Cold ion outflow from the terrestrial atmosphere:

Sources, mechanisms and consequences

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with inputs from
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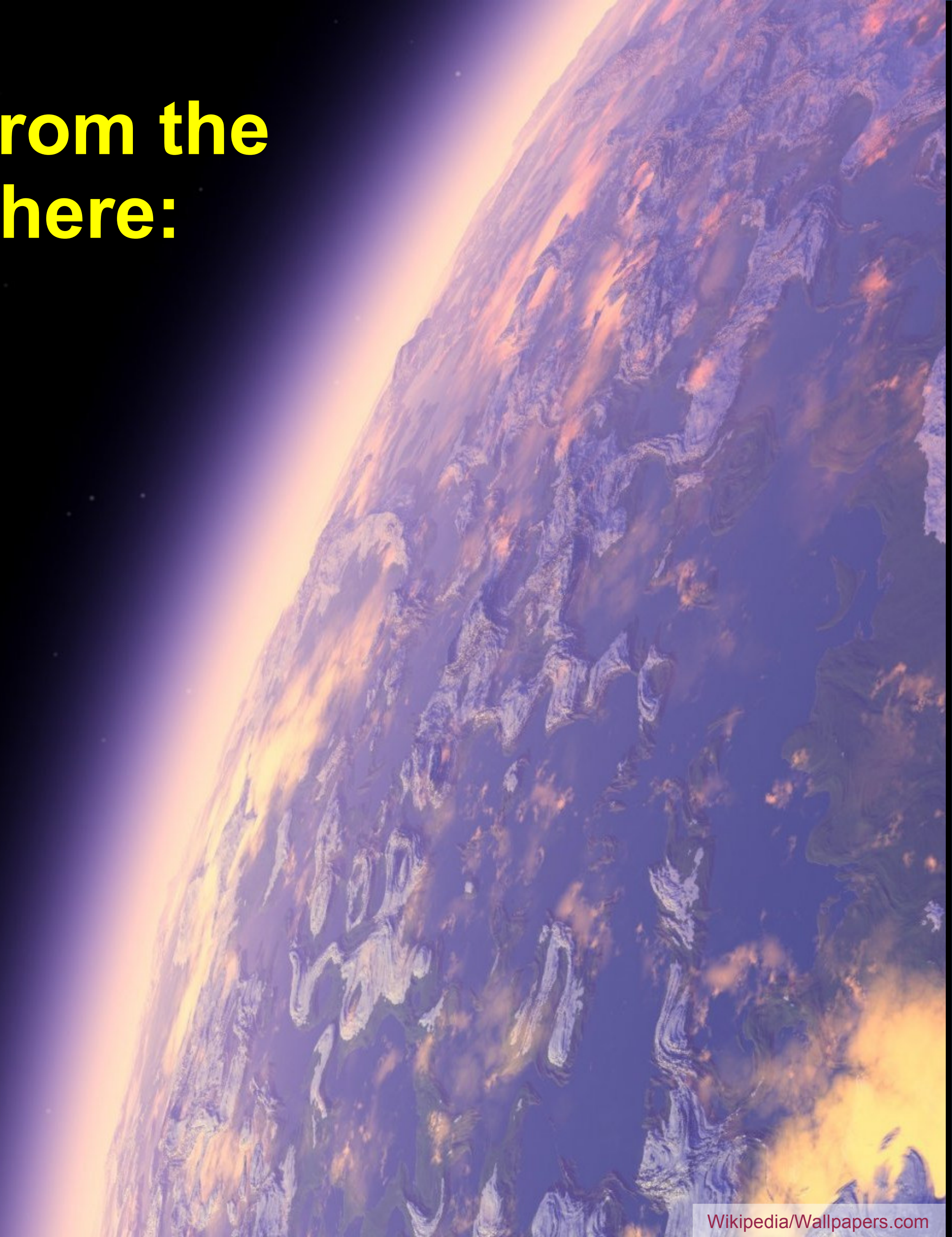
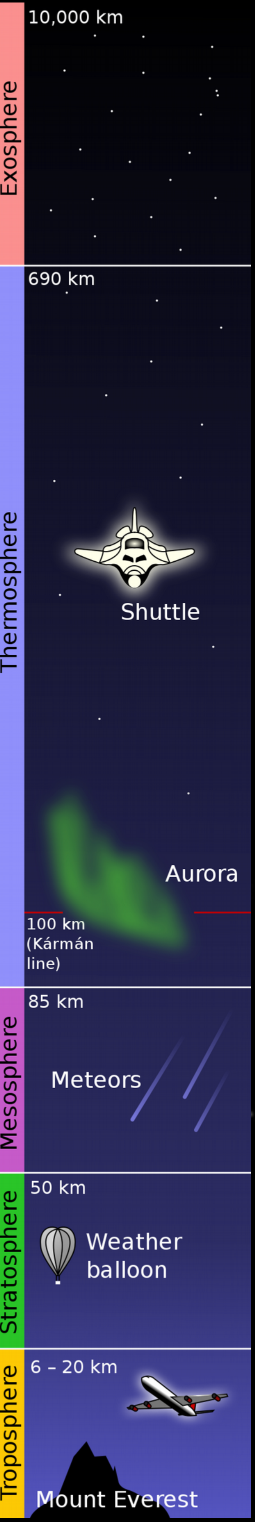


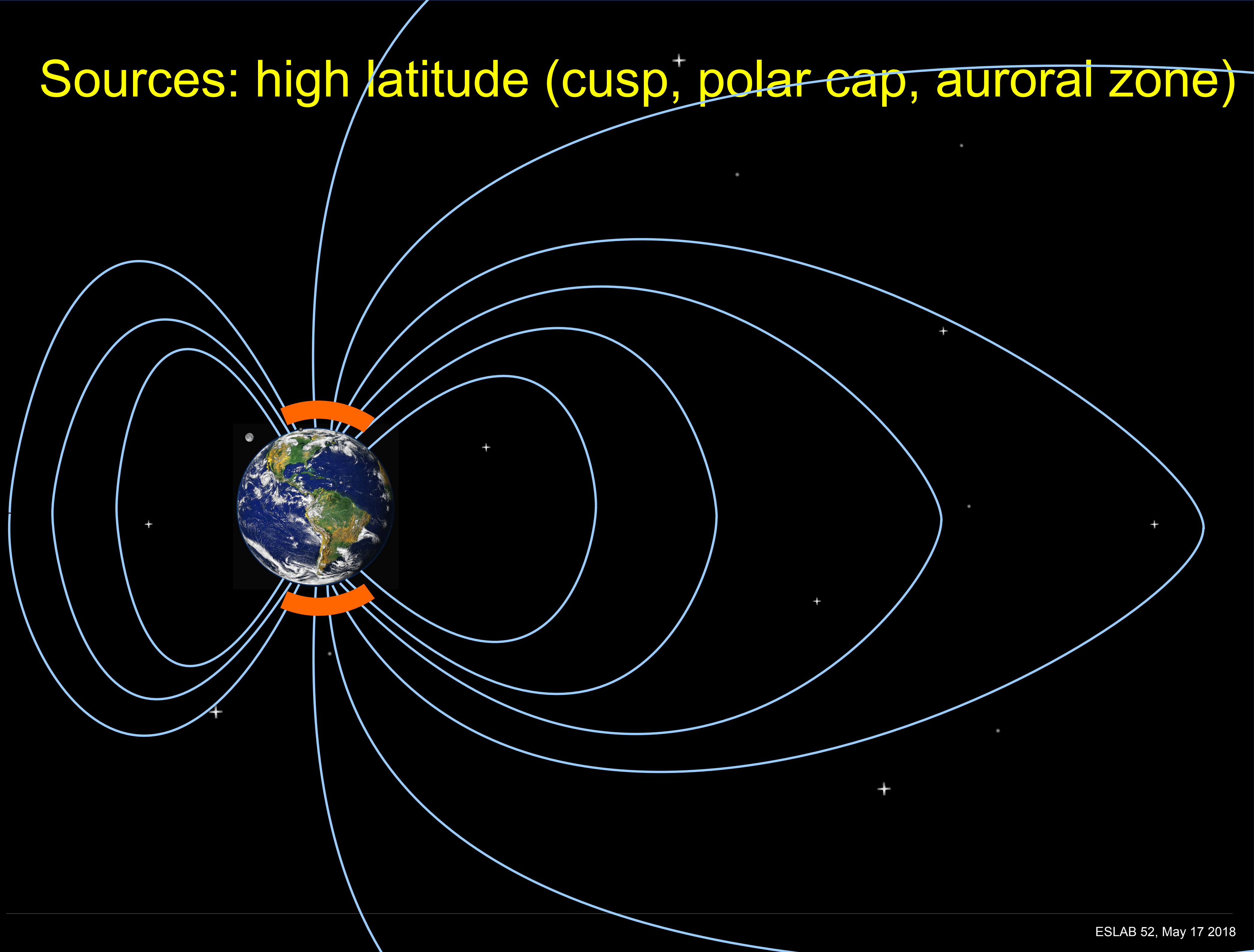
Earth:

* Composition N, O, H

* Ionization mainly from EUV



Sources: high latitude (cusp, polar cap, auroral zone)



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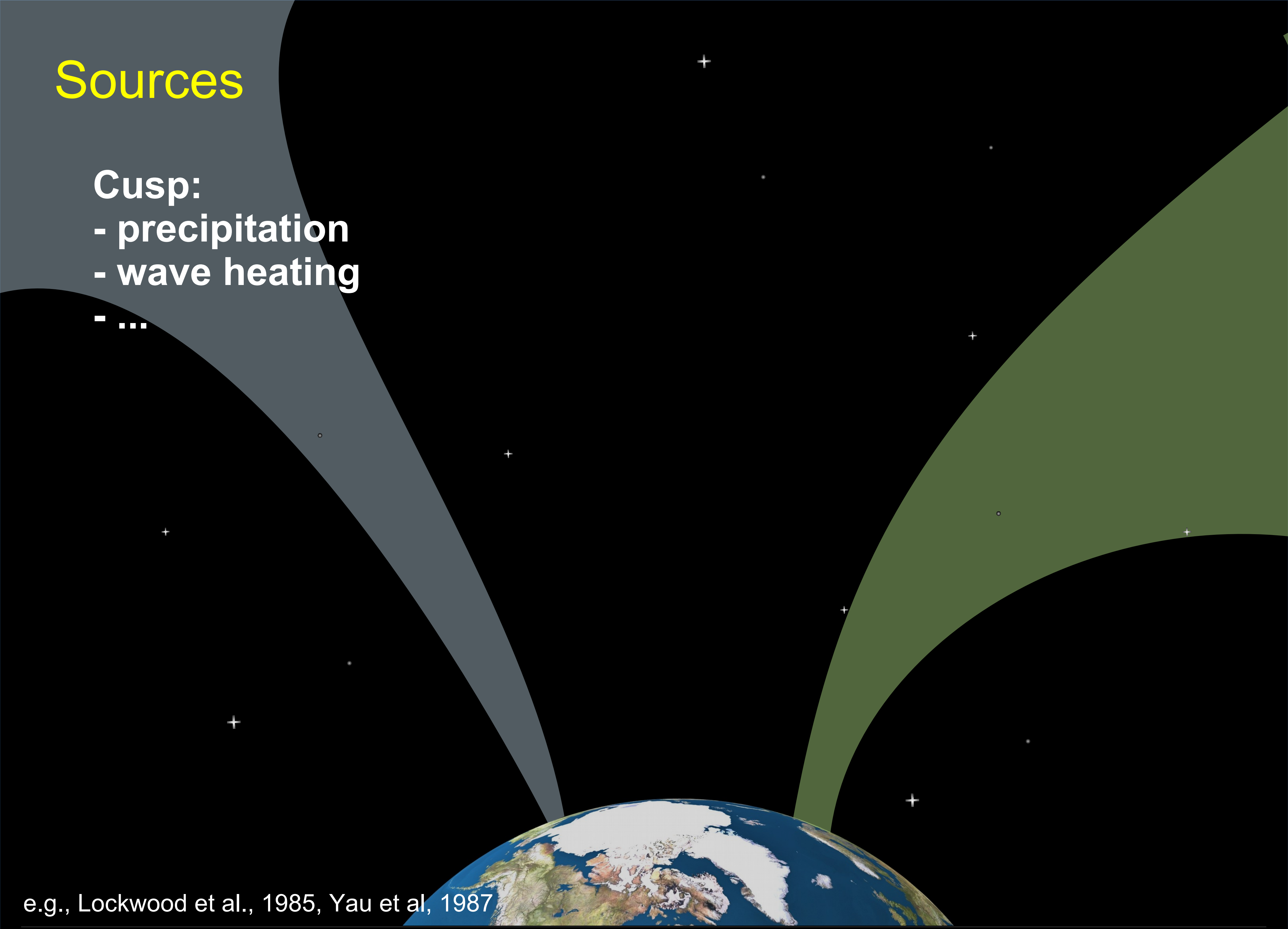

Cusp:
- precipitation
- wave heating
- ...

e.g., Lockwood et al., 1985, Yau et al, 1987

Sources

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- precipitation
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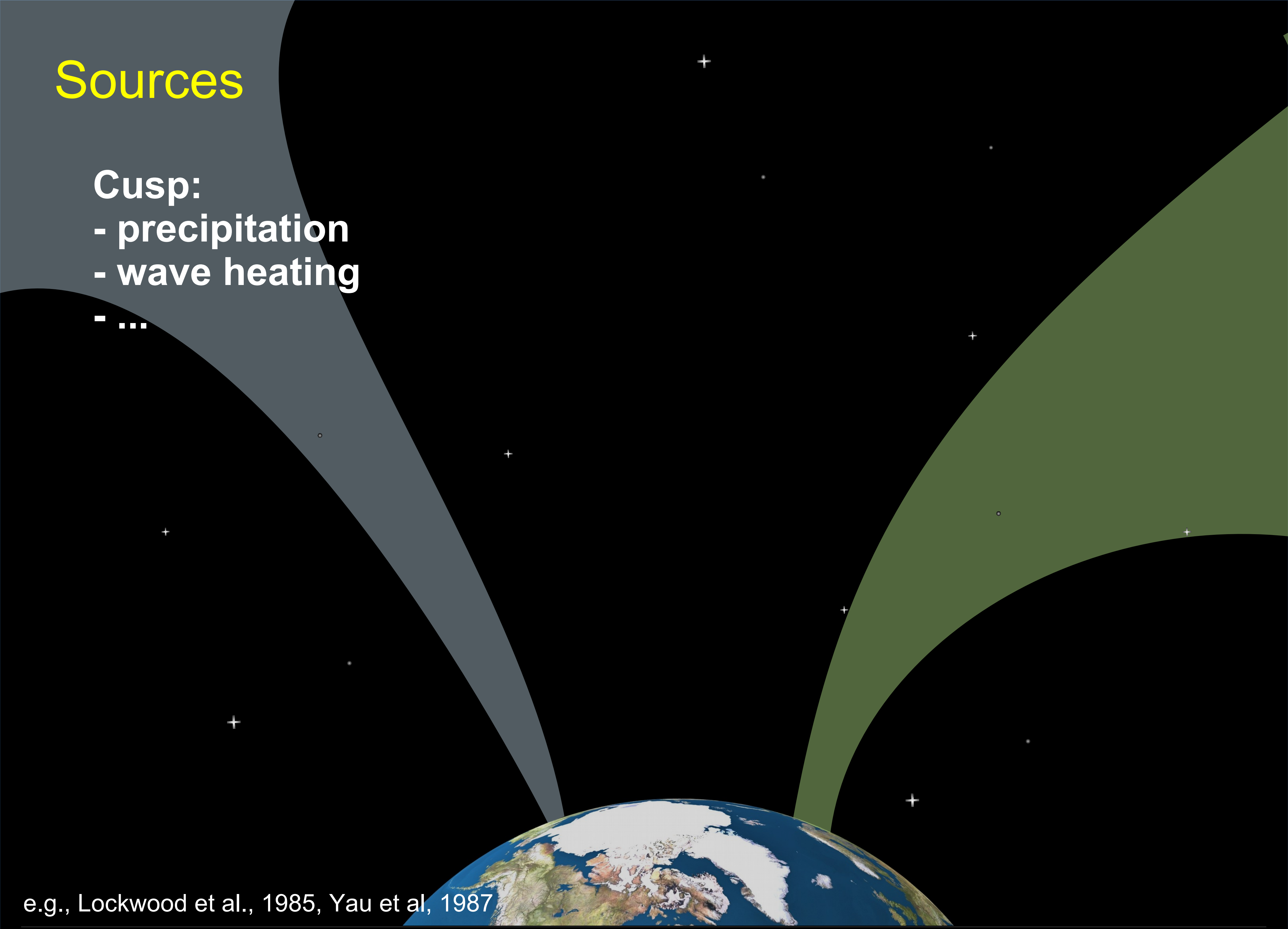

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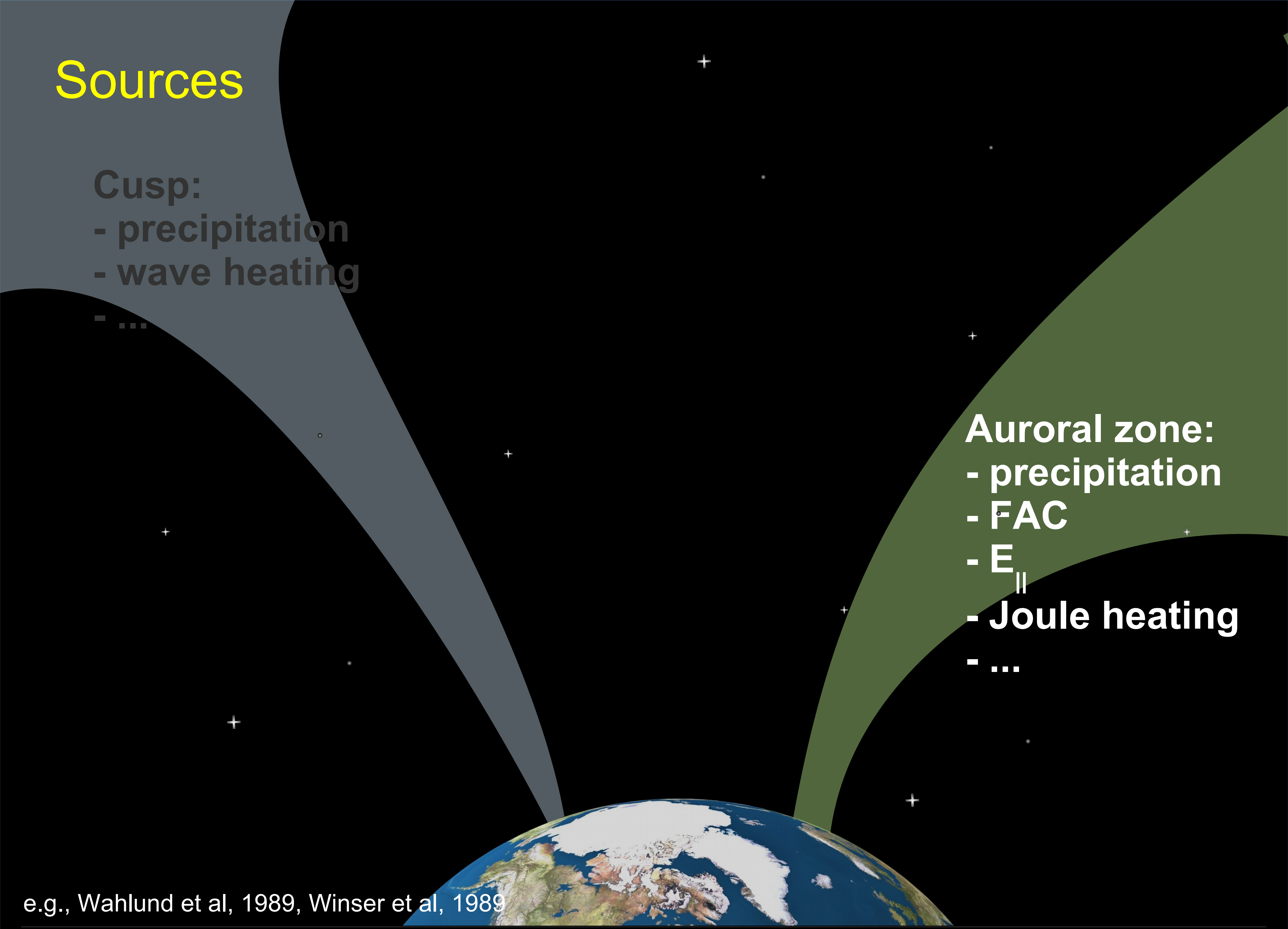
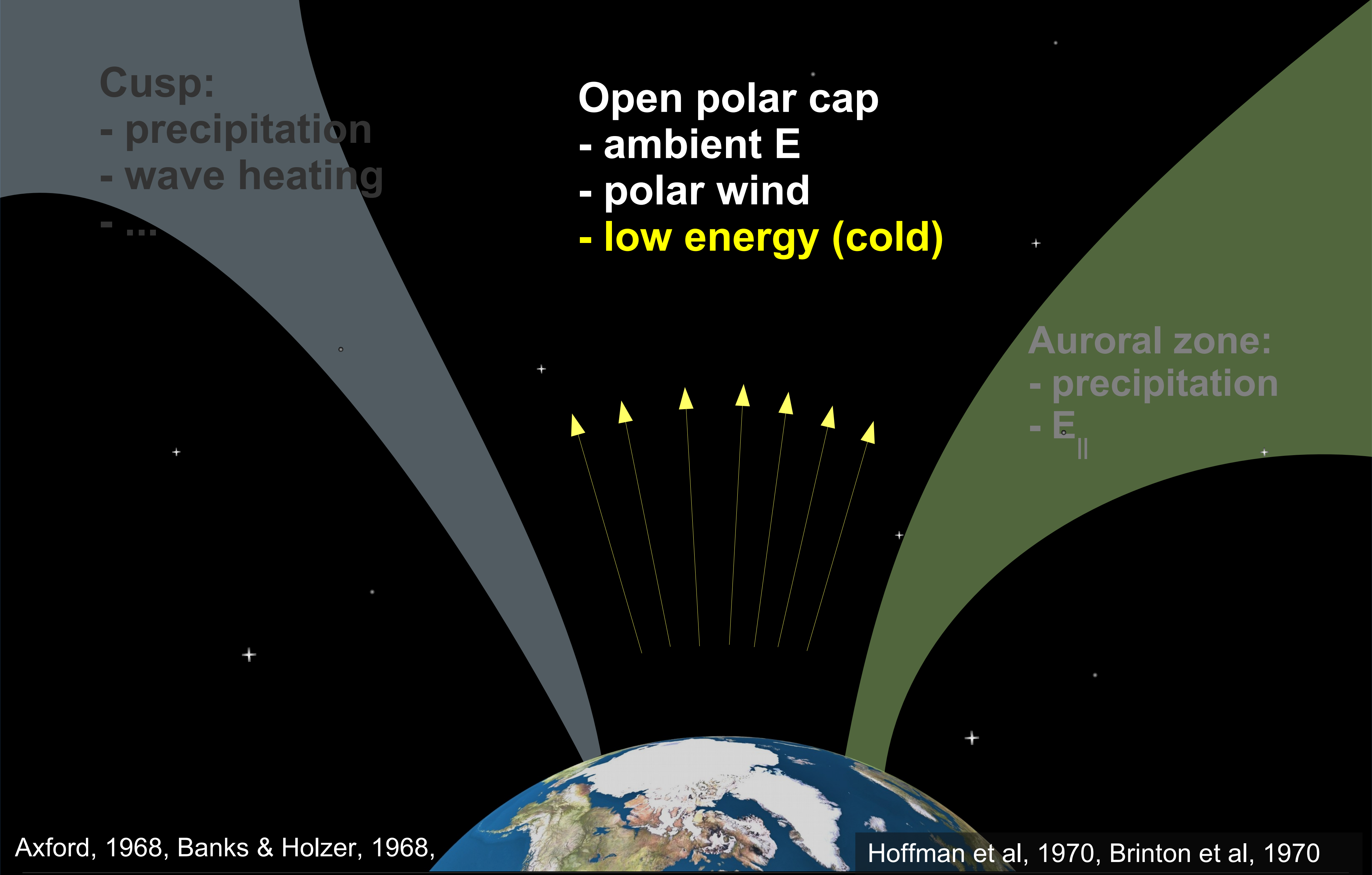


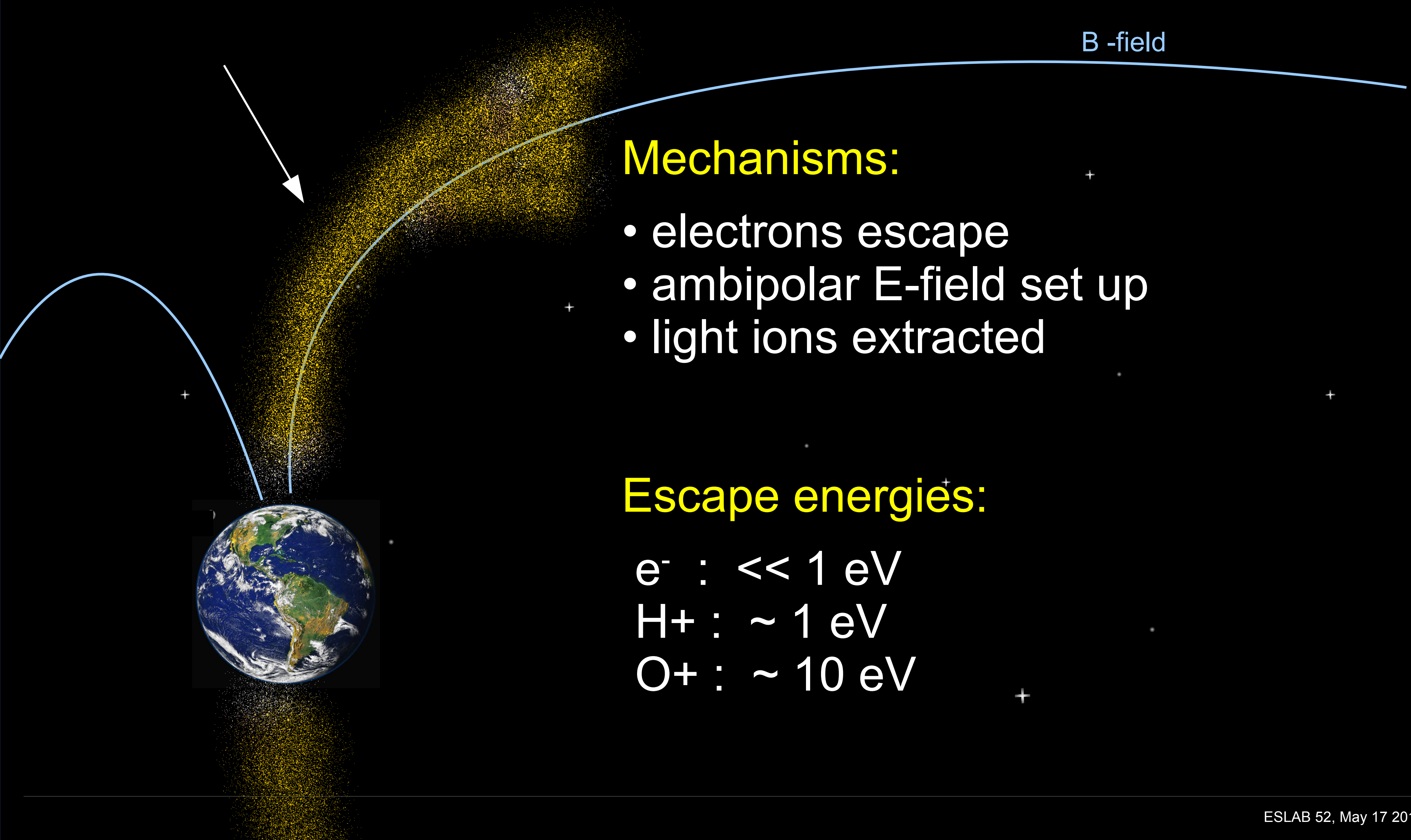
e.g., Wahlund et al, 1989, Winser et al, 1989

Sources



Axford, 1968, Banks & Holzer, 1968, Hoffman et al, 1970, Brinton et al, 1970

Mechanisms



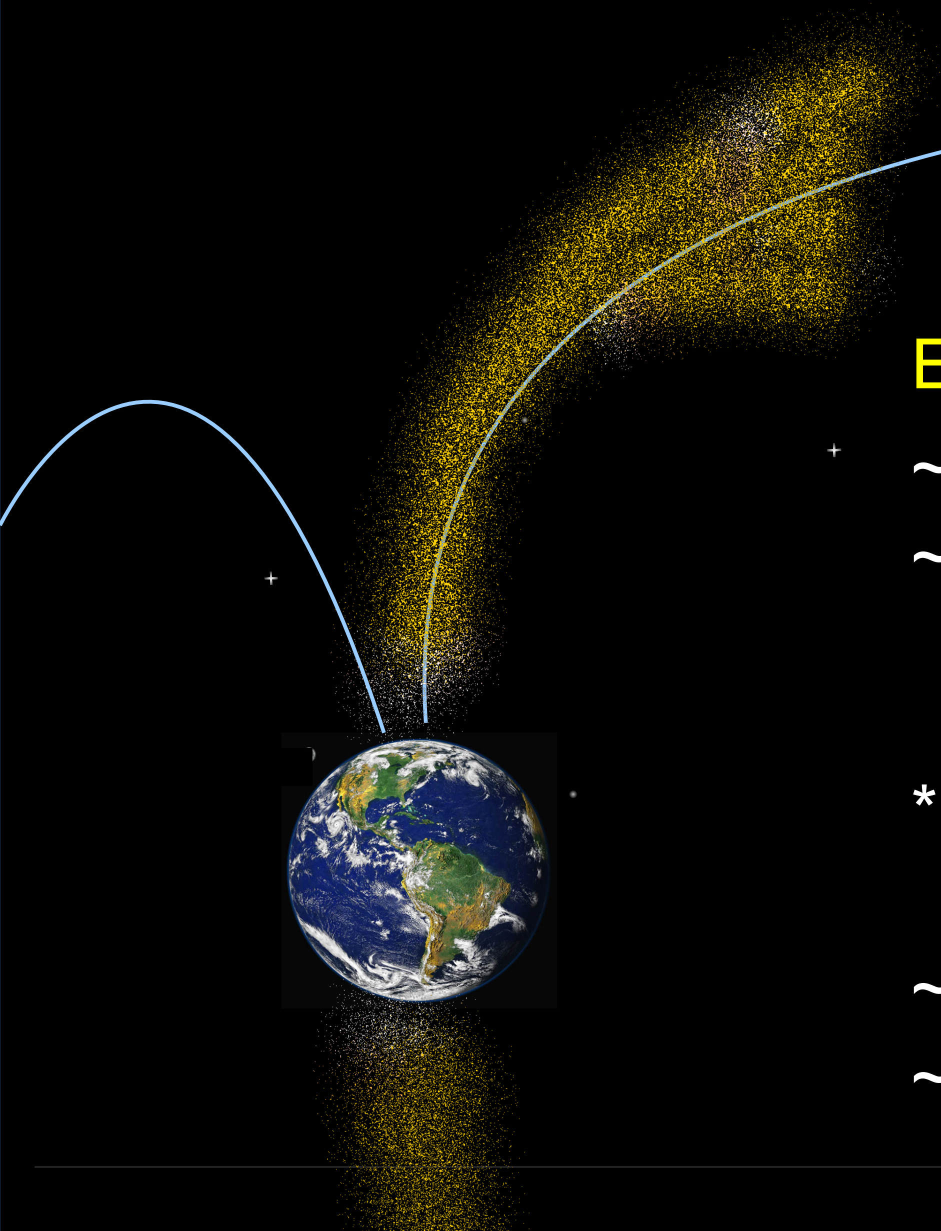
Mechanisms:

- electrons escape
- ambipolar E-field set up
- light ions extracted

Escape energies:

e^- : << 1 eV
H+ : ~ 1 eV
O+ : ~ 10 eV

Ion outflow from polar cap regions



Escape rates, Earth:

~1e25 to 1e26 ions/sec

~50'000 – 100'000 t/year

(strongly modulated by EUV, IMF)

* mainly H^+ and O^+ (despite 78% N)

~10% downtail loss into solar wind

~90% recirculated in M'sphere

Transport and forces

$$\frac{dv_{\|}}{dt} = \underbrace{\frac{eE_{\|}}{m}}_{\text{E-field}} + \underbrace{\mu \nabla_{\|} B}_{\text{mirror force}} + \underbrace{\vec{v}_E \cdot \frac{d\hat{b}}{ds}}_{\text{centrifugal acc}} + \underbrace{\frac{F_{TH\|}}{m}}_{\text{thermal/pressure}} - \underbrace{\vec{g}_{\|}}_{\text{gravity}}$$

Field aligned acceleration of cold ions are primarily governed by :

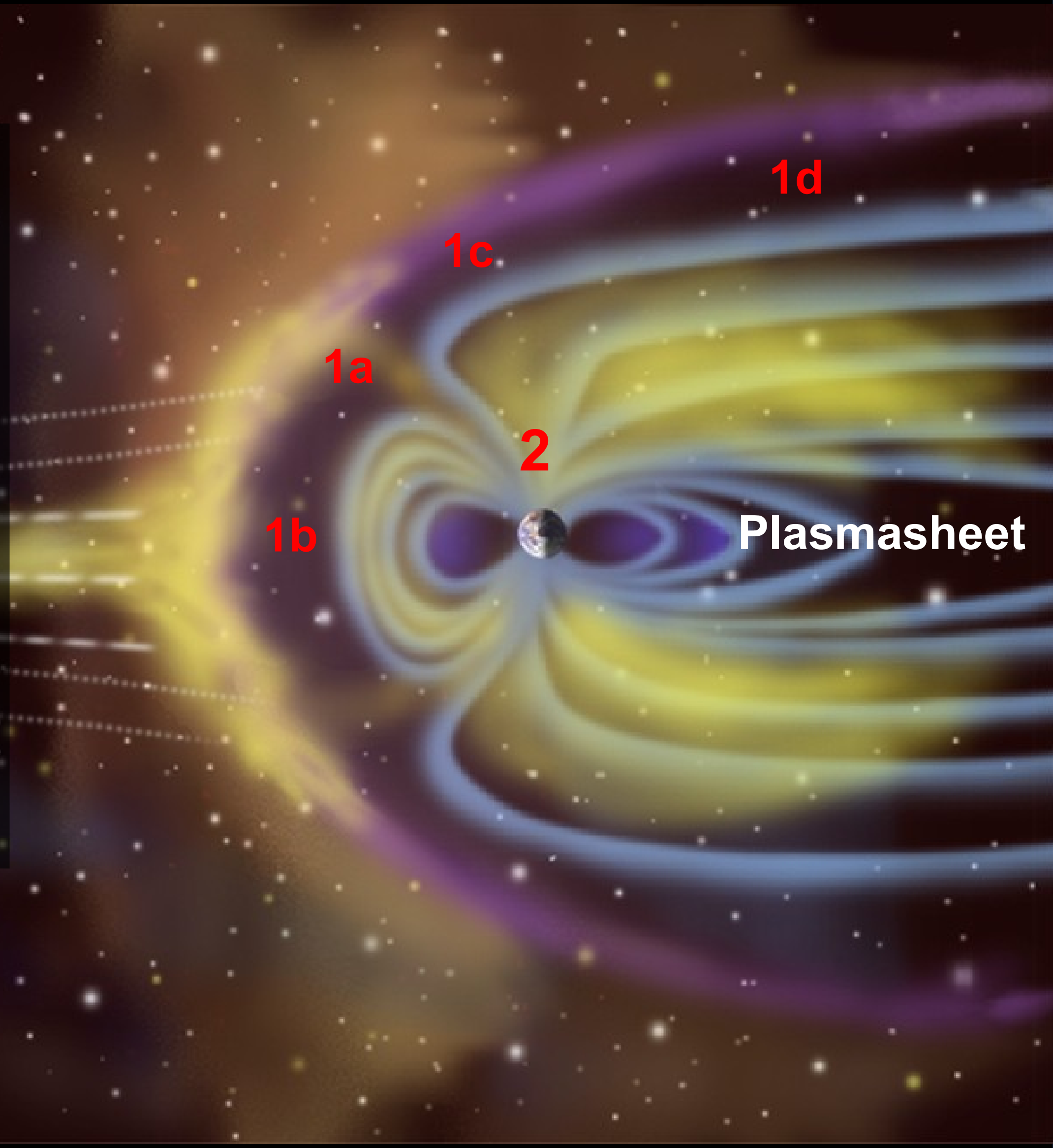
* Gravity (low altitudes)
* Mirror force (low altitude)
* Centrifugal force (intermediate altitudes)
* Electric fields (relevant at low altitudes otherwise $E_{\|} \sim 0$)

...for comparison .. other sources

Supply rates :

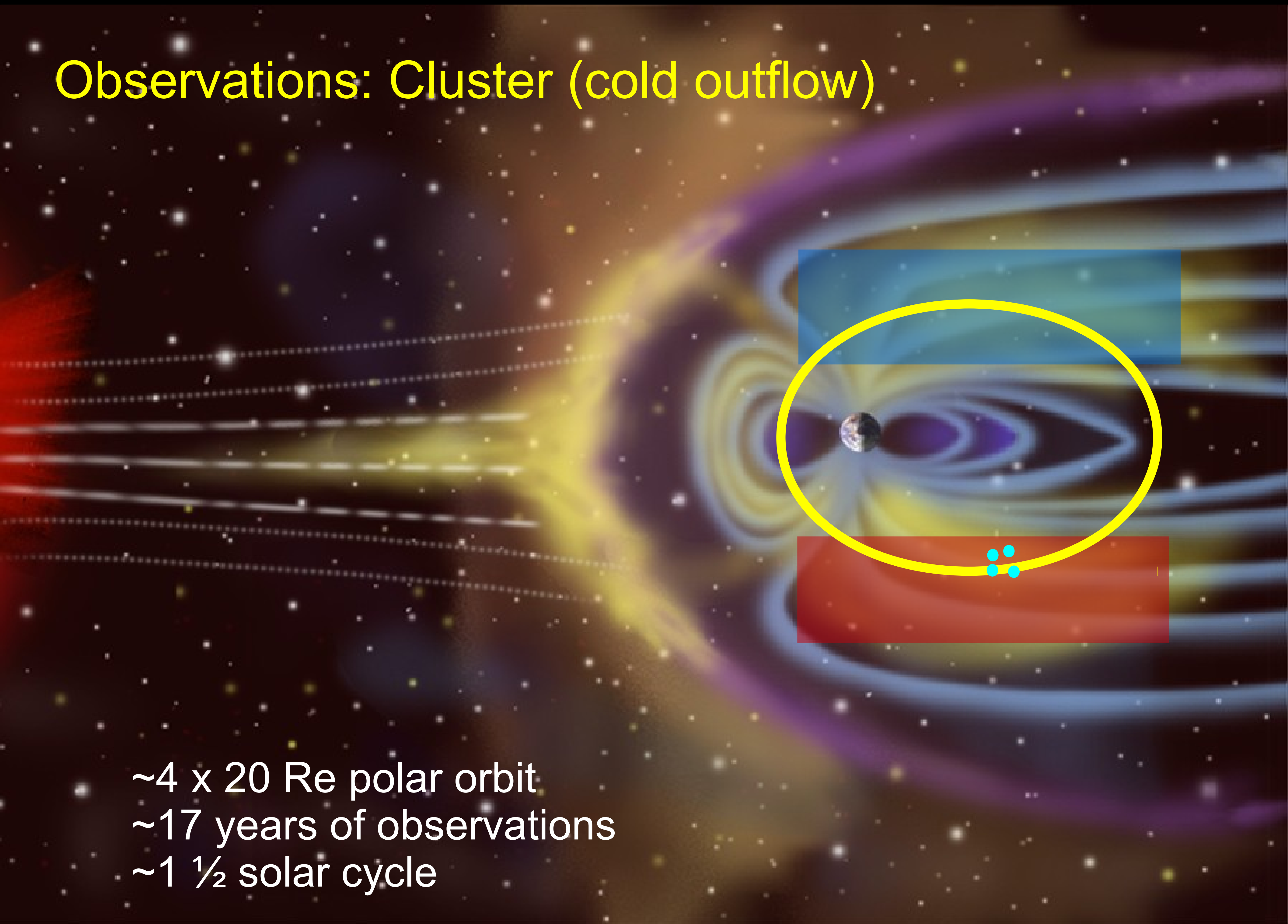
* Solar wind : 10^{24} -10^{27} s^{-1} [1,2]
* High latitude : up to 10^{27} s^{-1} [3]

* Terrestrial outflow ~10^{26} s^{-1} [4]
  "Cold" (~ 10's eV) dominating [5]



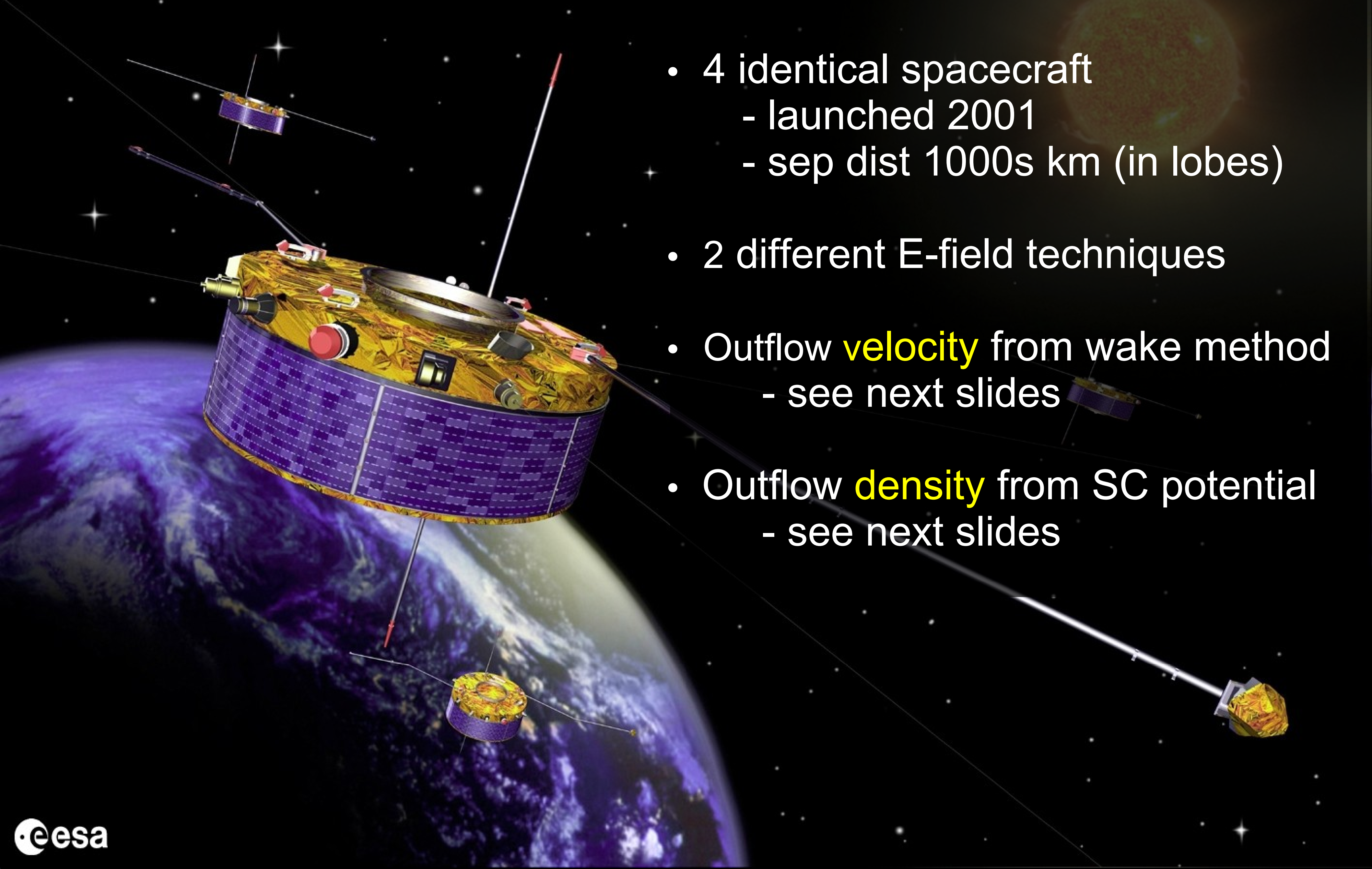
[1] Cowley et al, 1980
[2] Walker et al, 1995
[3] Shi et al, 2013
[4] Yau et al, 1999
[5] André & Cully, 2012, Andre, 2016

Observations: Cluster (cold outflow)



~4 x 20 Re polar orbit
~17 years of observations
~1 ½ solar cycle

Cluster results

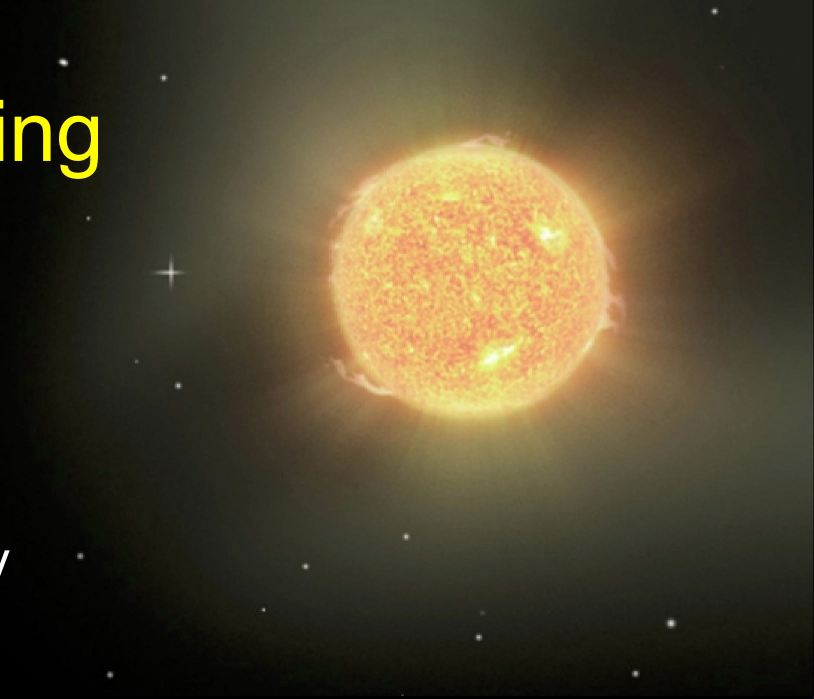


- 4 identical spacecraft
  - launched 2001
  - sep dist 1000s km (in lobes)
- 2 different E-field techniques
- Outflow velocity from wake method
  - see next slides
- Outflow density from SC potential
  - see next slides

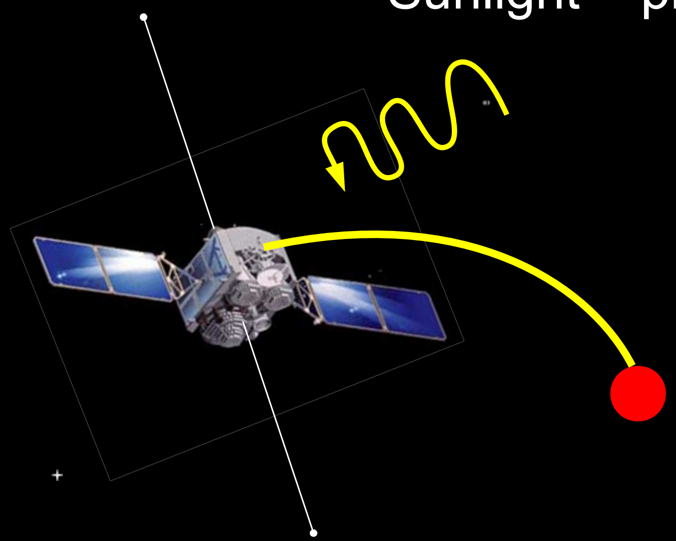
Cluster observations

- Cold ion outflow
    - Cluster advantages
- Modulations
    - Solar illumination
    - Geomagnetic activity
- North-South asymmetries

Cluster: Utilize spacecraft charging

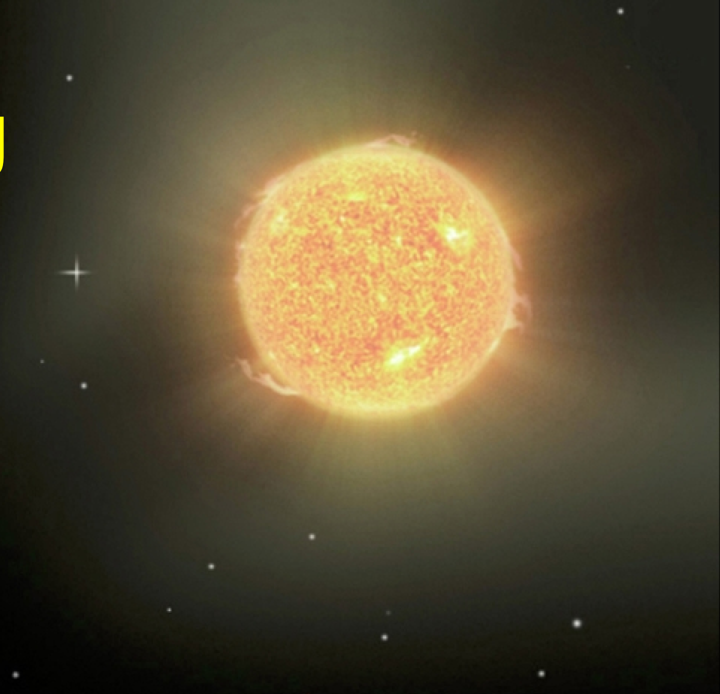


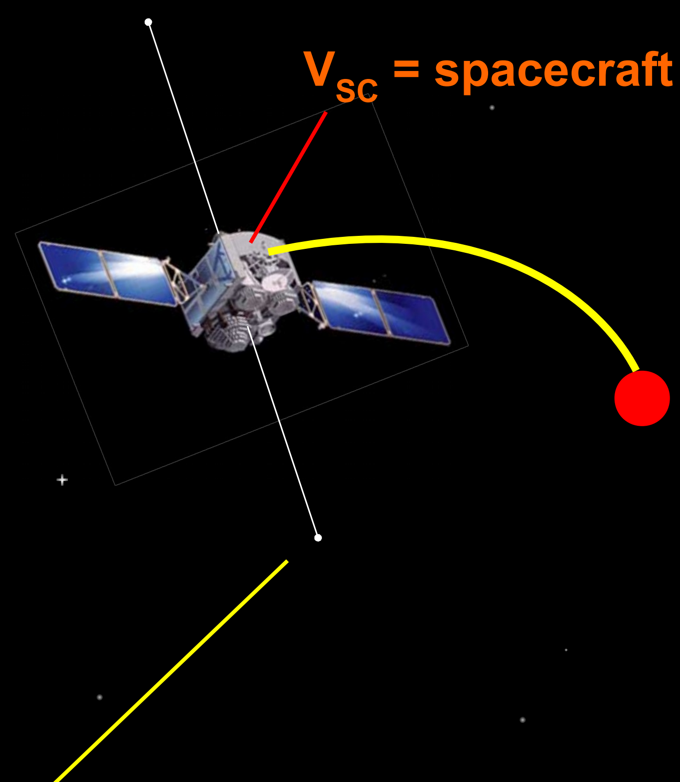
Sunlight = photons, E = h γ



e- (photo electron → current)

Cluster: Utilize spacecraft charging





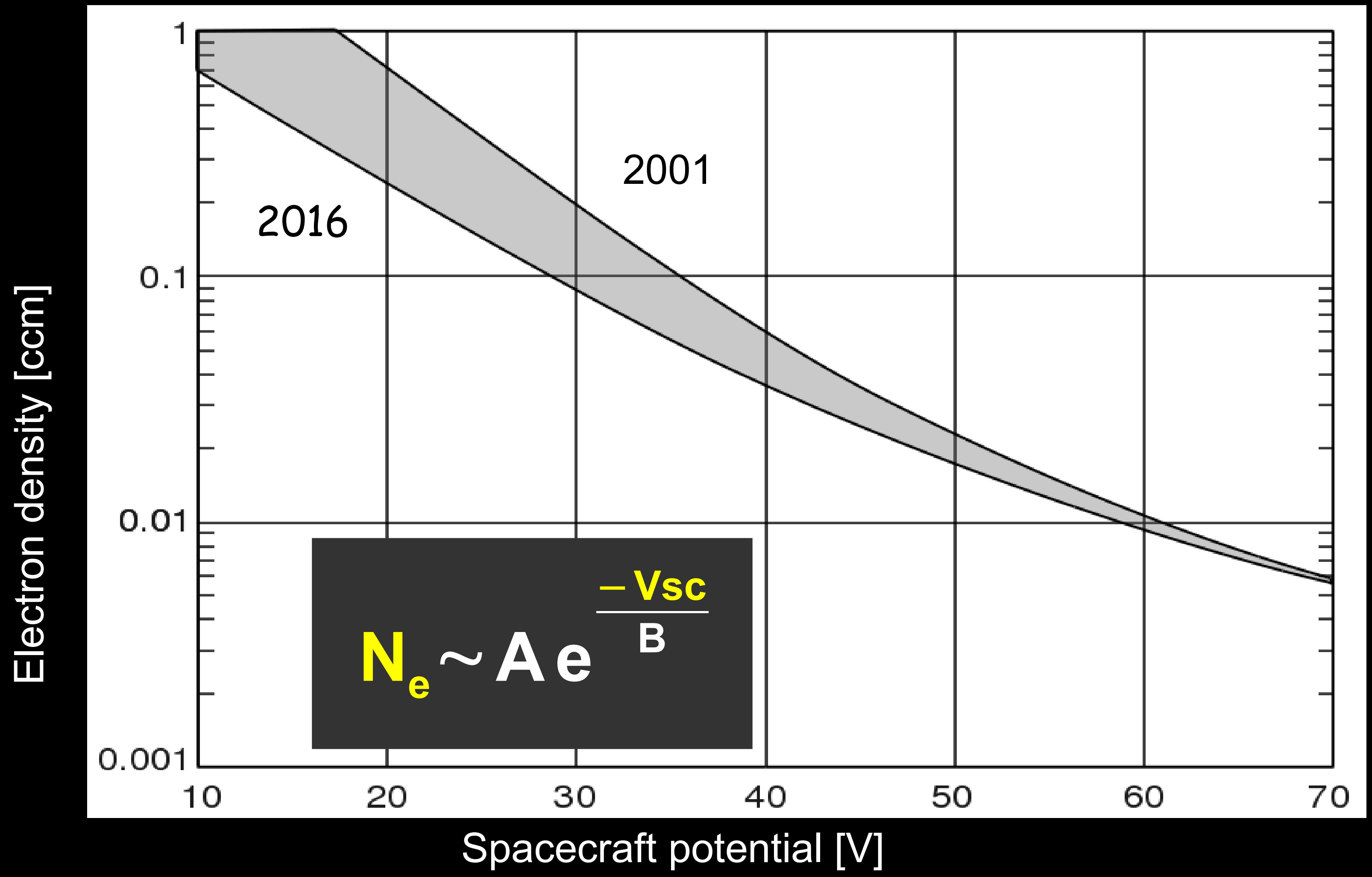
V_{SC} = spacecraft potential

e- (photo electron → current)

Unless current balanced, spacecraft will be positively charged to V_{SC}

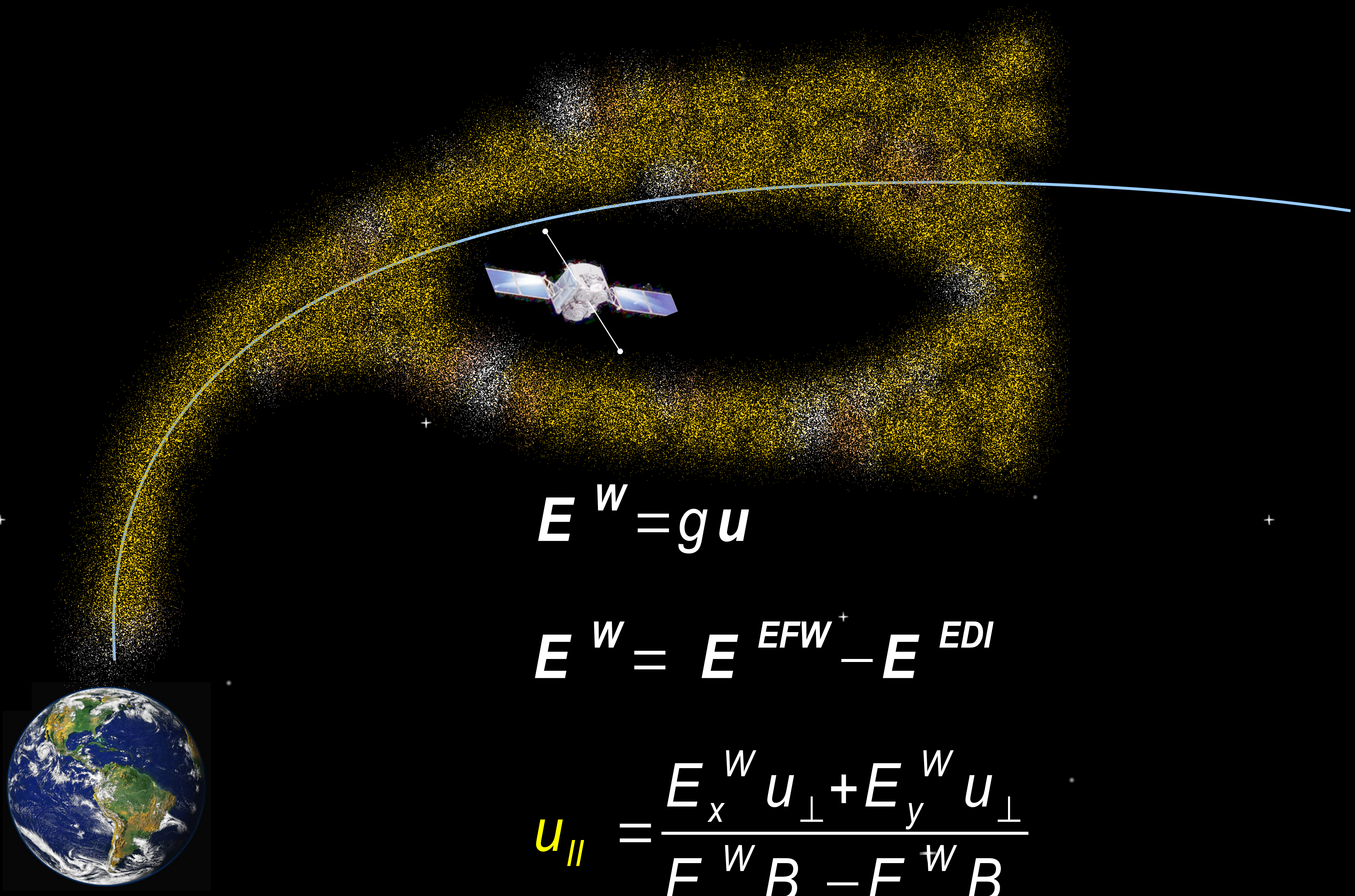
$V_0 \sim V_P$ = ambient plasma = 0 V

Cluster: Plasma density from spacecraft potential



Lybekk et al, 2012 (based on earlier works by Grard, Laakso, Pedersen...)

Outflow velocity - ‘wake method’



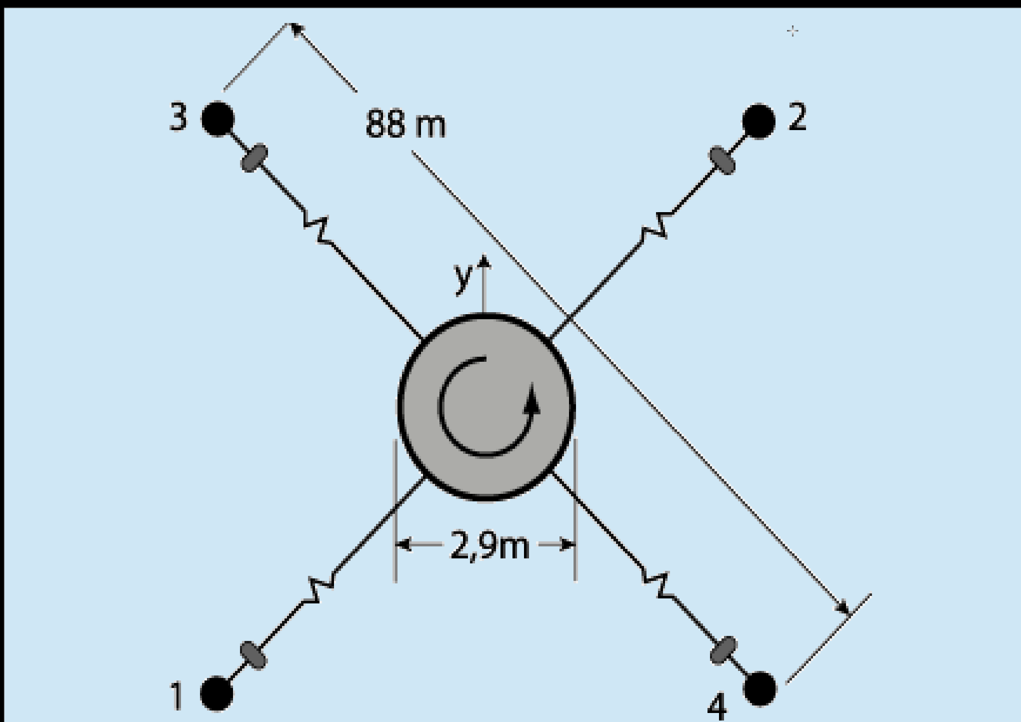
$$\mathbf{E}^{W} = g\,\mathbf{u}$$

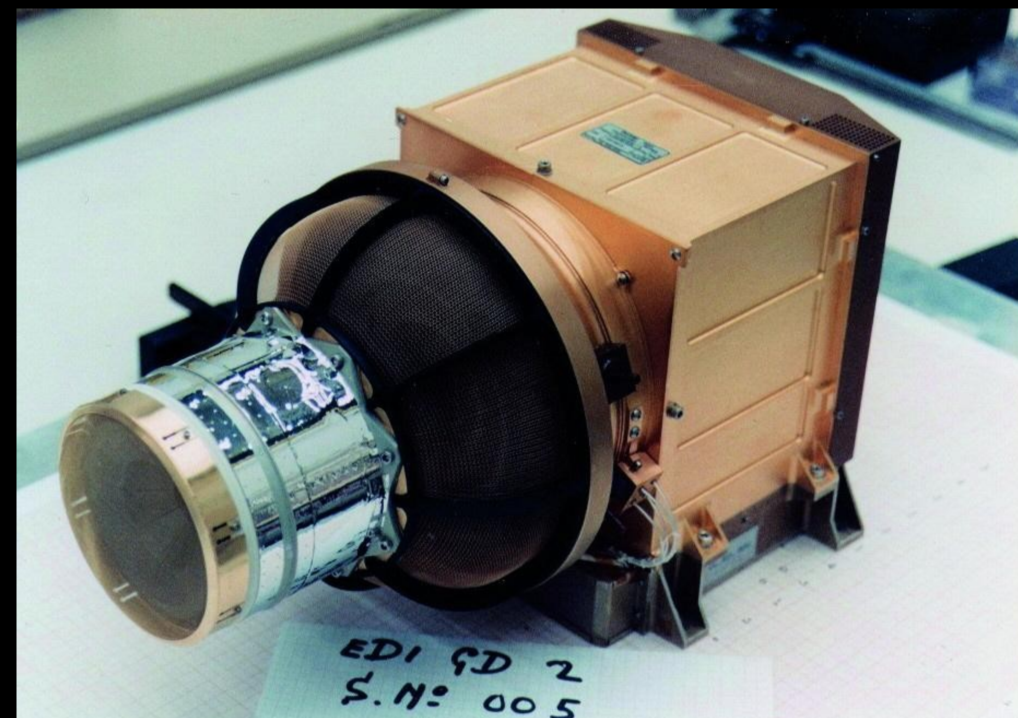
$$\mathbf{E}^{W} = \mathbf{E}^{EFW} - \mathbf{E}^{EDI}$$

$$u_{||} = \frac{E_x^{W} u_{\perp} + E_y^{W} u_{\perp}}{E_y^{W} B_x - E_x^{W} B_y}$$

Engwall et al, 2009

Key feature : 2 electric field experiments





EFW :

*** ~100 m scale**

*** measures E_{WAKE}**

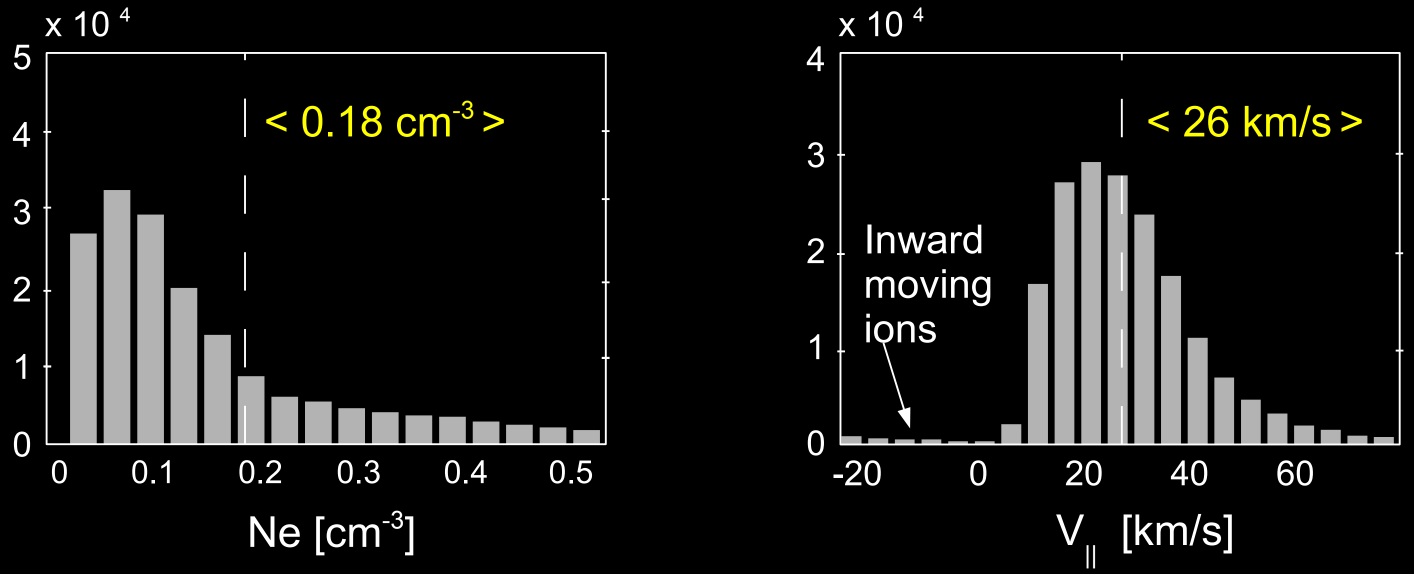
EDI :

*** 1keV electron scale**

*** not affected by wake**

*** measures E_{CONV}**

Outflow rates, cold ions



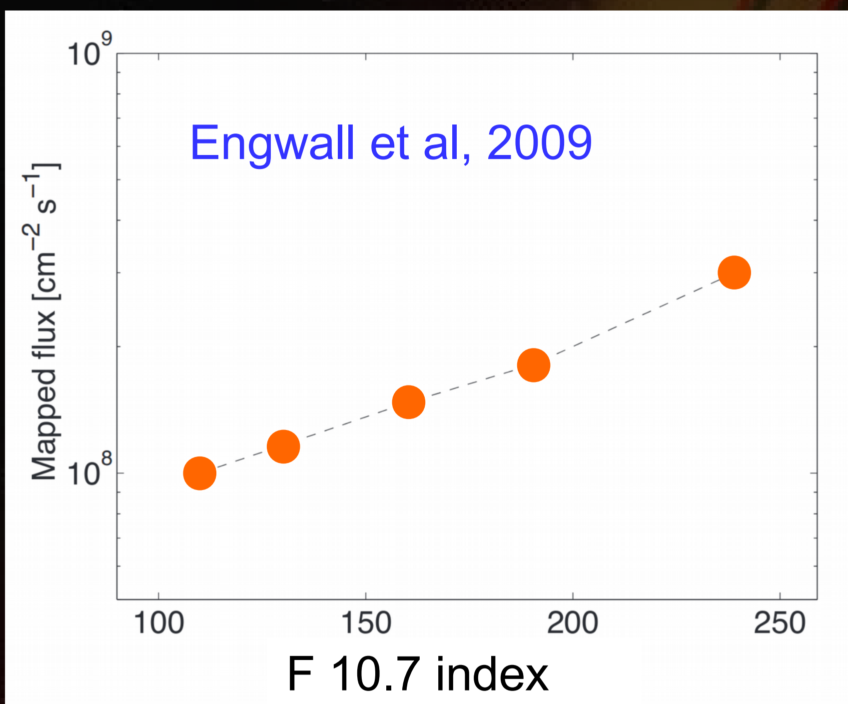
* Average outflow rate ~10^{26} ions/s

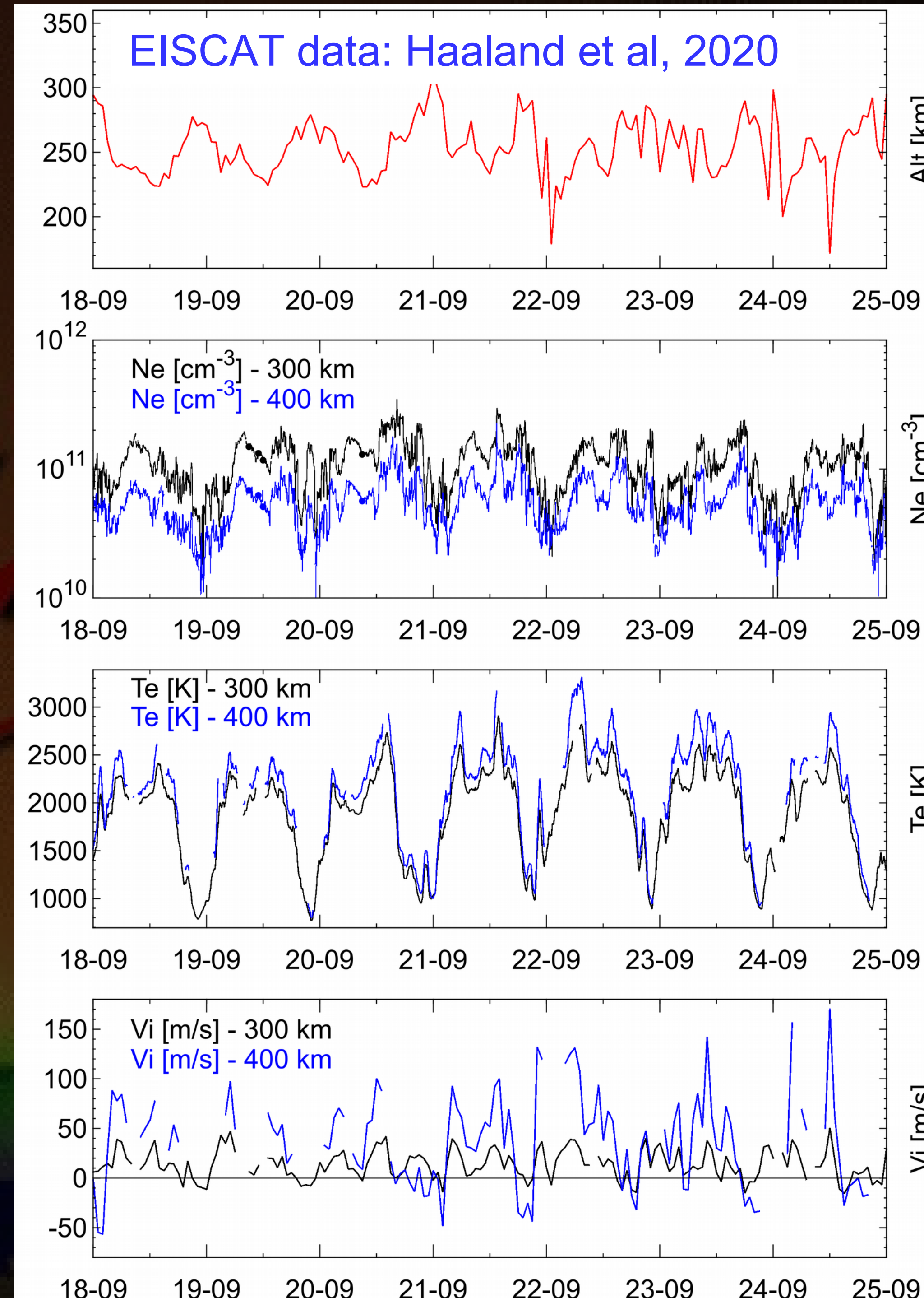
* Cold, ("invisible"), ions constitute a dominant part of the total outflow

After Engwall et al, 2009, André et al, 2015

Modulations:
Solar illumination

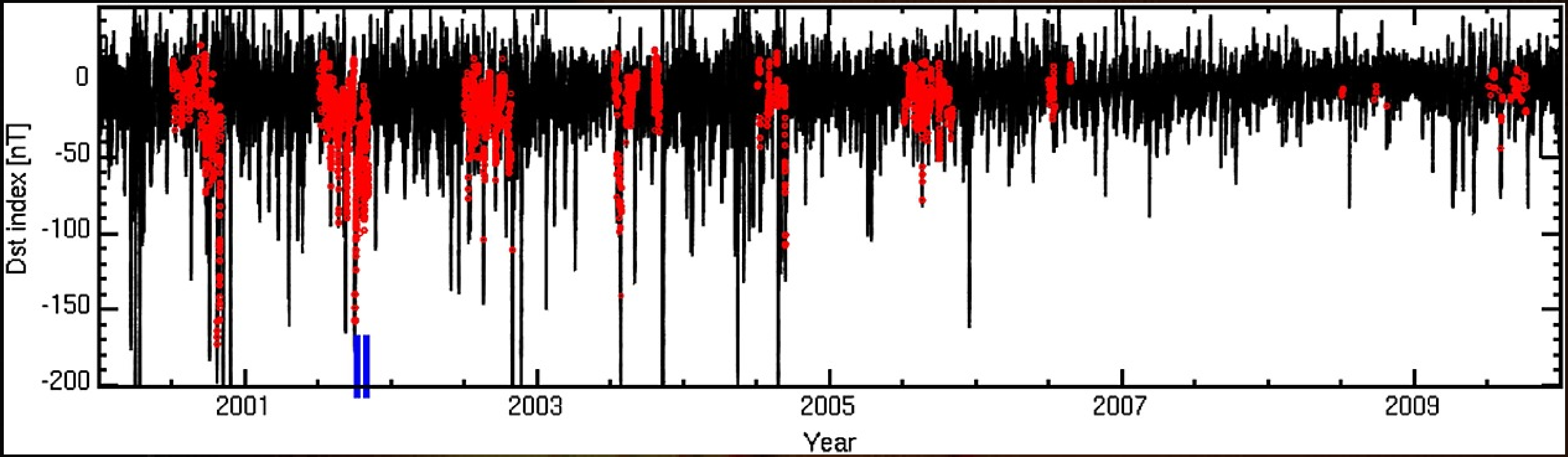
- daily
- seasonal
- solar cycle

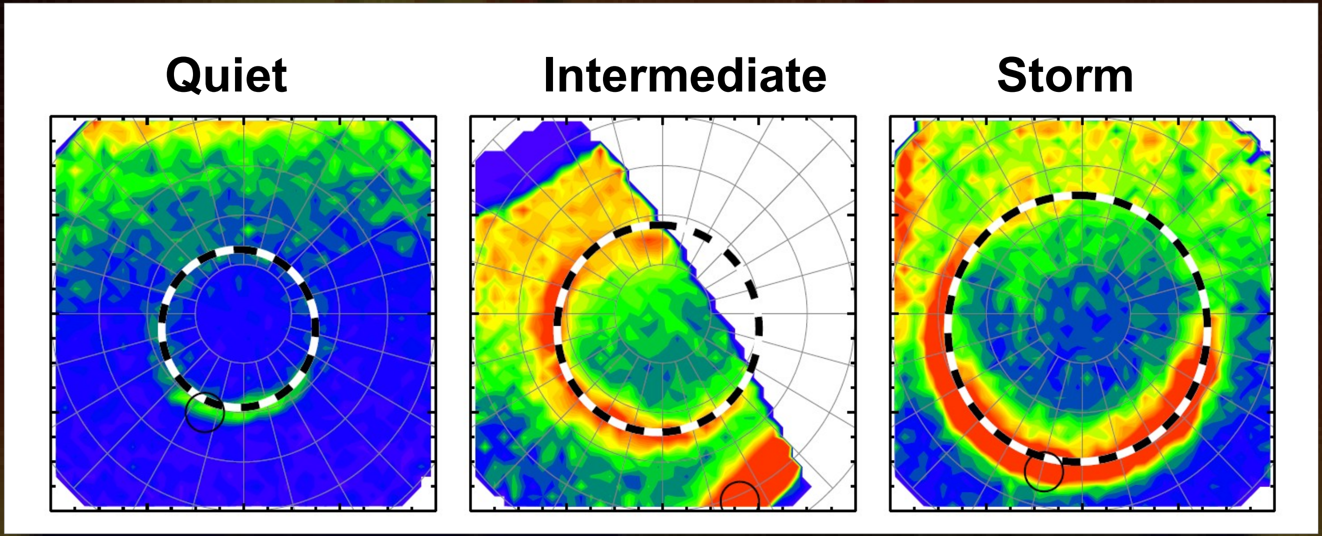




Also Maes et al, 2016,2017

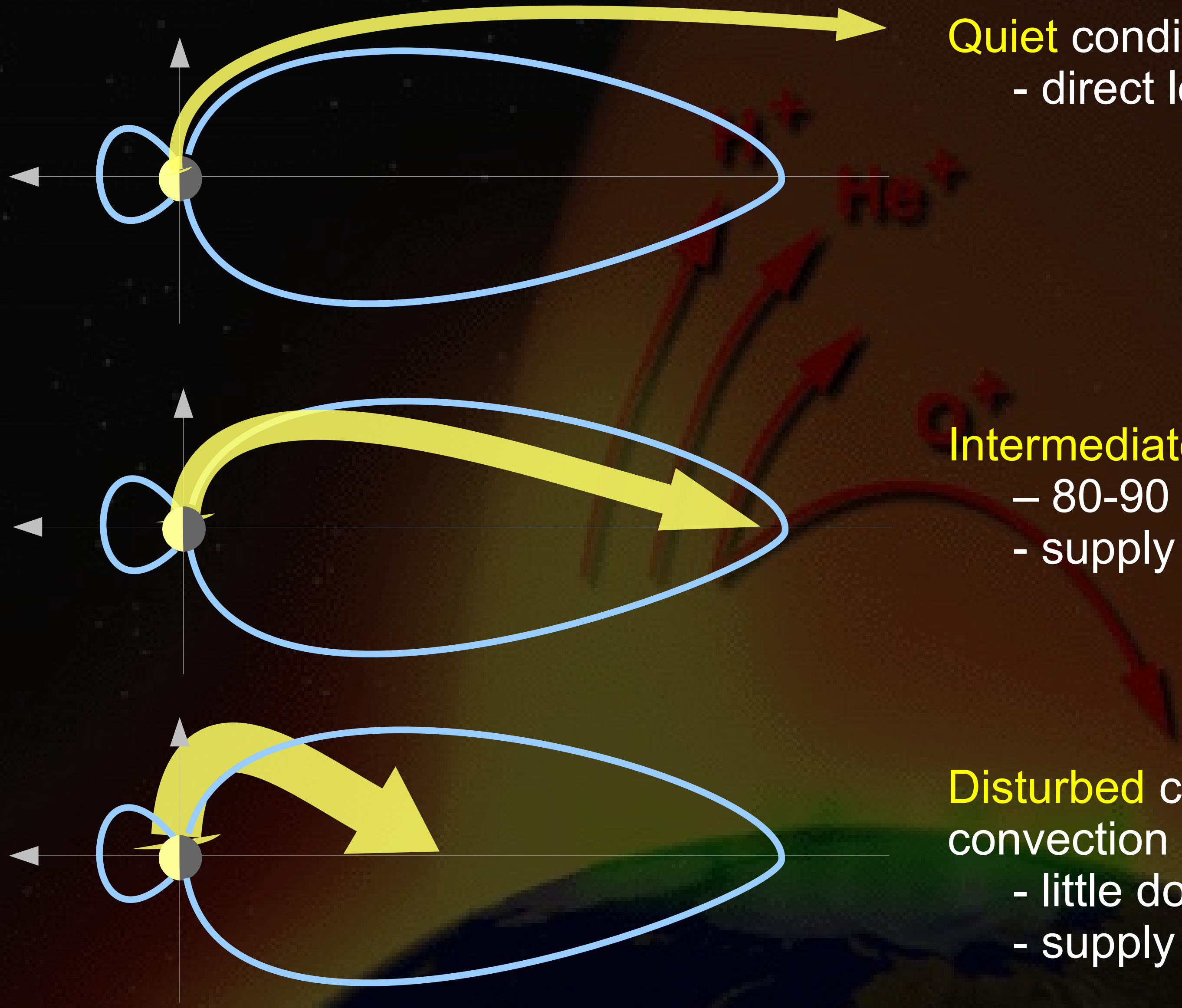
Modulations:
Geomagnectic activity: PC area + transport





Milan et al, 2009, Haaland et al, 2014

Consequences I : supply to plasma sheet



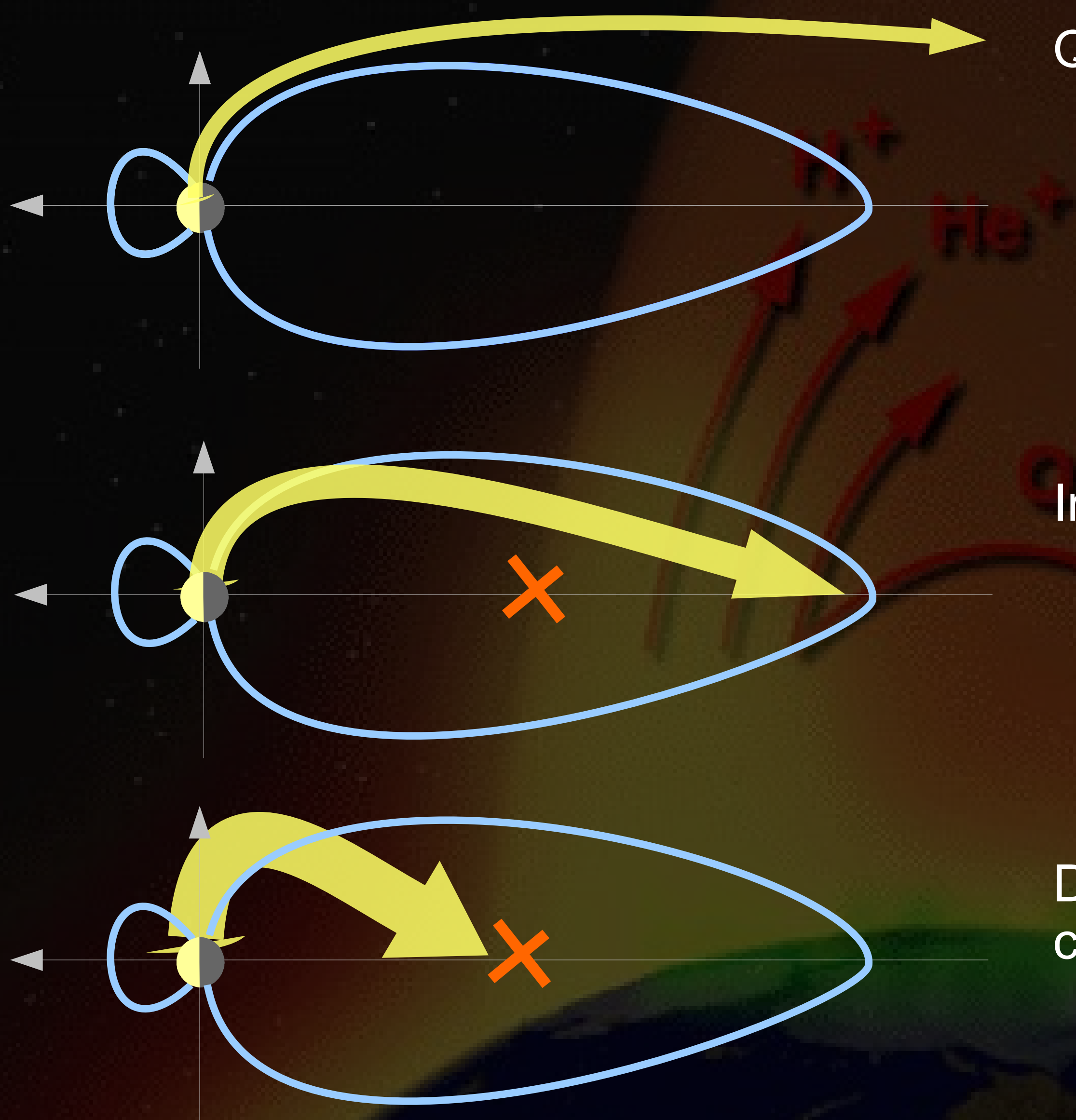
Quiet conditions, stagnant convection
- direct loss downtail

Intermediate geoactivity
– 80-90 % circulation
- supply far downtail

Disturbed conditions, strong convection
- little downtail loss
- supply close to Earth

Haaland et al, 2014, 2017

Consequences I : supply to plasma sheet



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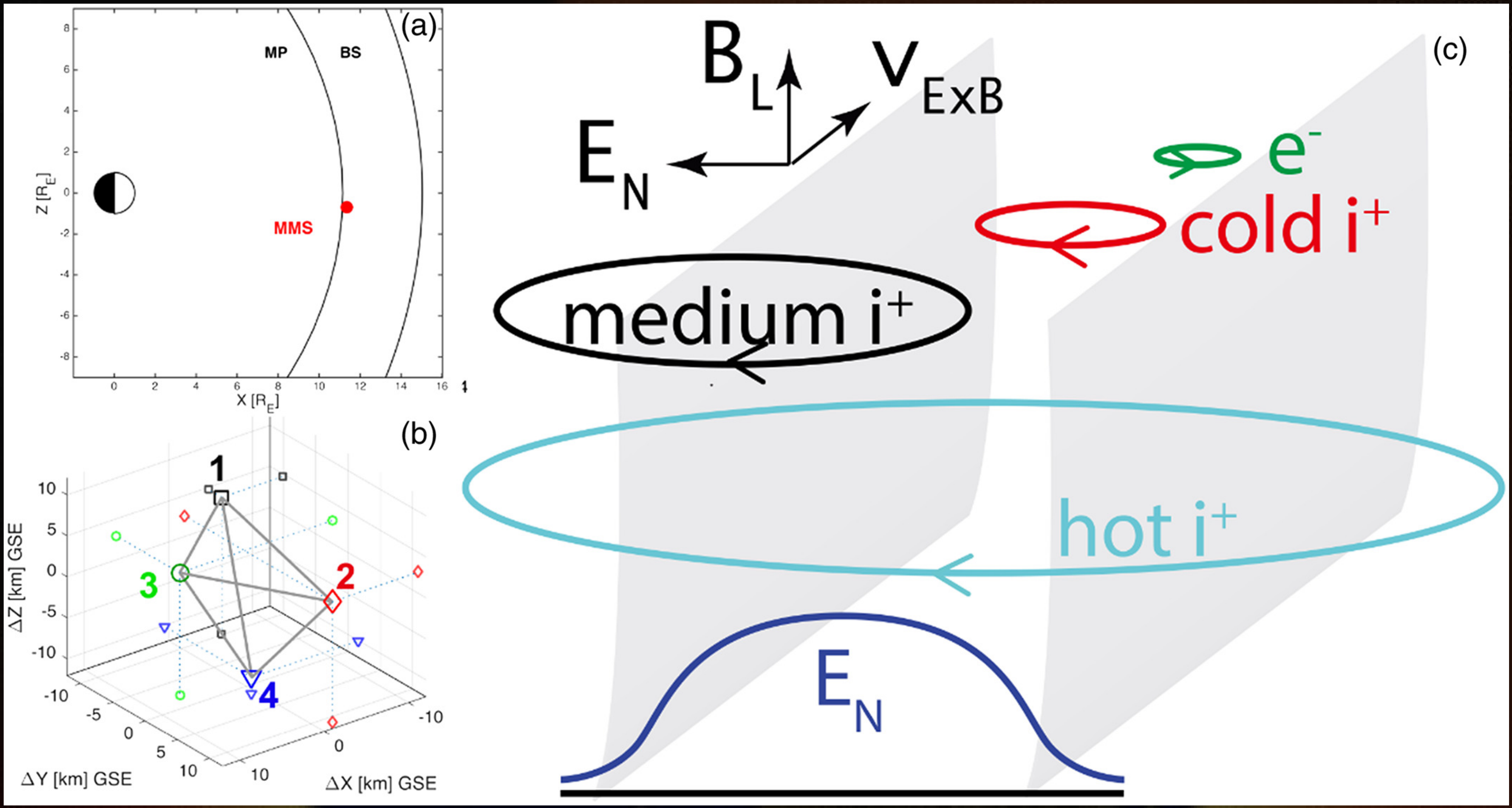
Haaland et al, 2014, 2017

Consequences II - microphysics:
Intermediates scale in reconnection – reduce Hall currents



Andre et al, 2016 (also Andre et al 2010, Walsh et al, 2015, Borovsky et al, 2015, Toldedo-Redondo et al, 2016)

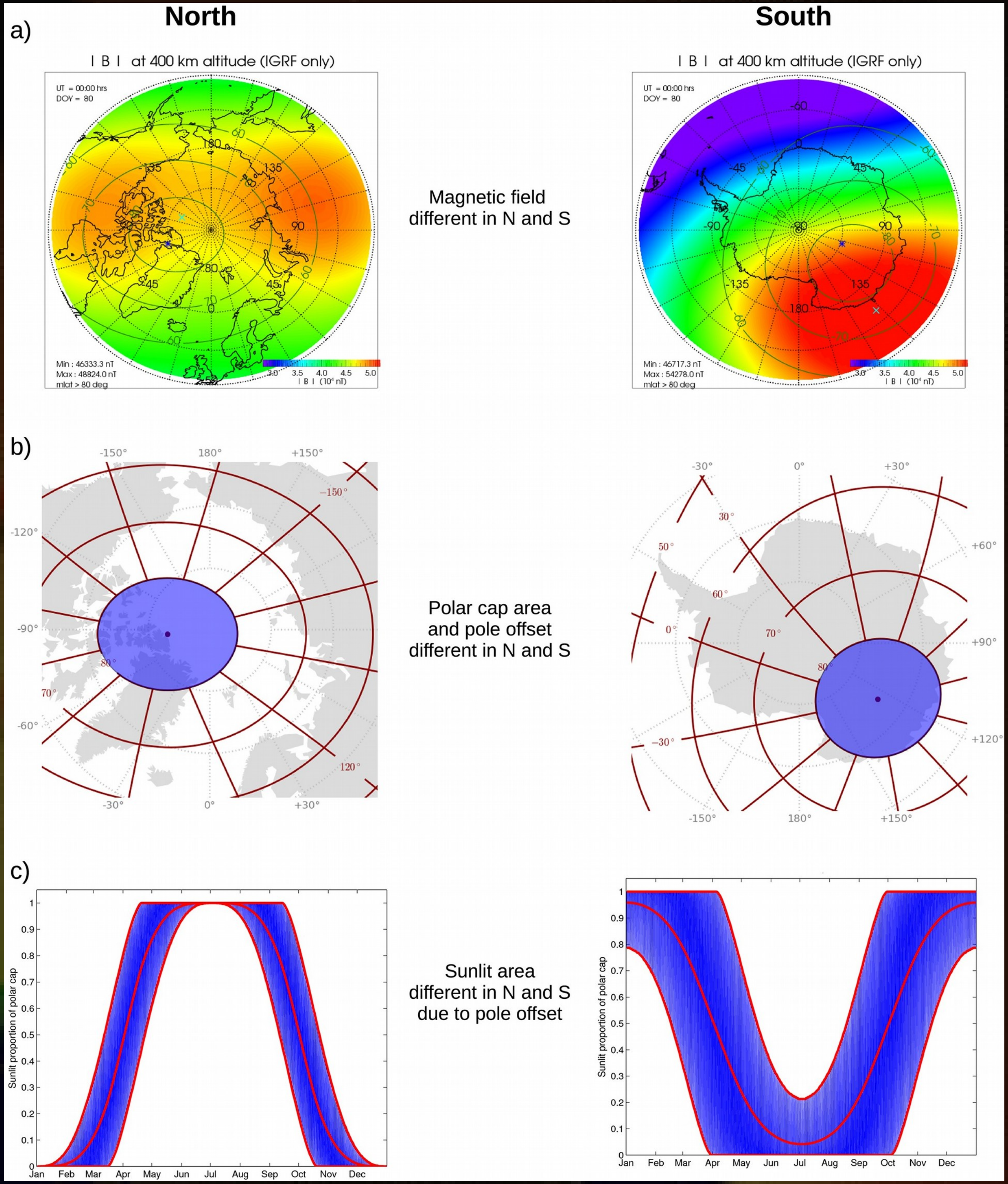
North – south asymmetries ?

- B-field different

- dipole offset

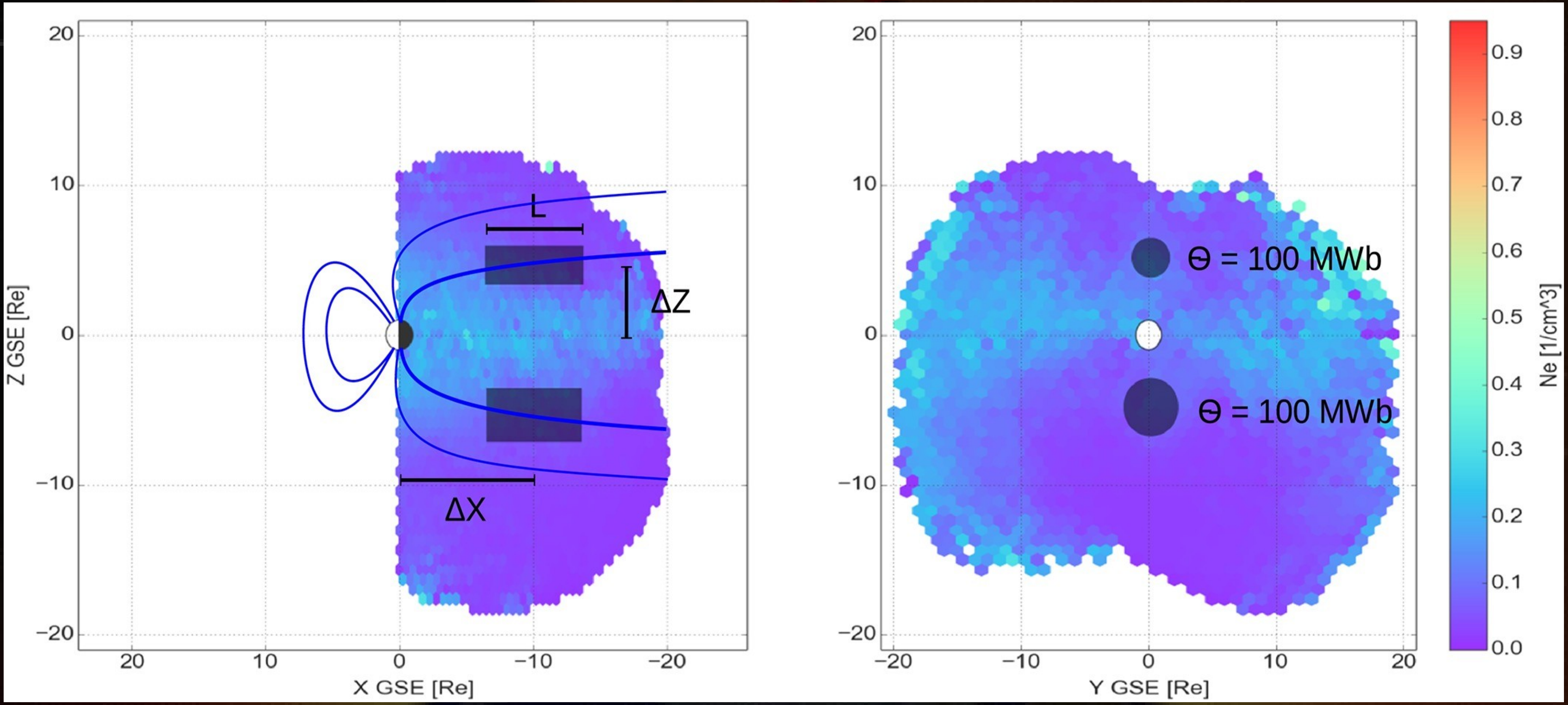
- polar cap area

- effective illumination



North – south asymmetries

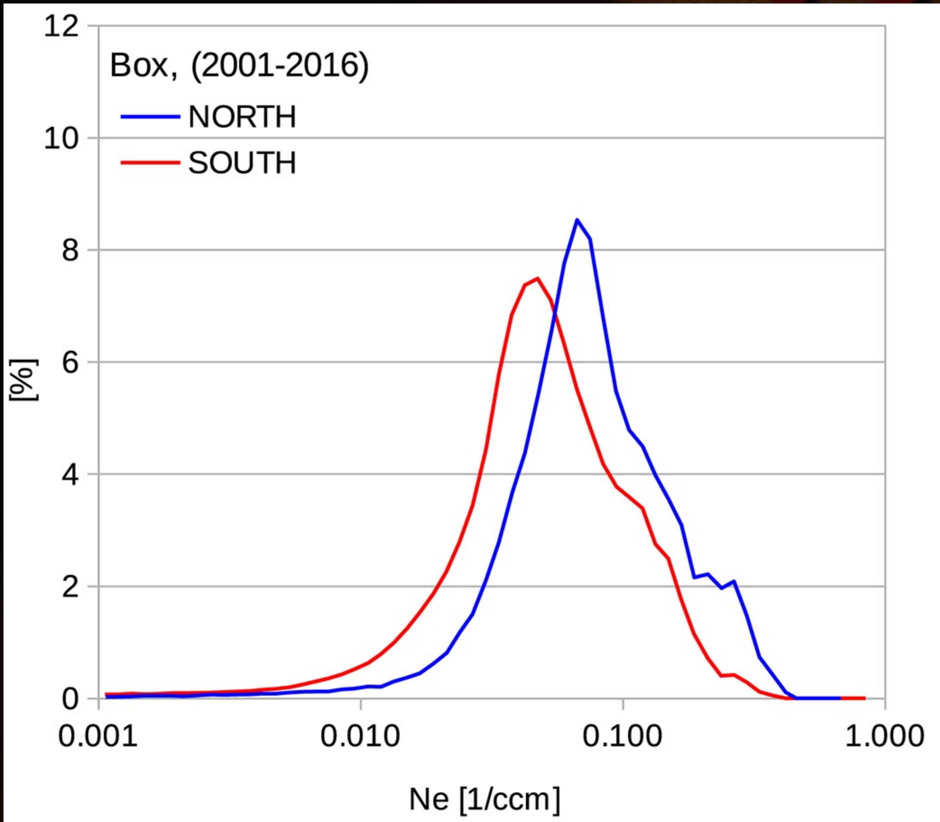
Cluster lobe densities 2001-2016 :

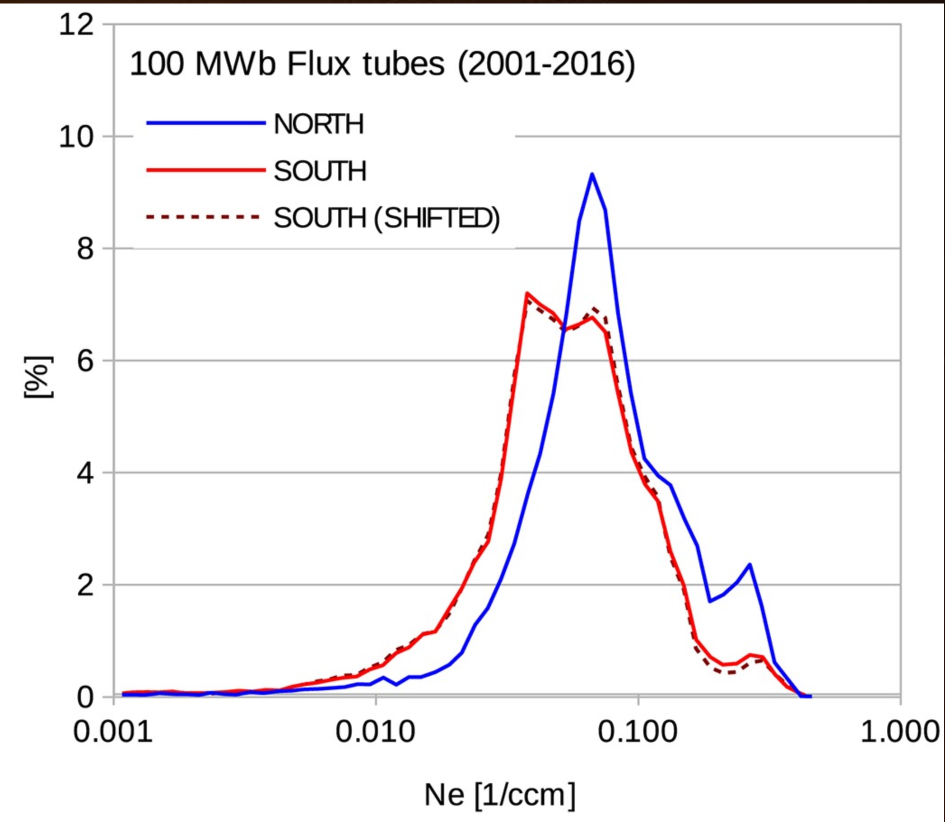


Haaland et al, 2017

North – south asymmetries

Cluster lobe densities 2001-2016 :
Higher outflow from Northern hemisphere





Haaland et al, 2017

Summary

- 50’000 – 100’000 tonnes of ions escape per year from Earth
  - strongly modulated by solar illumination
  - ..but also geomagnetic activity, precipitation..
  - constrained by production (ionospheric plasma density)

- ~90% recirculated – only 10% direct downtail loss
  - governed by transport/convection

- ionosphere = significant contributor to magnetospheric plasma

- cold plasma influence microphysics
  - modify/quench reconnection (reduce Hall curr)

- North- south asymmetry
  - local differences in N and S ionosphespheres

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Task 2 – Scientific Working Groups

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http://gpsm.spacescience.ro/europlanet2018/