Terrestrial ion behavior in space

M. Yamauchi

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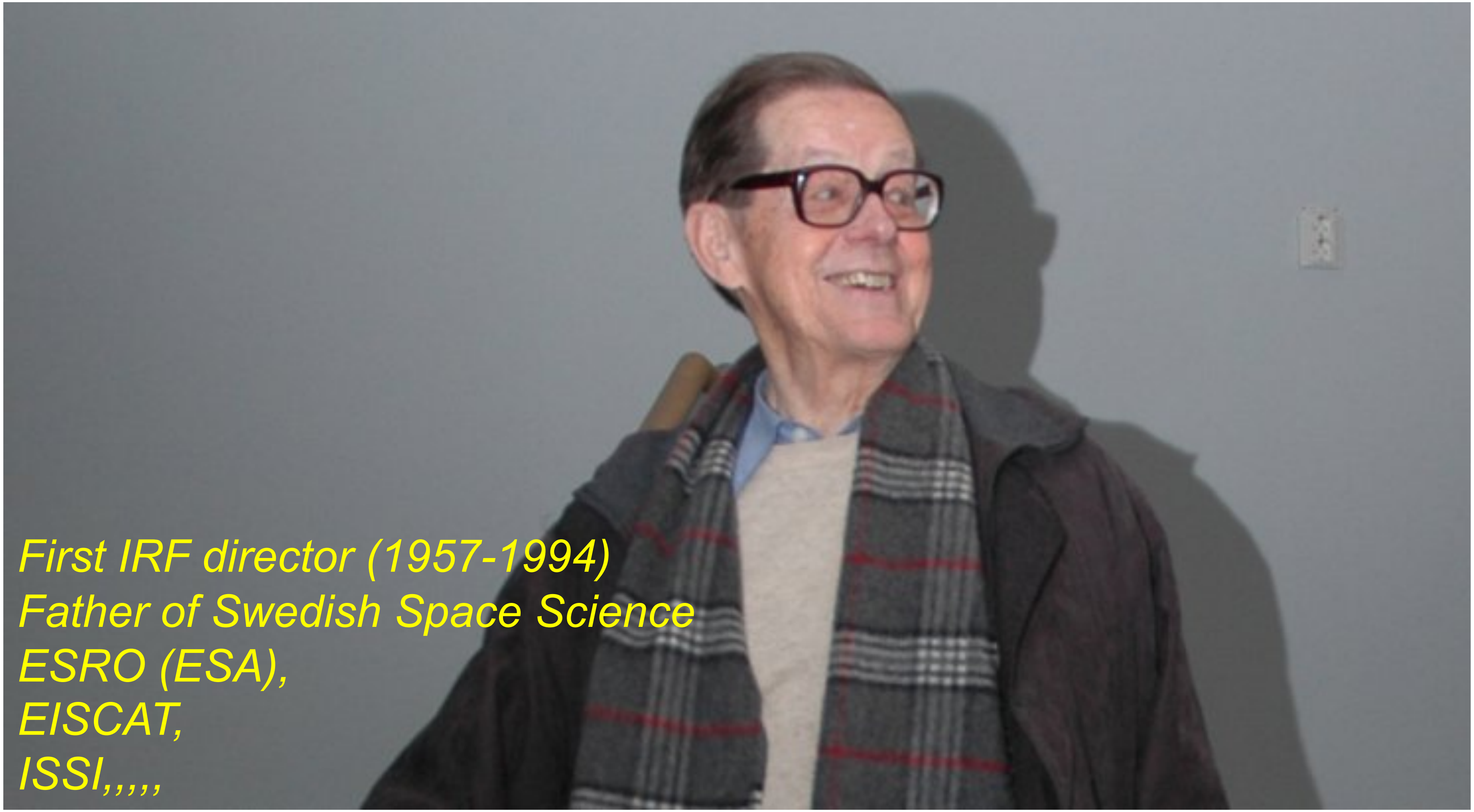
Photography encouraged

I dedicate this talk to

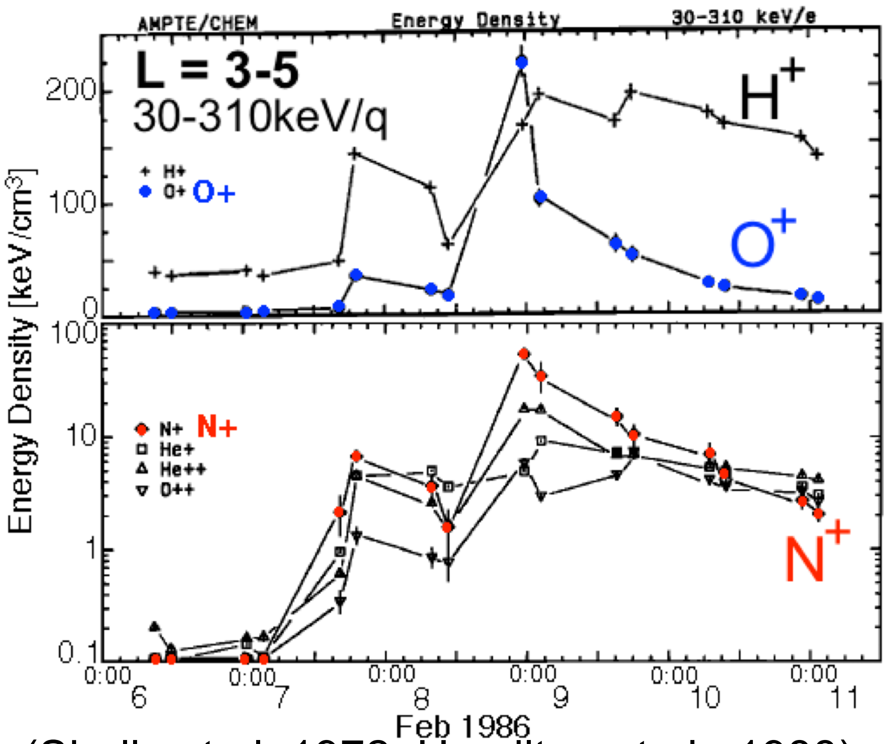
Prof. Emer. Bengt Hultqvist (1927-2019)

First recipient of Julius Bartels Medal (1996)



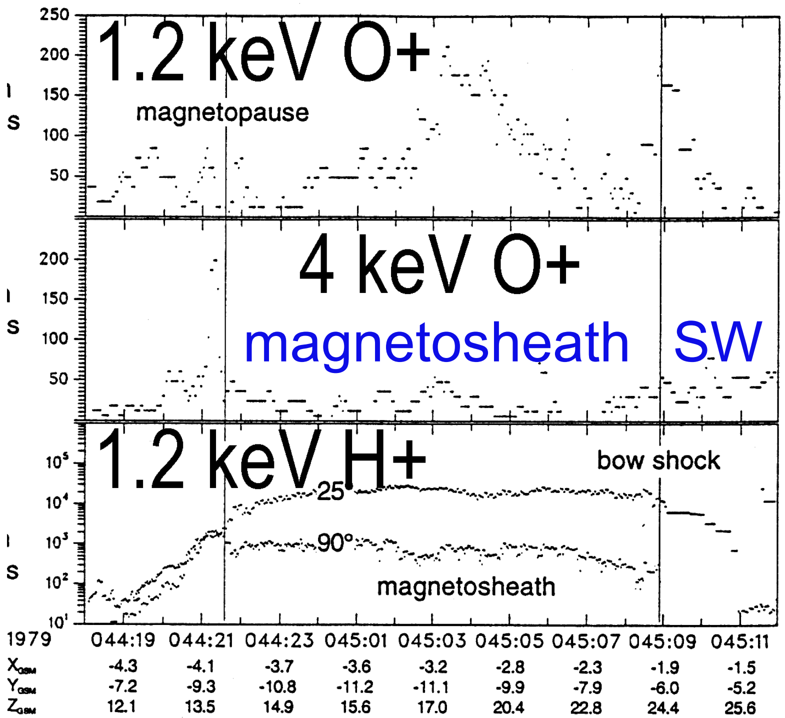
Full of ionospheric ions in space (1970's)

O⁺ and N⁺ (magnetosphere)



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

O⁺ (solar wind)



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

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Outline

1. **Three types of outflow** and primary destinations: cold (re-filling, supersonic), superthermal, & hot

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**

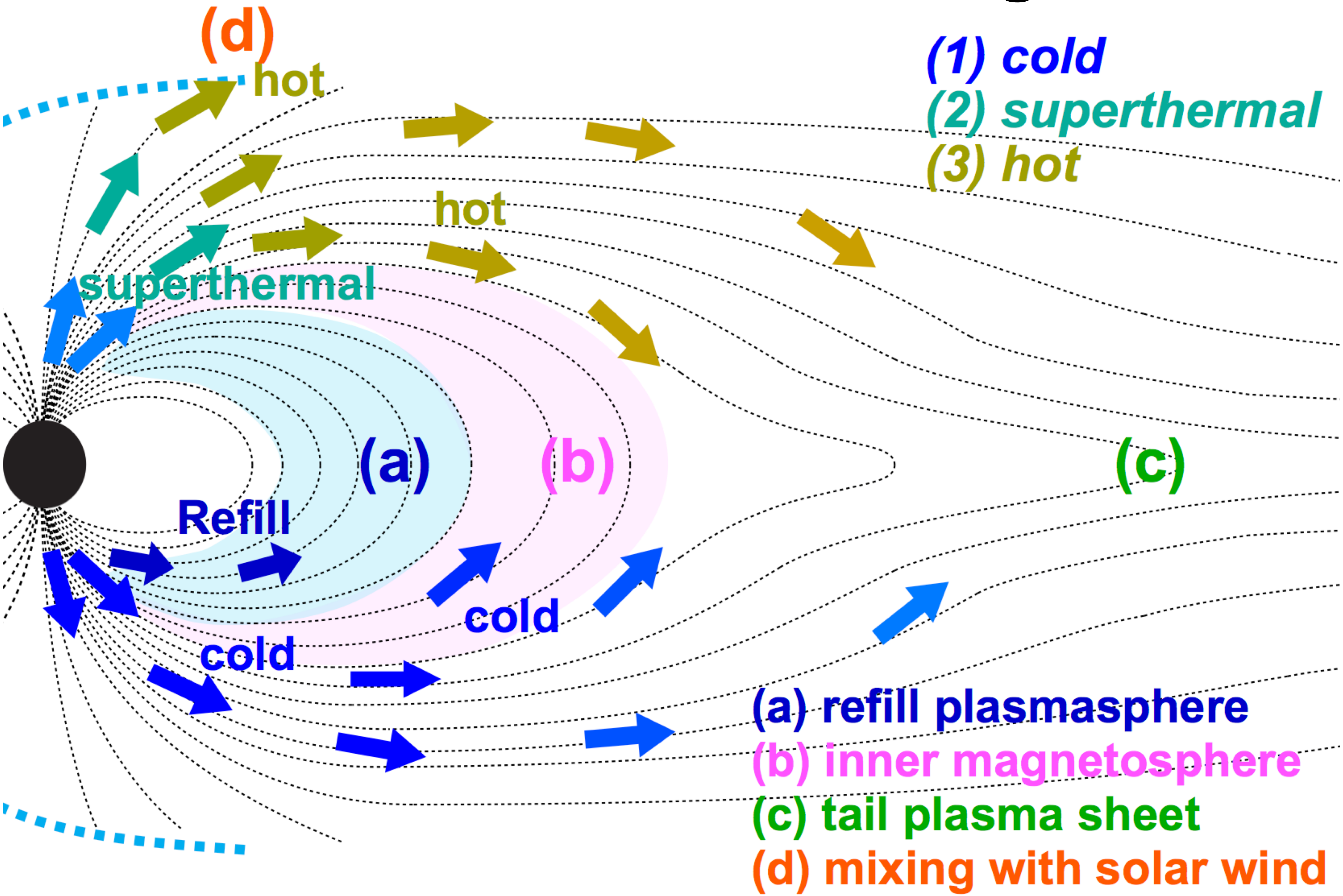
3. Consequence of **ion escape** (under-estimated effects):
- **local energy conversion** through mass-loading
- **Evolution of the Earth** in geological scale (then cannot ignore **neutral**)

Sorry no time for

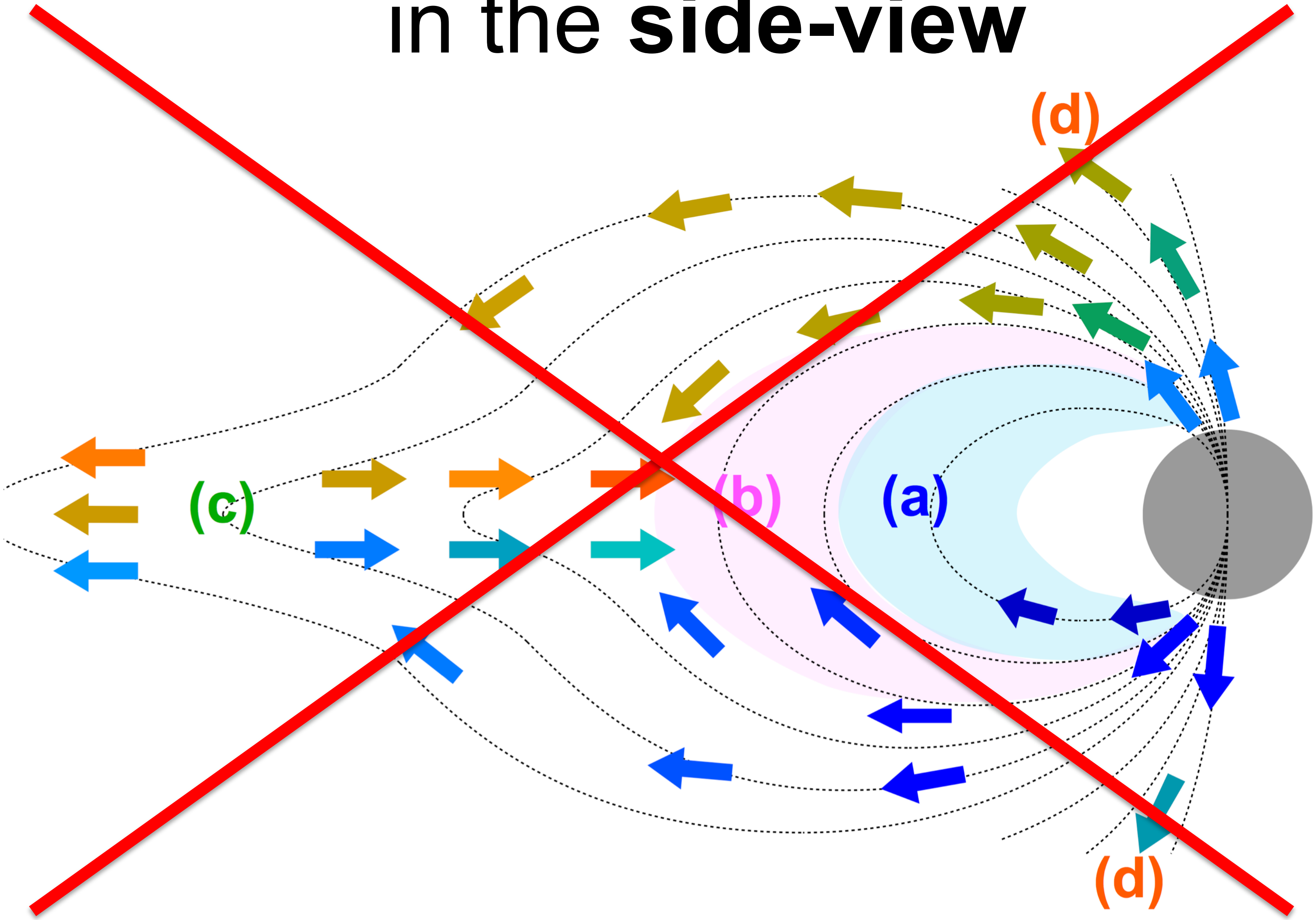
4. Other **active roles** of planetary ions: Martian bow shock, various SW injection

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

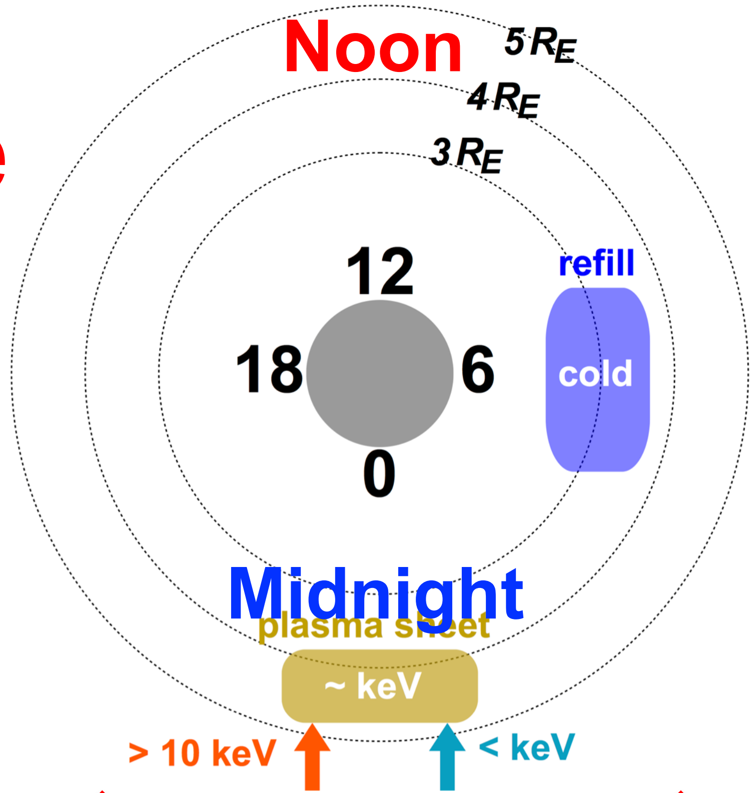
Destinations of outflowing ions

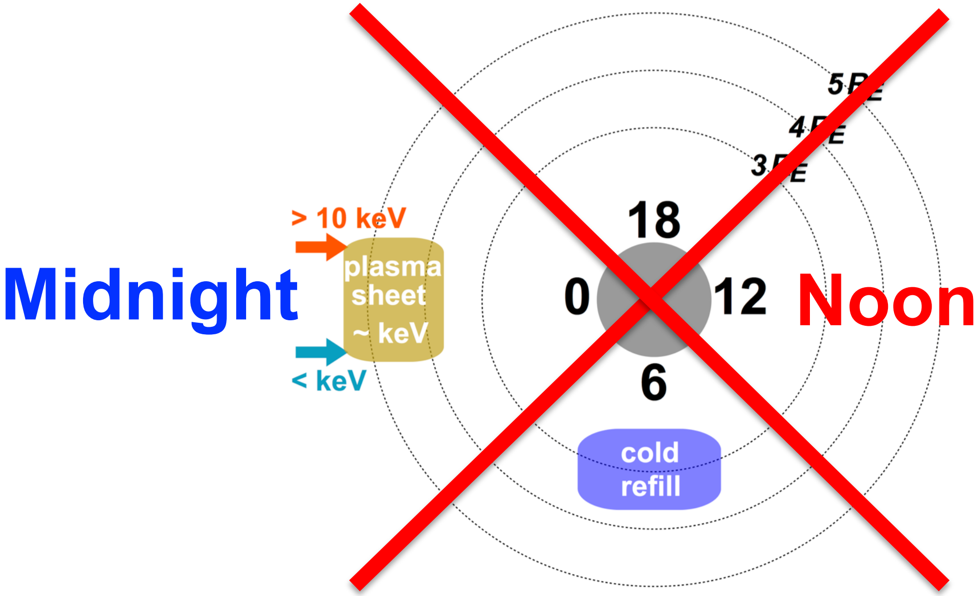


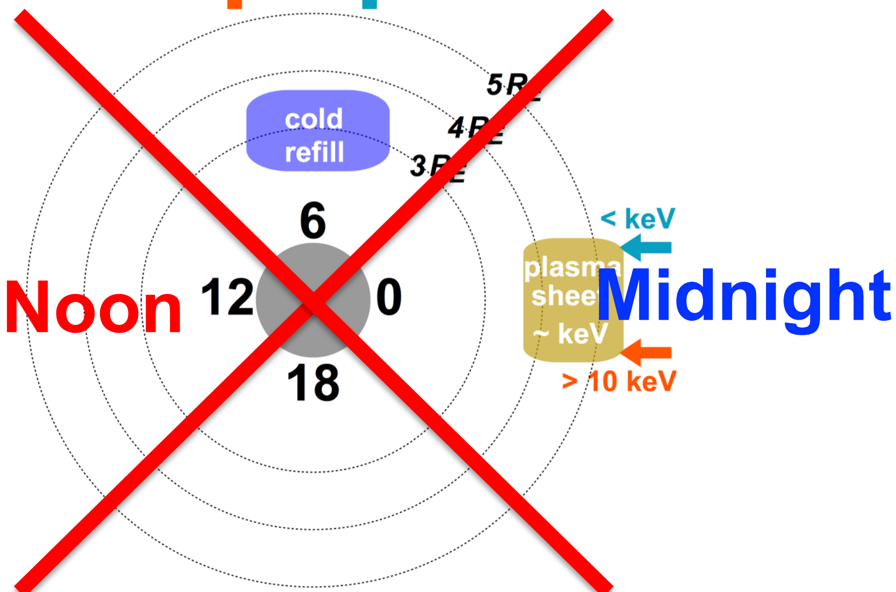
In this presentation, Sun is left in the **side-view**



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







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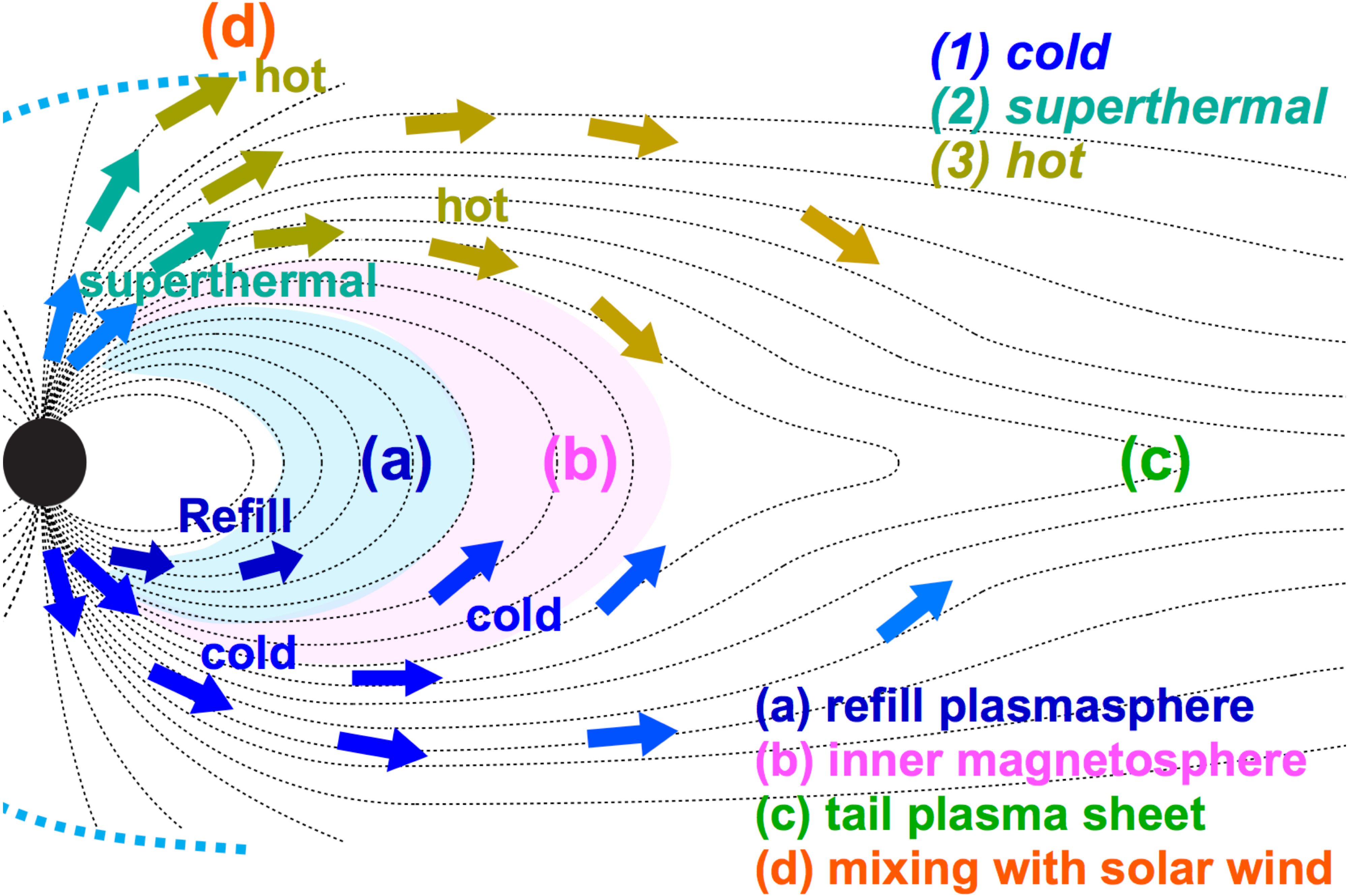
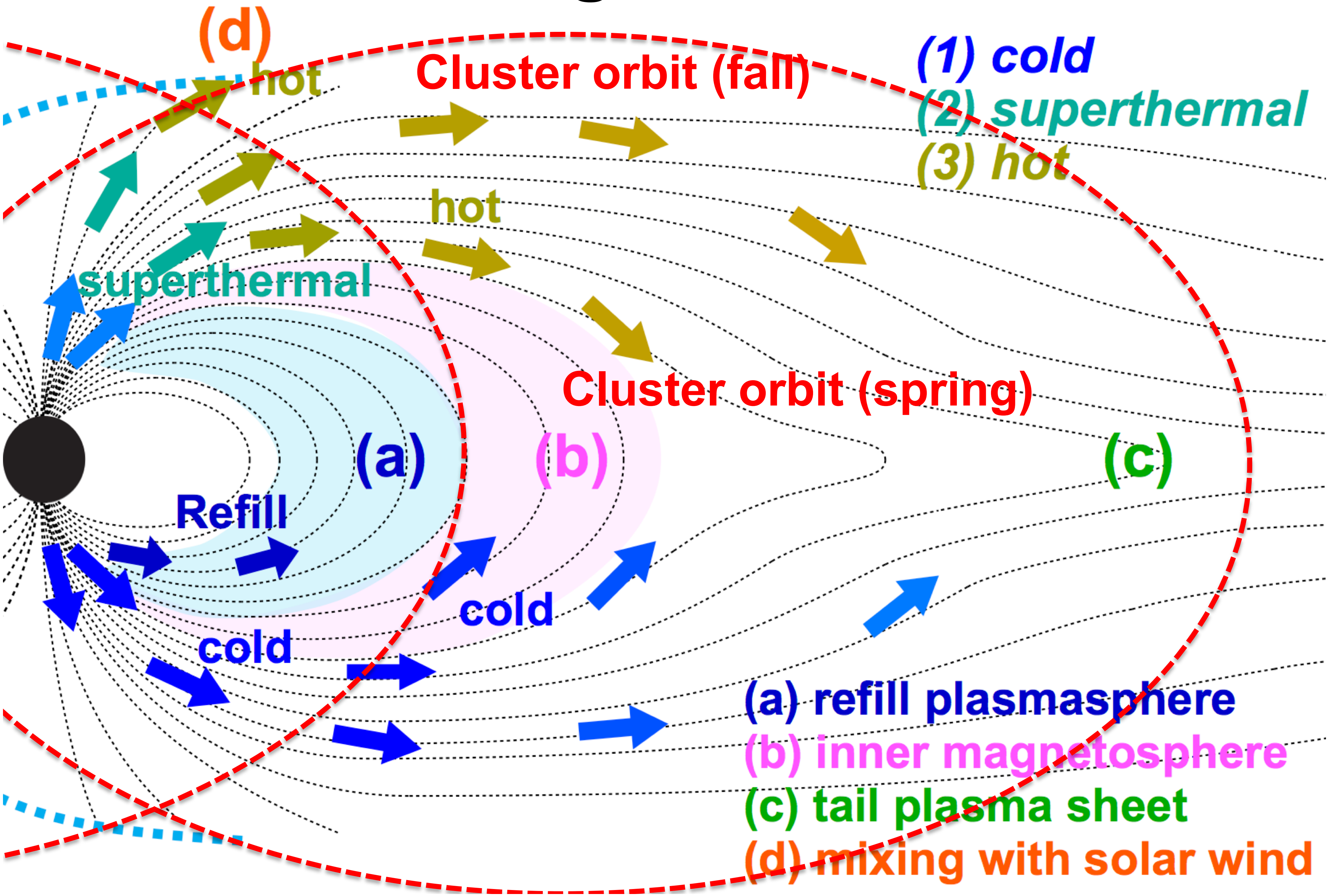
Destinations of outflowing ions



Advantage of Cluster

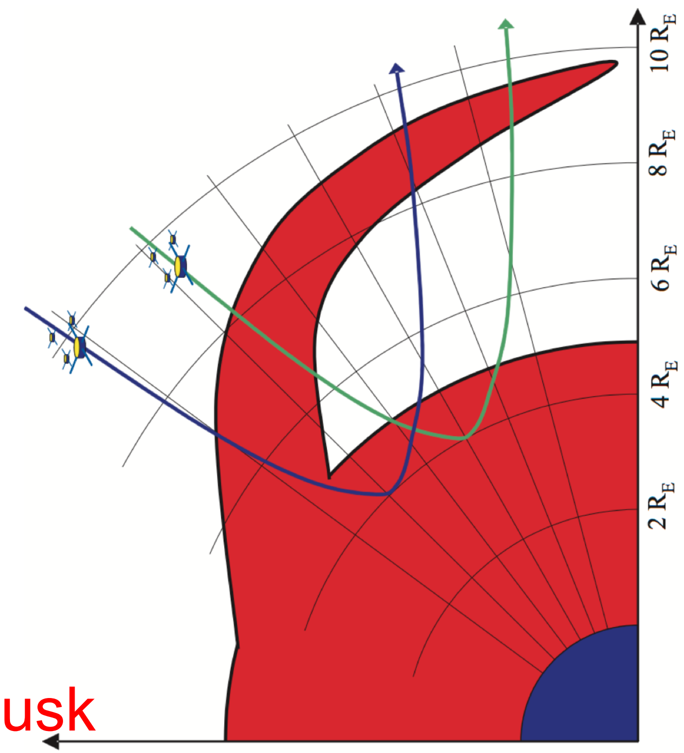


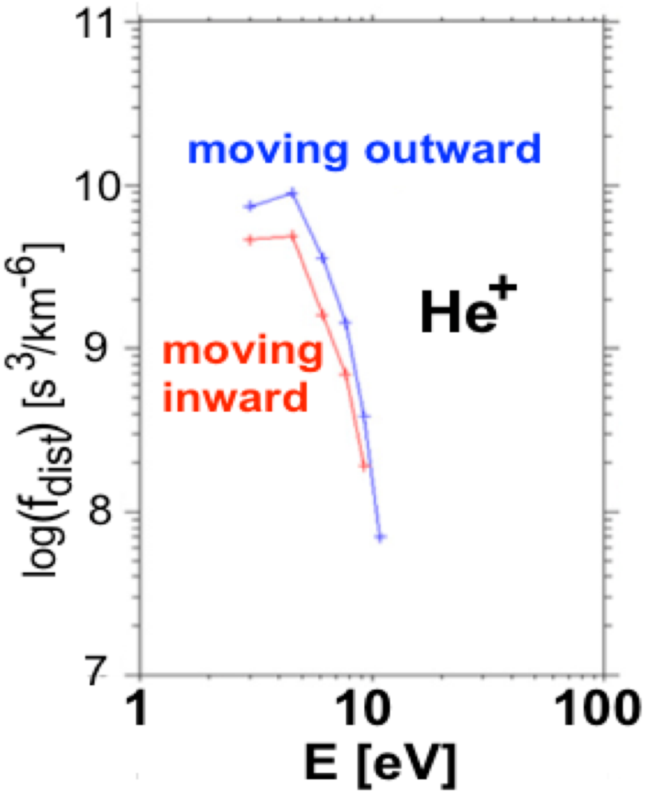
Three types of ion outflow (Earth)

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

(i) **plume** is formed & **detached** (ii) outward **wind** (≈ 1.4 km/s)

(Darrouzet et al., 2008)





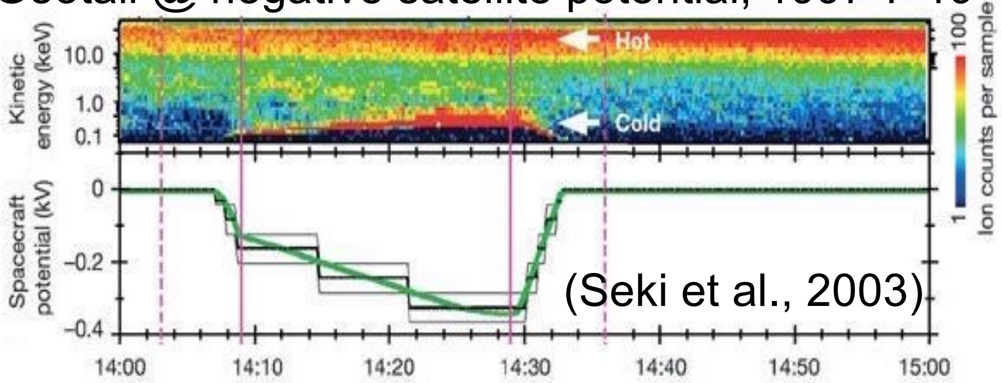
H^+ loss rate ~ 10^{27} s^{-1}, but short time & **$O^+/H^+ \le 0.01$**

H^+ loss rate ~ 5 x 10^{26} s^{-1}, but **$O^+/H^+ \le 0.01$**

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

Massive flow (cold H+ ~ **10^{26} s^{-1}**) to the plasma sheet (**cold dense** component) ≠ plasmasphere

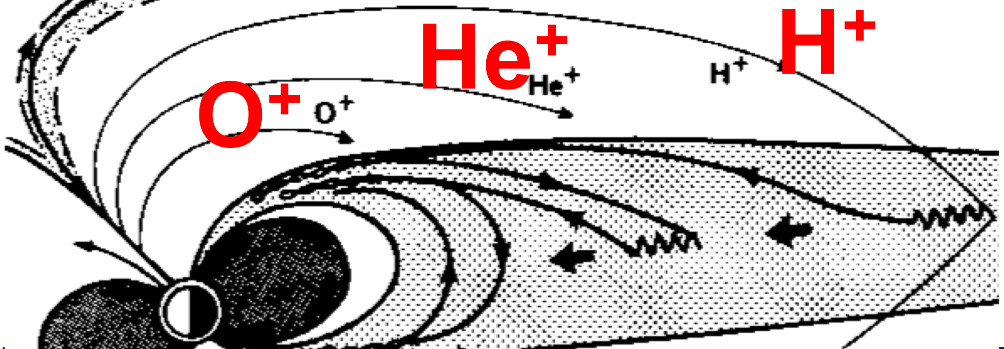
Geotail @ negative satellite potential, 1997-7-19



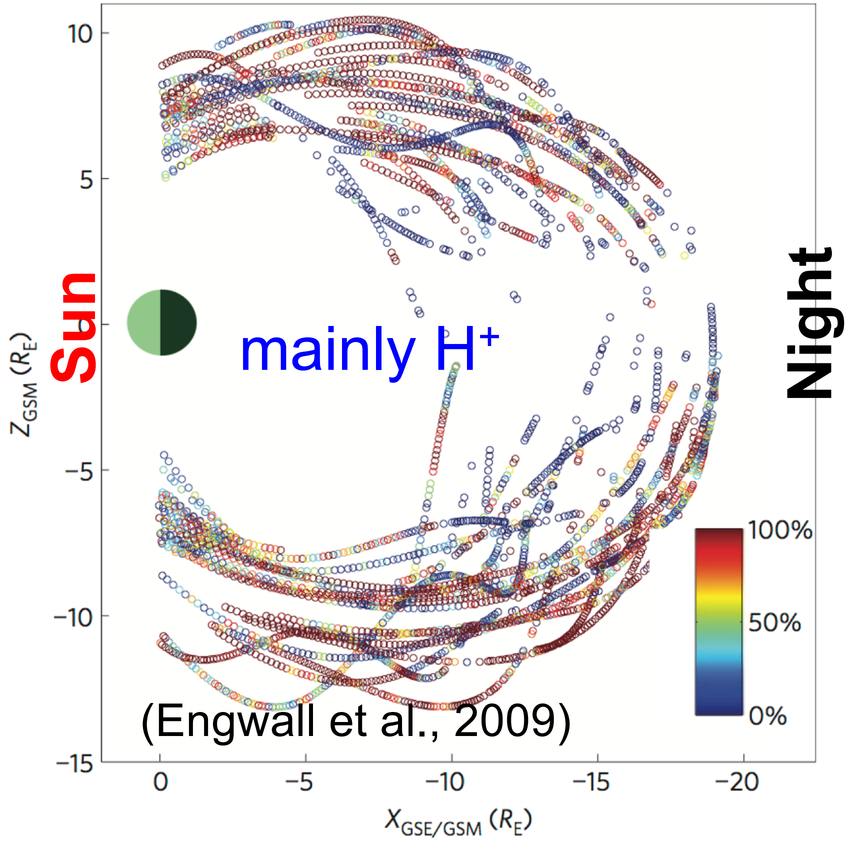
(Seki et al., 2003)

"**cold**" view of destination

(Chappel et al. 1987)



Cluster EFW (3 months data)



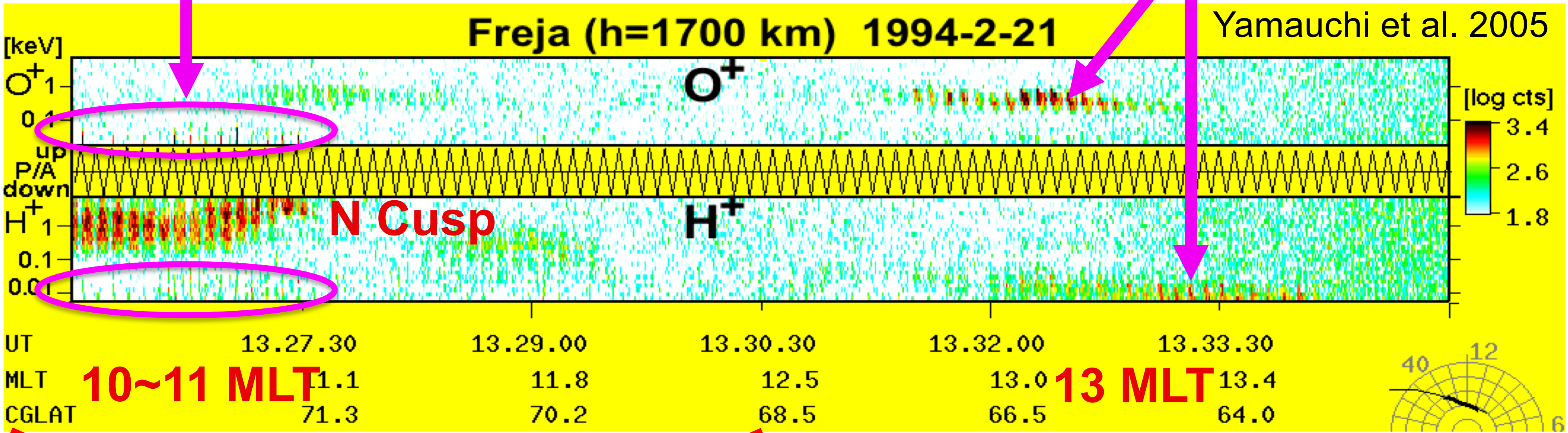
(Engwall et al., 2009)

However, O^+ is very little

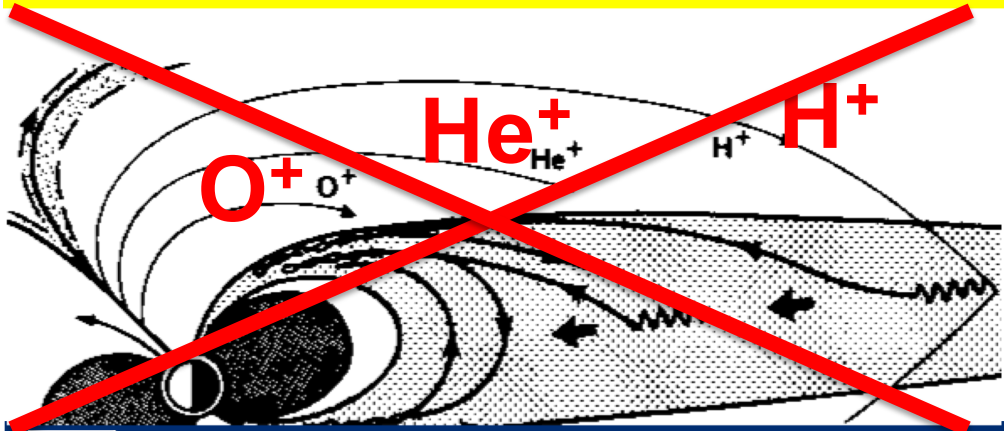
(2) Superthermal H^+ & O^+

They are observed only at low altitude (Freja, FAST, Akebono)
⇒ further **accelerated to become (3) hot**

outflow from the cusp **IMF By ~ –60 nT** **Injection** from southern cusp



(Yamauchi et al., 2005)



E_O/E_H = 15-20 ⇒ $V_O \sim V_H$

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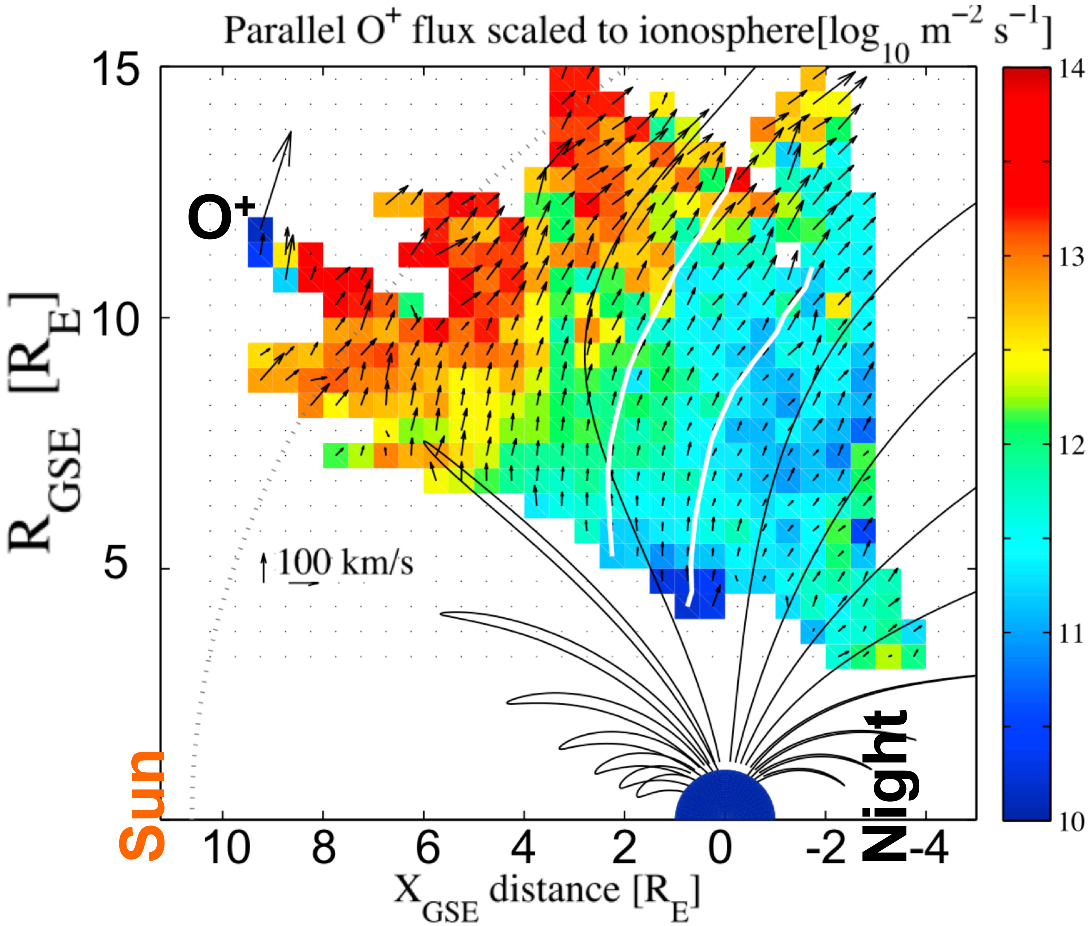
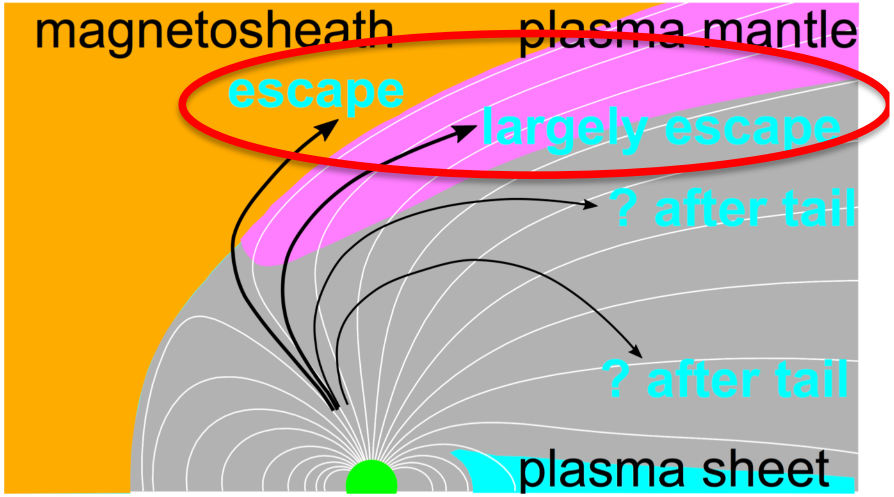
Kiruna, Sweden

(3) Hot H^+ & O^+

Cluster statistics @2001-2005

(Nilsson et al., 2012)





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

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

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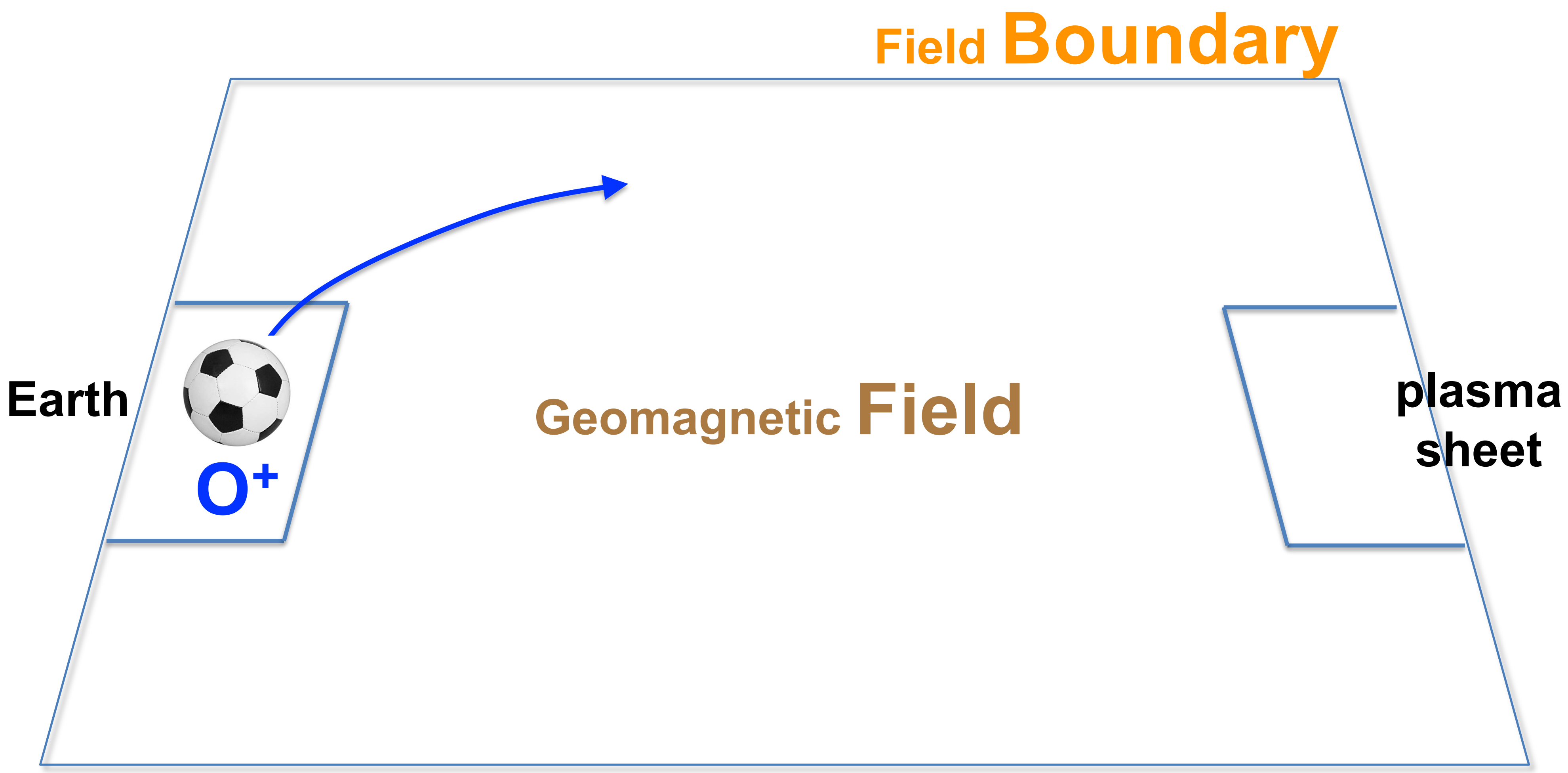

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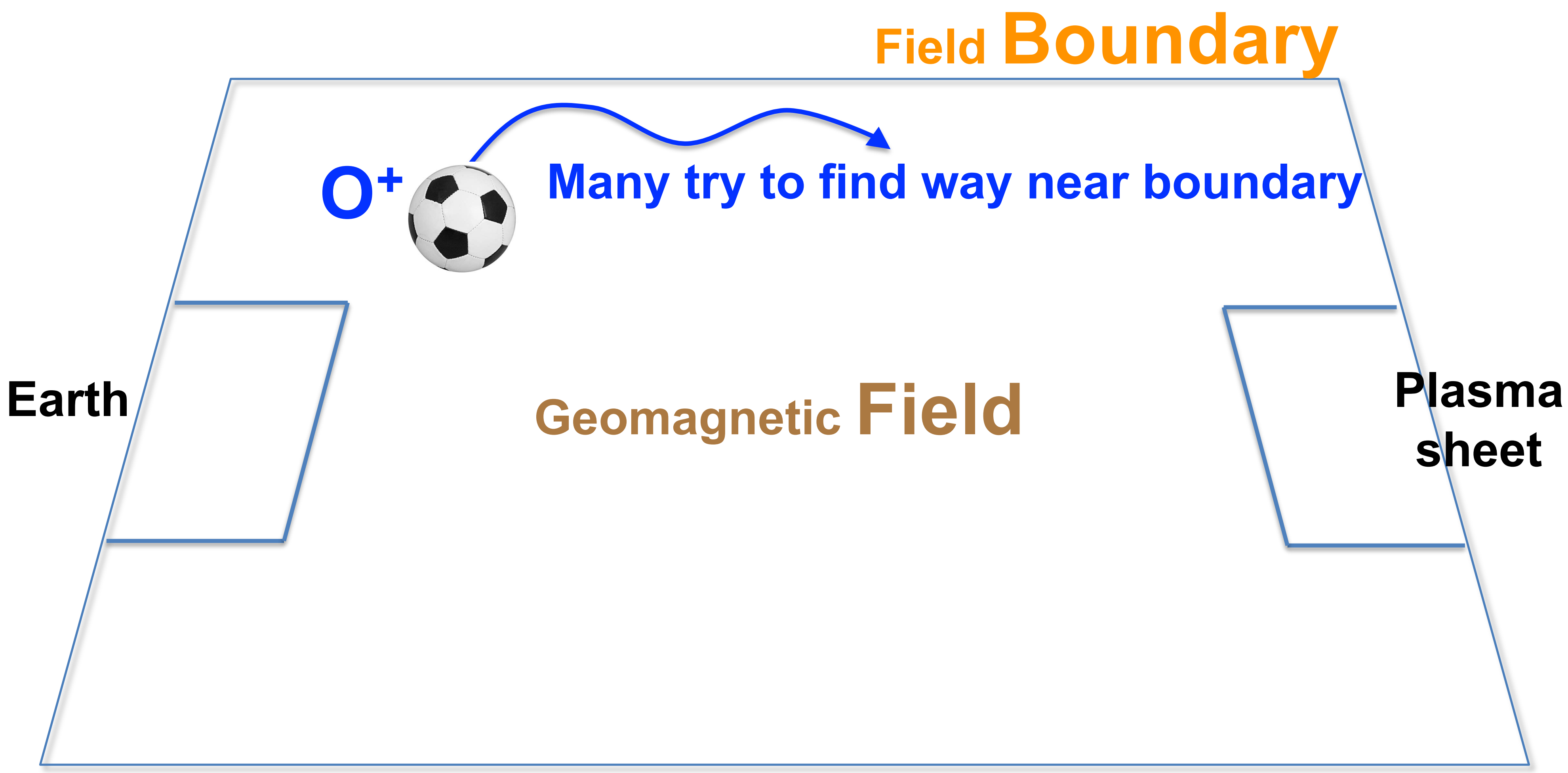
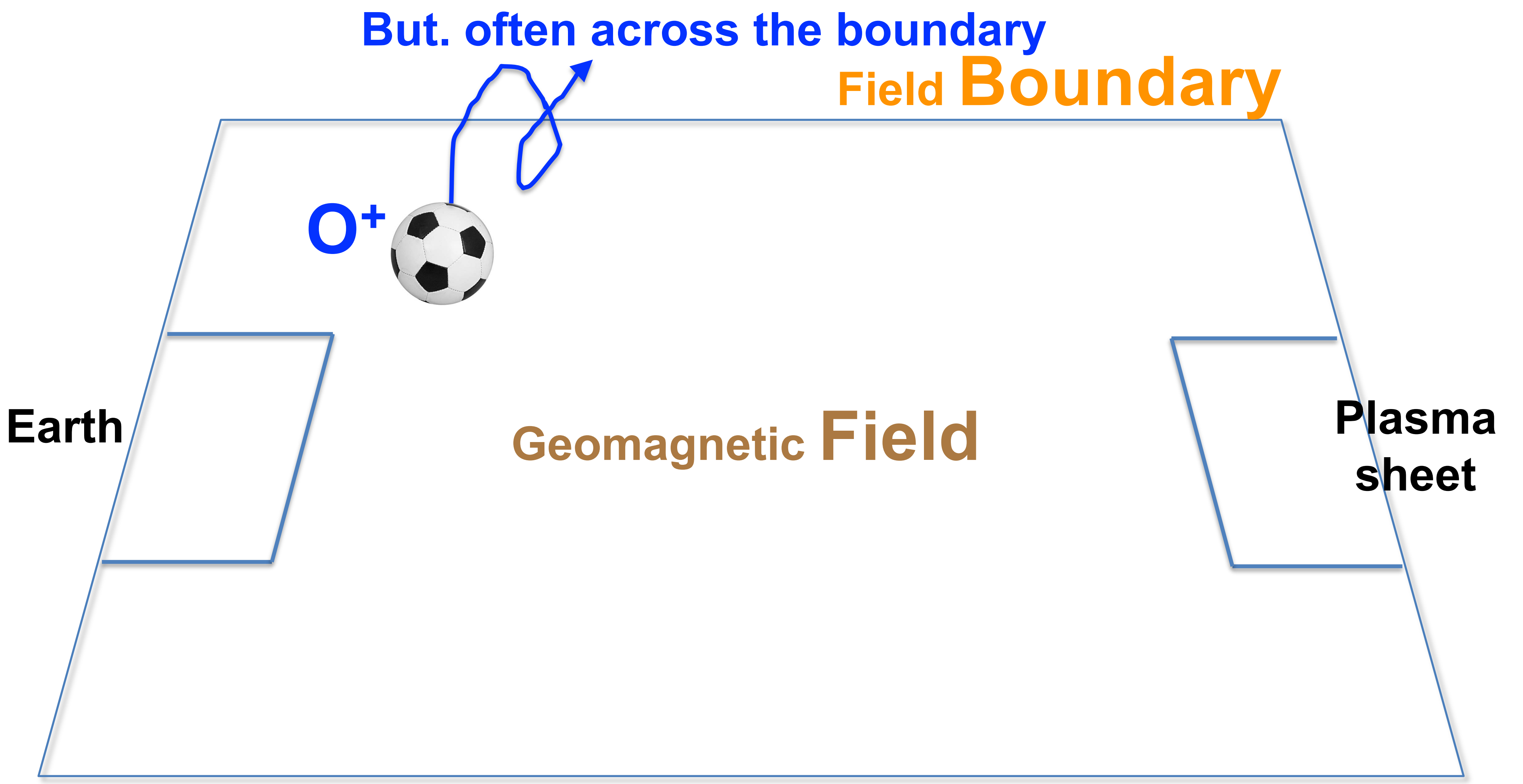
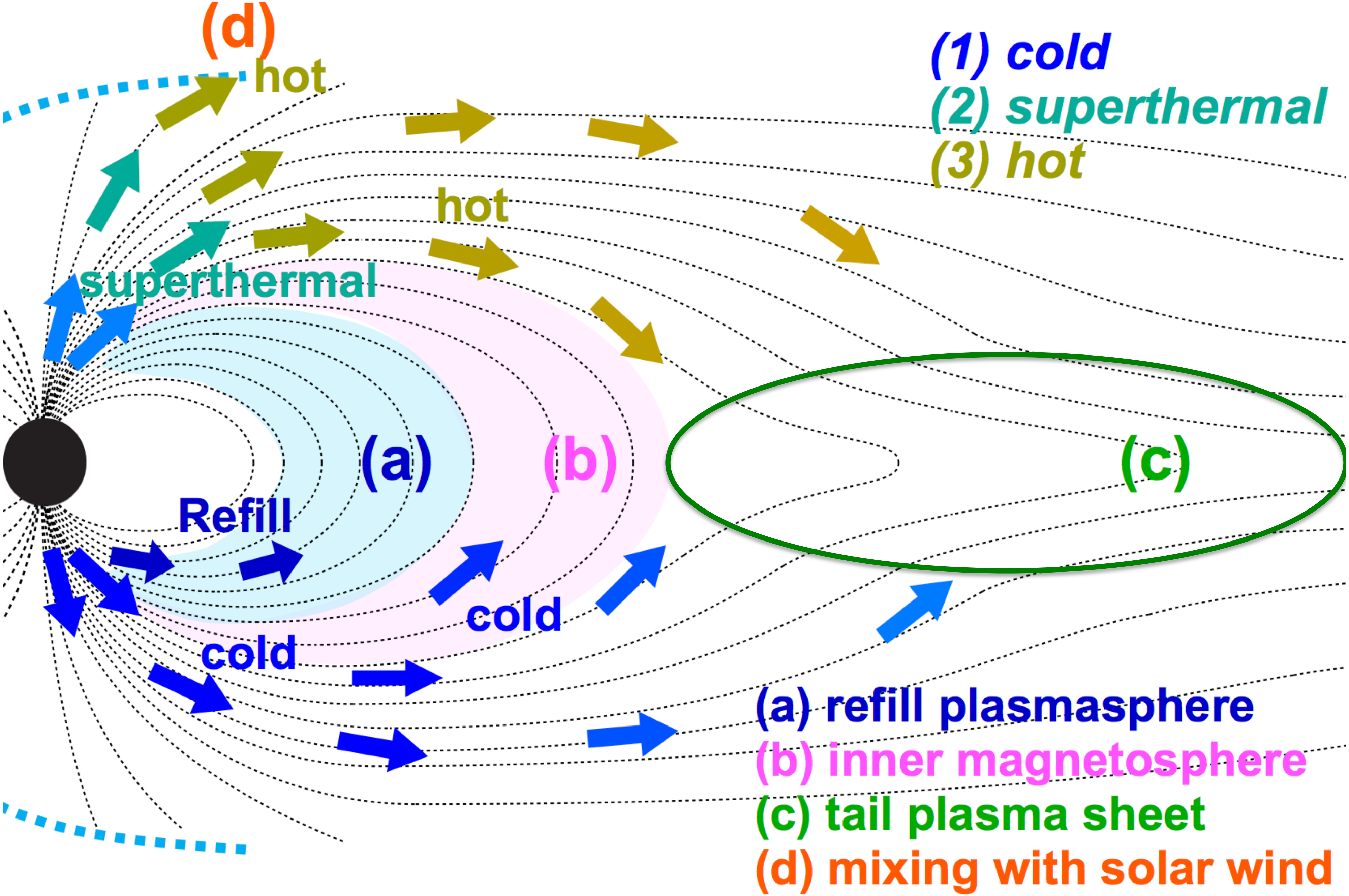

Field Boundary
O^+
Many try to find way near boundary
Earth
Geomagnetic Field
Plasma
sheet


But. often across the boundary
Field Boundary
O+
Earth
Geomagnetic Field
Plasma sheet

Fate of ions in (c) the magnetotail



Fate of ions in the magnetotail

cold ions are also energized ⇒ Cluster/CIS can detect all

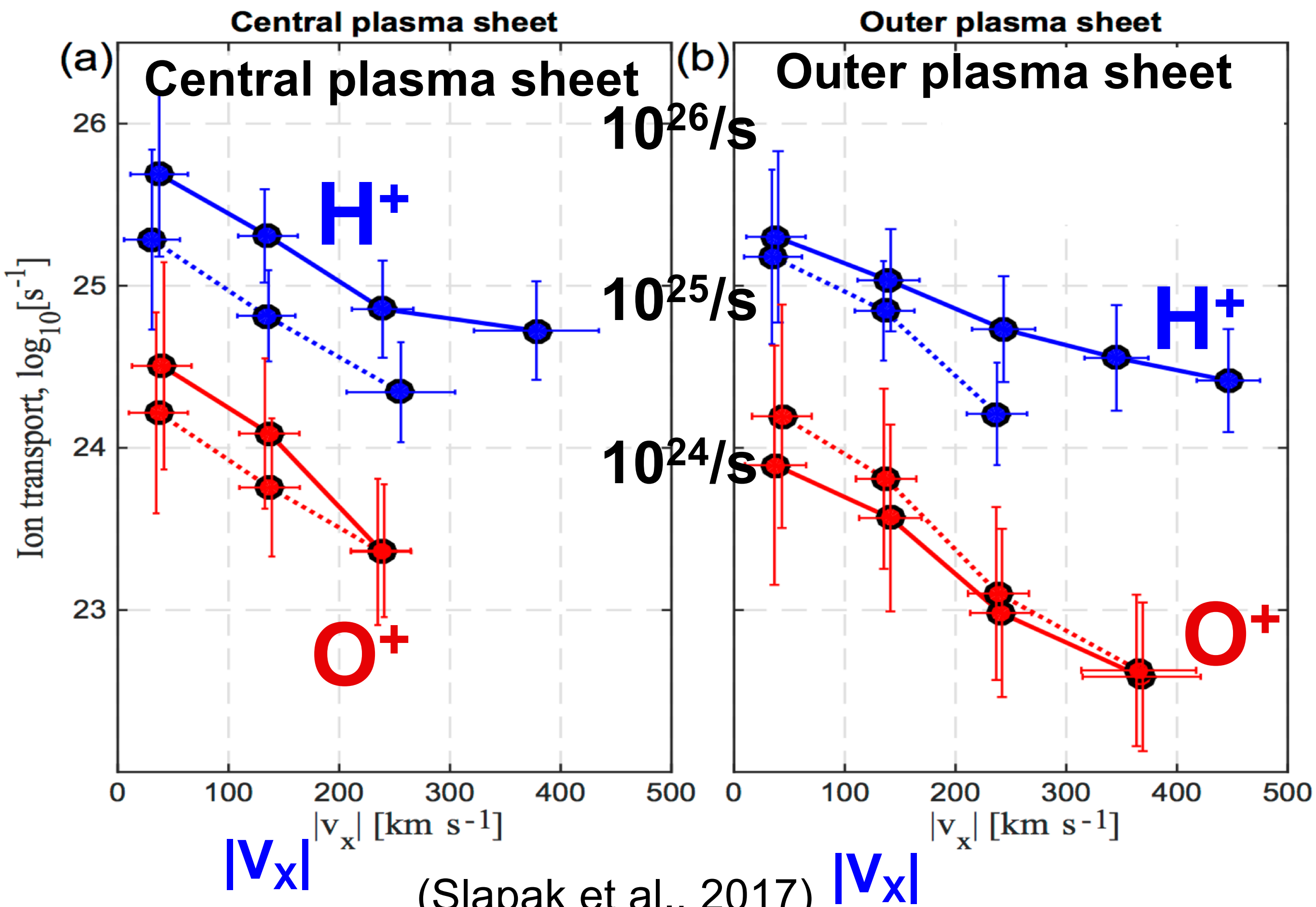
Cluster/CIS
(2001-2005)

Earthward O^+
~0.6×10^{25} s^{-1}

Tailward O^+
~0.5×10^{25} s^{-1}

= nearly half-half

⇒ Net Earthward
~ 10^{24} s^{-1}



(Slapak et al., 2017)

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

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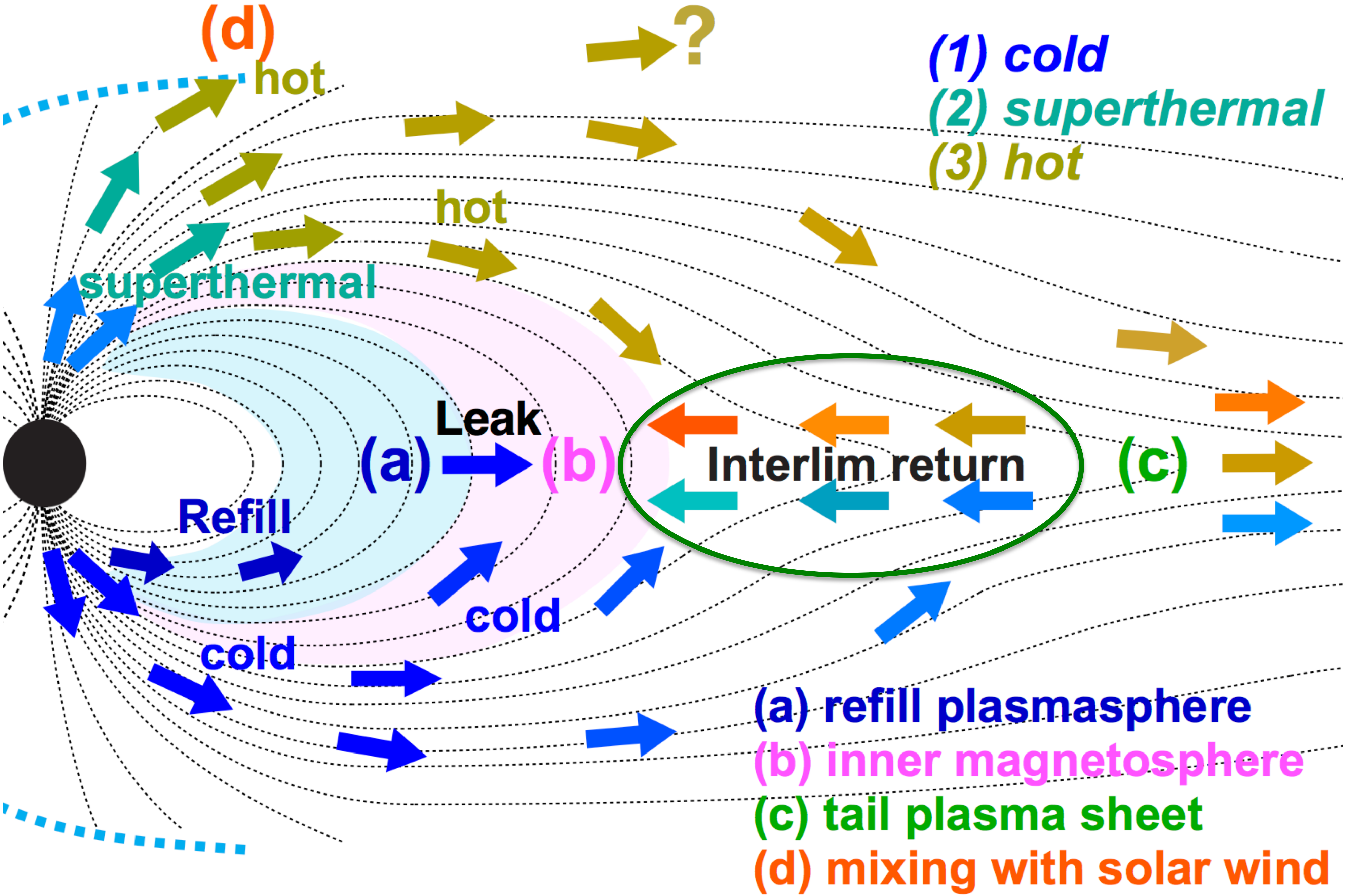
Fate of returned flow



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- expected/unexpected **mass-dependency**

3. Consequence of **ion escape** (under-estimated effects):

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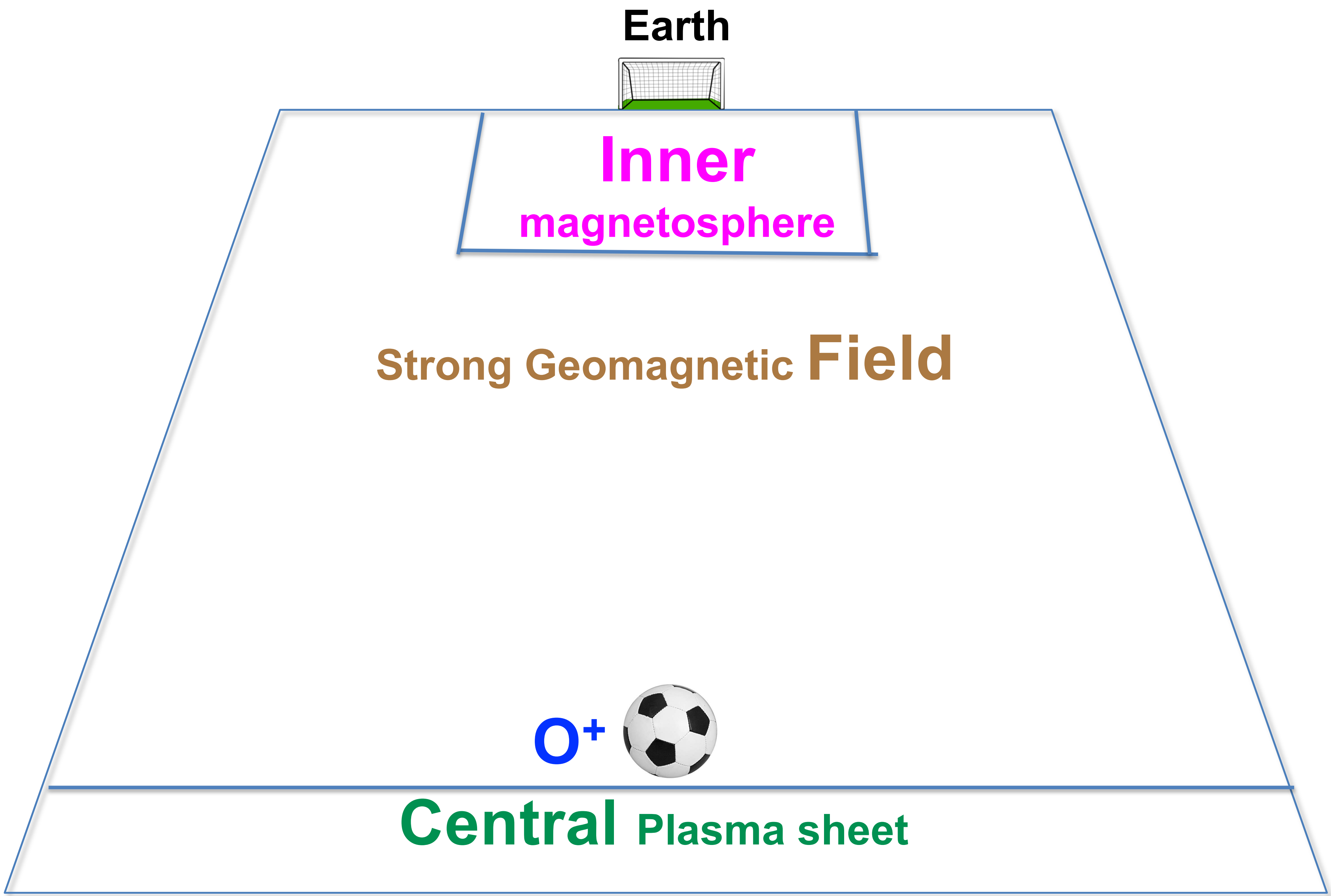
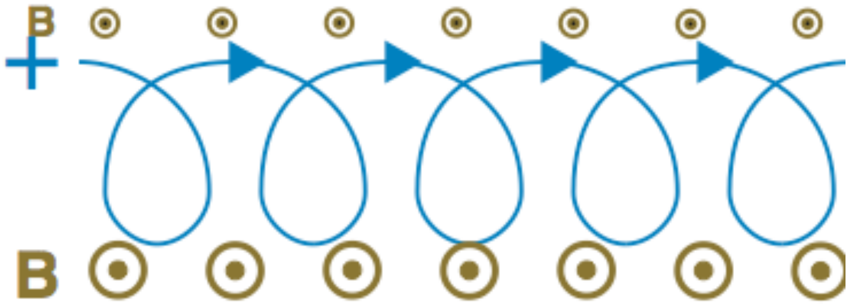
- **Evolution of the Earth** in geological scale (then cannot ignore **neutral**)


Earth
Inner
magnetosphere
Strong Geomagnetic Field
O+
Central Plasma sheet

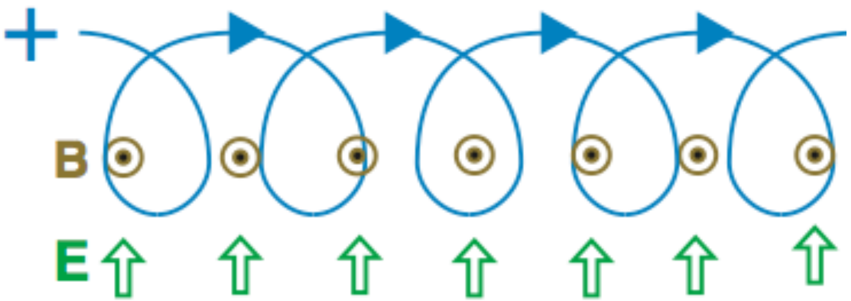
Ion drift under strong B-field



Magnetic drift (energy-dependent)

* gradient-B & curvature drift

⇒ dominant for > 10 keV



ExB drift (energy-independent)

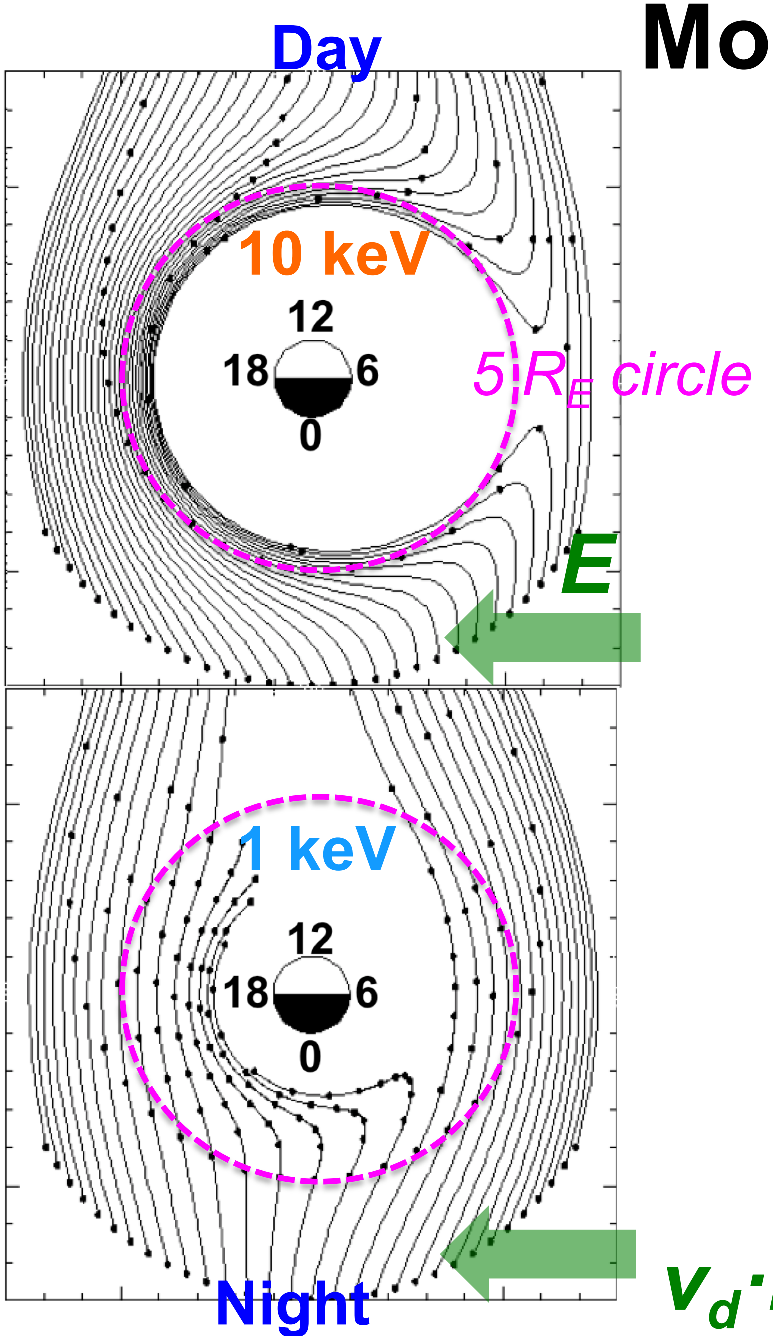
* co-rotation & external E-field

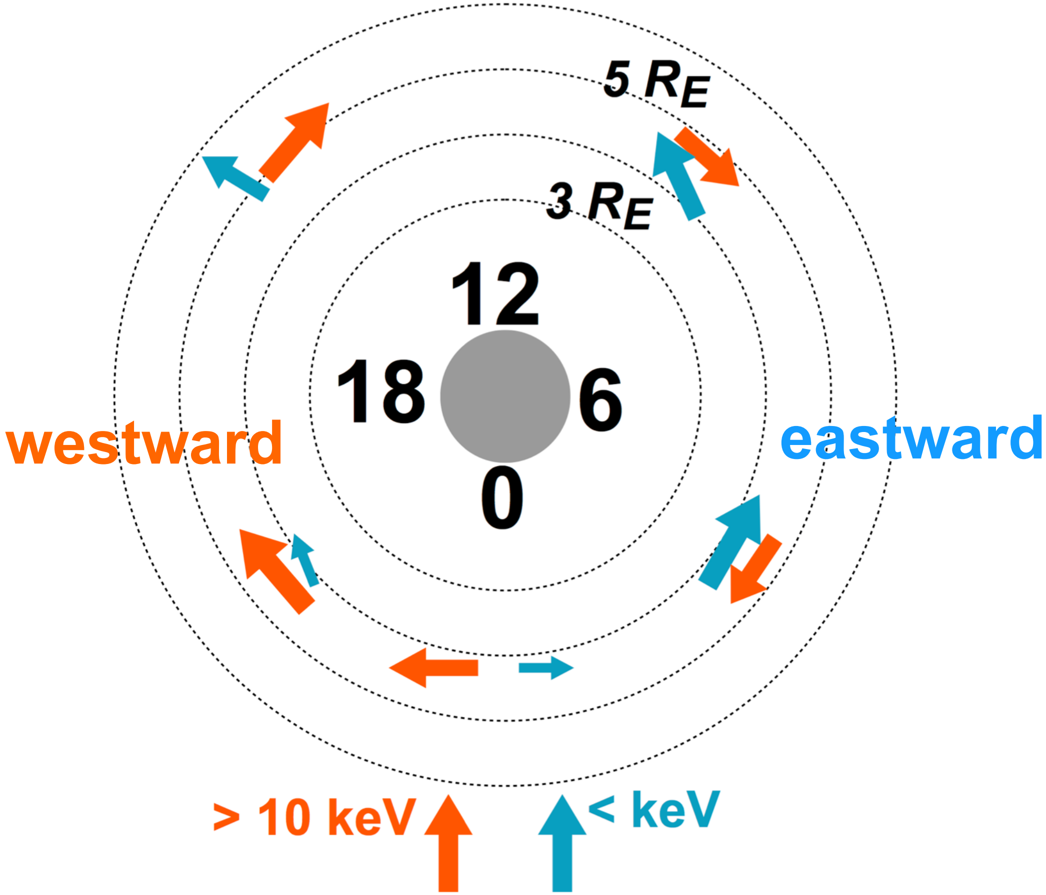
⇒ dominant for < 0.1 keV

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

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

Model Combining both drifts



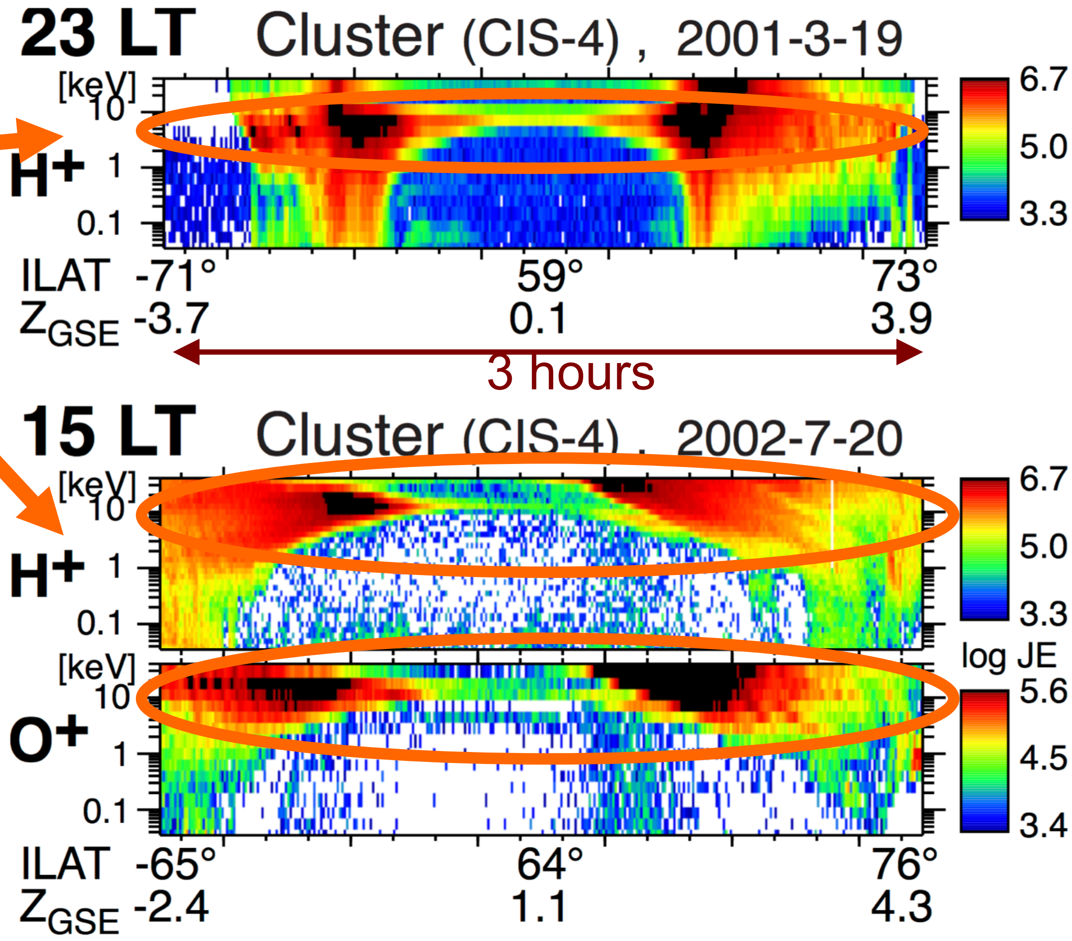


For all of H^+, He^+, and O^+
But, this is **just a model**

$v_d \cdot E > 0$ ⇒ 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)

Yes, mass-independent for given energy

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

Highly elliptic orbit ⇒ traverses inner magnetosphere quickly

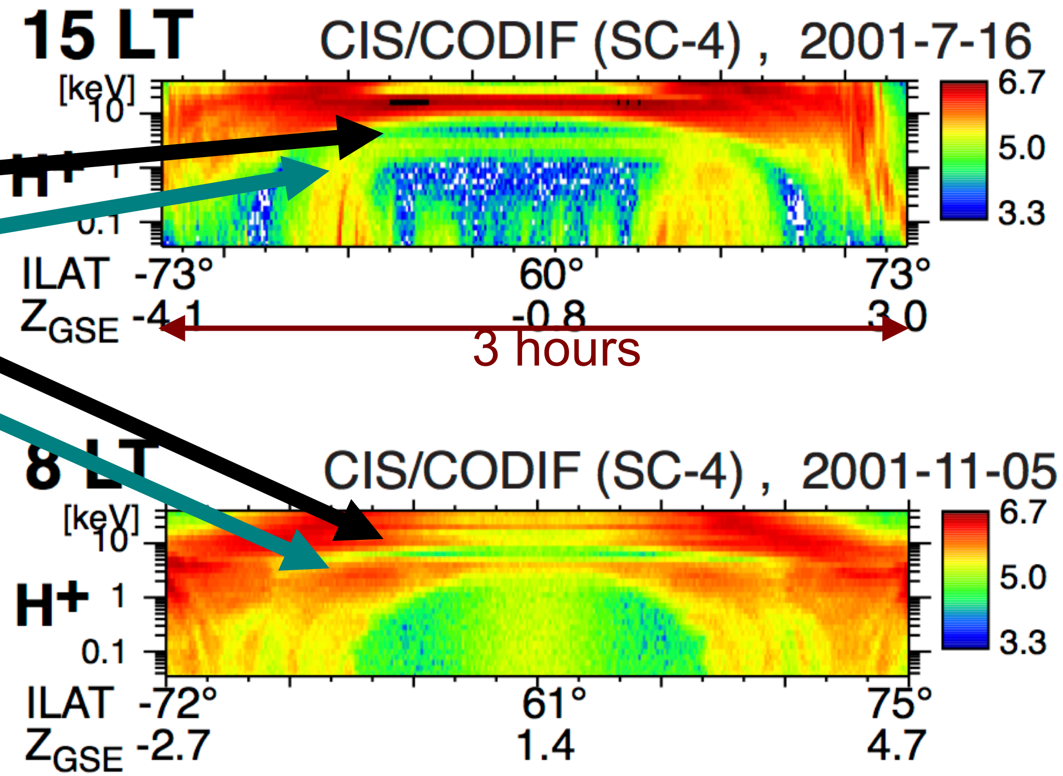
Old "textbook" view of returned ions 2

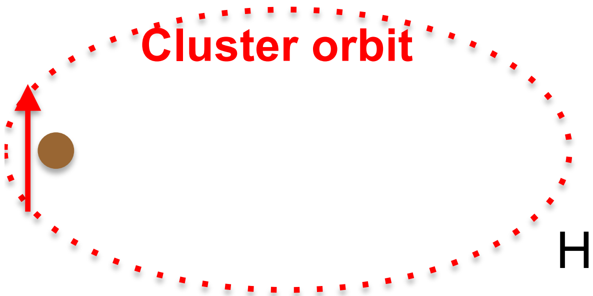
>10 keV (westward)

energy gap

< 5 keV (eastward)

Ion observation (Cluster)





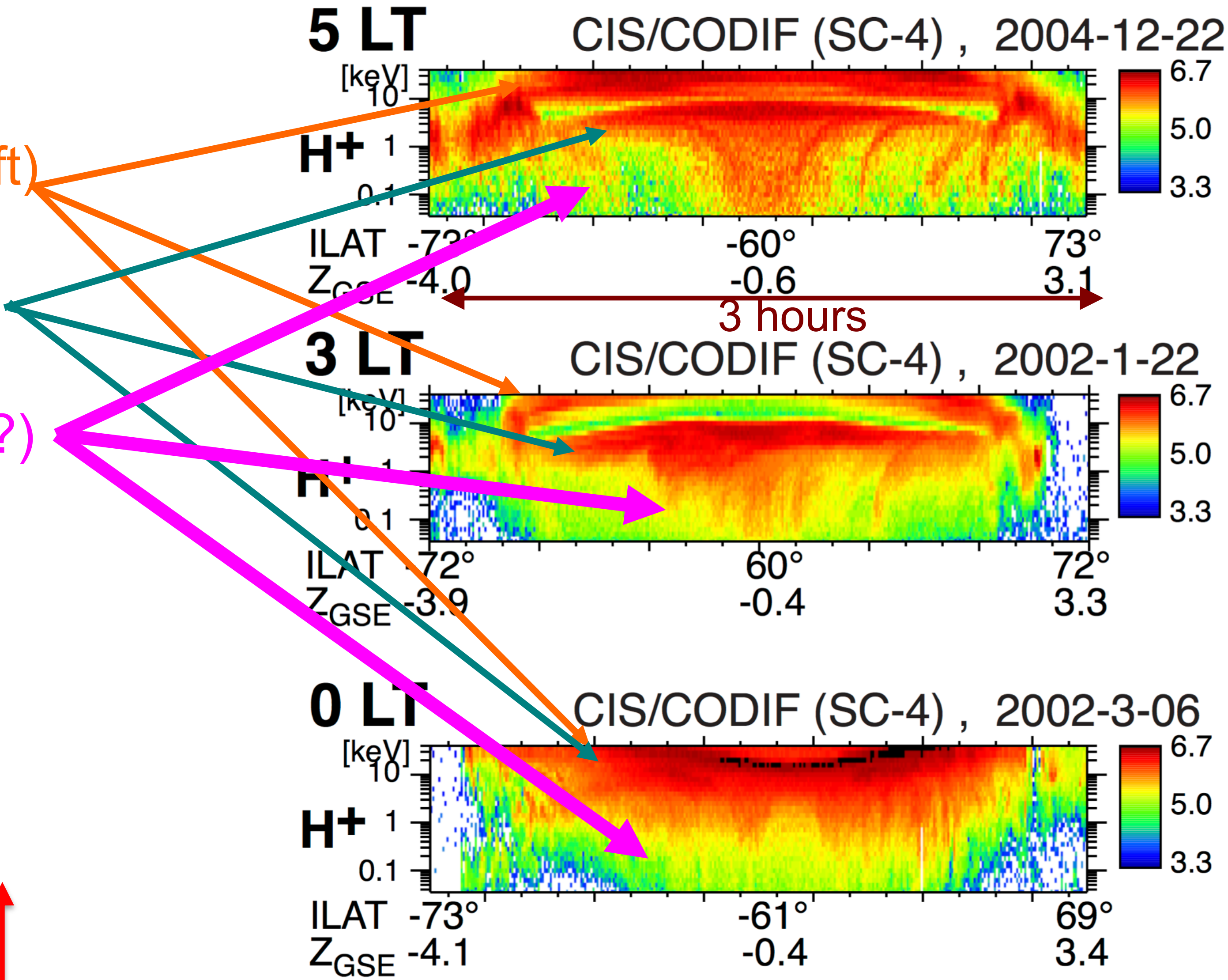
Highly elliptic orbit ⇒ traverses inner magnetosphere quickly

Reality: three basic populations

accelerated plasma sheet (westward drift)

plasma sheet (eastward ExB drift)

sub-keV stripes (???)



Highly elliptic orbit ⇒ traverses inner magnetosphere quickly

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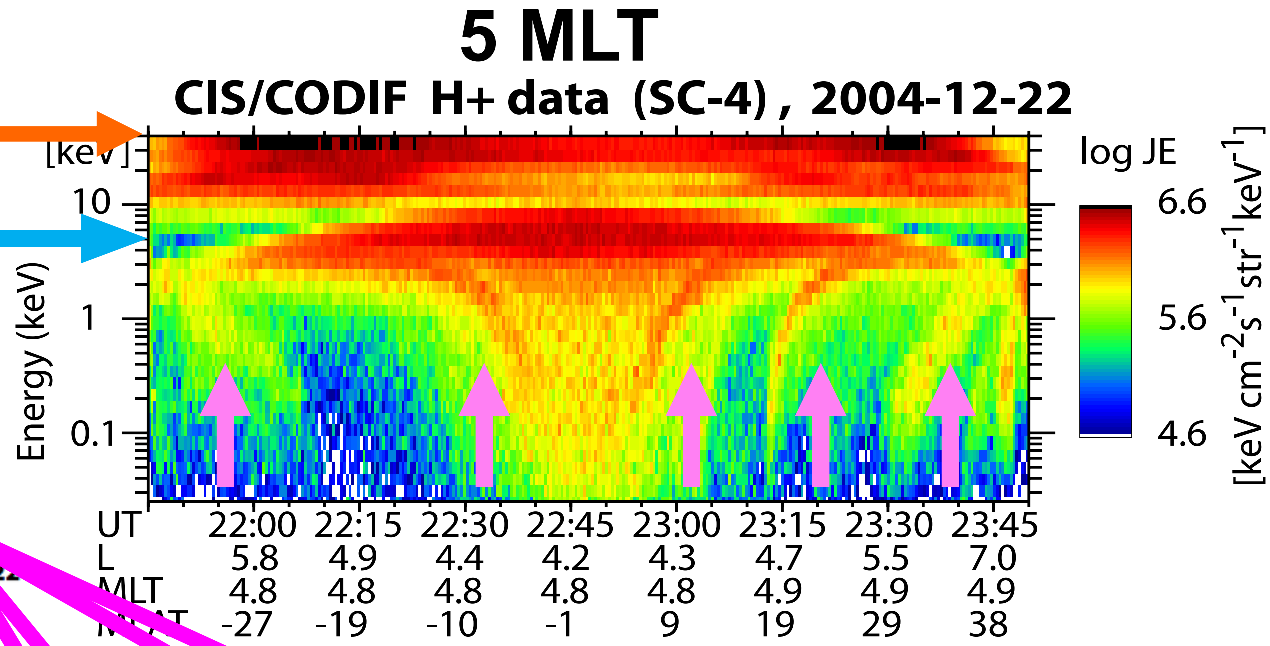
Kiruna, Sweden

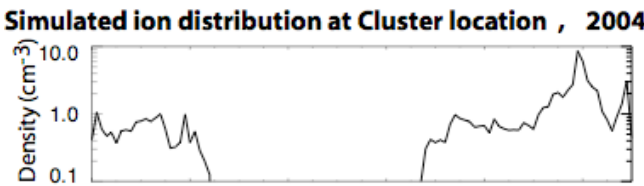
Three basic populations

accelerated plasma sheet (westward drift)

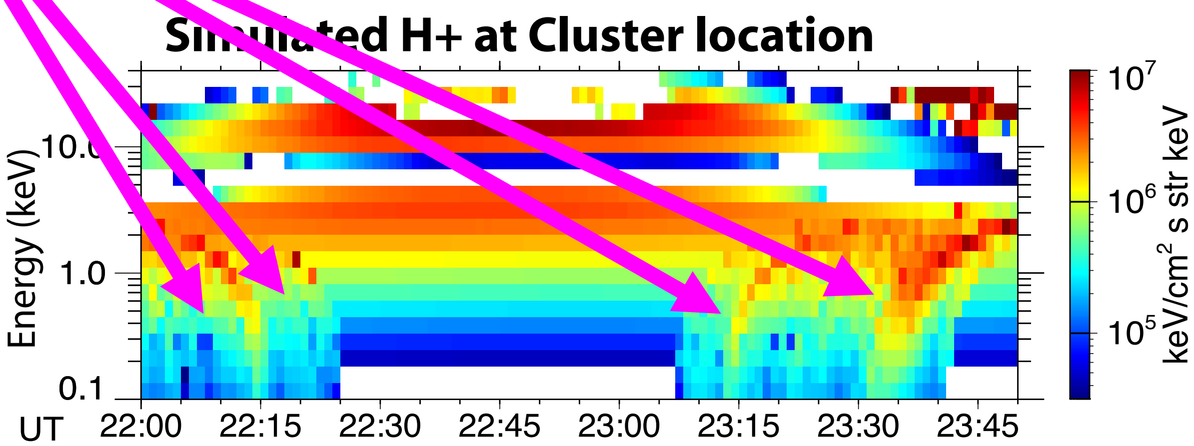
plasma sheet (eastward ExB drift)

superthermal (<50 eV) intermittent supply





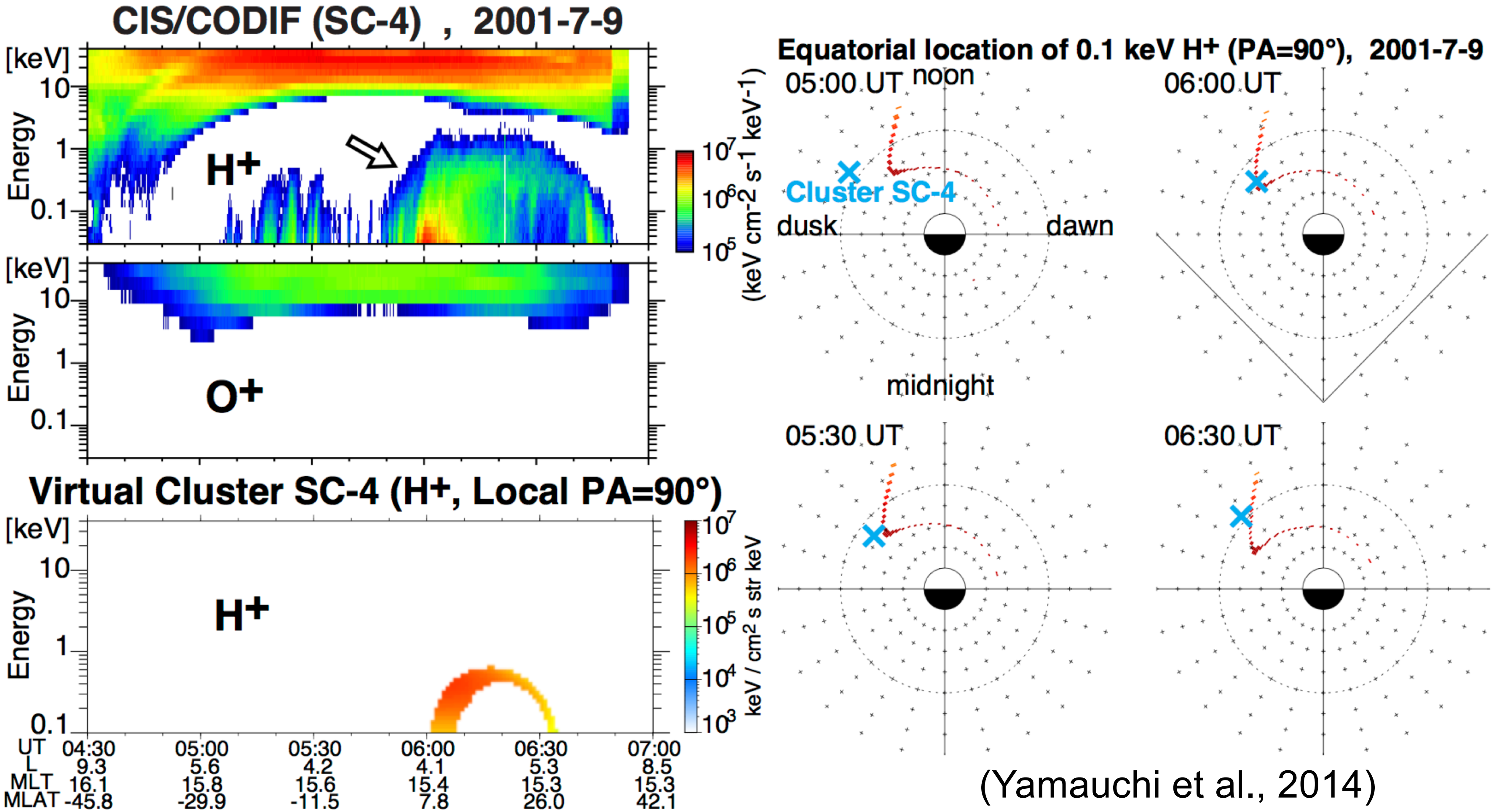
Simulation



(Yamauchi et al.,2009)

Can ExB drift really explain?

15 MLT



(Yamauchi et al., 2014)

(1) **Afternoon sector** ⇒ Yes

(2) **Sudden appearance** in 2 hours ⇒ Yes

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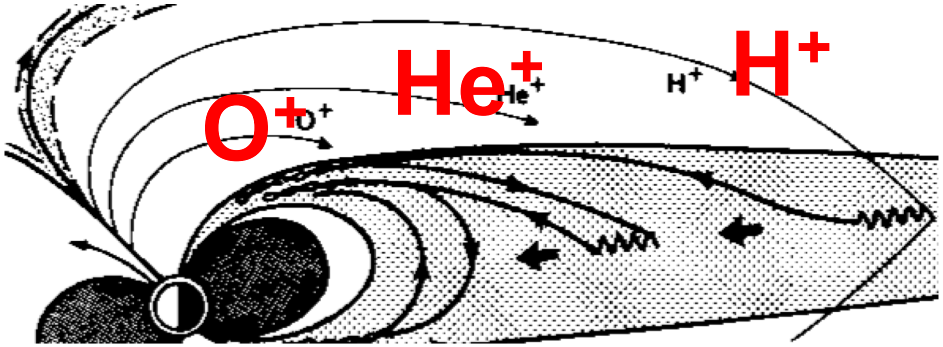
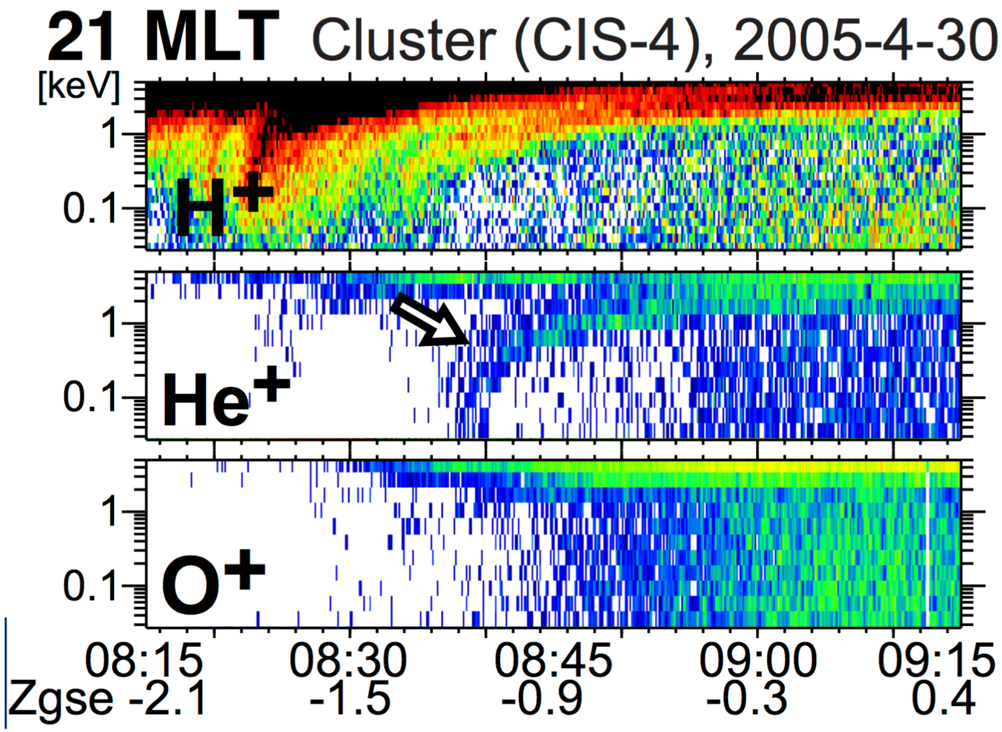
In fact, source locations are sometimes different between H^+ & He^+

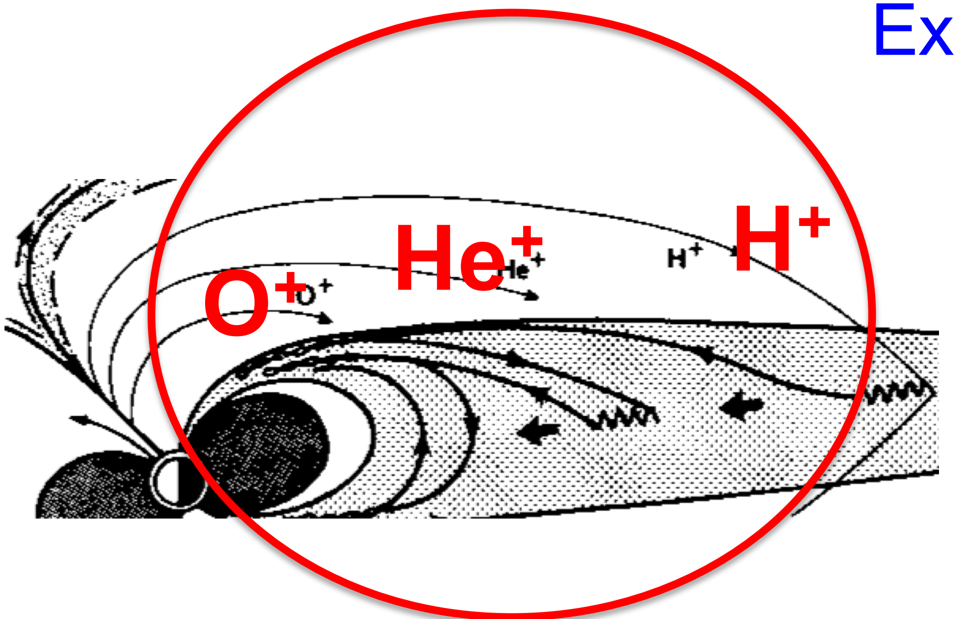


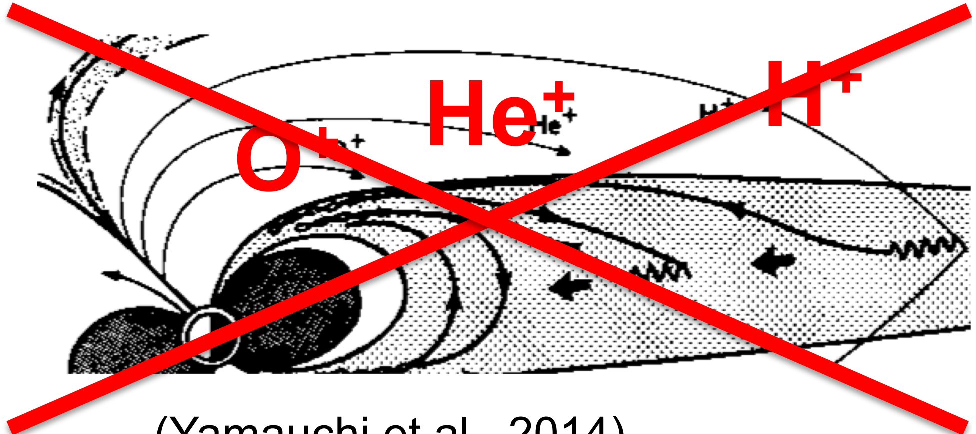


Well, real game is not that simple

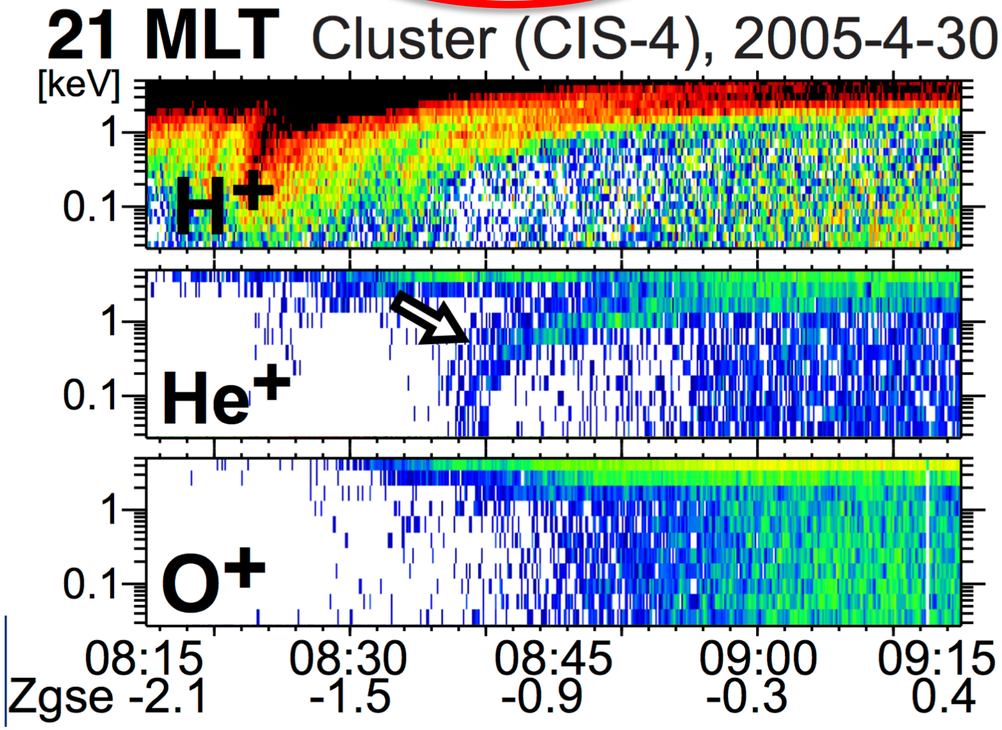
Ex. Out-of-phase between H^+ & O^+

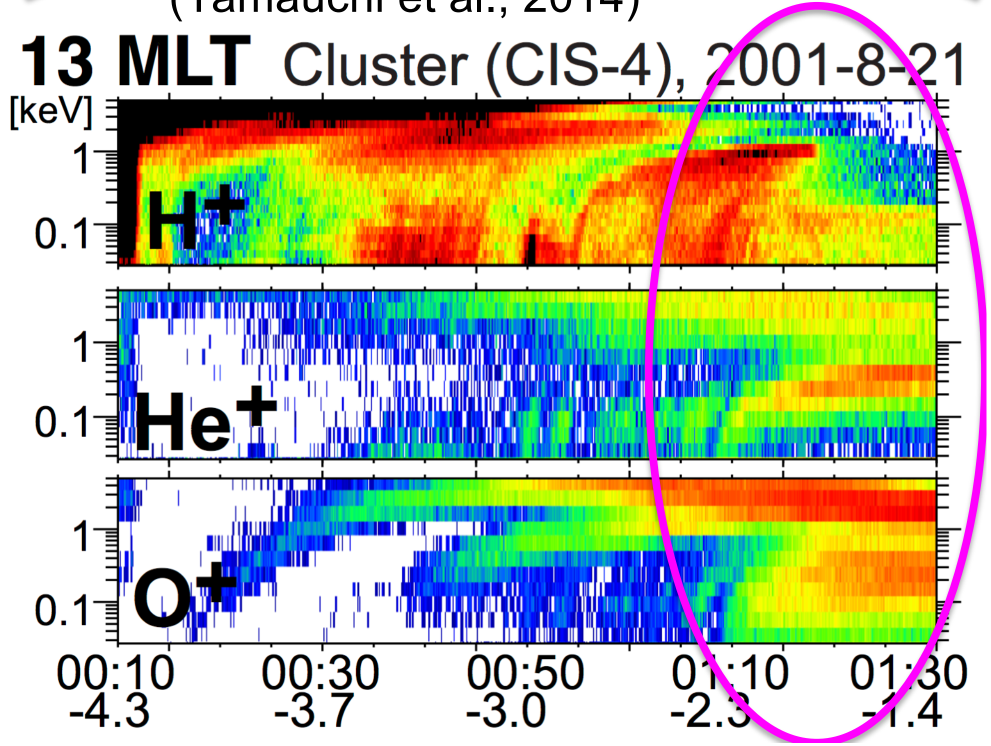
(I still do not have answer)





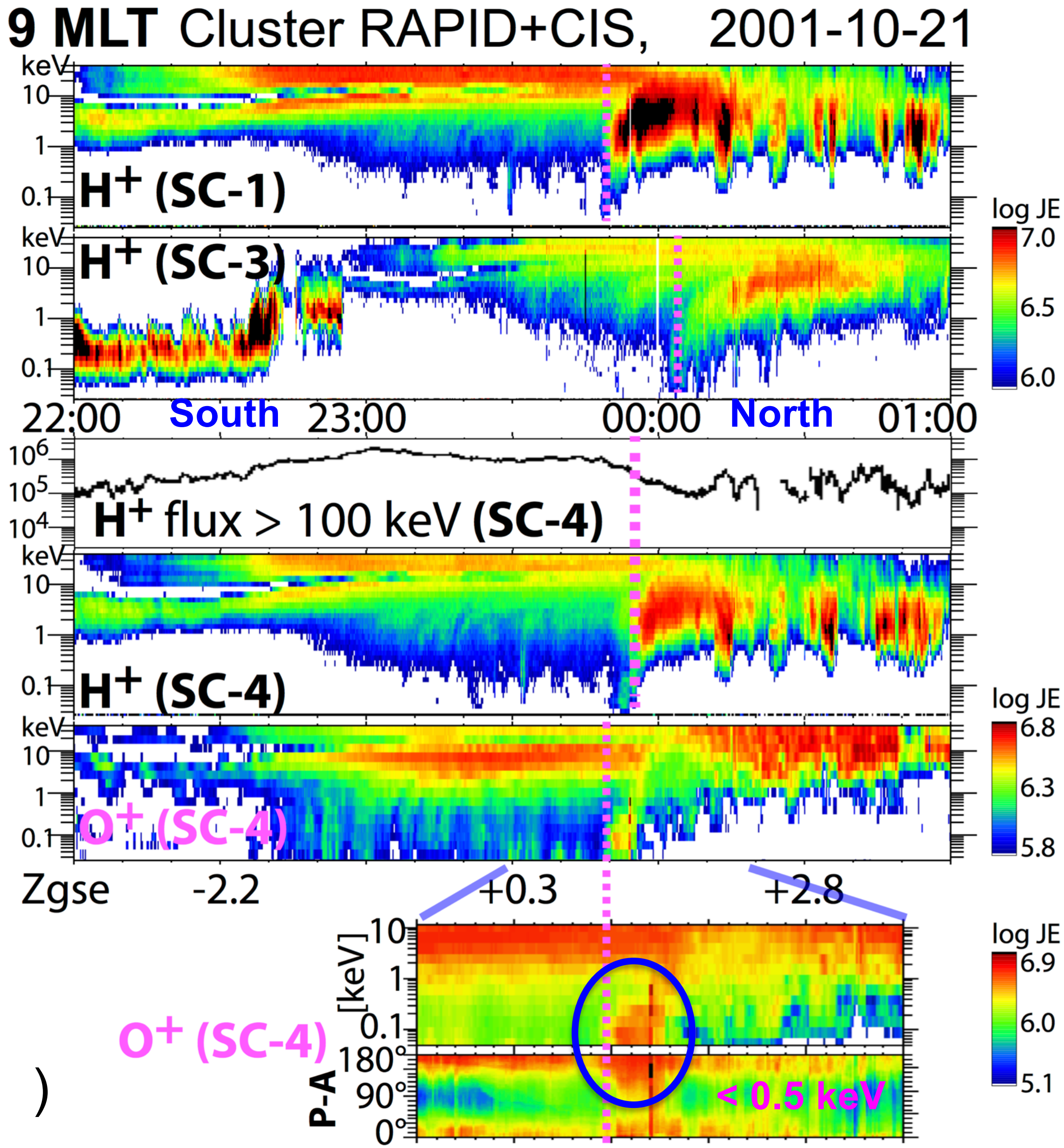
(Yamauchi et al., 2014)





Other O⁺ source during substorm?

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



Different H⁺ arrival time to 9 MLT

&

E =1-3 mV/m (V_E = 3~10 km/s)

O⁺ < 0.2 keV (< 50 km/s)

&

pitch angle = **180°** (not 0°)

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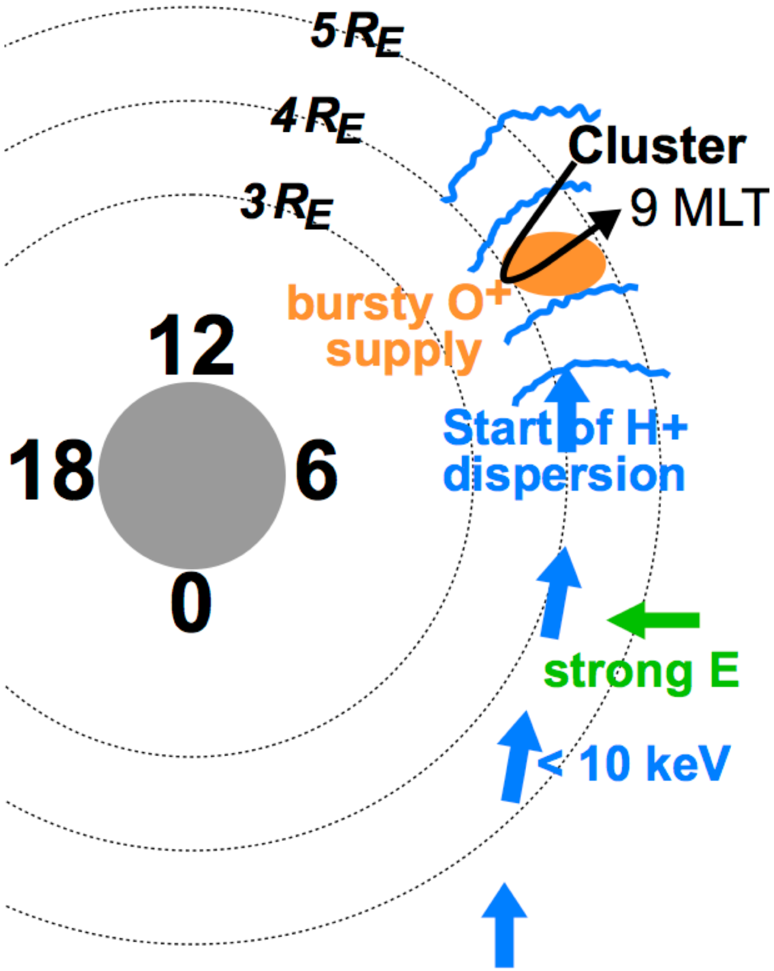
Kiruna, Sweden

Derived ion motion



H$^+$ timing analyses

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

O$^+$ signature

⇒ 20-30 min from northern ionosphere along B

⇒ **O$^+$ outflow** started **near 9 MLT at ~23:20 UT**

Both agree with substorm onset at 23:10 UT

(Yamauchi et al., 2006)

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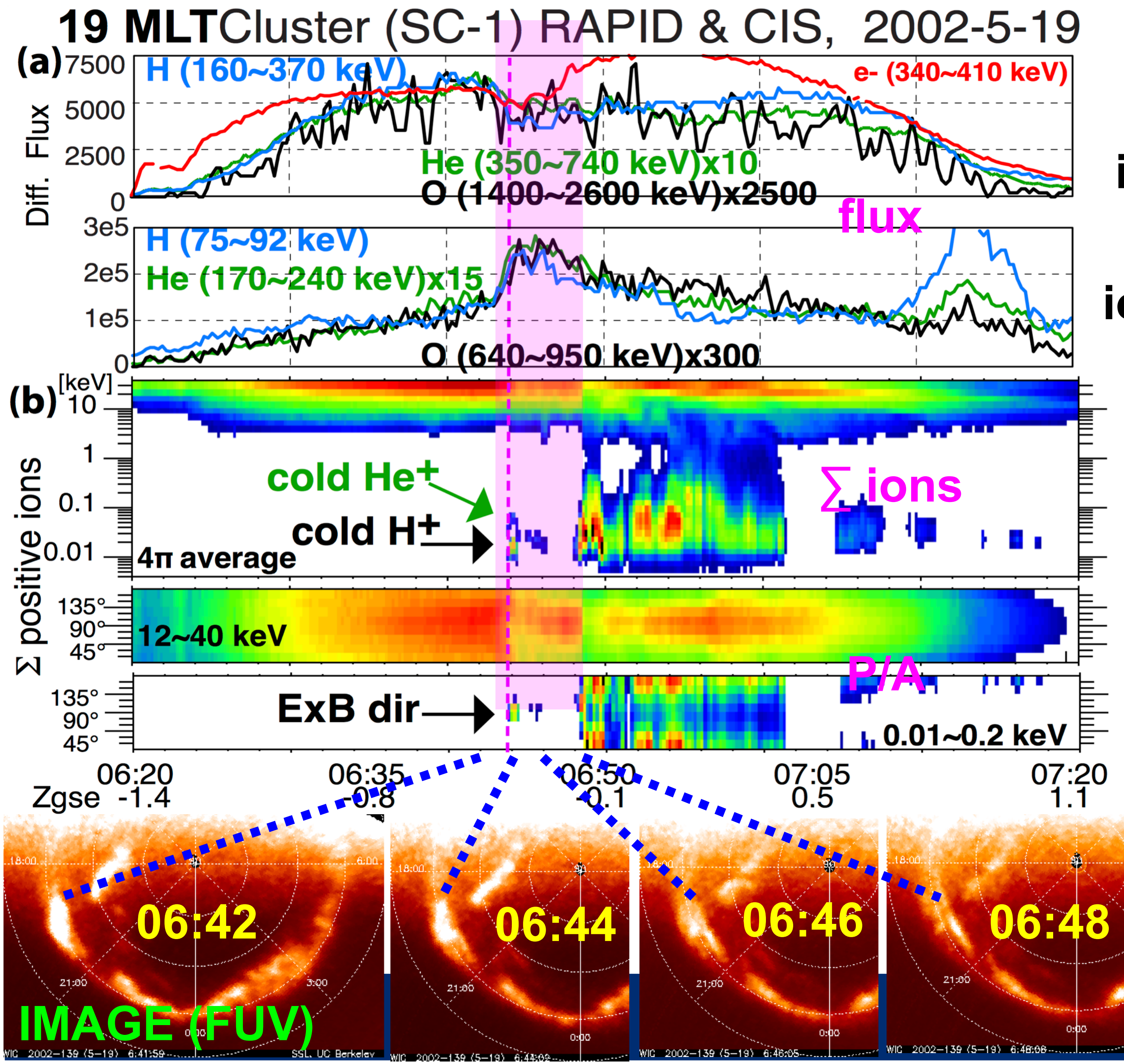
Another mass-mystery ⇒ same velocity



ions > 5000 km/s

ions ≈ 3000 km/s

Mass-dependent but **velocity-dependent**

Sudden strong E (~ 10mV/m) and **auroral bulge**

(Yamauchi et al., 2009)

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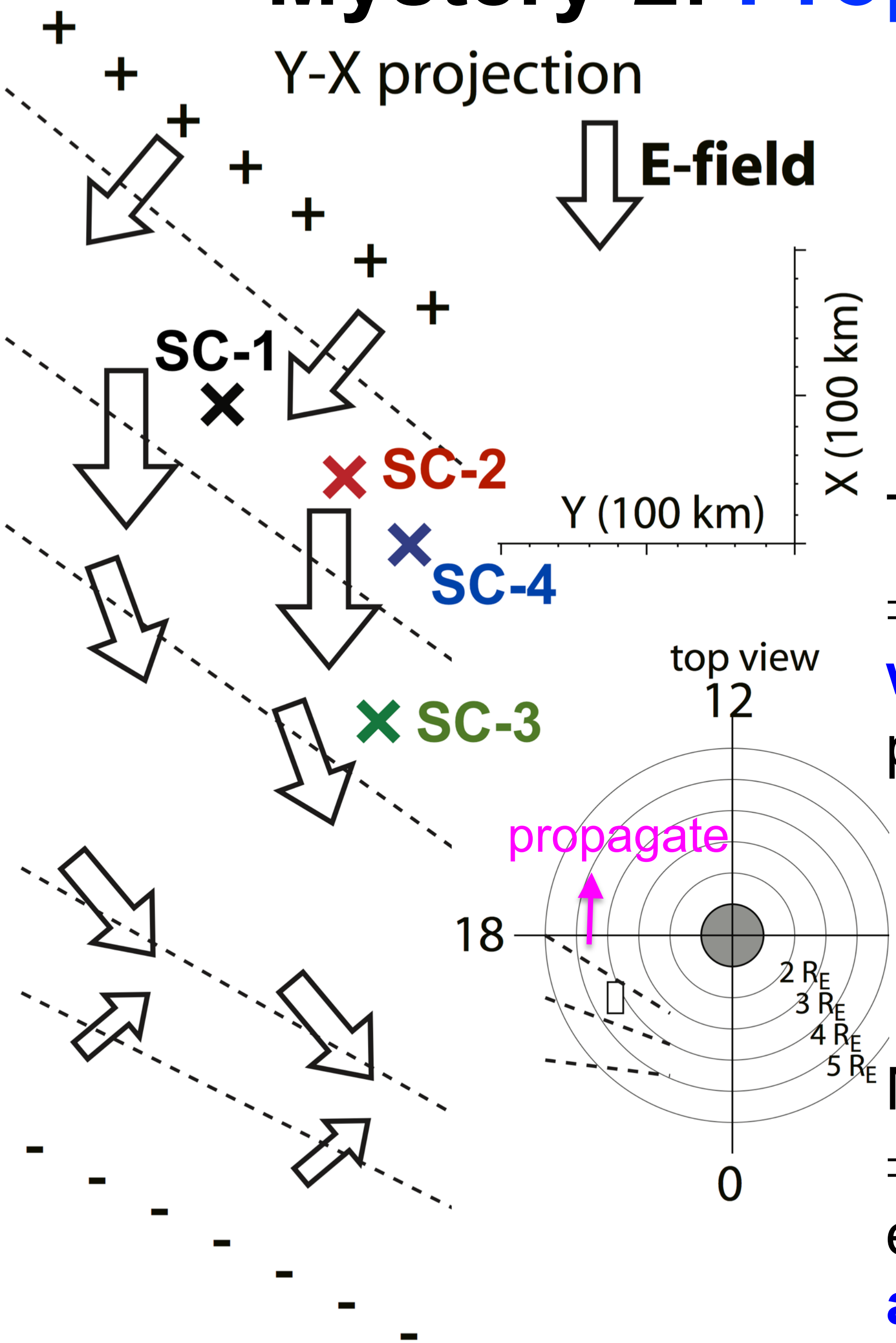
Kiruna, Sweden

Mystery-2: Propagating $E_\perp$ + aurora

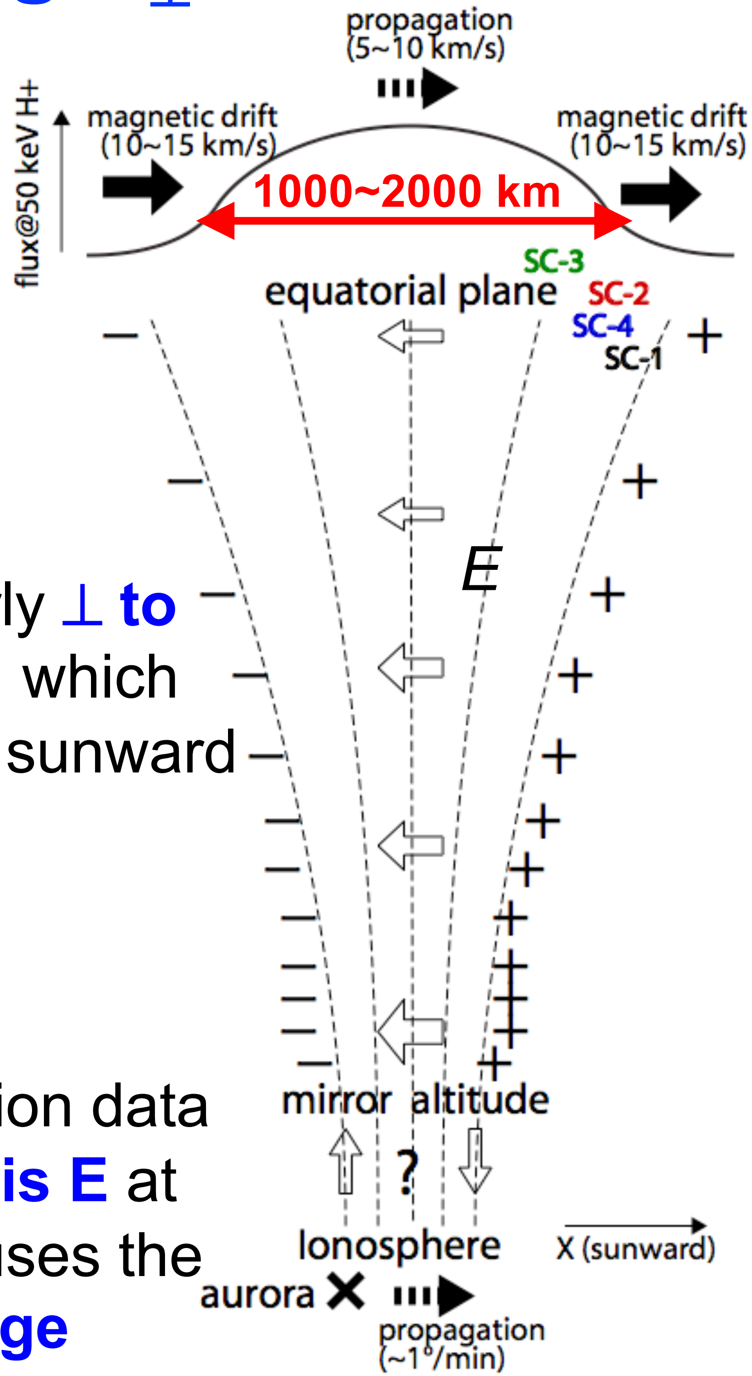


Timing

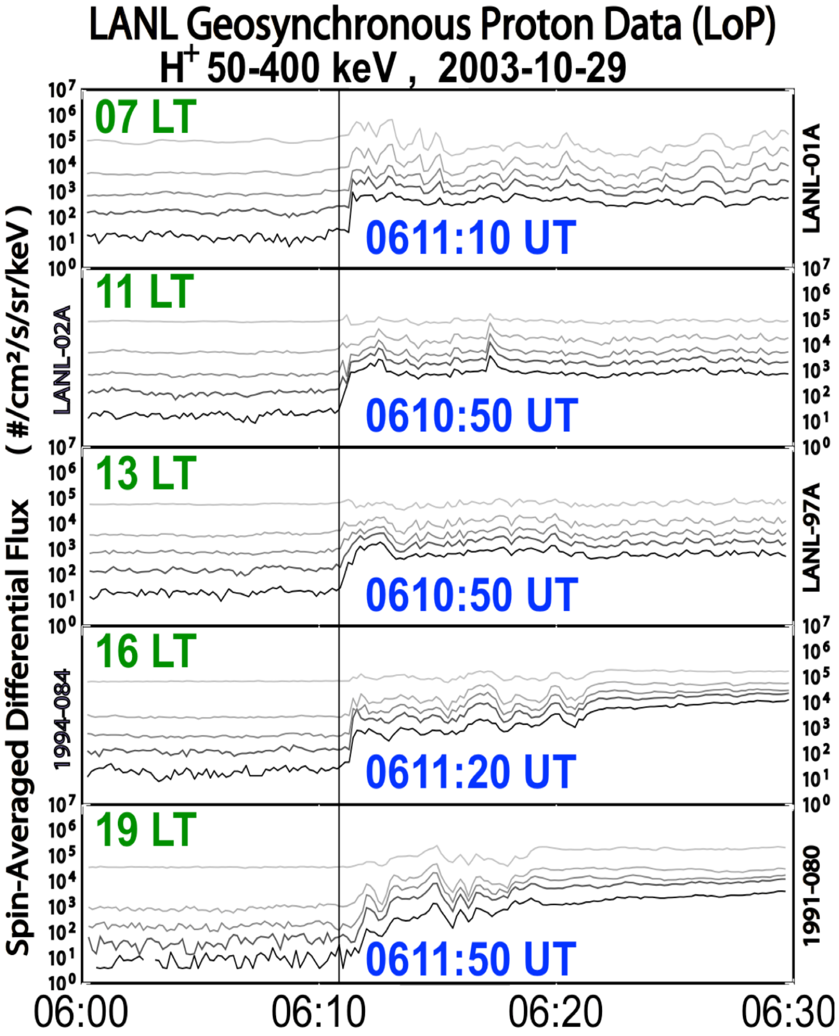
⇒ ***E*** is nearly **⊥ to wave front**, which propagates sunward

Mapping & ion data

⇒ **ΔV by this E** at equator causes the **auroral bulge**

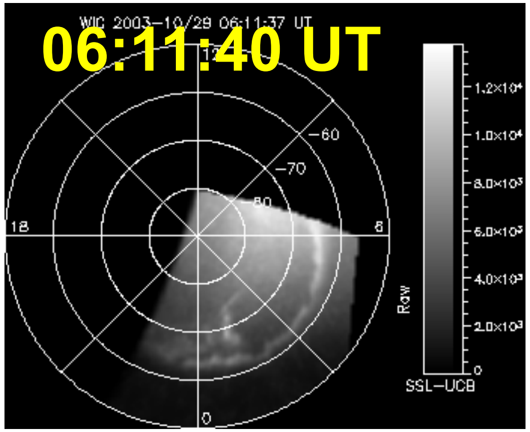


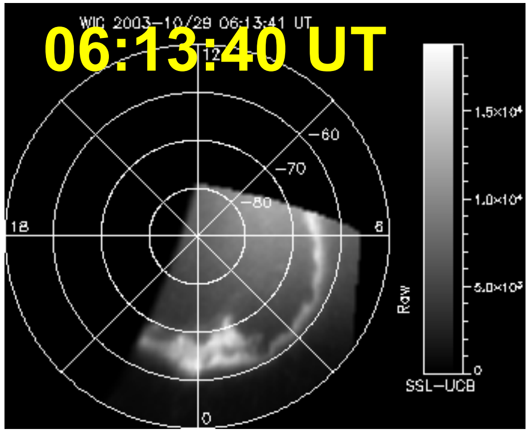
Other example of **propagation**



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

⇒ **arrival at MP: ~ 06:10 UT**





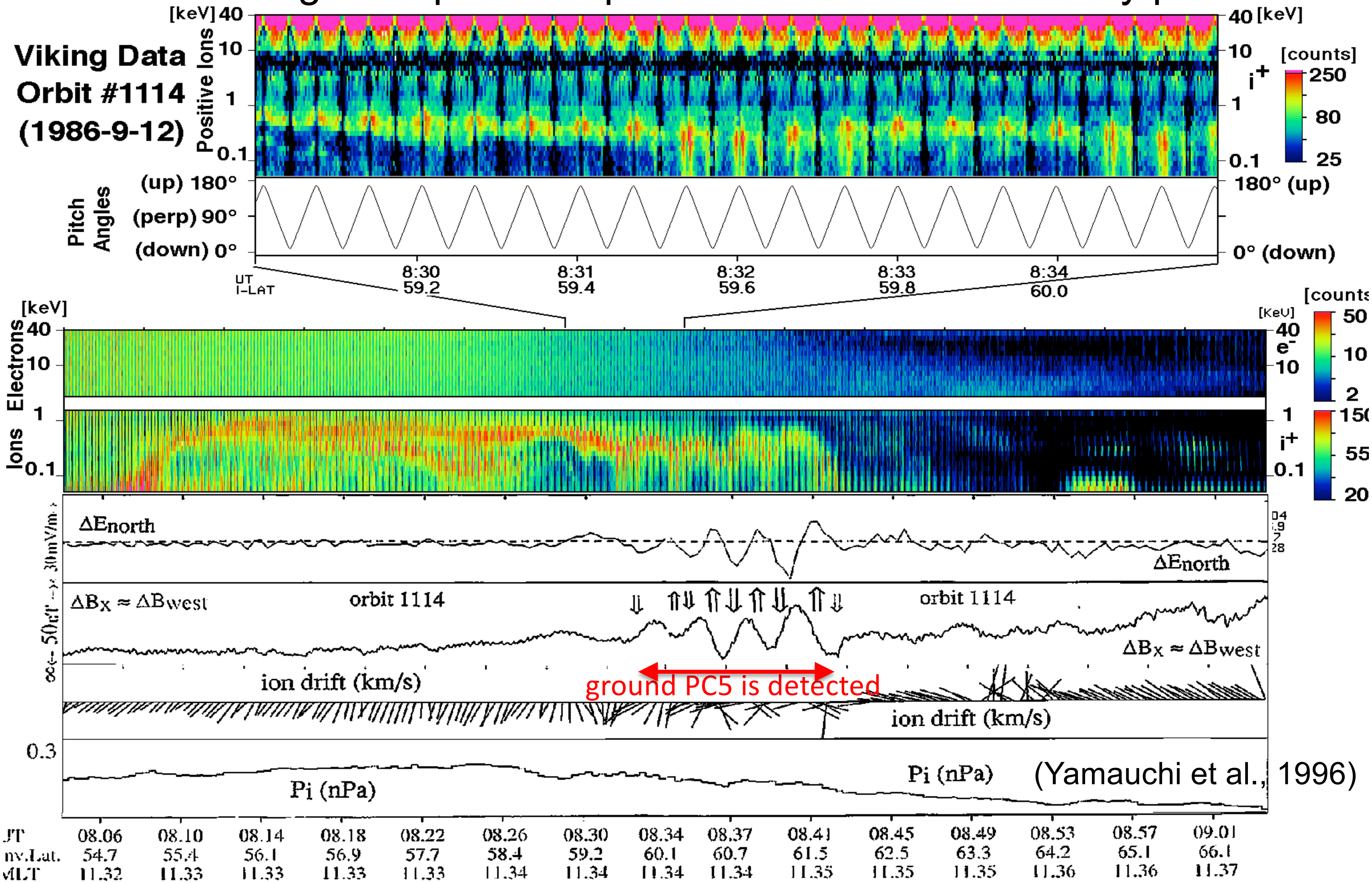
Shock swept the inner magnetosphere (0.3 R_E/s)

Dipolarization + substorm onset ~ 06:12 UT

⇒ Unlike previous case, **the sweeped shock triggered this particular substorm onset** (Yamauchi et al., 2006)

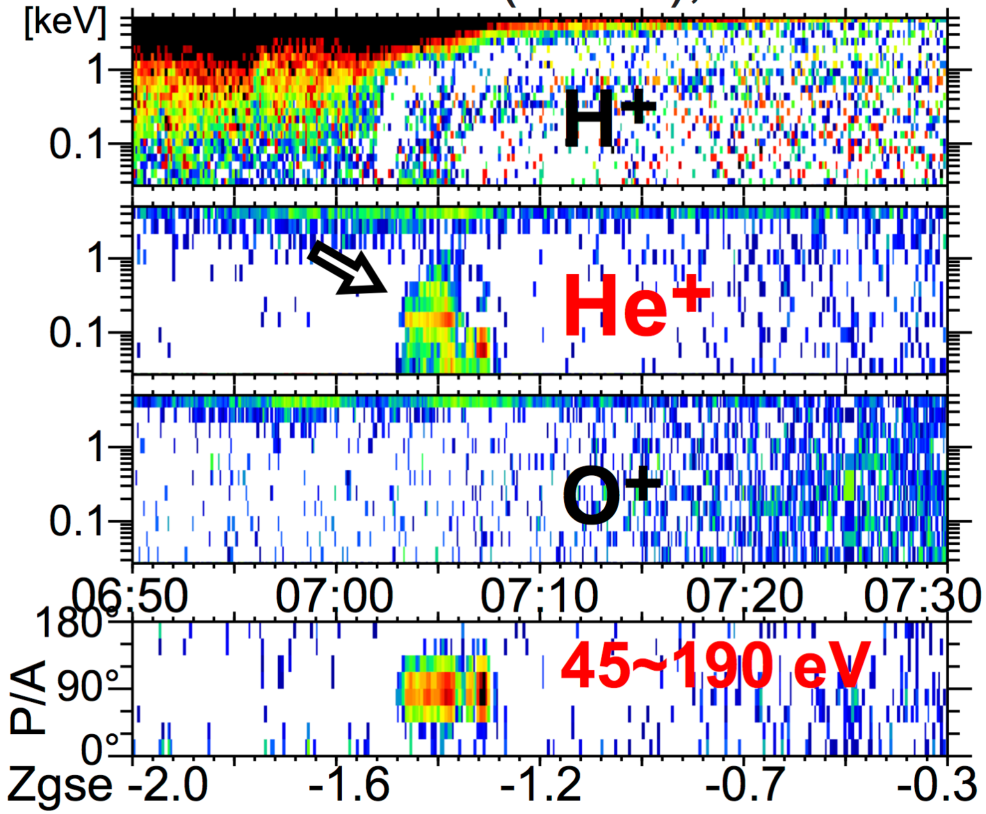
Mystery-3: Energization

Viking's unique example of **conic acceleration** by pc5

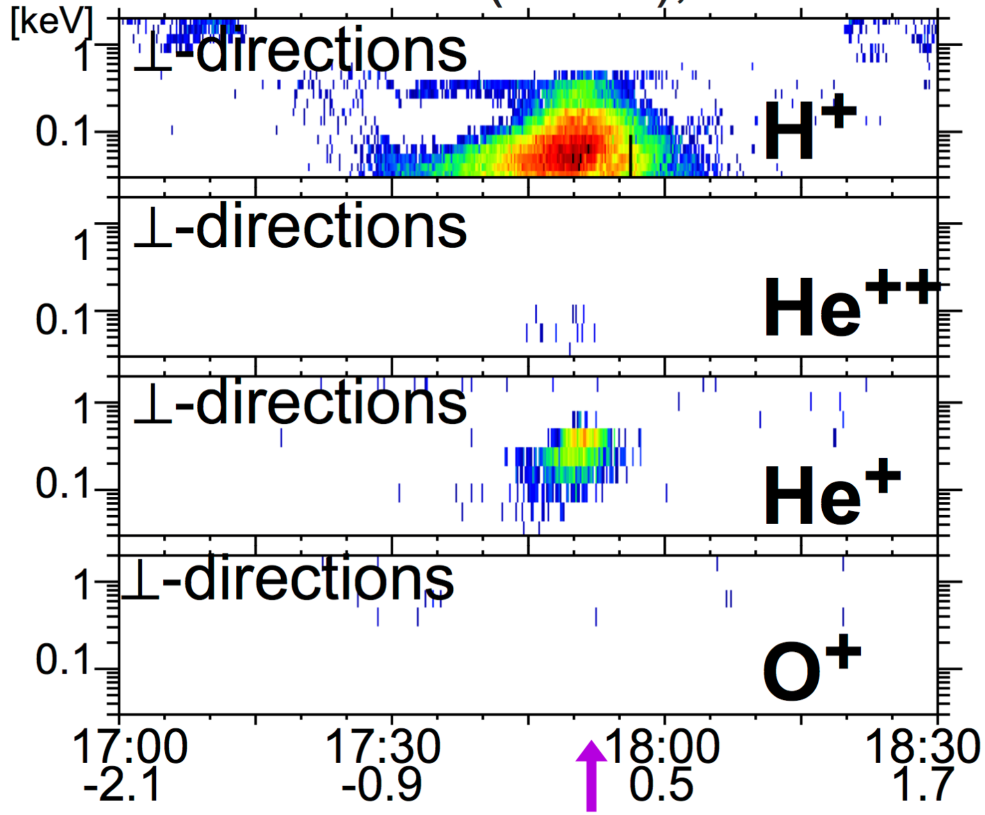


Local ⊥ heating in the plasmasphere

20 MLT Cluster (CIS-4), 2004-5-04



4 MLT Cluster (CIS-4), 2002-1-03



Rare but probably related to substorms

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

(Yamauchi et al., 2014)

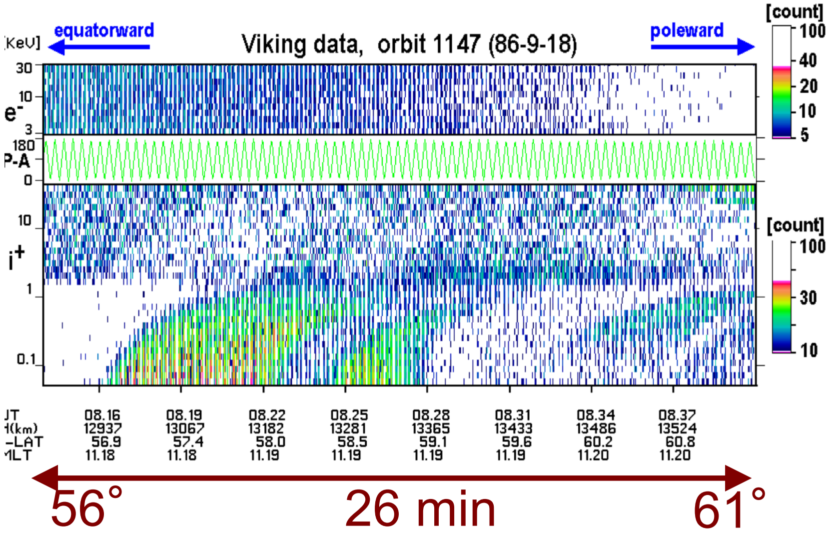
Confined to equator with τ ~ 1 hour

Why variable E_{He}/E_H (=1~4)?
(I still do not have answer)

(Yamauchi et al., 2012)

Decay

Viking observations



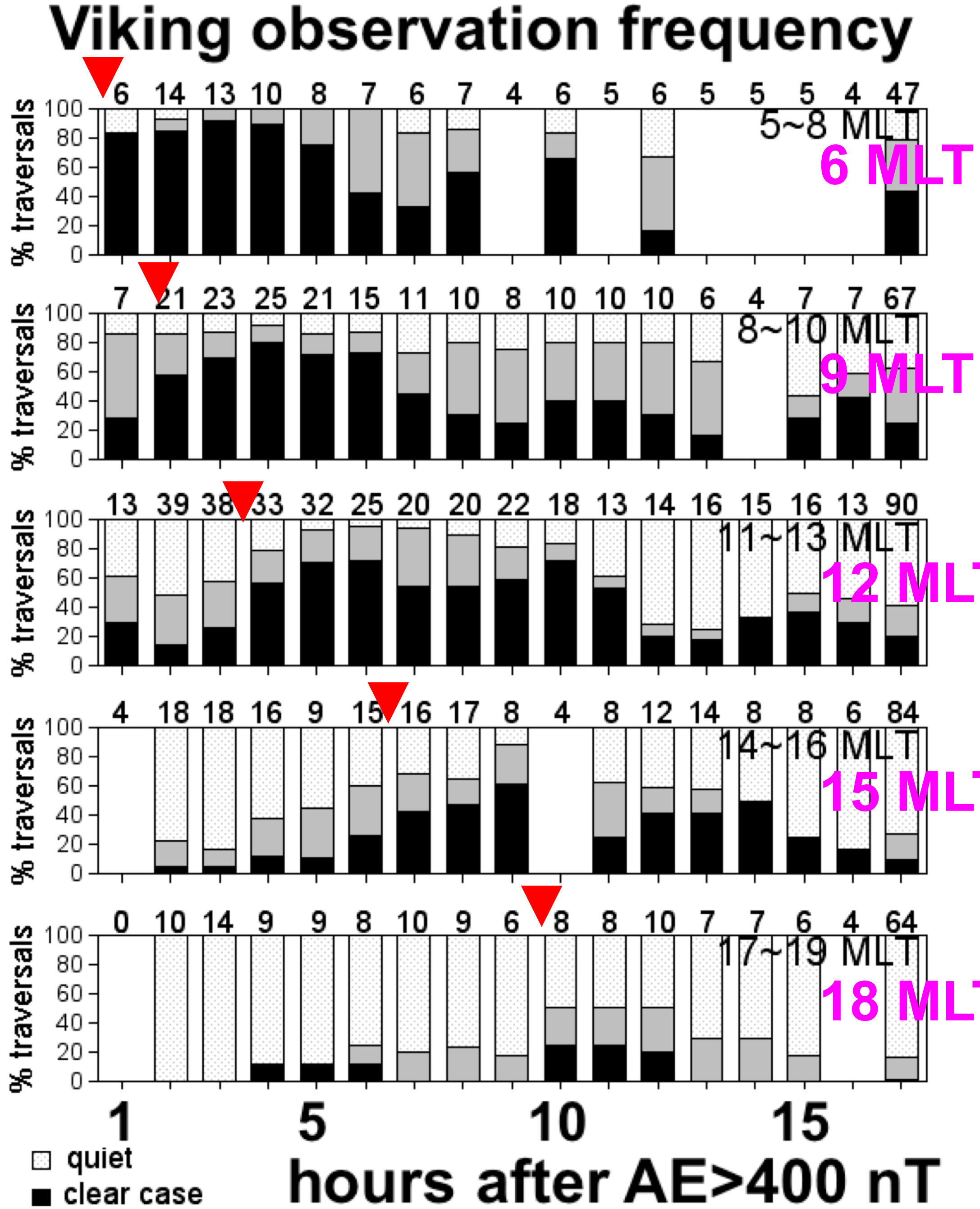
After high AE activities.

(1) Moves eastward **very fast**

⇒ **fossil of substorm filling**

(2) **Quick decrease for 12-18 MLT**

(Yamauchi and Lundin, 2006)



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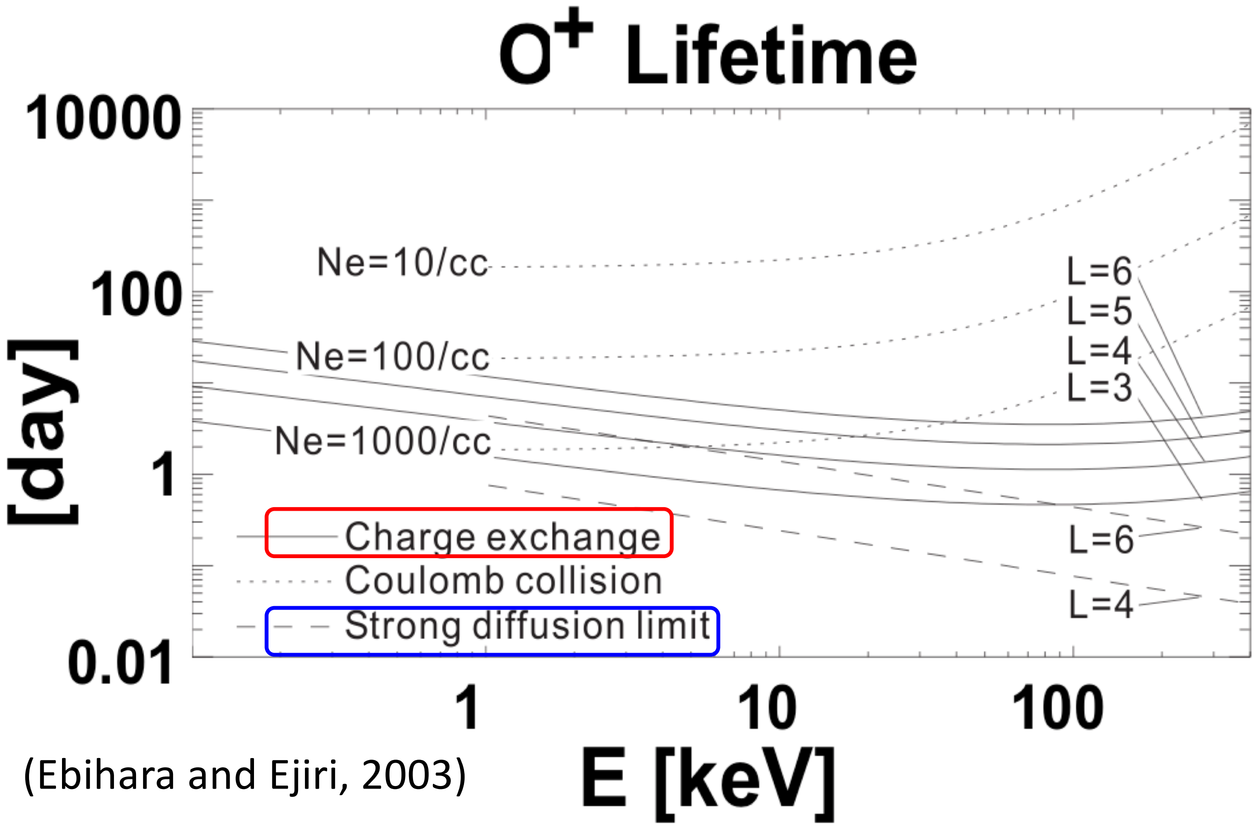
Why decay? (1) loss to the ionosphere

(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

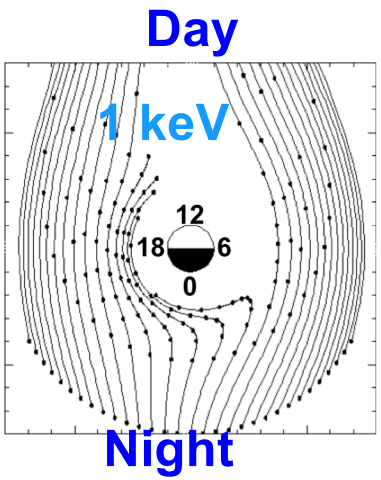


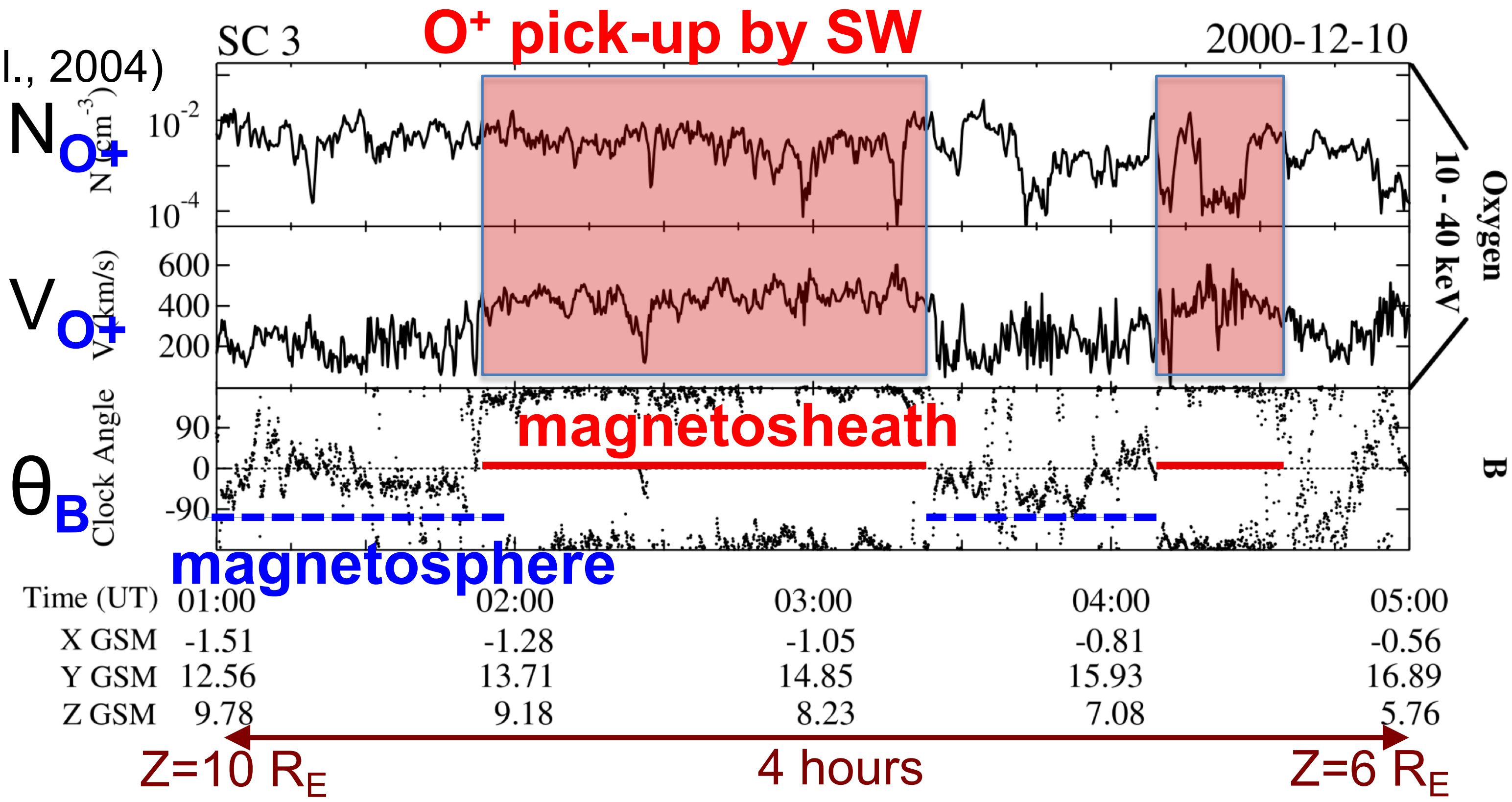
(Ebihara and Ejiri, 2003)

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

Why decay? (2) Magnetopause shadowing

(Marcucci et al., 2004)





ExB drift **overshoots** magnetopause ⇒ **magnetopause (MP) shadowing**

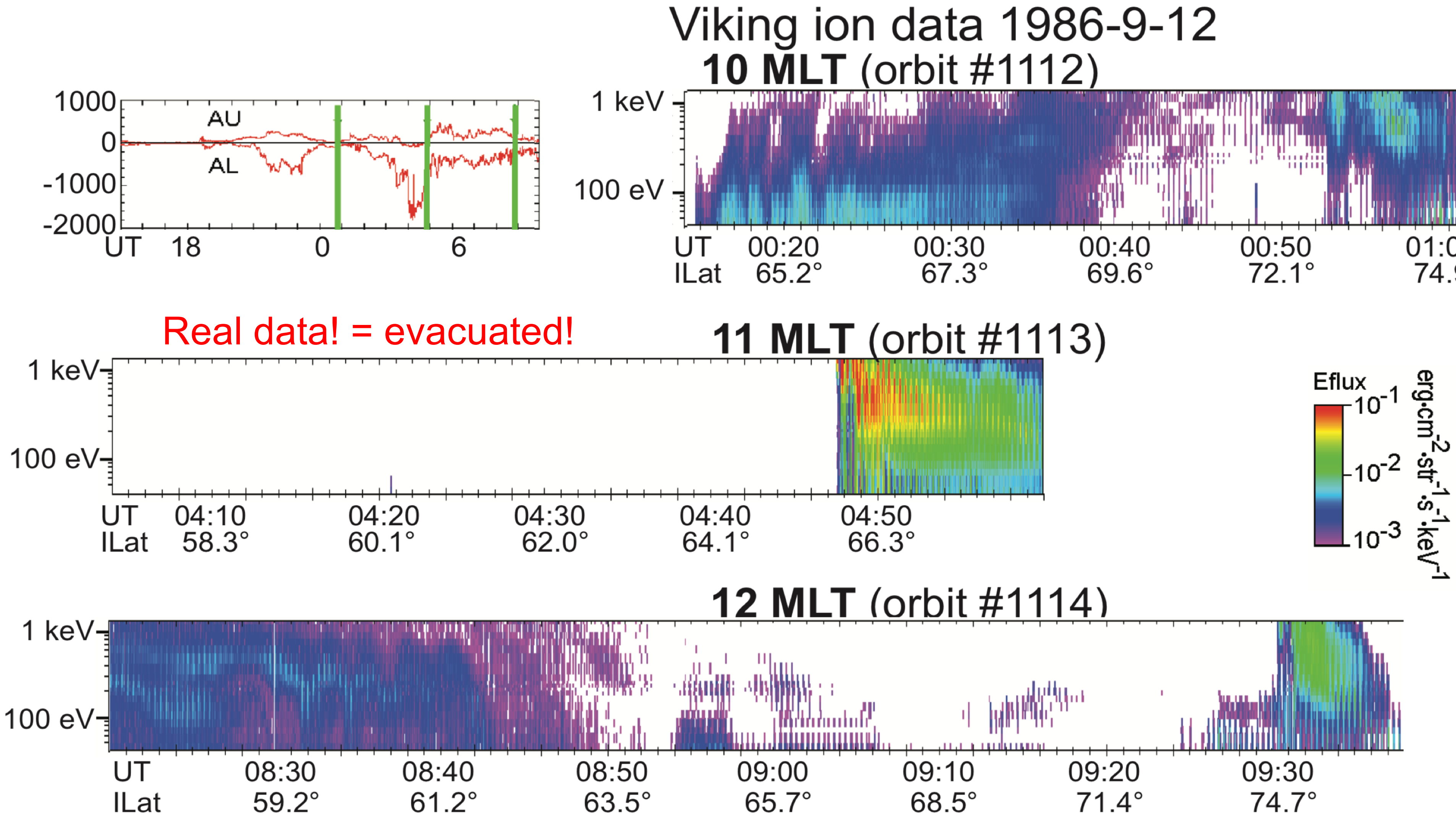
≈ 1/3 of input O^+ during storm

(Zong et al., 2001)

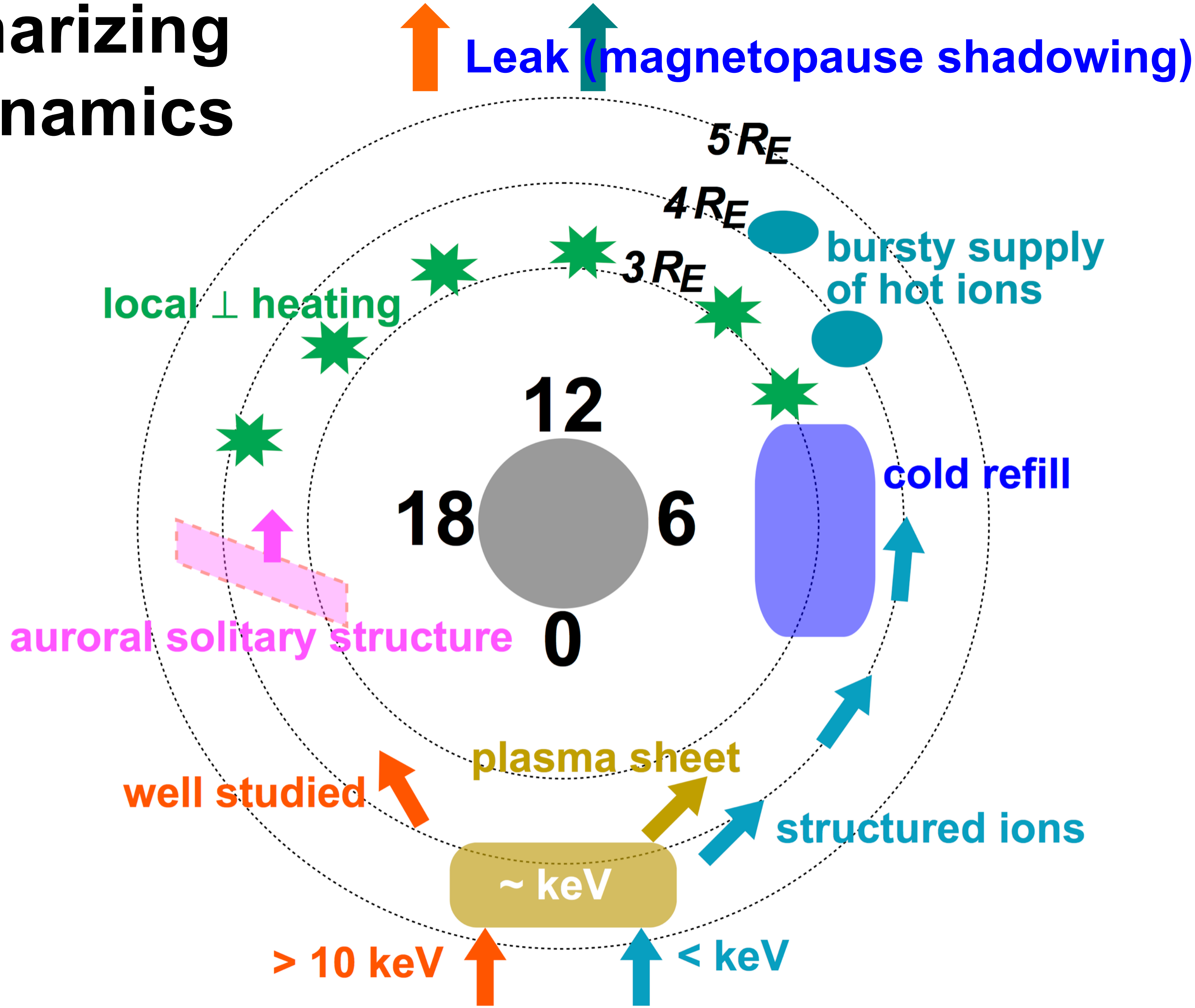
⇒ works for all drifting ions (cold + hot + energetic)

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

Ion **evacuation** by substorm E-field



Summarizing ion dynamics



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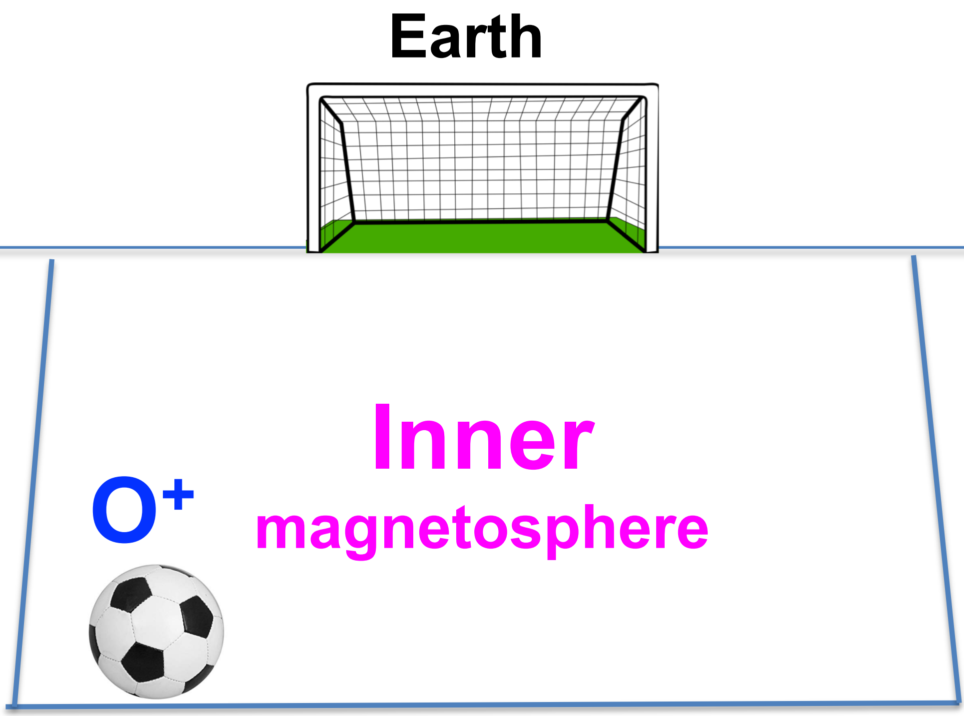


A lot of "unexpected" phenomena

Differential attack (location and time)

Changing speed

Mass of attack

Replling

Surge

Only few can "goal" to the Earth

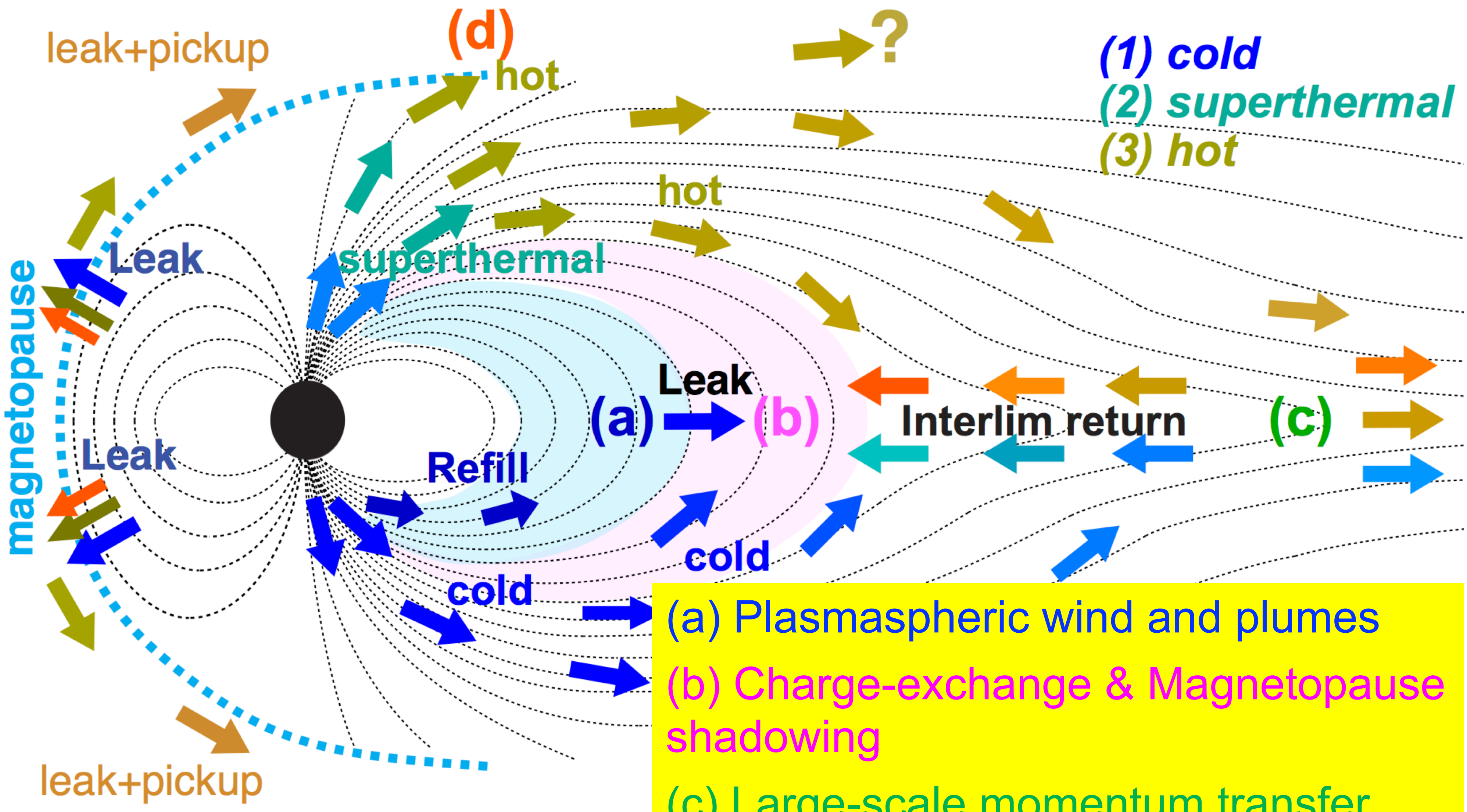
Outline

1. **Three types of outflow** and primary destinations: cold (re-filling, supersonic), superthermal, & hot

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. Consequence of **massive ion escape** (under-estimated effects):
- **local energy conversion** through mass-loading
- **Evolution of the Earth** in geological scale (then cannot ignore **neutral**)

Main escape mechanisms for present Earth



(a) Plasmaspheric wind and plumes

(b) Charge-exchange & Magnetopause shadowing

(c) Large-scale momentum transfer

(d) Ions accelerated by field reach SW

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Known escape rate with Cluster

(a) polar outflow of hot O^+ ($\times 10^{25}$ s^{-1})
magnetosheath O^+ (**escape**) ~ **0.7**
plasma mantle O^+ (**mostly escape**) ~ **2**

or, $N_{O+}/N_{H+} \approx 1\%$,
i.e., ρ_{O+}/ρ_{H+} = 10-20%,

(Nilsson et al. 2012, Slapak et al., 2017a)

(b) magnetotail hot O^+ ($\times 10^{25}$ s^{-1})
tailward O^+ (escape) ~ **0.5**
earthward O^+ ~ **0.6** ⇒ **roughly half escapes later**
(Slapak et al., 2017b)

(c) plasma sheet cold H^+ ($\times 10^{25}$ s^{-1}, with O/H ratio < 10^{-2} **?**)
3 ~ 10 (for H^+) ⇒ more than half escapes
(Eriksson et al. 2006, Engwall et al., 2009)

(d) plasmaspheric cold H^+ and He^+ ($\times 10^{25}$ s^{-1}, with O/H ratio ~ 10^{-2})
Plume : **peak 100 (for H^+)**
Wind : **50 (for H^+)**
(Darrouzet et al. 2009, 2013)

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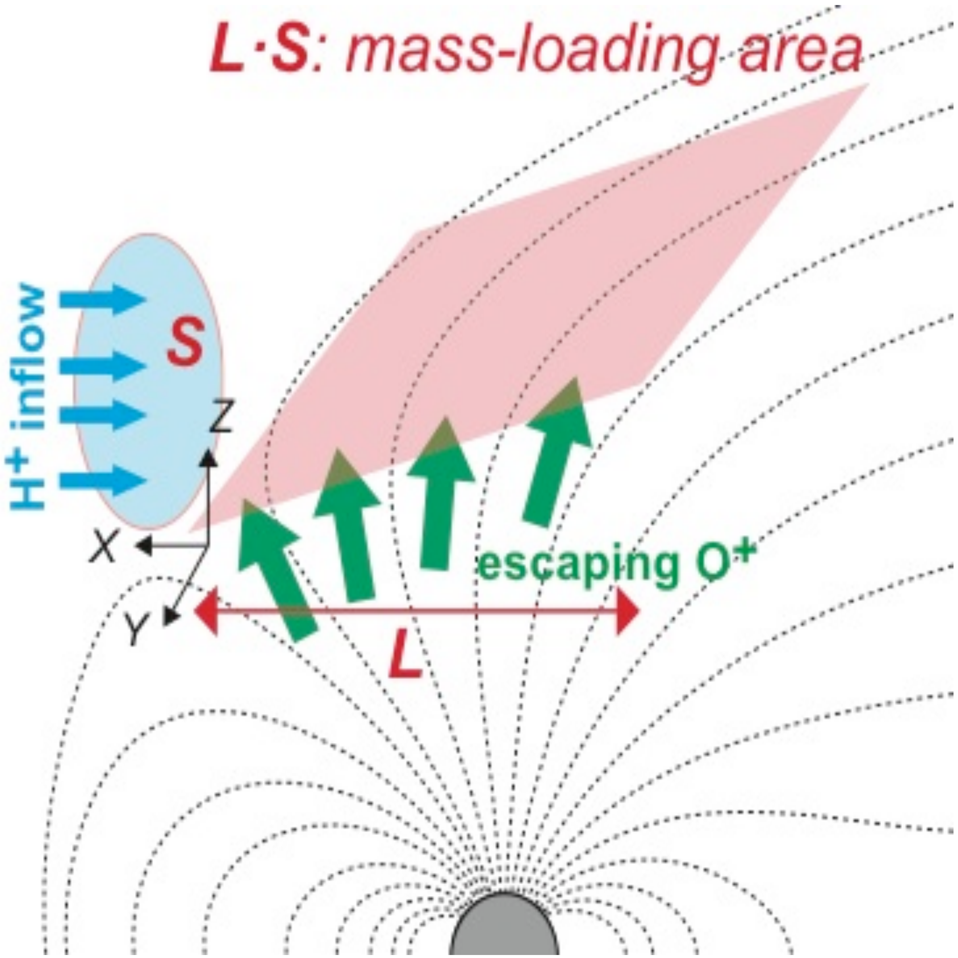
O^+ inside solar wind = Mass Loading

Mass loading = inelastic mixing conserving momentum
⇒ kinetic energy **K is not conserved**
($\Delta K/K = \Delta u/u$ = deceleration rate)

example 1: comets and Mars
(loading of pickup ions)

example 2: cusp & plasma mantle
(mixing of escaping O^+)



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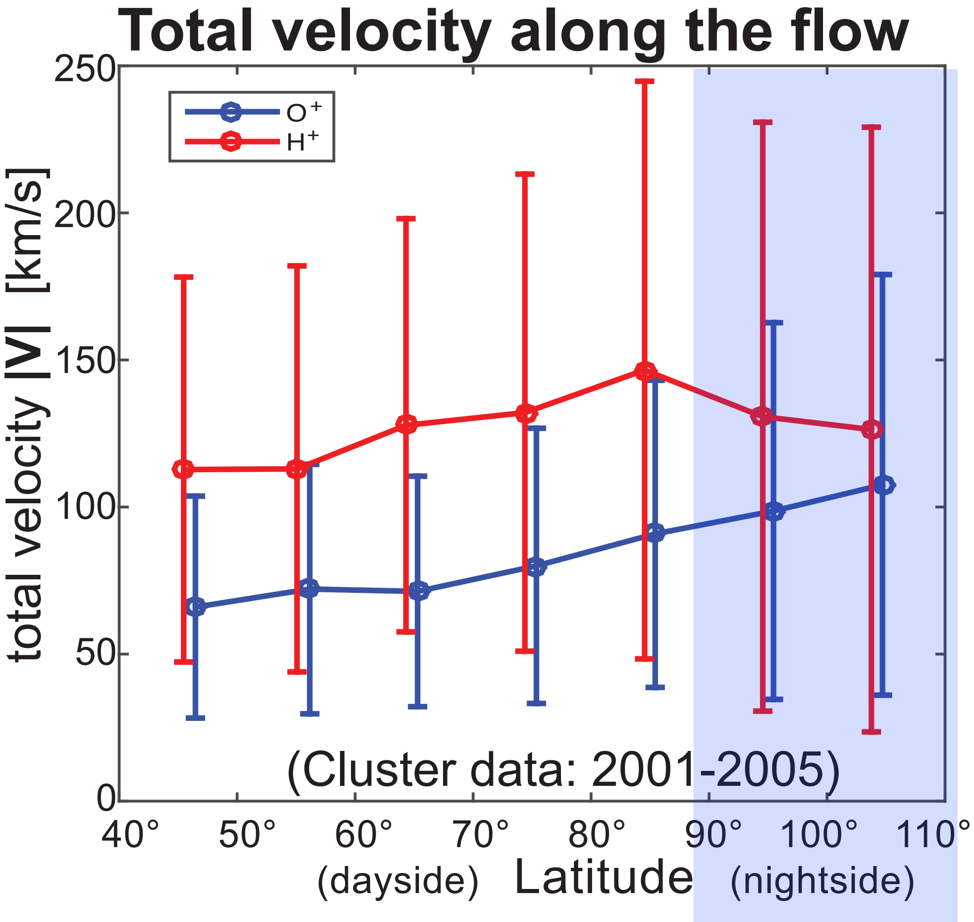
In fact Cluster obs. indicates Mass Loading



(Yamauchi and Slapak, 2018)

V_{O+} increases while V_{H+} decreases

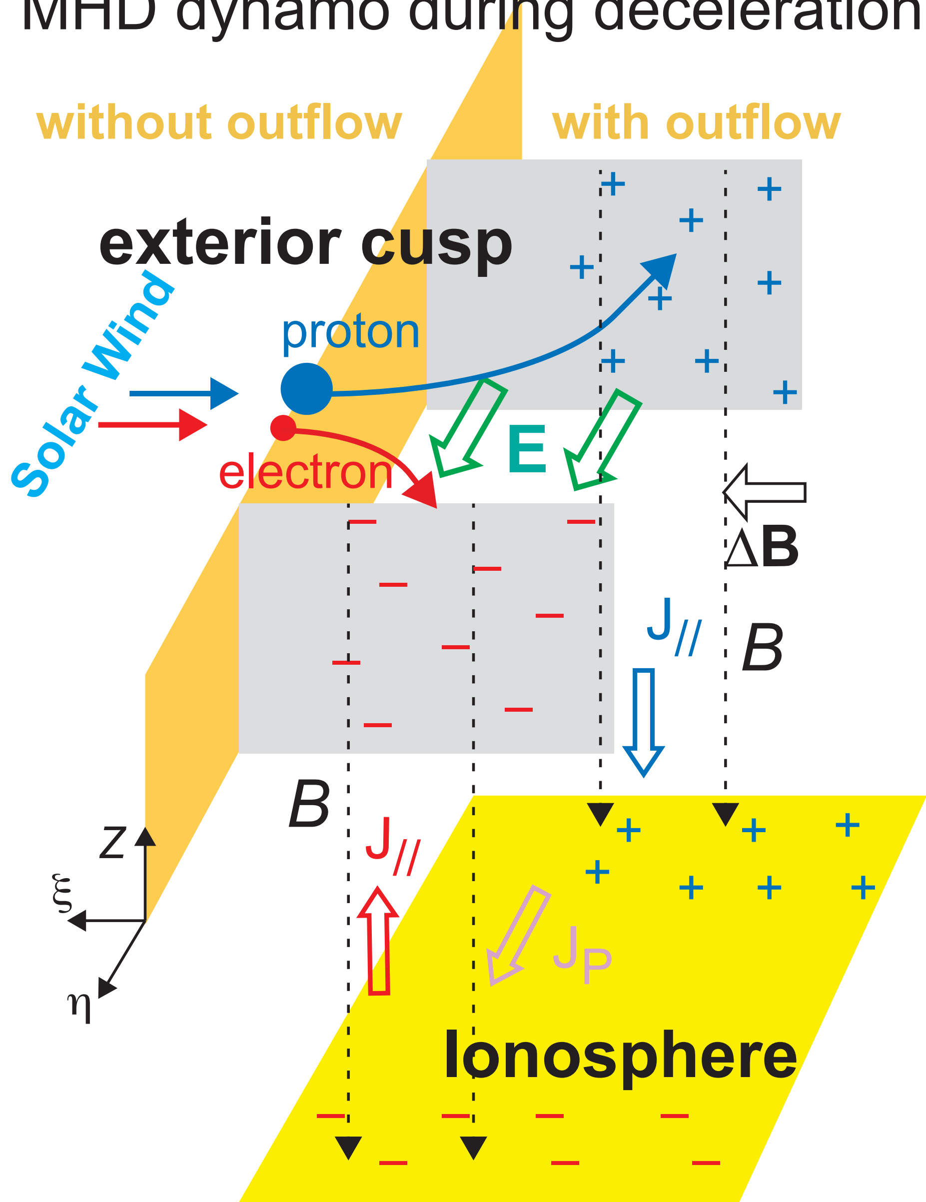
⇒ **Mixing is indeed inelastic toward the common velocity**

⇒ $\Delta K/K = \Delta u/u$

(K=kinetic energy)

In fact Cluster obs. indicates Mass Loading

MHD dynamo during deceleration



Where does ΔK (kinetic energy) go?

= Ionosphere! Because, connected by geomagnetic field (same mechanism as "open" magnetosphere)

⇒ **Two type of "open"**:

- looking from the Earth (Dungy type), and
- looking from the solar wind (Vasyliunas type)

Energy conversion by Mass Loading

If final $V_{O+} \approx V_{H+}$, ΔK is independent of ionospheric conductivity:

$$\Delta K \approx (-1/4) \cdot u^2_{SW} \cdot F_{load}$$

(where **F** is O^+ mixing rate to the solar wind) (Yamauchi and Slapak, 2018)

(1) $\Delta K \approx 10^{9\text{-}10}$ **W** for $F_{load} \approx m_O{*}10^{25\text{-}26}\ s^{-1}$

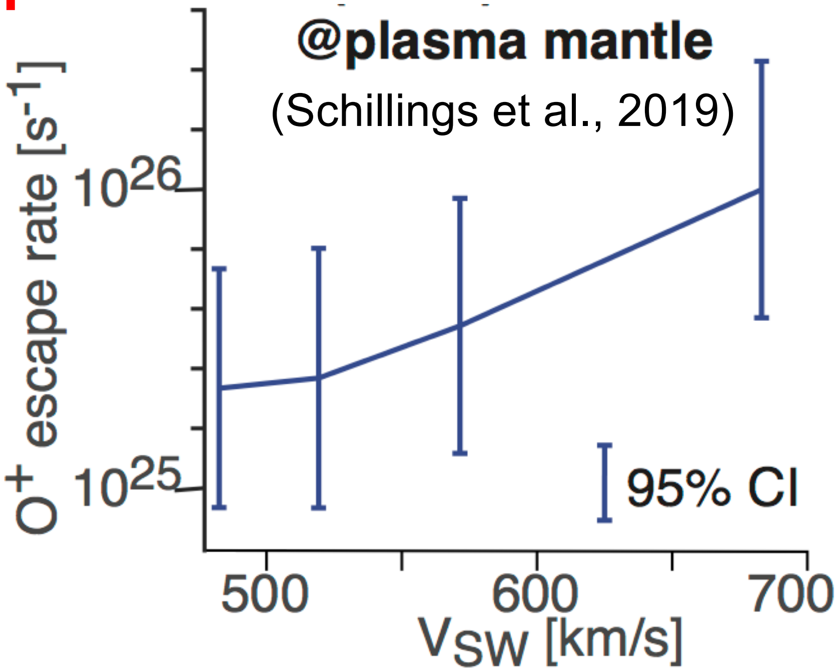
⇒ **Can explain cusp current system**

(amount + independency)

(2) We expect $F_{load} \propto \Delta K$

(through ionospheric heating)

⇒ Large u_{SW} increases O+ escape? ⇒ **YES**



(3) O+ outflow influence the SW injection?

⇒ Various types of injection?

(not all are understood)

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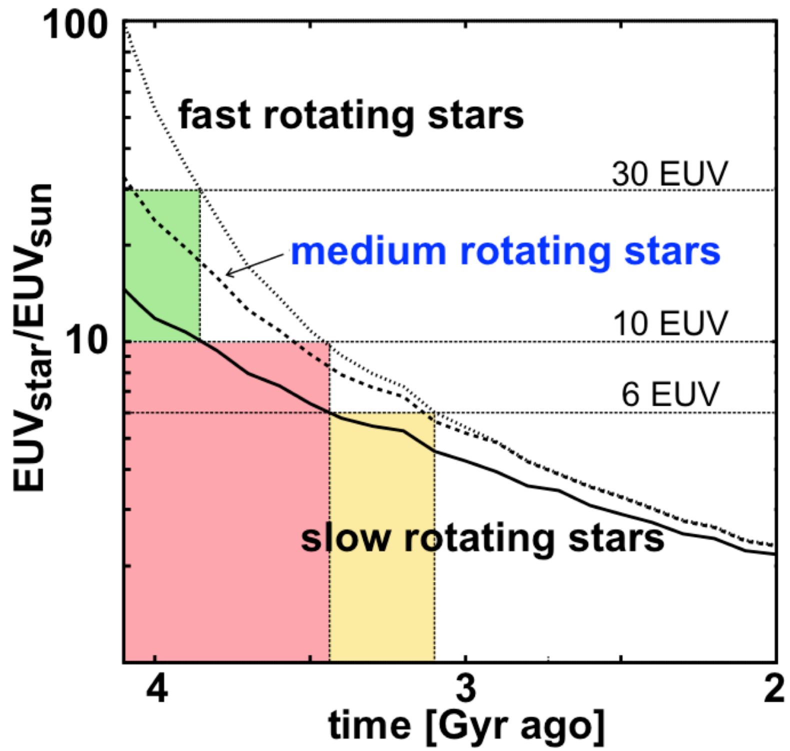
Scaling to the past : high EUV + P_{SW}

Ancient solar forcing (young M-stars)

(a) **much higher EUV flux** than present
(b) **faster solar wind** than present
(c) **much faster rotation** than present
⇒ stronger solar dynamo
⇒ **stronger flare / CME / SEP** (Solar Energetic Particle)

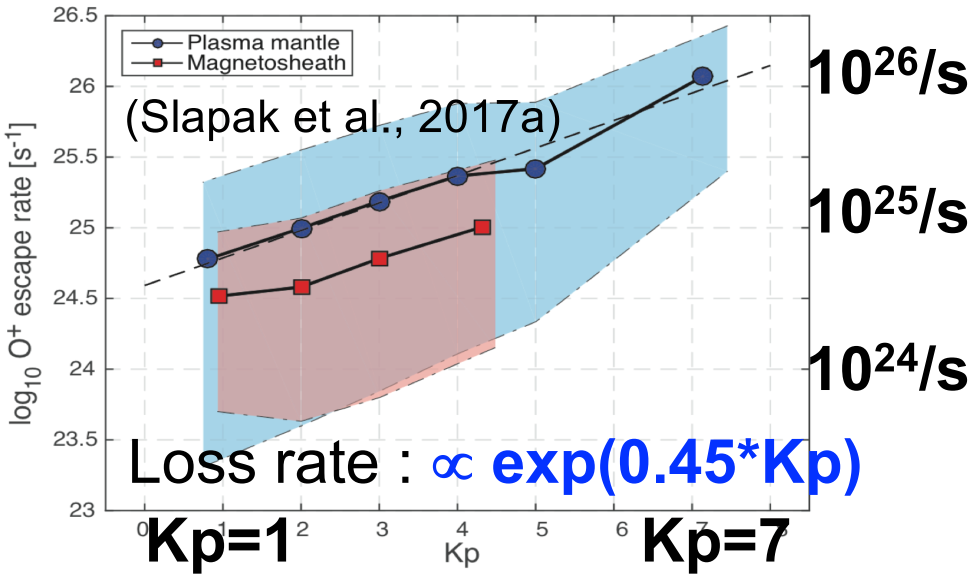
(e.g., Wood, 2006)

⇒ We scale **Kp=10** or use **extreme events** as proxy of the past

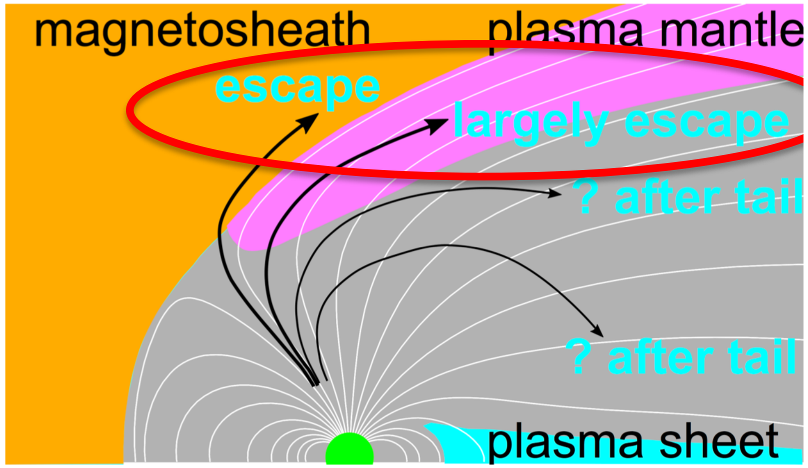


(Tu et al. 2015, Lammer et al., 2018)

Cluster Statistics of **strong SW & EUV** in the past



Cluster@2001 – 2005



For **direct escape only** (O^+ mixing into the solar wind), we expect **10^{27} s^{-1} for Kp=10**

(We examined also with coupling function, Shillings et al., 2019)

⇒ $10^{27} s^{-1}$ x **1 Gyr** ($3 \cdot 10^{16}$ sec) = $3 \cdot 10^{43}$
= **70% of present atmospheric O_2**
(15% of N_2)

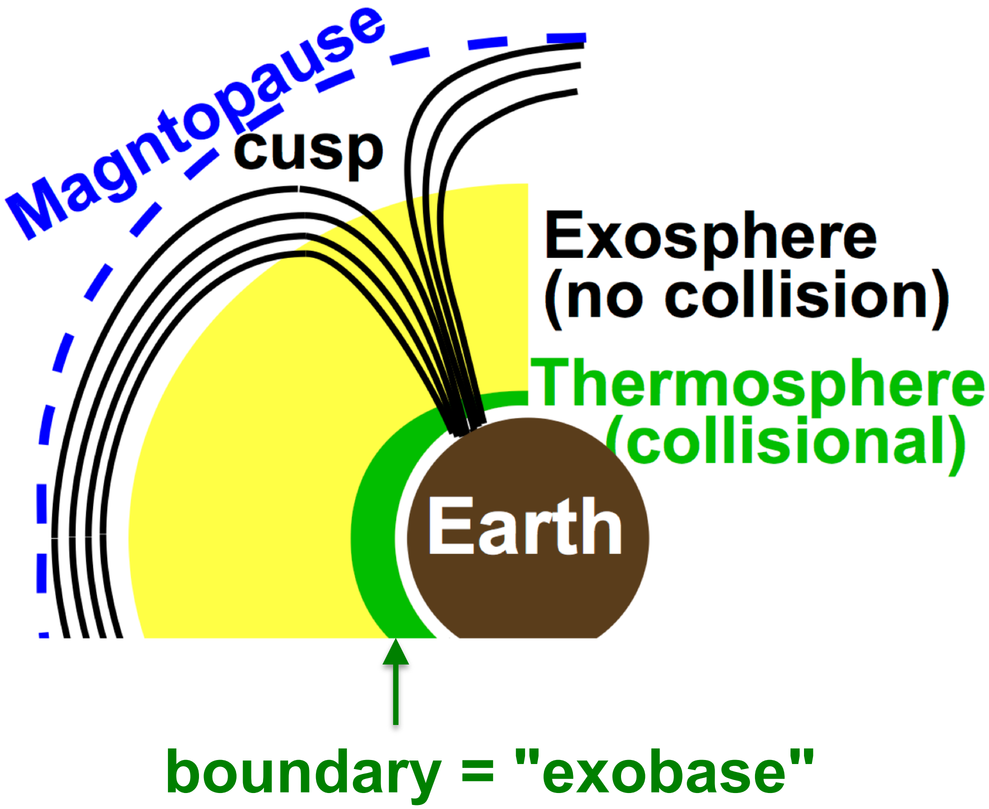
⇒ **cannot ignore**

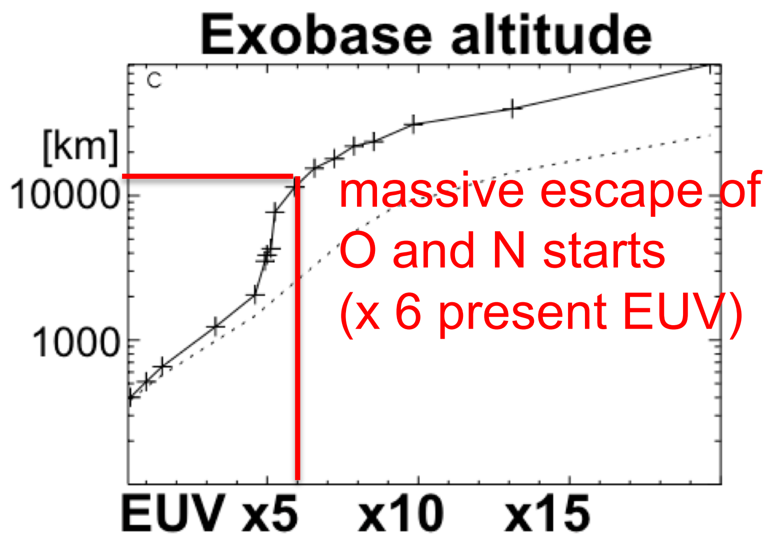
A few % change in O/N ratio does affect bacteria activity (e.g., Loesche, 1969)

Past escape ⇒ must know neutrals

Ancient solar forcing (young M-stars)

(a) **much higher EUV flux** than present
- ⇒ thermosphere **expands**
- ⇒ **neutral escape** becomes large





for N_2 atmosphere (Tian et al., 2008)

height	500 km	2000 km	10000 km
veloicity	10.8 km/s	9.8 km/s	**7.0 km/s**
O	9.7 eV	8.0 eV	**4.1 eV**
N	8.5 eV	7.0 eV	**3.6 eV**

before		after	extra energy
O_2^+ + e-	⇒	2O	1–7 eV
N_2^+ + e-	⇒	2N	3–6 eV

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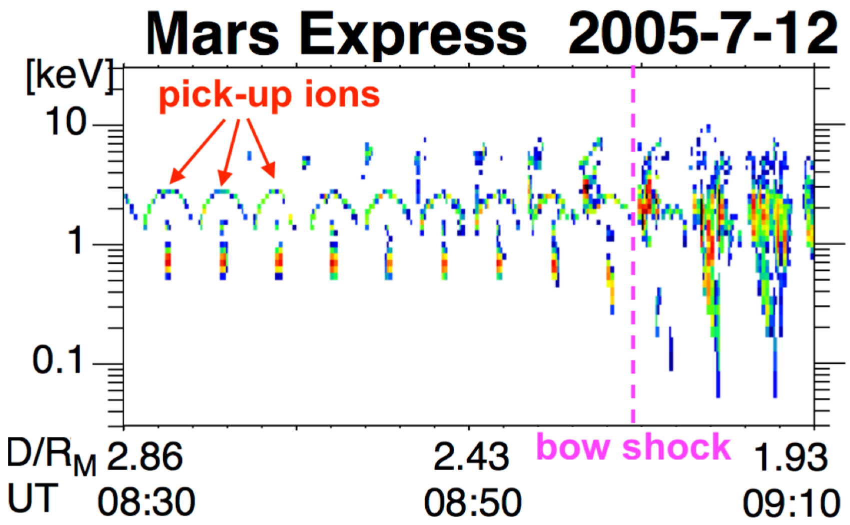
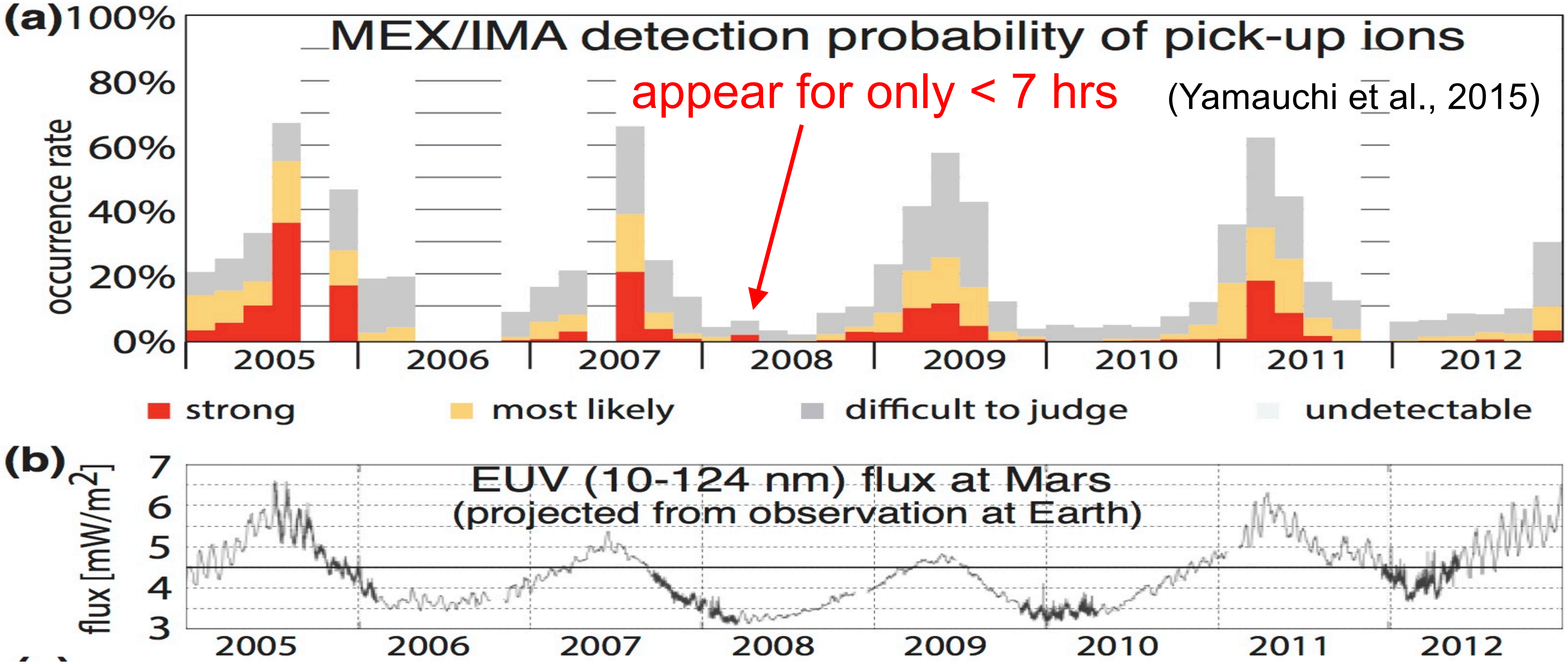
In fact, exosphere drastically responds to EUV

Newly-formed cold ions (pickup ions) at Mars

⇒ **x 10 increase for <50% increase in EUV** during 1 Mars year

⇒ expansion of exosphere is much more than any simple models





atmospheric escape from ancient Earth

mechanism	present Earth	ancient Earth?
Jeans escape	-	yes? (need to understand present exosphere)
Hydrodynamic blow off	-	yes? (need to understand present exosphere)
Momentum exchange	-	yes? (need to understand present exosphere)
Photochemical energization	-	yes
Charge-exchange	yes	? (need to understand ring current)
Atmospheric sputtering	-	yes? (need to understand past cusp)
Ion pickup	-	yes
Ions accelerated by field reach SW	YES !	yes
Large-scale momentum transfer & instabilities	yes	yes? (need to understand past magnetosphere)
Magnetopause shadowing (ions)	yes	yes? (need to understand past ring current)
Plasmaspheric wind and plumes	yes	yes? (need to understand past plasmasphere)

neutrals

both mixed

ions

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Summary

Terrestrial ion behavior has inter-disciplinary aspect on

- Substorms
- Solar wind injection and energy conversion
- Magnetospheric dynamics
- Ionospheric physics
- Ion-neutral interaction
- Space weather
- Evolution of atmosphere and biosphere

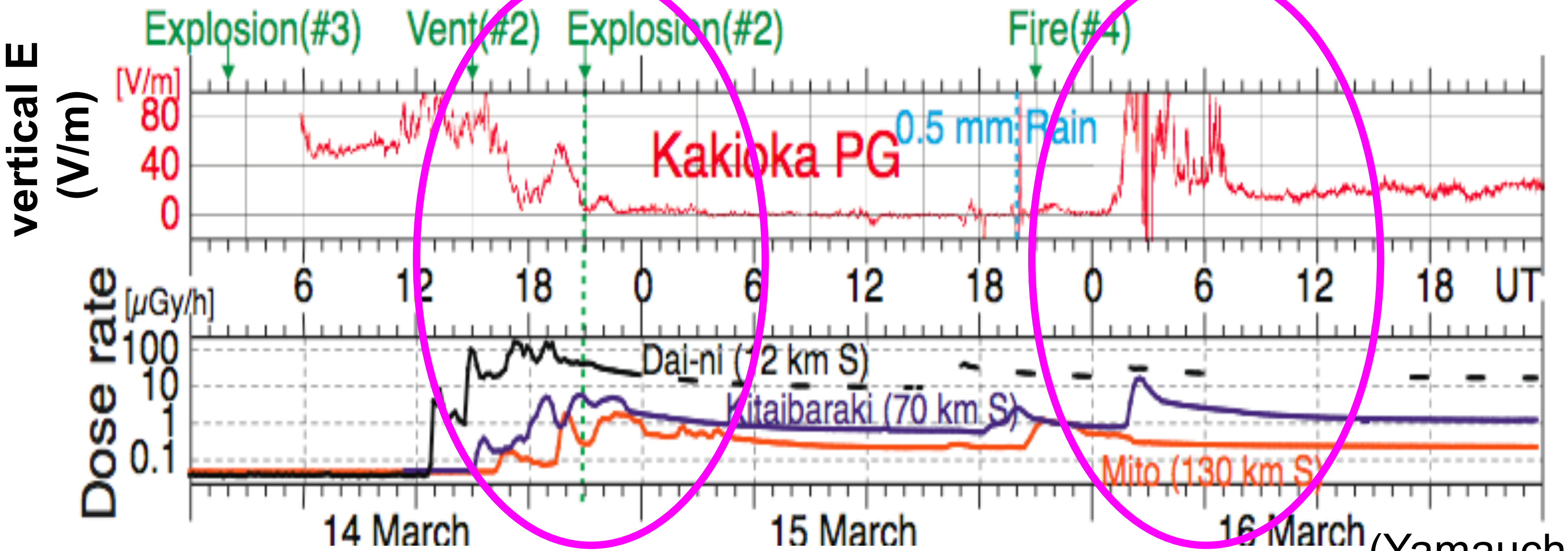
and

- Radioactive hazard

After Fukushima accident, we retrieved motion of radionuclide that ionizes molecules

vertical **E** **= 60 V/m: low σ**

vertical **E** **= 0 V/m: high σ**



(Yamauchi et al., 2012)

Arrival (= high σ) **Blow up by wind (= low σ)**

Summary

- Out of three type of outflow (cold filling, cold supersonic outflow, hot outflow), **hot O^+ alone cause >10 $^{25\text{-}26}$ s^{-1}** mainly though direct entry into the solar wind **in the polar region**.

- Inner Magnetosphere is a **zoo of "un-understood" ions**.

- **Terrestrial** (planetary) **ions plays active roles** in the solar wind interaction with the magnetosphere (extra “open” hole in the open magnetosphere).

- Ion escape influences **evolution of the Earth** in geological scale
  ⇒ *We still need missions to study "escape" (Friday morning).*

- Knowledge of ion dynamics even allows **monitoring radioactive materials**

Thank you

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