Plasma transport by kinetic Alfvén wave

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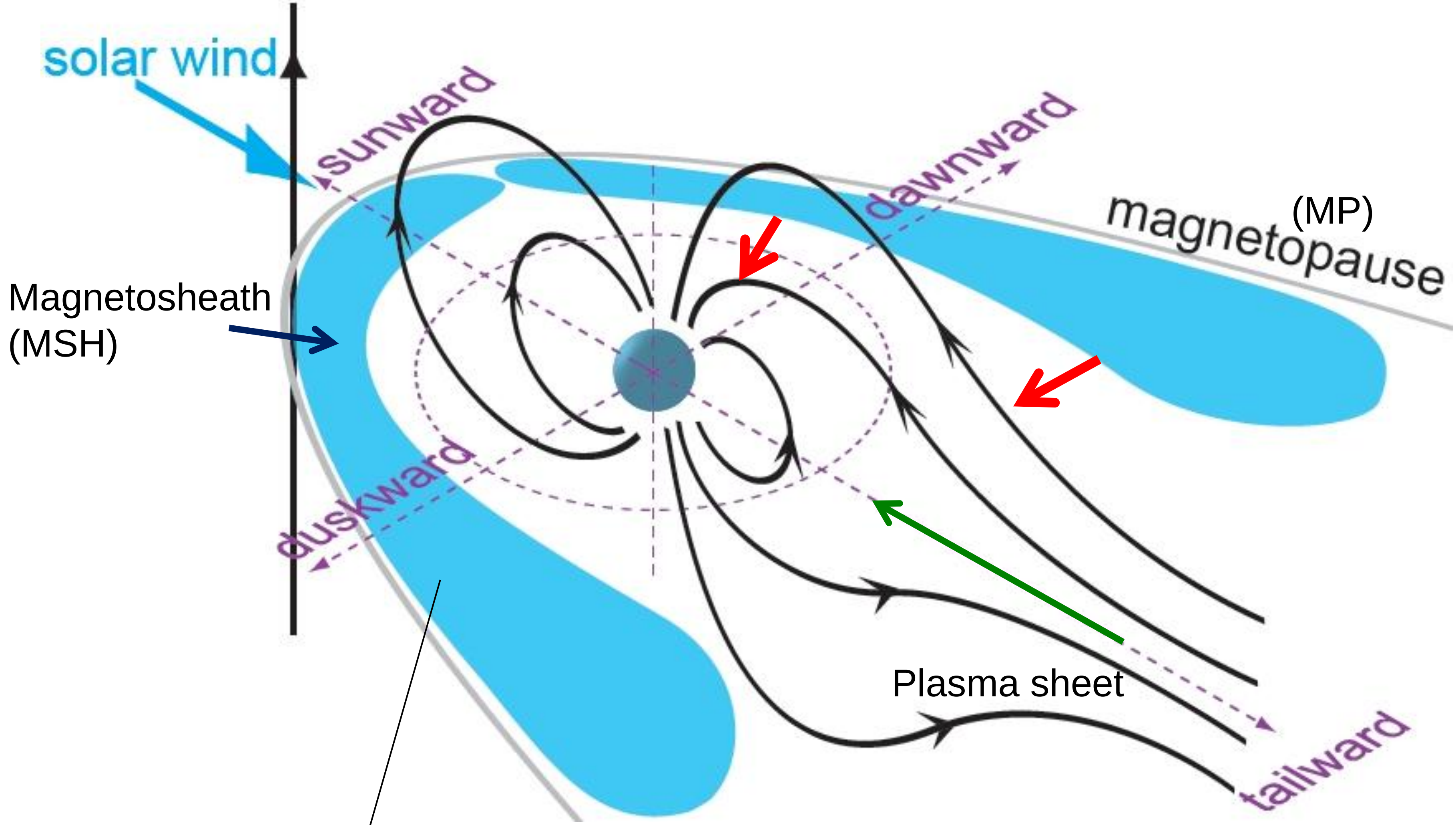
Notation

- MSP：MagnetoSPhere　磁気圏
- MSH：MagnetoSHeath　マグネトシース
- MP：MagnetoPause　磁気圏境界面
- LLBL：Low-Latitude Boundary Layer　低緯度境界層
- KAW：Kinetic Alfvén Wave　運動論的アルヴェン波
- k：wavenumber　波数
- λ：wavelength 波長
- ρ：gyro-radius　ジャイロ半径
- FLR：finite Larmor radius　有限ラーマー半径効果
- D：Diffusion coefficient　拡散係数　$[L^2T^{-1}]$

$k=2\pi/\lambda$

Plasma transport

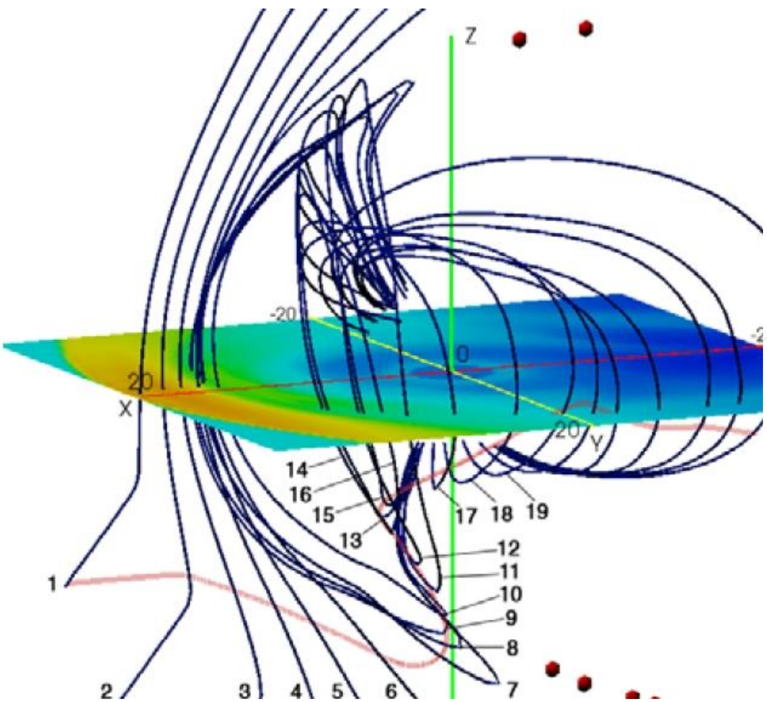


Low-Latitude Boundary Layer (LLBL)
Cold-Dense Plasma Sheet (CDPS)

Magnetopause

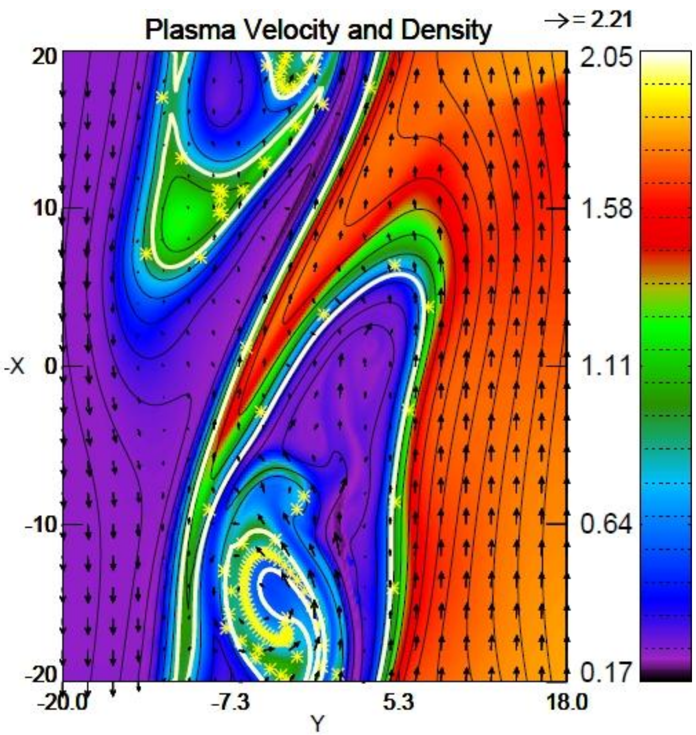
- High-latitude lobe reconnection [e.g., Li et al., 2005]
- Diffusive processes by
    - Kelvin-Helmholtz vortices [e.g., Nykyri & Otto, 2001]
    - Kinetic Alfvén wave [Hasegawa et al., 1978; Chaston et al., 2008]

high-latitude lobe reconnection



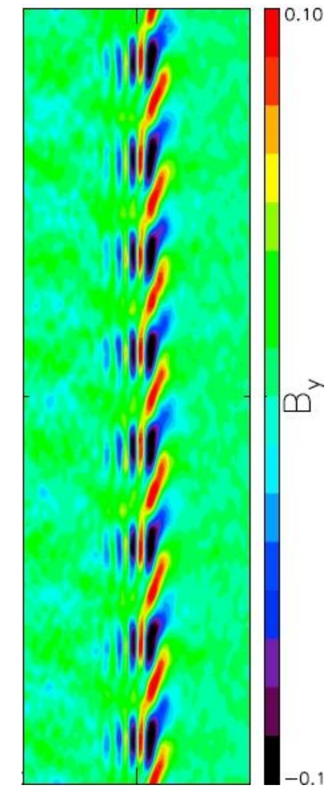
Li et al., 2005

KH vortices



Nykyri & Otto, 2001

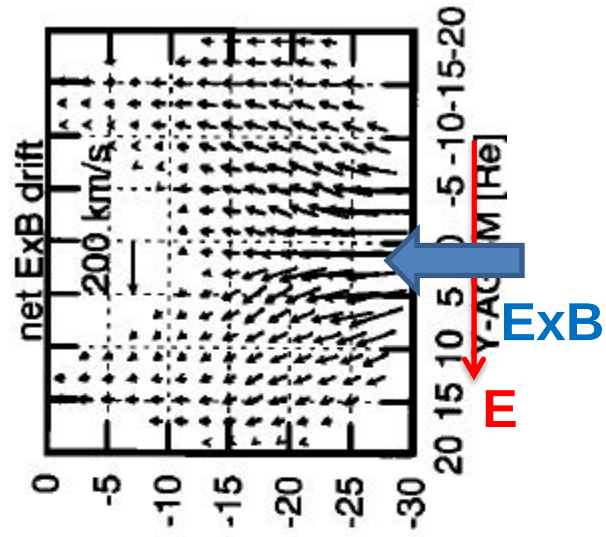
kinetic Alfvén wave



Lin et al., 2010

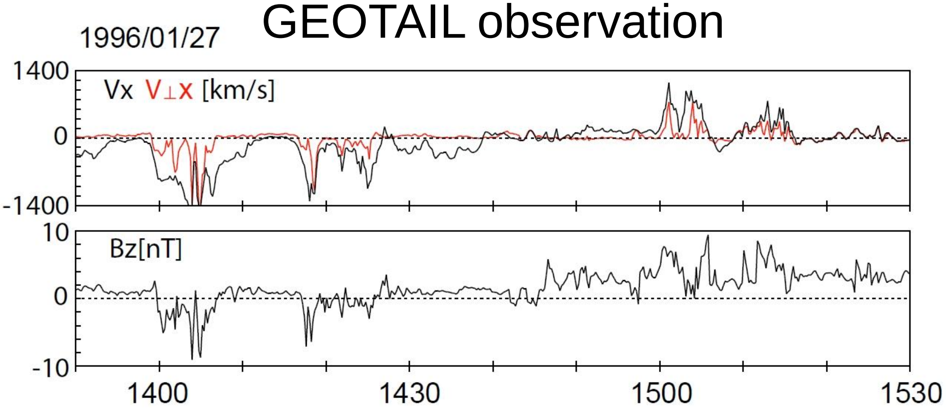
Plasma sheet

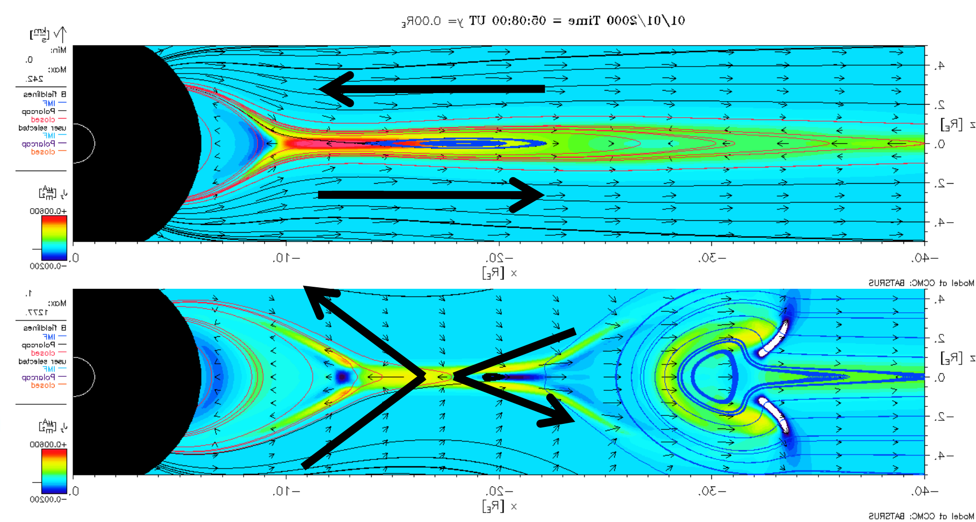
- Magnetospheric convection
  - 40~90 km/s [Baumjohann et al., 1989]
  - $\mathbf{V}_i = \mathbf{E} \times \mathbf{B}/B^2 + \mathbf{B} \times \nabla P_i / e n_i$
- Bursty bulk flow [e.g., Angelopoulos et al., 1994]
  - infrequent event (< 10% in PS)
  - transport 60~100% of energy and M-flux in PS
  - transport mass to GEO for ~40% of BBFs [Izutsu, 2009, M-thesis]
- Magnetic reconnection
  - Magnetic field energy is converted to particle kinetic energy.
  - diffusion region mediated by KAW [Chaston et al., 2009]



Hori et al., 2000

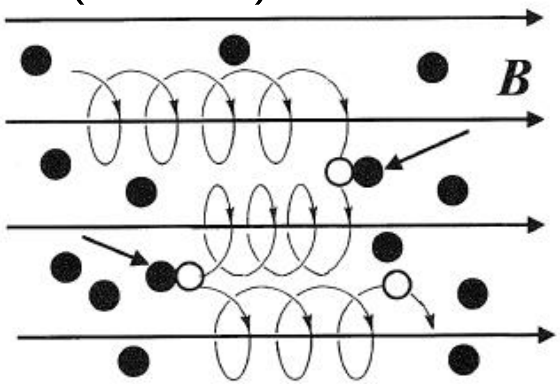
GEOTAIL observation



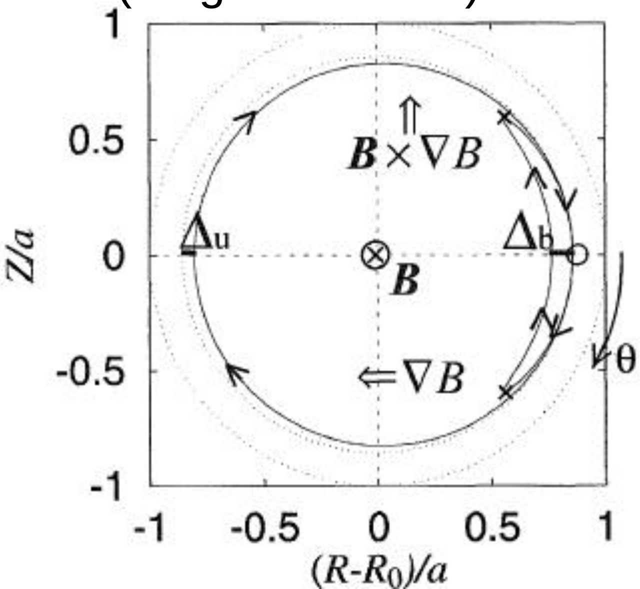


Fusion Plasma

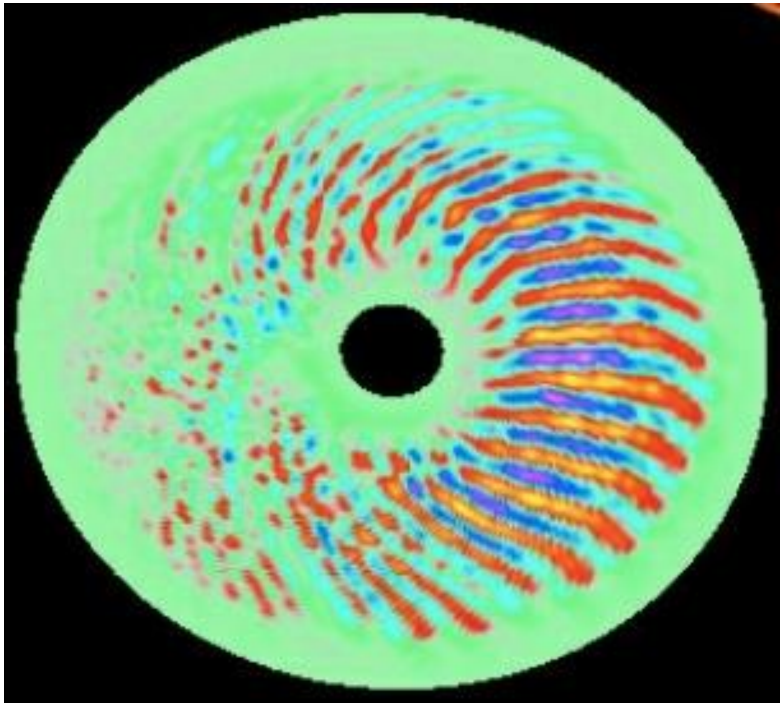
Classical transport
(collision)



Neoclassical transport
(magnetic mirror)



Anomalous transport
(wave)



TARGET: Plasma transport by wave-particle interaction

- Waves are ubiquitous in space.
  - corona
  - solar wind
  - shock
  - magnetosheath
  - magnetopause
  - magnetosphere
    - cold-dense plasma
    - tail reconnection
    - bursty bulk flow
  - inner magnetosphere

heating by KAW

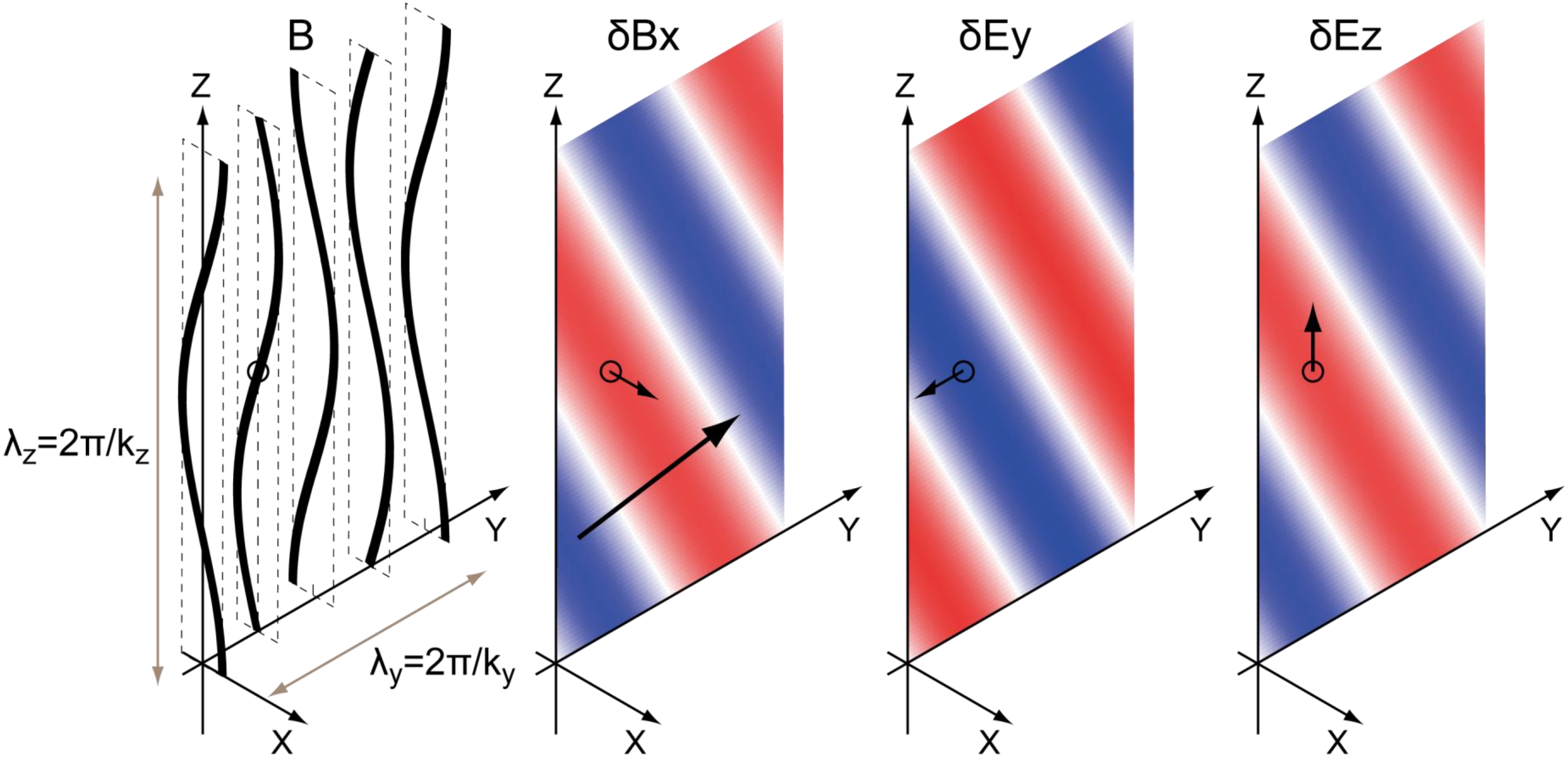
generation of KAW

diffusion by KAW

diffusion by KAW

- Role of waves?
  - transport in velocity-space (heating / acceleration)
  - **transport in real-space**
    - **diffusion by kinetic Alfvén wave (KAW)**

Kinetic Alfvén Wave (KAW)



Shear Alfvén Wave ($k_y\rho_i \ll 1$)

$$\frac{\omega}{k_z} = v_A \quad \left(\frac{\omega}{k} = v_A \cos\theta\right)$$

$$\frac{\delta E_y}{\delta B_x} = -v_A, \quad \frac{\delta E_z}{\delta E_y} = 0$$

Kinetic Alfvén Wave ($k_y\rho_i \sim 1$)

[Stasiewicz, 2000]

$$\frac{\omega}{k_z} = v_A\left\{1 + \left(1 + \frac{T_e}{T_i}\right)k_y^2\rho_i^2\right\}^{\frac{1}{2}}$$

$$\frac{\delta E_y}{\delta B_x} = -v_A\left(1 + k_y^2\rho_i^2\right)\left[1 + \left(1 + \frac{T_e}{T_i}\right)k_y^2\rho_i^2\right]^{-\frac{1}{2}}, \quad \frac{\delta E_z}{\delta E_y} = -\frac{\frac{T_e}{T_i}(k_z\rho_i)(k_y\rho_i)}{1 + k_y^2\rho_i^2}$$

Diffusion by low-frequency wave

Hasegawa and Mima, 1978 (HM1978)

- Quasi-linear theory (weak turbulence) [Stix, 1992]
  - small perturbation valid to use f_0 for linear theory
  - phase-mixed wave spectrum
- Drift-kinetic equation
  - $\omega / \Omega c << 1$
  - **$\rho / \lambda_\perp \sim k_\perp \rho << 1$**

  ↓
- Diffusion coefficient

ω: angular frequency of wave
$\lambda_\perp$ ($k_\perp$): perpendicular wavelenth (wavenumber)
Ωc : gyro-frequency
ρ: gyro-radius

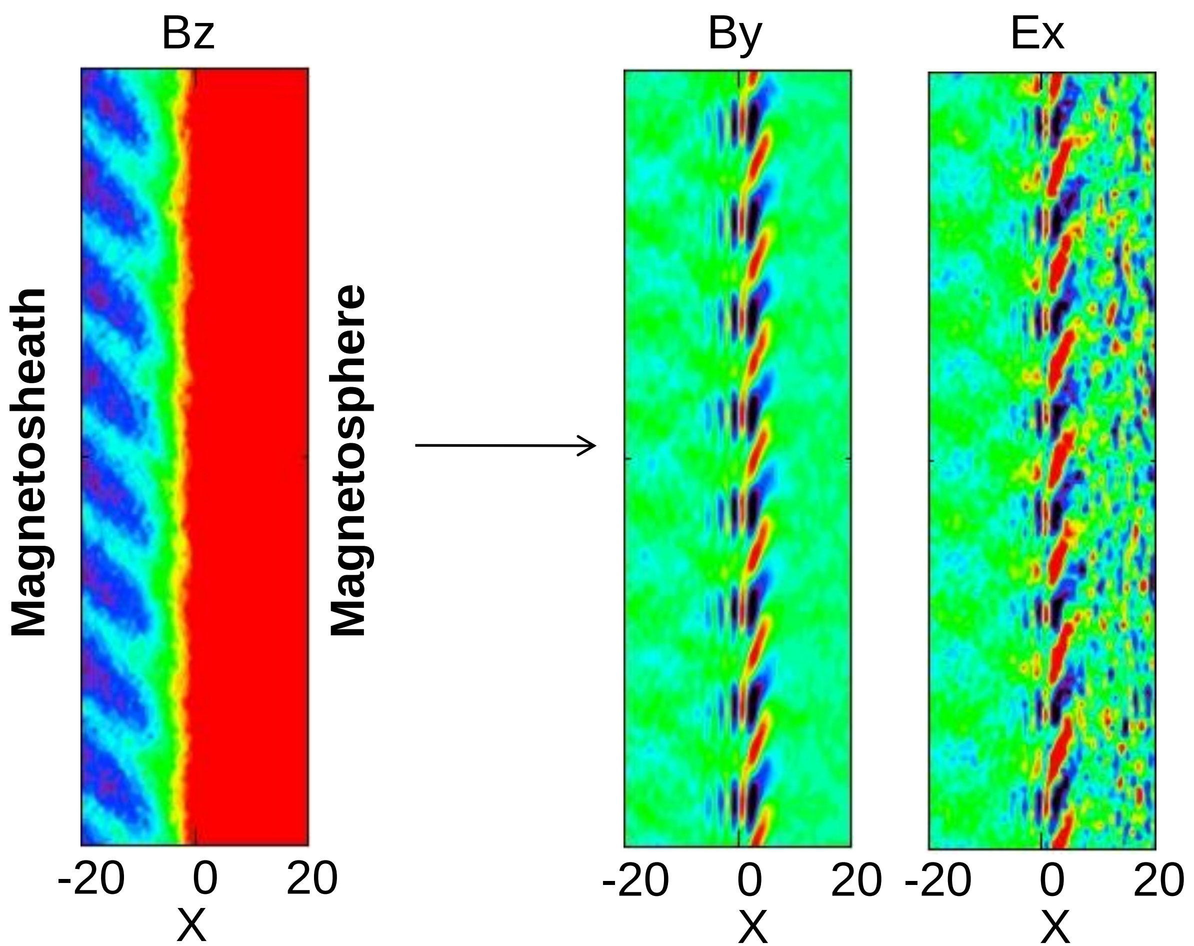
$$D_s = \frac{\sqrt{\pi}}{2} \sum_k \frac{k_y^2}{k_z^2} \left(\frac{|E_{zk}|}{B_0} \right)^2 \frac{1}{|k_z| v_{th,s}} \exp\left(-\frac{v_A^2}{v_{th,s}^2} \right)$$

  - only resonant particles diffuse in ±X-direction
  - Di for KAW is used in many researches on LLBL formation [Chaston et al., 2007, 2008, 2009]

  - **However, $\lambda_\perp$ of KAW is comparable to ρi → $k_\perp \rho i \sim 1$!!**

Generation mechanism of KAW

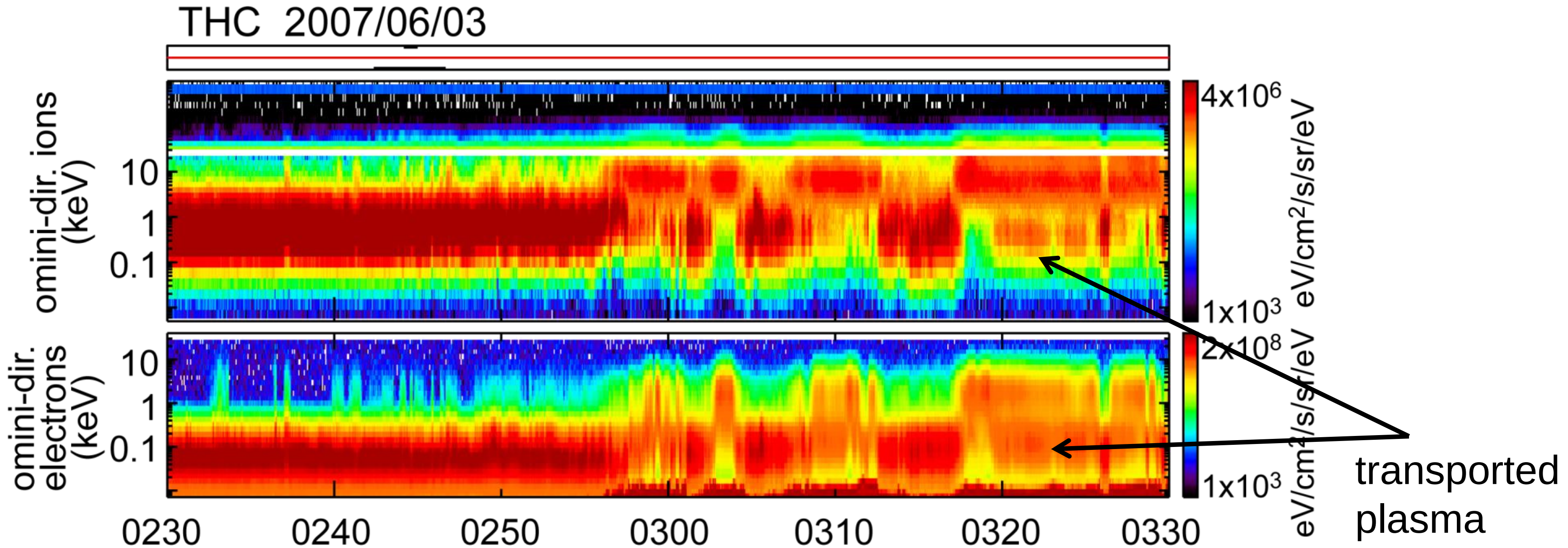
- Mode conversion of compressional wave @Alfvén resonance

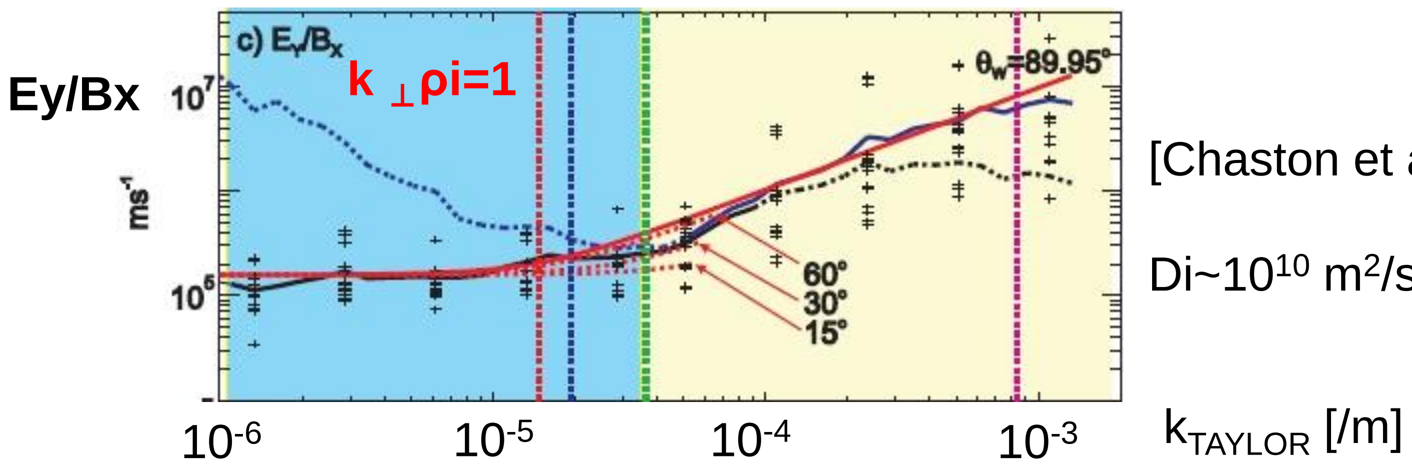


Lin et al., 2010

- **Such waves cannot diffuse plasma normal to the magnetopause!**
  - **Need Bx & Ey to diffuse in +X-direction**

Observation of KAW





[Chaston et al., 2008]

$D_i \sim 10^{10}$ m^2/s

Can KAW really diffuse plasma into the magnetosphere?

Problems on transport by KAW

- KAW is oblique wave with $\lambda_\perp \sim \rho i$.

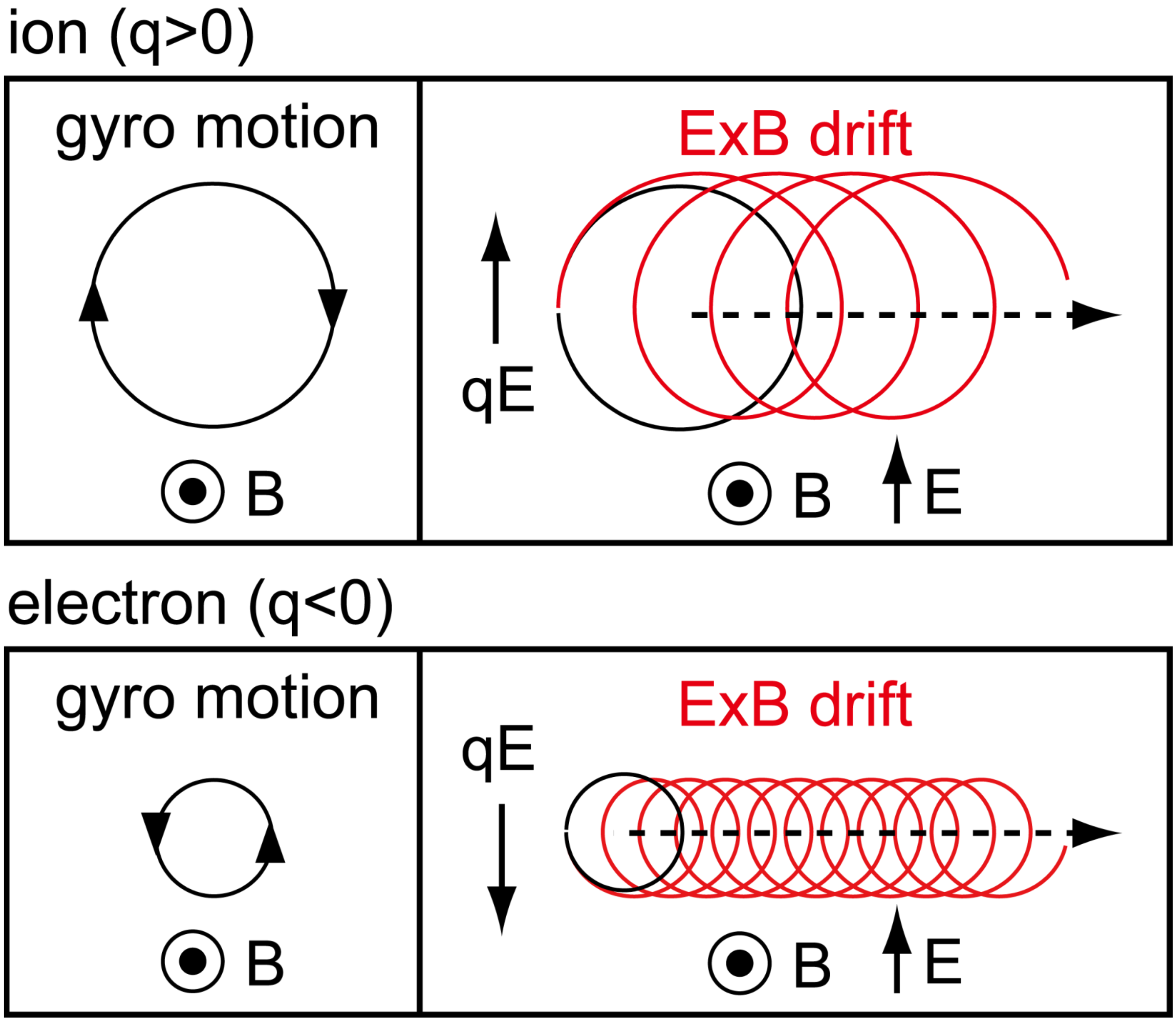
1. Strength of transport by KAW is estimated based on quasi-linear theory assuming $\lambda_\perp >> \rho i$.
2. KAW generated from mode-conversion @MP cannot diffuse plasmas normal to MP (cannot make LLBL)
3. Whether observed KAW really diffuses plasma into the MP has not been revealed.

Solutions

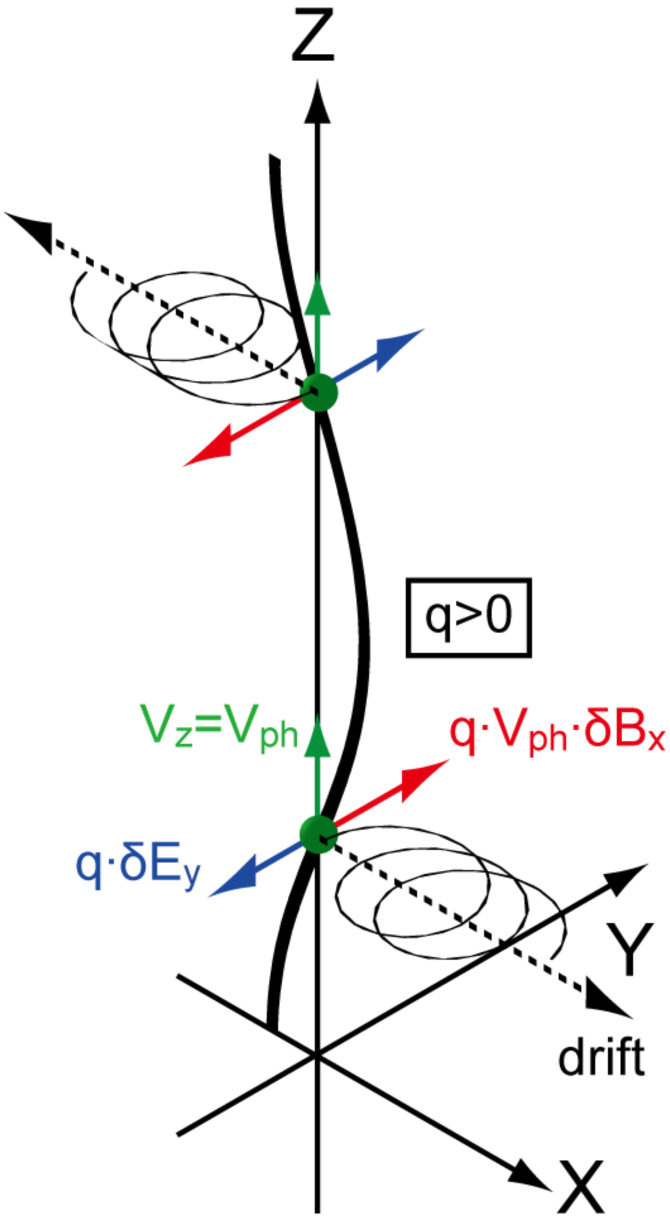
2 → 3D simulation (Hybrid or PIC) future work!

1 & 3 → Re-consider fundamental physics of transport by KAW

E x B drift


ion (q>0)
gyro motion
B
ExB drift
qE
B
E
electron (q<0)
gyro motion
B
ExB drift
qE
B
E

A new viewpoint of transport mechanism in KAW

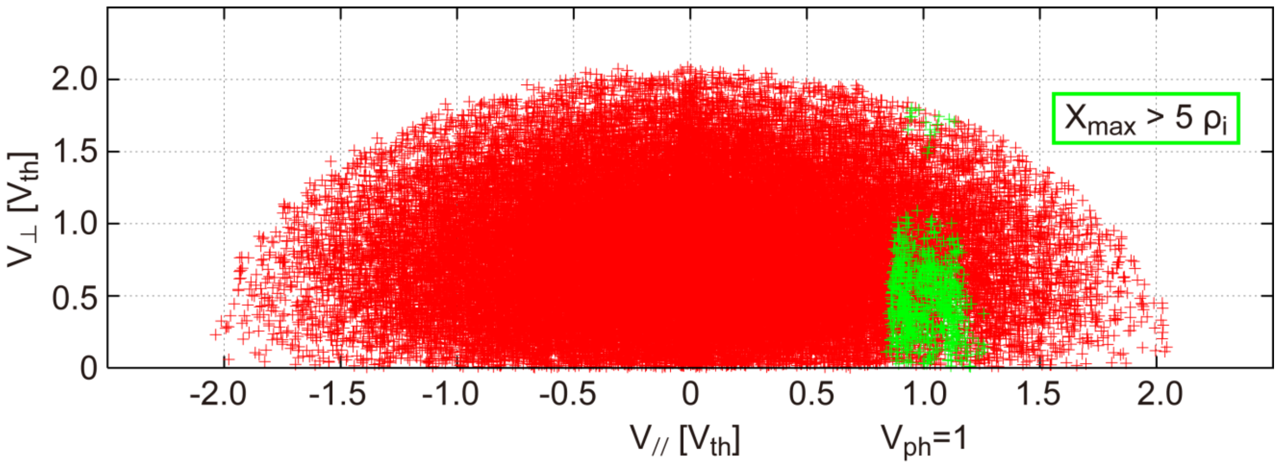


$$m_j \frac{dv_y}{dt} = q_j\left(\delta E_y + v_z \delta B_x - v_x B_0\right)$$

$$\text{When} \quad v_z = v_{ph} = \frac{\omega}{k_z}, \quad \delta E_y + v_z \delta B_x = \frac{k_y}{k_z}\delta E_z \neq 0$$

- Resonant ions ($v_z=v_{ph}$) drift in +(−) X direction where δBx>0 (<0)
  - away from the initial magnetic field
  - known as "diffusion"
- Resonant ions with $2\rho_i< \lambda_\perp/2$ can diffuse.
  - FLR effect may lower Di by a factor or an order
- All resonant electrons can drift in the same direction as ions
- Note that //-propagating wave & oblique shear Alfvén wave cannot diffuse plasma since $(\delta \mathbf{E}+\mathbf{v}_{ph,z} \times \delta \mathbf{B})_\perp=0$.

Confirmation by test-particle simulation



<Parameters>

β=5.0

Te/Ti=0.2

$k_z{}^* \rho_i = 6.4\times10^{-2}$ ($\lambda z = 98\rho_i$)

$k_y{}^* \rho_i = 1.8$ ($\lambda y = 3.4\rho_i$)

$\omega/\Omega_{ci} = 6.5\times10^{-2}$ ($T/T_{ci}=15$)

$V_{ph}=1.0$

$dBx/B_0 = -0.1$

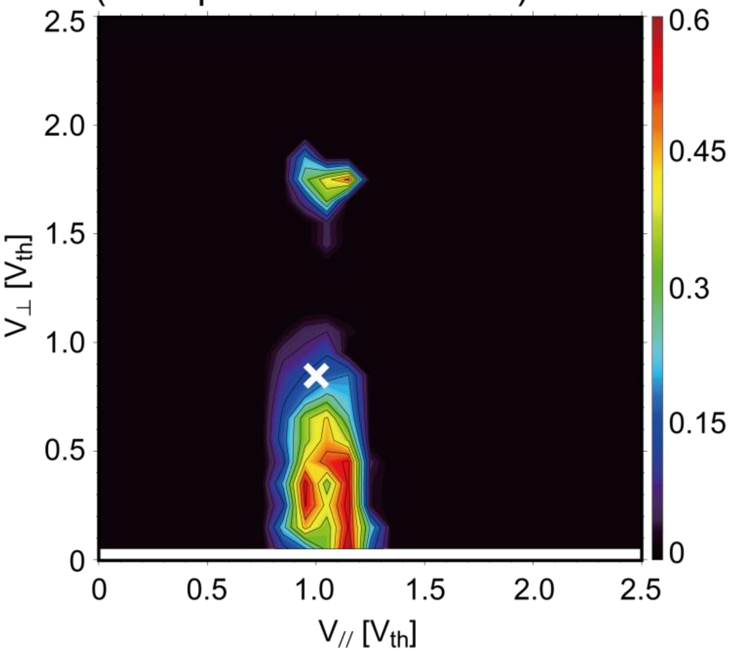
$dEy/E_0 = 8.7\times10^{-2}$

$dEz/E_0 = -4.7\times10^{-4}$

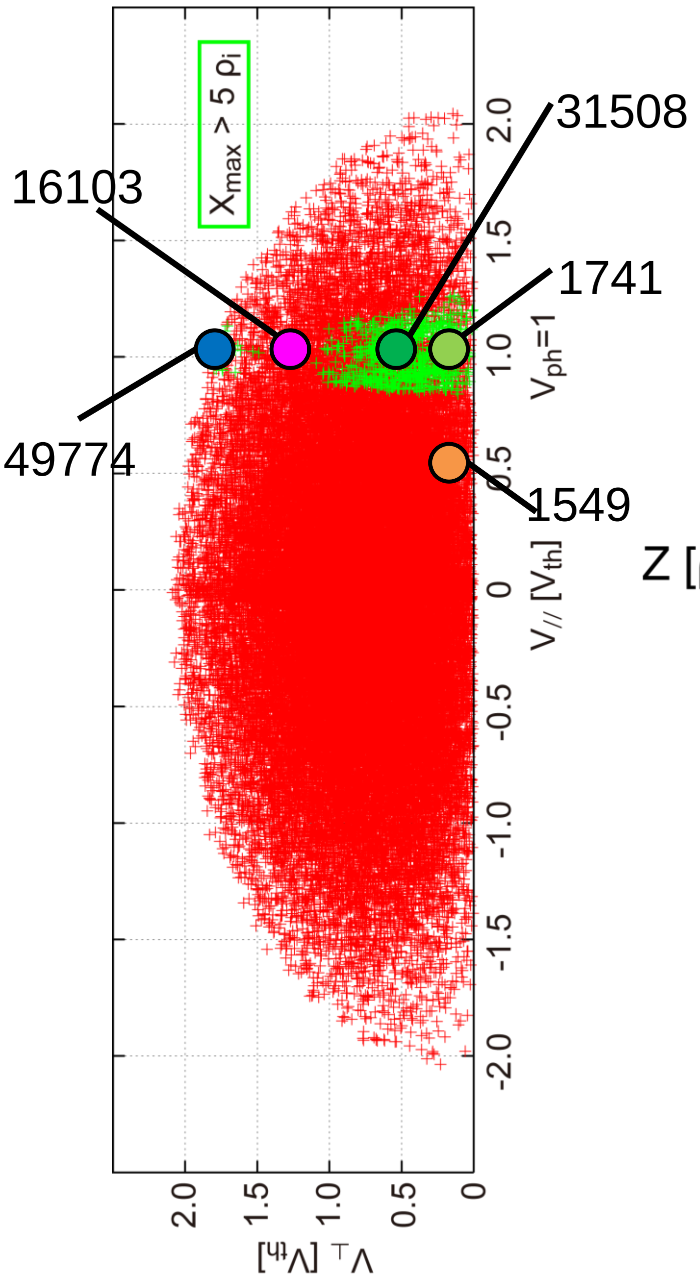
PHI=1.88

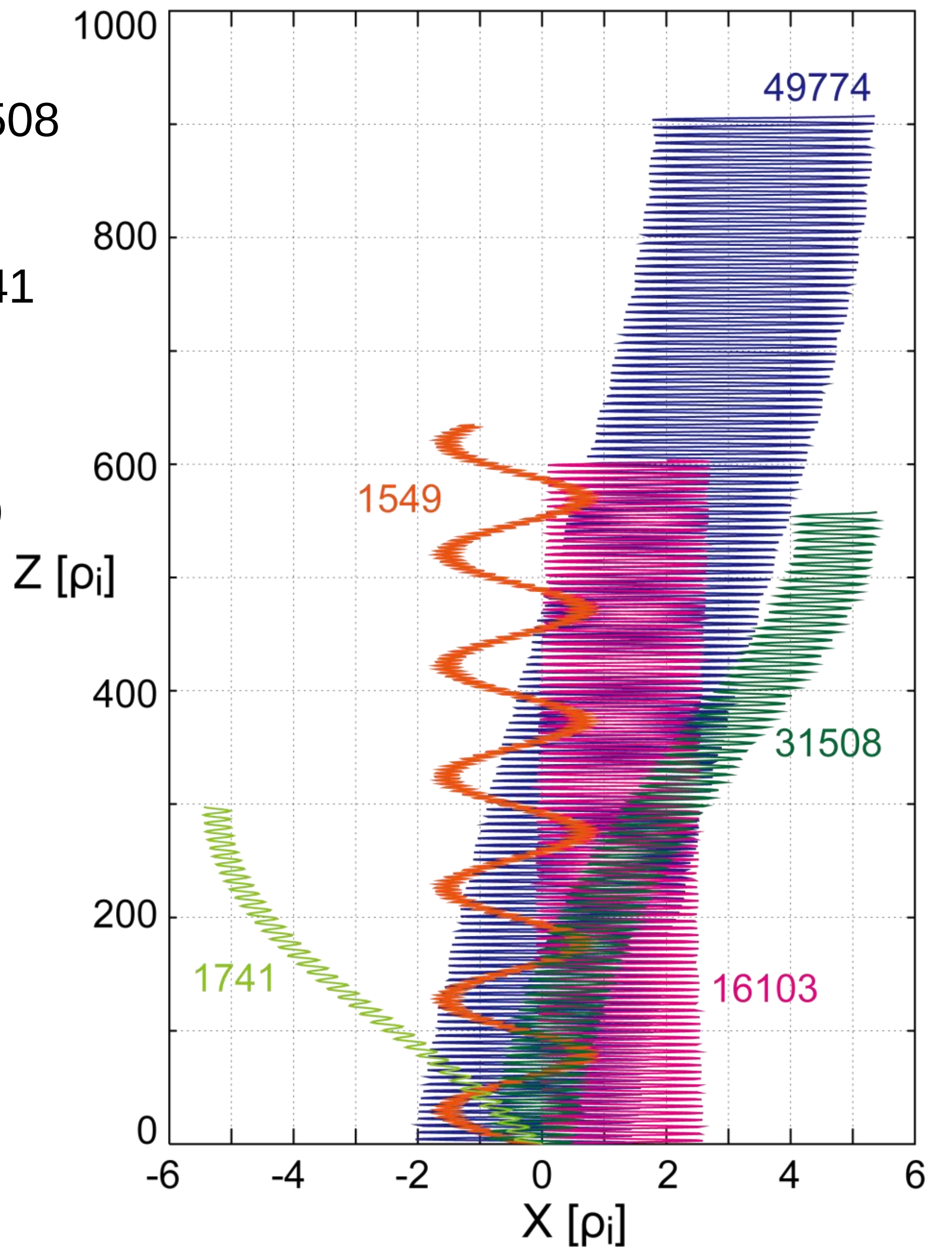
5×10^4 particles

Source/Transported
(Test-particle simulation)



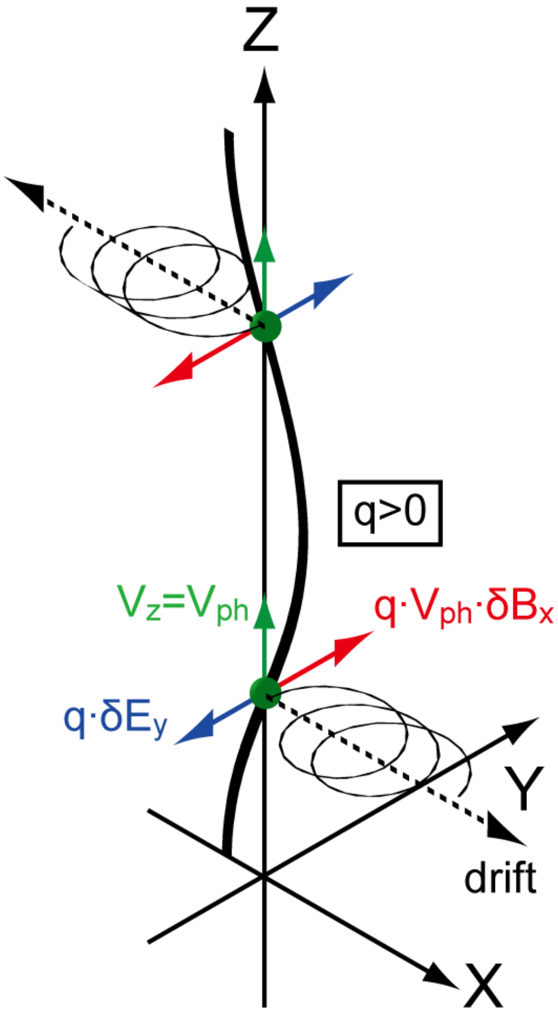
Confirmation by test-particle simulation





Summary

- A new viewpoint for physics of plasma transport by kinetic Alfvén wave was presented.
  - Particles in almost the same phase of the wave drift away from the initial magnetic field
    - // : $V_{//}=V_{ph}= \omega/k_{//}$ specific energy
    - ⊥ : $\rho_i<\lambda_\perp/4$ lower energy



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