THE UNIVERSITY OF TOKYO

Kinetic Magneto-Rotational Instability in Accretion Disk

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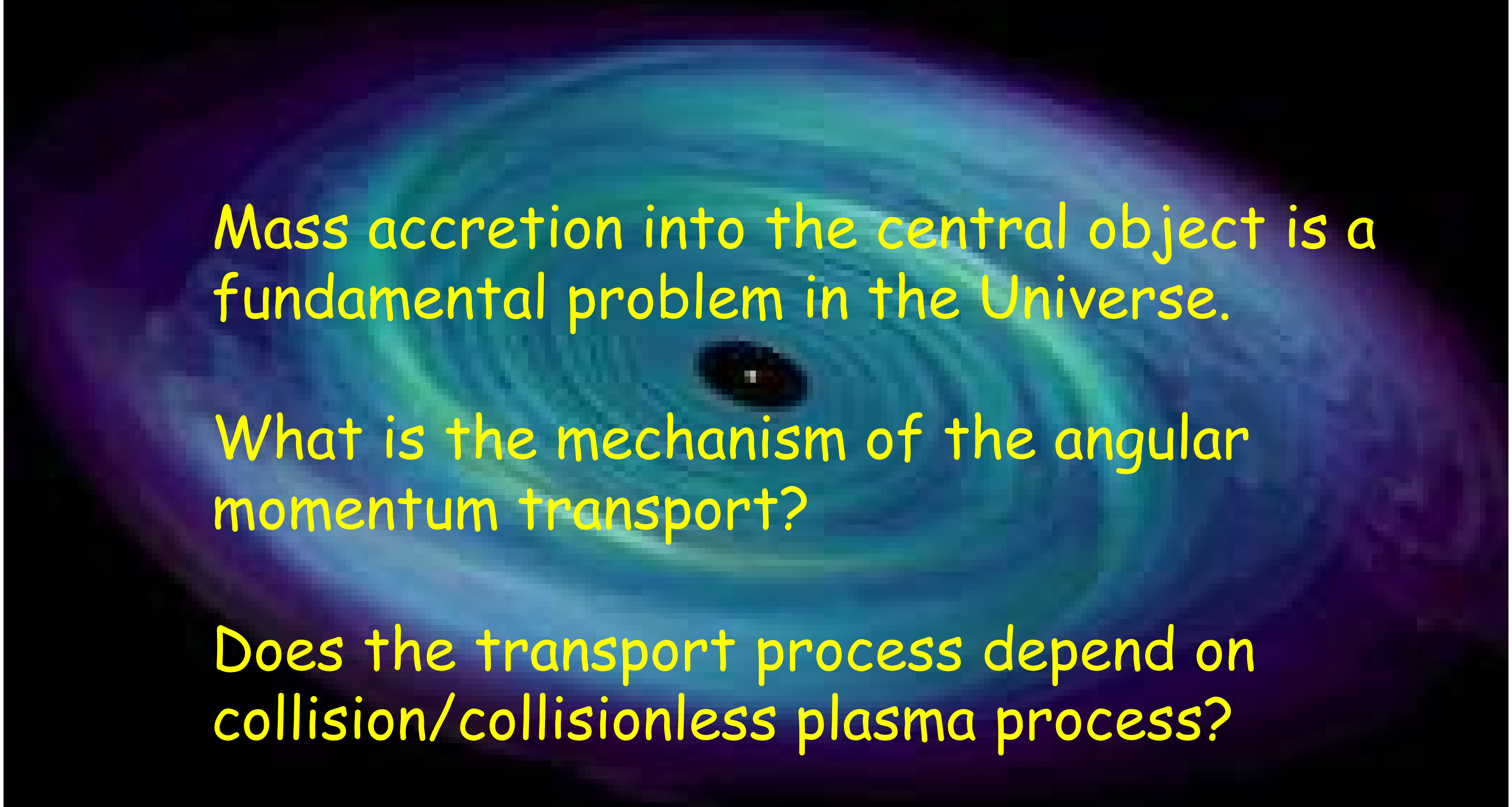
Disk Accretion

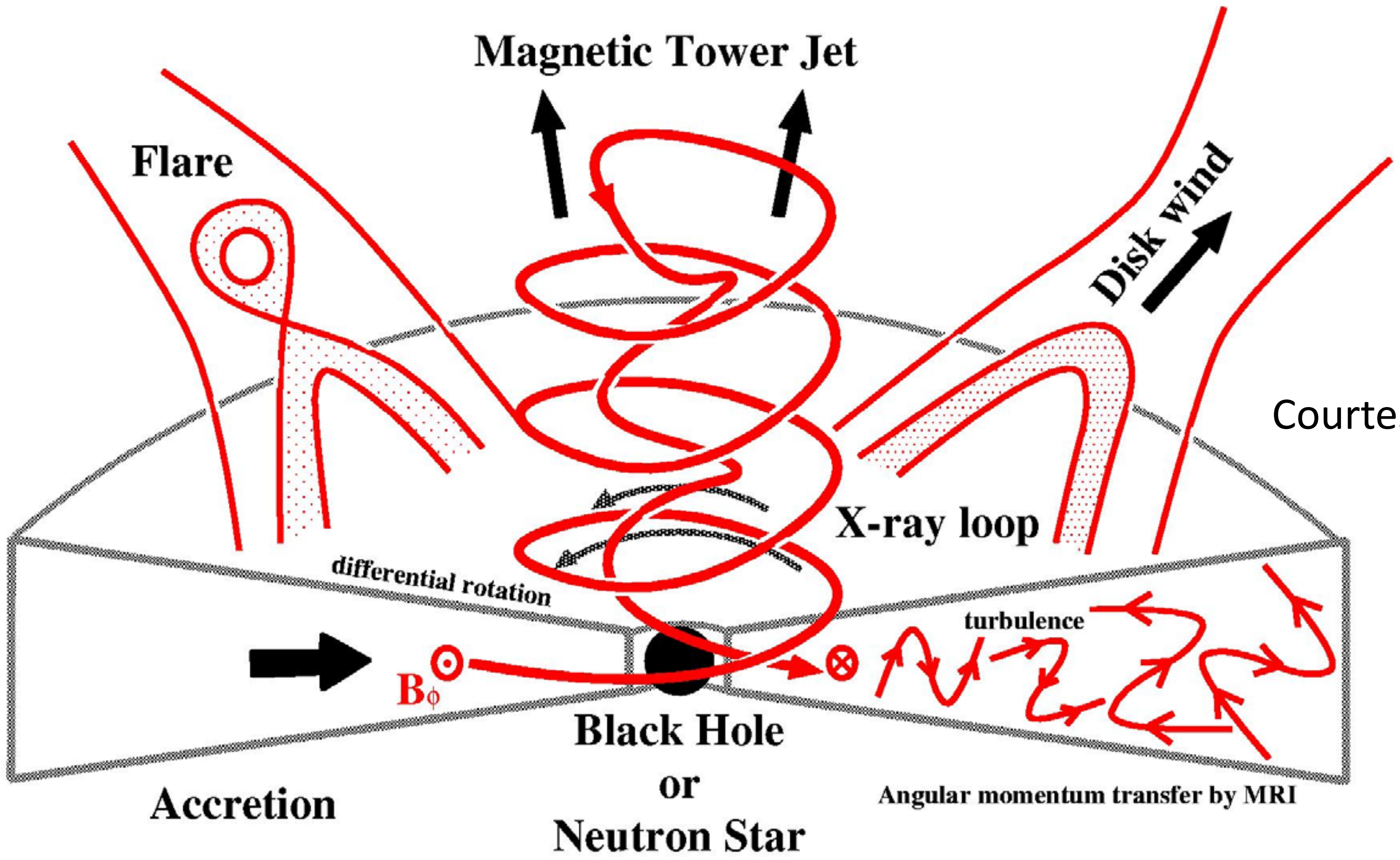


Mass accretion into the central object is a fundamental problem in the Universe.

What is the mechanism of the angular momentum transport?

Does the transport process depend on collision/collisionless plasma process?

Plasma processes in Accretion Disk

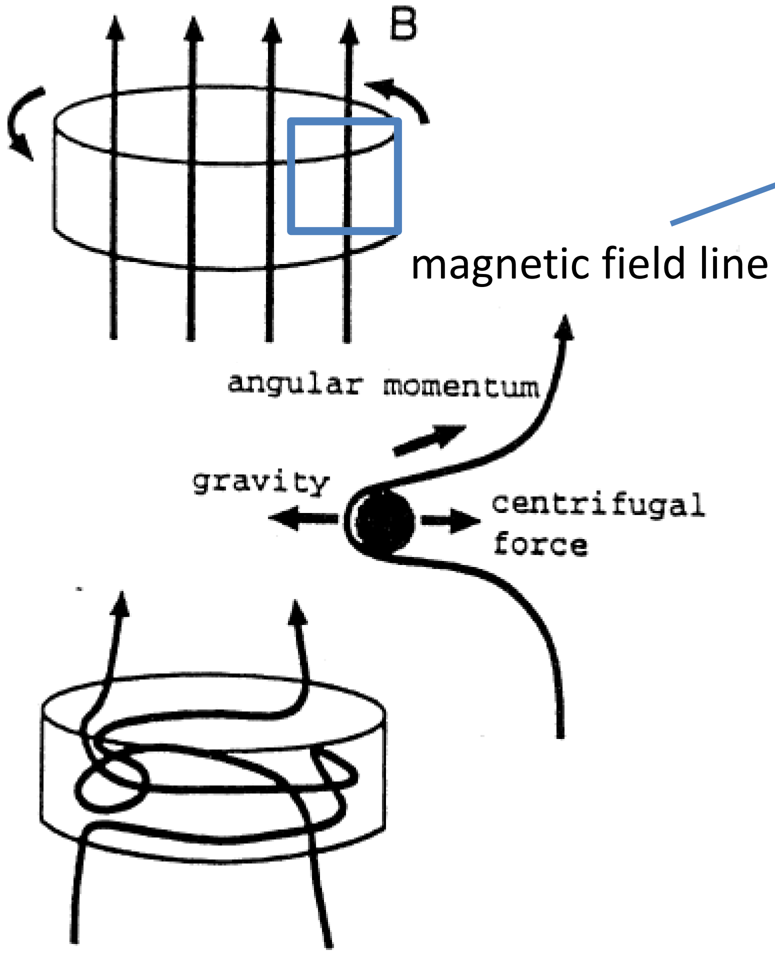


Courtesy of Kato

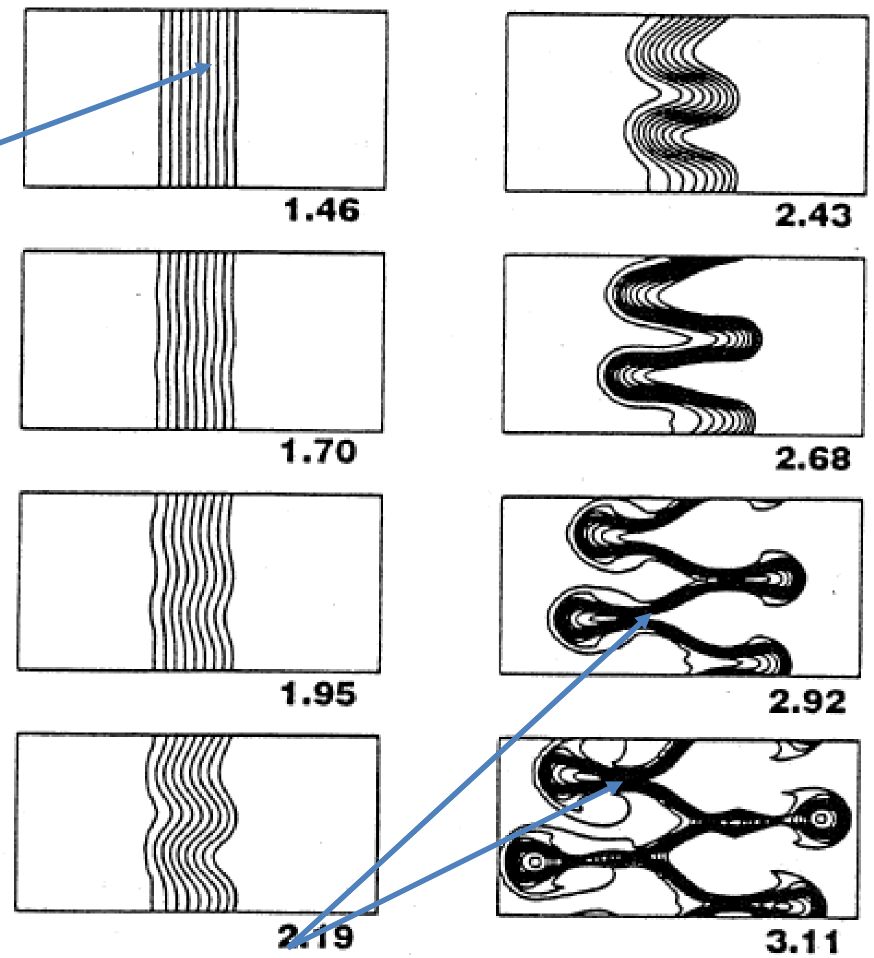
Magneto-Rotational Instability (MRI)

Velikov 1958, Chandrasekhar 1961, Balbus & Hawly 1991, Matsumoto & Tajima 1995, Sano & Inutsuka 2001,...

Magneto-Rotational Instability (MRI)



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



magnetic reconnection

Balbus and Hawley, 1998

Collisionless Accretion Disk & MRI

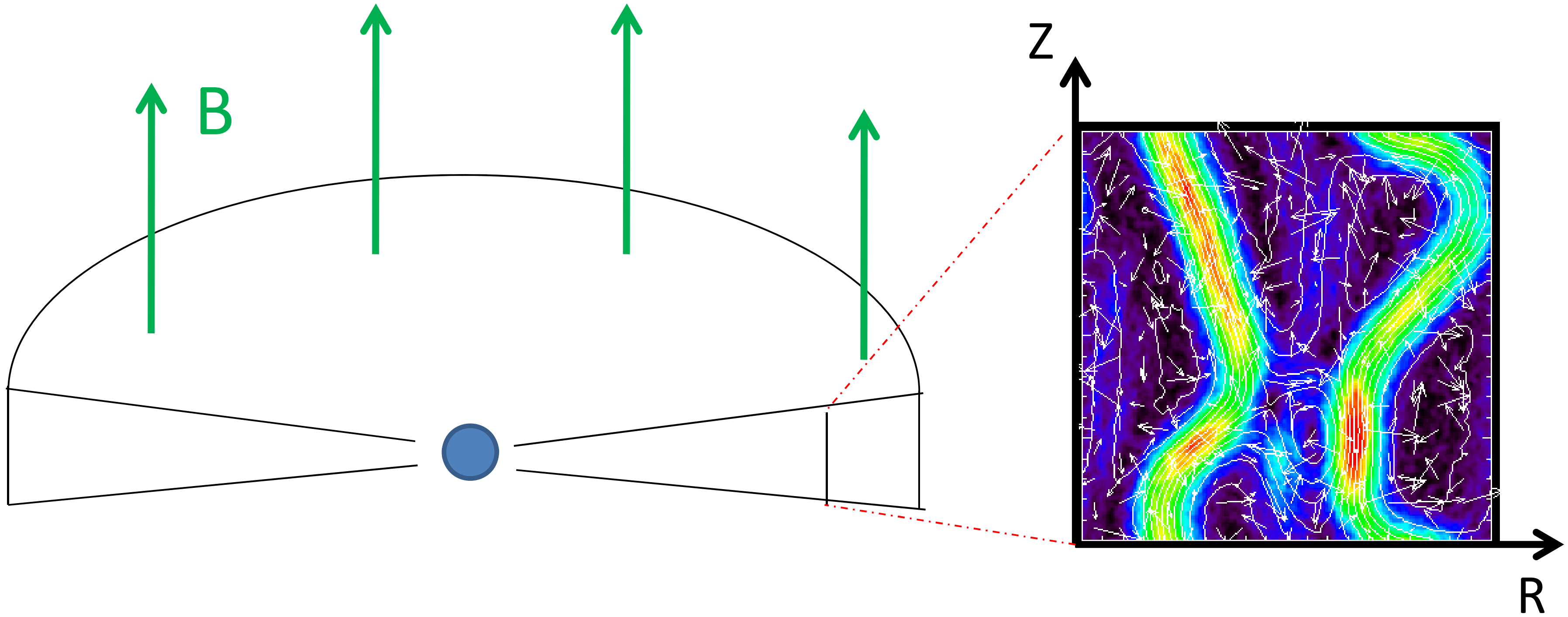
- ✓ Accretion Disk around Massive Black Halls (e.g., Sgr A*)
- ✓ Radiatively Inefficient Accretion Flow (RIAF)
- ✓ Nonthermal electrons, power law index p~1.3 < 2

(e.g., Narayan+ 1998; Quataert+ 2002; Yuan+ 2003;
Aharonian+ 2008; Kusunose & Takahara 2012,...)

- ✓ MRI by using 2d & 3d particle-in-cell simulations
- ✓ Nonthermal particle acceleration with a hard spectrum
- ✓ Enhancement of Shakura-Sunyaev's "α-parameter", i.e., $\alpha_{collisionless}/\alpha_{MHD}$ =O(10-100)

Collisionless magnetic reconnection plays a dynamically important role on both particle acceleration and α-parameter

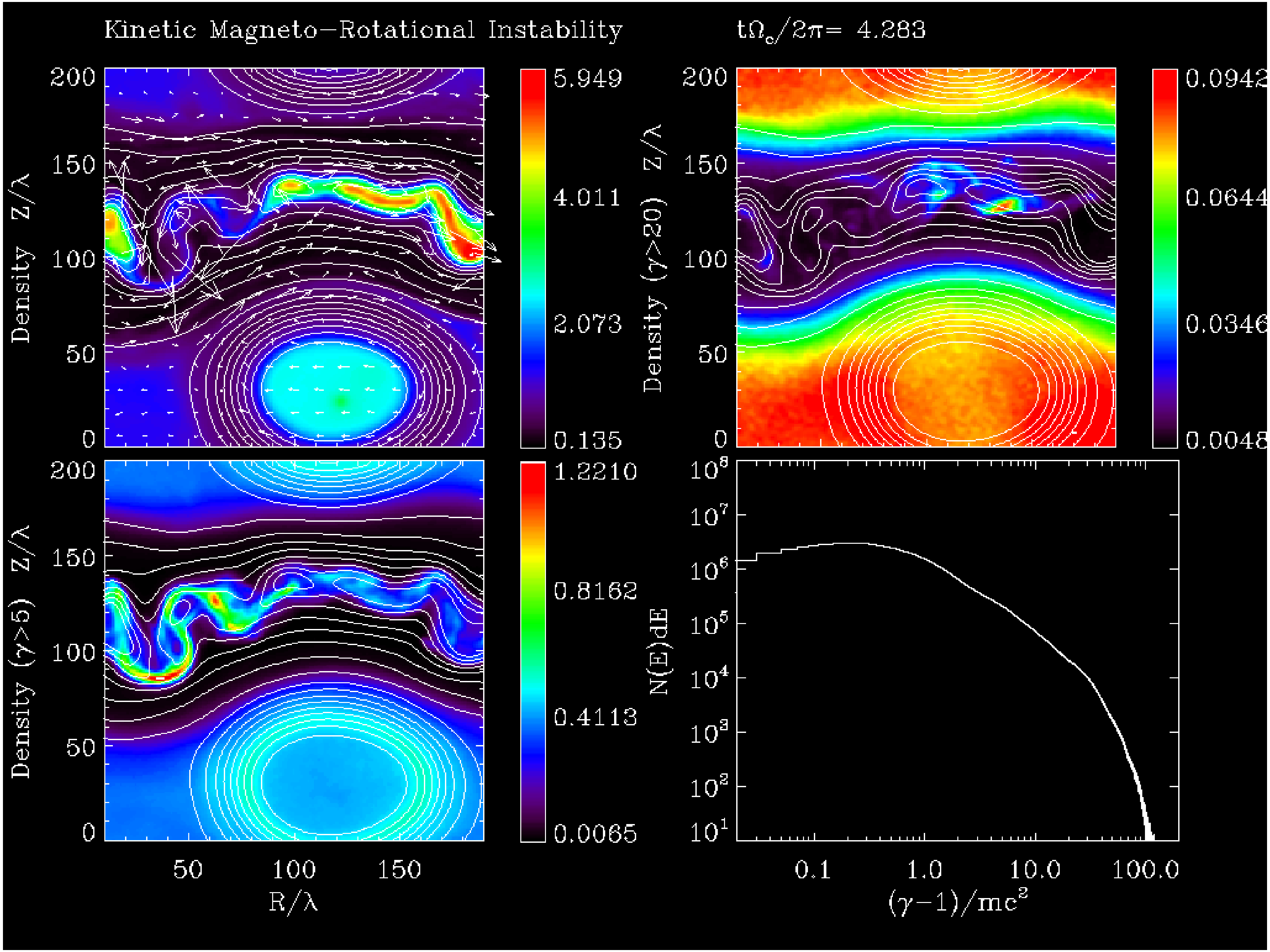
Collisionless MRI in 2d PIC simulation



Kepler rotation Ω, $\Omega / \Omega_c = 0.1$,
β=1540,   200x200 grids 8000 particles/cell,
open shearing box boundary,   electron-positron plasma

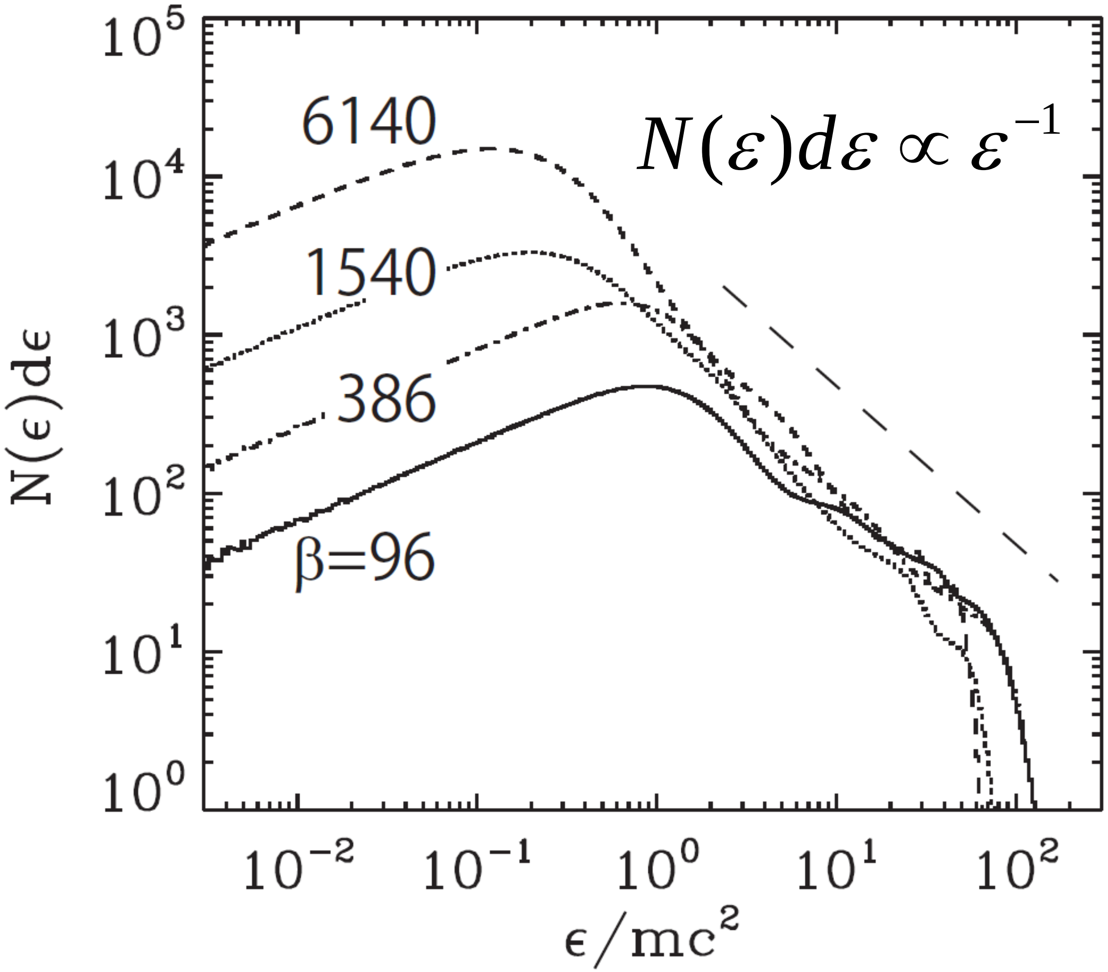
MH ApJ 2013

cf. Requelm + ApJ 2012; Shirakawa & MH PoP 2014



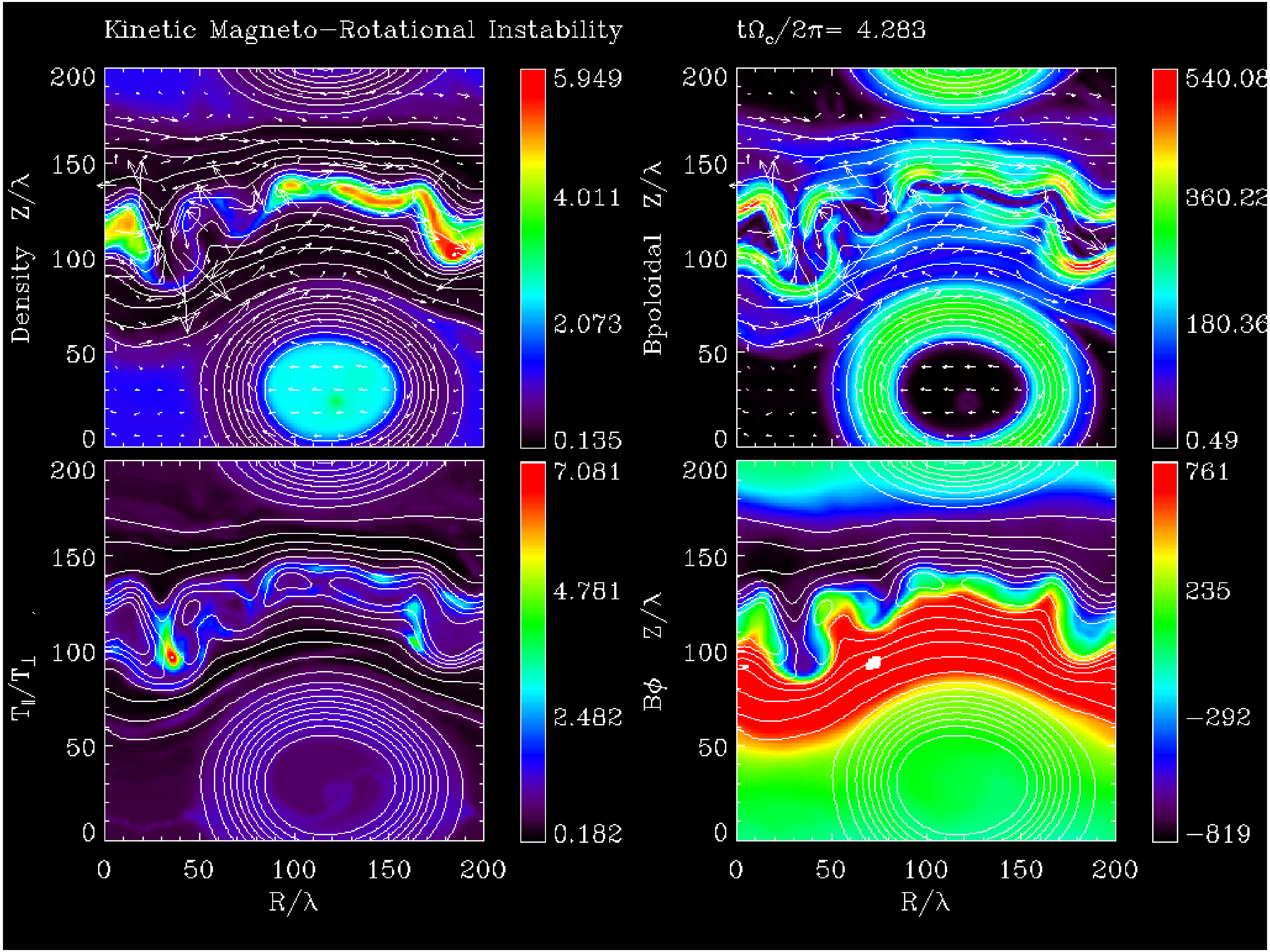
Kinetic Magneto-Rotational Instability
$t\Omega_c/2\pi$= 4.283
Density Z/λ
5.949
4.011
2.073
0.135
Density (γ>20) Z/λ
0.0942
0.0644
0.0346
0.0048
Density (γ>5) Z/λ
1.2210
0.8162
0.4113
0.0065
N(E)dE
R/λ
(γ−1)/mc²

Energy Spectra during MRI-Reconnection



Dependence of initial plasma beta is weak

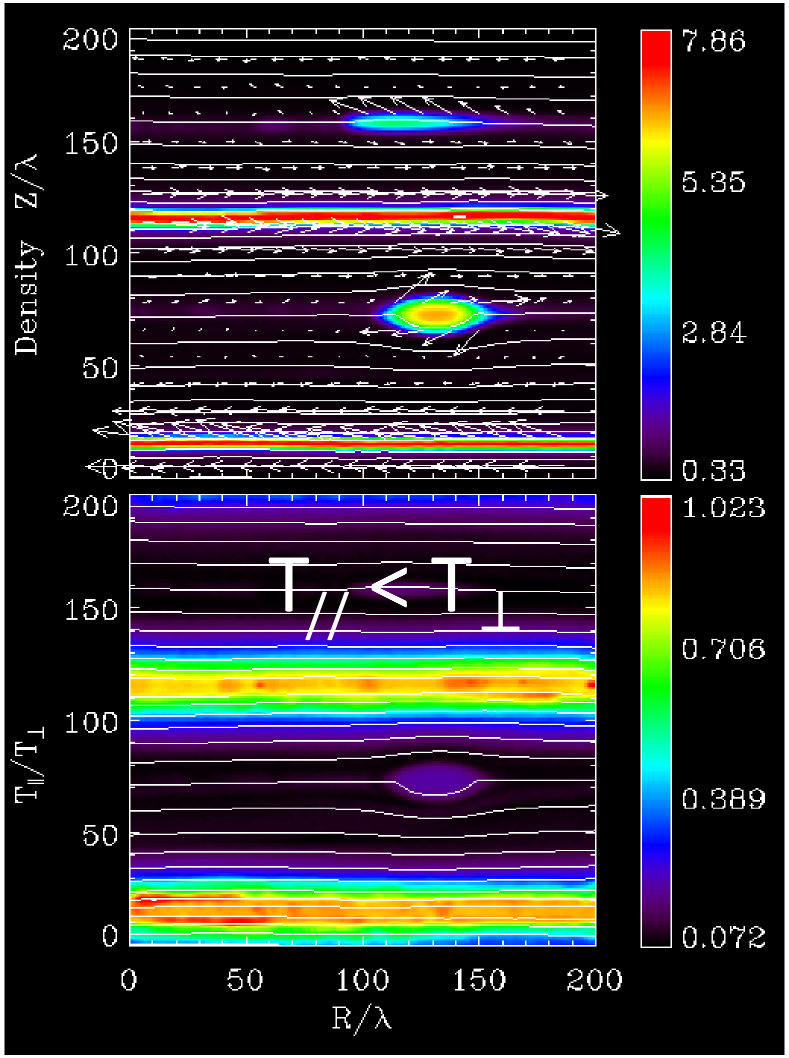
cf. Zenitani & MH ApJ 2001, MH & Lyubarsky SSR 2012



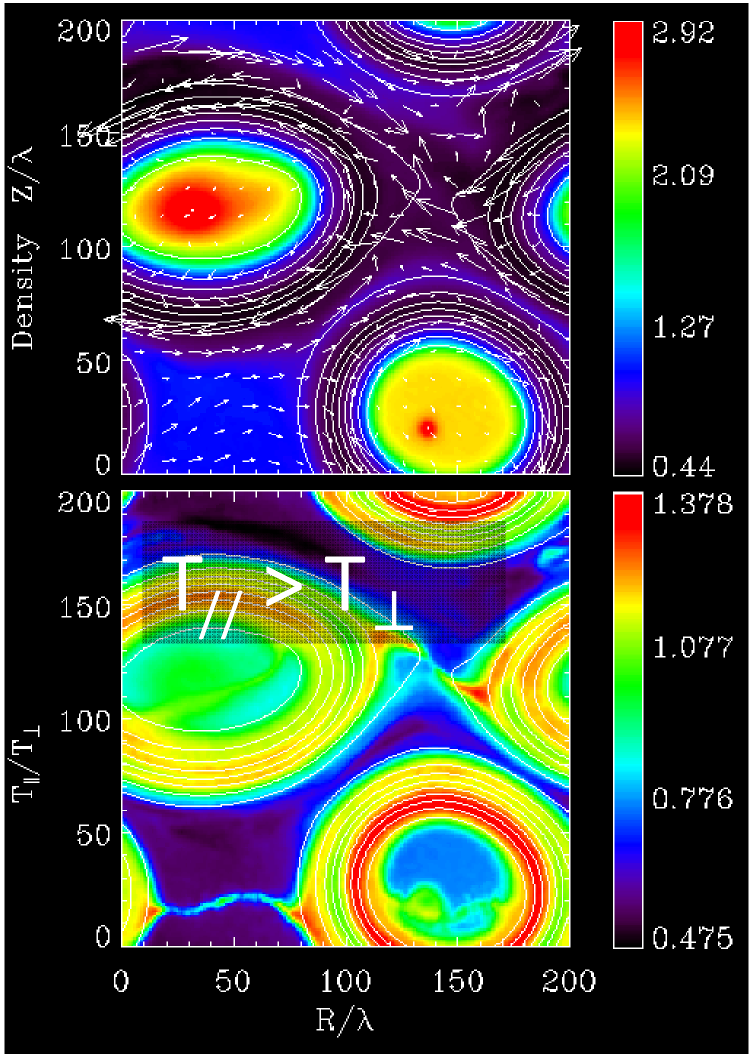
Kinetic Magneto−Rotational Instability
tΩ_c/2π= 4.283
Density Z/λ
Bpoloidal Z/λ
T∥/T⊥
Bφ Z/λ
R/λ
R/λ
5.949
4.011
2.073
0.135
540.08
360.22
180.36
0.49
7.081
4.781
2.482
0.182
761
235
−292
−819

Onset of Reconnection

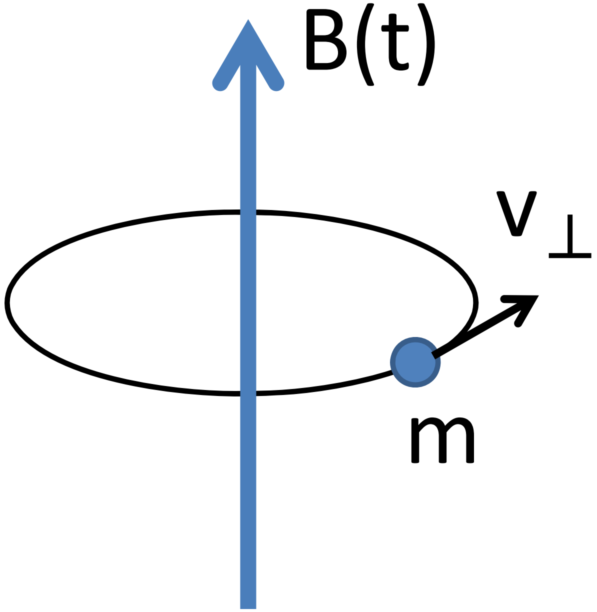
Before onset of Reconnection

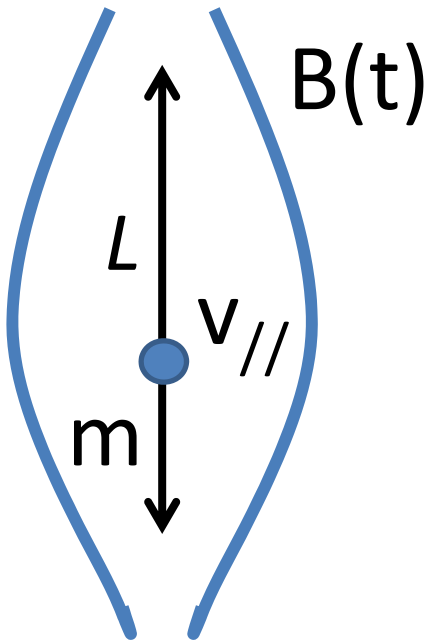


After onset of Reconnection



Pressure Anisotropy





gyro-motion
(1st adiabatic invariant)

bounce-motion
(2nd adiabatic invariant)

$$\frac{v_\perp^2}{B} \Rightarrow \frac{p_\perp}{\rho B} = cnst.$$

$$v_{//}^2 L^2 \propto \frac{v_{//}^2 B^2}{\rho^2} \propto \frac{p_{//} B^2}{\rho^3} = cnst.$$

$$(BS = cnst. \quad \rho LS = cnst.)$$

Production of Pressure Anisotropy during MRI & Reconnection

CGL (Chew-Goldberger-Low) or
Double adiabatic theory

$$\frac{D}{Dt}\left(\frac{p_\perp}{\rho B}\right) = 0, \qquad \frac{D}{Dt}\left(\frac{p_{//} B^2}{\rho^3}\right) = 0$$

$$\mathrm{MRI:}\ \ B\ \mathrm{large} \Rightarrow p_\perp > p_{//}$$

Istropization by mirror inst. & ion-cyclotron inst.

(Quataert+ ApJ 2002; Sharma+ ApJ 2006)

$$\mathrm{Reconnection:}\, B\ \mathrm{weak} \Rightarrow p_{//} > p_\perp$$

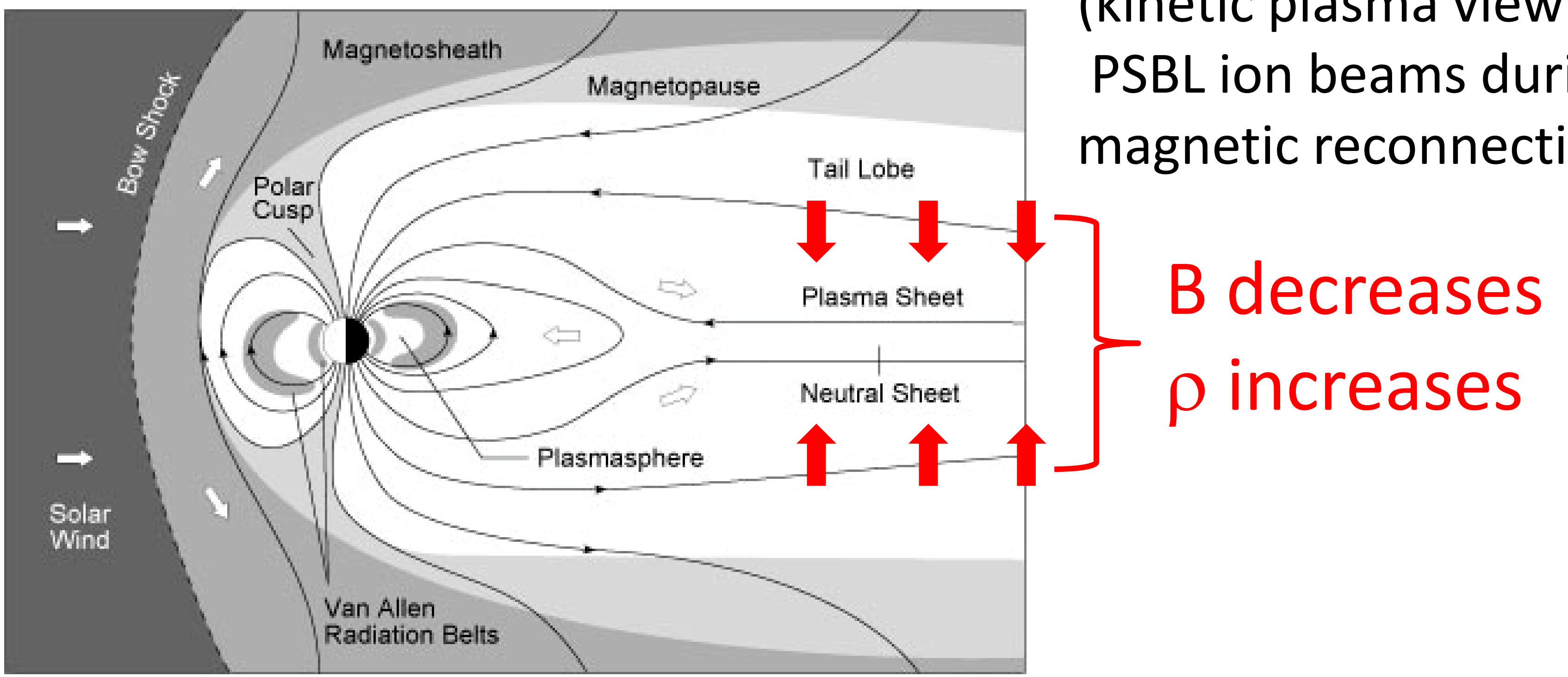
Istropization by Alfven waves generated by ion beam inst. etc.

(e.g. MH+ 1998; Higashimori & MH 2015)

Anisotropic pressure in Earth's magnetotail

Double adiabatic theory/CGL approximation

$$\frac{D}{Dt}\left(\frac{p_\perp}{\rho B}\right)=0,\ \frac{D}{Dt}\left(\frac{p_{//}B^2}{\rho^3}\right)=0 \quad \Rightarrow p_{//} > p_\perp$$



(kinetic plasma viewpoint:
PSBL ion beams during
magnetic reconnection)

(e.g. MH+ JGR 2000; Artemyev+ JGR 2014)

Role of Reconnection in Collisionless MRI

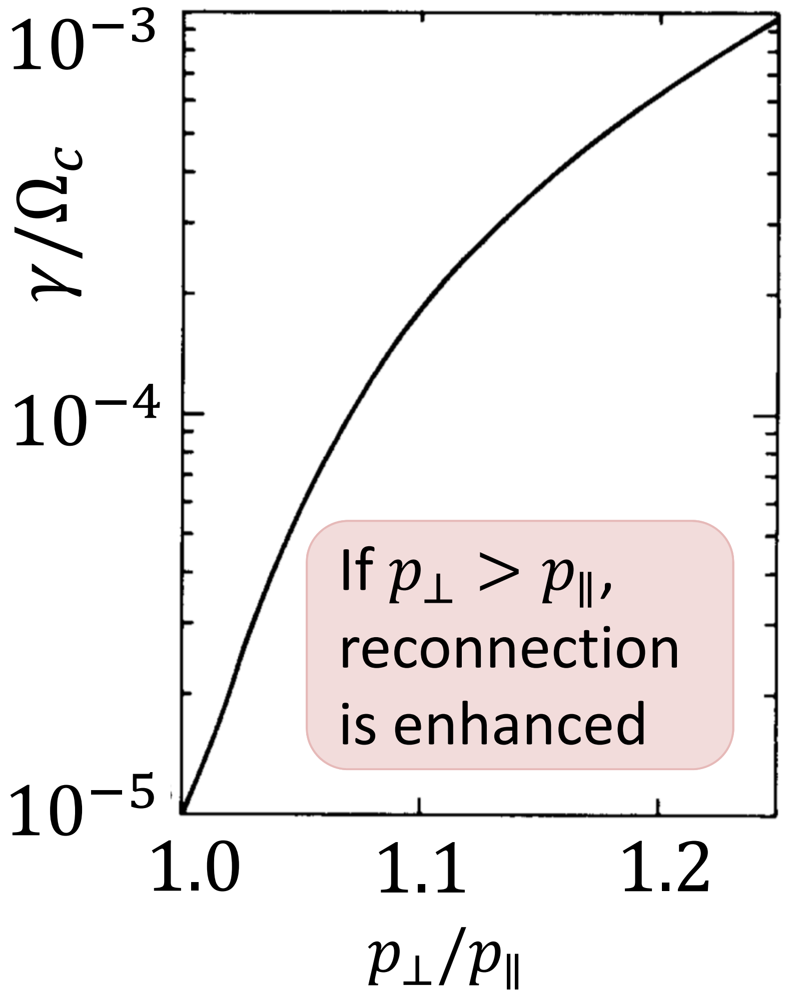
- ✓ Dynamic evolution of reconnection is strongly controlled by pressure anisotropy

(e.g., Laval & Pellat 1968; Chen & Palmadesso 1984; MH 1987)

Tearing mode theory

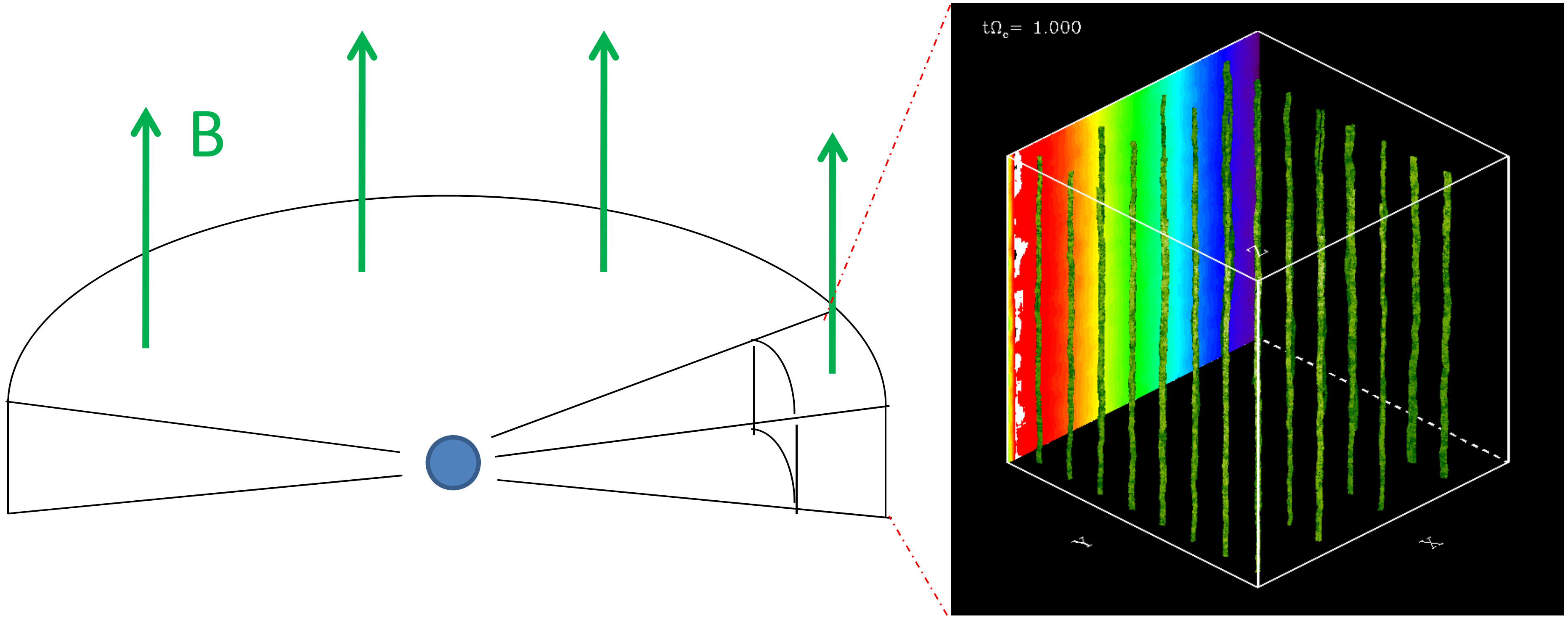
$$\frac{\gamma}{kv_{th}} \approx \left(\frac{p_\perp}{p_{//}} - 1\right) + \left(\frac{r_g}{\delta}\right)^{3/2} \left(\frac{1-k^2\delta^2}{k\delta}\right)$$

Chen and Palmadesso 1984



If $p_\perp > p_\parallel$, reconnection is enhanced

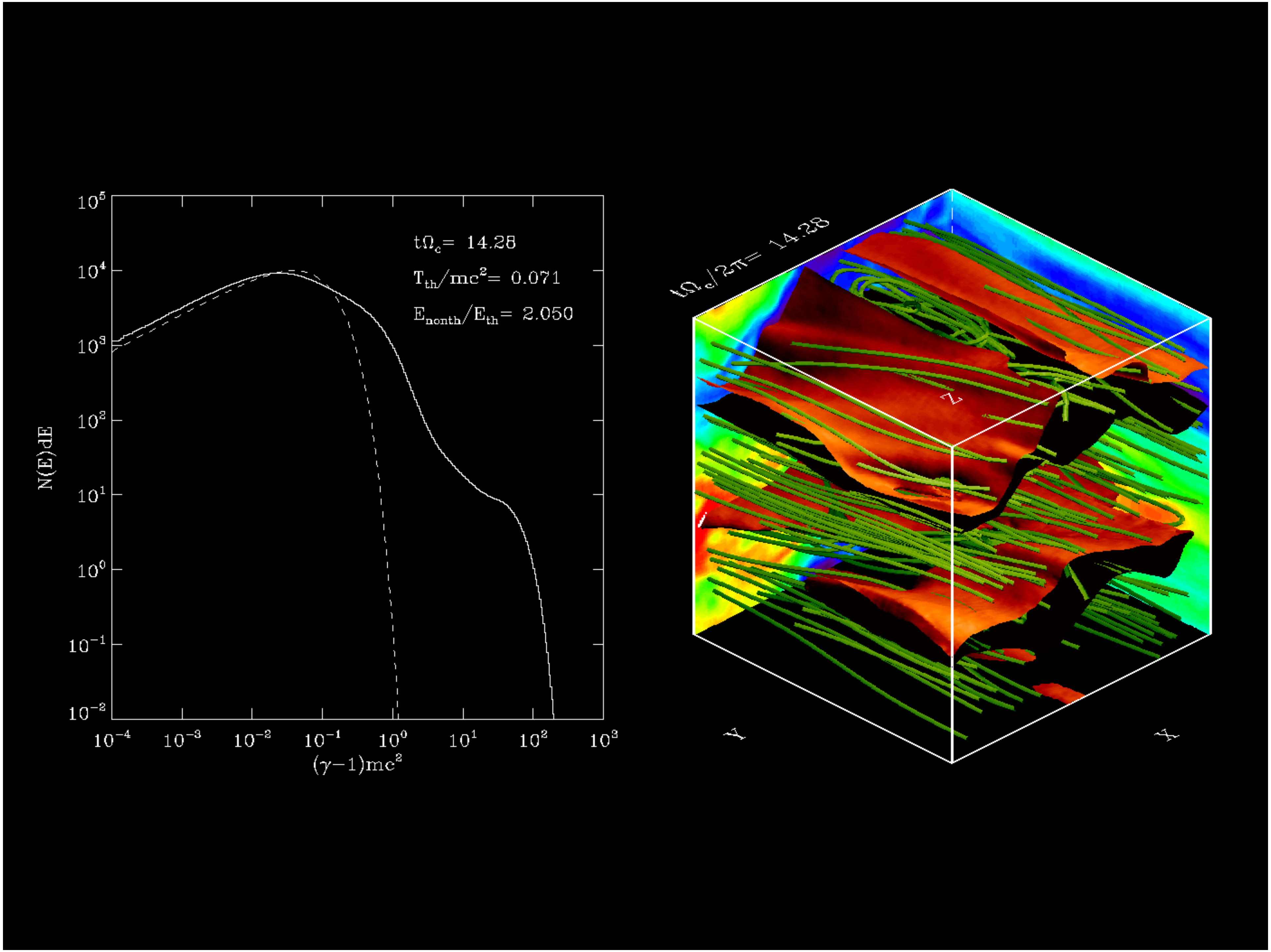
Angular Momentum Transport in 3d PIC simulation



β=1540, Kepler rotation Ω
300x300x300 grids 40 particles/cell,
open shearing box boundary,
electron-positron plasma

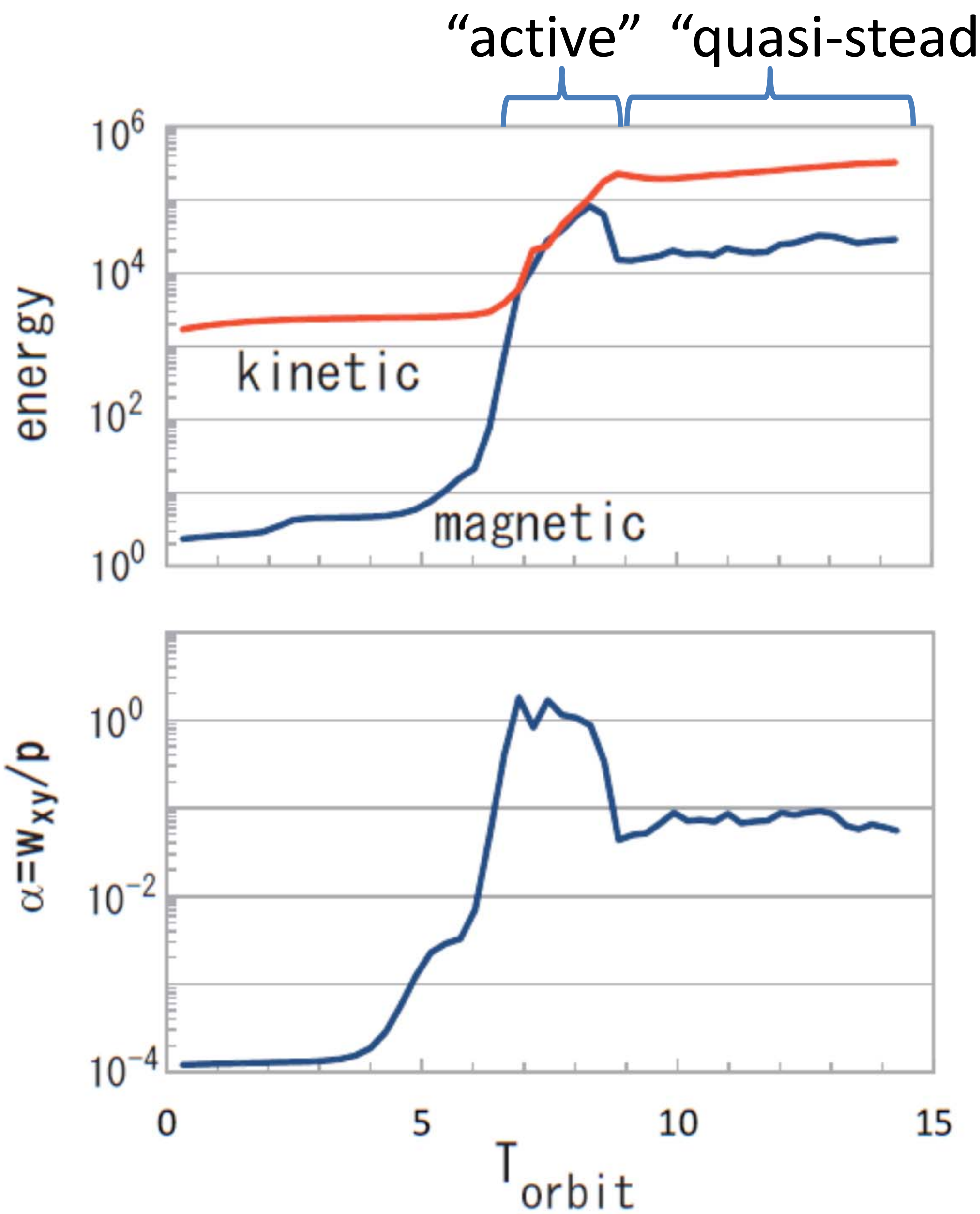
green: magnetic field lines
color contour: angular velocity

MH PRL 2015



tΩc= 14.28
Tth/mc2= 0.071
Enonth/Eth= 2.050
N(E)dE
(γ−1)mc2
tΩc/2π= 14.28
Z
Y
X

Energy and Stress Tensor Evolutions



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

stress tensors

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

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

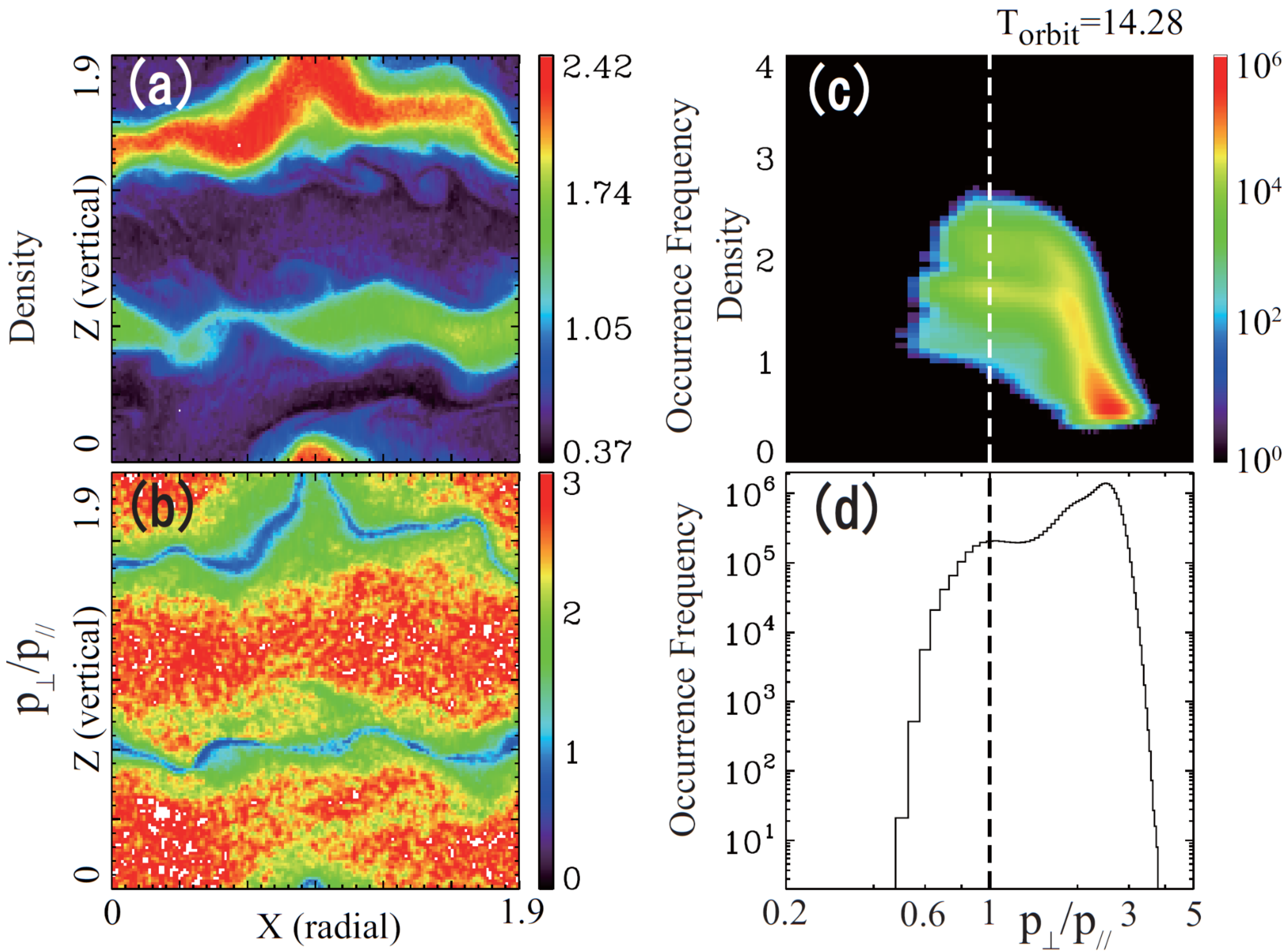
$$= -\frac{2B_x B_y}{B^2}\frac{B^2}{8\pi p} \approx \frac{B^2}{8\pi p} = \frac{1}{\beta}$$

α(kinetic) ~ O(0.1)

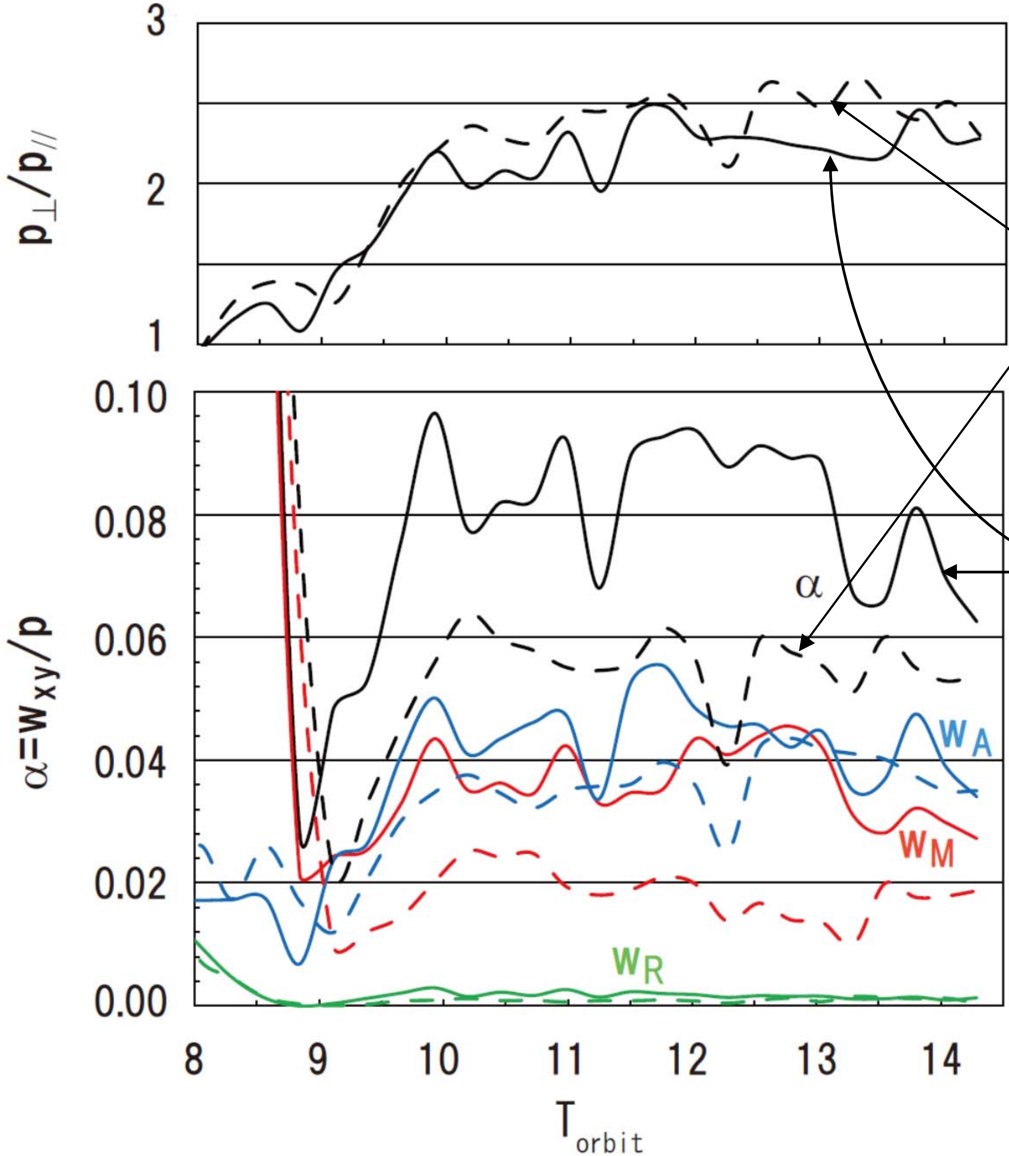
α(kinetic)/α(MHD) > 10 -100

(e.g., Hawley+ 1995; Sano+ 2004…)

Reconnection is suppressed by $p_\parallel > p_\perp$



$$\frac{d\vec{p}}{dt} = e\left(\vec{E} + \frac{\vec{v}}{c} \times (\vec{B} + \delta\vec{B})\right) - m\gamma\left(2\Omega_0 \times \vec{v} - 2q\Omega_0^2 x\hat{x}\right)$$



$\delta\vec{B}$: random field in channel flow

With pitch-angle scattering model

$\delta\vec{B} = 0$

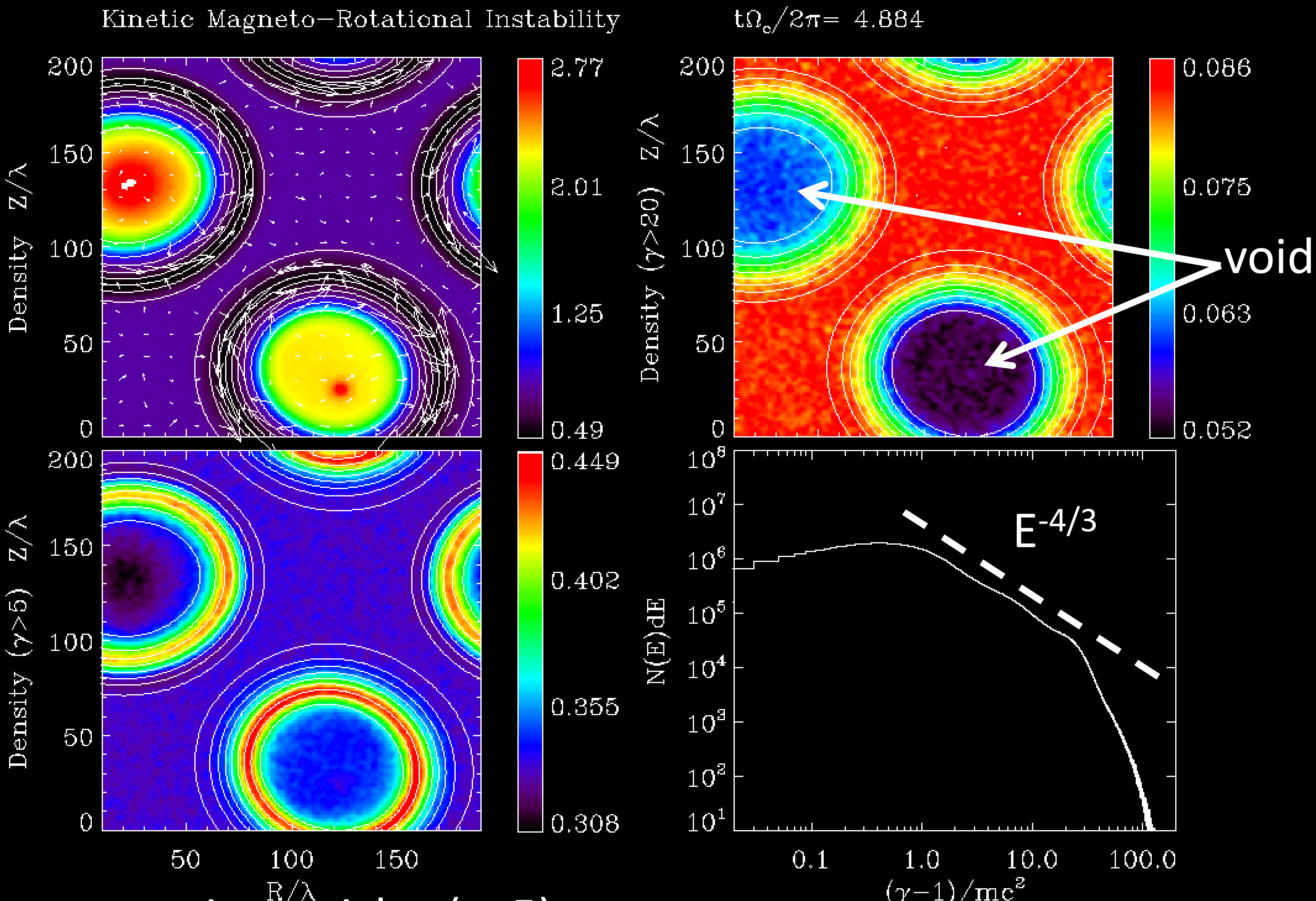
Without pitch-angle scattering model

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

w_R $\quad w_M$ $\quad w_A$

thermal plasma is confined inside magnetic islands

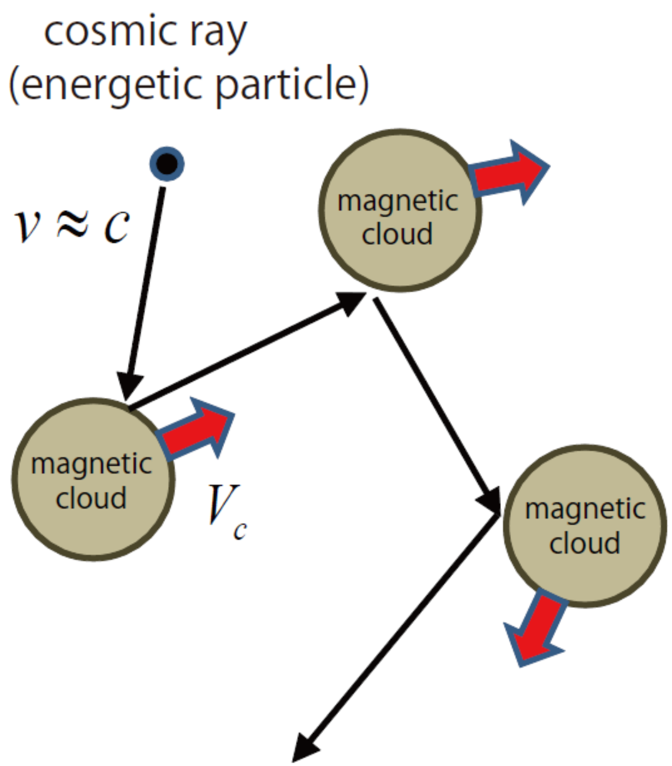
high energetic particles (γ>20) are located outside magnetic islands



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

Fermi-Reconnection Acceleration in Many Magnetic Islands

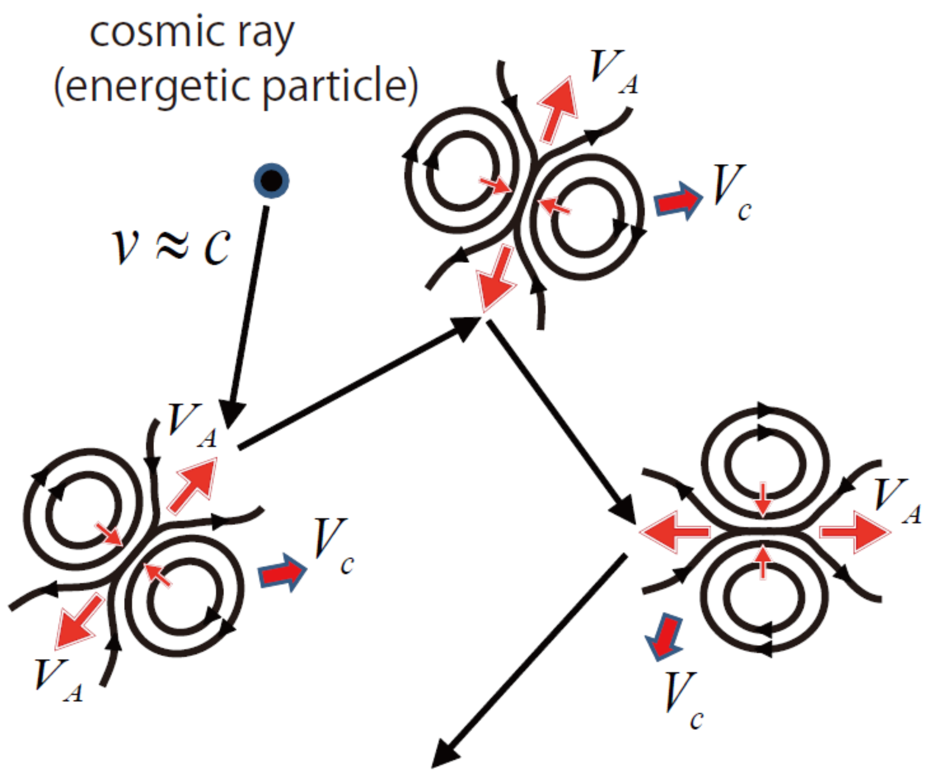
2nd order Acceleration



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

Fermi, Phys. Rev. (1949)

1st order Acceleration



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

MH PRL (2012); MH & Lyubarsky SSR (2012)

Summary

"Particle Acceleration" and "Angular Momentum Transport" during MRI in Collisionless Accretion Disk

- $T_\perp > T_{//}$ during MRI evolution
- Enhanced reconnection rate due to $T_\perp > T_{//}$
- Strong particle acceleration by reconnection

- $T_\perp < T_{//}$ in current sheet by reconnection
- Suppressed onset of reconnection due to $T_\perp < T_{//}$
- Large B field and enhanced "α (alpha) parameter"