

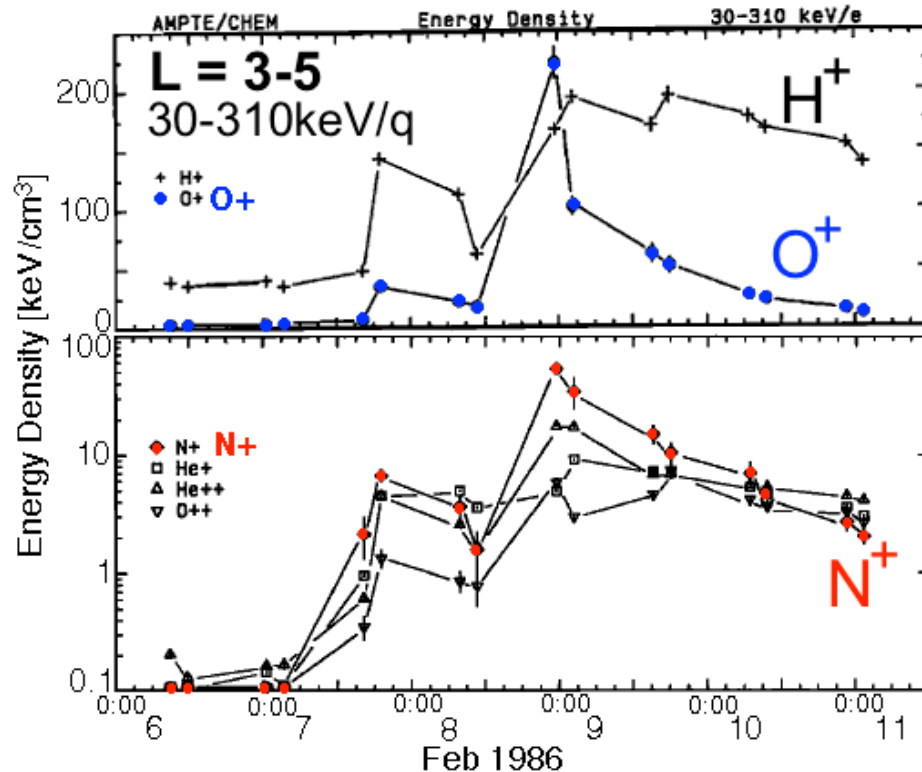
Fate of outflowing ions from the Earth's ionosphere: current knowledge and remaining questions

Sorry, no time for acceleration/heating mechanisms

M. Yamauchi

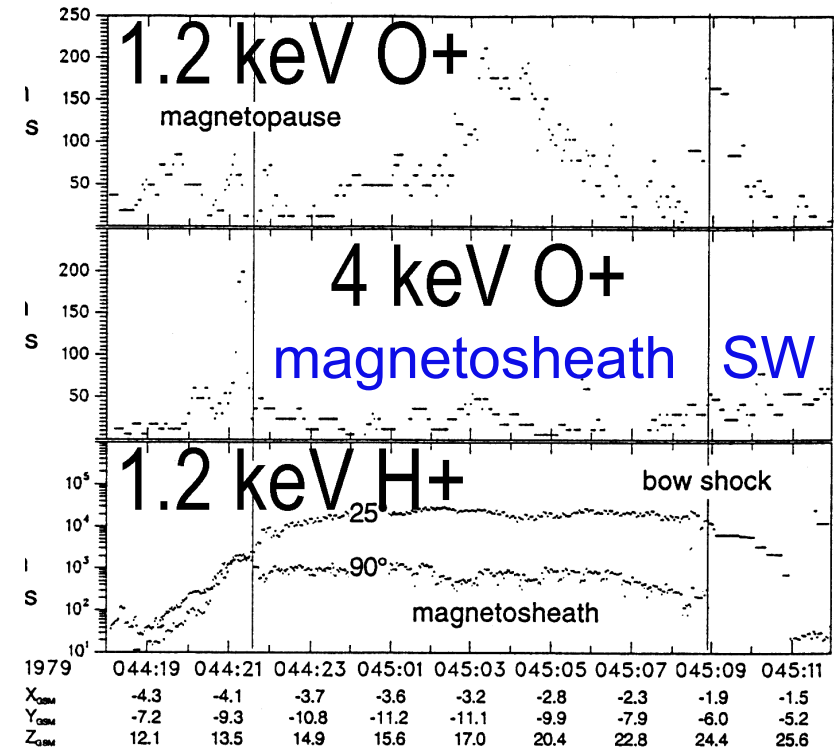
Full of ionospheric ions in space (1970's)

O^+ and N^+ (magnetosphere)



(Shelly et al., 1972, Hamilton et al., 1988)

O^+ (solar wind)



(Lundin et al., 1980, Eklund et al., 1997)

Our Tasks: For each species, circulation/escape routes, energization along the route, budget, temporal variation, and active roles both short/long term

Outline

(1) **Types of outflow** (cold filling, cold/superthermal outflow, hot outflow) and **primary destinations**

(2) Ions that are not directly escaping: **Inner Magnetosphere** as a zoo of ions

- time-variable multiple sources
- time-variable **E-field**
- **local energization**
- expected/unexpected **mass-dependency**

(3) Amount of **ion escape** and its consequence:

- **Evolution of the Earth** in geological scale (then cannot ignore **neutral**)

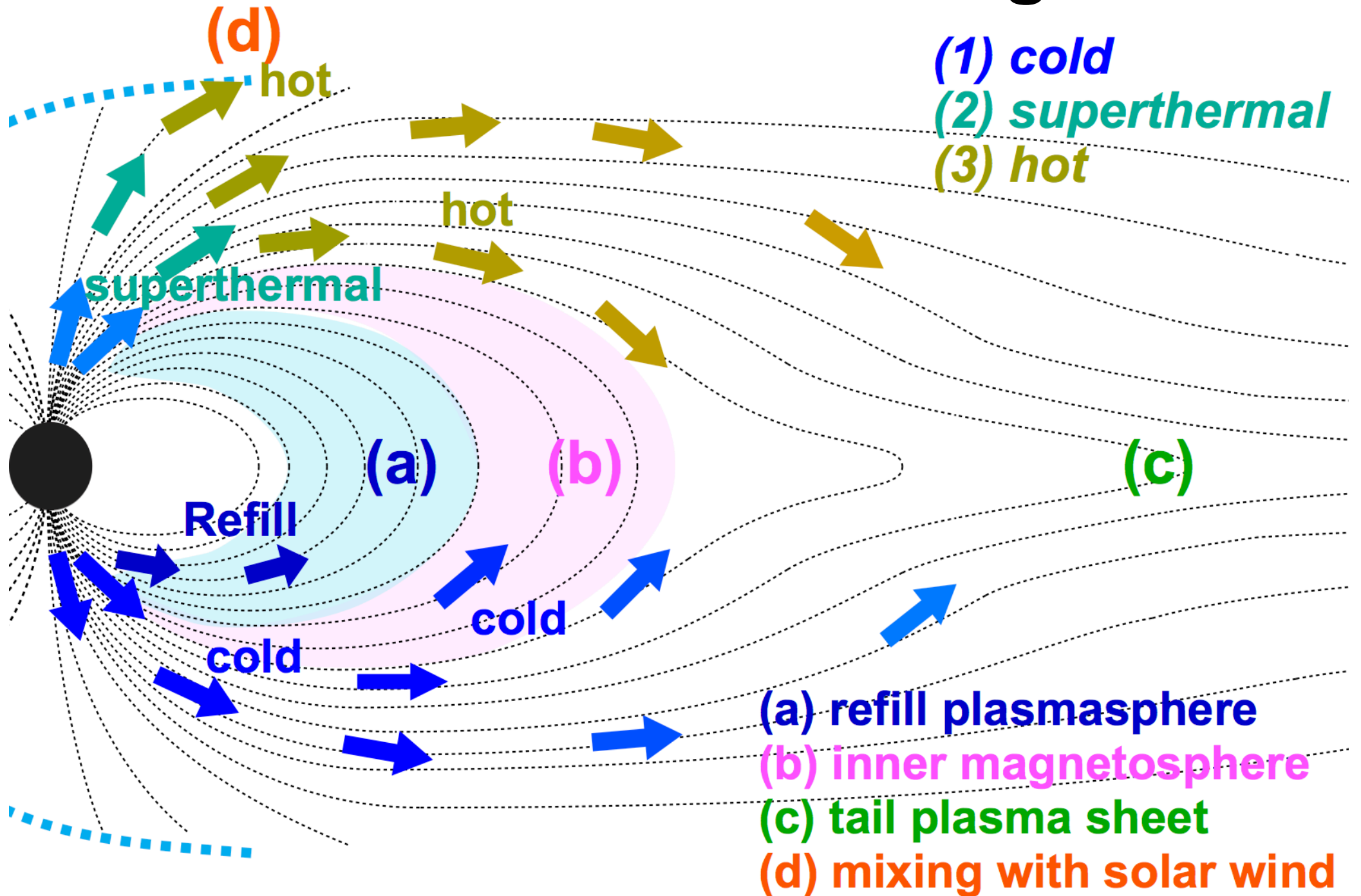
If we have time.....

(4) **Active roles** of terrestrial (planetary) ions

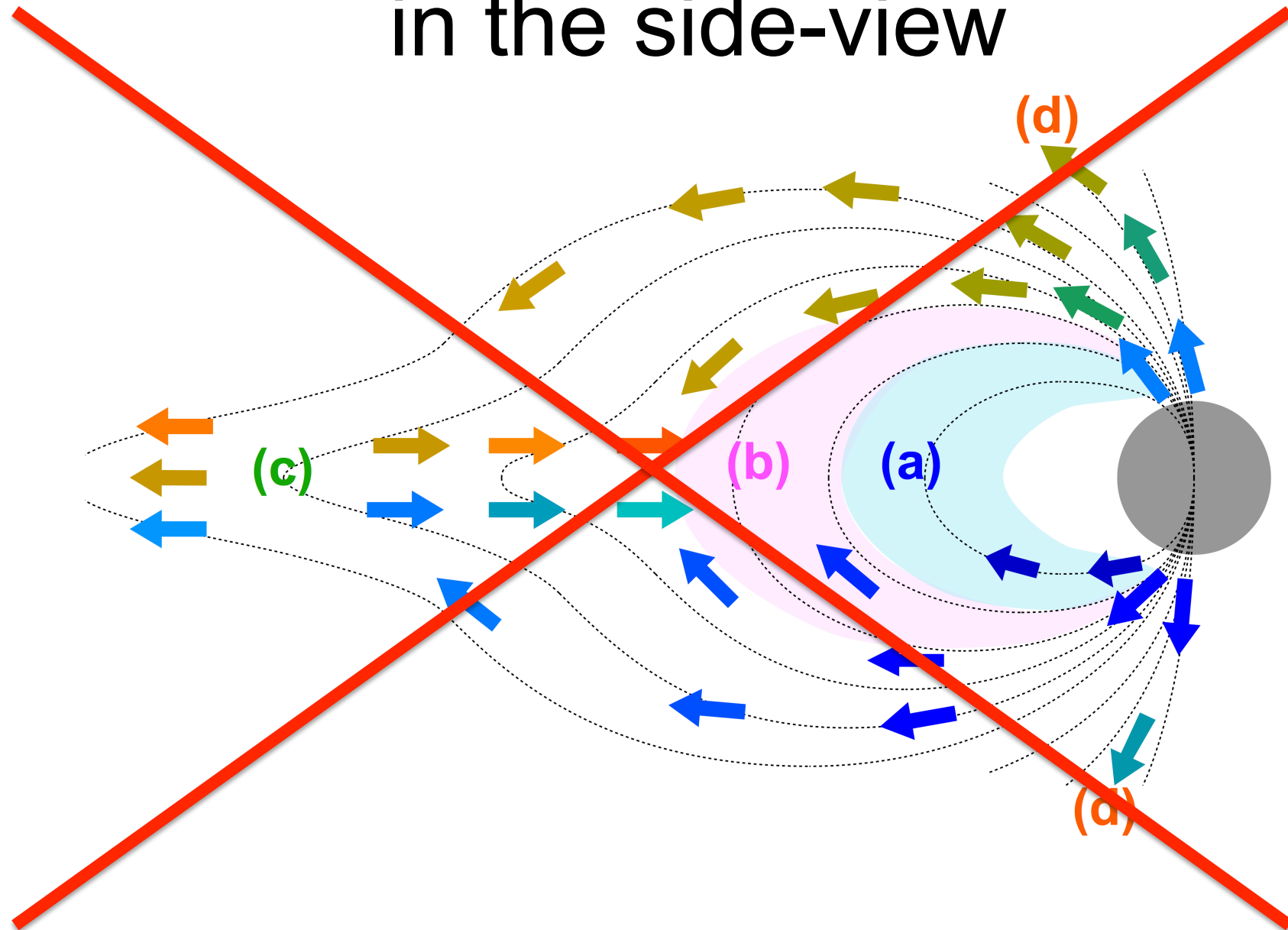
- in **local energy conversion** through mass-loading
- in **bow shock** structure and **foreshock** formation

(5) Ions in the neutral atmosphere: Unique method **to monitor ionizing radiation**

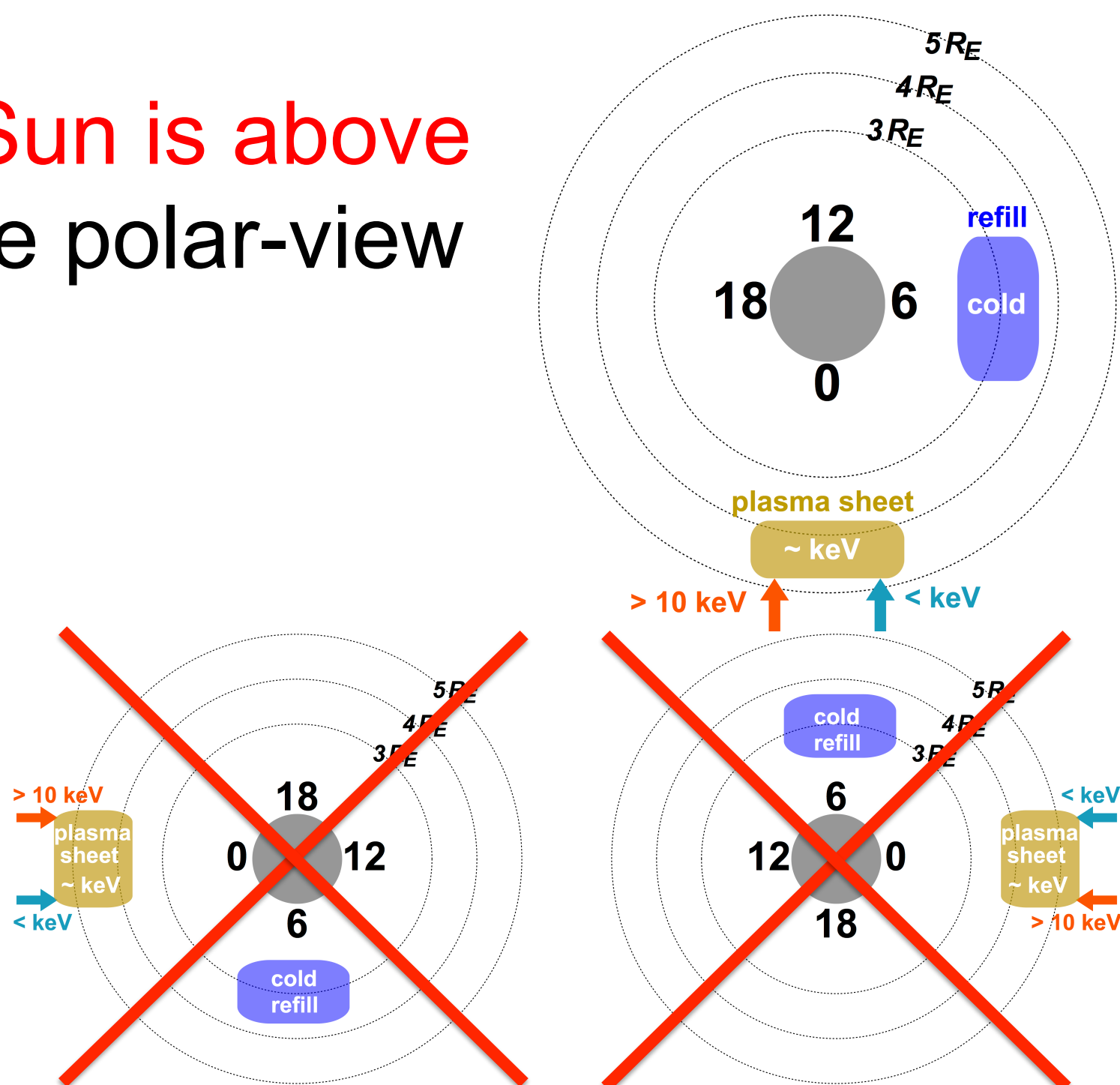
Destinations of outflowing ions



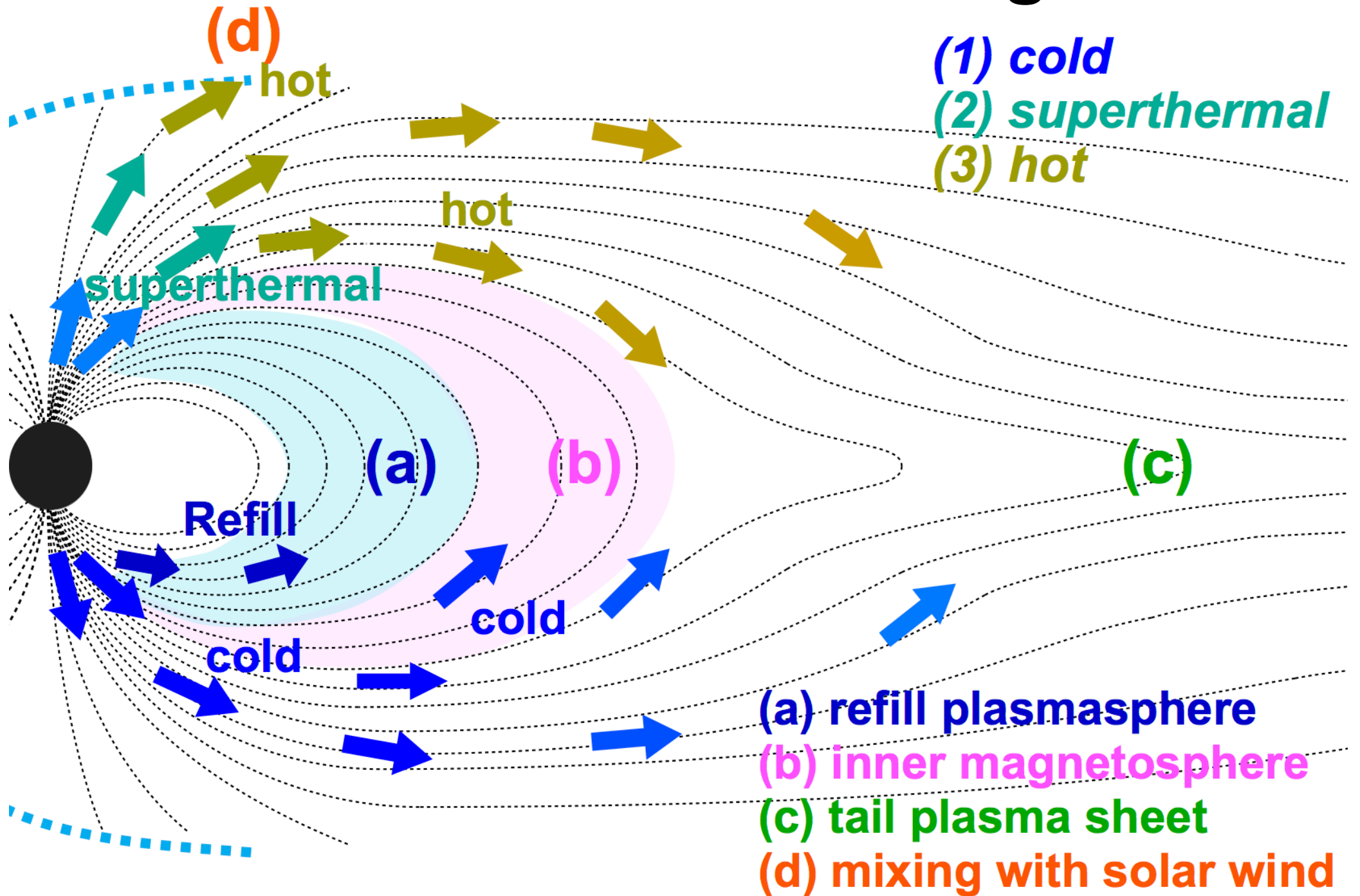
In this presentation, **Sun is left**
in the side-view



and **Sun is above**
in the polar-view



Destinations of outflowing ions

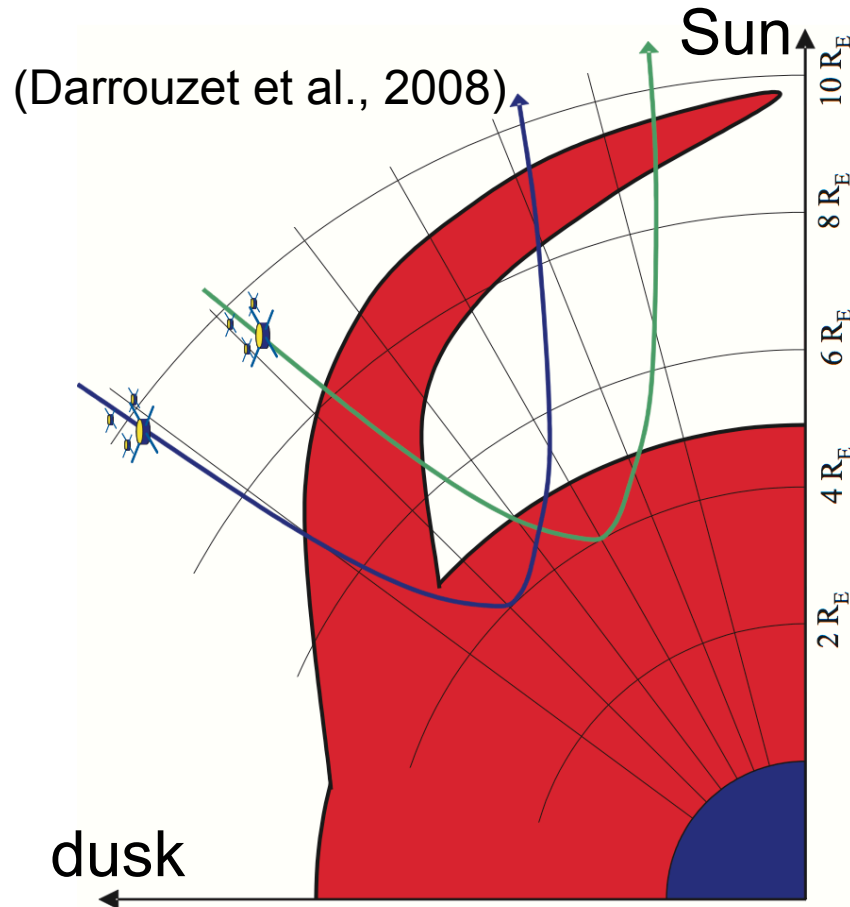


Three types of ion outflow (Earth)

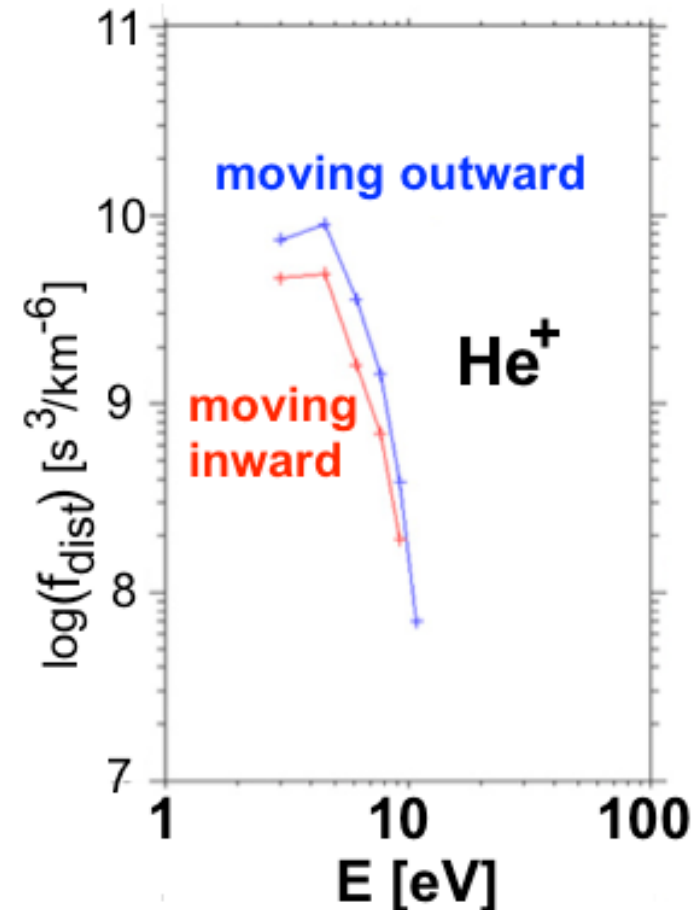
(1a) Refill plasmasphere=(a) with cold H^+ & He^+ after

(i) plume is formed & detached

(ii) outward wind (≈ 1.4 km/s)



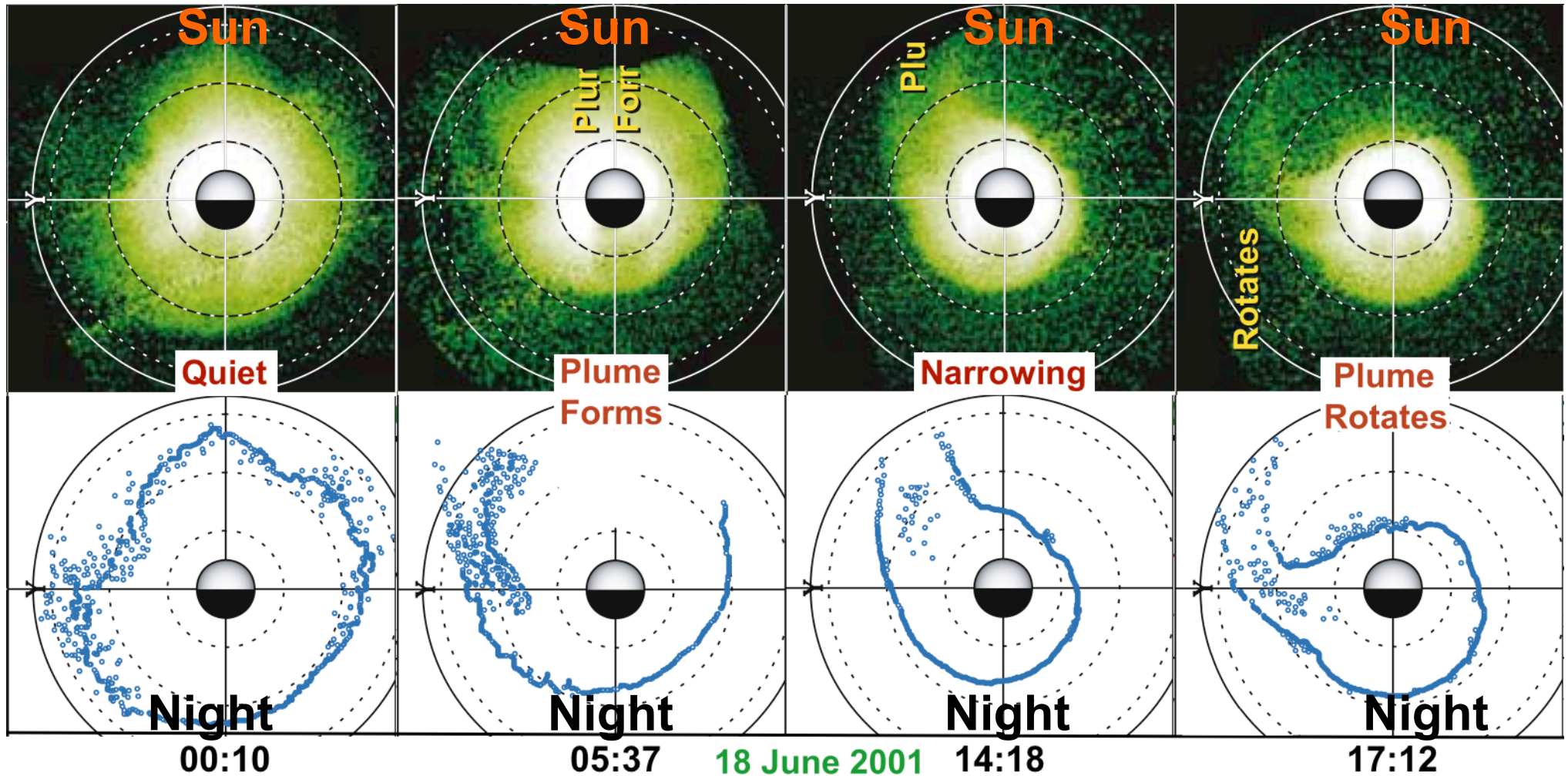
H^+ loss rate $\sim 10^{27} \text{ s}^{-1}$,
but short time & $\text{O}^+/\text{H}^+ \leq 0.01$



H^+ loss rate $\sim 5 \times 10^{26} \text{ s}^{-1}$,
but $\text{O}^+/\text{H}^+ \leq 0.01$

Three types of ion outflow (Earth skip?)

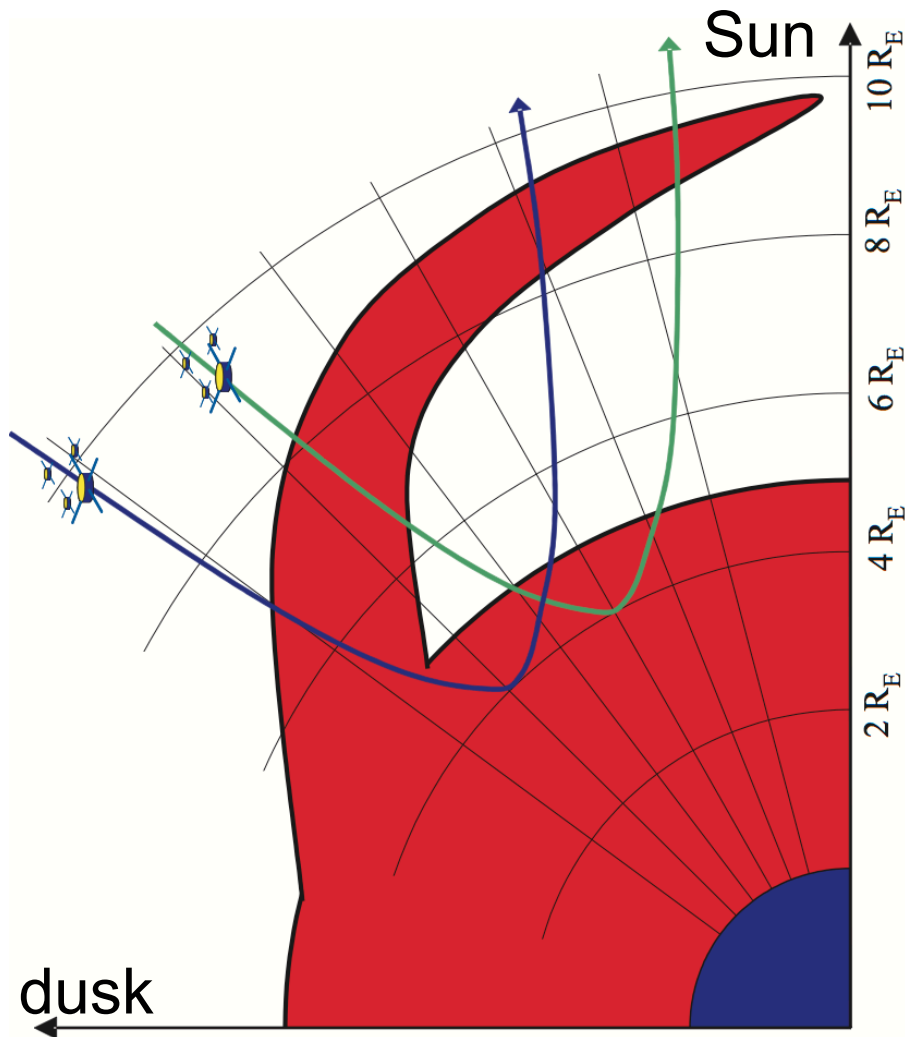
(1a) Refill plasmasphere=(a) with cold H^+ & He^+ after detaching or expansion ($10^{26-27}/s$) IMAGE FUV observation (Goldstein, 2006)



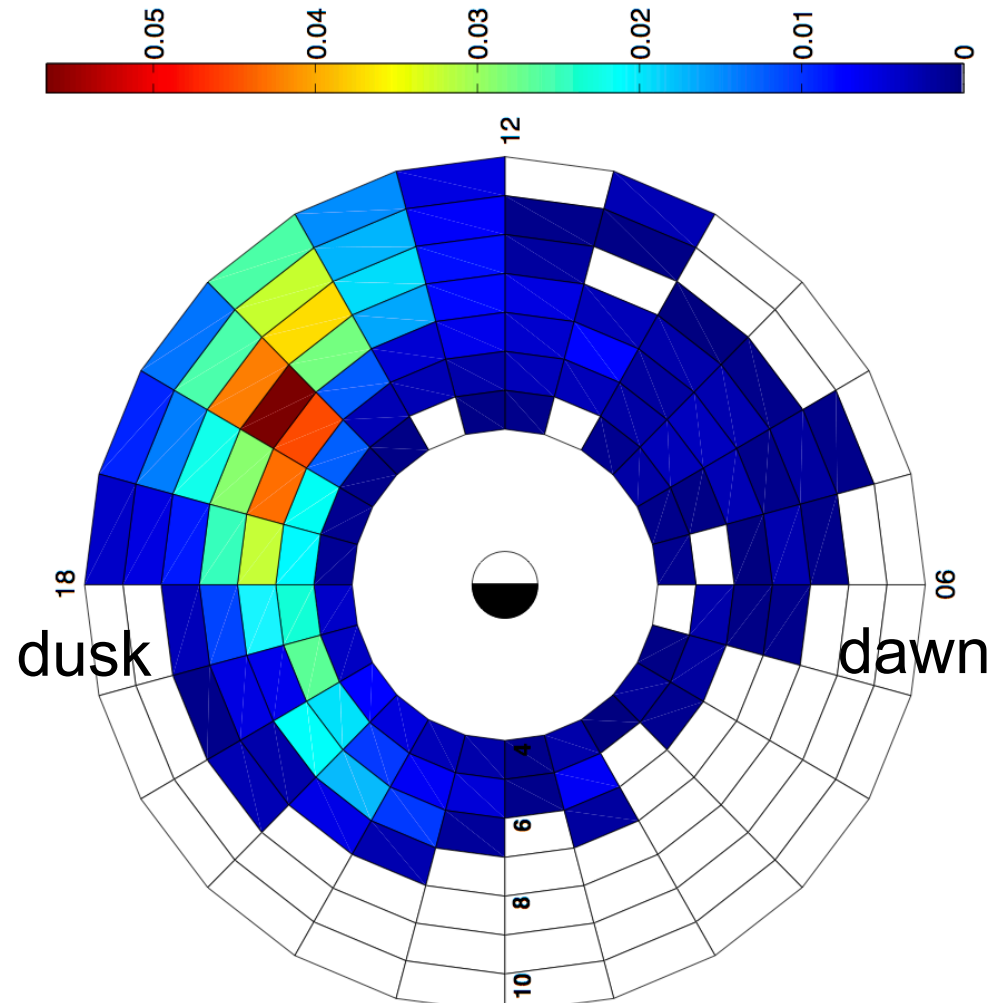
However, O^+ is much less ($<10^{25}/s$)

(1a) Loss of plasmaspheric cold H^+ & He^+ (n skip?)

Detached Plume



(Darrouzet et al., 2008)

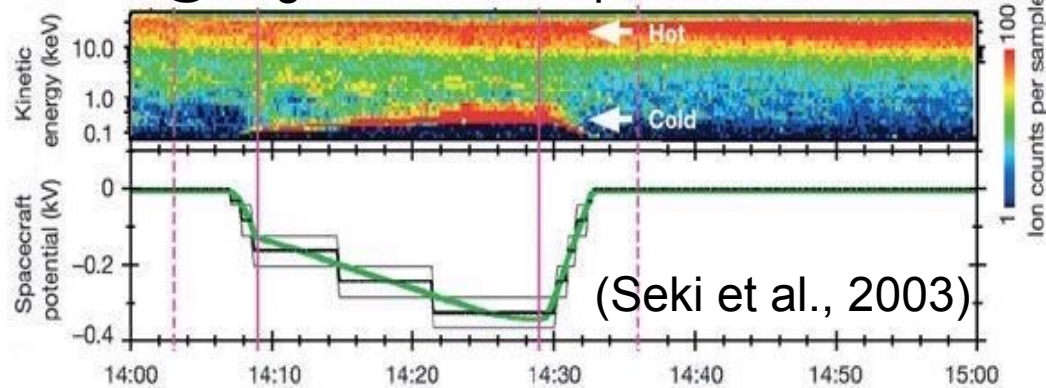


H^+ loss rate $\sim 10^{27} \text{ s}^{-1}$,
but short time & $O^+/H^+ \leq 0.01$

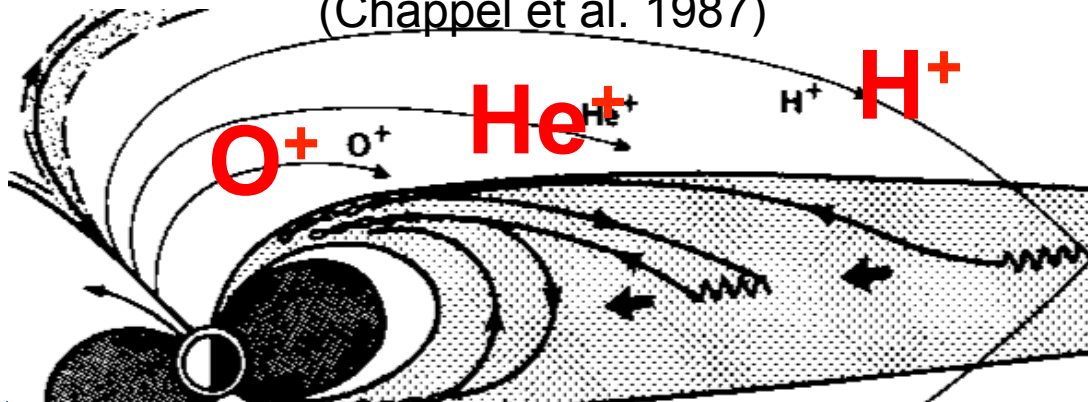
(1b) Supersonic flow of cold H^+ (& some He^+)

Massive flow (cold $H^+ \sim 10^{26} \text{ s}^{-1}$) to the plasma sheet ("cold dense" **plasma sheet** component) $\neq$ plasmasphere

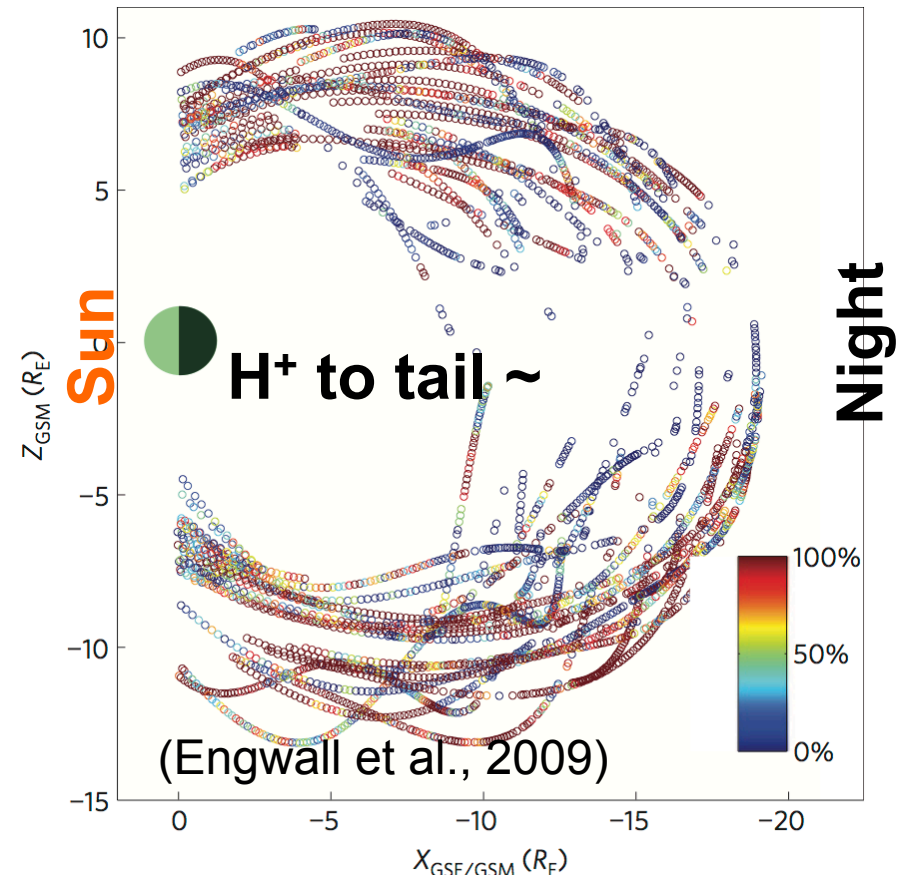
Geotail @ negative satellite potential, 1997-7-19



"cold" view of destination
(Chappel et al. 1987)



Cluster EFW detection
(SC-3, July-Oct, 2002)



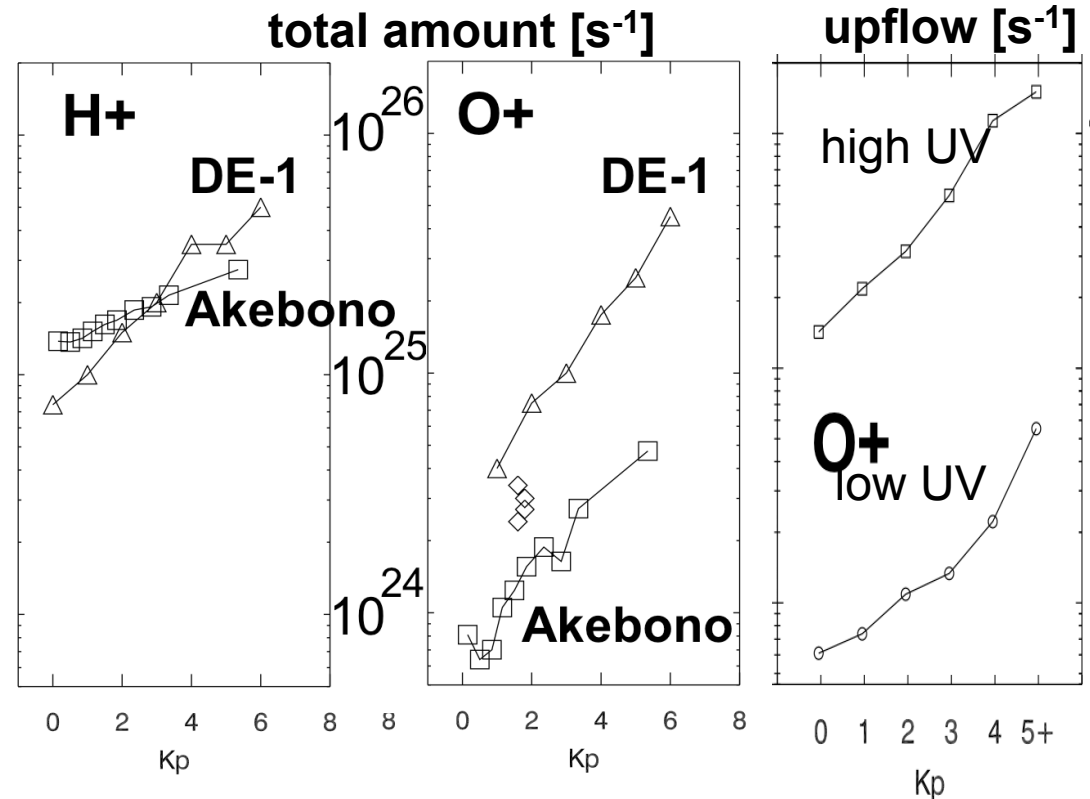
However, O^+ is very little

(2) Superthermal H^+ & O^+ (< 20 eV)

skip?

(< 20 eV at 1500 km altitude)

O^+ outflow $\sim 10^{25-26} s^{-1}$



Akebono, $< 70 eV @ 9000 km$, 1989-1998

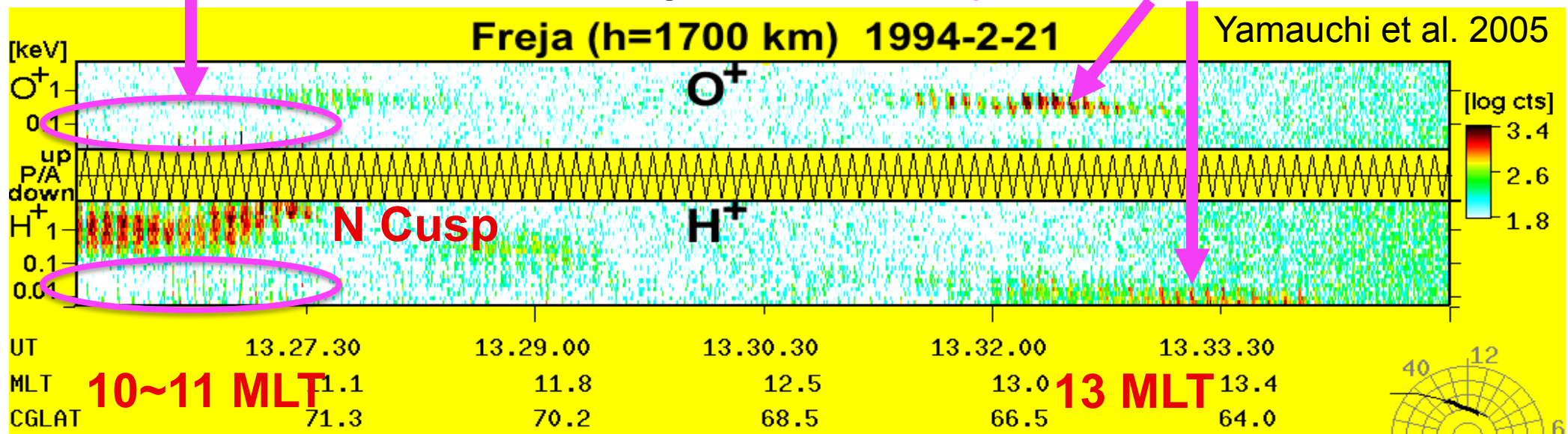
(Cully et al., 2003)

(2) Superthermal H^+ & O^+

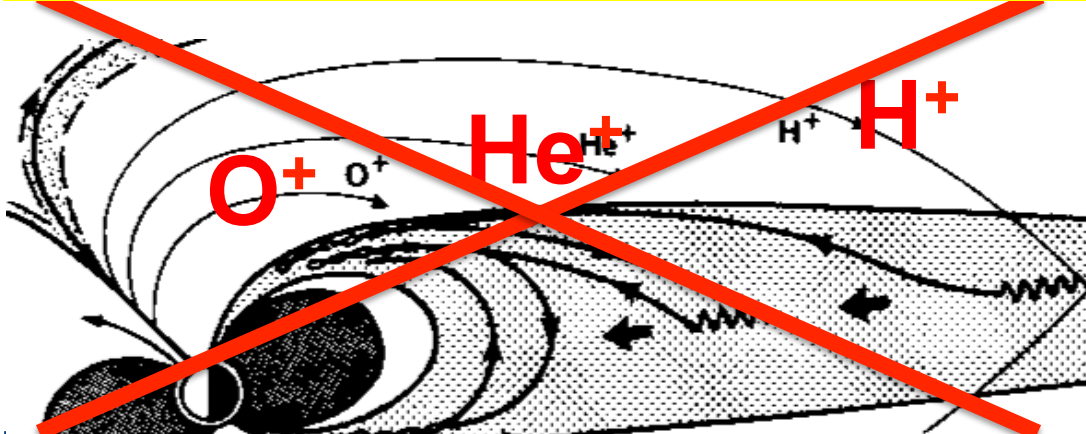
(2) Superthermal (< 20 eV at 1500 km altitude)

⇒ further **accelerated to become (3) hot**

outflow from the cusp IMF $B_y \sim -60$ nT **Injection** from southern cusp



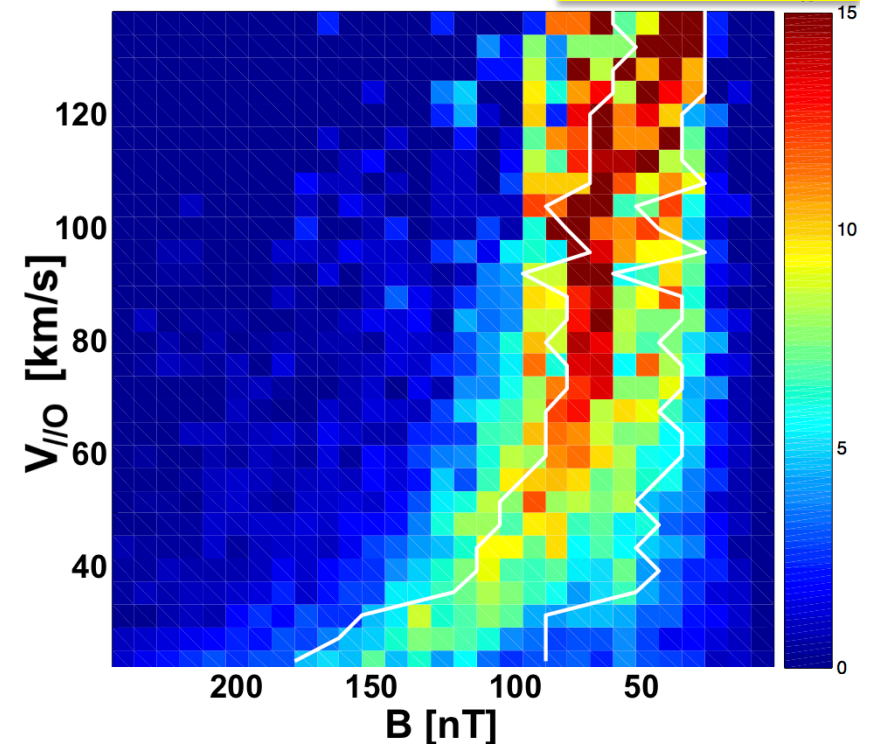
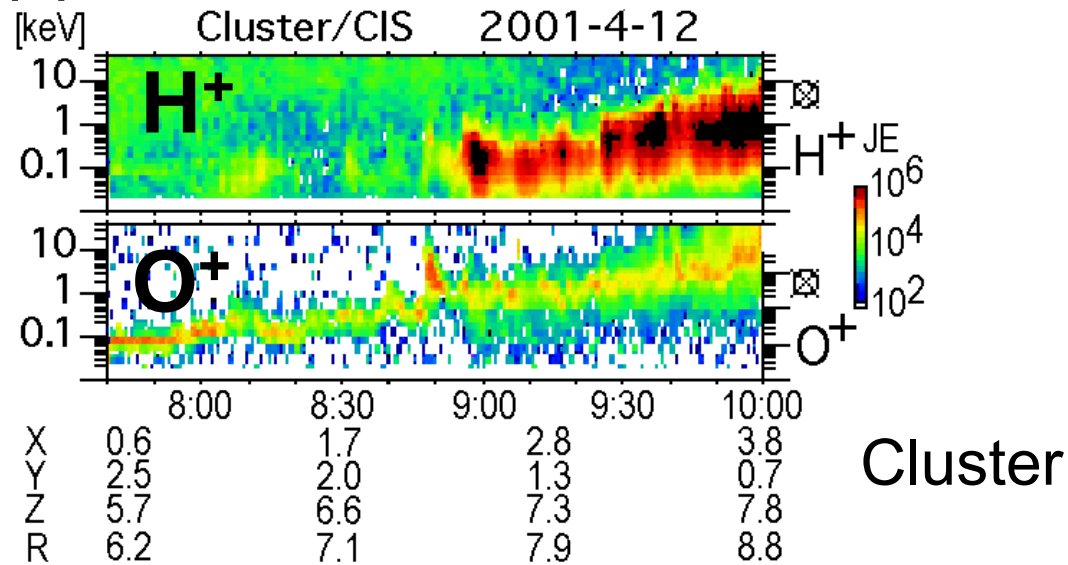
(Yamauchi et al., 2005)



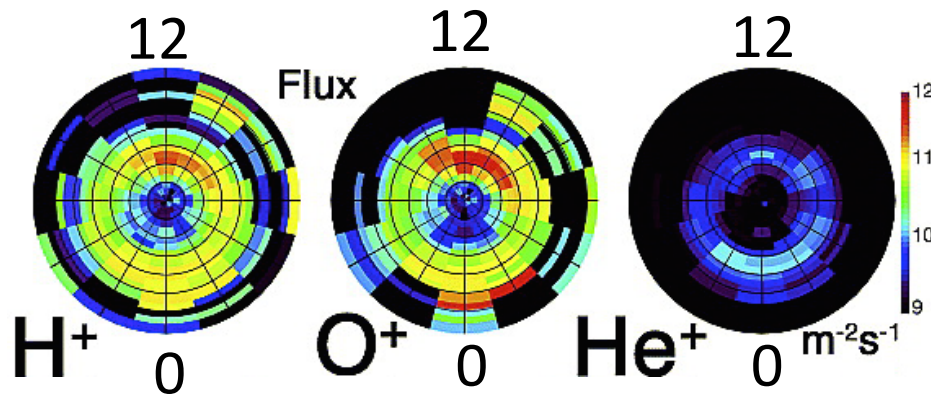
$$E_O/E_H = 15-20 \Rightarrow v_O \sim v_H$$

Three types of ion outflow (Earth skip?)

(3) H^+ & O^+ are accelerated !



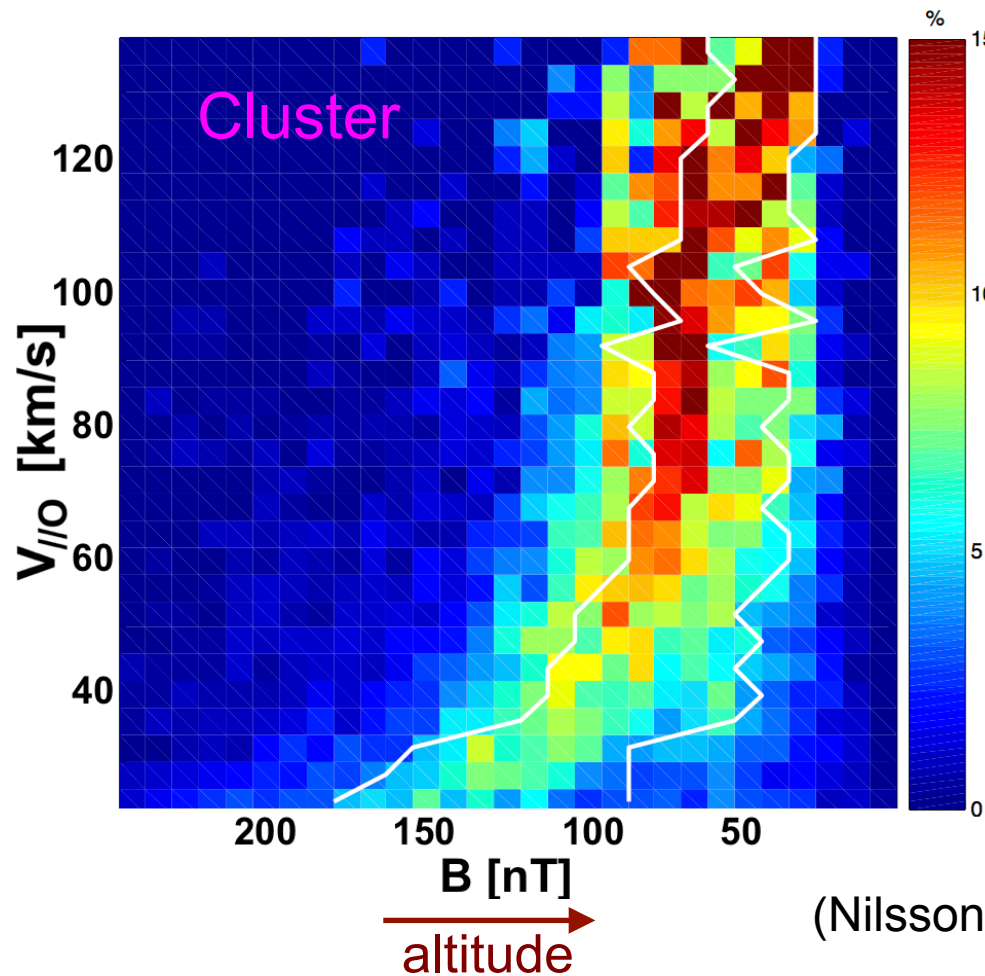
(Nilsson et al., 2006)



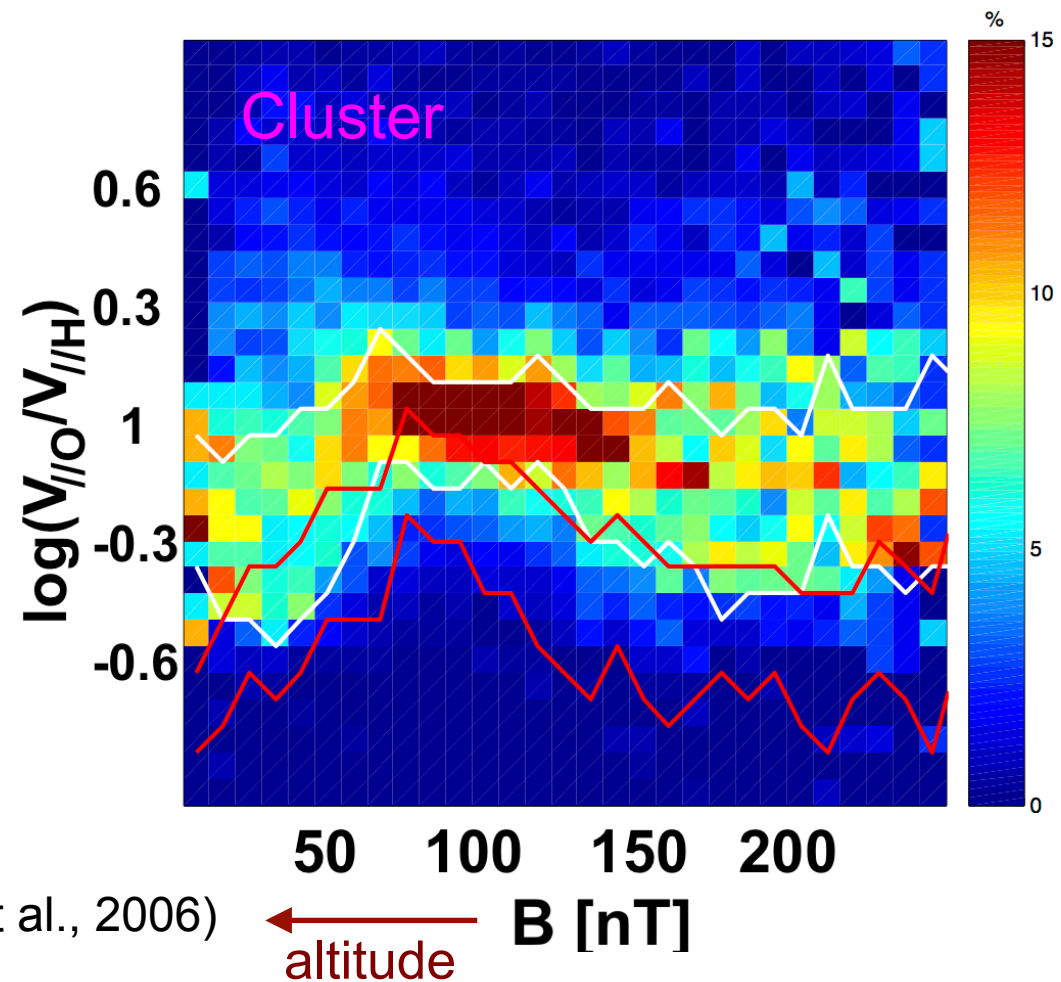
Polar@8000km@quiet time, 1996-1998
(Peterson et al., 2008)

(3) Hot H^+ & O^+

skip



(Nilsson et al., 2006)



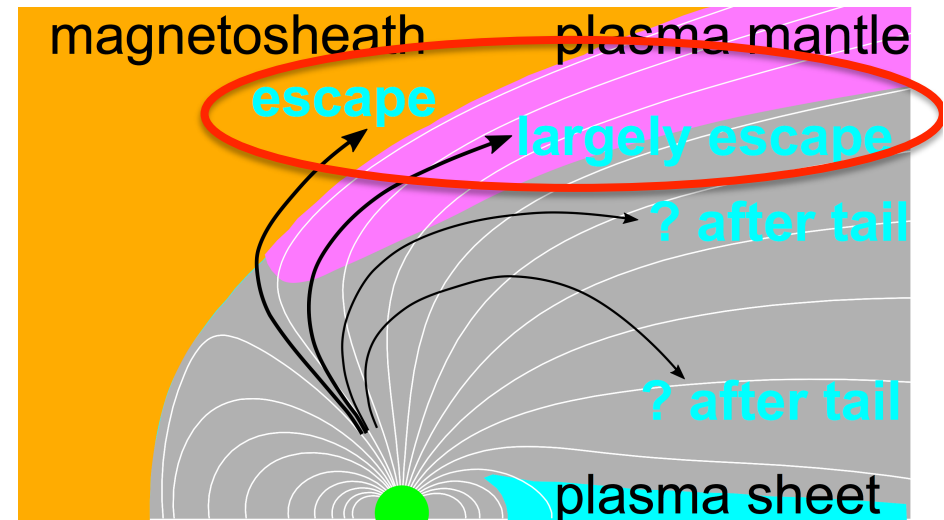
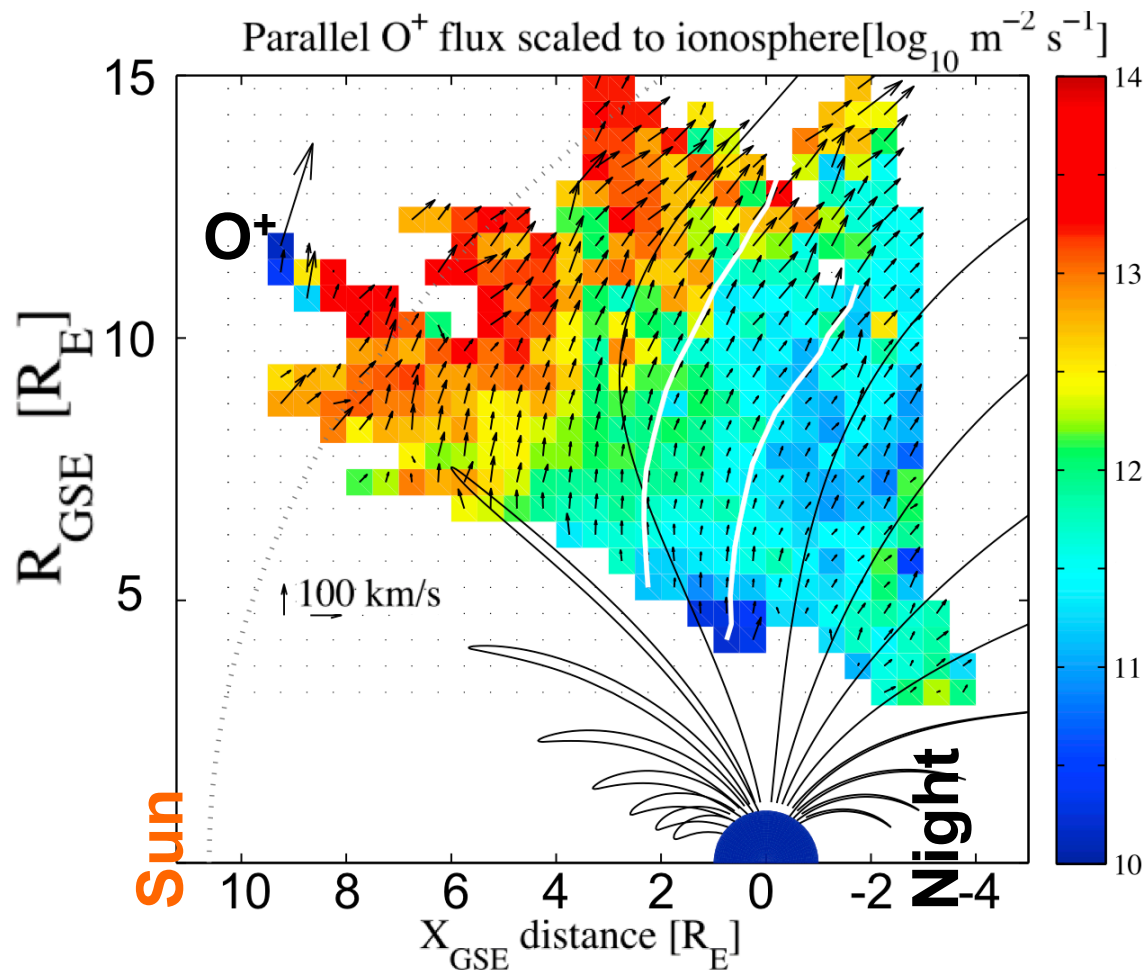
O^+ (& H^+) are accelerated as altitude increases

At all altitude, outflow velocity $V_{||}$ is the same between H^+ and O^+

(3) Hot H^+ & O^+

Cluster statistics @2001-2005

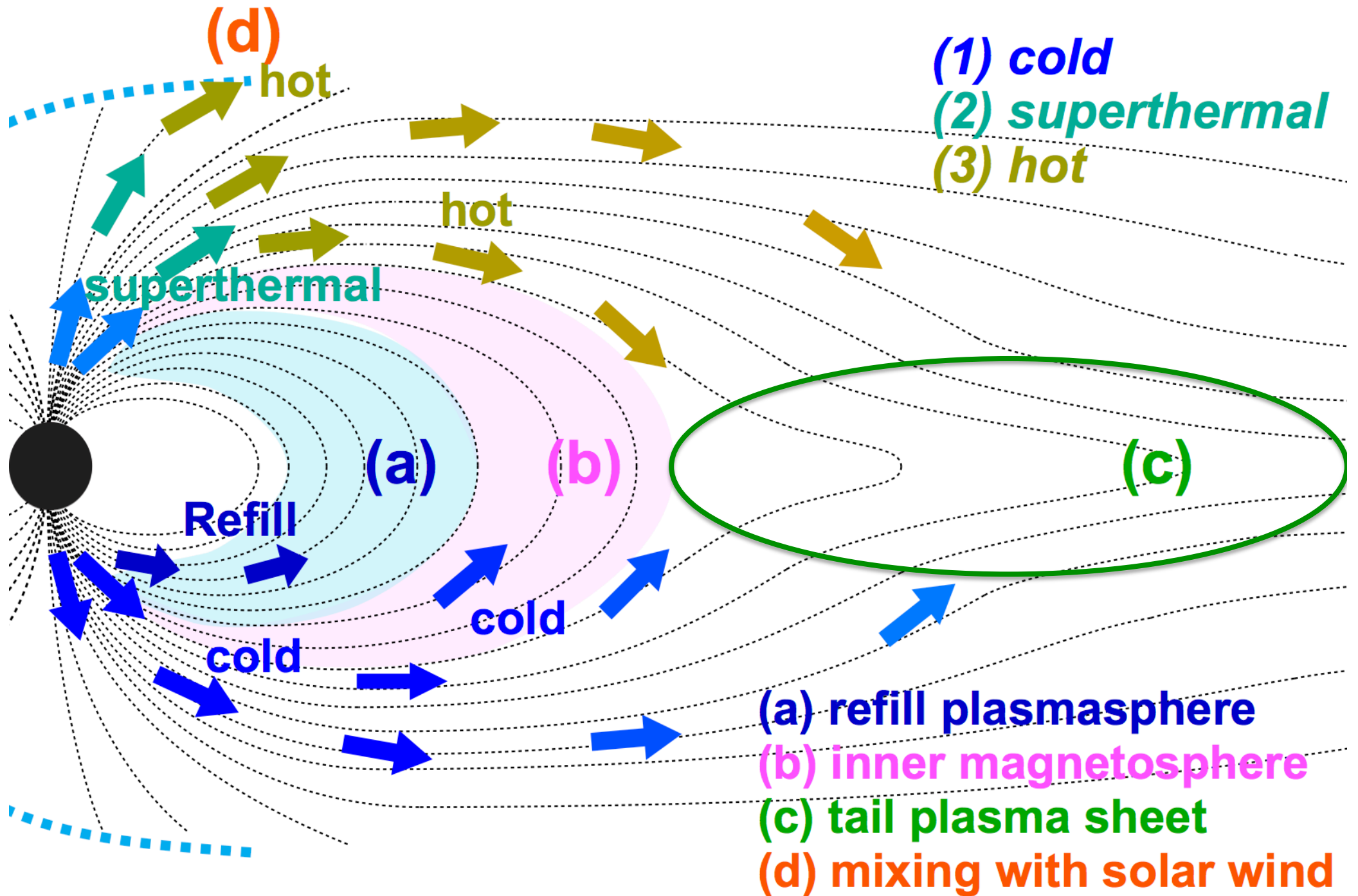
(Nilsson et al., 2012)



n_{O^+} in plasma mantle
 $\sim 1\%$ of solar wind
 $\Rightarrow$ major escape route !

O^+ loss rate $\sim 10^{25-26} s^{-1}$

Fate of ions in (c) the magnetotail



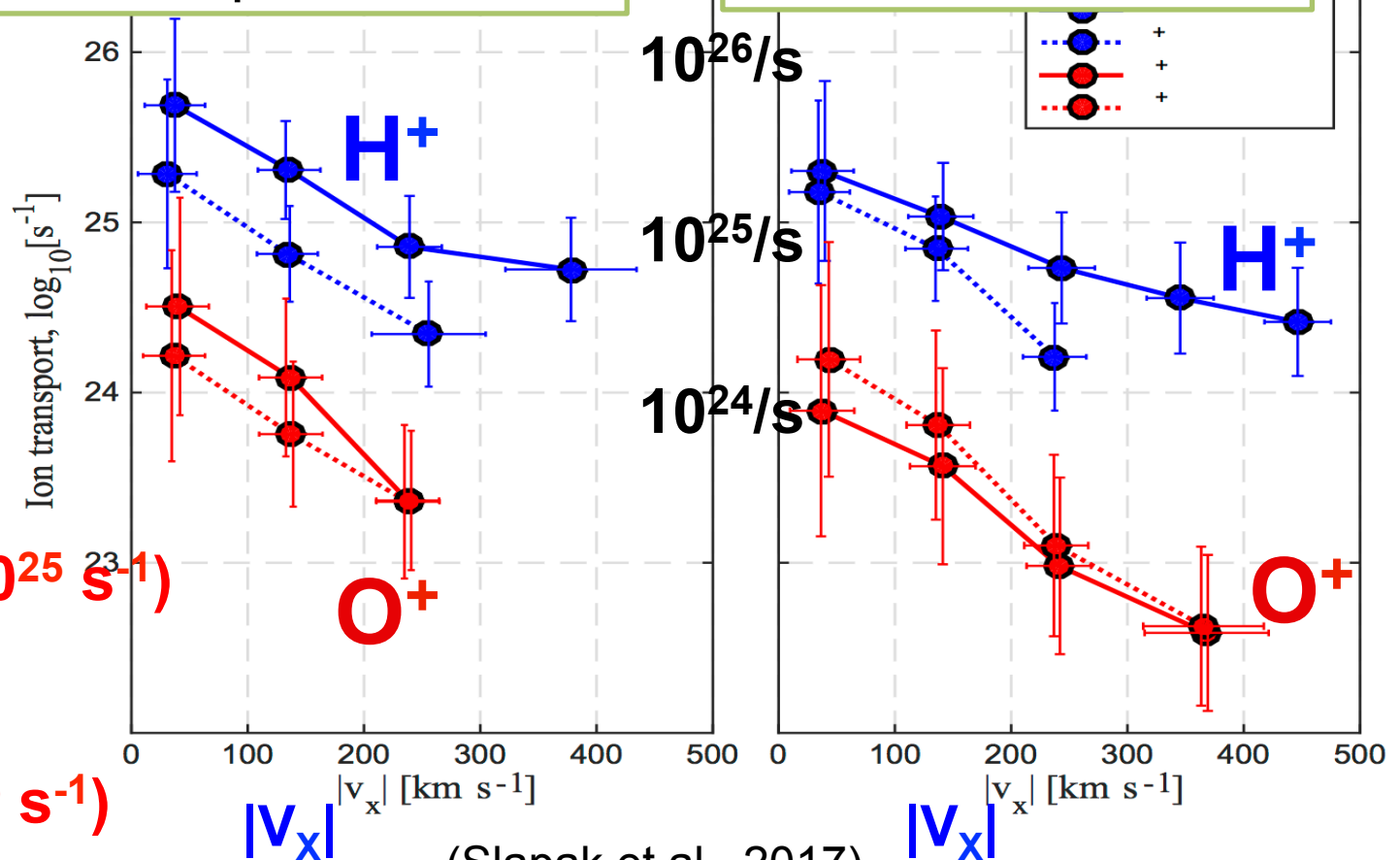
Fate of ions in the magnetotail

cold ions are also energized $\Rightarrow$ Cluster/CIS can detect all

Cluster/CIS
(2001-2005)

Central plasma sheet

Outer plasma sheet

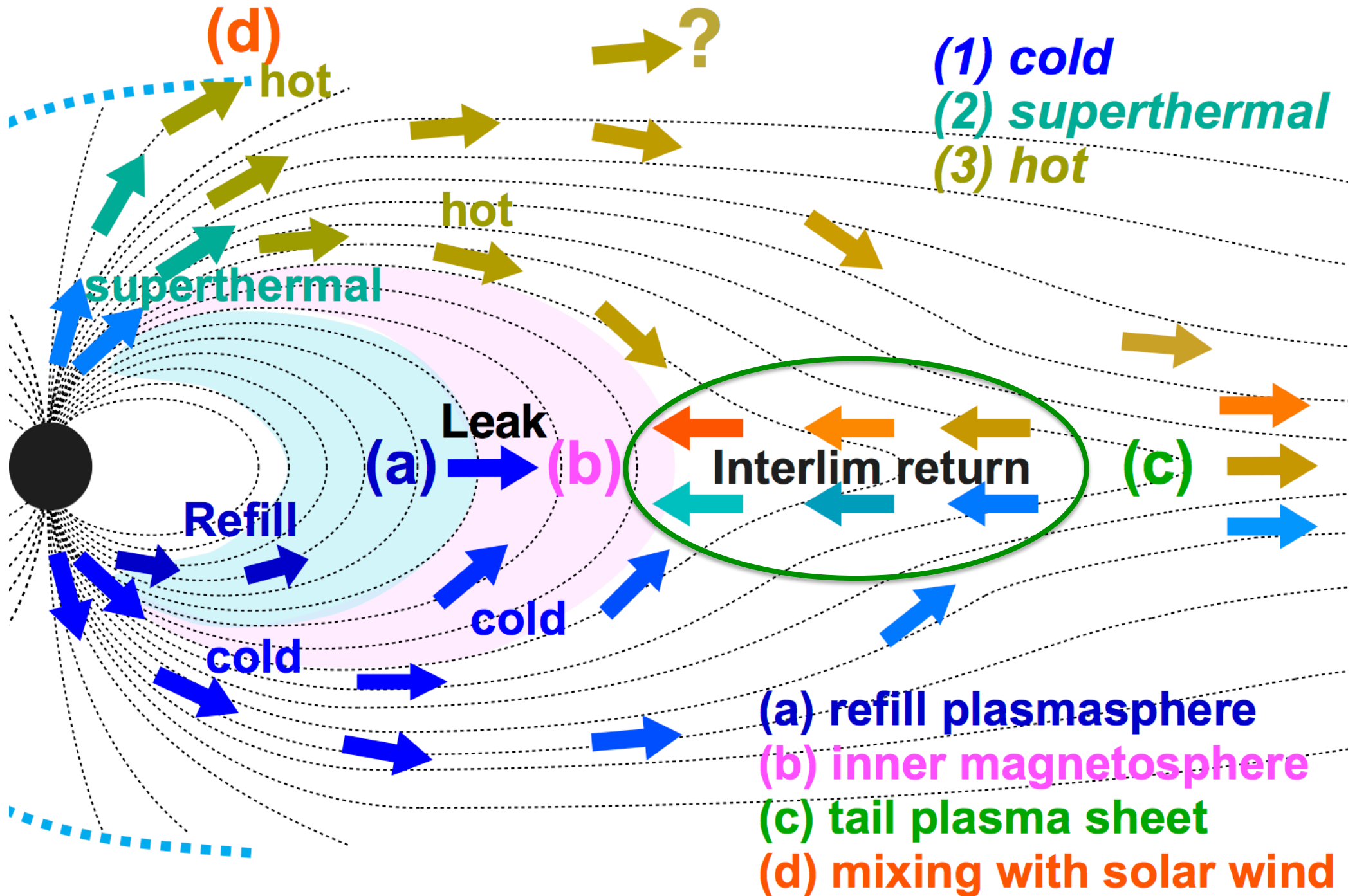


earthward ($O^+ \sim 0.6 \times 10^{25} \text{ s}^{-1}$)

tailward ($O^+ \sim 0.5 \times 10^{25} \text{ s}^{-1}$)

cf. direct escape: $O^+ \sim 10^{25-26} \text{ s}^{-1}$

Fate of returned flow



Outline

(1) **Types of outflow** (cold filling, cold/superthermal outflow, hot outflow) and **primary destinations**

(2) Ions that are not directly escaping: **Inner Magnetosphere** as a zoo of ions

- time-variable multiple sources
- time-variable **E-field**
- **local energization**
- expected/unexpected **mass-dependency**

(3) Amount of **ion escape** and its consequence:

- **Evolution of the Earth** in geological scale (then cannot ignore **neutral**)
⇒ *We still need missions to study destinations and effect (Friday morning)*

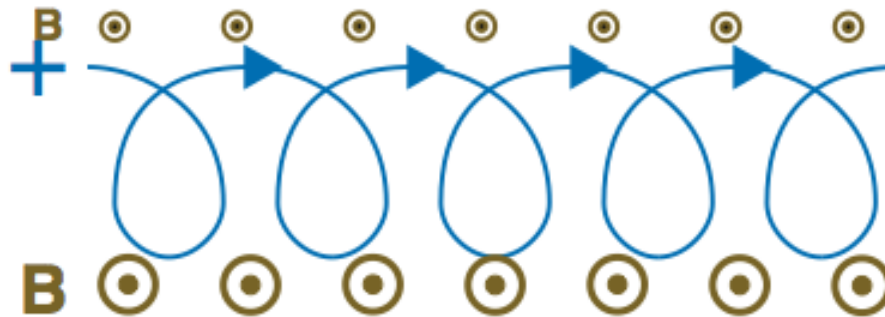
If we have time.....

(4) **Active roles** of terrestrial (planetary) ions

- in **local energy conversion** through mass-loading
- in **bow shock** structure and **foreshock** formation

(5) Ions in the neutral atmosphere: Unique method **to monitor ionizing radiation**

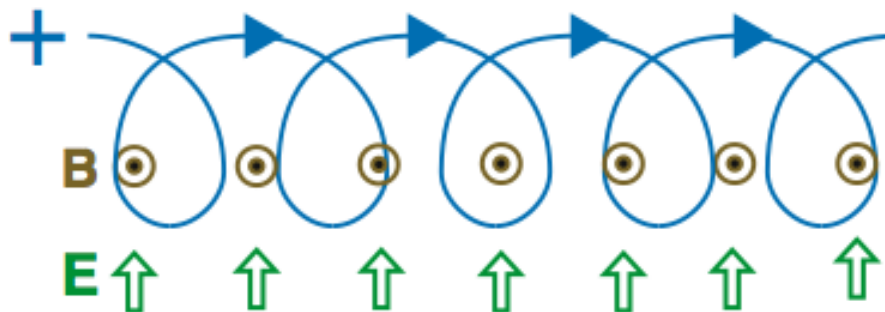
Ion drift under strong B-field



Magnetic drift (energy-dependent)

* gradient-B & curvature drift

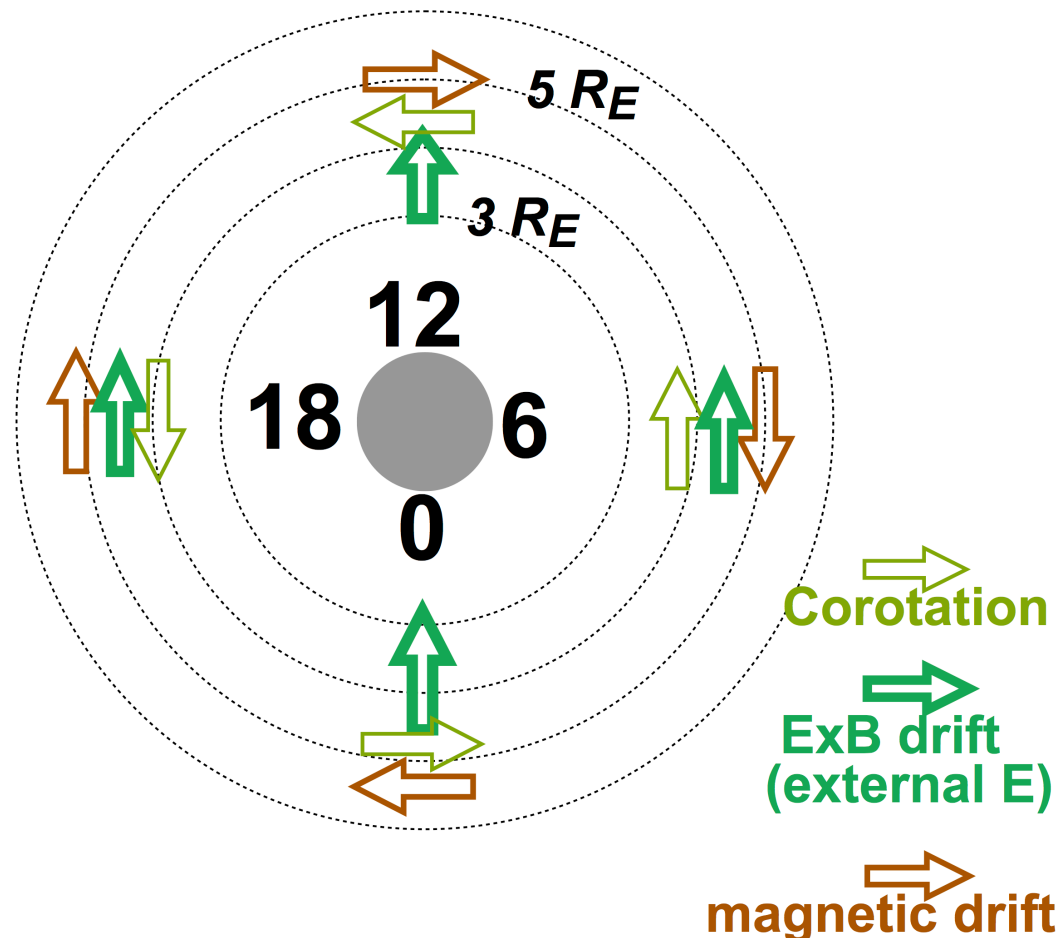
⇒ dominant for > 10 keV



ExB drift (energy-independent)

* co-rotation & external E-field

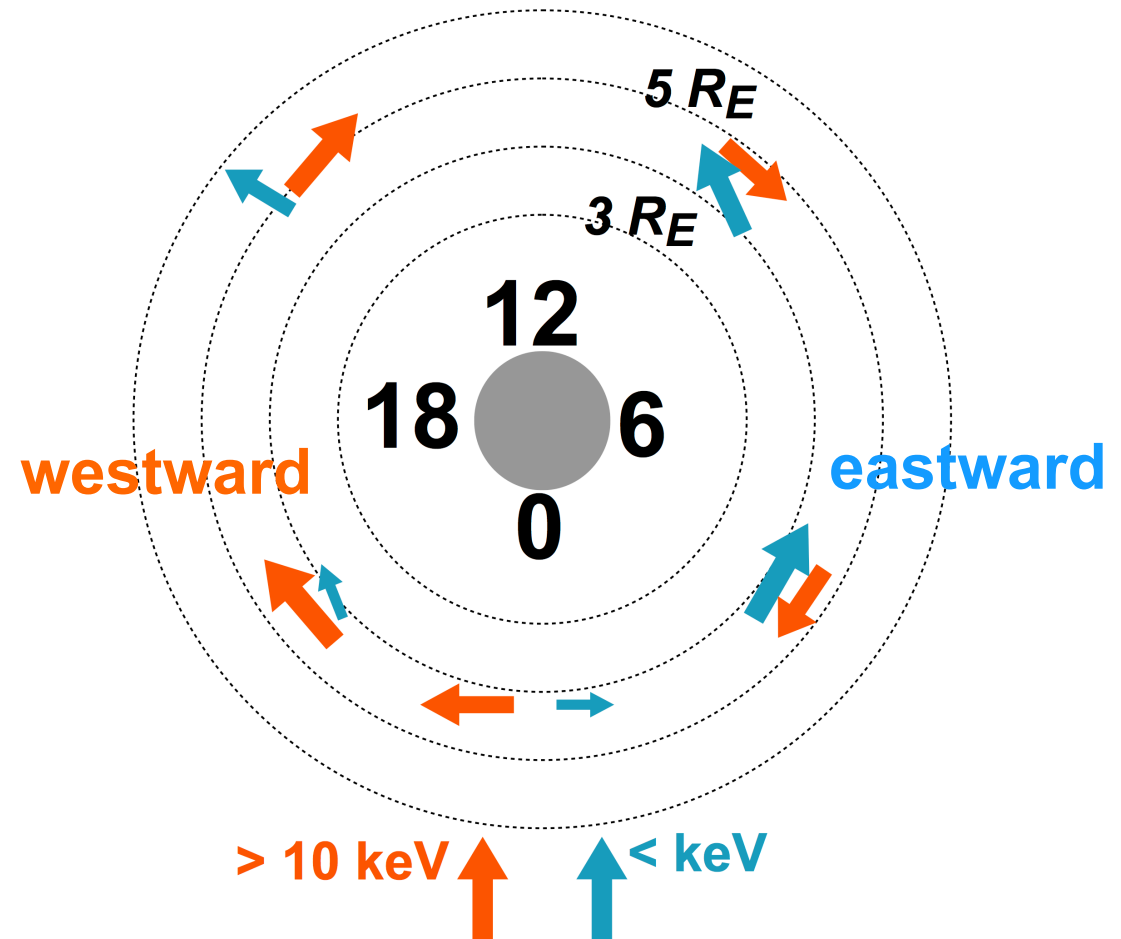
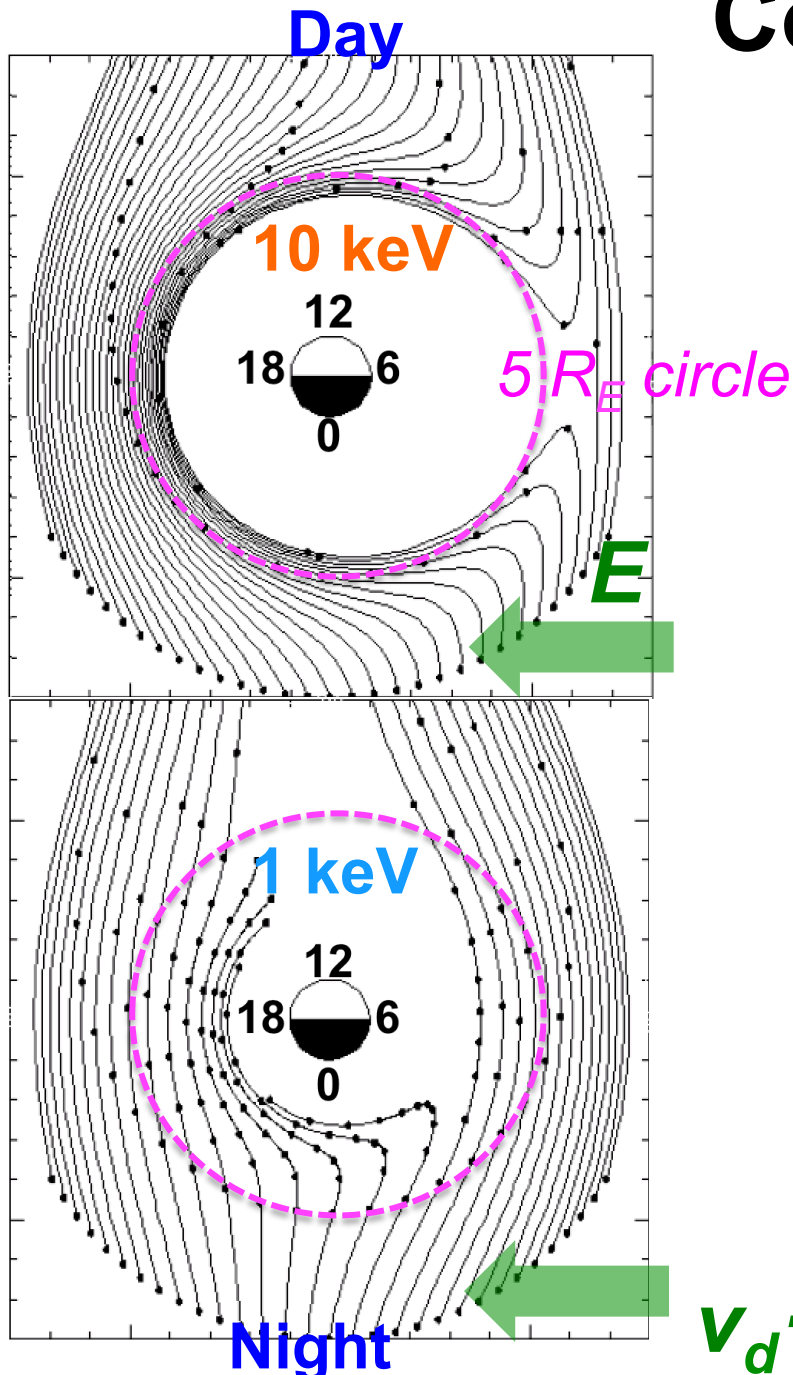
⇒ dominant for < 0.1 keV



Both drifts are **mass-independent**
for given energy

⇒ H^+ , He^+ , & O^+ **should drift together**

Combining both drifts



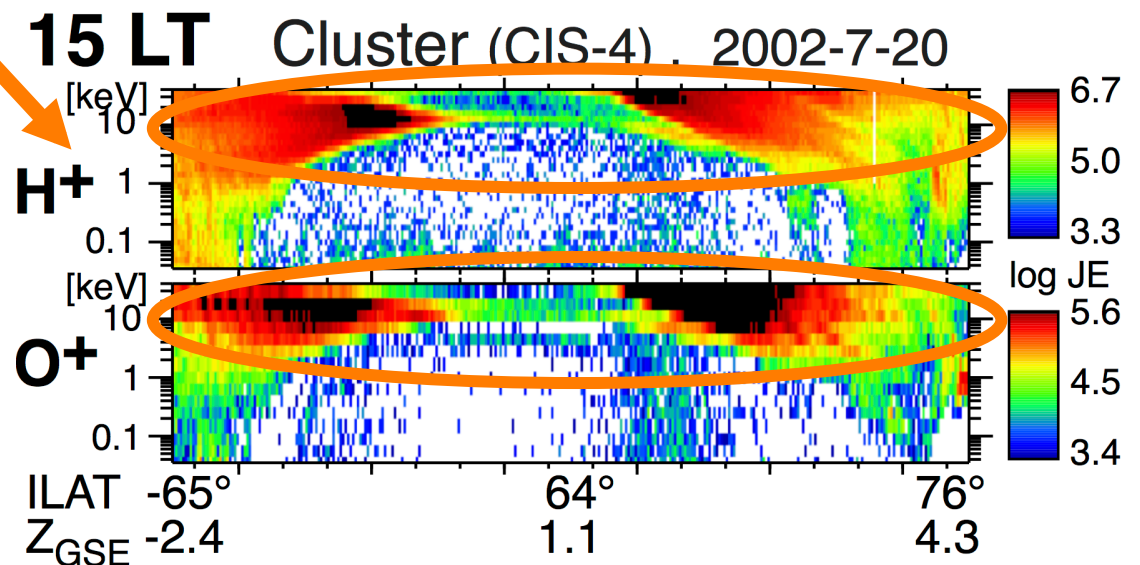
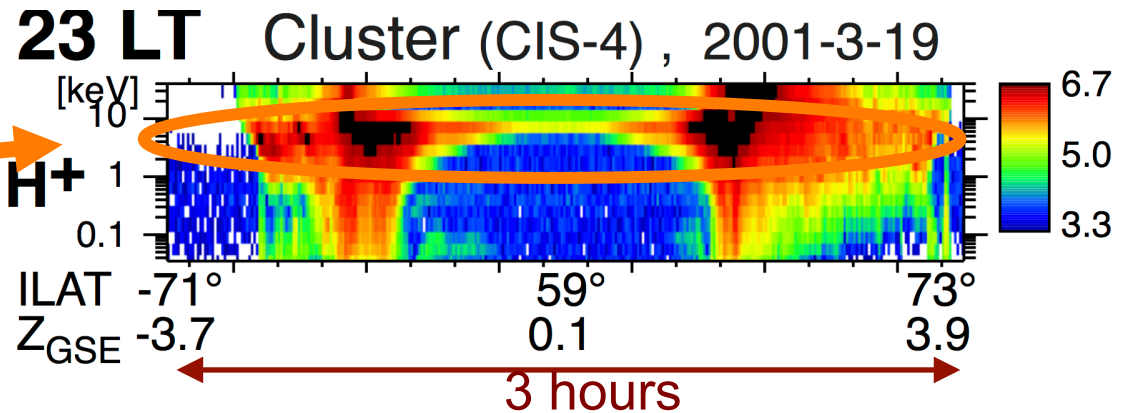
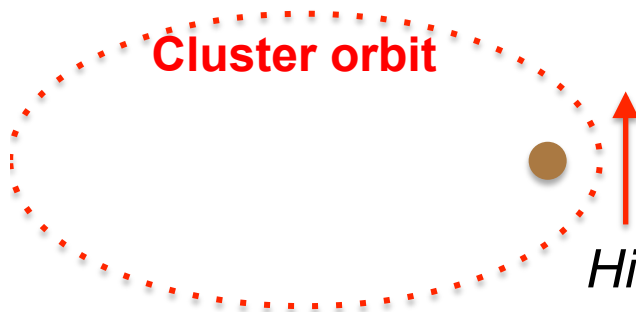
But, this is **just a model**

$$v_d \cdot E > 0 \Rightarrow \text{adiabatic energization}$$

Old "textbook" view of returned ions 1

>10 keV (westward)

Cluster ion spectrogram:
all shows energy flux density (JE)
but not flux (J)



mass-independent for given energy

⇒ **source location of H⁺ & O⁺ is the same**

Highly elliptic orbit ⇒ traverses inner magnetosphere quickly

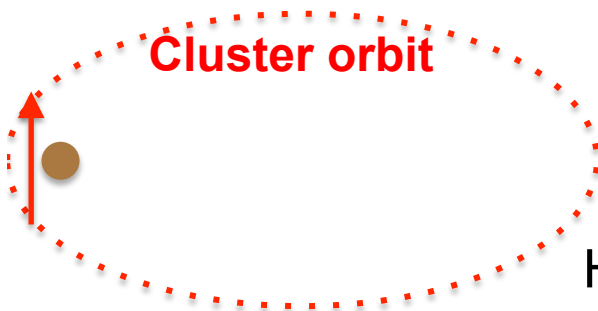
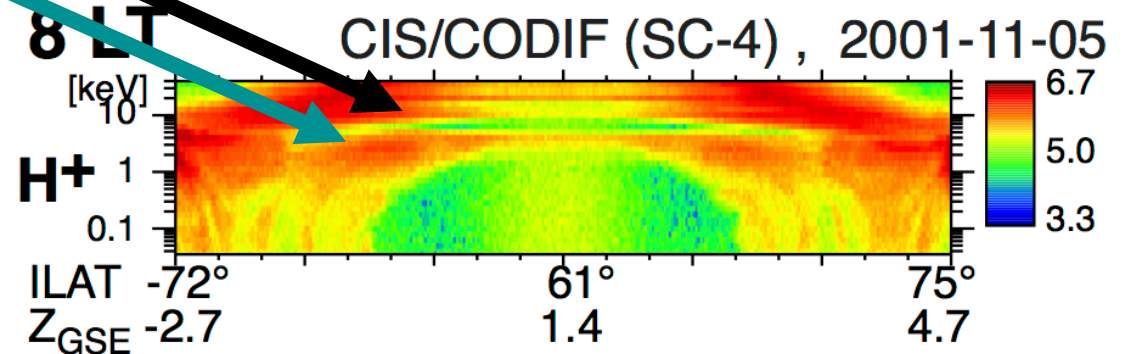
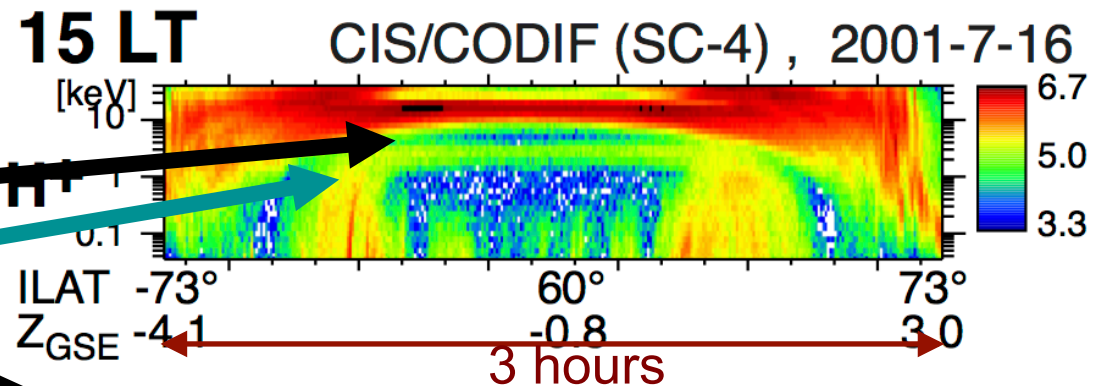
Old "textbook" view of returned ions 2

>10 keV (westward)

energy gap

< 5 keV (eastward)

Ion observation (Cluster)



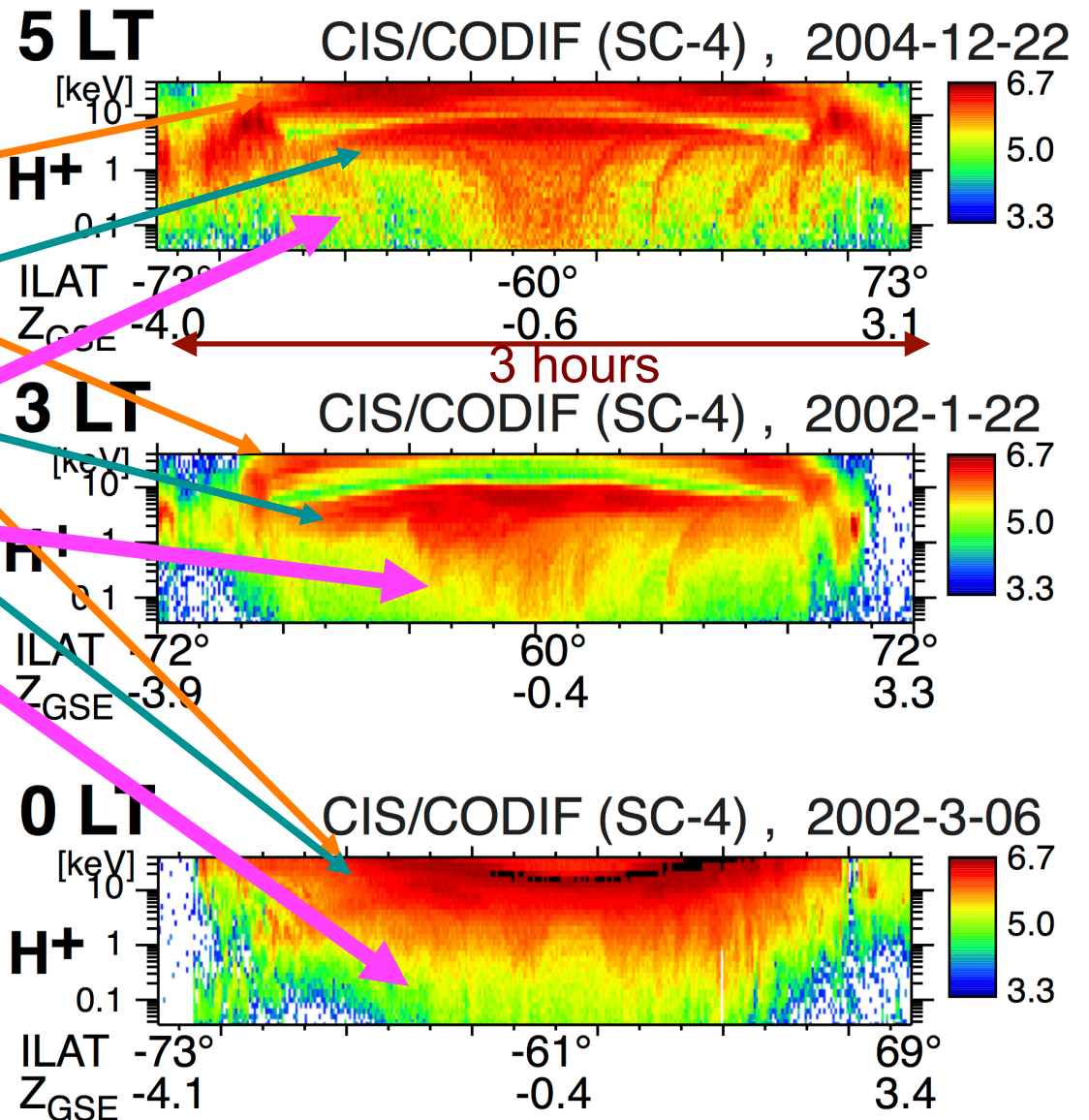
Highly elliptic orbit $\Rightarrow$ traverses inner magnetosphere quickly

Reality: **three** basic populations

accelerated plasma
sheet (westward drift)

plasma sheet
(eastward ExB drift)

sub-keV stripes (???)



Highly elliptic orbit $\Rightarrow$ traverses inner magnetosphere quickly

observations of sub-keV trapped ion ring current (=sub-auroral) region

- * Aureol 1 (400~2500km, 00-06 MLT): Sauvaud et al., 1980
increases after substorms.
- * DMSP F6/F7 (800 km, 0830 MLT): Newell & Meng, 1986
correlated with Kp (some hours delay), event may last a day.
- * Viking (2~3 R_E , dayside): Yamauchi et al., 1996a,b
"Dispersed structures",
modulation by pc-5 pulsation.
- * Freja/Viking/Munin: Yamauchi et al., 2005
O⁺ at low-altitude / H⁺ at high-altitude
- * Viking (2~3 R_E , dayside): Yamauchi and Lundin, 2006
Fossil of substorm (AE) activities, but not storm (Dst) .
morning source?

others: Shelley et al., 1972; Chappel et al., 1982

Three basic populations

accelerated plasma
sheet (westward drift)

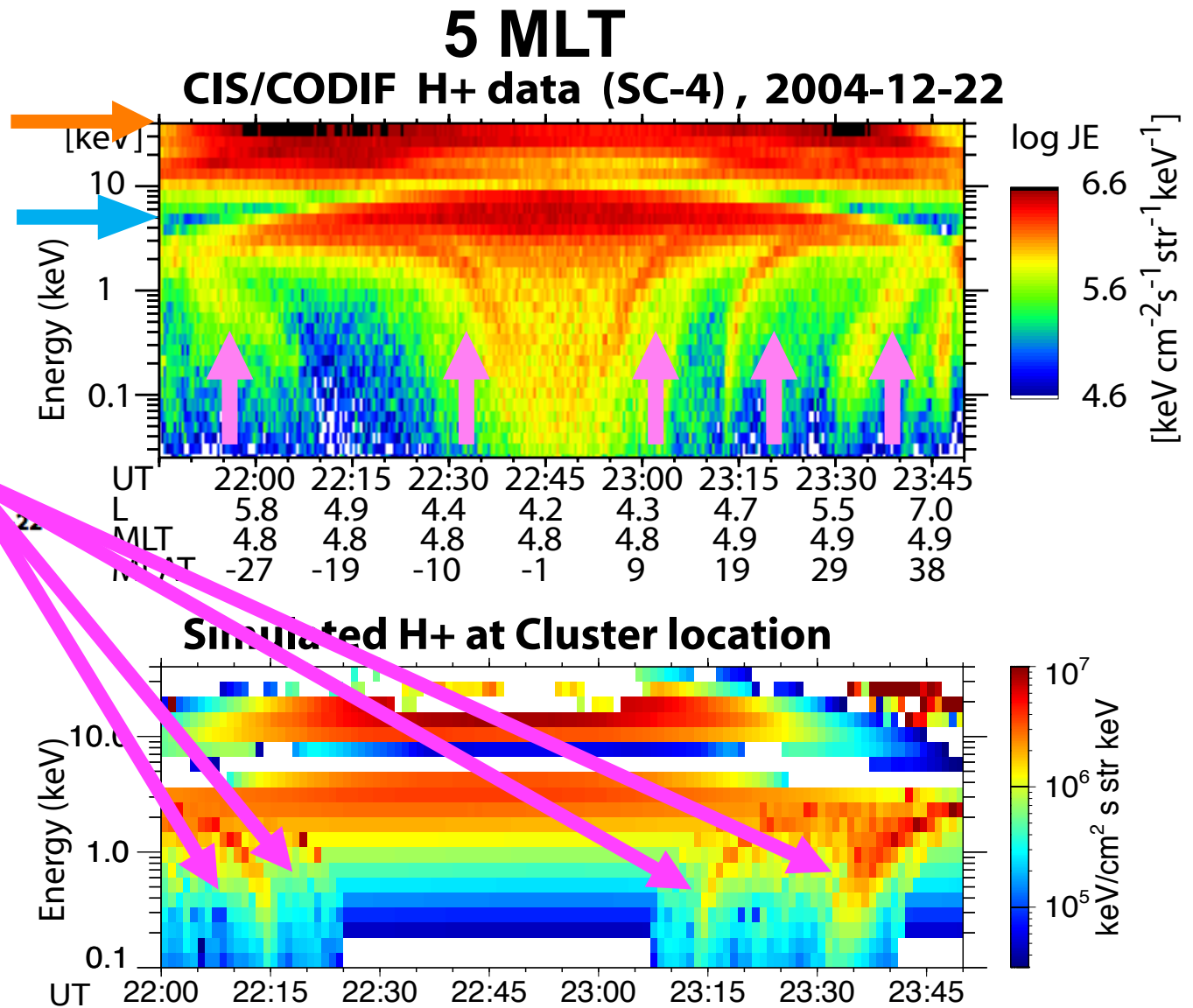
plasma sheet
(eastward ExB drift)

superthermal (<50 eV)
intermittent supply

Simulated ion distribution at Cluster location, 2004-12-22



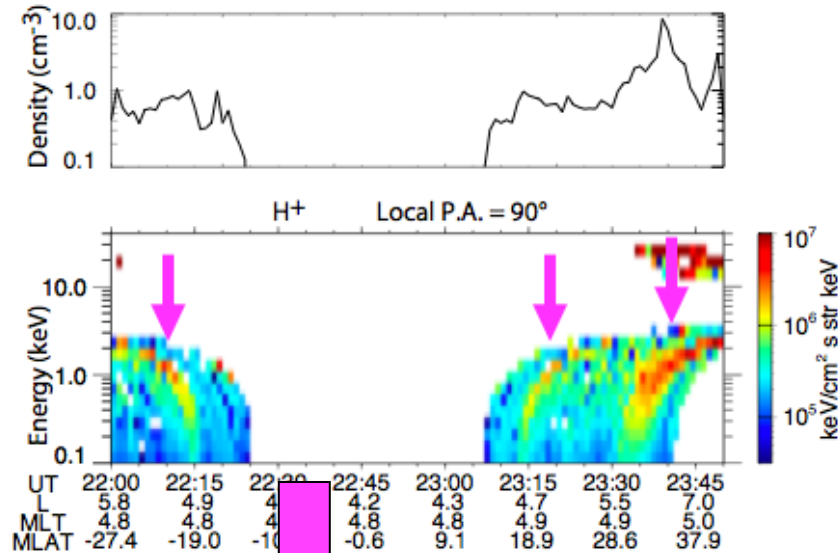
Simulation



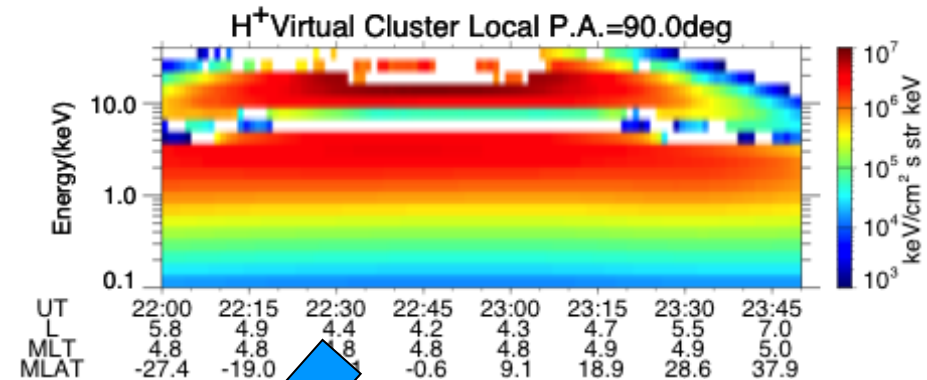
(Yamauchi et al., 2009)

Third population = cold source skip?

Simulated ion distribution at Cluster location , 2004-12-22



both component together

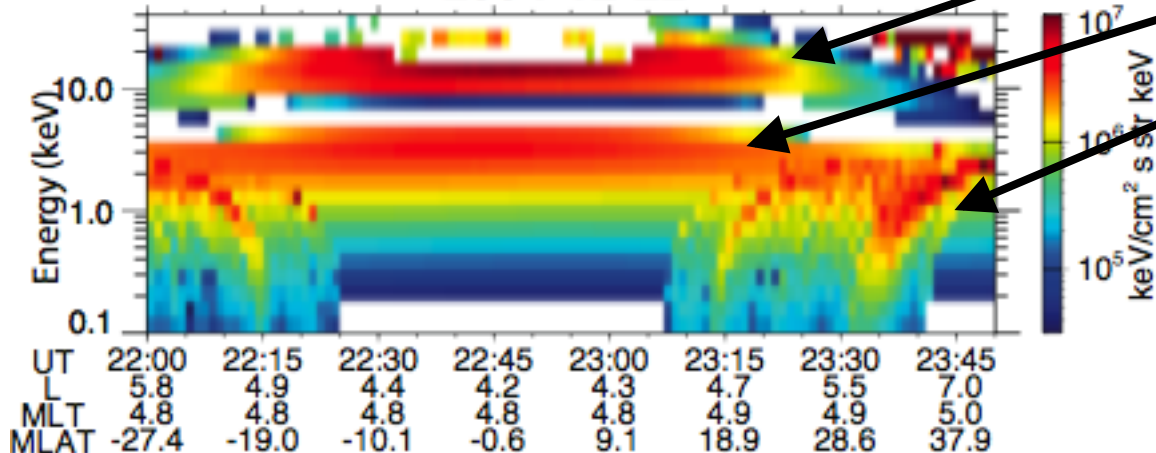


band-2: westward drift

band-1: eastward drift

wedge

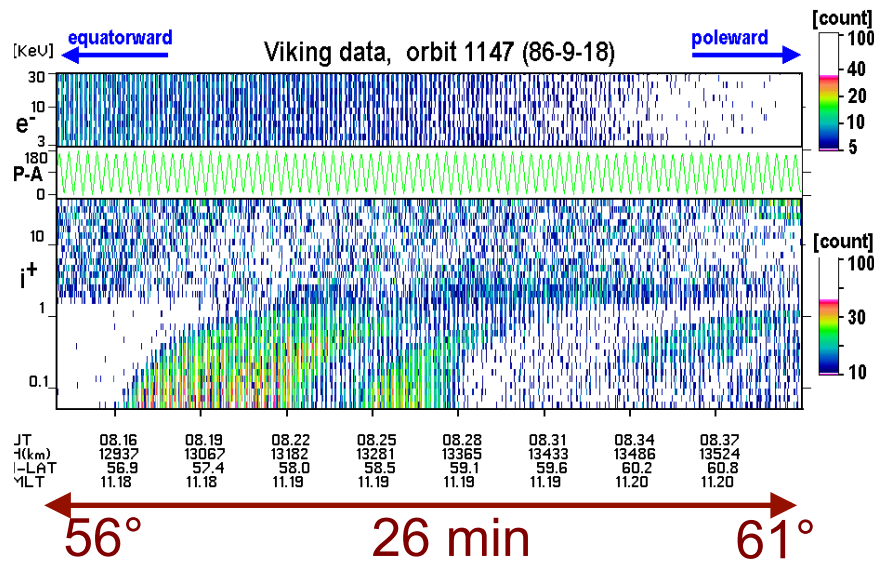
Simulated H⁺ energy flux (P/A=90°) at Cluster location
2004-12-22



Simultaneous reconstruction of three components confirms rational of our source estimate.

(Yamauchi et al.,2009)

Viking statistics



After high AE activities.

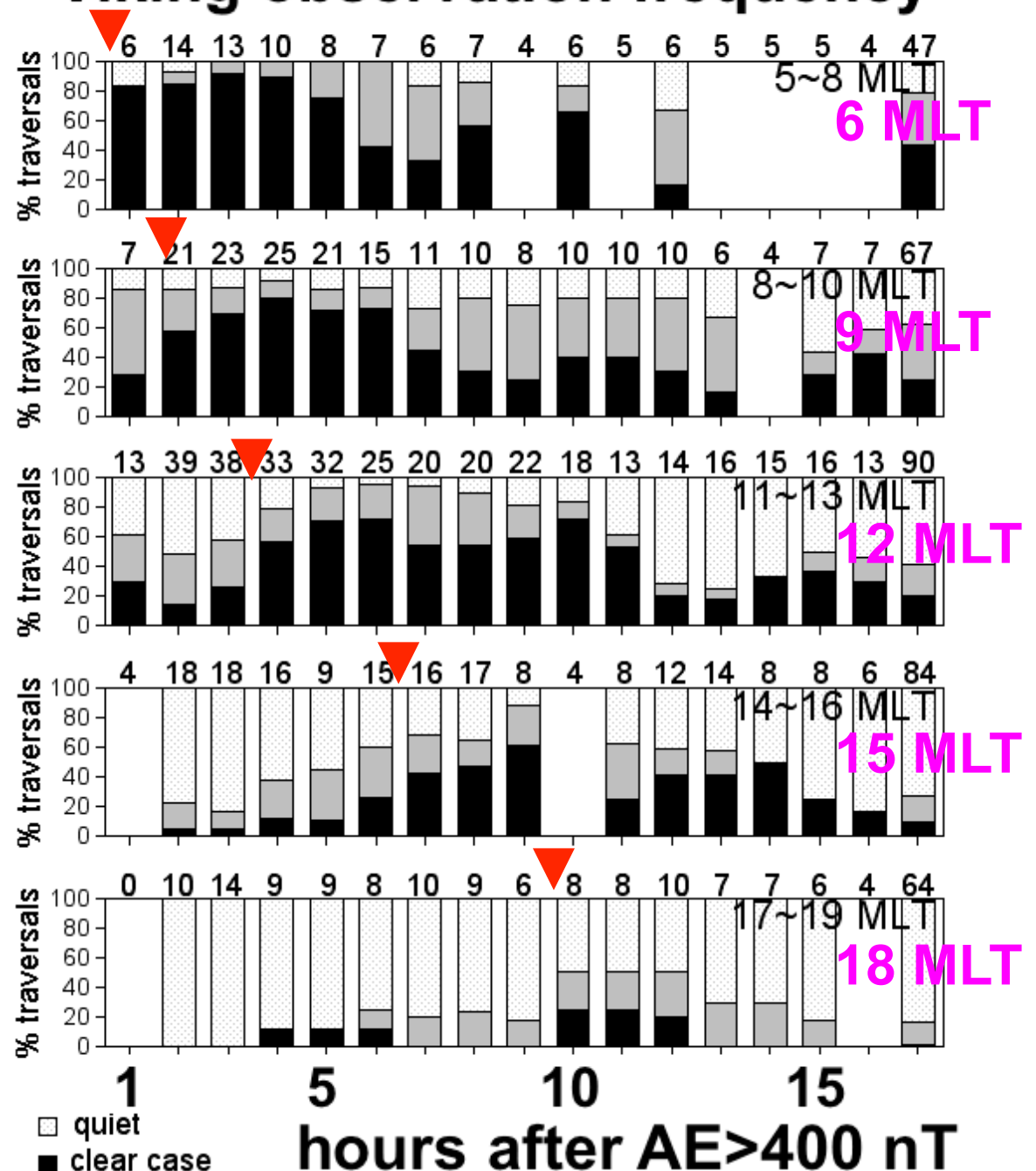
(1) Moves eastward **very fast**

(2) Decrease in time

⇒ **fossil of substorm filling**

(Yamauchi and Lundin, 2006)

Viking observation frequency



Loss of low-energy ions

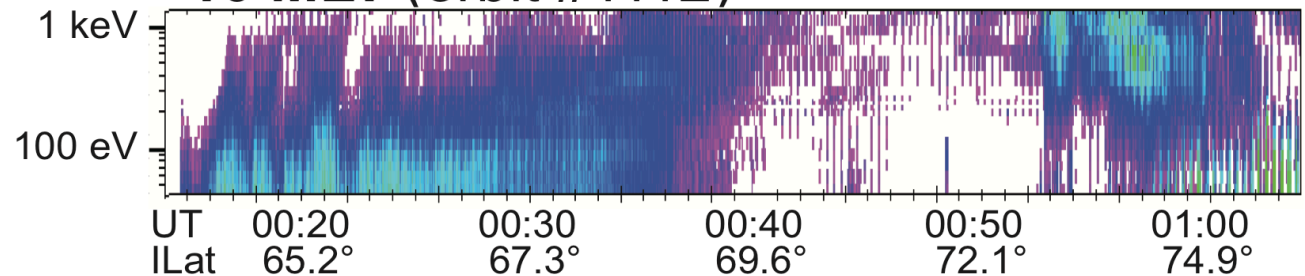
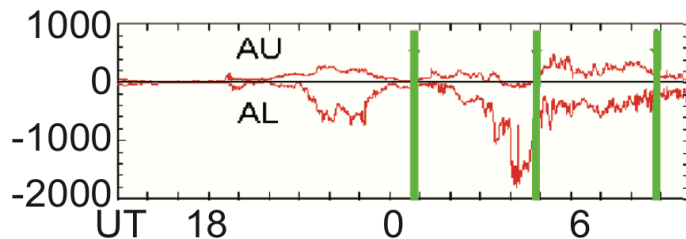
skip

ExB drift **moves ions** toward dayside by drift

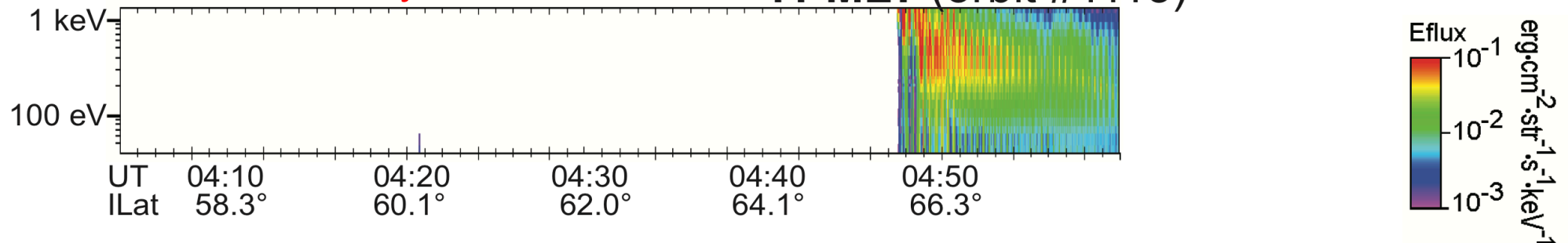
⇒ **magnetopause (MP) shadowing**

≈ **1/3 of input O^+** during storm (Zong et al., 2001)

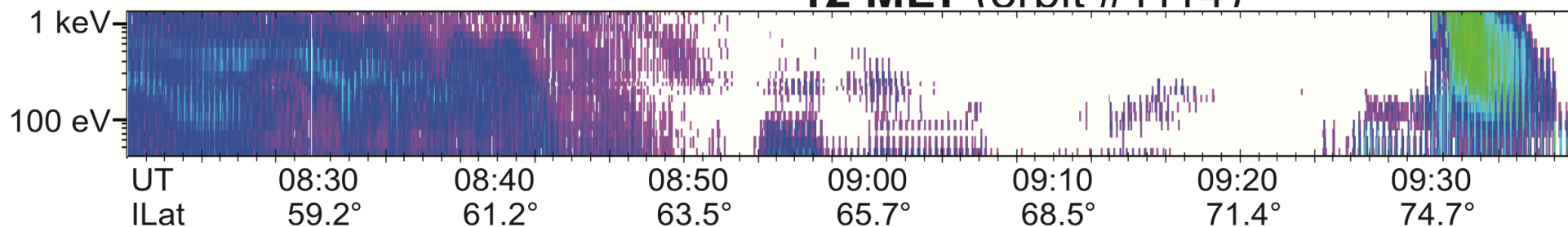
Viking ion data 1986-9-12
10 MLT (orbit #1112)



Ion was evacuated by enhanced E-field 11 MLT (orbit #1113)

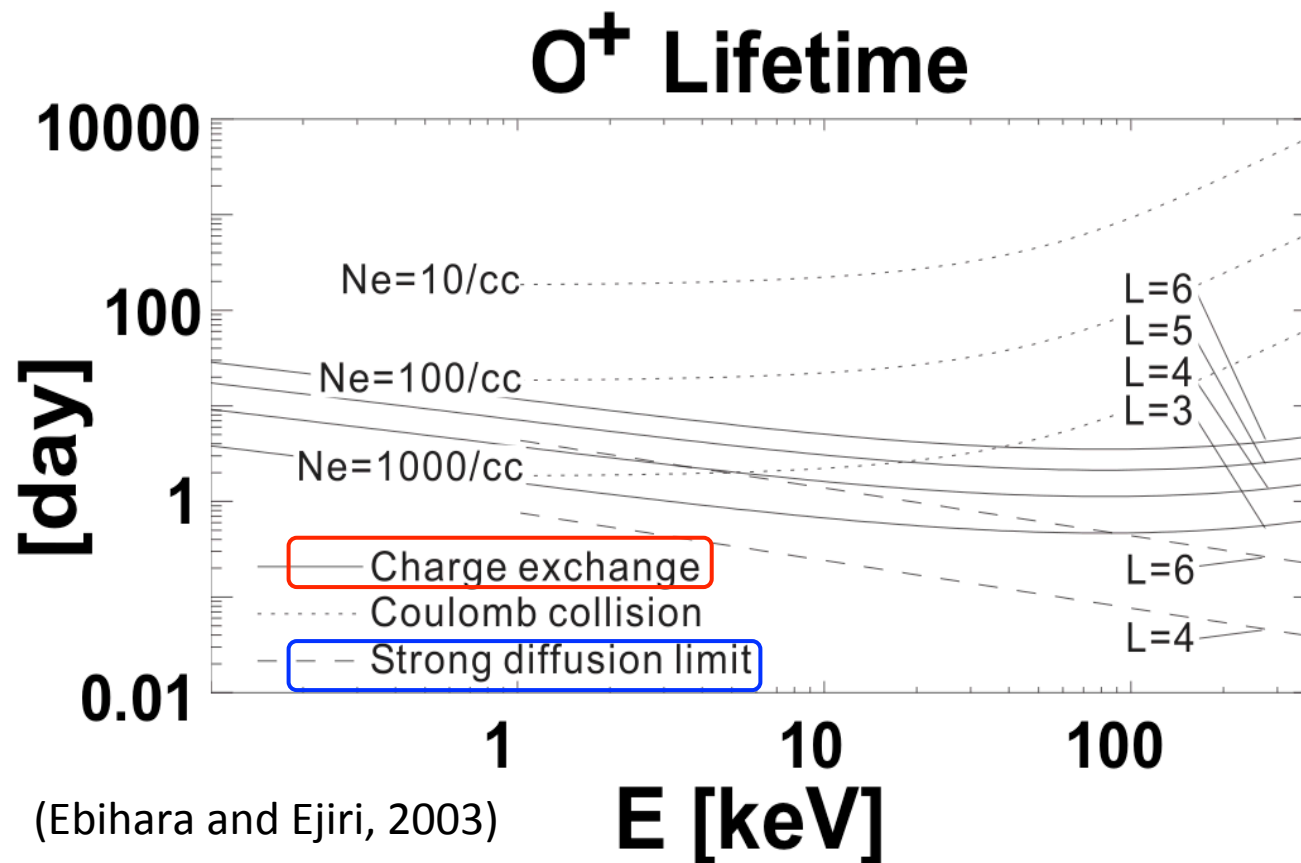


12 MLT (orbit #1114)



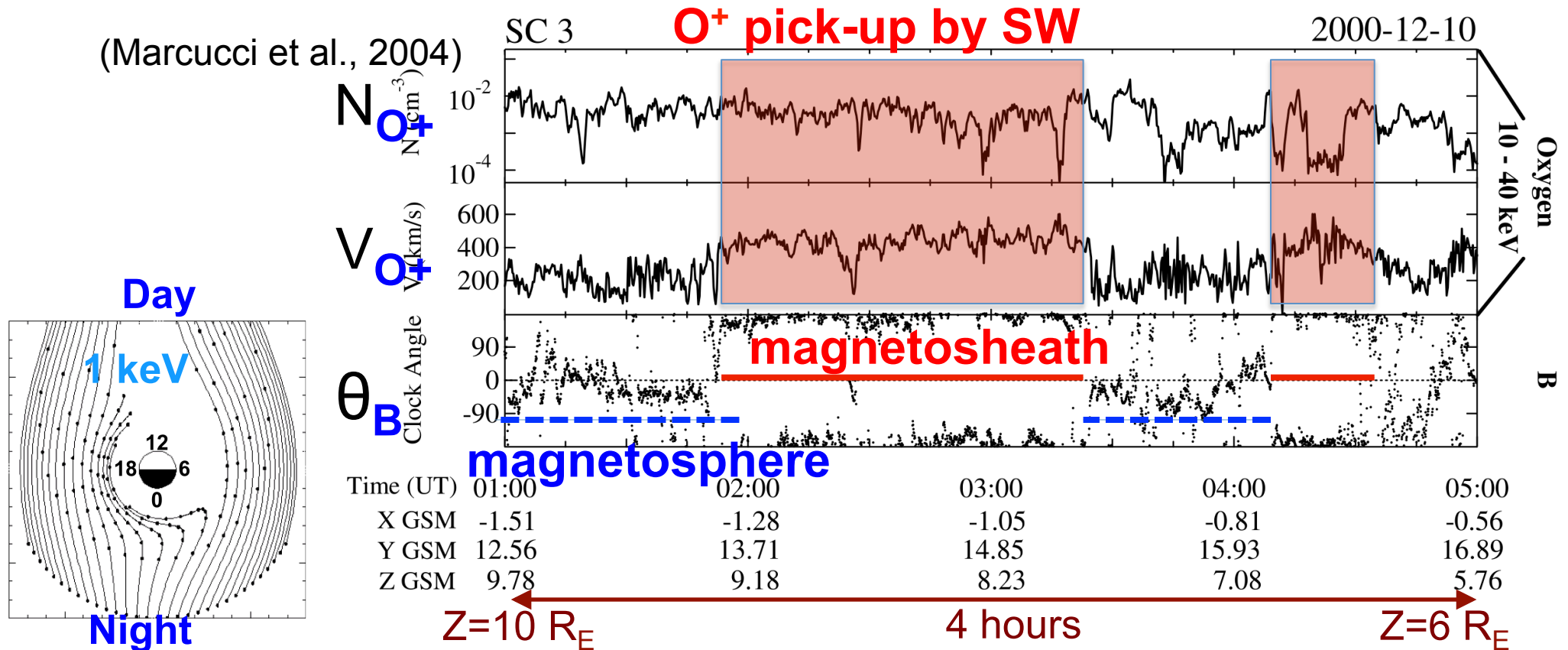
Why decay? (1) loss to the ionosphere

- (i) $O^+ < 1$ keV: mainly **Charge exchange** during mirroring (high n_n)
 $\Rightarrow$ **half will be lost**
- (ii) $O^+ > 1$ keV: mainly **Strong pitch-angle diffusion** to loss cone
 $\Rightarrow$ **real return**



Simulation for all O^+
 $\Rightarrow$ **half will be lost**
(except leak)

Why decay? (2) Magnetopause shadowing



ExB drift **overshoots** magnetopause $\Rightarrow$ **magnetopause (MP) shadowing**

$\approx 1/3$ of input **O⁺** during storm

(Zong et al., 2001)

$\Rightarrow$ works for all drifting ions (**cold + hot + energetic**)

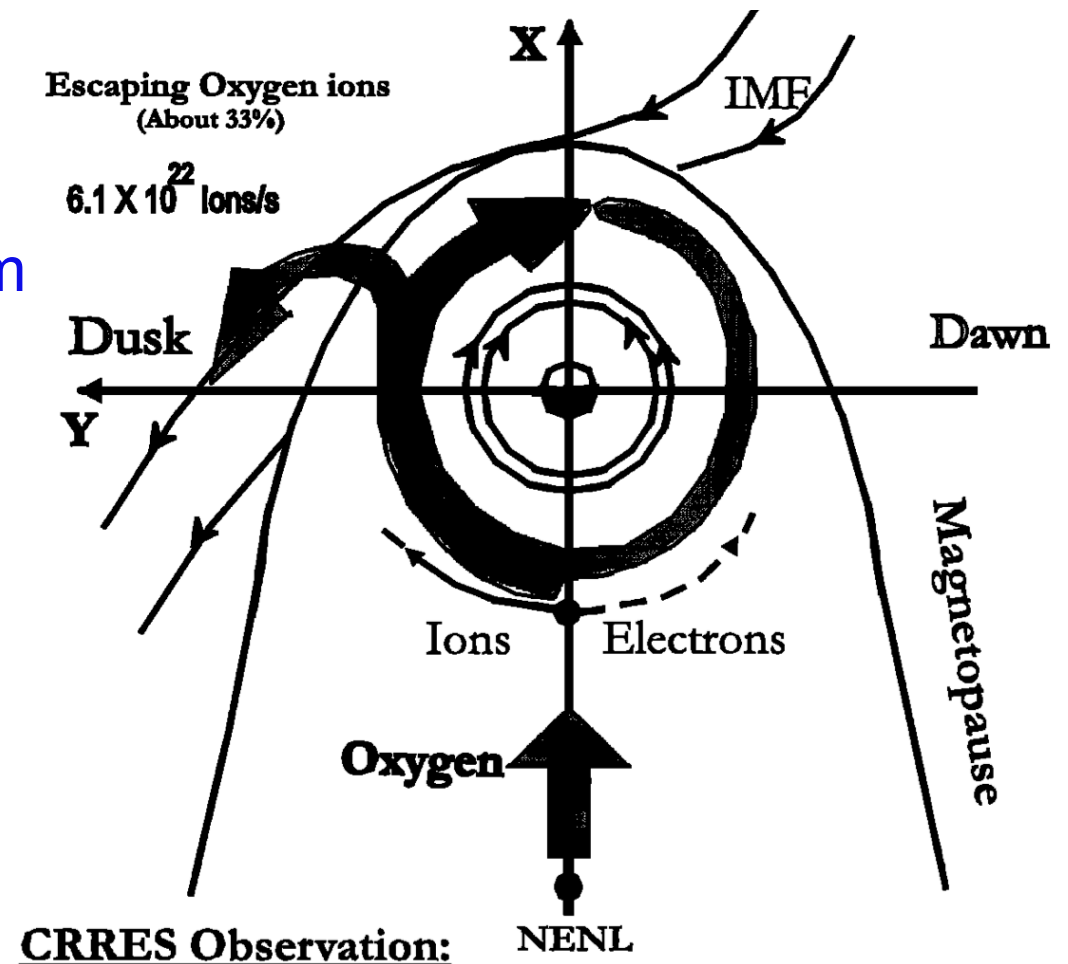
note: Largest **at mid-latitude** rather than equator (because of bouncing motion)

MP shadowing

skip?

model + Geotail obs. (Zong et al., 2001)

about 1/3 of input O^+ during storm



$D_{\pi} = 100 \text{ nT}$

Ring Current

1.6×10^{28} Oxygen ions

Input rate:

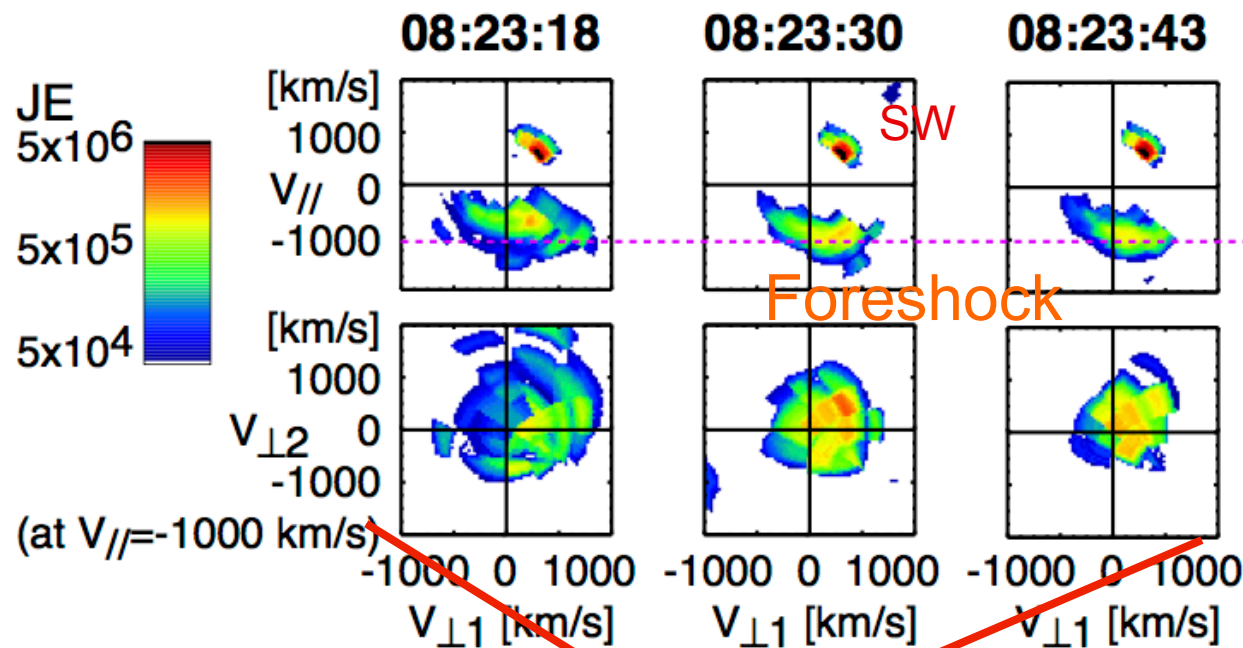
$1.8 \times 10^{23} / \text{s}$

MP shadowing (Upstream obs.)

skip?

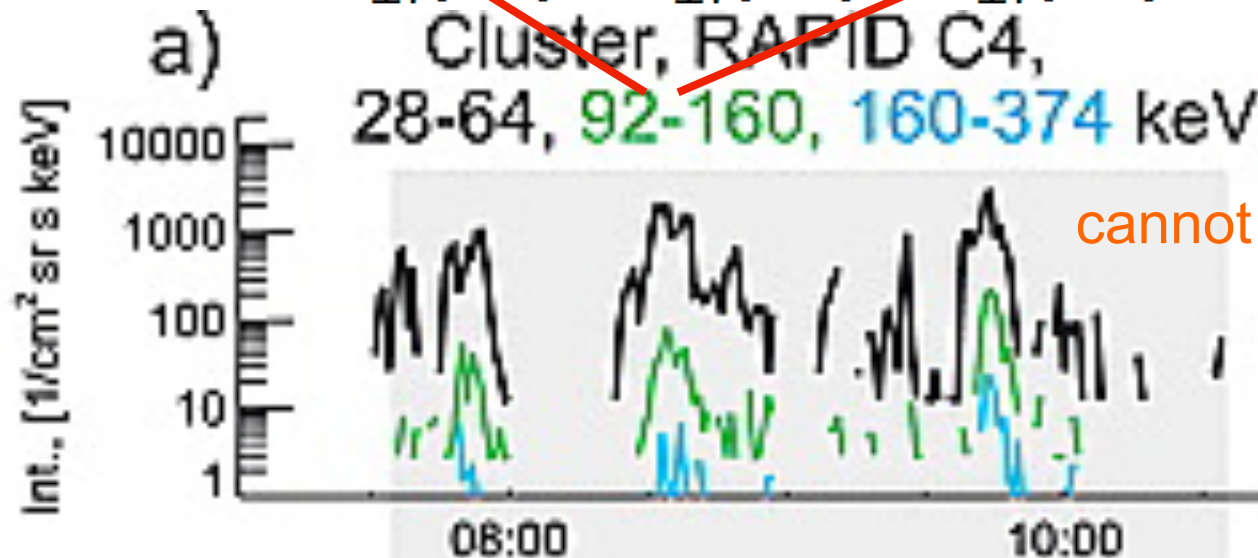
Cluster/RAPID: leaked ring-current ions(?) move upstream

SC-1 CIS/HIA 2007-1-18



upstream the bow-shock
(RAPID/CIS)

Foreshock = gyrotropic beam



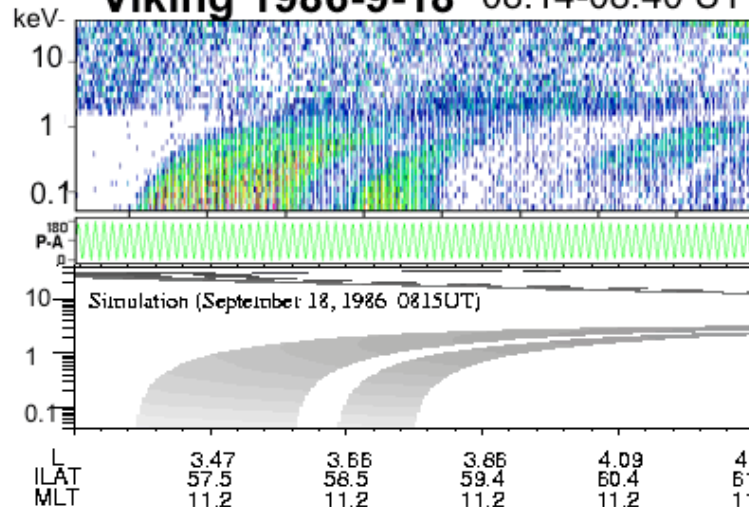
cannot be Fermi-acceleration

(Kronberg et al., 2011)

Viking summary of sub-keV ions (3 R_E)

skip?

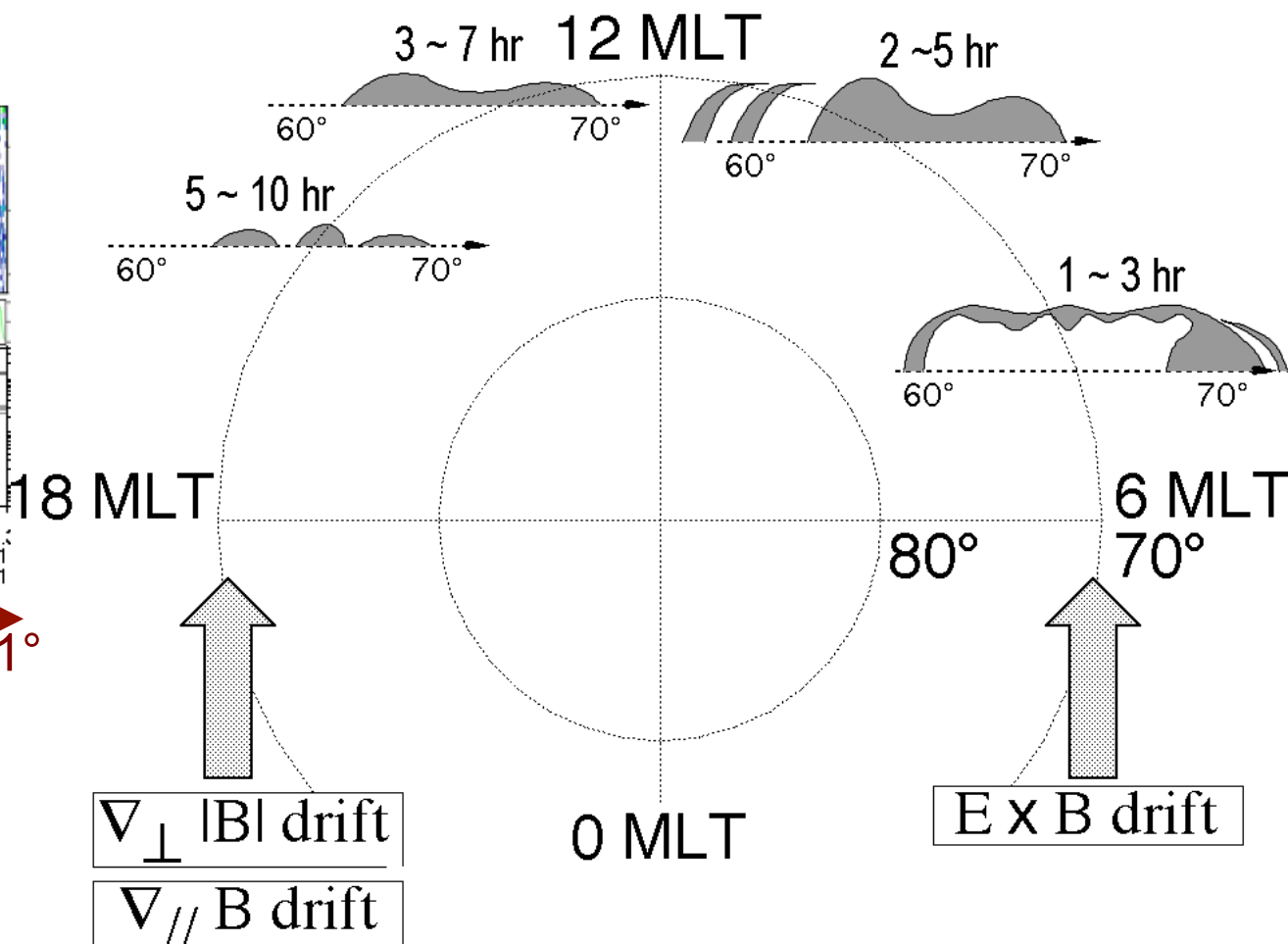
Viking 1986-9-18 08:14-08:40 UT



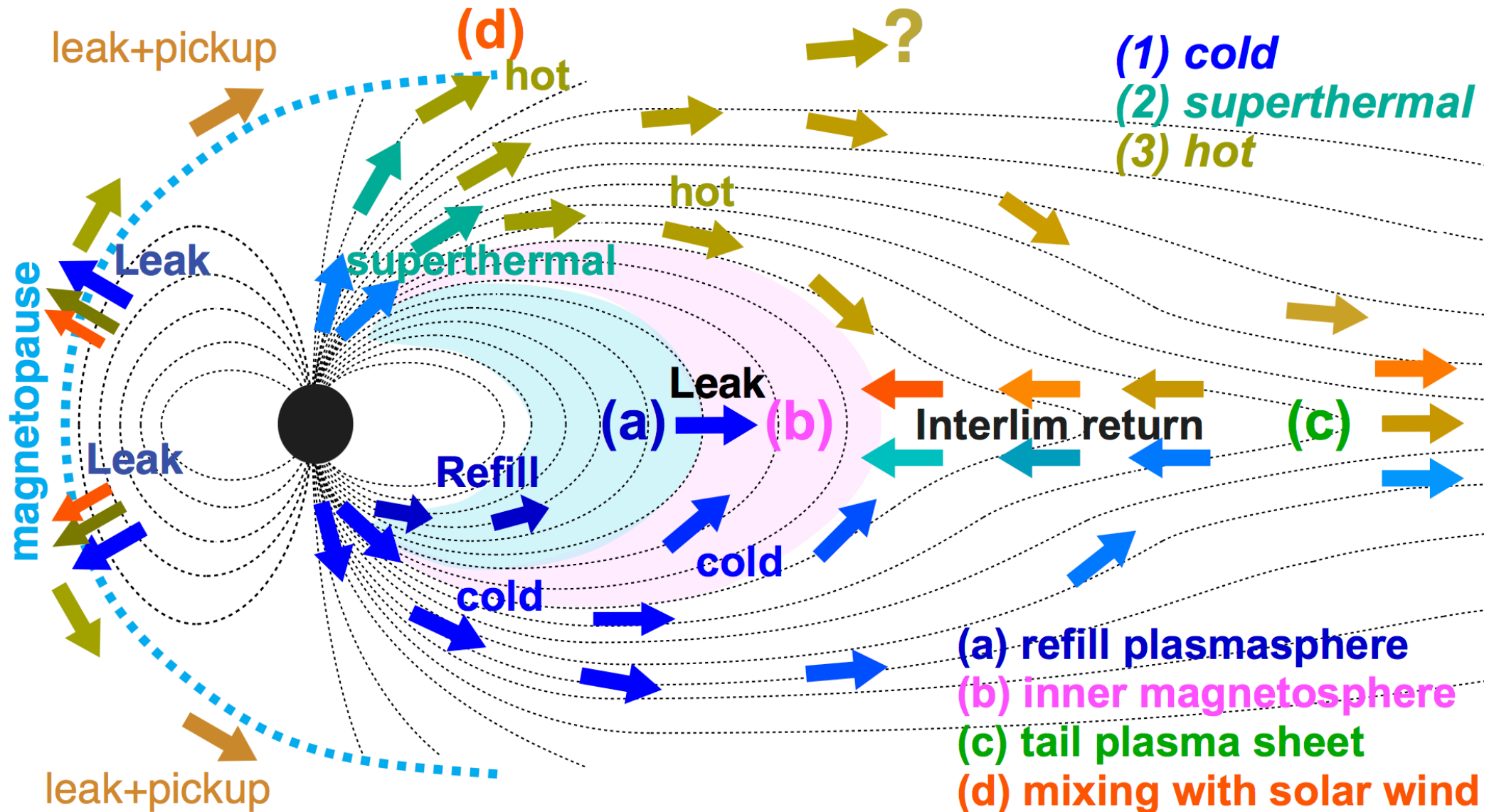
56° ← 26 min → 61°

Ions moved much faster, and more eastward than simple model

⇒ Key in simulation is **E-field** and **loss rate**

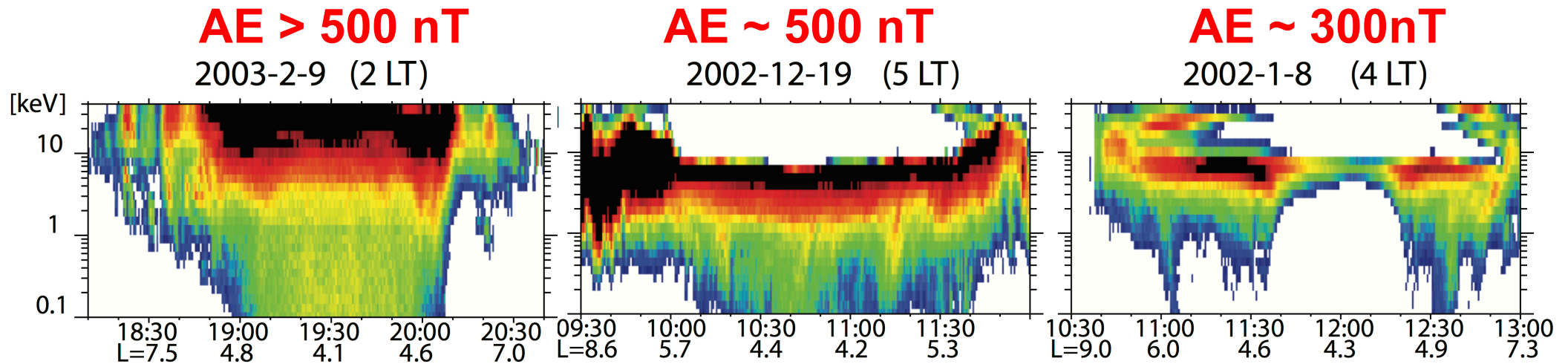


Adding leak in the destinations



Look more into E-field

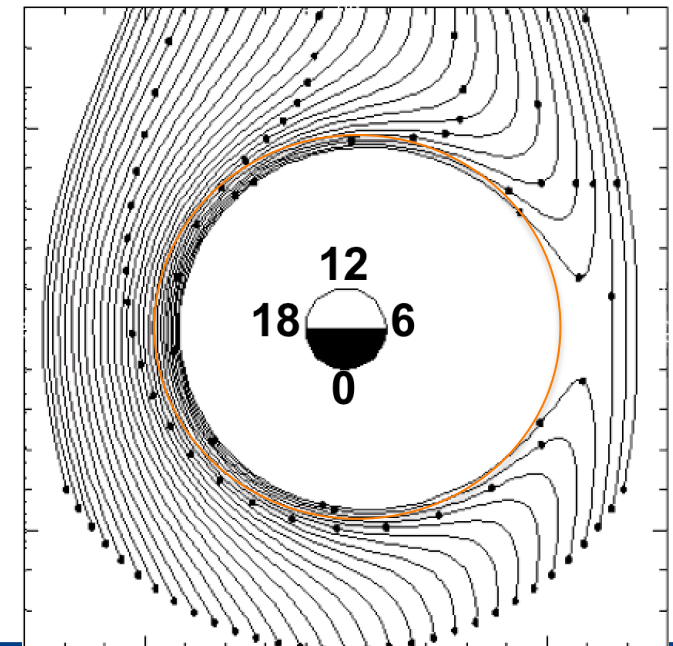
skip



Demarcation energy in dawn side ($\sim 5 R_E$)

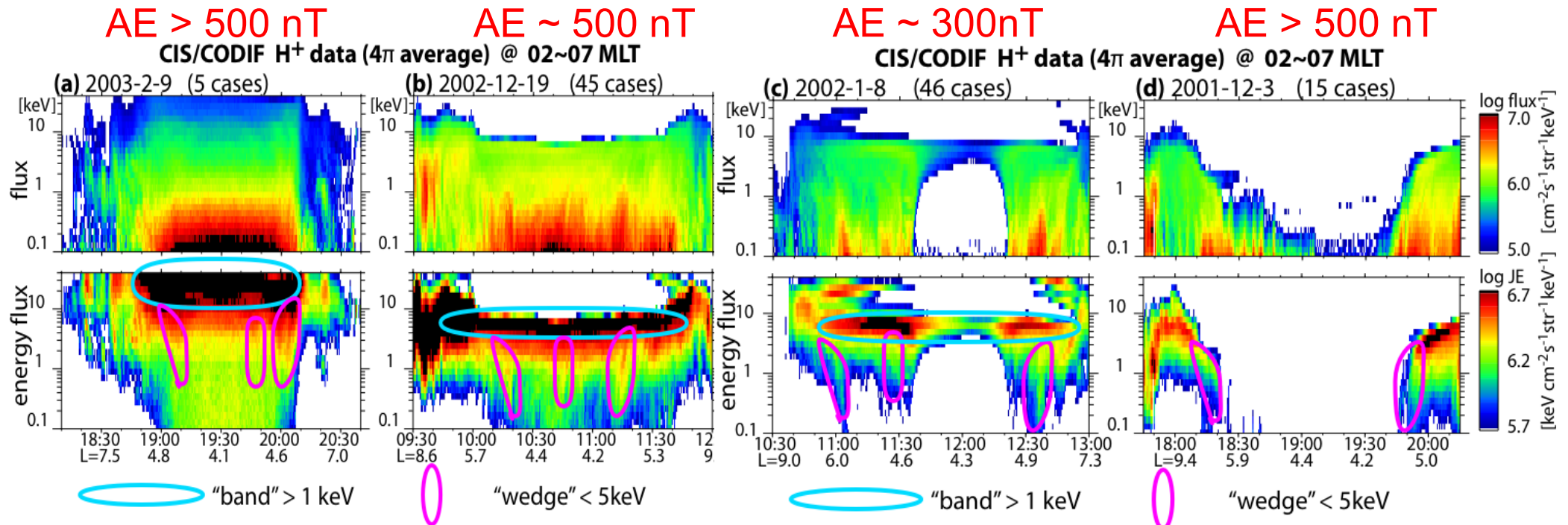
- (1) depends on **strength of substorm (E-field)**
- (2) **> 40 keV** for strong substorm

$\Rightarrow$ Local screw of **E-field** (later simulation confirmed)



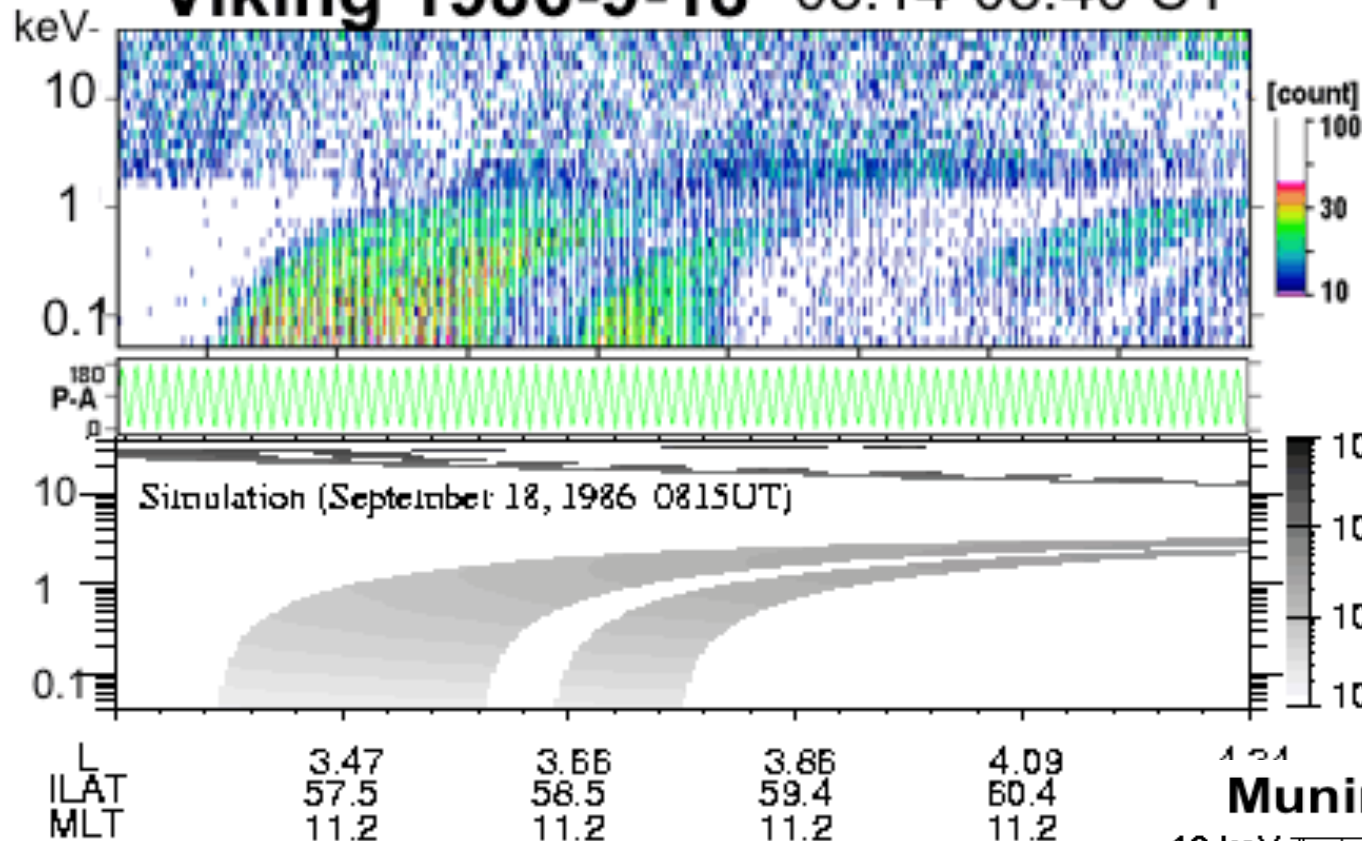
Demarcation energy depends on E-skip?

2-7 MLT



for last 6 hours	spectrogram pattern			
Peak AE	(a)	(b)	(c)	(d)
< 300 nT	0	4	26	10
300~500 nT	0	8	17	1
> 500 nT	5	33	3	4

Viking 1986-9-18 08:14-08:40 UT



skip?

Ion observation

(Yamauchi et al., 1996)

Viking (3 R_E)

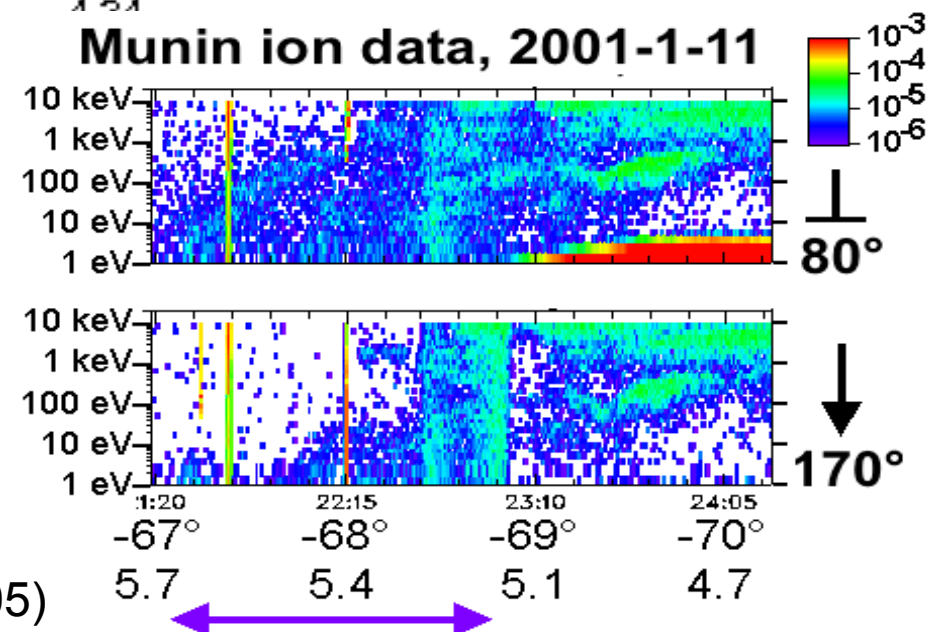
simulation

(Ebihara et al., 2001)

sub-keV part = mirror at low altitude
 $\Rightarrow$ finite // component !
 $\Rightarrow$ filling tail from the ionosphere

Munin (1700 km)

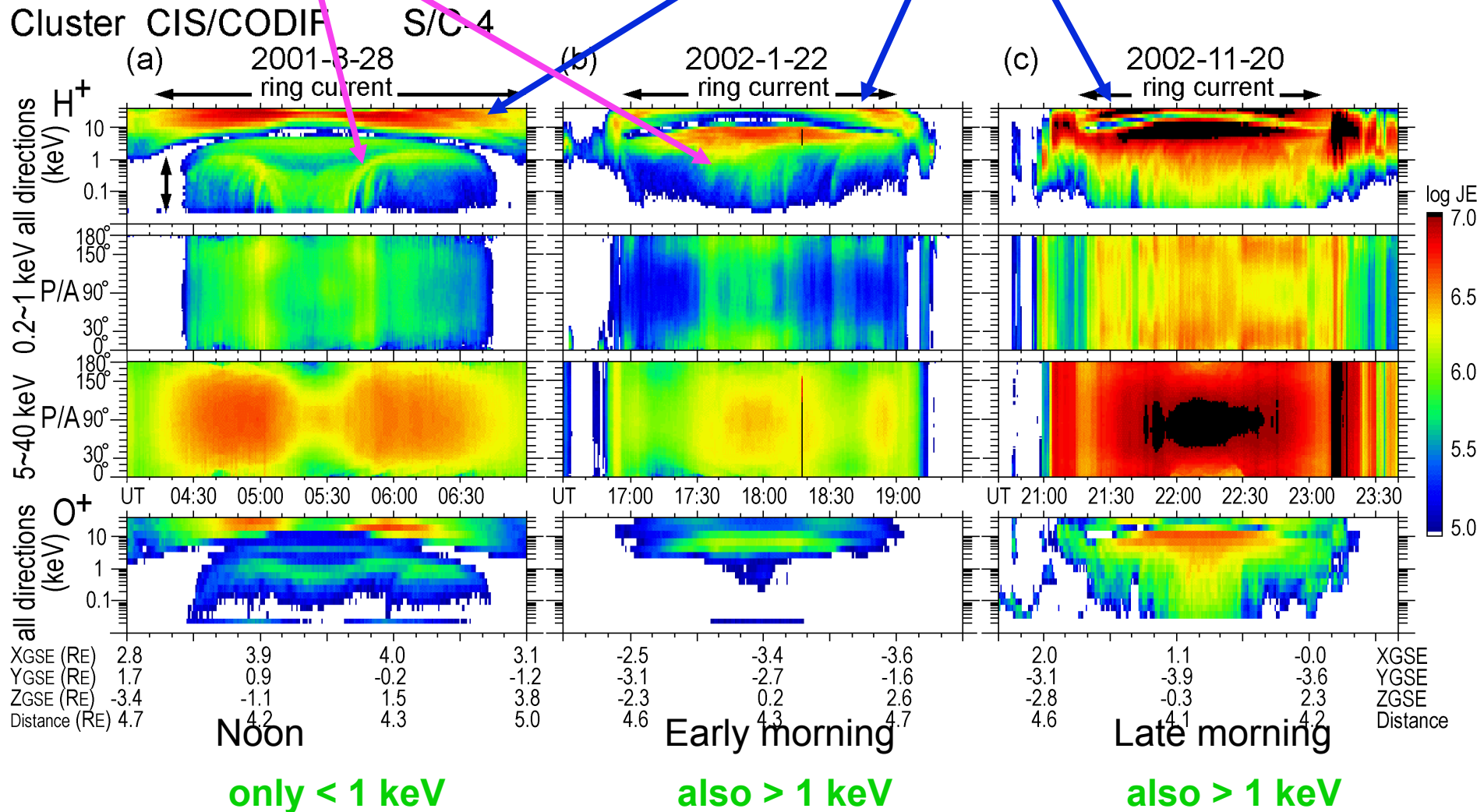
(Yamauchi et al., 2005)



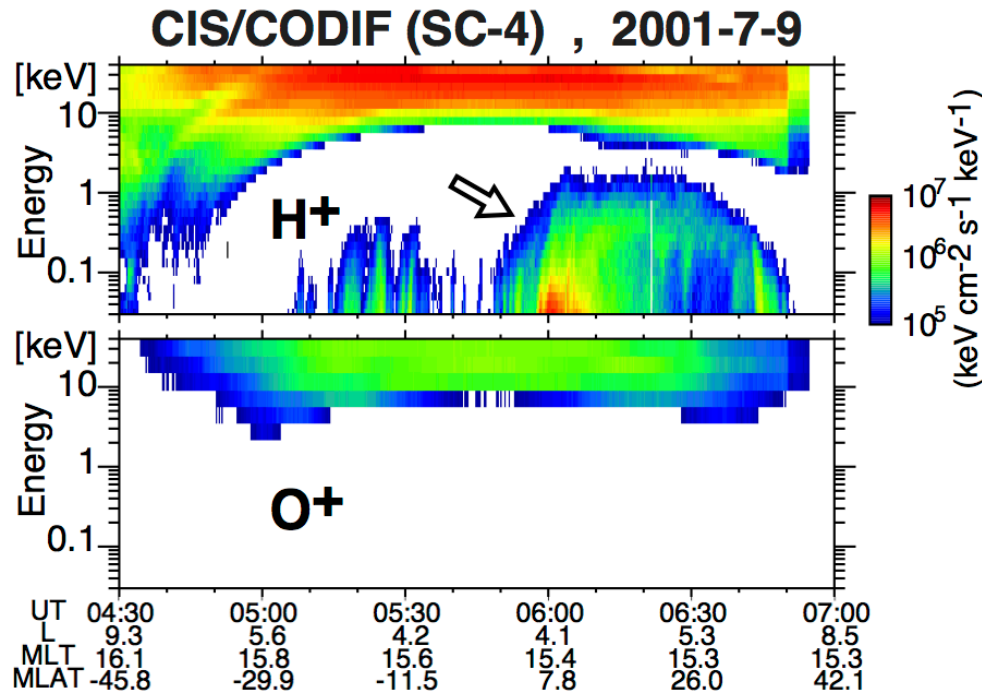
LT dependence (Cluster~Viking)

skip?

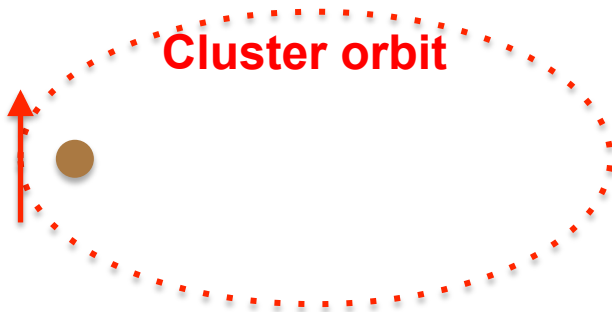
Eastward (electric) drift Westward (magnetic) drift



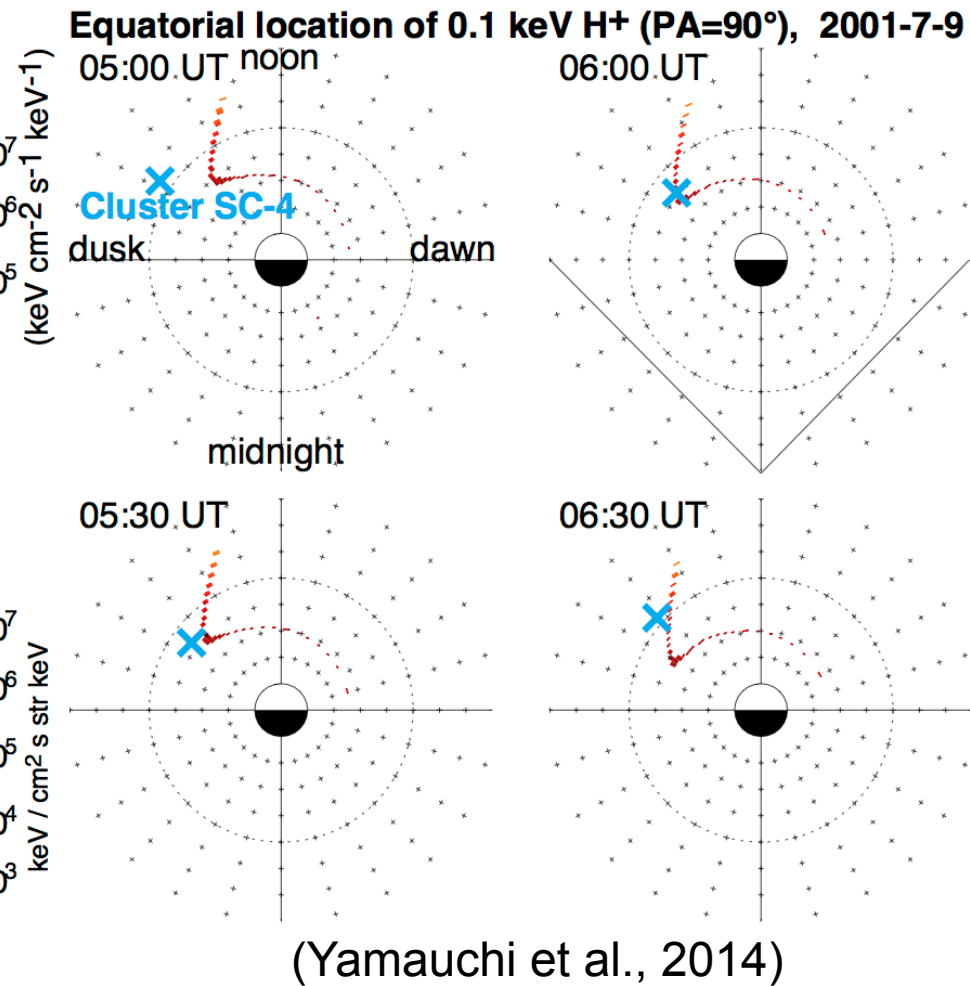
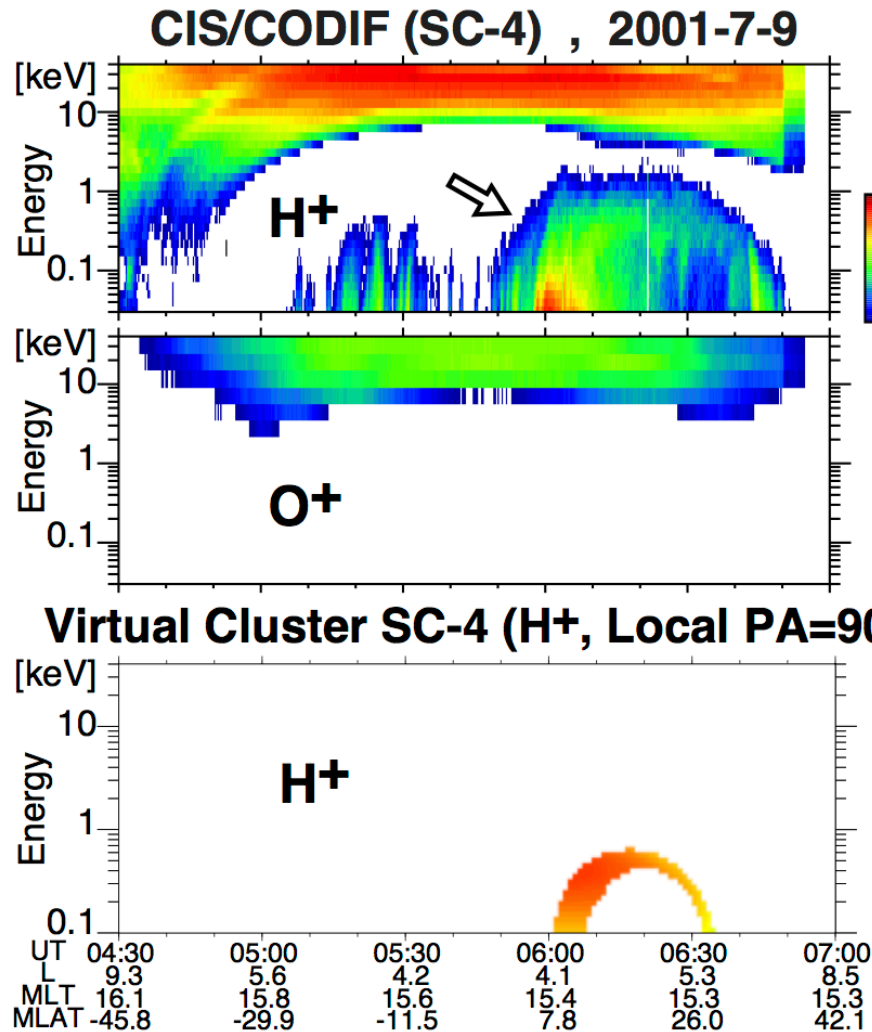
Can ExB drift really explain quick change?



Quick traversal $\Rightarrow$ change of
bouncing ions can be detected



Can ExB drift really explain quick change? **YES !**



The model assumed loss of ions only by (1) **Charge exchange** and (2) through dayside magnetopause (**Magnetopause shadowing**), because (3) **pitch-angle diffusion** (to loss-cone) is negligible for ions < 1 keV

Ion source during substorm?

(multiple onset, AE = 365nT@23:10)

Timings/locations of H⁺

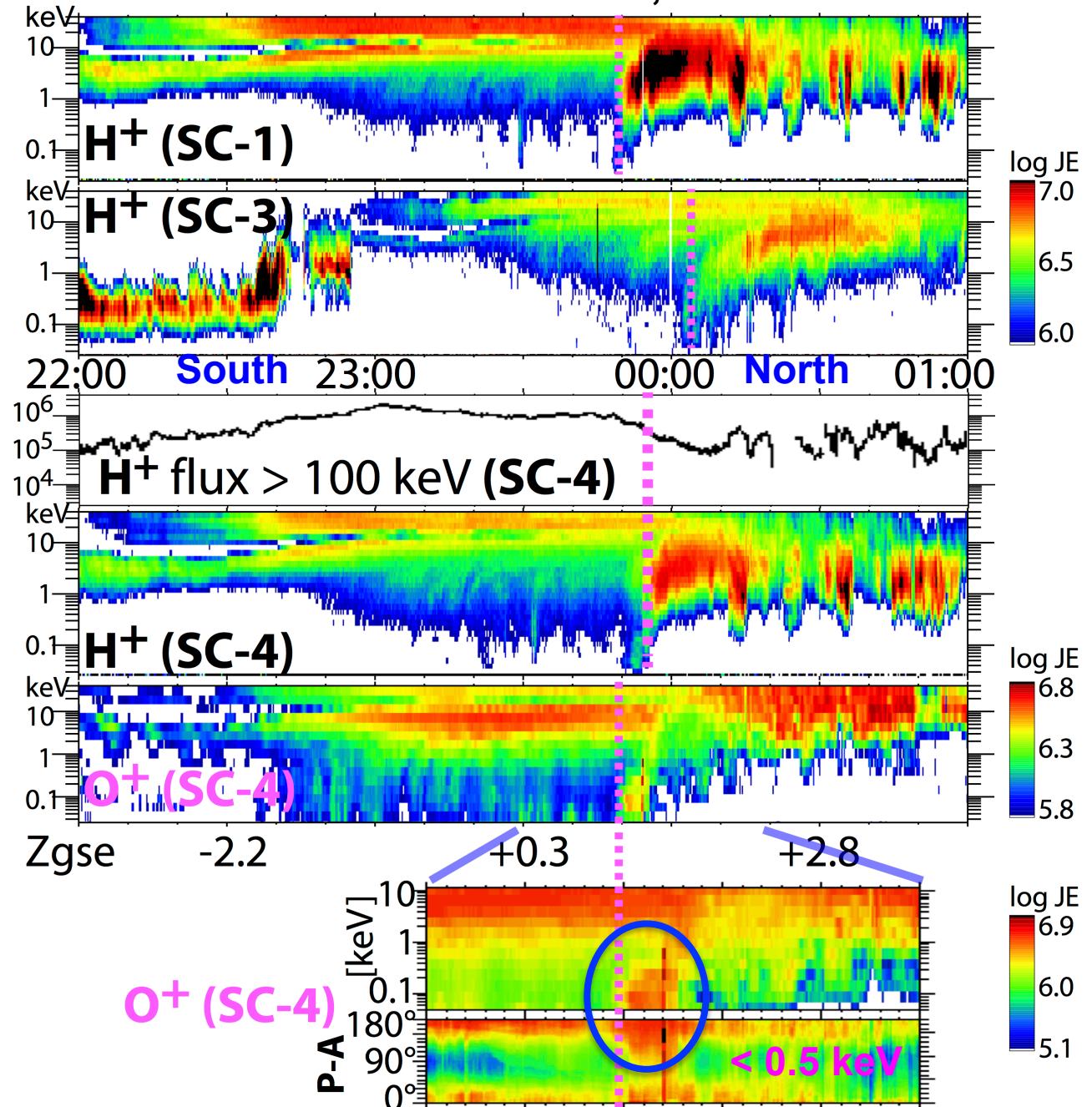
signature + observed E = 1-3 mV/m ($V_E = 3\sim 10$ km/s)

⇒ H⁺ dispersion started
6~7 MLT and ~ 23:10 UT

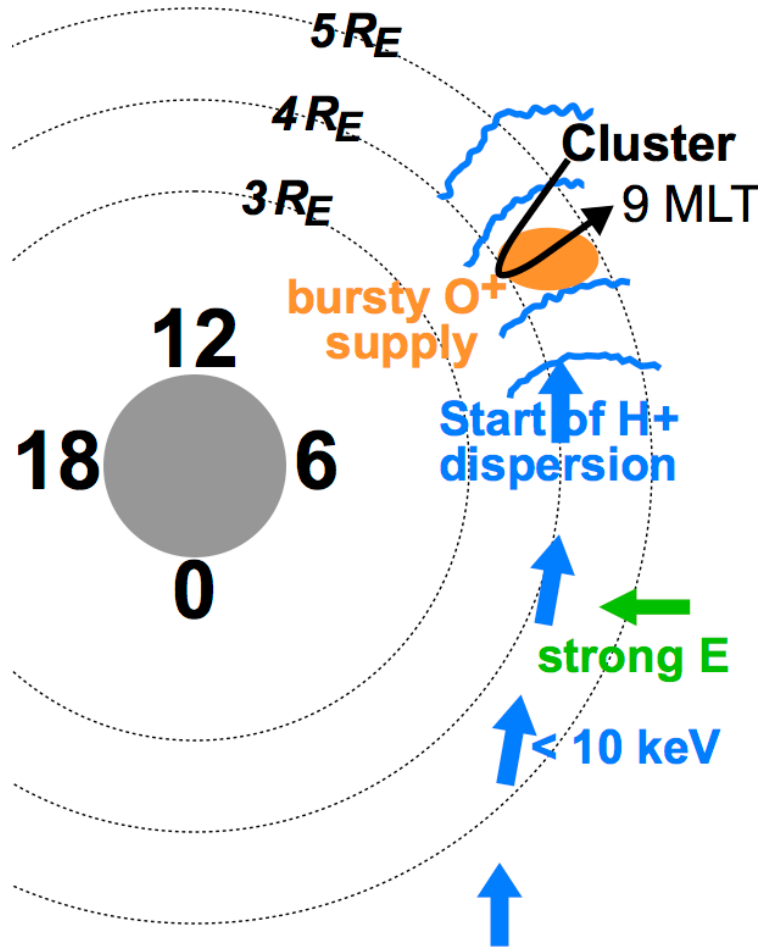
O⁺ < 50 km/s (<0.2 keV) with pitch angle **180°** (>0°)

⇒ 20-30 min from **northern ionosphere** along B (started **~23:20 UT near 9 MLT**)

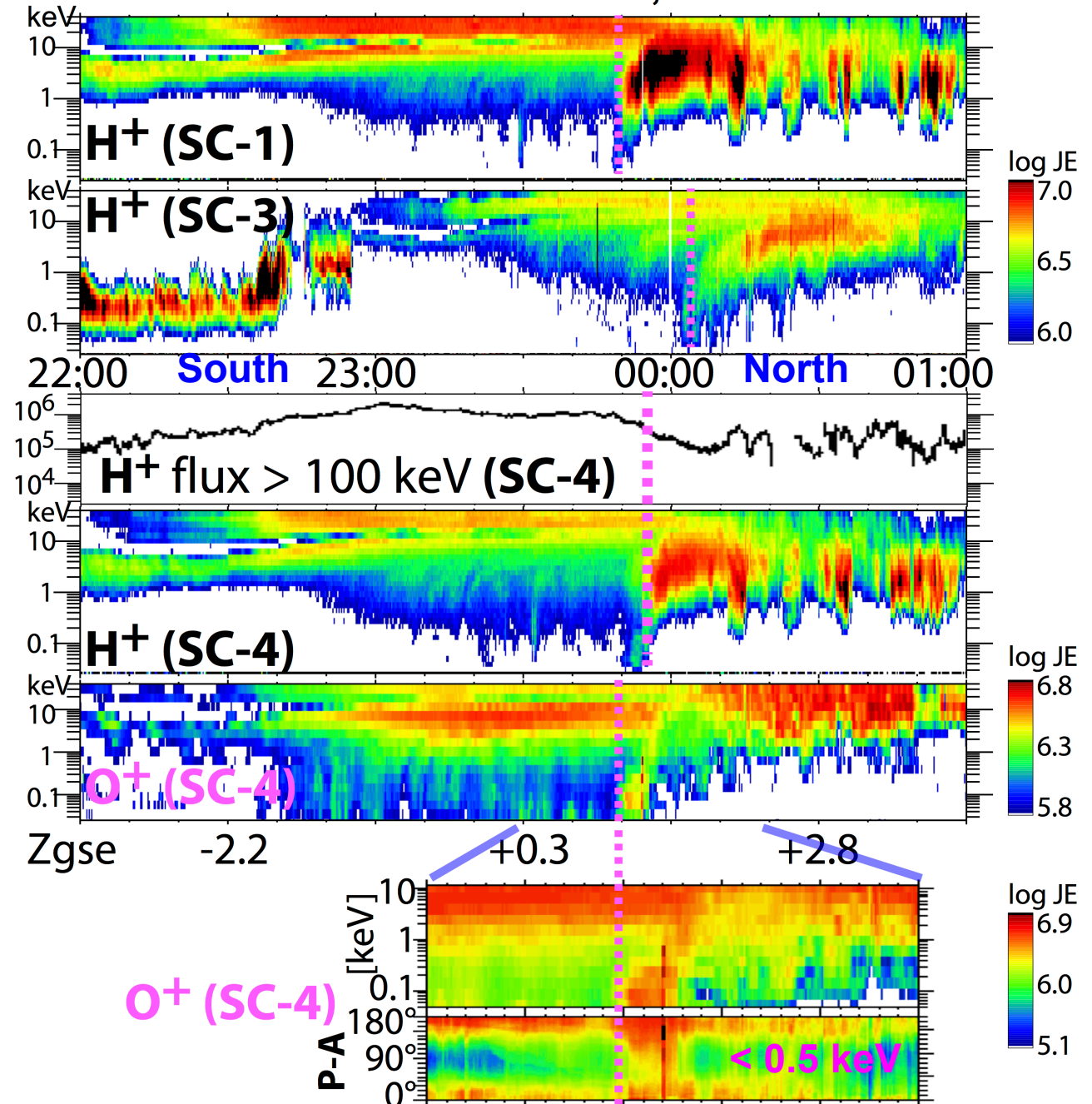
9 MLT Cluster RAPID+CIS, 2001-10-21



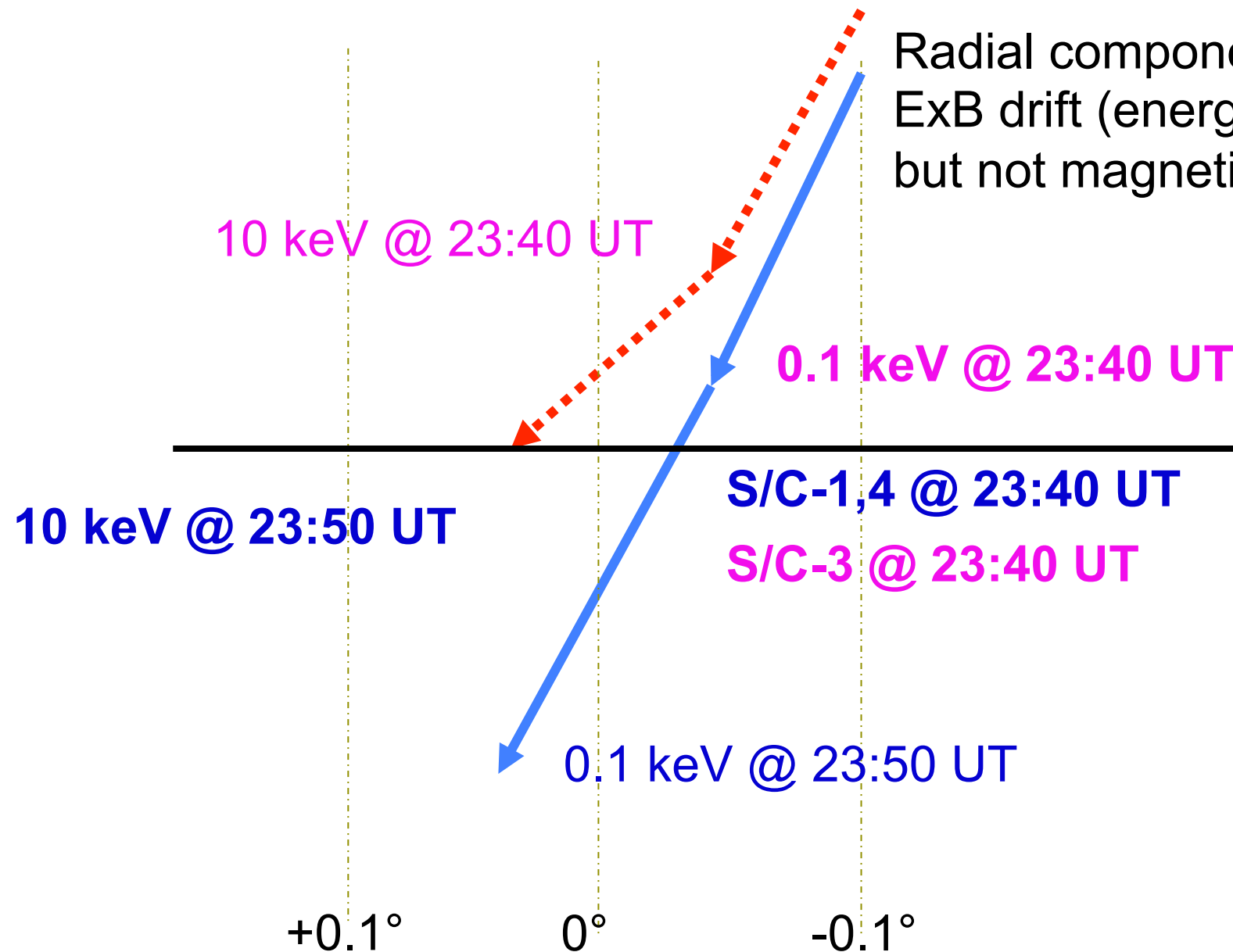
Derived ion motion



9 MLT Cluster RAPID+CIS, 2001-10-21



skip?



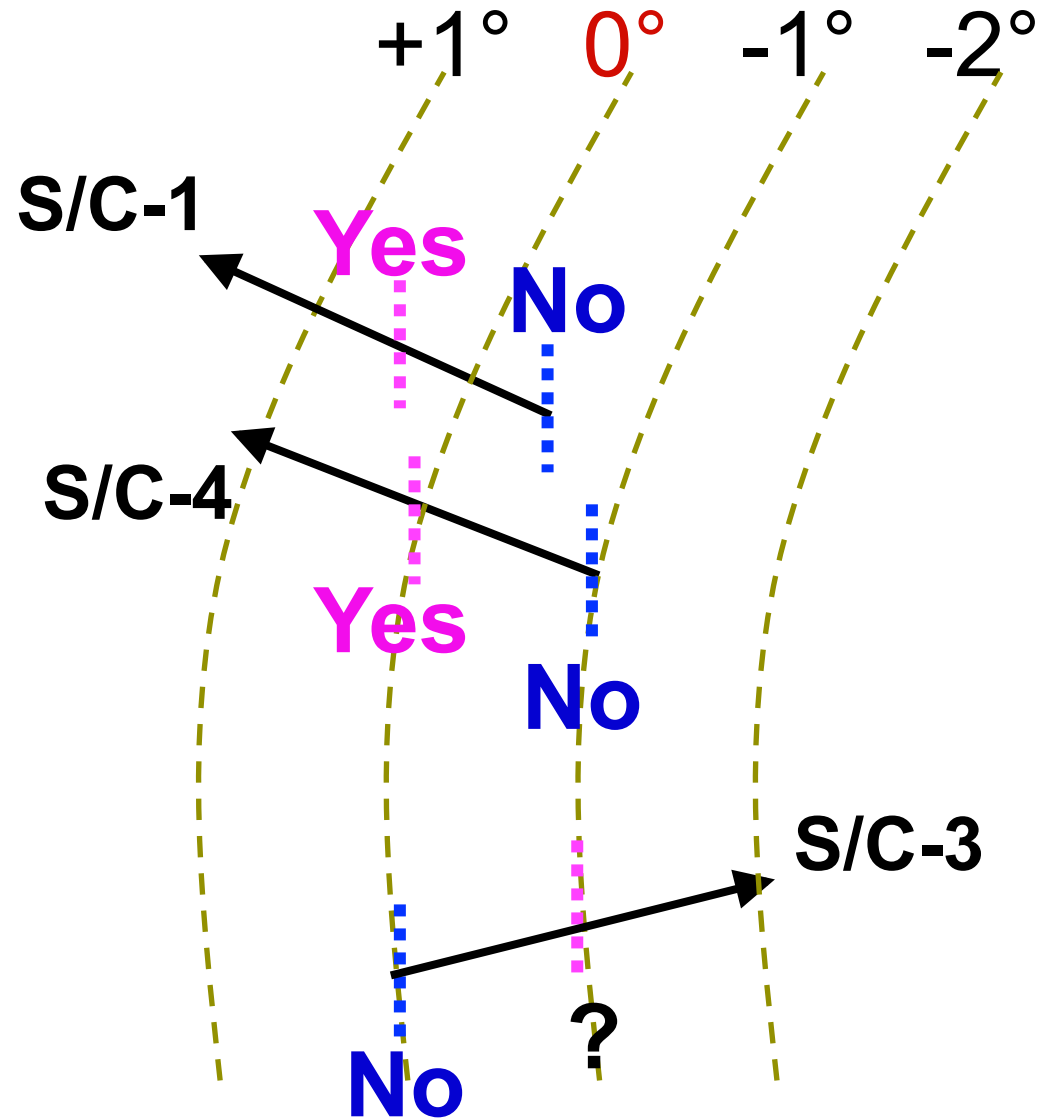
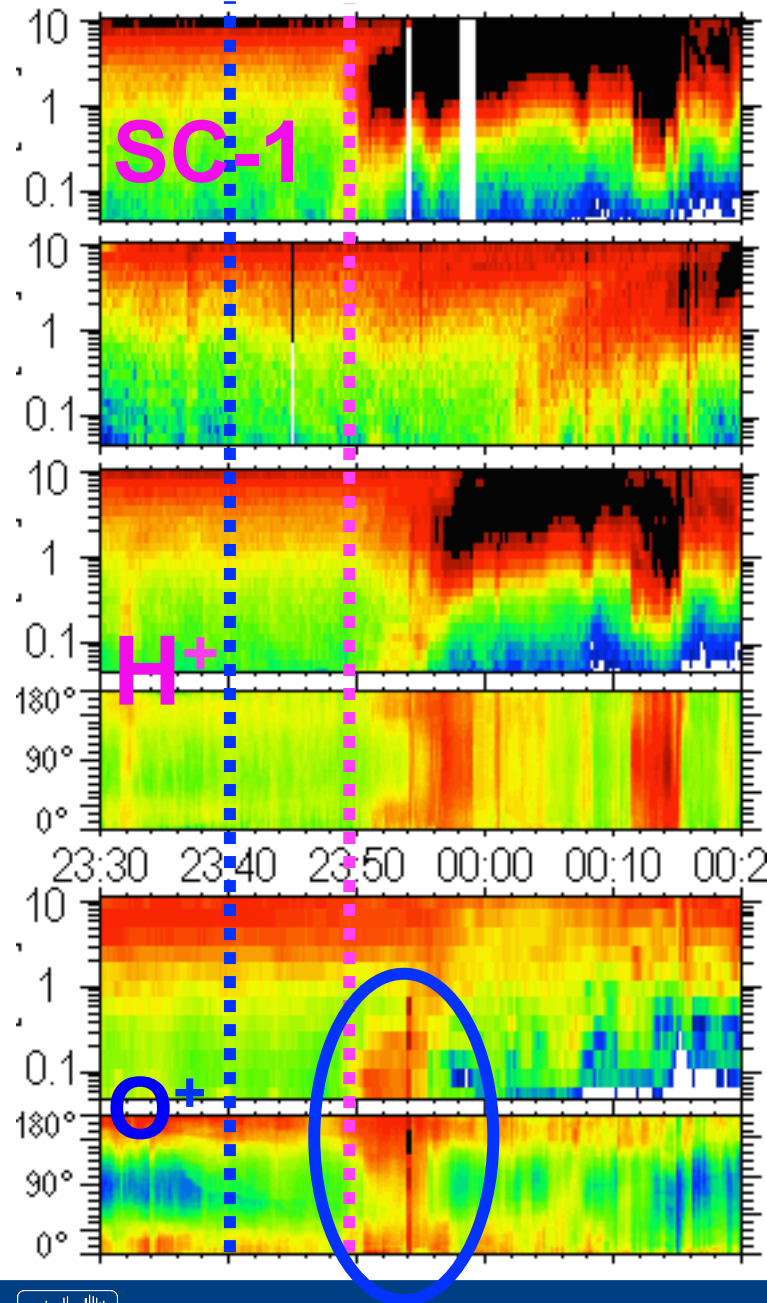
Radial component is only from ExB drift (energy independent) but not magnetic drift

NoYes

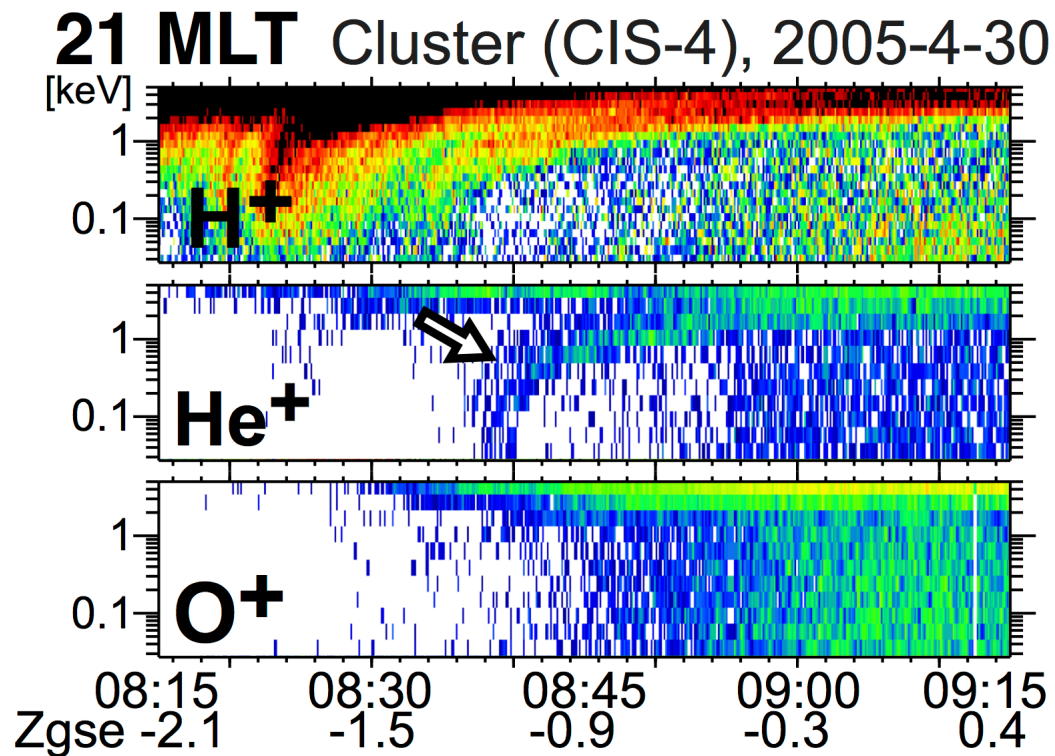
2001-10-21

skip?

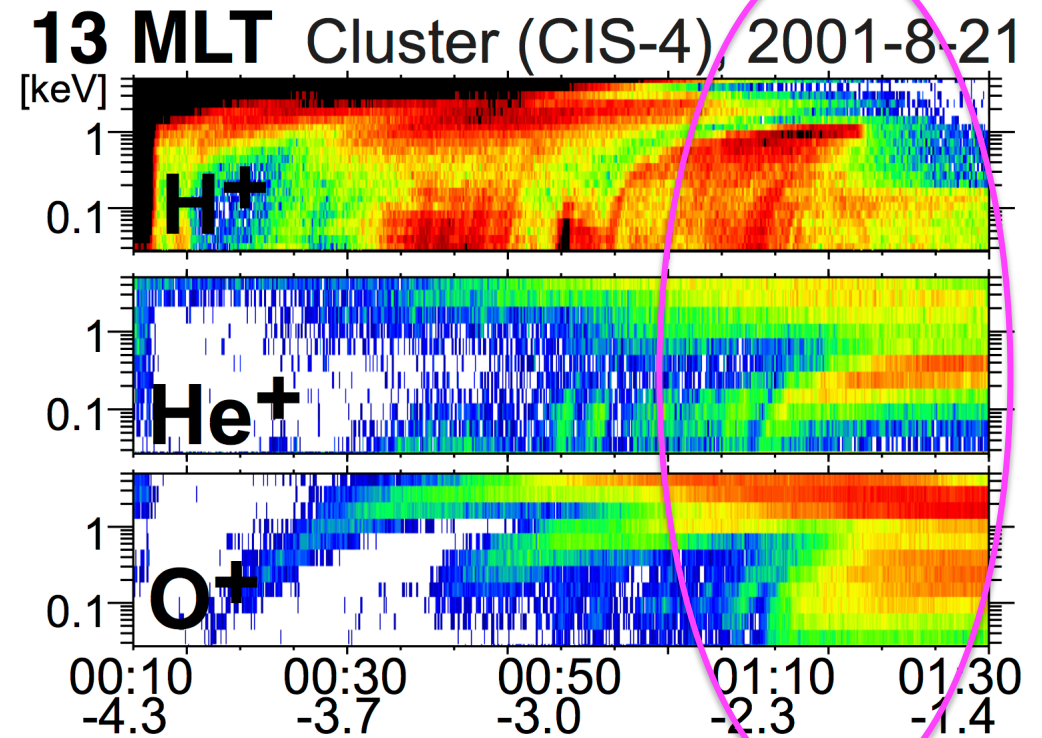
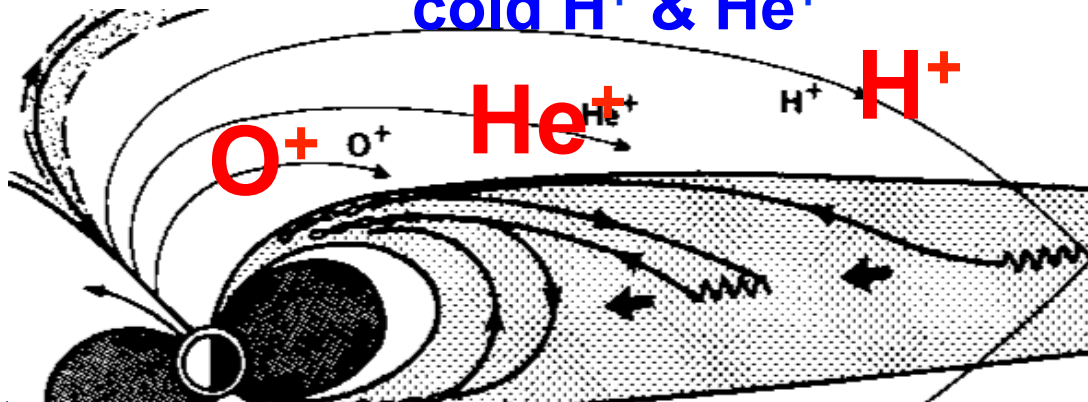
H⁺ stripes @ 9 MLT?



Mass dependency of drifting ions?

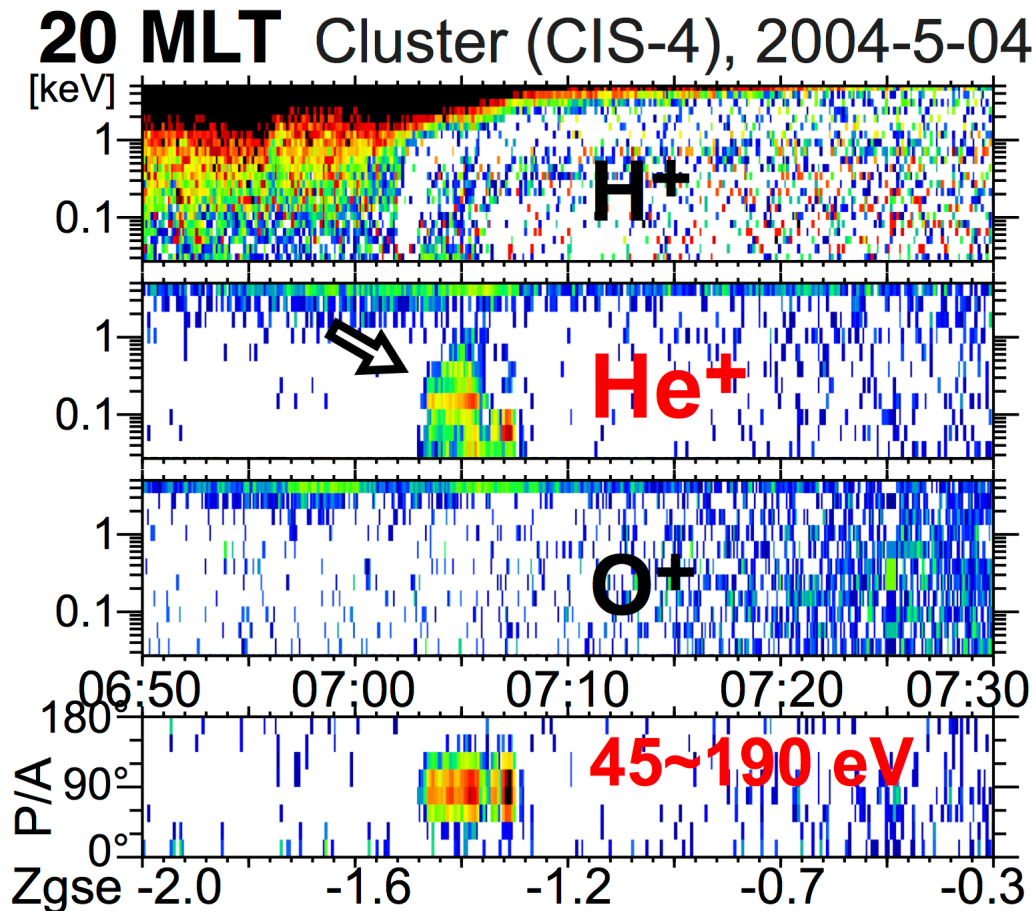


Different start location between
cold H^+ & He^+



Why H^+ & O^+ are out of
phase?
(I still do not have answer)

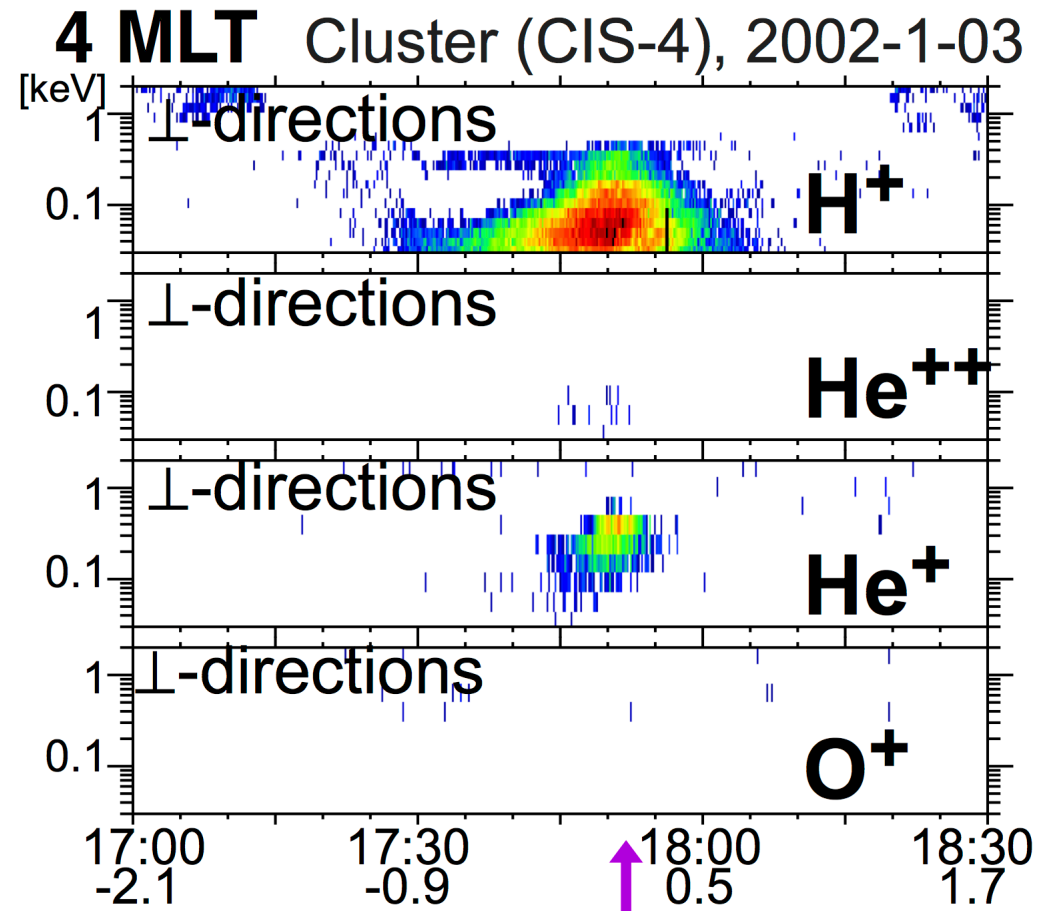
Local $\perp$ heating in the plasmasphere



Rare but probably related to substorms

**Why only He & not equator?
(I still do not have answer)**

(Yamauchi et al., 2014)



Confined to equator with $\tau \sim 1$ hour

**Why variable E_{He}/E_H ($=1\sim4$)?
(I still do not have answer)**

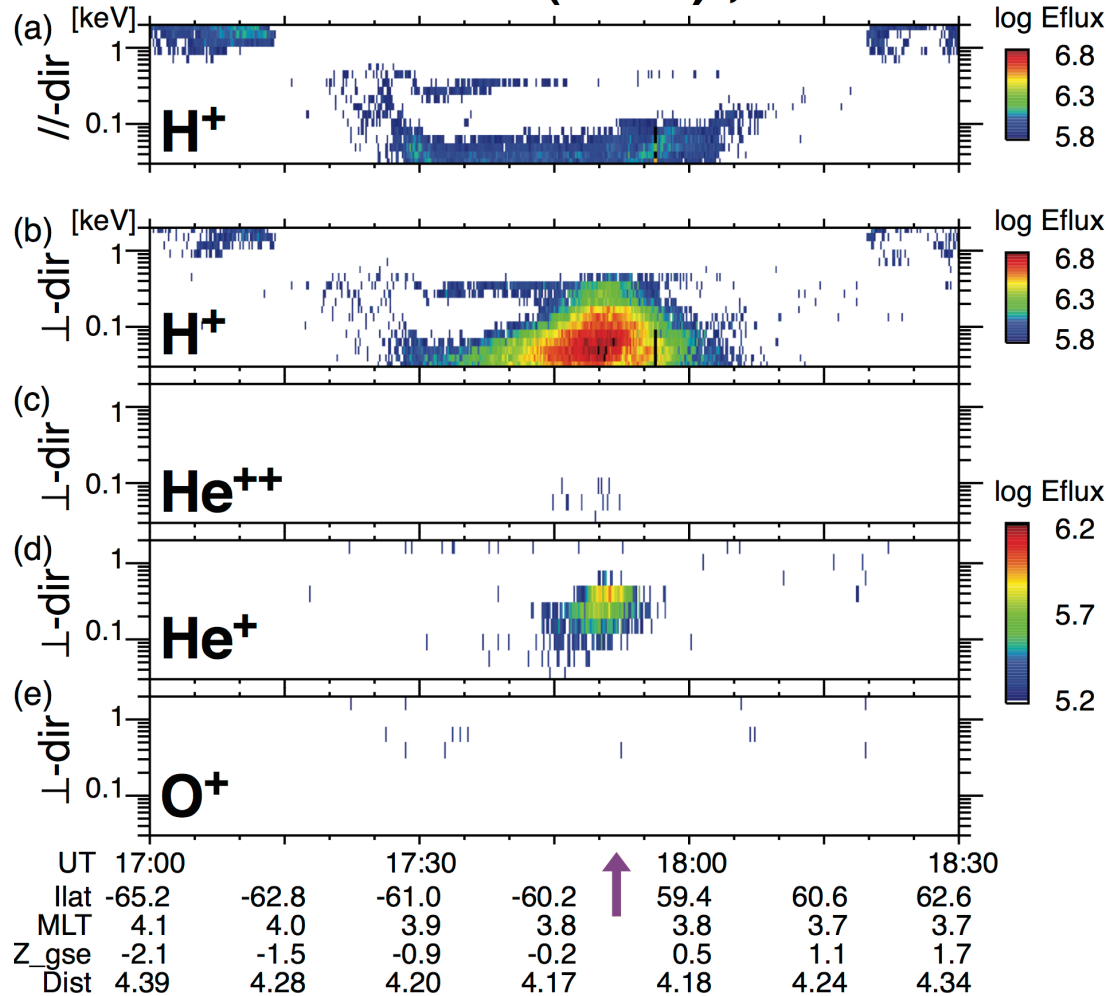
(Yamauchi et al., 2012)

Heating in the inner magnetosphere

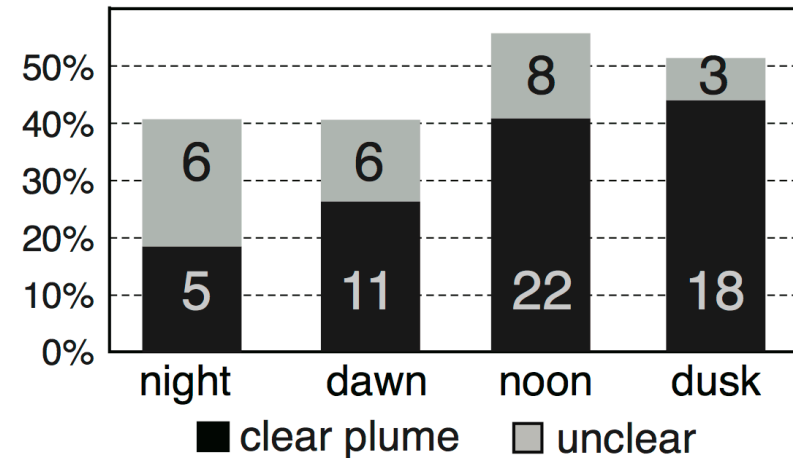
skip?

⊥ heating

CIS/CODIF data (SC-4) , 2002-1-3



Observation of Equatorial Warm Ion Plume
Cluster CIS/CODIF data (SC-4, 2001-2002)

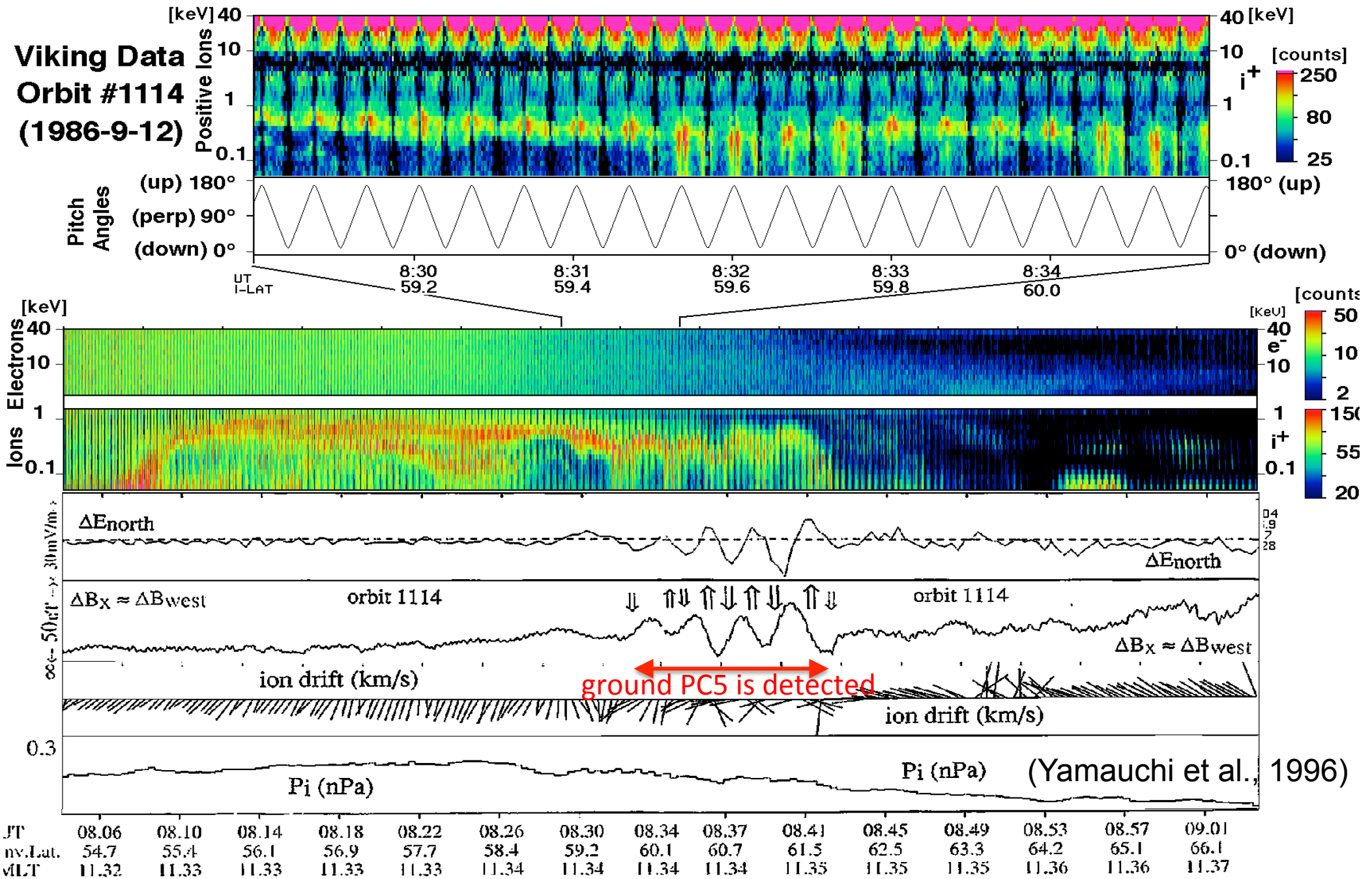


- (1) Trapped (pitch angle $\sim 90^\circ$) and confined to Equator
- (2) nearly 50% in the noon and dusk sectors, and 35% in night-dawn.
- (3) Variable content of He^+ . (majority is less than 5%)
- (4) Variable energy ratio between He^+ and H^+ (1 to 4), contrasting to the previous report.
- (5) Time scale of about an hour.

(Yamauchi et al., 2012)

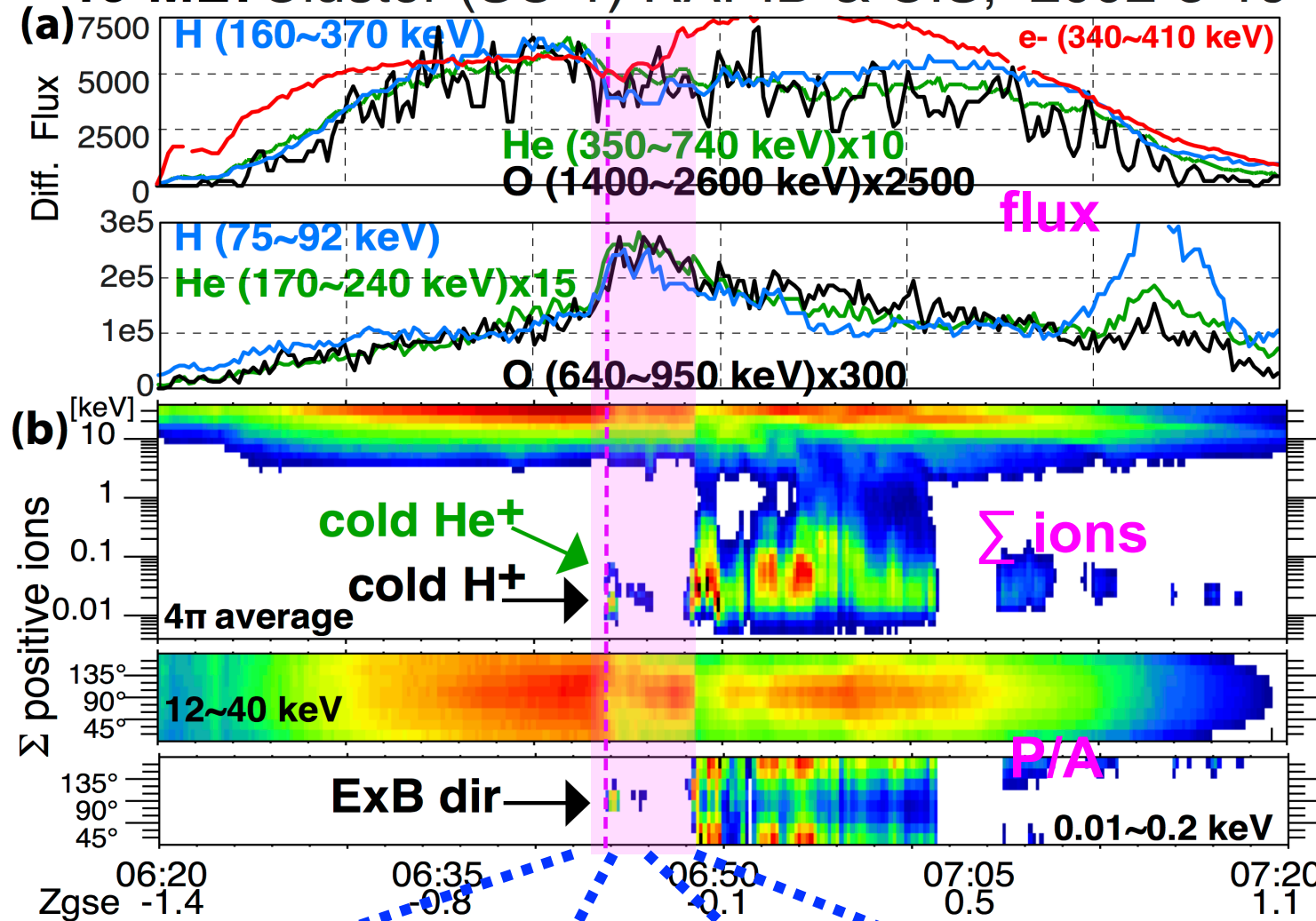
Other energization in the inner magnetosphere: 1

conic acceleration (But, this is **unique case** in all Viking/Freja/Cluster)



Other energization in the inner magnetosphere: 2

19 MLT Cluster (SC-1) RAPID & CIS, 2002-5-19



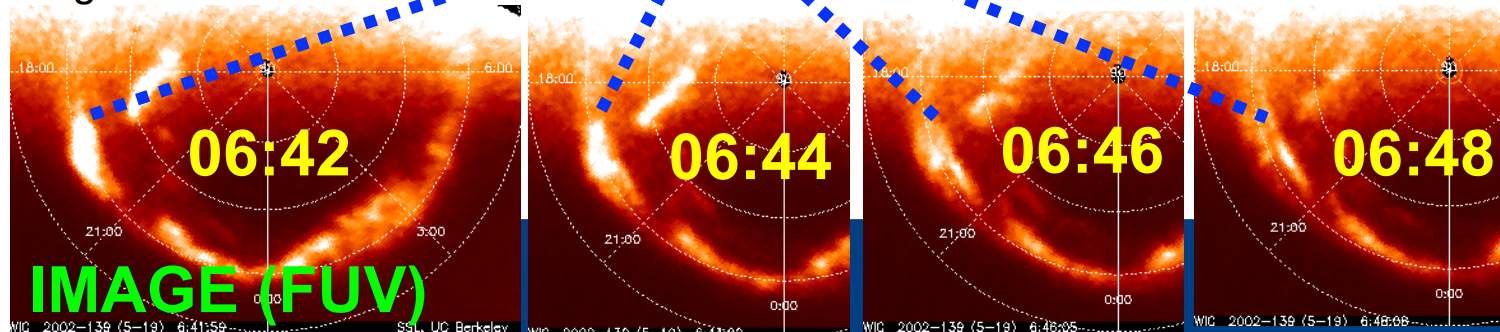
ions > 5000 km/s

ions $\approx$ 3000 km/s

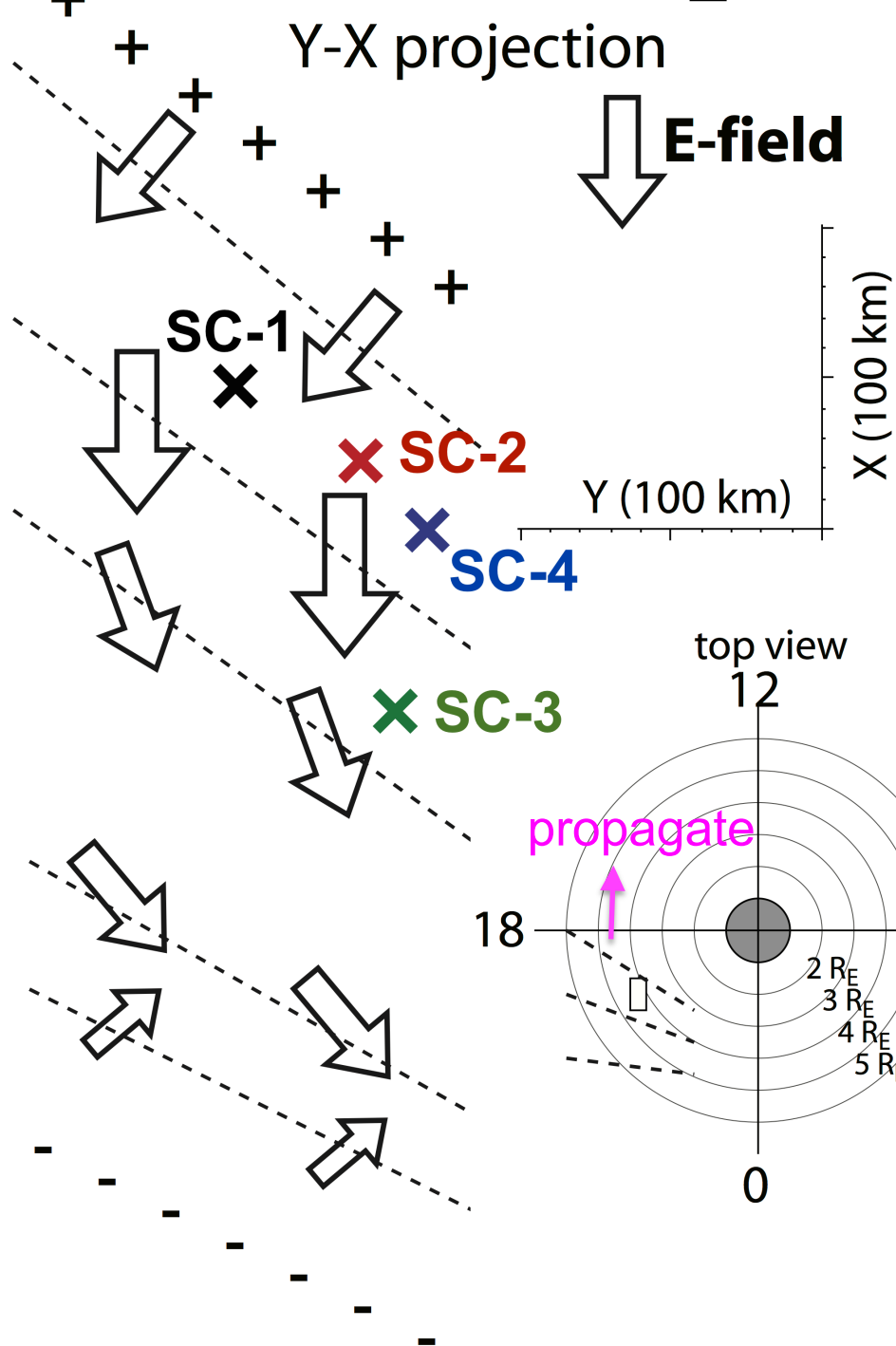
Sudden strong E
(~ 10 mV/m)

&

Mass-dependent
ion behavior
($v_{\text{ion}} \sim 3000$ km/s
is the key!)



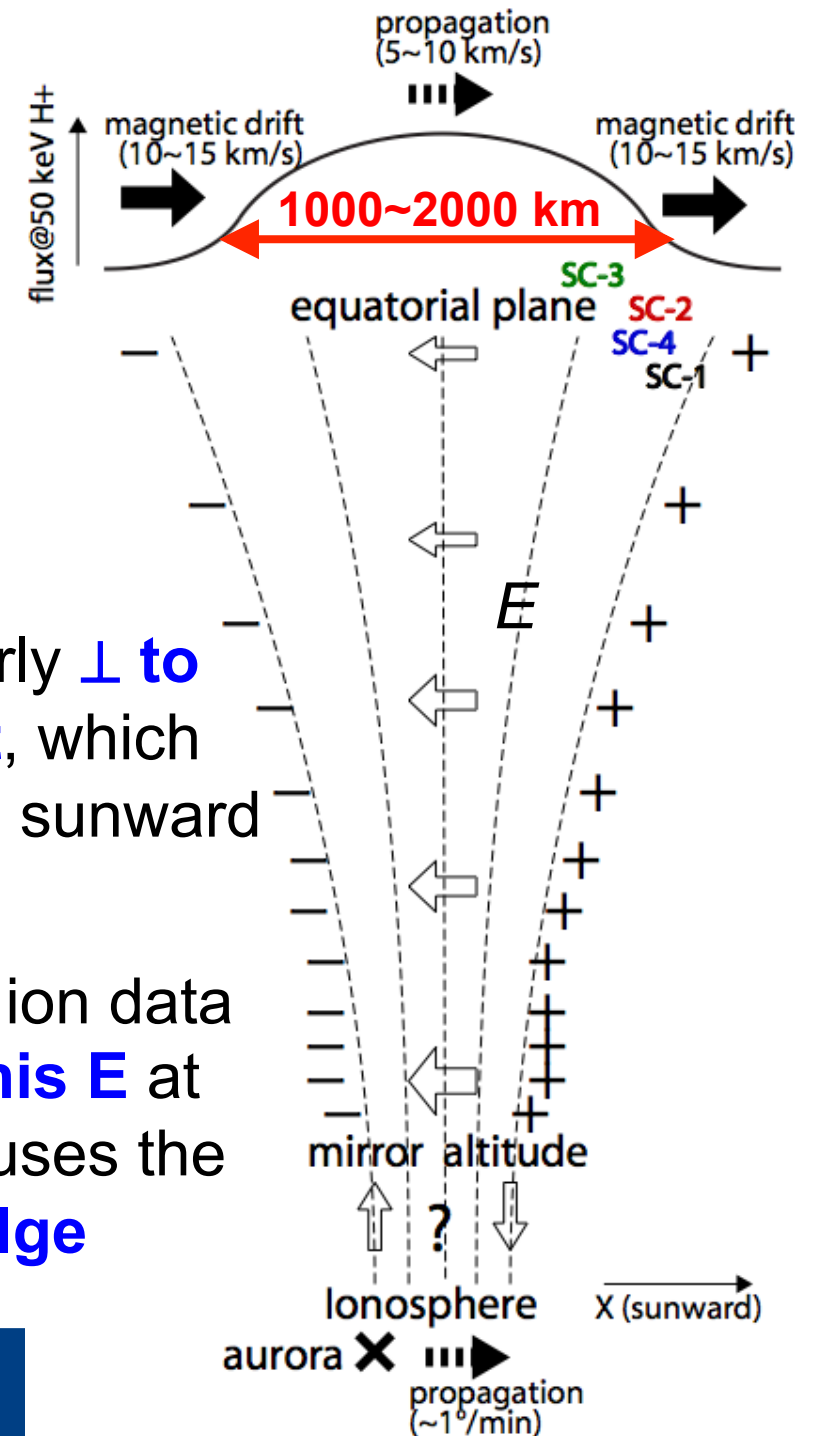
Propagating $E_{\perp}$ structure



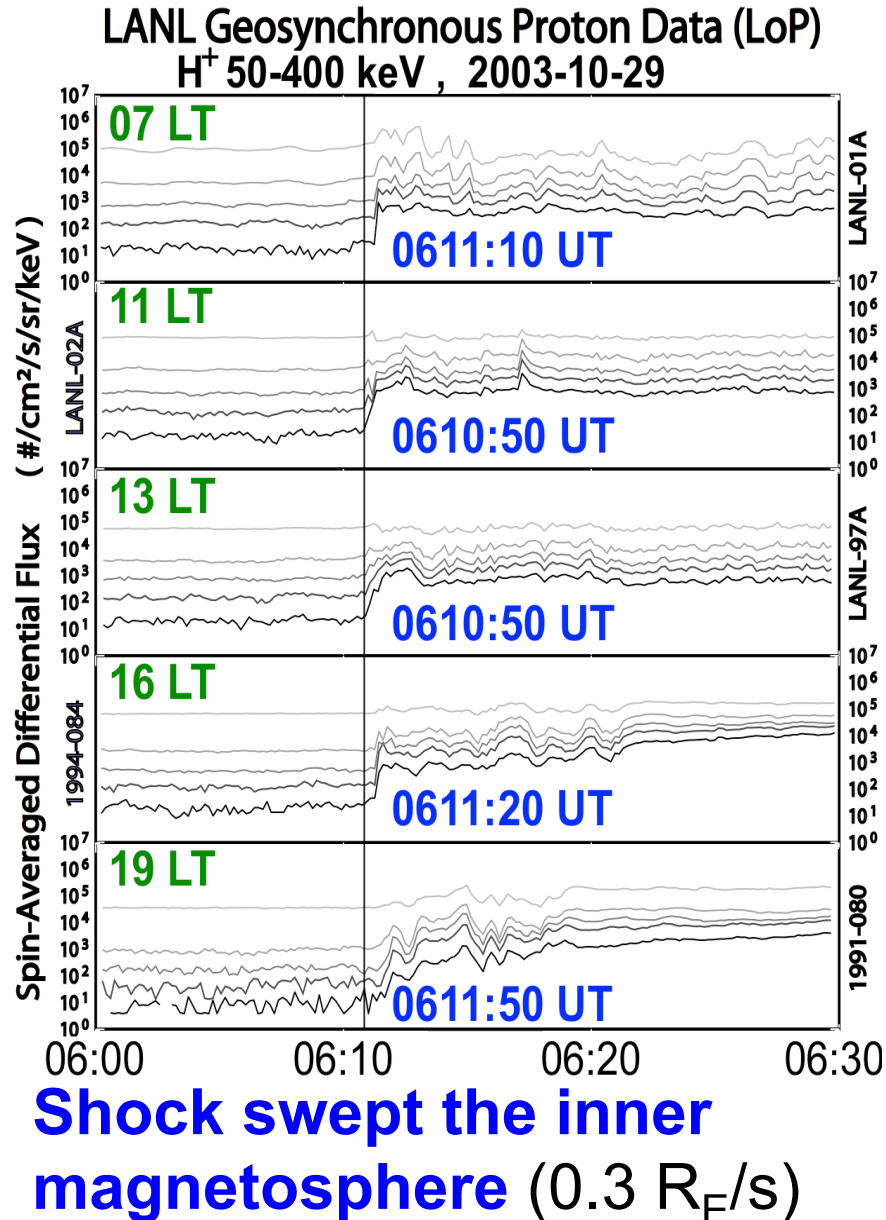
Timing

$\Rightarrow$ E is nearly $\perp$ to wave front, which propagates sunward

Mapping & ion data
 $\Rightarrow \Delta V$ by this E at equator causes the auroral bulge



Shock (CME front) may also propagate



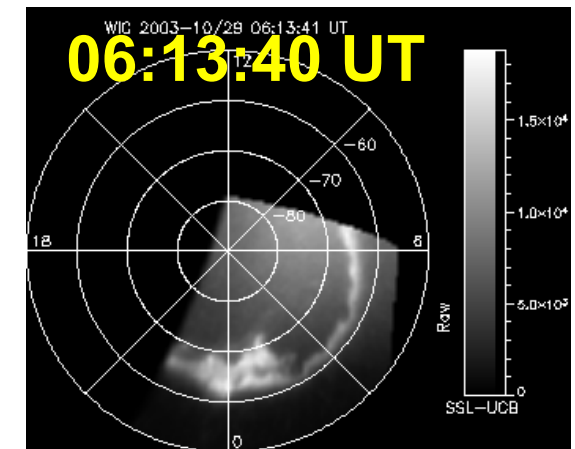
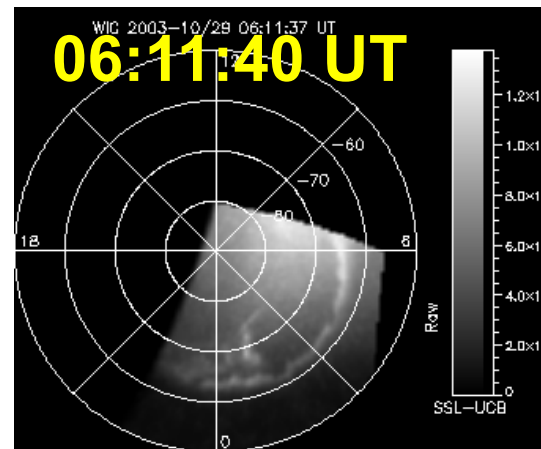
ACE: 0558:20 UT / +221 R_E

GTL: 0609:40 UT / +26 R_E

Wind: 0619:30 UT / -156 R_E

ground B: 0611:20 UT

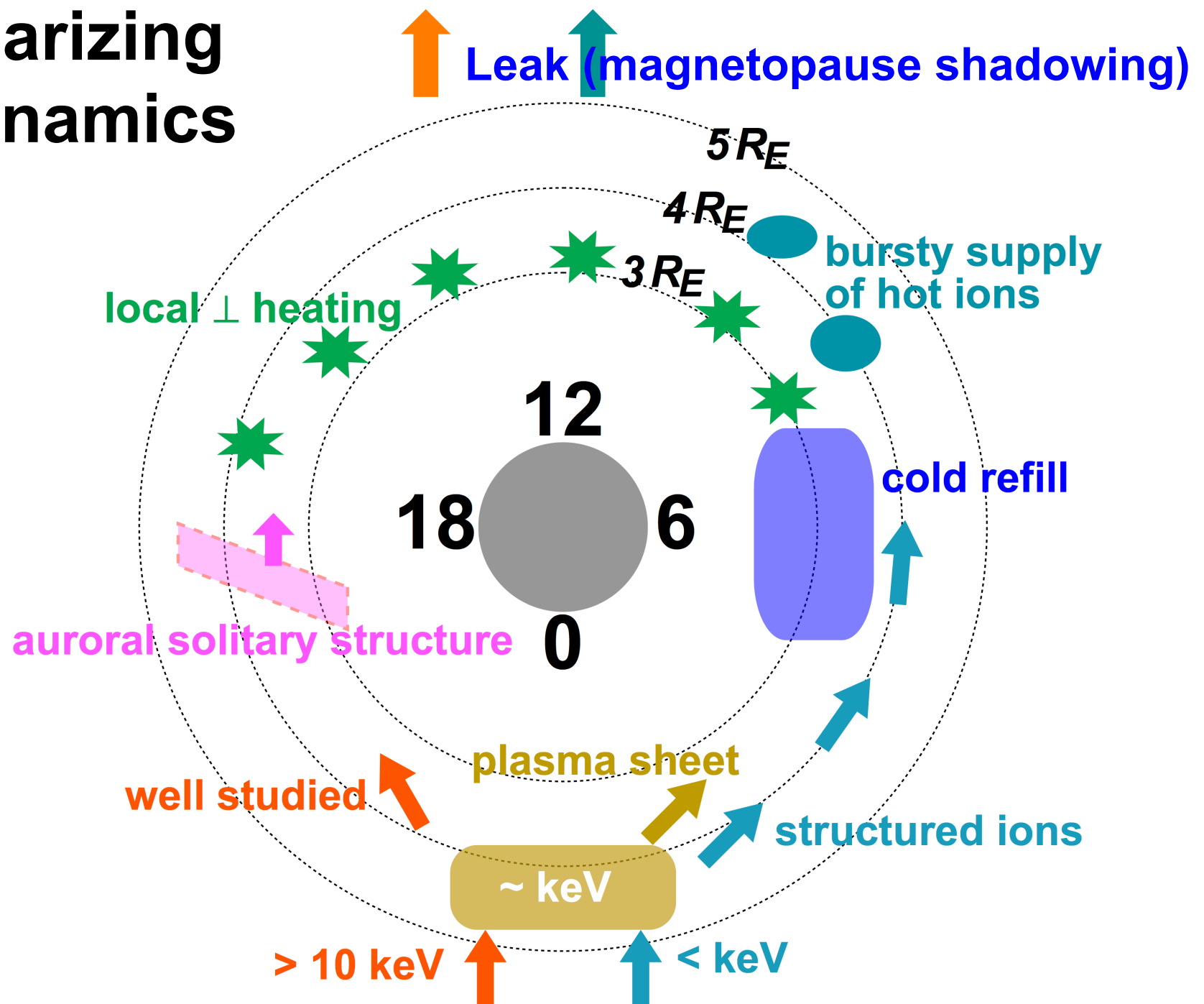
$\Rightarrow$ arrival at MP: $\sim$ 06:10 UT



Dipolarization + substorm onset $\sim$ 06:12 UT

$\Rightarrow$ Shock triggered this particular substorm onset

Summarizing ion dynamics



Summarizing ion escape route

