Plasma Heating during Turbulent Kinetic Magnetic Reconnection in Two Dimensions

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Outline

- Magnetic reconnection is ubiquitous in fusion and astrophysical plasmas, which allows topological change of field lines, and converts field energy into plasma flow and heat.
- In weakly collisional plasmas, phase mixing processes, such as Landau damping or finite Larmor radius (FLR) effects, have shown to enhance heating during reconnection by creating oscillatory structures in velocity space. [Numata & Loureiro, JPP (2015)]
- It is well known that turbulence accelerates reconnection by enabling multiple reconnection sites in the current sheet. [Lazarian and Vishniac (1999)].
- Turbulence can also be an efficient heating mechanism of plasmas. Recent gyrokinetic simulations have revealed the nature of dissipation mechanism in electromagnetic turbulence. [Howes, et al (2010), Kawazura, et al (2018)]
- In this study, we perform gyrokinetic simulations of turbulent kinetic reconnection in two dimensions, and study how the energy is dissipated in weakly collisional plasmas. To do this, we newly develop a random forcing method in AstroGK code [Numata et al (2010)].
- Questions:

1. What is the ratio of heating between ions and electrons?
2. How it depends on plasma parameters (eg. β)?

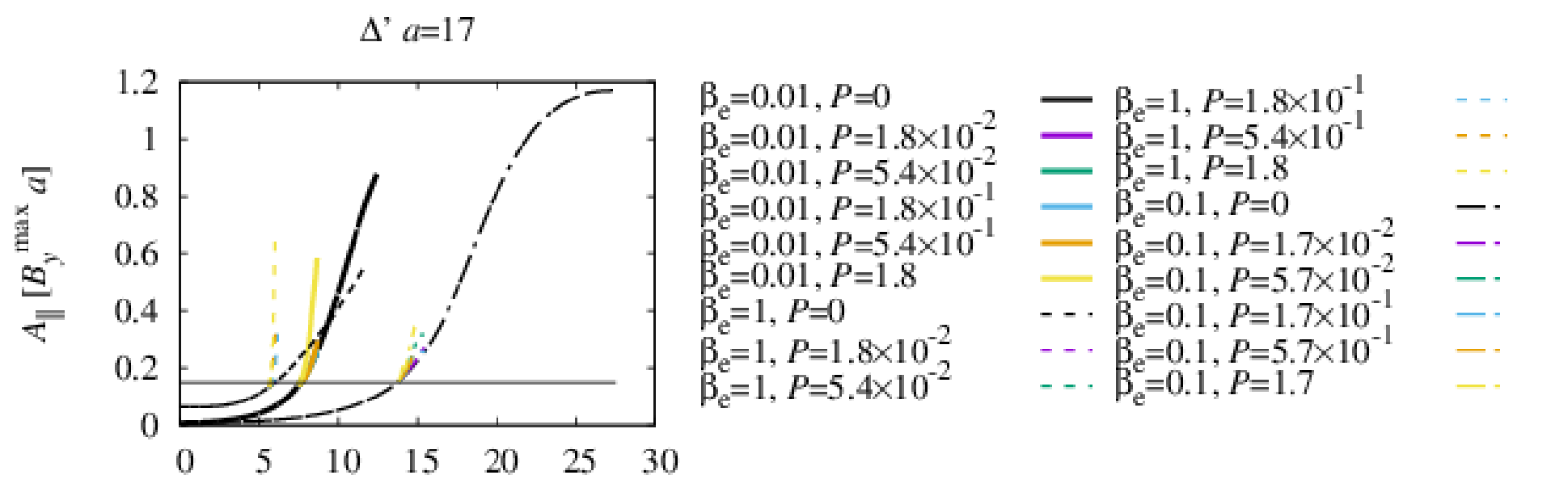
- Main Results:

We have newly implemented random forcing term in AstroGK code, and have performed simulations of magnetic reconnection with driven turbulence. Turbulence slightly accelerates reconnection. Turbulent eddies dissipate at ion scale, and enhances ion dissipation. Electron dissipation does not change very much due to turbulence. Similar tendency is observed for different β_e.

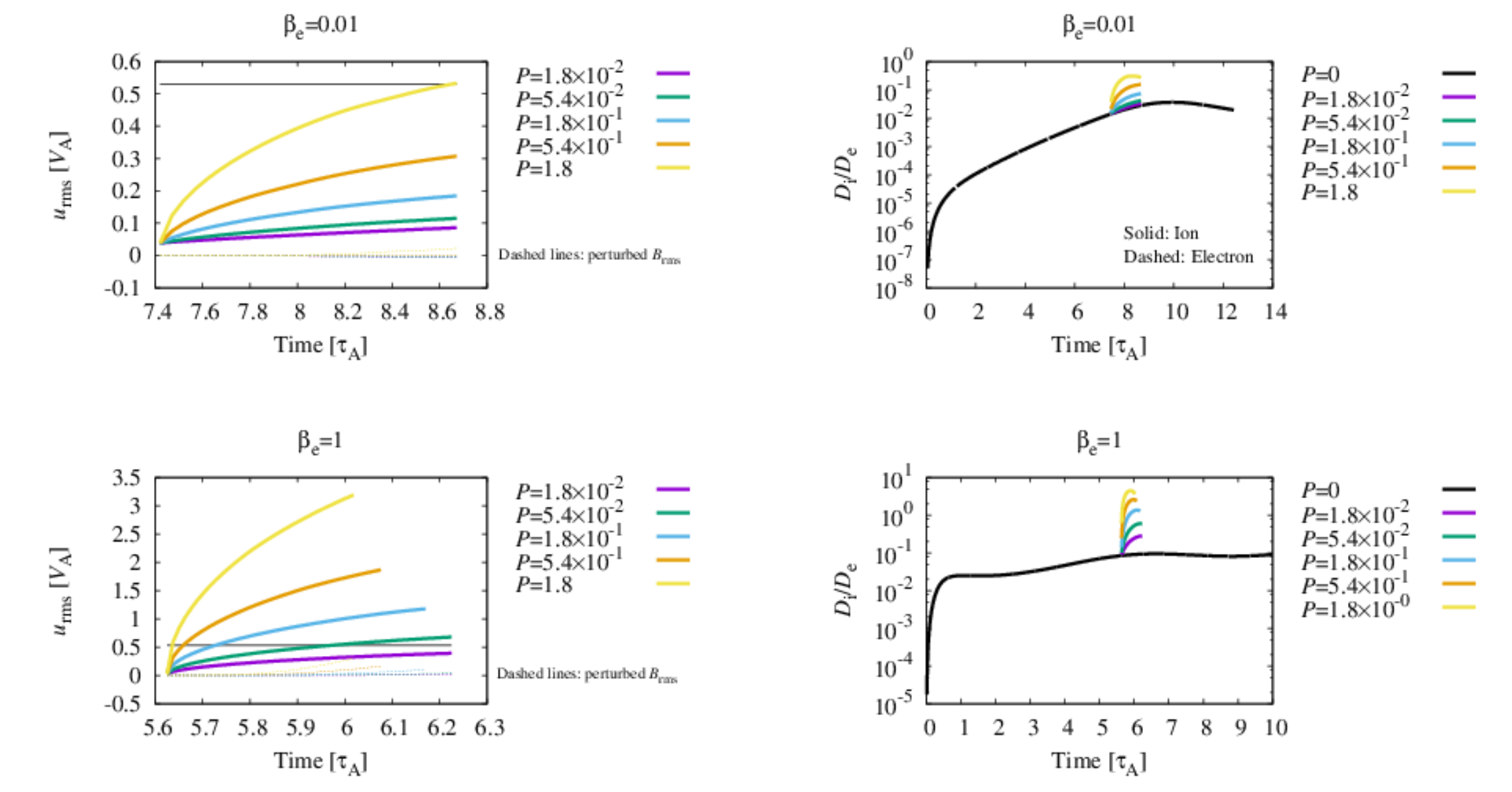
Simulation of Reconnection with Driven Turbulence

We perform gyrokinetic simulations of tearing mode reconnection following JPP (2015) [but, slightly different $\Delta' a \approx 17$], and induce turbulence by forcing with a constant power P (normalized by initial magnetic energy/τ_A] at scale comparable to the reconnection field ($k_{in}\, d_e < 1$).

Forcing is added when reconnection becomes active. Parameters to be scanned are P and β_e.

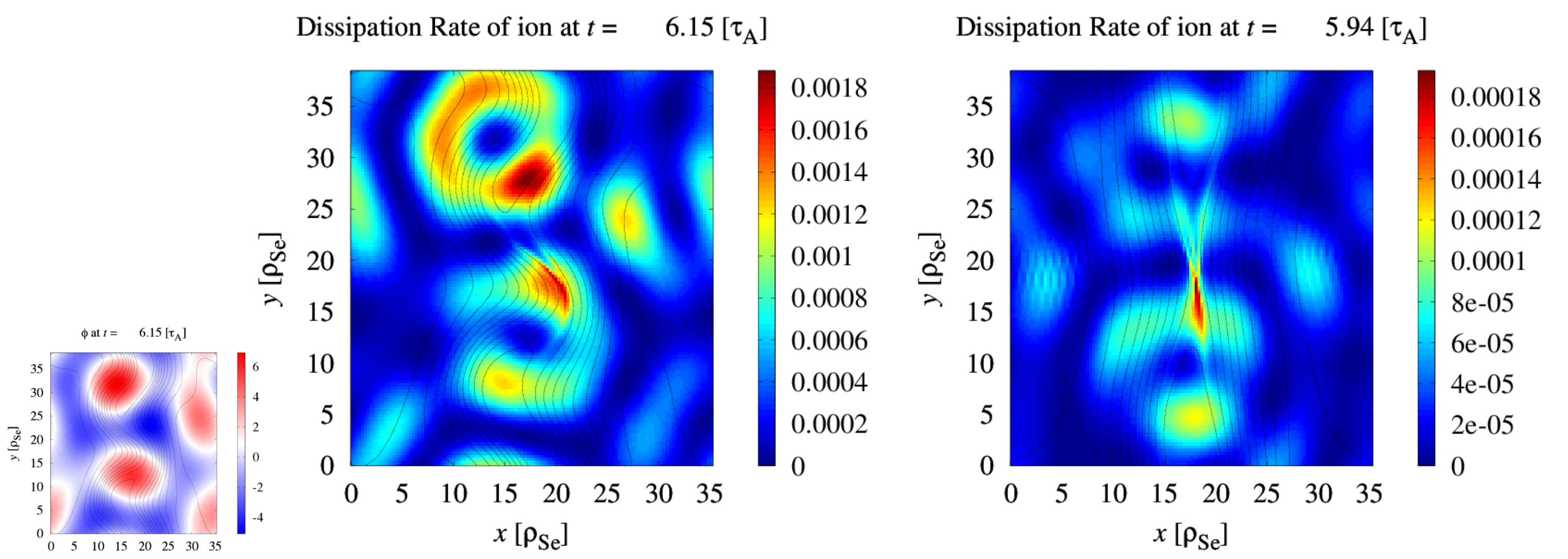


Flux at X point showing reconnection rate (slope). Reconnection is already fast because it is kinetic, and is slightly accelerated by turbulence



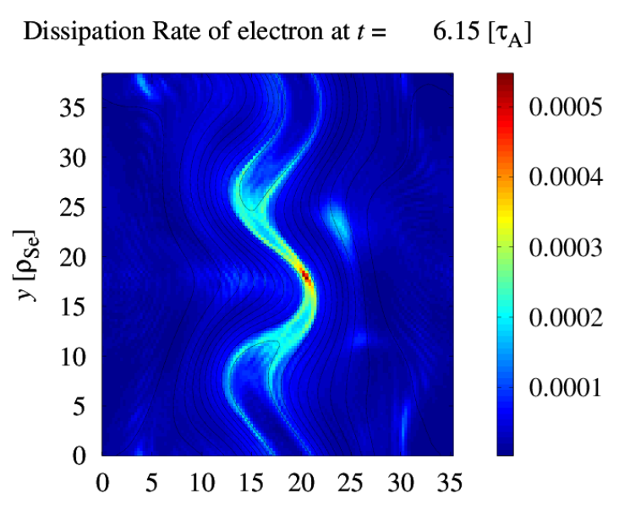
Given the same forcing power, the generated turbulent fluctuation level depends strongly on β_e

Large scale turbulent eddies are dissipated at ion scale, and enhance ion dissipation



Spatial distribution of ion dissipation for
Left) Stronger drive $P = 0.18$ ($u_{rms} > V_{A0}$)
Right) Weaker drive $P = 0.018$ ($u_{rms} < V_{A0}$)

Ion dissipation occurs along the eddies



Electron dissipation does not change very much by turbulence

Acknowledgment

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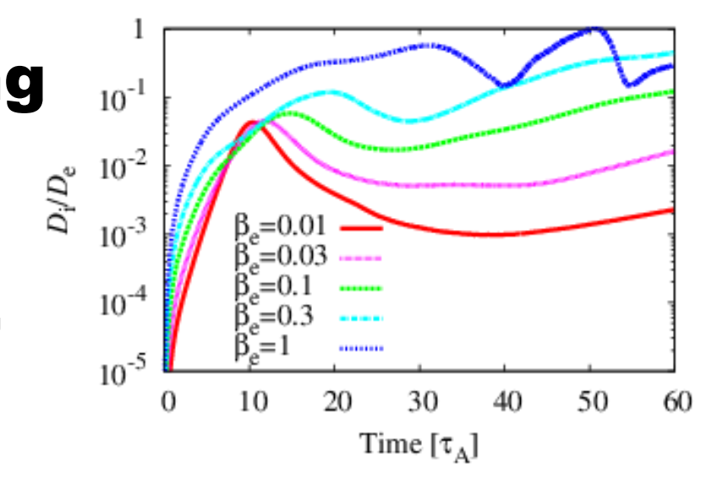
Heating via Phase Mixing

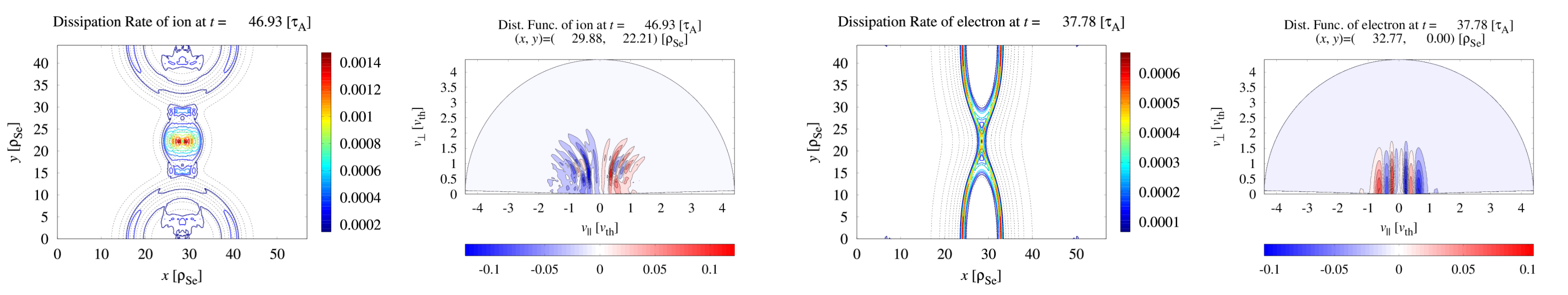
[summary of Numata & Loureiro (2015)]

Figures below show spatial distribution of dissipation rate of ions and electrons, and velocity space structures taken where the dissipation is strong.

Electron dissipation is mostly due to parallel phase mixing along field lines, while ion dissipation is localized at the reconnection site. For ions, both parallel and perpendicular phase mixing processes are active.



Ion heating is comparable to the electron heating for $\beta_e \sim 1$, and insignificant at lower values of β_e.



Random Forcing for Driving Turbulence

We have implemented 2D electrostatic forcing term in AstroGK
Features:

- Injected power is pre-determined
- No Alfven wave excitation (not to disturb reconnection physics)

We add an additional term in gyrokinetic equation

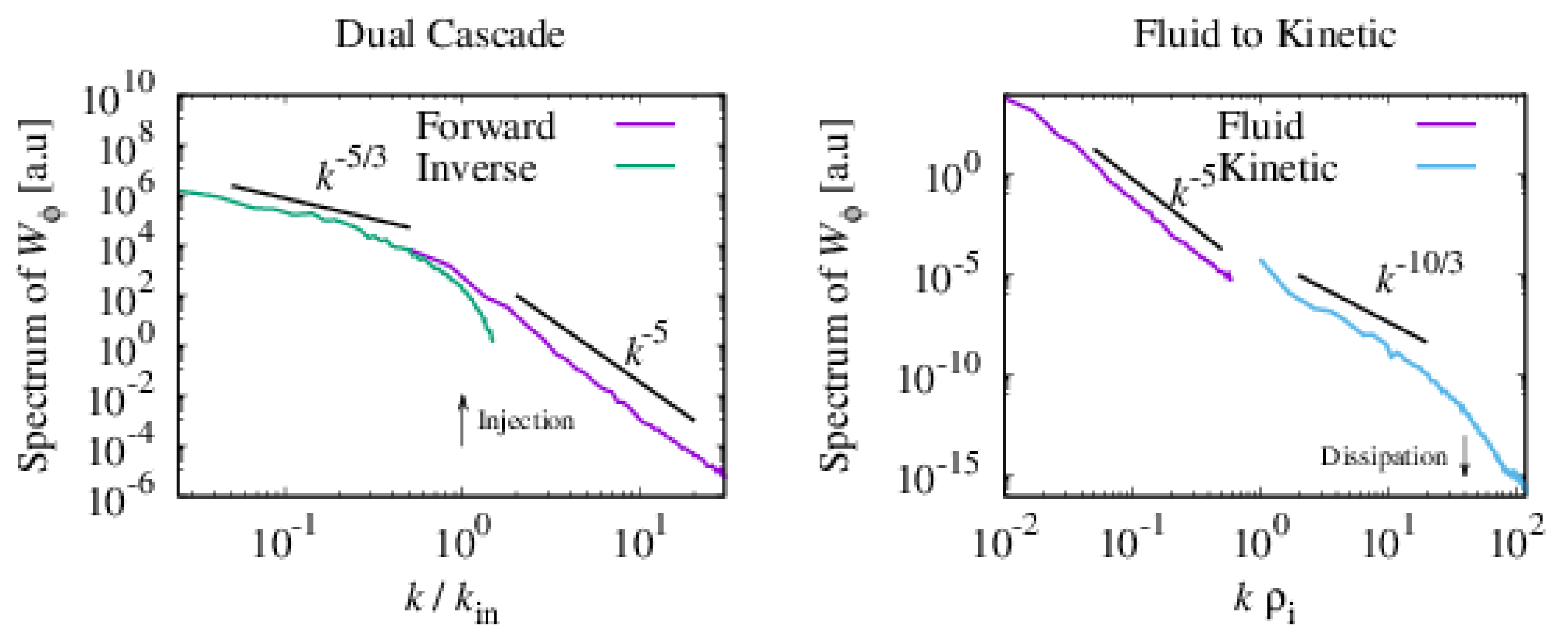
$$\frac{\partial g}{\partial t} = \cdots + A, \quad A = f_0 \Xi(\boldsymbol{v})\Phi, \quad \Xi(v) = e^{\frac{b^2}{4}}\left(\frac{N^f}{n_0} + \frac{T^f}{T_0}\left(\frac{v_\perp^2}{v_{th}^2} - 1 + \frac{b^2}{4}\right)\right)$$

yielding a forcing in the vorticity equation where $g = h - ({}^{qf_0}/_{T_0})\langle \phi - \boldsymbol{v}_\perp \cdot \boldsymbol{A}_\perp \rangle$, $\delta f = -({}^{q\phi}/_{T_0}) f_0 + h$, Φ, Ξ are profiles in configuration and velocity space, respectively. N^f, and T^f are input parameters.

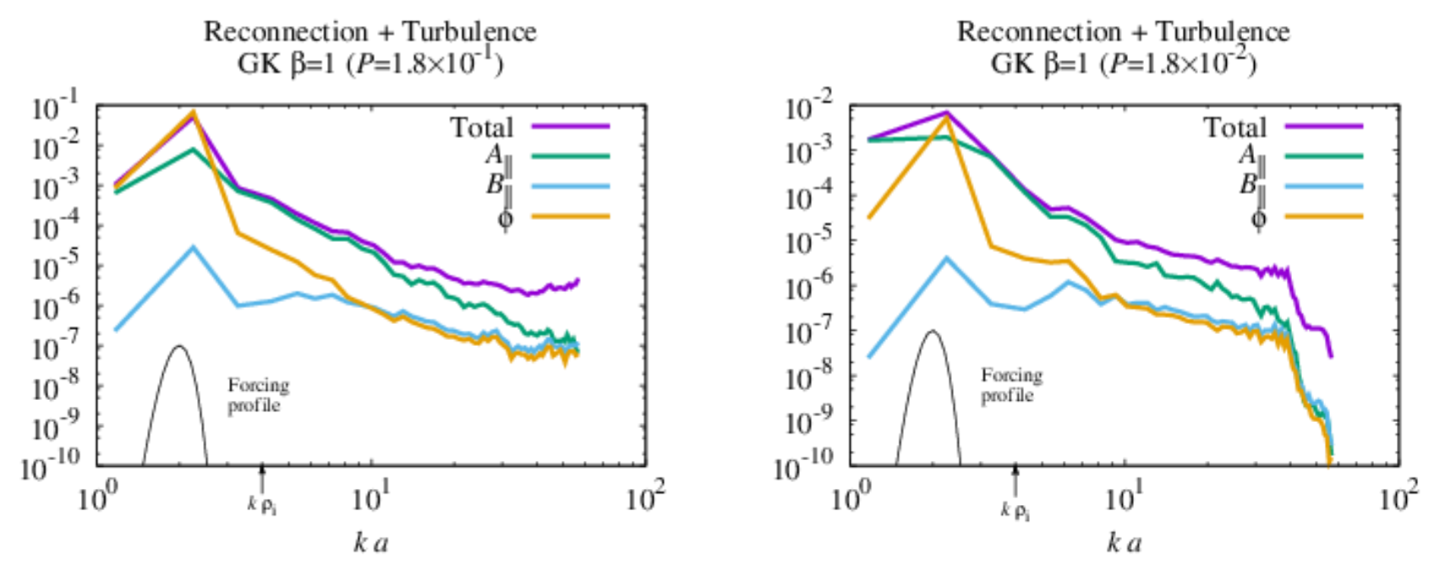
We choose Φ such that random forcing injects energy at a constant power. Such a method was proposed by Alvelius (1999). We consider the forcing is isotropic and localized in some specific scale,

$$\bar{P} = \frac{\bar{P}_0}{c} \exp\left(-\left(\frac{k-k_i}{k_w}\right)^2\right), \quad c = \int_0^\infty \exp\left(-\left(\frac{k-k_i}{k_w}\right)^2\right) dk$$

We have successfully demonstrated three cascade regimes for electrostatic turbulence using AstroGK [See Plunk et al JFM (2010) for scaling theory.]



Spectrum of ϕ^2 obtained from 3 separate runs
☐ Forward cascade: $k_{in} < k < \rho_i^{-1}$
☐ Inverse cascade: $k < k_{in} \sim \rho_i^{-1}$
☐ Kinetic ion entropy cascade: $k_{in} \sim \rho_i^{-1} < k$



Sub-Larmor scale energy spectra for $\beta_e = 1$ with stronger/weaker drives.

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