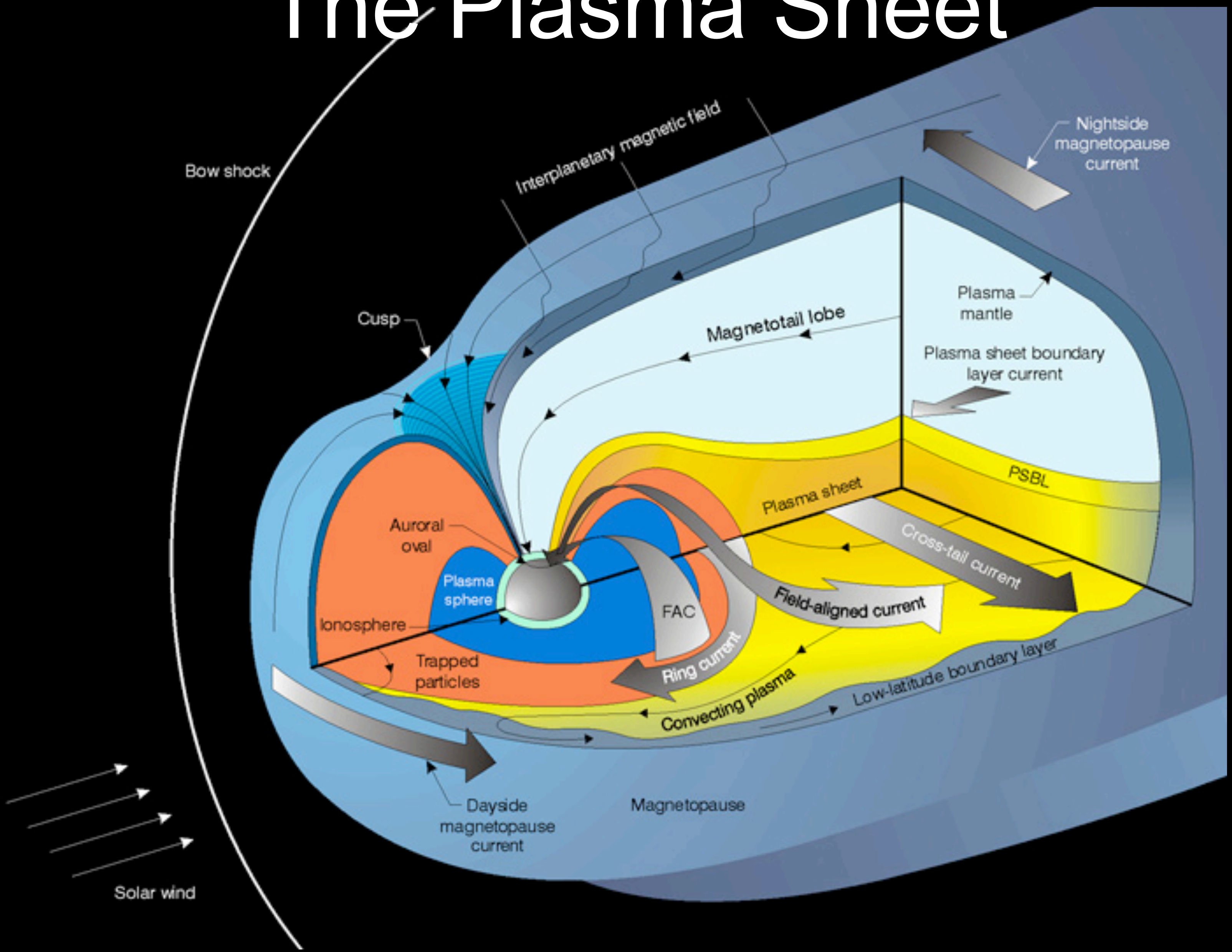
Challenges in Understanding Plasma Entry and Transport

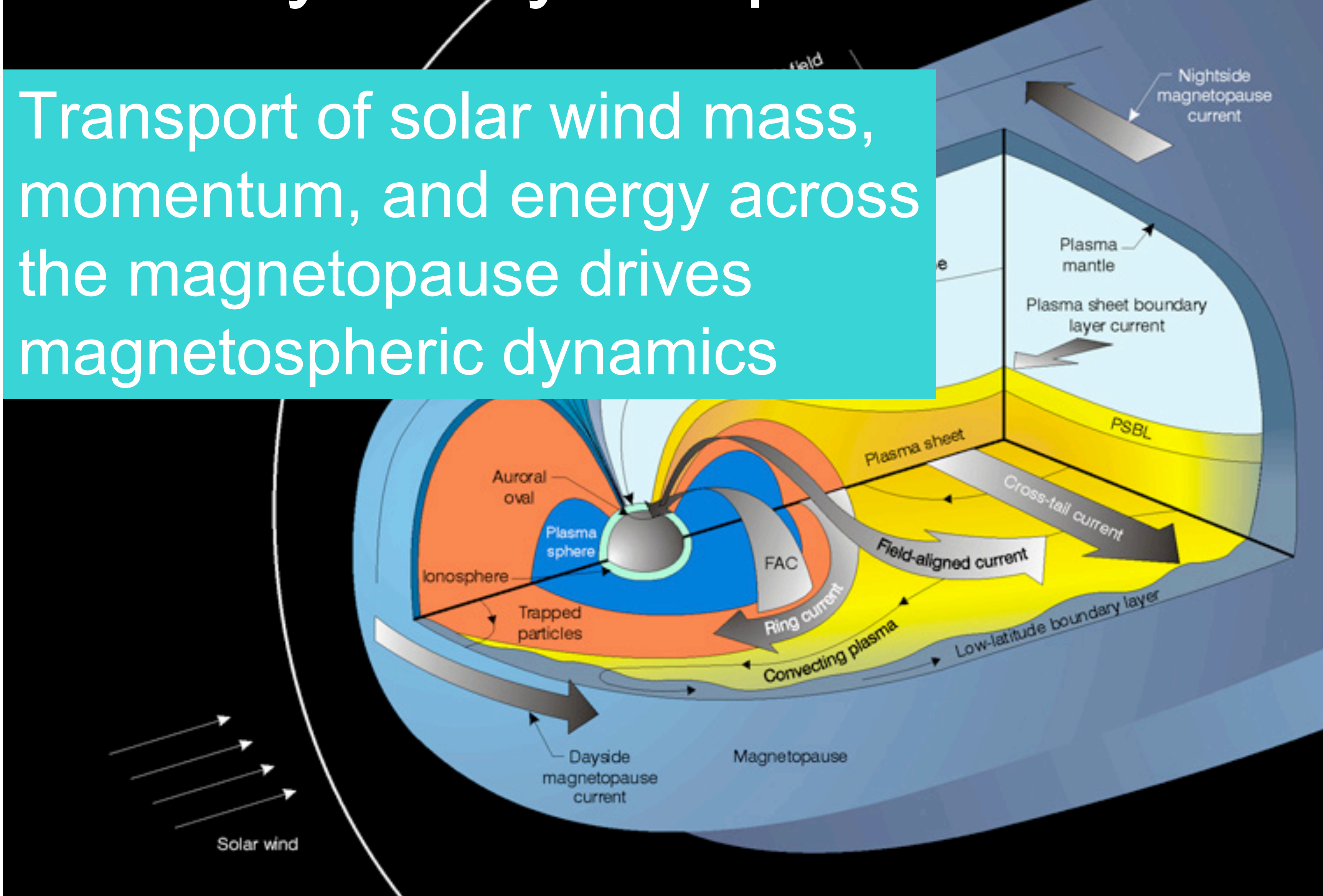
Thanks to discussions at the PET09 workshop in Fairbanks and contributions to the JGR special section on entropy

The Plasma Sheet

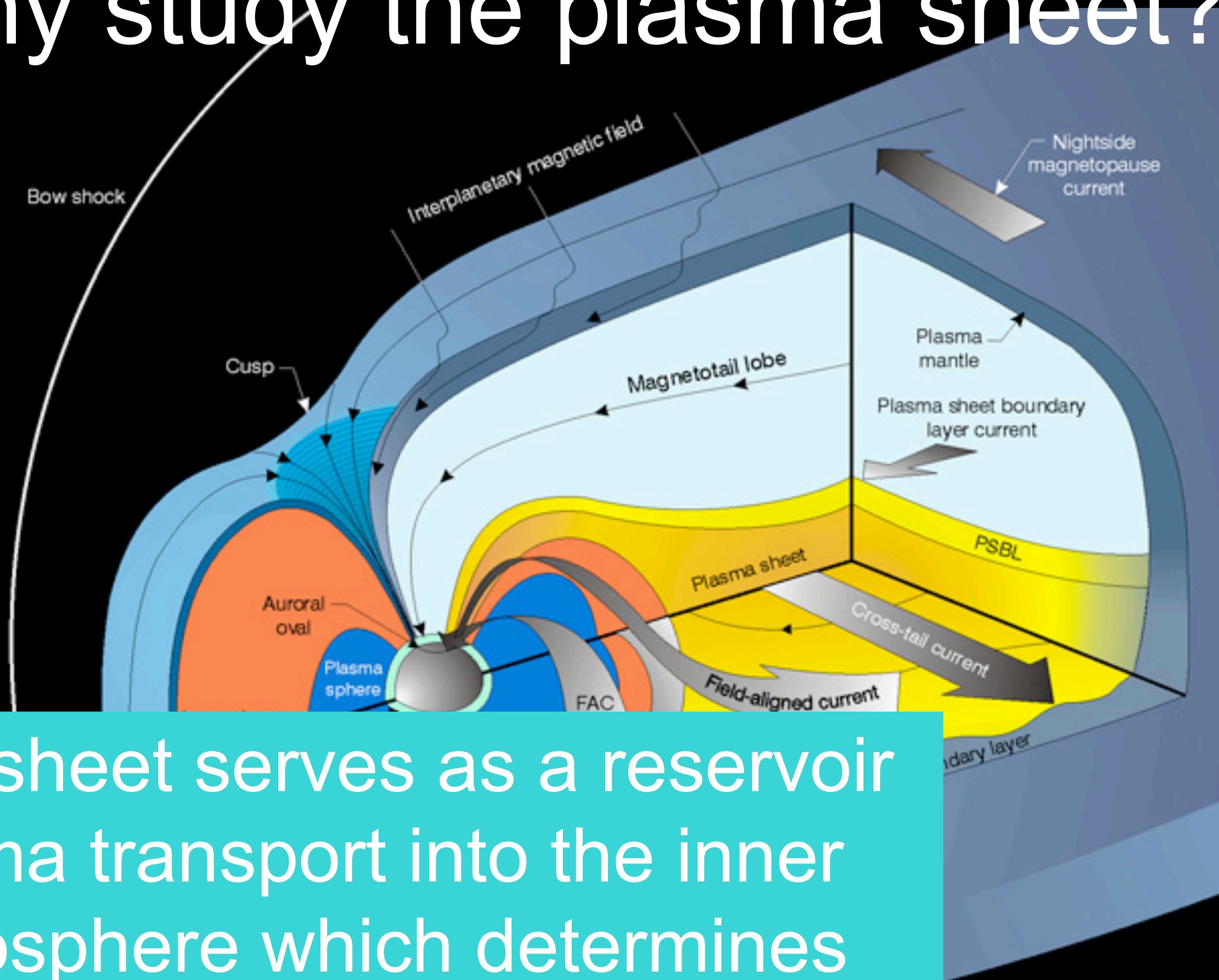


Why study the plasma sheet?

Transport of solar wind mass, momentum, and energy across the magnetopause drives magnetospheric dynamics



Why study the plasma sheet?

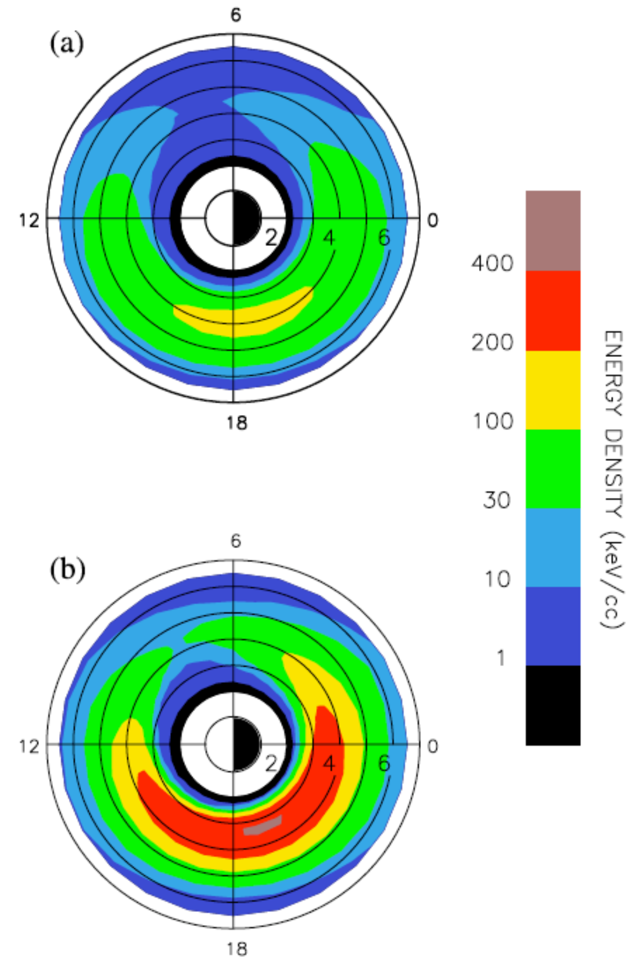


Plasma sheet serves as a reservoir for plasma transport into the inner magnetosphere which determines the geoeffectiveness of storms and substorms

Geoeffectiveness of CDPS

Hot (10keV) and Tenuous (0.8 cm^{-3})

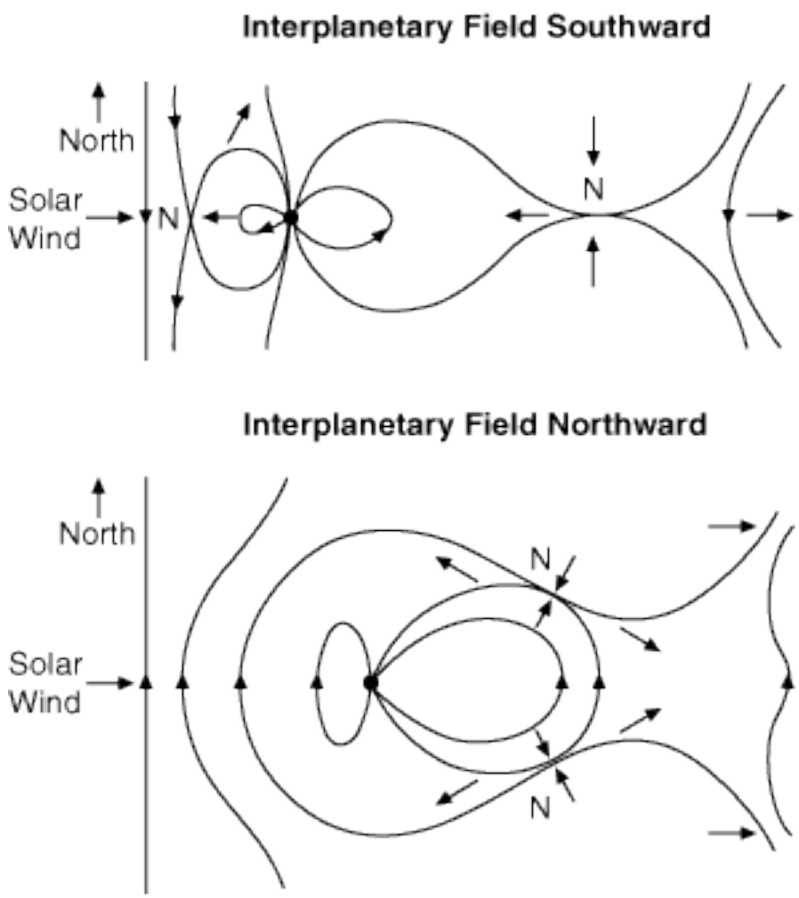
Cold (4keV) and Dense (2 cm^{-3})



Lavraud and Jordanova, 2007

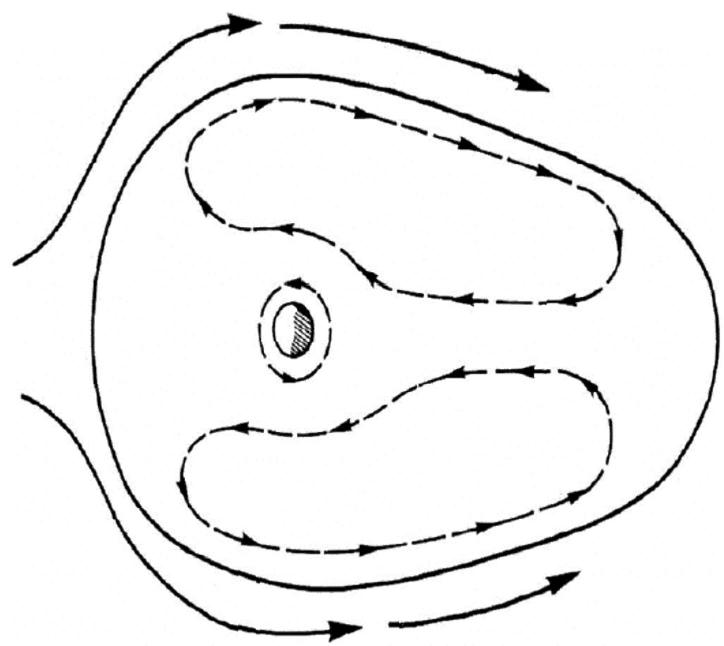
Basic Magnetopause Processes

Magnetic reconnection (Dungey,1961)



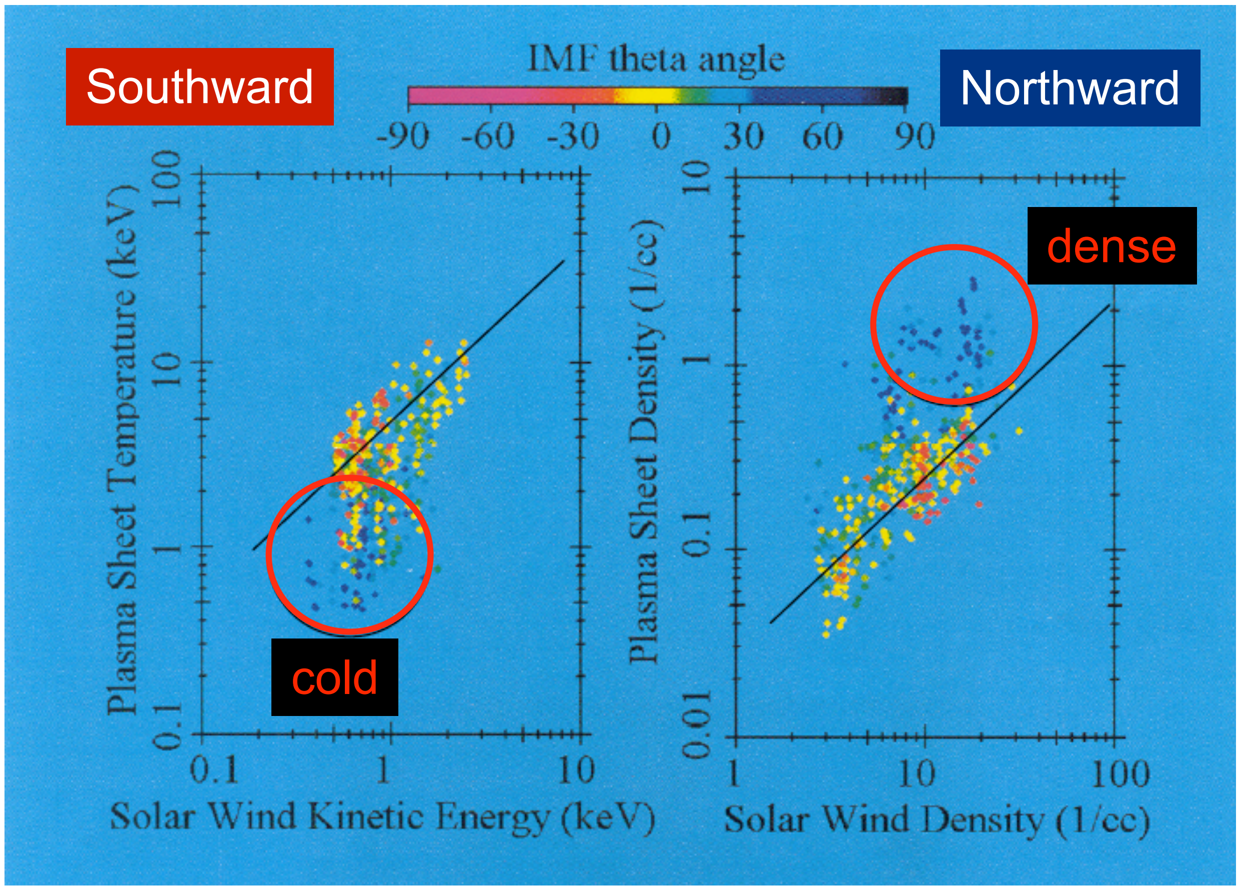
Viscous interaction (Axford and Hines, 1961)

- Diffusion (Micro-instabilities, turbulence)
- Kelvin-Helmholtz instability



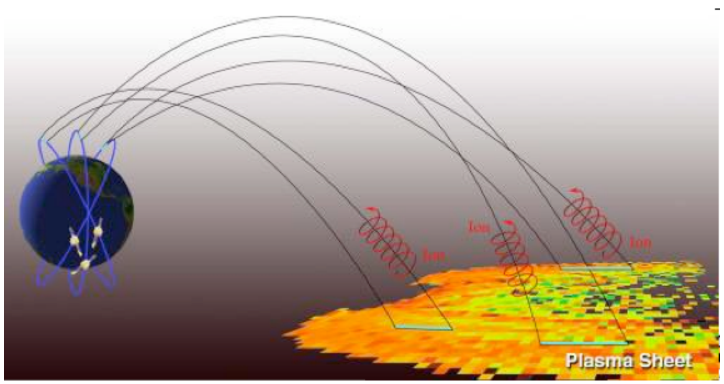
(Impulsive penetration (Lemaire and Roth, 1978))

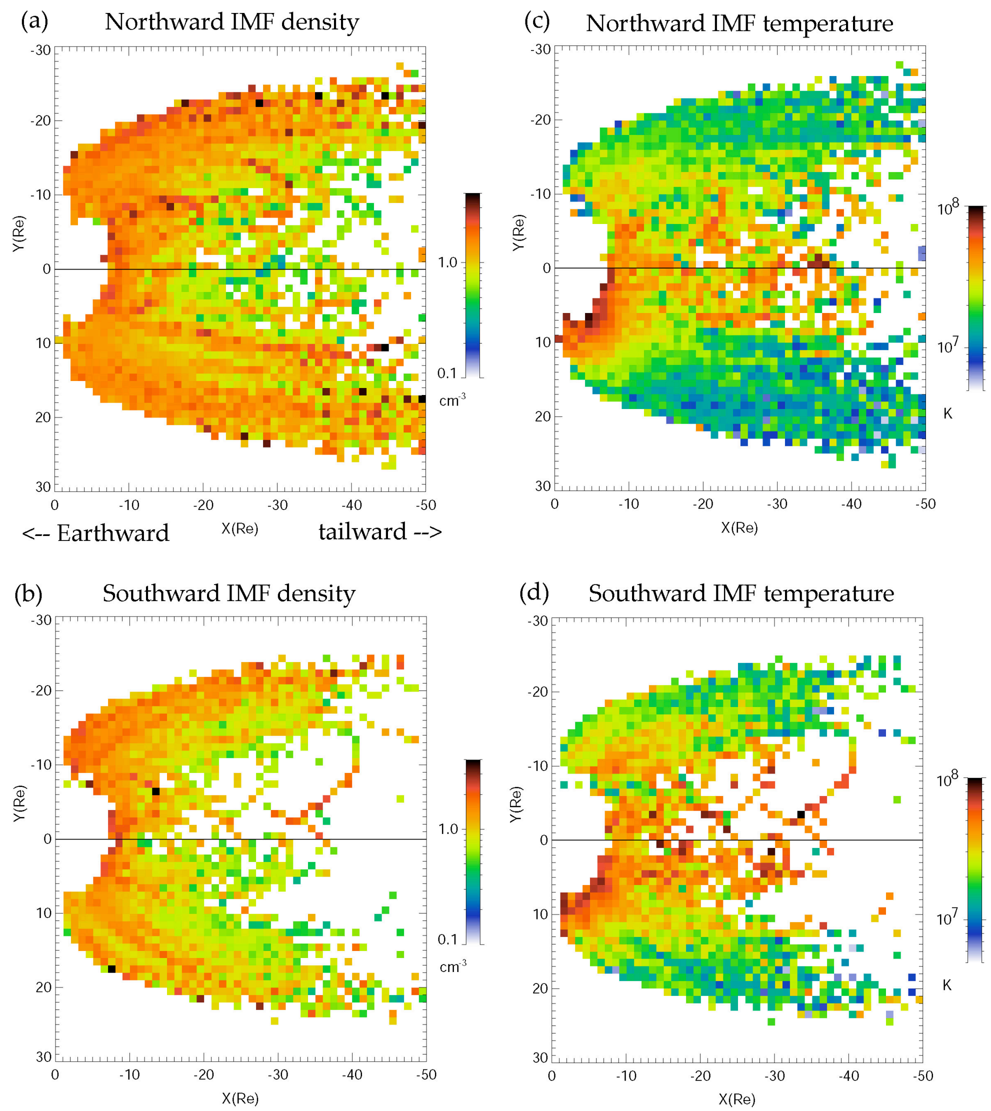
Plasma Sheet Morphology Depends on IMF Direction



Terasawa et al., 1997

Global Plasma Sheet Maps Show IMF Dependence



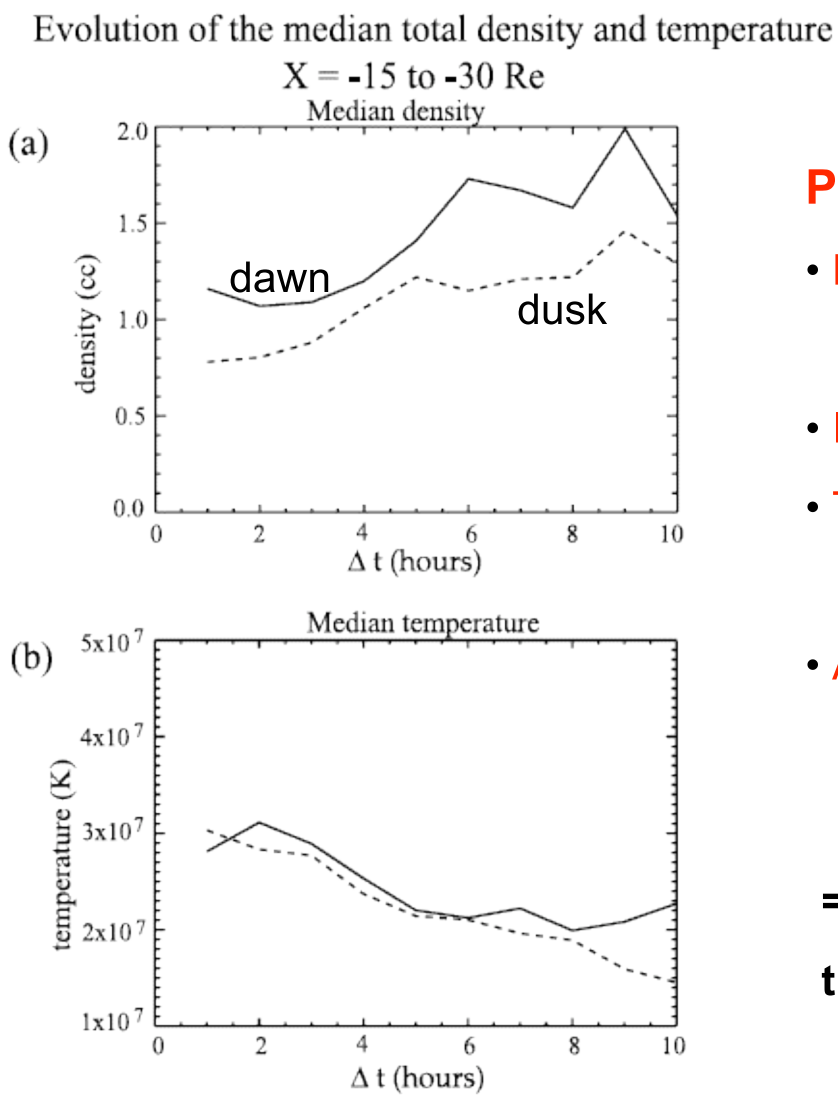


DMSP remote technique

- Isotropy (large curvature)
- B field mapping (T89)

Wing and Newell, 2003

Densification takes around 10 hours



Wing et al. (2006)

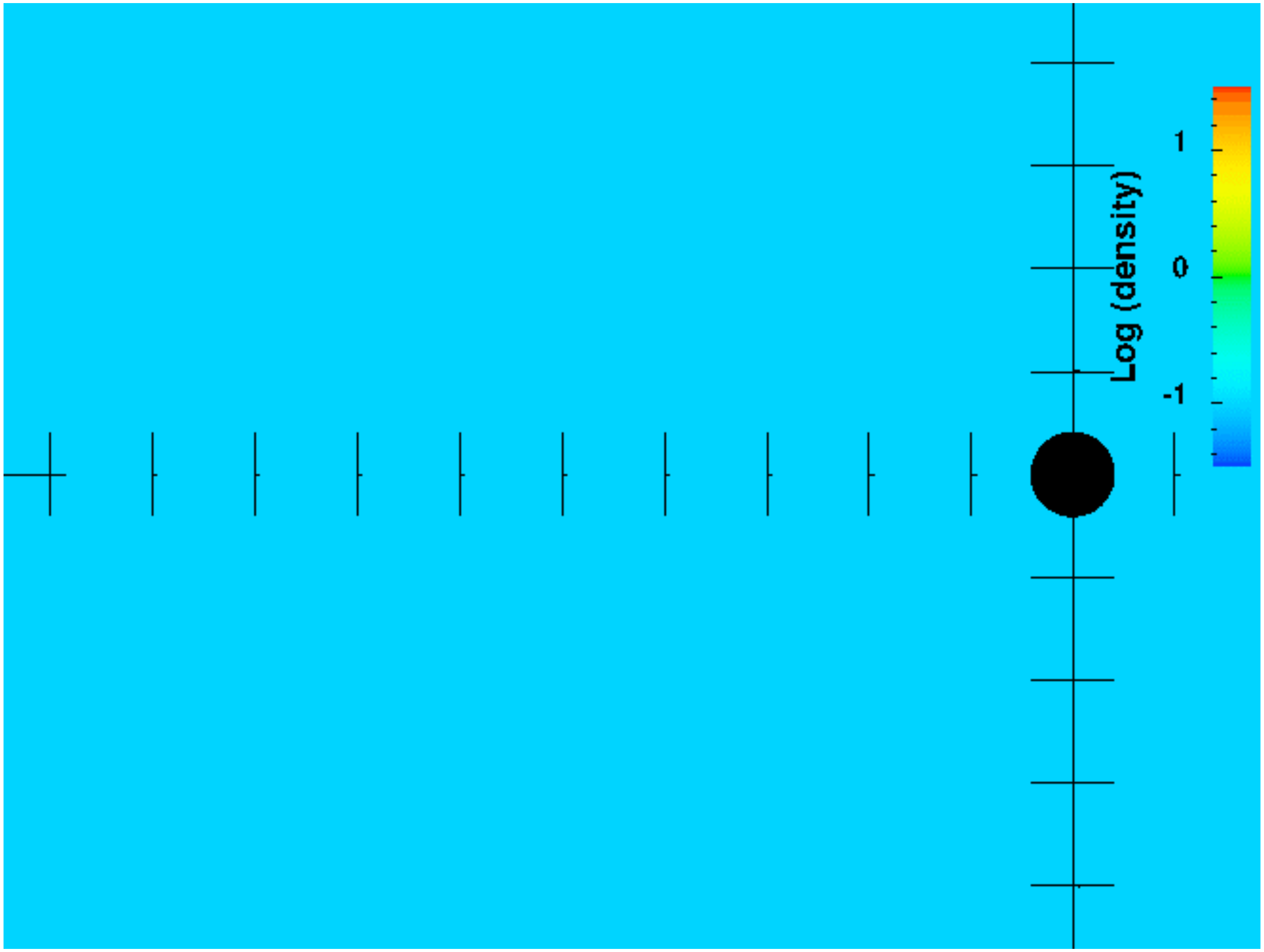
Properties inferred from DMSP:

- Rapid decrease of temperature at flank boundaries
- Increase of density first at flanks
- Timescale of density and temperature changes in the midnight meridian ~10 hr
- Asymmetries of the dawn-dusk flanks (distribution, density, temperature)

=> Plasma entry from magnetosheath along the flank boundaries

IMF Dependence and Global MHD

Lyon, 2009

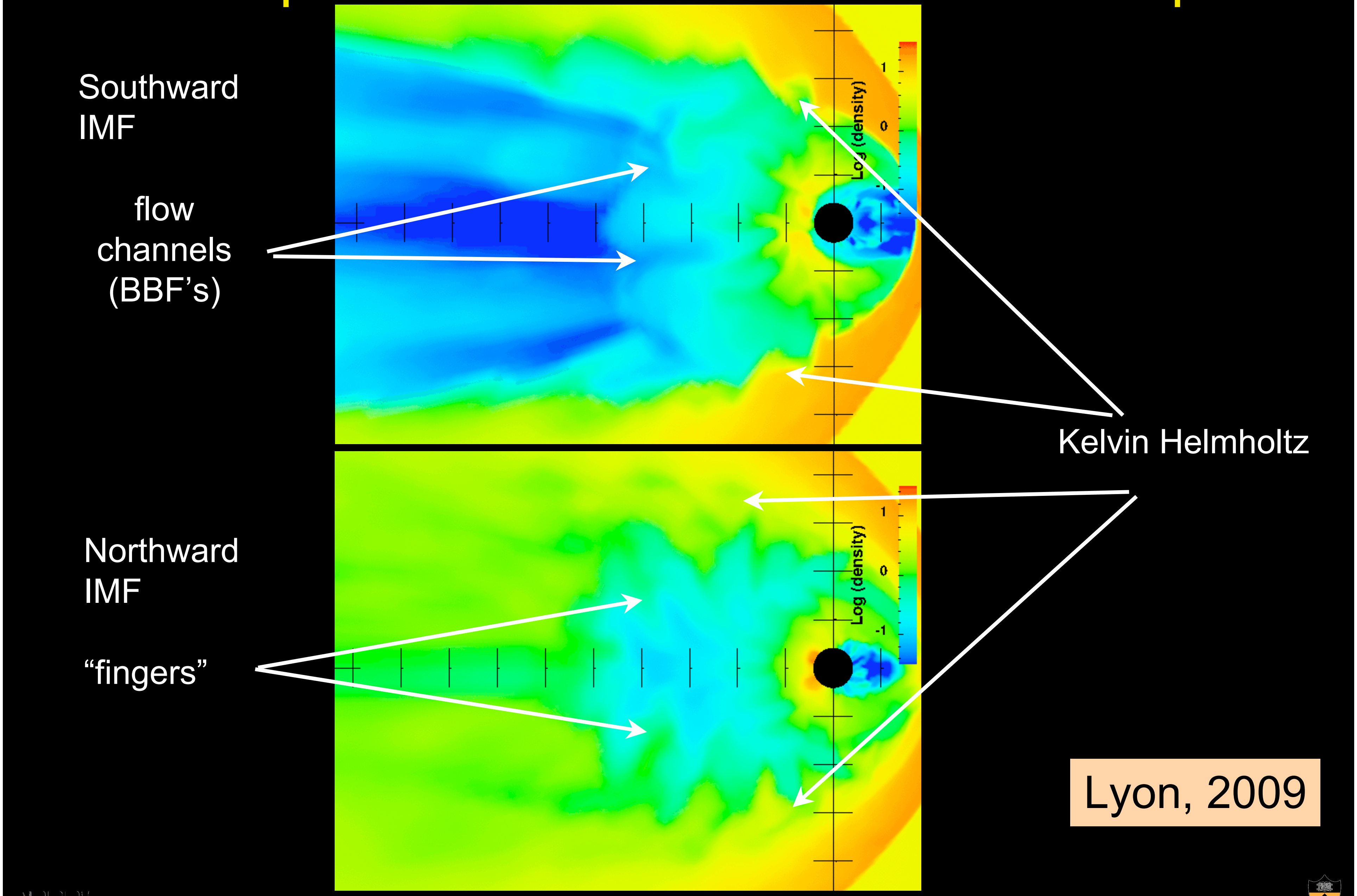


Northward turning

Southward turning

Substorm!

IMF Dependence of Plasma Sheet Transport



Southward IMF

- Transport dominated by intermittent periods of fast magnetospheric convection (expansion phase or bursty bulk flows)
- Questions:
  - How does the plasma sheet reform after periods of magnetic activity (is IMF By required)?
  - What nonadiabatic processes change entropy from mantle to plasma sheet values?
  - To what extent does steady convection conserve entropy?
  - How does entropy change during fast convection?
  - Why do entry processes conserve T_e/T_i?

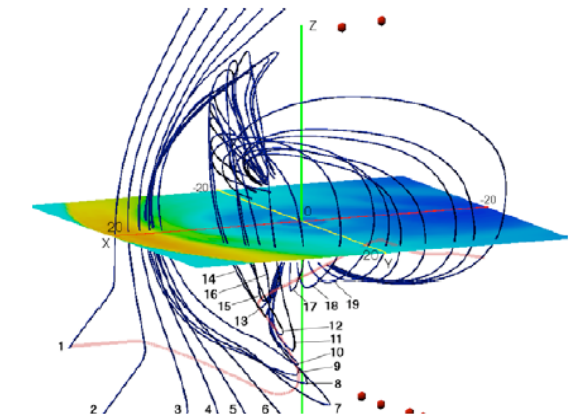
Northward IMF

- Dominated by the formation of a cold, dense plasma sheet with weak convection
- Questions:
  - How and where does plasma enter the plasma sheet (origin of asymmetries)?
  - Why are there distinct hot and cold populations even after long periods of IMF northward?
  - How does entropy change from magnetosheath to plasma sheet and by what mechanism?
  - How does cold material transport to the center of the plasma sheet (convection vs turbulent diffusion)?

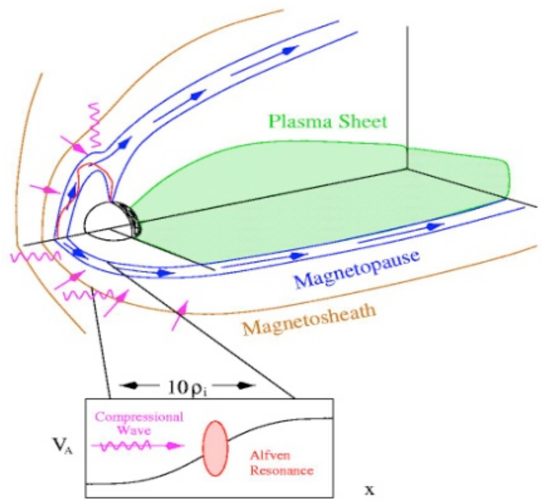
What is the origin of the cold population?

Mechanisms of Plasma Entry

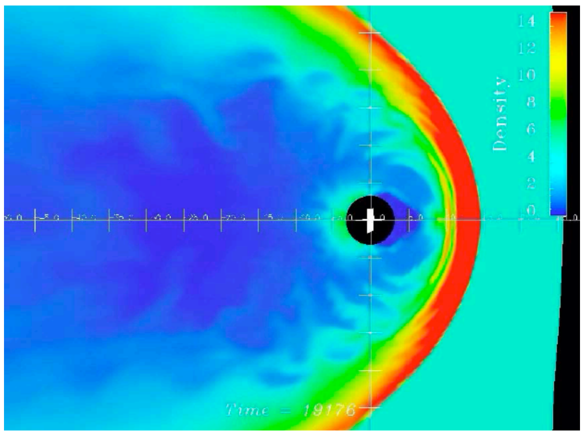
Reconnection	Kinetic Alfven Waves	Kelvin-Helmholtz Instability
Crooker, 1979; *Song and Russell, 1992*		*Otto and Fairfield, 2000*



Li et al., 2005



Johnson and Cheng, 1997



Lyon et al., 2007

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Mechanisms of Plasma Entry

Reconnection	Kinetic Alfven Waves	Kelvin-Helmholtz Instability

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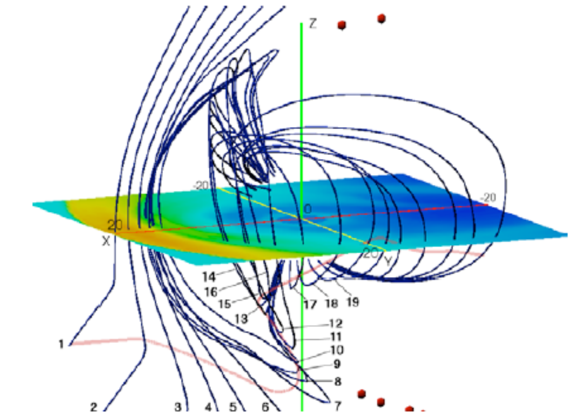
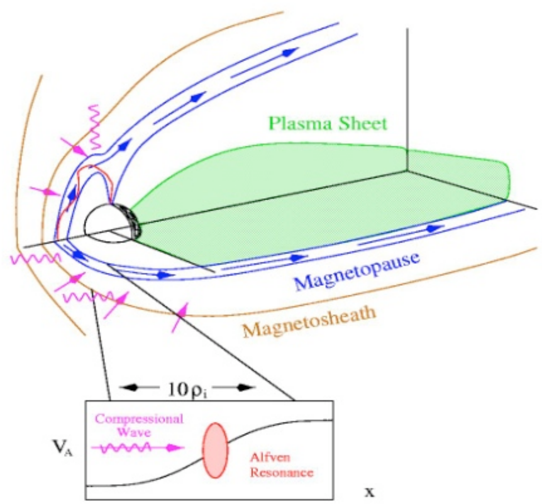
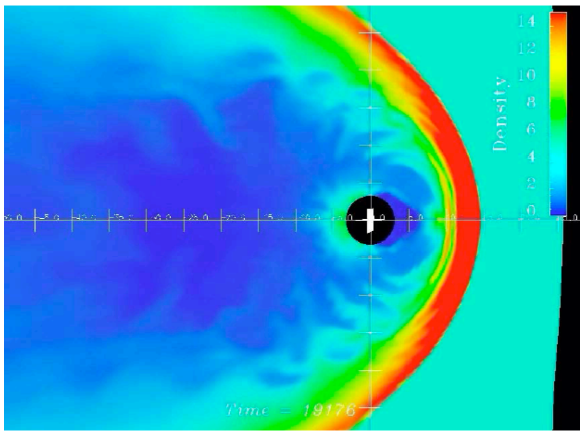


Li et al., 2005



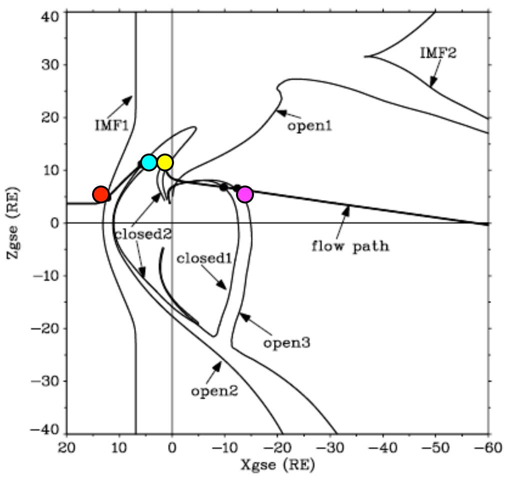
Johnson and Cheng, 1997

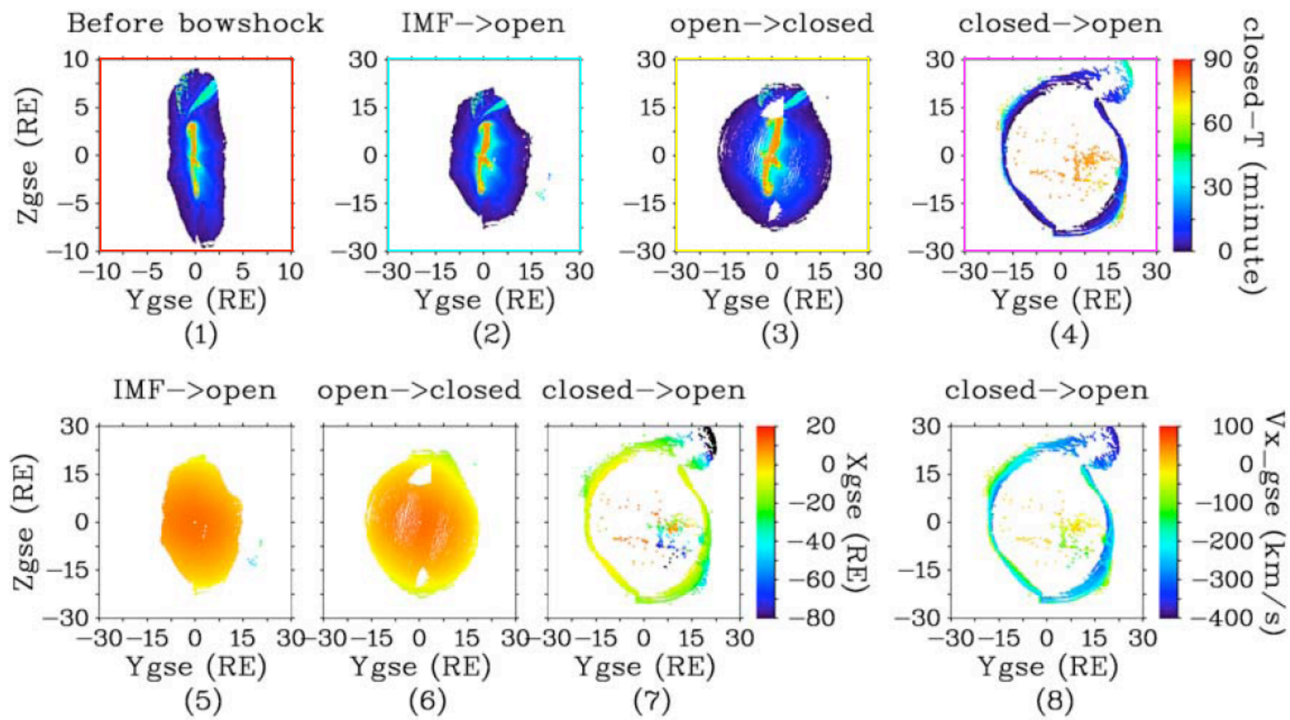


Lyon et al., 2007

Tailward of the Cusp Reconnection

dN/dt~10^{26}-10^{27} /s



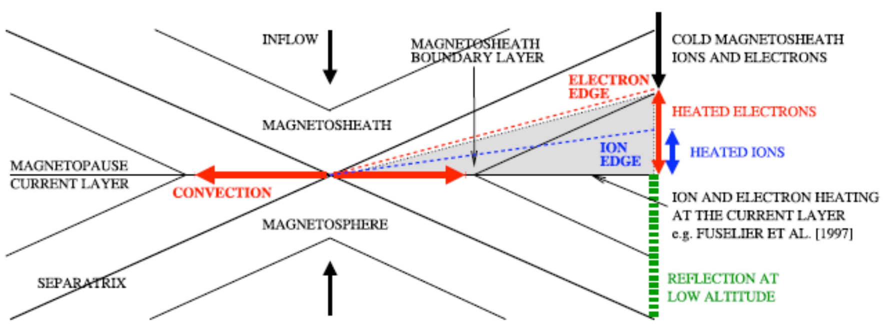


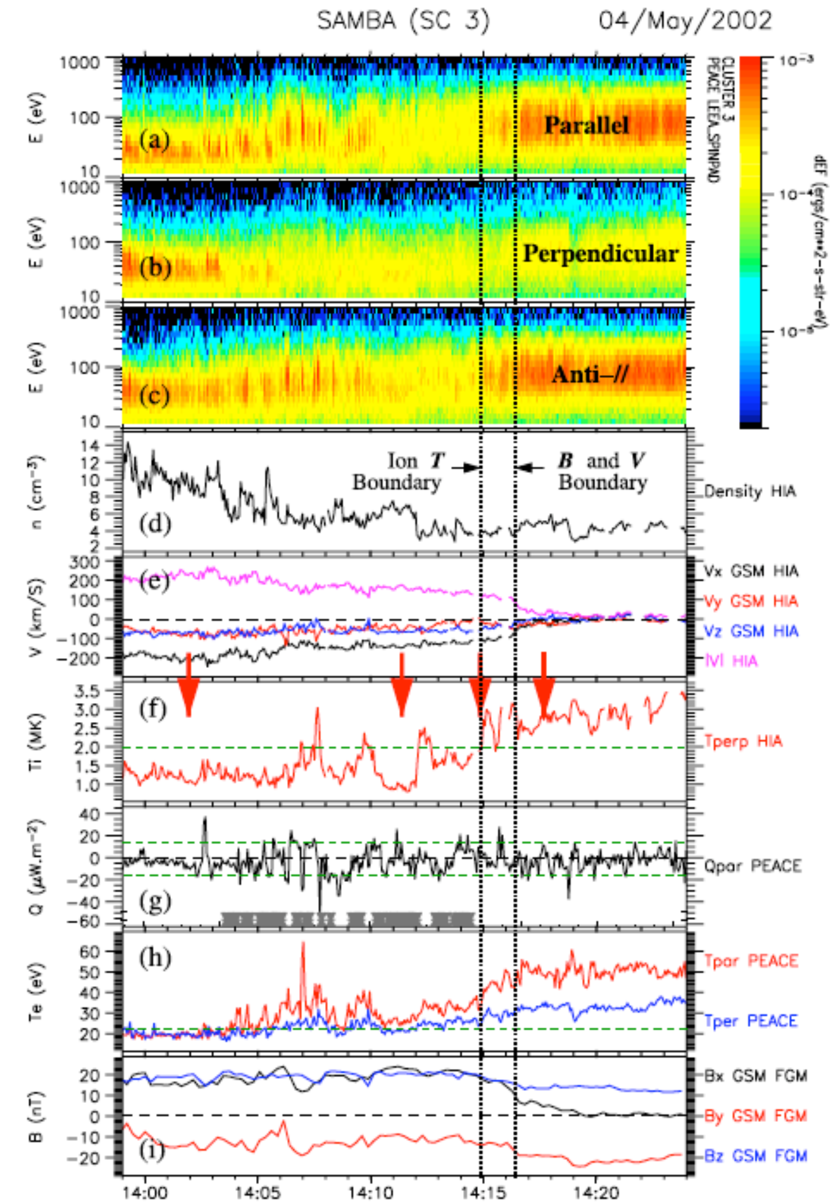
Li et al., 2008

Flank is populated by transient plasma
Captured plasma also populates the center of the tail plasma sheet

Observational Support

- Reconnection signatures
  - Bi-directional heated electrons indicating newly closed field lines
  - Magnetopause current layer structure (electron and ion edges)

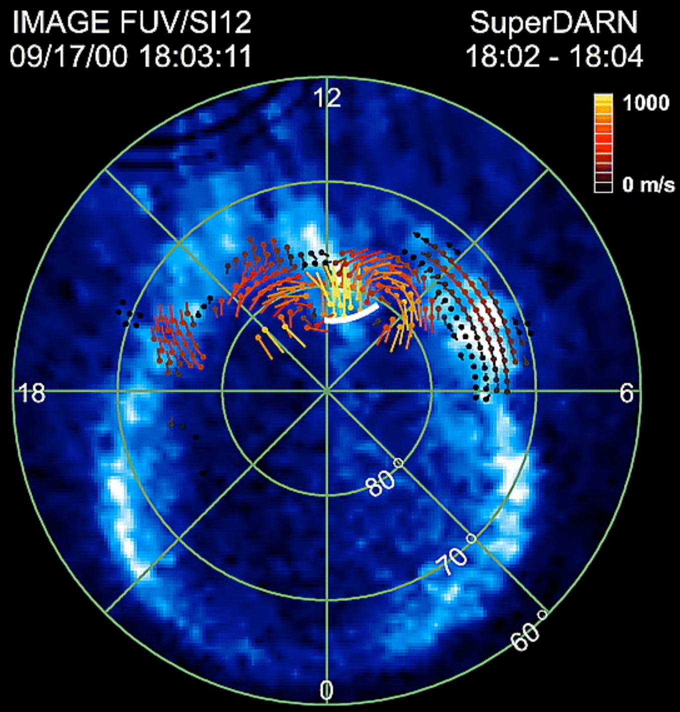




Lavraud et al., 2006

Observational Support

- Reconnection signatures
  - Bi-directional heated electrons indicating newly closed field lines
  - Magnetopause current layer structure (electron and ion edges)
- Convection patterns in the Ionosphere
- Entry Rate similar to what is required to maintain the plasma sheet 10^{26}-10^{27} particles/s

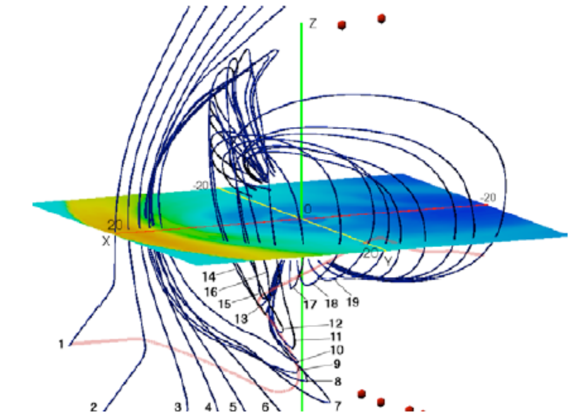


Chang et al., 2004

Mechanisms of Plasma Entry

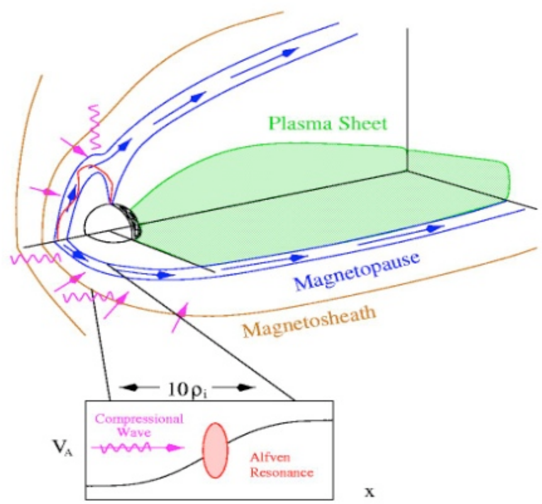
Reconnection

Crooker, 1979;
Song and Russell, 1992



Li et al., 2005

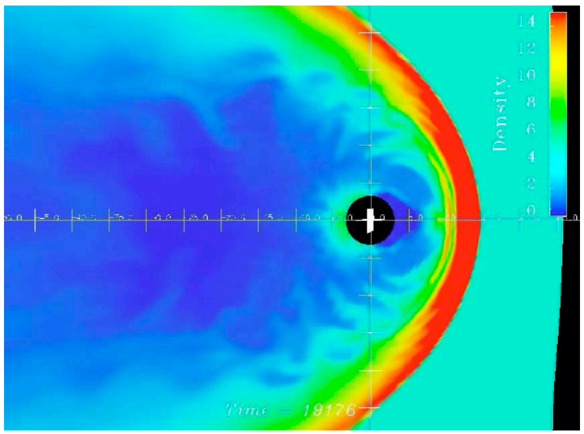
Kinetic Alfven Waves



Johnson and Cheng, 1997

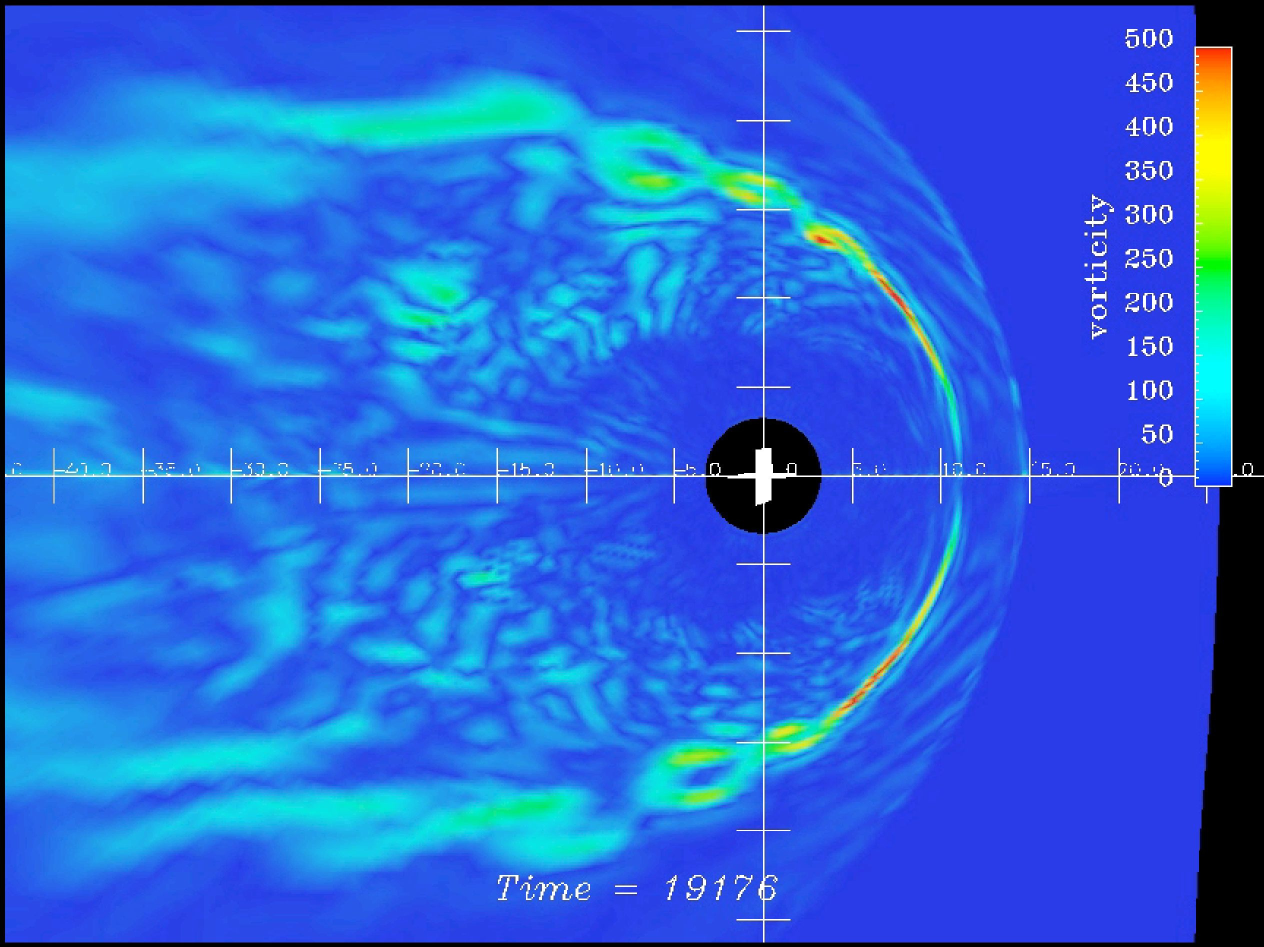
Kelvin-Helmholtz Instability

Otto and Fairfield, 2000



Lyon et al., 2007

Vorticity in High Resolution MHD Simulations Shows KH modes along the flank



Lyon, 2009

Kelvin-Helmholtz Modes:

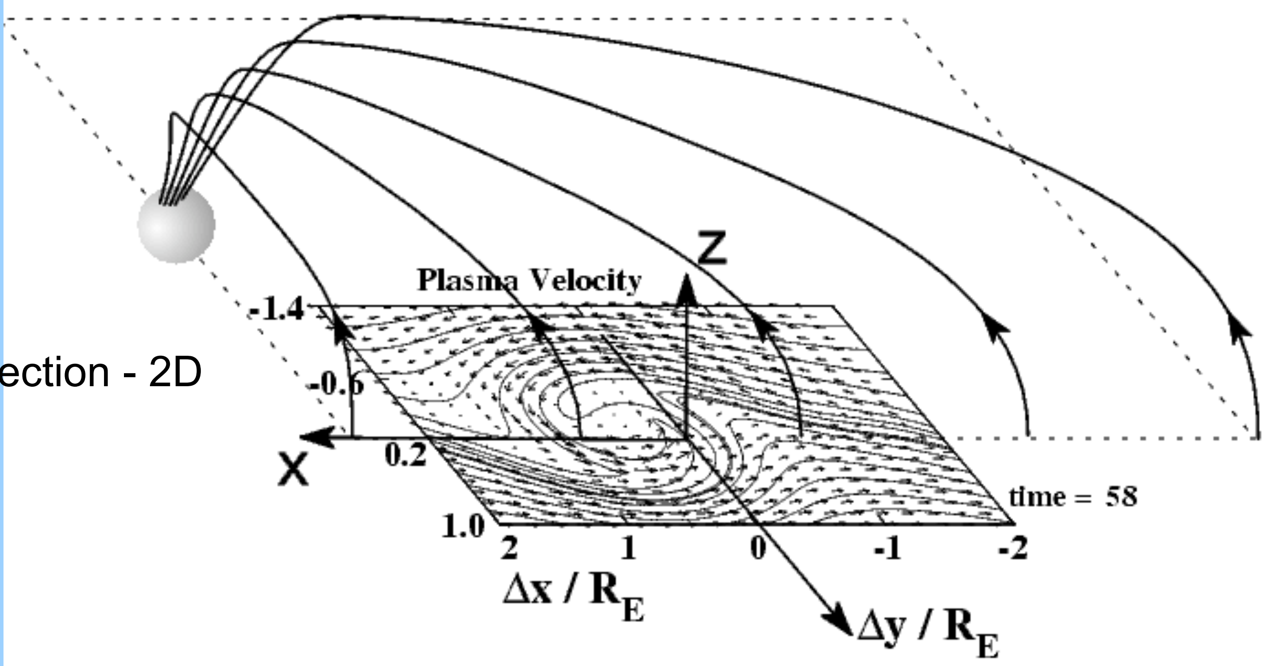
Otto, 2009

Observations (Scopke, Fairfield, Fujimoto, Hasegawa, Nykyri, etc.)

Simulation (Miura, Belmont, Wu, Wei, ..)

Miura: Viscous diffusion (momentum transport) coefficient: $D=10^9 m^2 s^{-1}$

Mass transport (Otto, Nykyri, Fujimoto, Nakamura)



- Kelvin-Helmholtz and Reconnection - 2D
- Three-Dimensional Dynamics
- Entropy Considerations

Stability: $$[(\mathbf{V}_1 - \mathbf{V}_2)\cdot \mathbf{k}]^2 > \frac{n_1 + n_2}{4\pi m_0 n_1 n_2}\left[(\mathbf{B}_1\cdot \mathbf{k})^2 + (\mathbf{B}_2\cdot \mathbf{k})^2\right]$$

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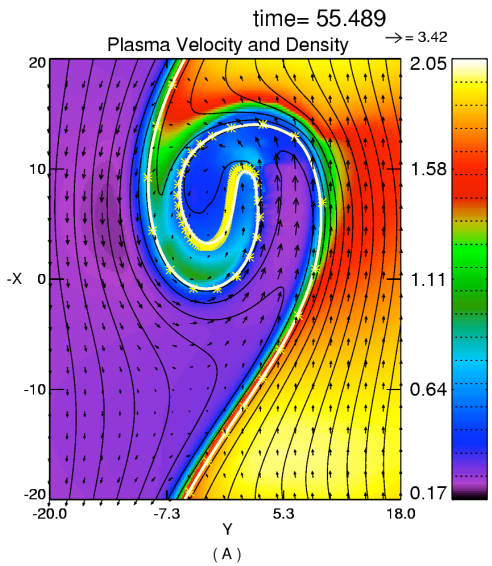
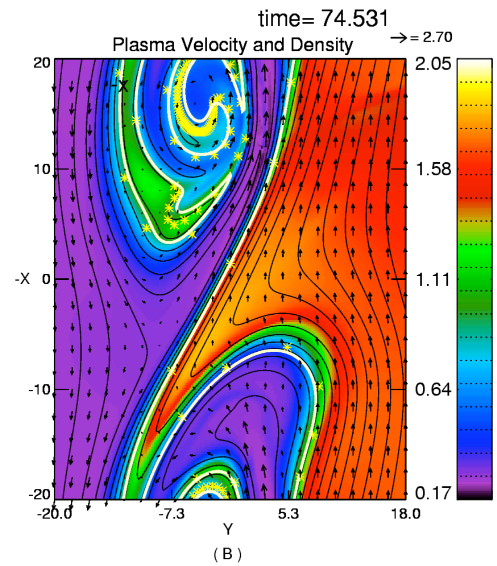
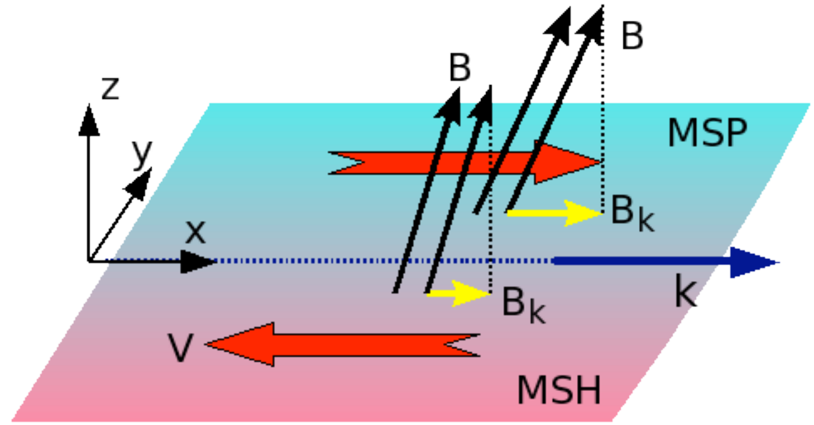
Reconnection + KH vortex

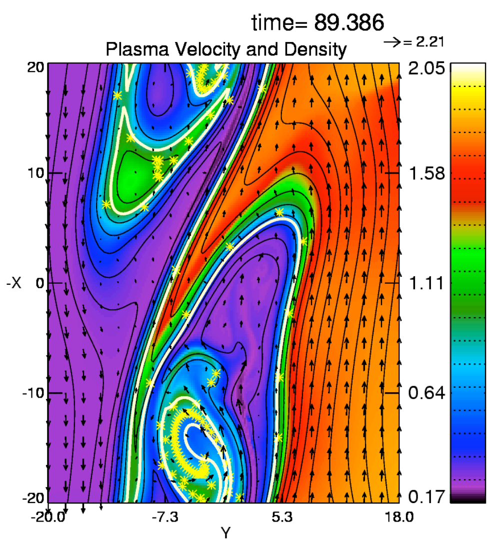


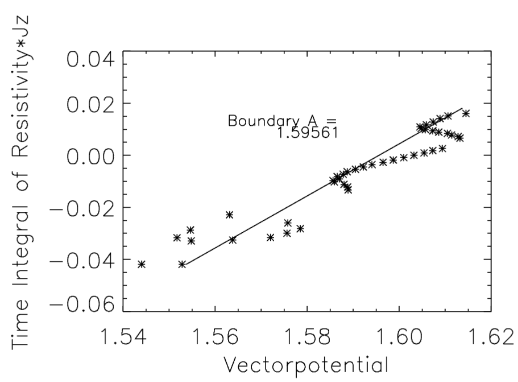
(A)



(B)





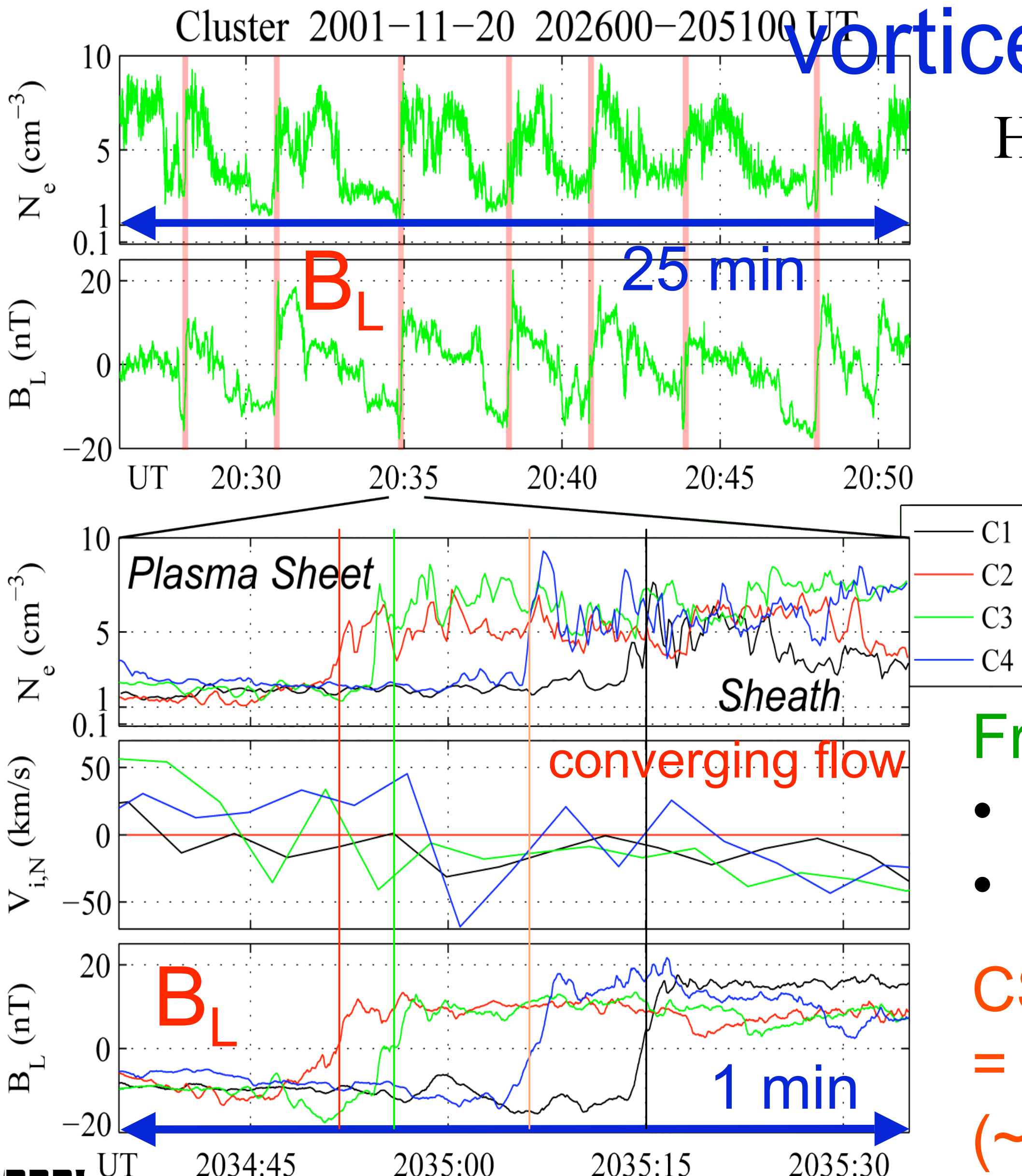


- Strong amplification of the magnetic field in the KH plane.
- Intense current layers in the KH vortex. Current does not neet to be present in the initial conditions!

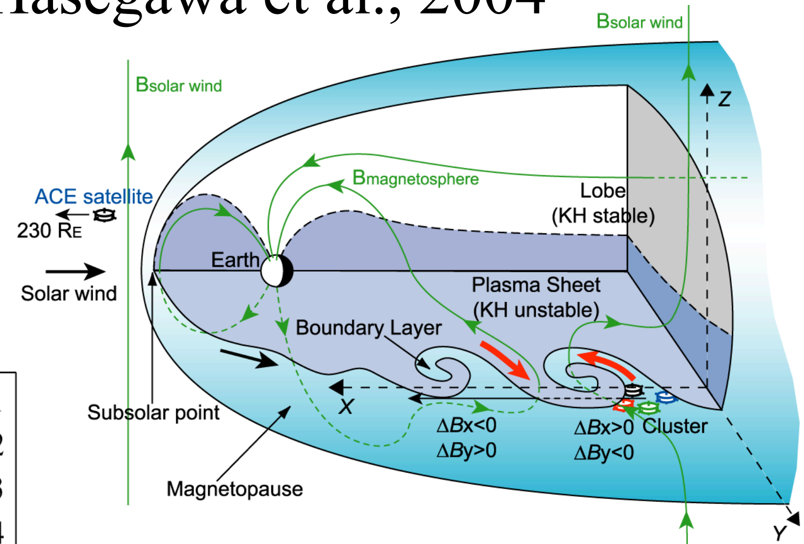
Plasma filaments are reconnected and become detached from the high density region!

Nykyri and Otto, 2001, 2003

Ion-scale current sheets at the edge of KH vortices seen by Cluster



Hasegawa et al., 2004

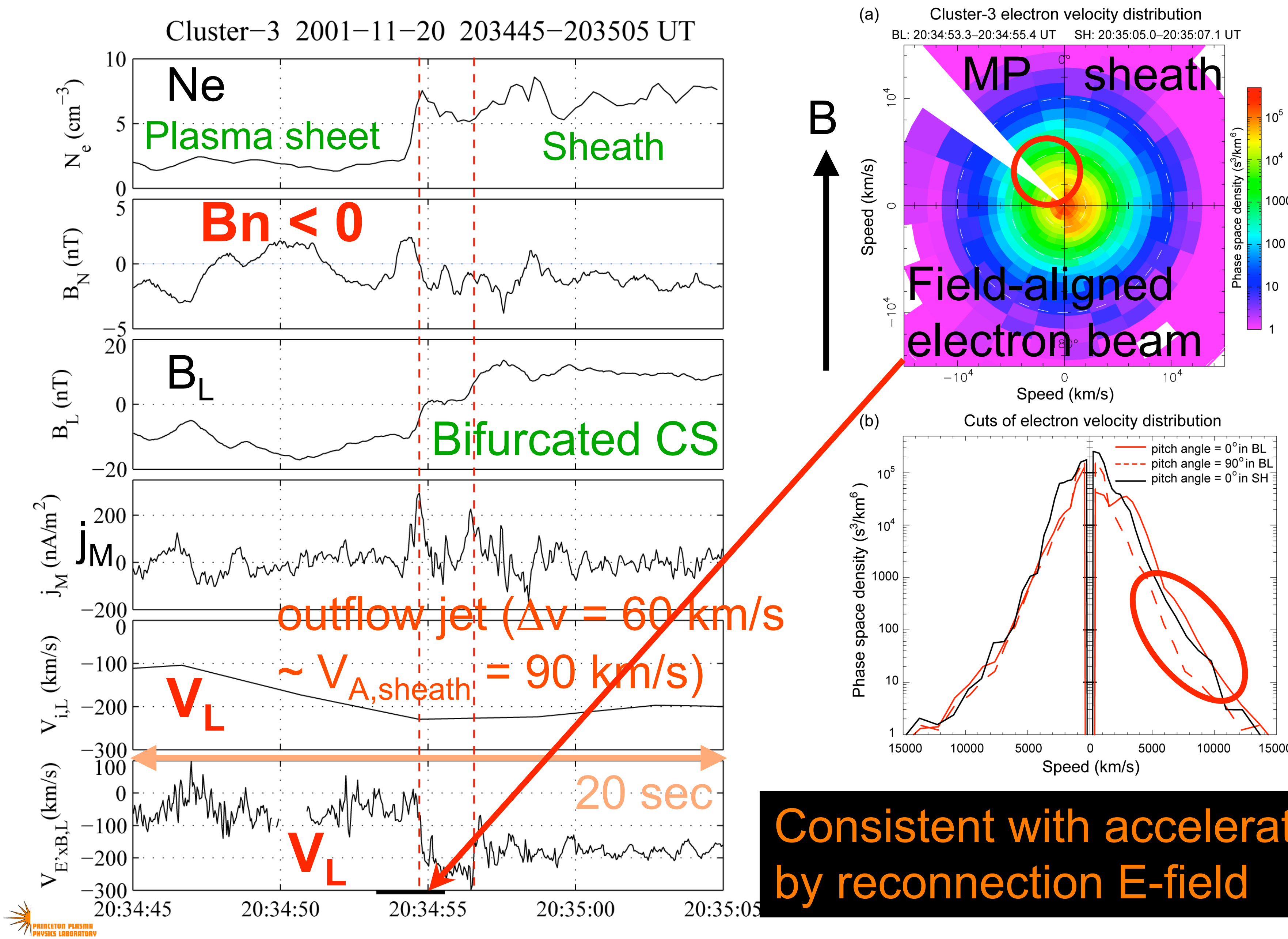


From 4-SC timing method:

- Vn ~ 80 km/s
- Crossing took ~3 sec.

CS thickness ~250 km
= 2-3 times ion inertia length
(~100 km)

Reconnection signatures seen by Cluster-3@19 MLT



Consistent with acceleration by reconnection E-field

Mechanisms of Plasma Entry

Reconnection

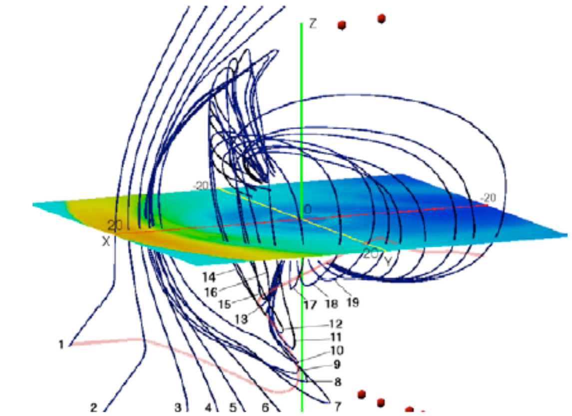
Kinetic Alfven Waves

Kelvin-Helmholtz Instability

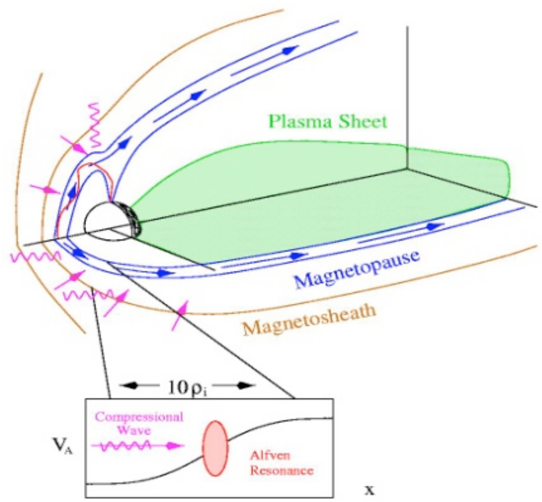
Crooker, 1979;

Song and Russell, 1992

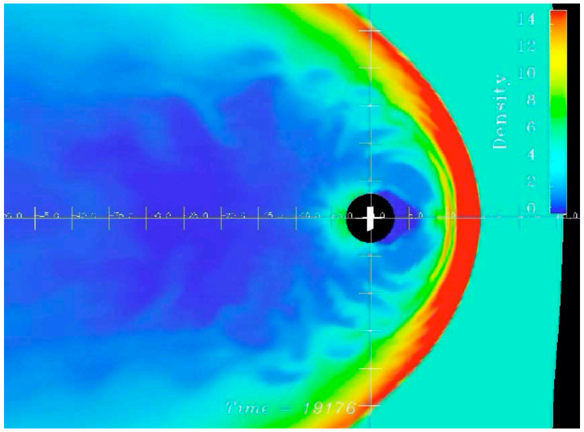
Otto and Fairfield, 2000



Li et al., 2005

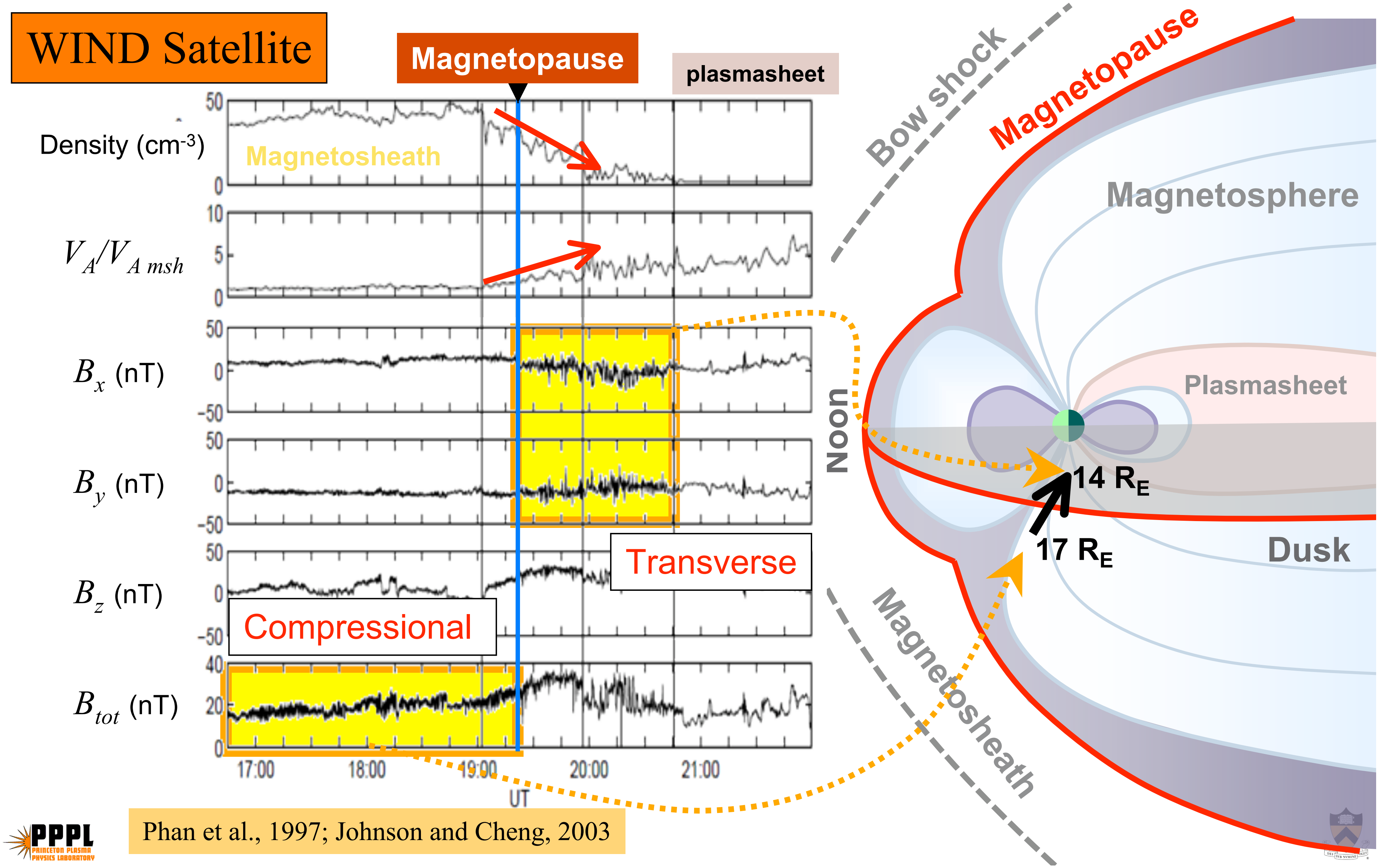


Johnson and Cheng, 1997



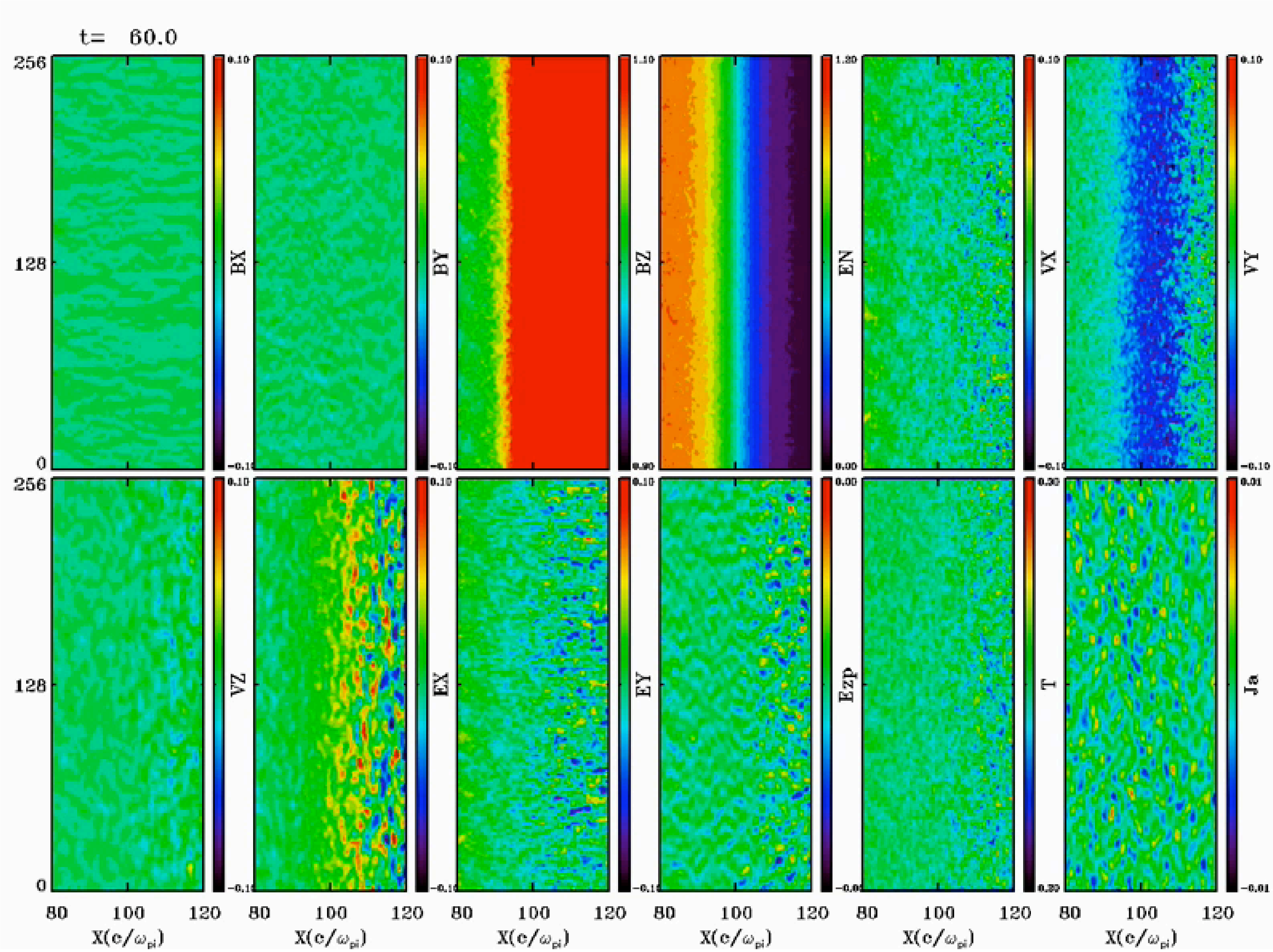
Lyon et al., 2007

Alfven waves plays an important role on magnetopause transport



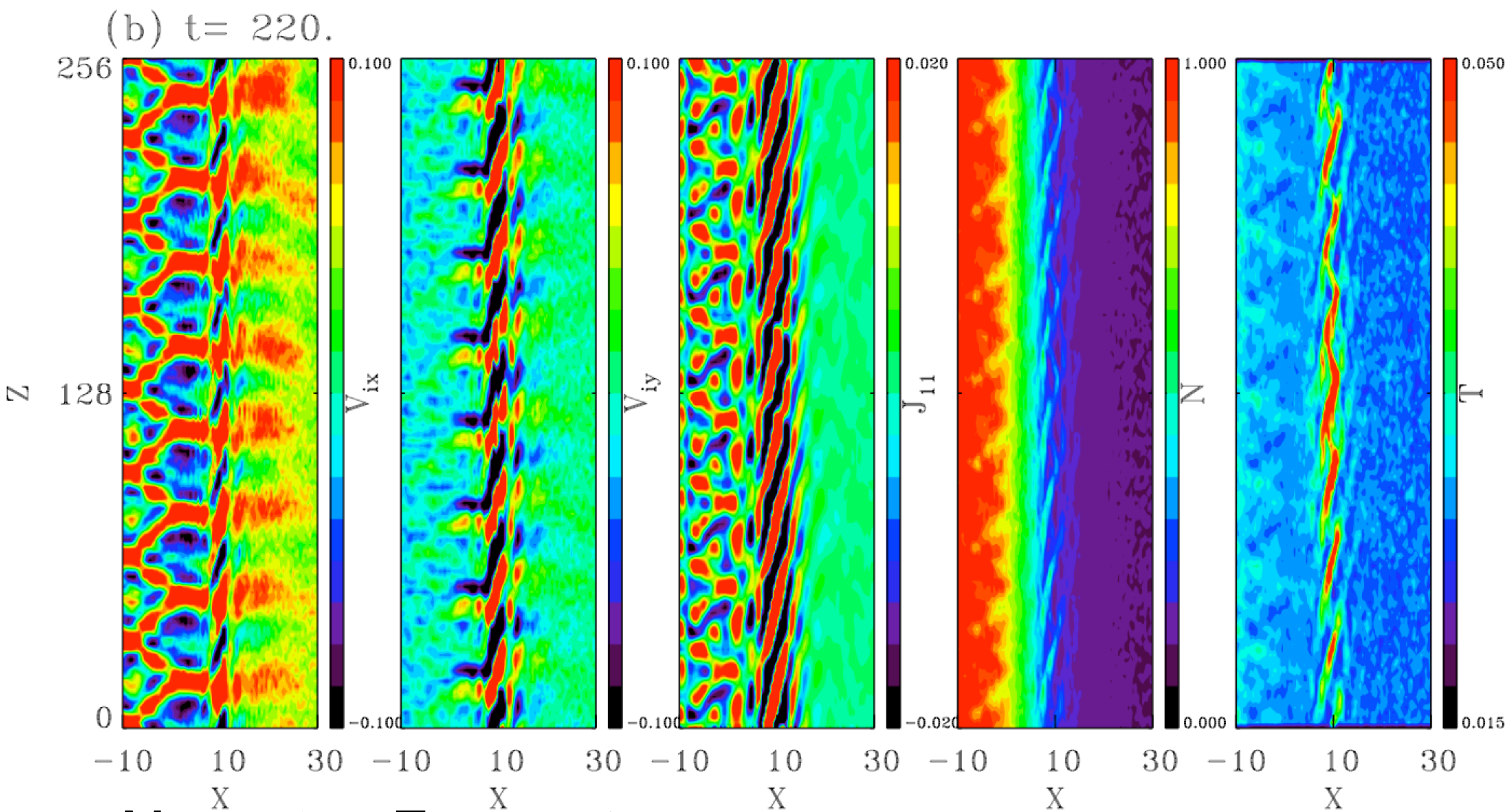
Phan et al., 1997; Johnson and Cheng, 2003

Hybrid Simulations



Lin et al., 2009

Transport of Mass, Momentum; Heating



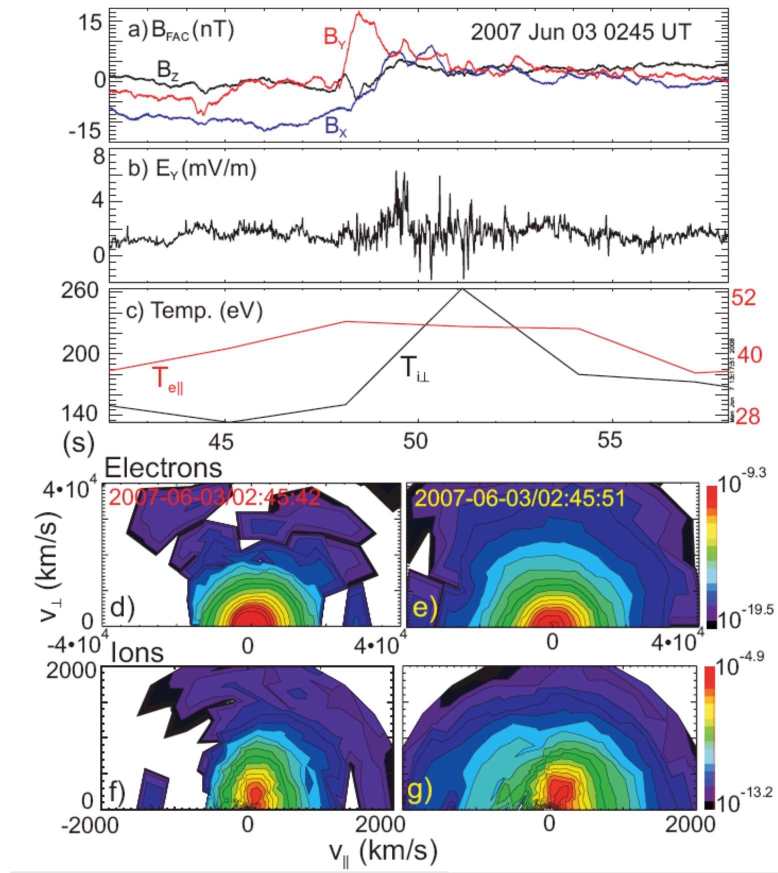
Momentum Transport

Mass Leakage

Heating

Observational Signatures of KAWs

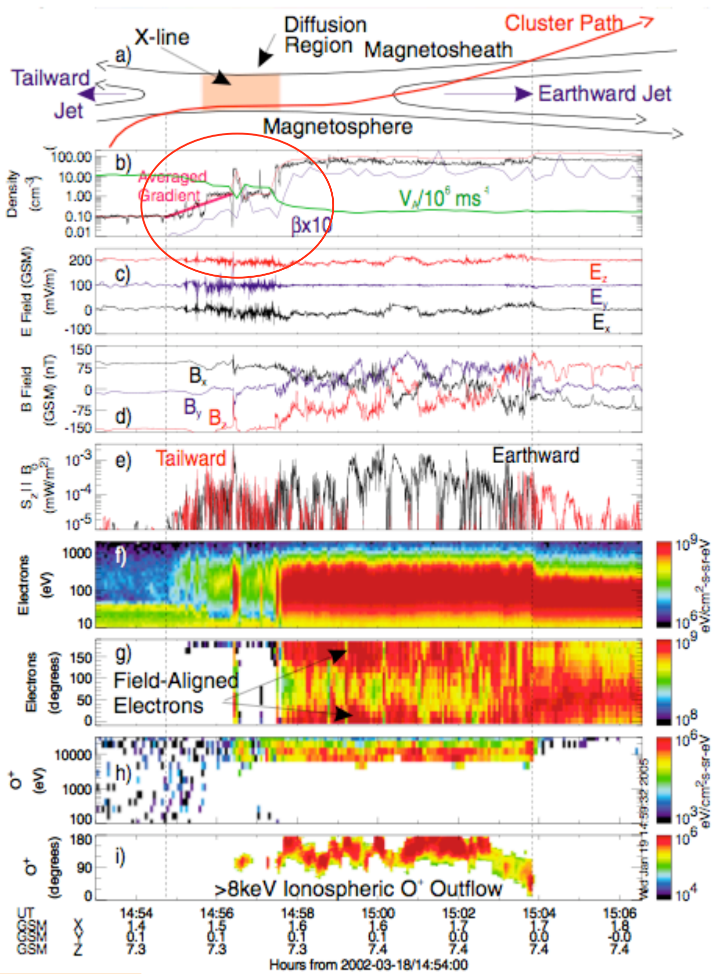
- Parallel Electron Heating
- Transverse Ion Heating
- Cluster wave observations satisfy KAW dispersion relation [Chaston et al., 2005, 2007, 2008]
- $\delta E/\delta B$ ratio
- Diffusion based on measured spectrum $D \sim 10^{10}\ m^2/s$



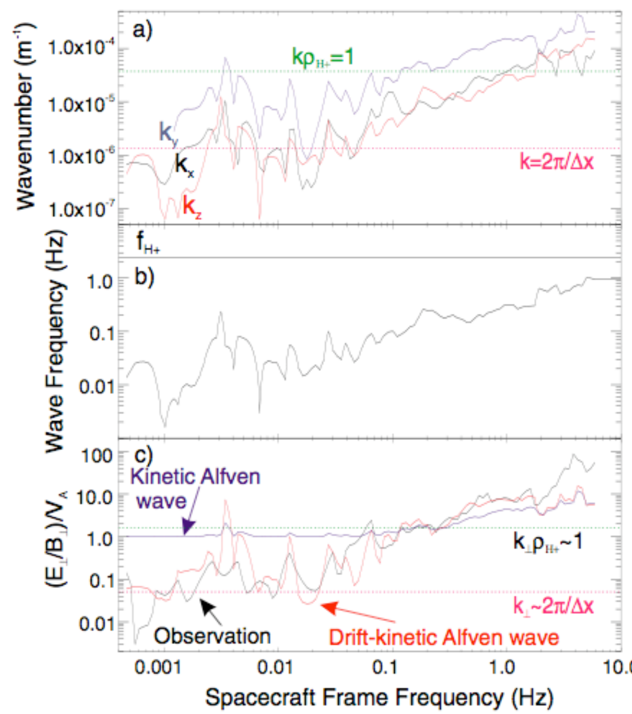
Chaston et al., 2008

Mechanisms are not Mutually Exclusive

Reconnection | **Kinetic Alfven Waves** | **Kelvin-Helmholtz Instability**



Kinetic Alfven waves are associated with reconnection



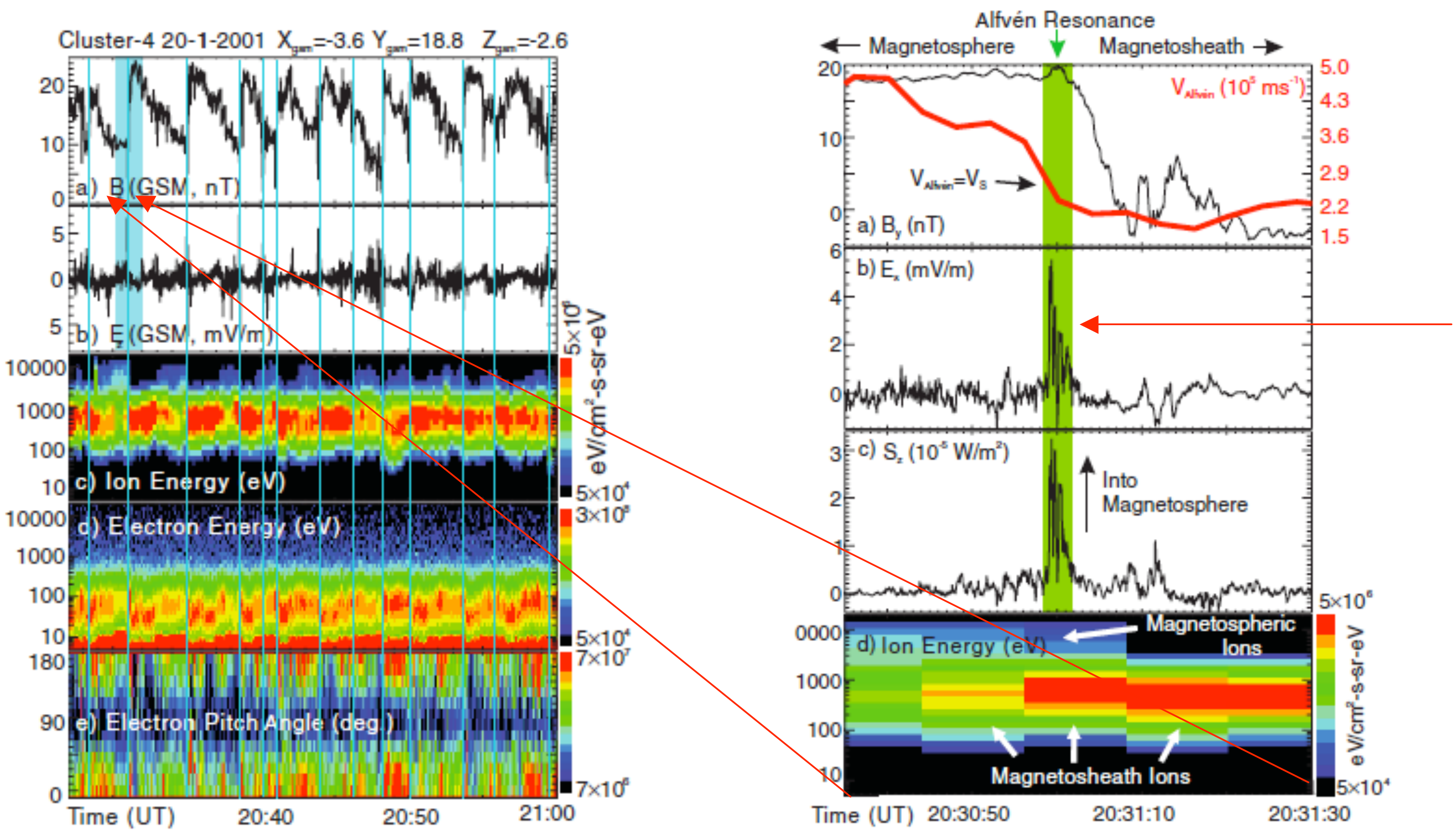
Chaston et al., 2005

Mechanisms are not Mutually Exclusive

Reconnection

Kinetic Alfven Waves

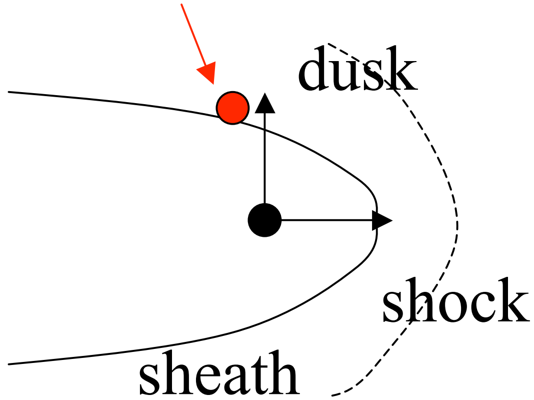
Kelvin-Helmholtz Instability

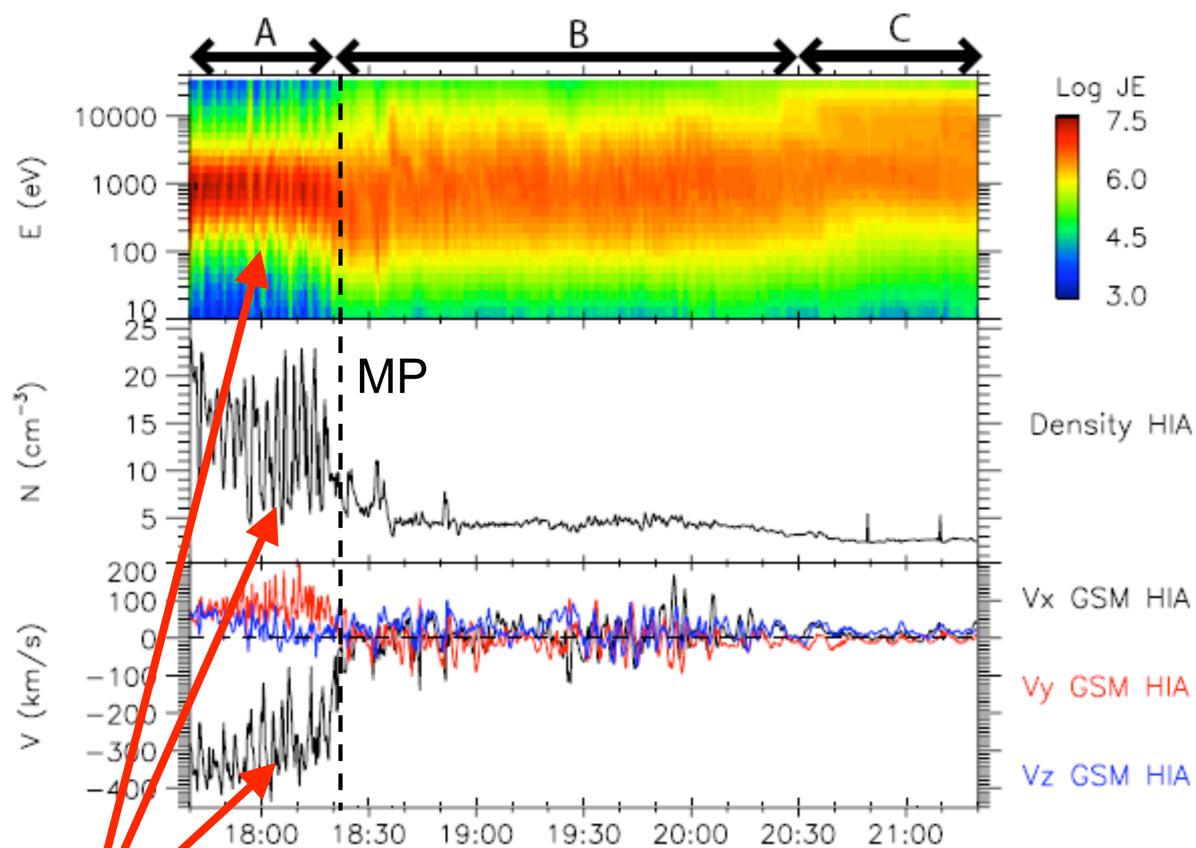


Chaston et al., 2007

Distinct populations in the LLBL may result from different entry mechanisms during this MP crossing

Double-Star spacecraft at dusk MP



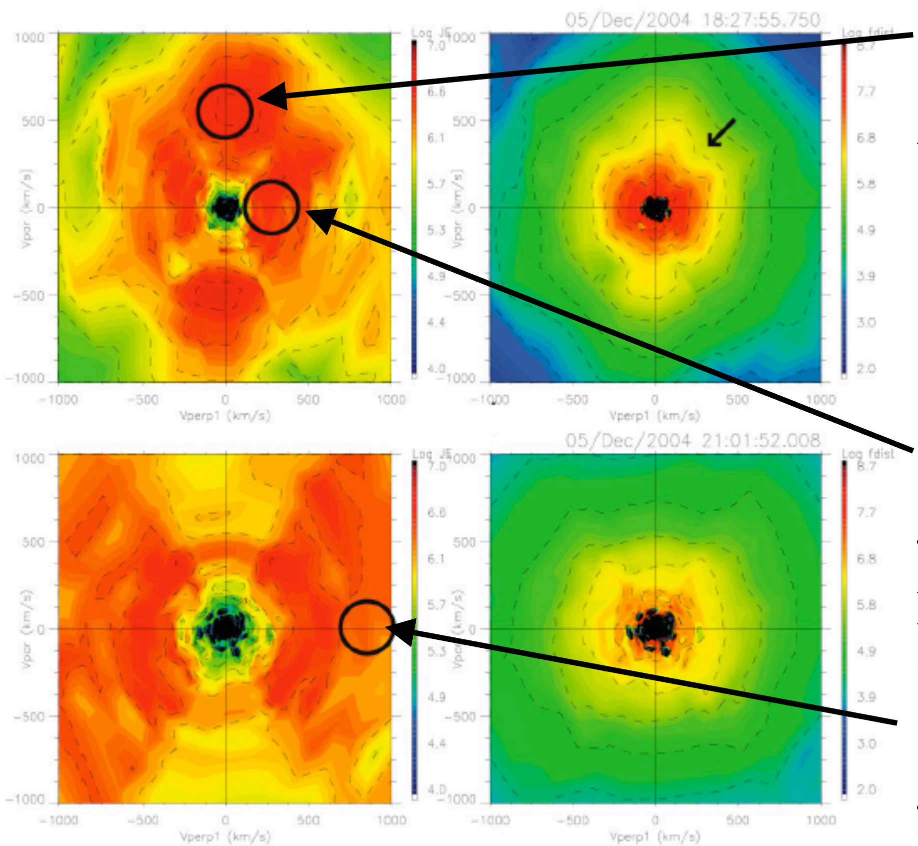


Fluctuations due to rolled-up KH vortices

Taylor and Lavraud, 2008

A: Magnetosheath
B: MP/Boundary layer
C: Inner BL/ plasma sheet

Three Distinct Populations Observed at K-H Unstable LLBL



Taylor and Lavraud, 2008

1) Cold population with parallel temperature anisotropy

- may be produced by reconnection in KHI [Nykyri et al., 2006, Nihsino et al, 2007]
- Double high latitude reconnection may also produce similar signature, but is unlikely cause during this interval

3) Cold population with perpendicular temperature anisotropy

Can be produced by Kinetic Alfven waves [Johnson and Cheng, 2001]

3) A typical hot magnetospheric population

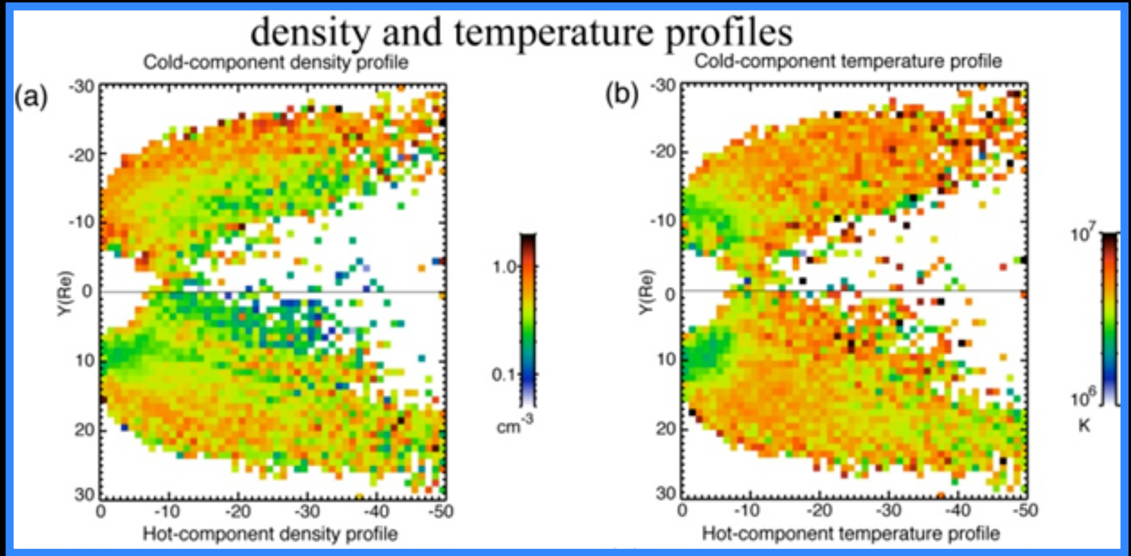
The two cold populations are distinct and may be signatures of different entry mechanisms

Constraints on Plasma Entry

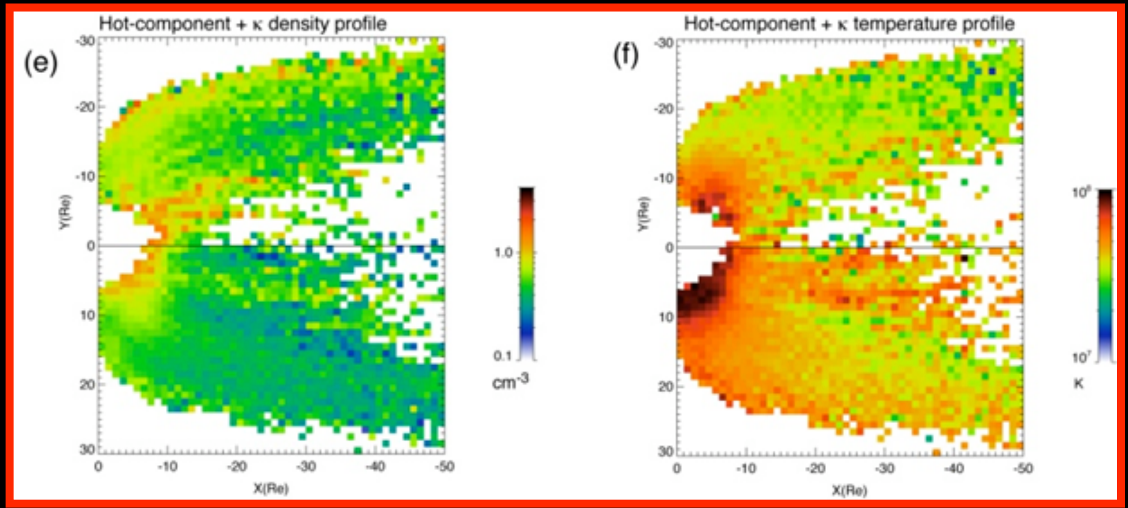
- Dawn-dusk asymmetries
- Phase space density
- Entropy
- Ion to electron temperature ratio

Asymmetries for Northward IMF

Cold plasma is dense along the flanks, hotter and denser on the dawn flank



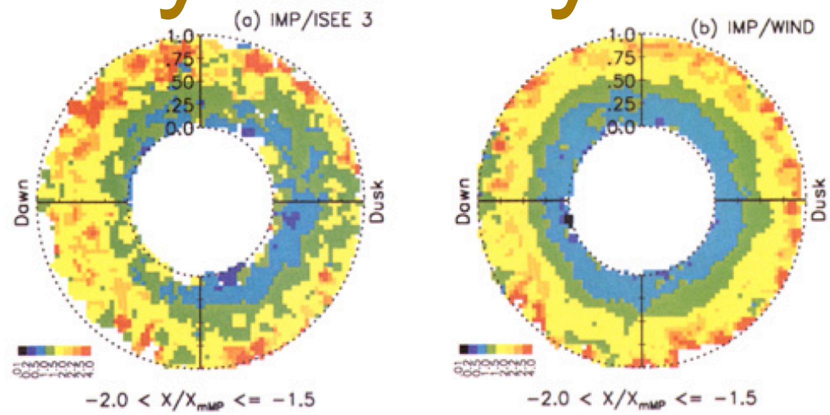
Hot plasma asymmetry in temperature



Wing et al., 2005

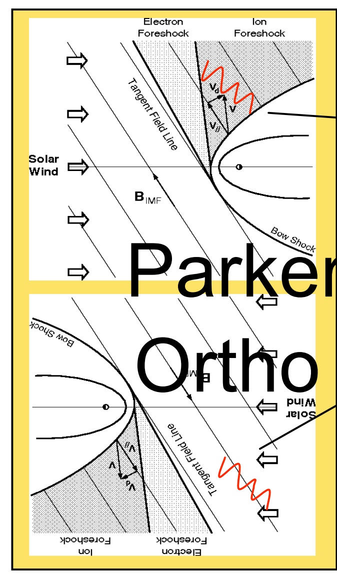
Source of the Asymmetry?

- Asymmetries in the magnetosheath?

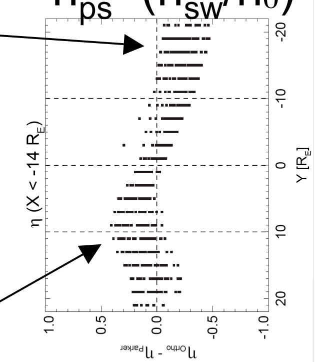


Paularena et al, 2007

- Parker spiral effect on transport processes?



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



Nagata et al, 2007

- Ionospheric conductance?

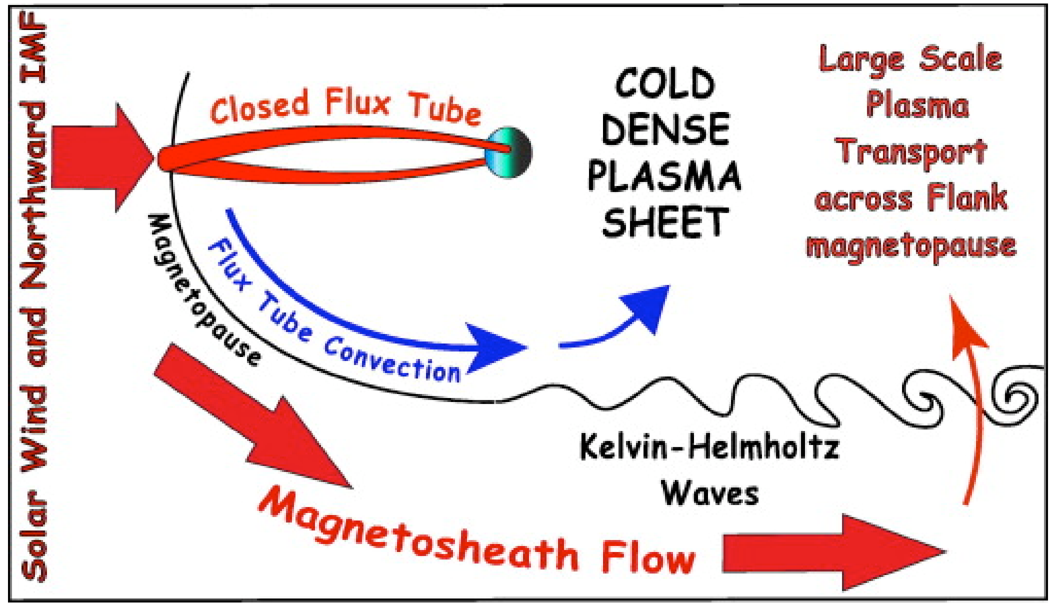
Li et al., 2007

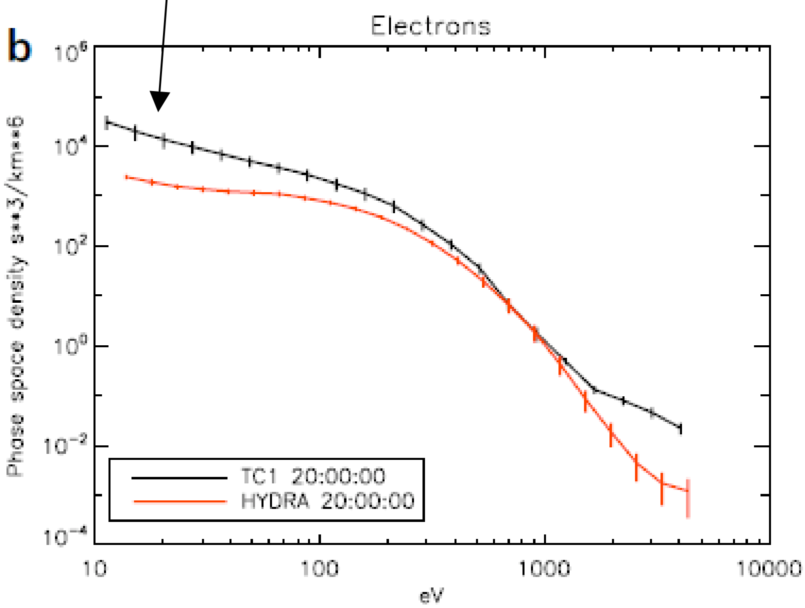
Constraints on Plasma Entry

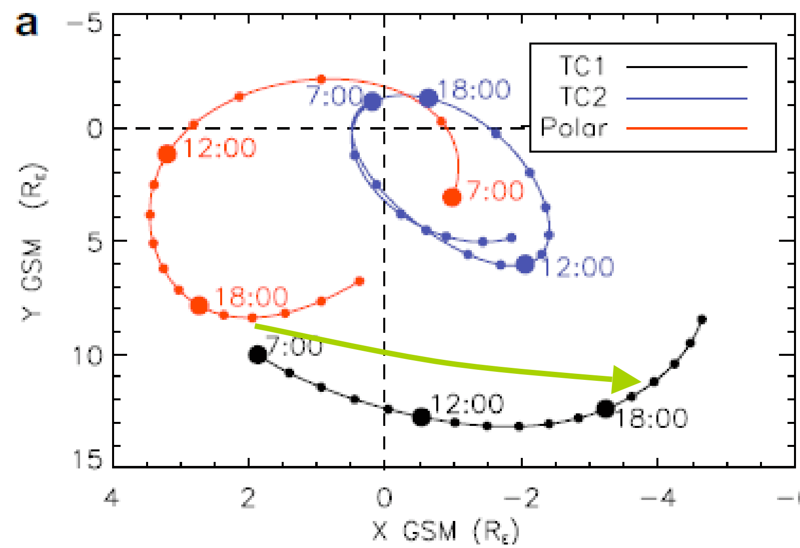
- Dawn-dusk asymmetries
- Phase space density
- Entropy
- Ion to electron temperature ratio

Phase Space Density

Additional phase space density required to explain flank measurements







Taylor et al., 2008

Constraints on Plasma Entry

- Dawn-dusk asymmetries
- Phase space density
- Entropy
- Ion to electron temperature ratio

Entropy as a Conserved Quantify

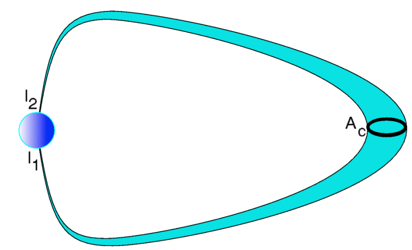
$$S = -\int d^3\mathbf{x} \int d^3\mathbf{v} \quad f log f$$

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{x}} + \frac{\mathbf{F}}{m} \cdot \frac{\partial f}{\partial v} = \left(\frac{\partial f}{\partial t}\right)_c$$

$$\frac{dS}{dt} = 0 \qquad\qquad S_0 = -\int f_0 \log f_0$$

Local vs Total Entropy

- Total Entropy: S=kN[3/2 log(T) - log(n) + σ_0];
- Entropy density (S/N)
  - $\sigma \sim \log(p/n^\gamma)$
  - $s = p/n^\gamma$ constant if entropy is conserved
- Entropy per unit flux
  - Related to frozen in condition



$$S = \int p^{1/\gamma} ds/B \sim M = \int \rho dV = \int \rho ds/B, \quad \gamma = 5/3$$

- Relation to entropy of the flux tube

$$\Sigma = \int \int \rho \sigma dV = \quad CM \log(S/M)$$

Equation of Energy

mass

$$\frac{\partial n_\alpha}{\partial t} + \nabla(n_\alpha \vec{v}_\alpha) = 0$$

momentum

$$\rho_\alpha \frac{d_\alpha \vec{v}_\alpha}{dt} + \nabla.(p_\alpha \mathbf{I} + \mathbf{\Pi}_\alpha) - \rho_\alpha \vec{g} - Q_\alpha \vec{E} - \vec{j}_\alpha \times \vec{B} = \vec{\mu}_\alpha$$

energy

$$\frac{d_\alpha p_\alpha}{dt} - \gamma_\alpha \frac{p_\alpha}{\rho_\alpha}\frac{d_\alpha \rho_\alpha}{dt} = (\gamma_\alpha - 1)\left\{-\nabla.\vec{\Phi}_\alpha - \sum_{l=1}^{3}\sum_{k=1}^{3}\Pi_{\alpha,kl}\frac{\partial v_l}{\partial x_k} + H_\alpha\right\}$$

Heat Flux

$$\vec{\Phi}_\alpha = \frac{1}{2}\rho_\alpha < u_\alpha^2 \vec{u}_\alpha >_\alpha = \frac{1}{2} m_\alpha \int f_\alpha \mid (\vec{w} - \vec{v}_\alpha) \mid^2 (\vec{w} - \vec{v}_\alpha) d^3\vec{w} \qquad (3.9)$$

Gyroviscosity

$$\Pi_{\alpha,kl} = P_{\alpha,kl} - p_\alpha \delta_{kl}$$

$$P_{\alpha,kl} = \rho_\alpha < u_{\alpha,k} u_{\alpha,l} >_\alpha = \int m_\alpha f_\alpha(\vec{r}, \vec{w}, t)(w_k - v_{\alpha,k})(w_l - v_{\alpha,l}) d^3\vec{w} \qquad (3.3)$$

Collisional Energy Exchange

$$H_\alpha = \int C_\alpha \frac{m_\alpha u_\alpha^2}{2} d^3\vec{w} \qquad (3.10)$$

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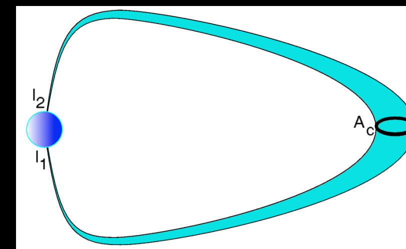
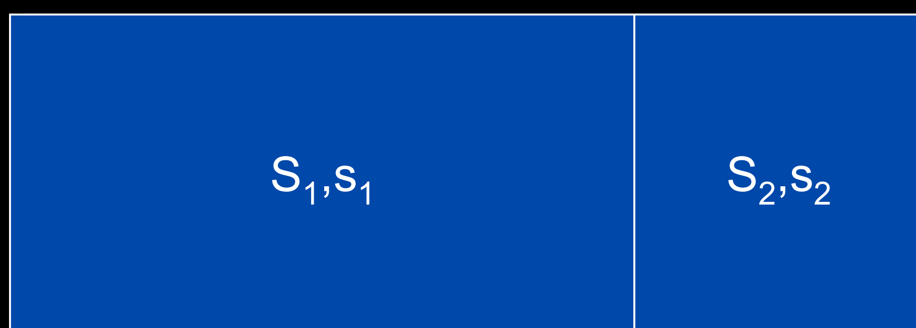
Intensive/Extensive Properties of Entropy



- Extensive (Total/Global)
  - $S=p^{1/\gamma} V$ where V is the flux tube volume
  - Proportional to mass and field-line length
- Intensive (Specific/Local)
  - $s=p/\rho^{\gamma}$ ---the adiabatic pressure law usually assumed in MHD

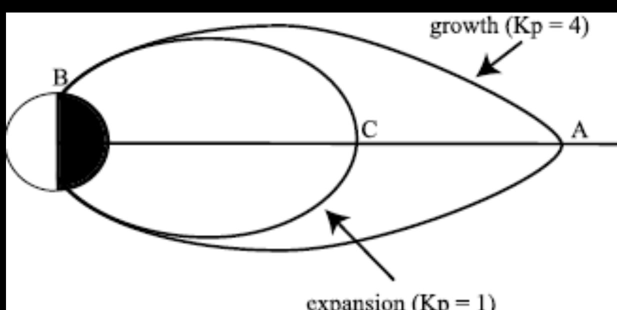
$S_1 + S_2 = S_T$

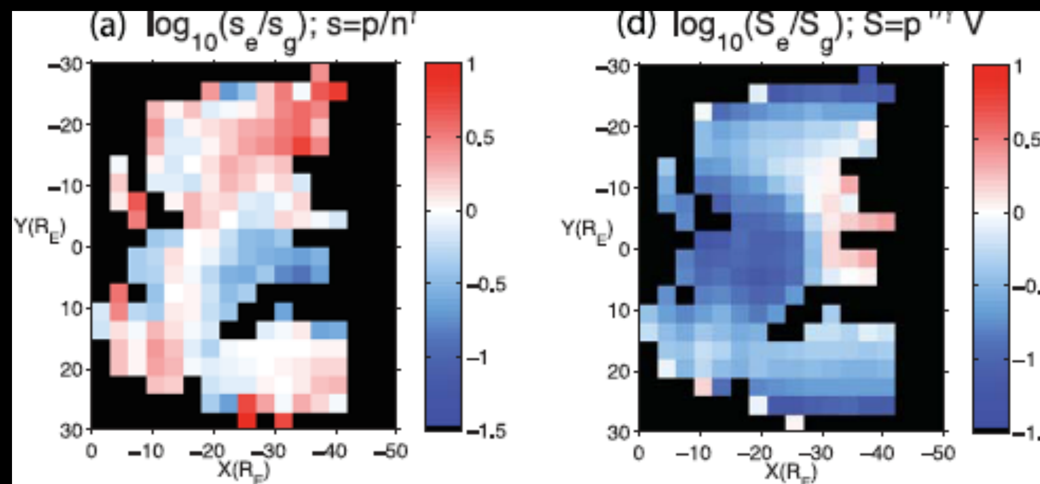
$s_1 = s_2 = s_T$



Example of the Extensive/Intensive Properties of Entropy

- Near Earth Plasma Sheet total entropy changes from substorm growth to expansion, but local entropy remains relatively unchanged

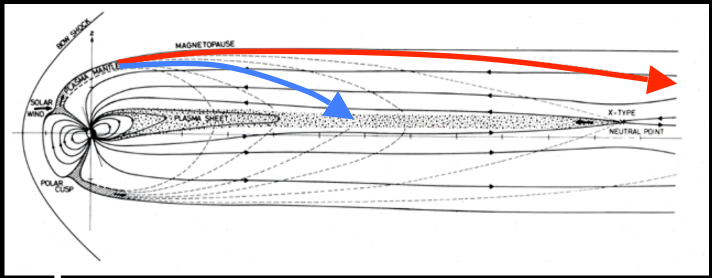




Wing and Johnson, 2009

Why Look at Entropy?

- Indicator of organization/stability
- Changes are an indicator of:
  - – a nonadiabatic process (wave particle interactions)
  - – mass loss from flux tubes
  - – heat loss from flux tubes
  - – integrity of the fluid element



S_T, s_T → S_1,s_1 S_2,s_2

How Can Entropy Increase in a Collisionless System?

Background Entropy Increases at the Expense of Fluctuations

$$f = f_0 + \delta f$$

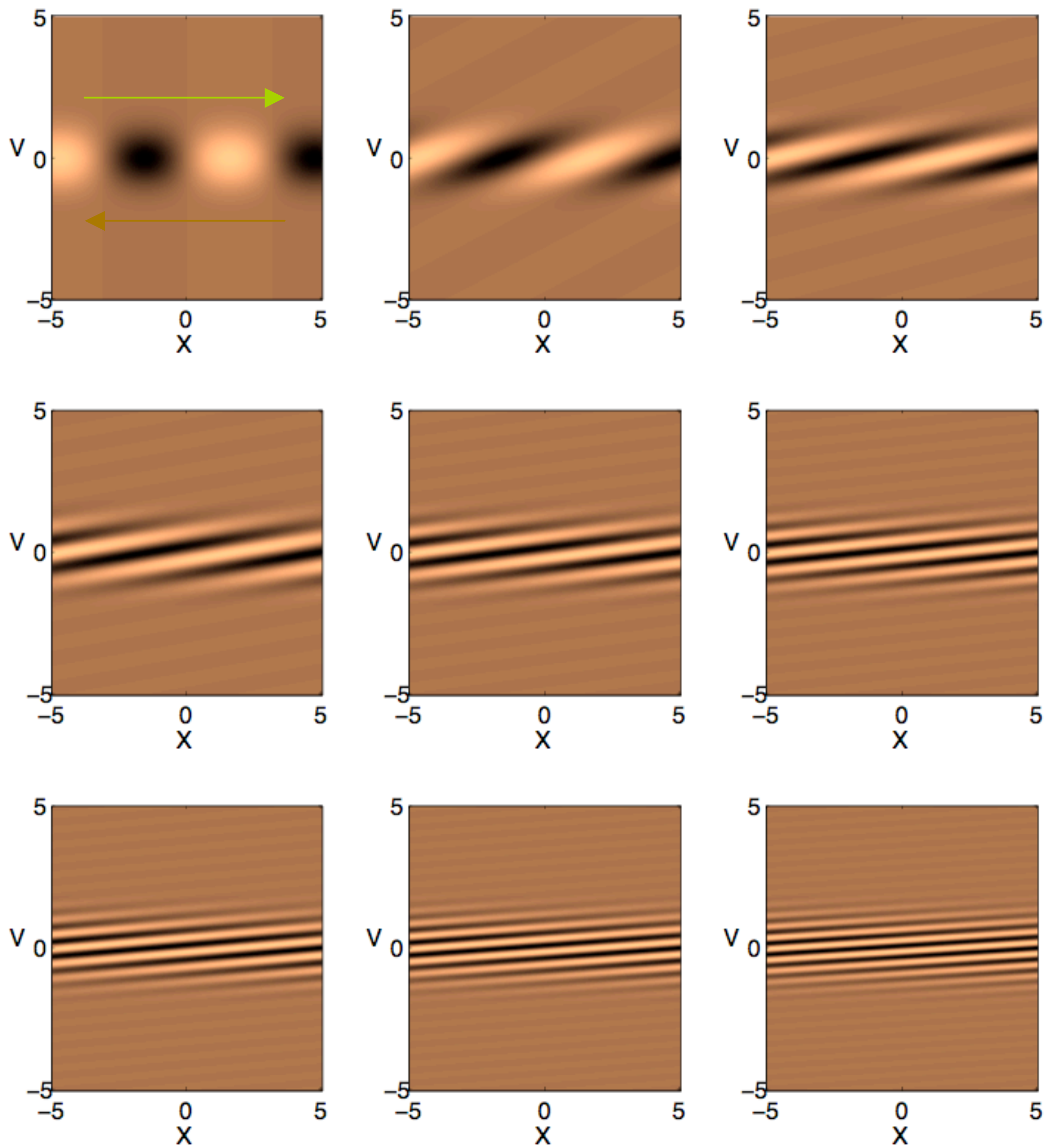
$$S = -\int f_0 \log f_0 - \int \delta f (1 + \log f_0) - \int \frac{\delta f^2}{f_0}$$

$$\bar{S} = S_0 - \int \frac{\overline{\delta f^2}}{f_0}$$ ⟵ Time Average

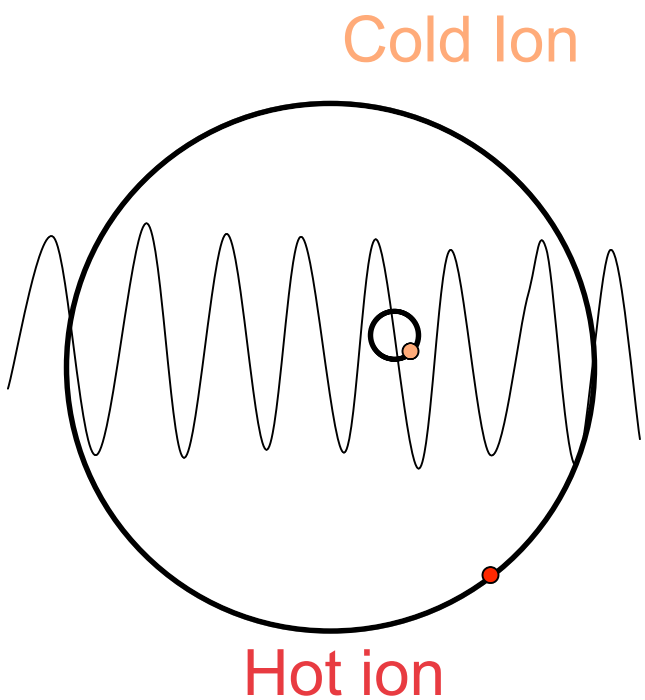
Spatial Structure→Velocity Space Structure

- $\partial f/\partial t + v\partial f/\partial x=0$
- $x = x_0 + vt$
- $f(x,v,0) = g(x,v)$
- $f(x,v,t) = g(x-vt,v)$
- $f_k \sim \exp(-ikvt)$

- $<\delta f> \rightarrow 0$
- $<(\delta f)^2>$ increases



Kinetic Alfven Waves and Loss of Entropy



- Hot ions ($k_\perp \rho_i >> 1$)
  - See small <E>
  - $V_d \sim \langle E \rangle \times B$ is small
- Cold Ions (($k_\perp \rho_I << 1$)
  - See large <E>
  - $V_d \sim \langle E \rangle \times B$ is large

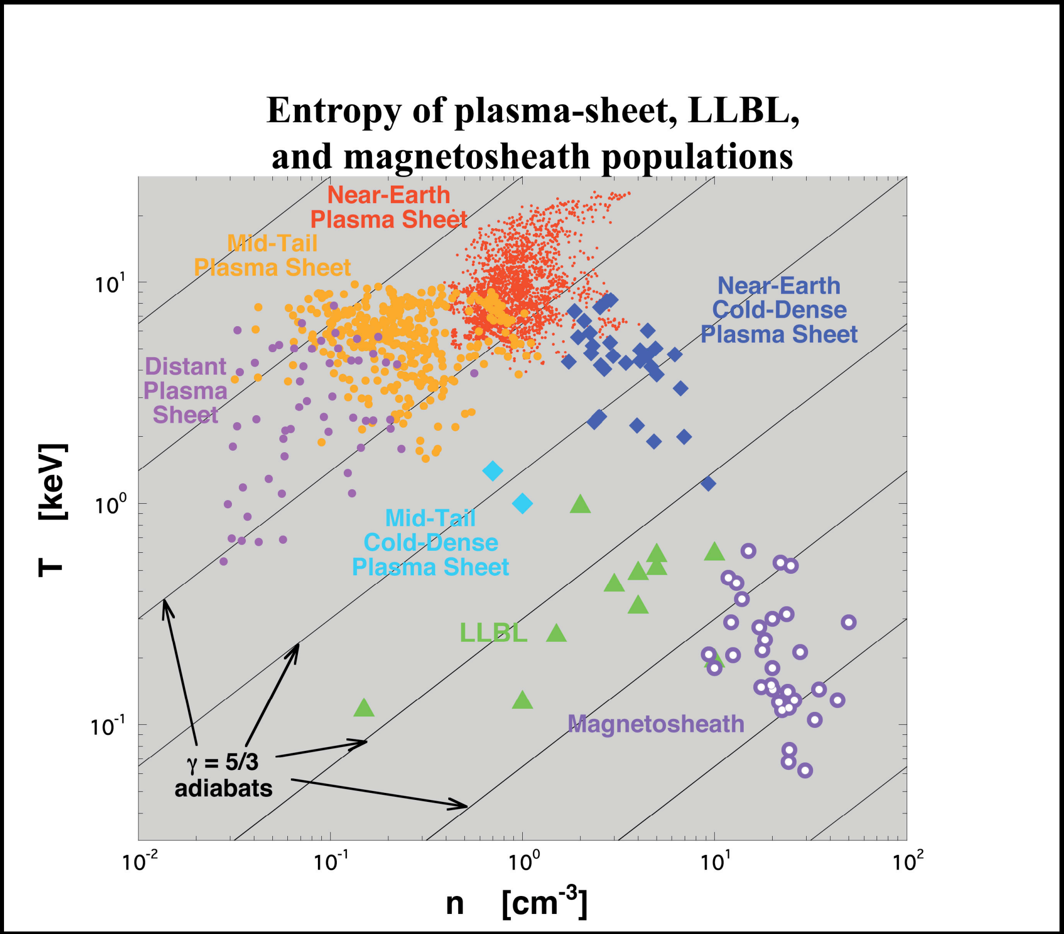
$\Rightarrow$ shear in velocity

Tatsuno et al., 2009

Entropy for Northward IMF

Entropy in the Magnetosphere

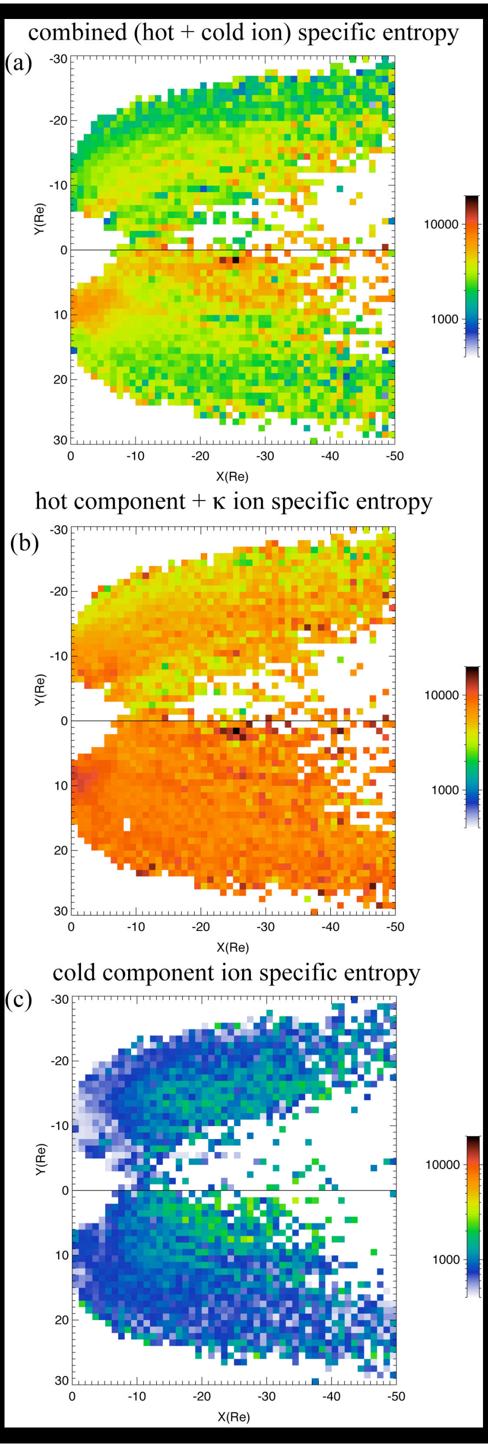
- Significant increase of entropy from sheath to CDPS
- Conservation in the convection direction?



Borovsky, 2005

Northward IMF Entropy Profiles

- Combined entropy has variation mostly in Y
- Hot entropy shows a dawn-dusk heat flux
- Cold entropy increases by a factor of 5 from flank to midnight in Y direction
- Gradients in PS entropy may reflect entropy changes at the boundary.



Johnson and Wing, 2009

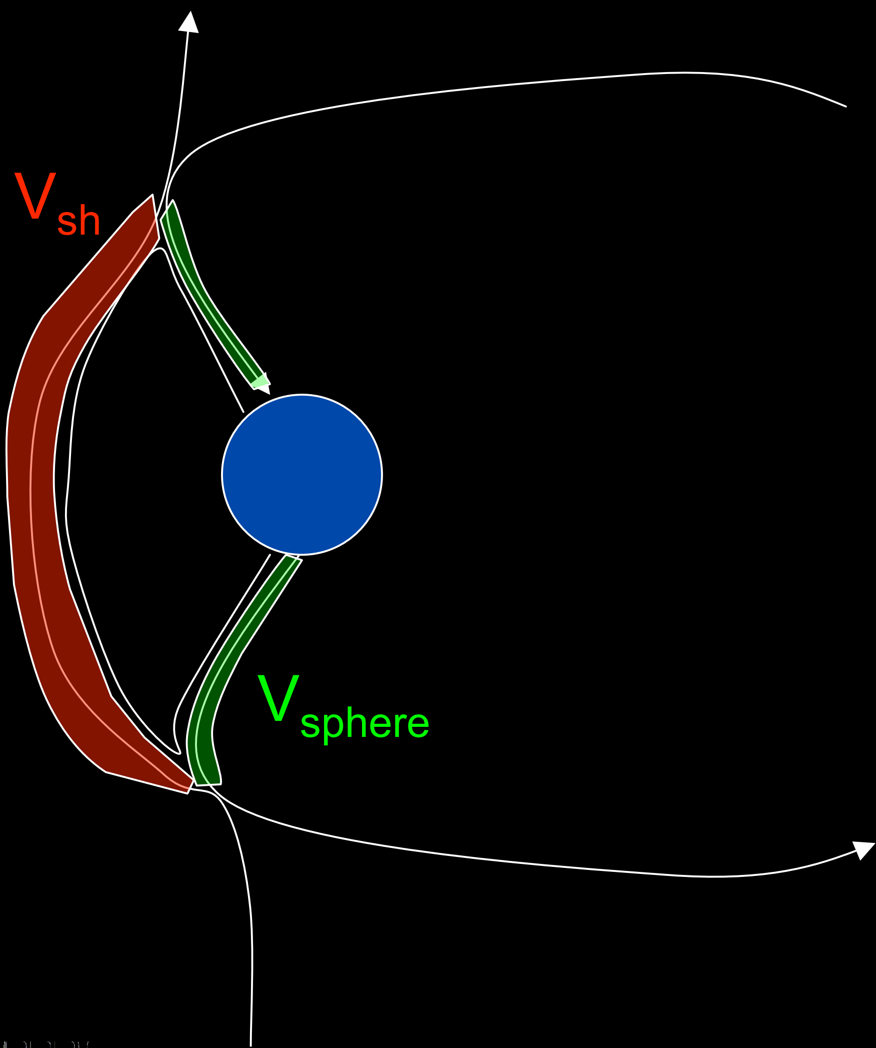
Important Questions about Entropy

- Why does the entropy of the nominal hot plasma sheet increase so much relative to the magnetosheath (a factor of 100)?
- Why does the entropy of the cold material increase by a factor of 5-10 or more?
- How does entropy change for hot and cold populations (considered separately?
- How does the combined single fluid (hot + cold) entropy change (note that it can be quite different from the hot and cold components)?
- What changes in entropy are expected for:
  - Tailward of cusp reconnection
  - Reconnection in KH vortices
  - Kinetic Alfven waves

How does cold population entropy change for cusp reconnection?

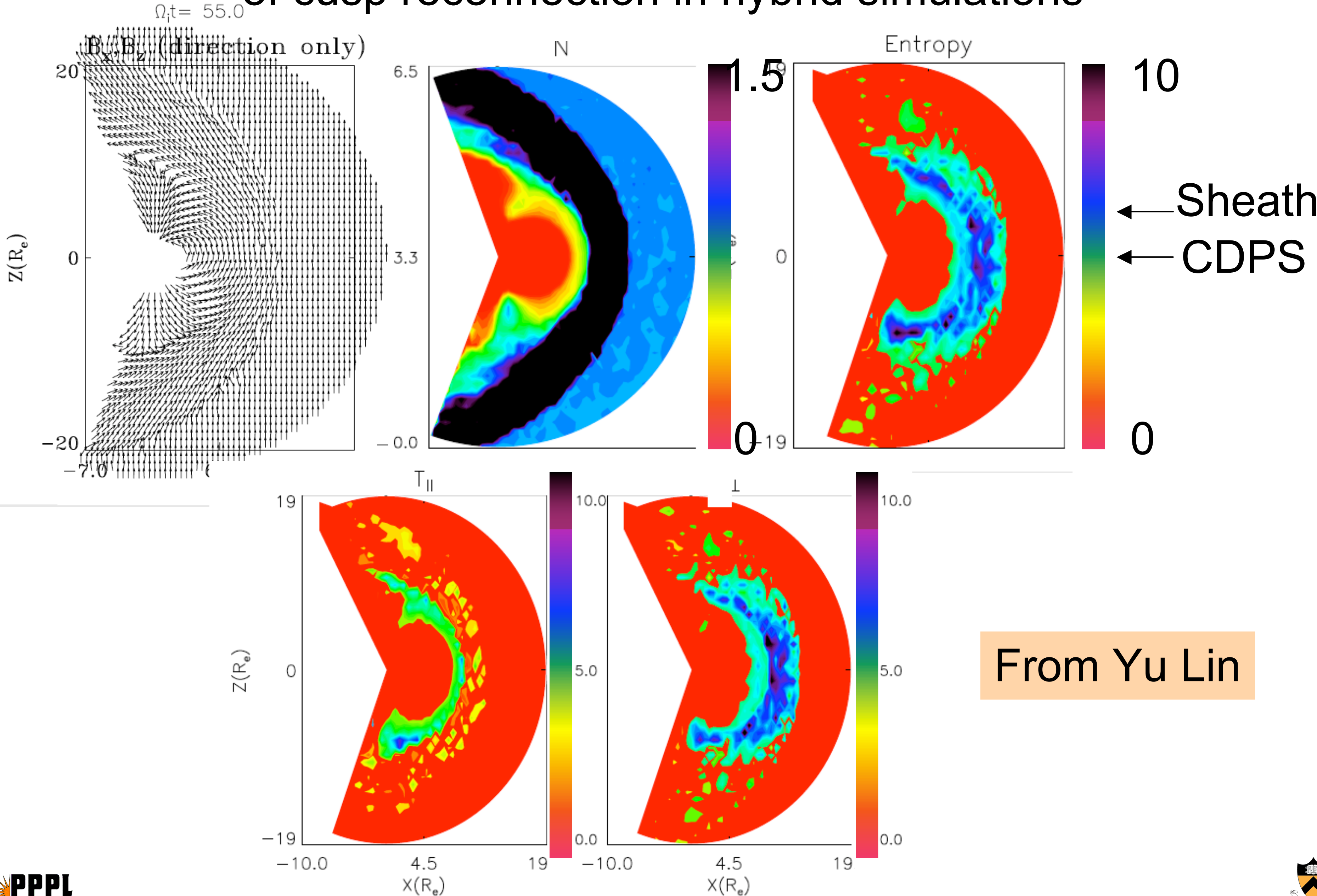
- Assume that the source population for the cold plasma is from the magnetosheath (much denser than lobe)
- In high beta plasma, expect little increase of entropy due to reconnection at the current layer
- Entropy of the cold population can increase as plasma expands into a reconnected flux tube if it was previously unpopulated with cold plasma
- Free expansion along the flux tube leads to a heat flux and is more likely an isothermal (rather than adiabatic) process
- V_{sh} = flux tube volume between separatrices~volume of sheath plasma captured
- V_{sphere} =flux tube volume between ionosphere and separatrices
- Assuming density becomes constant after a few bounce times, $\rho_{final} = \rho_{sh} V_{sh}/(V_{sh} + V_{sphere})$
- $s_f = s_{sh} (1 + V_{sphere}/V_{sh})^{\gamma-1}$
- $\Delta s/s \approx (\gamma - 1)(V_{sphere}/V_{sh})$

Cold Population Local Entropy Can Be Increased a small amount by Reconnection



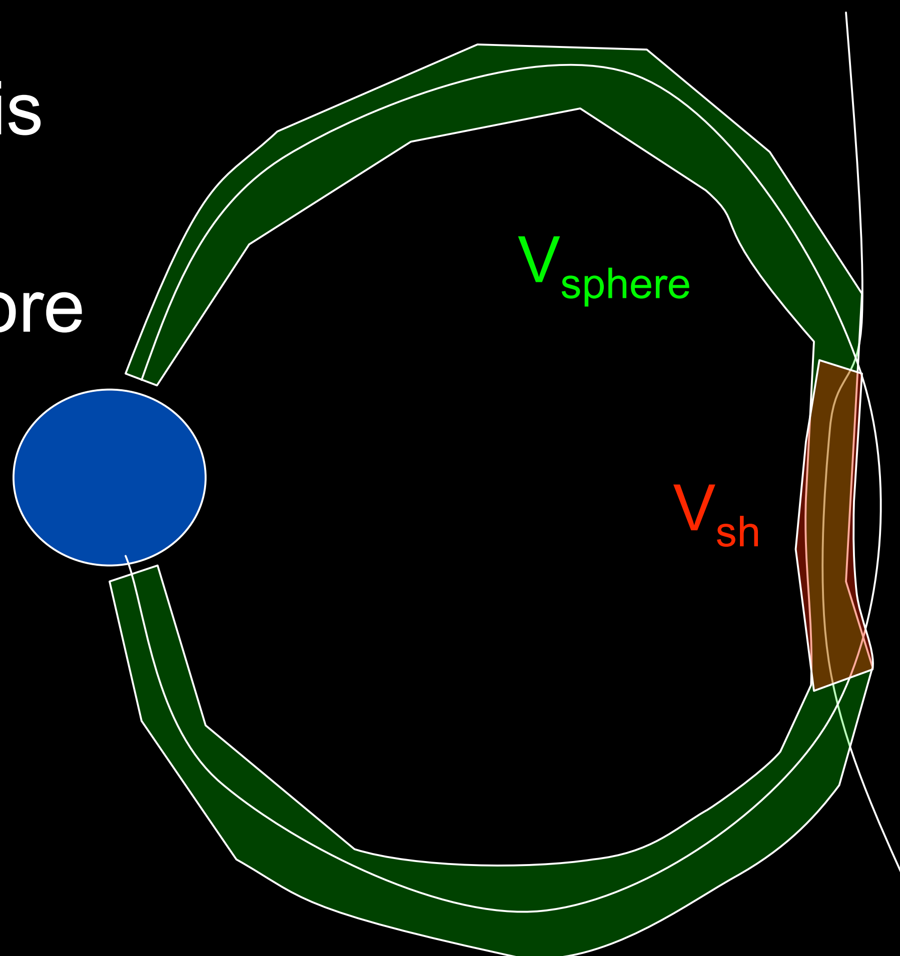
- $V = \int ds/|B|$, $n = N/V$
- $\Delta s/s = (\gamma-1)\,(V_{sphere}/V_{sh})$
- $\Delta s/s < 1$
- But, the captured plasma cannot increase s very much which implies losses or heating?

Entropy does not increase significantly across the MP for tailward of cusp reconnection in hybrid simulations



Kelvin-Helmholtz can increase the local entropy of the entering cold population significantly

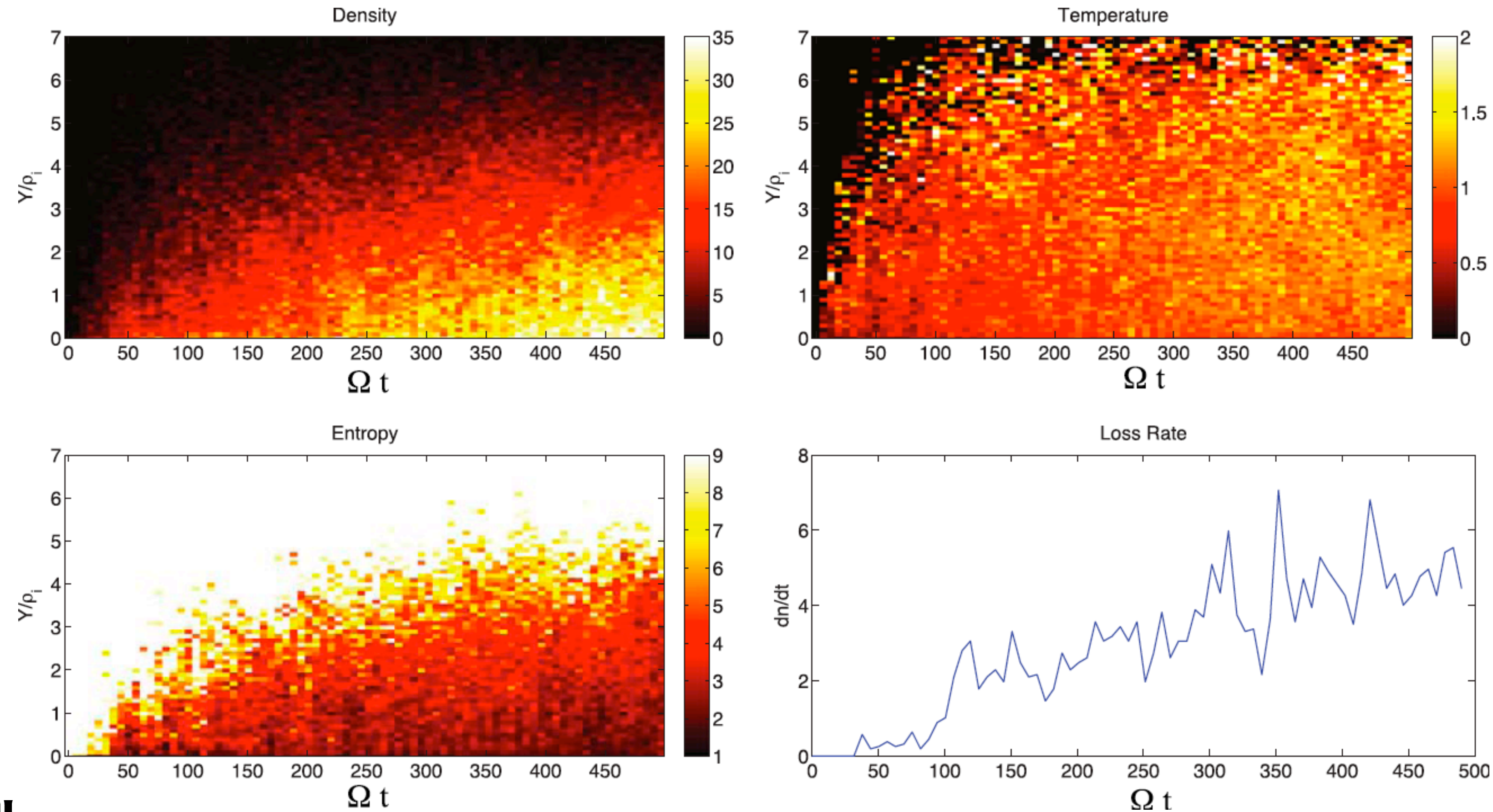
- In this case much less magnetosheath plasma is captures
- Entropy can increase more



- $s_f = s_0\ (1+V_{sphere}/V_{sh})^{\gamma-1}$
- $s_f >> s_0$ if $V_{sphere}/V_{sh} >> 1$

KAWs can increase the local entropy of entering cold plasma

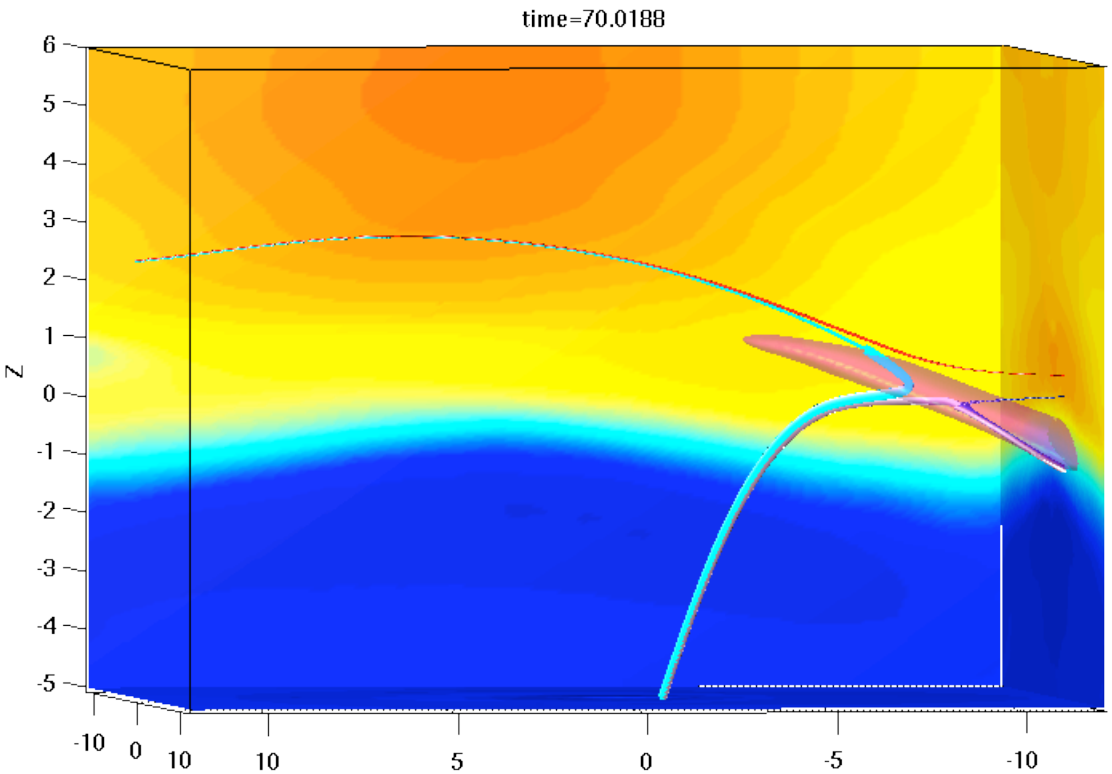
- KAWs lead to heating and diffusion which can increase entropy by order of magnitude



Total Entropy for Cusp Reconnection

- Total flux tube entropy provides a constraint where flux tubes can convect in the tail (single fluid approach)
- Larger total entropy flux tubes could move deeper in the tail (subject to conservation of entropy)
- Consider how the total reconnected flux tube volume depends on component vs antiparallel (near null point) reconnection

Total Entropy H=P$^{1/\gamma}$V (considering both hot and cold plasma) has contributions from both the magnetosheath and magnetosphere portions of the field line. When the field line passes through a null the value of H can be larger



If reconnection right at null, then

$$H = 8 \times 10^4$$

$$H_{est} = H_{msp} + H_{msh}$$

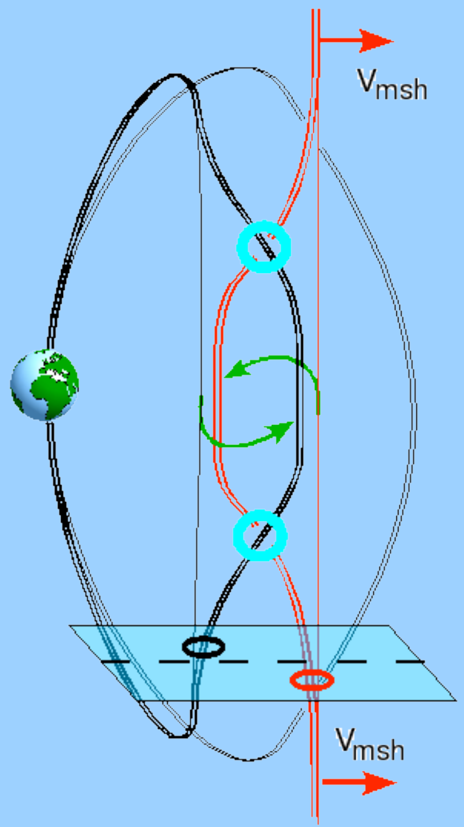
$$H_{est} \approx 1 \times 10^4 \ (\text{at} \sim 9\text{R}_\text{E}) + 3 \times 10^4$$

$$H_{est} \approx 4 \times 10^4$$

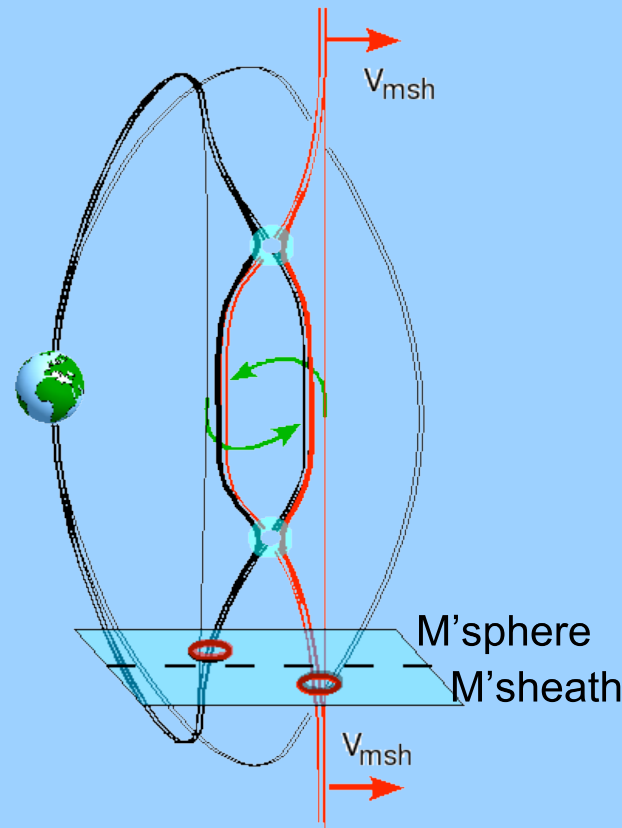
Factor of 2

Adamson, 2009

Mass and Entropy Transport - Method



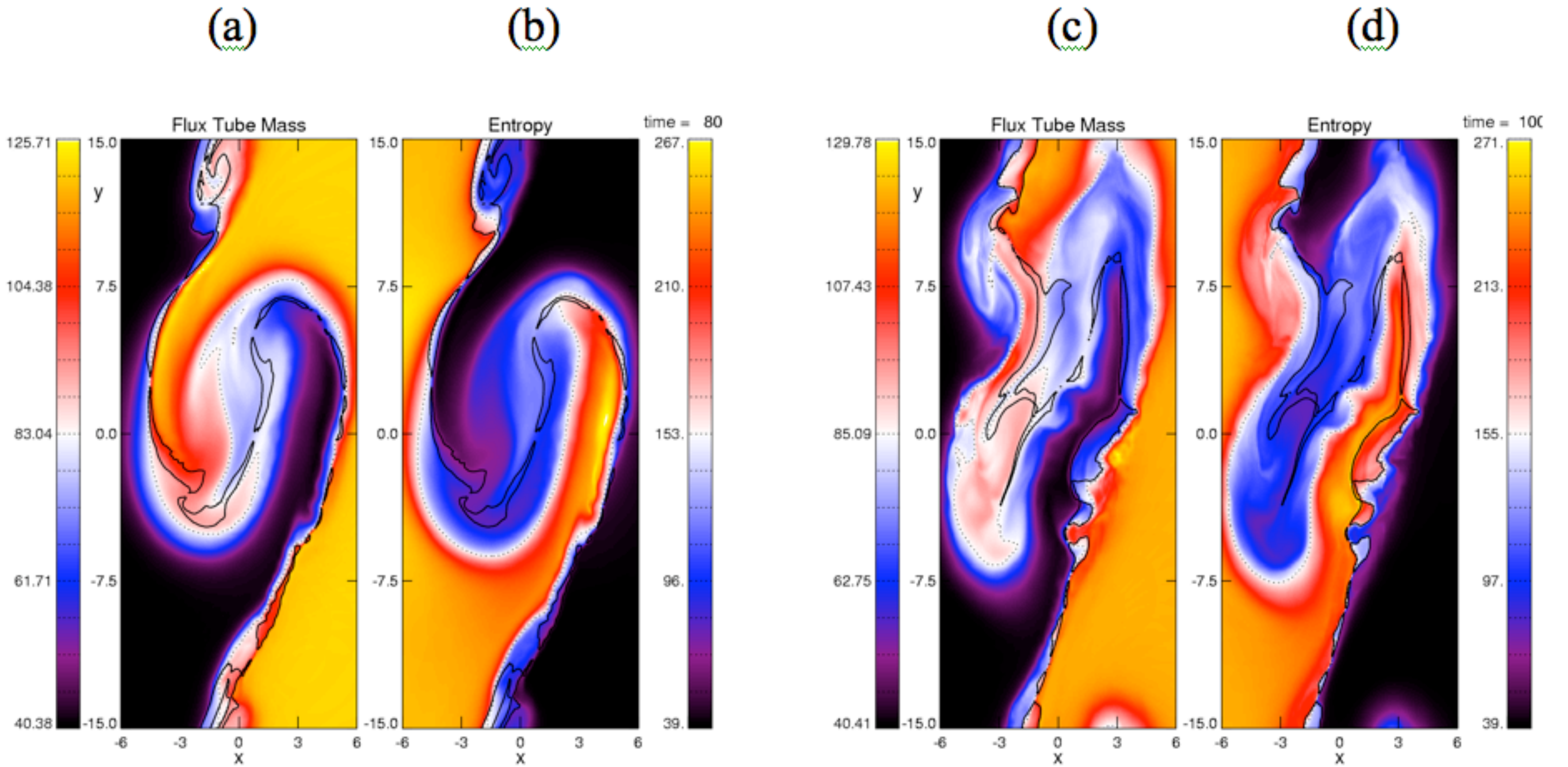
Before reconnection



After reconnection

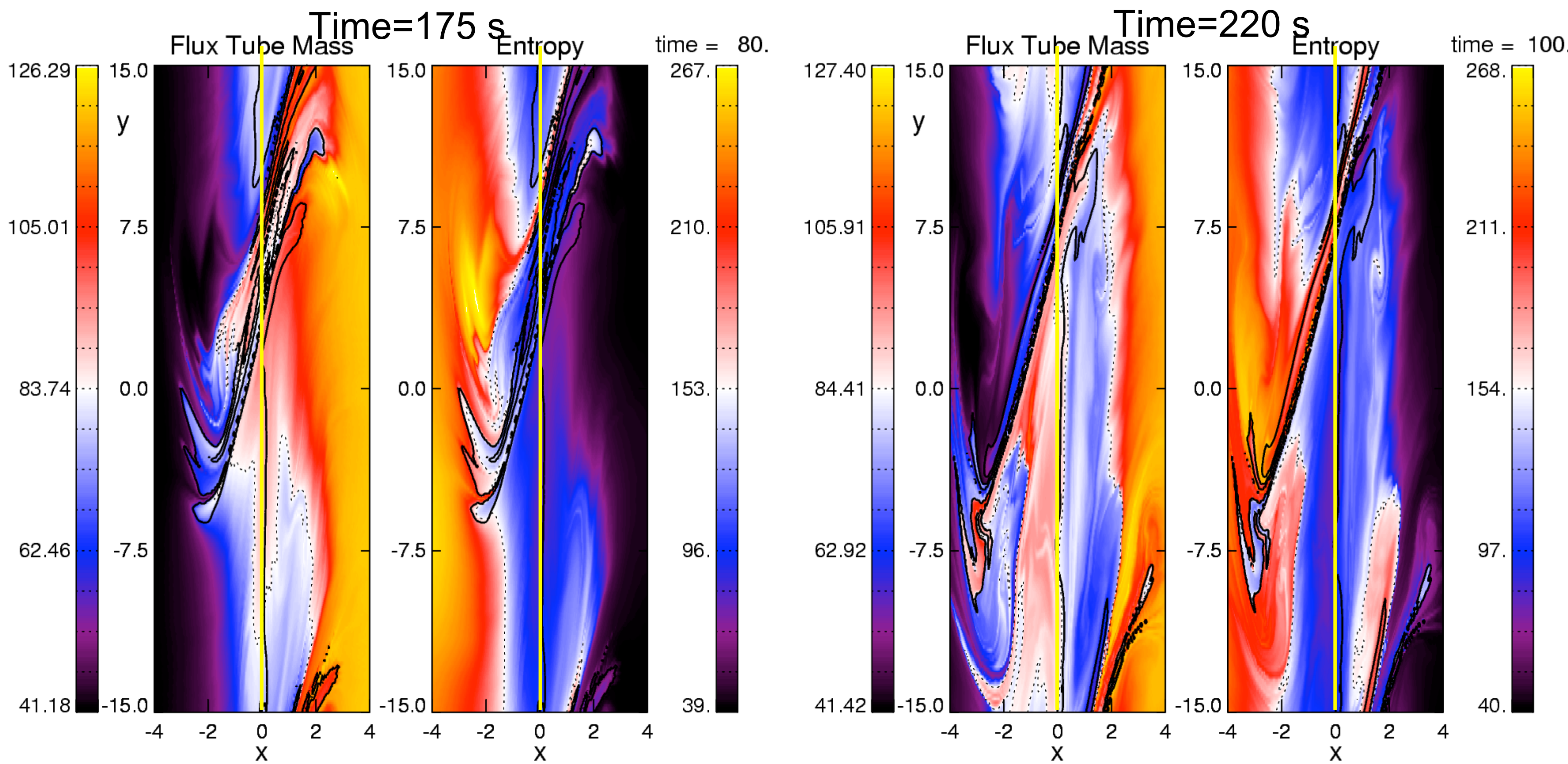
Otto, 2009

Local MHD Simulations show that reconnection leads to field lines being populated by cool magnetosheath and hot magnetospheric plasma with intermediate values of flux tube averaged entropy (includes hot + cold populations in single fluid)



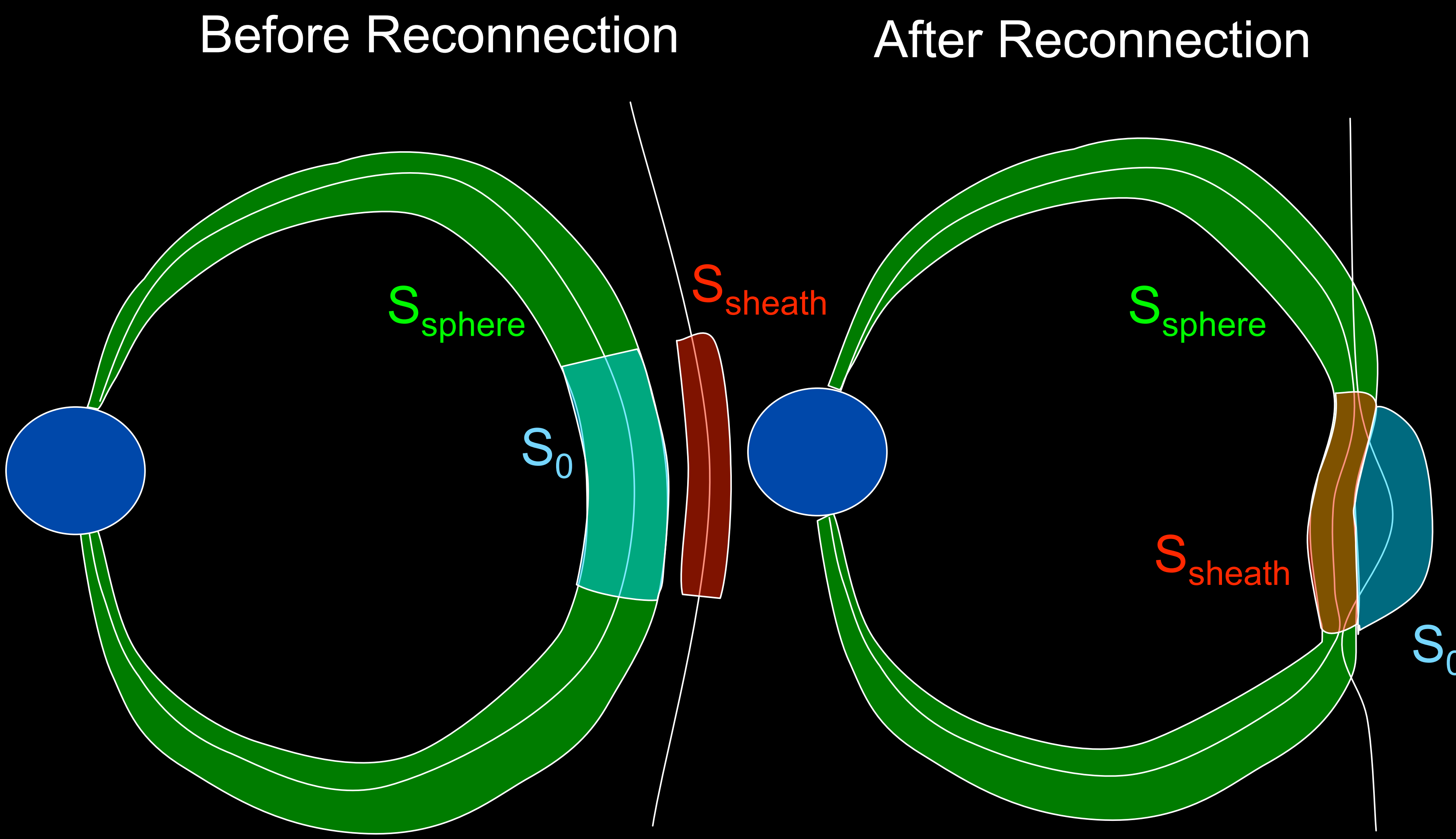
Otto, 2009

Flux Tube Mass and Entropy Mapped to Southern Boundary confirms that field lines that were originally with footpoints in the magnetospheric region become populated with magnetosheath plasma such that the entropy is reduced as a result of mixing of the hot magnetospheric population and cold magnetosheath population (this includes hot+cold populations)



- Average mass transport velocity > 10 km/s
- (Average) Entropy of newly captured plasma average between MSP and MSH values.

Total Entropy Change for KH Reconnection

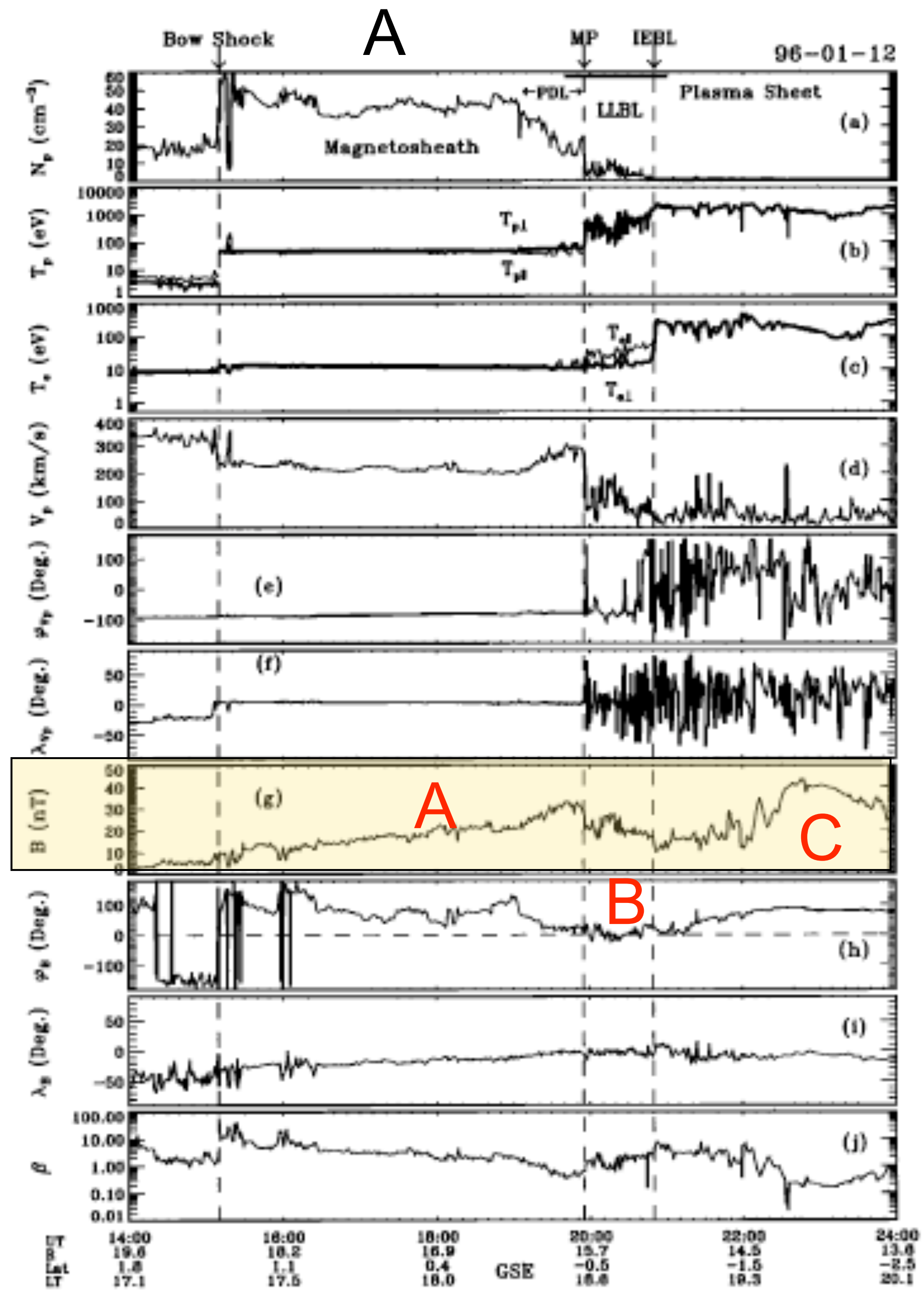


Change of Total Entropy

- $S = \int p^{1/\gamma}\, ds/|B|$
- S is additive
- $\Delta S = S_{sh} - S0$
- $\Delta S/S \sim 1/\gamma\, (\Delta p/p) + (\Delta V/V)$
- $\Delta V/V \approx -\Delta B/B$
- $\Delta p/p = -\,(2/\beta)\,(\Delta B/B)$
- $\Delta S/S = -(\Delta B/B)\,(1 + 2/\beta\gamma)$
- $\Delta S/S = (\Delta p/p)(\beta/2 + 1/\gamma)$
- Negative for Bsh>Bsphere or psh<psphere
- Commonly Observed at MP crossings (related to depletion layer)
- $$\left(PV^{5/3}\right)'\left(V' - P'\mu_o \int \frac{ds}{B^3}\right) < 0$$ Interchange

MP crossing

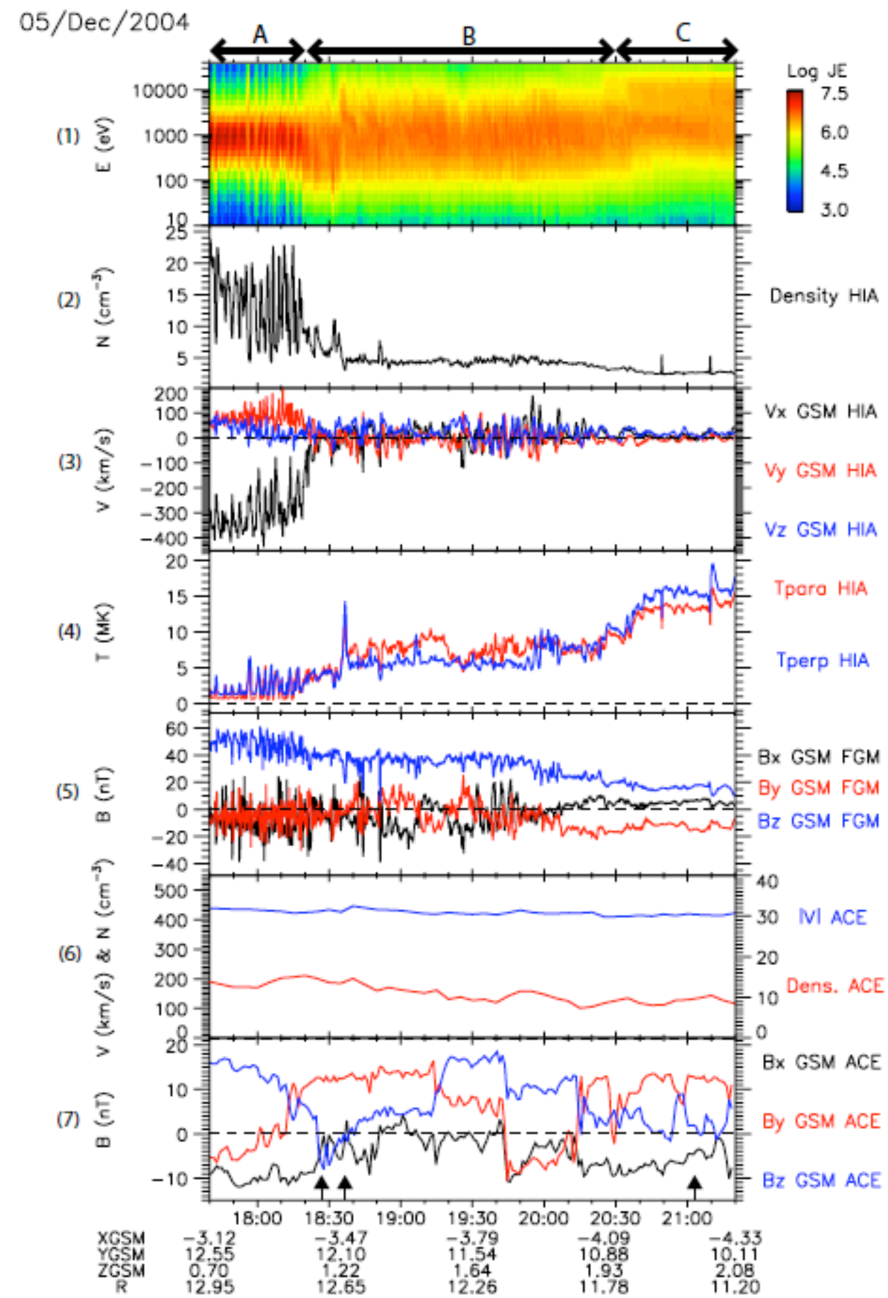
- Crossing
  - A: sheath
  - B: LLBL
  - C: Plasma Sheet
- $B_{sh} > B_{LLBL,PS}$



Phan et al., 1997

MP crossing

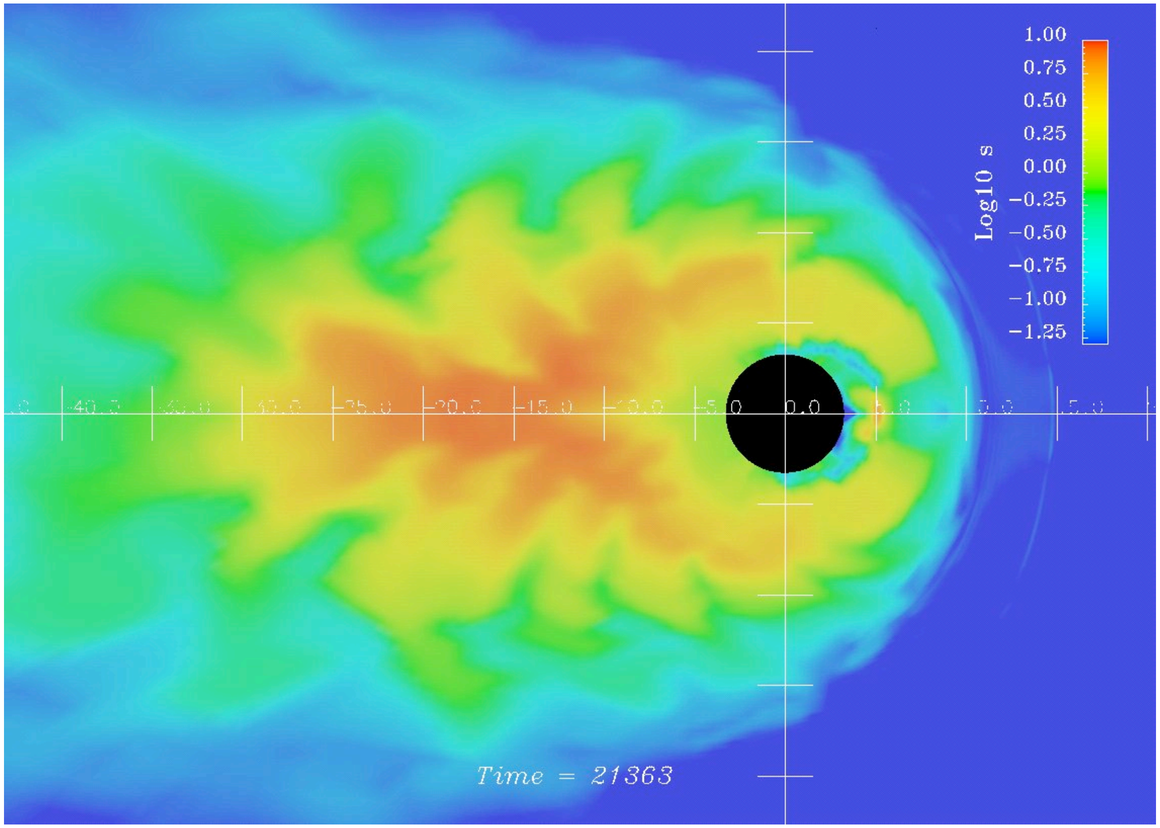
- Crossing
  - A: sheath
  - B: LLBL
  - C: Plasma Sheet
- $B_{sh} > B_{LLBL}$



Taylor and Lavraud, 2008

Entropy Reduction Can lead to Interchange Instability

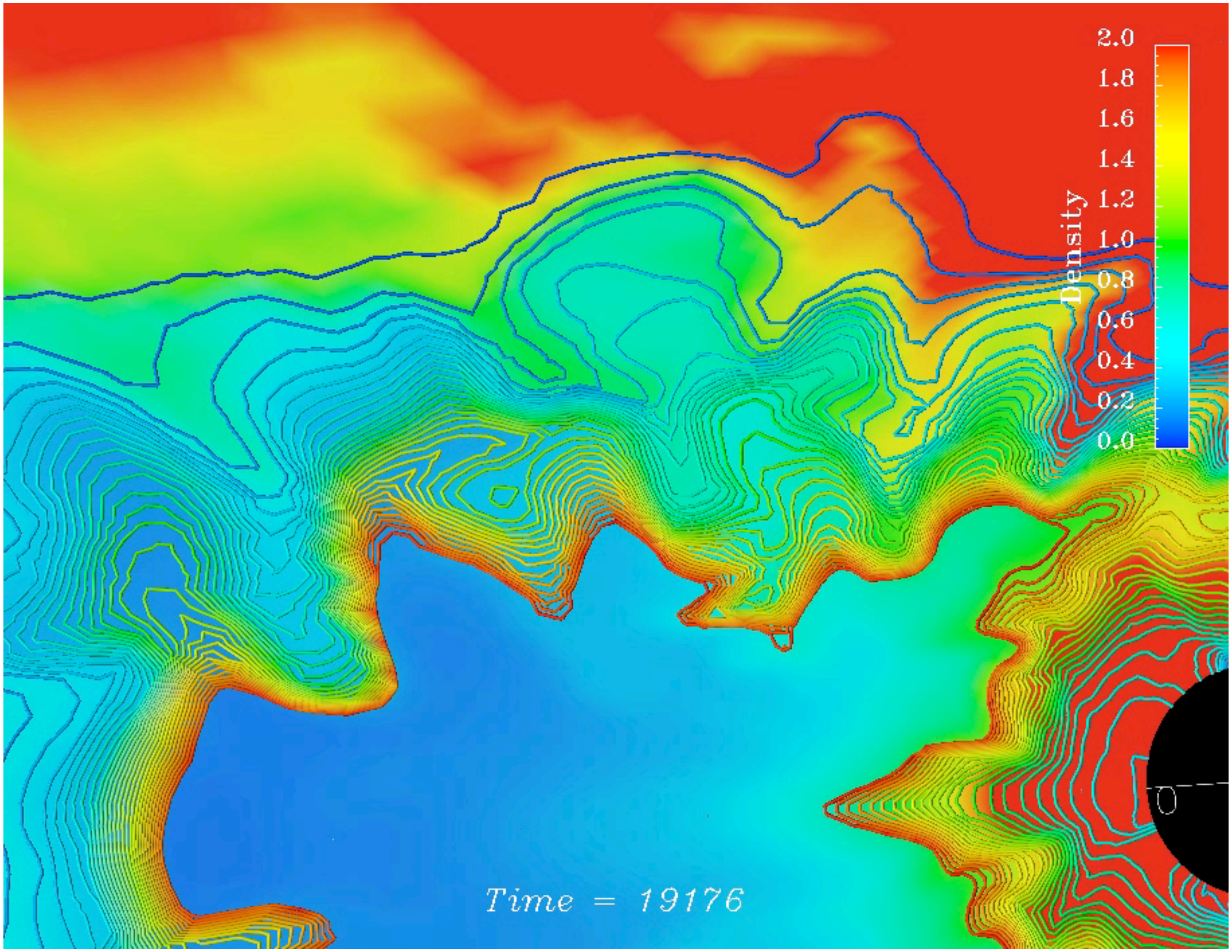
- Once material is injected (low entropy magnetosheath) it becomes interchange unstable and goes inward.



Lyon, 2009

Density and specific entropy

Lyon, 2009



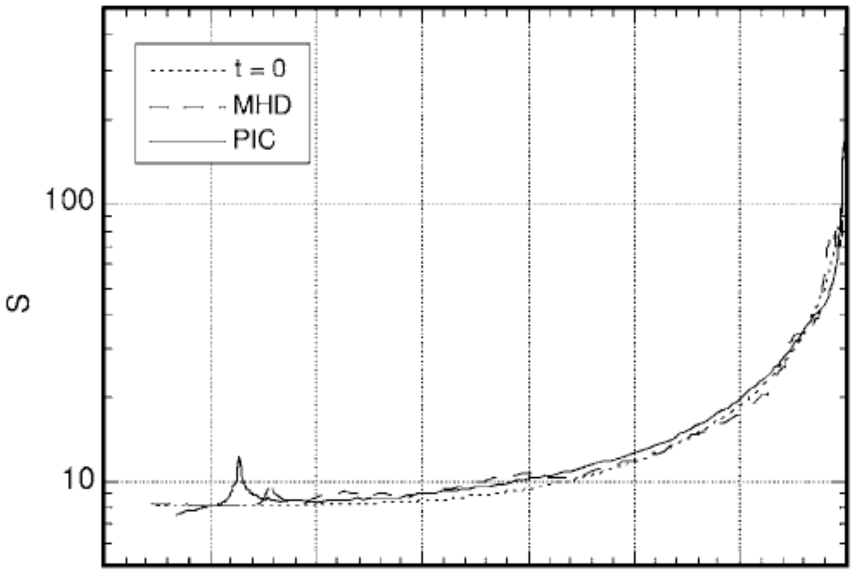
Conclusions on Entropy and the CDPS material

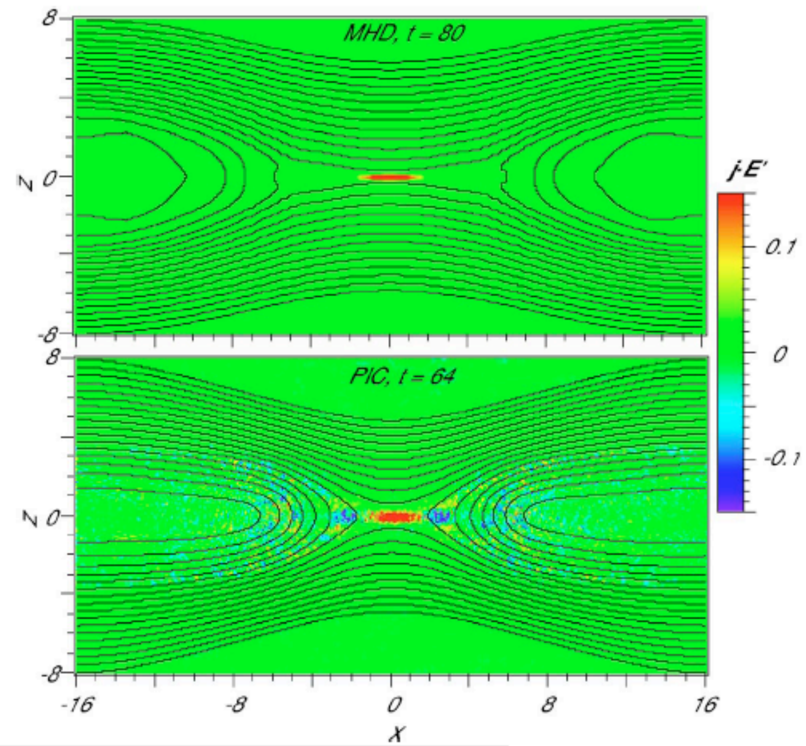
- Local Entropy of cold population
  - Can increase by expansion into the magnetospheric part of the flux tube after reconnection
  - Increases more for KH than for tailward of the cusp reconnection
  - Increases signficantly for KAWs
- Local entropy of hot and cold plasma
  - Should decrease on closed field lines by the addition of cold, dense magnetosheath plasma
- Total entropy of the hot and cold plasma
  - Can be larger for antiparallel (near null) reconnection
  - Could decrease when there is reconnection in KH vortices if $B_{sheath} > B_{sphere}$
  - Reduction of entropy would lead to interchange instability

Entropy and the origin of the hot population from reconnection?

Entropy and Reconnection

- MHD and PIC simulations show little change in total entropy ($\beta = 0.2$)





Birn et al., 2006

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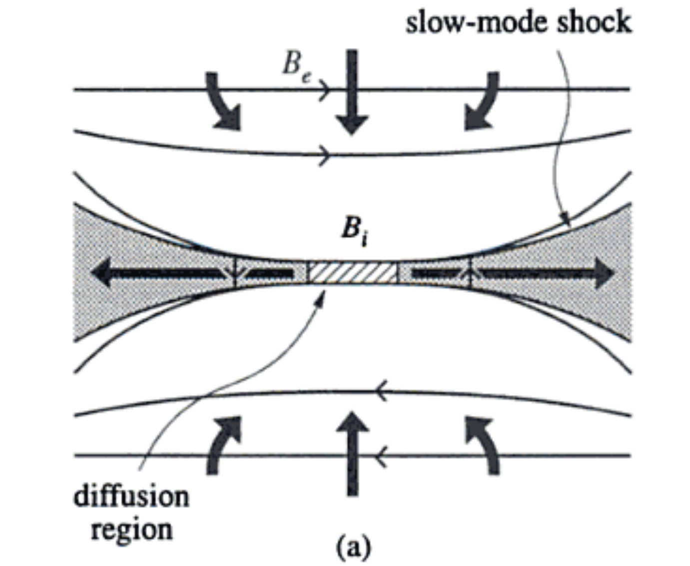
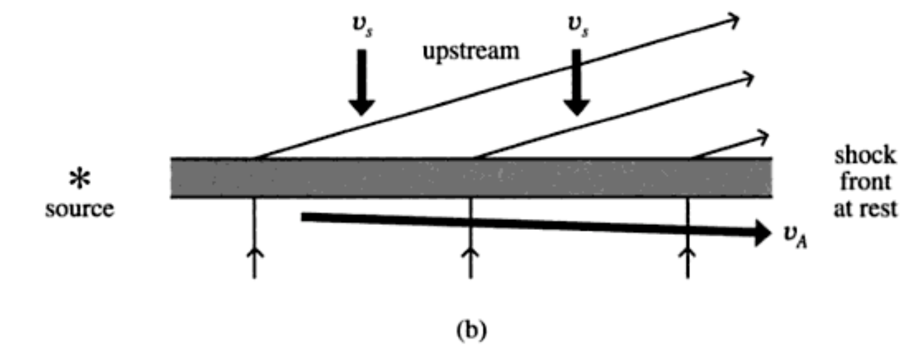
Switch Off Shocks

Petschek Model



Switch off Shock



Priest and Forbes, 2000

Entropy Change at a Slow Shock

Compression:

$$X = \frac{\rho_d}{\rho_u} = 1 + \frac{1}{\gamma\beta + \gamma - 1}\left(1 - \frac{(\gamma\beta - 1)}{\gamma(\beta + 1)}r^2\right)$$

Pressure increase:

$$\frac{p_d}{p_u} = X\left[1 + \frac{\gamma - 1}{\gamma\beta}\left(1 - r^2\right)\right]$$ ~ $(\beta+1)/\beta$

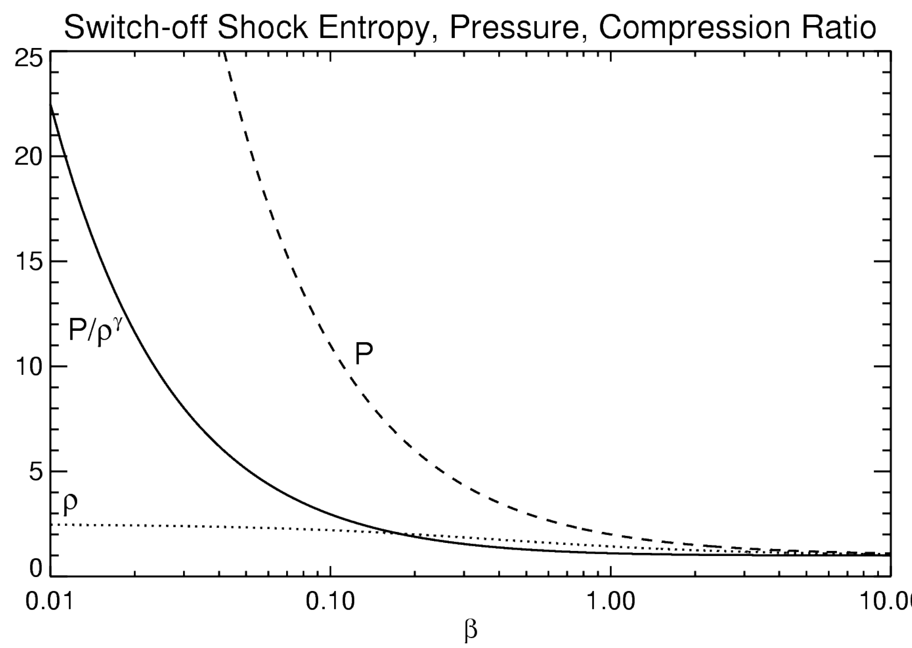
Entropy increase:

$$\frac{S_d}{S_u} = \frac{p_d/p_u}{(\rho_d/\rho_u)^\gamma} = X^{1-\gamma}\left(1 + \frac{\gamma - 1}{\gamma\beta}\left(1 - r^2\right)\right)$$

r is reconnection rate

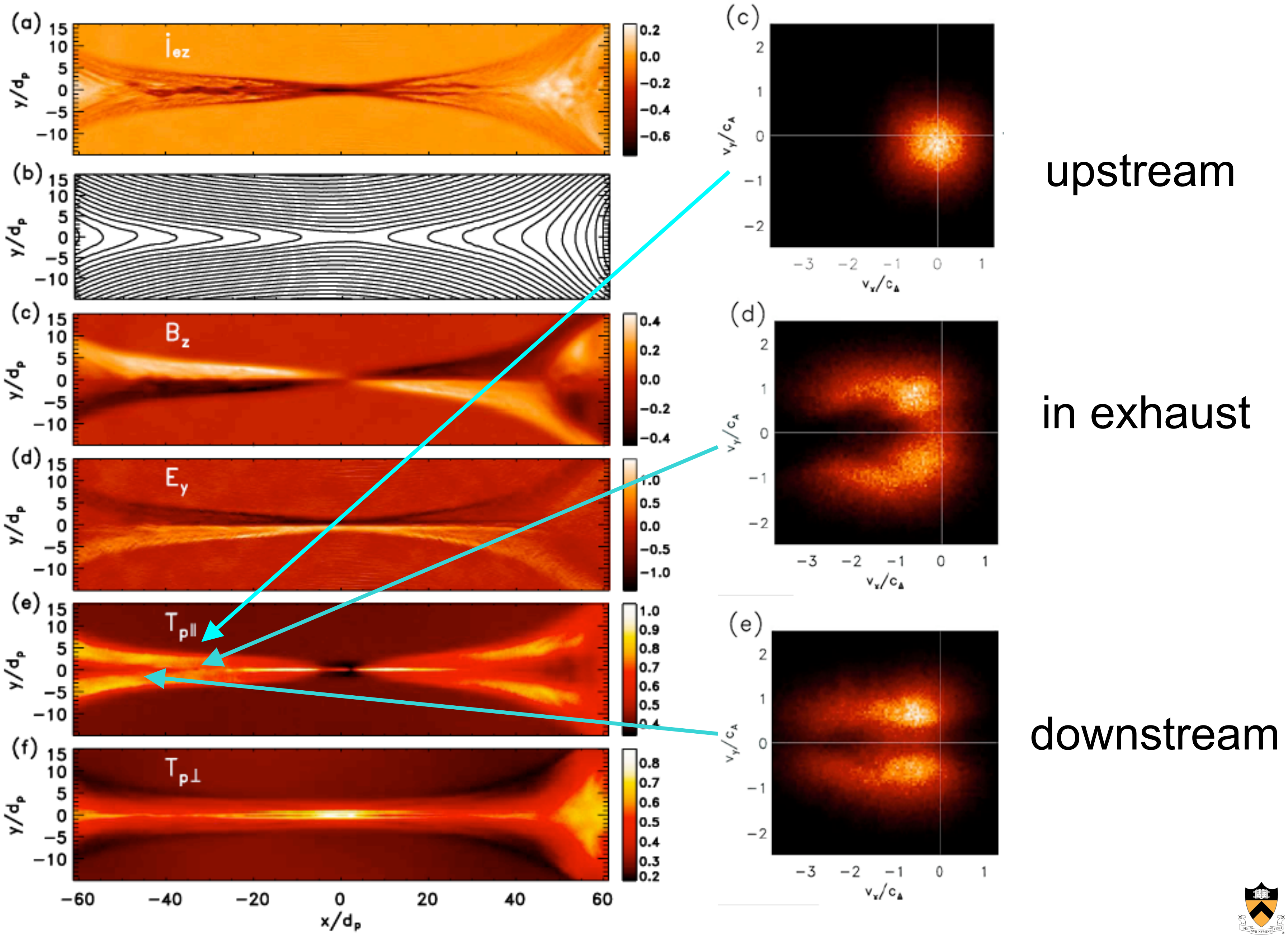
=> Local entropy can increase significantly **only** for very low plasma β.

Otto, 2009



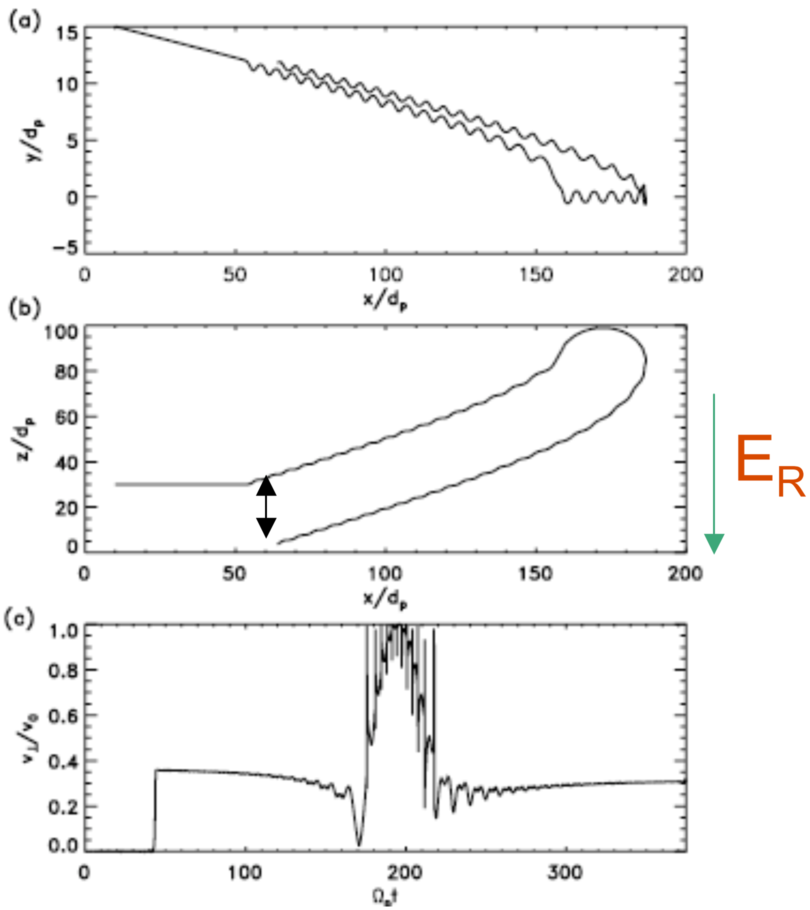
“Slow Shocks” (Full Particle Simulations)

Drake et al., 2009



Heating in Reconnection Jets

$\kappa = \Omega_y/\omega_b$



Drake et al., 2009

$$T_{\parallel} = m_i v_0^2 \frac{B_{0x}^2}{B_0^2}$$

$$T_{\perp} = \frac{1}{2} m_i v_0^2 \frac{B_{0z}^2}{B_0^2}$$

$$T = (T_{\parallel} + 2T_{\perp})/3 = \frac{1}{3} m_i v_0^2$$

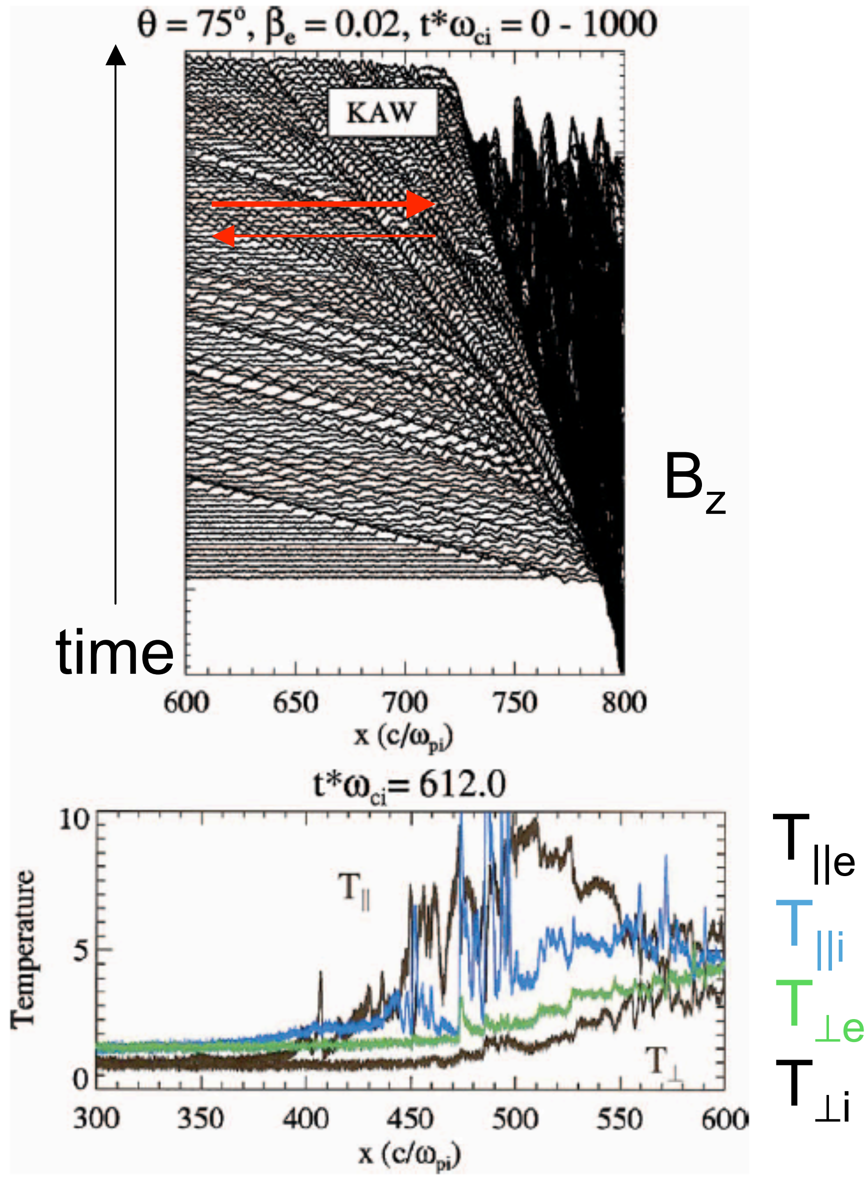
Slow Shock Limit

$$\Delta n = \frac{3}{2} n_0 \qquad \Delta T_p = \frac{1}{5} m_p c_A^2$$

KAWs Heat Particles at a Slow Shock

- Dispersive KAWs develop in the upstream region ($\beta_i=\beta_e=0.1$)
- Develop from backstreaming ions
- Electrons and ions are heating in the parallel direction

Yin et al., 2007

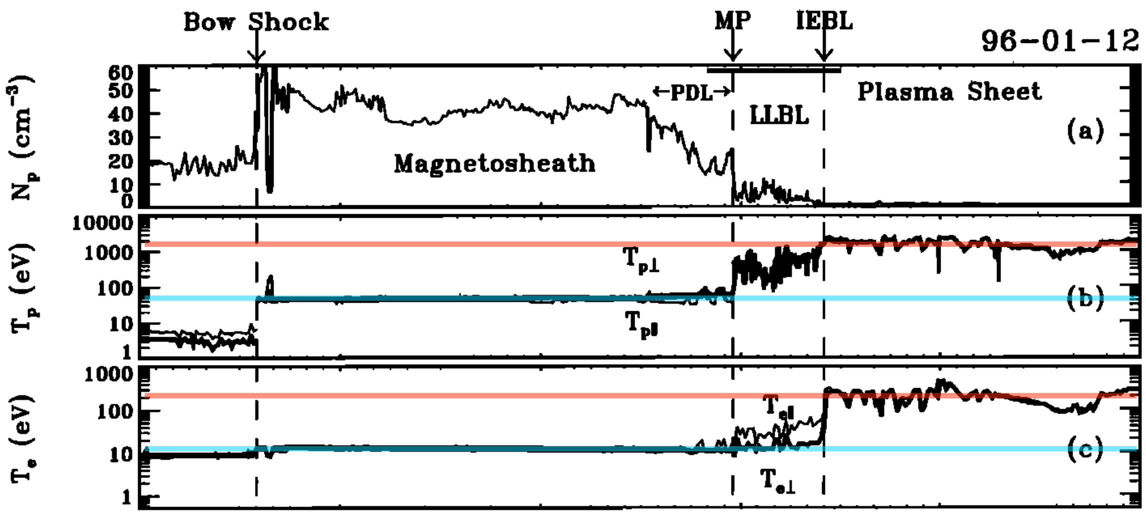


Constraints on Plasma Entry

- Dawn-dusk asymmetries
- Phase space density
- Entropy
- Ion to electron temperature ratio

Electron to Ion Temperature Ratio

WIND Sheath→Plasma Sheet

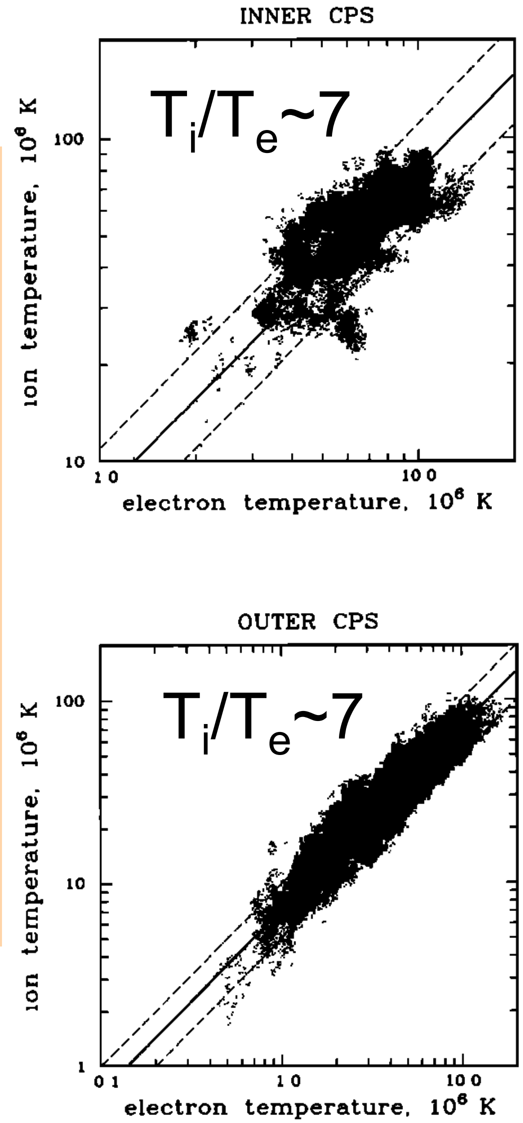


T_i/T_e~(60eV/10eV)~6 in sheath

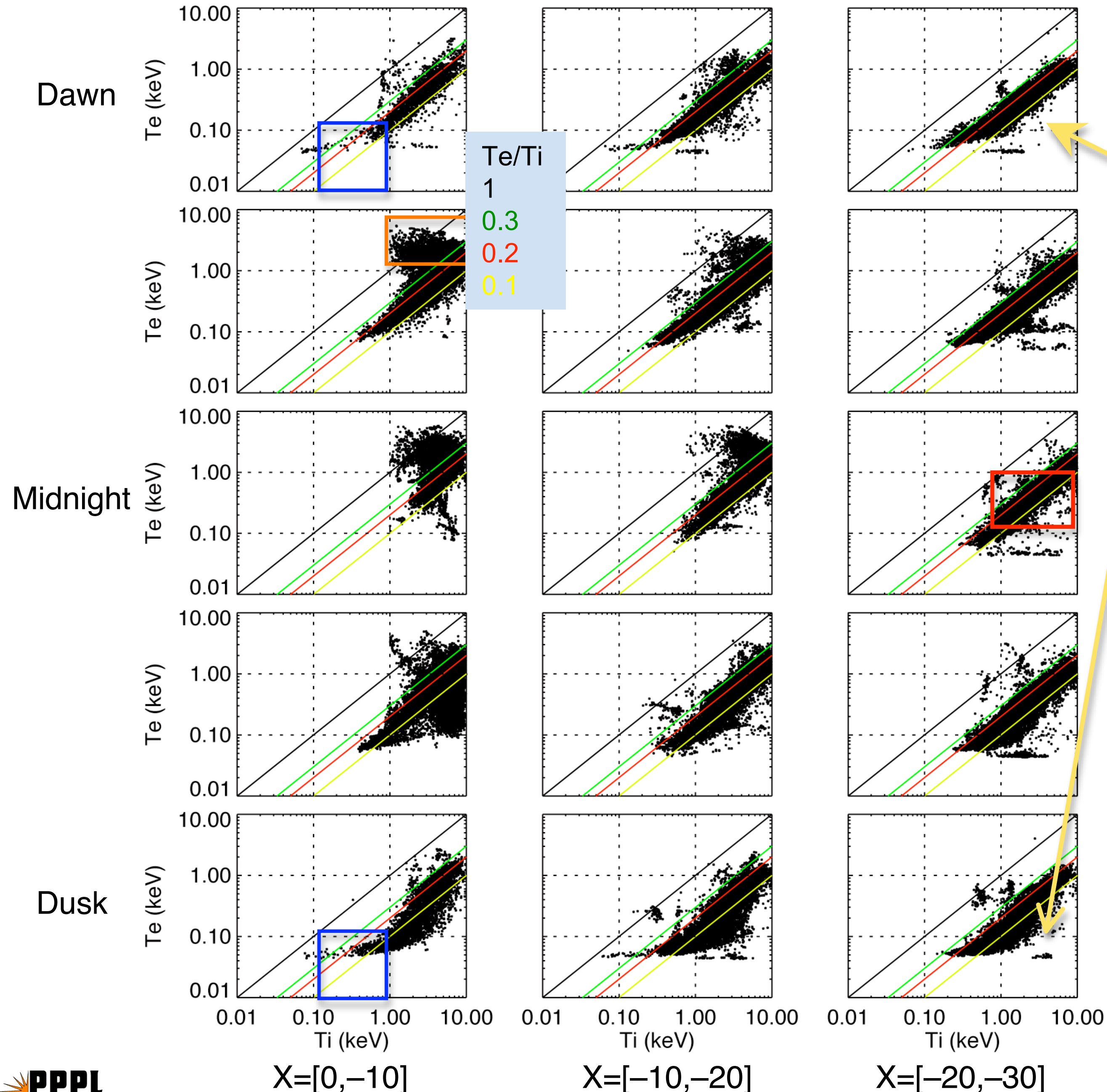
T_l/T_e~(1500eV/200eV)~7.5 in PS

Phan et al., 1996

Baumjohann et al., 1989



Ti vs Te (All)



Ti > 1 keV
Te > 0.1 keV
0.1 < Te/Ti < 0.3

Dawn-dusk asym.
Te/Ti lower pre-midnight

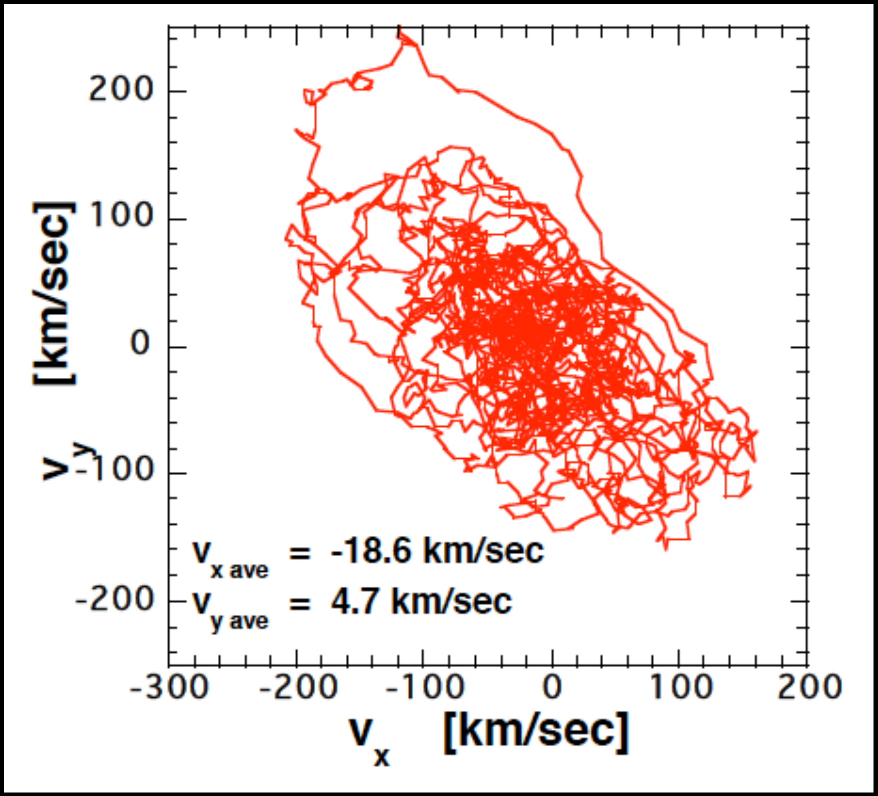
Ti < 1, Te < 0.1 keV
Near the flanks
Te/Ti extends higher than 0.3

Dawn-dusk asym.
Te > 1 keV
Near Earth post-midnight

Wang, 2009

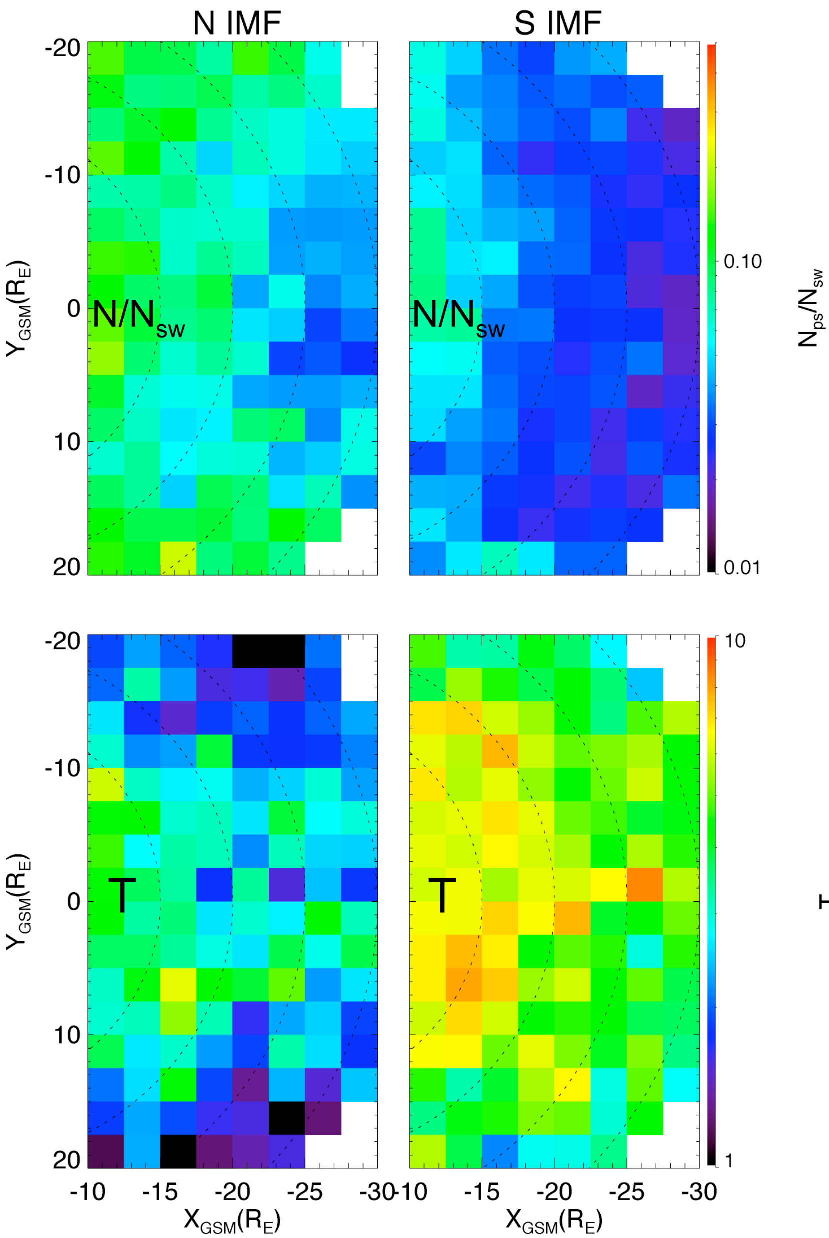
Turbulent vs Convective Transport

Turbulent flows in the tail are often much stronger than average flows



2 hour interval, from J. Borovsky 2004

N and T difference between N and S IMF



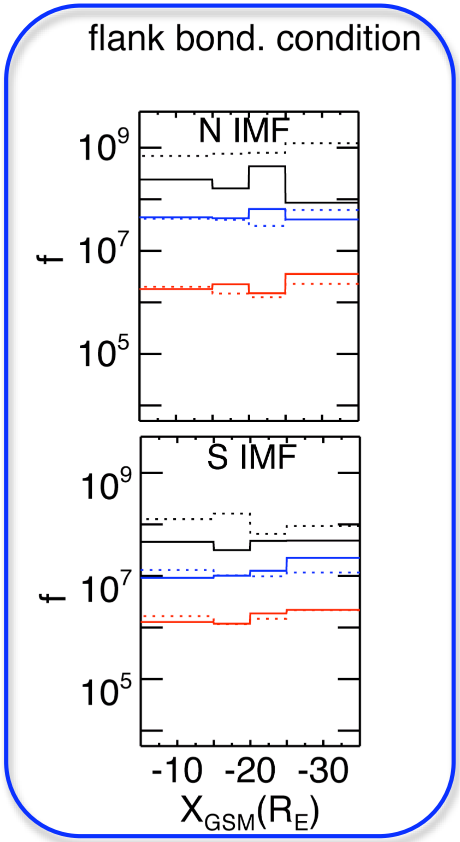
Wang, 2009

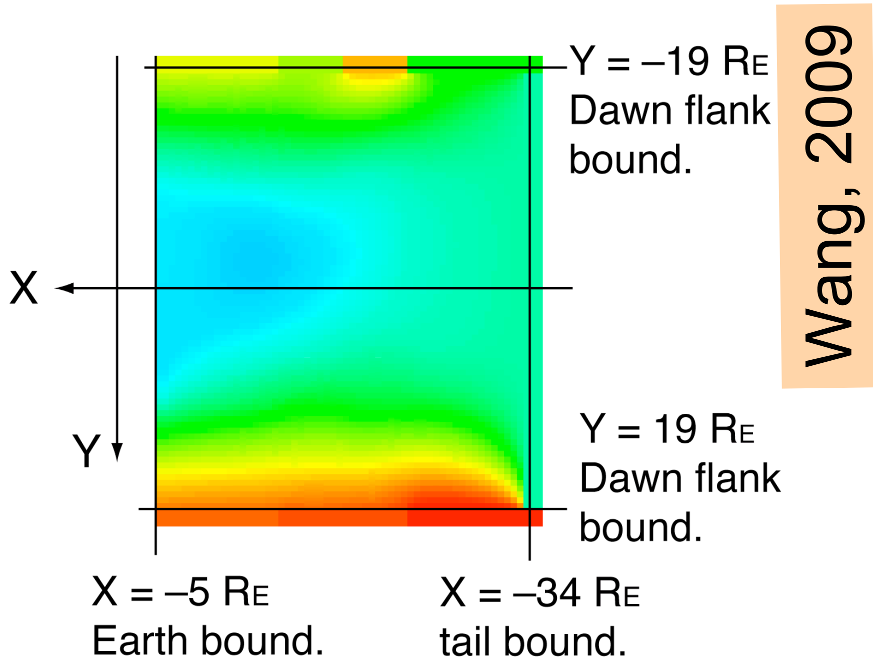
More cold and dense plasma during N IMF

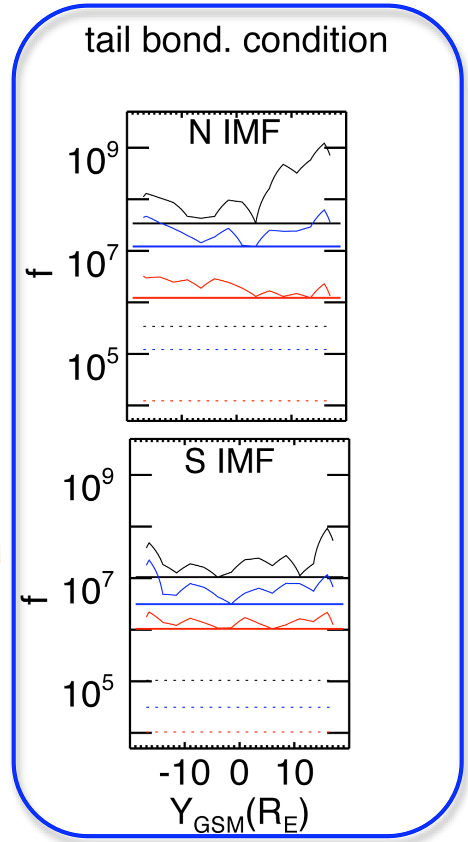
Colder and denser near the flanks

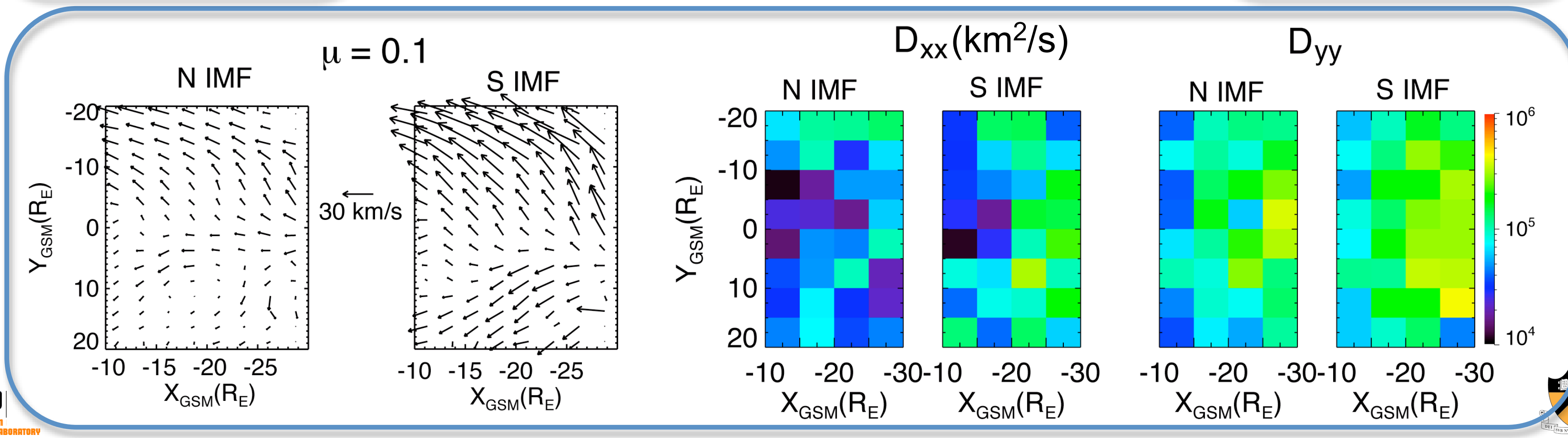
Simulate drift and diffusion of particles from tail and flank

$$\partial f/\partial t = -V_x \cdot \partial f/\partial x - V_y \cdot \partial f/\partial y \text{ (drift)}$$
$$+\partial(D_{xx} \cdot \partial f/\partial x)/\partial x + \partial(D_{yy} \cdot \partial f/\partial y)/\partial y \text{ (diffusion)}$$

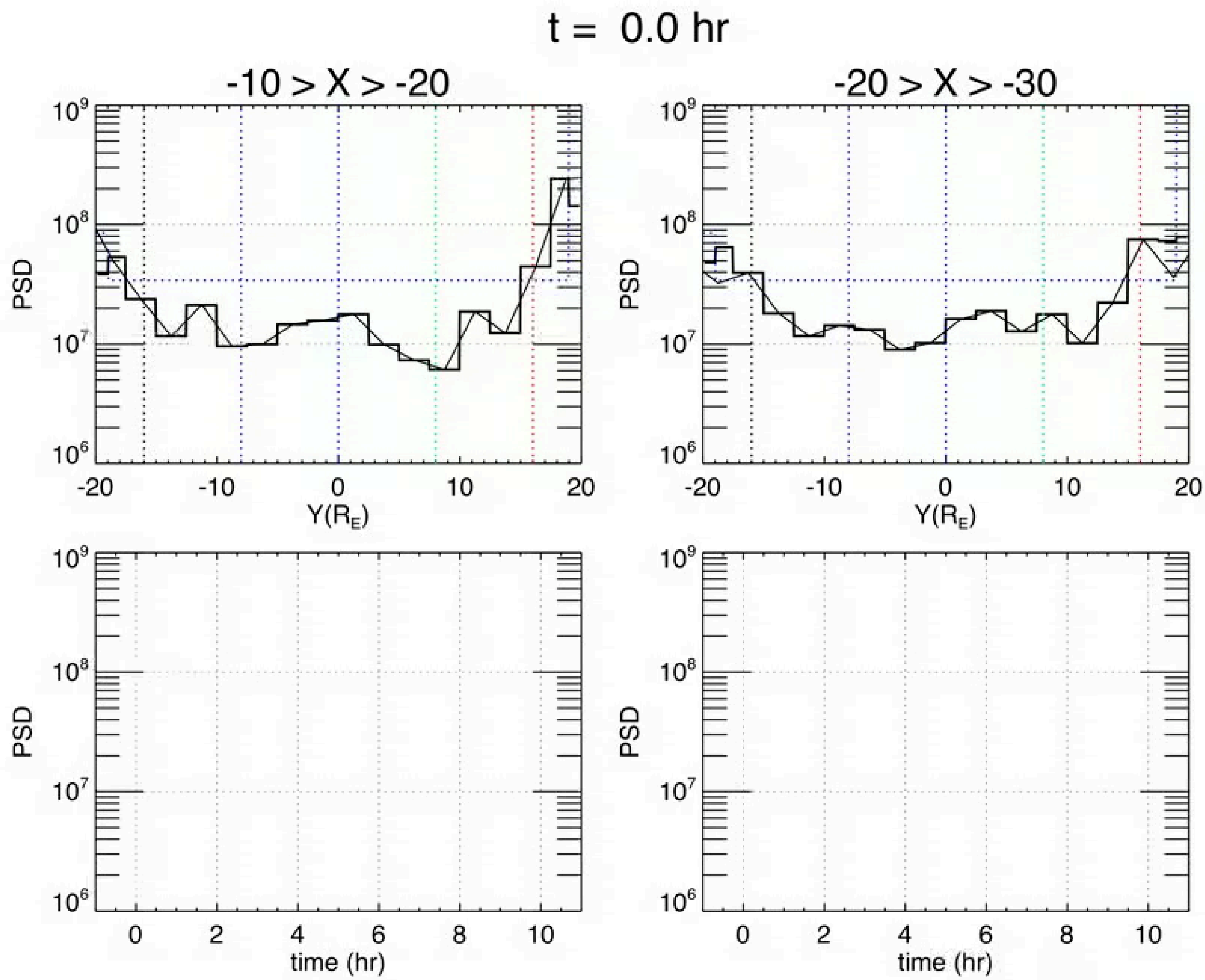








Filling of the Plasma Sheet



Wang, 2009

Southward to Northward IMF

Some Final Challenges

- A serious challenge for the future is to understand the role of entropy in the formation of the plasma sheet
  - How does it increase by orders of magnitude?
  - Can it help identify transport paths?
  - What is the role of turbulence in changing entropy?
  - What role does it play in transport of plasma to the center of the plasma sheet (interchange)?
- What is the role of entropy in plasma sheet transport
  - Is it a good constraint for slowly evolving plasma sheet?
  - Can it help explain formation of thin current sheets?
  - What changes occur during substorms?
  - Pressure inconsistency?
- Another challenge is to understand why the temperature ratio is preserved from the sheath to plasma sheet
  - It is not required by force balance
  - Is the plasma sheet heating mechanism consistent