Fall 2007 AGU Meeting
Dec 10, 2007

SM11A-0321

Signatures of Resonant Mode Conversion at the Magnetopause

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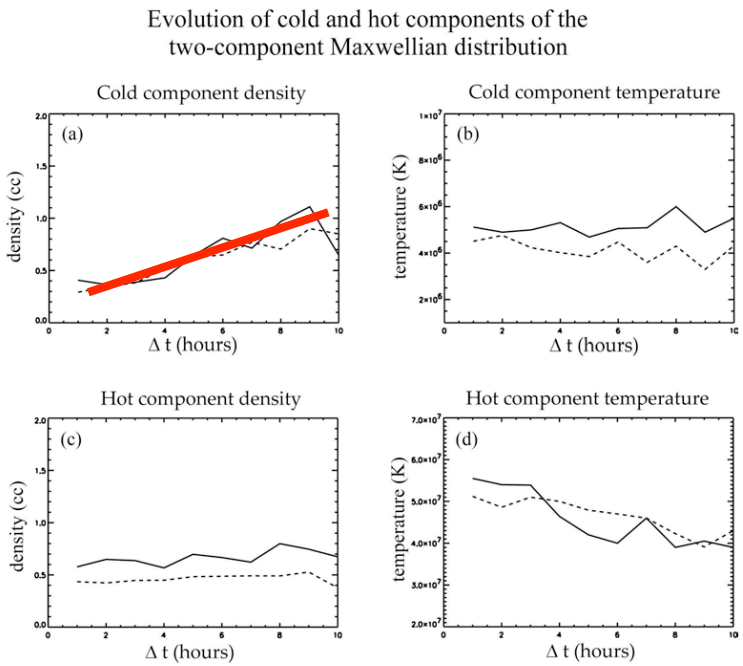
Motivation

- 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

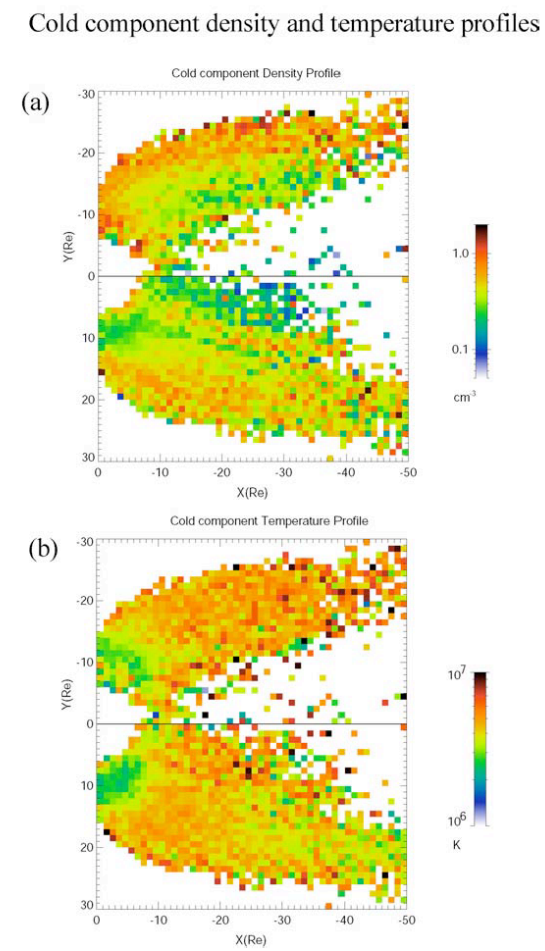
Boundary Layer for Northward IMF

Densification

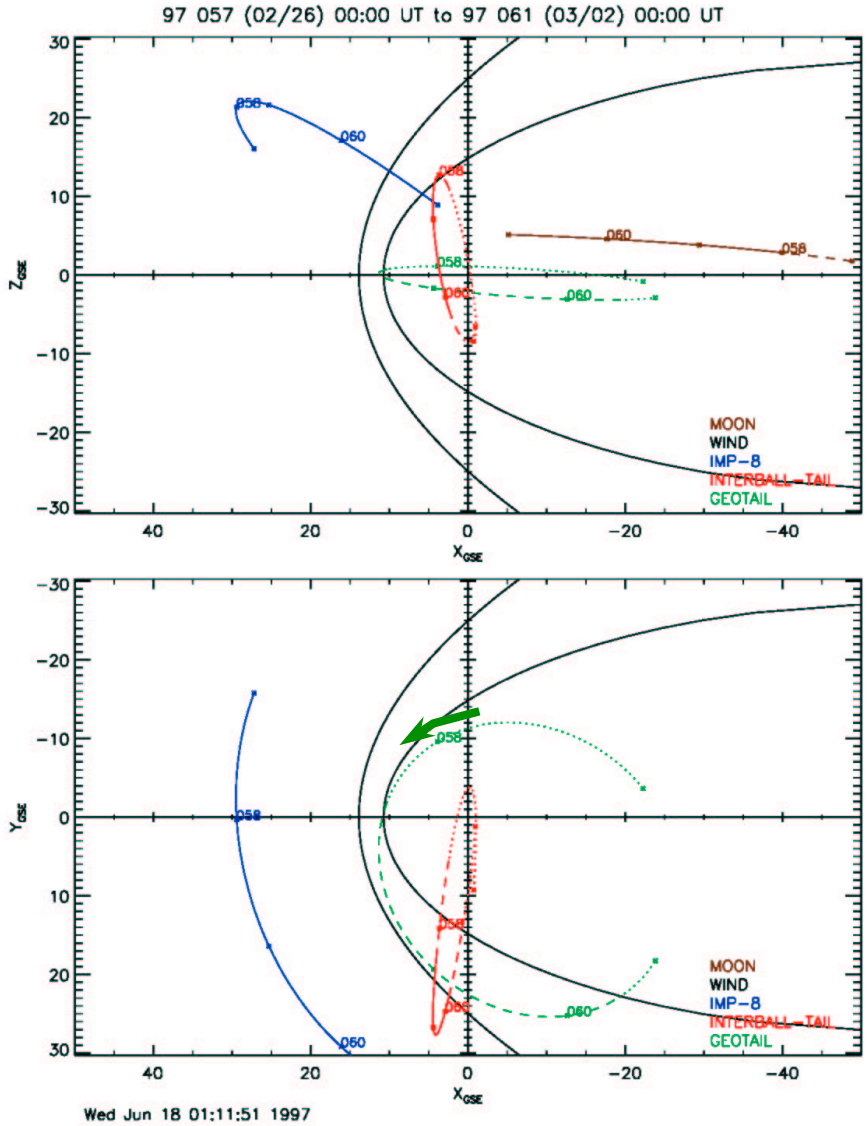


[Wing, 2005]

Asymmetry



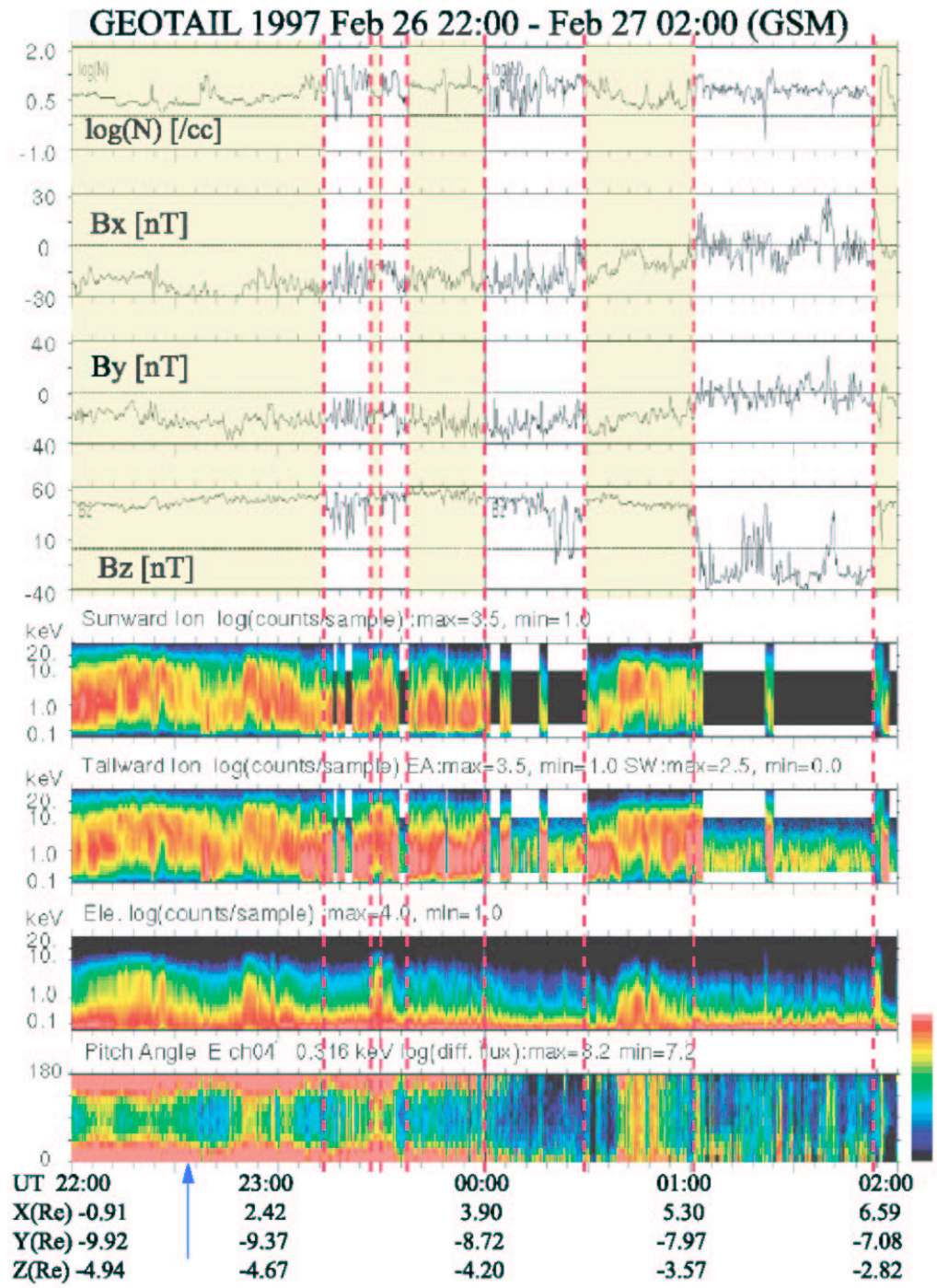
Geotail---Feb 26, 1997



GEOTAIL Magnetopause Crossing

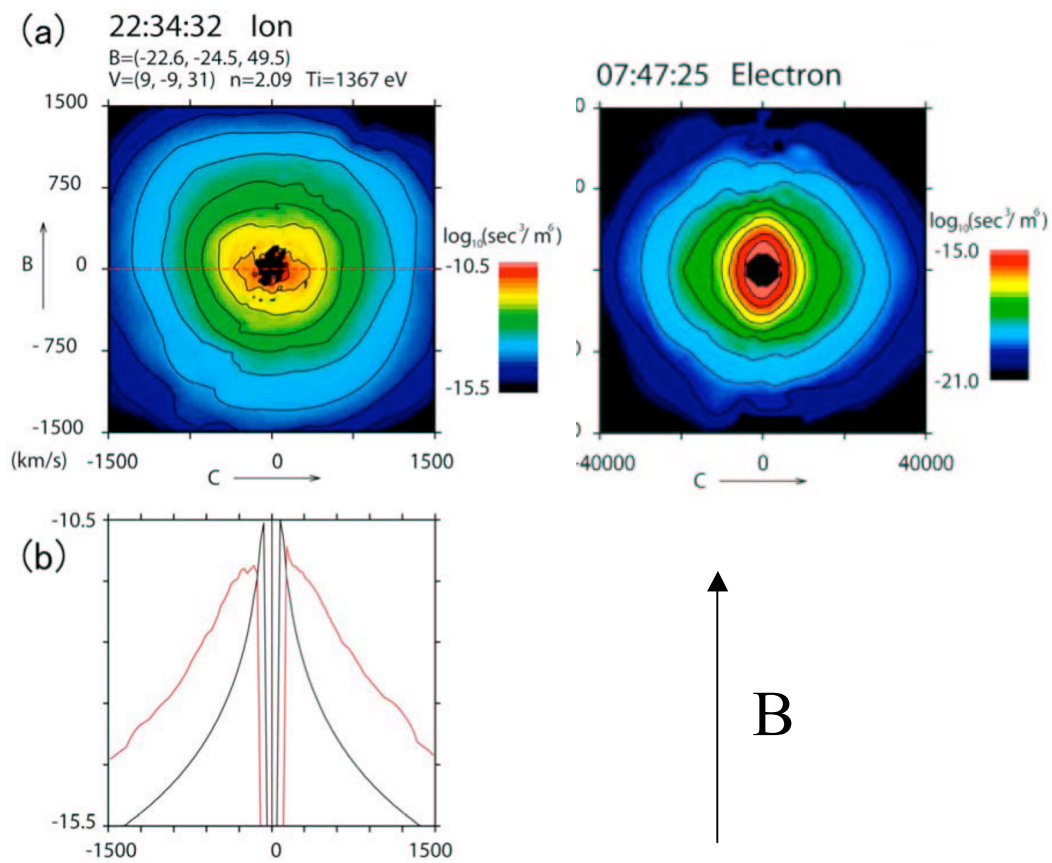
- Dawnside LLBL to dayside magnetosheath
- Northward IMF for 2 hours prior to interval
- Dense ions in LLBL
  - ♦ slow flow
  - ♦ indistinct from sheath ions
- Counterstreaming electrons
  - ♦ closed field lines
- Large Compressional Fluctionations in Sheath

[Hasegawa et al., 2003]



Particle Distributions

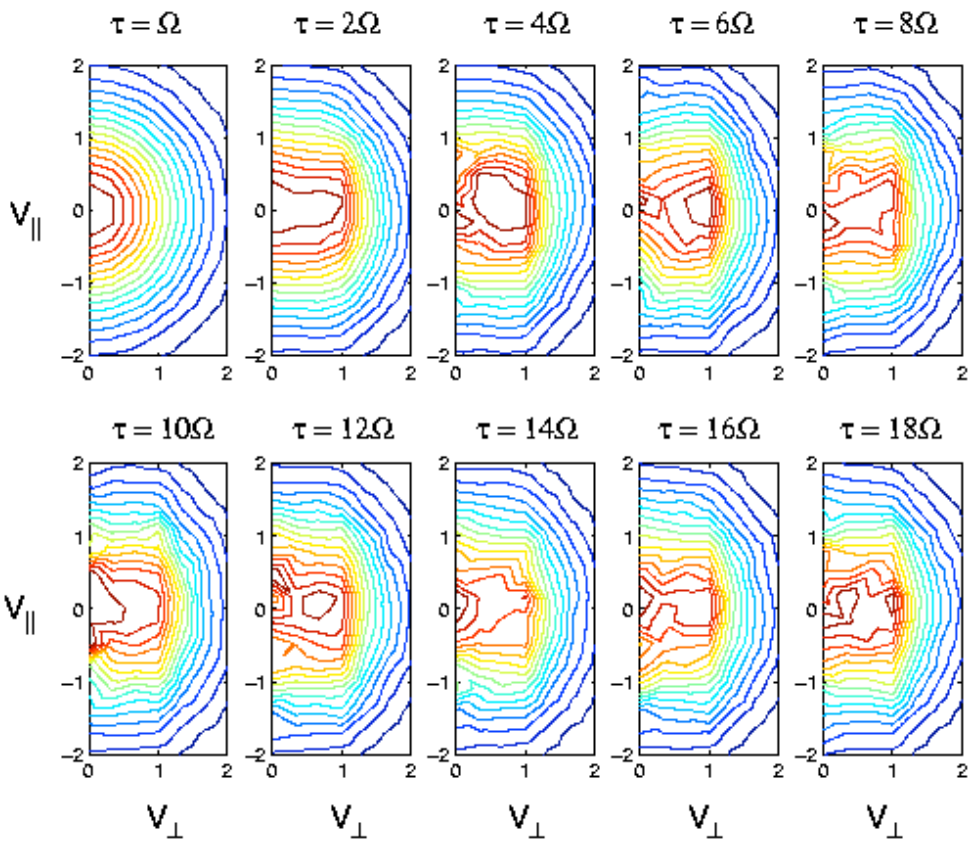
- Ions
  - Low energy: anisotropi
  - High energy: isotropic
  - No distinct populations
  - Not D-shaped
- Electrons
  - Field-aligned
  - Counterstreaming



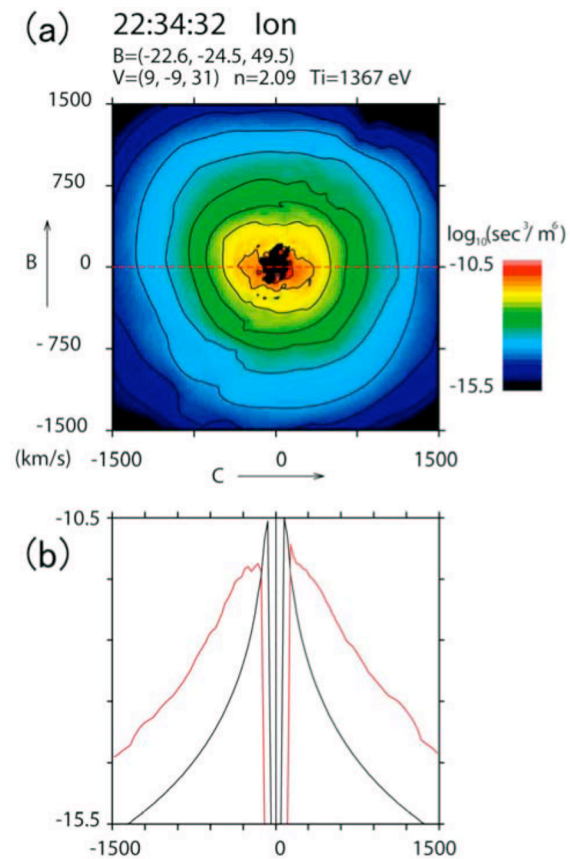
[Hasegawa et al., 2003]

Core Heating of Ion Distribution

Distribution: Kinetic Alfven Wave

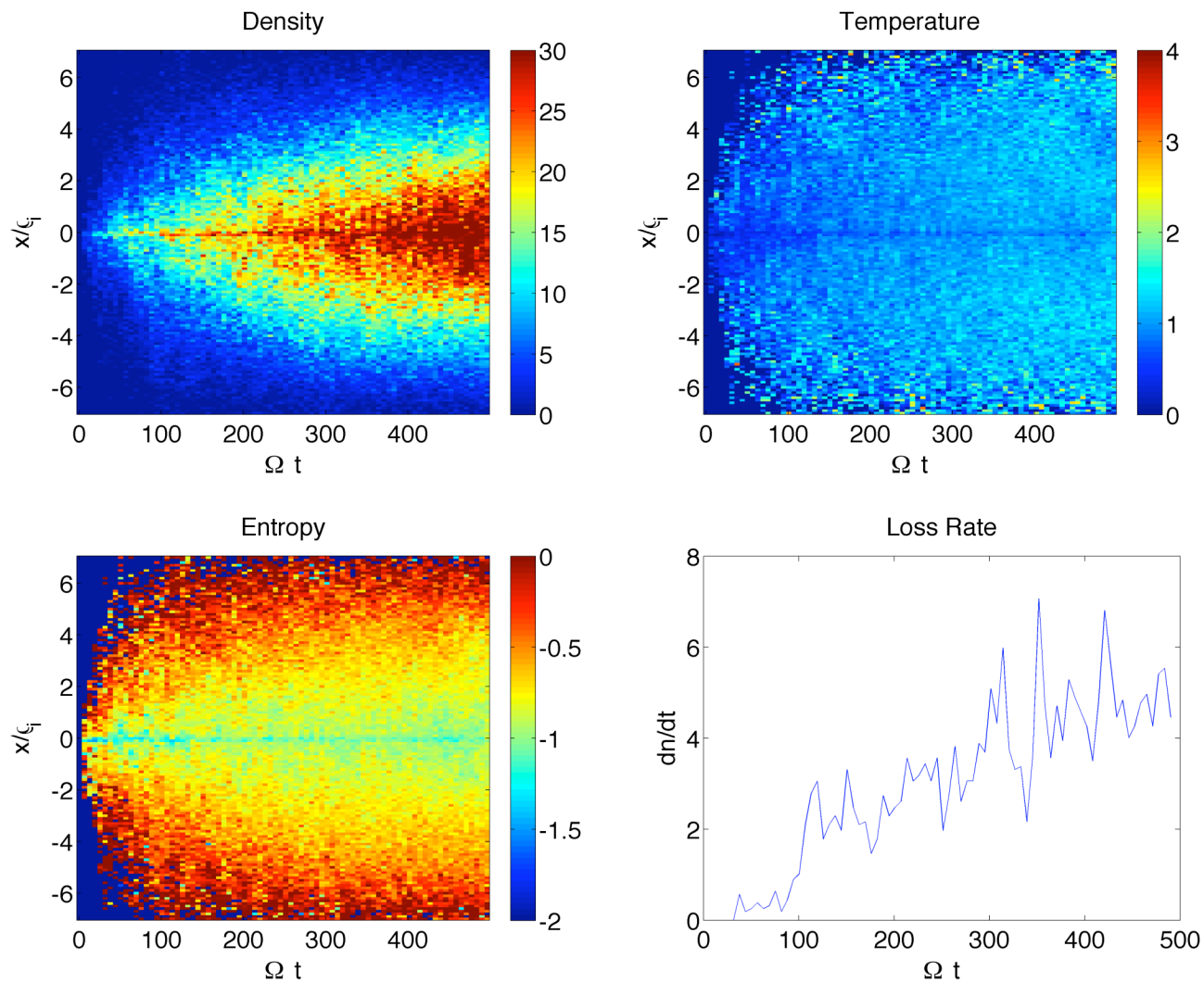


Observed Distribution:

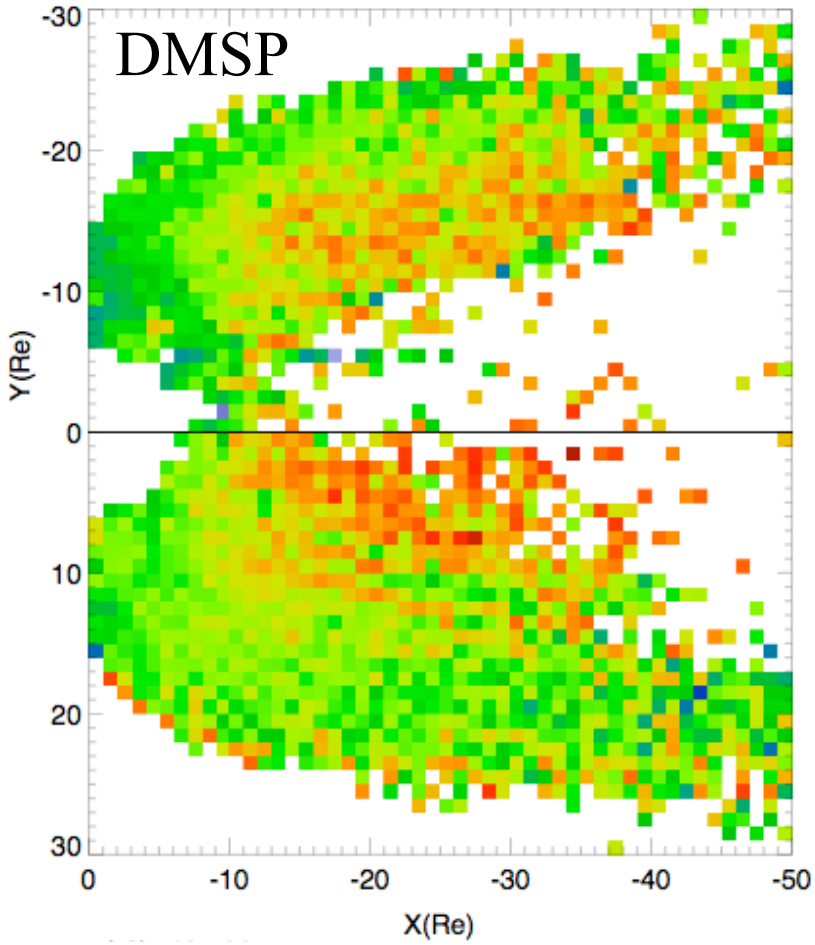


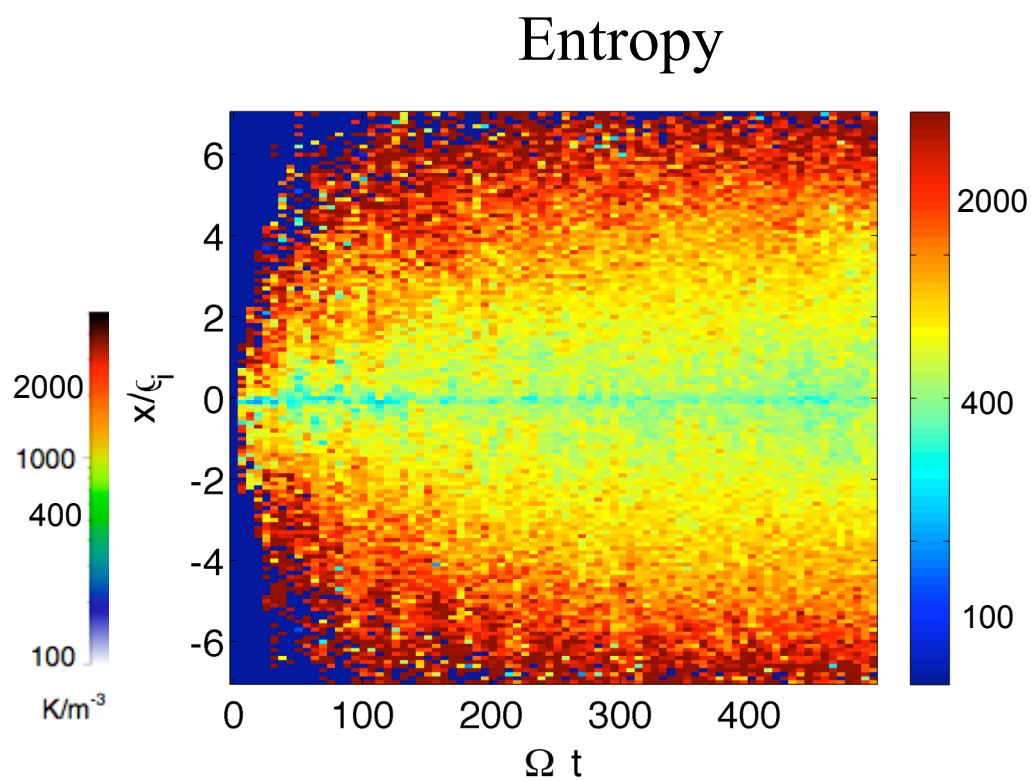
[Hasegawa et al., 2003]

Diffusion due to KAW



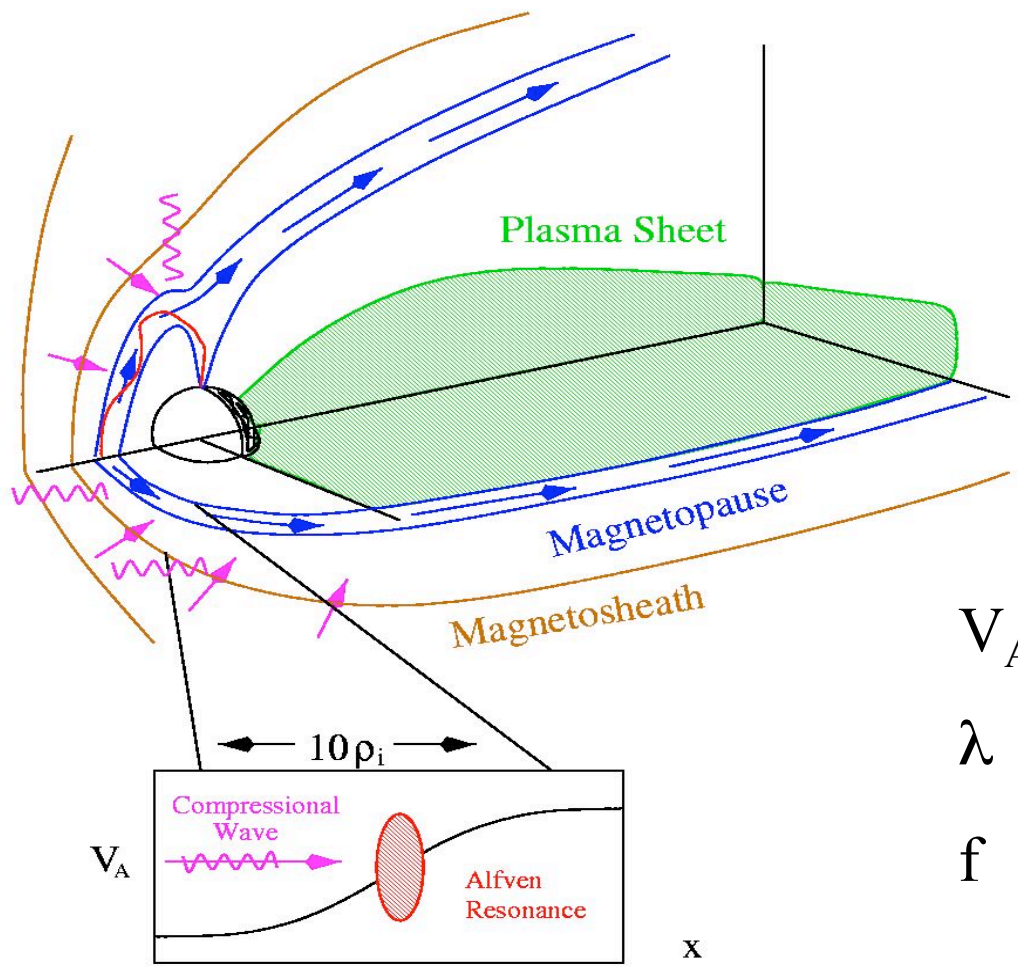
Specific Entropy (P/n^{γ})↑5





Simulation of KAW

Kinetic Alfvén Waves at the Magnetopause

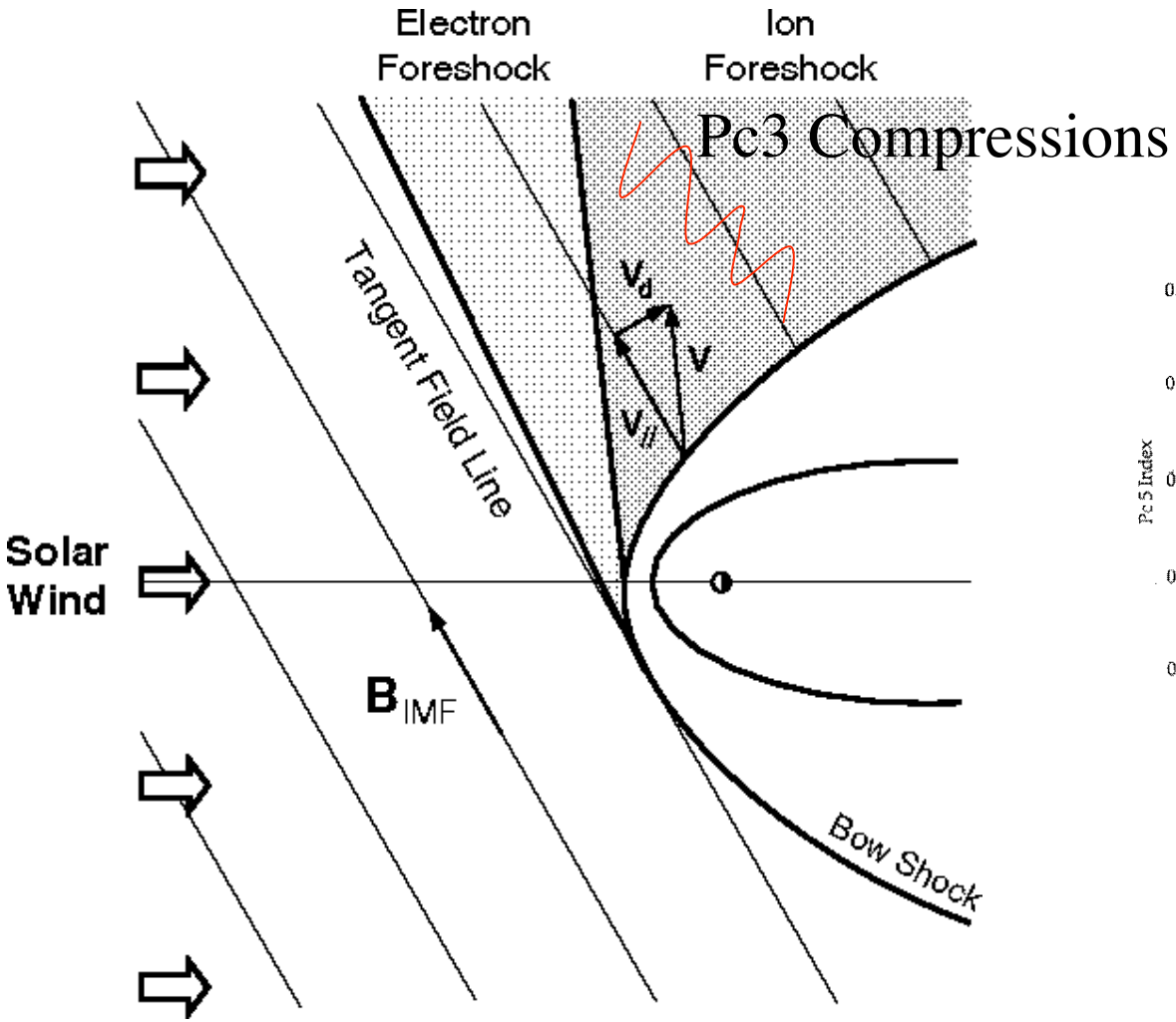


$V_A \sim 200 km/s$

$\lambda \sim R_E$

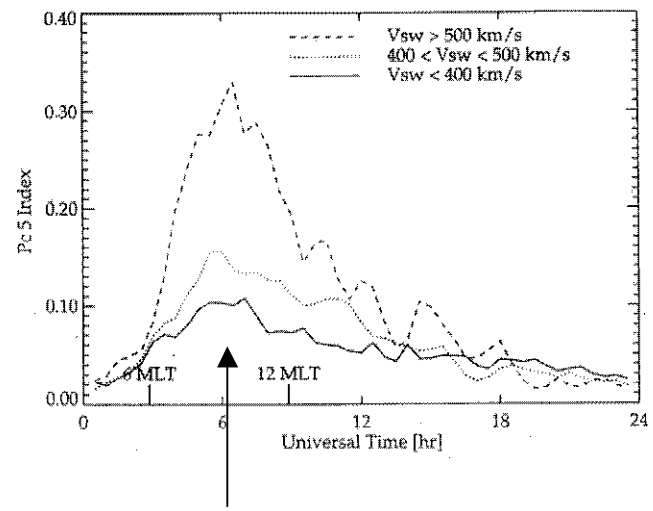
$f \sim 30$ mHz

Asymmetry and KAW



Engebretson, 1998

ULF index

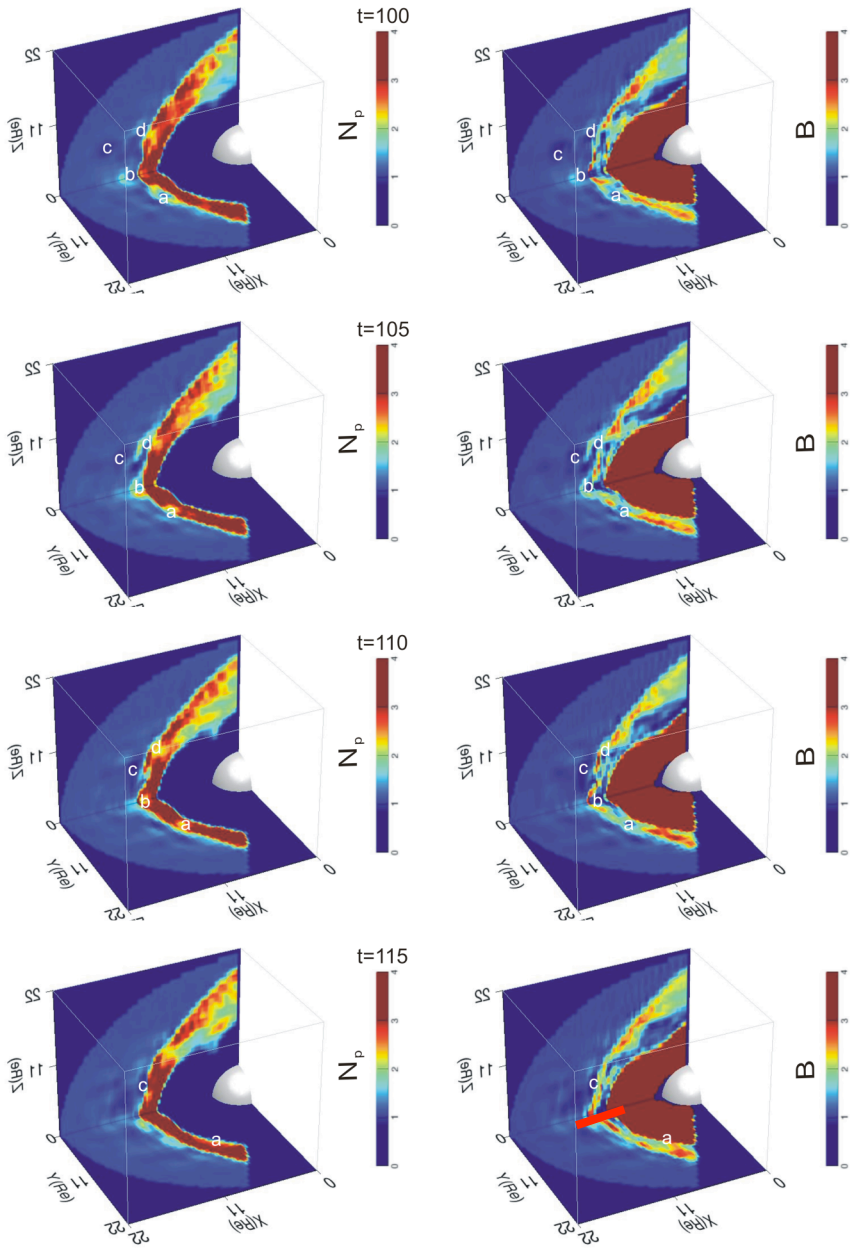


Ground Wave Power Peaks for 3hr<LT<9hr

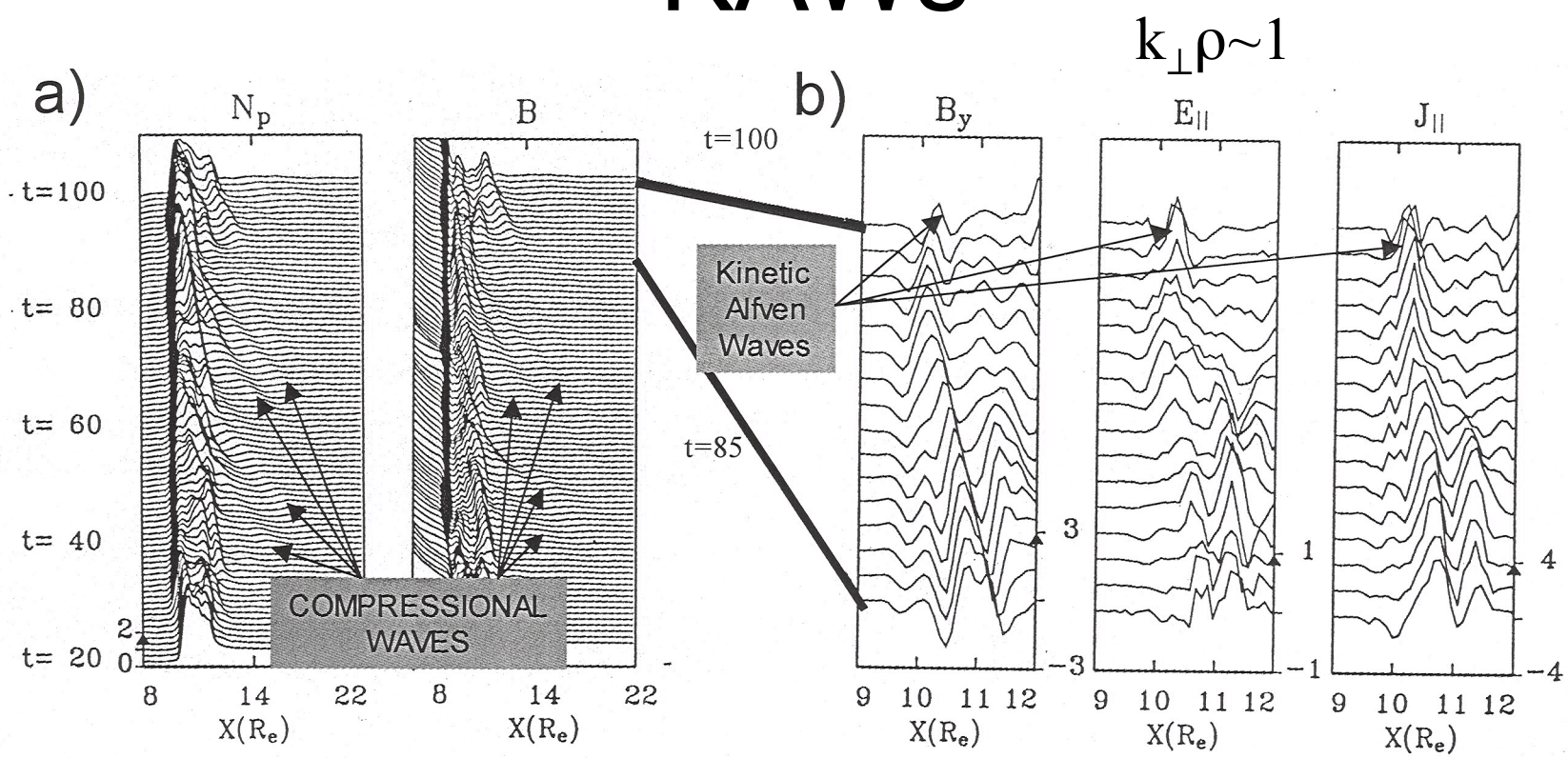
Hybrid Simulations of KAWs

- 3D Hybrid Simulations
- Foreshock Cavities Compress the Magnetopause

[Lin and Wang, 2005]



Mode Conversion of Compressional Waves to KAWs

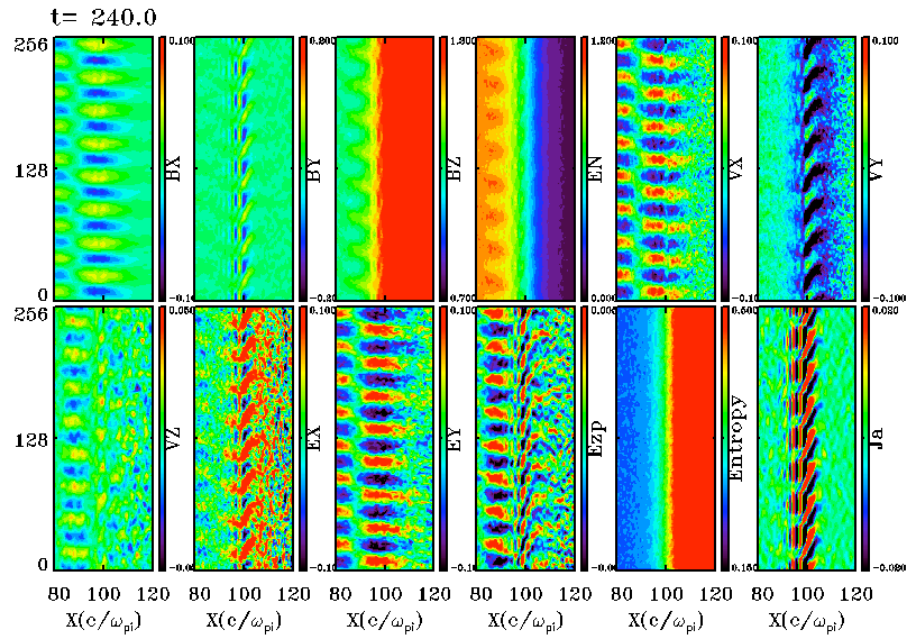


See SM51A-1276

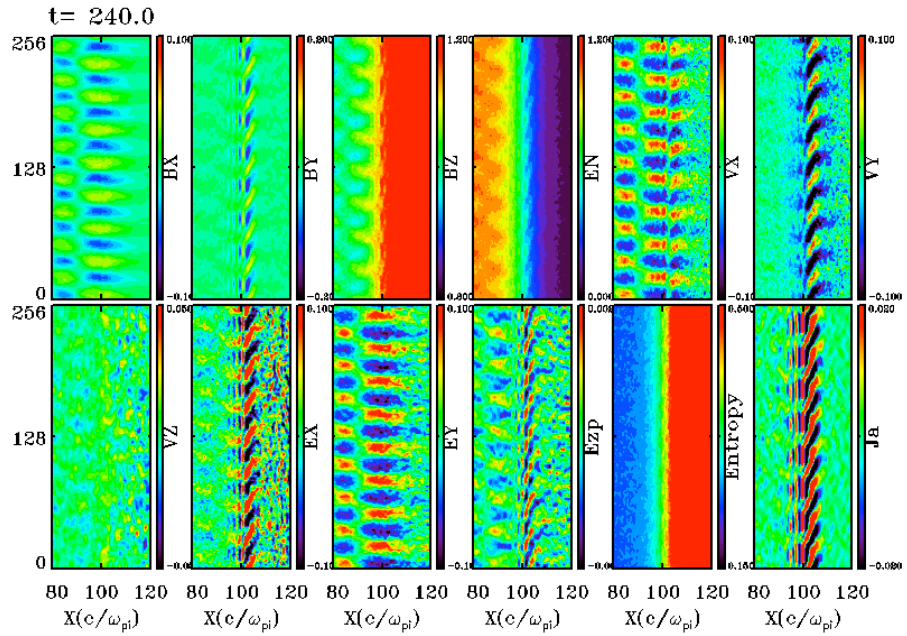
[Lin and Wang, 2005]

Analysis of Hybrid Simulations

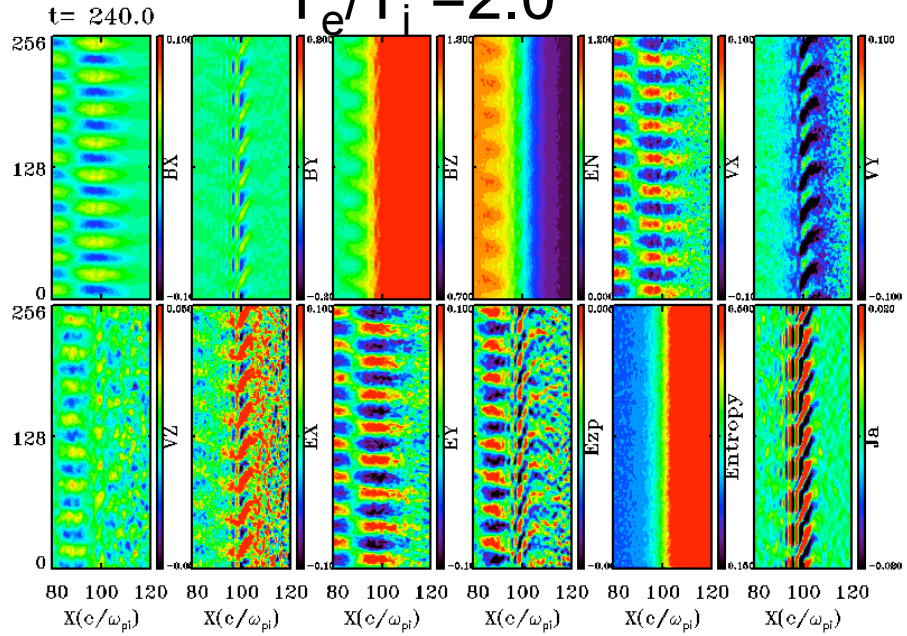
- To compare with theory
  - Absorption (Poynting Flux)
  - $E_{||}$ (non-MHD)



$T_e/T_i = 0.4$



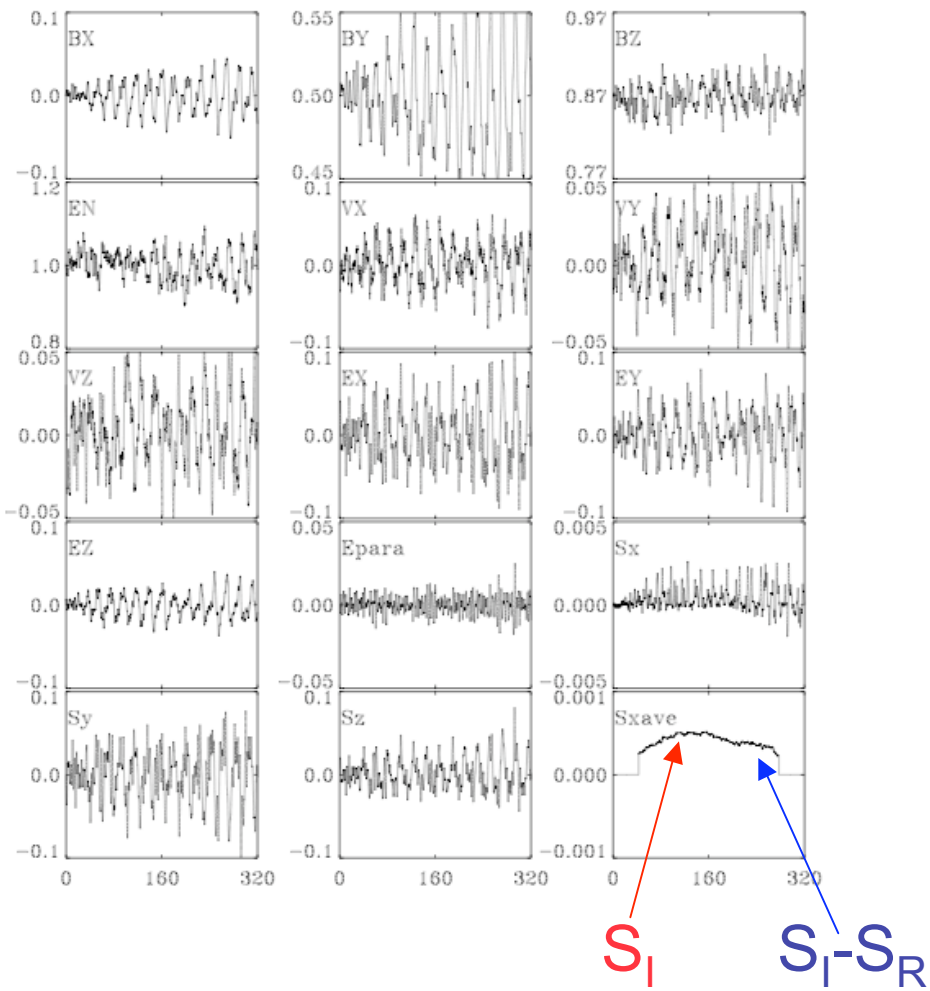
$T_e/T_i = 2.0$



Parallel Electric Field

- $E_{||}=(T_e/T_i)\rho_i^2\nabla_{||}\nabla\cdot(E_\perp)/(1 + k_\perp^2\rho_i^2)$
  $\sim E_x(k_x\rho_i)(k_{||}\rho_i)(T_e/T_i)/(1 + k_x^2\rho_i^2)$

Poynting Flux



- Compute S_x
- Compare incident and reflected PF

Puzzle

- Significant Poynting flux at θ=0 was absorbed ($\tan(\theta) = k_y/k_{||}$)
- MHD equations do not give any coupling between compressional and Alfven waves when k_y=0.

Theoretical Analysis

- Consider scattering and absorption of incident compressional wave
- Approximations:
  - Examine scattering problem for a wave of fixed frequency
  - Linearized equations
  - Cold Plasma Equations
    - Resonance shift due to diamagnetic effects
    - Kinetic effects resolve resonance
  - $\omega << \Omega_e, \omega_{pe}$

Wave Equation

Equations for collisional fluid plasma with 1-D solution for propagation along B. Energetic Ions treated with an integral equation.

$$\nabla^2\mathbf{E} - \nabla(\nabla\cdot\mathbf{E}) + \frac{\omega^2}{c^2}\boldsymbol{\varepsilon}'(s)\cdot E = 0$$

$$\boldsymbol{\varepsilon}'(s) = S(\mathbf{I} - \mathbf{bb}) - iD(\mathbf{e}_1\mathbf{b}\times\mathbf{e}_2 - \mathbf{b}\times\mathbf{e}_1\mathbf{e}_1) + P\mathbf{bb}$$

$$S = 1 - \sum_j \frac{\omega_{pj}^2(\omega + i\nu_j)}{\omega[(\omega + i\nu_j)^2 - \Omega_j^2]}$$

$$D = 1 - \sum_j \frac{\omega_{pj}^2\Omega_j}{\omega[(\omega + i\nu_j)^2 - \Omega_j^2]}$$

$$P = 1 - \sum_j \frac{\omega_{pj}^2}{\omega(\omega + i\nu_j)}$$

Reduced Equations

$$\frac{c}{\omega R_E}\frac{dY}{dz} = MY \qquad Y = \begin{pmatrix} E_y \\ \frac{dE_y}{dz} - in_y E_x \end{pmatrix}$$

$$M = \begin{bmatrix} \frac{n_y D}{n_\parallel^2 - S} & 1 + \frac{n_y^2}{{n_\parallel}^2 - S} \\ \frac{({n_\parallel}^2 - R)({n_\parallel}^2 - L)}{{n_\parallel}^2 - S} & \frac{-n_y D}{n_\parallel^2 - S} \end{bmatrix}$$

Low Freq, k_y=0 case: $R=L=S=c^2/V_A^2$; $D/S \sim \omega/\Omega_i$

$$\frac{c}{\omega R_E}\frac{dY}{dz} = MY \qquad Y = \begin{pmatrix} E_y \\ \frac{dE_y}{dz} - i n_y E_x \end{pmatrix}$$

$$M = \begin{bmatrix} \cancel{\frac{n_y D}{n_\parallel^2 - S}} & 1 + \cancel{\frac{n_y^2}{n_\parallel^2 - S}} \\ \frac{(n_\parallel^2 - R)\cancel{(n_\parallel^2 - L)}}{\cancel{n_\parallel^2 - S}} & \cancel{\frac{-n_y D}{n_\parallel^2 - S}} \end{bmatrix}$$

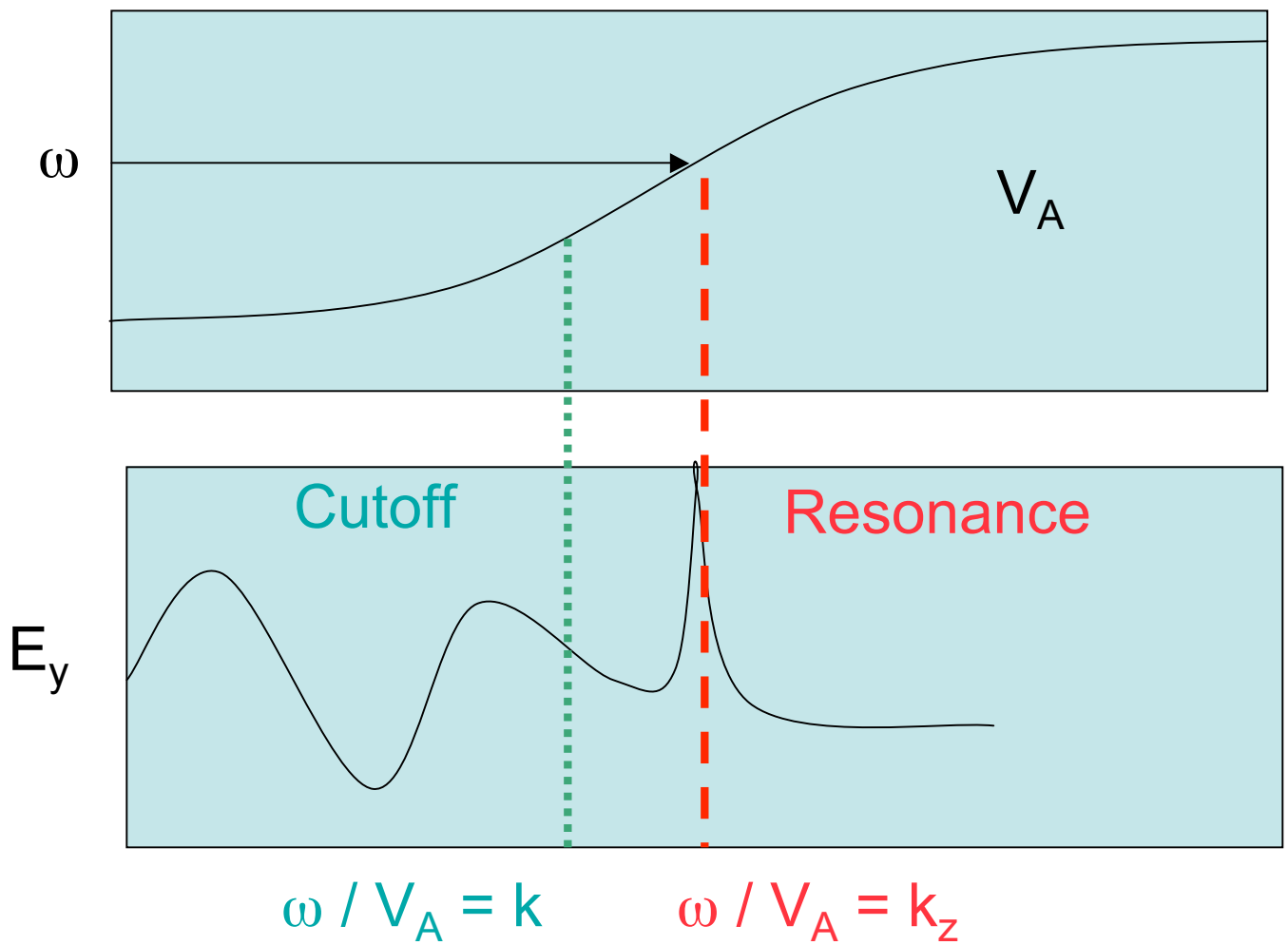
Low Frequency Limit

$$\epsilon \frac{d}{dz}\left(\frac{1}{\epsilon}\frac{dY_1}{dz}\right) = (k^2 V_A^2 - \omega^2) Y_1$$

$$\epsilon = 1 - \omega^2/(k_{\parallel}^2 V_A^2)$$

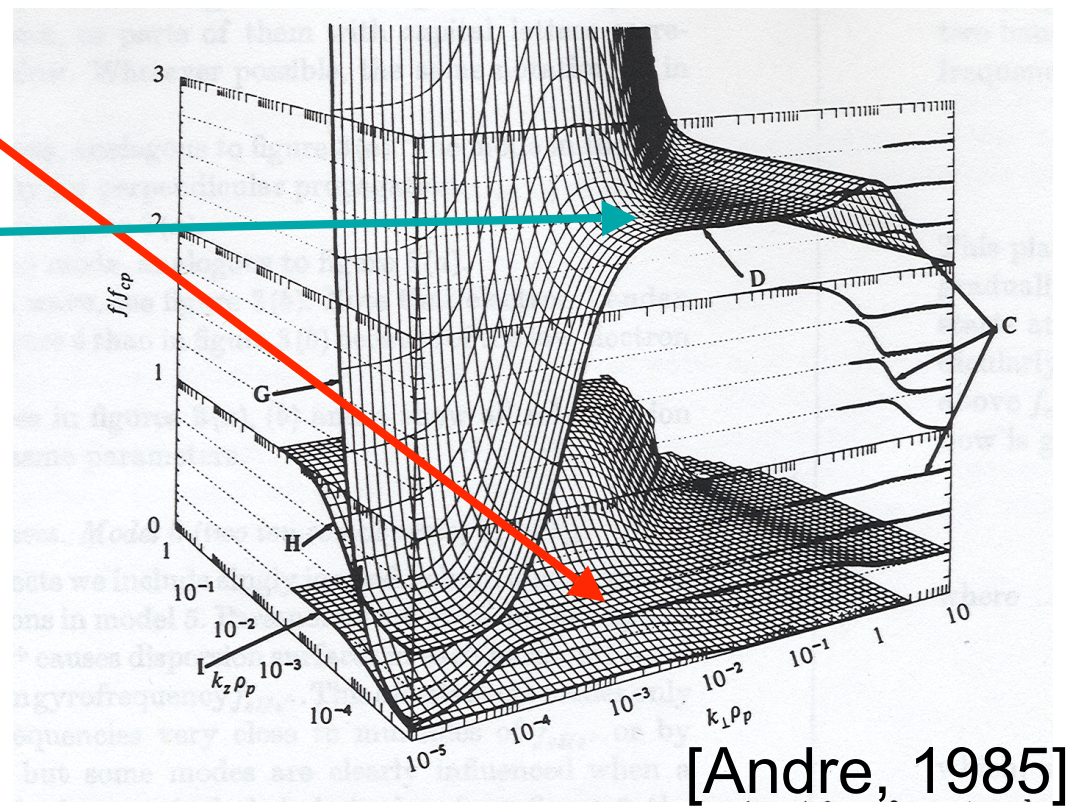
- Equation for a compressional wave
- Alfven resonance

Physical Picture



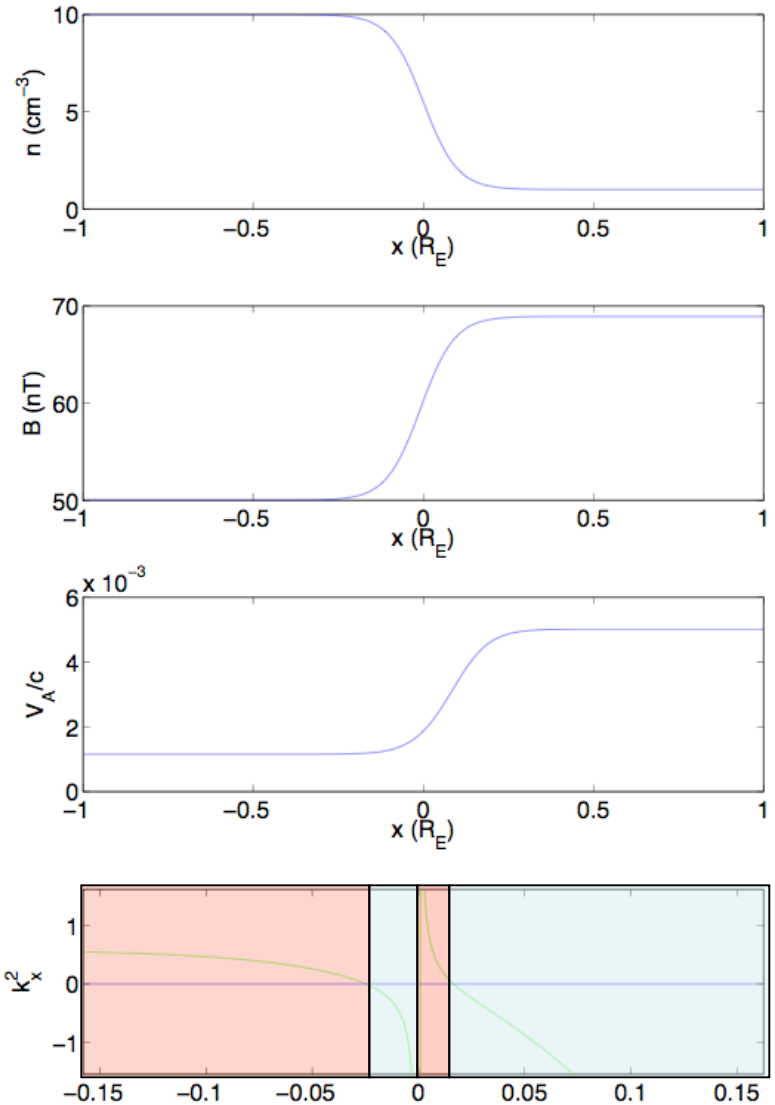
The ($n_{||}^2$=S) resonance

- At low frequency is the Alfven resonance
- Ion-ion hybrid
- Lower hybrid



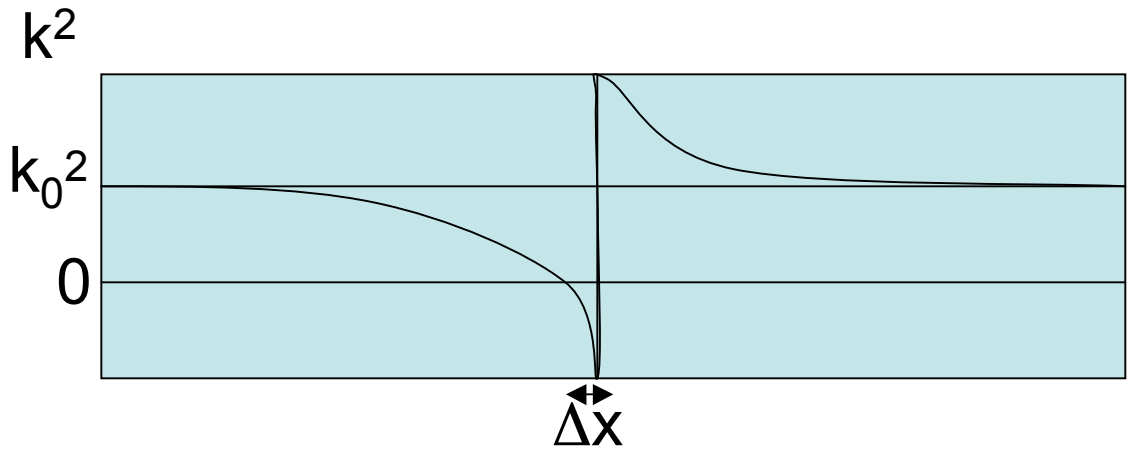
[Andre, 1985]

Model Profiles



- Consistent with Hybrid Simulation Profiles (β_{sh}=1)
- Note the cutoff-resonance-cutoff

Budden Tunneling



$T = e^{-\eta}$
$R = 1 - e^{-2\eta}$ $\Rightarrow$
$A = 1 - R^2 - T^2$

$\Leftarrow$

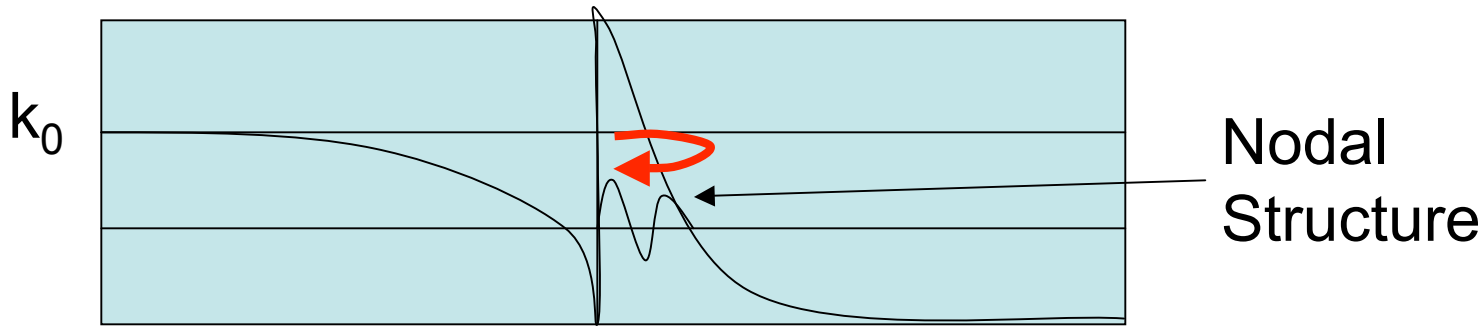
$T = e^{-\eta}$
$R = 0$
$A = 1 - T^2$

Very Efficient

$\eta = (\pi/2) k_0 \Delta x \sim \pi^2 \Delta x / \lambda$

The cutoff-resonance-cutoff

$\eta \sim 5\Delta x/\lambda$



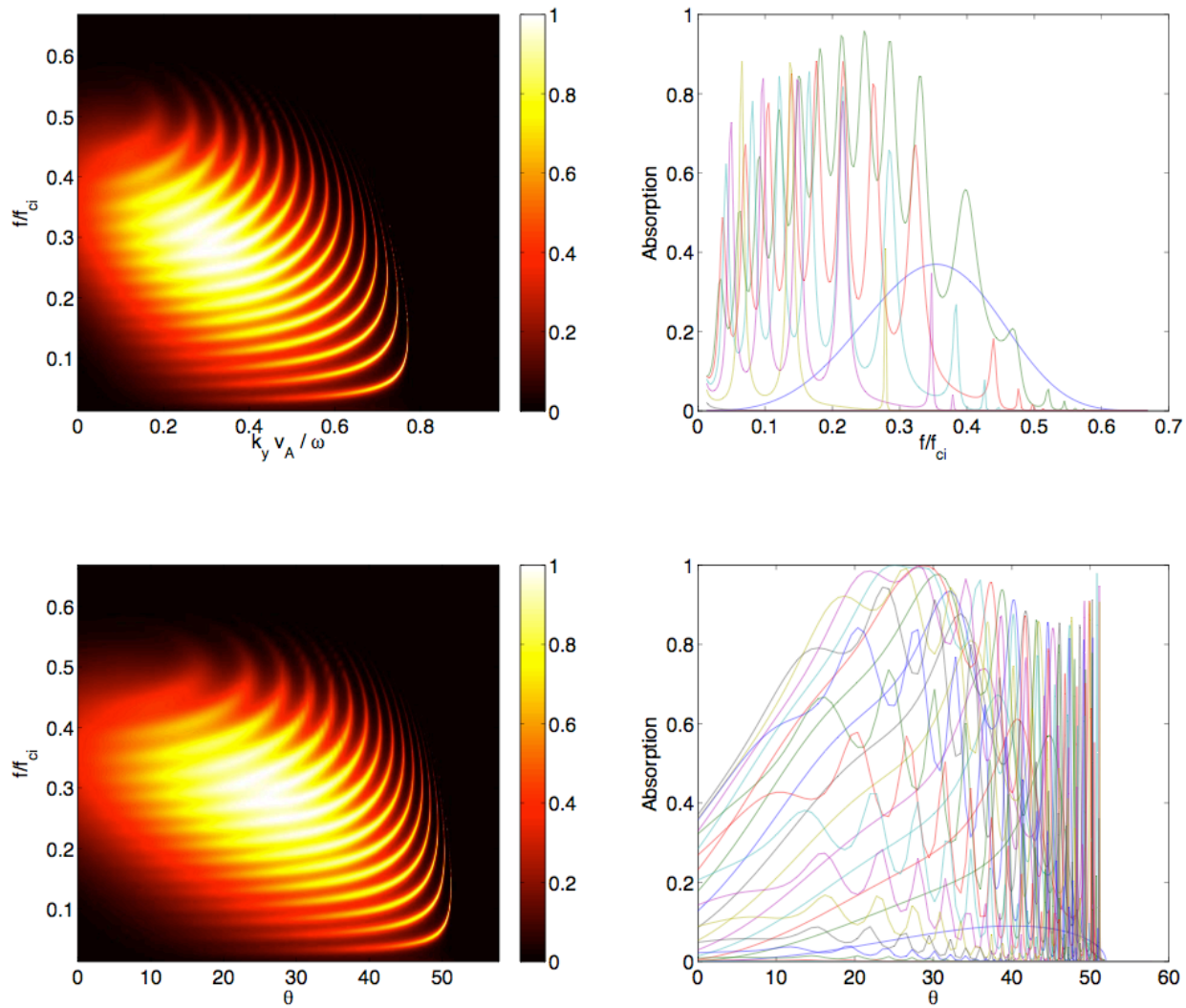
$T = e^{-\eta}$
$R = 1 - e^{-2\eta}$ $\Rightarrow$
$A = 1 - R^2 - T^2$
$A = T^2(1 - T^2)$

$\Leftarrow$

$T = e^{-\eta}$
$R = 0$
$A = 1 - T^2$

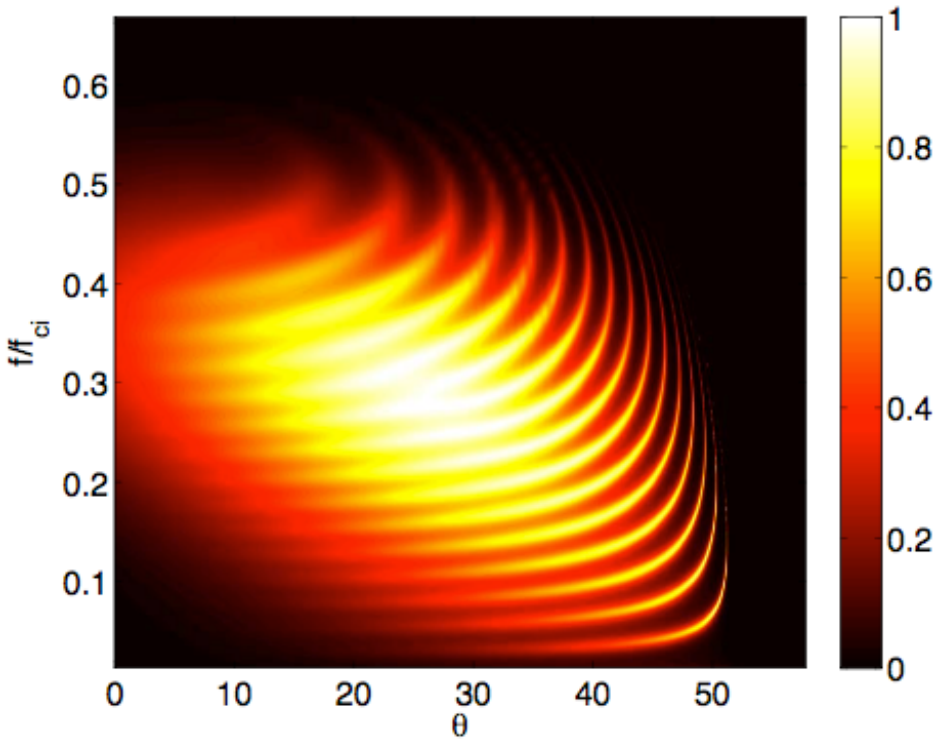
Very Efficient

Absorption



Normalized to f_{ci} in magnetosheath

Hybrid Simulations



Hybrid Results:

- $\theta = 30$
  - A=0.55 @ f/fci=0.147
    A=0.6 @ f/fci=0.3927
- $f/f_{ci}=0.3927$
  - A=0.4 @ θ=0
  - A=0.6 @ θ=30
- θ=30
  - A=0.6 @ Te/Ti=0.4
  - A=0.1 @ Te/Ti=1-2

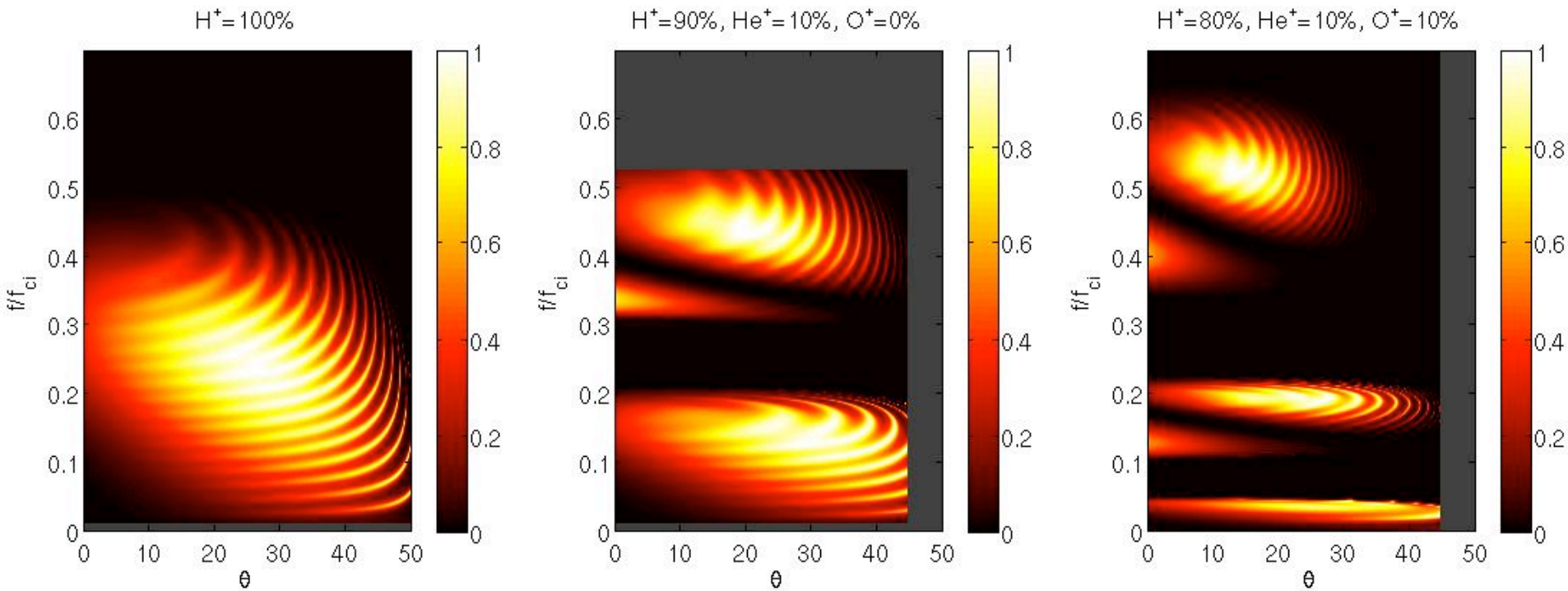
Increased Energy Deposition

- Results from non-MHD effect
- Maximizes around 0.3 f_{ci}
- Heavy ions
- f~20mHz for oxygen@dayside MP

Ongoing/Future Tasks

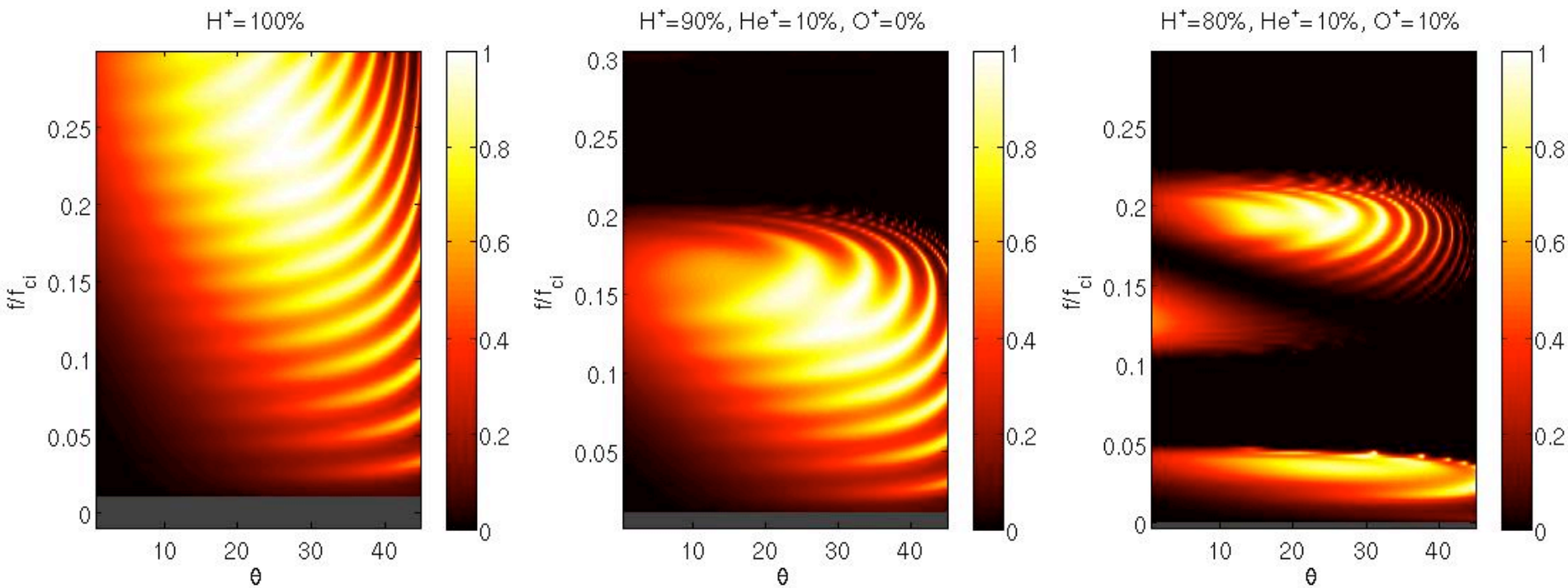
- Hybrid simulations of mode conversion
- Comparison with theory
- Alfven resonance with heavy ions
- Coupling of K-H modes with Alfven resonance
- Transport and Entropy

Effect of Heavy Ions

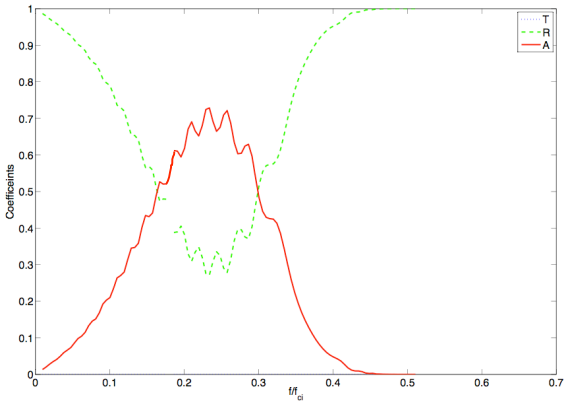


Normalized to f_{ci} at resonance

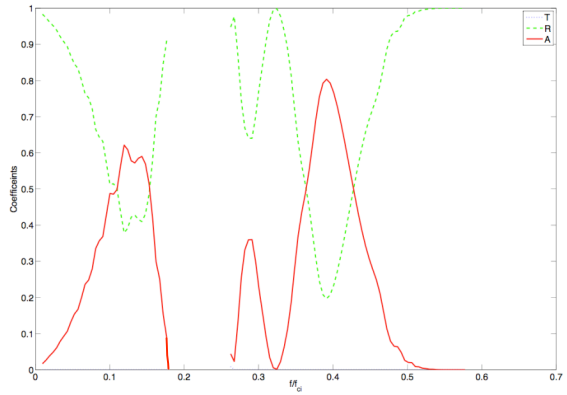
Effect of Heavy at Low Frequency



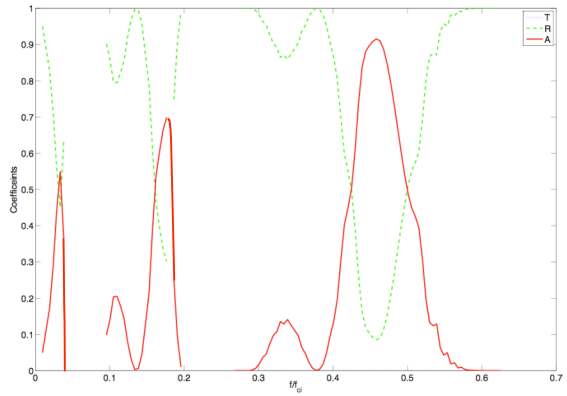
Multiple Ions



- Hydrogen Only

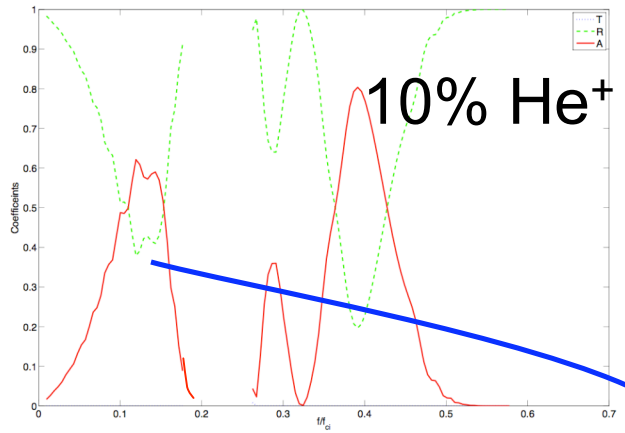


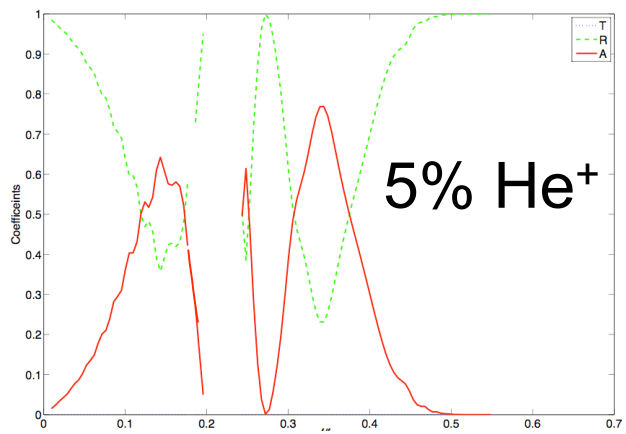
- 10% He^+

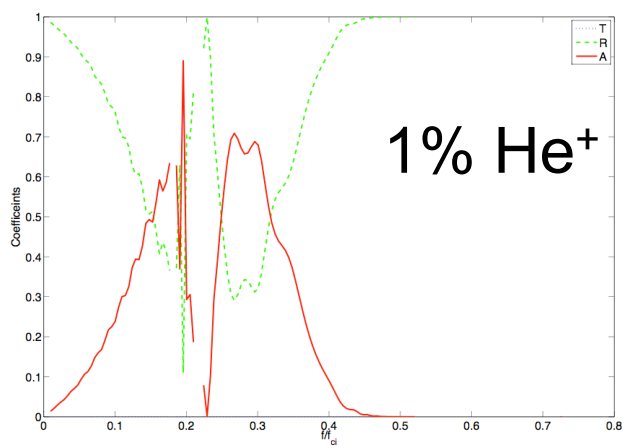


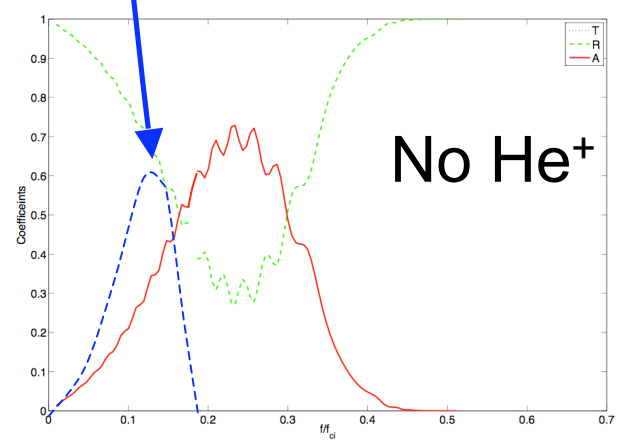
- 10% He^+, 10% O^+

Heavy Ion Concentration

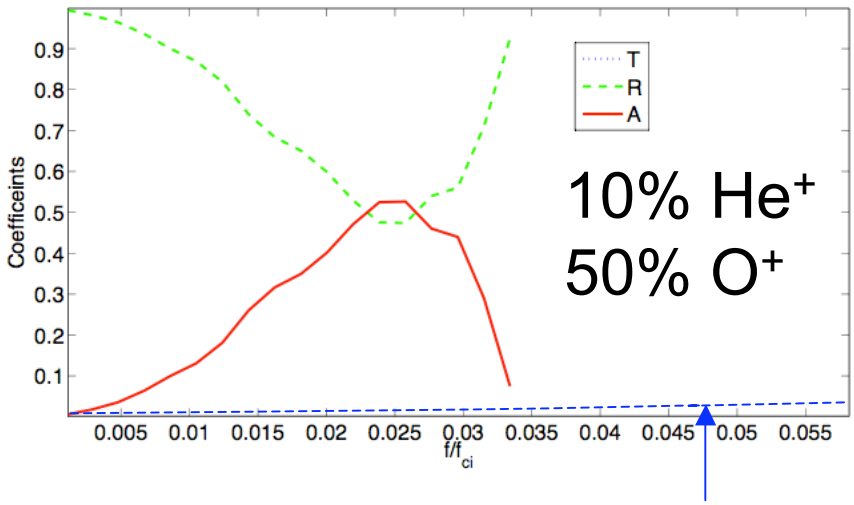








Oxygen Band (25 mHz)



Without Heavy Ions

- Heavy ions greatly enhance energy absorption at the Alfven resonance at low frequency

Summary

- Hybrid simulations indicate significant mode conversion and energy deposition
- Theory is consistent with hybrid results
- Theory also predicts heavy ions can significantly affect resonance efficiency
- Diffusive transport can be both efficient and significant