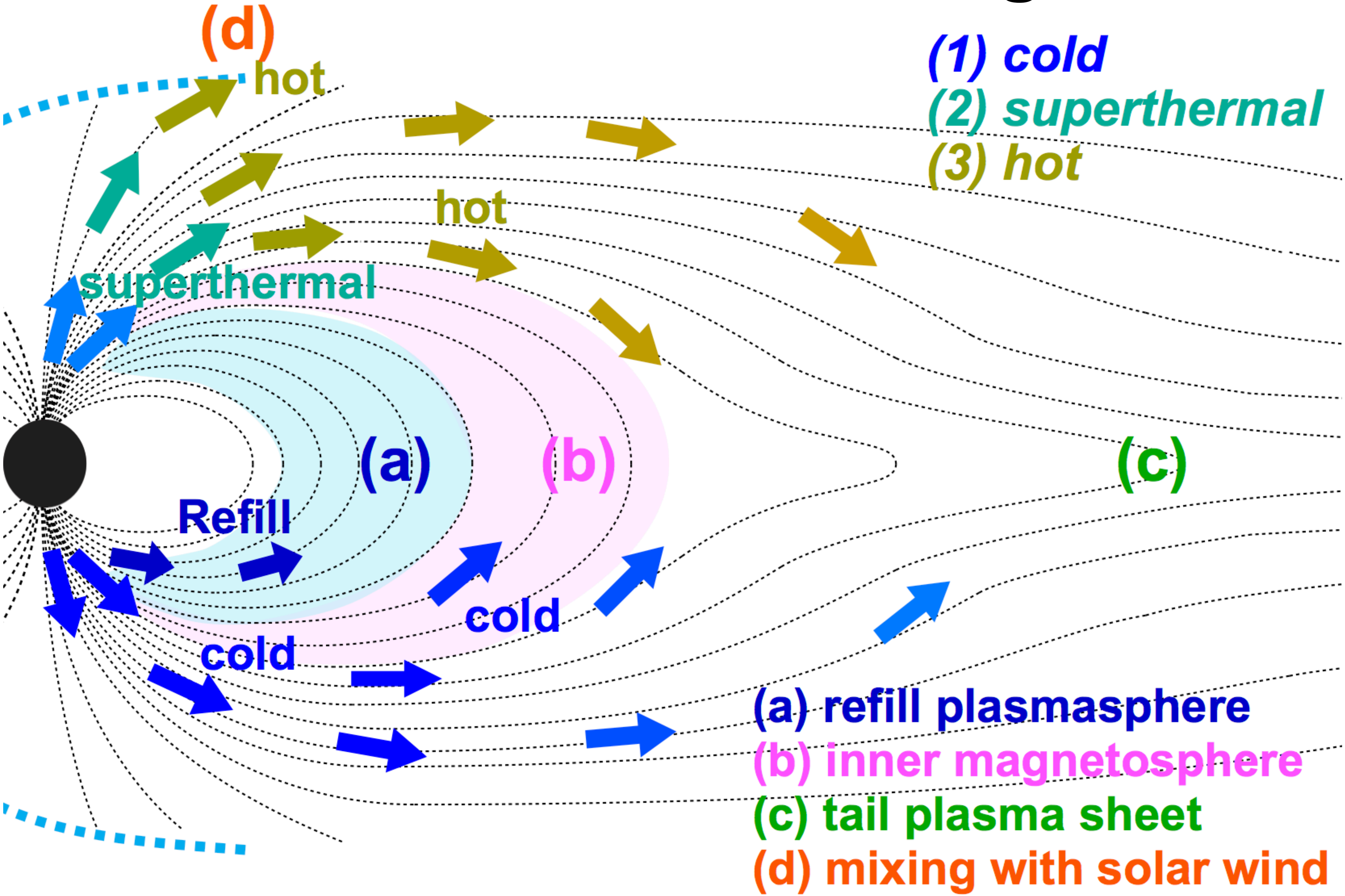
Cluster findings on the heavy ion dynamics and budget

M. Yamauchi[1] and I. Dandouras[2]

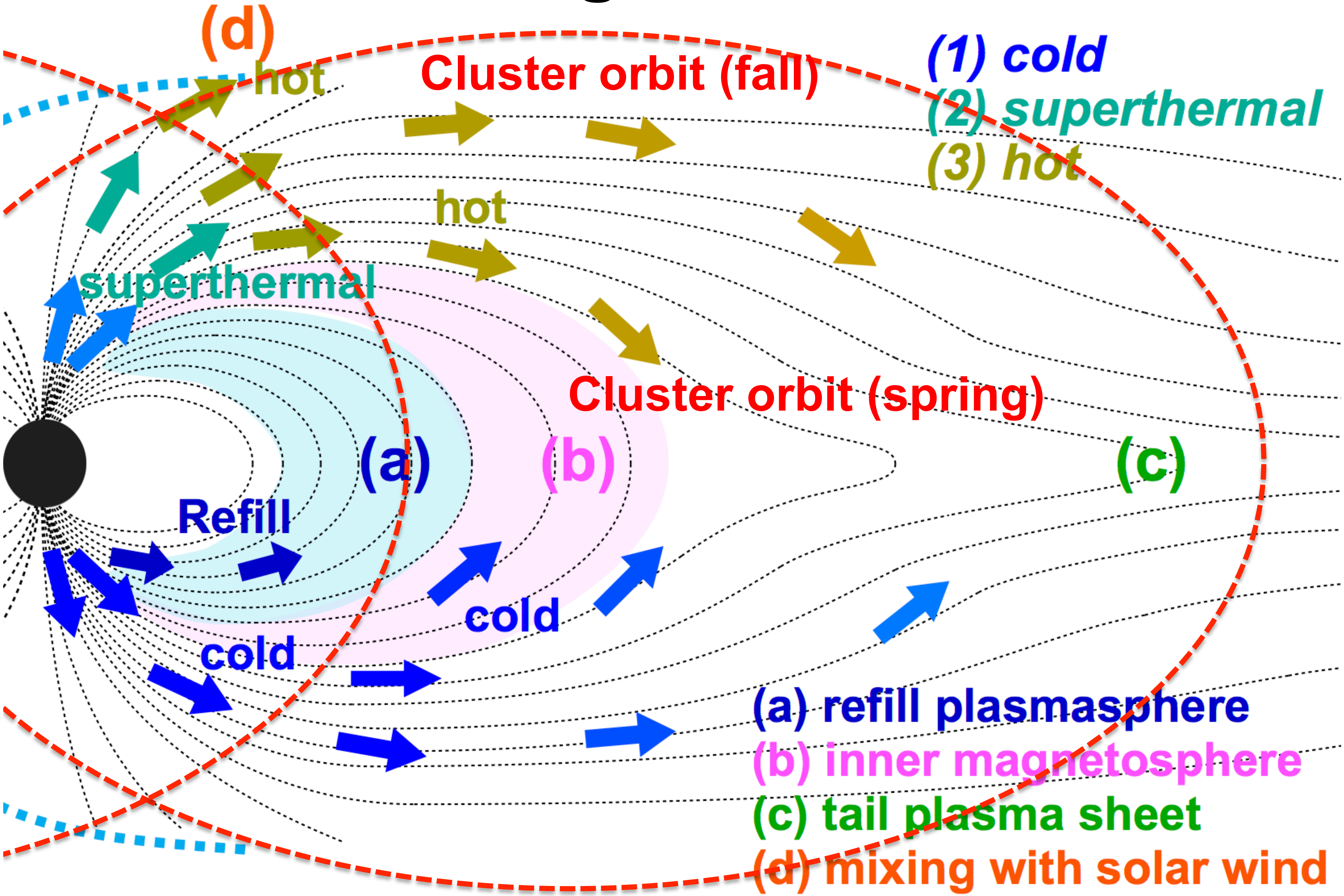
1. *Swedish Institute of Space Physics (IRF), Kiruna*
2. *Institut de Recherche en Astrophysique et Planétologie (IRAP), Toulouse*

Work combines results from CIS-Kiruna team (Hans Nilsson, Rikard Slapak, Audrey Schillings etc)

Destinations of outflowing ions



Advantage of Cluster



Outline

(1) O^+ in the **magnetosheath and plasma mantle** (thanks to the orbit)

⇒ (a) Important route for O^+ escape.

(b) Substantial mass loading and SW dynamo.

(2) O^+ in the **magnetosphere** also escapes

⇒ (a) Magnetotail: more tailward.

(b) Inner magnetosphere: more than half are lost

(1)+(2) Total amount (flux) of heavy ion escape

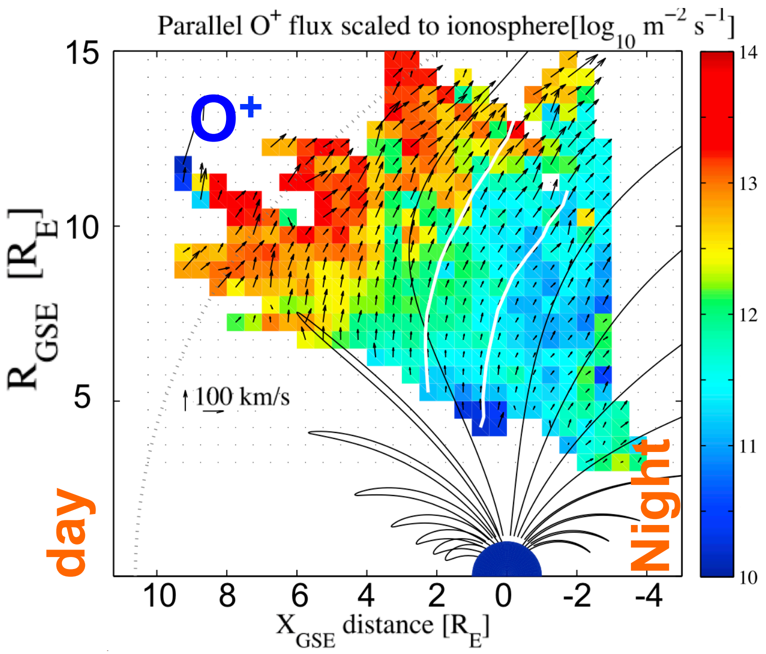
$\sim 10^{25\text{-}26}$ per second.

(3) Returning O^+ (and H^+/He^+) forms **"zoo" of keV & sub-keV ion distribution**

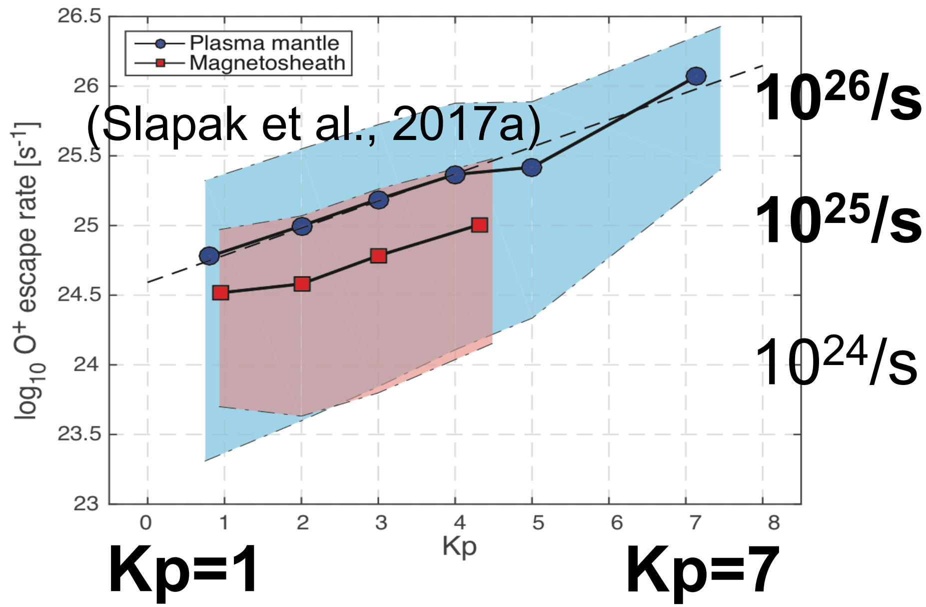
⇒ (a) Time-dependent E-field is important for sub-keV "zoo".

(b) Mass-dependent energy distribution (against drift/fluid theory).

(1a) mantle/sheath: CIS O⁺ (2001-2005)

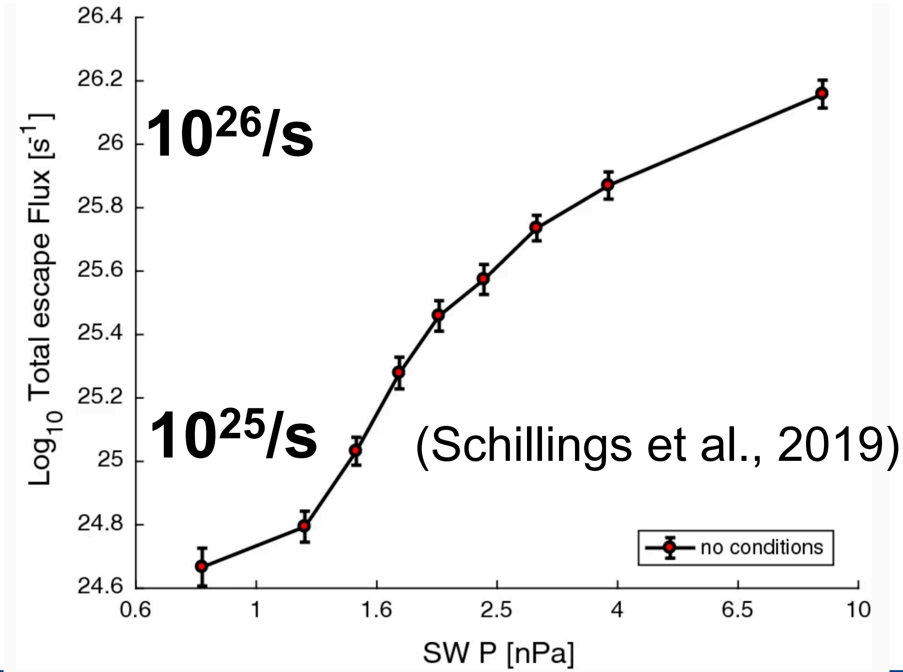


(Nilsson et al., 2012)



O⁺ direct loss ~ $10^{25\text{-}26}$/s

$\propto \exp(0.45 \cdot Kp)$



M. Yamauchi
Kiruna, Sweden

(1b) O^+ inside solar wind = Mass Loading

Mass loading = inelastic mix
⇒ **kinetic energy (K) is not conserved**
($\Delta K/K = \Delta u/u$= deceleration rate)
⇒ Electric energy ⇒ **ionosphere via $J_{//}$**

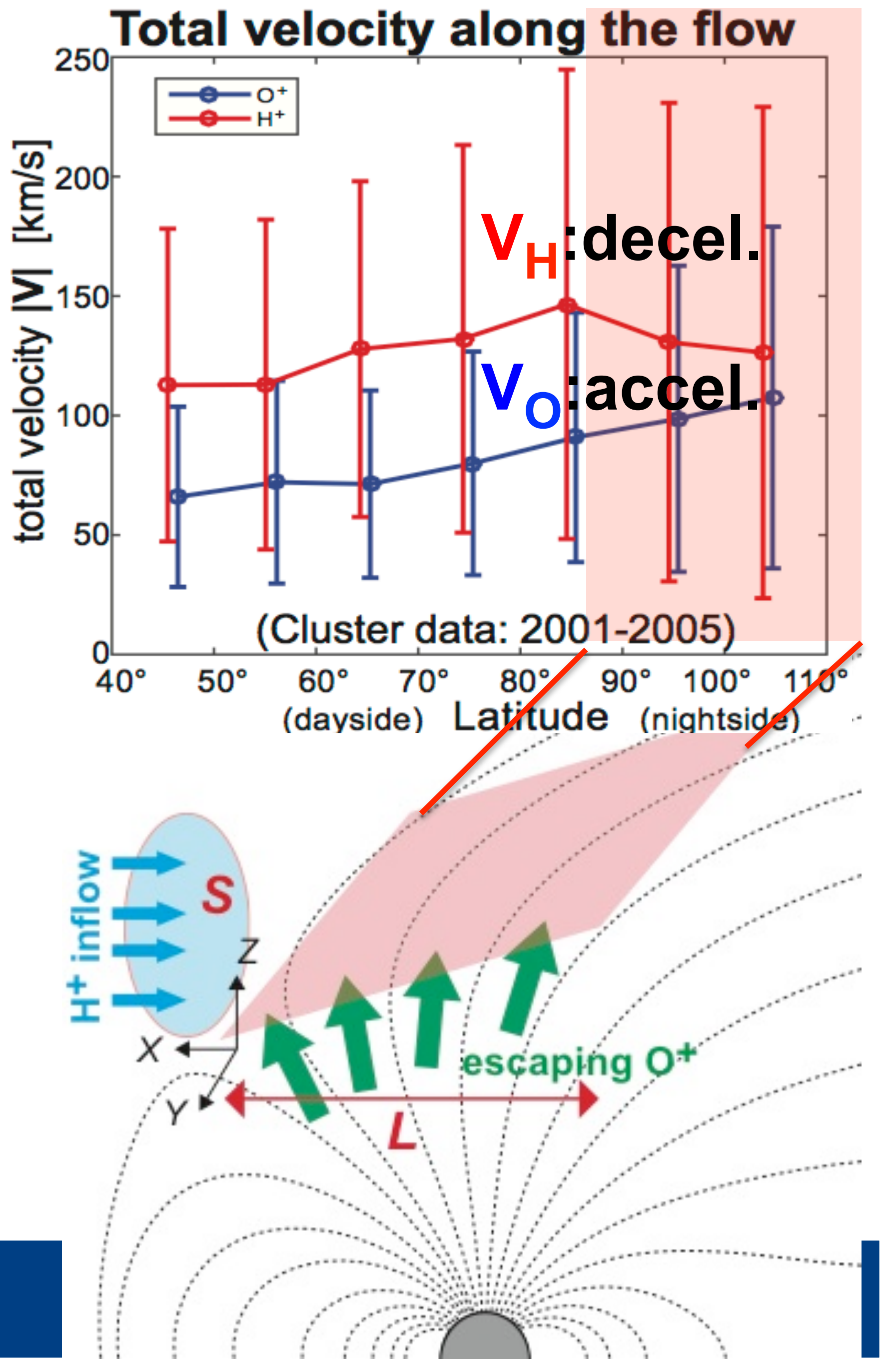
amount is substantial

$\Delta K \approx (-1/4)\cdot u^2_{SW}\cdot$loaded-mass-flux

$\approx 10^{9\text{-}10}$ **W** for O^+ flux $\approx 10^{25\text{-}26}$/s

⇒ Explains **cusp current** system
(both amount + independency)

(Yamauchi and Slapak, 2018)



- **IMF B_Z < 0: extra open (but deceleration)**
- **IMF B_Z > 0: extra deceleration = stagnate**
⇒ multiple injection by M-I coupling?

Outline

(1) O^+ in the magnetosheath and plasma mantle (thanks to the orbit)

⇒ (a) Important route for O^+ escape.

(b) Substantial mass loading and SW dynamo.

(2) O^+ in the magnetosphere also escapes

⇒ (a) Magnetotail: more tailward.

(b) Inner magnetosphere: more than half are lost

(1)+(2) Total amount (flux) of heavy ion escape

~ $10^{25\text{-}26}$ per second.

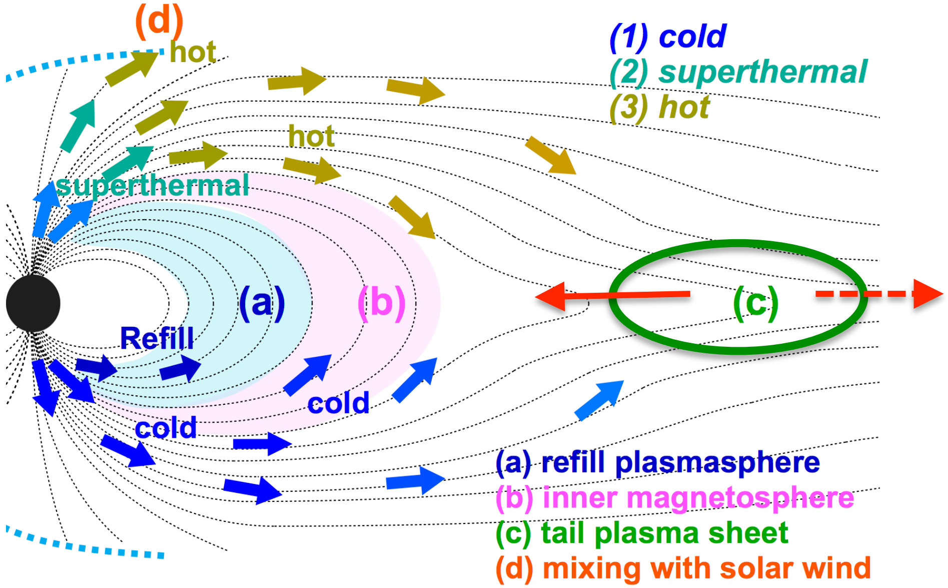
(3) Returning O^+ (and H^+/He^+) forms "zoo" of keV & sub-keV ion distribution

⇒ (a) Time-dependent E-field is important for sub-keV "zoo".

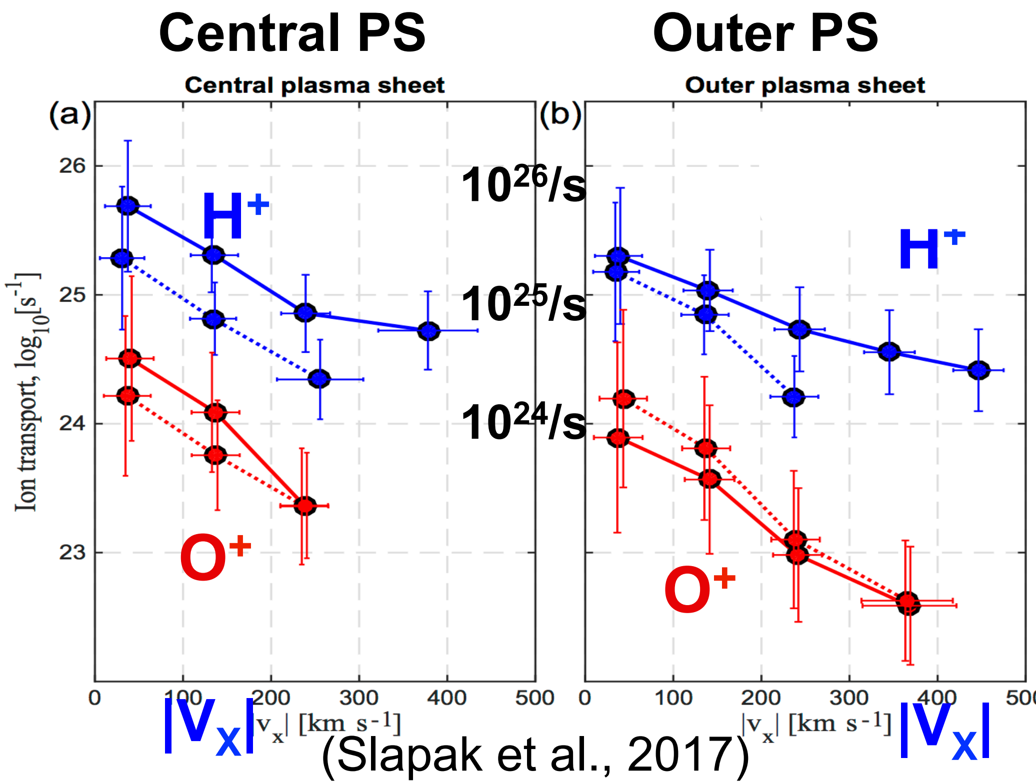
(b) Mass-dependent energy distribution (against drift/fluid theory).

(2a) Fate of ions: tail plasma sheet

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



Cluster/CIS (2001-2005)



nearly half-half

⇒ **Net Earthward $O^+ \sim 10^{24}$ s^{-1}**

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

earthward ($O^+ \sim 0.6\times10^{25}$ s^{-1})

tailward ($O^+ \sim 0.5\times10^{25}$ s^{-1})

M. Yamauchi
Kiruna, Sweden

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**

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

(b) magnetotail 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^+ (**<0.3 for O^+**) ⇒ 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^+ (average **<0.1 for O^+**)

Wind : **50** for H^+ (**<0.5 for O^+**)

(Darrouzet et al. 2009, Dandouras et al. 2013)

But important at 3 Gyr ago

Outline

(1) O^+ in the magnetosheath and plasma mantle (thanks to the orbit)
⇒ (a) Important route for O^+ escape.
(b) Substantial mass loading and SW dynamo.

(2) O^+ in the magnetosphere also escapes
⇒ (a) Magnetotail: more tailward.
(b) Inner magnetosphere: more than half are lost

(1)+(2) Total amount (flux) of heavy ion escape
~ $10^{25\text{-}26}$ per second

(3) Returning O^+ (and H^+/He^+) forms "zoo" of keV & sub-keV ion distribution
⇒ (a) Time-dependent E-field is important for sub-keV "zoo".
(b) Mass-dependent energy distribution (against drift/fluid theory).

Outline

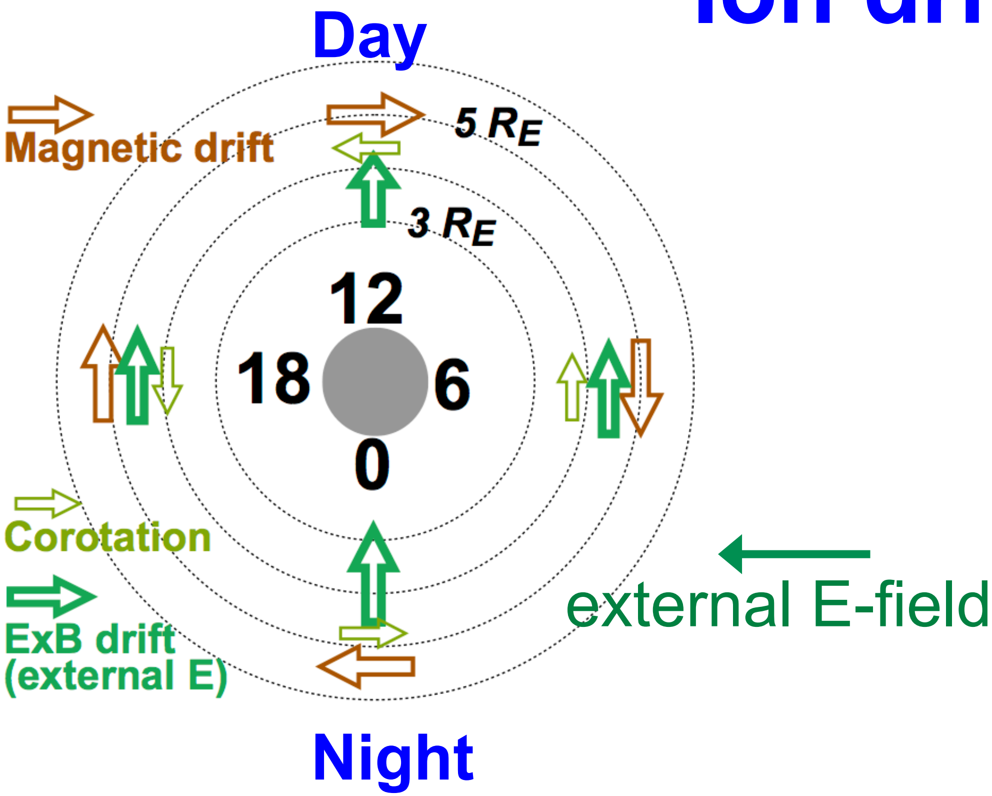
(1) O^+ in the magnetosheath and plasma mantle (thanks to the orbit)
⇒ (a) Important route for O^+ escape.
(b) Substantial mass loading and SW dynamo.

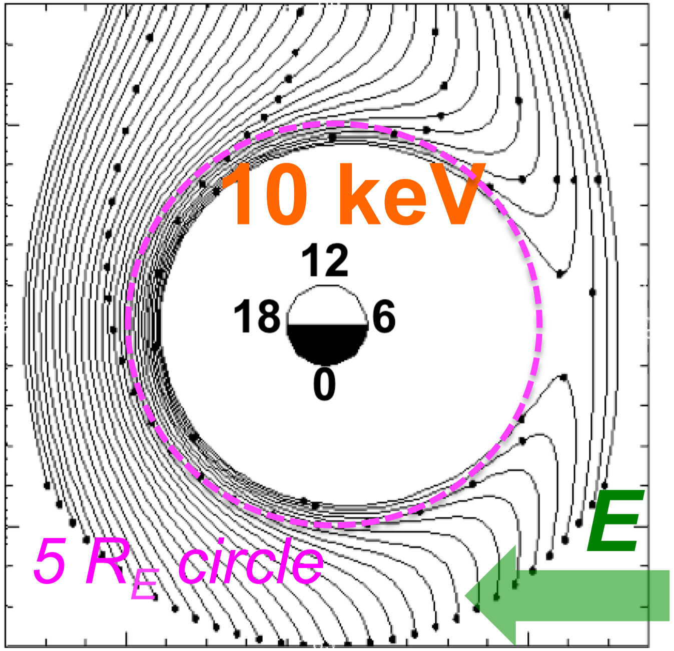
(2) O^+ in the magnetosphere also escapes
⇒ (a) Magnetotail: more tailward.
(b) Inner magnetosphere: more than half are lost

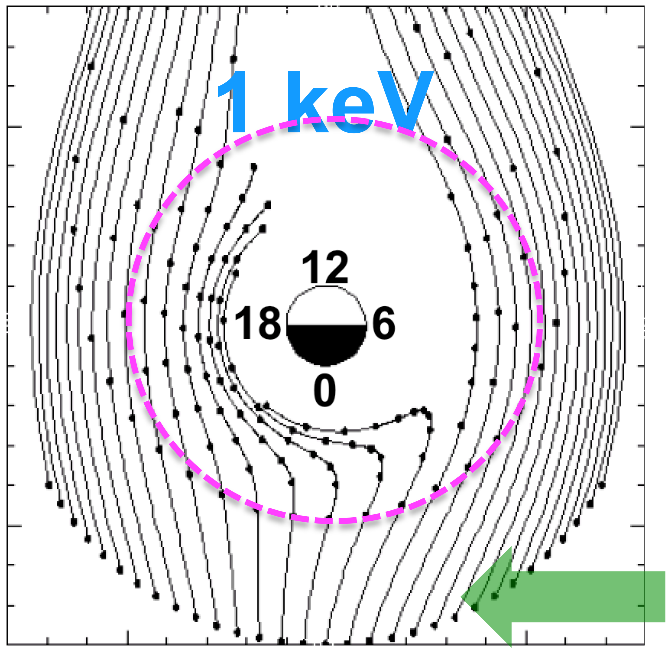
(1)+(2) Total amount (flux) of heavy ion escape
~ $10^{25\text{-}26}$ per second.

(3) Returning O+ (and H+/He+) forms "zoo" of keV & sub-keV ion distribution
⇒ (a) Time-dependent E-field is important for sub-keV "zoo".
(b) Mass-dependent energy distribution (against drift/fluid theory).

Ion drift







electric drift: $|V_E|$ = |E|/|B| only

magnetic drift: $|V_B|$ ∝ Energy and B only

$$V_B = \frac{3g(\alpha)W}{qRB}$$

⇒ **same V_{Drift}** for same energy **for all mass**

But, this is **just a model**

$v_d \cdot E > 0$ ⇒ adiabatic energization

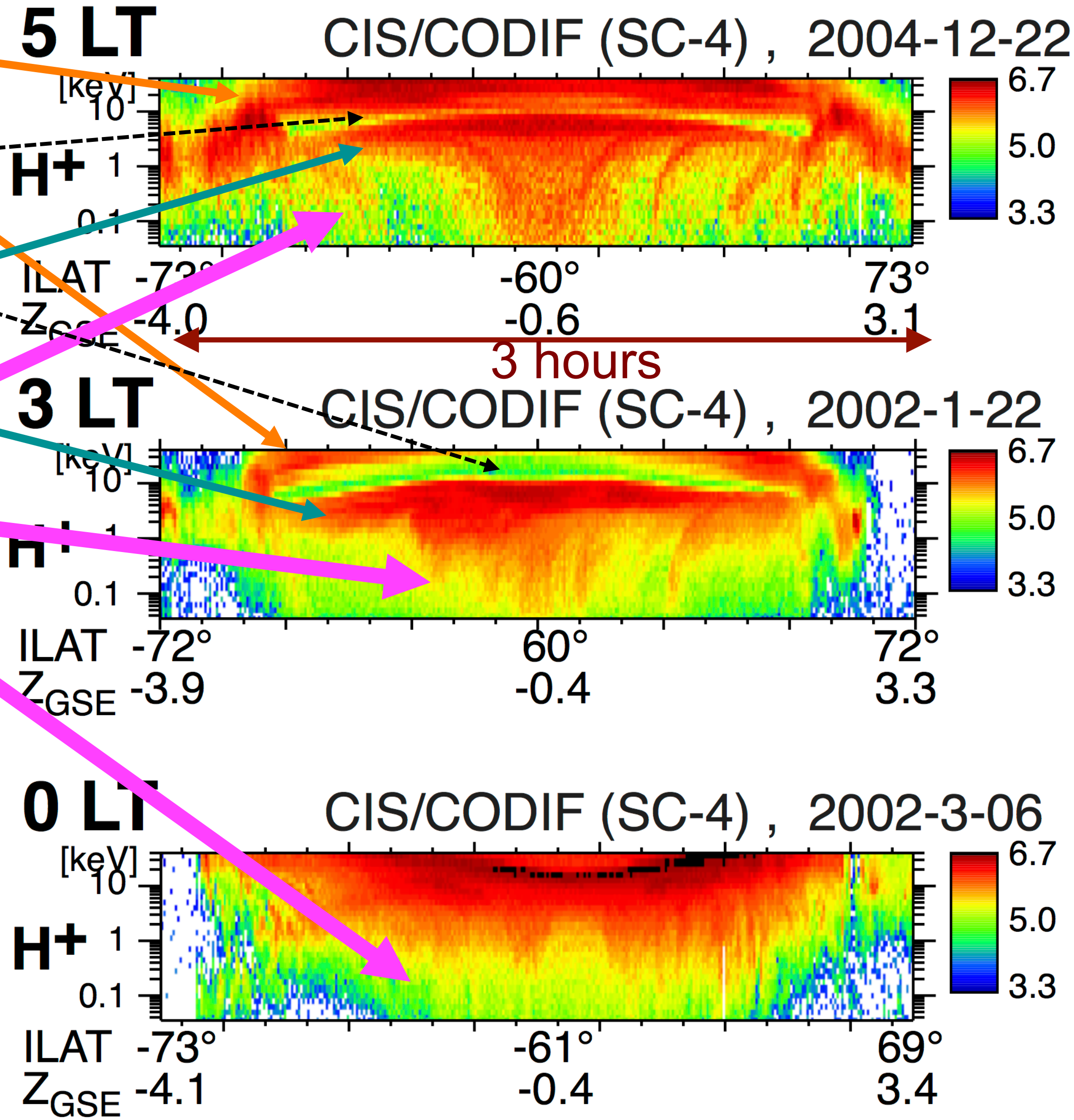
Three basic populations

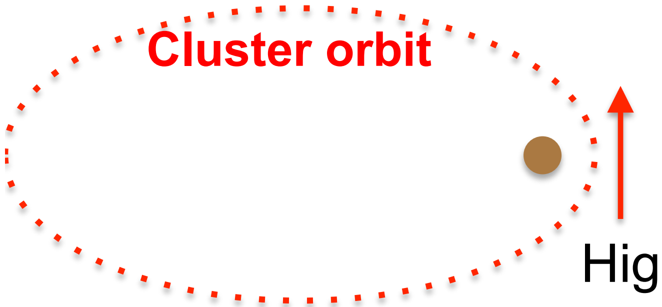
accelerated plasma sheet (westward drift)

energy gap

plasma sheet (eastward ExB drift)

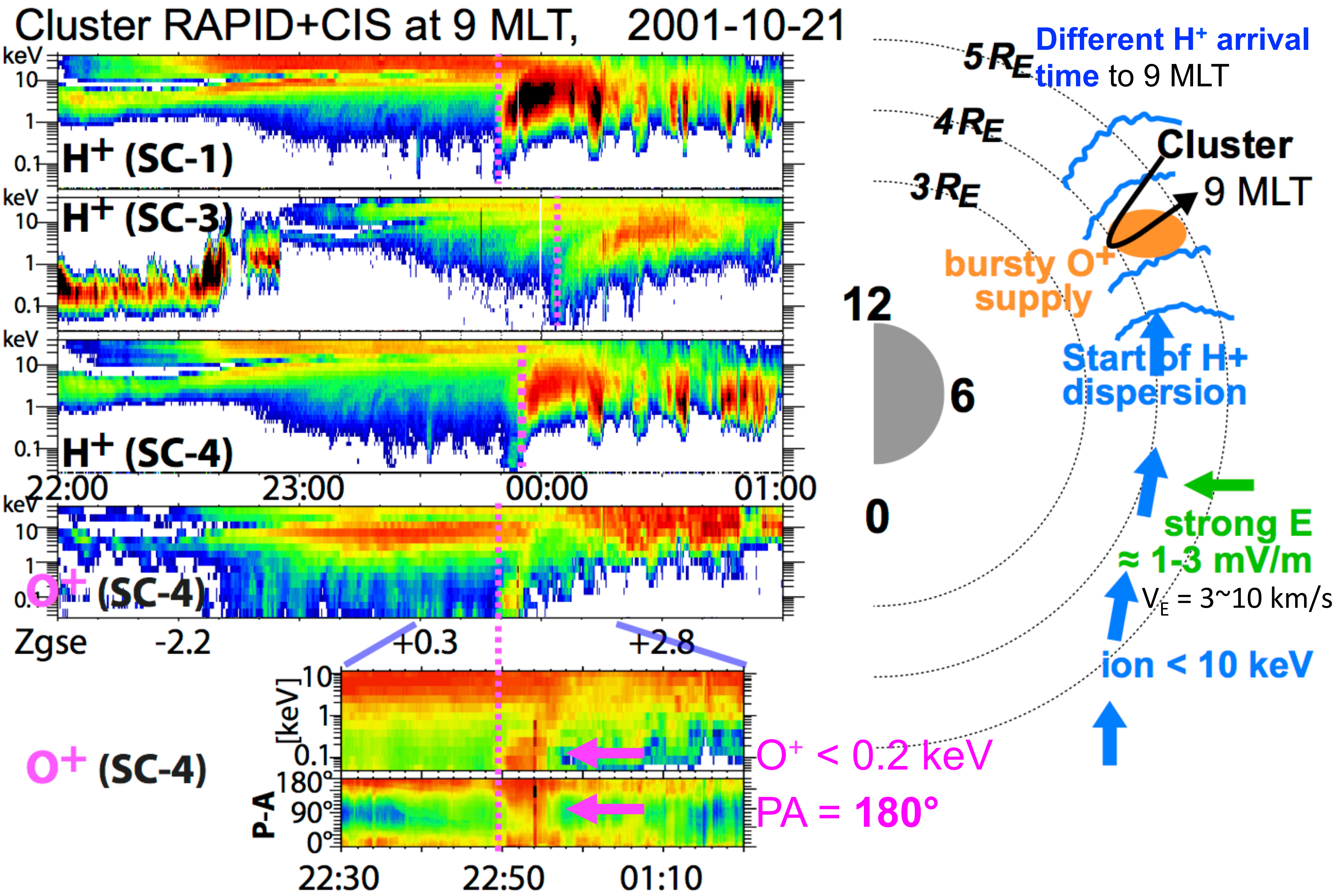
superthermal (<50 eV) intermittent supply





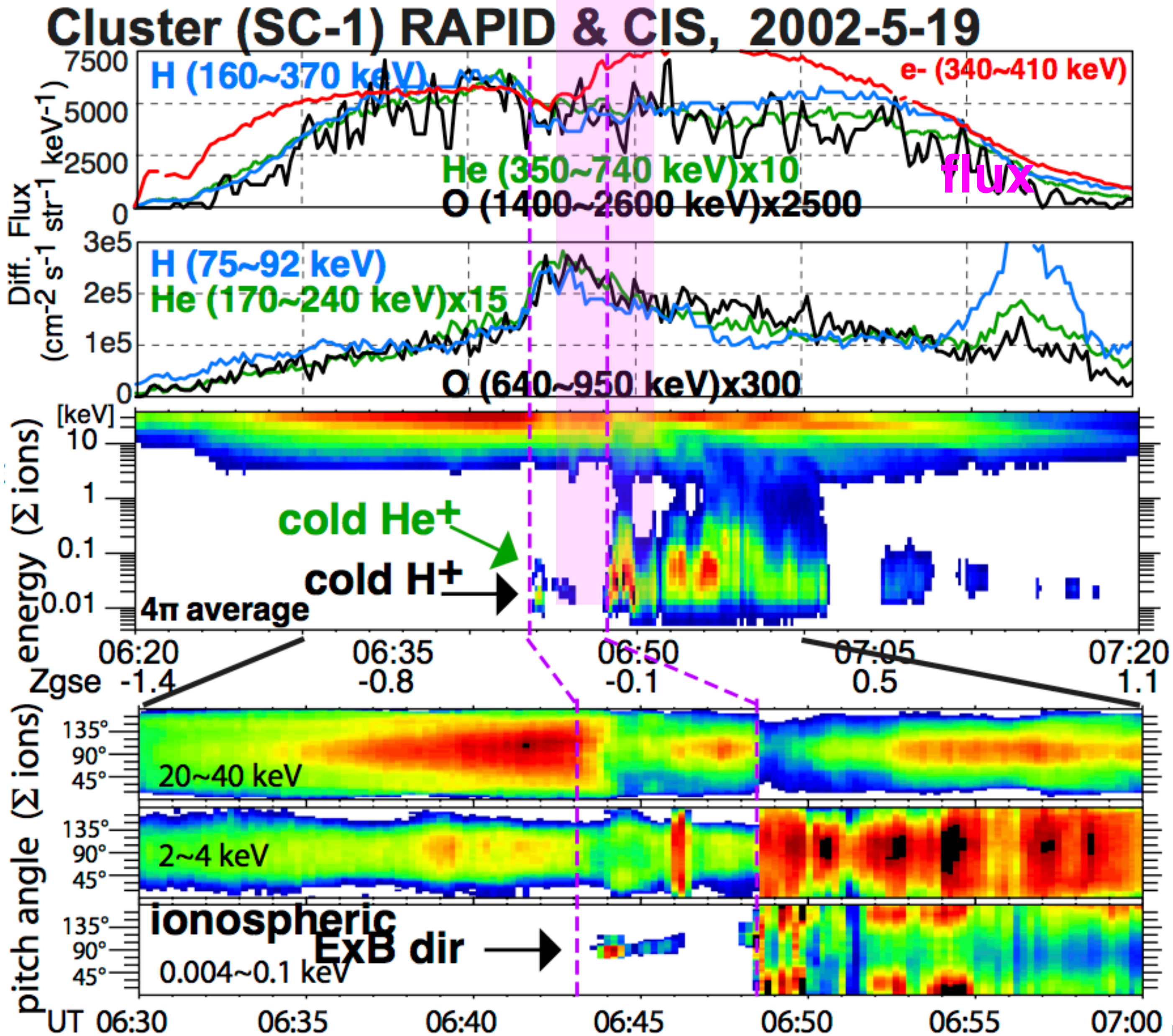
Highly elliptic orbit ⇒ traverses inner magnetosphere quickly

dayside source vs drift motion @substorm



mass mystery 1: Velocity-dependent drift

cf. same V_{Drift} for same energy



ions > 5000 km/s

ions ≈ 3000 km/s

@Sudden E

(~ 10mV/m)

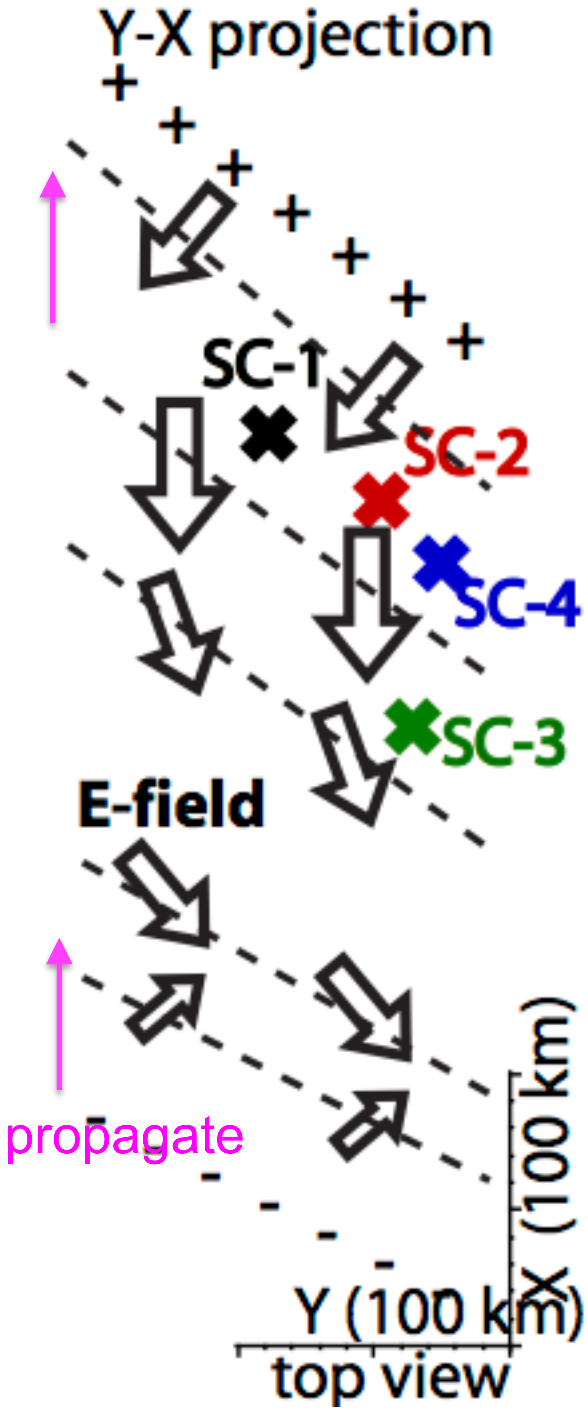
CIS ∑ions

PA ∑ions

(Yamauchi et al., 2009)

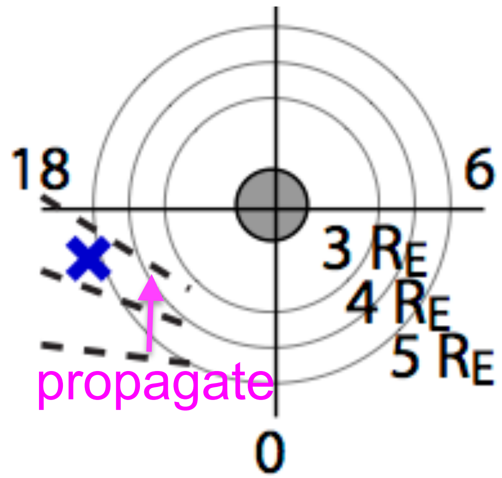
M. Yamauchi
Kiruna, Sweden

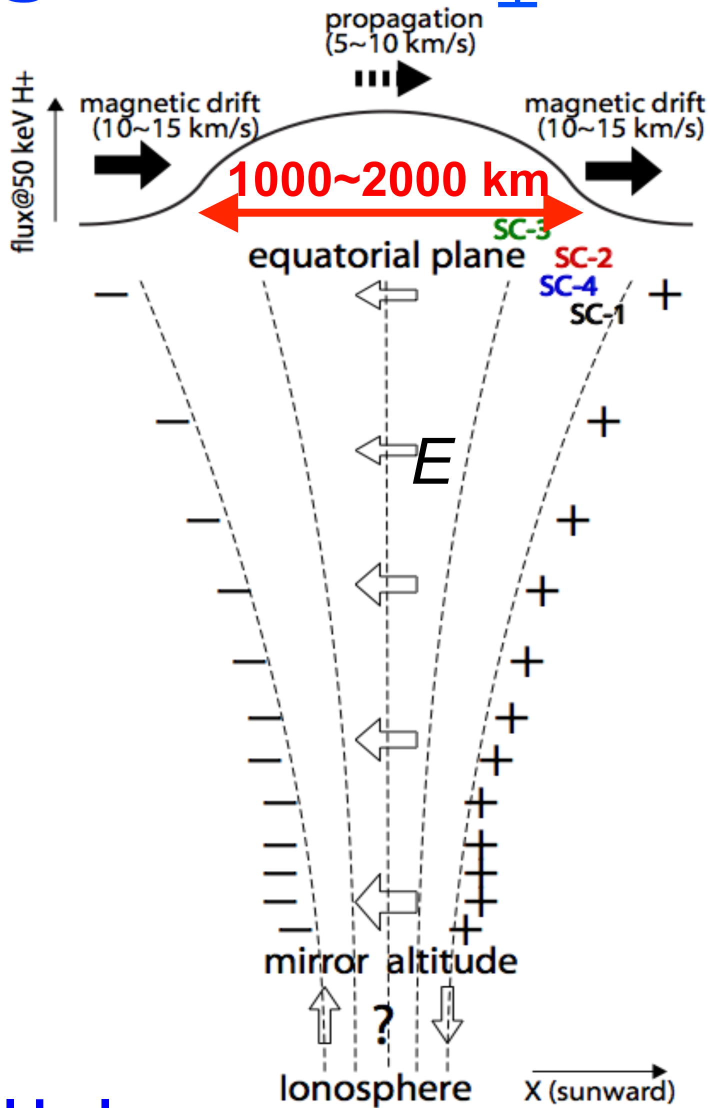
This event = @Propagating auroral $E_{\perp}$



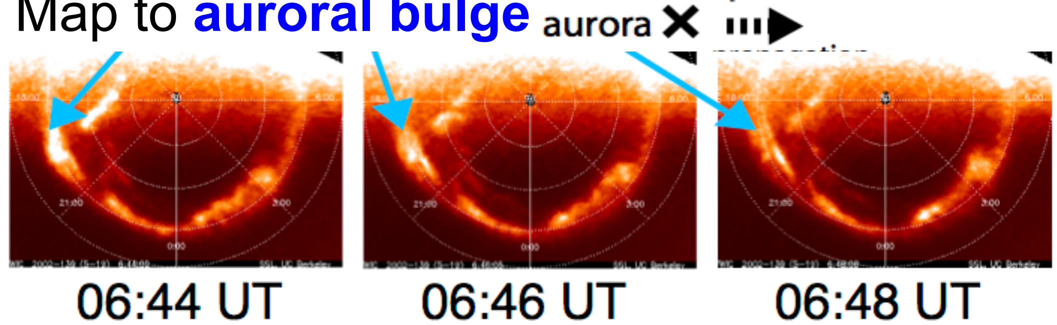
Timing by SC1 - SC4

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



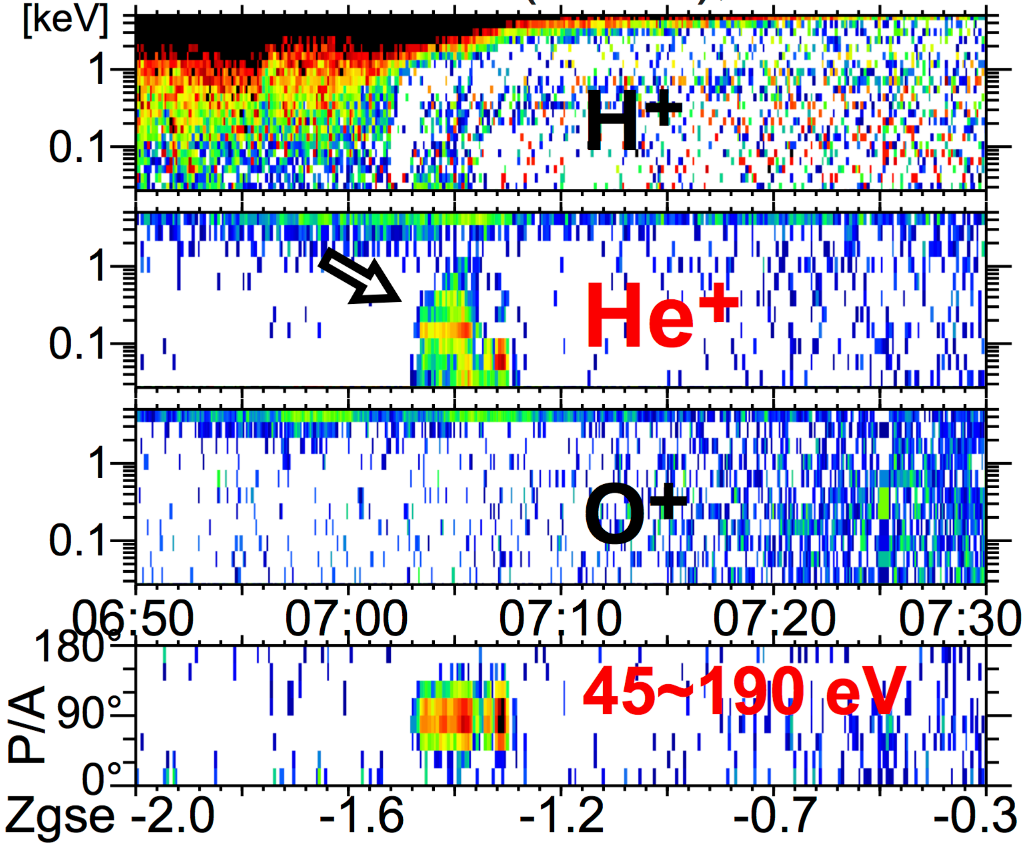


Map to **auroral bulge**

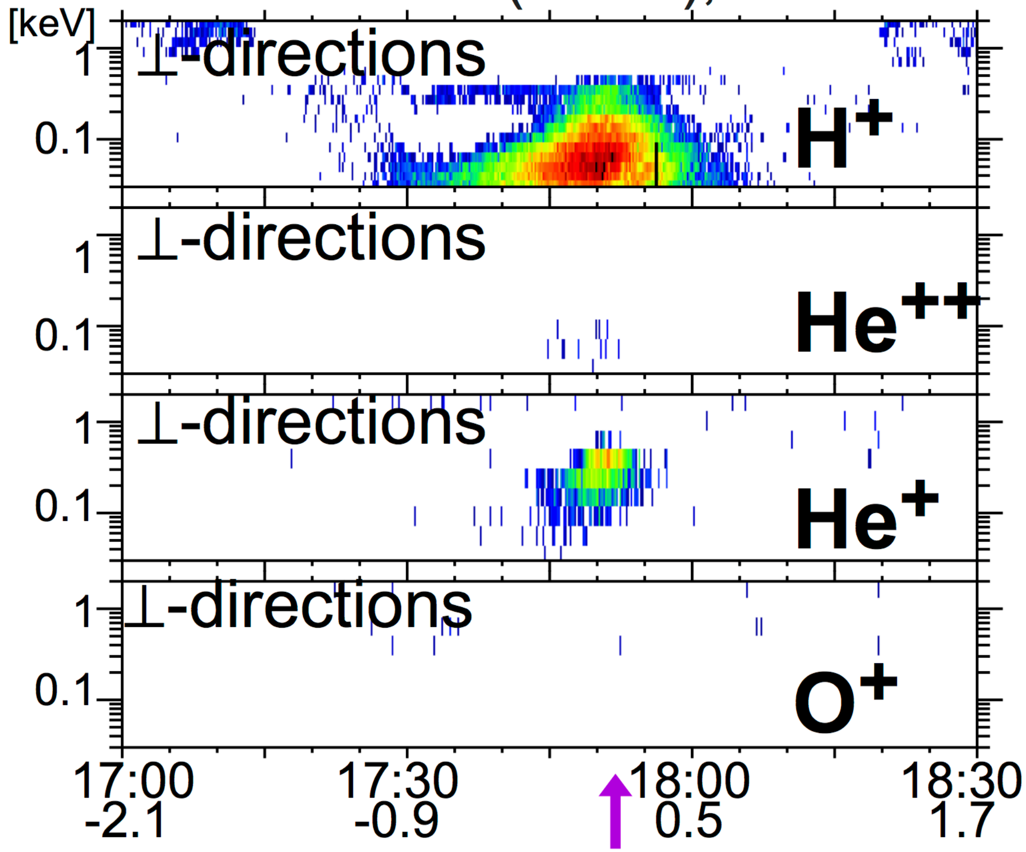


mass mystery 2: Local ⊥ heating

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)

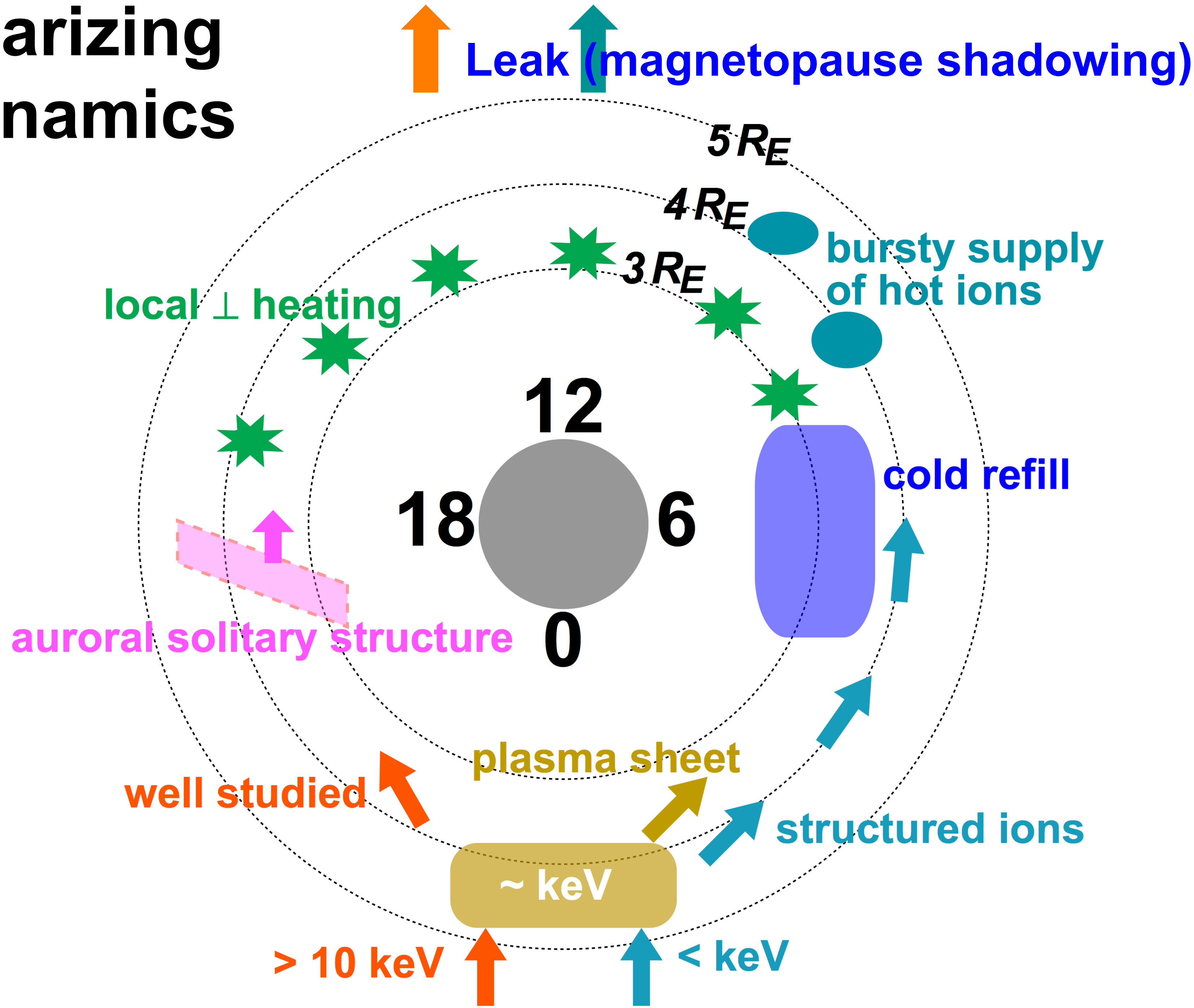
(Yamauchi et al., 2014)

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)

Summarizing ion dynamics



M. Yamauchi
Kiruna, Sweden

Summery

(1) **Hot O^+ escape** ($10^{25\text{-}26}$ s^{-1}) to the solar wind **in the polar region**

- Sufficient amount to explain the cusp current system
- Strong dependence on Kp/Solar wind

⇒ We expect >**10^{27} s^{-1}** in early Earth

(2) Nearly half of **O^+** in the magnetosphere also escapes ($10^{25\text{-}26}$ s^{-1})

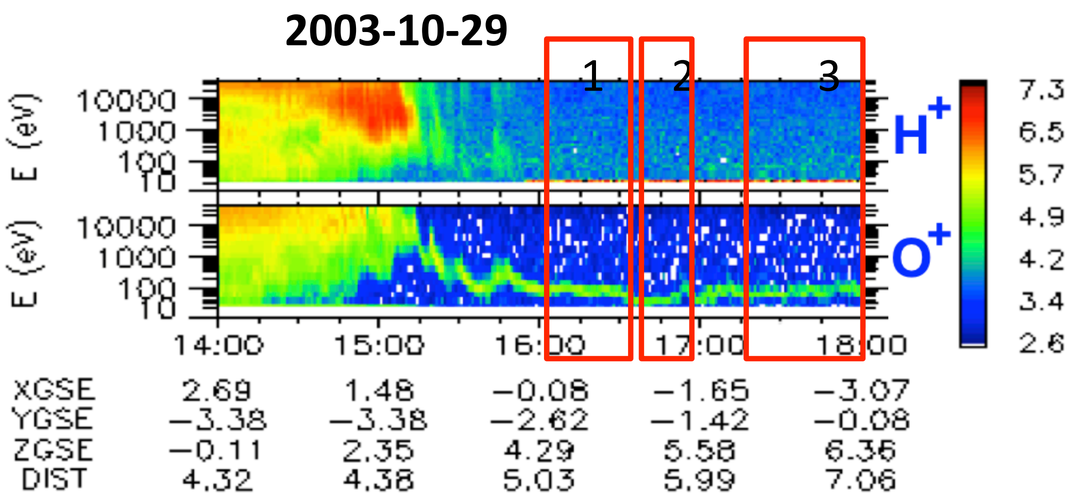
⇒ together with (1), may affect evolution of life

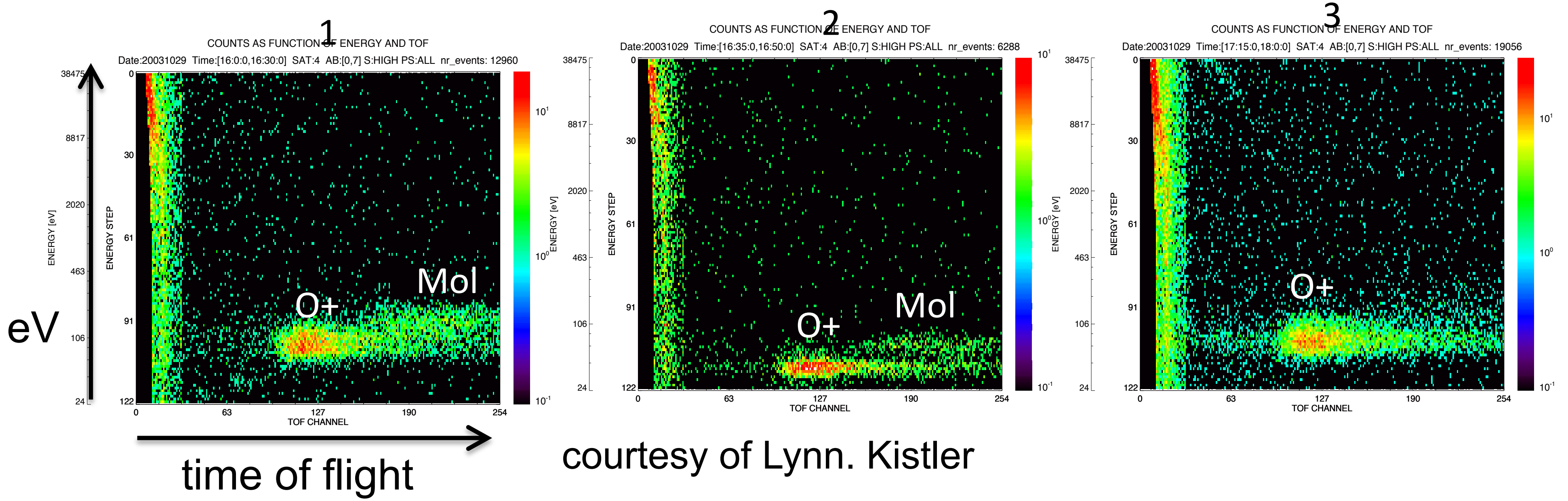
(3) Returning (+directly entering) ions **form "zoo" of ion distribution**

- We now understand sources/routes of all components
- But some mystery (particularly mass-dependency) remains

(4) Cluster even observed molecular ions (O_2^+ or NO^+ or N_2^+)

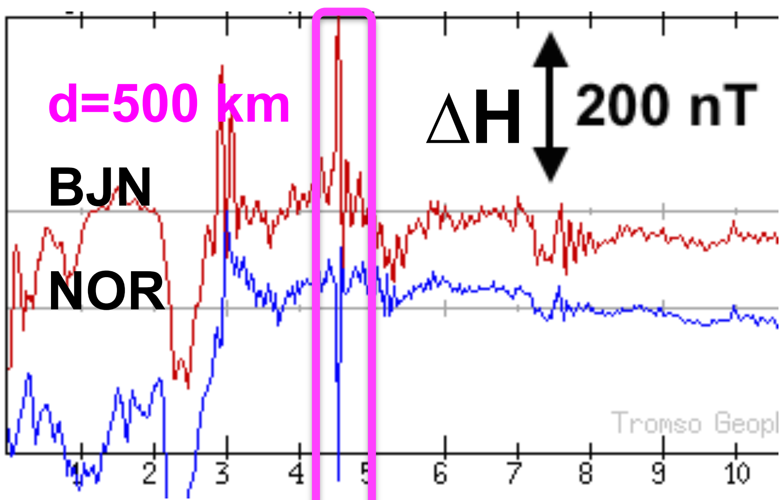
Molecular ions detected by CIS

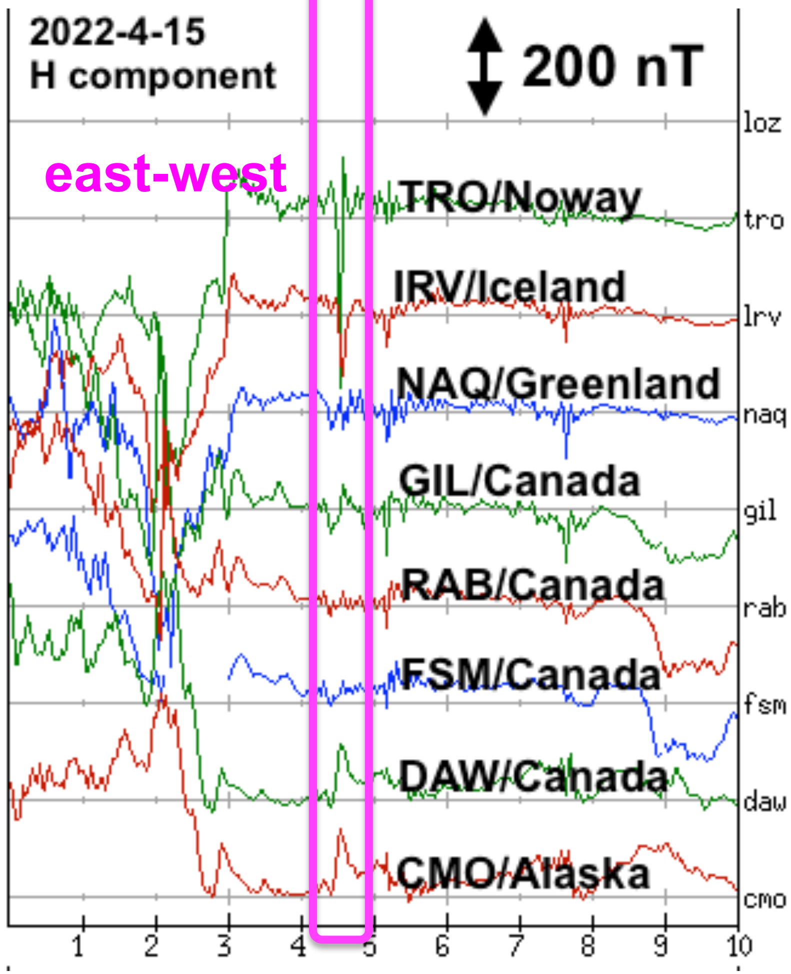


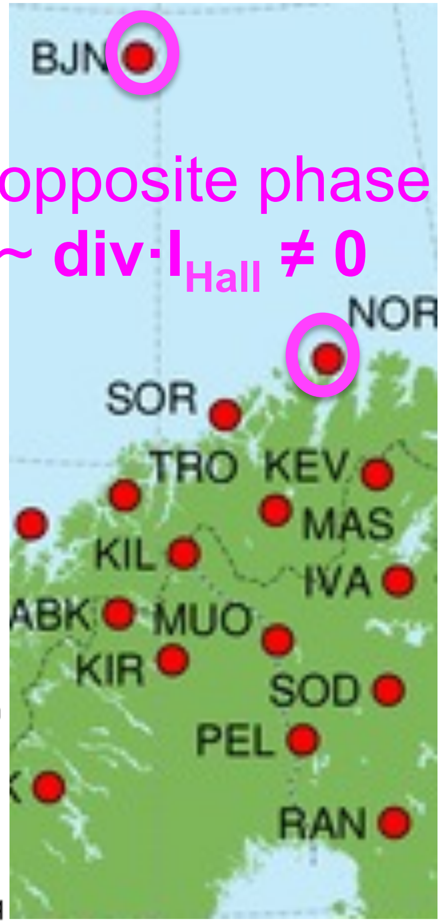


courtesy of Lynn. Kistler

⇒ ISSI activity now (topic that requires future mission)







opposite phase
~ div·I_{Hall} ≠ 0

DSCOVR@L1
V_{SW}=480 km/s
B_Z=+11 nT

04:00 UT: 27.5/cm^3
04:01 UT: 29.1/cm^3
04:02 UT: 31.3/cm^3
04:03 UT: 27.8/cm^3
04:04 UT: 26.6/cm^3

SOHO@L1
V_{SW}=530 km

03:52 UT: 17.5/cm^3
03:57 UT: 17.7/cm^3
04:02 UT: 18.6/cm^3
04:07 UT: 14.7/cm^3

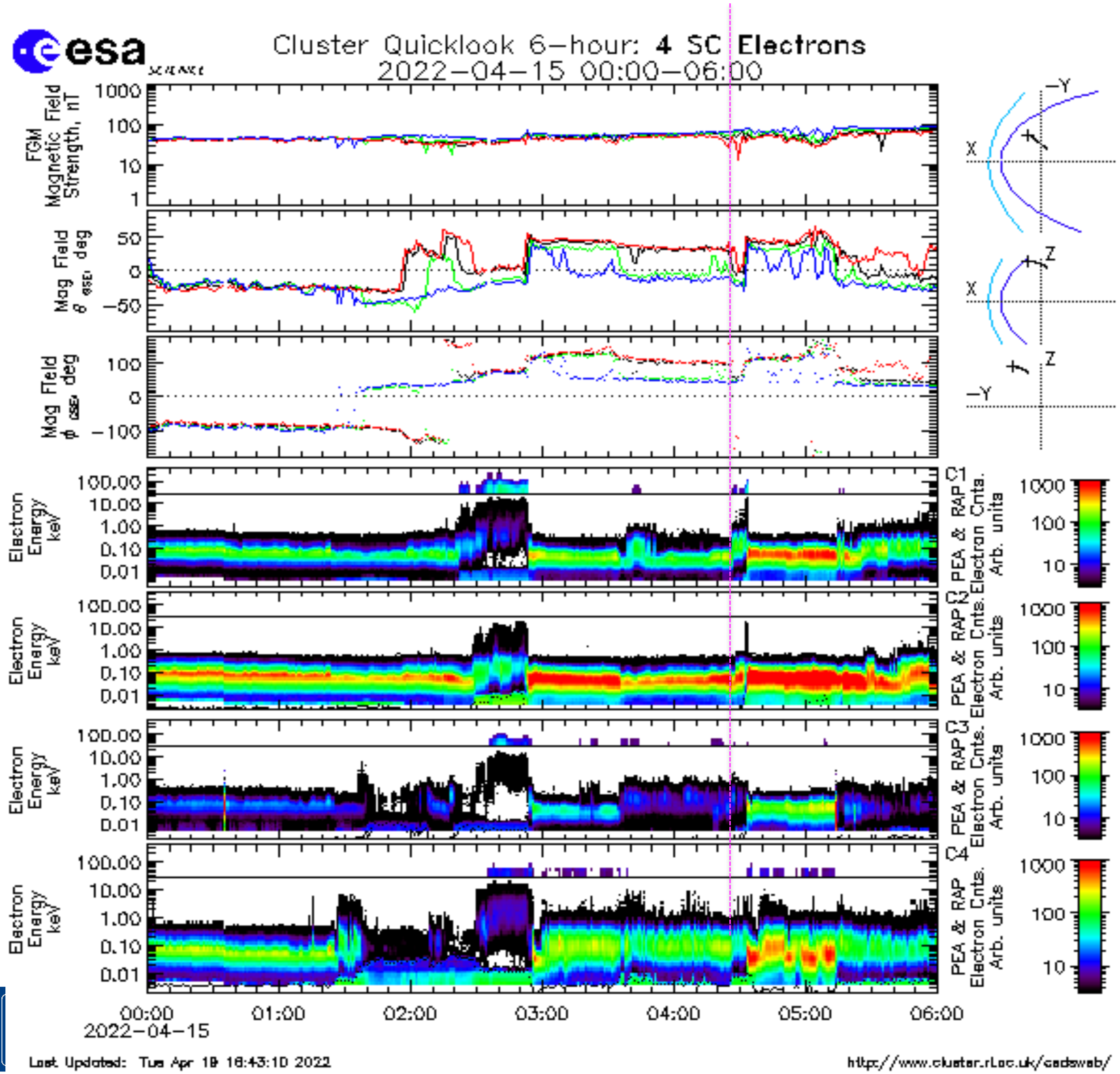
ACE@L1
V_{SW}=500 km/s
B_Z=+12~14 nT

3:45 UT: 0.9/cm^3
3:50 UT: 0.7/cm^3
3:55 UT: 1.4/cm^3
4:00 UT: 0.8/cm^3
4:05 UT: 0.7/cm^3

High-latitude: Sudden commencement level big
Isolated spike in **dawn over > 80°longitude**
⇒ no similar event in past

Low-latitude: Sudden commencement-like
compression (wide dayside)

M. Yamauchi
Kiruna, Sweden



MAG

Bz dip @ SC-2 then SC-4

electron

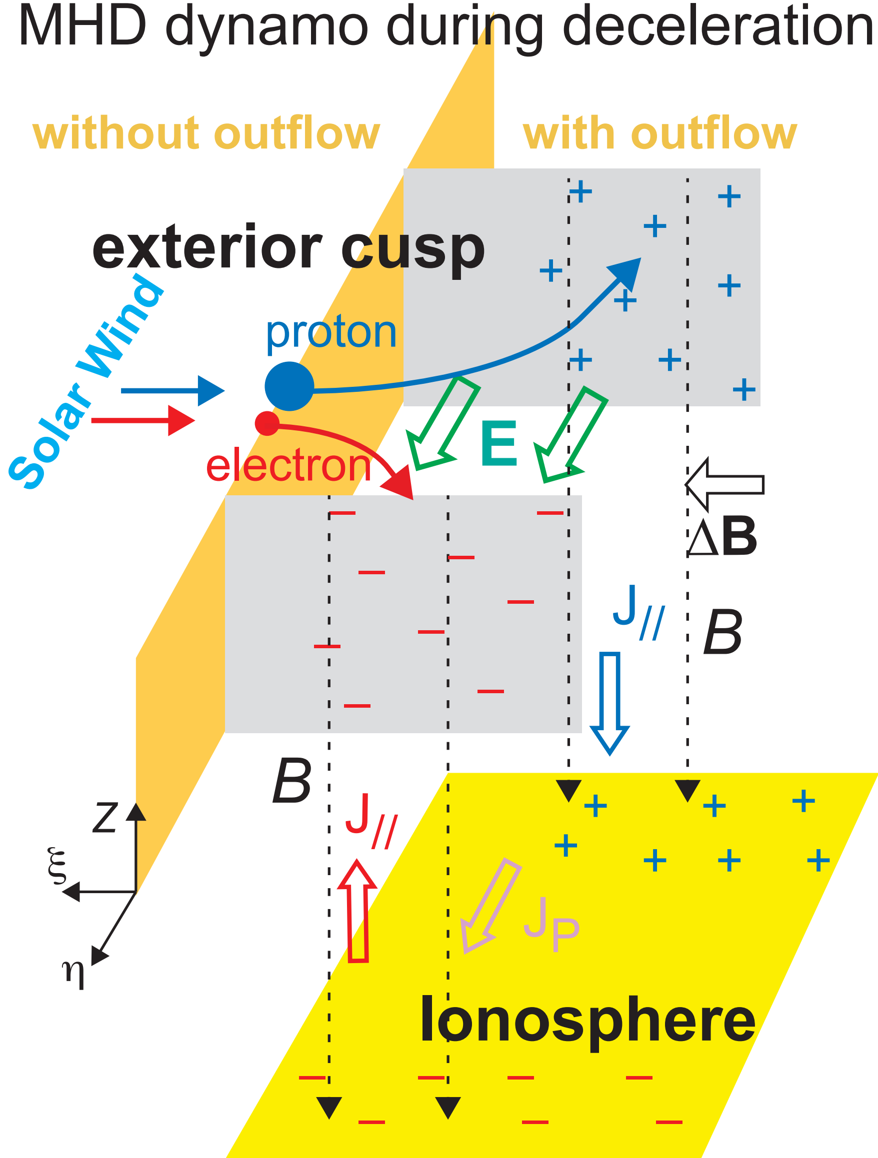
M. Yamauchi
Kiruna, Sweden

Extra slides: Budget

M. Yamauchi
Kiruna, Sweden

Consequence of localized Mass Loading

MHD dynamo during deceleration



$\Delta K \approx (-1/4)\cdot u^2_{SW}\cdot$loaded-mass-flux

$\approx$ **$10^{9\text{-}10}$ W** for O^+ flux $\approx 10^{25\text{-}26}$/s

⇒ Explains **cusp current** system

(both amount + independency)

⇒ **Two type of "open"**:

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

Energy 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}

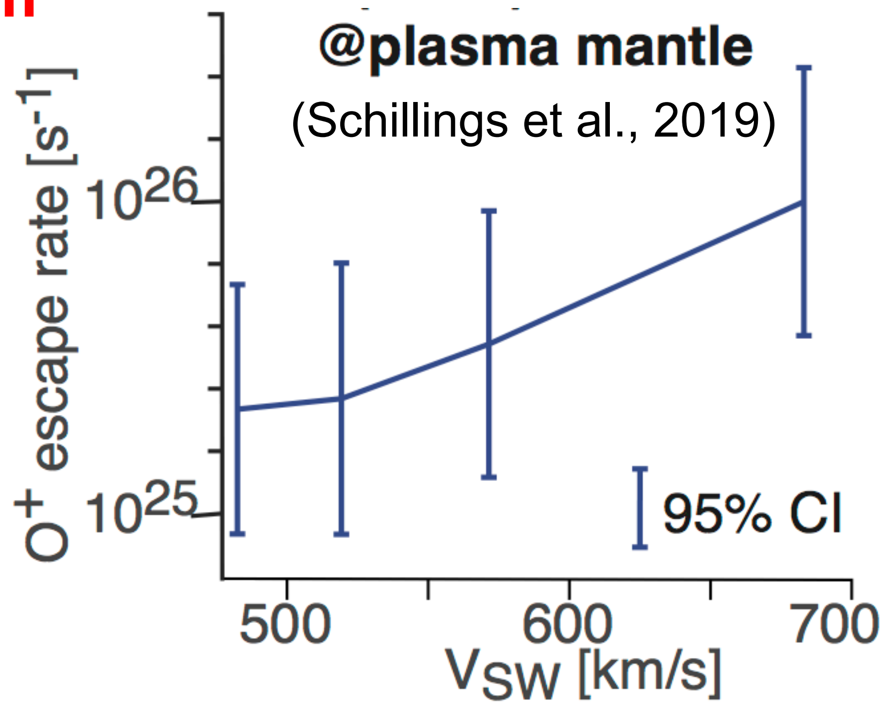
⇒ **Can explain cusp current system**

(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?**

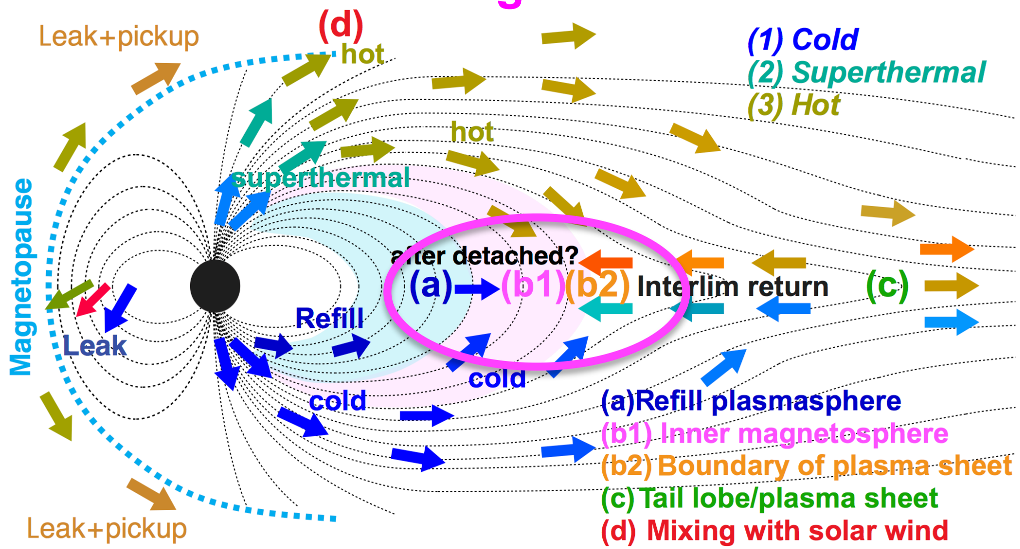
(not all are understood)

M. Yamauchi
Kiruna, Sweden

(2b) Fate of ions: inner magnetosphere

Zoo of different route: return O^+ + direct entry O^+ + cold O^+ refill

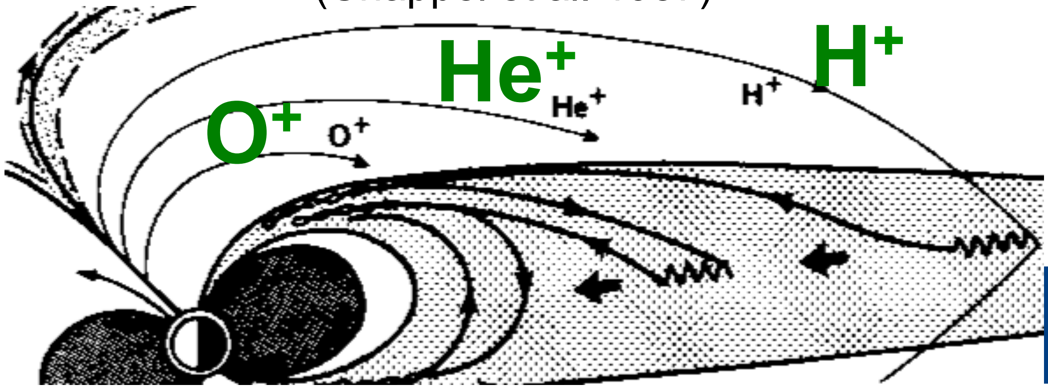
Returned O^+ from magnetotail



(i) Magnetopause shadowing (100% escape)
(ii) Charge exchange (50% escape)
(iii) Pitch-angle scattering to loss-cone (return)

direct supply of **suprathermal O^+** (ii + iii only)

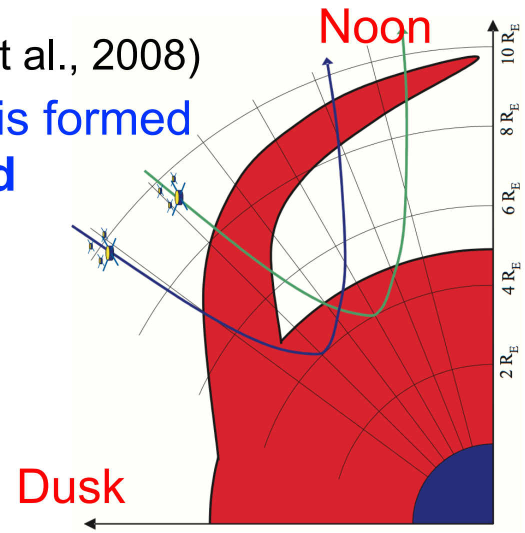
(Chappel et al. 1987)



Cold O^+ refill

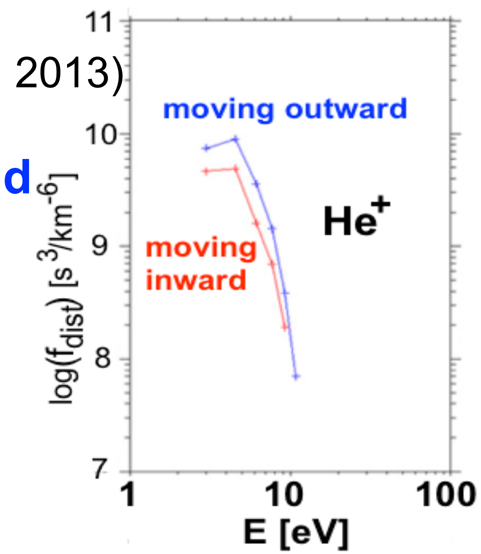
(Darrouzet et al., 2008)

(iv) **plume** is formed & **detached**



(Dandouras et al., 2013)

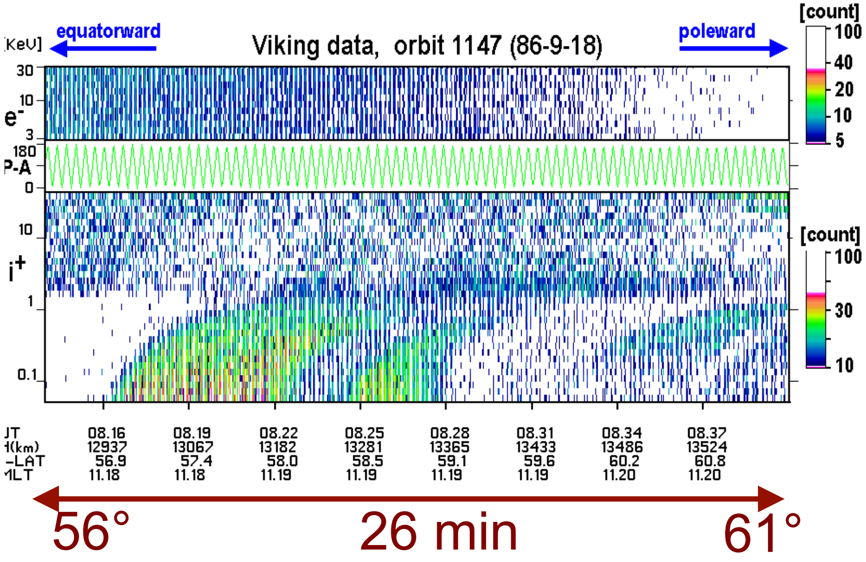
(v) outward **wind** (≈ 1.4 km/s)



M. Yamauchi
Kiruna, Sweden

Decay

Viking observations



After high AE activities.

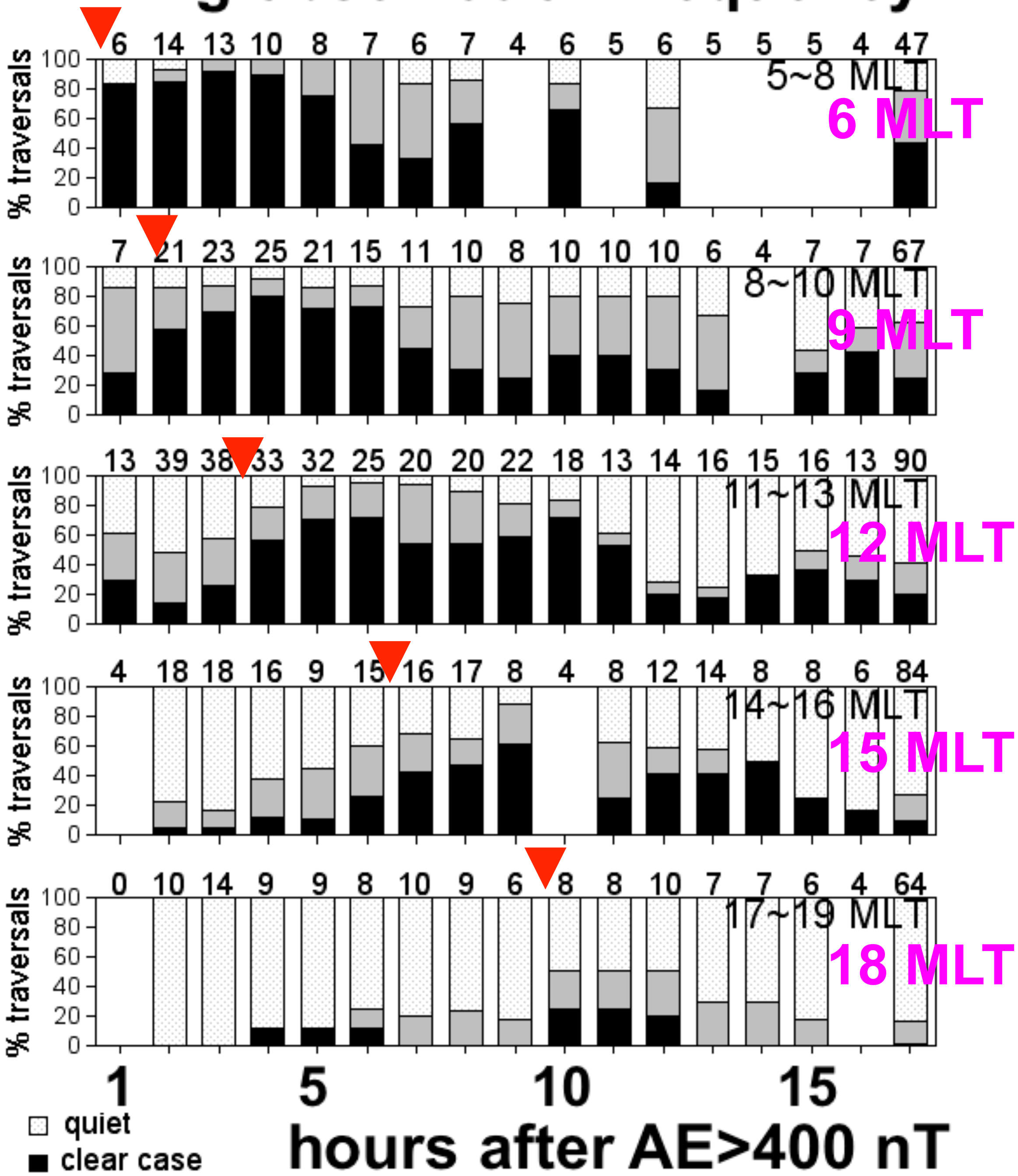
(1) Moves eastward **very fast**

⇒ **fossil of substorm filling**

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

(Yamauchi and Lundin, 2006)

Viking observation frequency

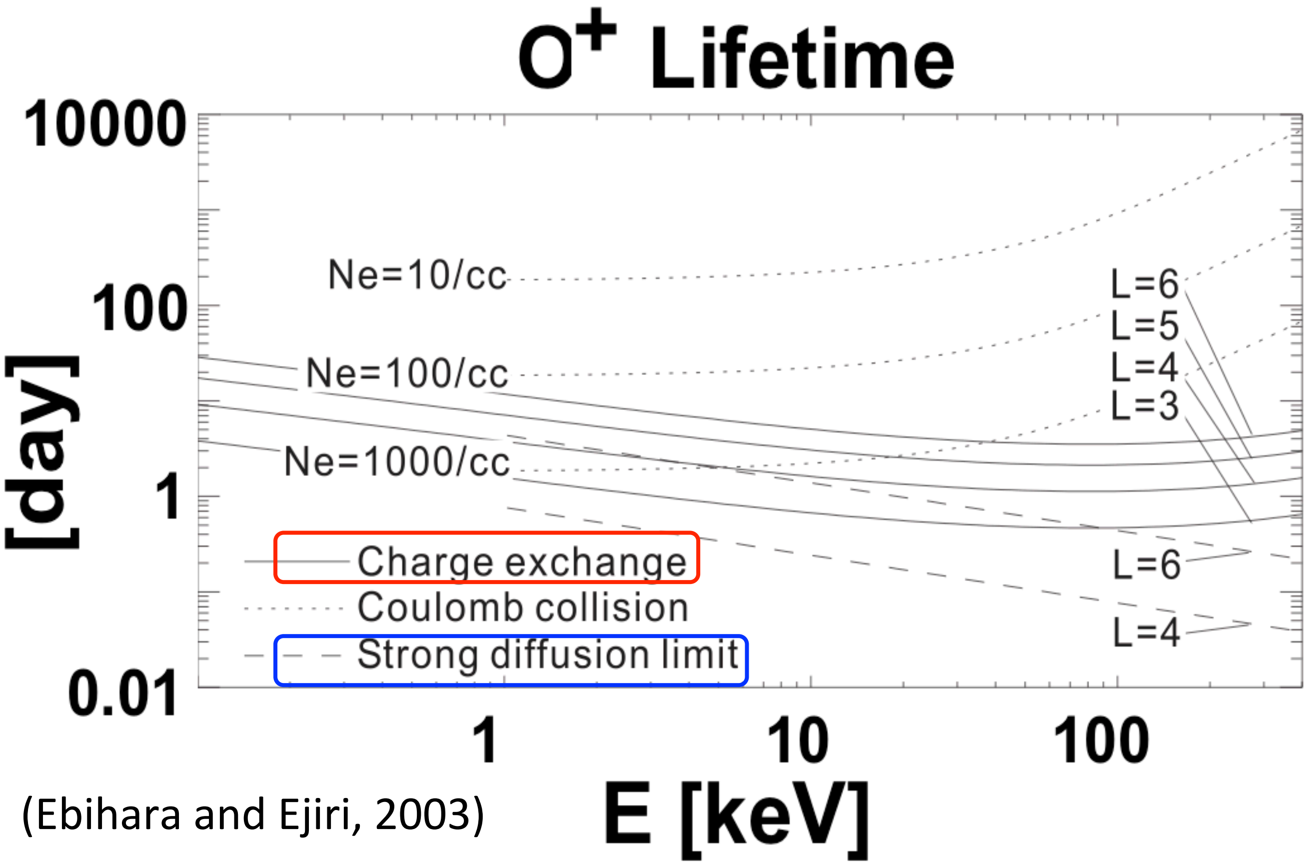


M. Yamauchi
Kiruna, Sweden

Why decay? (1) loss to the ionosphere

(i) O^+ < 1 keV: mainly **Charge exchange** during mirroring (high n_n)
⇒ half will be lost

(ii) O^+ > 1 keV: mainly **Strong pitch-angle diffusion** to loss cone
⇒ real return



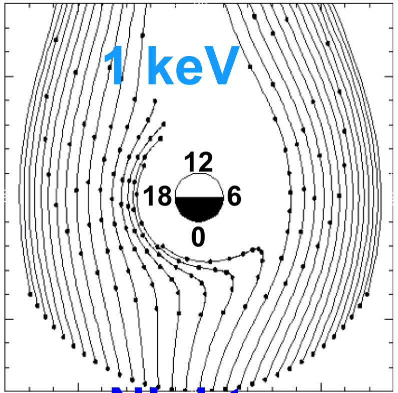
(Ebihara and Ejiri, 2003)

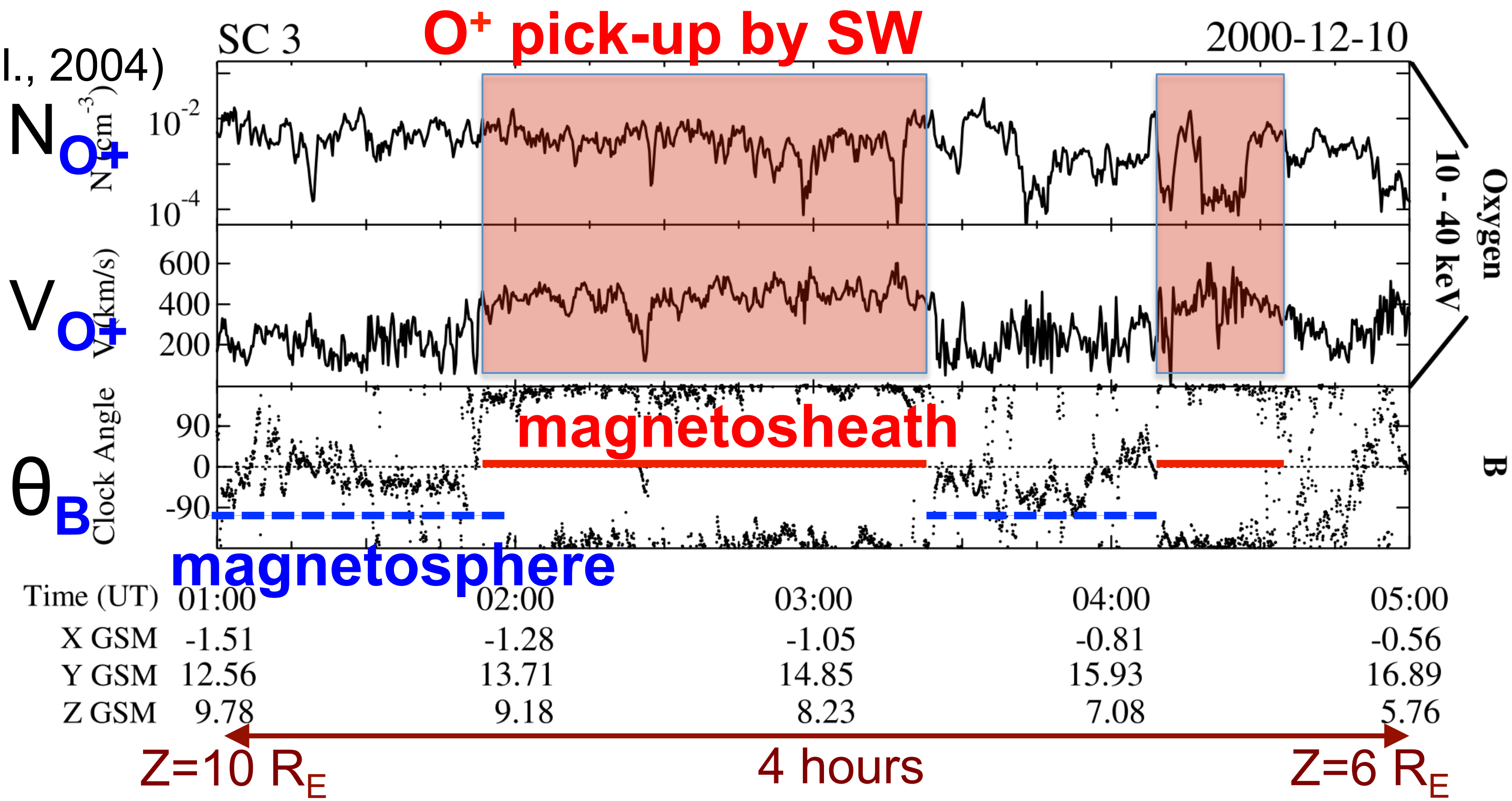
Simulation for all O^+
⇒ **half will be lost**
(except leak)

M. Yamauchi
Kiruna, Sweden

Why decay? (2) Magnetopause shadowing

(Marcucci et al., 2004)





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

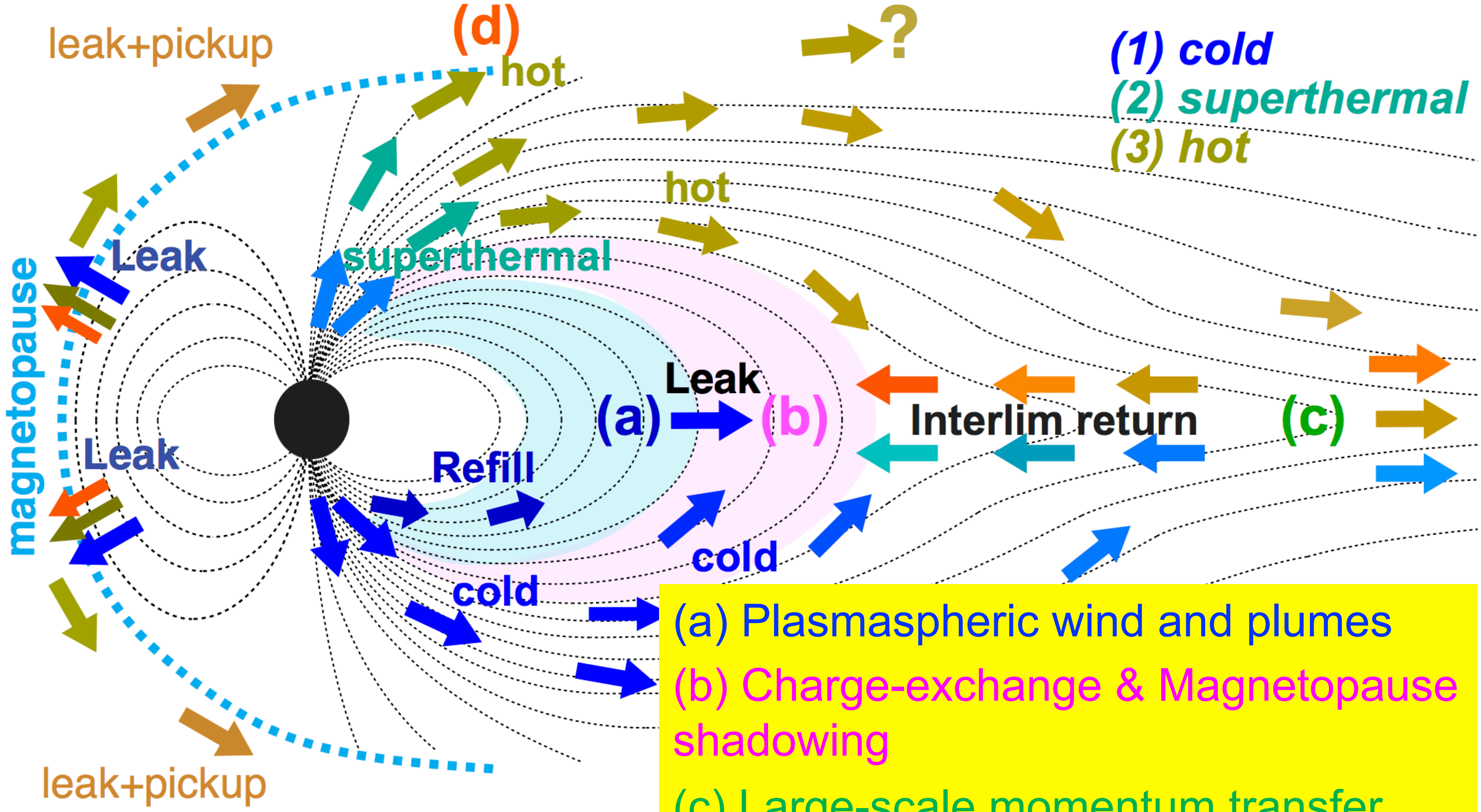
≈ **1/3 of input O^+** during storm

(Zong et al., 2001)

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

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

Main escape mechanisms for present Earth



(a) Plasmaspheric wind and plumes

(b) Charge-exchange & Magnetopause shadowing

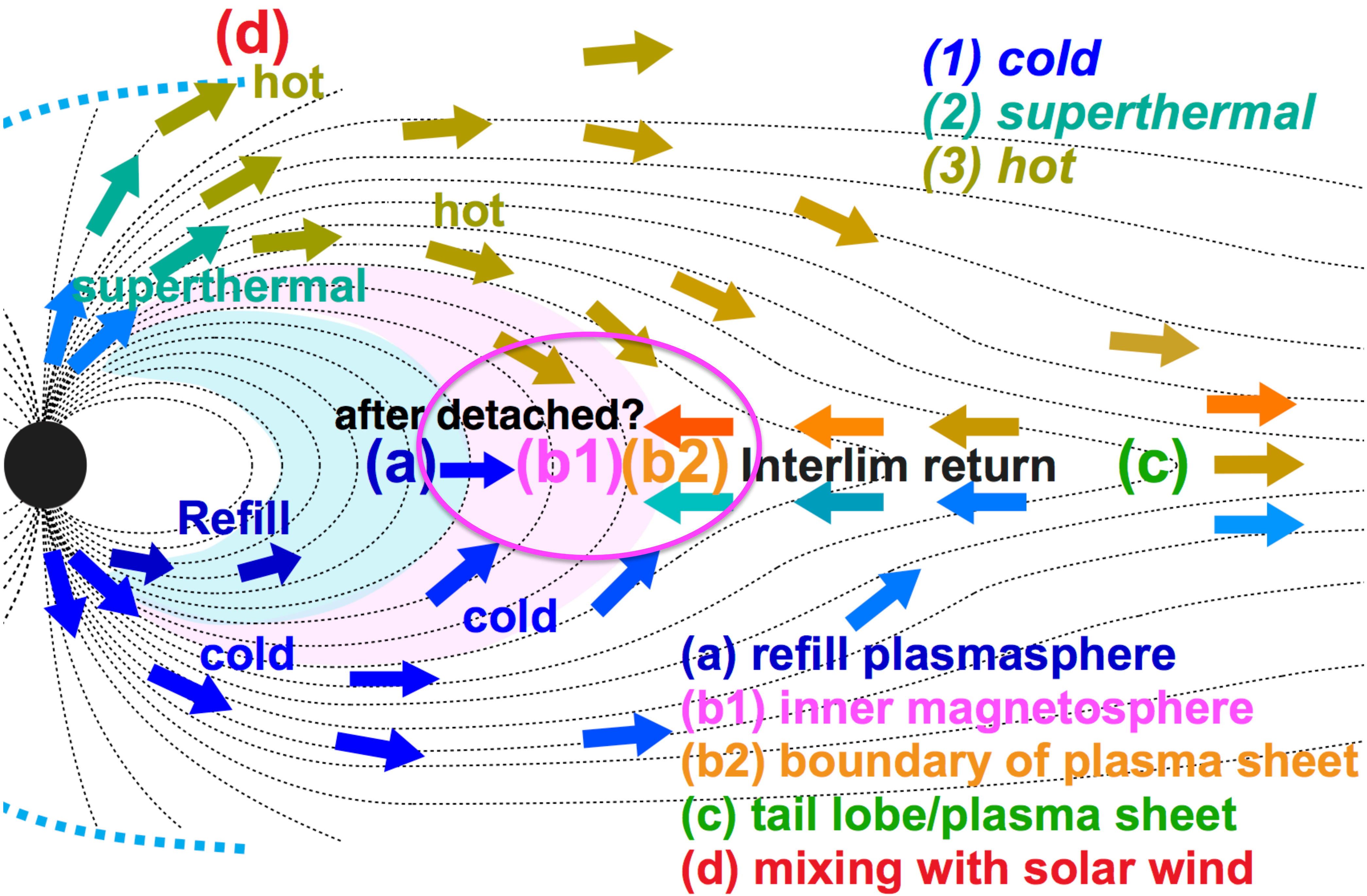
(c) Large-scale momentum transfer

(d) Ions accelerated by field reach SW

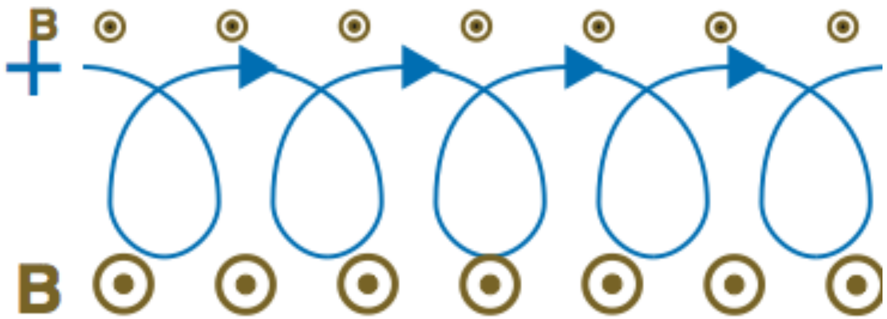
Extra slides: Zoo

M. Yamauchi
Kiruna, Sweden

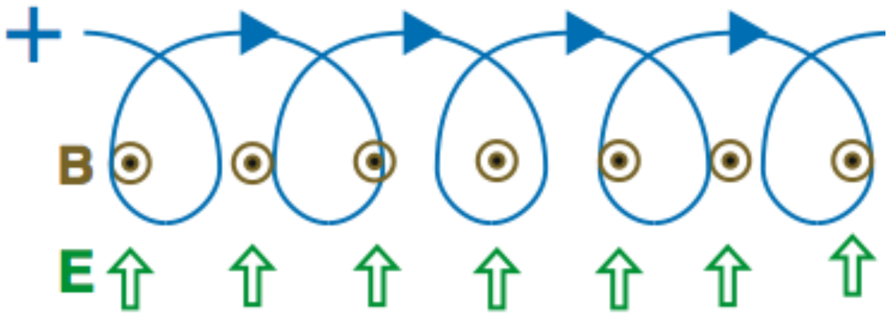
Fate of returned flow



Ion drift under strong B-field



Magnetic drift (energy-dependent)
 * gradient-B & curvature drift
 ⇒ dominant for > 10 keV

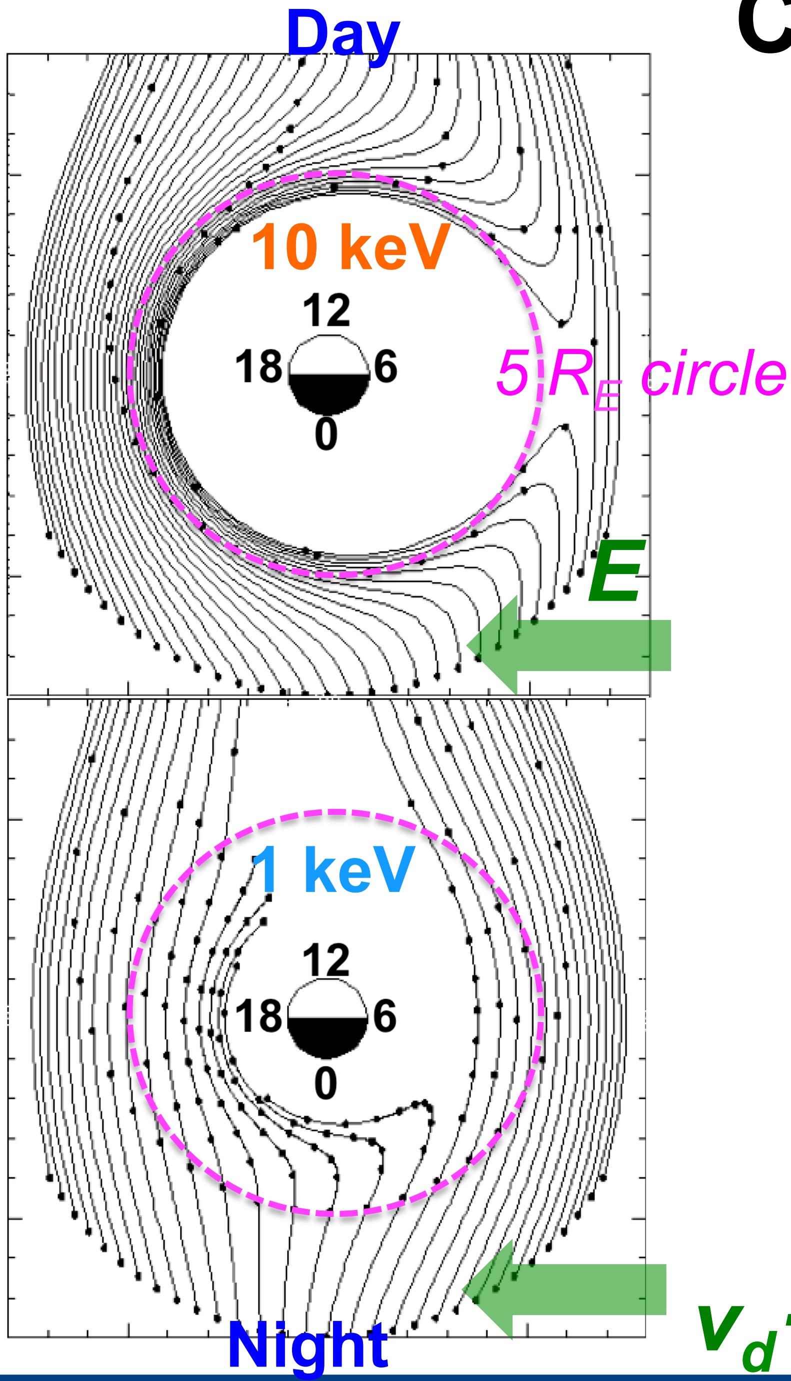


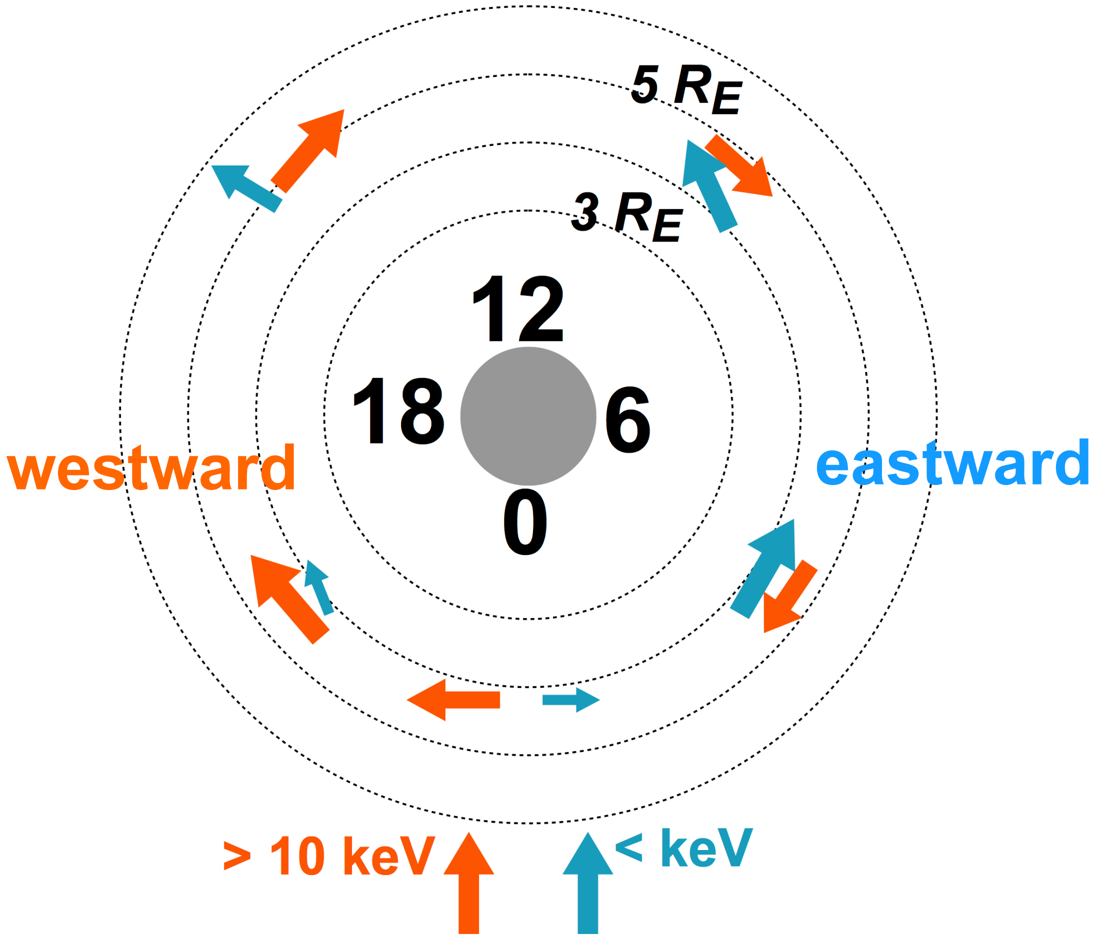
ExB drift (energy-independent)
 * co-rotation & external E-field
 ⇒ dominant for < 0.1 keV

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

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

Combining different drifts





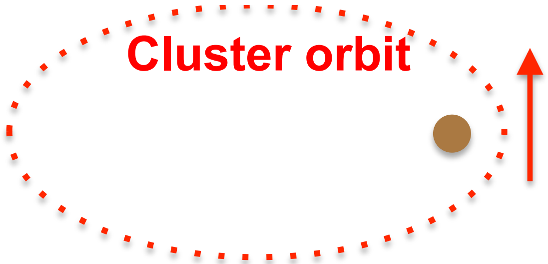
For all of H^+, He^+, and O^+

But, this is **just a model**

$v_d \cdot E > 0$ ⇒ adiabatic energization

M. Yamauchi
Kiruna, Sweden

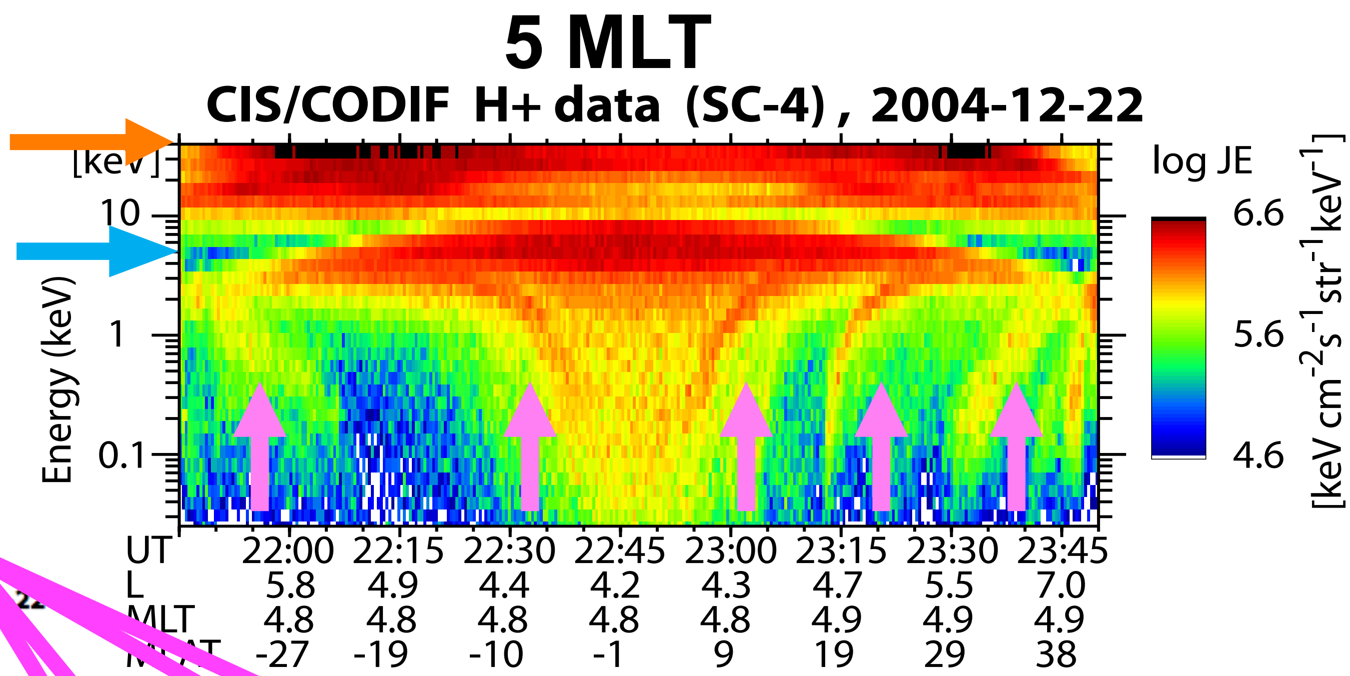
Three basic populations

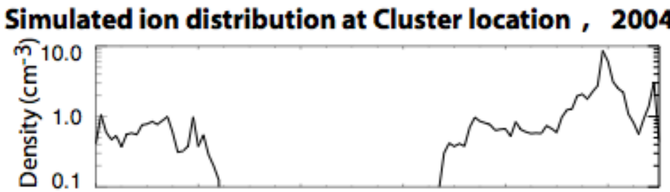


accelerated plasma sheet (westward drift)

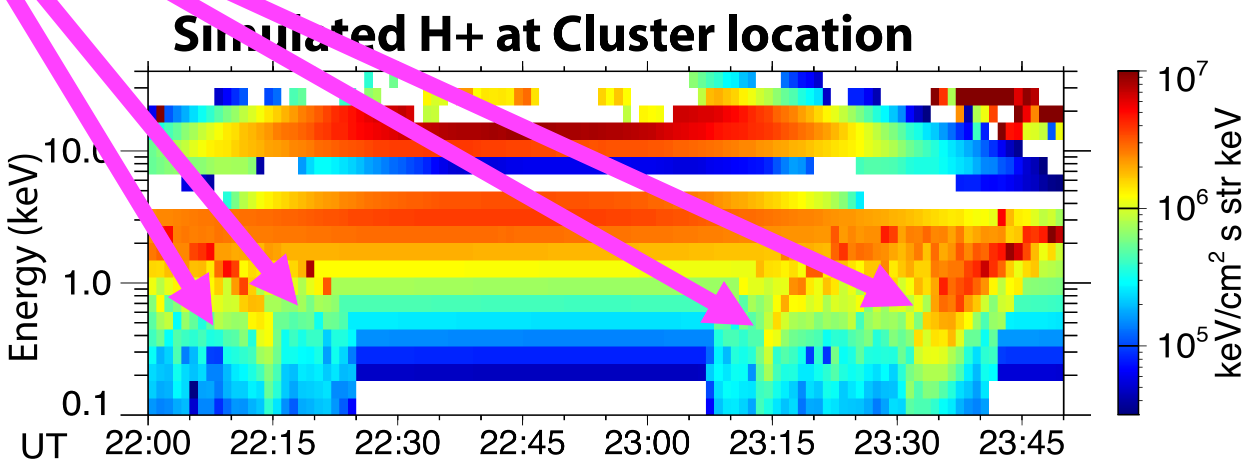
plasma sheet (eastward ExB drift)

superthermal (<50 eV) intermittent supply





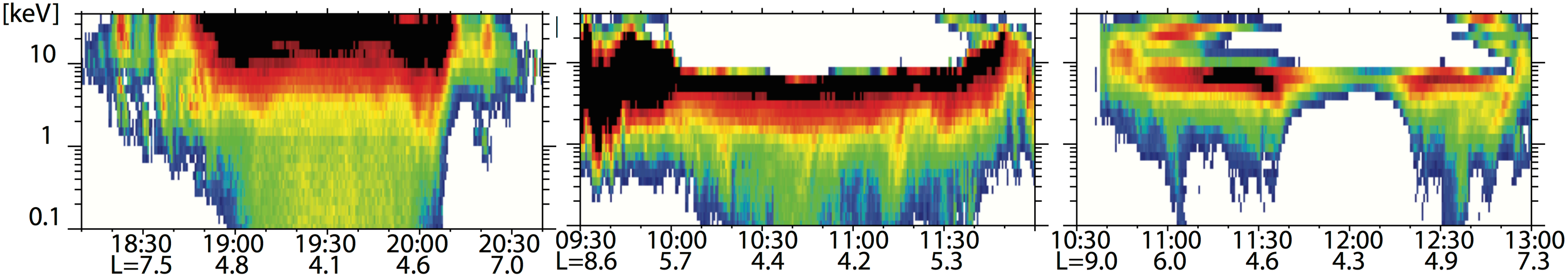
Simulation



(Yamauchi et al.,2009)

Morphology changes with E-field

AE > 500 nT 2003-2-9 (2 LT) | **AE ~ 500 nT** 2002-12-19 (5 LT) | **AE ~ 300nT** 2002-1-8 (4 LT)



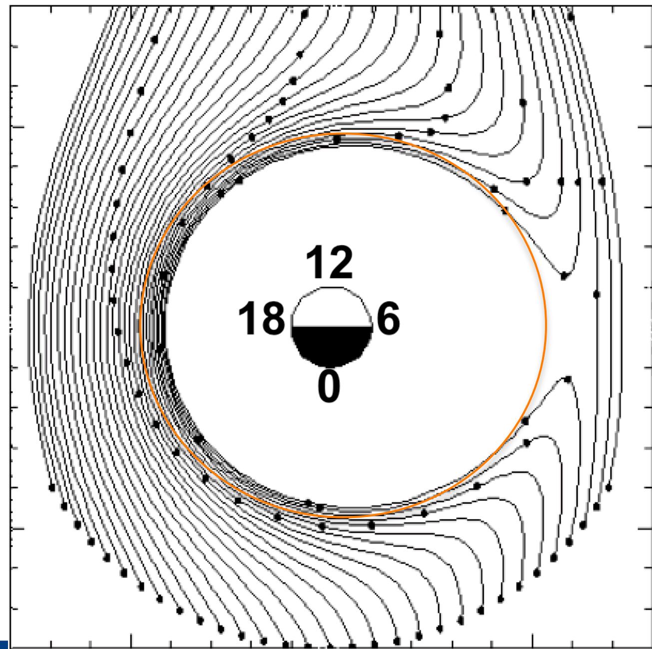
(Yamauchi et al., 2009)

Demarcation energy in dawn (~ 5 R_E):

> 40 keV for strong substorm

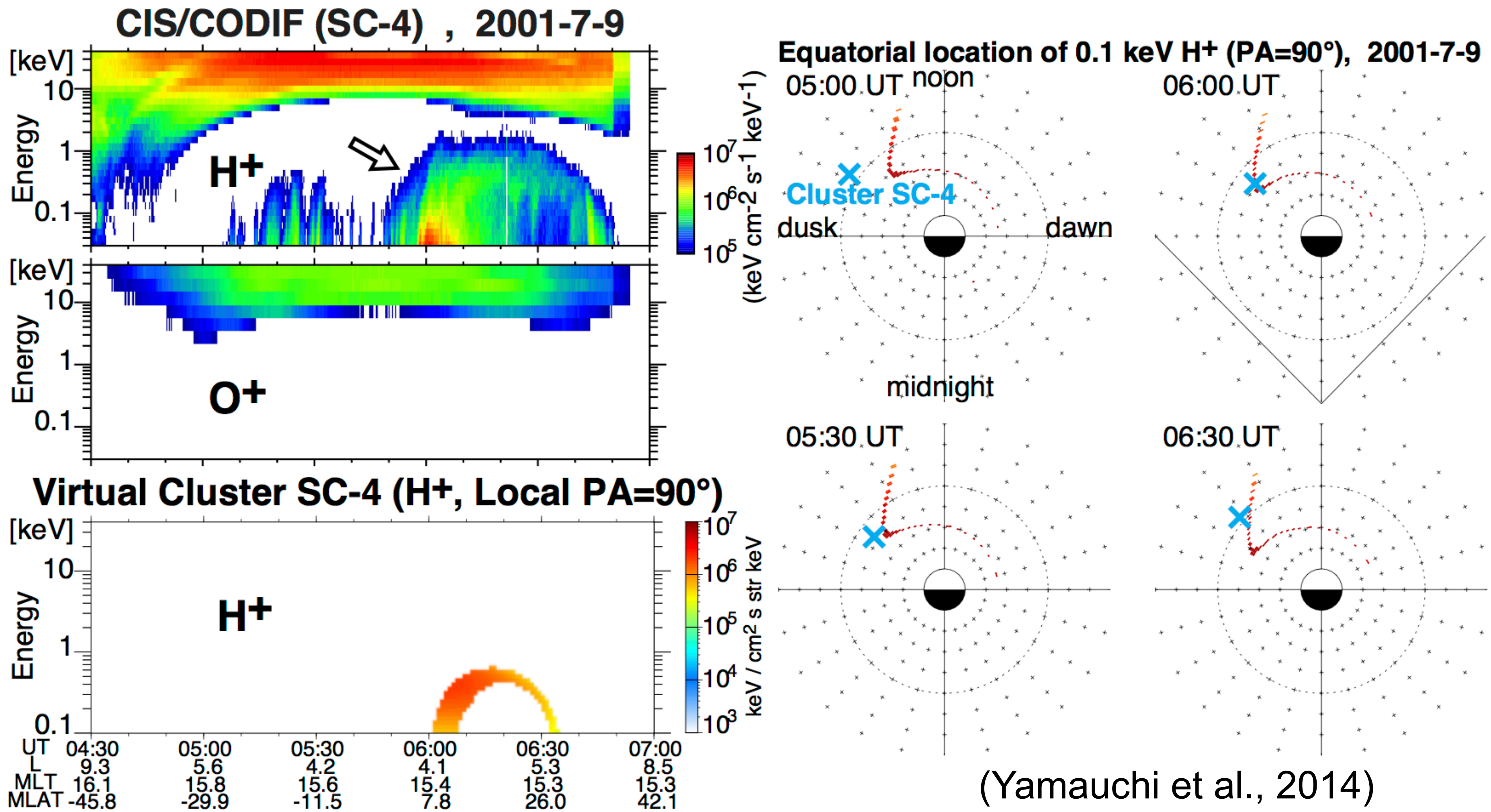
⇒ Dawn **E-field is stronger** than expected

⇒ Local screw of **E-field**
(later simulation confirmed)



Can ExB drift really explain?

15 MLT



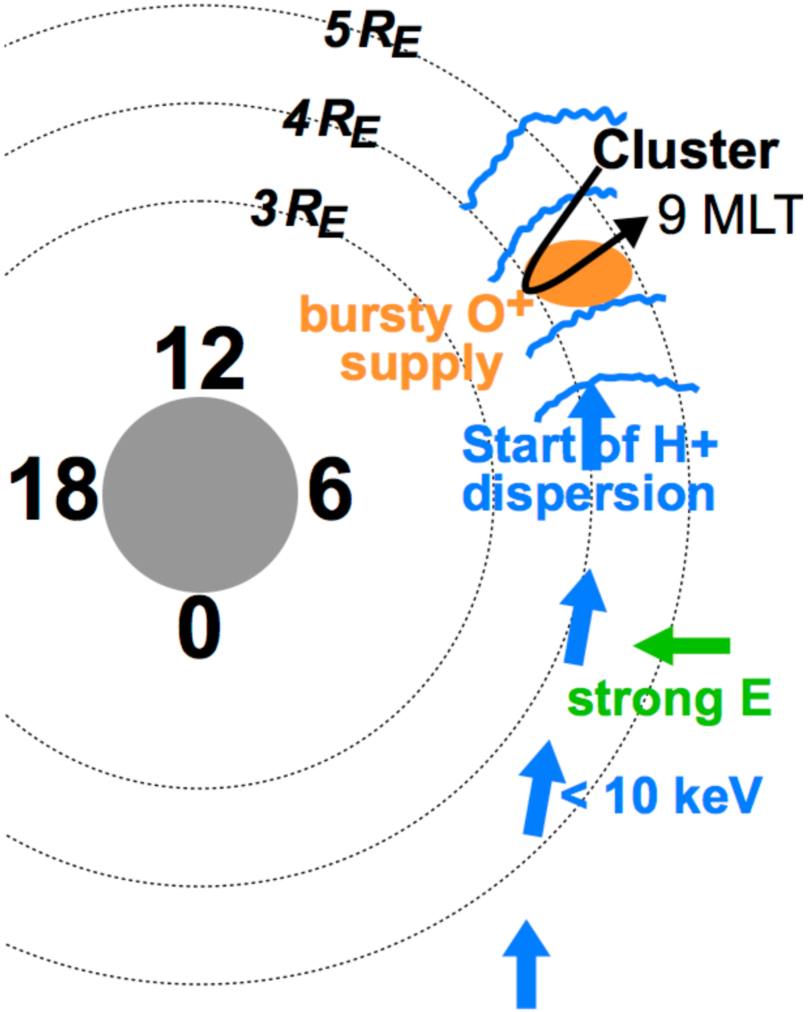
(Yamauchi et al., 2014)

(1) **Afternoon sector** ⇒ Yes

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

M. Yamauchi
Kiruna, Sweden

Derived ion motion



(Yamauchi et al., 2006)

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

38

Extra:

Evolution of the Earth in geological scale

(then cannot ignore **neutral**)

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

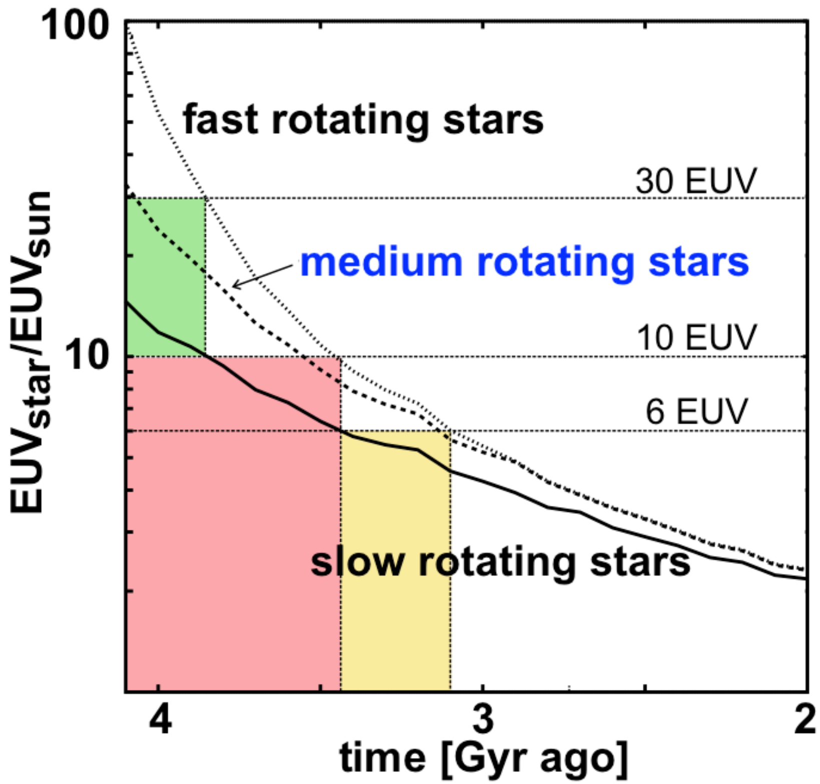
⇒ stronger solar dynamo

⇒ **stronger flare / CME / SEP**

(Solar Energetic Particle)

(e.g., Wood, 2006)

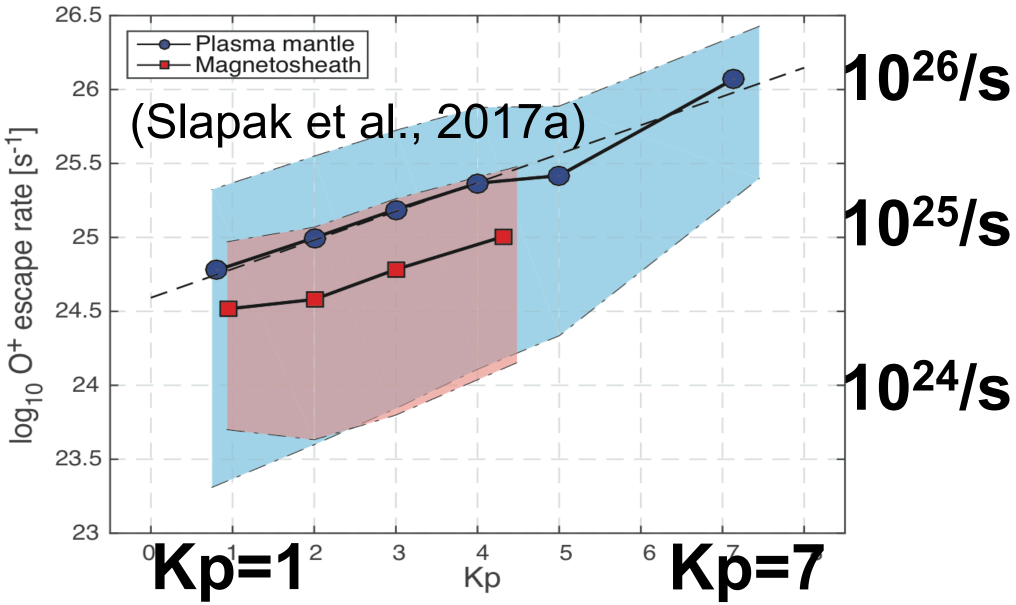
⇒ We scale **Kp=10** or use **extreme events** as proxy of the past



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

M. Yamauchi
Kiruna, Sweden

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)

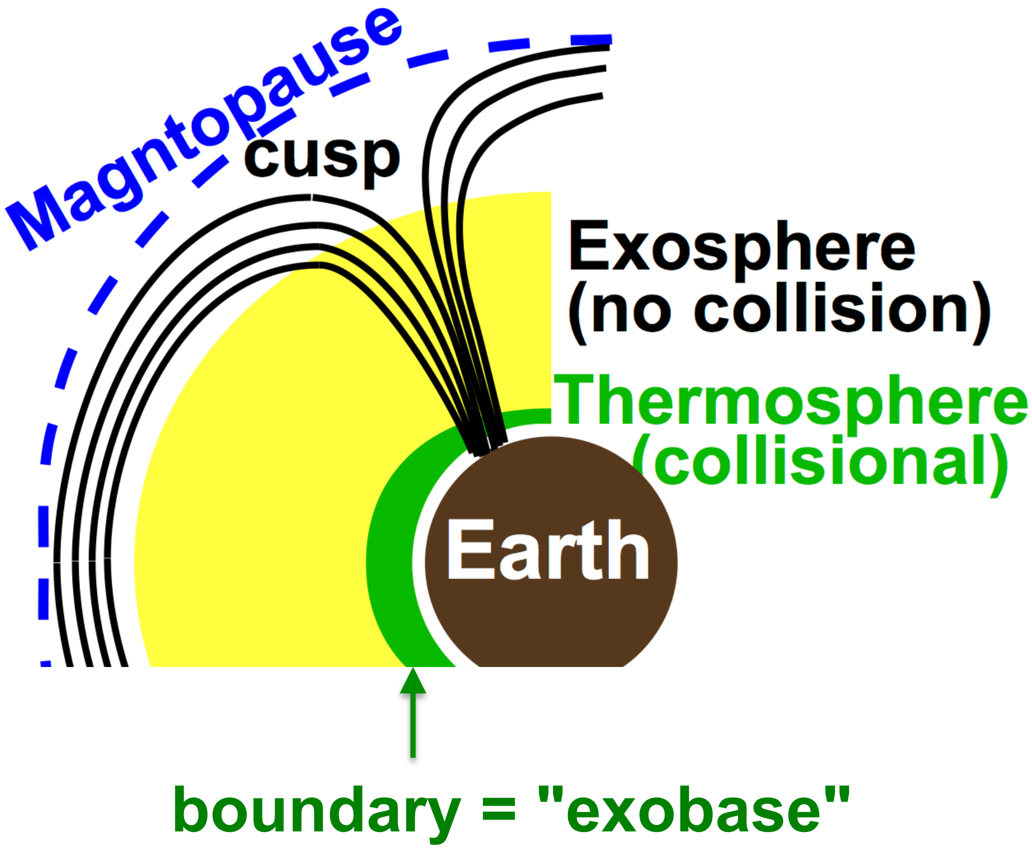
⇒ **cannot ignore**

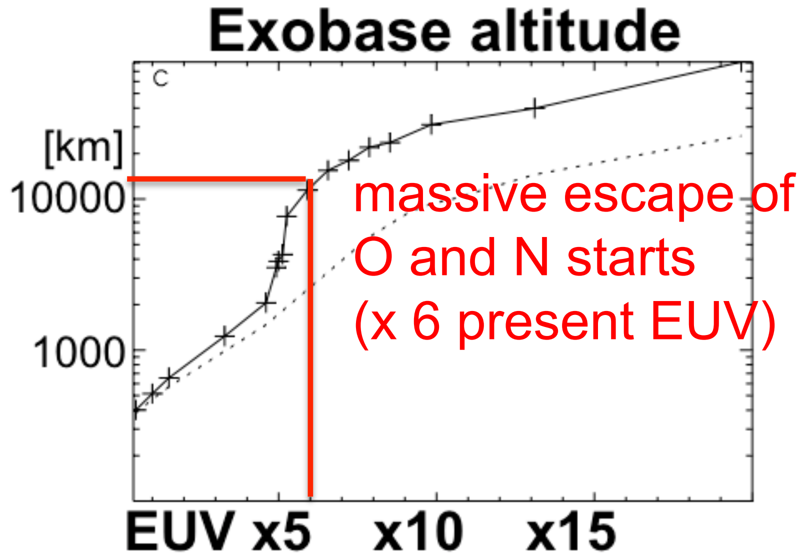
A few % change in O/N ratio does affect bacteria activity (e.g., Loesche, 1969)

Past escape ⇒ must know exobase

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

Past atmospheric composition fluctuated

Observed O/N ratio fluctuate in 0.1 byr : **not easy to explain by bioactivity** ⇒ escape matters?

O_2 concentration

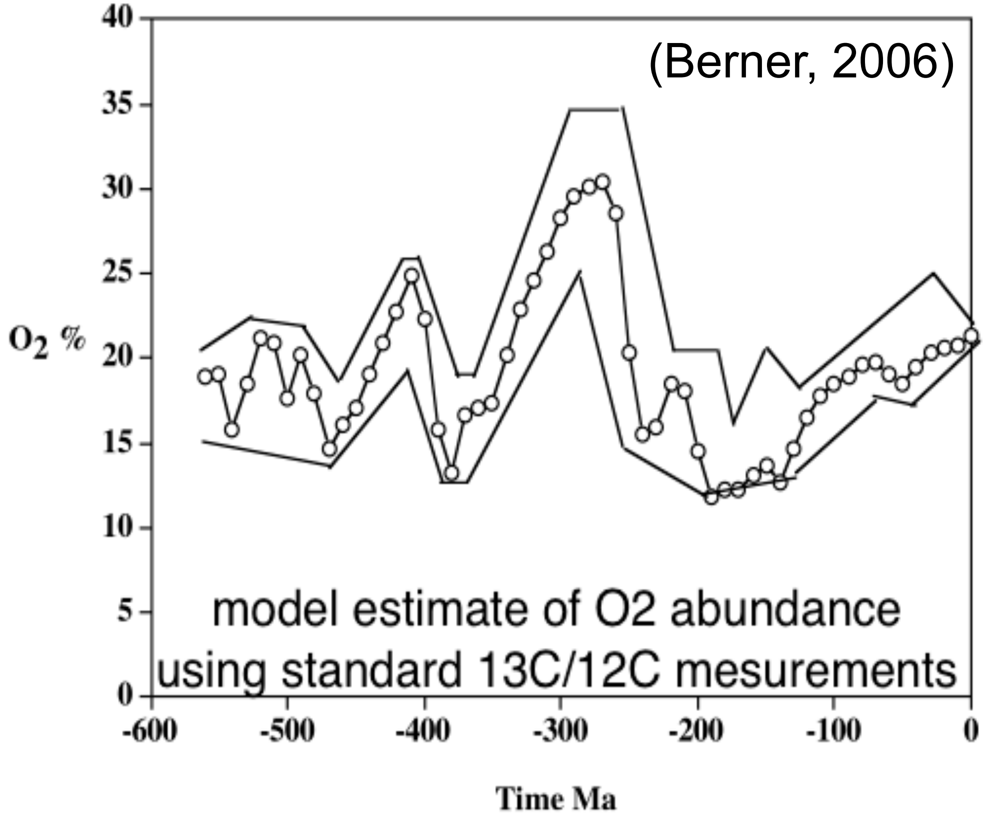


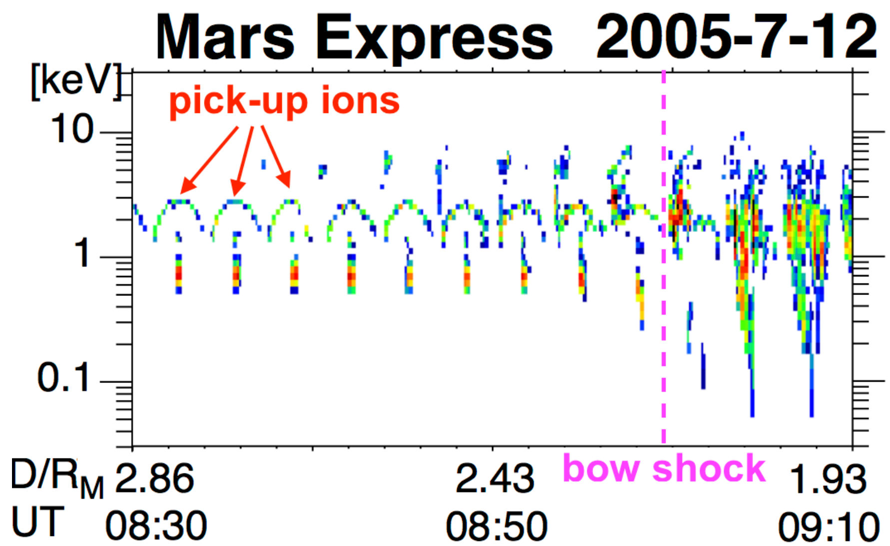
Fig. 20. Plot of O_2 vs time for the standard GEOCARBSULF model with

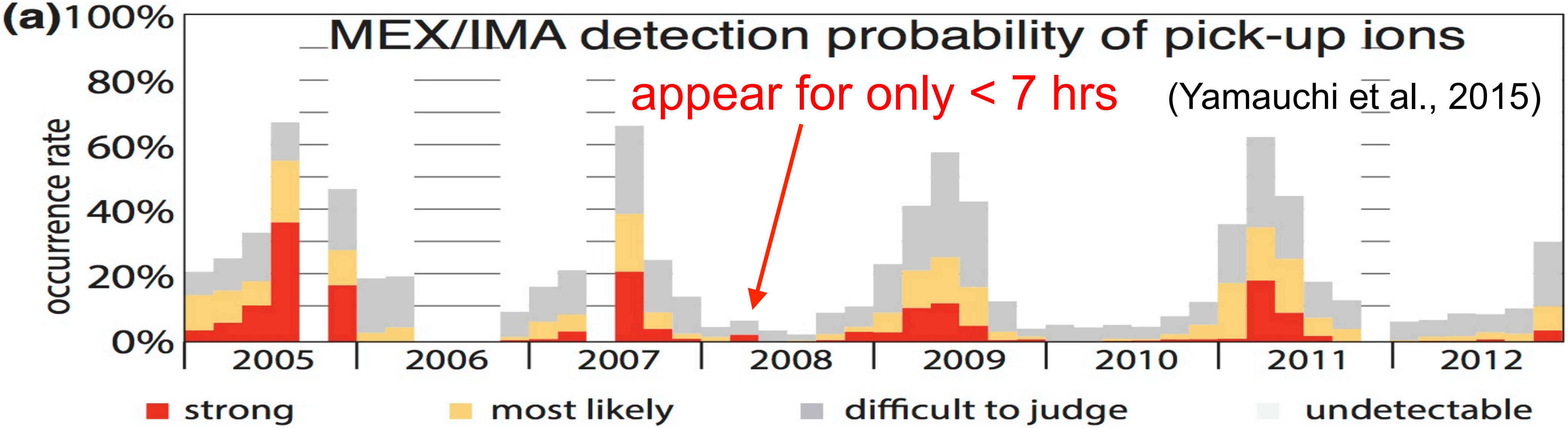
In fact, exosphere drastically responds to EUV

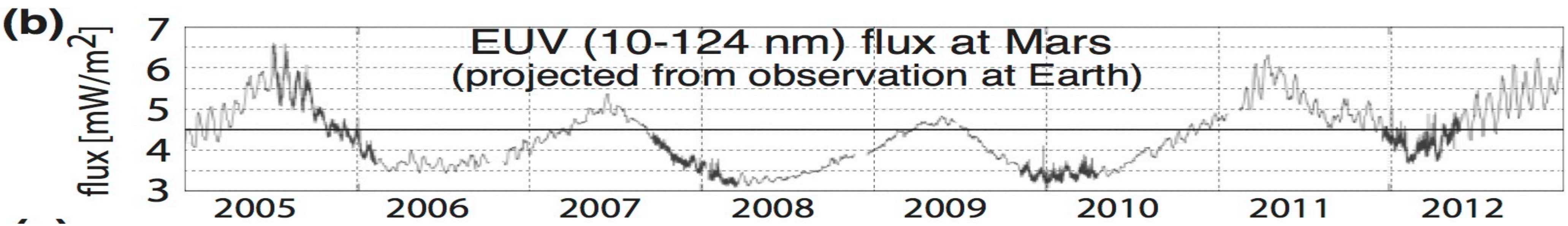
Newly-formed cold ions (pickup ions) at Mars

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

⇒ expansion of exosphere is much more than any simple models







Past escape ⇒ must know past ionosphere

Ancient solar forcing (young M-stars

(a) **much higher EUV flux** than present

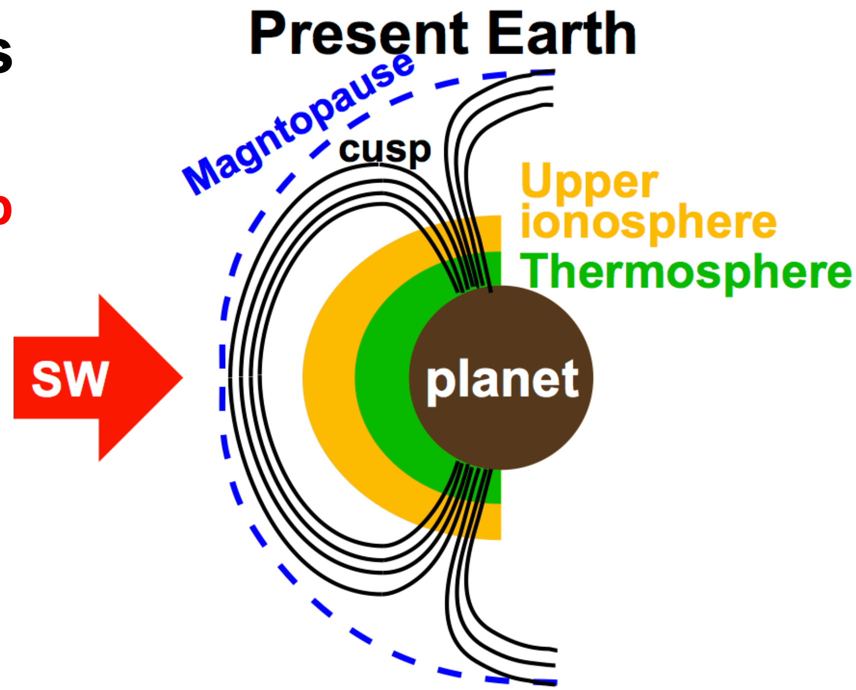
⇒ thermosphere **expands** ⇒ **neutral escap**

(b) **higher P_{sw}** than present

(c) **much faster rotation** than present

⇒ stronger solar dynamo

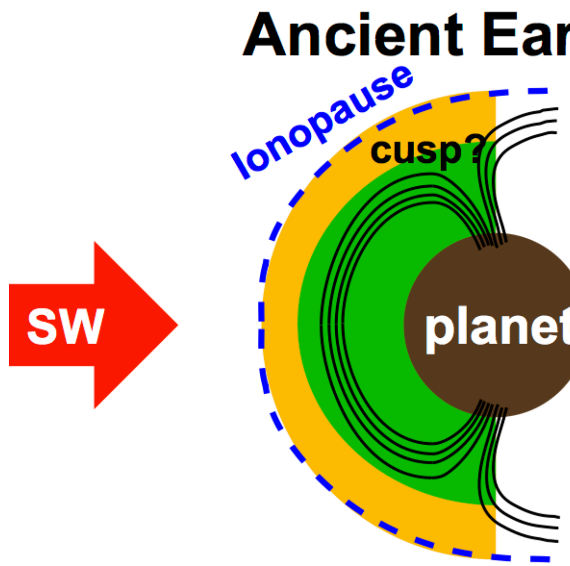
⇒ **frequent & intense flare/SEP (Solar Energetic Particle)** ⇒ **ion escape**



Ancient Earth

(d) **less geomagnetic field** than present

⇒ magnetosphere **shrinks**



Mars like interaction?

(Yamauchi and Wahlund, 2007)

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

M. Yamauchi
Kiruna, Sweden

Extra slides (molecular)

Sources of "very heavy" ions

(molecular + silicate/metallic)

Si^{+}, Fe^{+}

O^{6+}, Fe^{12+}

N_2^{+}, NO^{+}, O_2^{+}

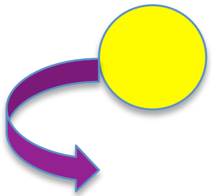
Solar wind – magnetosphere interaction

- directly from SW

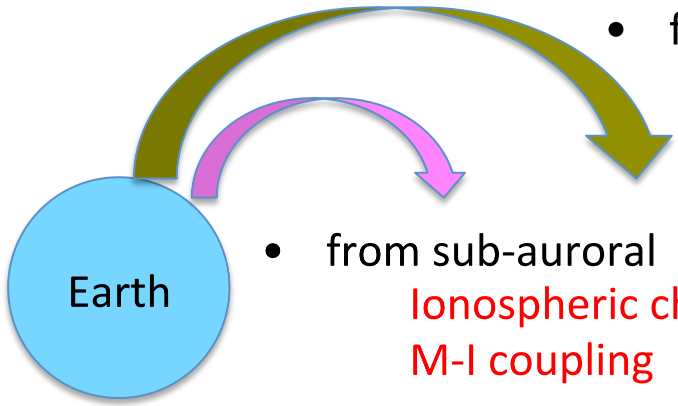
Atmospheric evolution
M-I coupling

- from high-latitude

Solar wind – surface interaction
Micrometeorite – surface interaction



Moon



- from sub-auroral

Ionospheric chemistry/physics
M-I coupling

- exospheric:
- sputtered by SW and ionized:
- reflected + neutralized SW

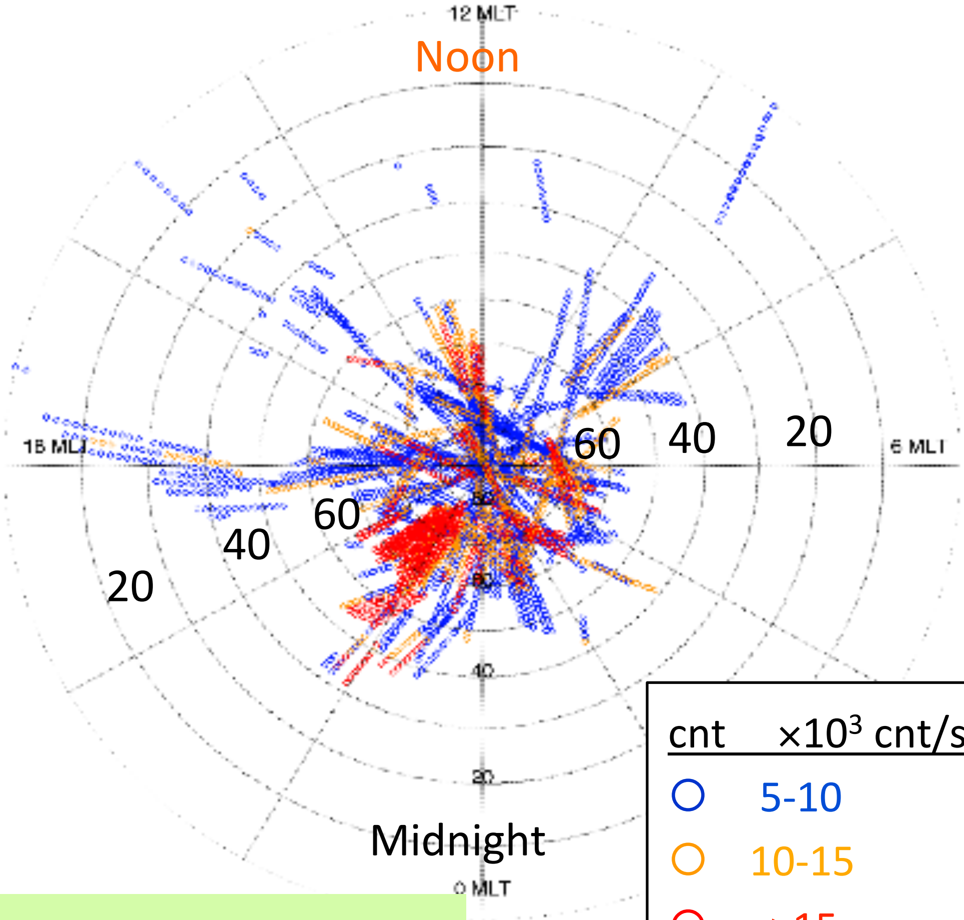
and picked up to > 50 keV

Question is source of low-charge state:

- Moon vs. high-latitude?
- How much from low-latitude?
- metal layer/space debris contribution?

Some molecular ions may reach the magnetosphere

N_2^+-NO^+-O_2^+ at 300-1500 km (Swarm-E)



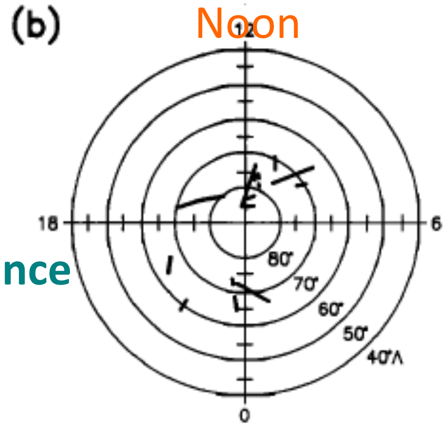
cnt	$\times 10^3$ cnt/s
O	5-10
O	10-15
O	>15

Courtesy: V. Foss, 2019

low-cnt events = extend to low latitudes
high-cnt events = only high latitudes

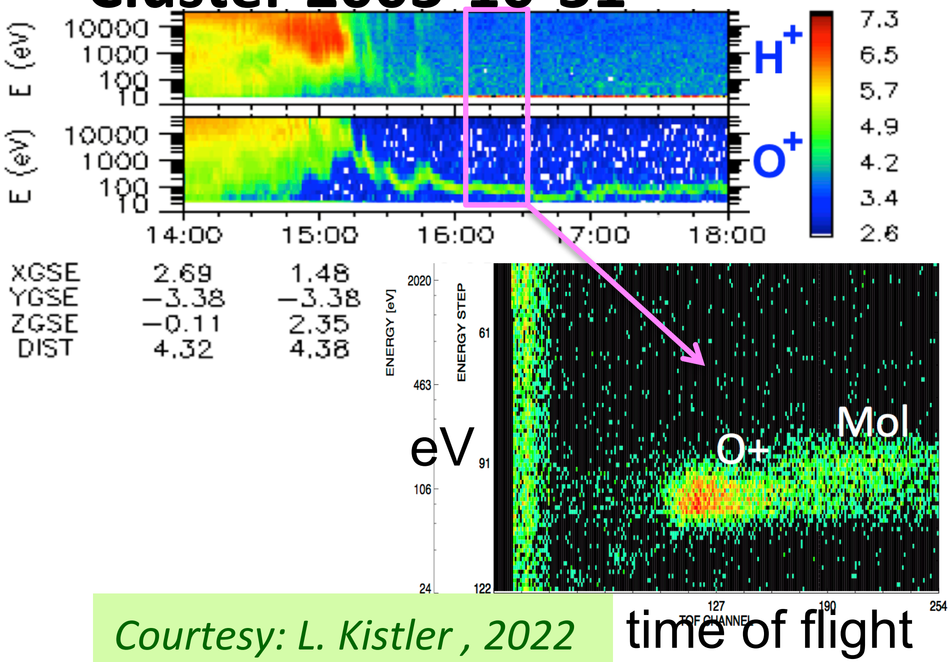
N_2^+-NO^+-O_2^+ at 6,000-10,000 km (Akebono, Yau et al.)

Molecular ion occurrence



Generally only from high latitude

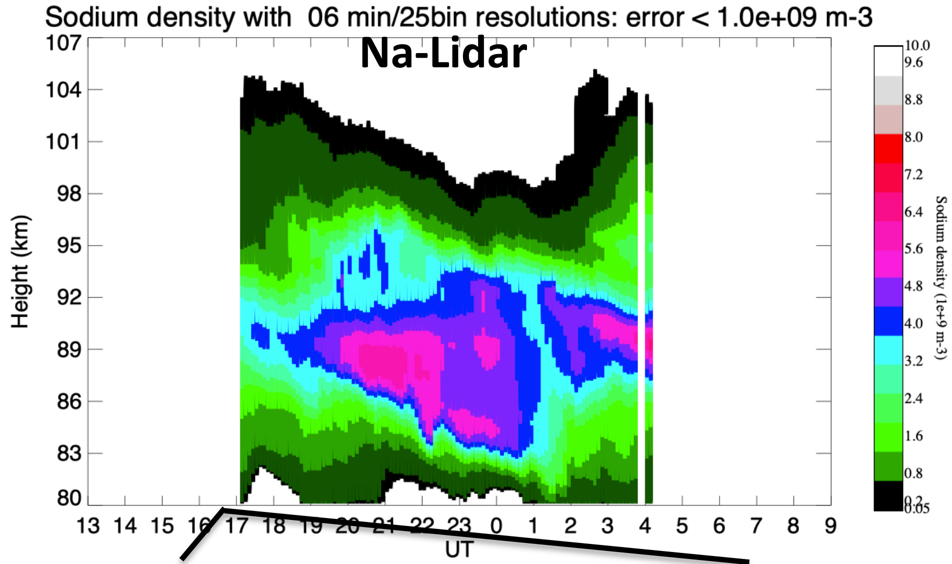
Cluster 2003-10-31

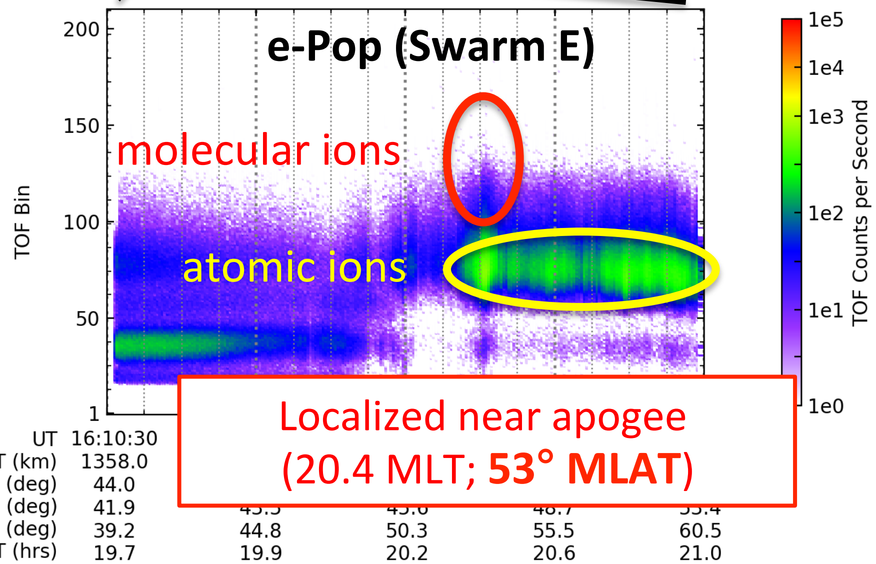


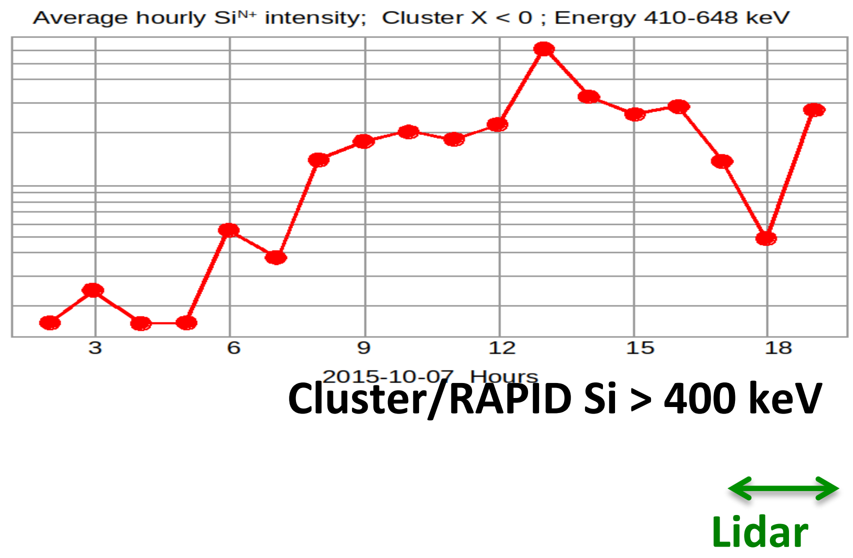
Courtesy: L. Kistler , 2022

M. Yamauchi
Kiruna, Sweden

Relation to sodium layer and low-latitude source: 2015-10-07 CME event

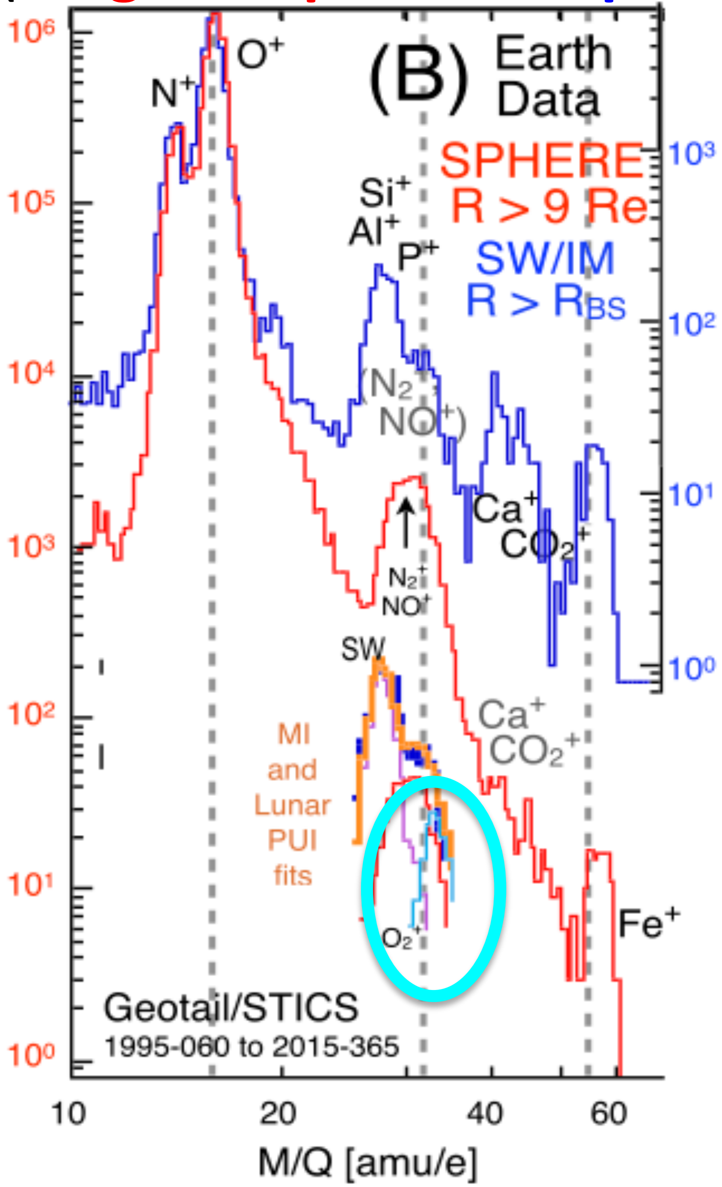






Could reach magnetosphere?

Low charge-state energetic ions
(magnetosphere vs upstream)



Geotail/STIC statistics (Christon et al, 2020 fig 5)