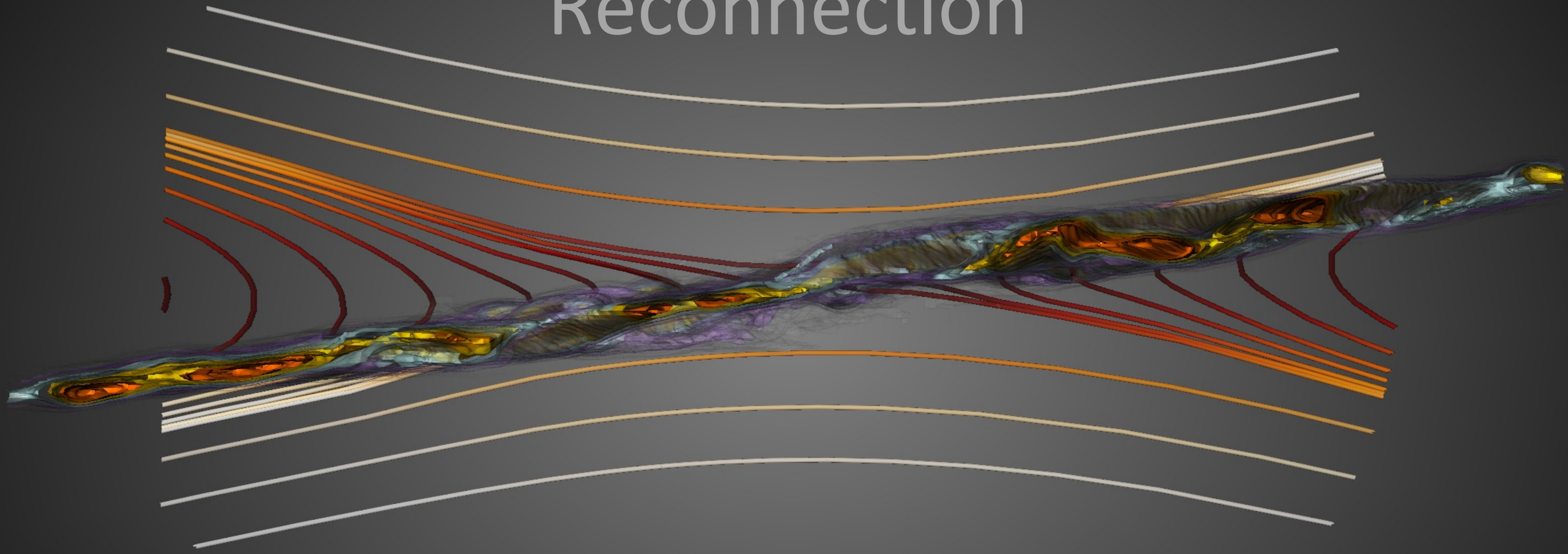
Anomalous Momentum Transport in Fast Electron Heating and The Role in Reconnection



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Long History of Turbulent Reconnection

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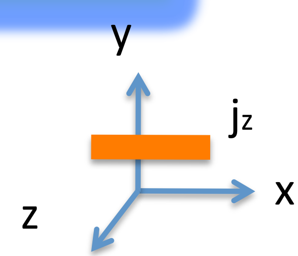
- The concept of turbulence-induced anomalous resistivity was proposed (1962, Sagdeev), then applied to reconnection (Davidson, Papadopoulos, Huba …, since 1970)
- Since 1980s, MHD turbulenct reconnection including anomalous viscosity was studied (Bhattacharjee,…)
- Since 1990s: **1)** MRX experiment revived the interest in turbulent reconnection (Ji, Yamada, Kulsrud...); VTF electron hole experiment (Egedal, Fox…). **2)** Observations of turbulent reconnection at magnetosphere (Bale, Mozer, Cindy, Oieroset, Eastwood). **3)** Galaxy and cluster scale turbulent reconnection (Lazarian, Eyink, Vishniac …).
- Since 2000, PIC simulations joined to explore this problem (Daughton, Pritchett, Drake…)
- ***In 2011, 3D PIC simulation (Che, Drake and Swisdak) confirmed that turbulence produced by electron velocity shear instability can break magnetic field lines and accelerate reconnection process.***

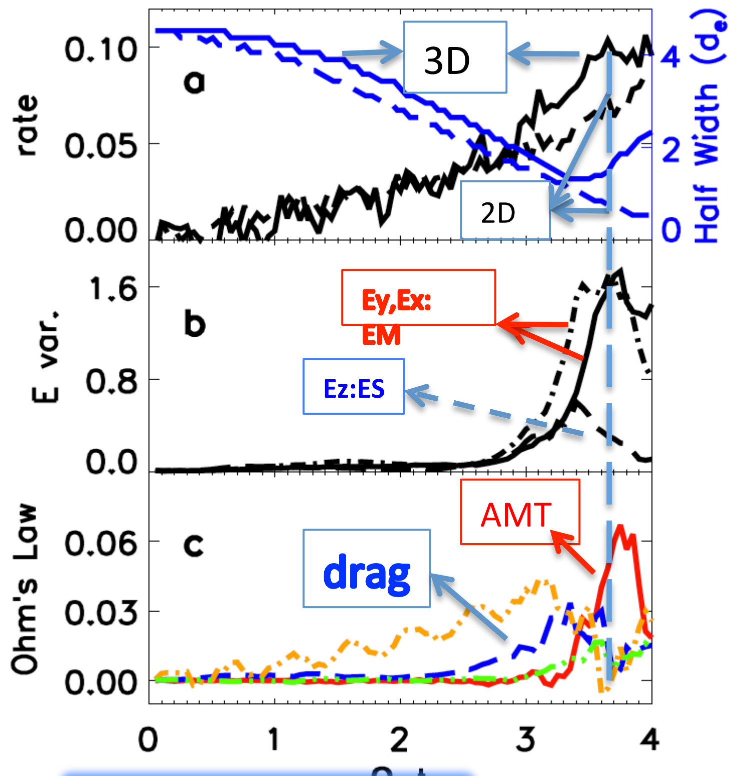
Electron Velocity Shear Instabilities in 3D Magnetic Reconnection

3D PIC magnetic reconnection simulation with a guide field. Mass ratio is 100, periodic boundary. During simulation intense electron beams form around x-line which drive electrostatic streaming instabilities at early stage and polarized electromagnetic electron velocity shear instabilities at late stage. ***Streaming instabilities*** produce ***strong anomalous heating*** and ***electron shear instabilities*** produce strong ***anomalous momentum transport***. However, we observed it was ***anomalous momentum transport*** to accelerate magnetic reconnection process.

(Che, Drake, Swisdak, *Nature, 2011*)



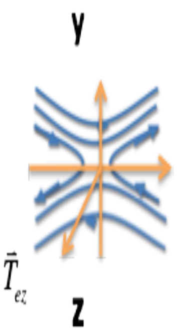
Anomalous Momentum Transport (AMT) Accelerates Magnetic Reconnection



2D: no turbulence

(Che, Drake, Swisdak, *Nature, 2011*)

Ensemble-averaged general Ohm's law:



$$\langle E_z\rangle + \frac{1}{c}(\langle \vec{v}_e\rangle \times \langle \vec{B}\rangle)_z = -\frac{\vec{\nabla}\cdot\langle \vec{P}_{ez}\rangle}{e\langle n_e\rangle} - \frac{m_e}{e}\left(\frac{\partial \langle v_{ez}\rangle}{\partial t} + \langle \vec{v}_{e\perp}\rangle\cdot\vec{\nabla}\langle v_{ez}\rangle\right) + D_{ez} + \vec{\nabla}\cdot\vec{T}_{ez}$$

Including Anomalous thermal momentum transport

$$D_{ez} = \frac{1}{\langle n_e\rangle}\langle \delta n_e \delta E_z\rangle$$

Turbulence Drag: anomalous resistivity

$$\vec{T}_{ez} = -\frac{1}{e\langle n_e\rangle}\left\langle \delta p_{e\perp}\left(\delta v_{ez} + \frac{e}{m_e c}\delta A_z\right)\right\rangle, \quad p_{e\perp} = m_e n_e v_\perp, \quad \vec{B} = \nabla\times\vec{A}$$

Turbulent electron momentum transport: anomalous viscosity.

What's the difference between AMT and AS? Can ES instability cause sufficient AMT?

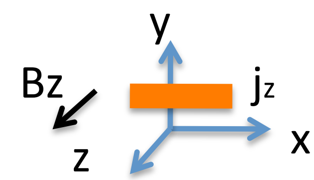
- **Can anomalous resistivity (AS) accelerate reconnection?**
- **What is the connection and difference between MHD and kinetic turbulent reconnection ? More precisely**

a) *Are the kinetic anomalous resistivity and MHD anomalous resistivity the same?*

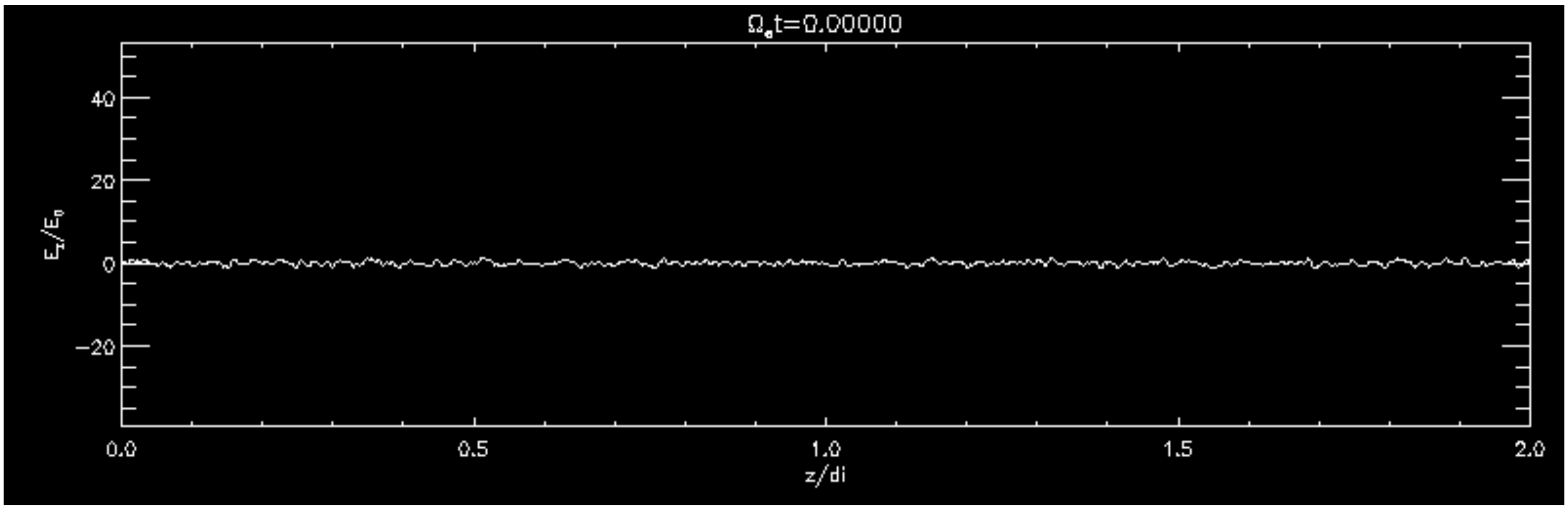
b) *Are the kinetic anomalous Viscosity and MHD anomalous Viscosity the same?*

- **Are the kinetic effects important on MHD scale (> ion inertial length)? (MHD people question kinetic)**
- **How far MHD turbulence is valid on small scale (electron inertial length)? (Kinetic people question MHD)**
- **And many more…**

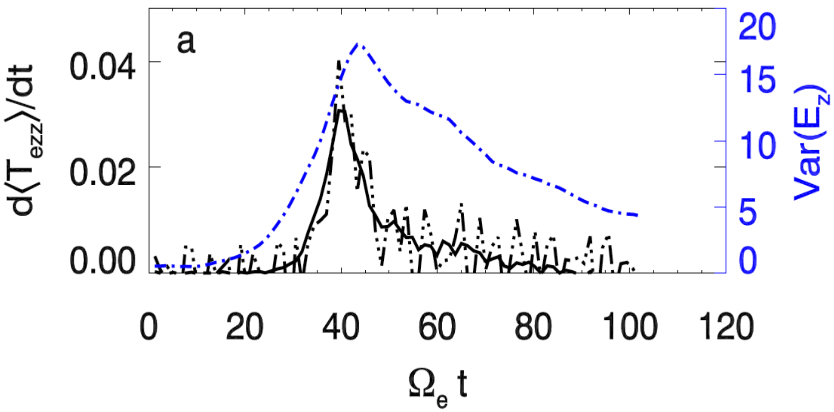
Anomalous Momentum Transport in Anomalous Heating



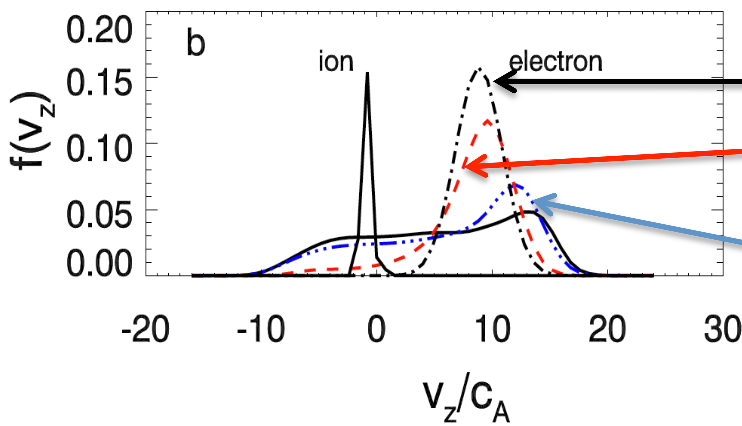
Ez in Z

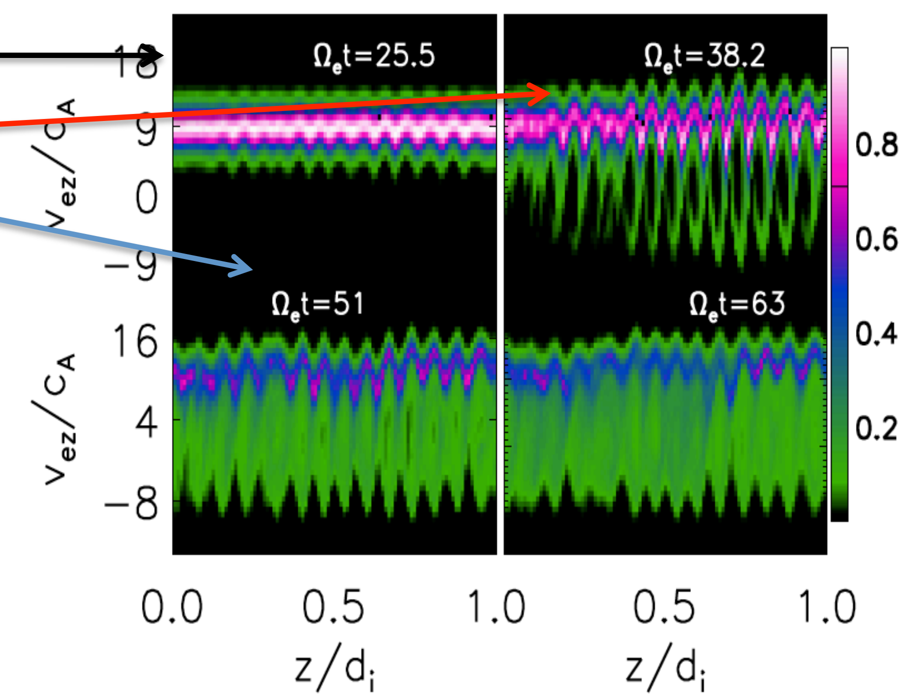


A 3D thin current sheet in xy plane with a guide field Bz in plasma with Ωe/ωe < 1. Mass ratio 100, Conductor boundary in y and period boundary conditions in x and z. Buneman instability parallel to B develops and increases 10 times electron temperature (Tezz) in ~20 electron gyro-periods.



a) Black-dotted:
$|dW/dt| = -m_e/2 \; d\langle j^2_{ez}/n_e \rangle/dt$
Solid: $d\langle T_{ezz} \rangle/dt$
Blue line: Ez variance

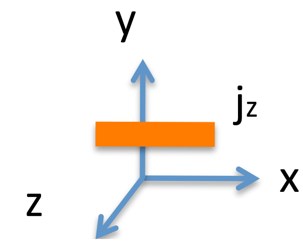




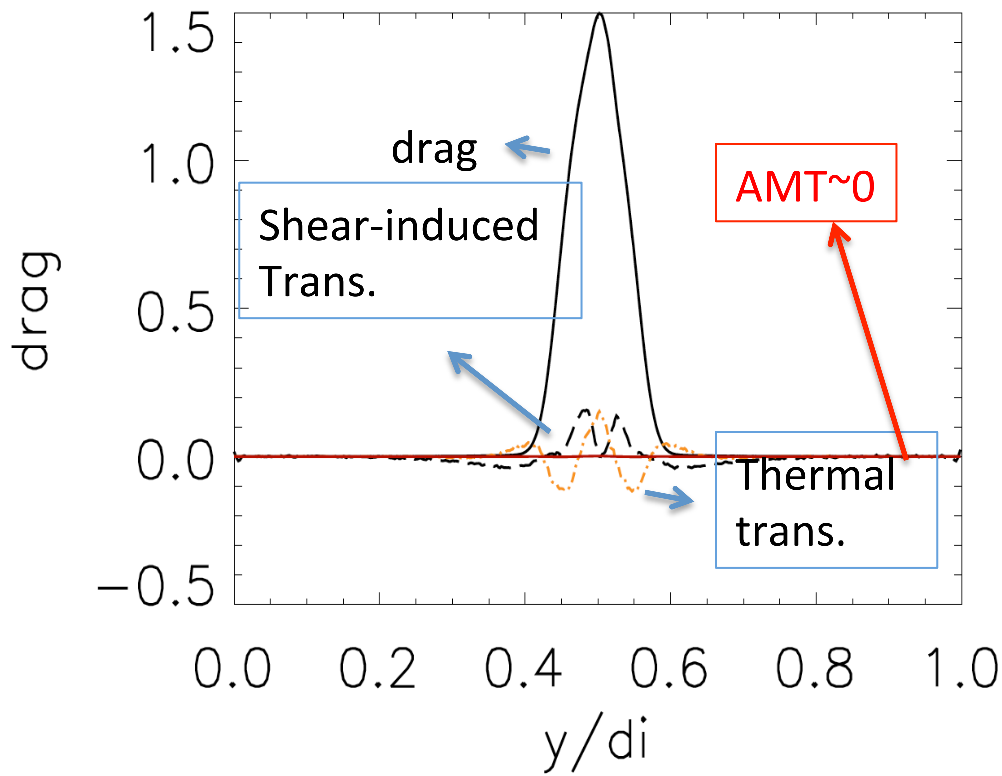
Momentum conversion parallel to B field:
From kinetic |dW/dt|

To thermal d<Tezz>/dt

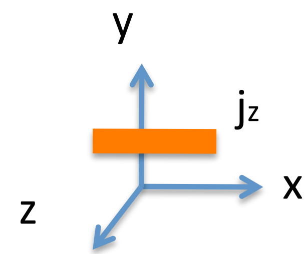
Anomalous Transport in xy Plane



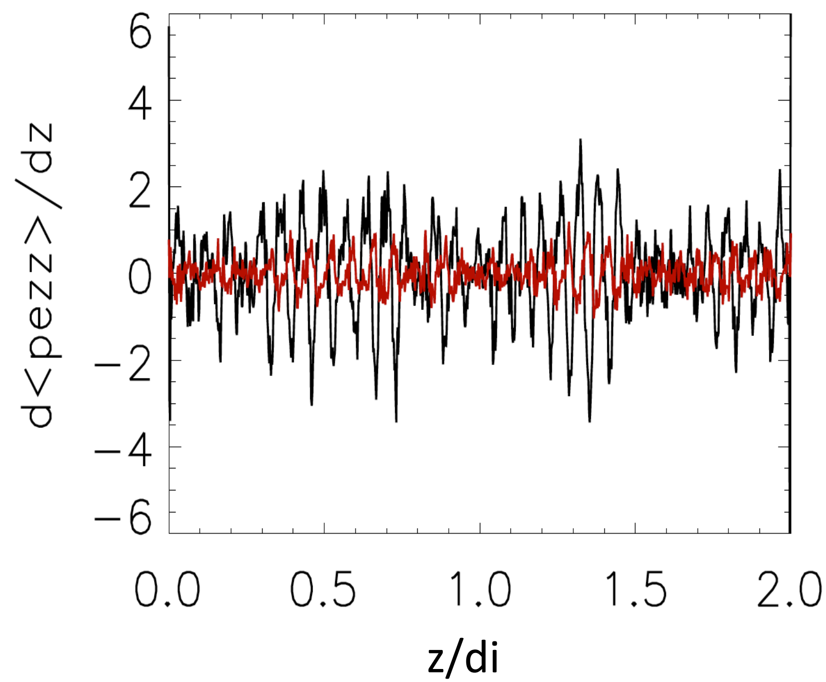
- In xy plane, electrostatic Buneman instability parallel to Bz field, induces very weak anomalous momentum transport in xy which means ES is unable to transfer momentum parallel to B to perpendicular and broaden current sheet .
- In strong guide magnetic reconnection in plasma with Ωe/ωe < 1, Buneman instability might be important, but its major contribution to support fast reconnection is from drag, ***its contribution to off-diagonal pressure and broadening of current sheet is weak.***



Anomalous transport in z



- Buneman instability parallel to Bz convert electron kinetic drift energy into thermal energy by Ez trapping electrons.
- It produces large anomalous viscosity transport and produces anomalous thermal momentum transport parallel to B field.
- However, the ***induced transport is localized, following the waves***.



Red :thermal trans. In z
Black: anomalous momentum trans in z

Connection between anomalous viscosity and thermal momentum transport *(pressure tensor)*

- They are related by (Che, et al. 2007, APS)

$$\overline{\mathcal{P}} \approx \overline{\mathcal{P}_b} - \frac{m}{q}(\overline{\delta \mathbf{j} \delta \mathbf{U}} + \overline{\delta \mathbf{U} \delta \mathbf{j}}) + m\overline{n}\overline{\delta \mathbf{U} \delta \mathbf{U}}$$

$$\mathcal{P}_b = m \int (\mathbf{v} - \overline{\mathbf{U}})(\mathbf{v} - \overline{\mathbf{U}}) f d\mathbf{v}$$

- Therefore, anomalous viscosity is always accompanied by anomalous thermal momentum transport. In fact both come from the stress tensor derived from Vlasov equation $\int f\vec{v}\vec{v}dv$.

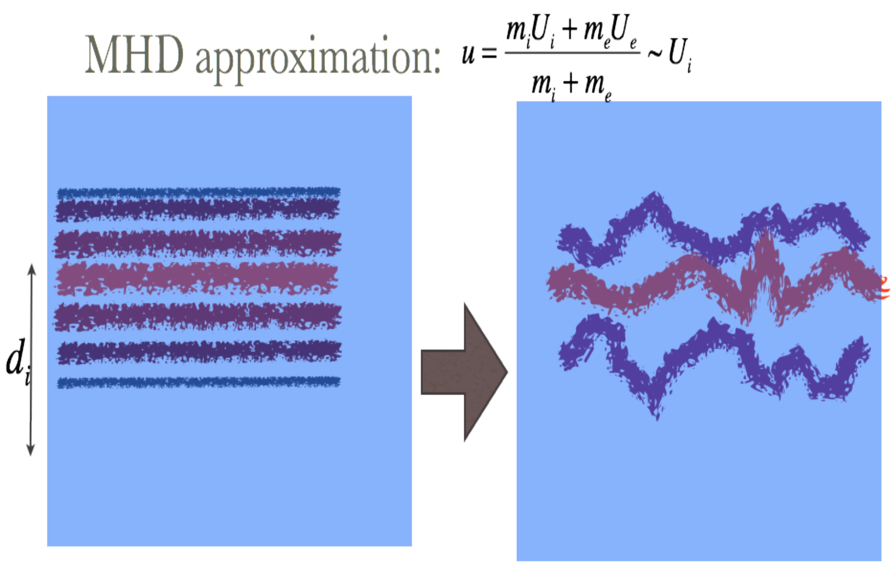
Summary

- Anomalous resistivity by streaming instabilities produces localized momentum transport (following the wavelength), and convert kinetic energy effectively into thermal energy.
- The impact of anomalous momentum transport during anomalous heating process on large scale process is restricted.

THANK YOU!

STAY HUNGARY! STAY FOOLISH!

What MHD might have missed?



blue color is ion velocity field and red color scale is electron velocity field, peaked at the center.

instability can occur by kinetic theory, by MHD, no turbulence.

- Miss contributions from electrons.

a) The breaking of field lines in electron diffusion region (Drake, Shay, Hesse, Prichett, Birn…).

b) Kinetic anomalous heating and momentum transport are collective which cause: 1) pressure, viscosity, resistivity: scalar-> tensor→ transport is spatial and time correlated. 2) MHD turbulence can not track down to small scale.

- Before we answer so many questions, we have to understand some basic things:

a) What is "*anomalous resistivity*"? Is it just a mathematical effective equality $\eta^* = \langle \delta n \delta E \rangle / J$? (more plus B filed dissipation)? Or more physics behind this equality?

b) What is "*anomalous momentum transport*"?

c) What are the connection and difference between these two "*anomalouses*"?