Spring AGU Meeting
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SM553A-03

Theory and Hybrid Simulations of Plasma Transport due to Kinetic Alfven Waves at the Magnetopause

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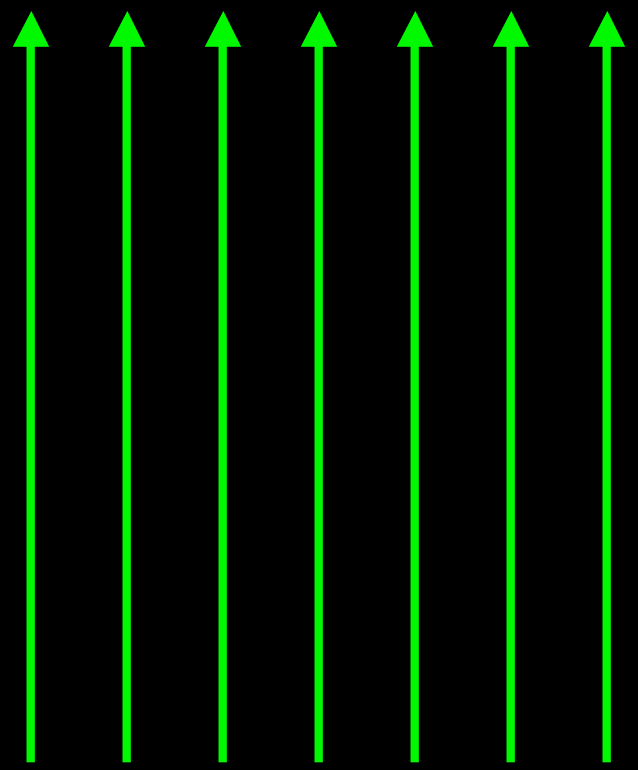
Motivation

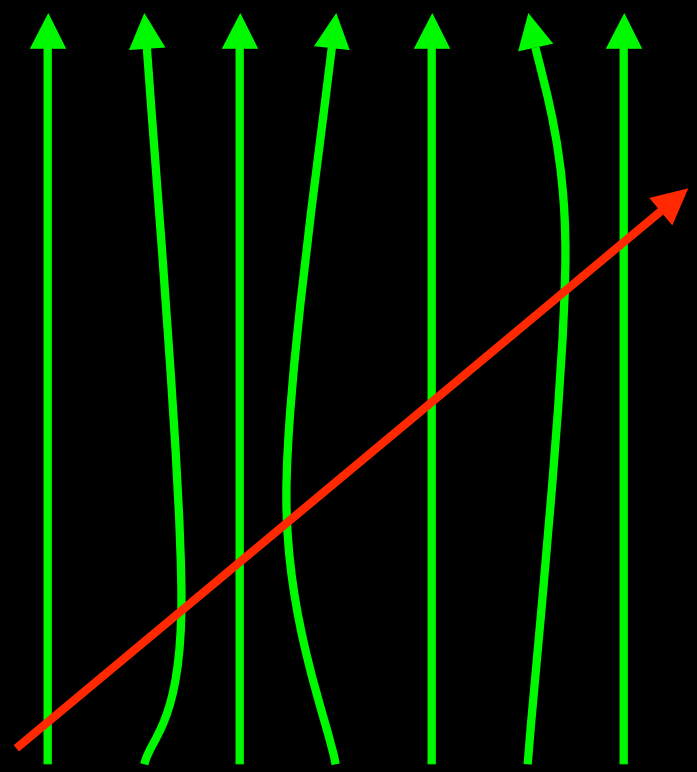
- Significant Observations:
  - Thick boundary layer for northward IMF
  - Heating of particles
  - Large amplitude transverse waves
  - Dawn-dusk asymmetries
  - Entropy increase across magnetopause
- Kinetic Alfven waves can explain these observational signatures and provide significant transport

Low Frequency Waves



Low Frequency Waves

$\omega = k V_A$

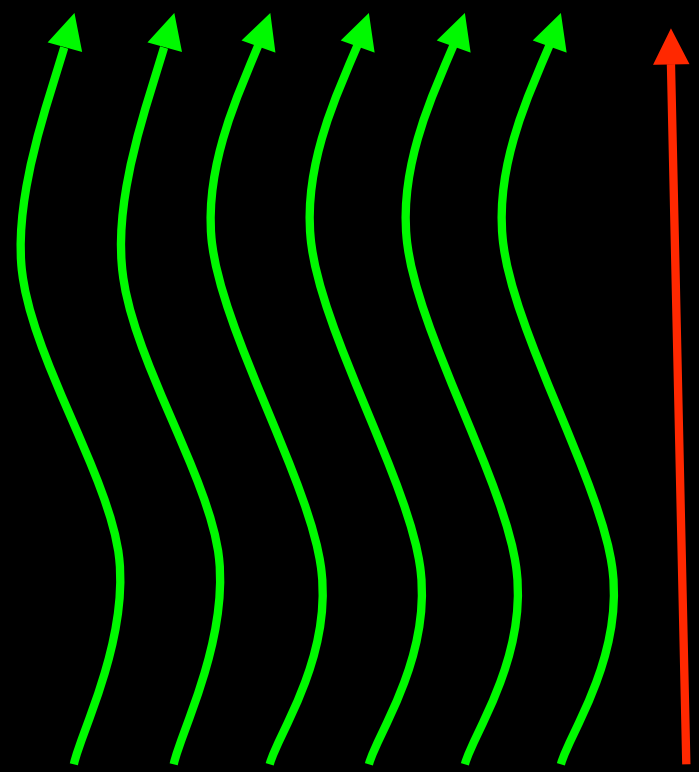


Carries Energy Across B

Compressional

Low Frequency Waves

$\omega = k_{||} V_A$



Carries Energy Along B

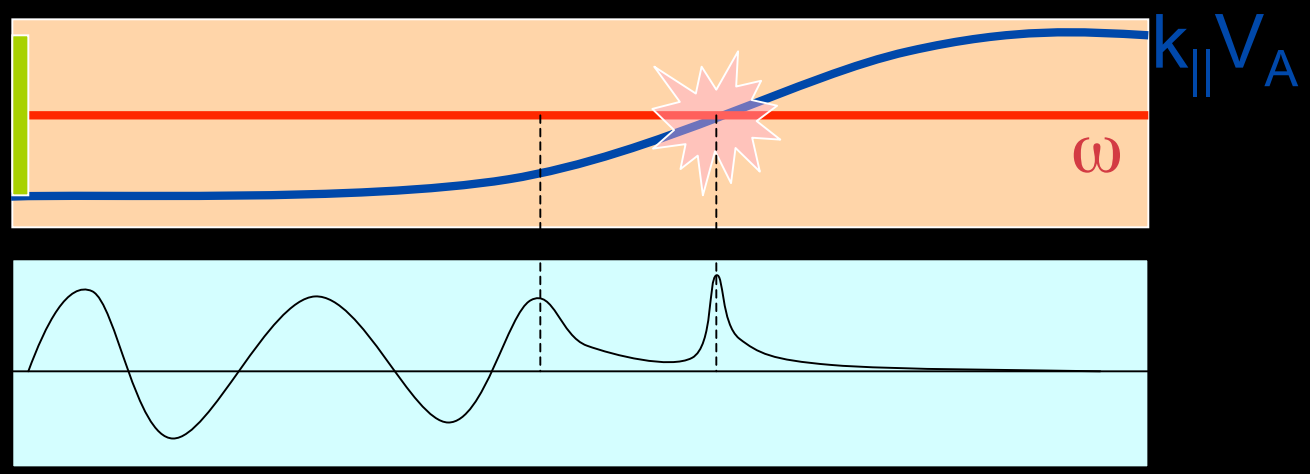
Shear Alfvén

Mode Coupling

Compressional Wave Equation

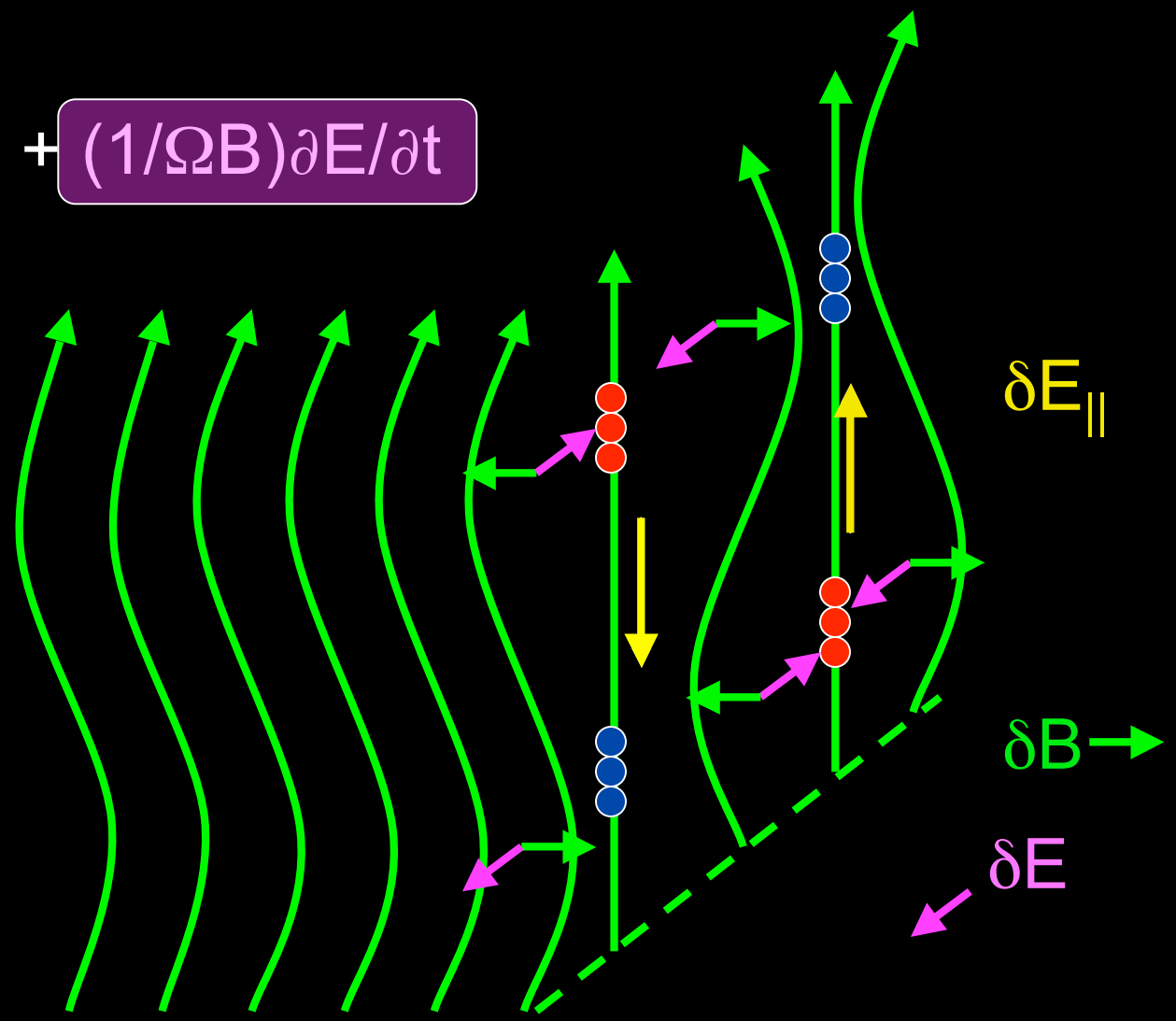
$$k_x^2=\omega^2/V_A^2 - k_{||}^2 - k_y^2$$

Alfven Continuum



Kinetic Alfvén Wave

$\delta V = E \times B / B^2 + (1/\Omega B)\partial E/\partial t$



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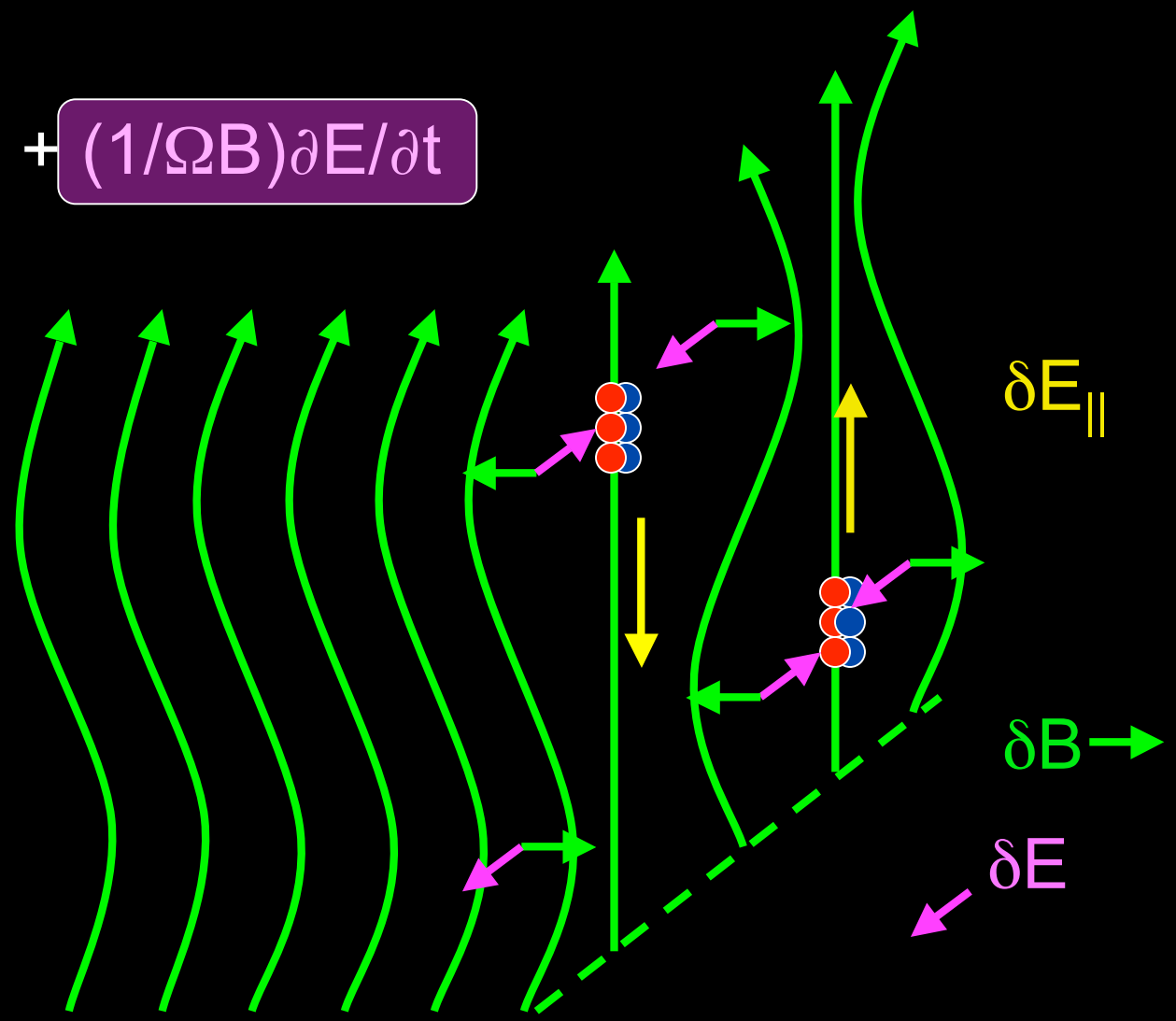
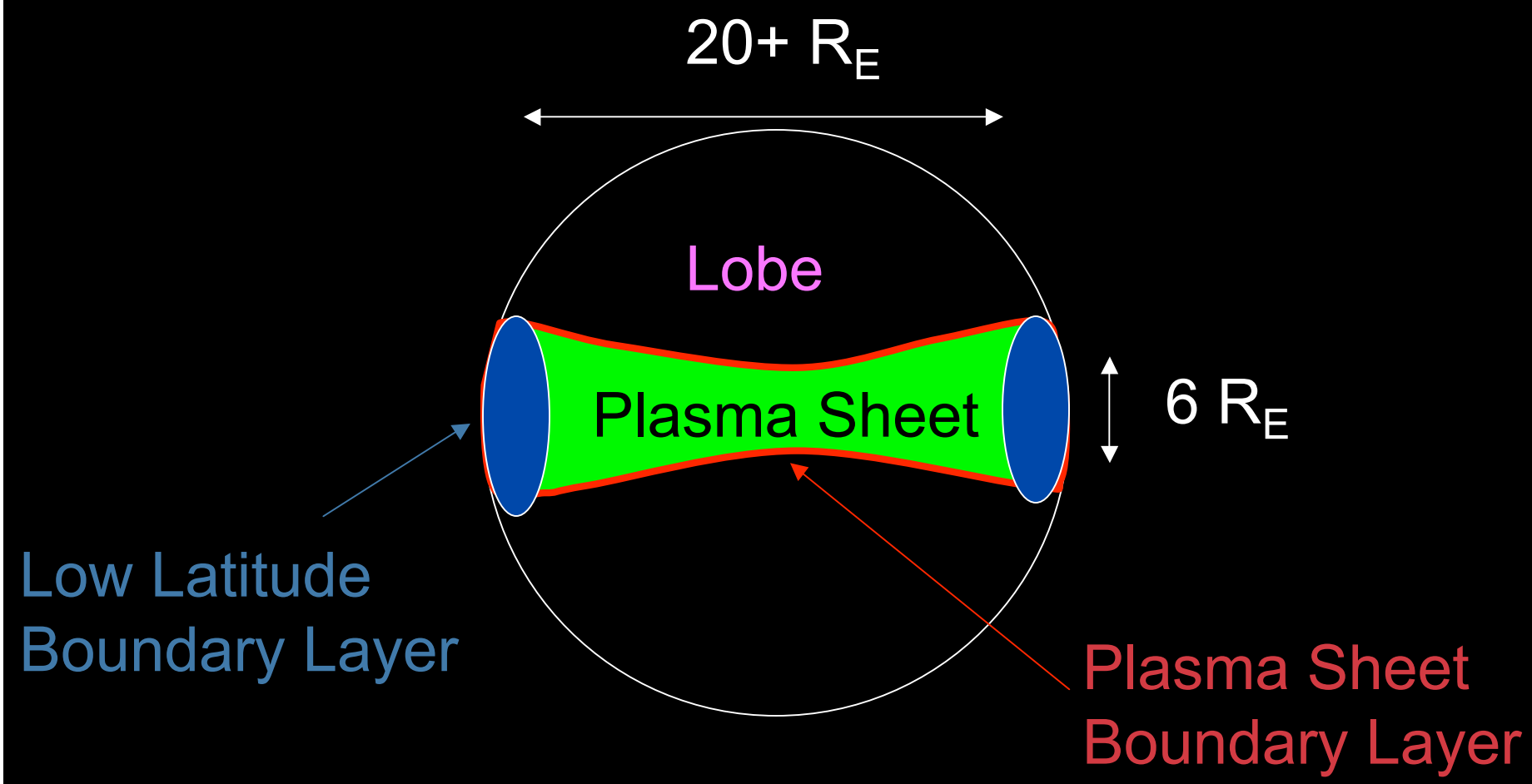
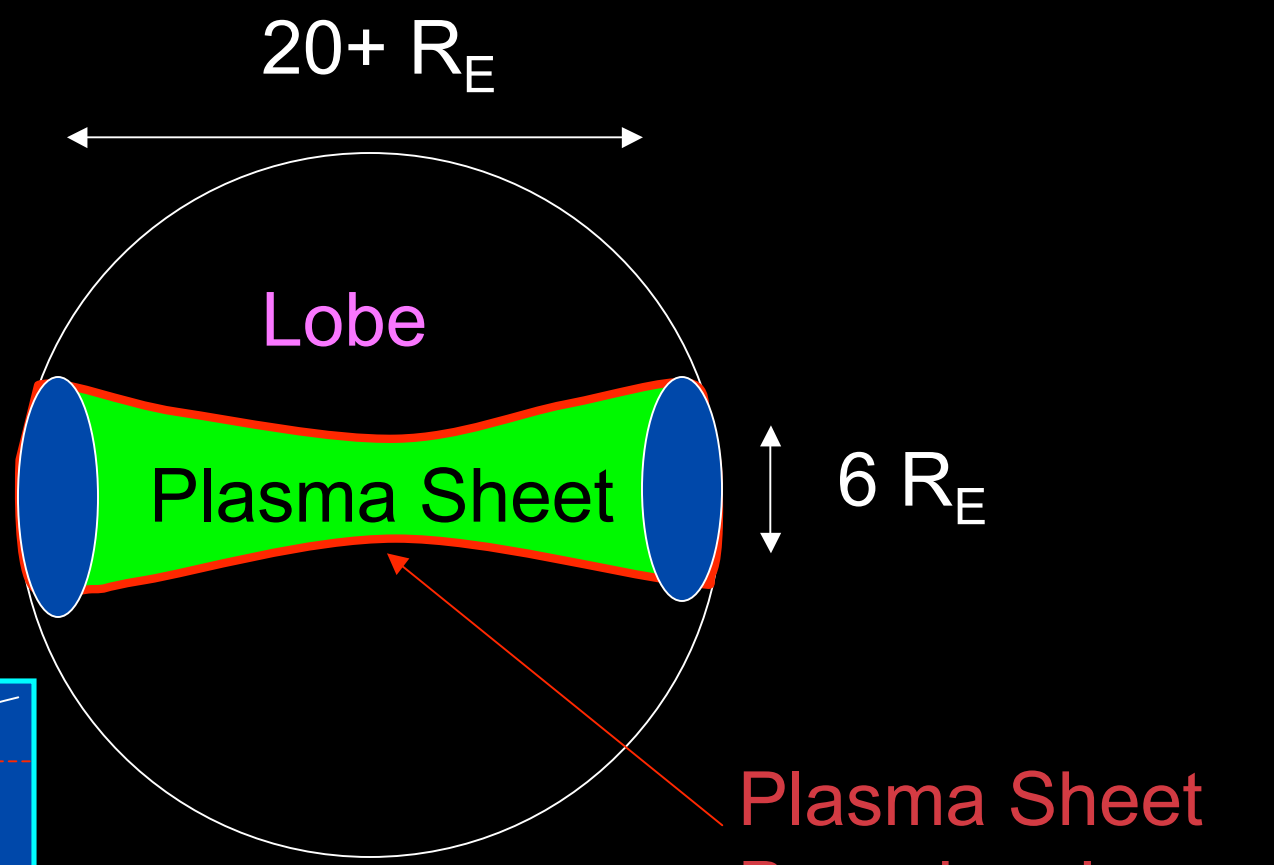
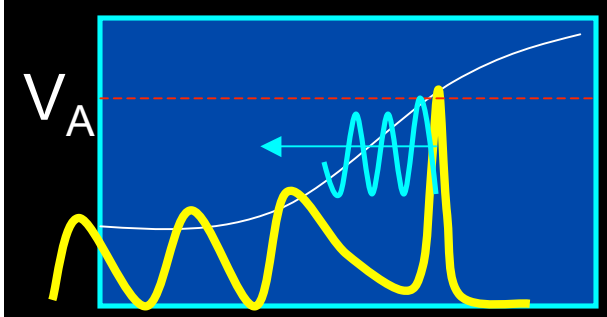


KAWs and Plasma Sheet

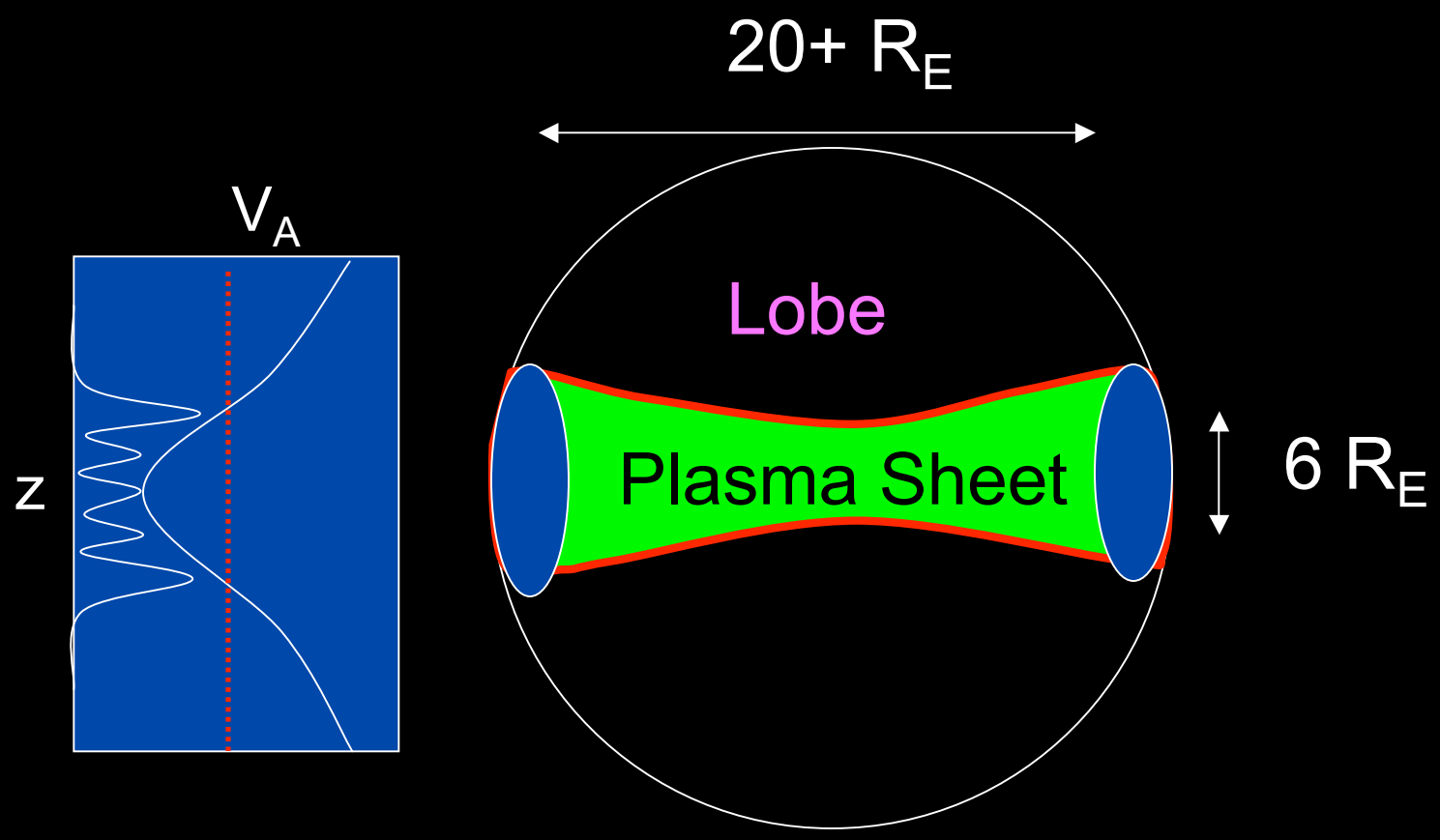


Flank Source



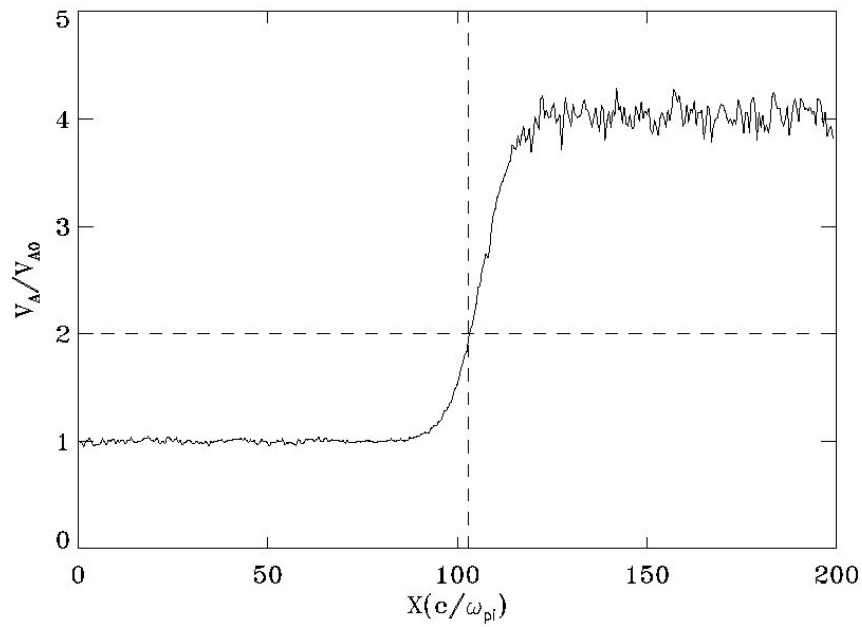


Plasma Sheet Source



Initial Profile of the Alfven Speed

incident wave
$\omega/(k_{||}V_A) = 2.0$



predicted resonance point in MP

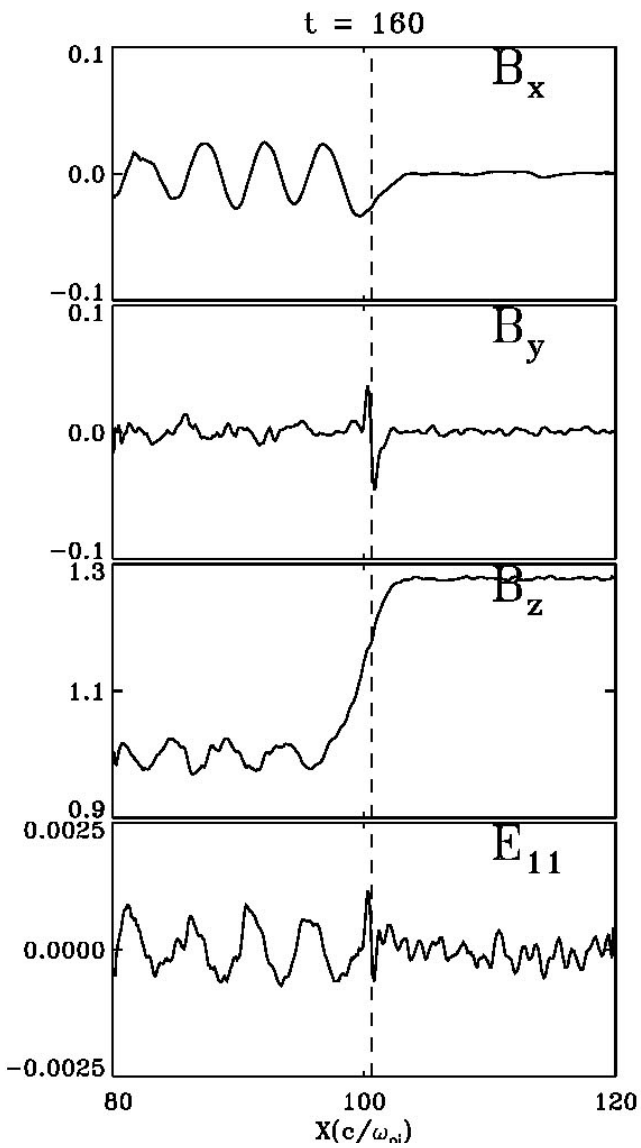
Case 1: $\theta=0°$, $\omega/(k_{||}V_A)=2.0$, $k_x(c/\omega_{pi})=0.28$, $k_z(c/\omega_{pi})= 0.20$,
$\omega/\Omega_i=0.39$, $\beta_i=0.5$, $T_e/T_i=0.4$, $\delta V/V_{A0}=0.04$.

Hybrid Simulations

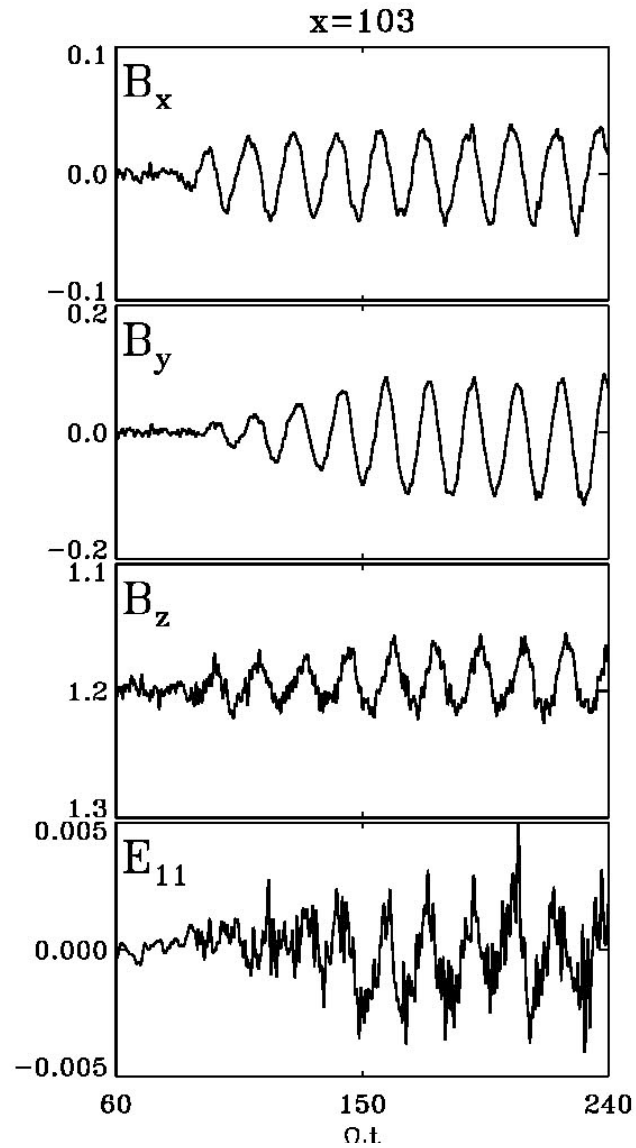
Artech365.com

Lin, Johnson, Wang, 2007

Spatial profiles: mode conversion to *thin* KAW at the resonant point x=103 c/ω_{pi}

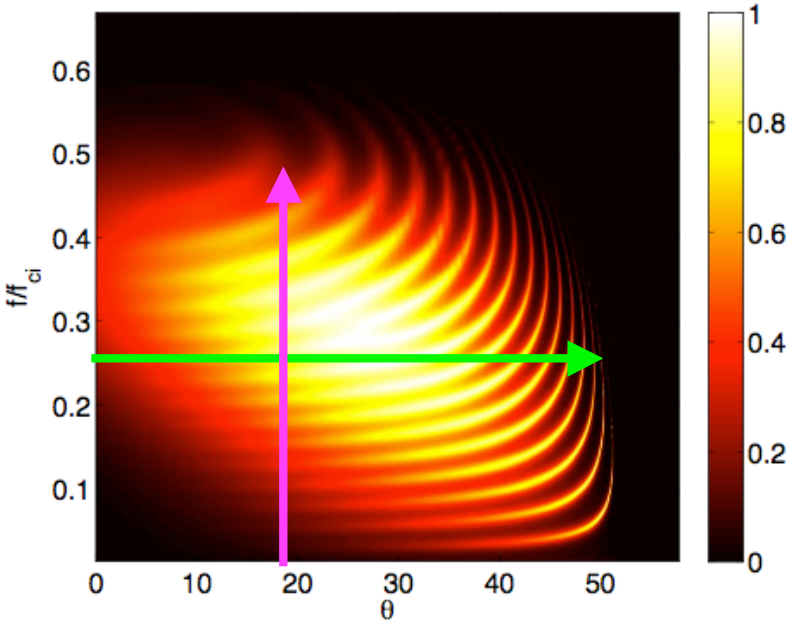


Time variations at the resonance point: incident wave reaches the MP at t~85Ω_i^{-1}

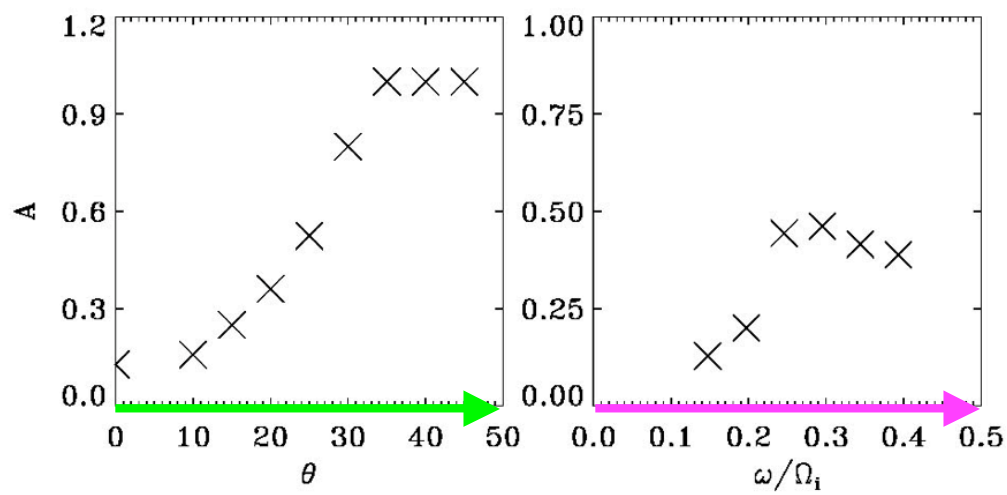


Theory/Simulation Comparison Absorption at Resonance

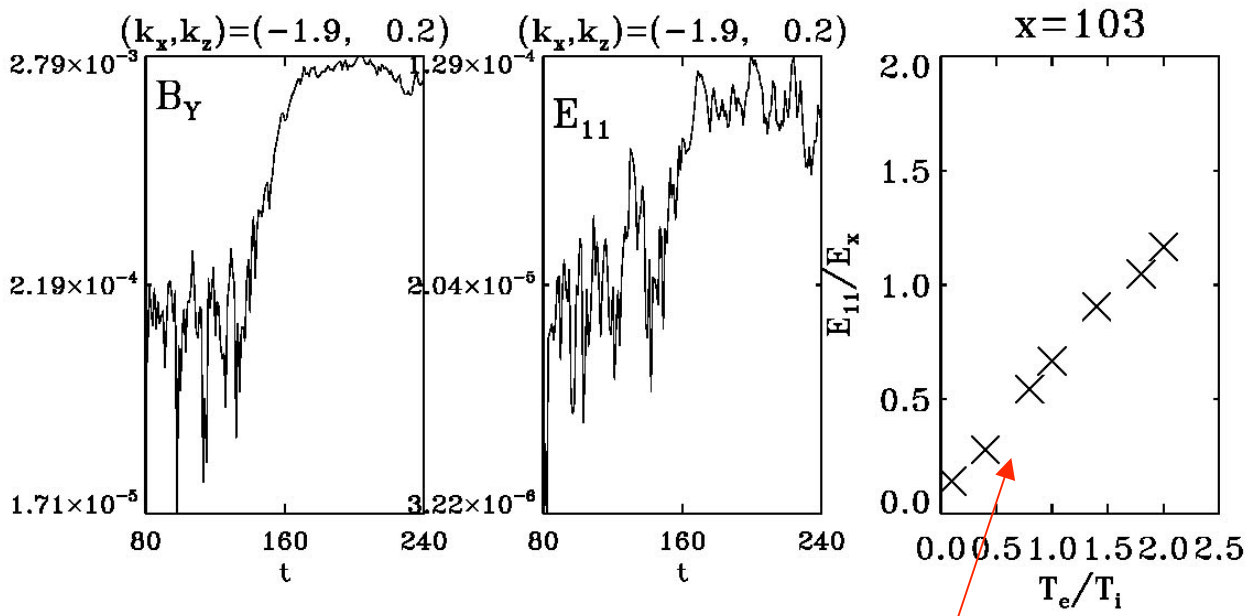
Analytic Theory



Hybrid Simulation

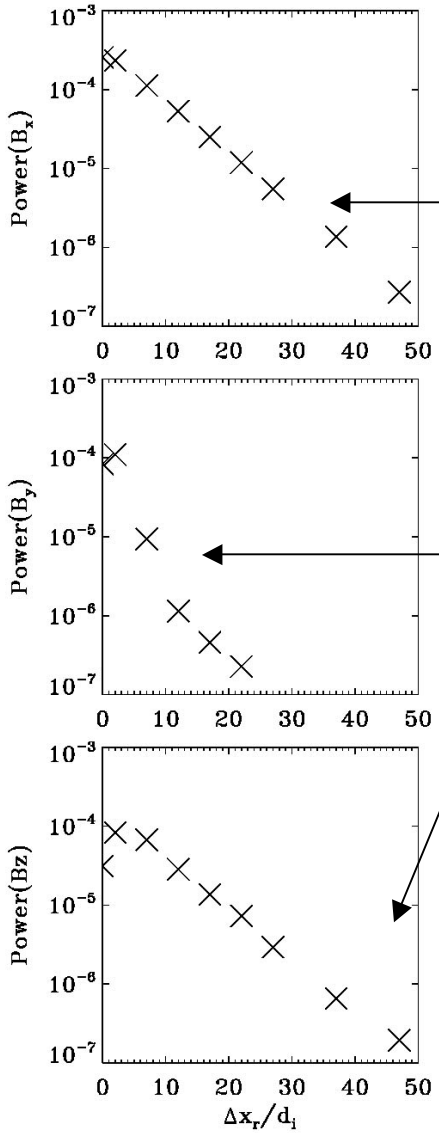


Theory/Simulation Comparison Parallel Electric Field



Linear dependence: *Theoretical formula* $E_{||} \sim E_x\ (k_x\rho_i)(k_{||}\rho_i)(T_e/T_i)(1+k_x^2\rho_i^2)$

Exponential Decay of Wave Beyond the Mode Conversion Region



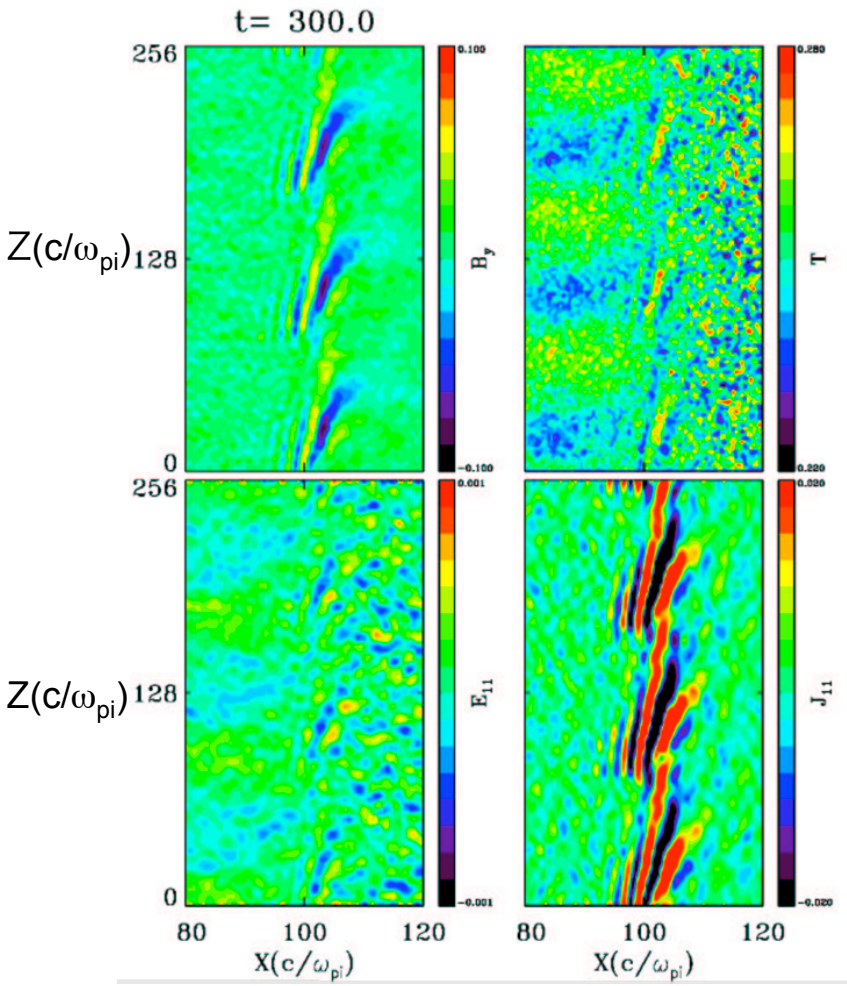
Compressional Wave

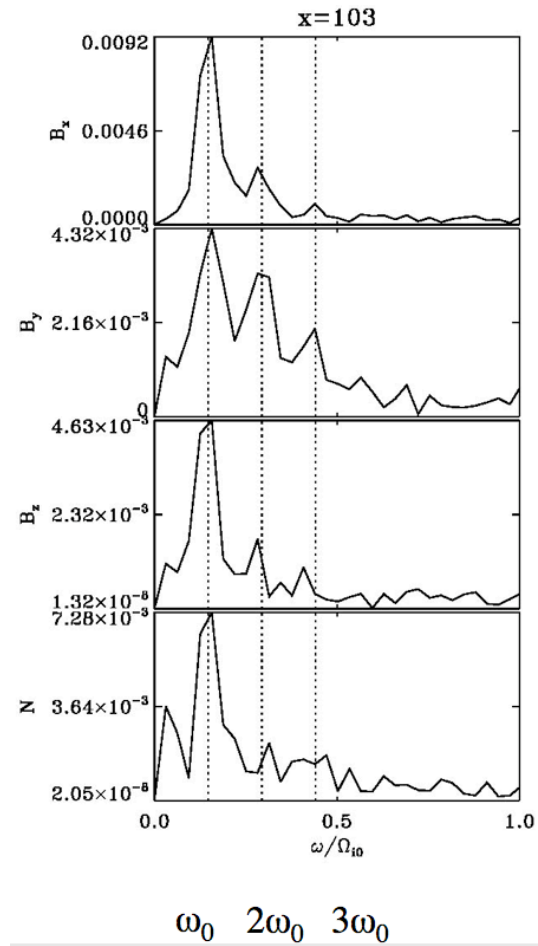
Kinetic Alfven Wave

Nonlinear Effects

- Passive Nonlinearity
  - Large amplitude at mode conversion
  - Driver excites harmonics $A_n \sim (A_0)^n$
- Steepening of incident compressional wave (wave speed depends on B, n)
  - Generates harmonics
  - Leads to a spectrum/bath of KAWS

Nonlinear Harmonic Generation



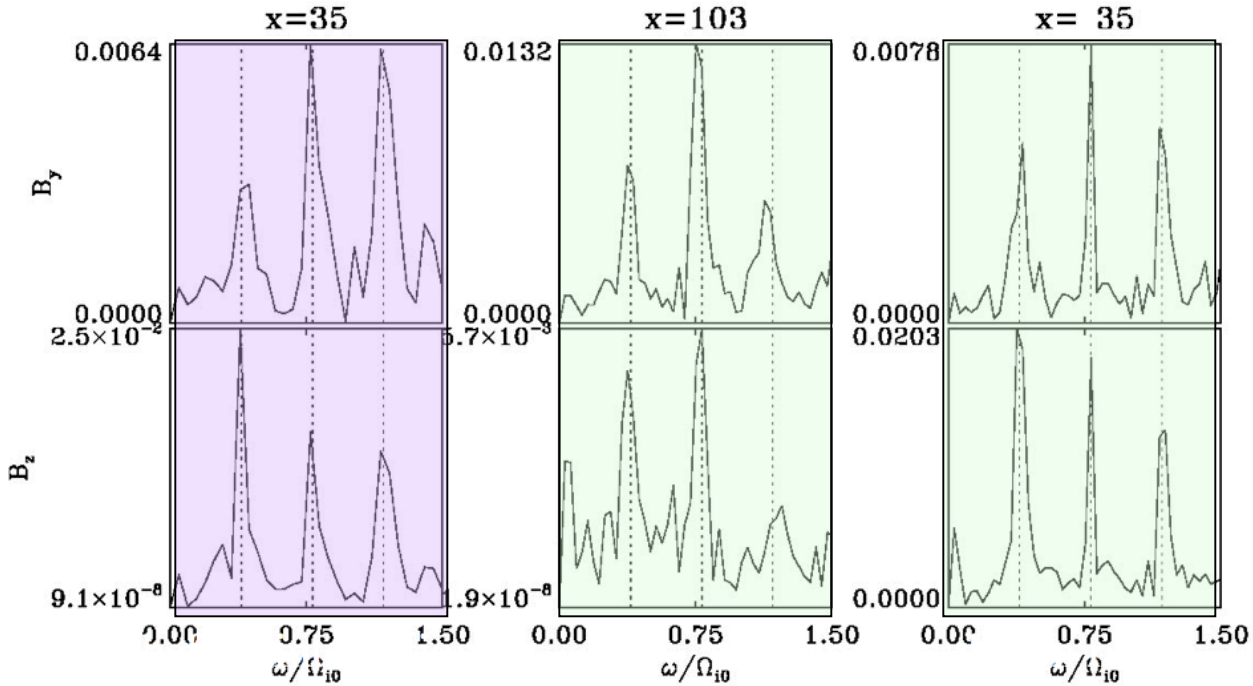


$\theta=0°$, $\omega/(k_{\parallel}V_A)=2.0$, $\omega/\Omega_i=0.147$, $T_e/T_i=0.2$, $\delta V/V_{A0}=0.04$.

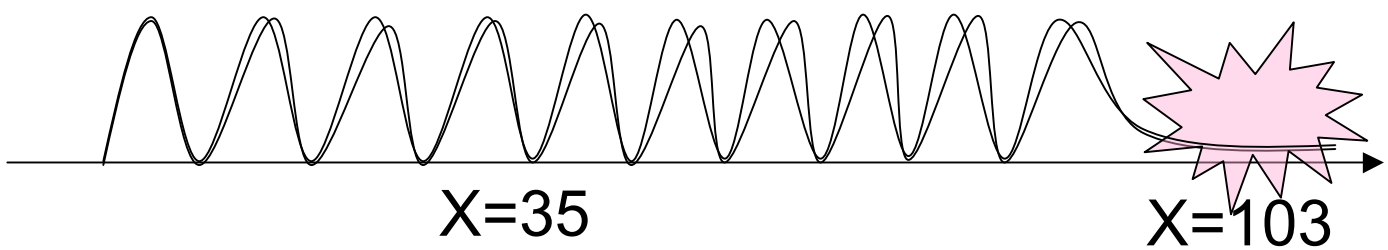
Nonlinear Harmonic Generation: Steepening of Incident Waves

$\omega = k_{||} V_A$

Before Mode Conversion



Entire Simulation

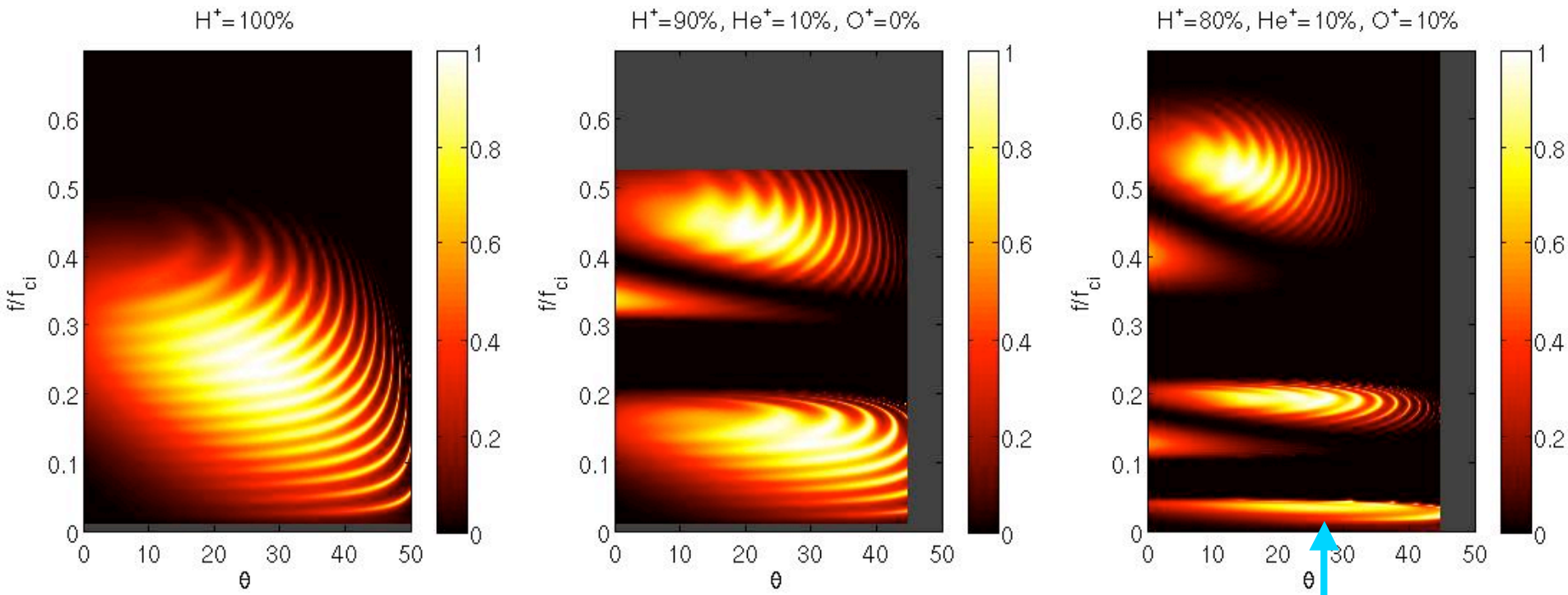


Heavy Ion Effects

	MSPBL			MSHBL		
Parameter	Dawn	Noon	Dusk	Dawn	Noon	Dusk
O^+ number density (cm^{-3})	0.014	0.021	0.053	4×10^{-3}	6×10^{-3}	0.011
O^+ mean energy (keV)	4.28	3.62	3.85	14.6	14.0	14.4
O^+ poleward velocity (km s^{-1})	57.0	66.9	52.0	88.0	162.5	119.4
O^+ normal velocity (km s^{-1})	2.4	−17.2	5.1	34.8	−16.5	15.6
Probability $P(r>1)$	0.031	0.042	0.306	~0	~0	~0

Bouhram, 2005

Effect of Heavy Ions



At MP~25 mHz
(Pc3 range)

Normalized to f_{ci} at resonance

KAW and Transport

Transport (Gyrokinetic)

$$\frac{\partial f}{\partial t} + \nabla \cdot (v_\parallel \mathbf{b} + \mathbf{V}_d^{(0)} + \bar{\mathbf{V}}^{(1)}) f + \langle \frac{d\mu}{dt} \rangle \frac{\partial f}{\partial \mu} + \langle \frac{dU}{dt} \rangle \frac{\partial f}{\partial U} = 0$$

$$\mathbf{V}_d^0 = \frac{1}{\Omega} \mathbf{b} \times \left(\frac{v_\perp^2}{2} \frac{\nabla B}{B} + v_\parallel^2 \kappa \right) \qquad \mathbf{V}_x^1 = \frac{\delta \mathbf{E} \times \mathbf{B}_0}{B_0^2} + v_\parallel \frac{\delta \mathbf{B}_\perp}{B_0} - \mathbf{v} \frac{\delta B_\parallel}{B_0}$$

$$\delta f \sim \frac{1}{\omega - k_\parallel v_\parallel - \omega_d} \bar{V}_x^{(1)} \frac{\partial f_0}{\partial x} + \ldots$$

$$\mathbf{E} = -i(\mathbf{k}\phi - \omega A_\parallel \mathbf{b})$$

$$A_\parallel = k_\parallel (\phi - \psi)/\omega$$

$$E_\parallel = -i k_\parallel \psi$$

$$\bar{V}_x^{(1)} \sim \frac{k_y}{\omega B_0} \left(\left((\omega - k_\parallel v_\parallel) \phi + k_\parallel v_\parallel \psi \right) J_0 + \frac{\omega v_\perp J_1 \delta B_\parallel}{k_\perp} \right)$$

Transport

$$\frac{\partial f_0}{\partial t} \sim -\frac{\partial}{\partial x}\langle \bar{V}_x^{(1)} \delta f \rangle + \ldots \sim \frac{\partial}{\partial x}\langle \frac{\bar{V}_x^{(1)} \bar{V}_x^{(1)}}{\omega - k_\parallel v_\parallel - \omega_d} \rangle \frac{\partial f_0}{\partial x} + \ldots$$

$$\frac{\partial f_0}{\partial t} \sim \frac{\partial}{\partial x}\left(\frac{k_y^2}{\omega^2 |k_z| B_0^2} \left| \omega_d \phi J_0 + (\omega - \omega_d)\psi J_0 + \frac{\omega v_\perp J_1}{k_\perp} \delta B_\parallel \right|^2 \pi \delta(v_\parallel - (\omega - \omega_d)/k_z) \right) \frac{\partial f_0}{\partial x}$$

$$\frac{\partial f_0}{\partial t} \sim \frac{\partial}{\partial x}\left(\frac{k_y^2}{\omega^2 |k_z| B_0^2} \left| \omega_d \phi + (\omega - \omega_d)\psi + \frac{\omega v_\perp^2}{2\Omega} \delta B_\parallel \right|^2 \pi \delta(v_\parallel - (\omega - \omega_d)/k_z) \right) \frac{\partial f_0}{\partial x}$$

$V_d \times \delta B_\perp$

$E_\parallel$

$\mu \nabla \delta B$

Resonant Particles

Quasilinear Transport

$qE_{||}$ force

$$D_{HM} \sim \pi \frac{k_y^2 \psi^2}{|k_z| B_0^2} f_{i,res} \sim \pi \frac{k_y^2 E_z^2}{k_z^2 |k_z| B_0^2} f_{i,res}$$

$D_{HM} \sim 2 \times 10^9 m^2/s$

$qV_D \times \delta B_\perp$

$$D_{V_d \times \delta B_\perp} \sim \pi \frac{k_y^2 \phi^2 \omega_d^2}{|k_z| B_0^2 \omega^2} f_{i,res} \sim \frac{k_y^2 v_i^2}{\omega^2} \left(\frac{\rho_i}{L_B}\right)^2 \left|\frac{\phi}{\psi}\right|^2 D_{HM}$$

$D > 100 D_{HM}$

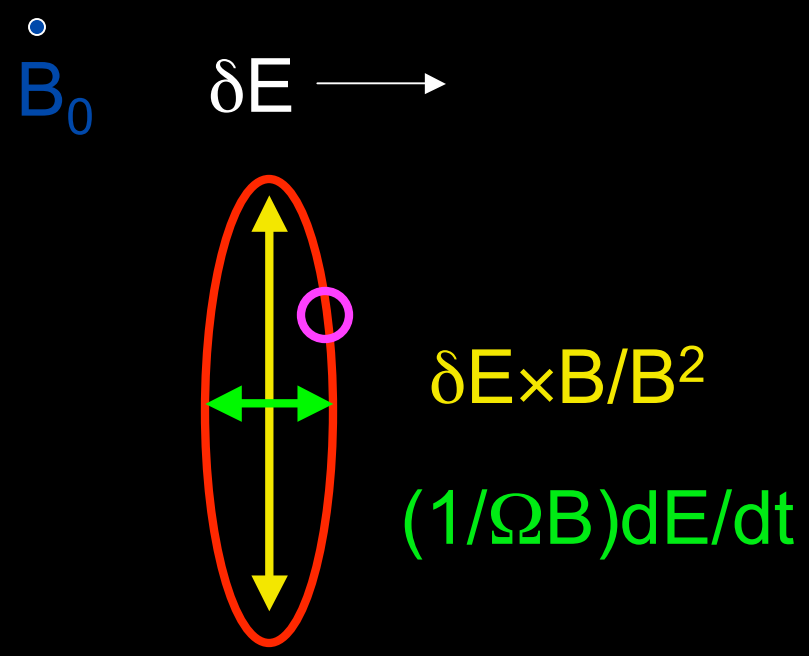
$-\mu \nabla \delta B$ force

$$D_{\mu \nabla \delta B} \sim 2\pi k_y^2 \rho_i^2 \frac{v_i^2}{|k_z|} \left|\frac{\delta B_{||}}{B_0}\right|^2 f_{i,res} \sim 2 \left|\frac{\delta B_{||}}{B_0}\right|^2 \left|\frac{T}{e\psi}\right|^2 D_{HM}$$

$>>1$

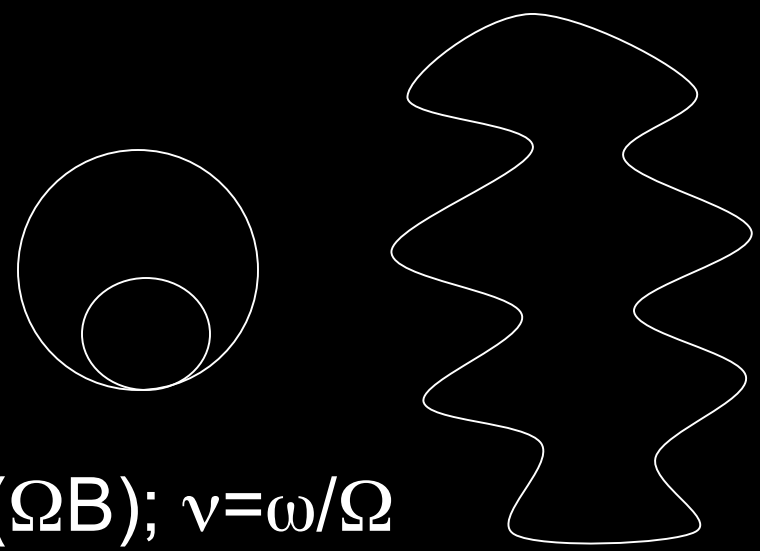
$D > 100 D_{HM}$

Coupling of Polarization Drift and Gyromotion



Gyromotion

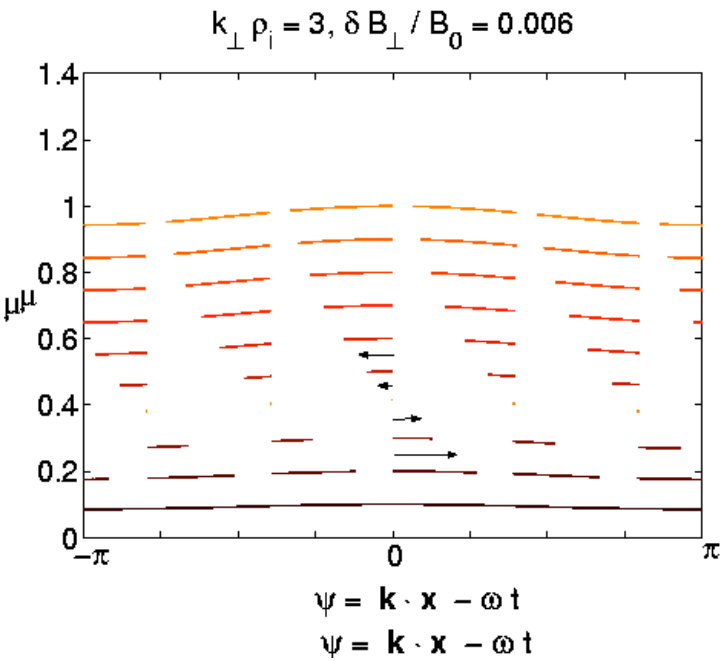
$$\ddot{\xi} = \sin(\kappa\xi - \nu t) - \xi$$

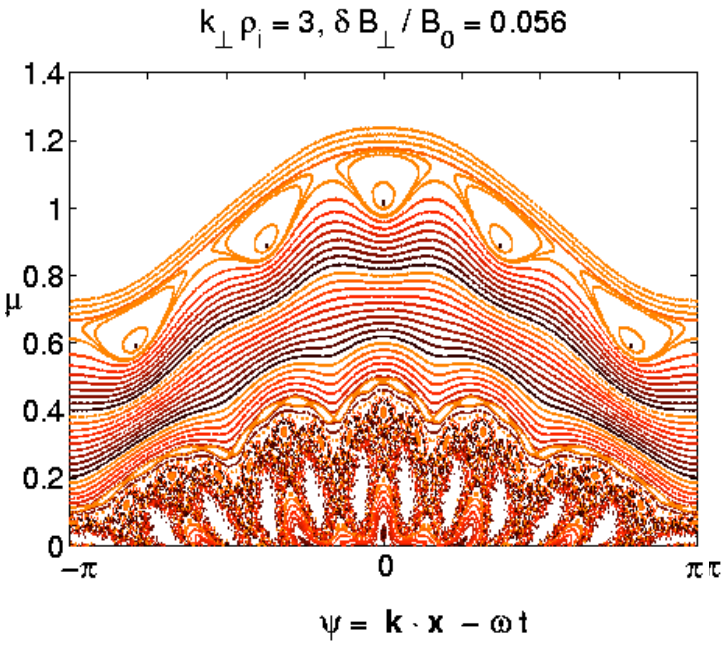


$$\frac{dv}{dt} = \frac{q}{m}E + v \times \Omega$$

$\kappa = k_y E/(\Omega B)$; $\nu = \omega/\Omega$

Onset of Stochasticity



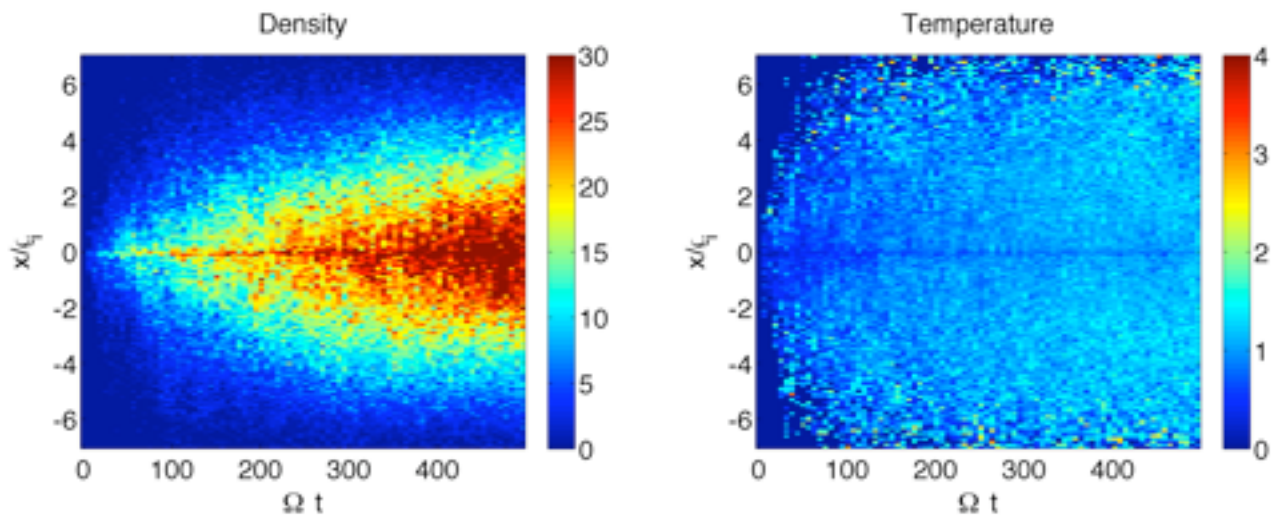


Johnson and Cheng, 2001

$\omega = \Omega/5$

$k_y x_p = k_y E_y/(B\Omega) \sim 1$

Significant Diffusion from KAW



$D \sim 2 \times 10^9\ m^2/s$

$dN/dt \sim 2 \times 10^{27}$ particles/sec

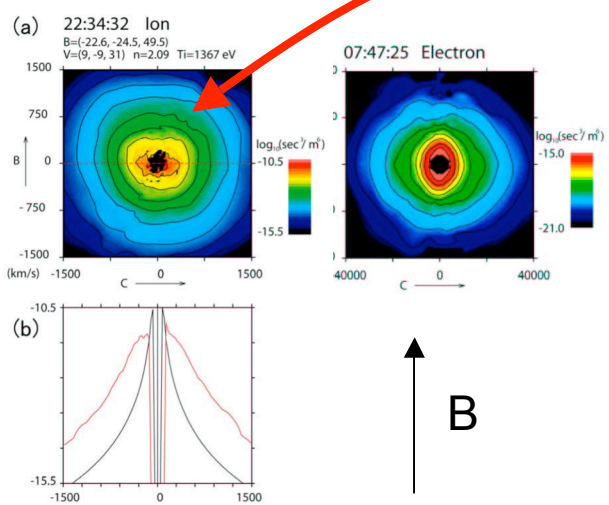
Three Significant Observations

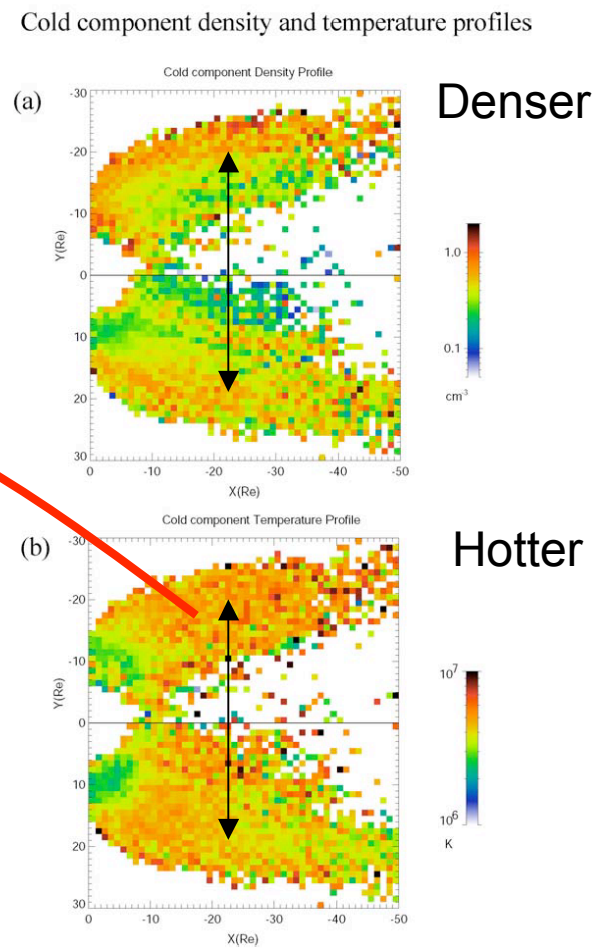
- Filling Rate
  - Wing, Johnson, Fujimoto, 2007
- Dawn-Dusk Asymmetry
  - Entry and Heating
  - Wing, Johnson, et al., 2005
- Increase of Entropy P/n^{γ} $T\uparrow$ $n\downarrow$
  - Johnson and Wing, 2007

Dawn-Dusk Asymmetries

In Situ and Remote Observational Constraints on the Entry Process

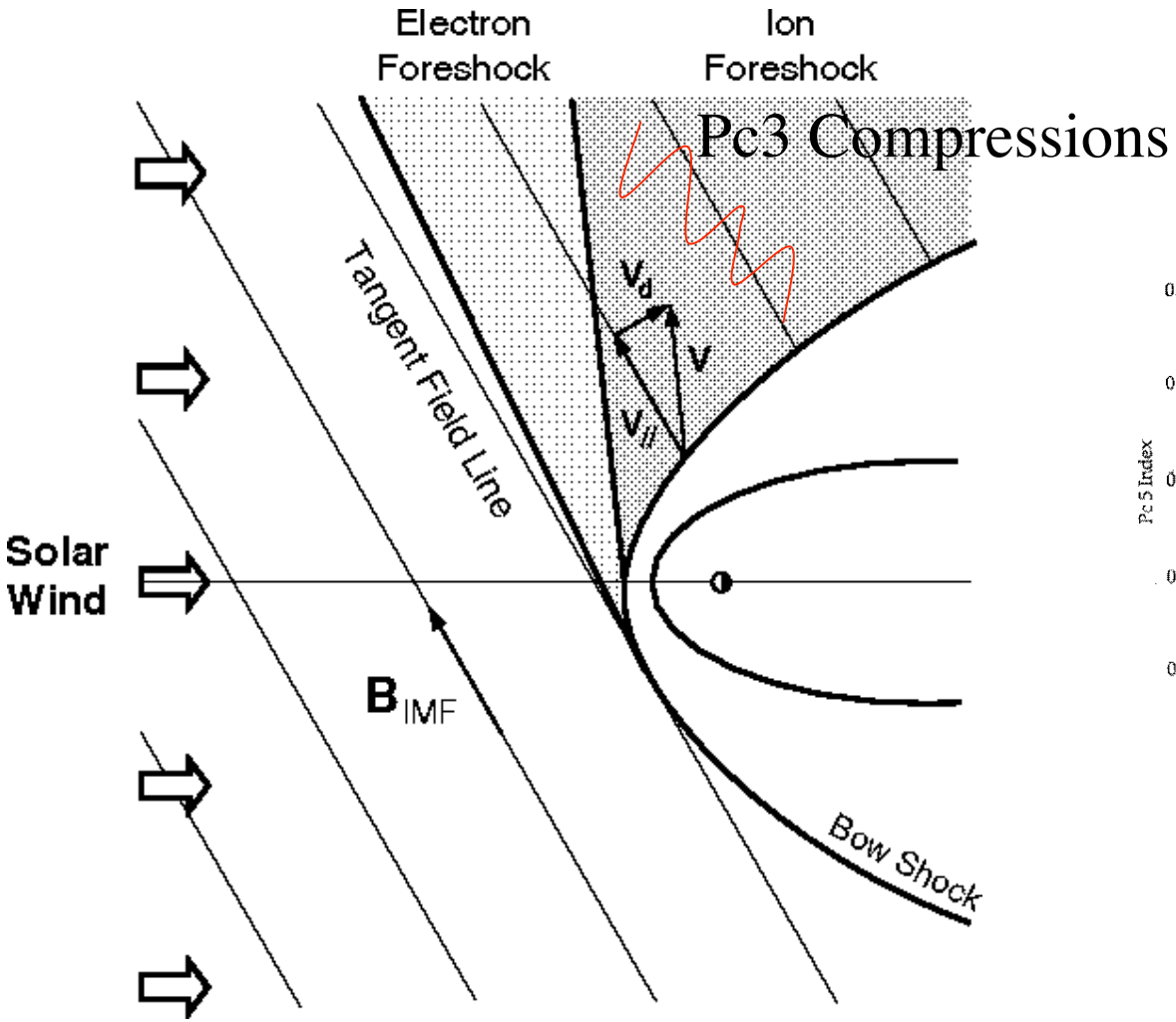
Hasegawa et al., 2004





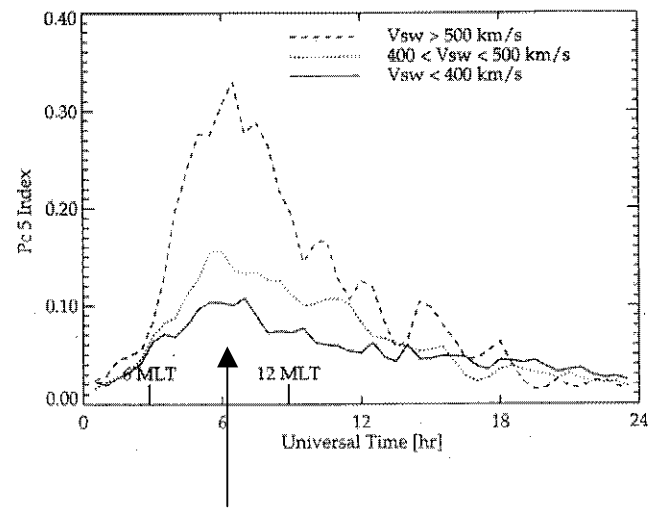
Wing, Johnson, Newell, and Ming 2005

Asymmetry and KAW



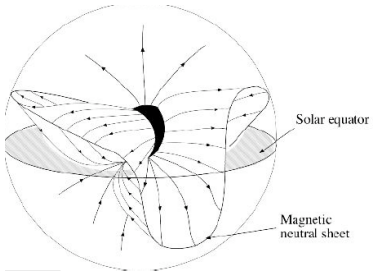
Engebretson, 1998

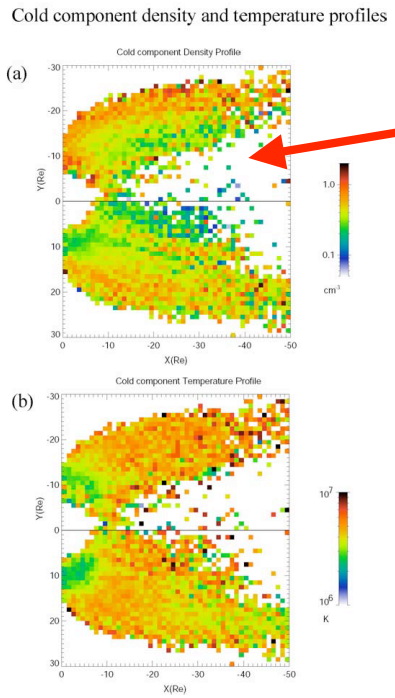
ULF index



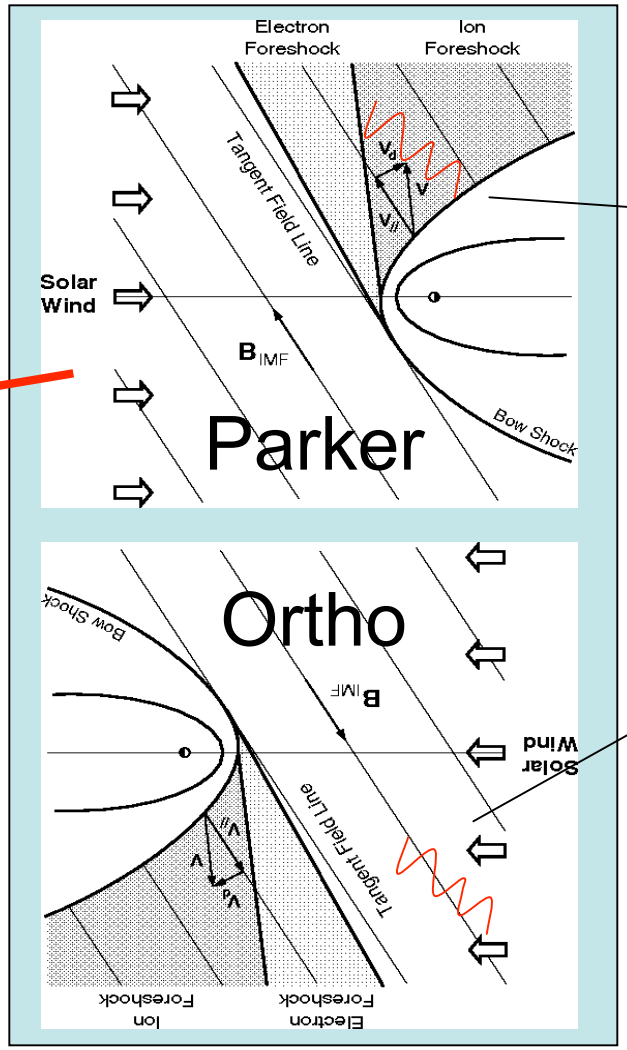
Ground Wave Power Peaks for 3hr<LT<9hr

Dawn-Dusk Asymmetry

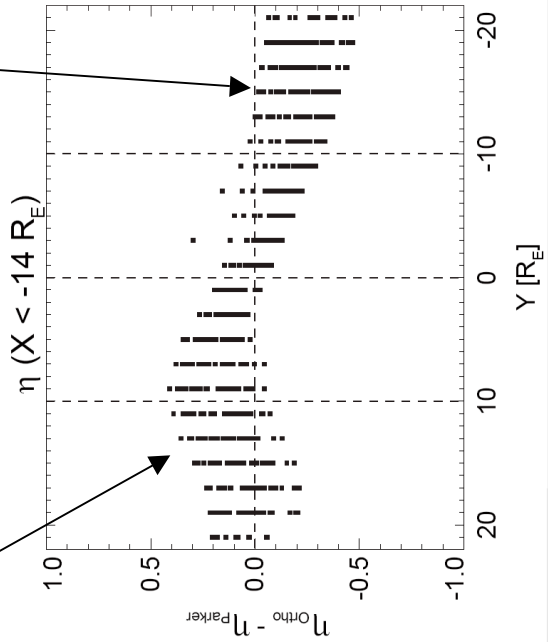




Wing, Johnson et al., 2005
DMSP



$n_{ps} \sim (n_{sw}/n_0)^{\eta}$

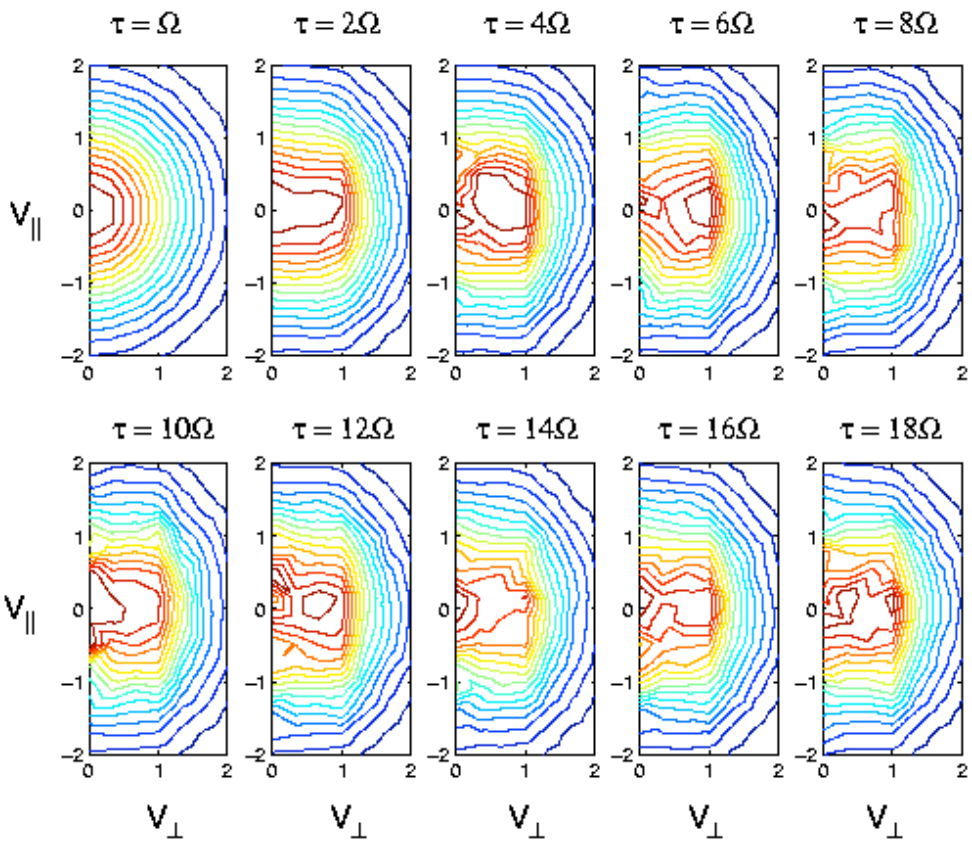


Nagata et al., 2007
Geotail

Heating and Entropy

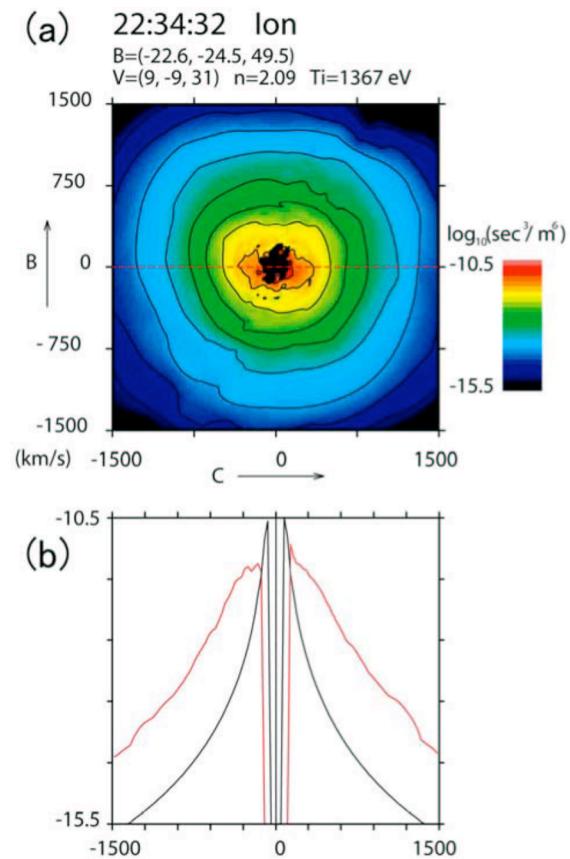
Heated Ions are Consistent with Nonlinear Wave-Particle Interactions

Theory



Johnson et al., 2001

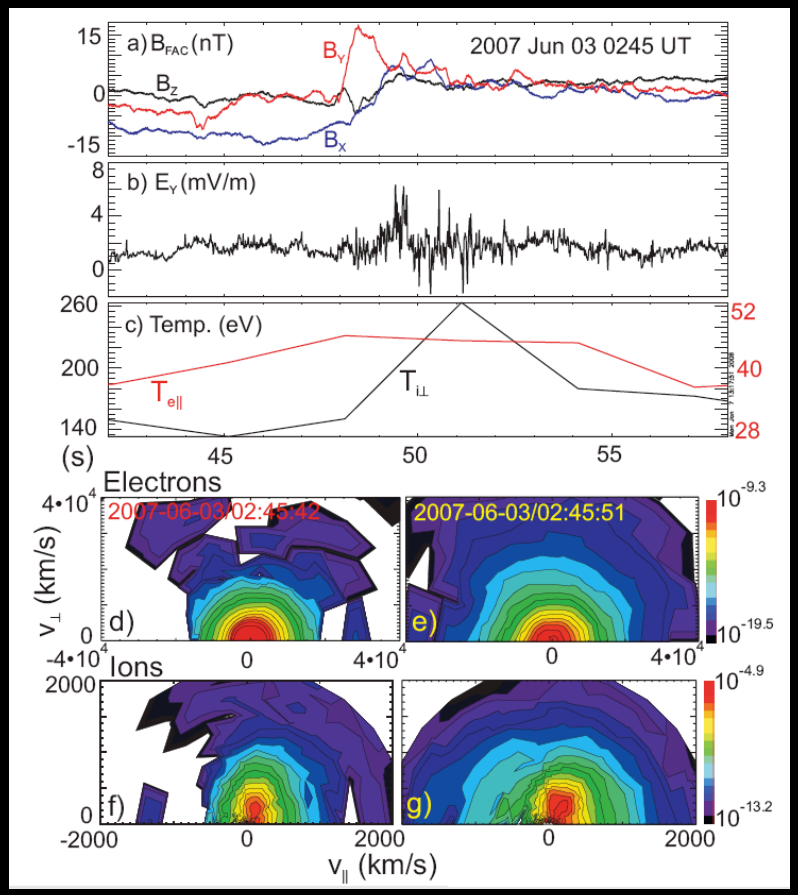
Observation



Hasegawa et al., 2003

Ion and Electron Heating (THEMIS)

Parallel Electron Heating



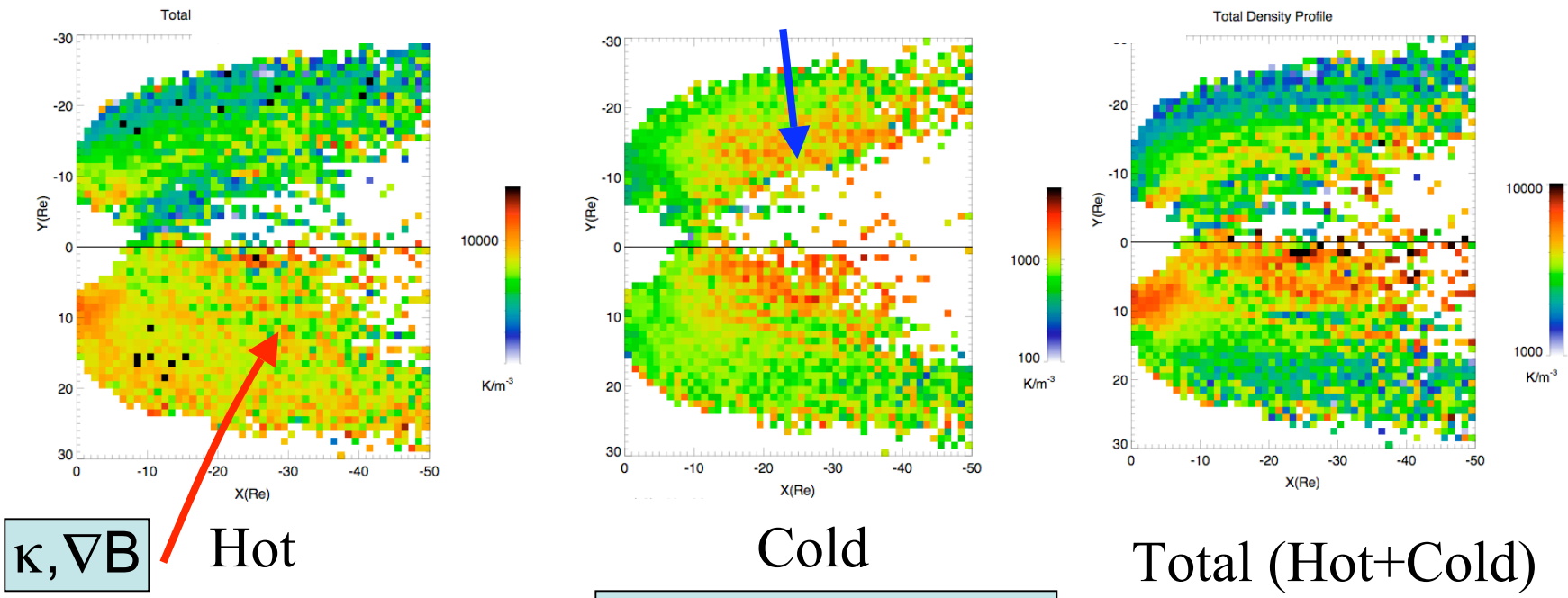
$k_x E_y/(\Omega B)>1$

Transverse Ion Heating

Chaston et al., 2007

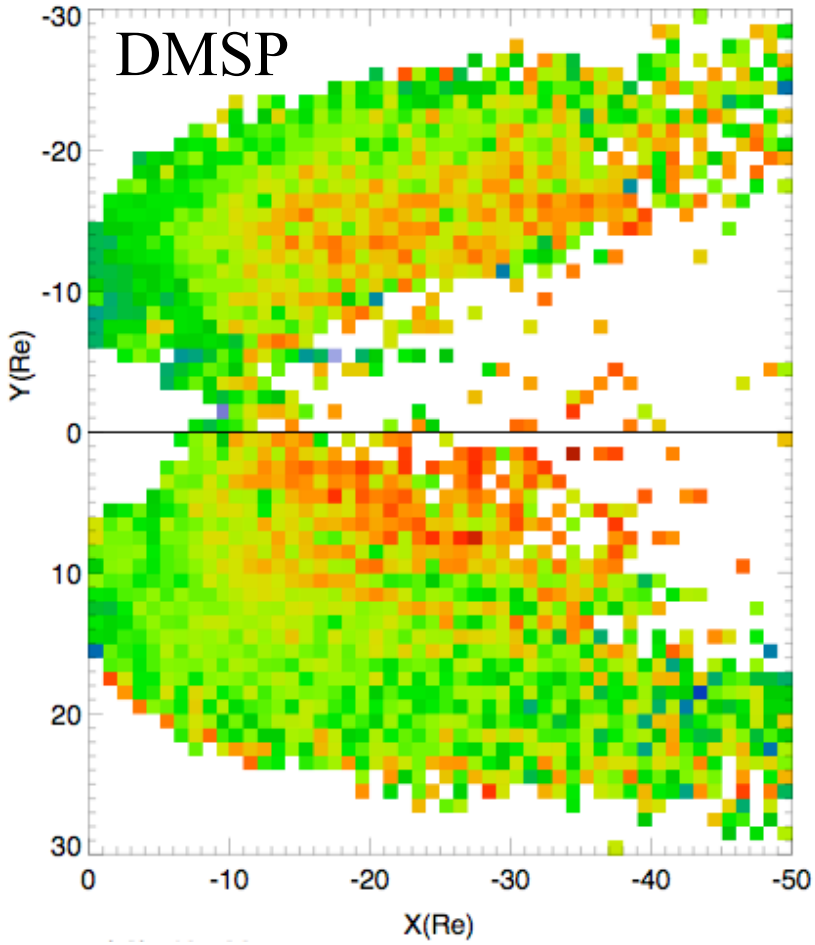
Specific Entropy (p/n^{γ})

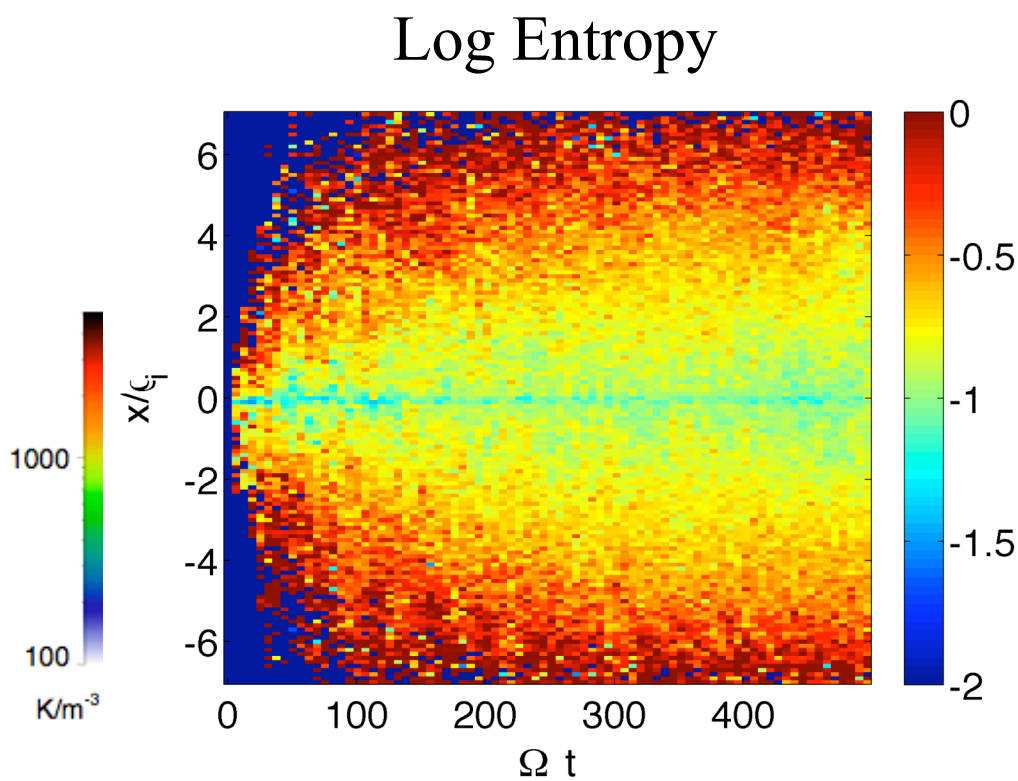
Dawnside Increase of
Cold Plasma Entropy



Johnson and Wing, 2007

Specific Entropy (P/n^{γ})↑5





Simulation of KAW

Challenges to Global Modeling

- Reconnection
  - Control location and rate?
  - Kinetic-scale waves
- Kelvin-Helmholtz
  - Resolution ($\gamma \sim k_y$)
  - Kinetic Effects (Diffusion vs Clumps)
- Kinetic Alfven Waves
  - Kinetic-MHD model
  - Global hybrid model