THE UNIVERSITY OF TOKYO

# Thermodynamical Approach of Energy Partition During Magnetic Reconnection

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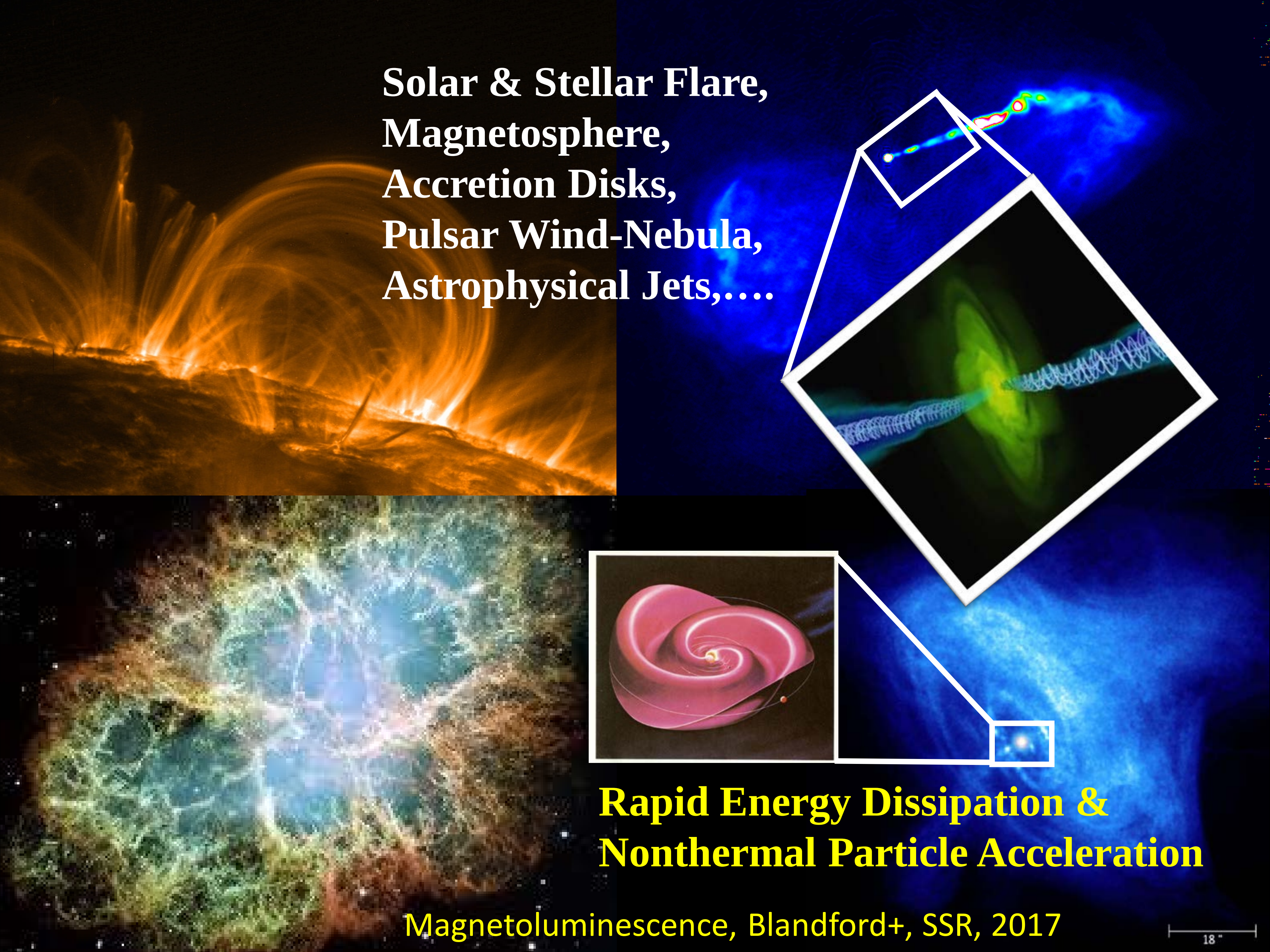

Solar & Stellar Flare,
Magnetosphere,
Accretion Disks,
Pulsar Wind-Nebula,
Astrophysical Jets,….
Rapid Energy Dissipation &
Nonthermal Particle Acceleration
Magnetoluminescence, Blandford+, SSR, 2017
18"

# 3D High Mach Number Shock

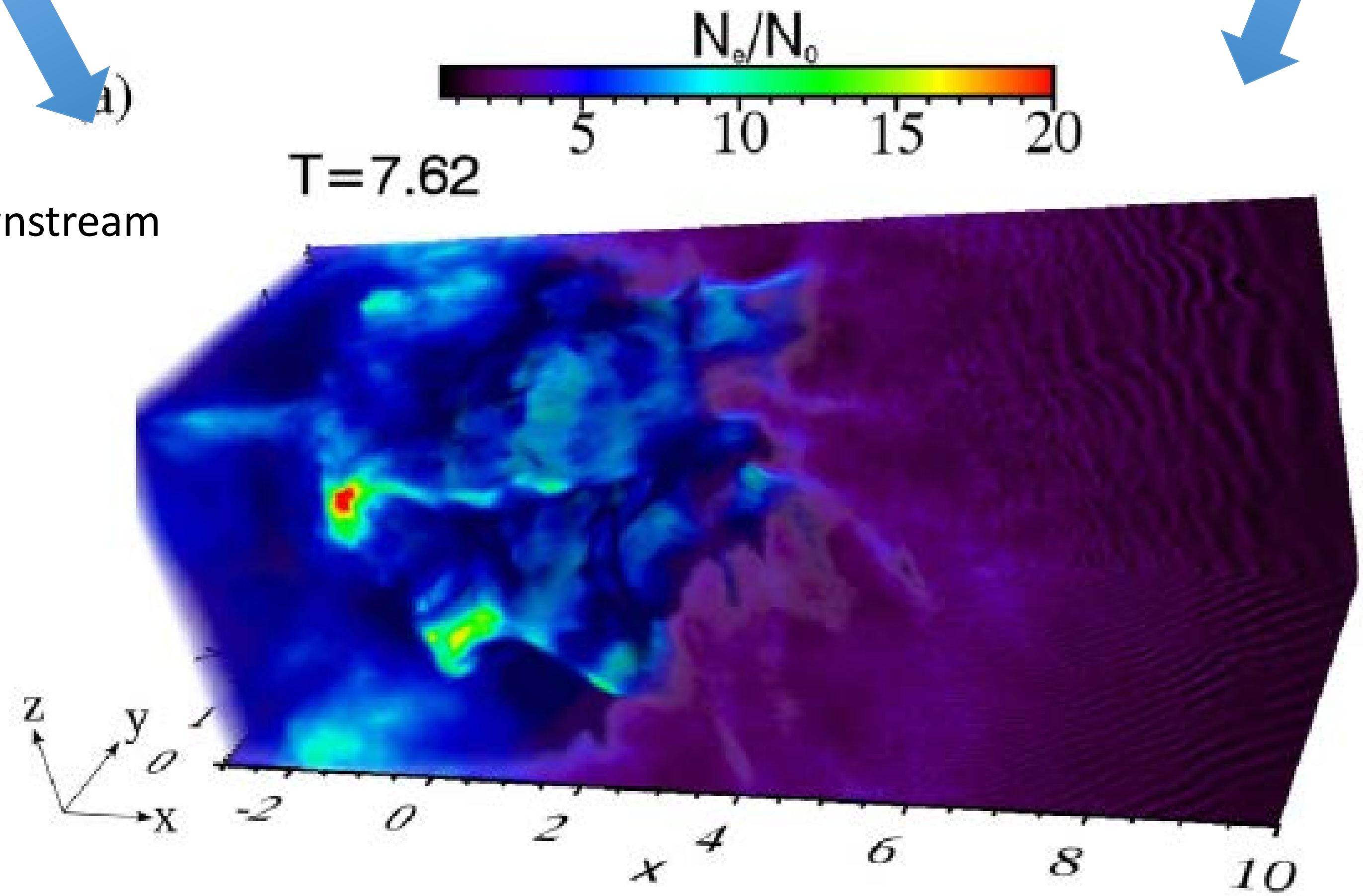
**Ion Weibel**

**Buneman**

upstream

downstream

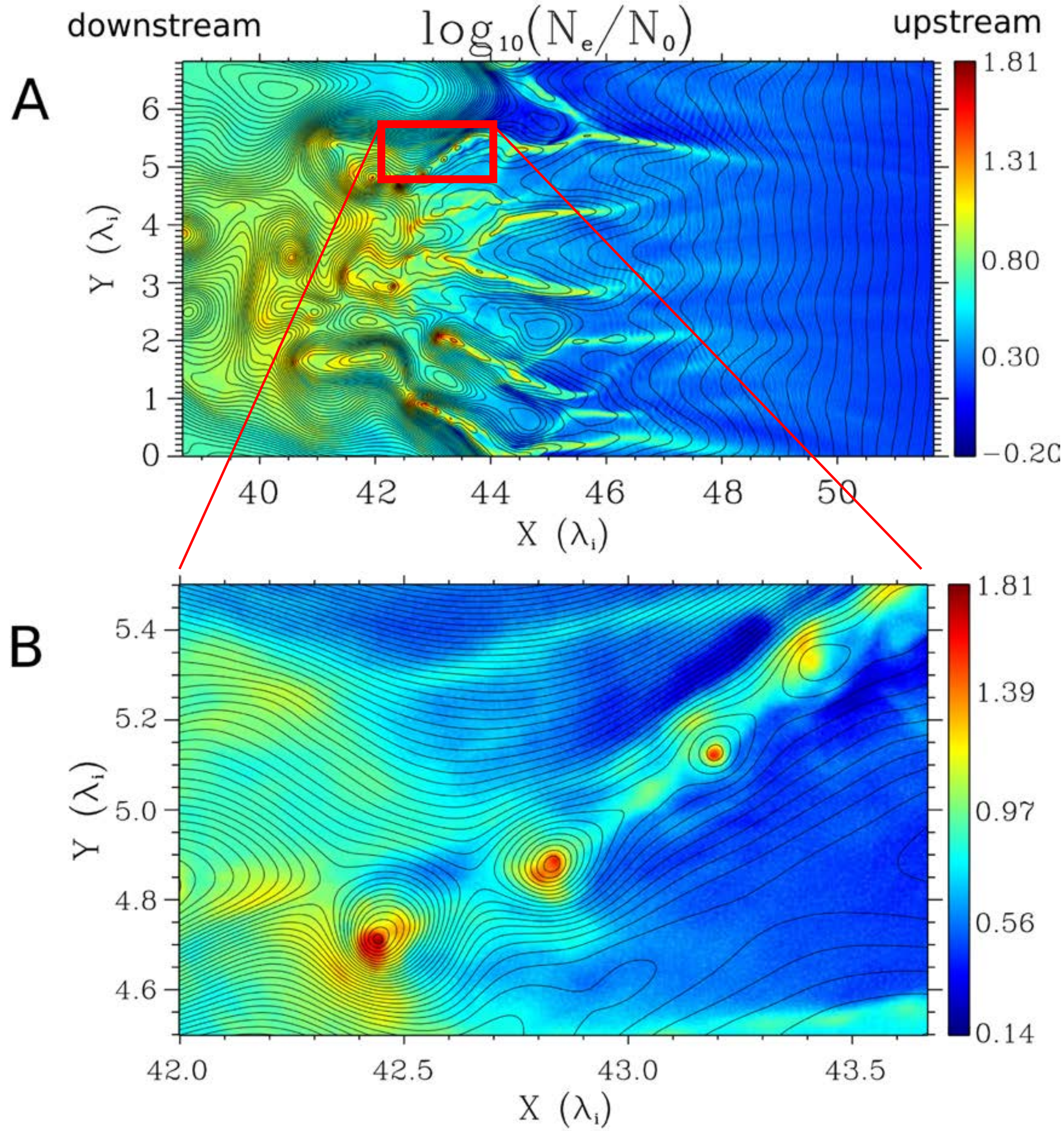
$M_A$=20, $m_i/m_e$=64, $\omega_{pe}/\omega_{ce}$=10




Matsumoto, Amano, Kato & MH, PRL 2017

# Ion Weibel and Magnetic Reconnection

$M_A$=42, $m_i/m_e$=225, $\omega_{pe}/\omega_{ce}$=10




fast flow

Ion reflection from shock front

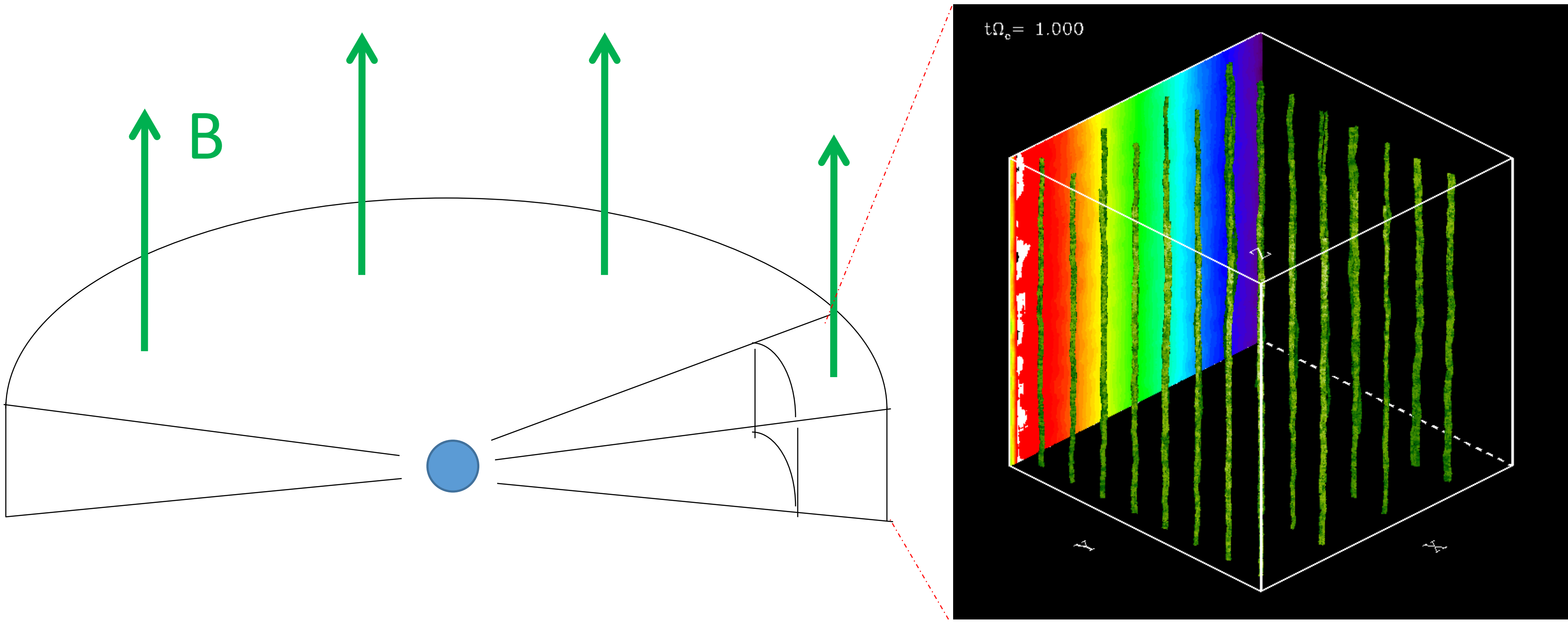
Temperature anisotropy

Weibel instability & B filed generation

Magnetic reconnection

Matsumoto, Amano, Kato & MH, Science 2015

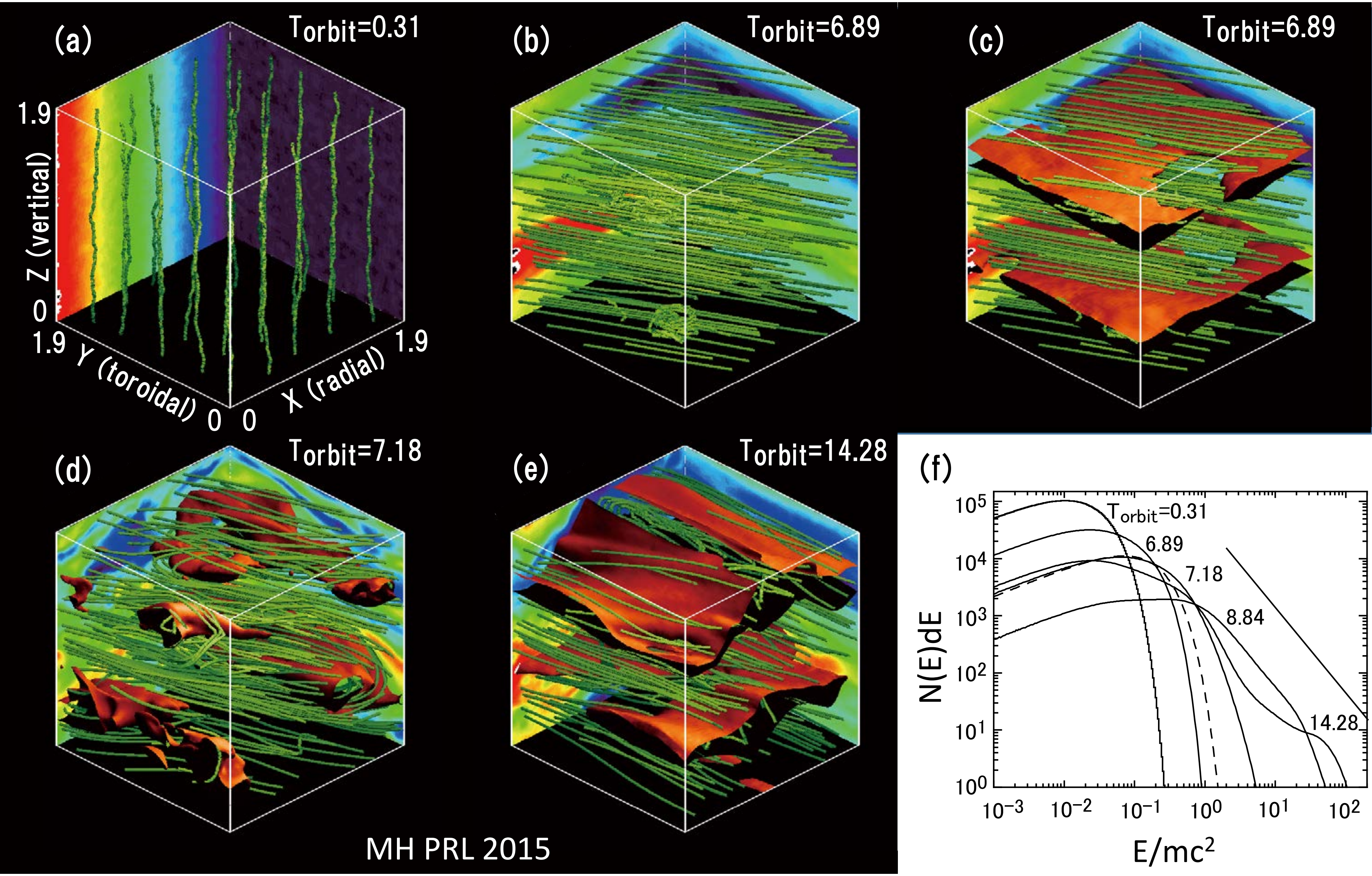
# MRI and Reconnection in PIC simulation




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

# Particle Acceleration in Accretion Disks




MH PRL 2015

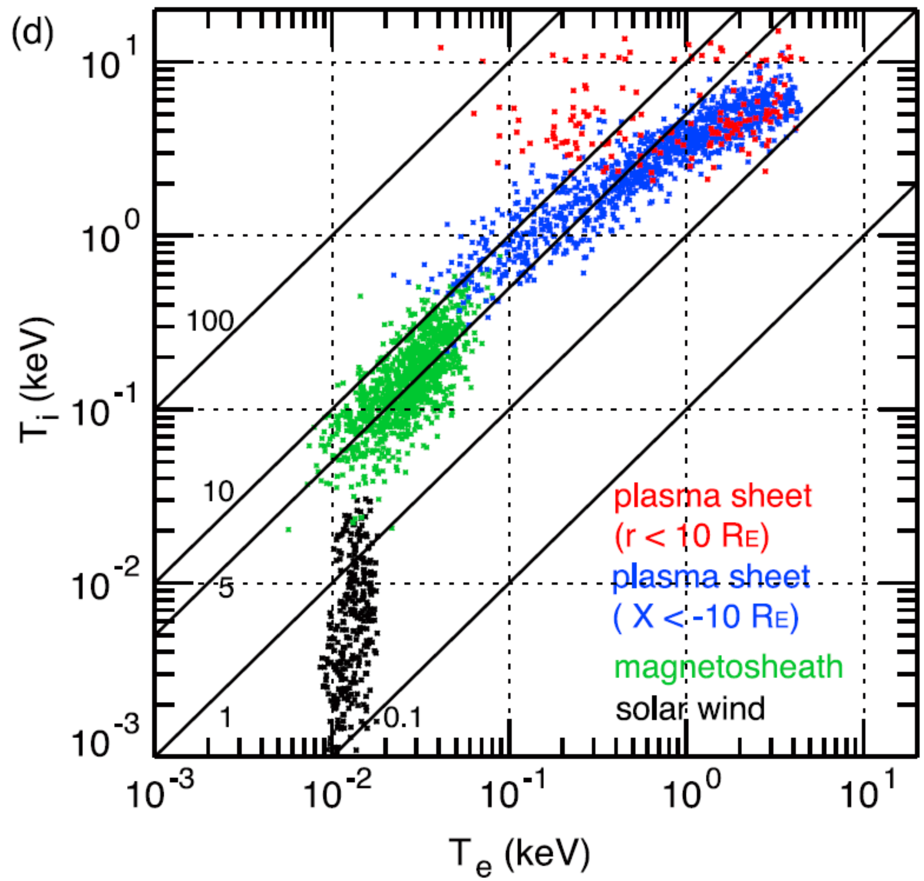
# Observations of Ti/Te

magnetosphere

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

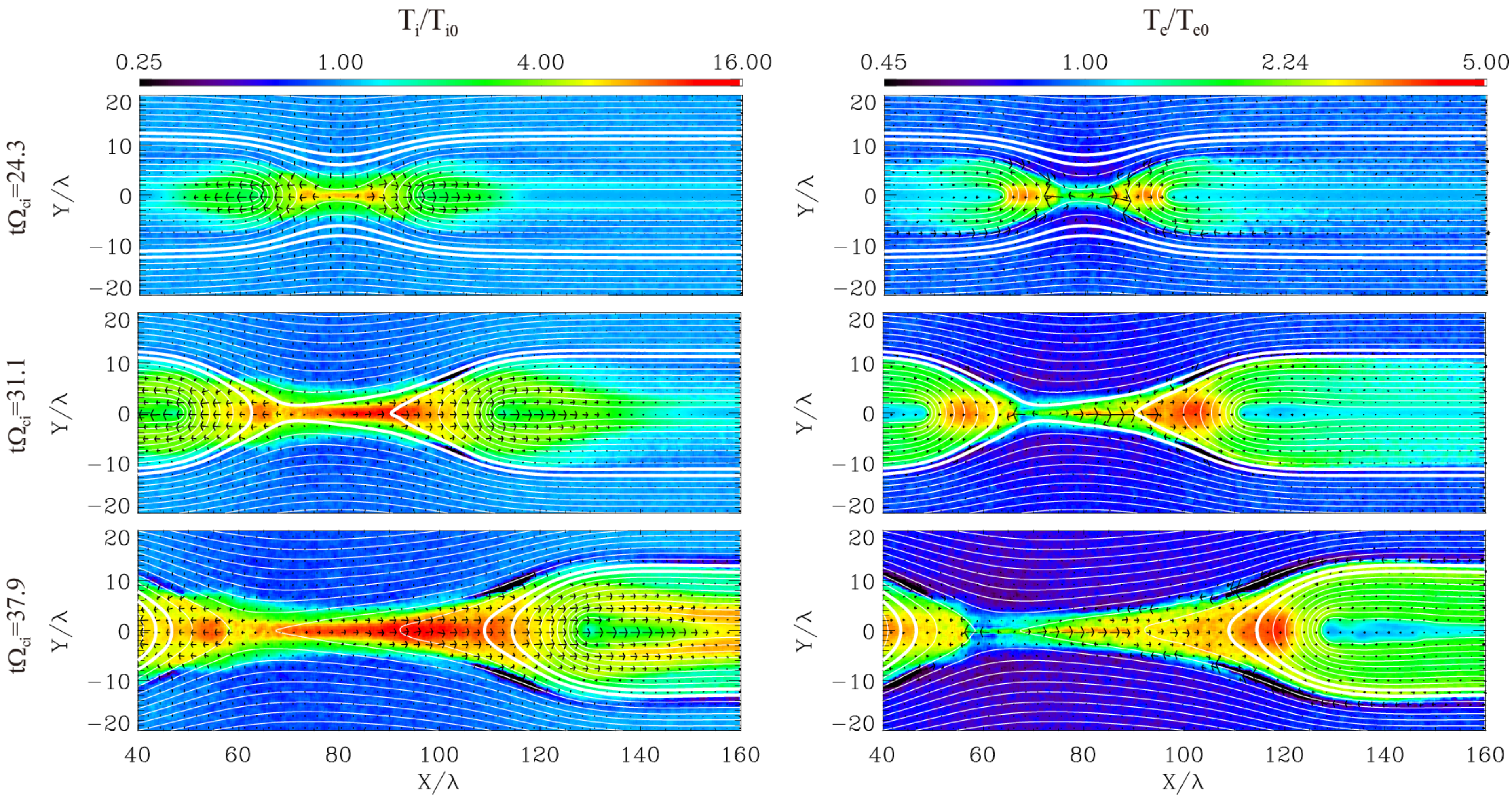
Hot ions are believed to be generated during magnetic reconnection…

(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

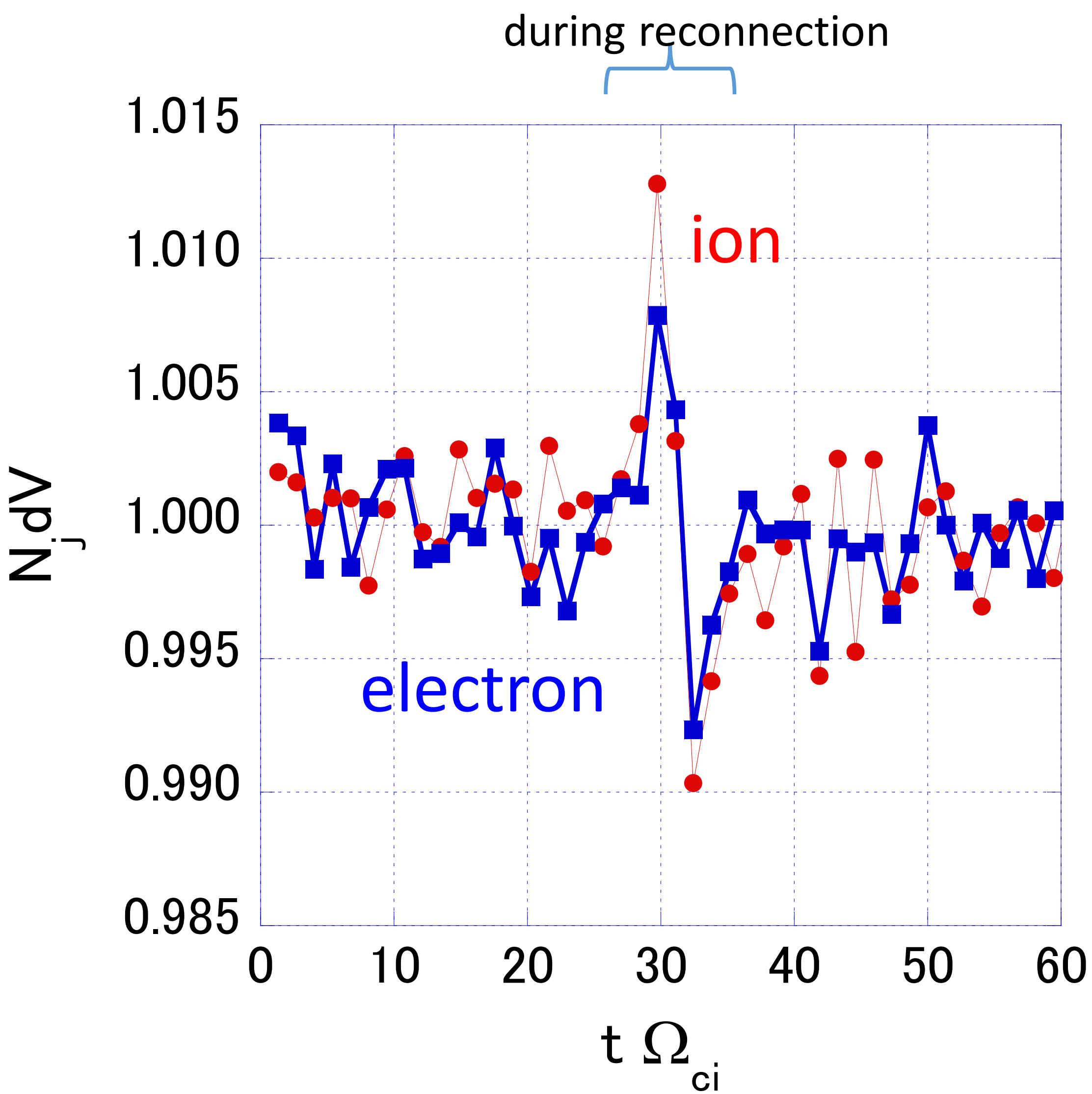
$$\vec{B}(x,y) = \nabla \times A_z(x,y)\vec{e}_z + B_z(x,y)\vec{e}_z$$

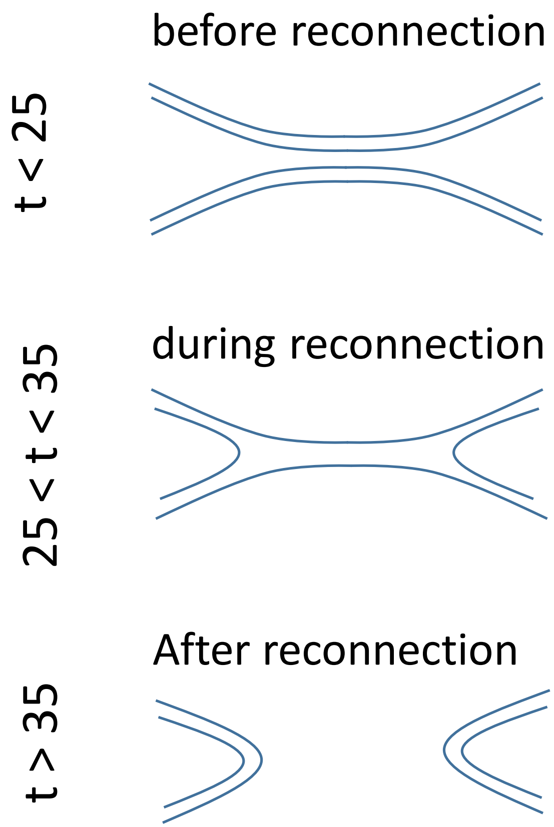
$$\frac{dx}{B_x(x,y)} = \frac{dy}{B_y(x,y)} \Leftrightarrow dA_z(x,y) = 0$$

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

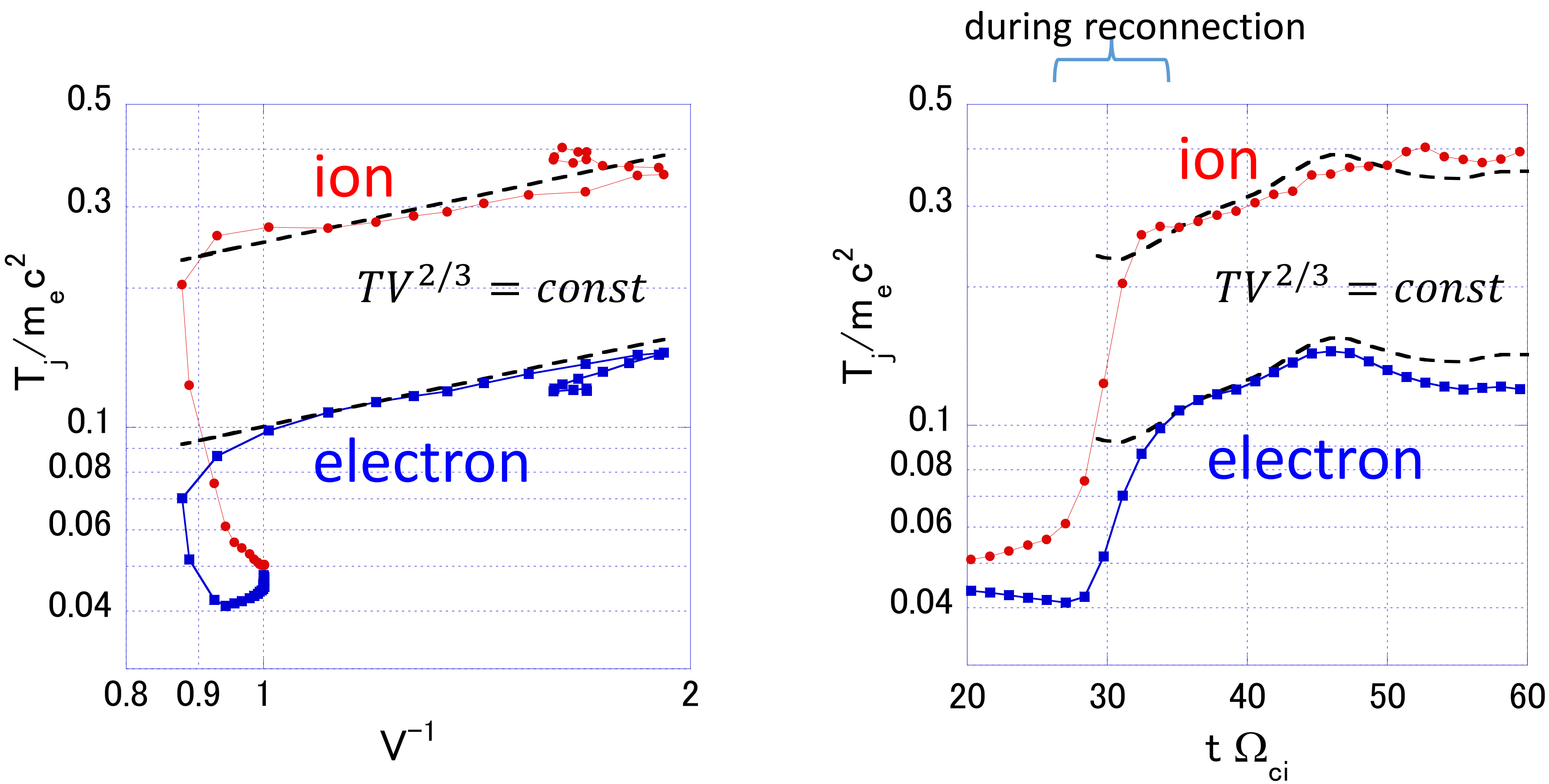
then $\left(\frac{\partial}{\partial t} + \vec{v} \cdot \nabla\right) A_z(x,y,t) = 0.$

# Time History of N in Flux Tube



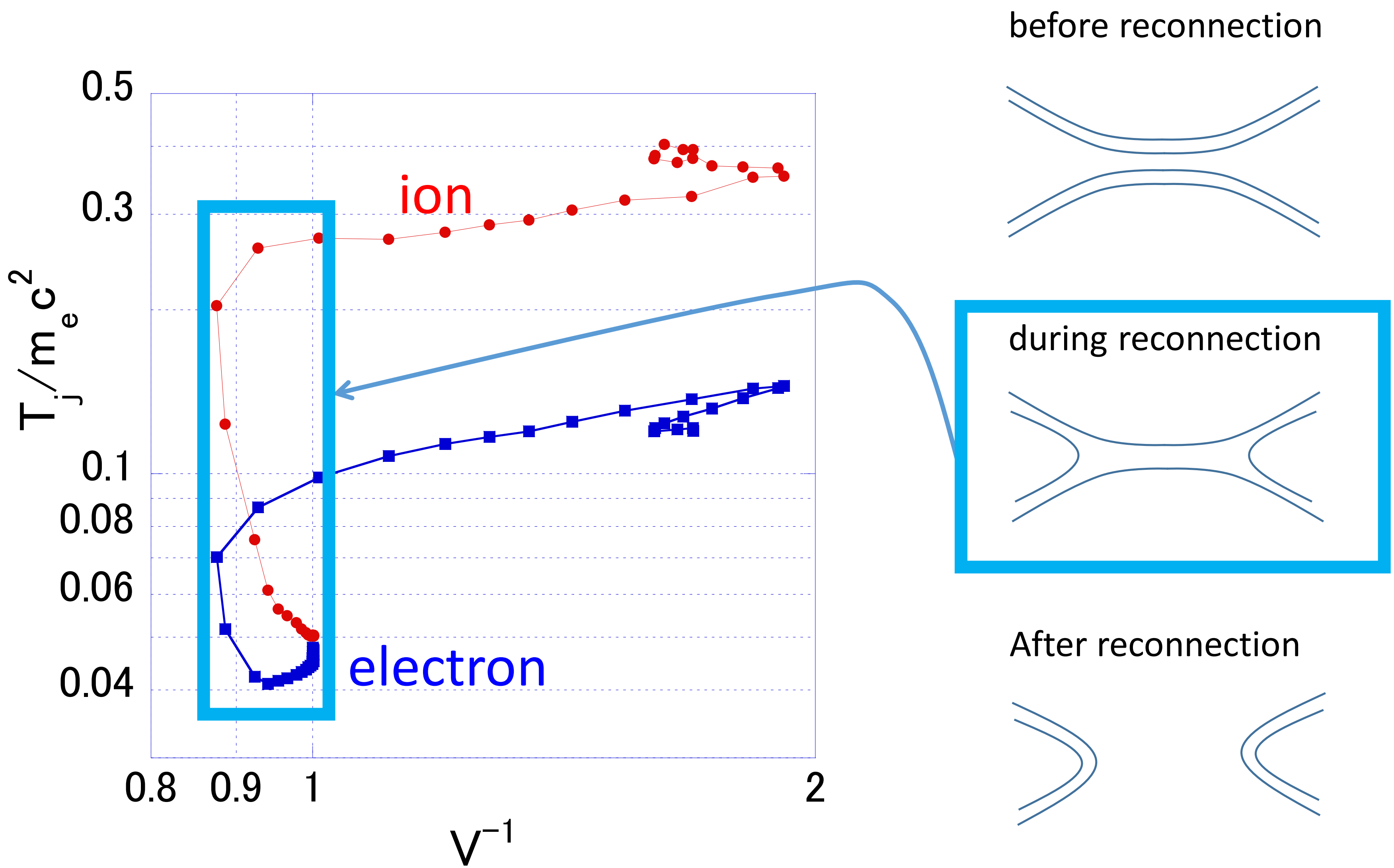



# T-V Relations



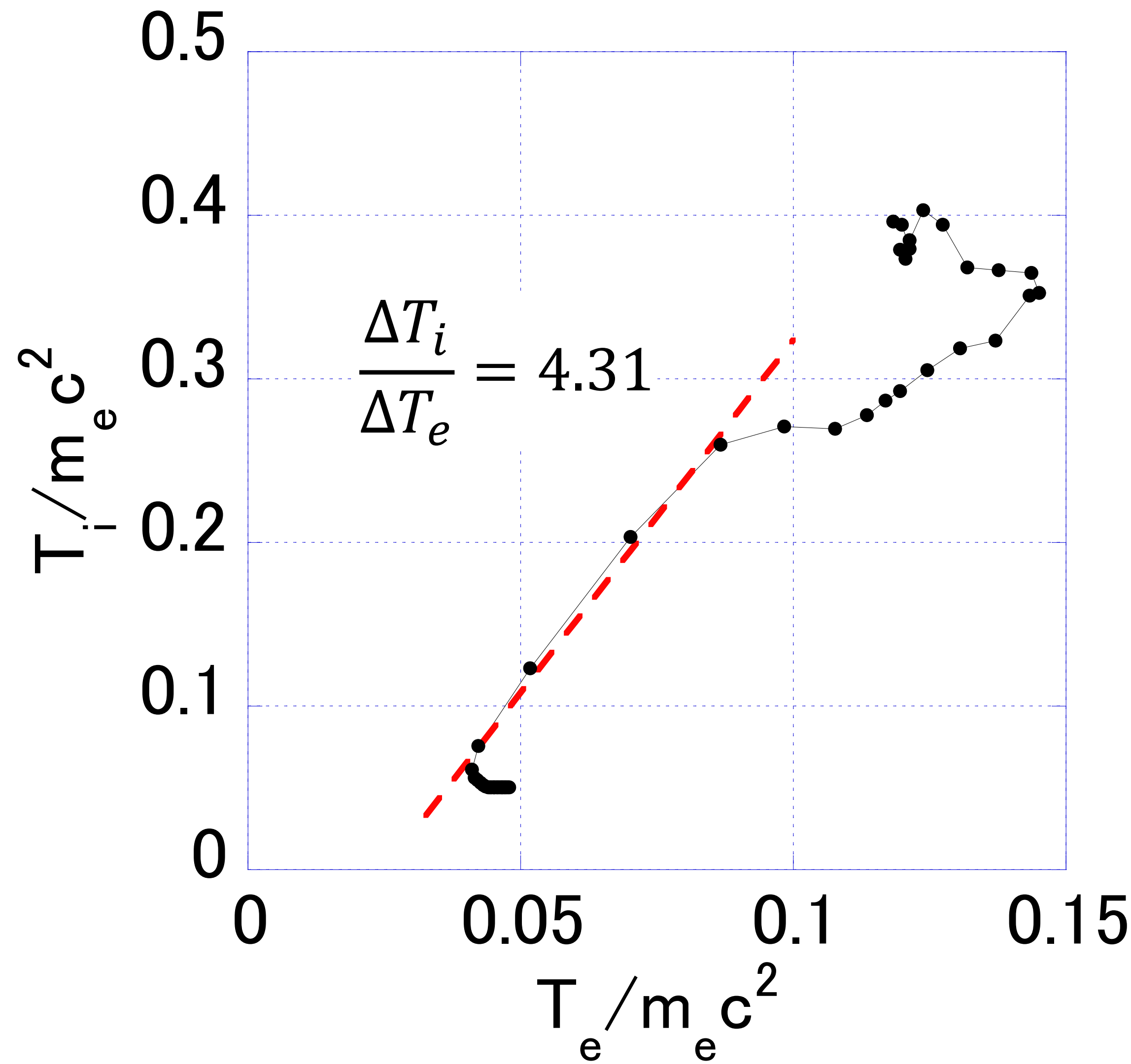

(V : Volume of Flux Tube)

# T - V relation




(V : Volume of Flux Tube)

# Time history of Ti and Te

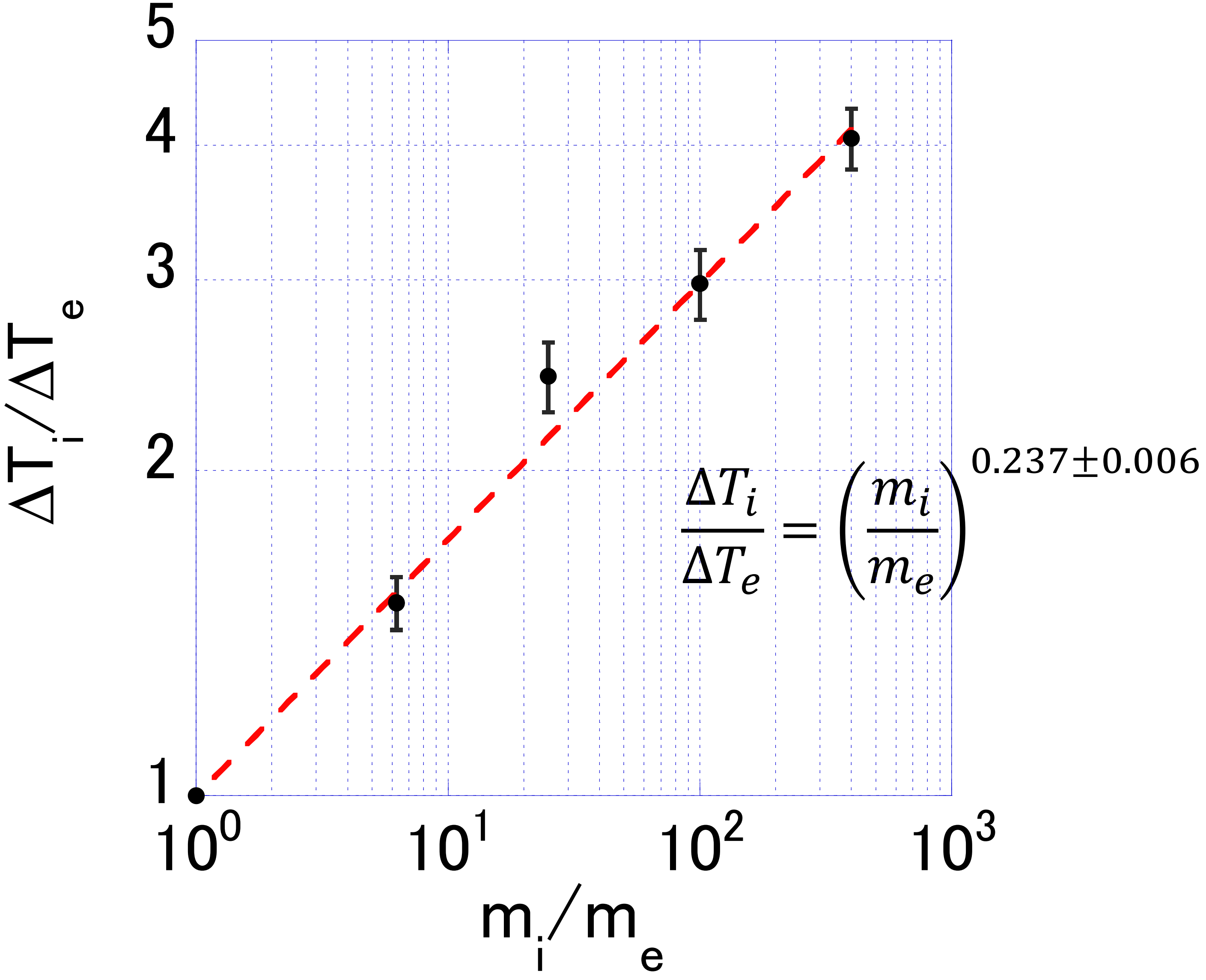



$$\frac{m_i}{m_e} = 400$$

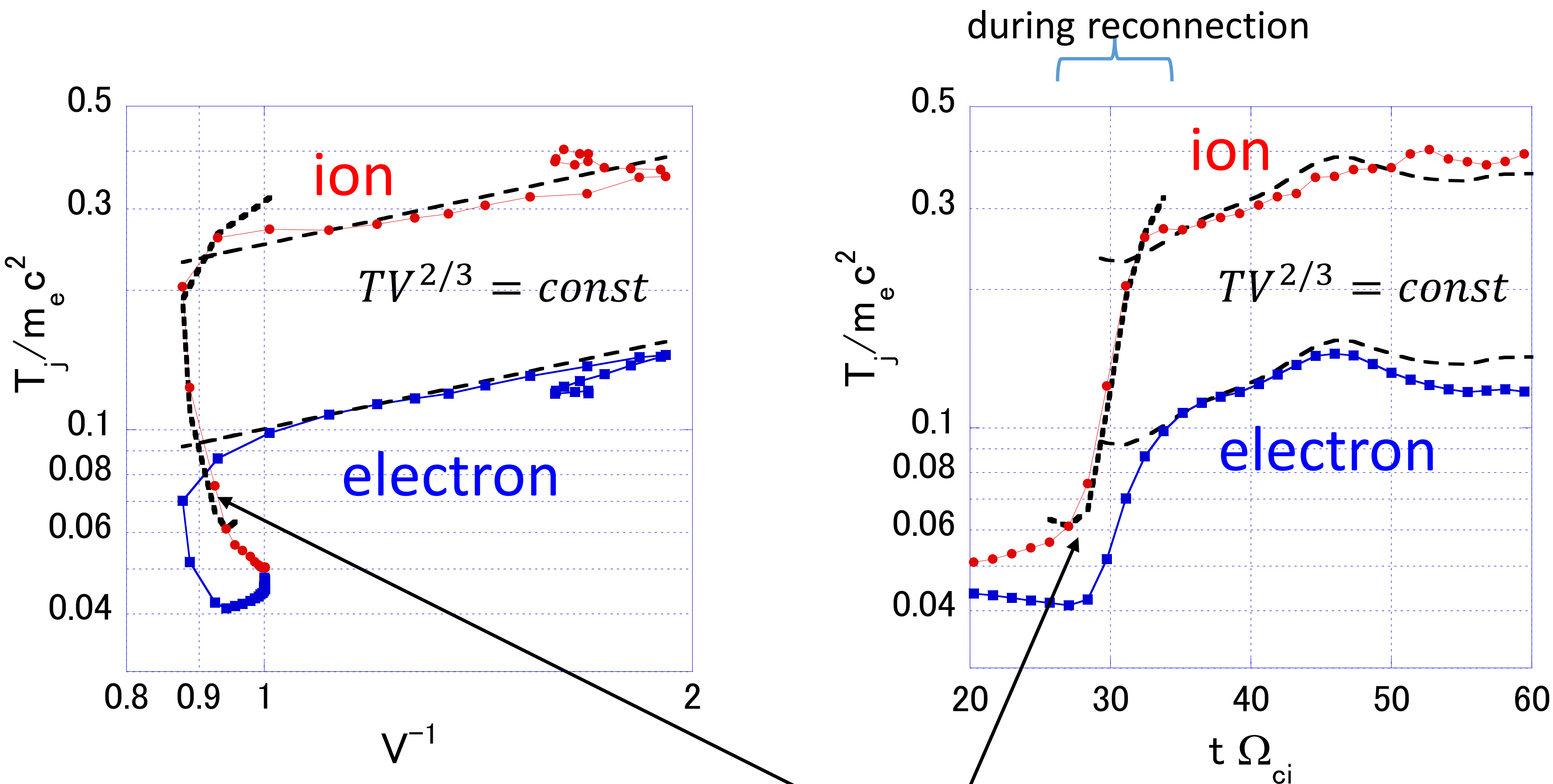
Average for Flux Tubes

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

# Mass dependence



# Thermodynamics of Reconnection

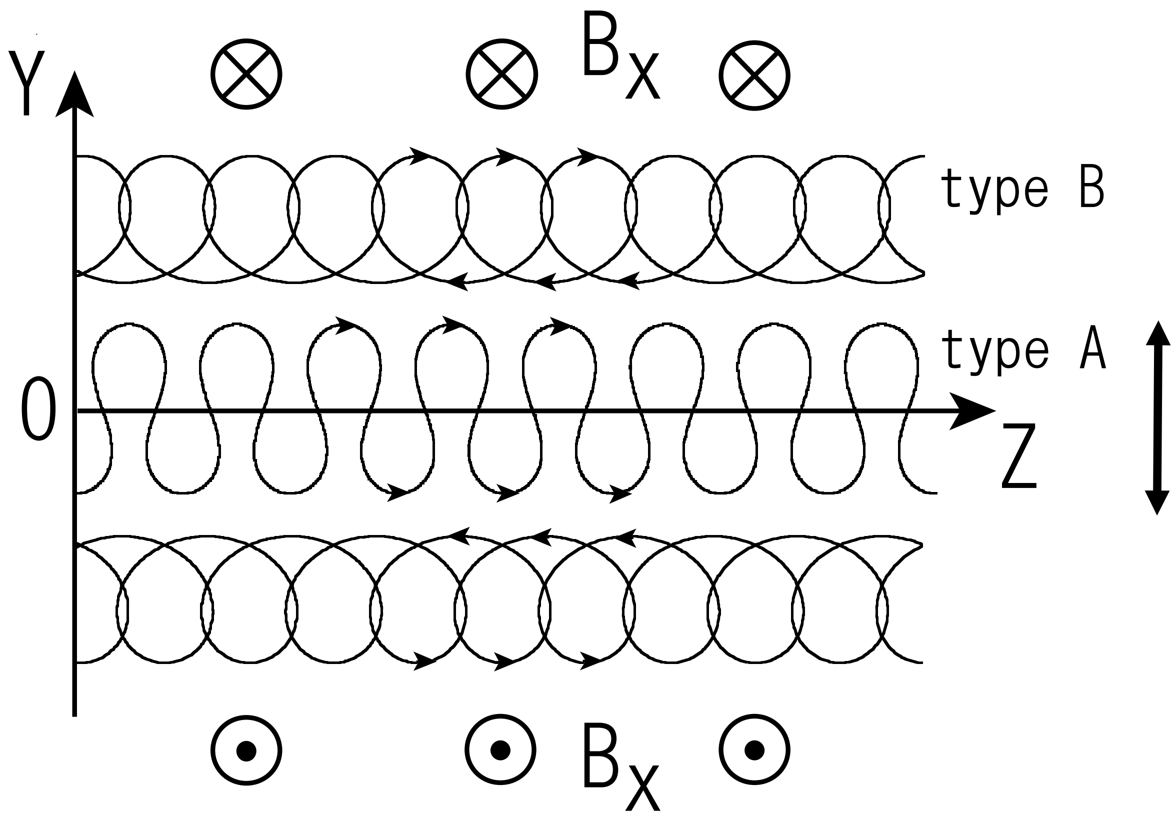



(V : Volume of Flux Tube)

Heating during Reconnection

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

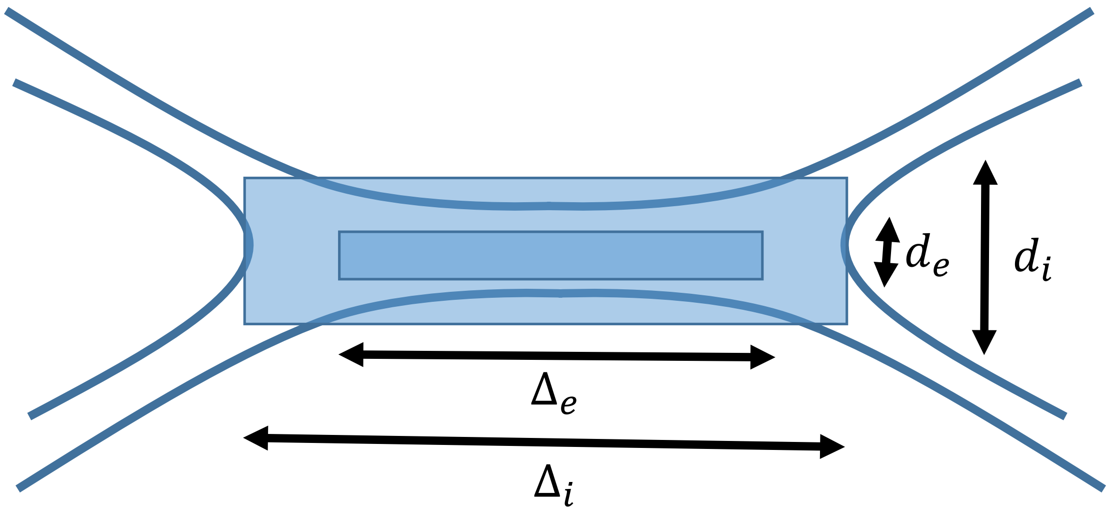
# meandering motion in diffusion region




meandering width

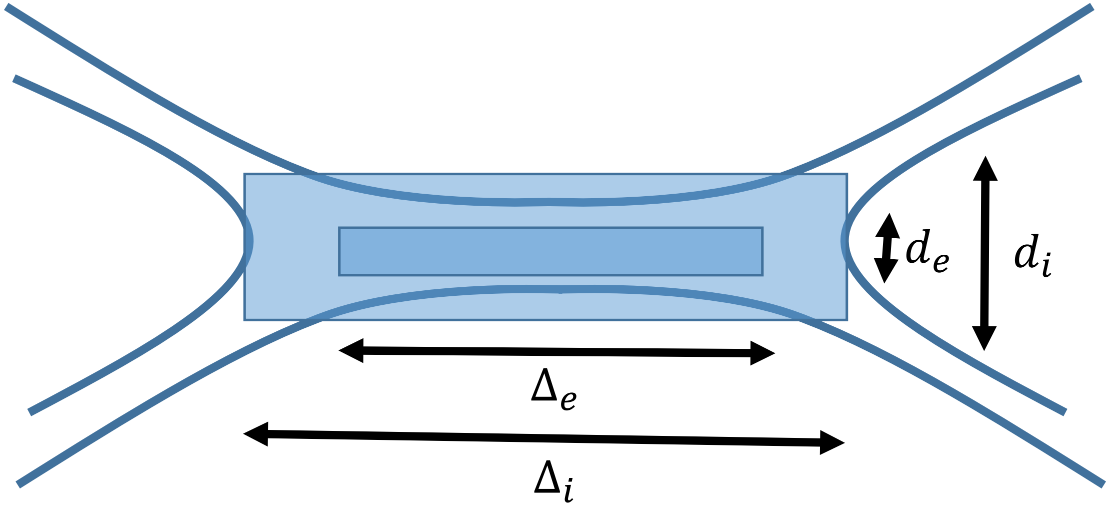
$$d_e = \sqrt{\frac{v_{th,e}\lambda}{\Omega_{ce}}} \propto (m_e T_e)^{1/4}$$

# 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)

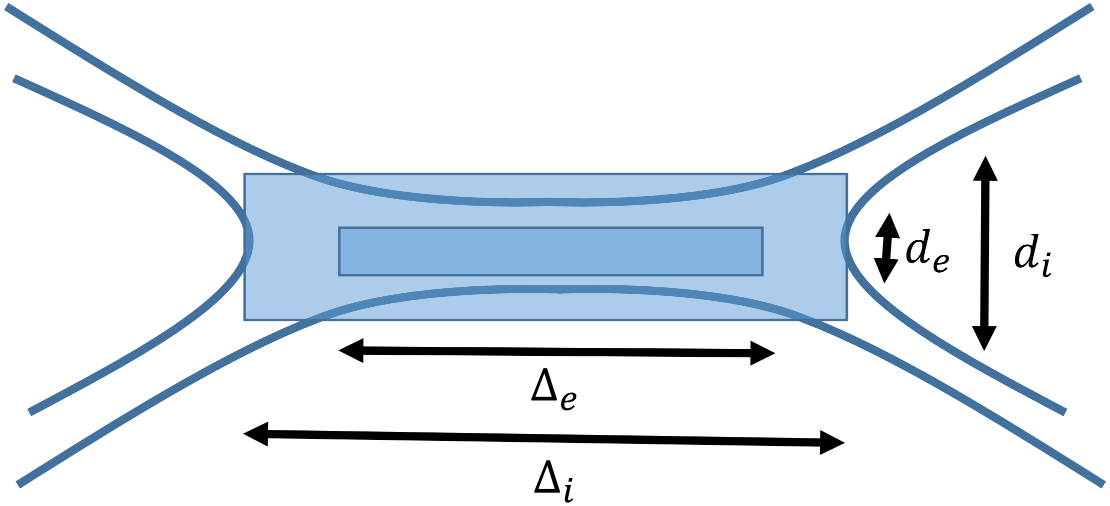



$$\frac{J_i}{J_e} = \frac{\sigma_i}{\sigma_e}\frac{E}{E} = \frac{\dfrac{ne^2}{m_i}\dfrac{\Delta_i}{v_{ix}}}{\dfrac{ne^2}{m_e}\dfrac{\Delta_e}{v_{ex}}} = \frac{m_e}{m_i}\frac{\Delta_i}{\Delta_e}\frac{v_{ex}}{v_{ix}},$$

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

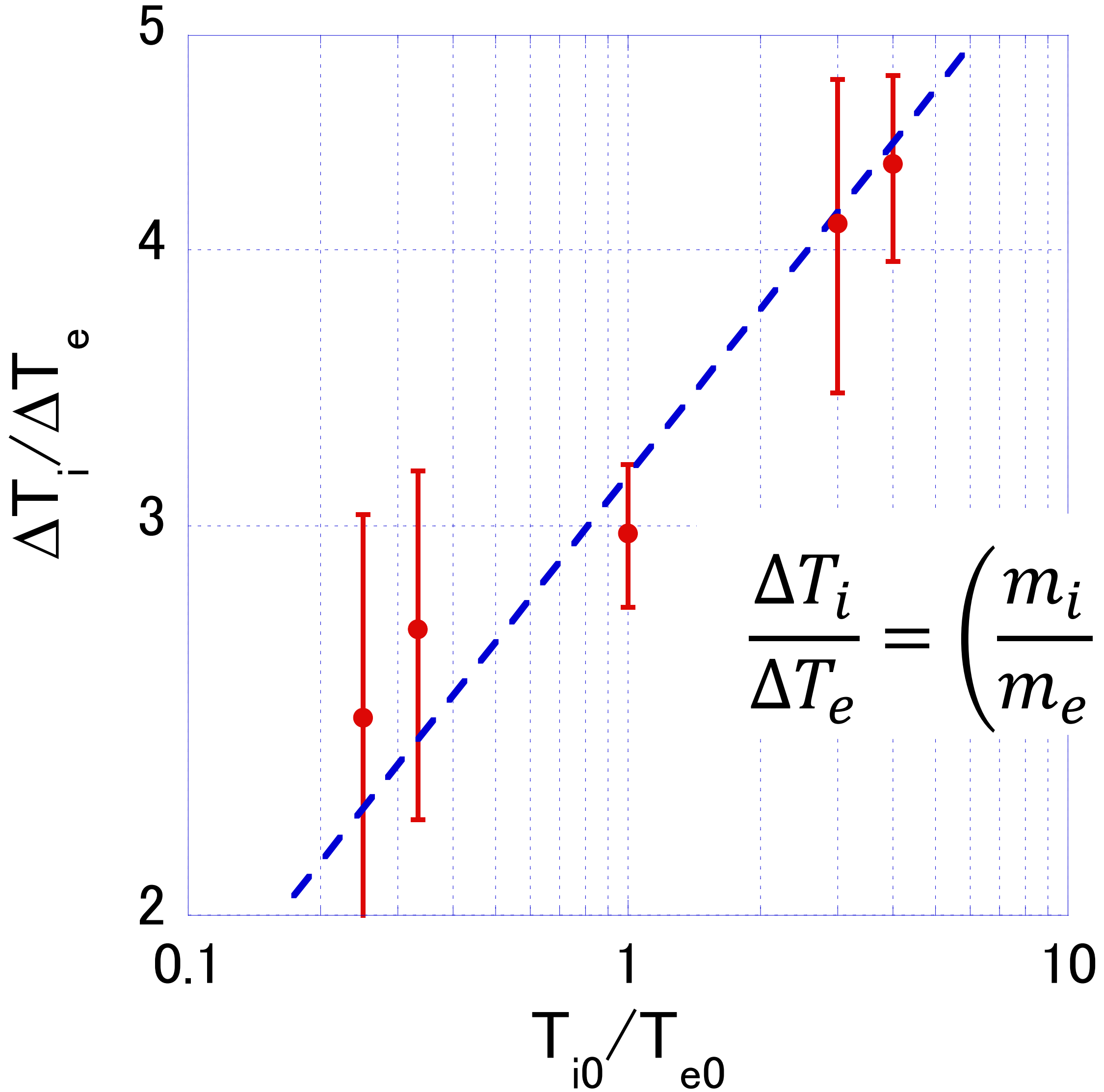
$$\frac{\Delta_i}{\Delta_e} = \left(\frac{v_{ix}}{\Omega_i}\frac{\Omega_{ce}}{v_{ex}}\right)^{1/2} \qquad \therefore \ \frac{J_i \Delta_i}{J_e \Delta_e} = 1$$

# Joule heating model (III)




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

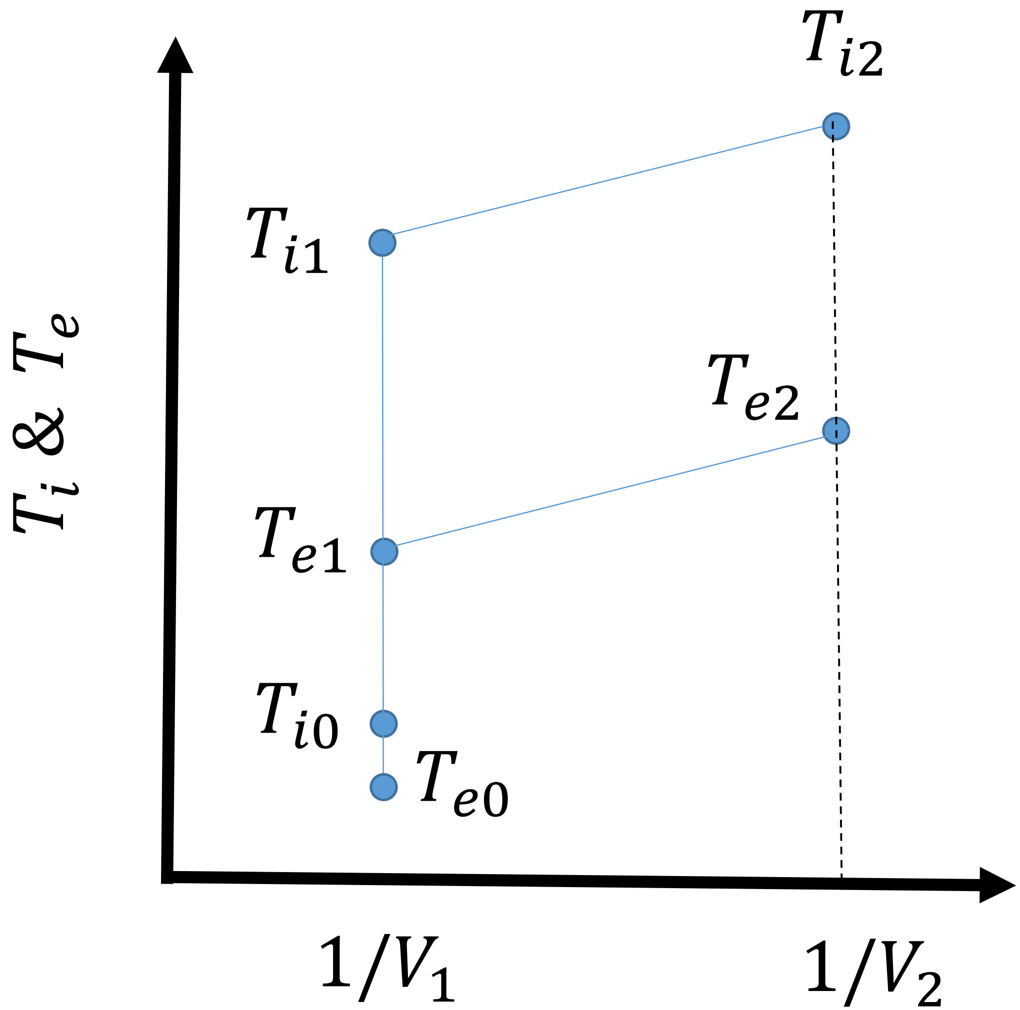
# Initial temperature dependence




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

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

# 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

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