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Collisionless Accretion Disks: Role of Reconnection in Anisotropic Plasmas

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Collisionless Accretion Disk & MRI

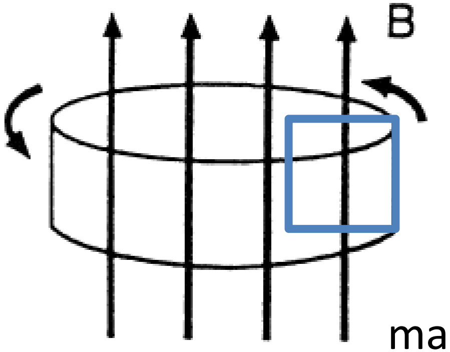
- ✓ Accretion Disk around Massive Black Halls (e.g., Sgr A*)
- ✓ Radiatively Inefficient Accretion Flow (RIAF)
- ✓ Nonthermal electrons, power law index p~1.3 < 2

(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)

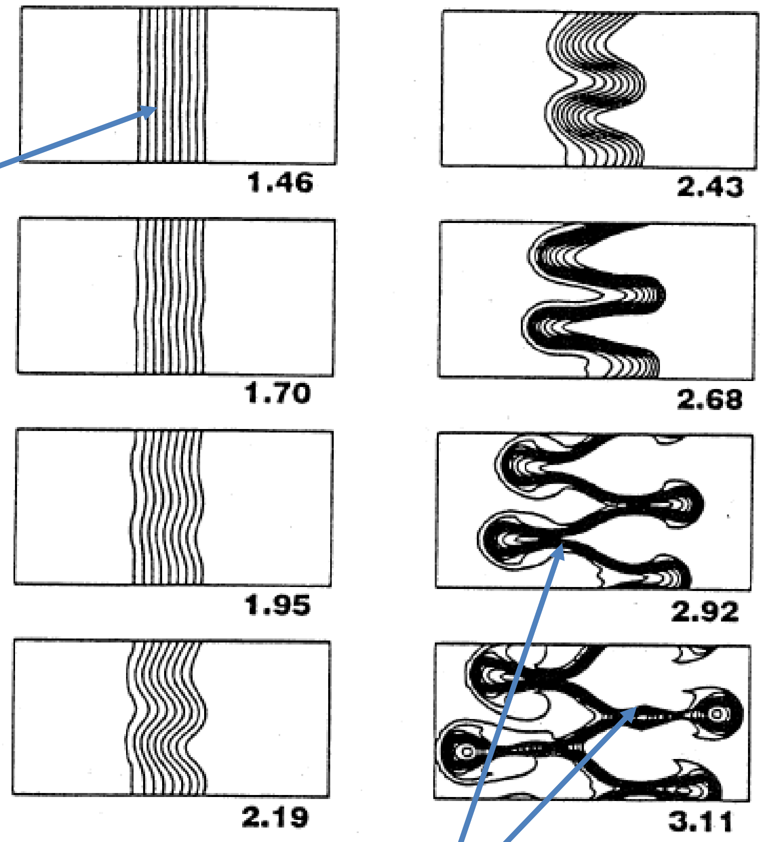
Collisionless magnetic reconnection plays a dynamically important role on both particle acceleration and α-parameter

Role of Reconnection in MRI



magnetic field line

Time evolution of MRI
Balbus and Hawley 1998

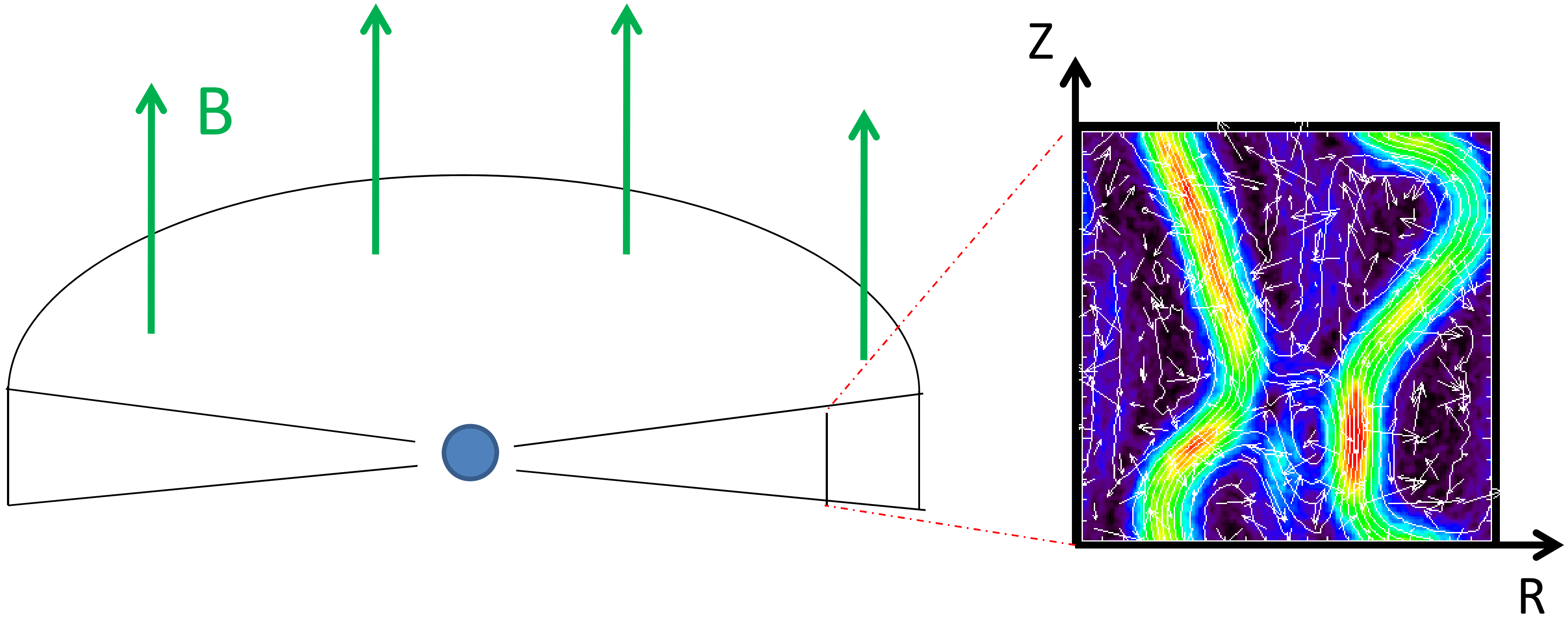


magnetic reconnection

- ✓ Saturation of B-field in MRI is determined by balance between “B-filed amplification by MRI” and “B-field dissipation by reconnection”
- ✓ Initial weak B-field (β>>1) → β~10

(e.g., Hawley+ 1995; Sano+ 2004…)

Collisionless MRI in 2d PIC simulation

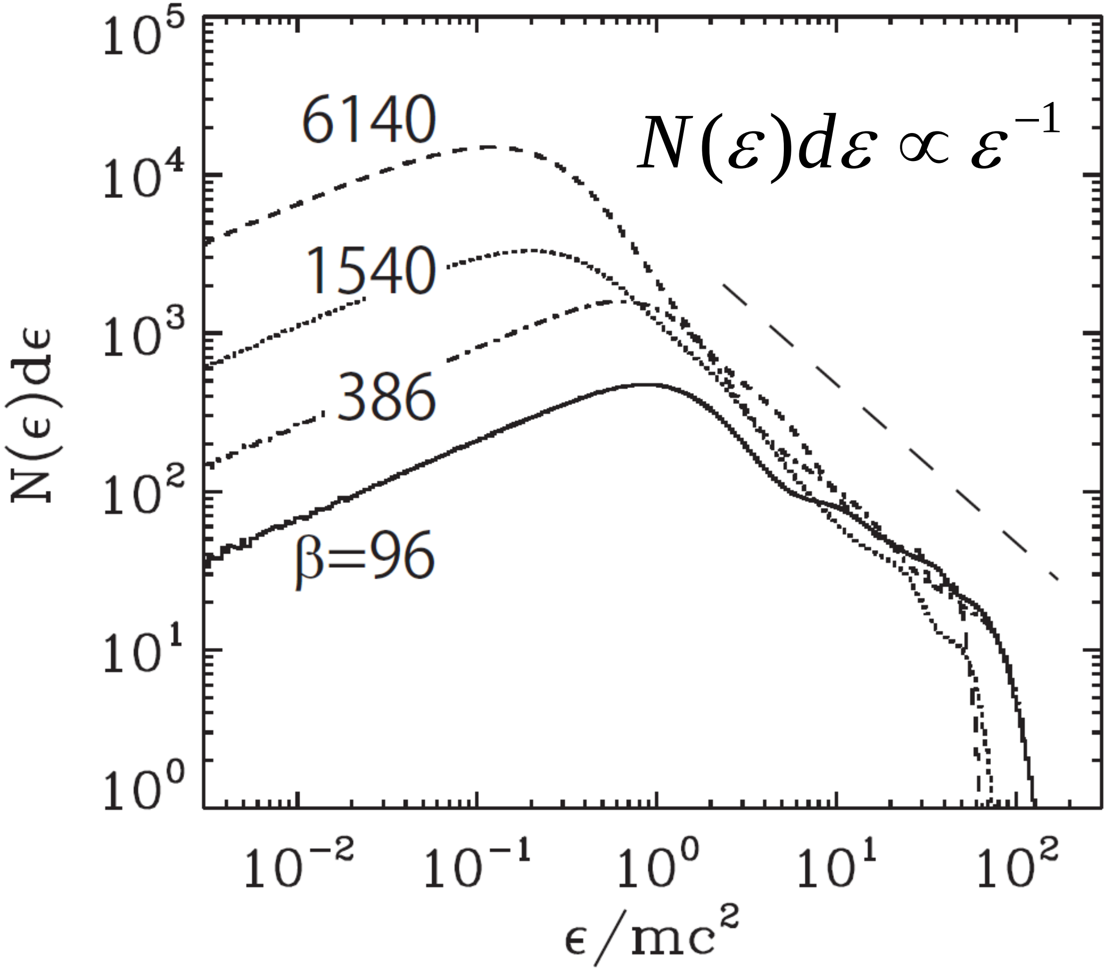


Kepler rotation Ω, $\Omega / \Omega_c = 0.1$,
β=1540, 200x200 grids 8000 particles/cell,
open shearing box boundary, electron-positron plasma

MH ApJ 2013

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

Energy Spectra during MRI-Reconnection

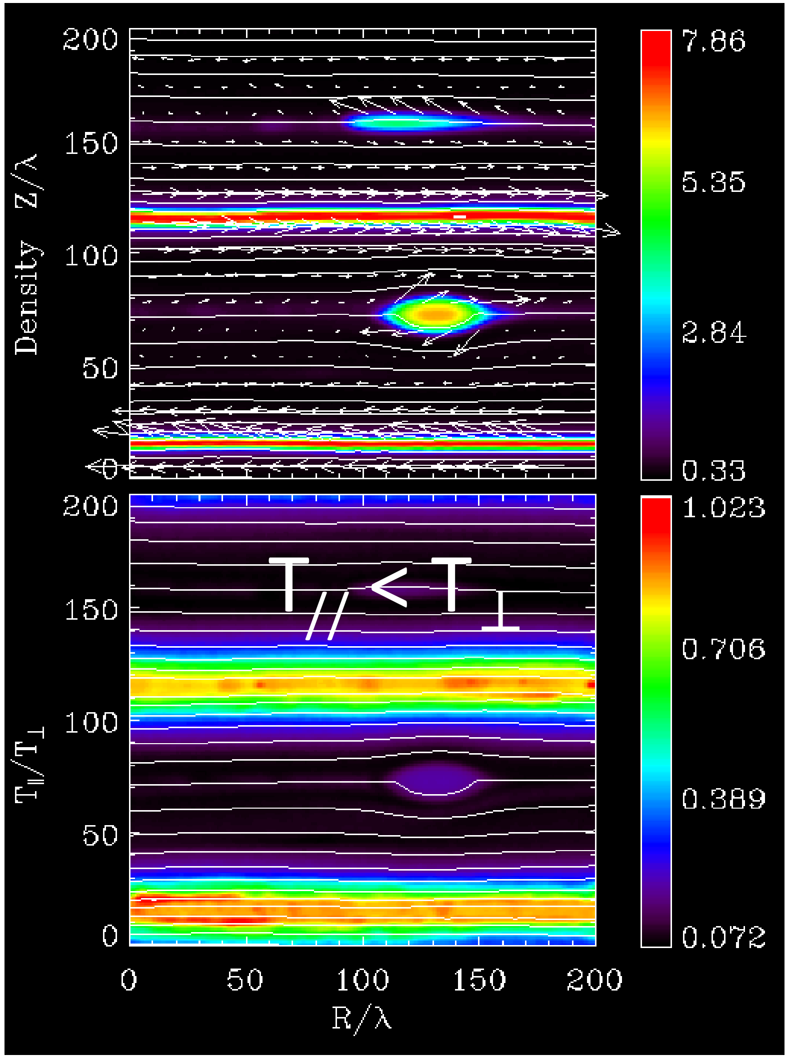


Dependence of initial plasma beta is weak

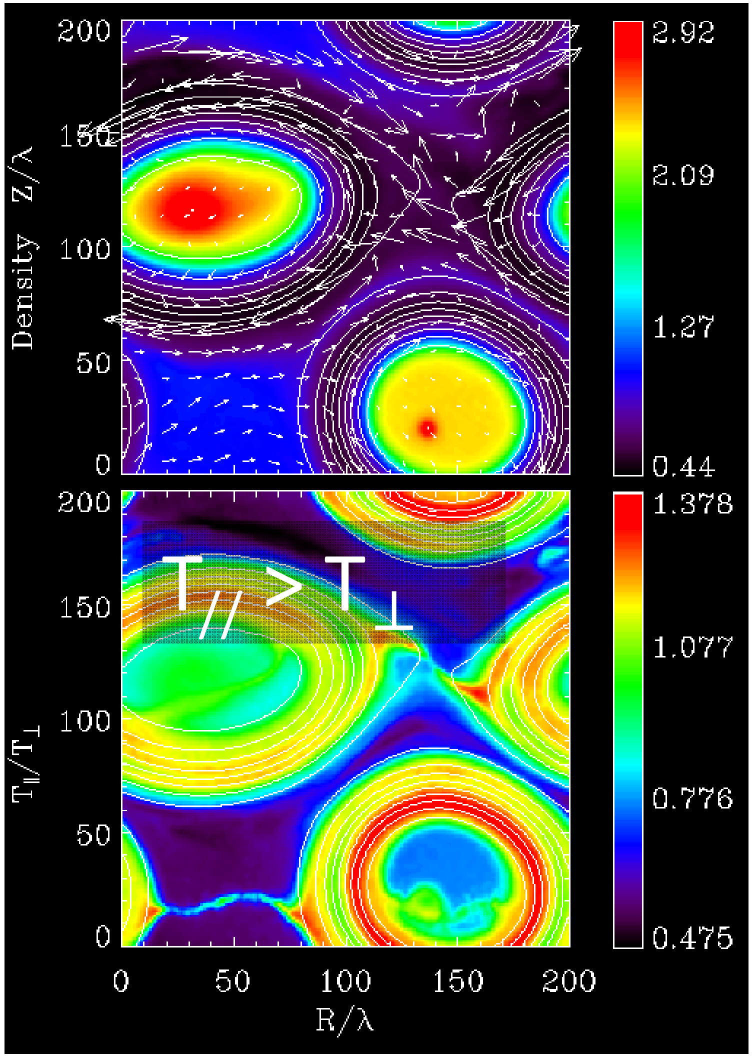
cf. Zenitani & MH ApJ 2001, reconnection talks in this meeting

Onset of Reconnection

Before onset of Reconnection



After onset of Reconnection



Production of Pressure Anisotropy during MRI & Reconnection

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

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

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

Istropization by mirror inst. & ion-cyclotron inst.

(Quataert+ ApJ 2002; Sharma+ ApJ 2006)

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

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

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

Role of Reconnection in Collisionless MRI

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

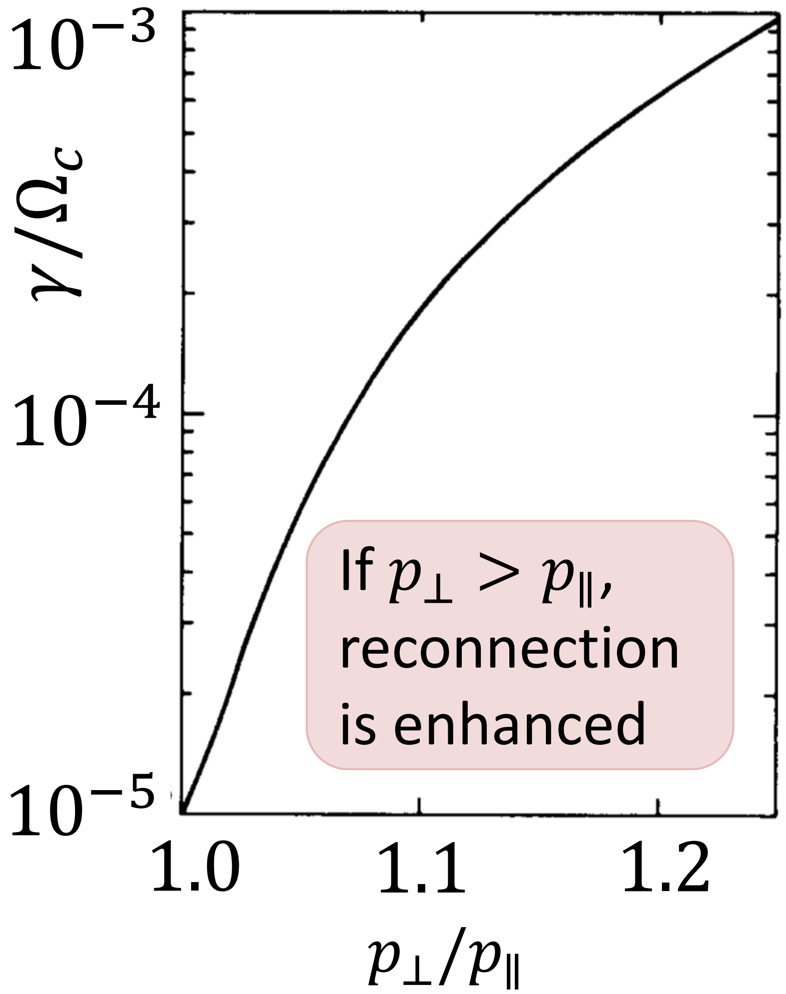
(e.g., Laval & Pellat 1968; Chen & Palmadesso 1984; MH 1987)

Tearing theory

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

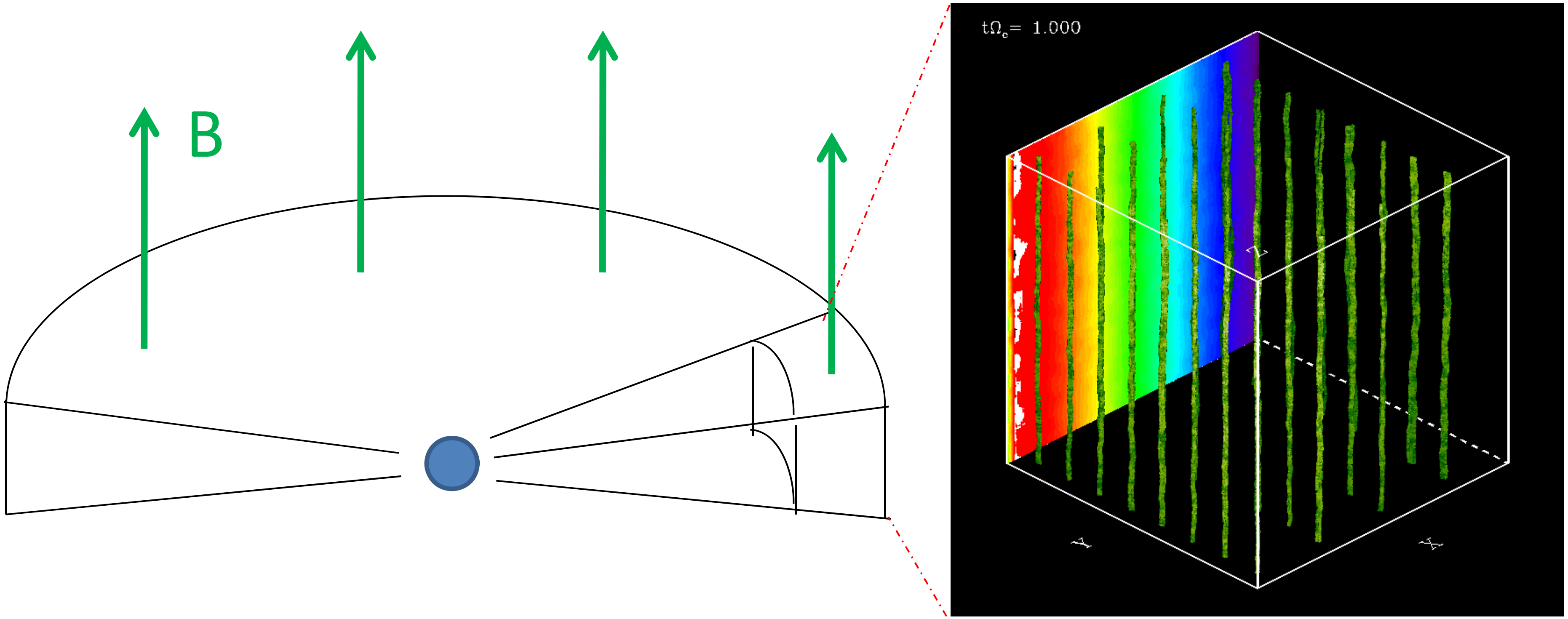
If $p_\parallel > p_\perp$,
reconnection is suppressed

Chen and Palmadesso 1984



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

Angular Momentum Transport in 3d PIC simulation

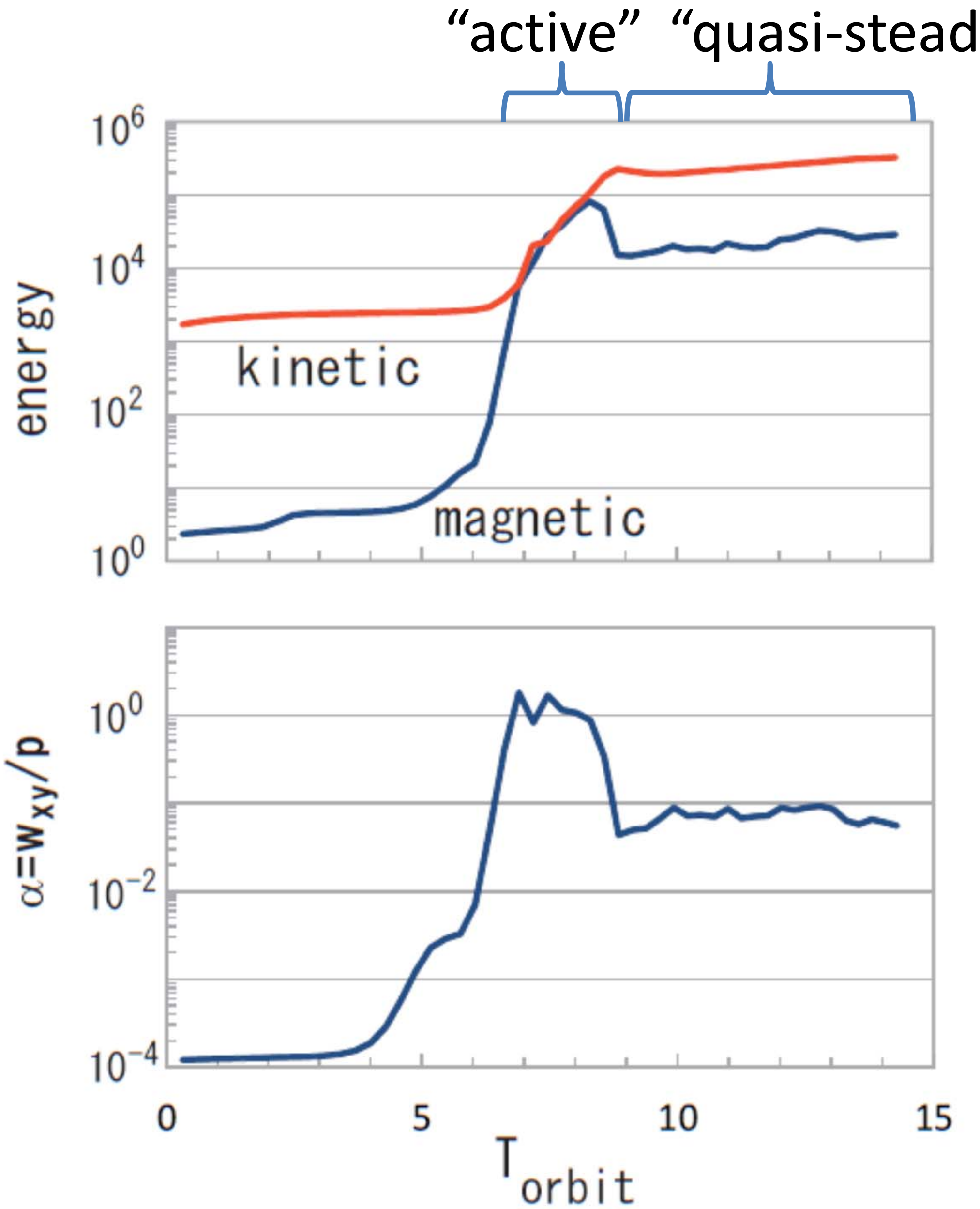


β=1540, Kepler rotation Ω
300x300x300 grids 40 particles/cell,
open shearing box boundary,
electron-positron plasma

green: magnetic field lines
color contour: angular velocity

MH PRL 2015

Energy and Stress Tensor Evolutions



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

stress tensors

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

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

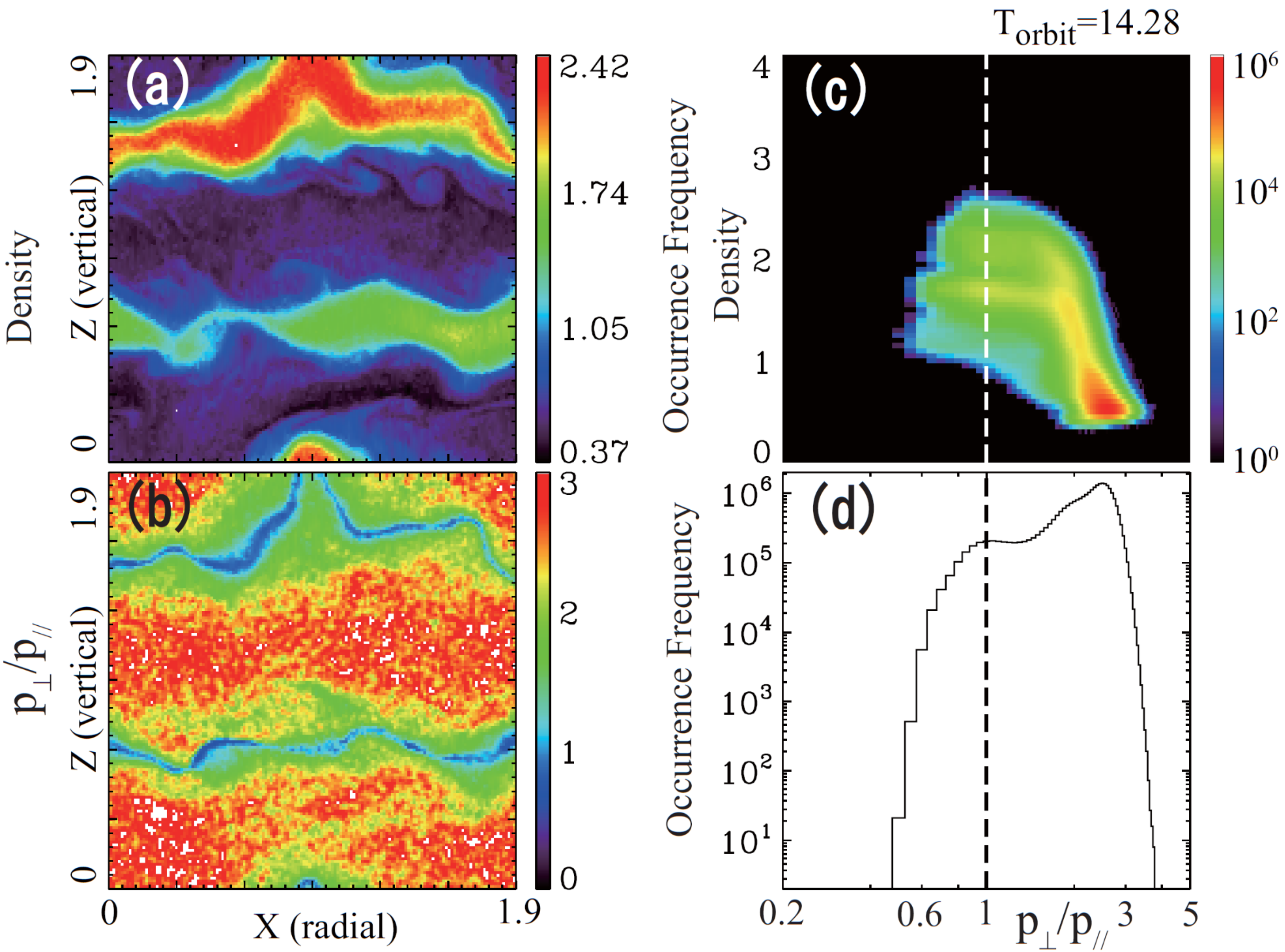
$$= -\frac{2B_x B_y}{B^2} \frac{B^2}{8\pi p} \approx \frac{B^2}{8\pi p} = \frac{1}{\beta}$$

α(kinetic) ~ O(0.1)

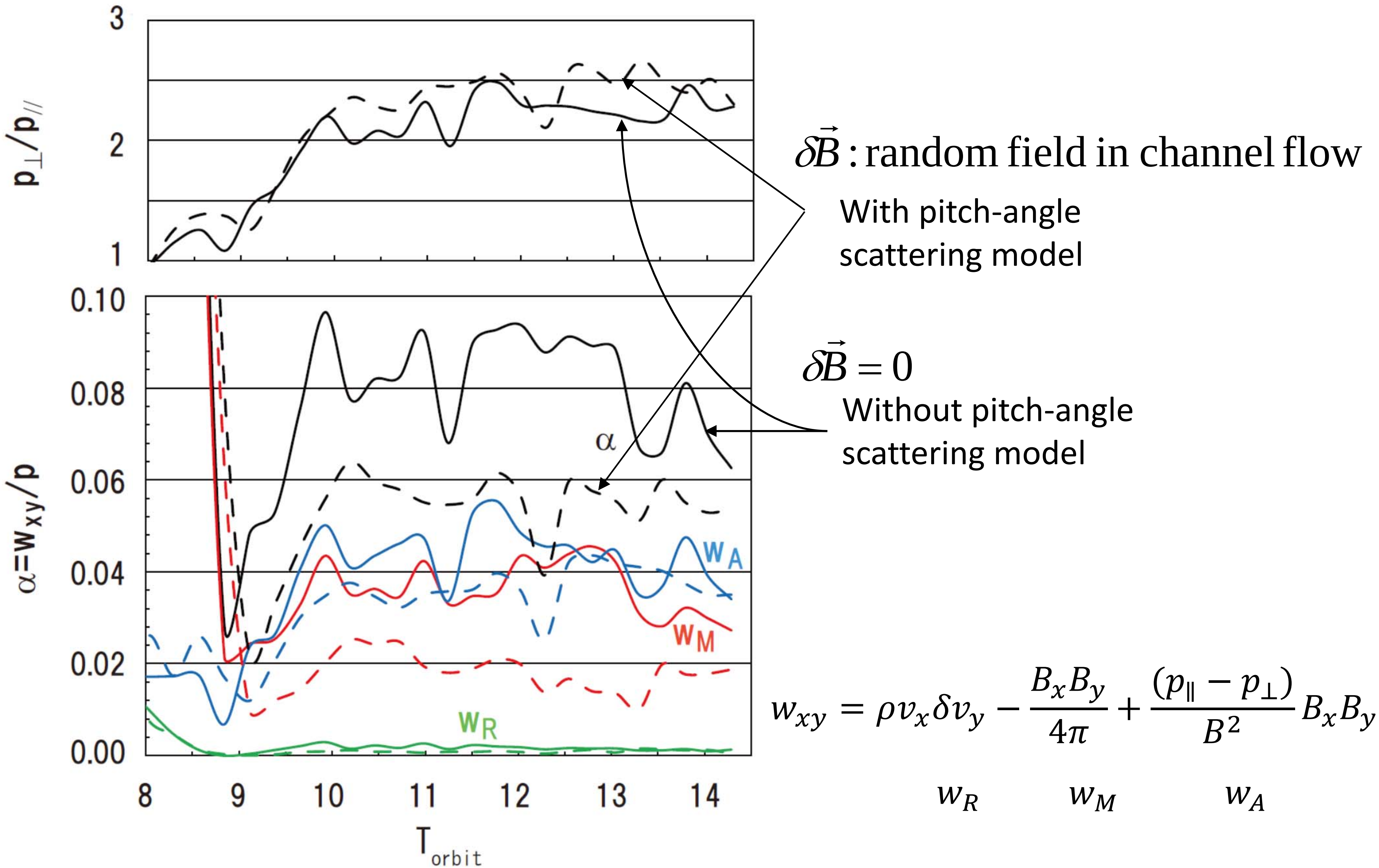
α(kinetic)/α(MHD) > 10 -100

(e.g., Hawley+ 1995; Sano+ 2004…)

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



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

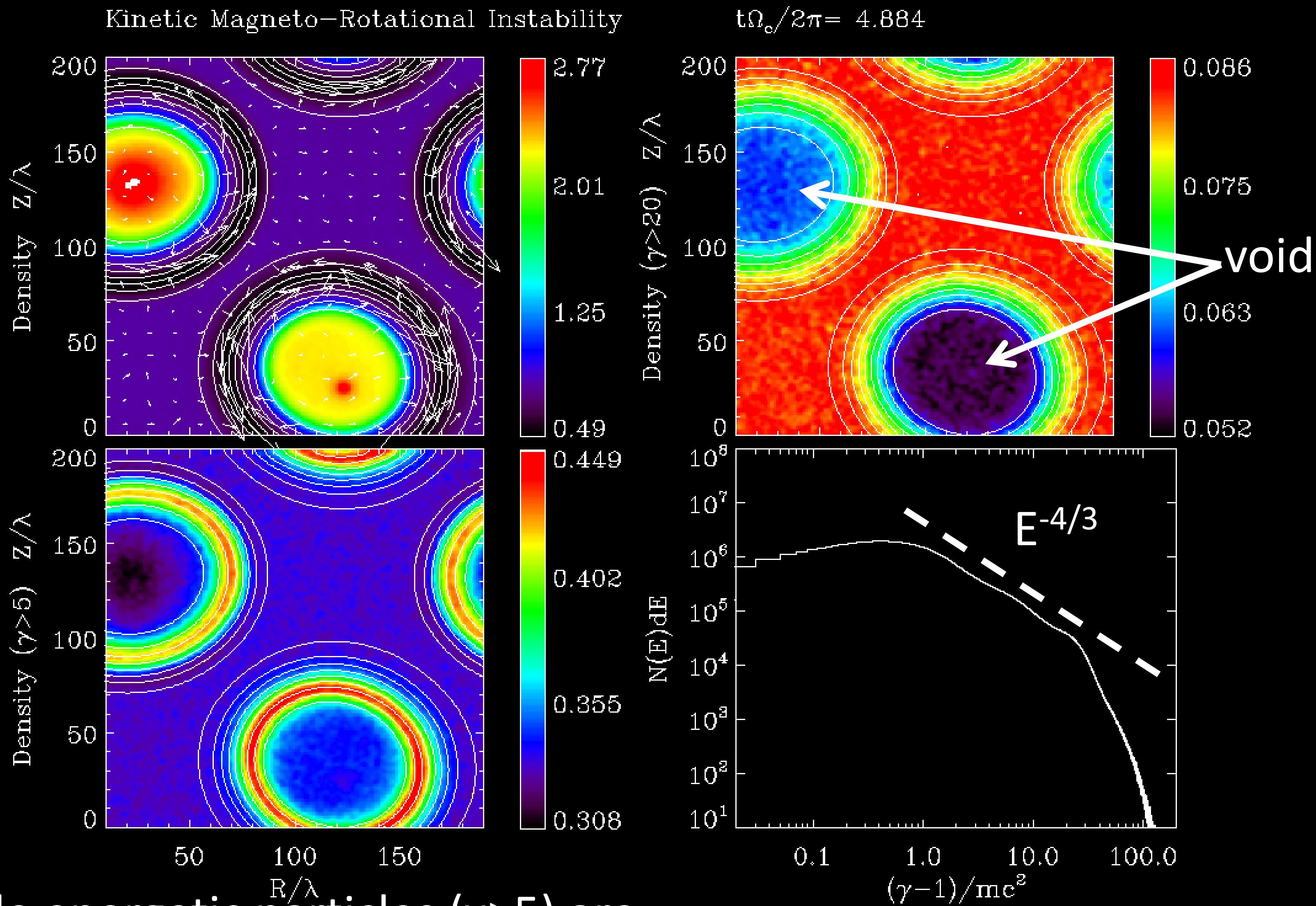


$$w_{xy} = \rho v_x \delta v_y - \frac{B_x B_y}{4\pi} + \frac{(p_\parallel - p_\perp)}{B^2} B_x B_y$$

w_R w_M w_A

thermal plasma is confined inside magnetic islands

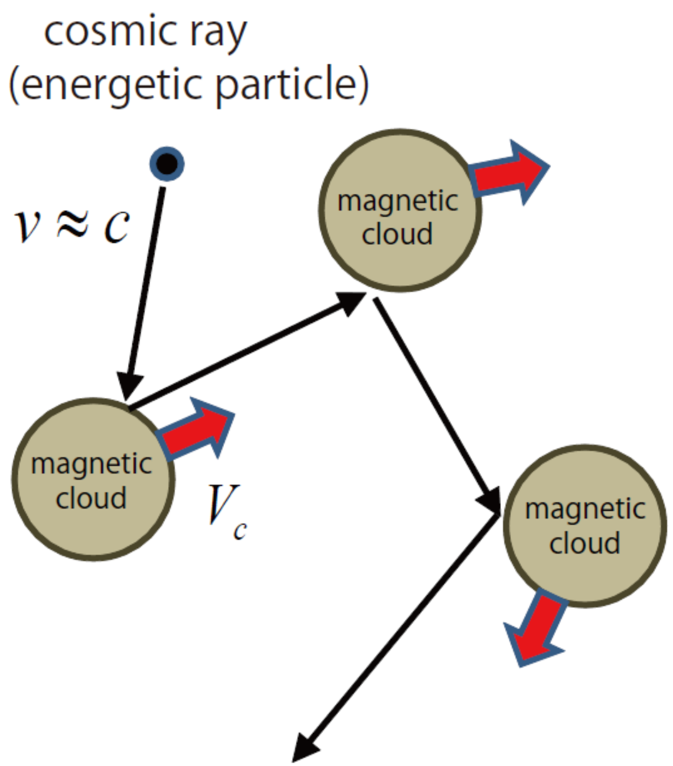
high energetic particles (γ>20) are located outside magnetic islands



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

Fermi-Reconnection Acceleration in Many Magnetic Islands

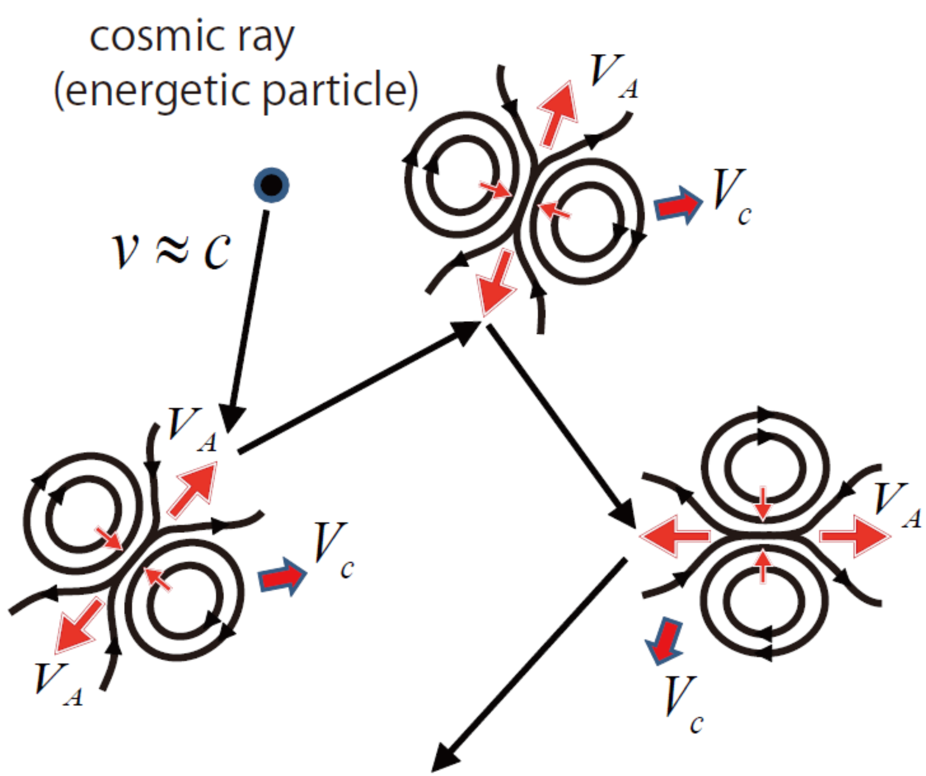
2nd order Acceleration



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

Fermi, Phys. Rev. (1949)

1st order Acceleration



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

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

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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 parameter”