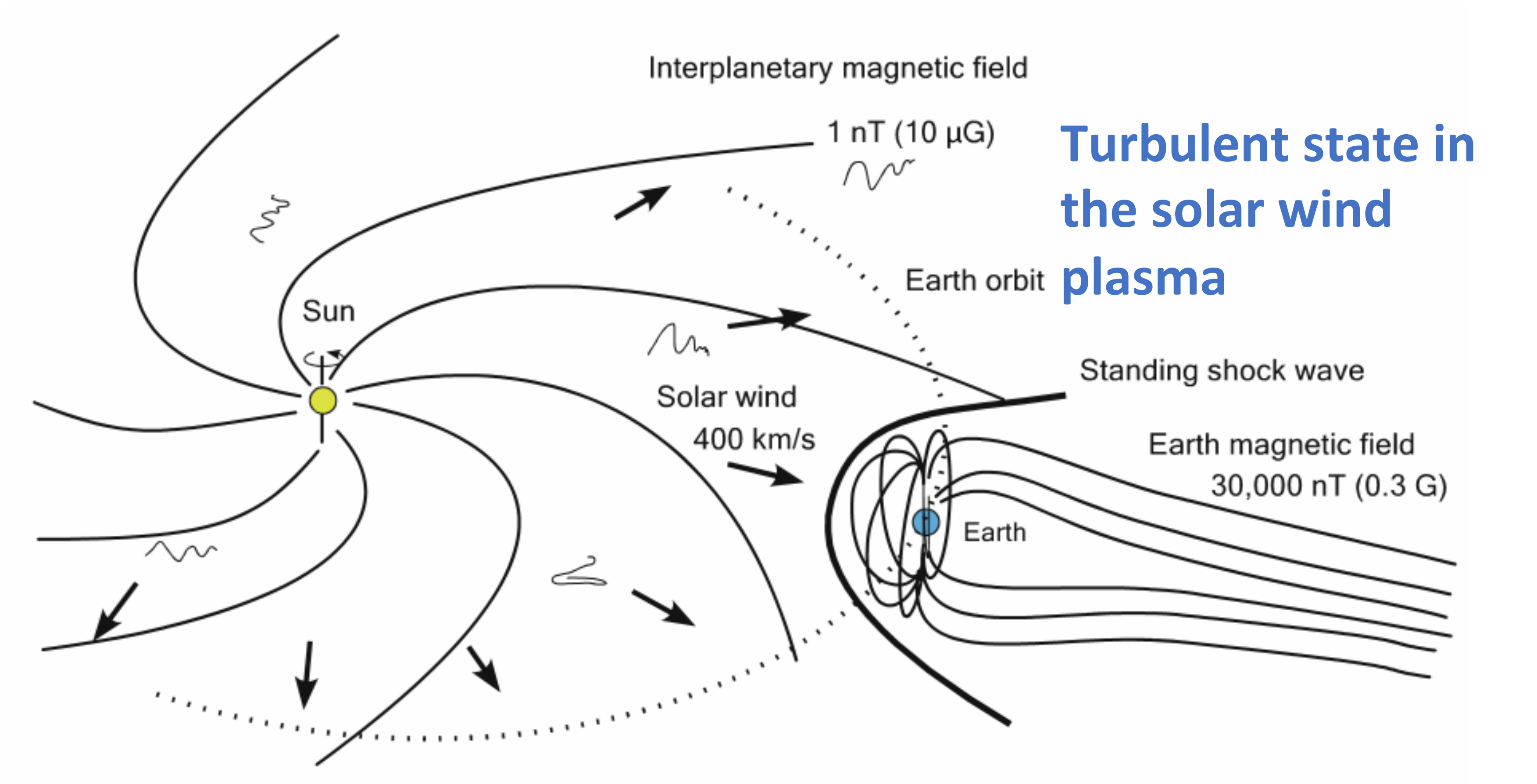
The influence of magnetosonic/ whistler mode turbulence on ion dynamics

S. Saito[1,3], Y. Nariyuki[2], and T. Umeda[3]

[1)] Graduate School of Science, Nagoya University
[2)] Faculty of Human Development, University of Toyama
[3)] Institute for Space-Earth Environmental Research, Nagoya University

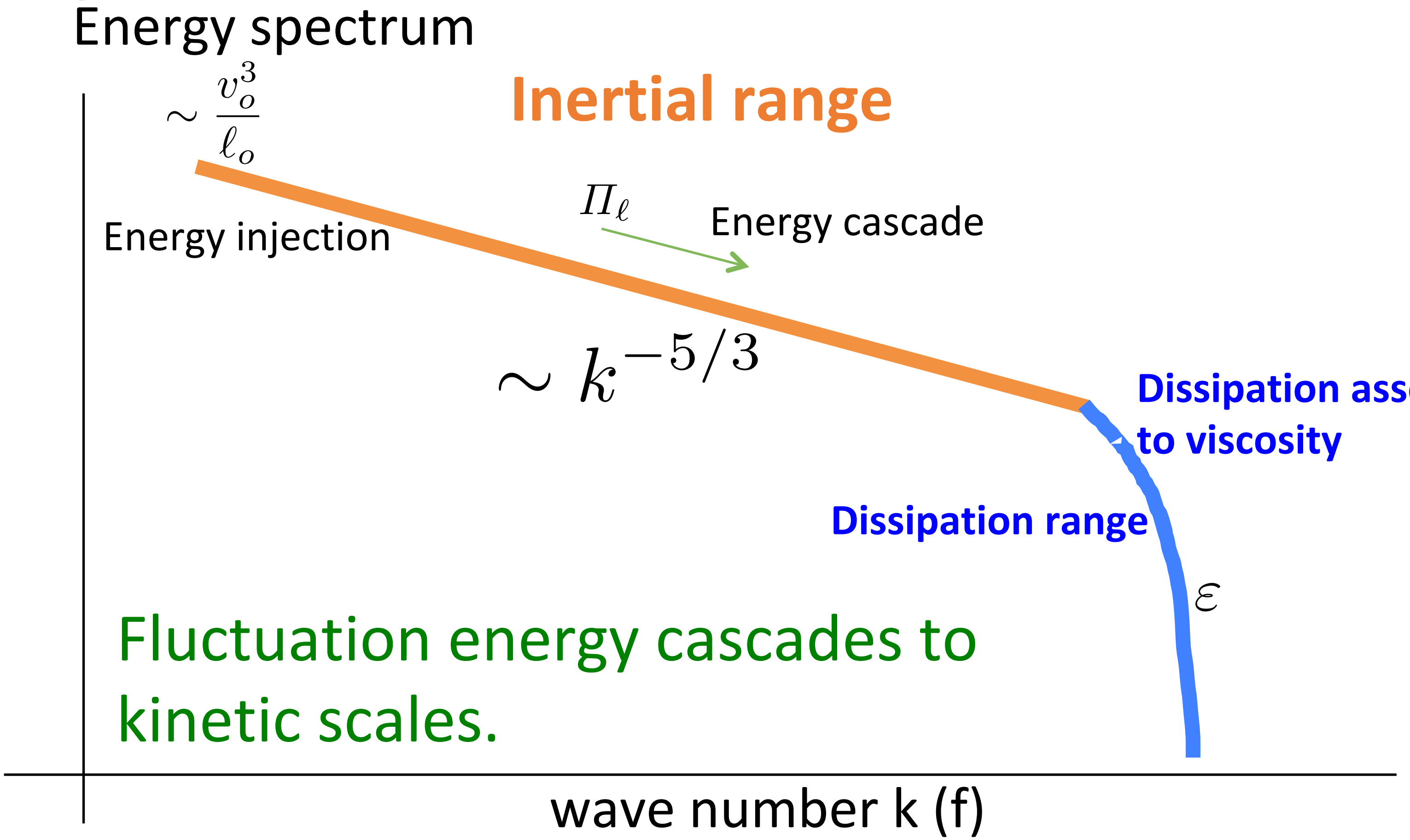
Solar wind turbulence



Turbulent state in the solar wind plasma

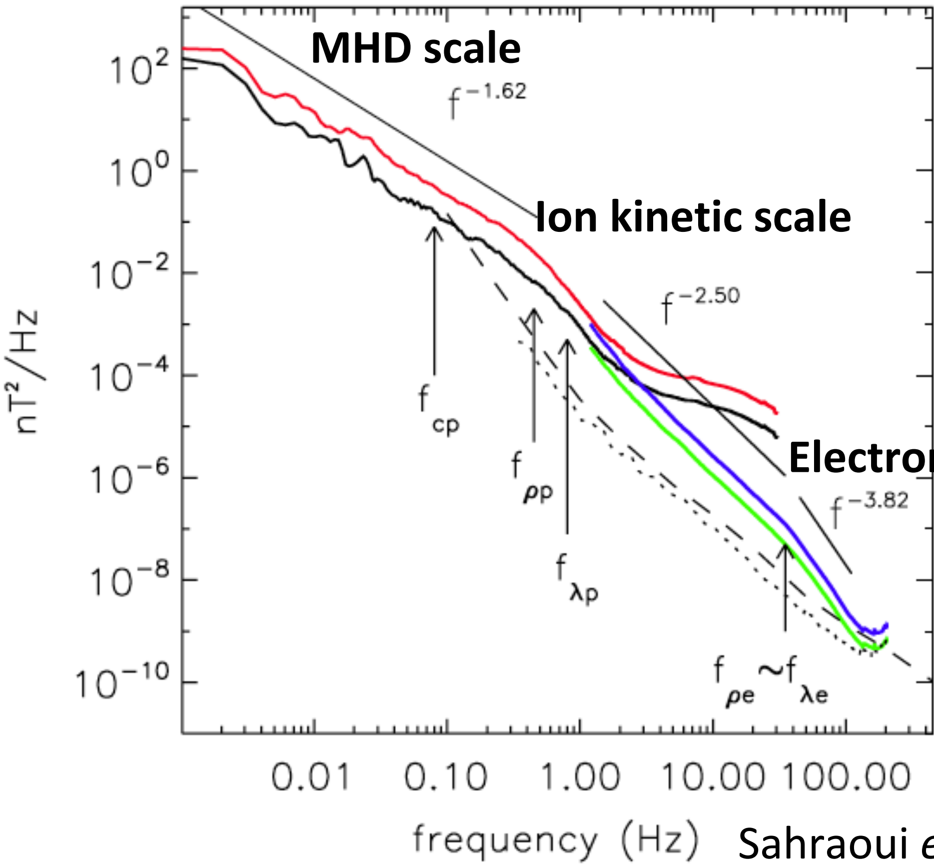
Fig.1.3 of Y.Narita (2012) Plasma Turbulence in the Solar System, DOI:10.1007/978-3-642-25667-7

Energy dissipation in fluid regime



Fluctuation energy cascades to kinetic scales.

Solar wind observations



Sahraoui *et al.* PRL 2009

CLASTER Observation：
FGM data (f < 33 Hz)
STAFF-SC data (1.5 < 225 Hz)

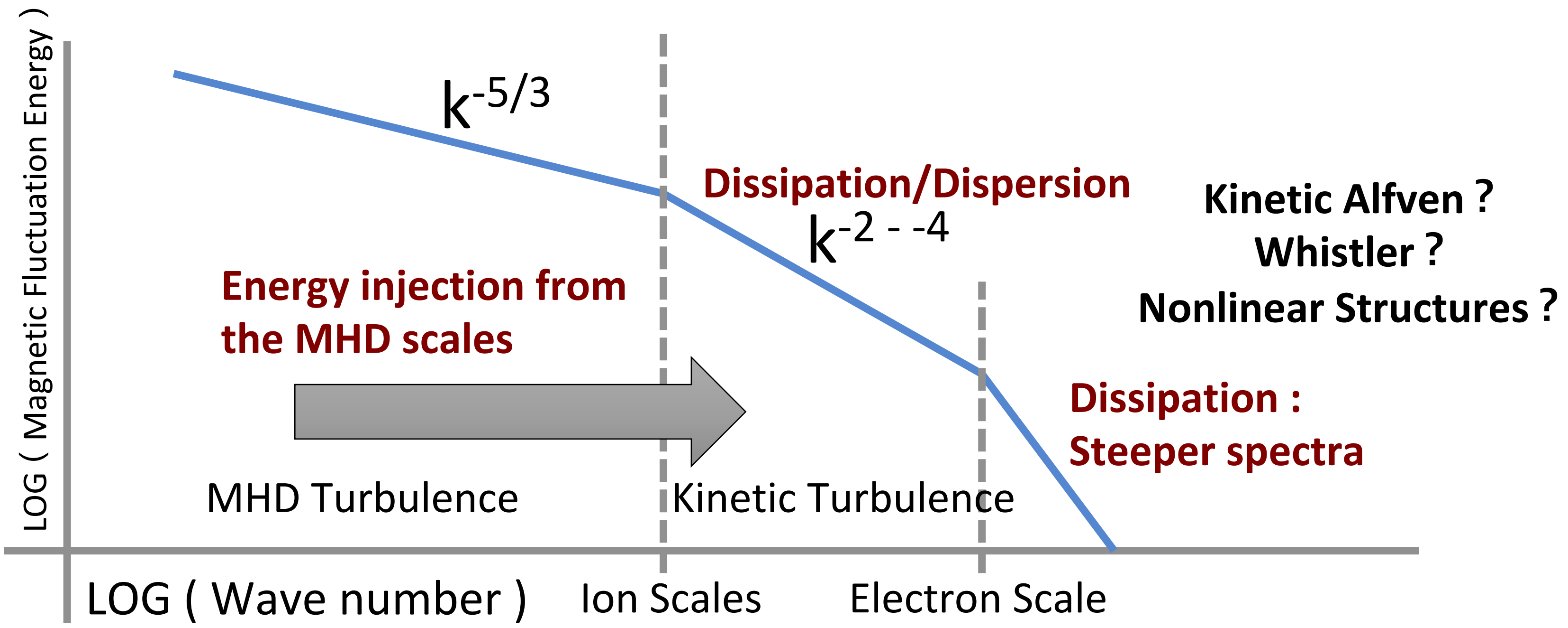
Energy Spectrum from MHD scale to electron scales

Two break points in the spectrum are found.

Energy can be transported to electron scales.

Kinetic turbulence

- Energy transport (cascade) process from the MHD turbulence
- Plasma heating process and turbulent dissipation process.



Purpose of the study

- To understand the role of magnetosonic/whistler (MSW) mode turbulence in kinetic scales
  - Demonstrate two-dimensional, fully kinetic, particle-in-cell simulation for self-consistently decaying MSW mode turbulence.
  - Focus on ion heating and acceleration

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Simulation model and parameters

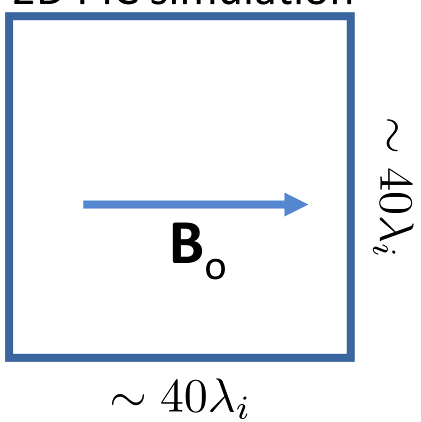
Feature of applied fluctuations:

- Number of modes at t=0: 42 modes (Initial wave phase is randomly set.)
- Initial magnetic fluctuation energy: about 10% of background magnetic field energy
- Velocity fluctuation of ions and electrons are derived from linear dispersion relation of whistler waves.

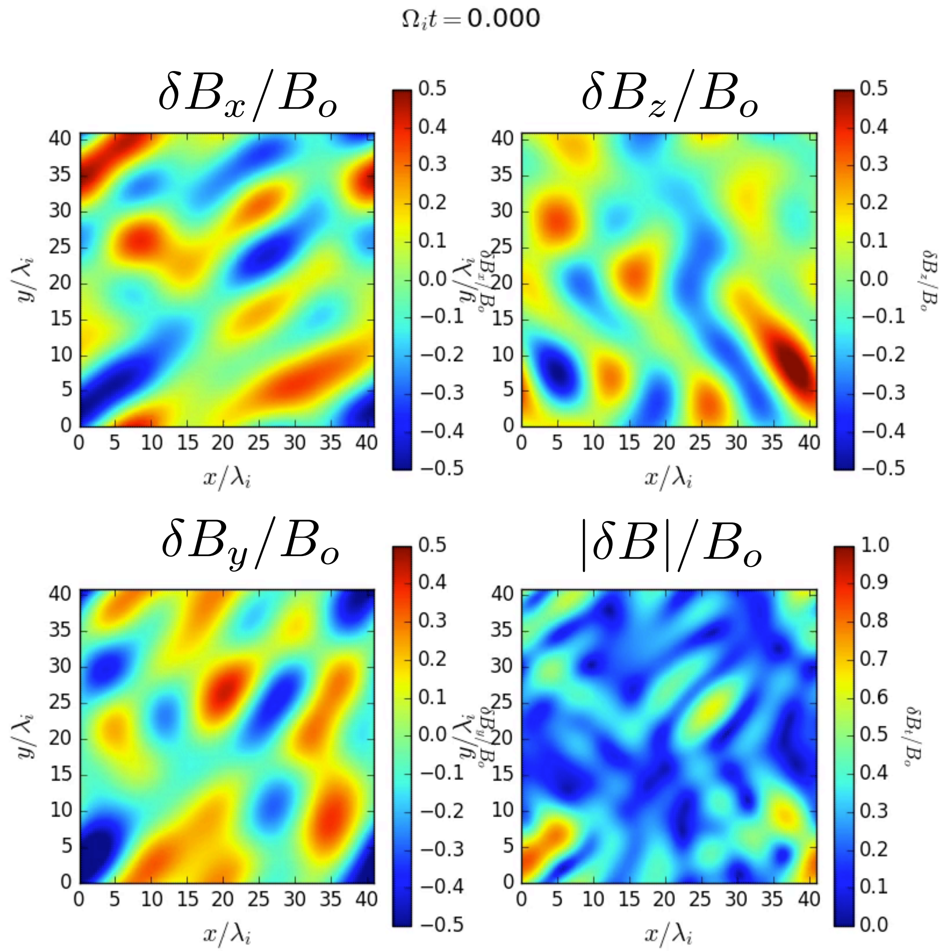
Simulation parameters:

- Background magnetic field: $(B_o,0,0)$
- $\beta_i=\beta_e=0.1$
- Mass ratio = 100
- Number of particle pairs: ~8.5×10^9

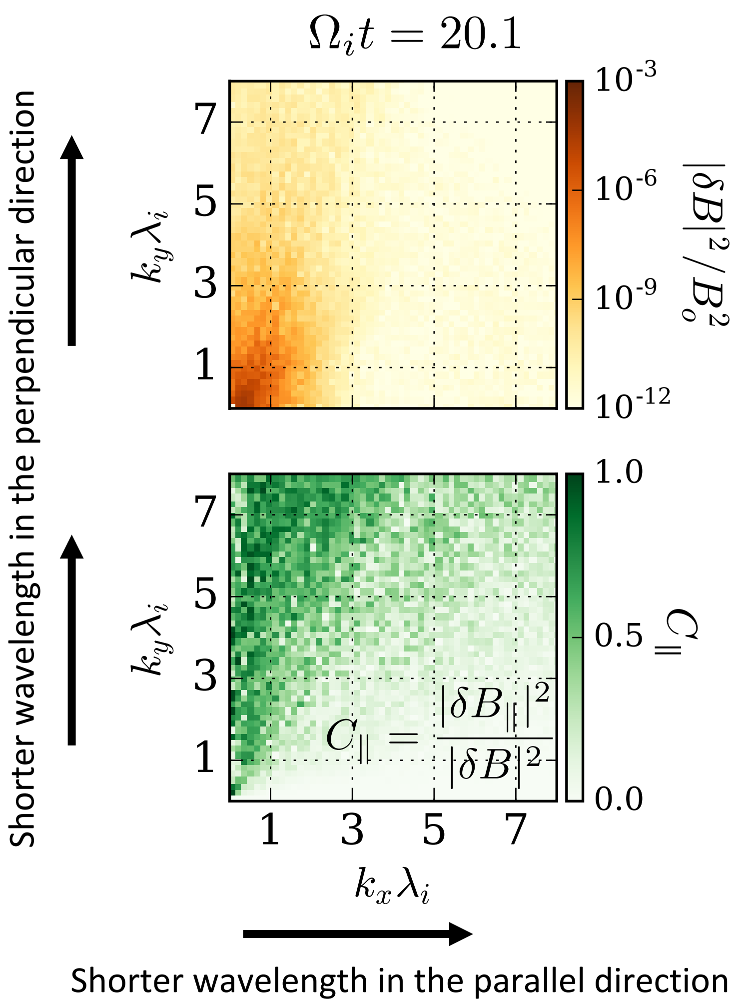
2D PIC simulation



Overview of development of magnetosonic-whistler turbulence



Nature of magnetic fluctuations



- Wavenumber spectrum of magnetic fluctuations
  - The fluctuation energy transports to smaller scales.
  - Fluctuations with $k_y > k_x$ tend to be dominant.

↓

Wavenumber anisotropy

- Wavenumber spectrum of magnetic compressibility
  - The fluctuations in the parallel direction become dominant at smaller scales.

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Enhancement of compressible fluctuations

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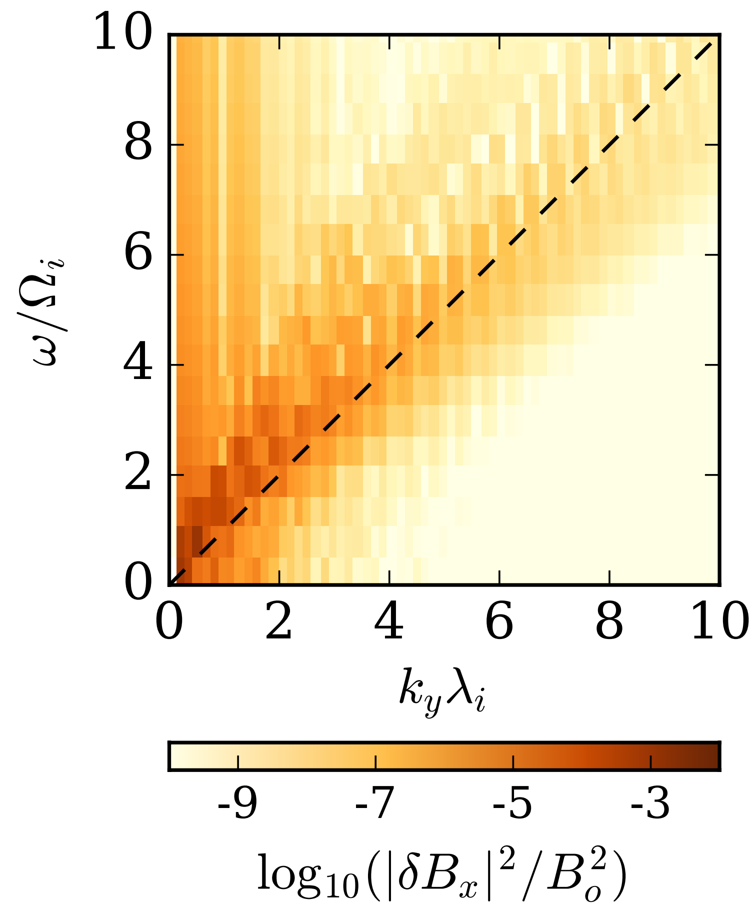
Frequency-wavenumber diagram



- Dispersion relation of compressive fluctuations that have the perpendicular wavenumber.
- The spectrum extends to frequencies higher than the ion cyclotron frequency
  - These are neither slow nor kinetic Alfven mode.
- Cascade to shorter scales as magnetosonic/whistler mode waves.
- Or higher-order ion Bernstein mode coupled with magnetosonic mode.
  - See. Lopez et al. (2017), Kinetic scale structure of low-frequency waves and fluctuations, ApJ.

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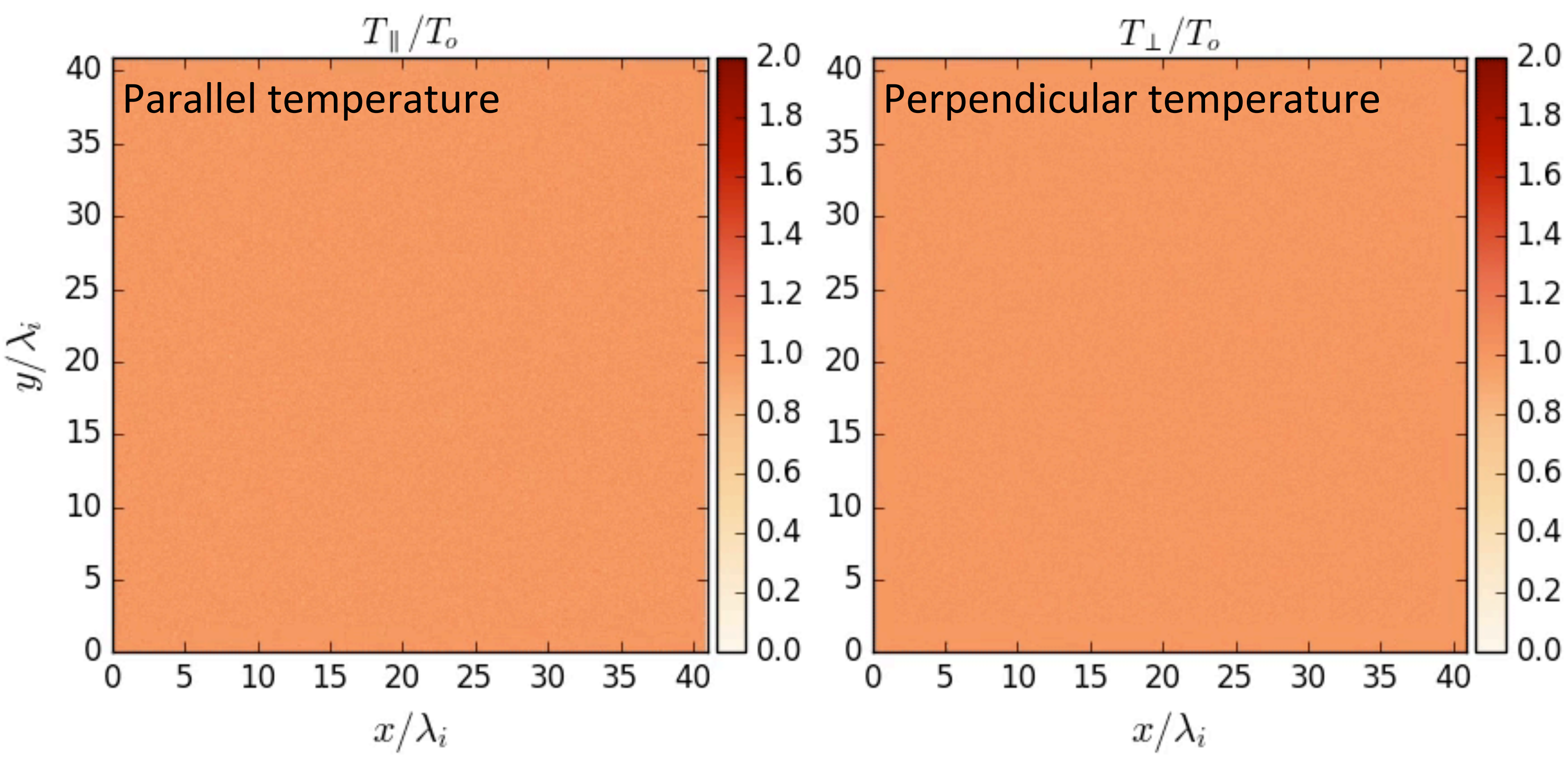
Ion Heating

The second moment of ion VDFs corresponds to ion temperature.

$\Omega_i t = 0.0$



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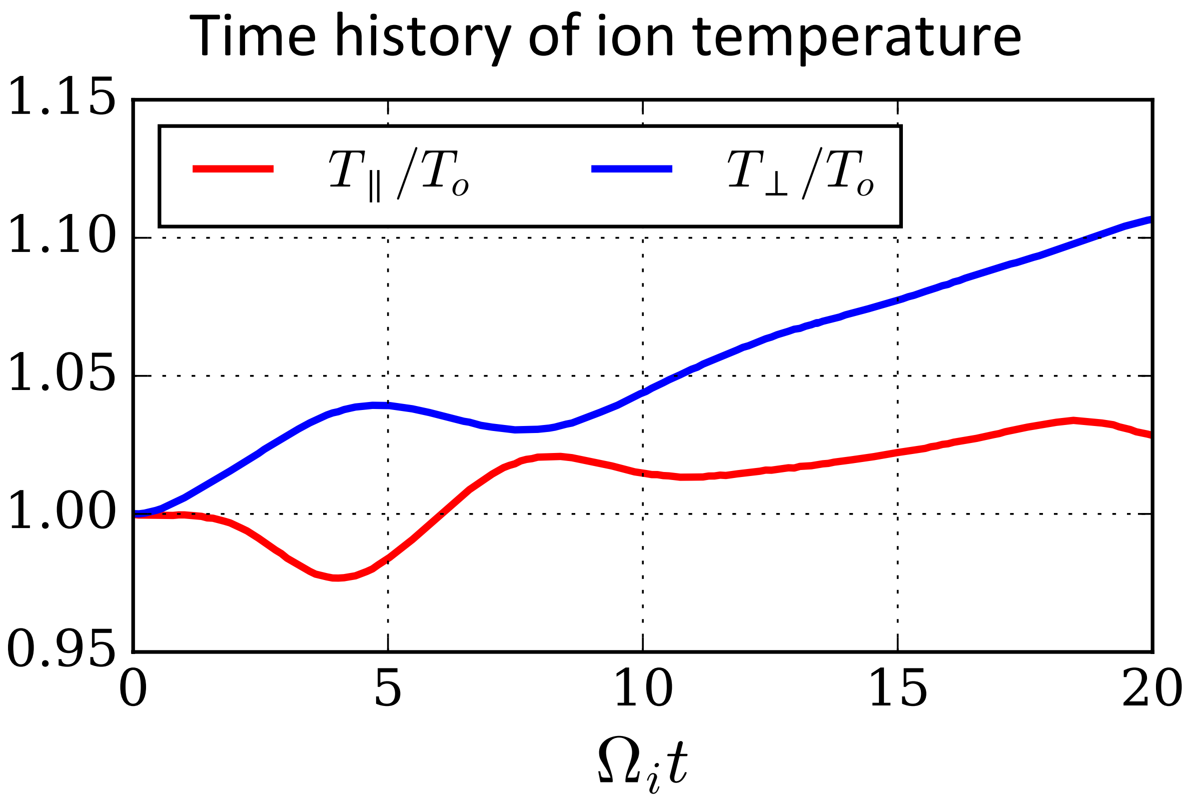
Efficient ion heating in perpendicular directions



Quasi-perpendicular propagating whistlers or ion Bernstein mode scatter ions in the perpendicular direction.

- Saito and Nariyuki (2014) Perpendicular ion acceleration in whistler turbulence, PoP
- Markovskii et al. (2010) Perpendicular proton heating due to energy cascade of fast magnetosonic wave in the solar corona

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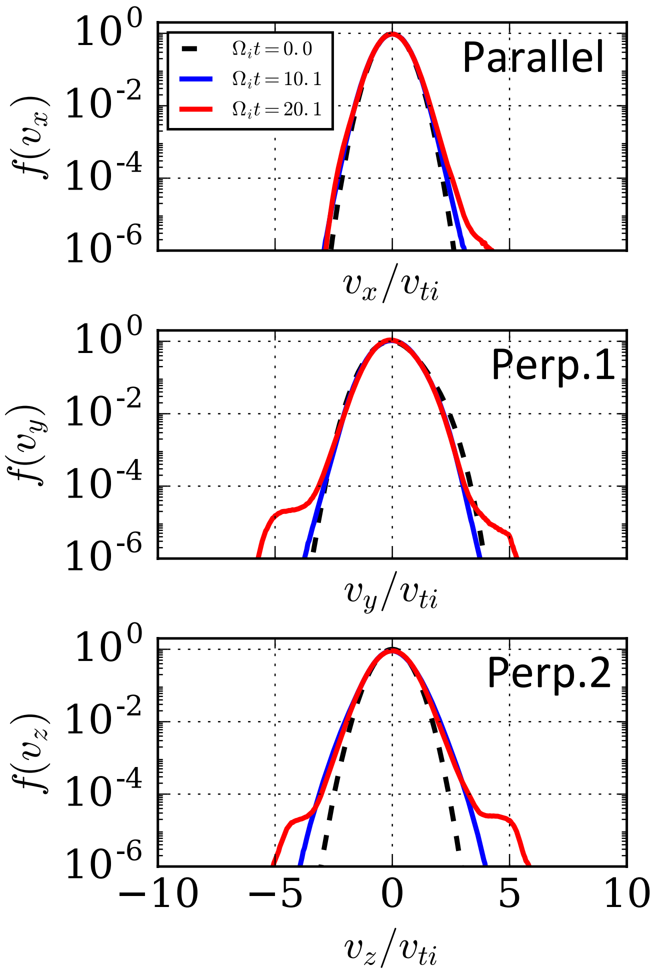
Velocity Distribution Function



- Dashed line: $\Omega_i t=0$
- Blue line: $\Omega_i t=10.1$
- Red line: $\Omega_i t=20.1$

VDFs of all ions in the system.

There is no remarkable acceleration in the parallel direction.

Some ions are accelerated in the perpendicular direction.

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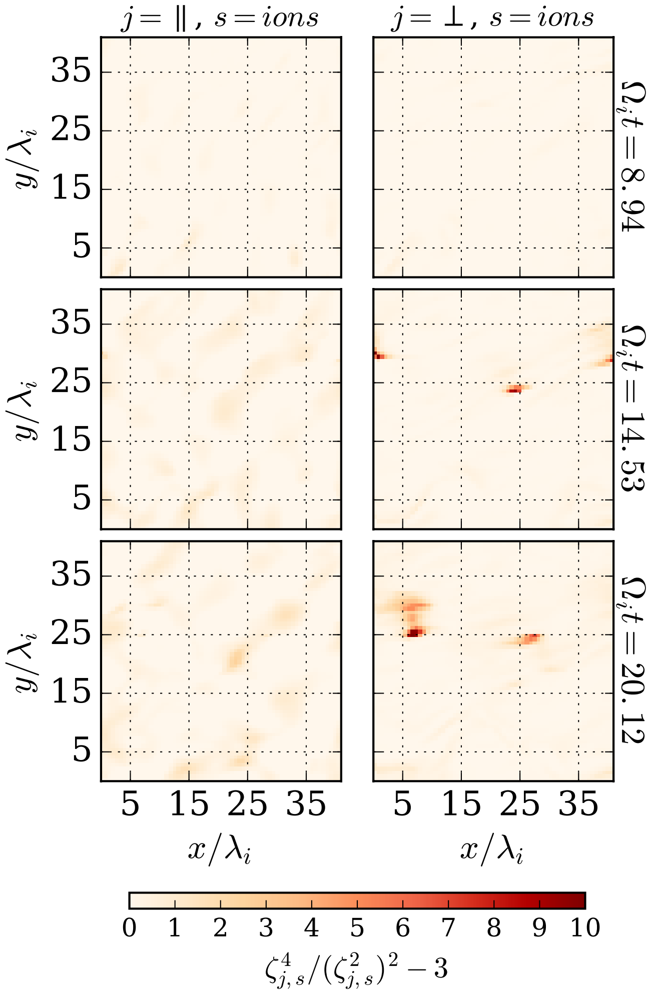
Flatness of ion VDFs



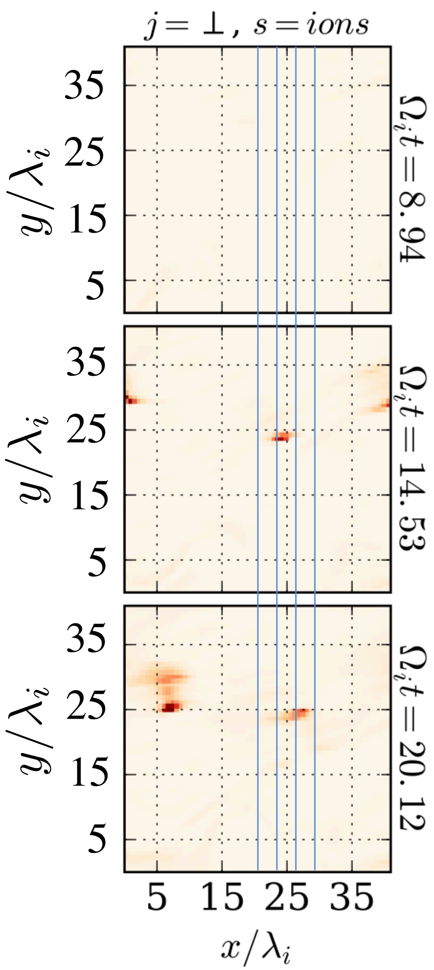
Flatness calculated from local VDF of ions.

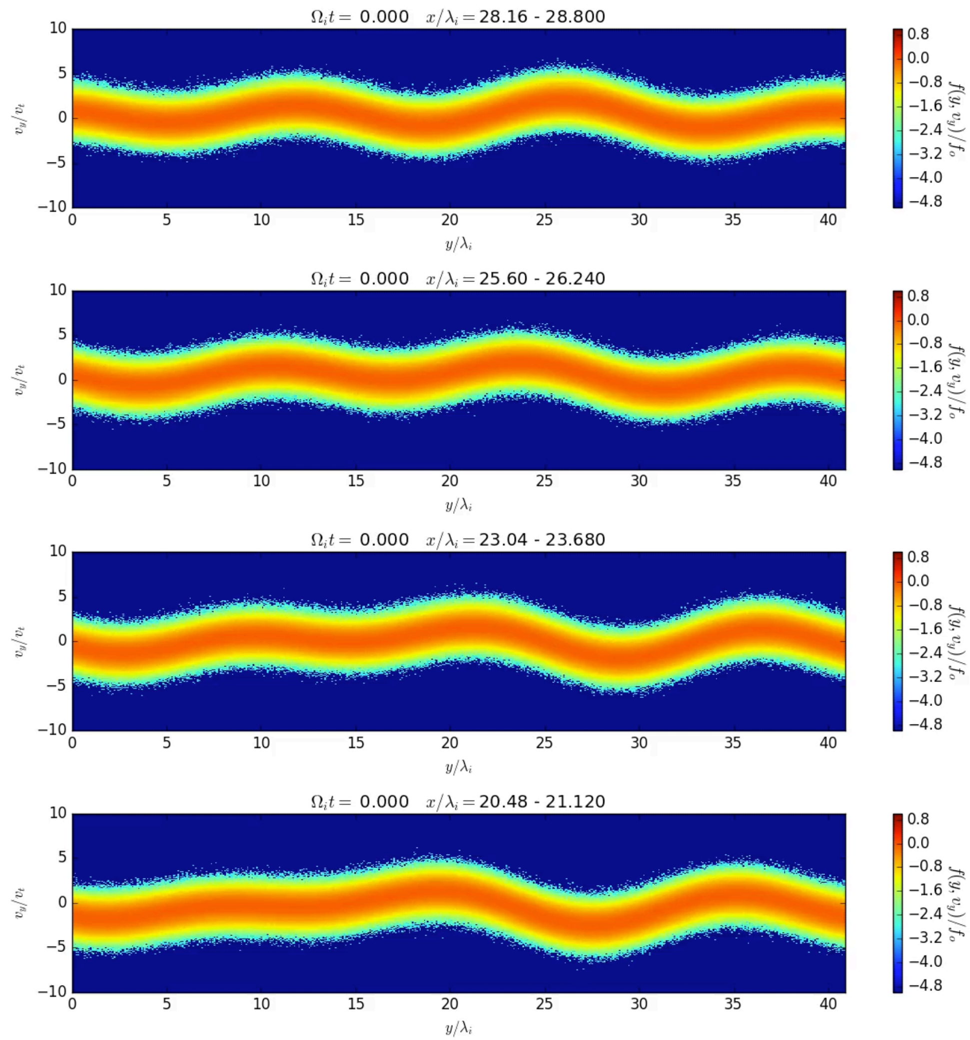
- Proxy to identify regions where ions are accelerated.
- Left panels: Flatness of VDFs in the parallel velocity
- Left panels: Flatness of VDFs in the perpendicular velocity

- Flatness in the parallel velocity is weaker than that in the perpendicular velocity.
- Flatness has large values at localized regions.

Intermittent ion acceleration in the perpendicular direction

Ion Phase Space Density





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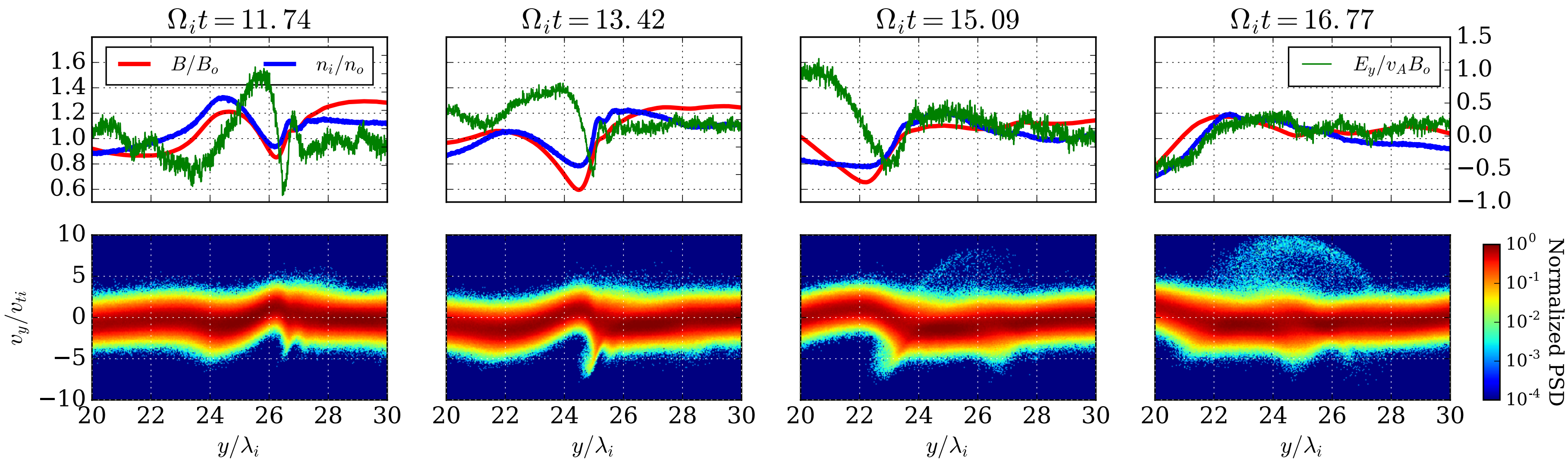
Intermittent Ion Acceleration



Fluctuation pattern of ion density resembles that of magnetic intensity.
→ Fast mode component.

Steepening of the fast mode accelerates some ions in the perpendicular direction.

- The electric potential (associated with E_y) moving with V_A reflect ions.
- The acceleration process is similar to surfatron acceleration or v_pxB acceleration

The steepening is due to the development of magnetosonic-whistler turbulence.
→ **The intermittent nature at small scales influences on ion dynamics.**

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Summary

- 2D3V Particle-In-Cell simulation for magnetosonic/ whistler mode turbulence

- Ion heating
  - Efficient perpendicular heating of ions

- Ion acceleration (Nonthermal Acc.)
  - Localized and intermittent acceleration of ions
  - Intermittent feature of magnetic fluctuations would be a source of ion acceleration.

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