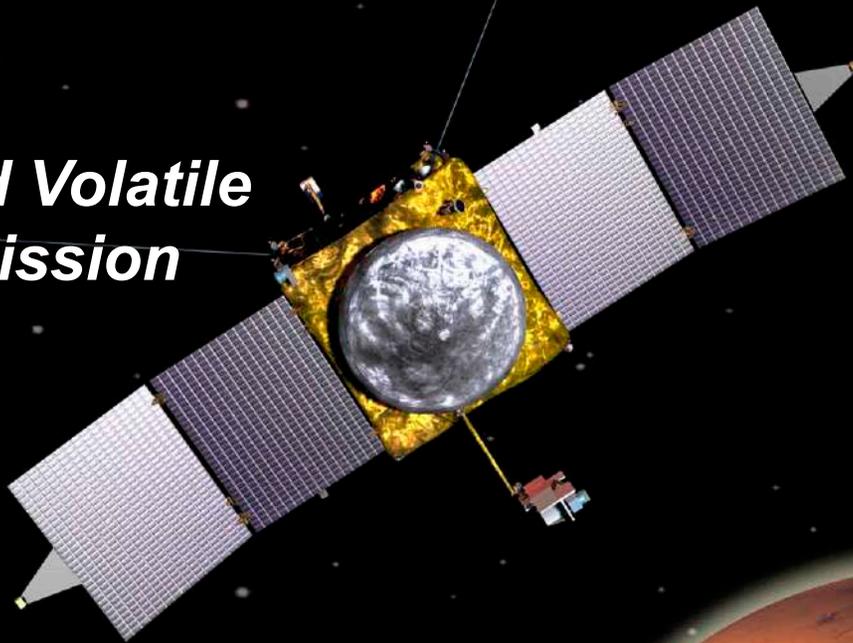




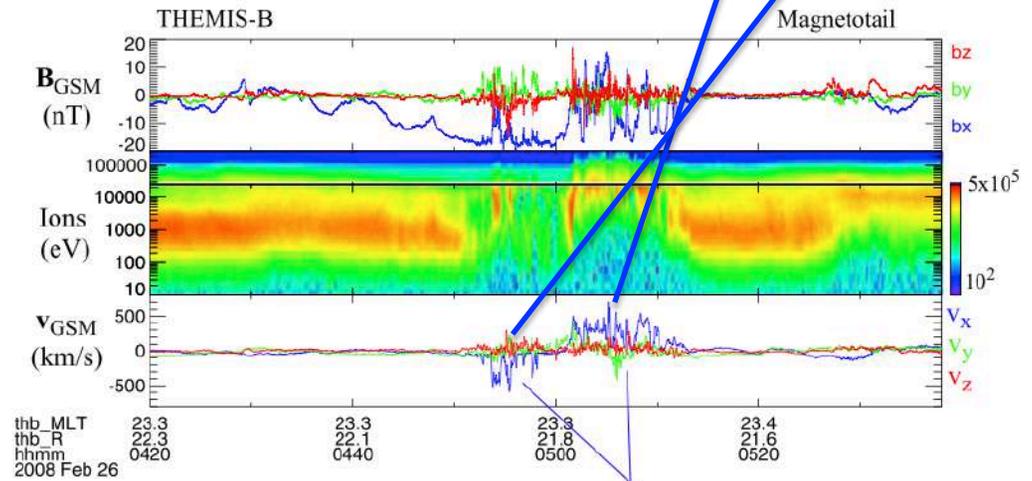
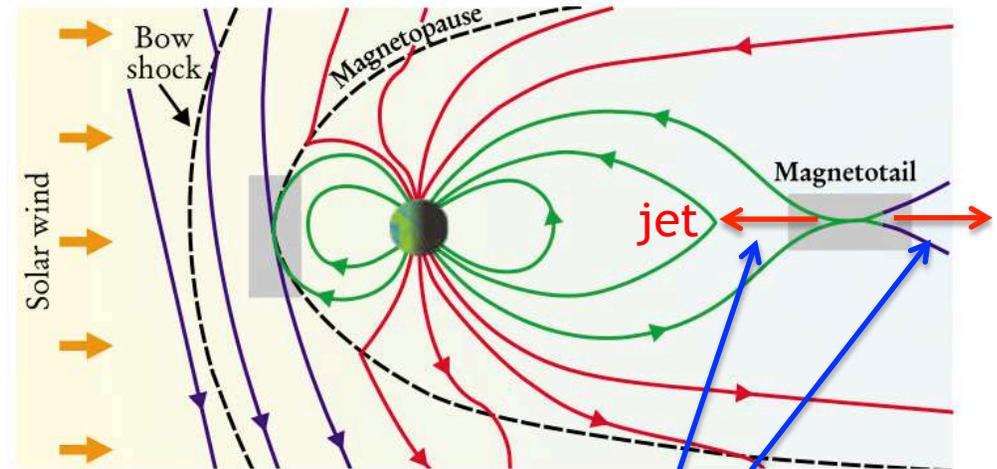
## ***Mars Atmosphere and Volatile Evolution (MAVEN) Mission***



Harada, Y., et al. (2015),  
Magnetic reconnection in the near-Mars  
magnetotail: MAVEN observations,  
*Geophys. Res. Lett.*, 42,  
doi:10.1002/2015GL065004.

# 磁気リコネクション

- 磁場構造の変化
- 磁気エネルギーを粒子エネルギーに変換
- 太陽系内の様々な領域で直接観測
- 火星誘導磁気圏での磁気リコネクションの有無、ローカルな物理過程、グローバルな役割は未解明の重要課題



[Paschmann et al., 2013]

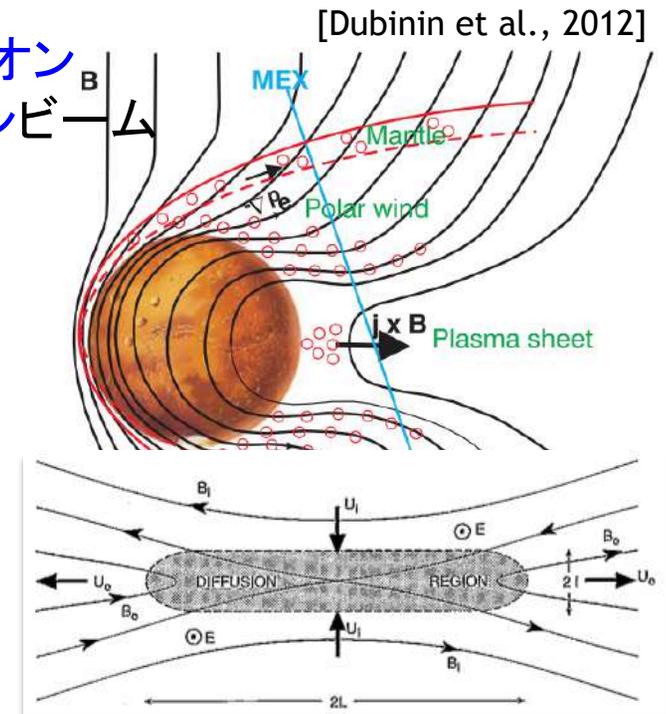
# 火星でのリコネクション観測

- 火星で観測されてきたリコネクションの兆候:
  - ✓ ホール磁場 [Eastwood et al., 2008; Halekas et al., 2009]
  - ✓ 電子加速・閉じた磁力線への電子捕捉 [Brain et al., 2006, 2007]
  - ✓ 磁気フラックスロープ [Brain et al., 2010; Hara et al., 2014a, 2014b]

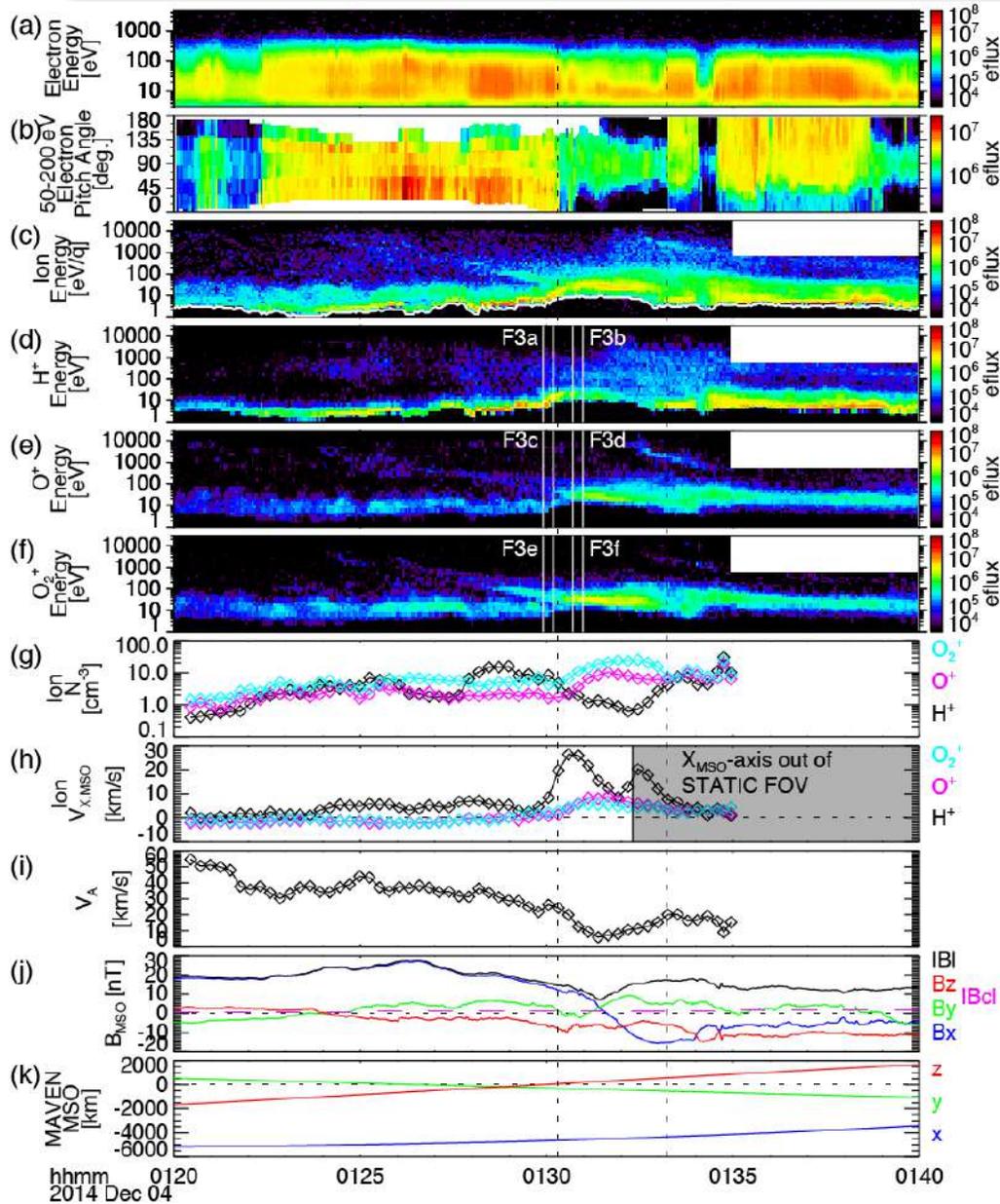
- 火星では未確認のリコネクションの兆候:

- 電流シート内の(イオン)アウトフロー
- アウトフロー領域のカウンターストリーミングイオン
- セパトリクスでのエネルギー分散を伴うイオンビーム

- 火星テイルには様々な物理過程によるテイル向きのイオン流が遍在
  - ✓ 一方で、リコネクションは反対方向のジェットのパアを生成
  - テイル電流シート内で火星向きのAlfvén速度のイオン流が存在するか？



# 火星テイルでのMAVEN観測



SWEA 電子エネルギー分布

SWEA 50-200 eV 電子ピッチ角分布

STATIC イオンエネルギー分布

STATIC H<sup>+</sup>エネルギー分布

STATIC O<sup>+</sup>エネルギー分布

STATIC O<sub>2</sub><sup>+</sup>エネルギー分布

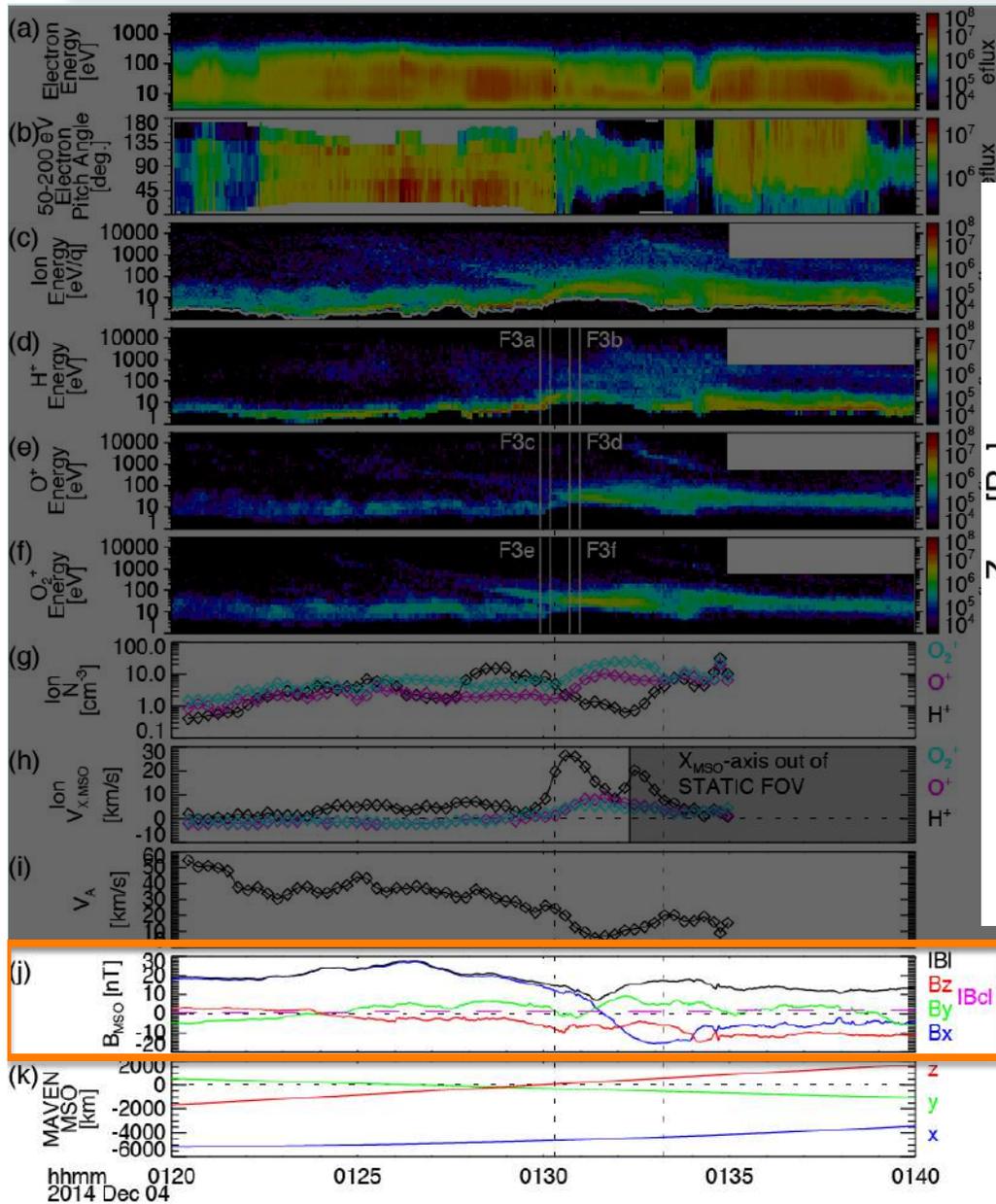
STATIC イオン密度

STATIC イオン速度X<sub>MSO</sub>成分

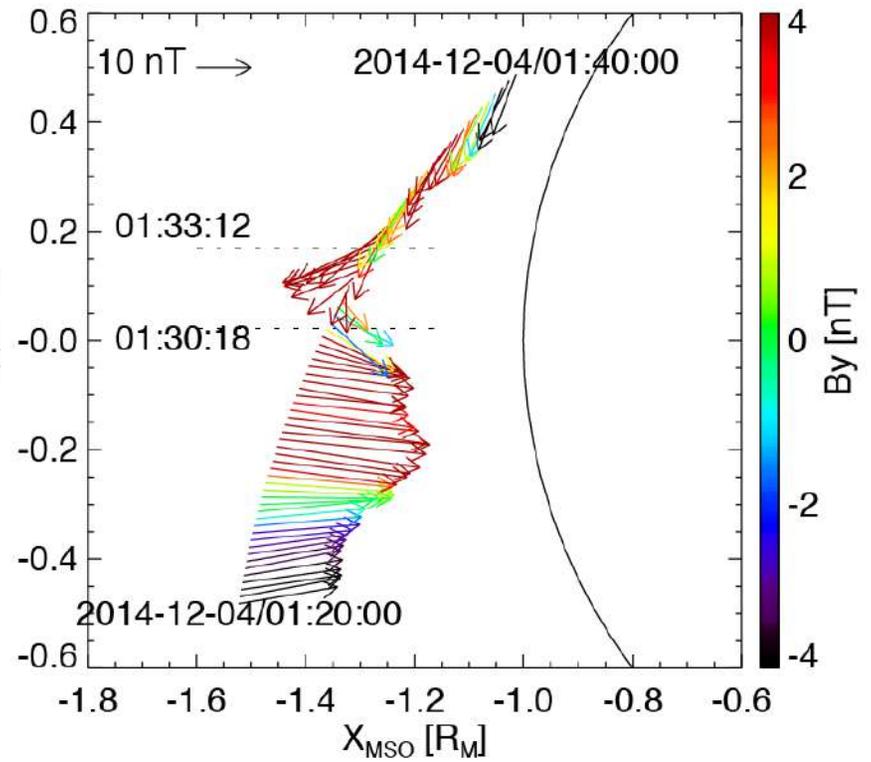
STATIC+MAG Alfvén速度

MAG 磁場

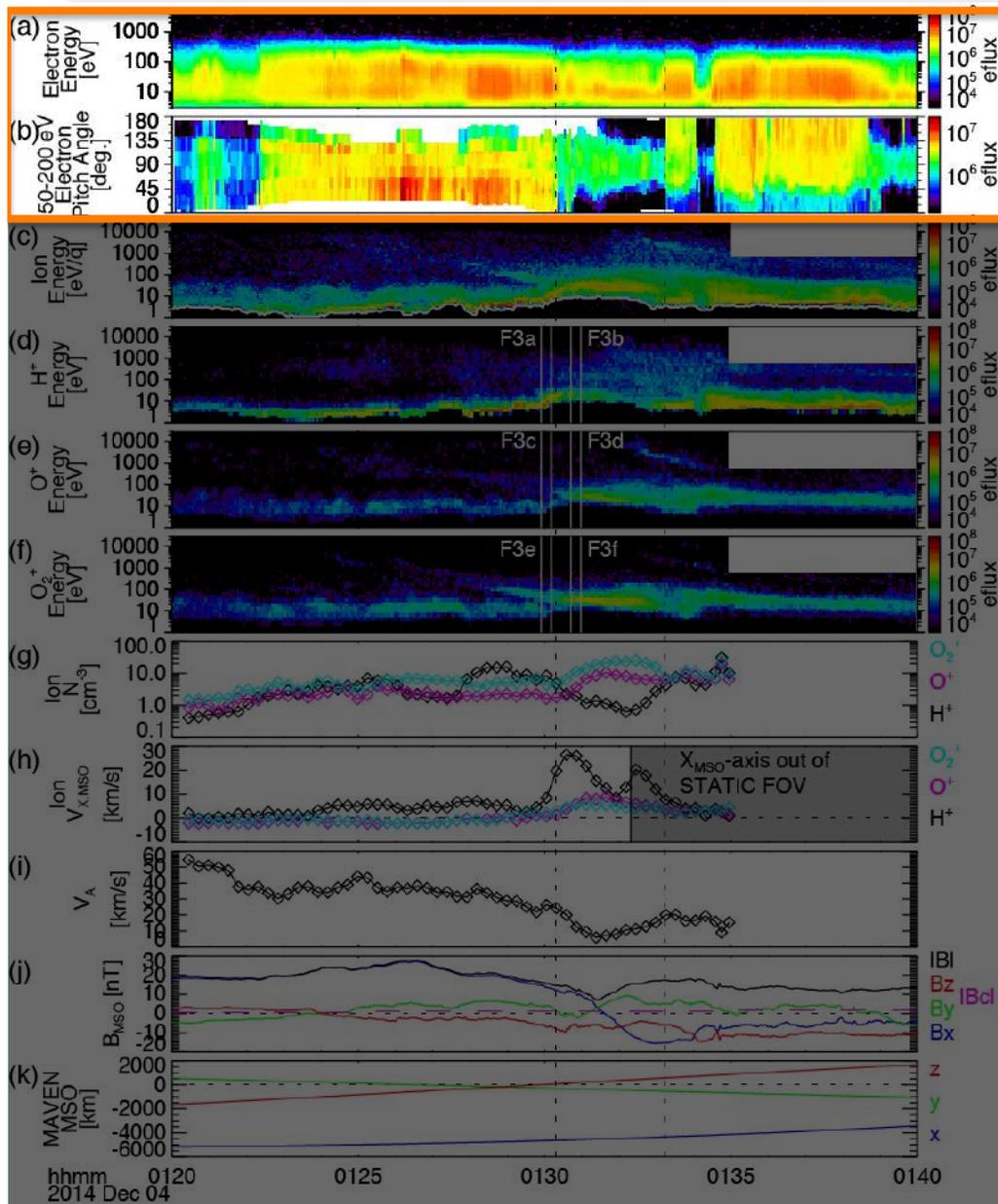
# テイル電流シート通過



火星テイルの中央で電流シートを通過



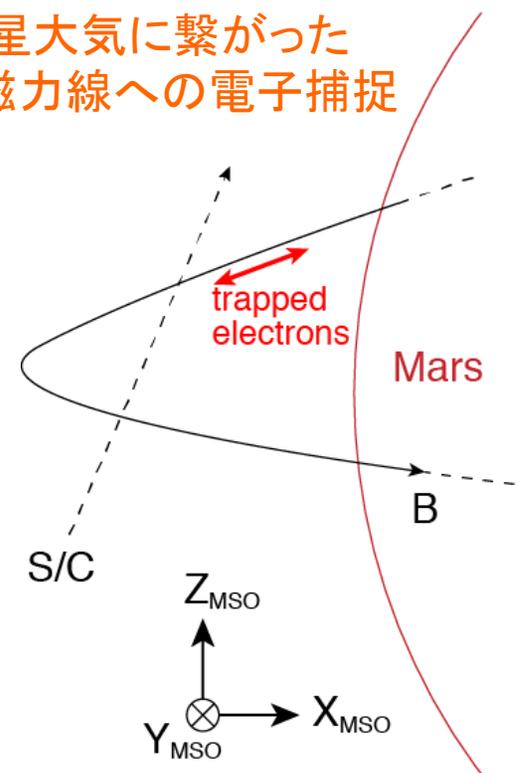
# 電子分布



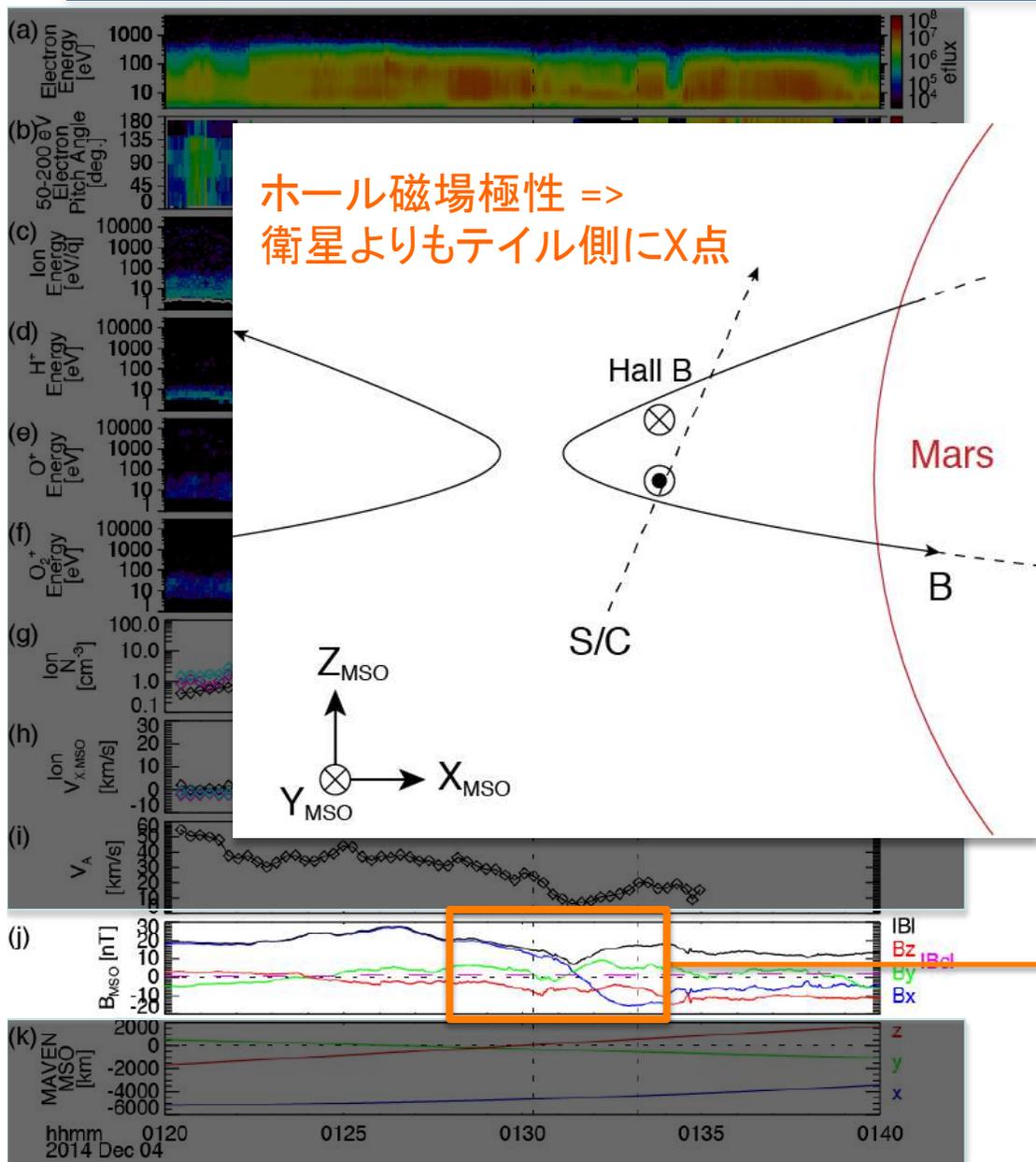
ホットな電子フラックスの減少

両側にロスコーン

両側が火星大気に繋がった  
「閉じた」磁力線への電子捕捉



# 磁場MVAホドグラム



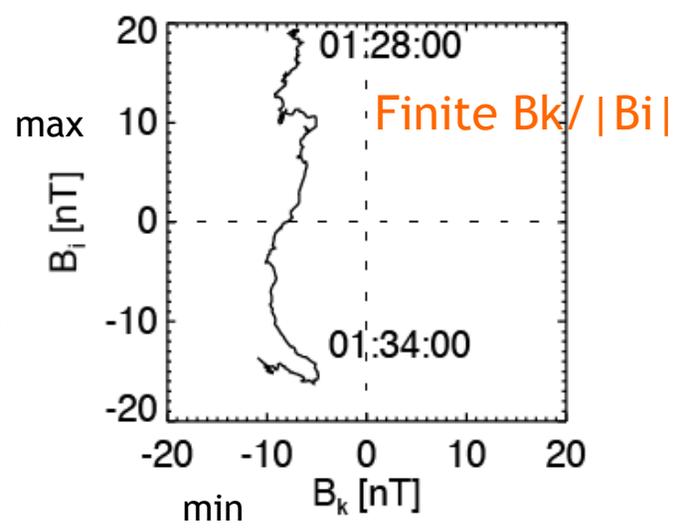
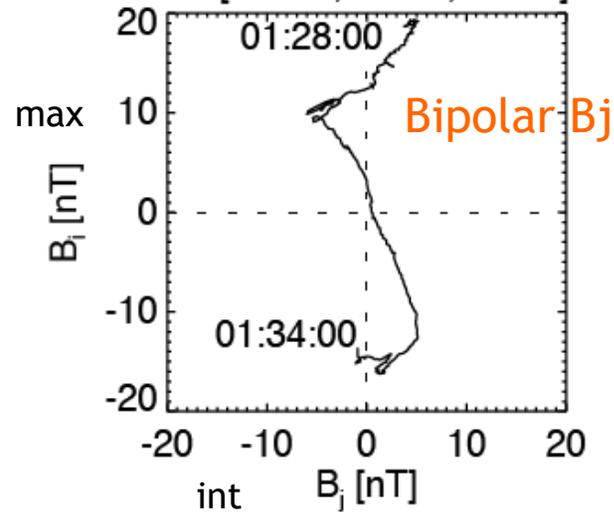
ホール磁場極性 =>  
衛星よりもテイル側にX点

b) MVA:  $\lambda_i/\lambda_j: 23, \lambda_j/\lambda_k: 4$

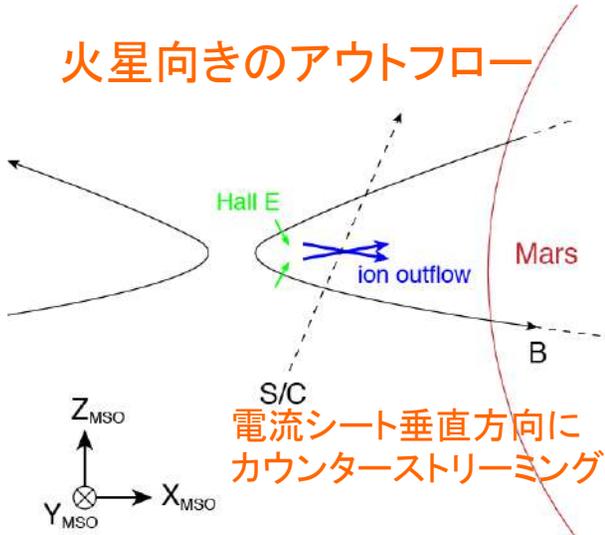
max  $i = [0.996, -0.062, 0.067]$

int  $j = [0.023, 0.878, 0.477]$

min  $k = [-0.088, -0.474, 0.876]$



火星向きのアウトフロー



# 閉じた磁力線内の イオン速度分布関数

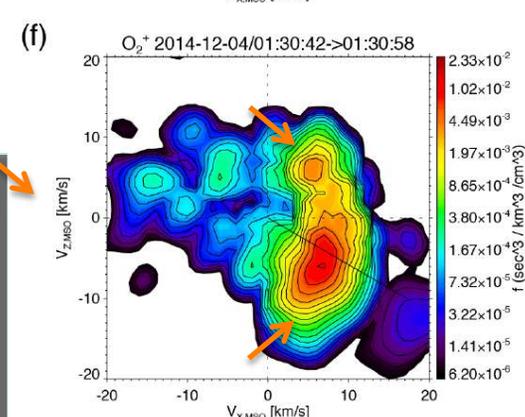
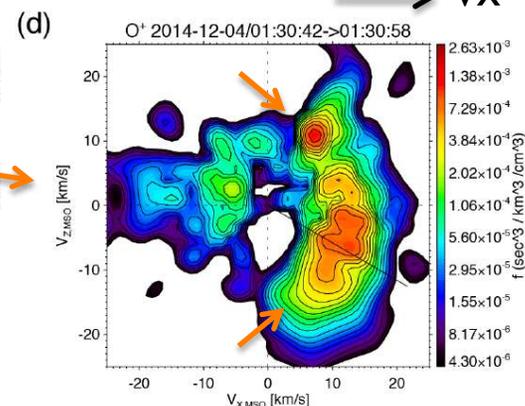
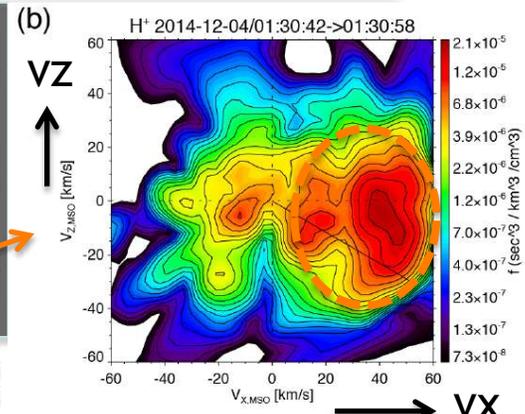
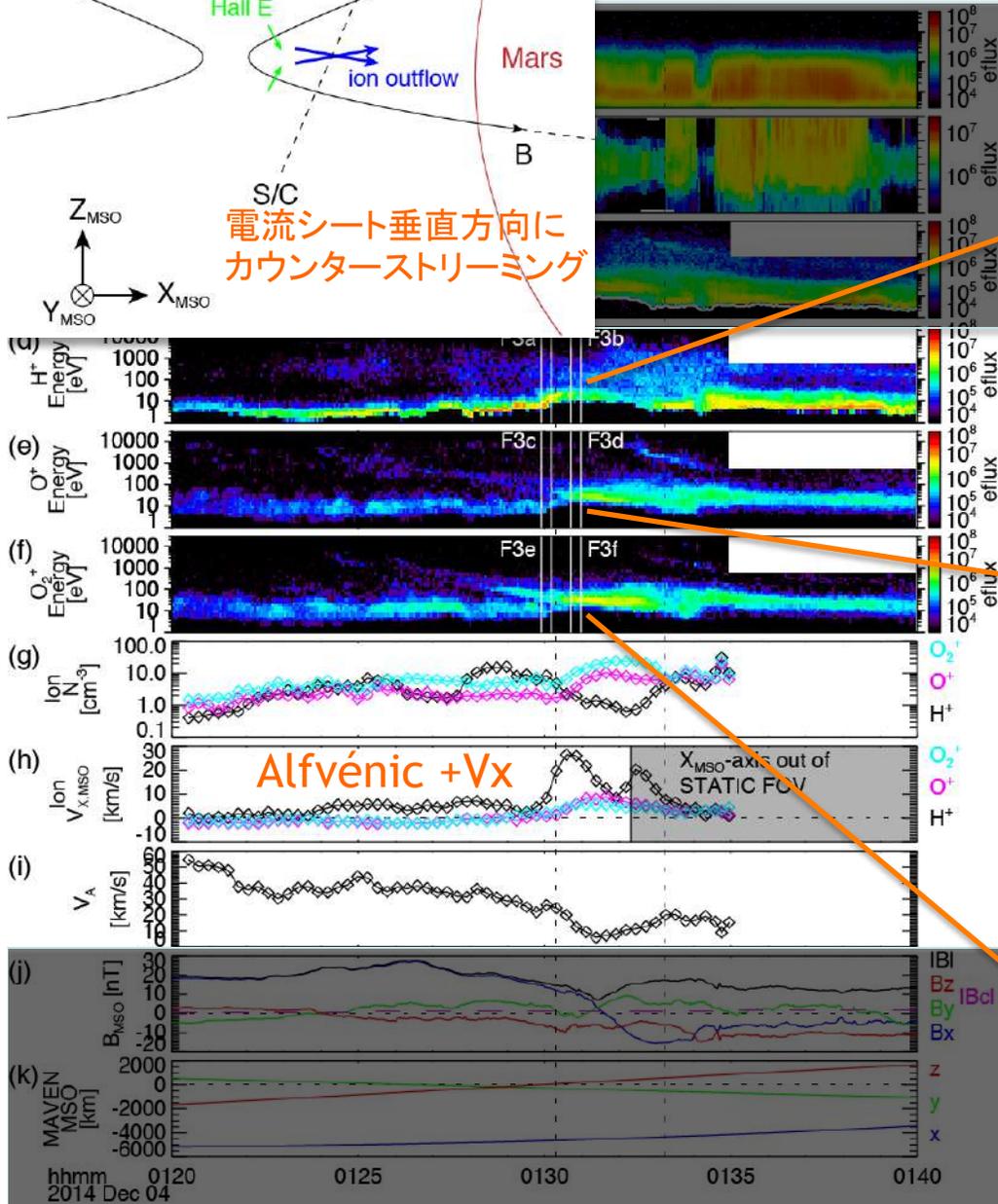


質量依存した  
火星向きの  
イオンバルク流

H<sup>+</sup>  
ブロードな分布

O<sup>+</sup>  
Z方向に  
カウンター  
ストリーミング

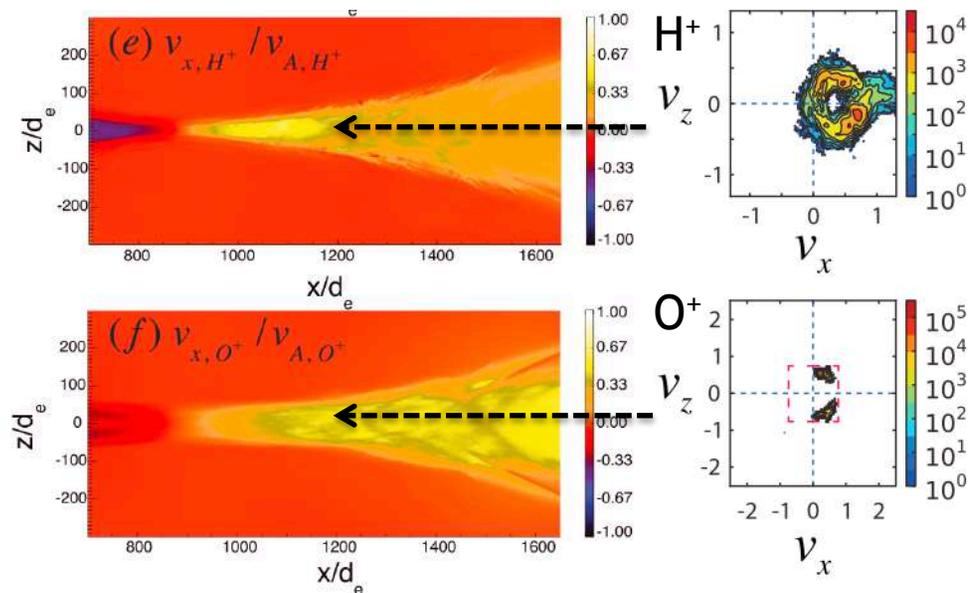
O<sub>2</sub><sup>+</sup>  
Z方向に  
カウンター  
ストリーミング



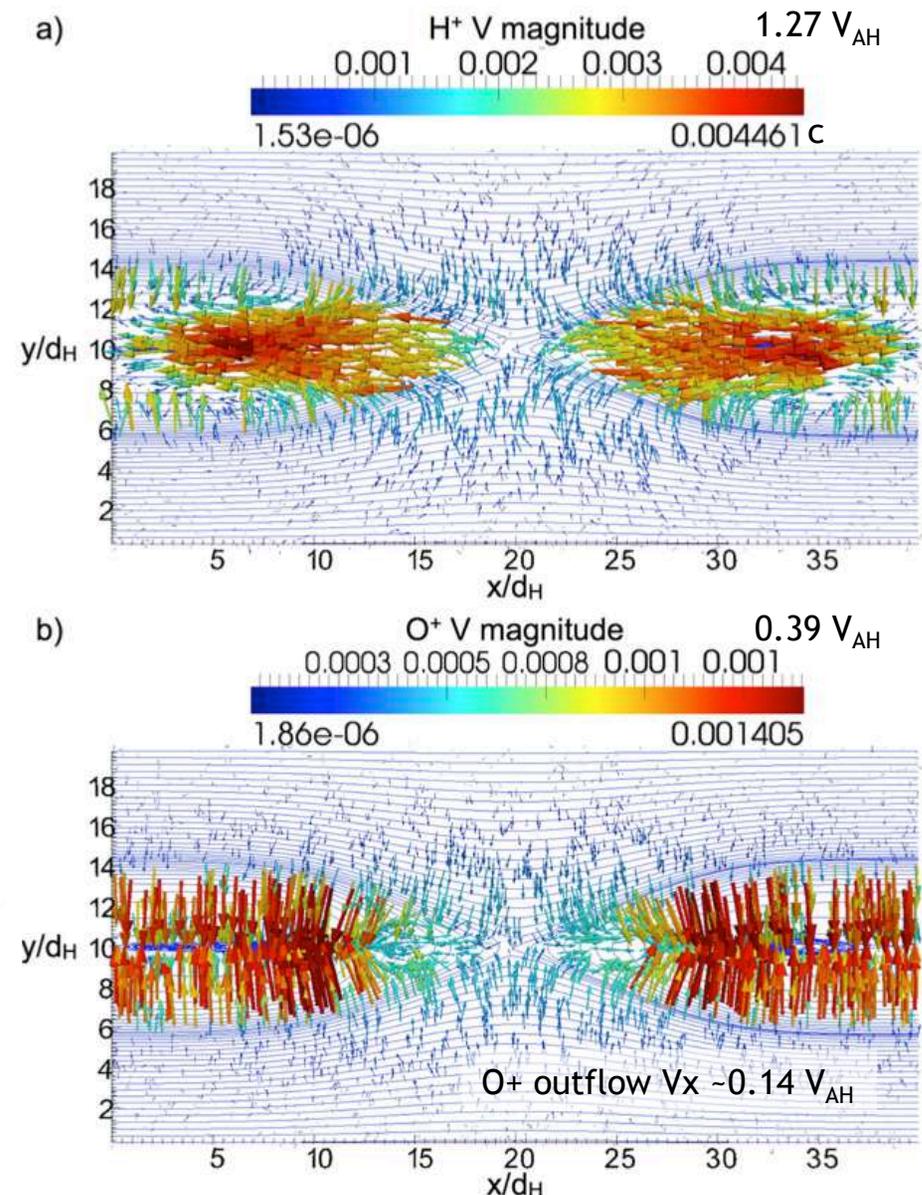
# 質量依存したイオンアウトフロー

[Markidis et al., 2011]

- 2.5D複数イオン種PICシミュレーション [Markidis et al., 2011; Liu et al., 2015]
- $H^+$ :  $H^+$ 拡散領域外で磁化 & 熱化、X方向にドリフト
- $O^+$ : 広い $O^+$ 拡散領域内ではまだ非磁化、主にホール電場で内向きに加速



[Liu et al., 2015]



$O^+$  outflow  $V_x -0.14 V_{AH}$

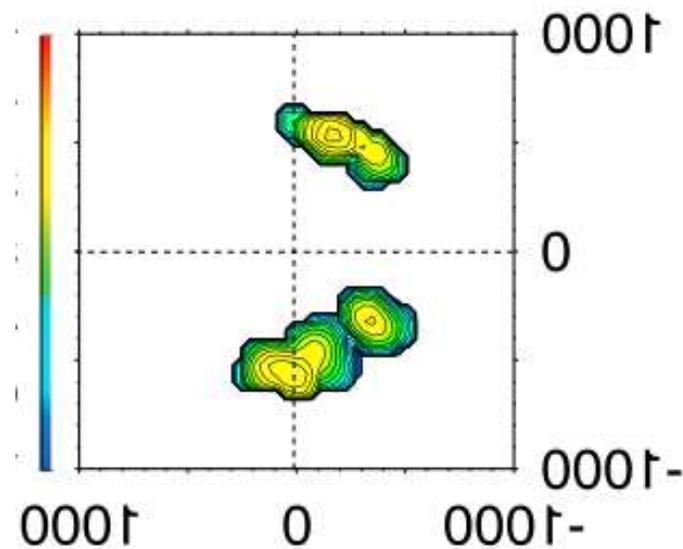
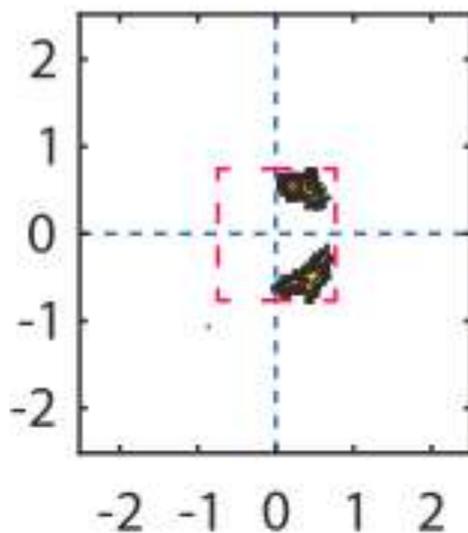
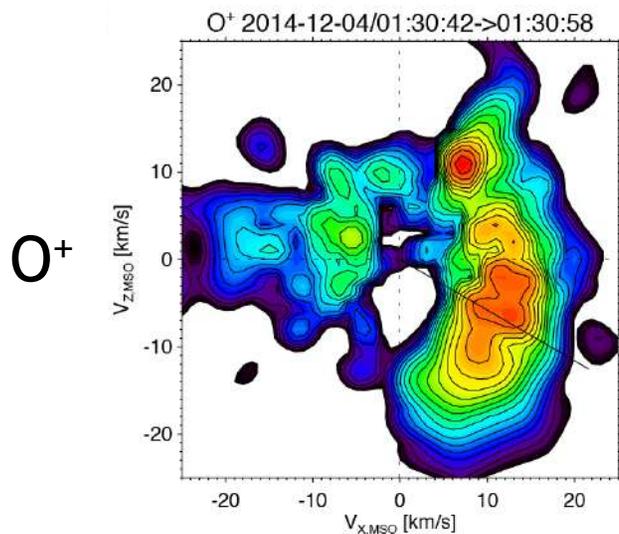
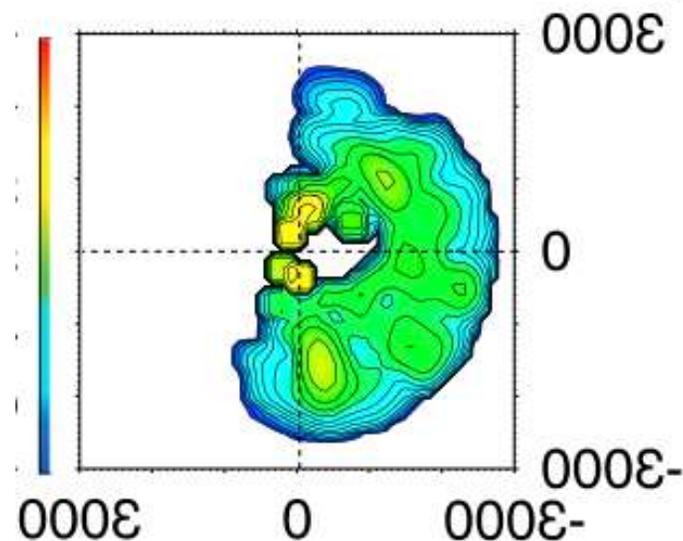
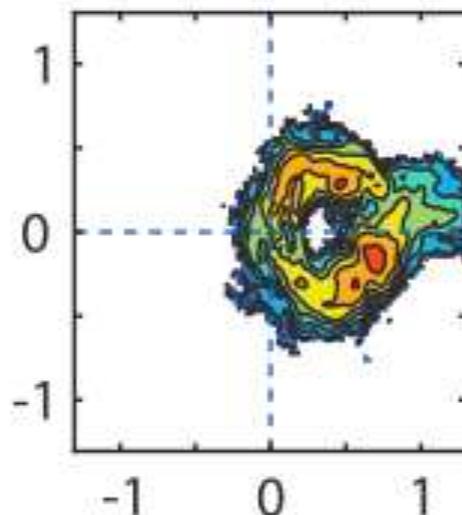
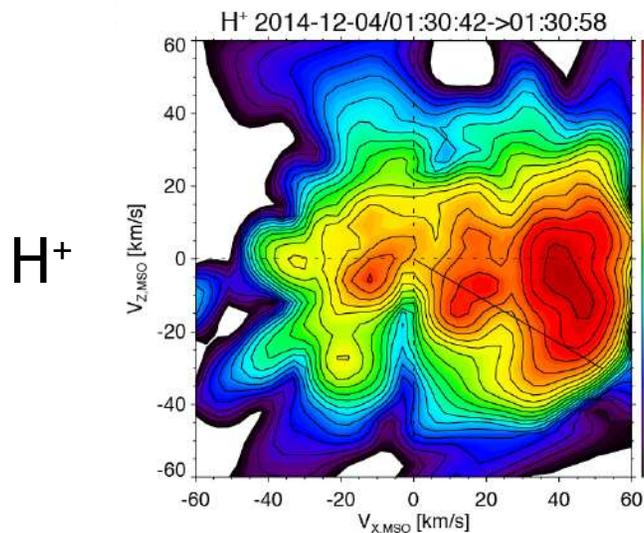
# イオン速度分布関数の比較

[Liu et al., 2015]

MAVEN obs at Mars

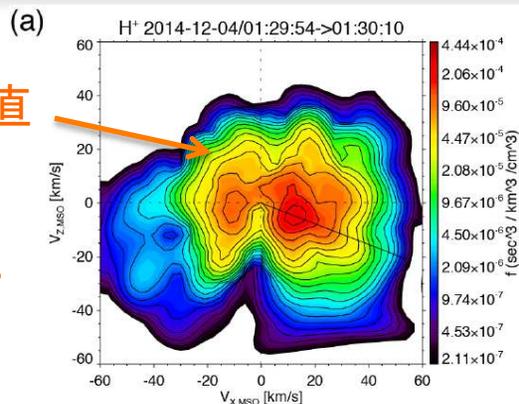
PIC sim

Cluster obs at Earth

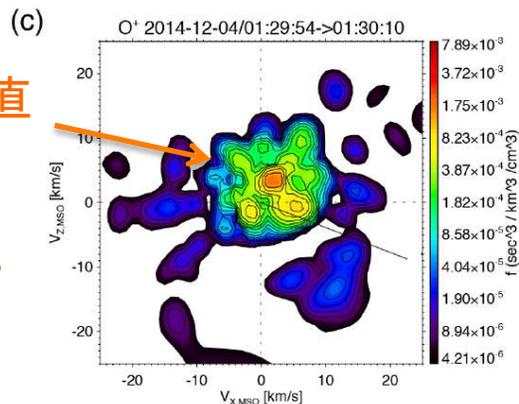


# 閉じた磁力線に入る直前の イオン速度分布関数

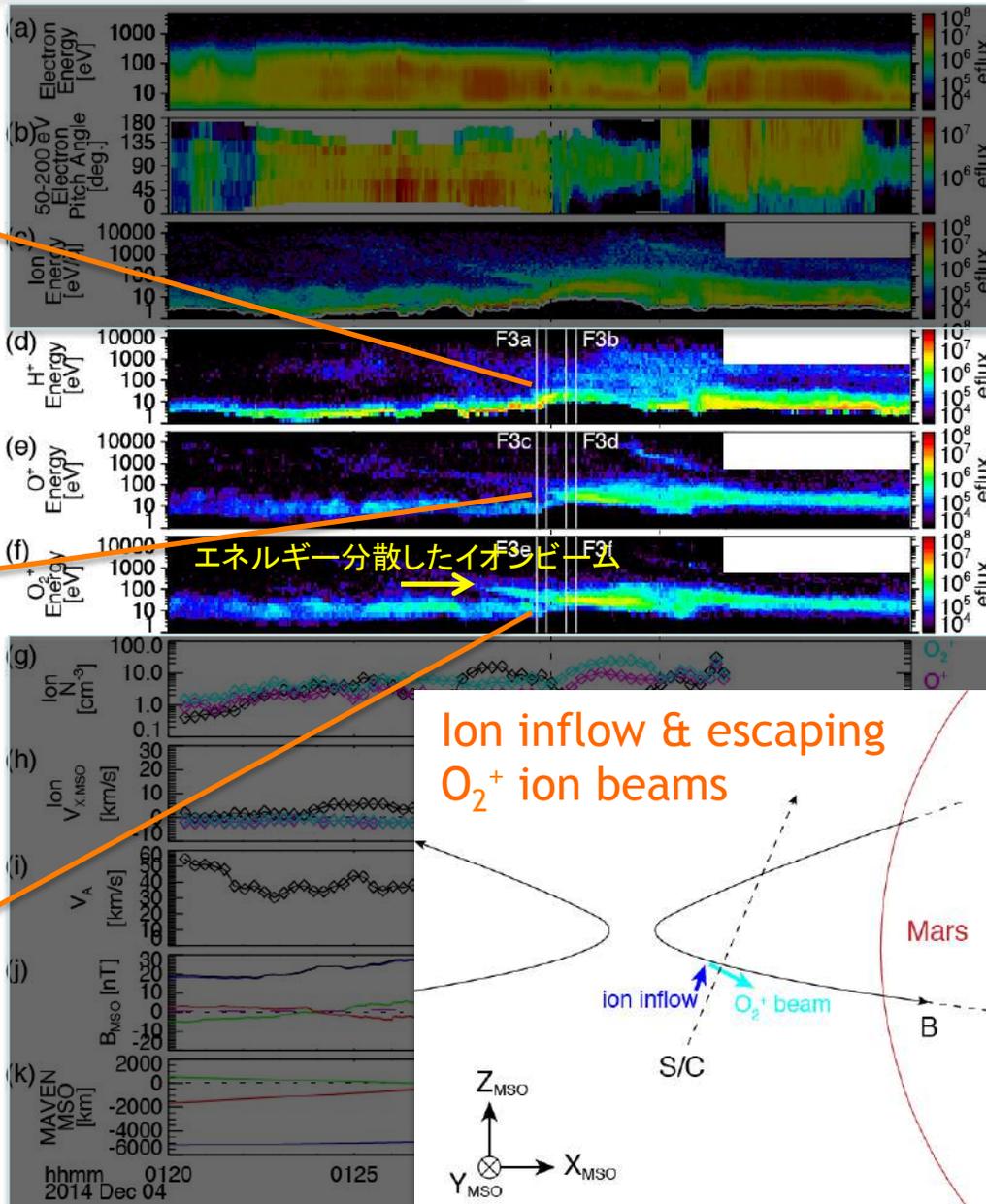
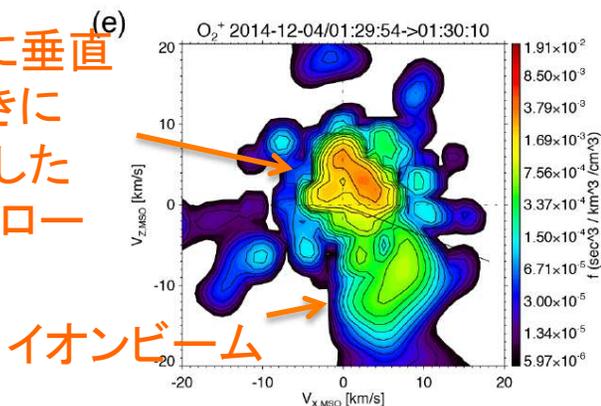
磁場に垂直  
+Z向きに  
シフトした  
インフロー



磁場に垂直  
+Z向きに  
シフトした  
インフロー

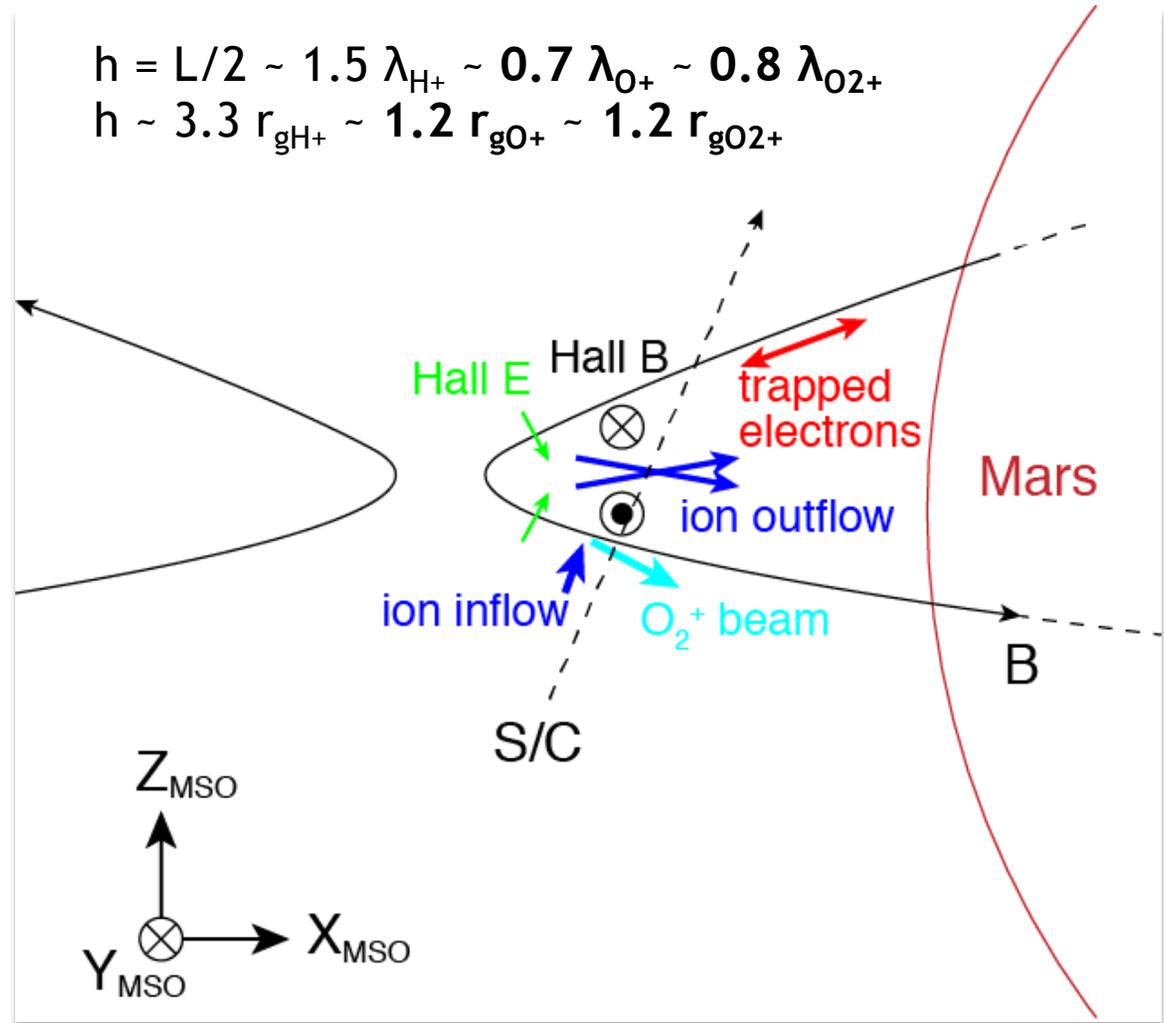


磁場に垂直  
+Z向きに  
シフトした  
インフロー

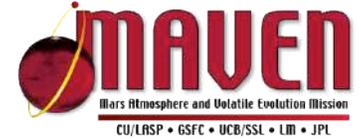


# 2014-12-04 イベントのまとめと 空間スケール推定

- 電流シートの厚さ:
  - $L = V_{SC, Normal} dt \sim 520 \text{ km}$
- イオン慣性長:
  - $\lambda_{H^+} \sim 174 \text{ km}$
  - $\lambda_{O^+} \sim 363 \text{ km}$
  - $\lambda_{O_2^+} \sim 314 \text{ km}$
- イオンジャイロ半径:
  - $r_{gH^+} \sim 78 \text{ km}$
  - $r_{gO^+} \sim 212 \text{ km}$
  - $r_{gO_2^+} \sim 214 \text{ km}$



# まとめと課題



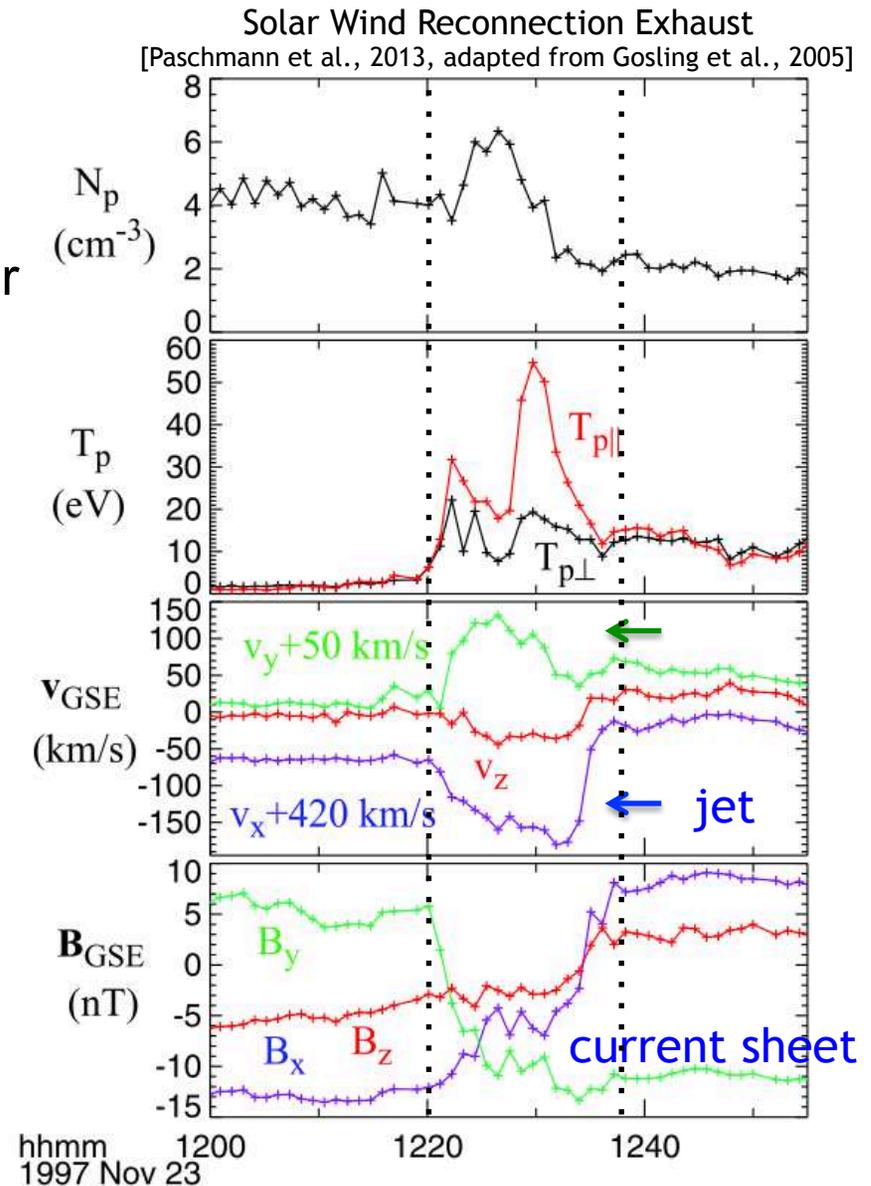
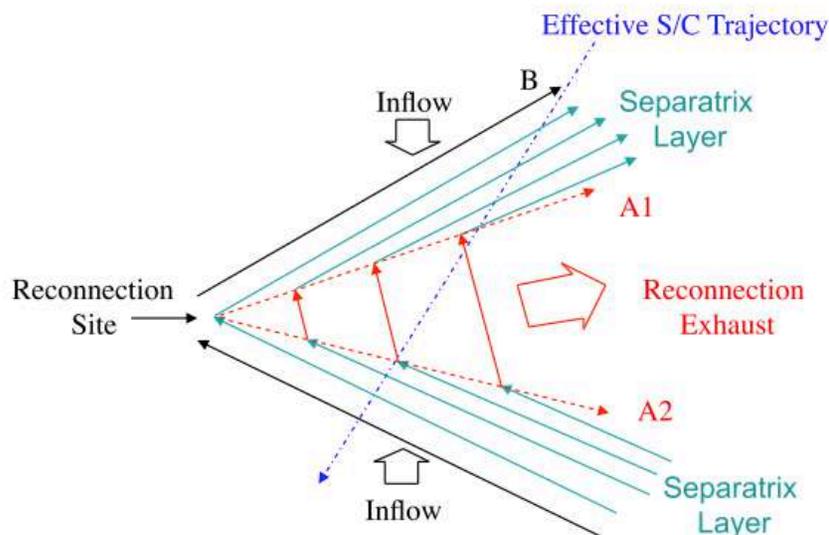
- MAVENによって火星テイルで電子・イオン・磁場を合わせた総合的なリコネクション観測が可能に
  - テイル電流シート内での火星向きのAlfvénicなイオン流
  - アウトフロー内でのカウンターストリーミングイオン
  - ホール磁場
  - 閉じた磁力線への電子捕捉
  - セパラトリクスでのエネルギー分散を伴う $O_2^+$ イオンビーム
- 複数イオン種が存在する状況での磁気リコネクション
  - リコネクション構造内でのイオンの運動の質量依存性
  - PICシミュレーション結果、地球テイルでの観測と調和的な観測(プロトンよりも遅い重イオンアウトフロー、電流シート垂直方向のカウンターストリーミング重イオン)
- 火星テイルリコネクションの統計的な特徴は？
  - 頻度、空間分布、上流パラメータへの依存性、イオン流出への影響、etc.
- モデルとの比較
  - グローバルな境界条件、ローカルな物理過程

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**BACKUP**

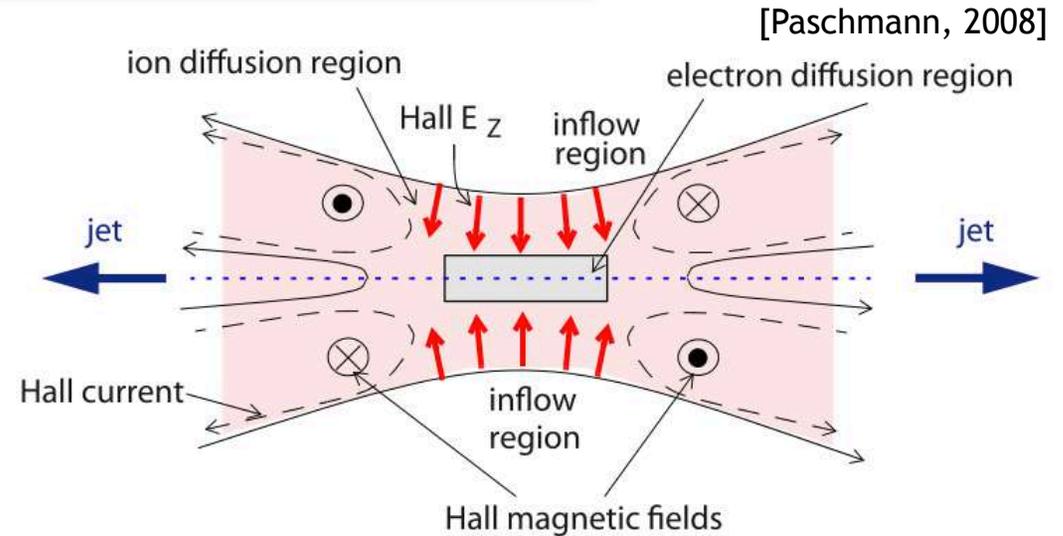
# Alfvénic Jets

- Alfvénic accelerated plasma flows within current sheets
  - Acceleration by a pair of rotational discontinuities and/or slow-mode waves/shocks
- Walén relation:  $\Delta \mathbf{V} = \pm \Delta \mathbf{V}_A$

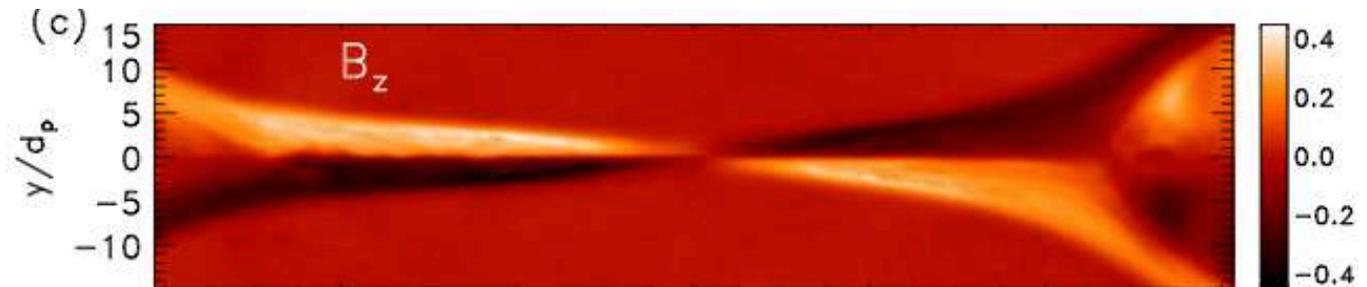


# Hall Magnetic/Electric Fields

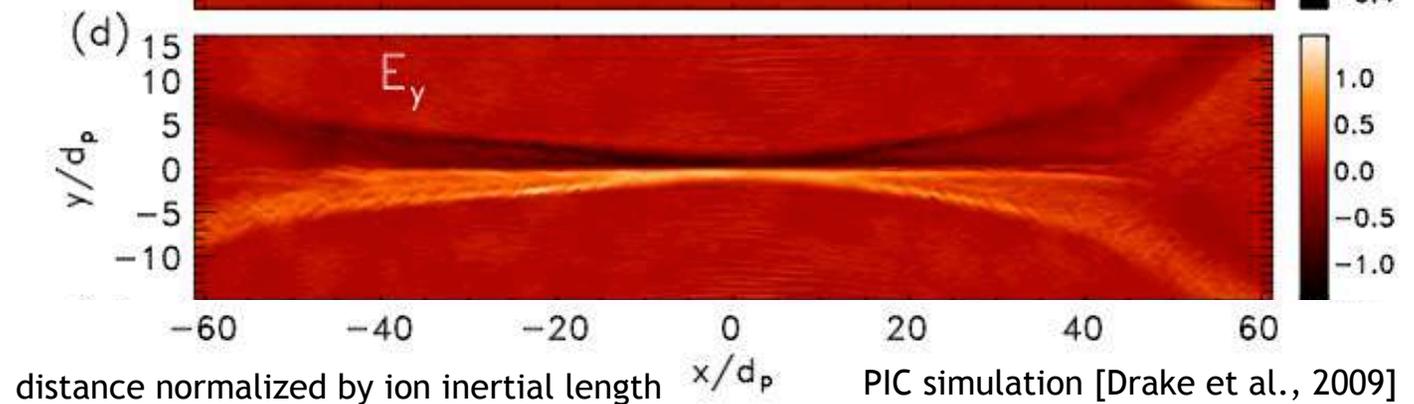
- Ion-electron decoupling around the ion diffusion region
- Hall current system w/ quadrupole B-field
- Inward Hall E-field



Out-of-plane B



In-plane normal E



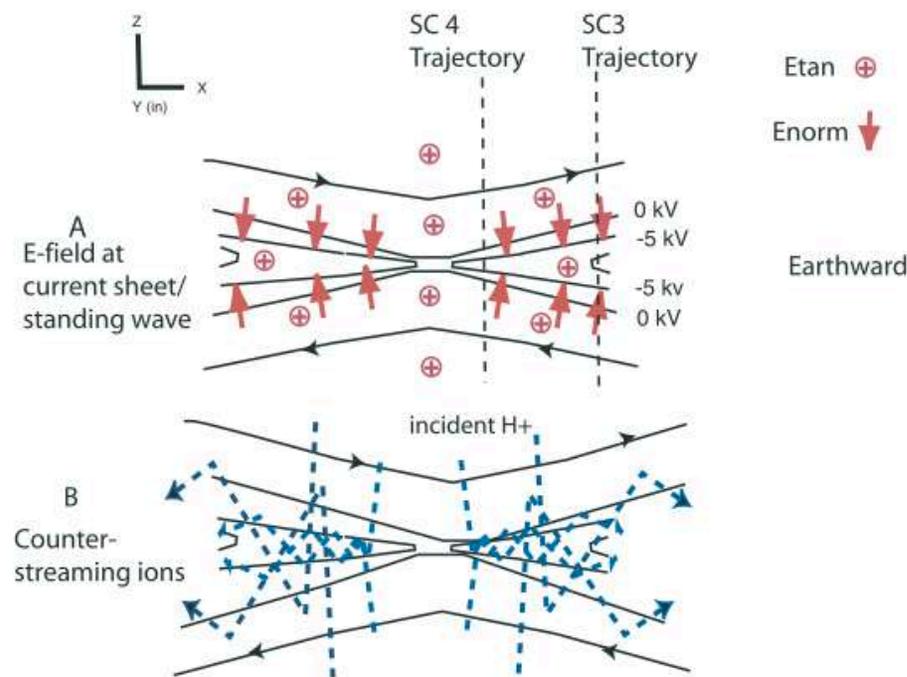
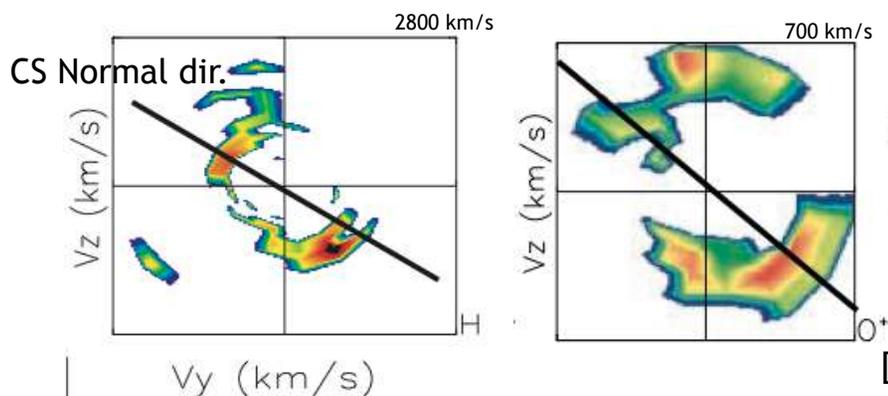
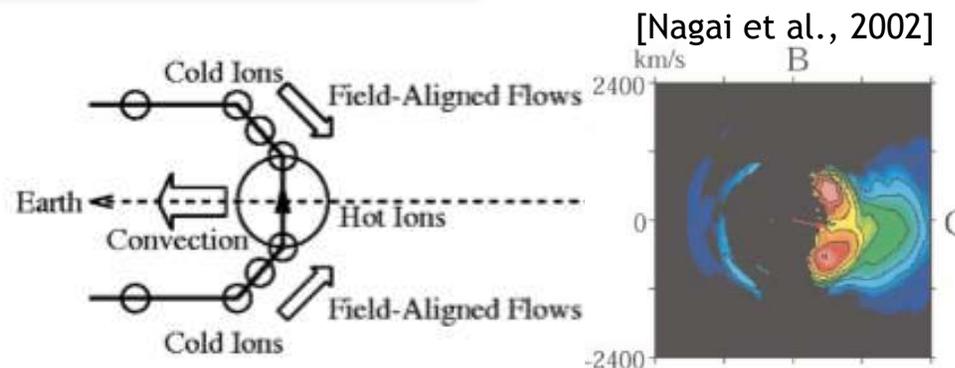
# Counter-streaming Ions

- Inter-penetration of ions from the two sides of the current sheet

➤ Two distinct beams along B

- Ion acceleration/bouncing by Hall E-field in the ion diffusion region

➤ Counter-streaming along the current sheet normal

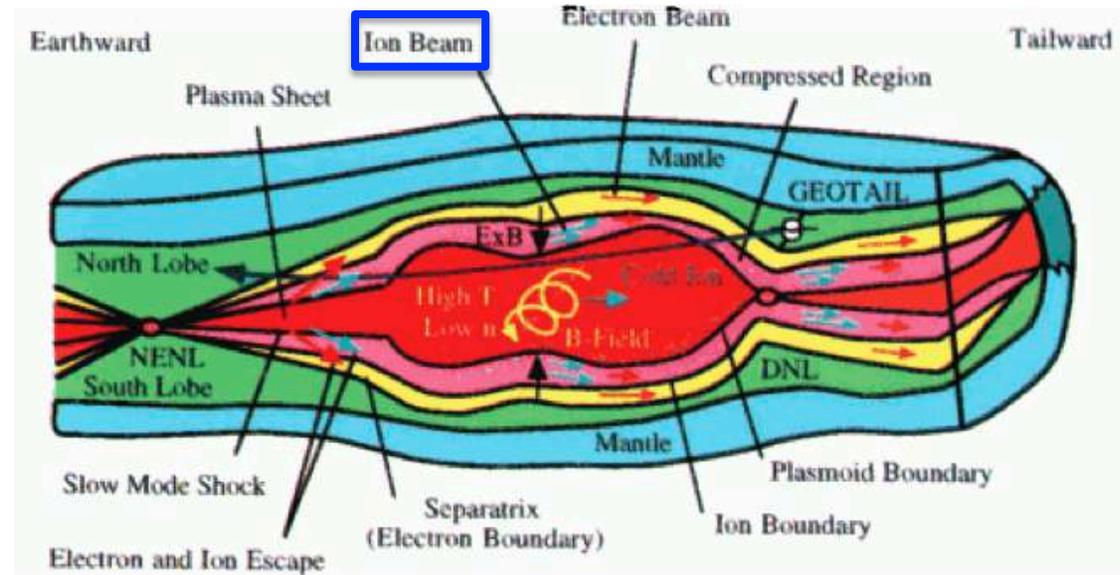


[Wygant et al., 2005]

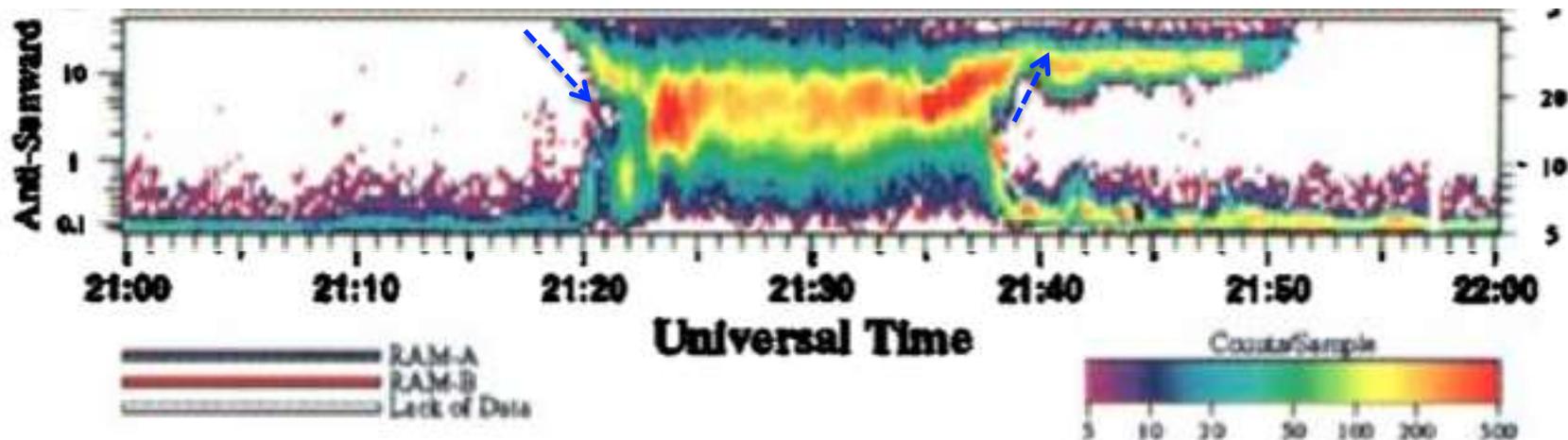
# Energy Dispersive Ion Beams

[Machida et al., 1994]

- Accelerated ion beams with energy dispersion in the separatrix region
  - Interpreted as spatial dispersion by inward convection

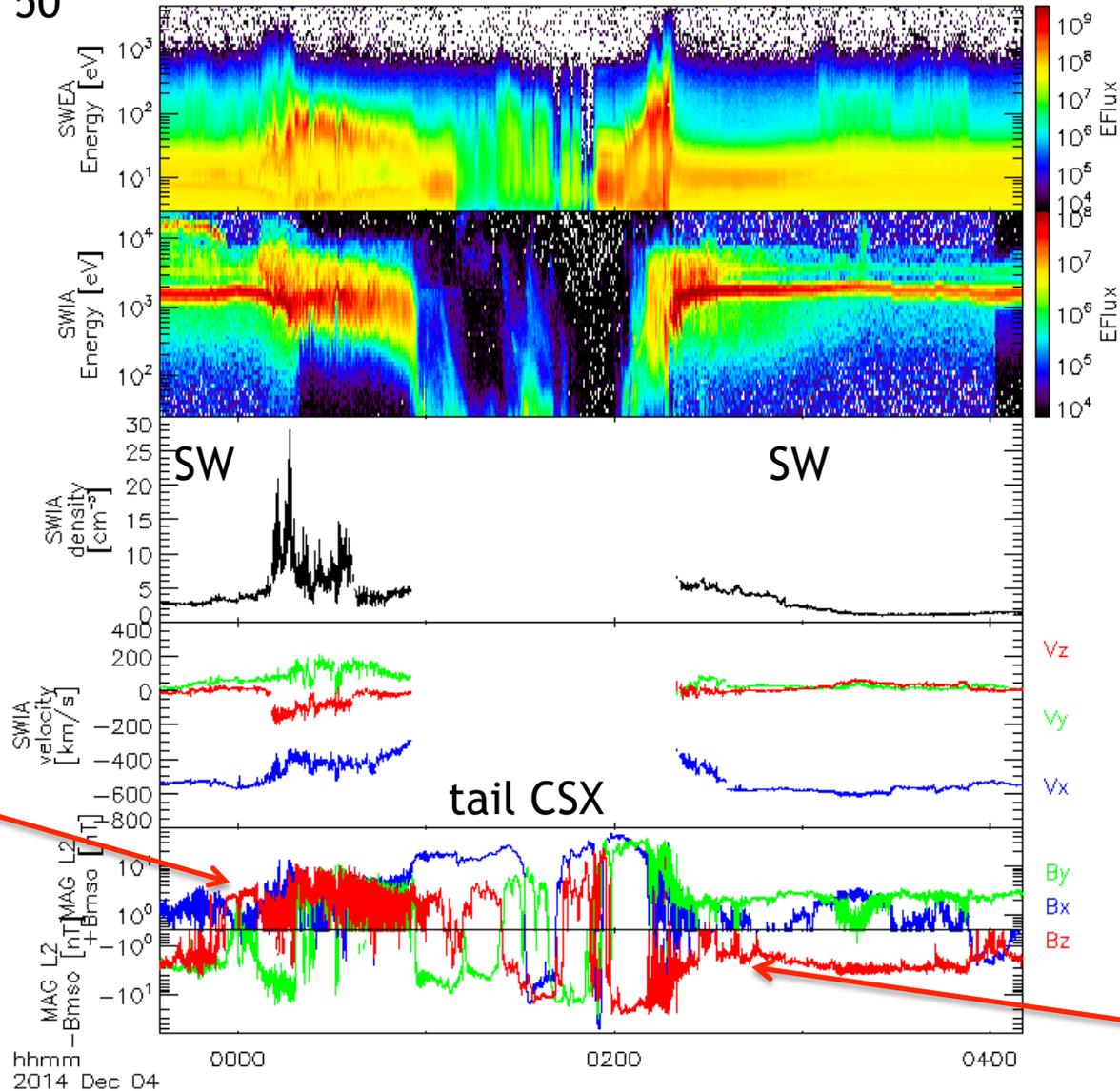


Earth's magnetotail [Mukai et al., 1998]



# Global Context

Sub-solar lon ~ 50°



$B_z > 0$   
just before  
inbound BS

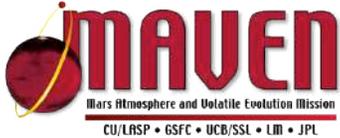
Variable IMF

SW  $P_{\text{dyn}} \sim 2 \text{ nPa}$

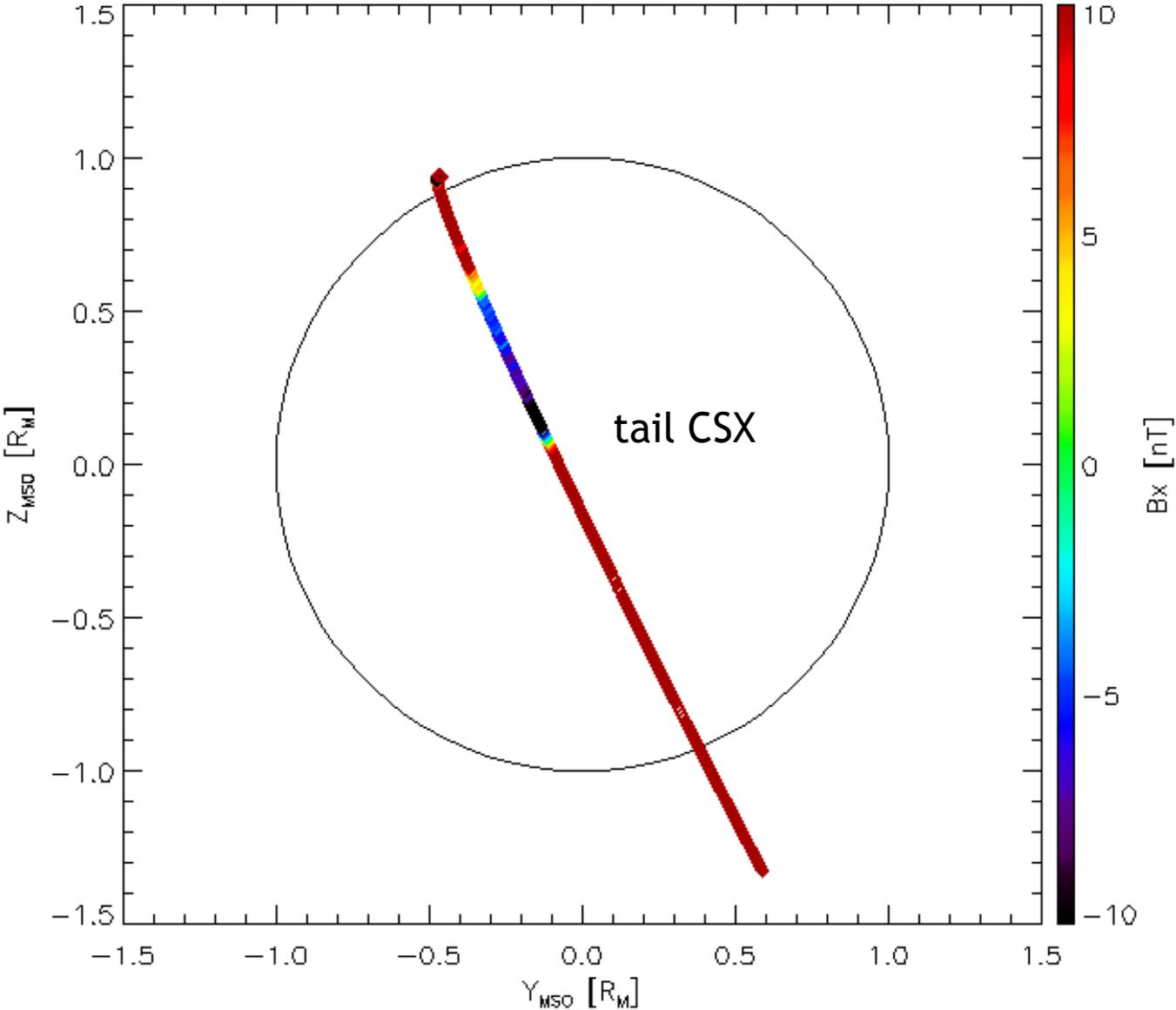
IMF  $B_z$  flipped  
-> magnetotail  
reconfiguration?

$B_z < 0$   
just after  
outbound BS

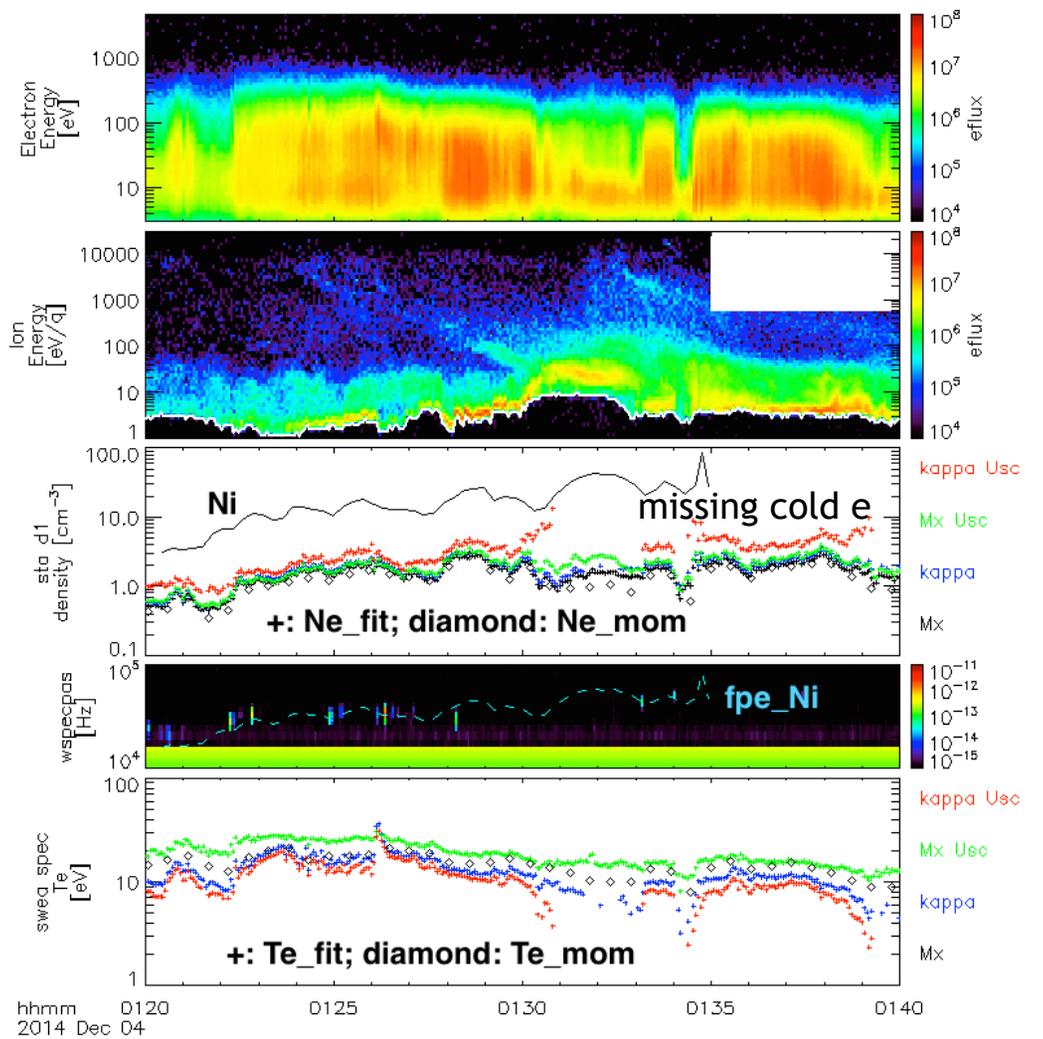
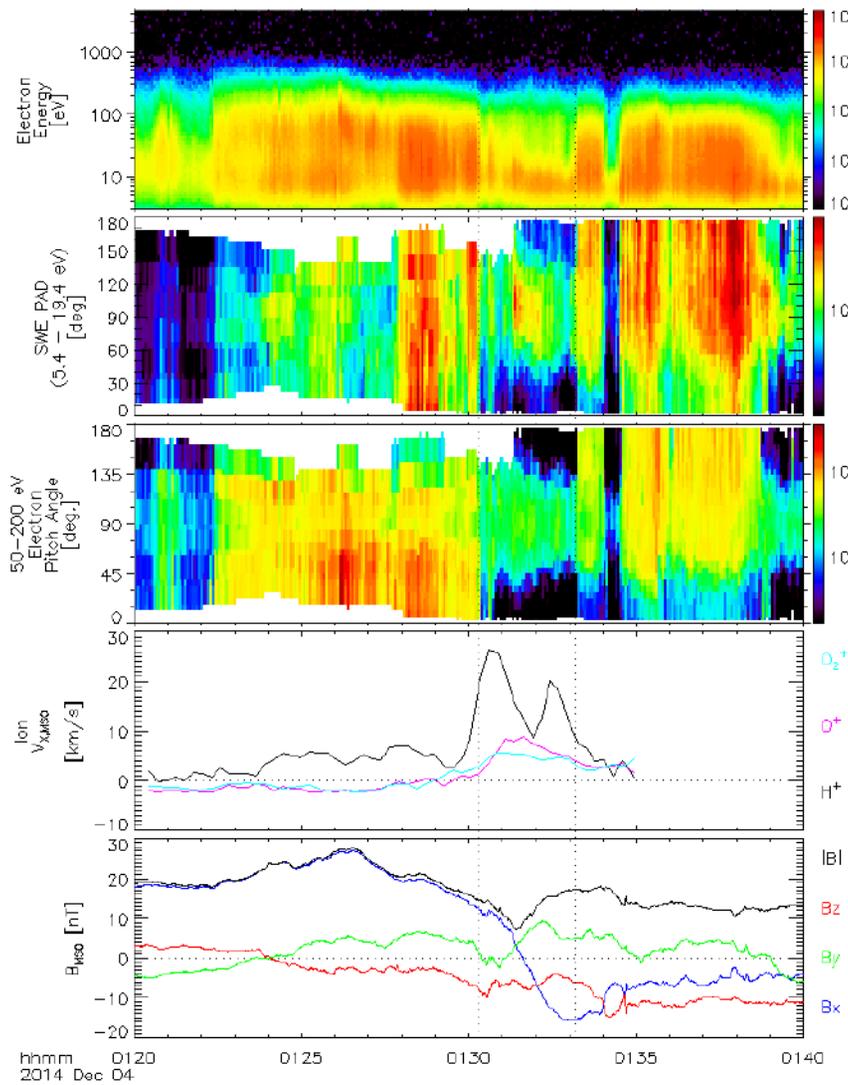
# MAVEN YZ Orbit



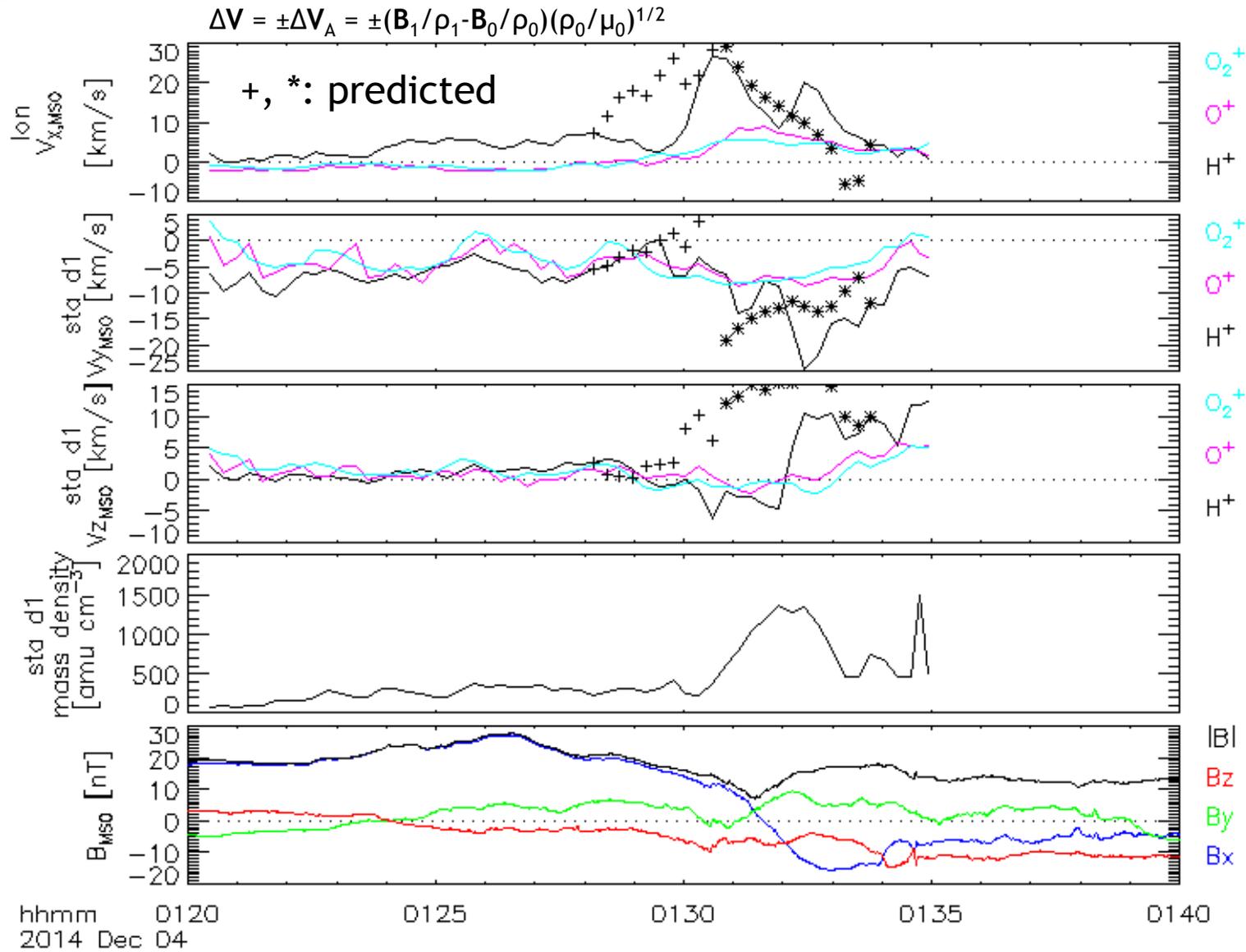
2014-12-04/01:00:00 - 02:00:00



# Electron Spectra



# Walén Test (MHD RD jump cond.)



# O<sub>2</sub><sup>+</sup> Energy Dispersion

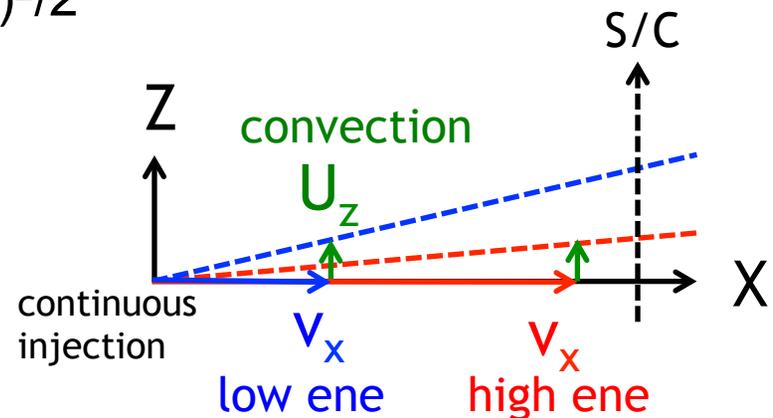
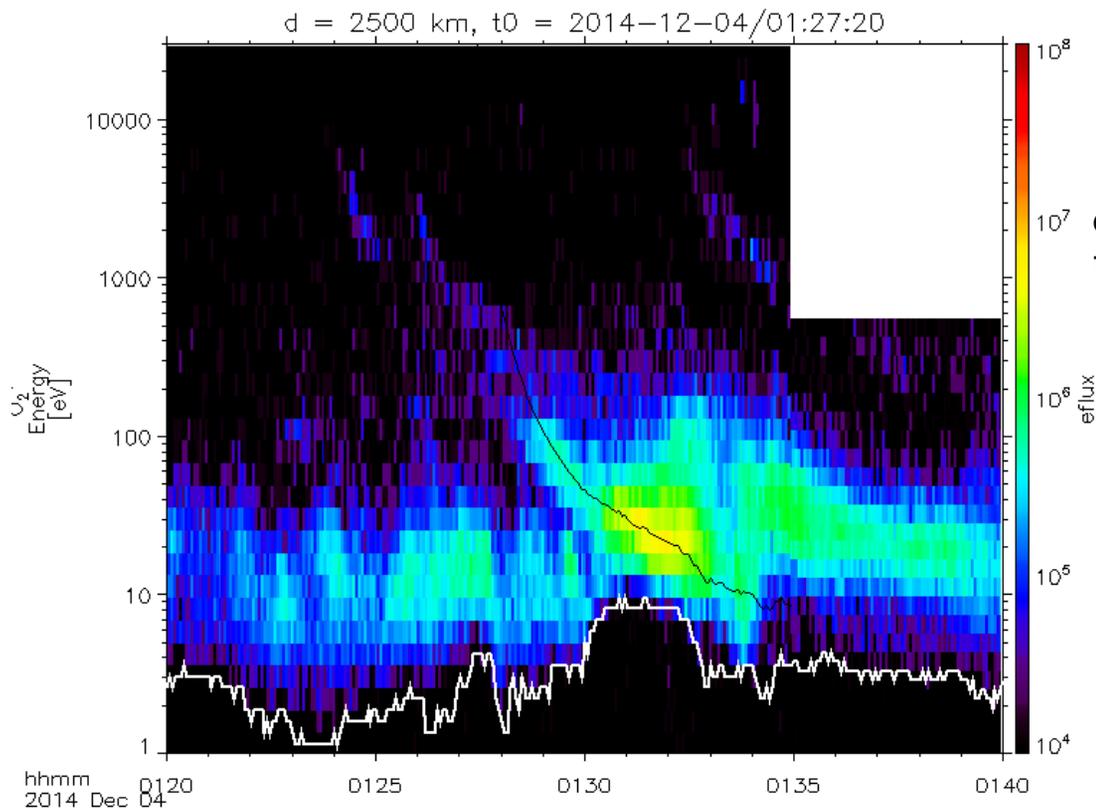
- Time dispersion:  $\Delta t = d/v$

➤  $E_i = m_i (d/\Delta t)^2/2$

- Spatial dispersion:  $\Delta t = \Delta Z/V_{z,SC}$ ,  $\Delta X/v_x = \Delta Z/U_z$

➤  $E_i \sim m_i v_x^2/2 = m_i (\Delta X/\Delta t * U_z/V_{z,SC})^2/2$

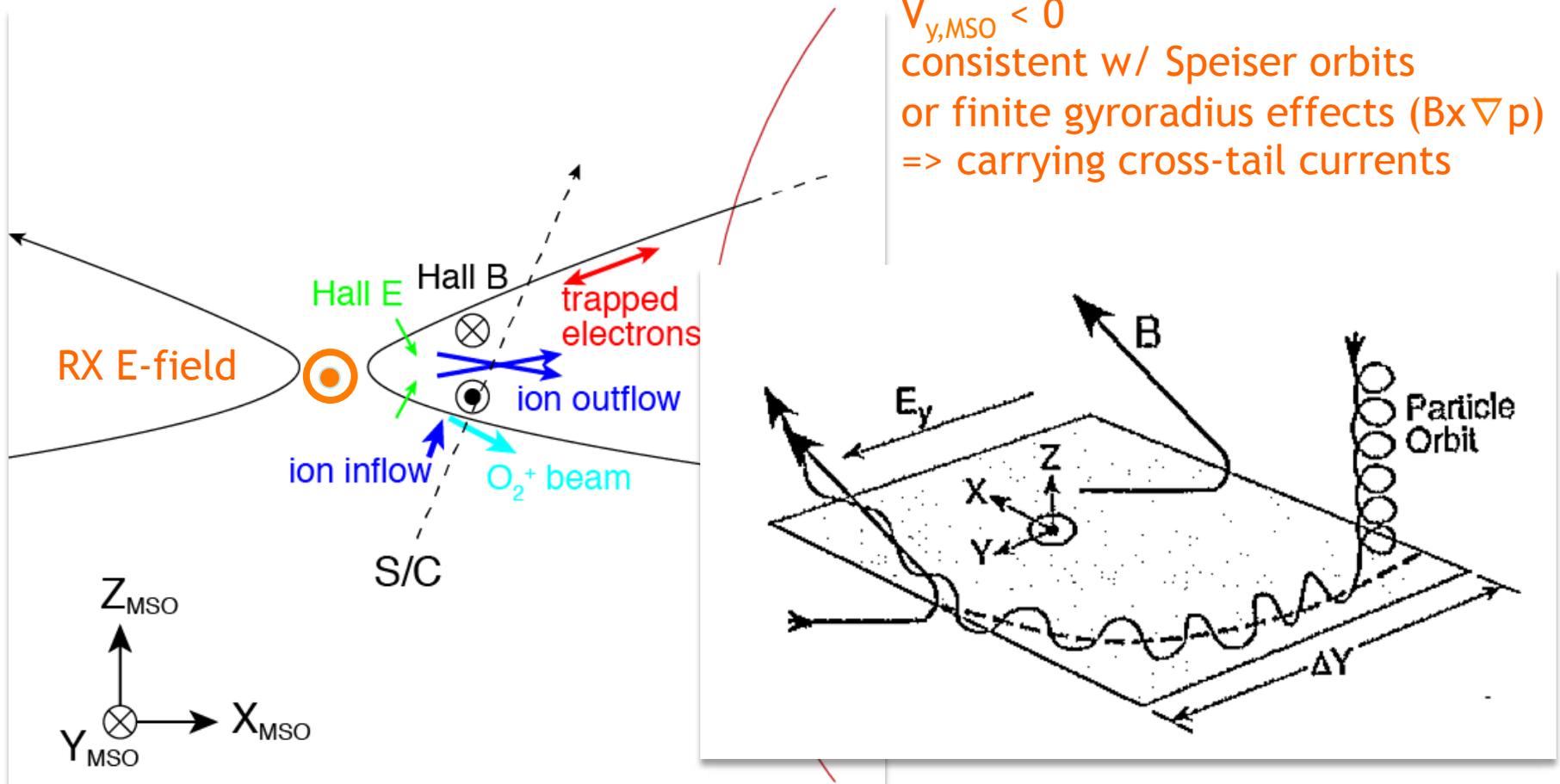
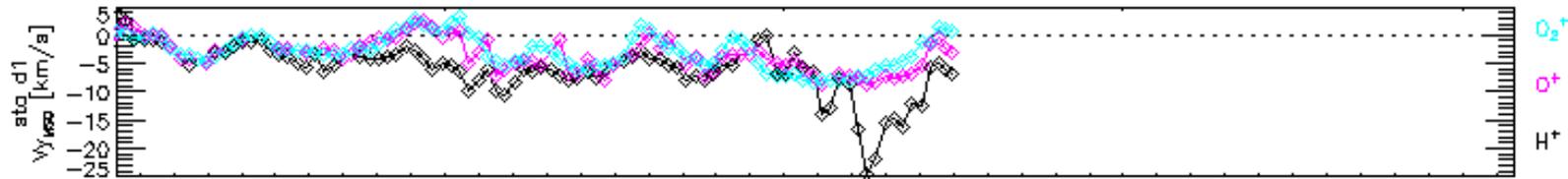
impulsive injection



$d$  or  $\Delta X * U_z/V_{z,SC}$   
~ 2500 km

(cf.  $V_{SC} \sim 3$  km/s)

# Ion $V_y$



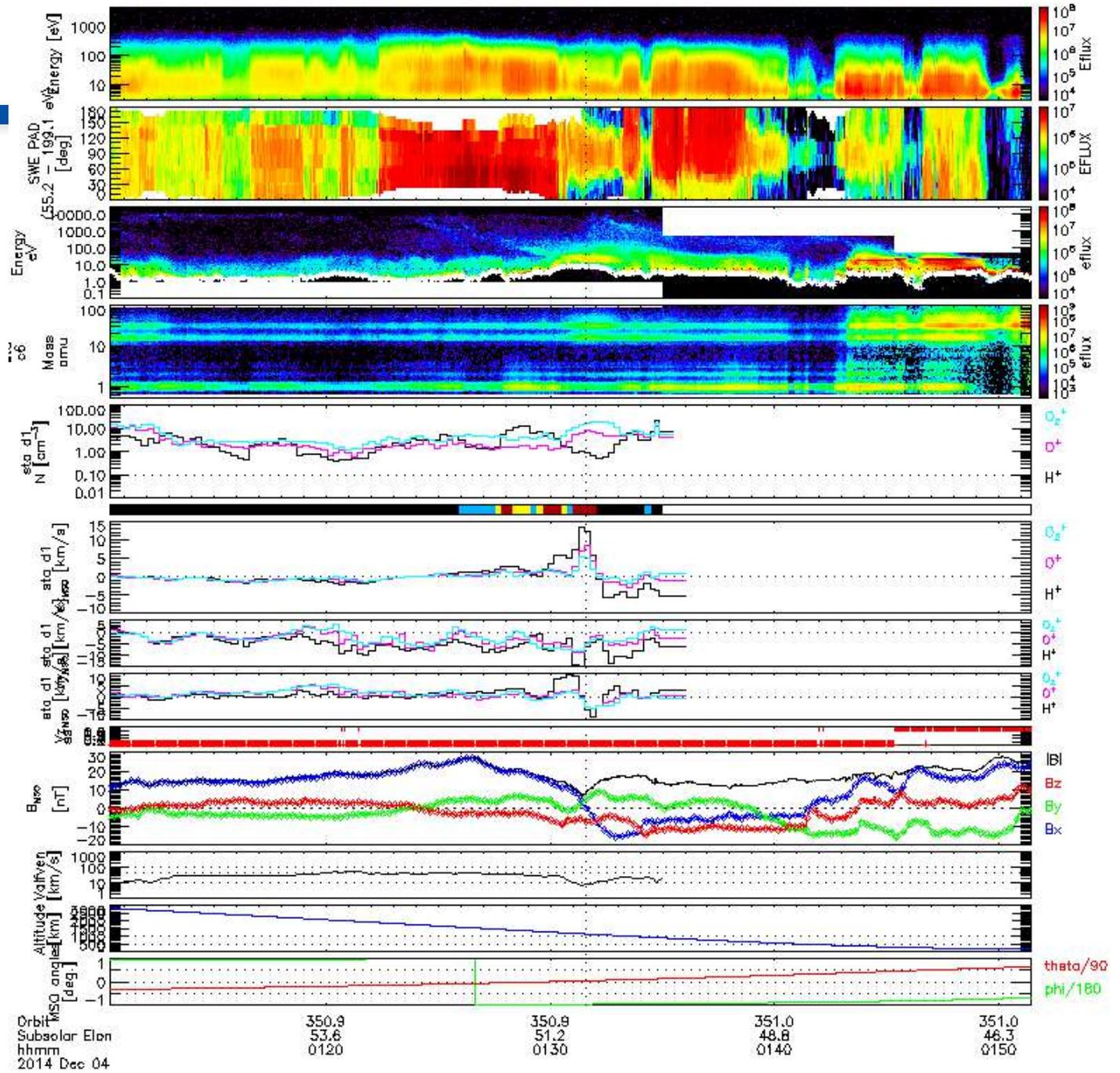
$V_{\perp}$



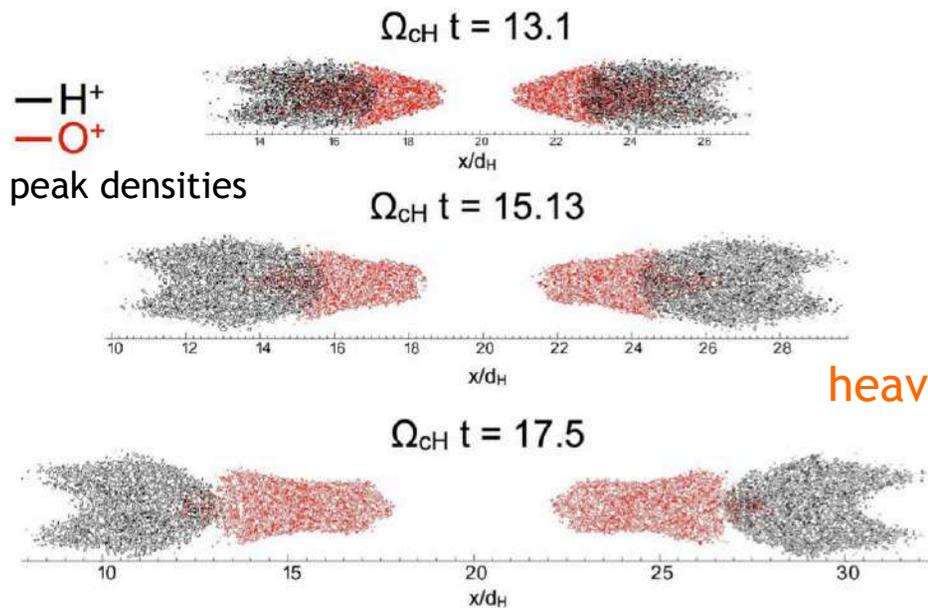
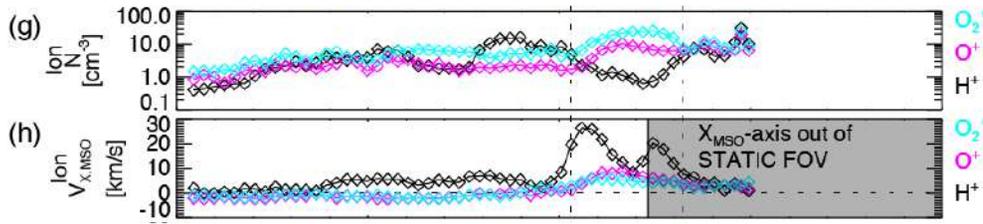
$V_{\perp x}$

$V_{\perp y}$

$V_{\perp z}$



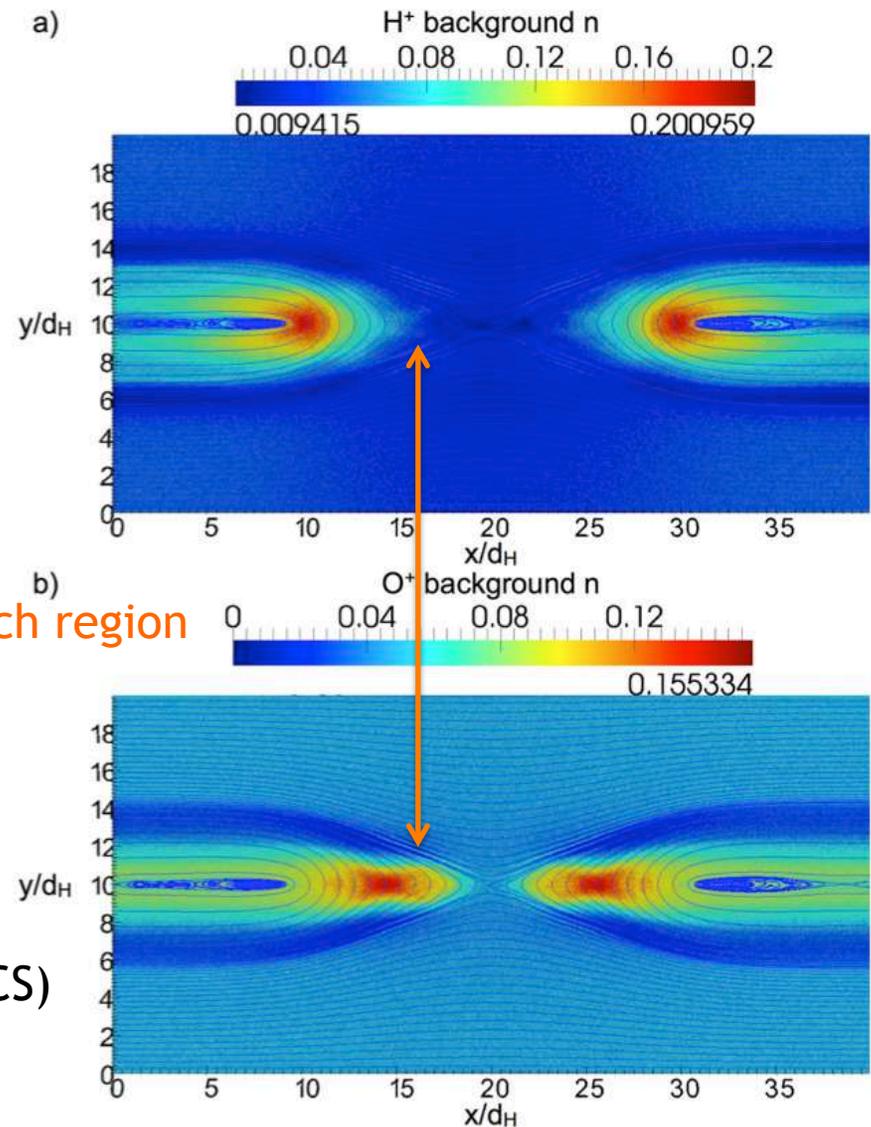
# $N_{H^+}$ v. $N_{O^+}$ , $N_{O_2^+}$



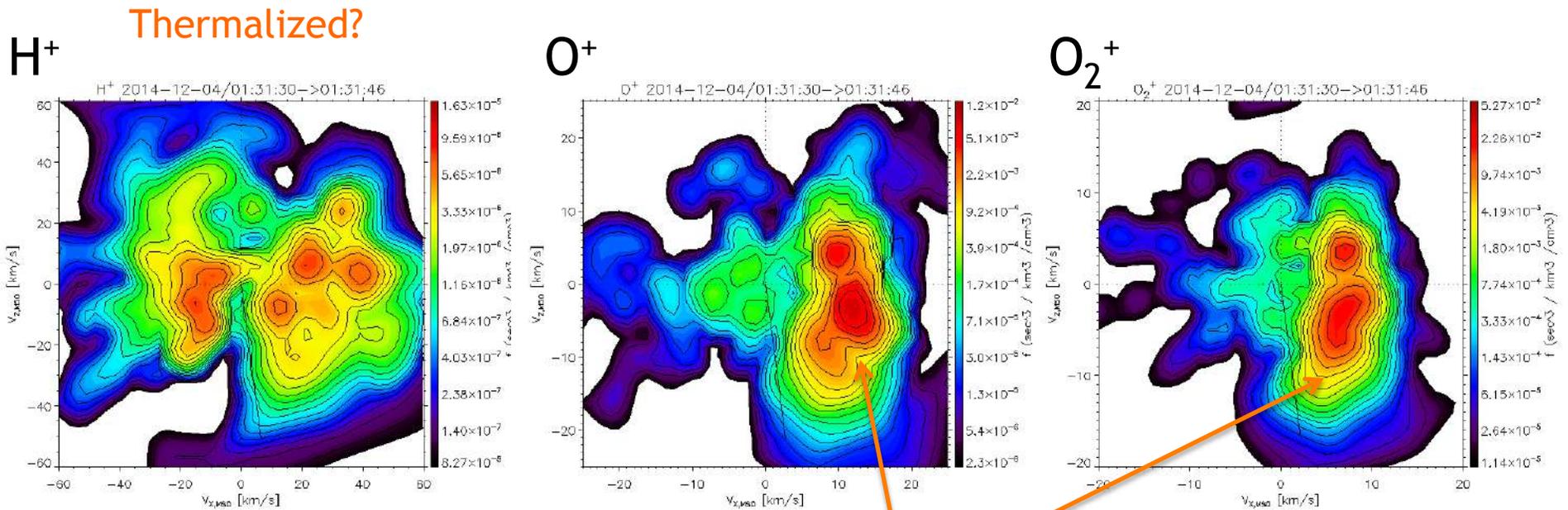
heavy rich region

(does not explain the  $N_{H^+}$  depression in the CS)

[Markidis et al., 2011]



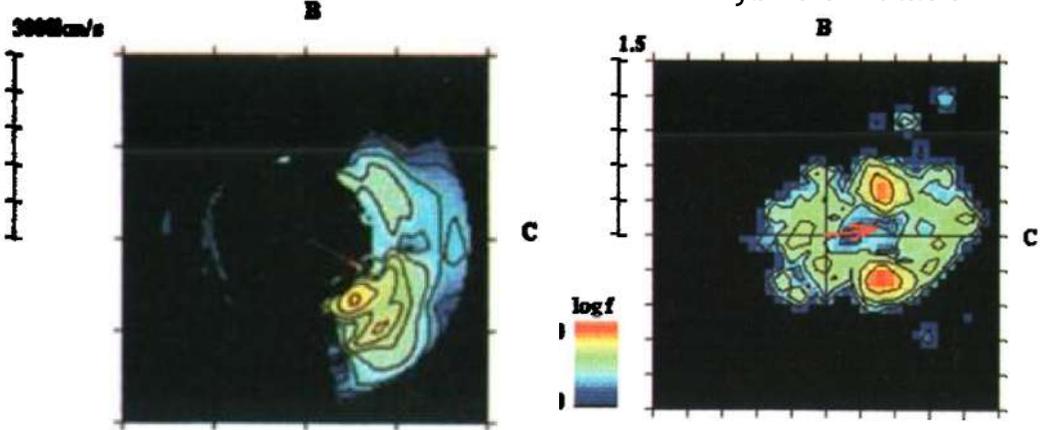
# Ion VDFs at dominant Bz



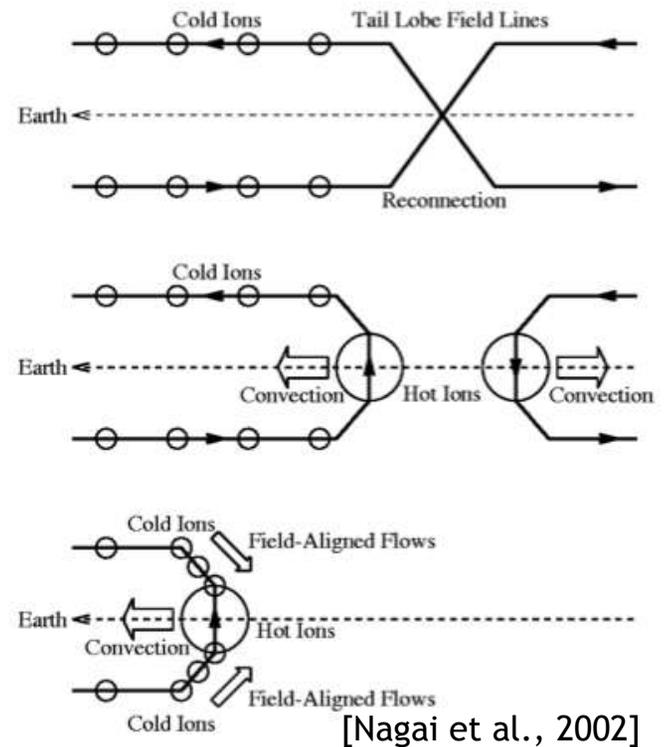
Counter-streaming ion beams  
nearly along B  
(Look like “classical” counter-streaming ion beams  
in reconnection exhausts)

# Counter-streaming Ions

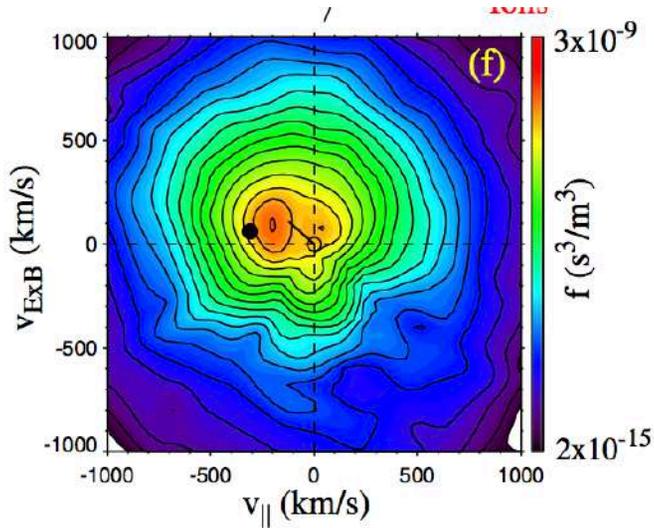
Terrestrial magnetotail [Fujimoto et al., 1996] Hybrid simulation



Mechanism of Counterstreaming Ions

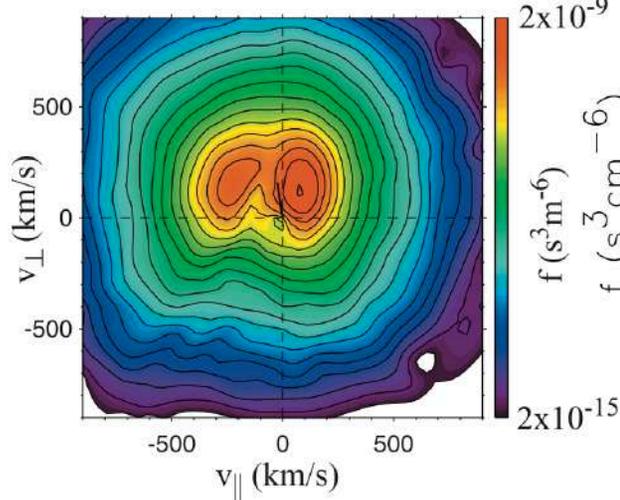


Terrestrial magnetopause [Phan et al., 2013]

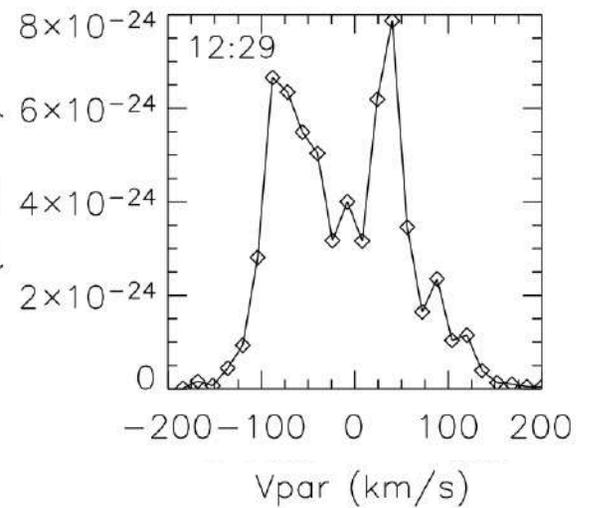


Terrestrial magnetosheath [Phan et al., 2007]

Cluster 1 HIA ions  
2003-01-14/06:12:05-06:12:17



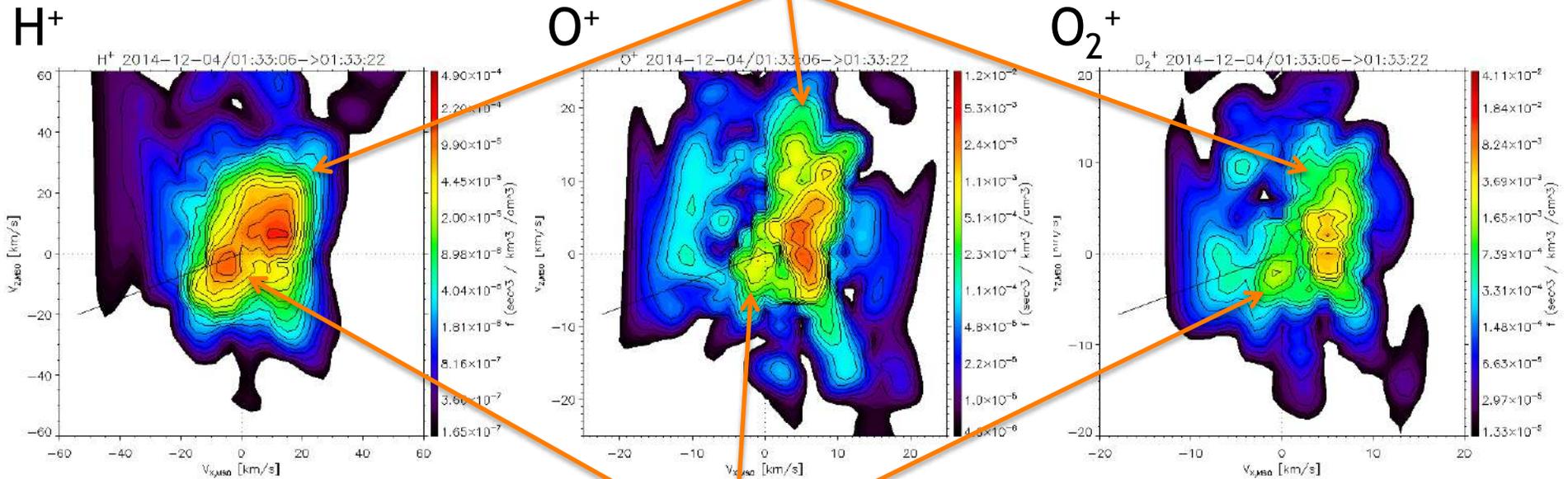
Solar Wind [Gosling et al., 2005]



# Ion VDFs Just North of Closed B

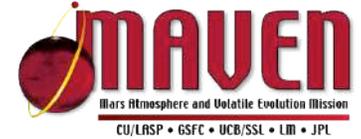
Mixture of outflow and inflow ions?

Outflow ions elongated along Z



Cold ion inflow  
w/ parallel velocity component  
(supplied from nightside ionosphere?)

# Current Sheet Parameters



- Current sheet width (assuming a static structure):  
 $V_{SC,Normal} dt \sim 520 \text{ km}$
- Ion inertial lengths (based on mean  $N_{i,PS}$ ):
  - $\lambda_{H^+} \sim 174 \text{ km}$  ( $N_{H^+} \sim 1.71 \text{ cm}^{-3}$ )
  - $\lambda_{O^+} \sim 363 \text{ km}$  ( $N_{O^+} \sim 6.31 \text{ cm}^{-3}$ )
  - $\lambda_{O_2^+} \sim 314 \text{ km}$  ( $N_{O_2^+} \sim 16.8 \text{ cm}^{-3}$ )
- Ion gyroradii (based on mean  $T_{i,PS}$  and  $B_{lobe} \sim 15 \text{ nT}$ ):
  - $r_{LH^+} \sim 64 \text{ km}$  ( $T_{H^+} \sim 44 \text{ eV}$ )
  - $r_{LO^+} \sim 185 \text{ km}$  ( $T_{O^+} \sim 23 \text{ eV}$ )
  - $r_{LO_2^+} \sim 177 \text{ km}$  ( $T_{O_2^+} \sim 10 \text{ eV}$ )
- Mean ion gyroradii (based on local  $T_i$  and  $B$ ):
  - $r_{LH^+} \sim 78 \text{ km}$
  - $r_{LO^+} \sim 212 \text{ km}$
  - $r_{LO_2^+} \sim 214 \text{ km}$