T_{e0}} \right)^{1/4}$$

Joule heating model (II)

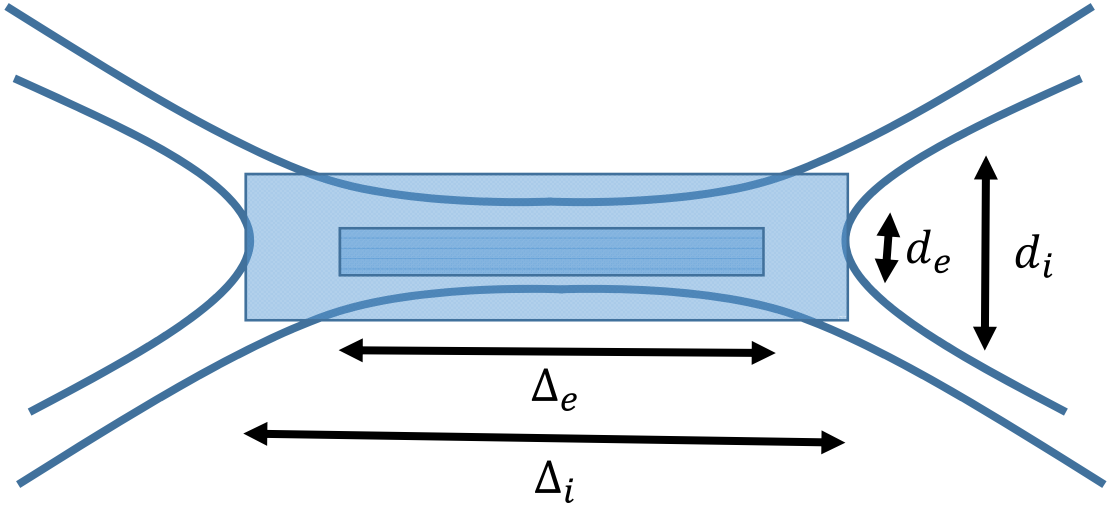


$$\frac{J_i}{J_e} = \frac{\sigma_i}{\sigma_e}\frac{E}{E} = \frac{\dfrac{ne^2}{m_i}\dfrac{\Delta_i}{v_{ix}}}{\dfrac{ne^2}{m_e}\dfrac{\Delta_e}{v_{ex}}} = \frac{m_e}{m_i}\frac{\Delta_i}{\Delta_e}\frac{v_{ex}}{v_{ix}},$$

(e.g., Coppi, Laval & Pellat, PRL 1966; Hoh, PoF 1996)

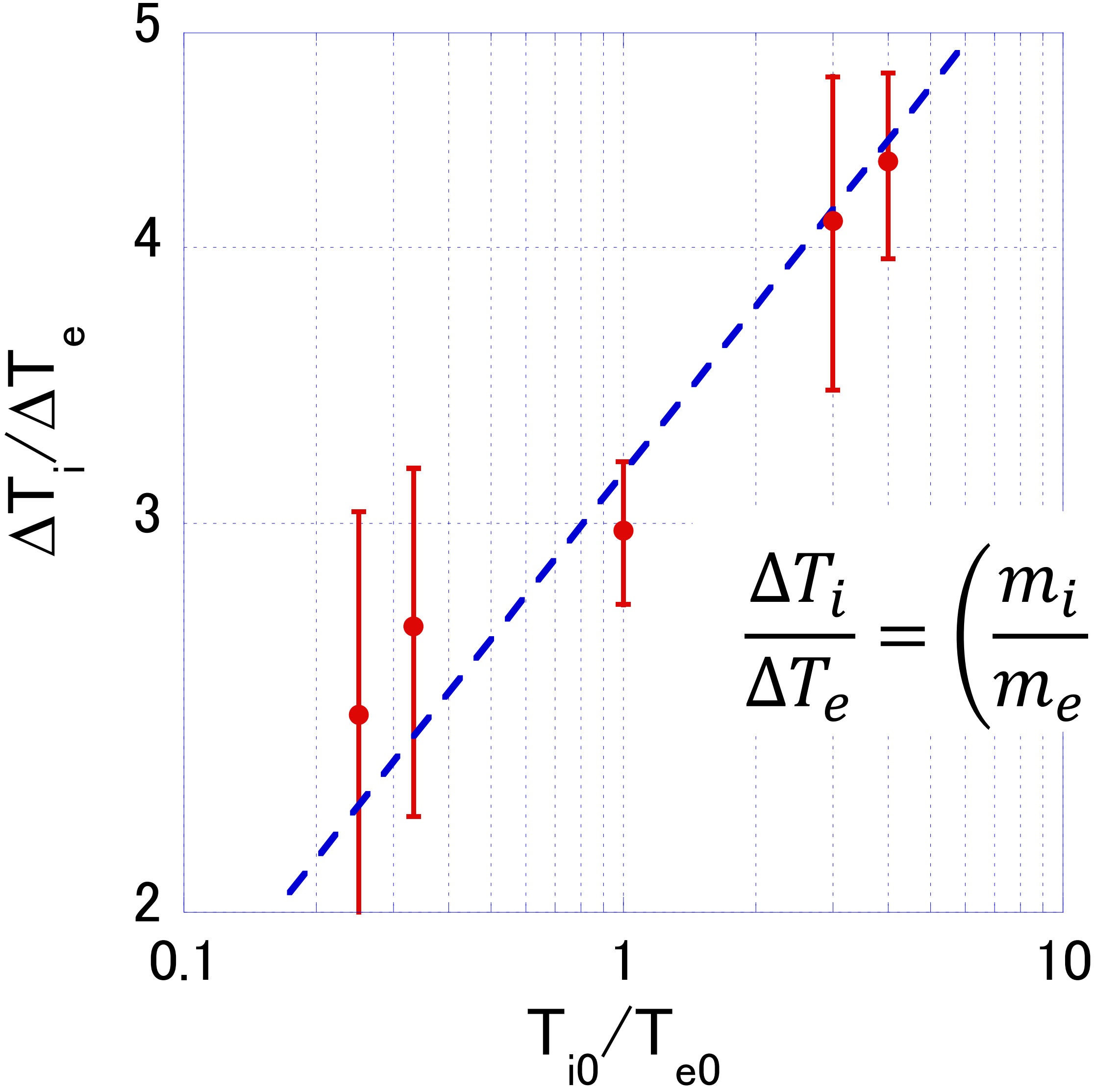
$$\frac{\Delta_i}{\Delta_e} = \left(\frac{v_{ix}}{\Omega_i}\frac{\Omega_{ce}}{v_{ex}}\right)^{1/2} \qquad \therefore\ \frac{J_i \Delta_i}{J_e \Delta_e} = 1$$

Joule heating model (III)



$$\frac{\Delta T_i}{\Delta T_e} = \frac{Ion\ Heating}{Electron\ Heating} = \frac{E \ \cdot J_i \Delta_i d_i}{E \ \cdot J_e \Delta_e d_e} = \left(\frac{m_i}{m_e} \frac{T_{i0}}{T_{e0}} \right)^{1/4}$$

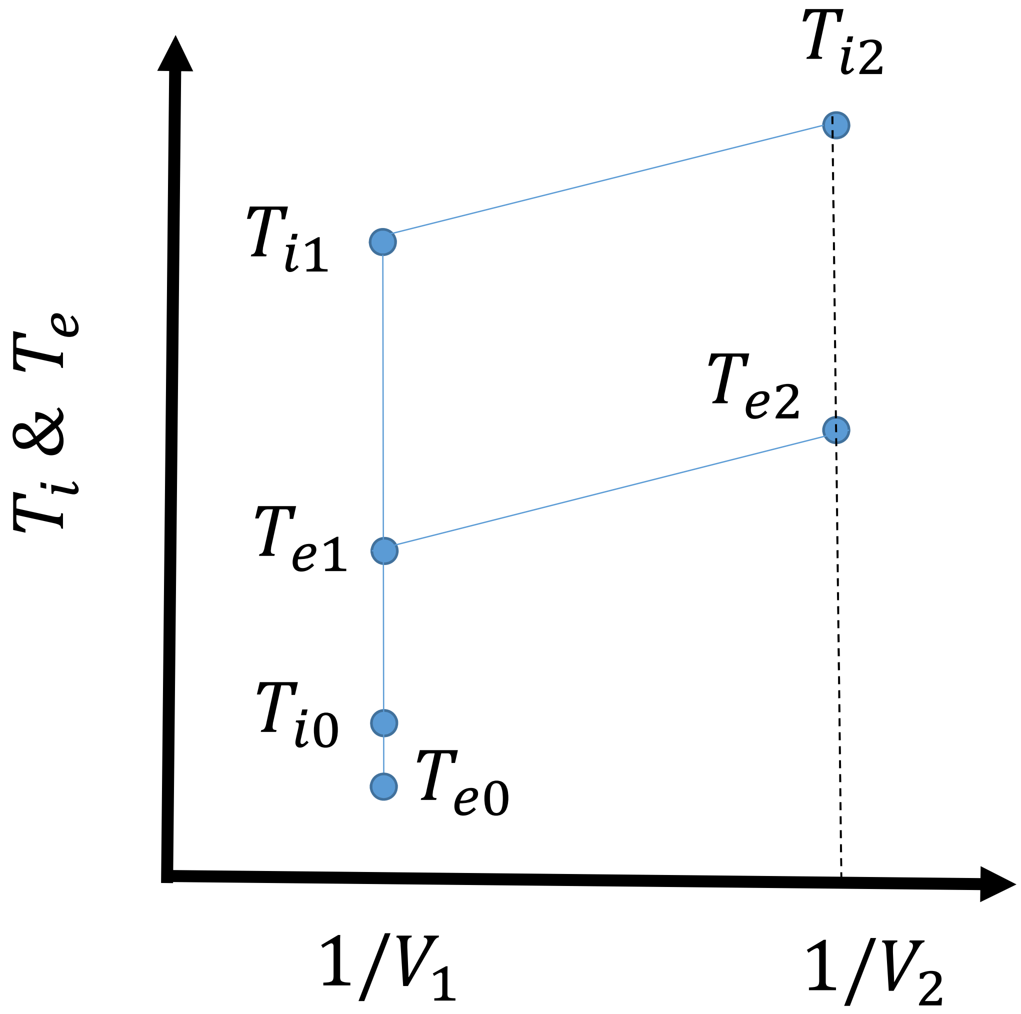
Initial temperature dependence



$$\frac{m_i}{m_e} = 100$$

$$\frac{\Delta T_i}{\Delta T_e} = \left(\frac{m_i}{m_e}\frac{T_{i0}}{T_{e0}}\right)^{1/4}$$

Thermodynamics of Reconnection



$$\frac{T_{i1} - T_{i0}}{T_{e1} - T_{e0}} = \left(\frac{m_i}{m_e}\frac{T_{i0}}{T_{e0}}\right)^{1/4}$$

$$\frac{T_{e2}}{T_{e1}} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} \quad \gamma = \frac{5}{3}$$

$$\frac{T_{i2}}{T_{i1}} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

Summary (Plasma Heating)

- Energy Partition of Ion & Electron during Magnetic Reconnection

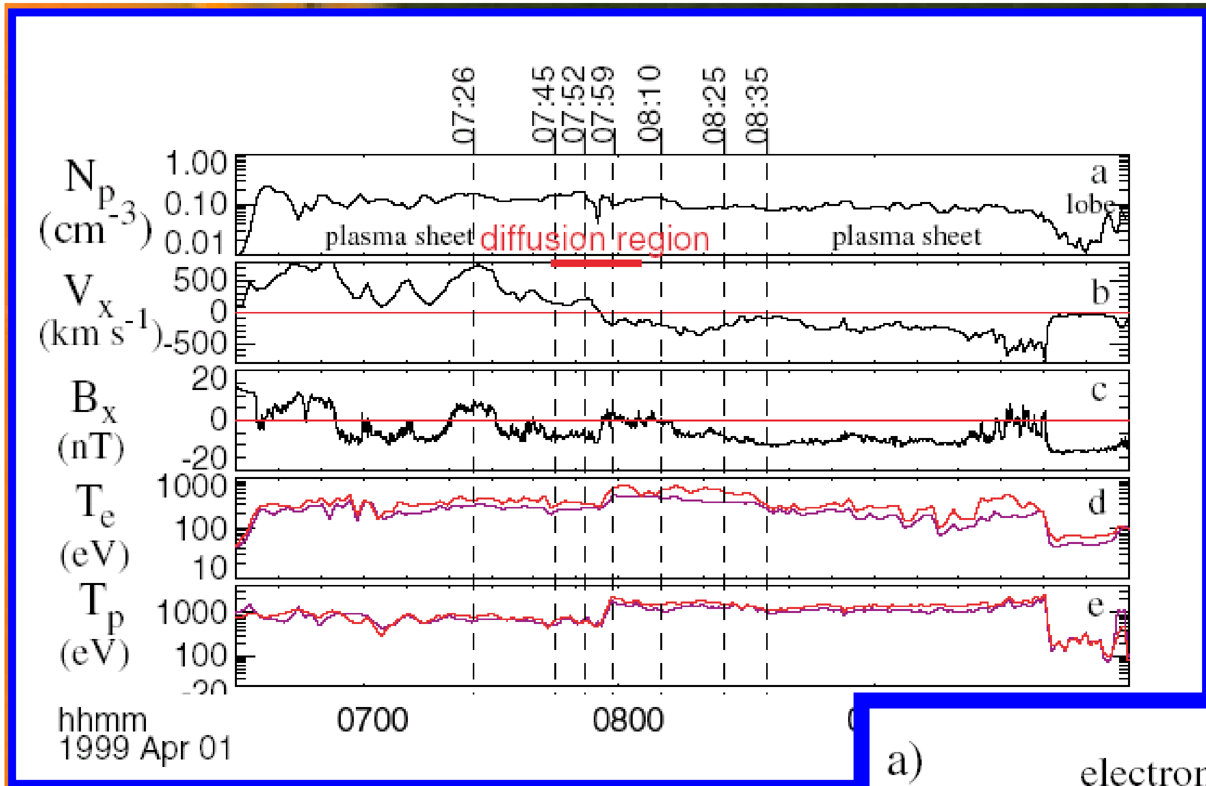
- Two distinct heating stages:
  - Effective Ohmic heating

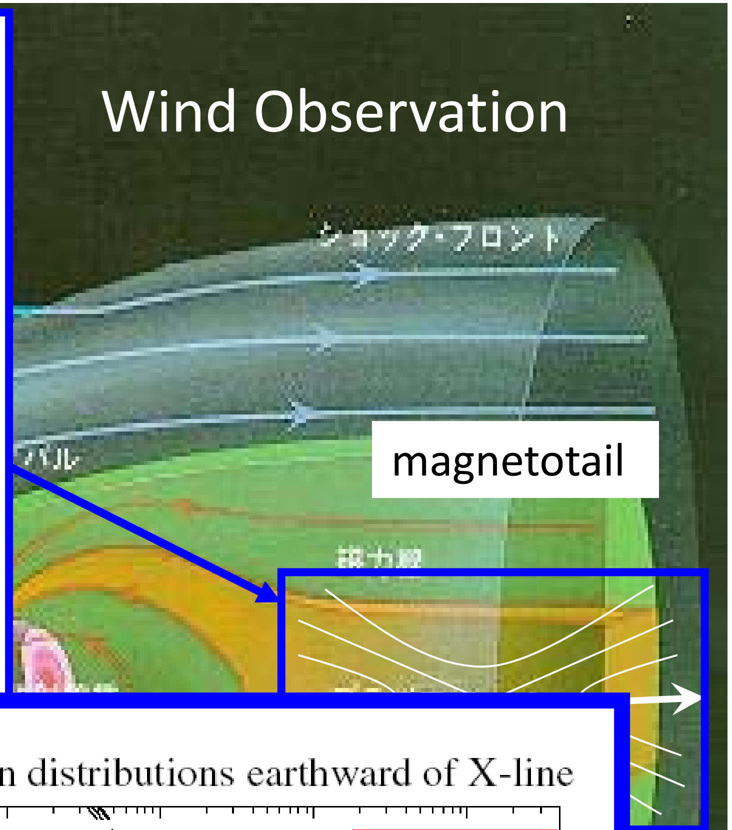
$$\frac{\Delta T_i}{\Delta T_e} = \left(\frac{m_i}{m_e}\frac{T_{i0}}{T_{e0}}\right)^{1/4}$$

  - Adiabatic Compression

$$\frac{D}{Dt}\left(TV^{\gamma-1}\right) = 0$$

Wind Observation



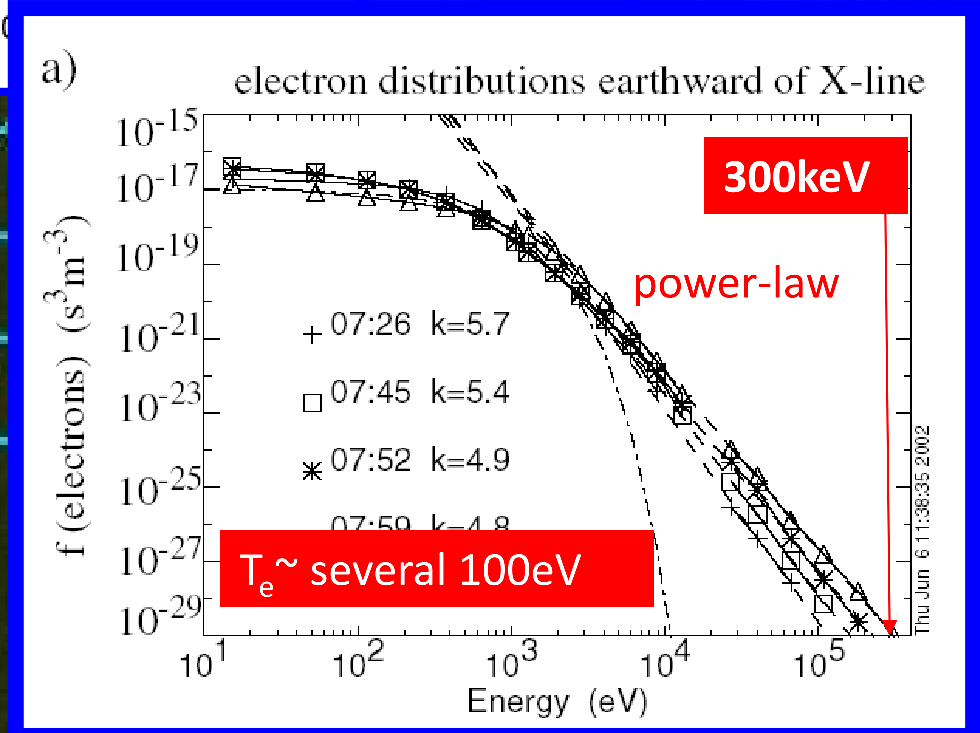


Reconnection signatures

・ flow reversal (Vx)

・ weak magnetic field (Bx)

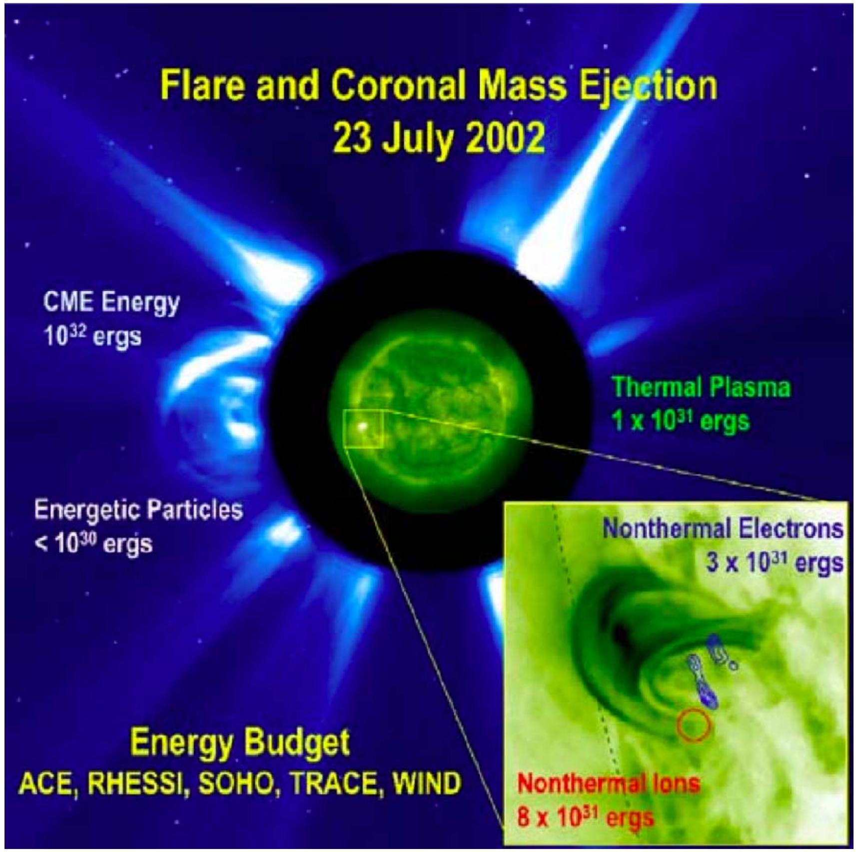
・ hot electron & ion plasmas (Te,Ti)



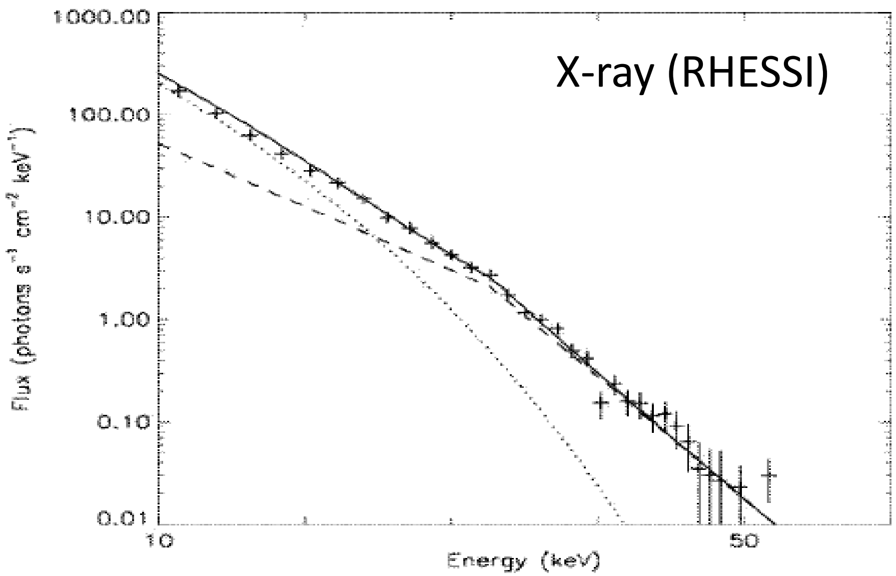
02

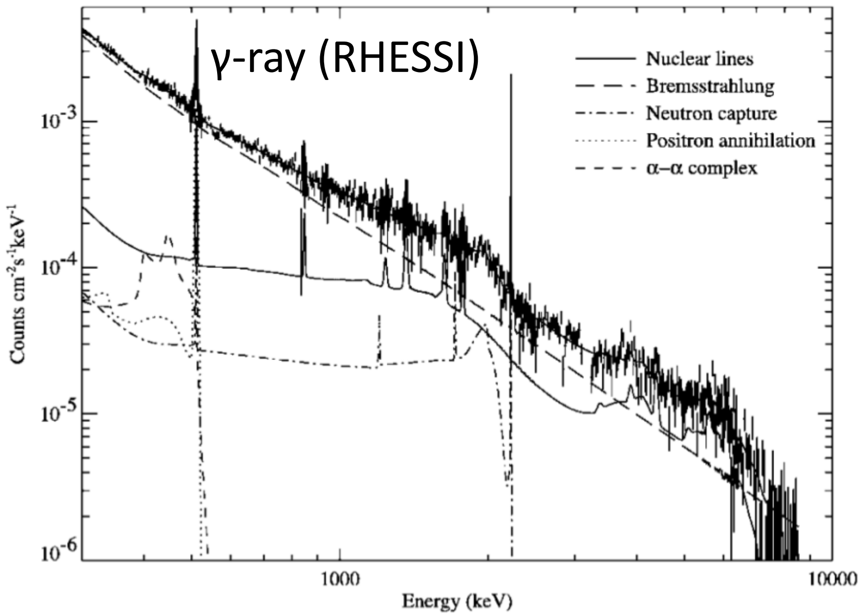
Energetic particles in Solar flares

(GOES class X4.8)



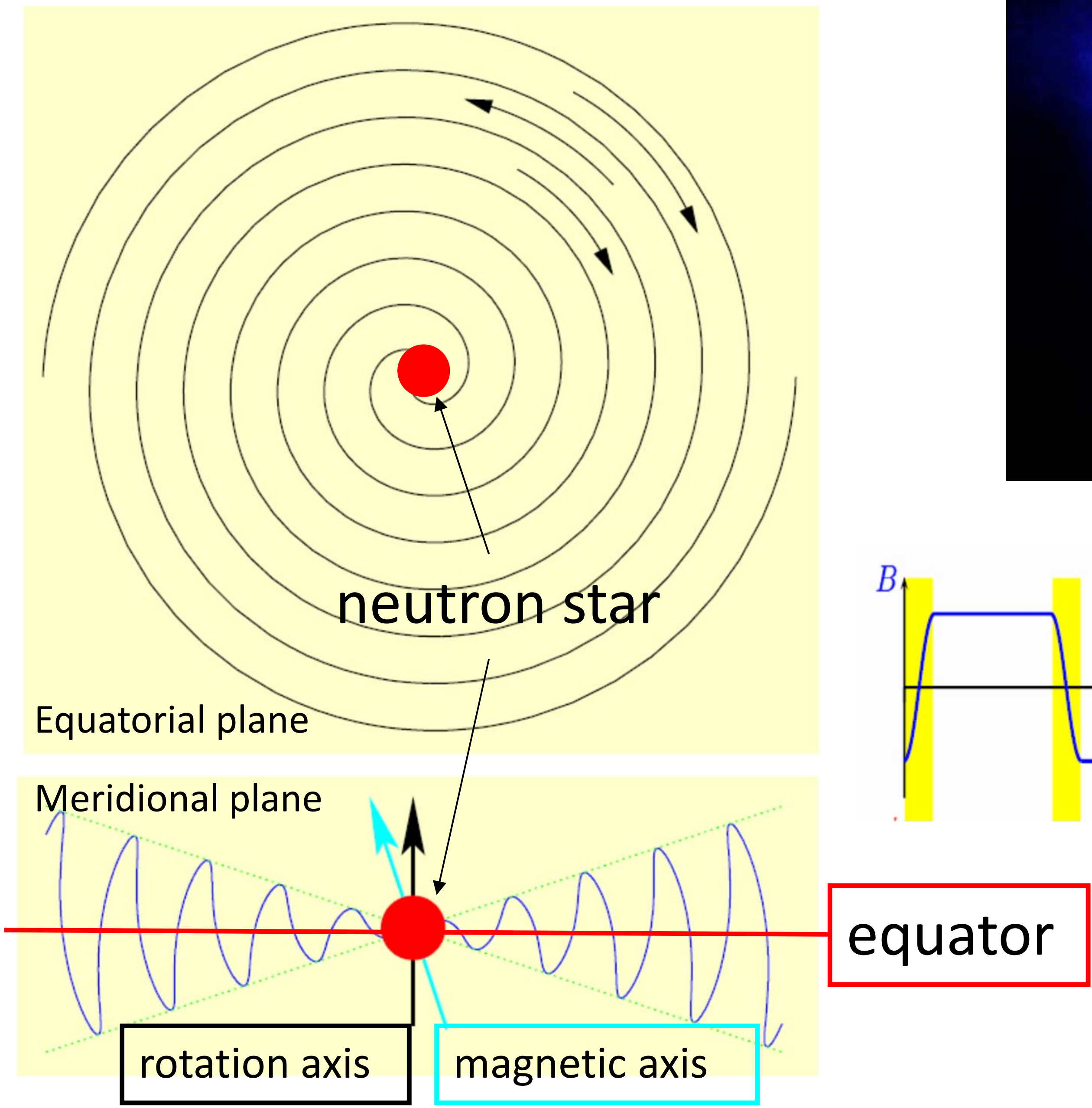
Emslie+ JGR 2004

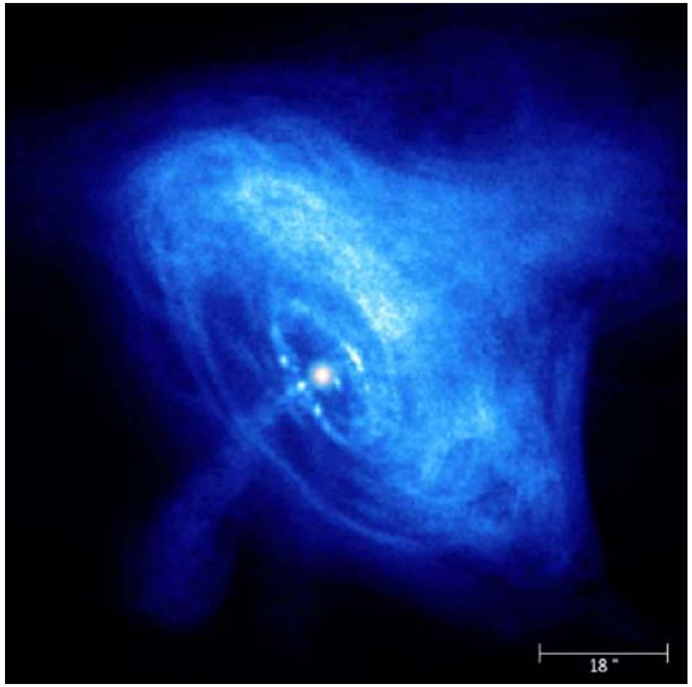


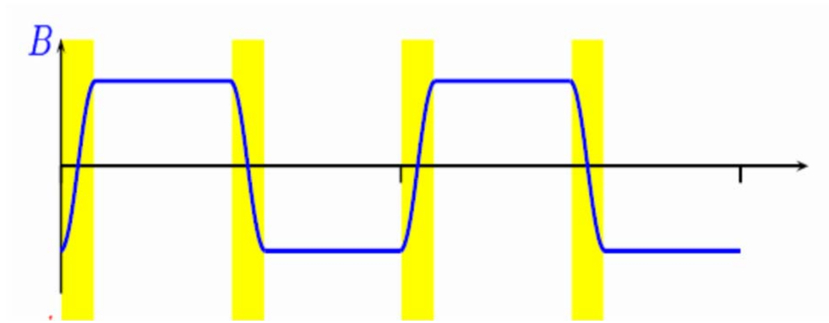


electrons up to tens of MeV,
ions up to tens of GeV
Lin+ ApJ 2003

Striped Wind in Crab Nebula

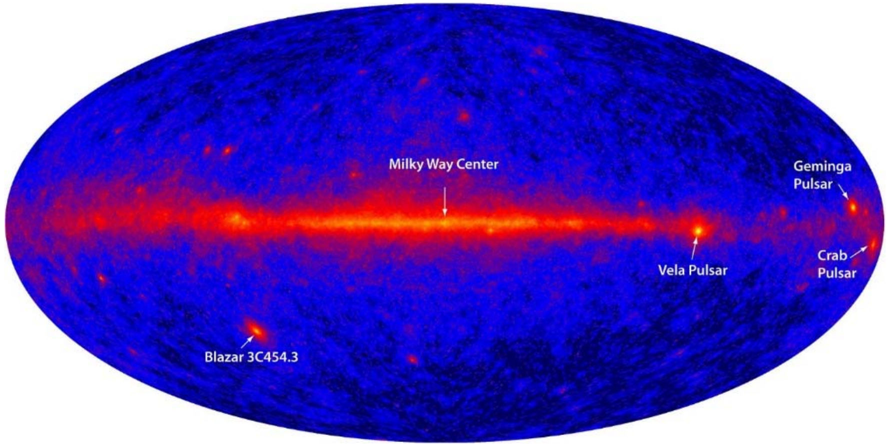




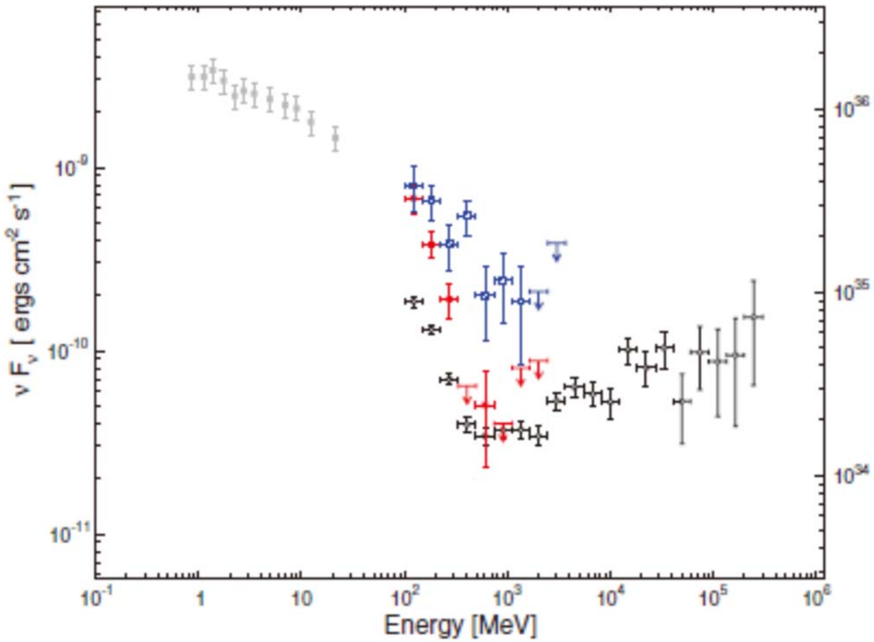


Coroniti, ApJ 1990,
Lyubarsky & Kirk ApJ 2001,
Kirk et al. PRL 2003

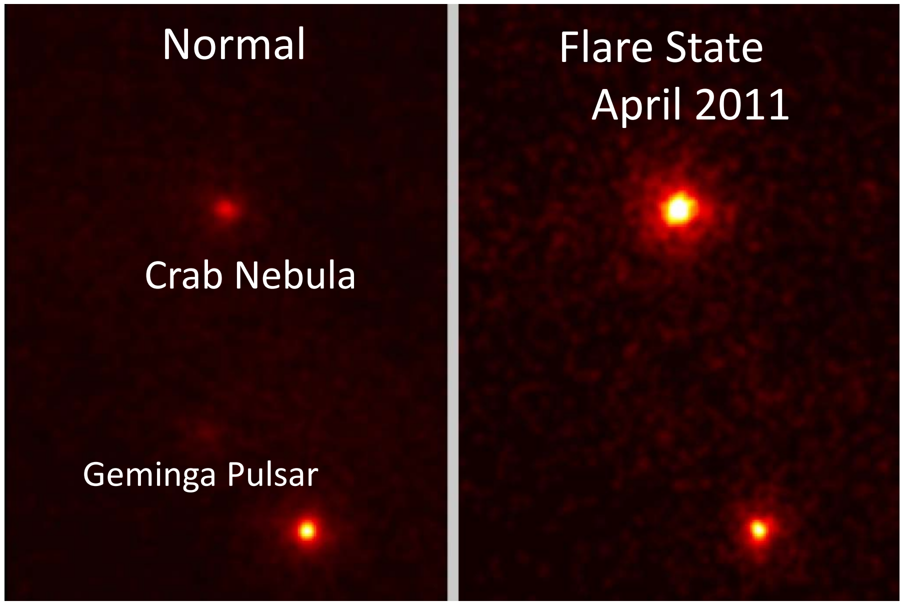
Gamma ray flares in Crab



Enhancement of gamma ray flux (E_γ > 100MeV)



(Tavani + Science 2011; Abdo + Science 2011)



Fermi LAT/R. Buehler

Radiation-reaction limit for synchrotron photon energy

Acceleration $F_e = eE$

Radiation loss $F_{rad} \approx \frac{2}{3} r_e^2 \gamma^2 B_\perp^2$

$F_e = F_{rad}$ $\gamma_{rad} = \left(\frac{3eE}{2 r_e^2 B_\perp^2} \right)^{1/2}$

Synchrotron photon energy

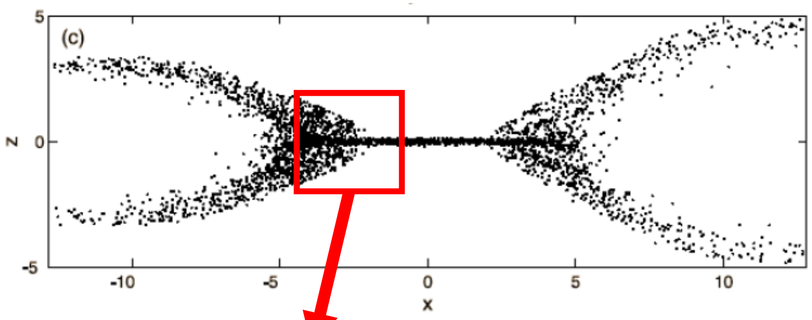
$$\varepsilon_{max} = \frac{3he}{4\pi mc} B_\perp \gamma_{rad}^2 = \frac{9}{4} \frac{mc^2}{\alpha_F} \frac{E}{B_\perp}$$

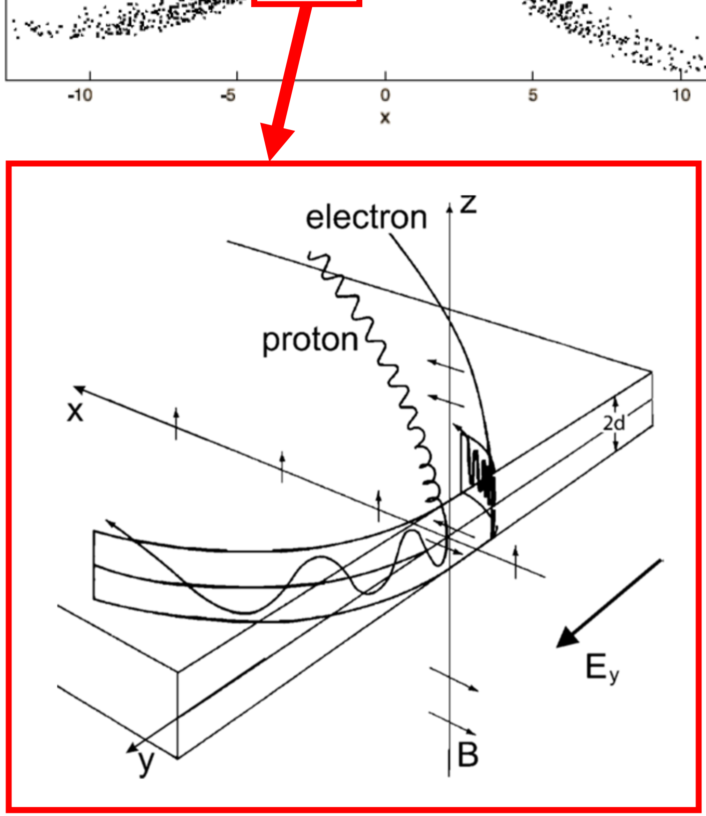
$\alpha_F \approx 1/137$
fine structure const.

$$E = B_\perp \rightarrow \varepsilon_{max} = 160 \text{ MeV}$$

Particle acceleration in X-type region

Pritchett PoP 2005

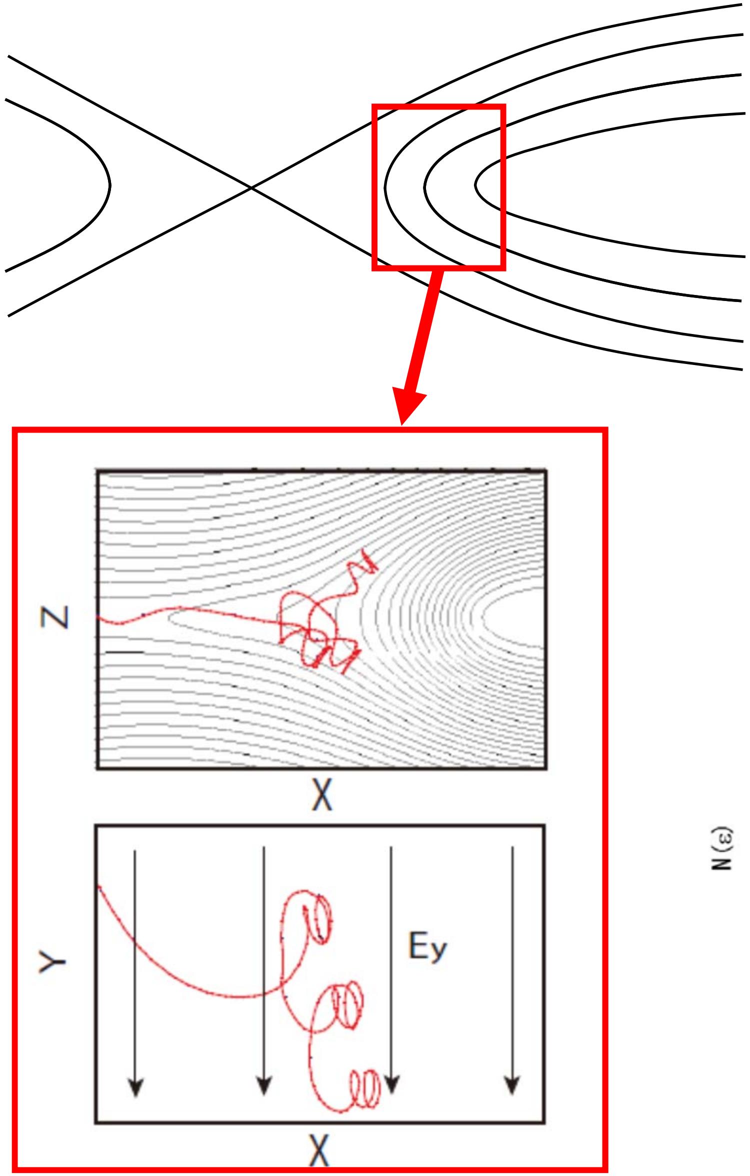




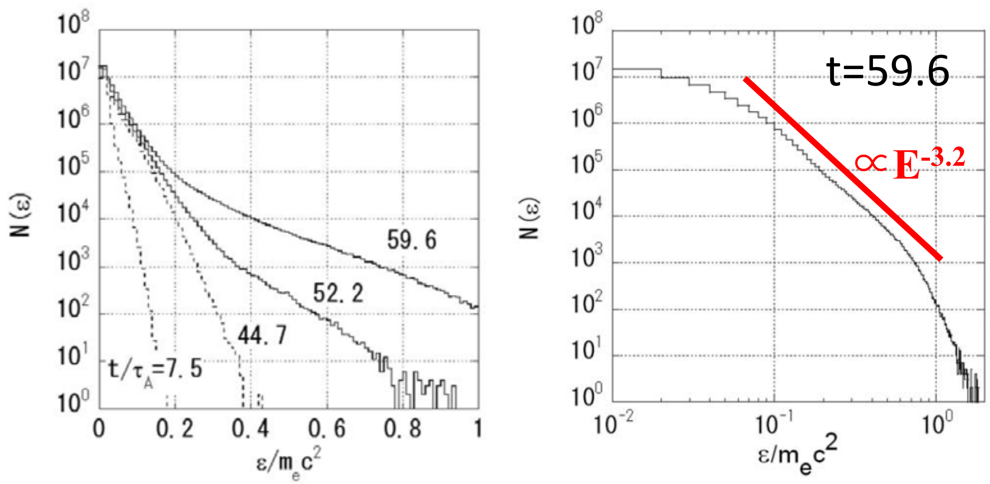
Speiser 1965

- Linear X-line acceleration
  - Direct resonance of particle with inductive electric field in weak magnetic field region
  - Almost free from radiation loss
  - Energetic particle flux is low because of the limited size of X-line

Acceleration in magnetic field pileup region

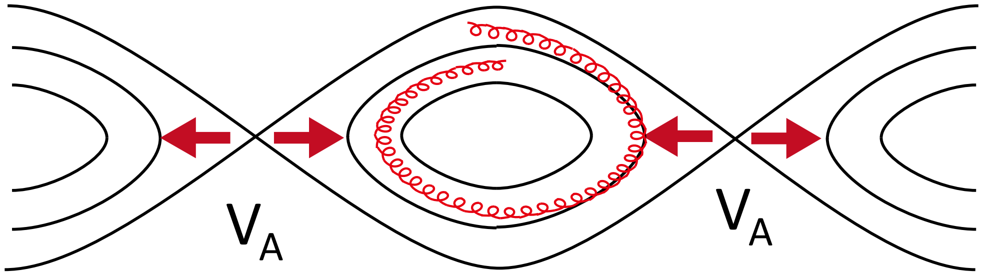


- Acceleraton in B-file pileup region
  - gradB & curvB drift acceleration around the magnetic field 2pileup region
  - If adiabatic, $p_\perp{}^2/B$=const.
  - Energetic particle flux is high



MH JGR 2005

Acceleration inside magnetic island

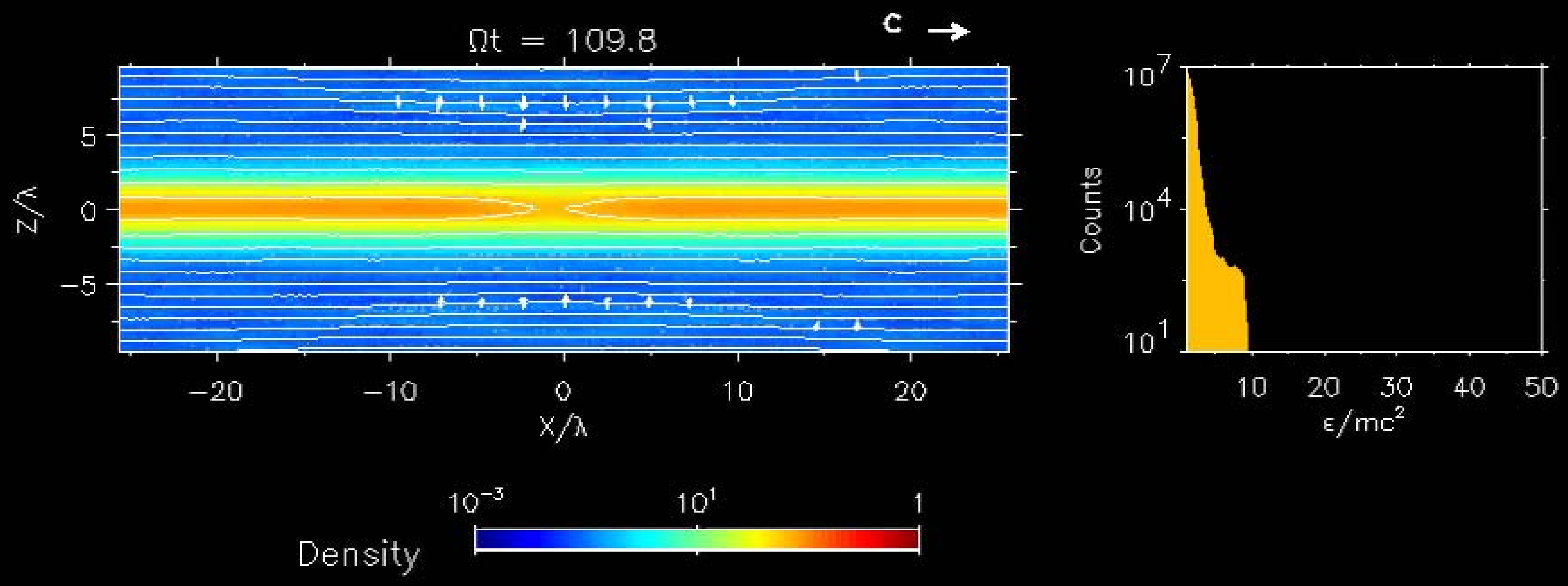


Drake+ Nature 2006

- Shrinking Island Acceleration
  - trapped particles inside the magnetic island
  - If adiabatic, $p_{//}L$=const.

Maximum attainable energy $E_{max} = eEL$

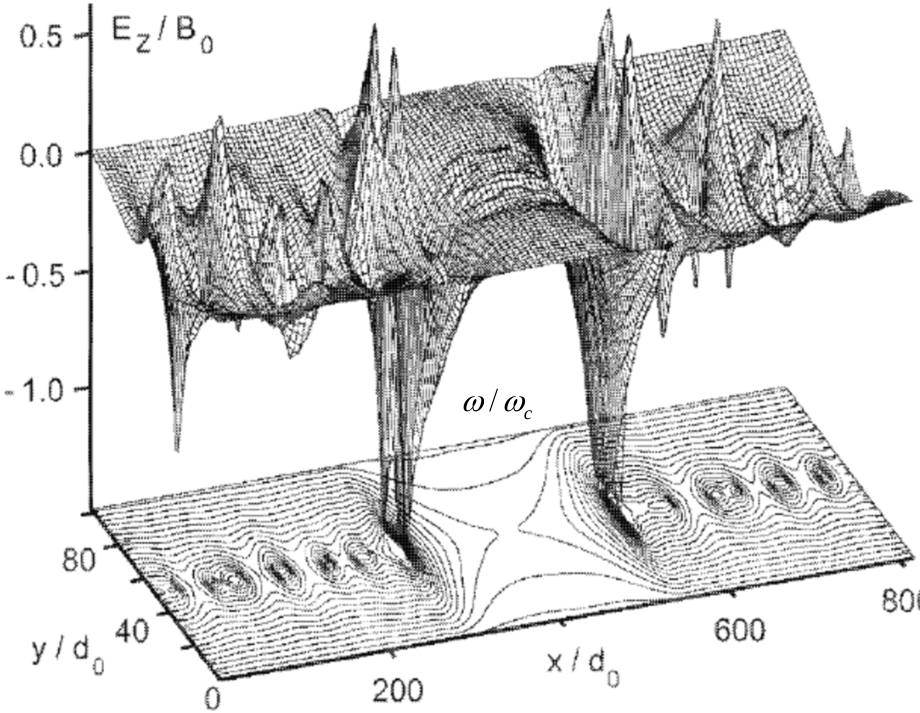
Relativistic Reconnection (electron & positron)



Non-thermal particle acceleration
due to relativistic Speiser motion

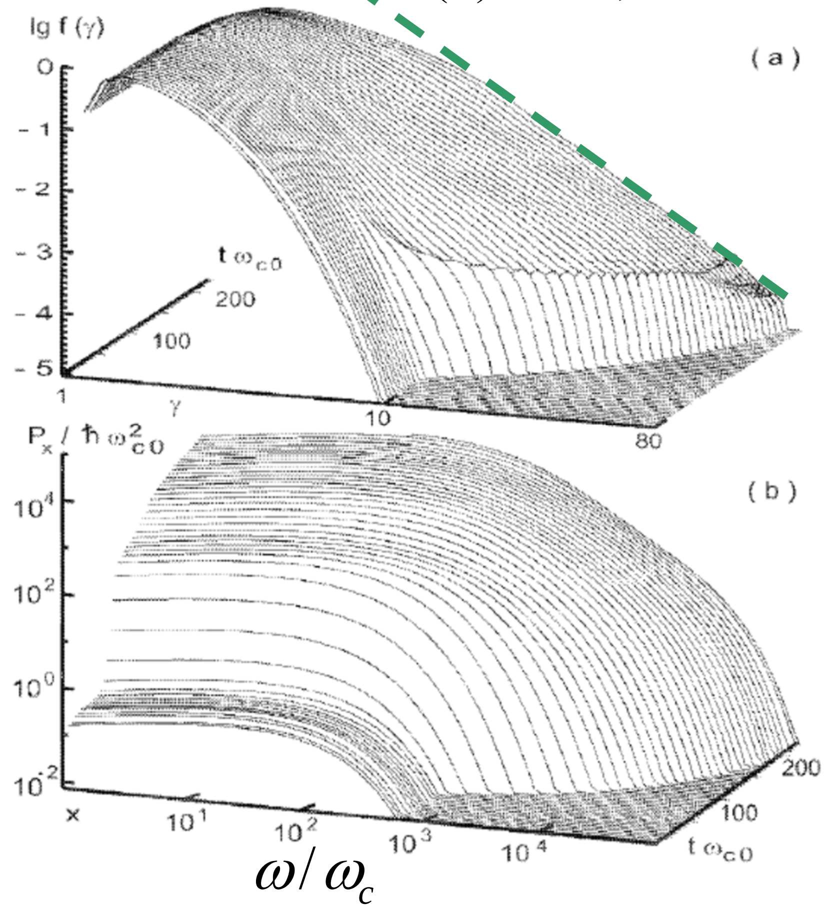
Zenitani & MH, ApJ 2001

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

Power-Law Spectrum in Reconnection

- Acceleration rate

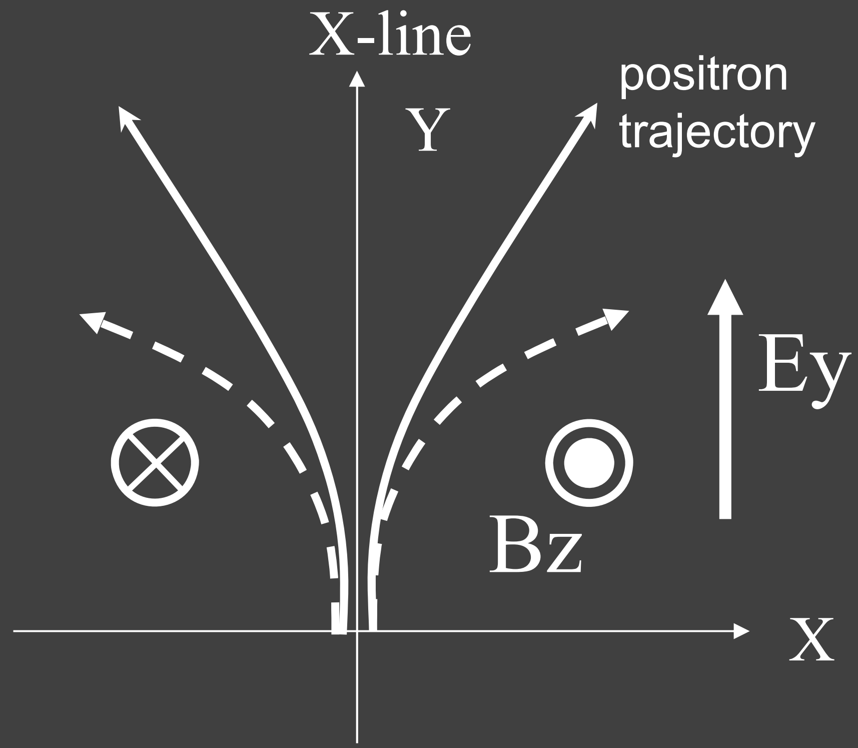
$$\frac{d\varepsilon}{dt} \approx eEc$$

- Loss rate

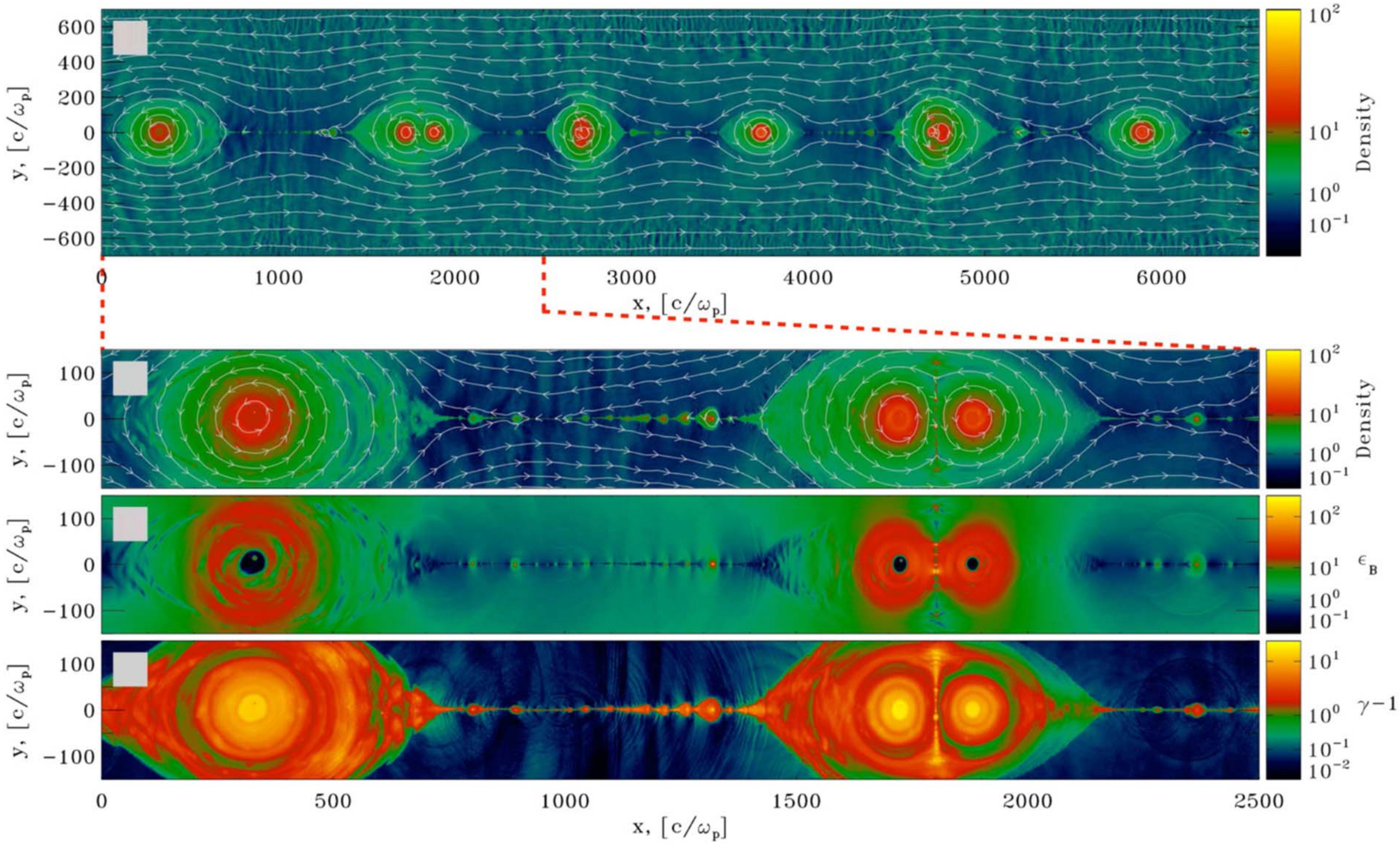
$$\frac{1}{N}\frac{dN}{dt} \approx -\frac{1}{\tau(\varepsilon)} \approx -\frac{m_0 c^2}{\varepsilon}\frac{eB}{m_0 c}$$

- Energy Spectrum

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

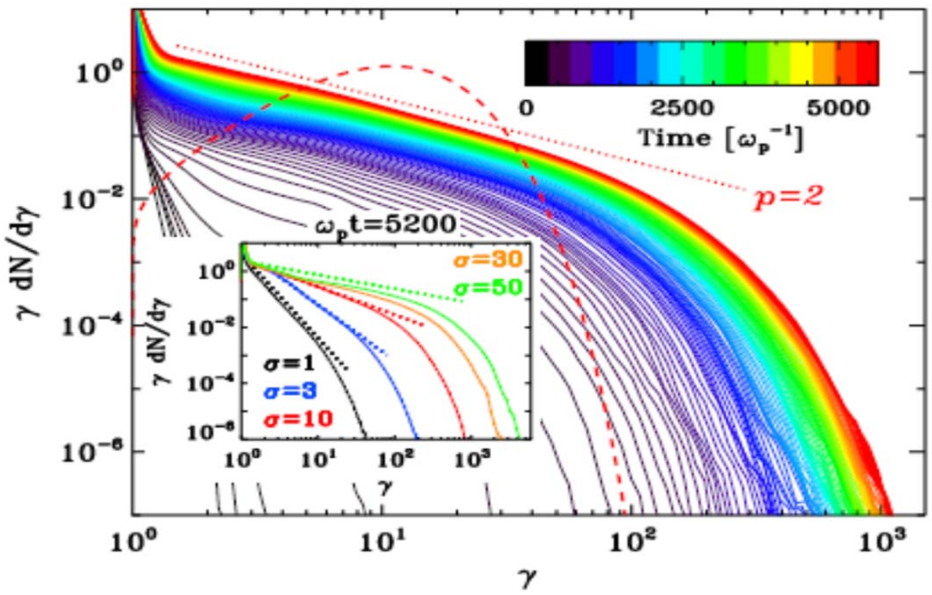


Plasmoid-dominated Reconnection



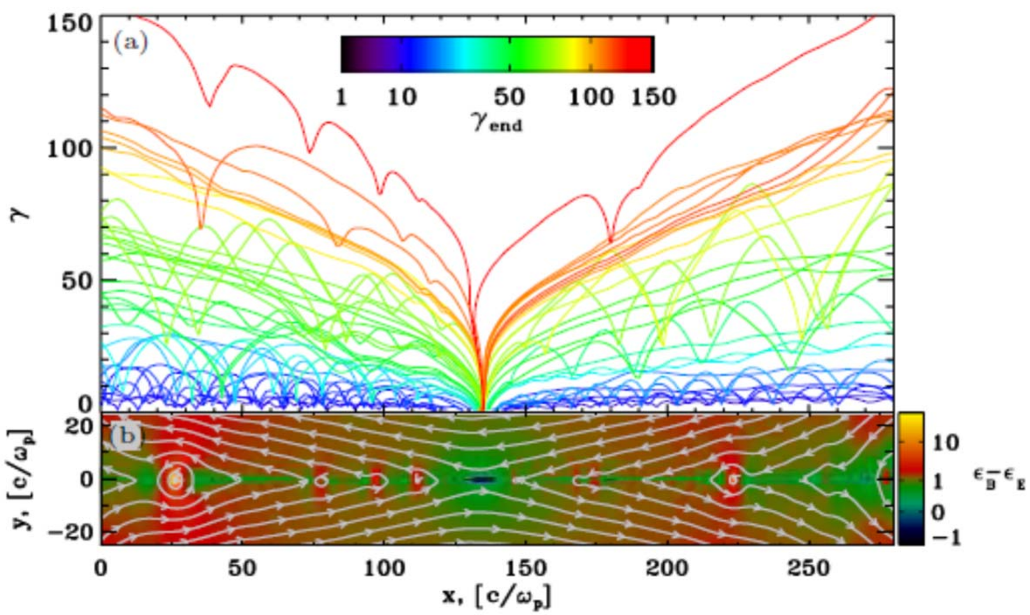
Sironi & Spitkovsky ApJL 2014

Harder Energy Spectrum for large σ



Sironi & Spitkovsky ApJL 2014

(cf. Cerutti+ ApJ 2012; Melzani+ AA 2014; Guo+ ApJ 2015,….)

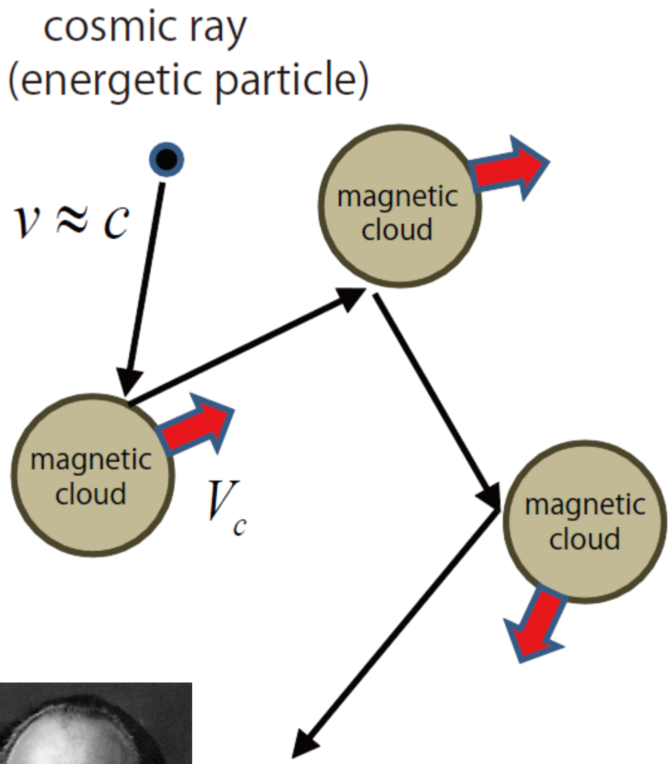


Main Acceleration occurs around X-type neutral point,

In addition, stochastic acceleration during the interaction with many plasmoids

Acceleration in many magnetic islands

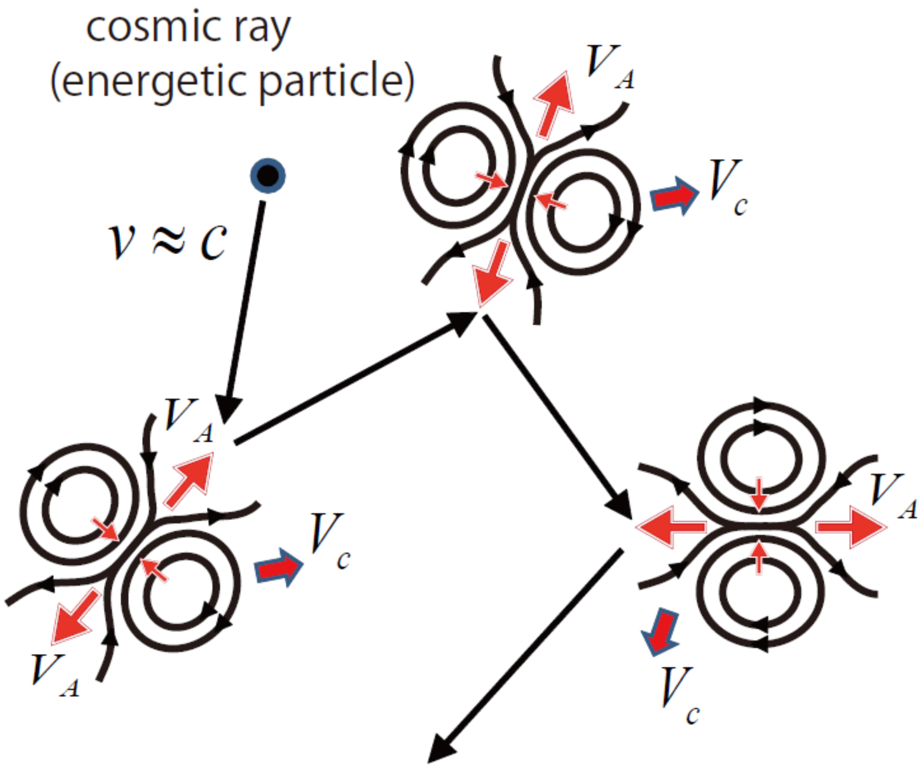
2nd order Acceleration



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

Fermi, Phys. Rev. (1949)

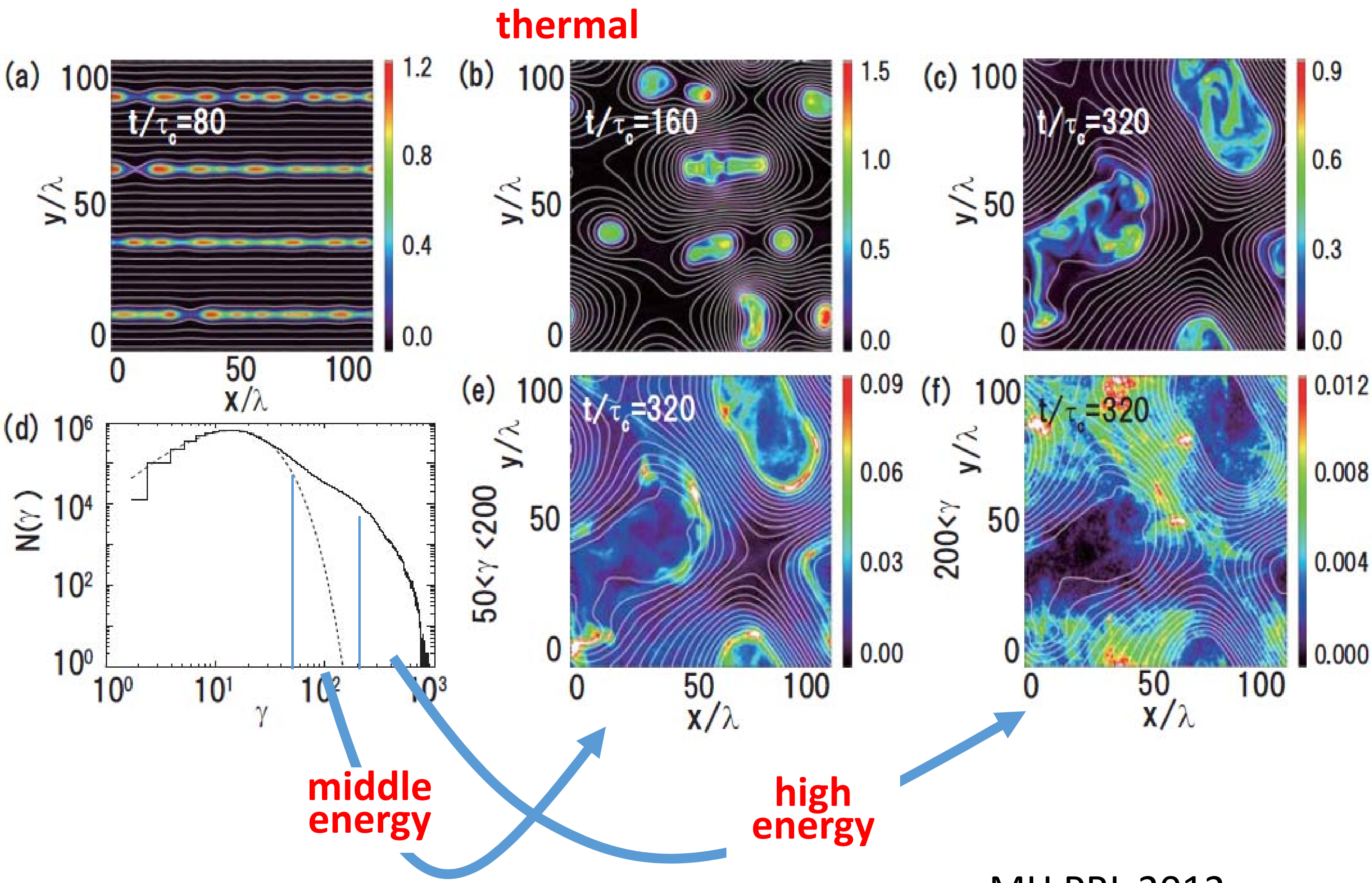
1st order Acceleration



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

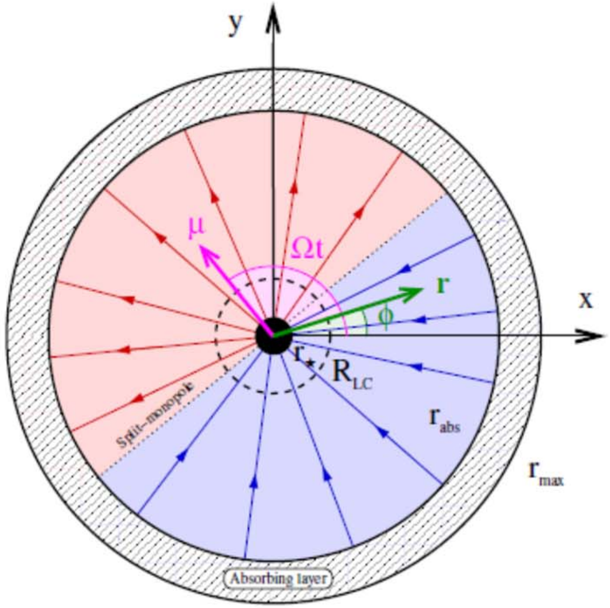
MH PRL (2012)

Acceleration in Many Magnetic Islands



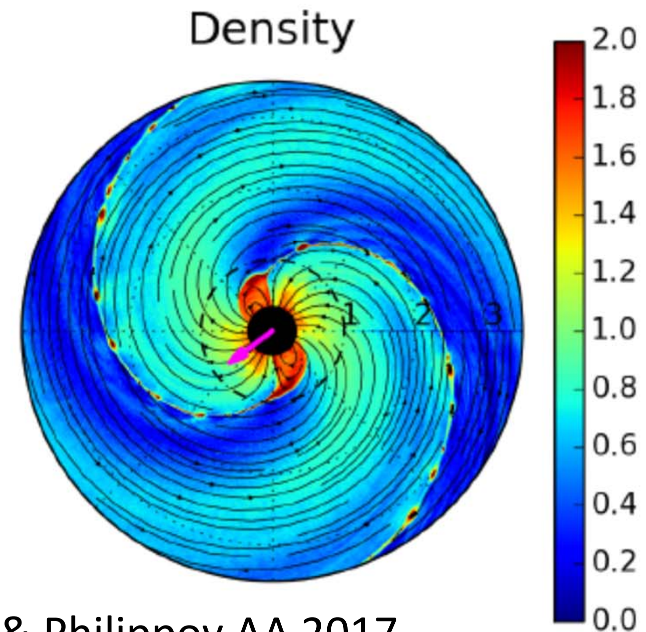
MH PRL 2012

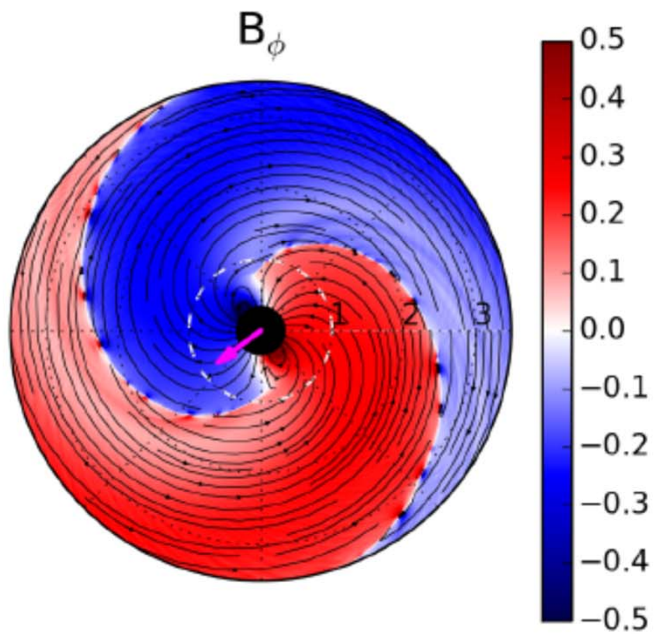
Reconnection in Striped Pulsar Wind



σ problem: High σ (inner magnetosphere) -> Low σ (Nebula) , magnetic field dissipation is necessary

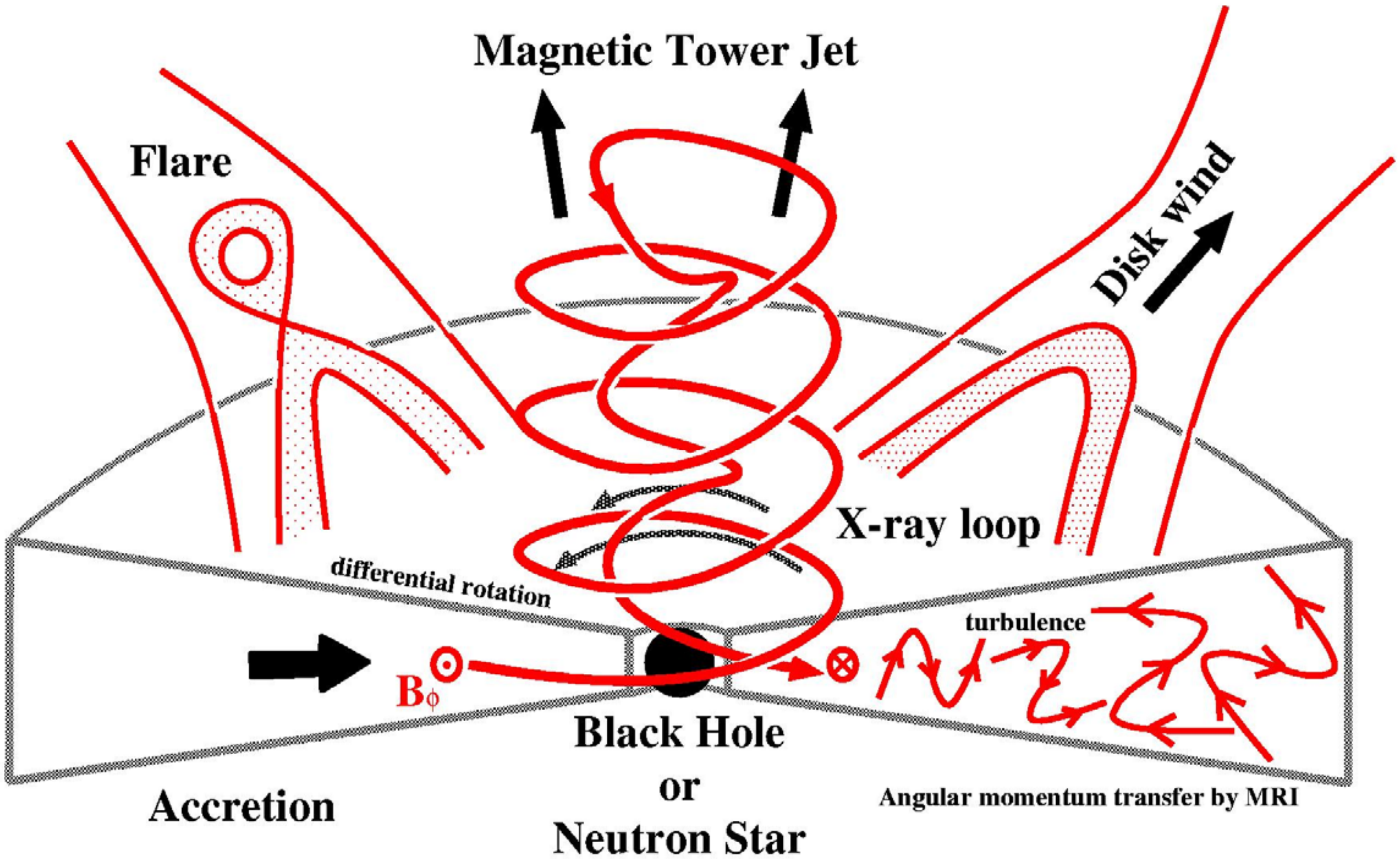
Simulation Setup:
2D PIC, Split-Monopole B model,
Radiation reaction,





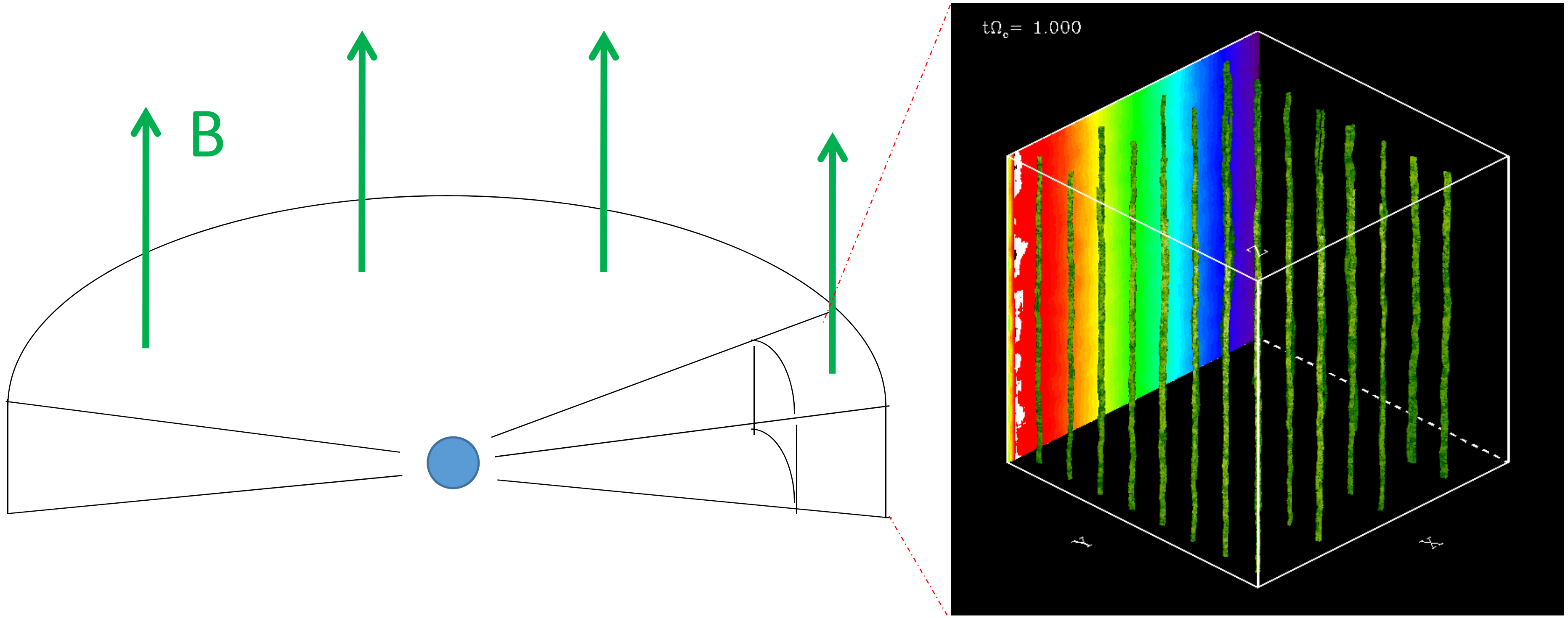
Cerutti & Philippov AA 2017

Reconnection in Accretion Disk



Courtesy of Kato

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 ApJ 2014, MH PRL 2015

Basic Equations

Local, non-inertia frame rotating with angular velocity Ω

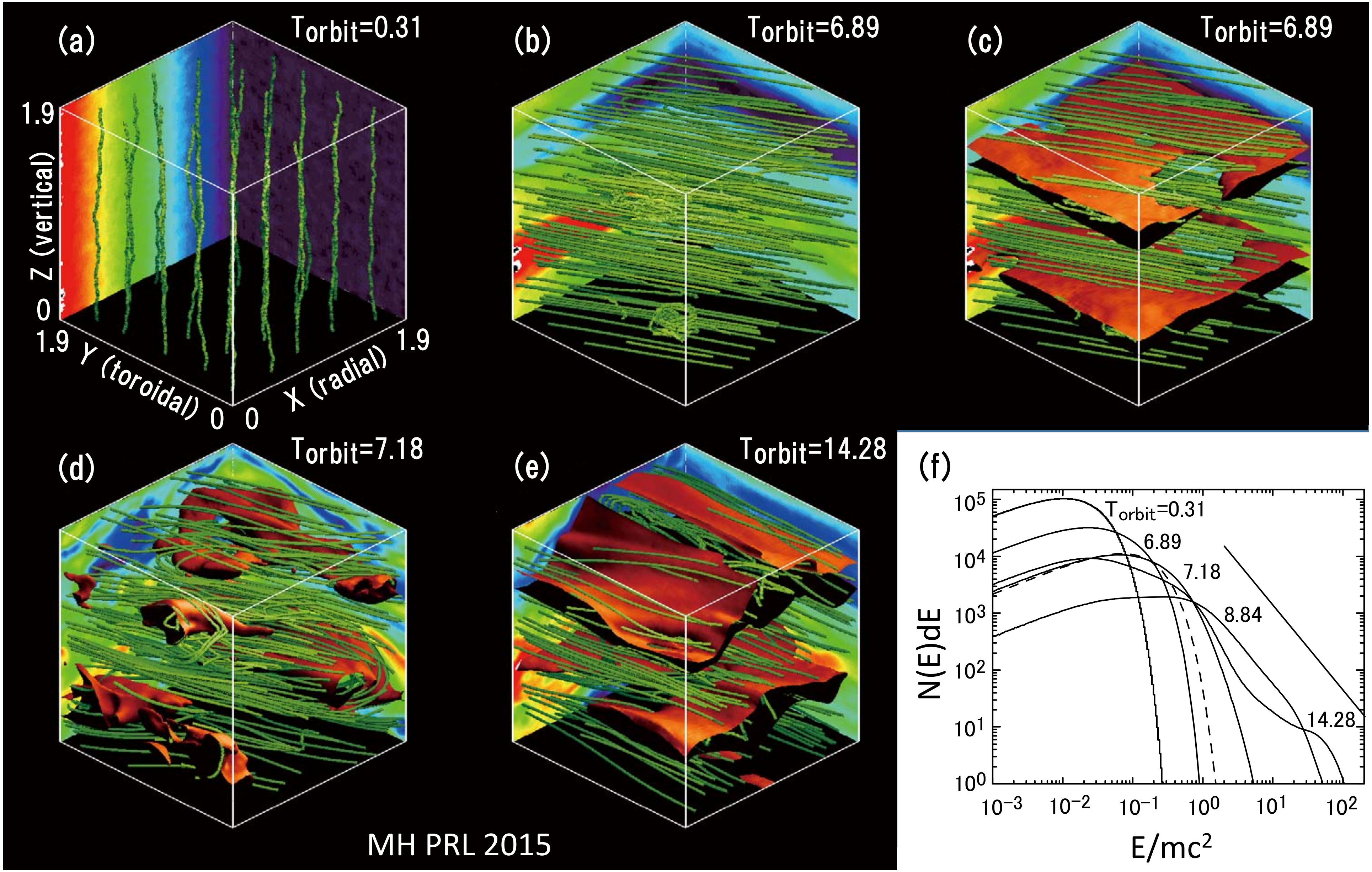
$$\begin{aligned}
\frac{1}{c}\frac{\partial \vec{B}}{\partial t} &= -\nabla \times \vec{E}, \\
\nabla \cdot \vec{B} &= 0, \\
\frac{1}{c}\frac{\partial}{\partial t}\left(\vec{E} - \frac{\vec{v}_0}{c} \times \vec{B}\right) &= \nabla \times \vec{B}^* - \frac{4\pi}{c}\vec{J}, \\
\nabla \cdot \left(\vec{E} - \frac{\vec{v}_0}{c} \times \vec{B}\right) &= 4\pi\rho_c,
\end{aligned}$$

$$\text{where } \vec{v}_0(r) = \Omega_0 \vec{e}_z \times \vec{r}$$

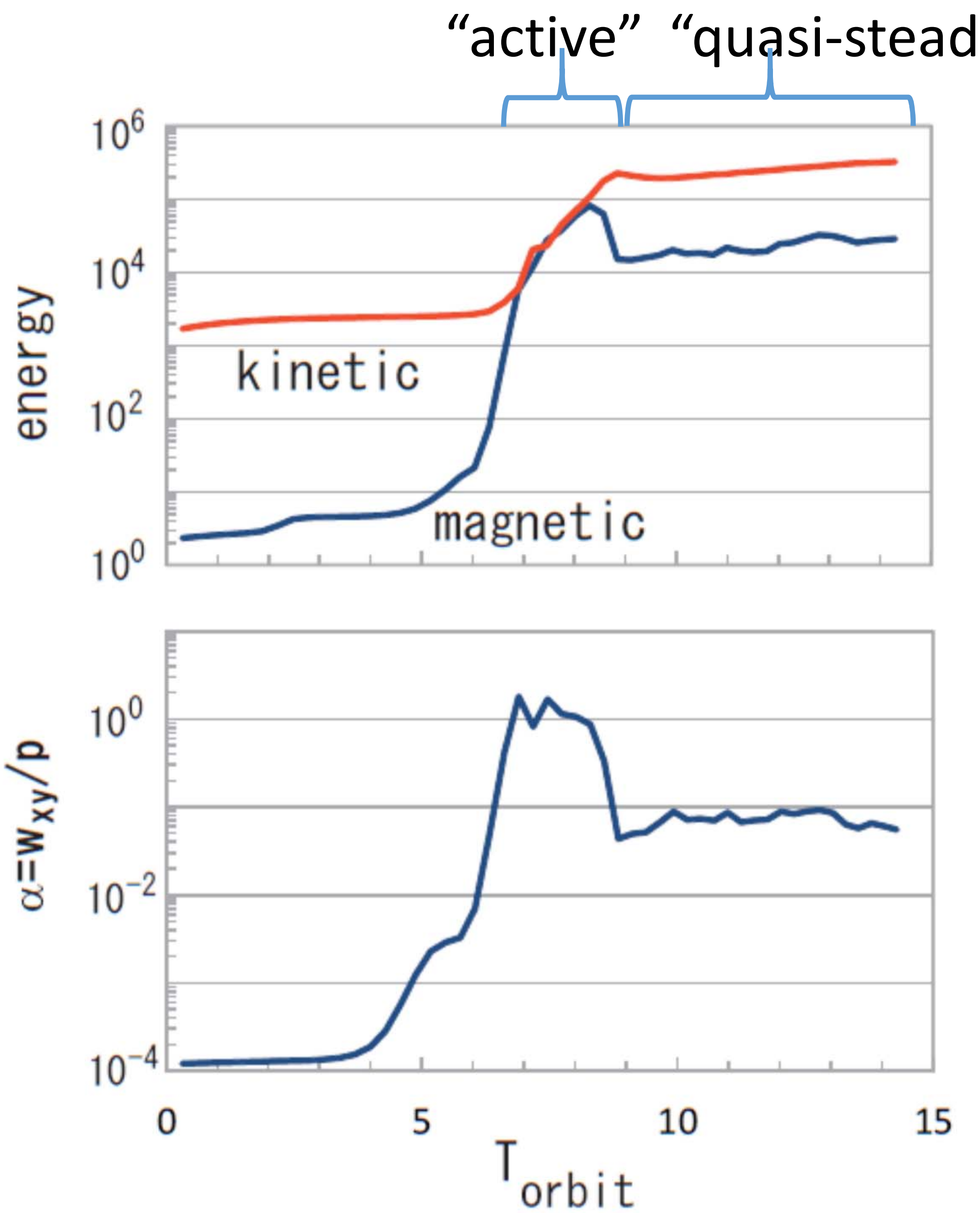
$$\begin{aligned}
\frac{d\vec{x}}{dt} &= \vec{v}, \\
\frac{d\vec{p}}{dt} &= e(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}) - m\gamma(2\vec{\Omega}_0 \times \vec{v} - 2q\Omega_0^2 x \vec{e}_x).
\end{aligned}$$

Keplerian disk with a tidal expansion

Particle Acceleration in Accretion Disks



Energy and Stress Tensor Evolutions



Initial plasma β = 1540,
active phase β ~ O(1)
quasi-steady-state β ~ O(10)

stress tensors

$$w_{xy} = \rho v_x \delta v_y - \frac{B_x B_y}{4\pi} + \frac{(p_{\parallel} - p_{\perp})}{B^2} B_x B_y$$

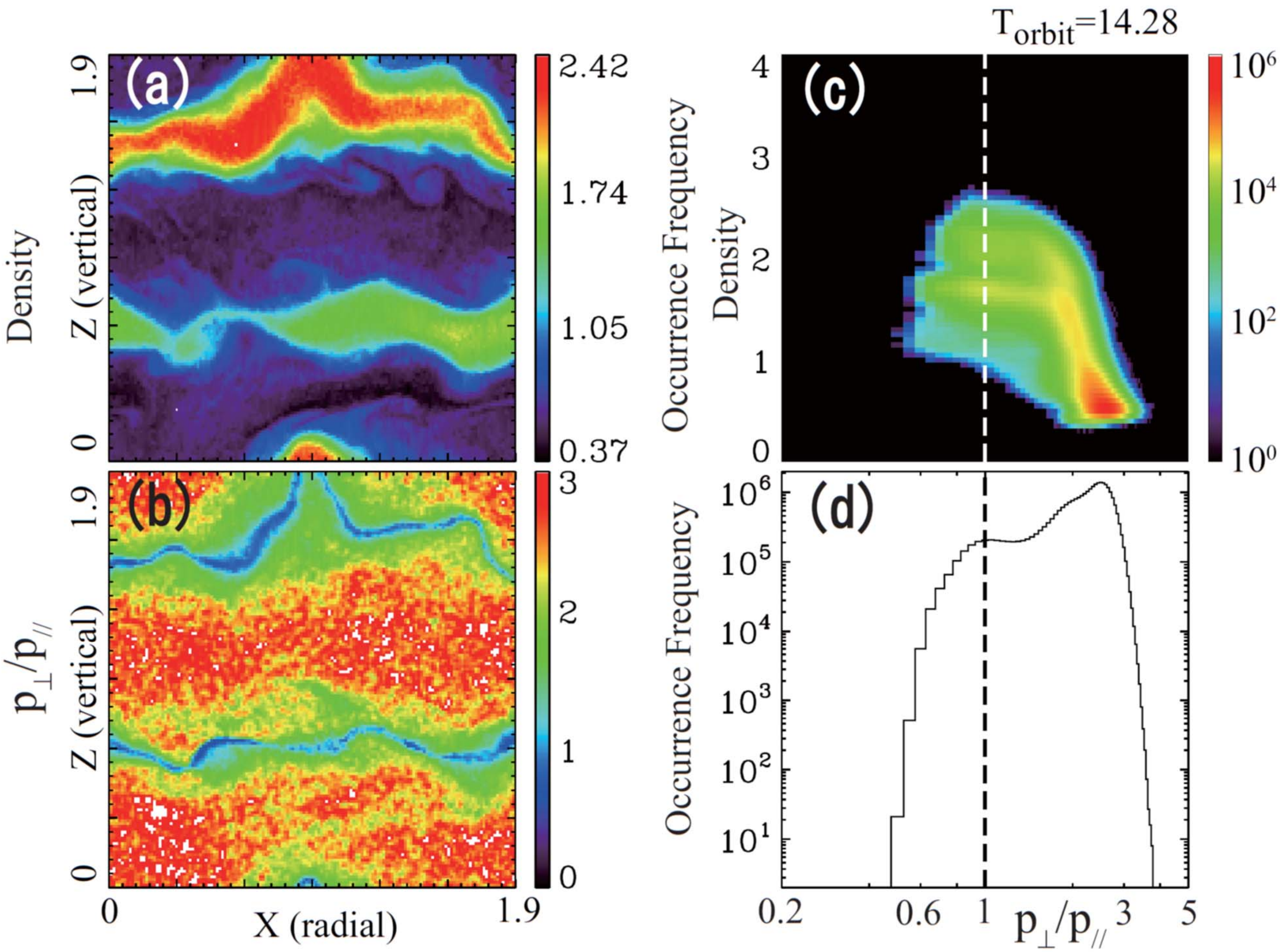
$$\alpha = \frac{w_{xy}}{p} \approx -\frac{B_x B_y}{4\pi p}$$

$$= -\frac{2 B_x B_y}{B^2} \frac{B^2}{8\pi p} \approx \frac{B^2}{8\pi p} = \frac{1}{\beta}$$

α(kinetic) ~ O(0.1)

α(kinetic)/α(MHD) > 10 -100

Reconnection is suppressed by $p_{\|} > p_{\perp}$



Summary (Particle Acceleration)

- Many astrophysical objects suggest that magnetic reconnection can generate nonthermal particles

- Plasmoid-dominated reconnection with many magnetic islands (X-type acceleration, 1st order Fermi acceleration, rapid energy dissipation,…)

- Reconnection in global astrophysical systems such as accretion disks & pulsar wind (nonthermal particles, enhanced angular momentum transport,...)

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