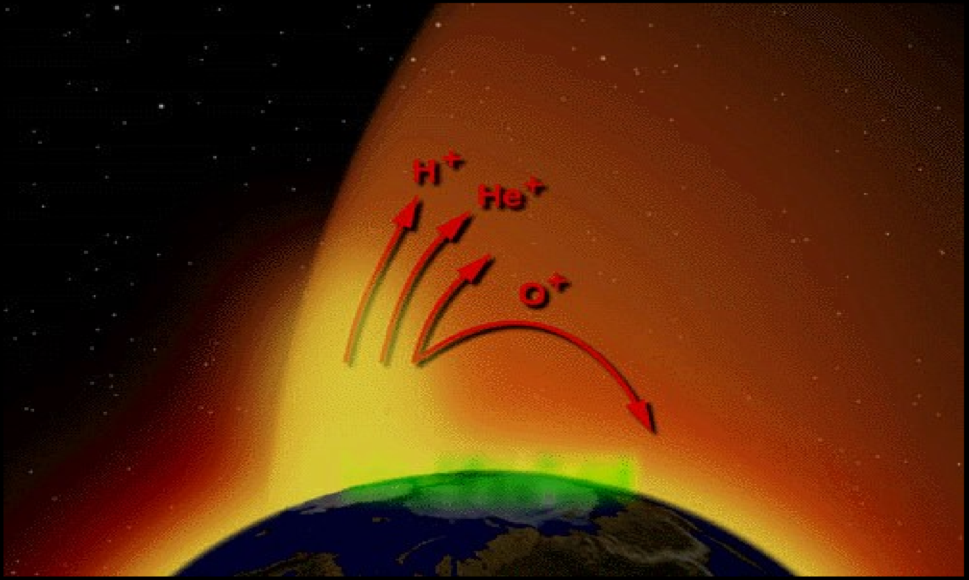
Cold Ion Outflow from the Polar Cap



S. Haaland, M. Andre, L. Baddeley, A. Barakat,
R. Chappell, V. Eccles, A. Eriksson, C. Johnsen, K. Li,
L. Maes, R. Schunk, D. Welling

Outline of talk

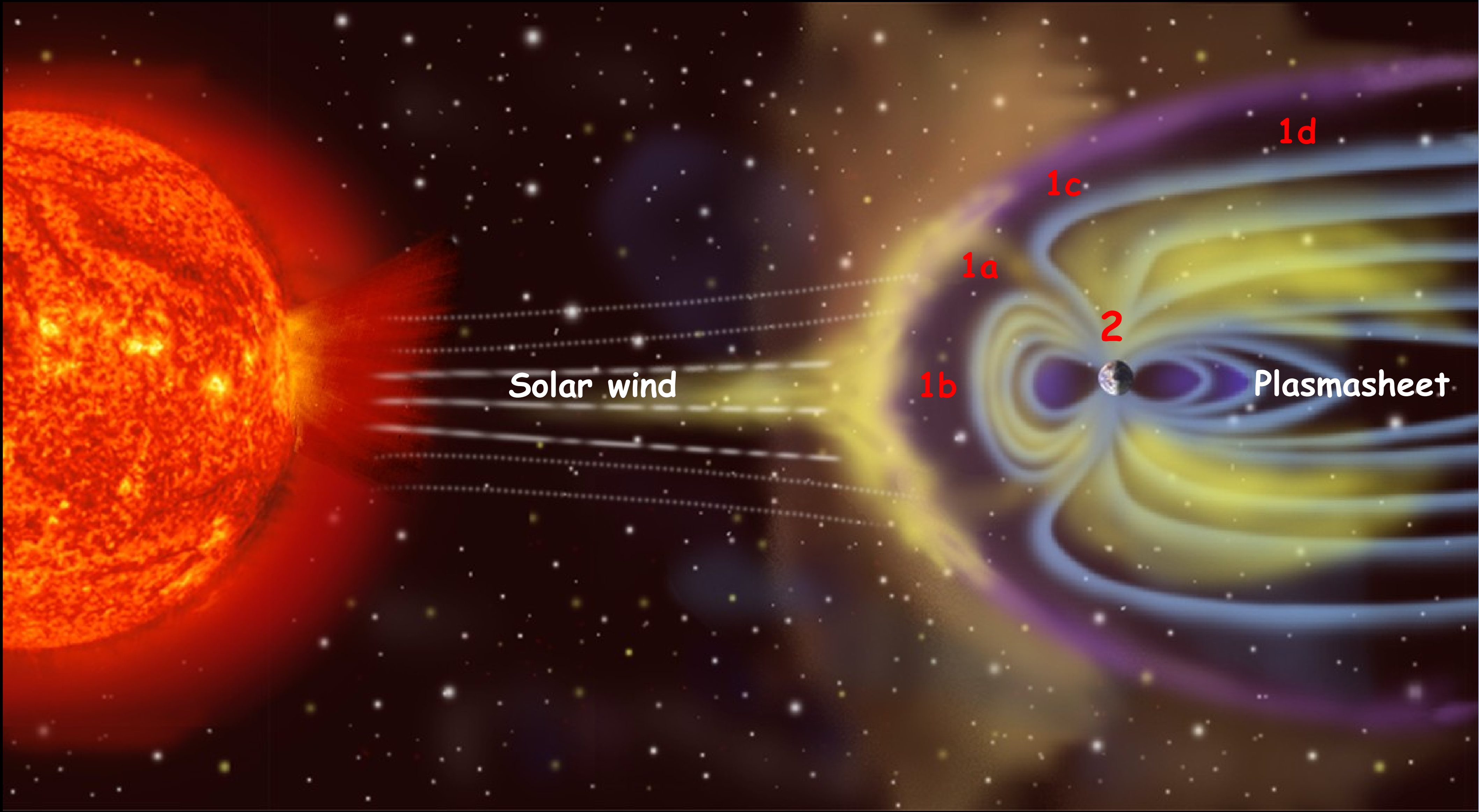
* Motivation: Why do we care?
  - "Cold" ions and "Polar Cap"

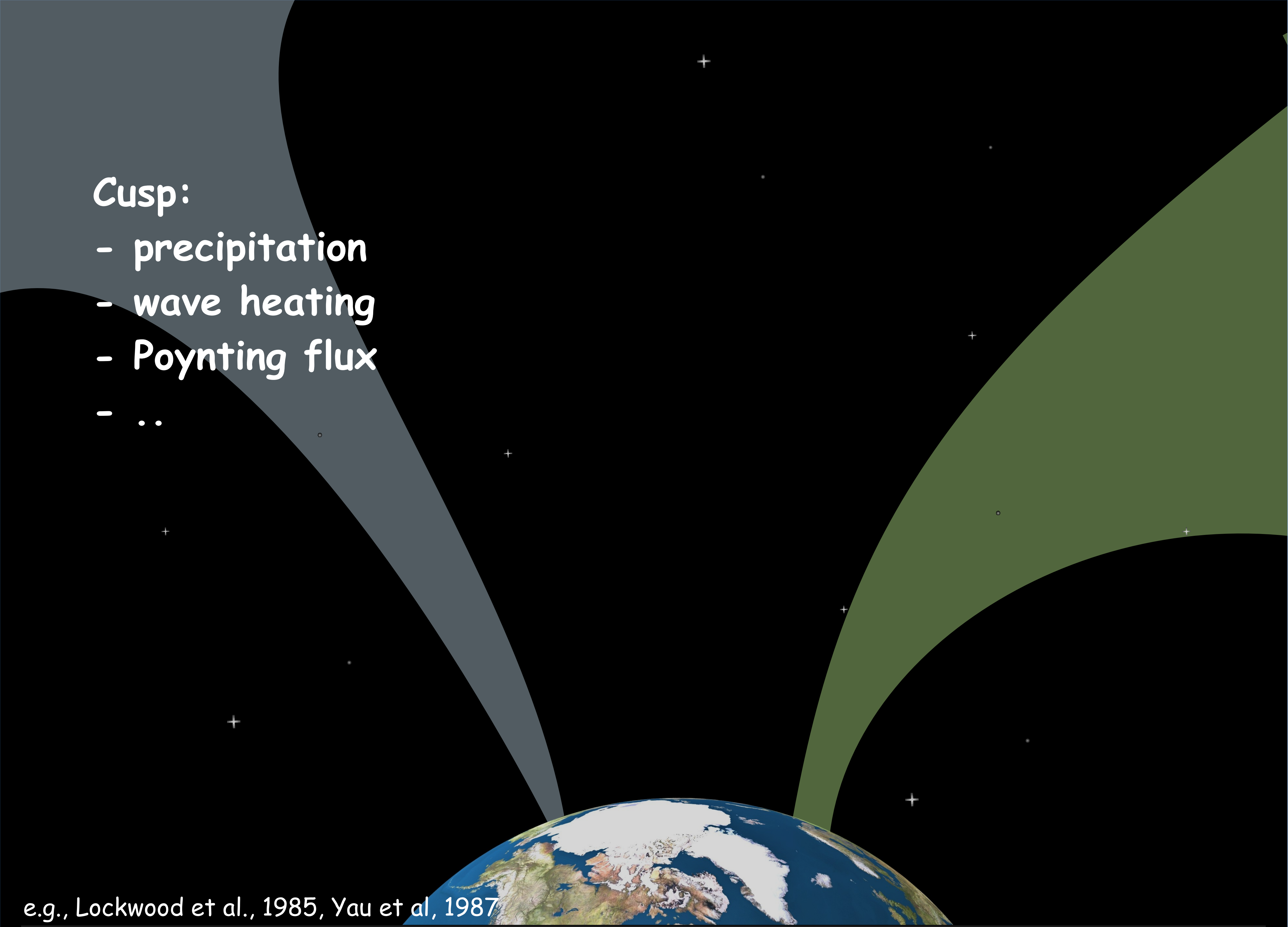
* Why are ions escaping ?

* Observations
  - flux
  - role of solar activity and geoactivity
  - source & fate; lost or recirculated ?

* Global context
  - mass and matter balance

Sources of plasma for the Earth's magnetosphere

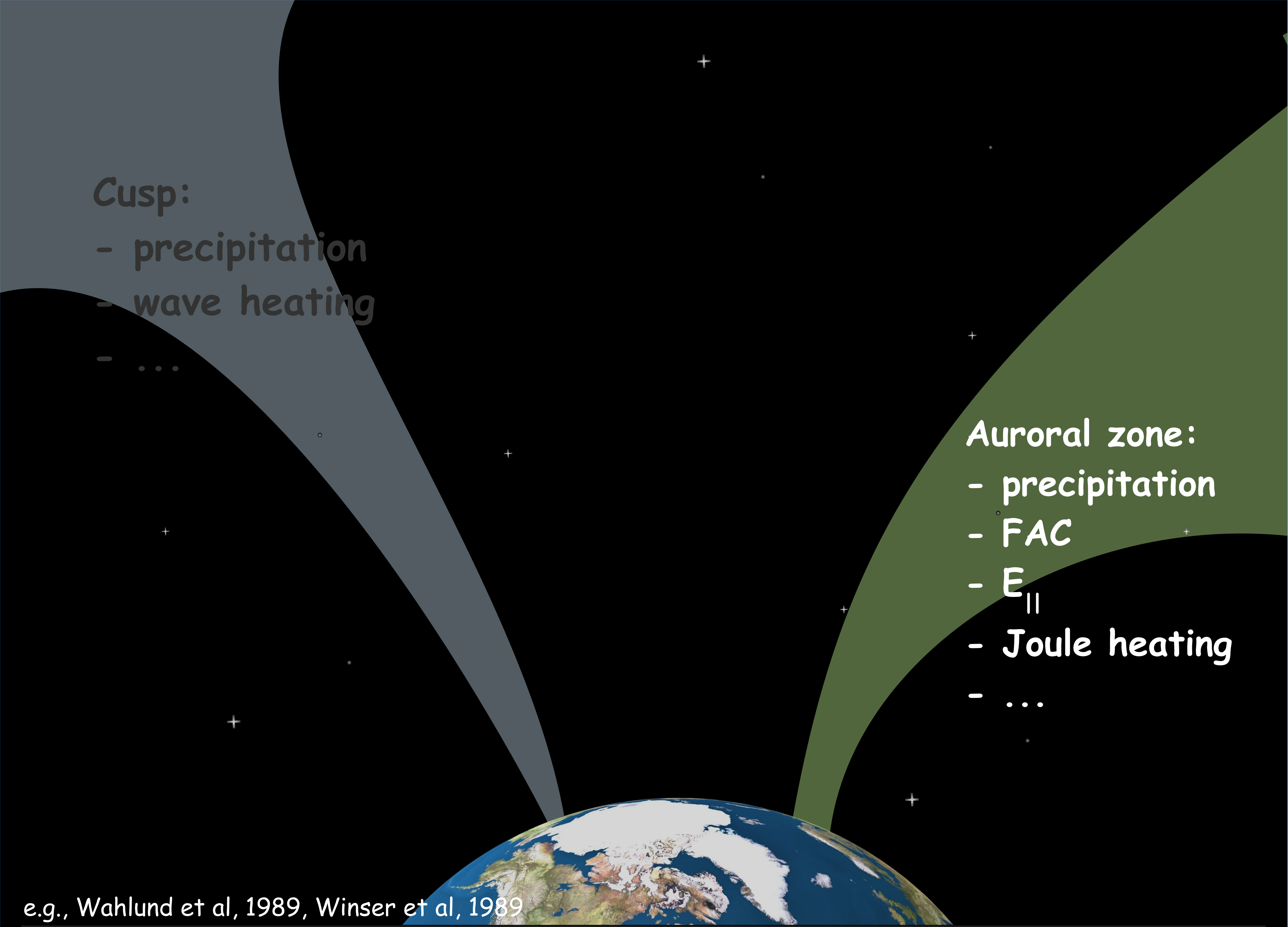




Cusp:

- precipitation
- wave heating
- Poynting flux
- ..

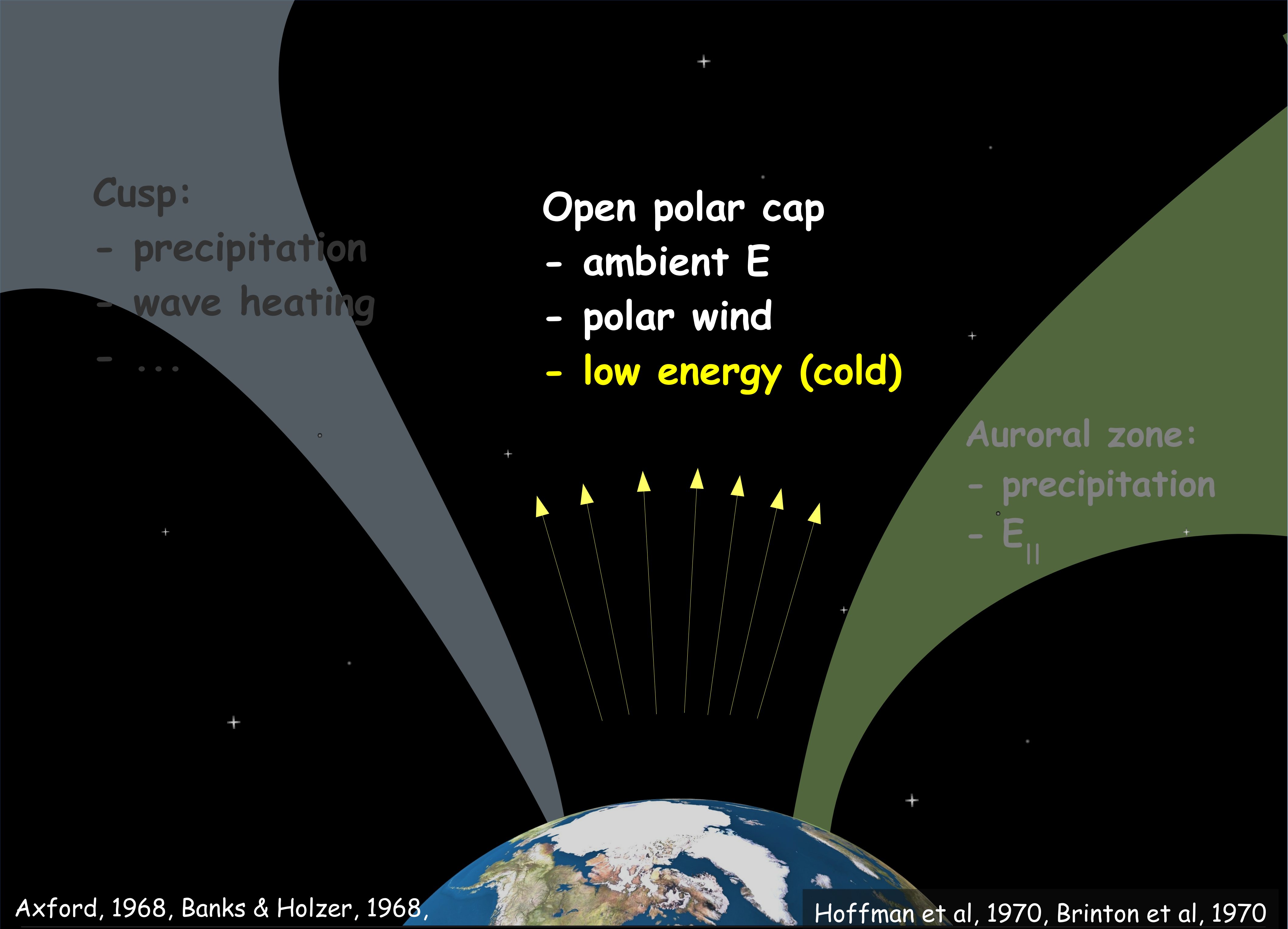
e.g., Lockwood et al., 1985, Yau et al, 1987



Cusp:
- precipitation
- wave heating
- ...

Auroral zone:
- precipitation
- FAC
- $E_{||}$
- Joule heating
- ...

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



Cusp:
- precipitation
- wave heating
- ...

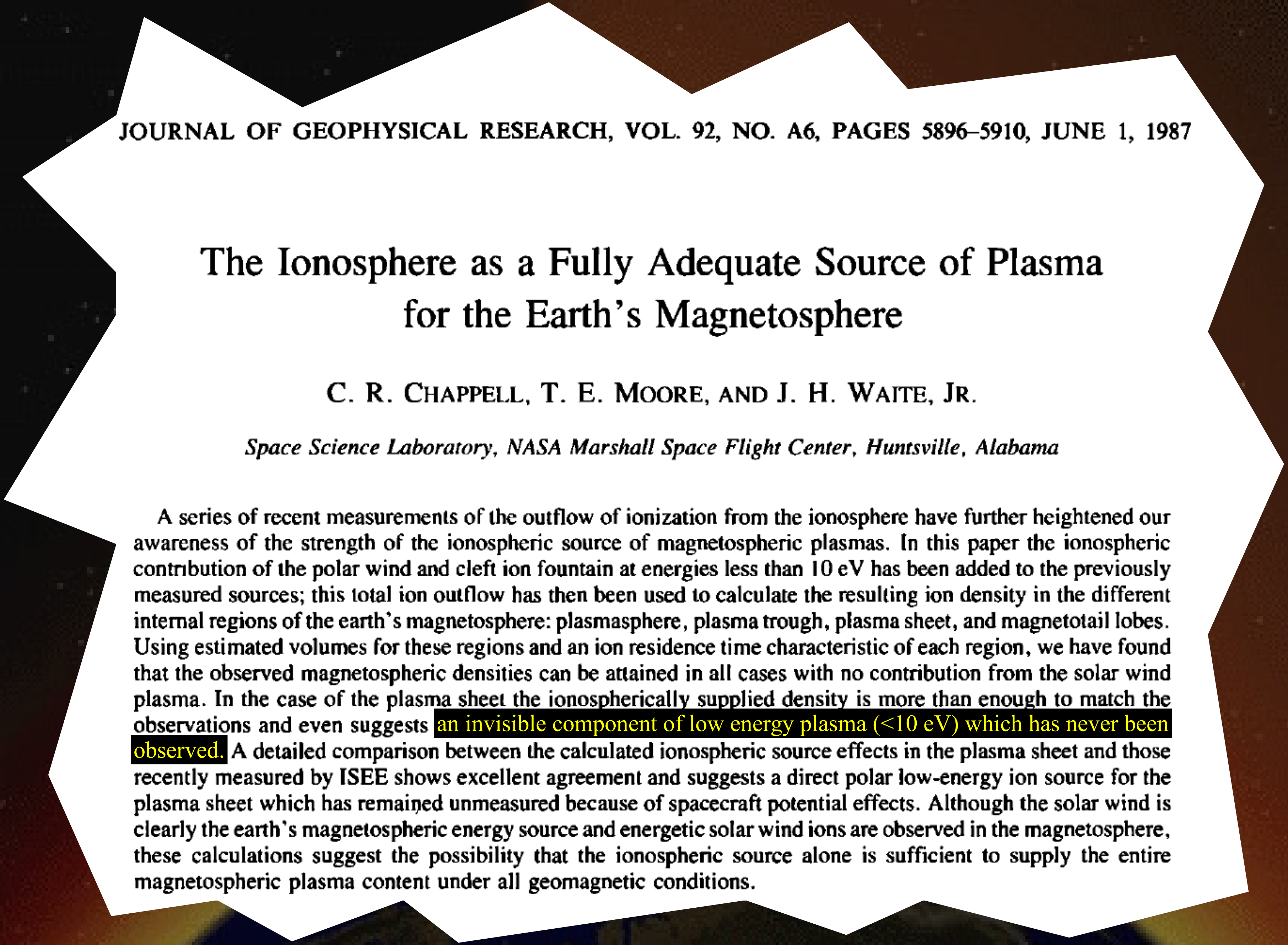
Open polar cap
- ambient E
- polar wind
- low energy (cold)

Auroral zone:
- precipitation
- $E_{||}$

Axford, 1968, Banks & Holzer, 1968,

Hoffman et al, 1970, Brinton et al, 1970

Motivation : why do we care about cold ion outflow ?



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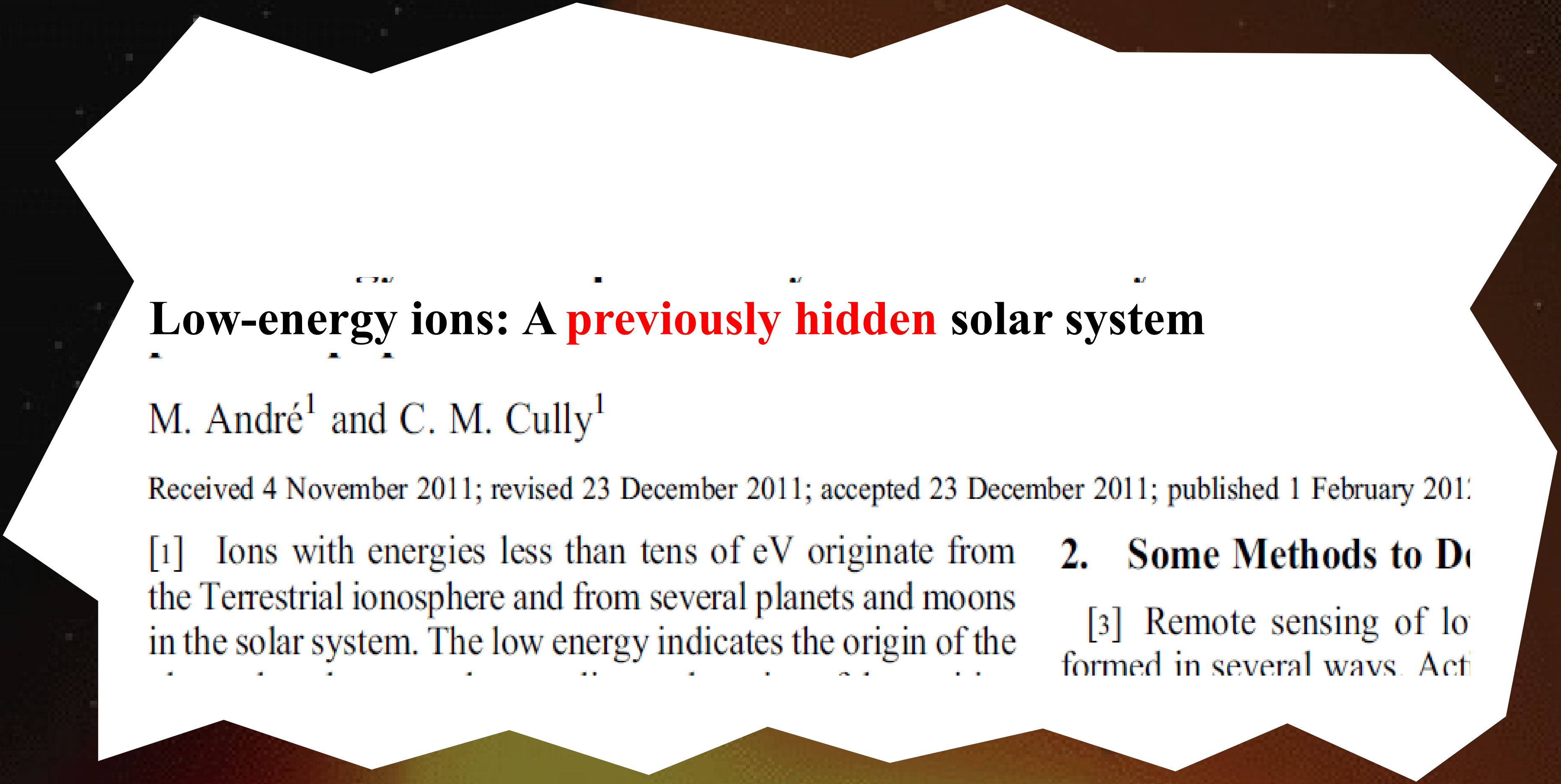
The Ionosphere as a Fully Adequate Source of Plasma for the Earth's Magnetosphere

C. R. CHAPPELL, T. E. MOORE, AND J. H. WAITE, JR.

Space Science Laboratory, NASA Marshall Space Flight Center, Huntsville, Alabama

A series of recent measurements of the outflow of ionization from the ionosphere have further heightened our awareness of the strength of the ionospheric source of magnetospheric plasmas. In this paper the ionospheric contribution of the polar wind and cleft ion fountain at energies less than 10 eV has been added to the previously measured sources; this total ion outflow has then been used to calculate the resulting ion density in the different internal regions of the earth's magnetosphere: plasmasphere, plasma trough, plasma sheet, and magnetotail lobes. Using estimated volumes for these regions and an ion residence time characteristic of each region, we have found that the observed magnetospheric densities can be attained in all cases with no contribution from the solar wind plasma. In the case of the plasma sheet the ionospherically supplied density is more than enough to match the observations and even suggests an invisible component of low energy plasma (<10 eV) which has never been observed. A detailed comparison between the calculated ionospheric source effects in the plasma sheet and those recently measured by ISEE shows excellent agreement and suggests a direct polar low-energy ion source for the plasma sheet which has remained unmeasured because of spacecraft potential effects. Although the solar wind is clearly the earth's magnetospheric energy source and energetic solar wind ions are observed in the magnetosphere, these calculations suggest the possibility that the ionospheric source alone is sufficient to supply the entire magnetospheric plasma content under all geomagnetic conditions.

Motivation : why do we care about ion outflow ?



Low-energy ions: A previously hidden solar system

M. André[1] and C. M. Cully[1]

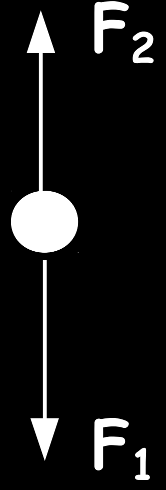
Received 4 November 2011; revised 23 December 2011; accepted 23 December 2011; published 1 February 201

[1] Ions with energies less than tens of eV originate from the Terrestrial ionosphere and from several planets and moons in the solar system. The low energy indicates the origin of the

2. Some Methods to D

[3] Remote sensing of lo
formed in several ways. Act

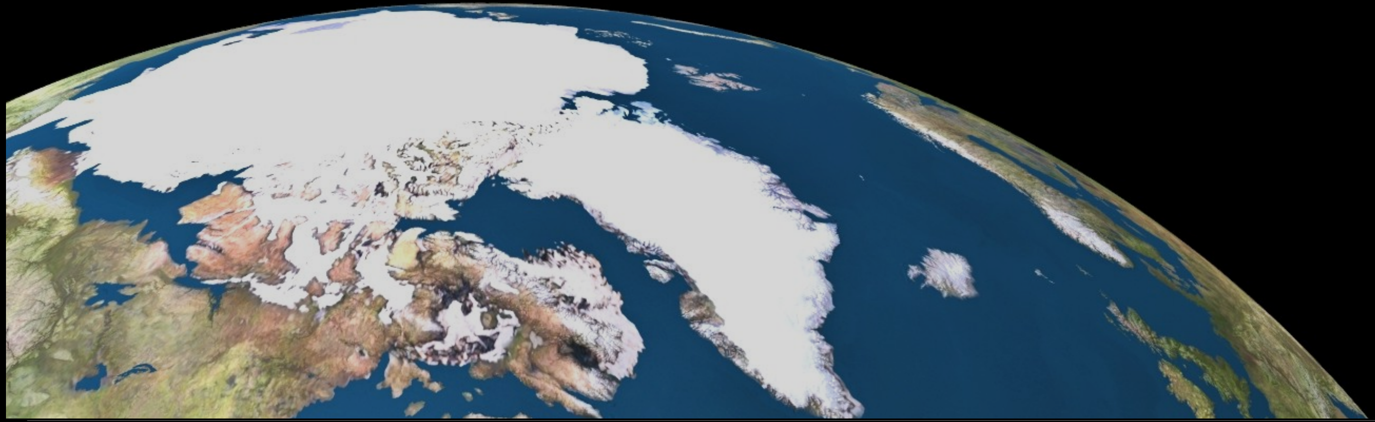
Forces : Why do matter escape ?

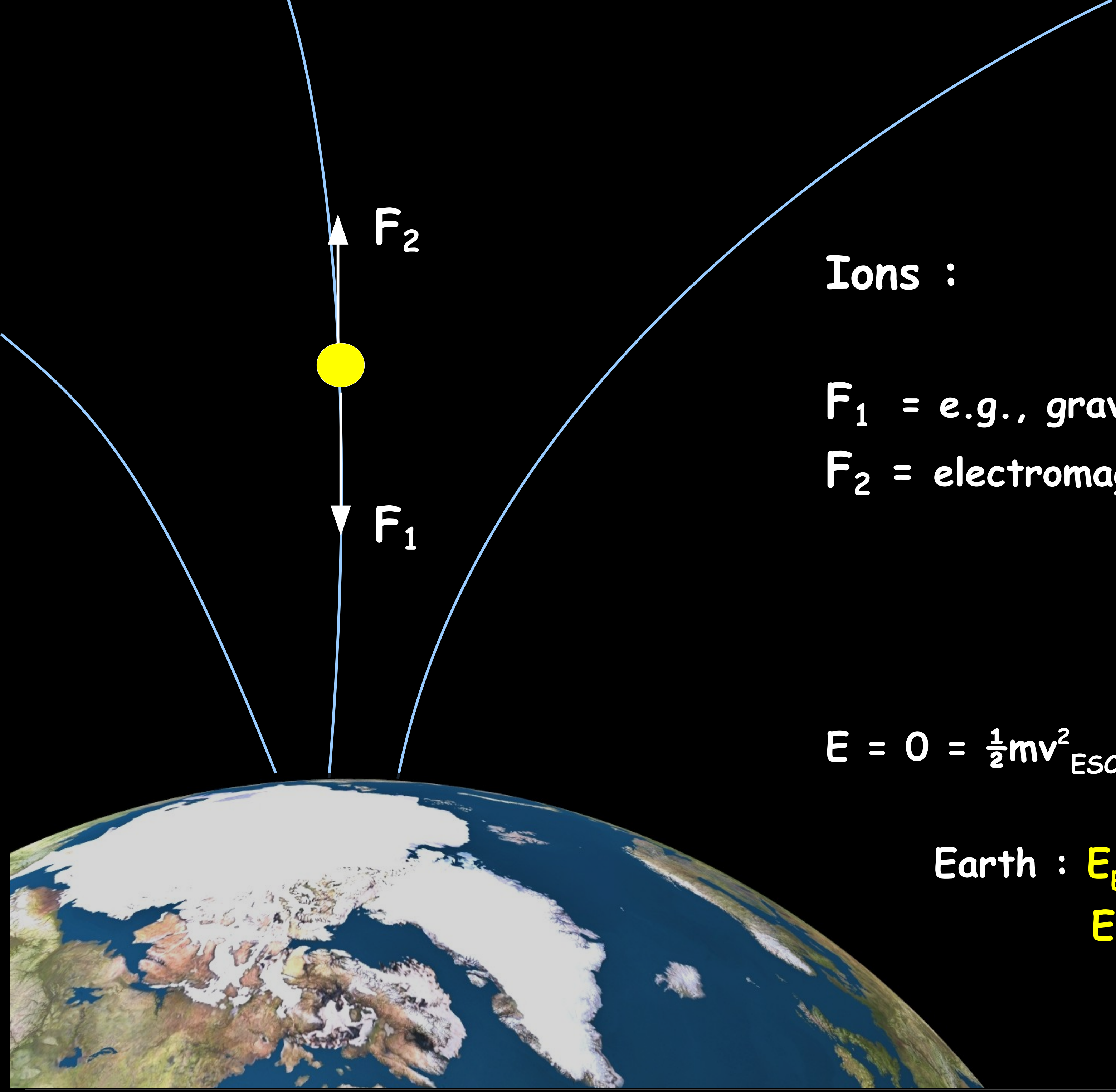


Neutrals :

F_1 = ~ gravity

F_2 = e.g., thermal pressure





Ions :

F_1 = e.g., gravity

F_2 = electromagnetic forces

$$E = 0 = \tfrac{1}{2}mv^2_{ESC} - gMm/r$$

Earth : $E_{ESC\ H+} \sim 0.7\ \text{eV}$

$E_{ESC\ O+} \sim 10\ \text{eV}$

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

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 $E_{||} \sim 0$)

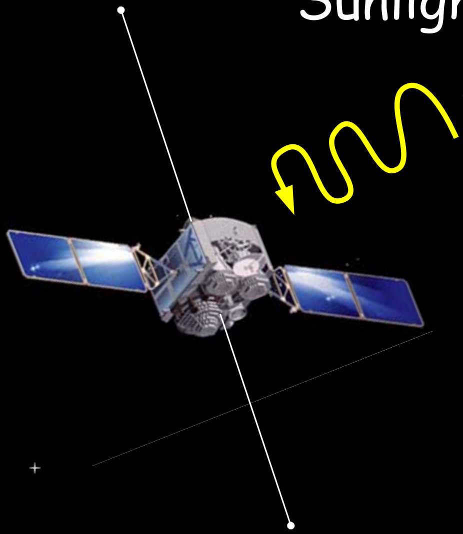
$$\frac{dv_{||}}{dt} = \overset{\overset{\text{E-field}}{\downarrow}}{\frac{eE_{||}}{m}} + \underset{\underset{\text{mirror force}}{\uparrow}}{\mu \nabla_{||} B} + \overset{\overset{\text{centrifugal acc}}{\downarrow}}{\vec{v}_E \cdot \frac{d\,\hat{b}}{ds}} + \underset{\underset{\text{thermal/pressure}}{\uparrow}}{\frac{F_{TH\,||}}{m}}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

Polar wind ambient electric field

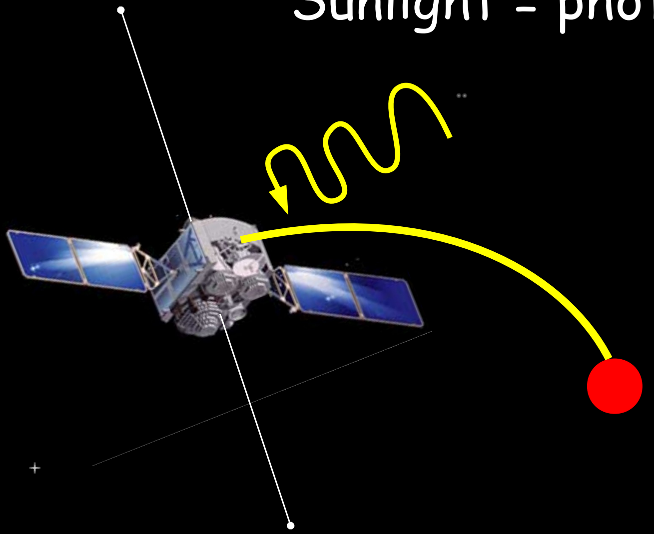
* Set up be escaping electrons
* Total potential drop 1 – 20 V (Su et al, 1998, Kitamura et al, 2012,2013)

Spacecraft charging

Sunlight = photons, E = h v



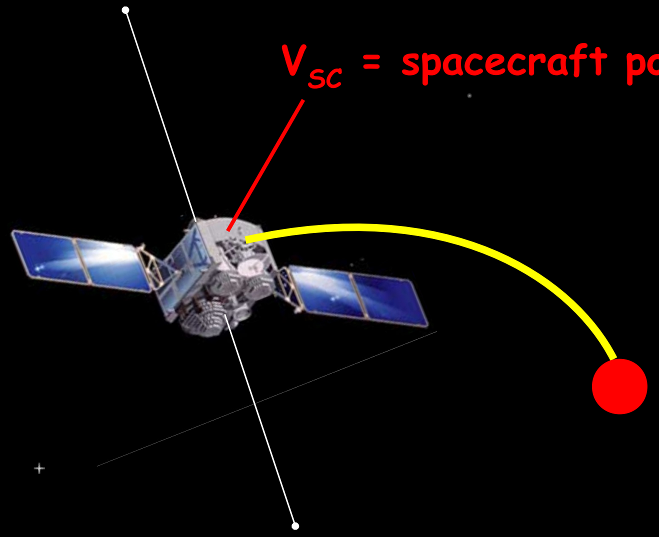
Spacecraft charging



Sunlight = photons, $E = h v$

e- (photo electron → current)

Spacecraft charging



V_{SC} = spacecraft potential

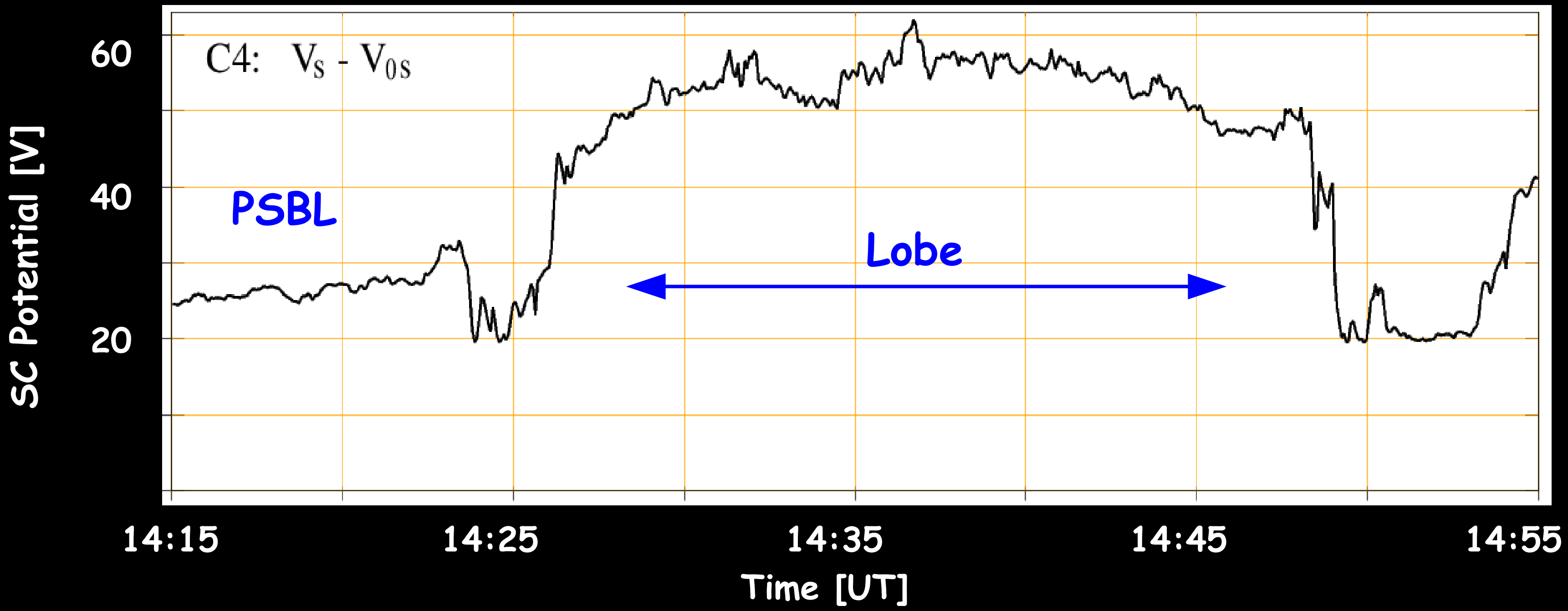
e- (photo electron → current)

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

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

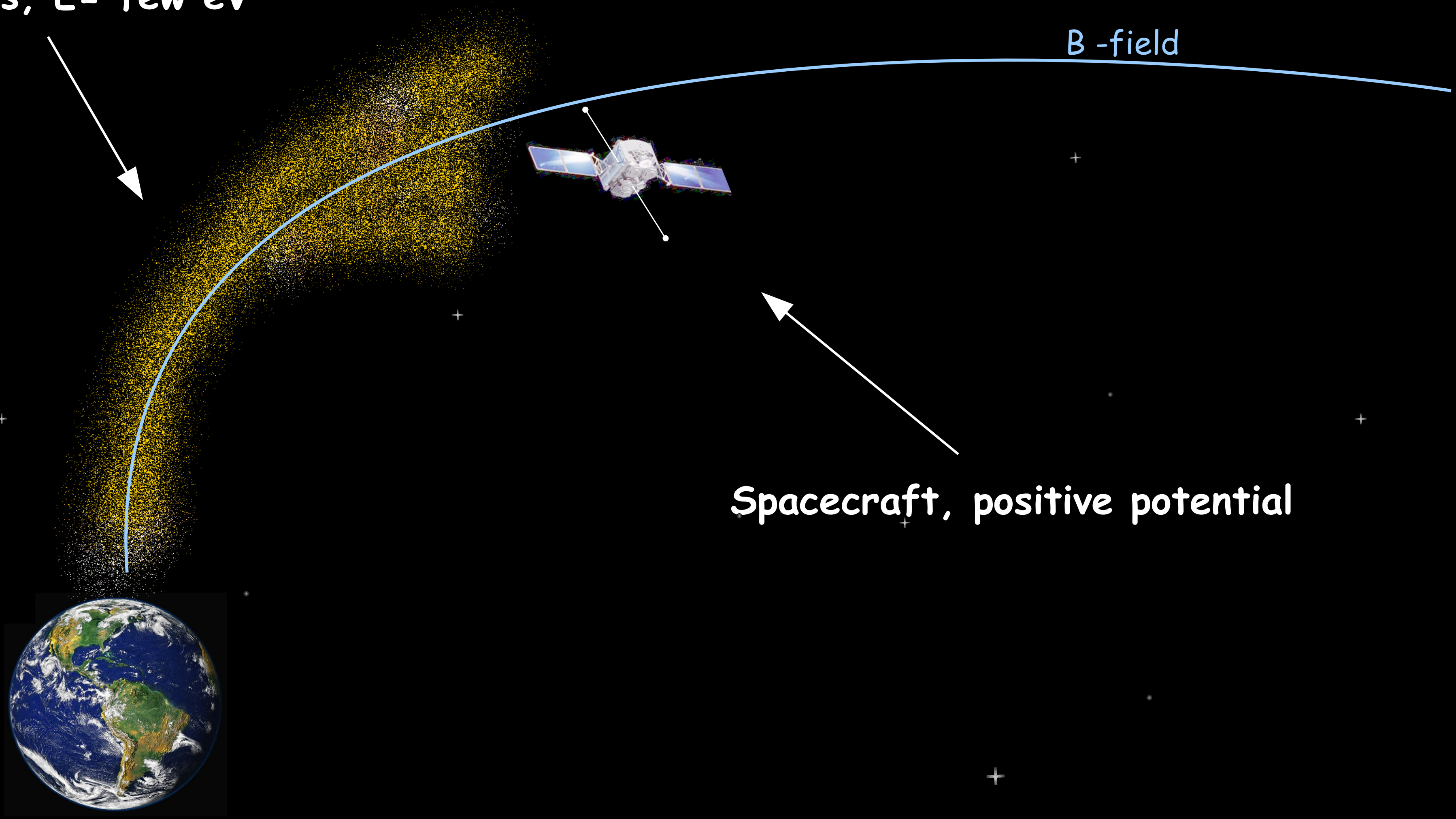
Spacecraft charging

V_{SC} – V_P from Cluster C4 on 11 Aug 2002



After Lybekk et al, 2012, Figure 10

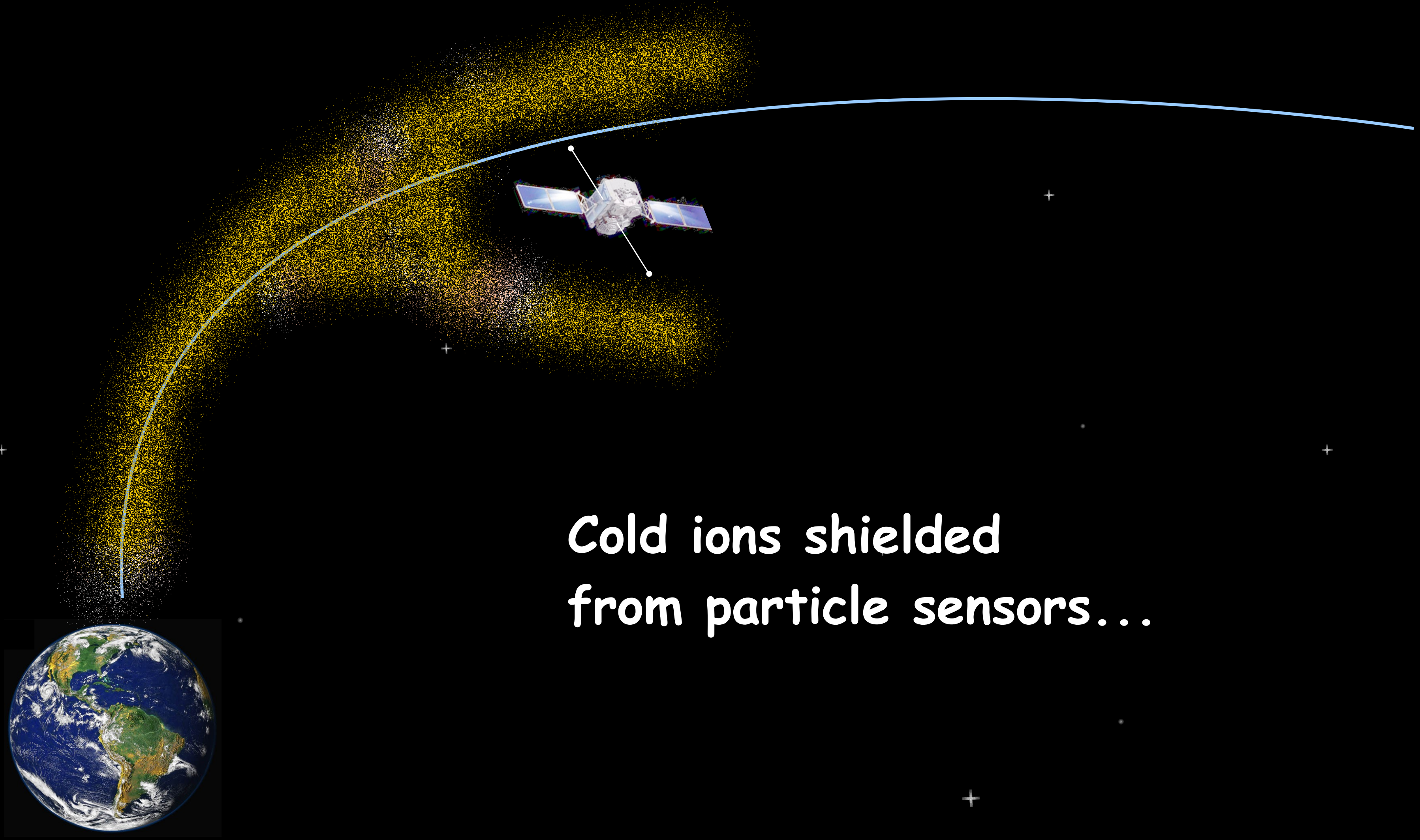
Spacecraft charging



Cold ions, E= few eV

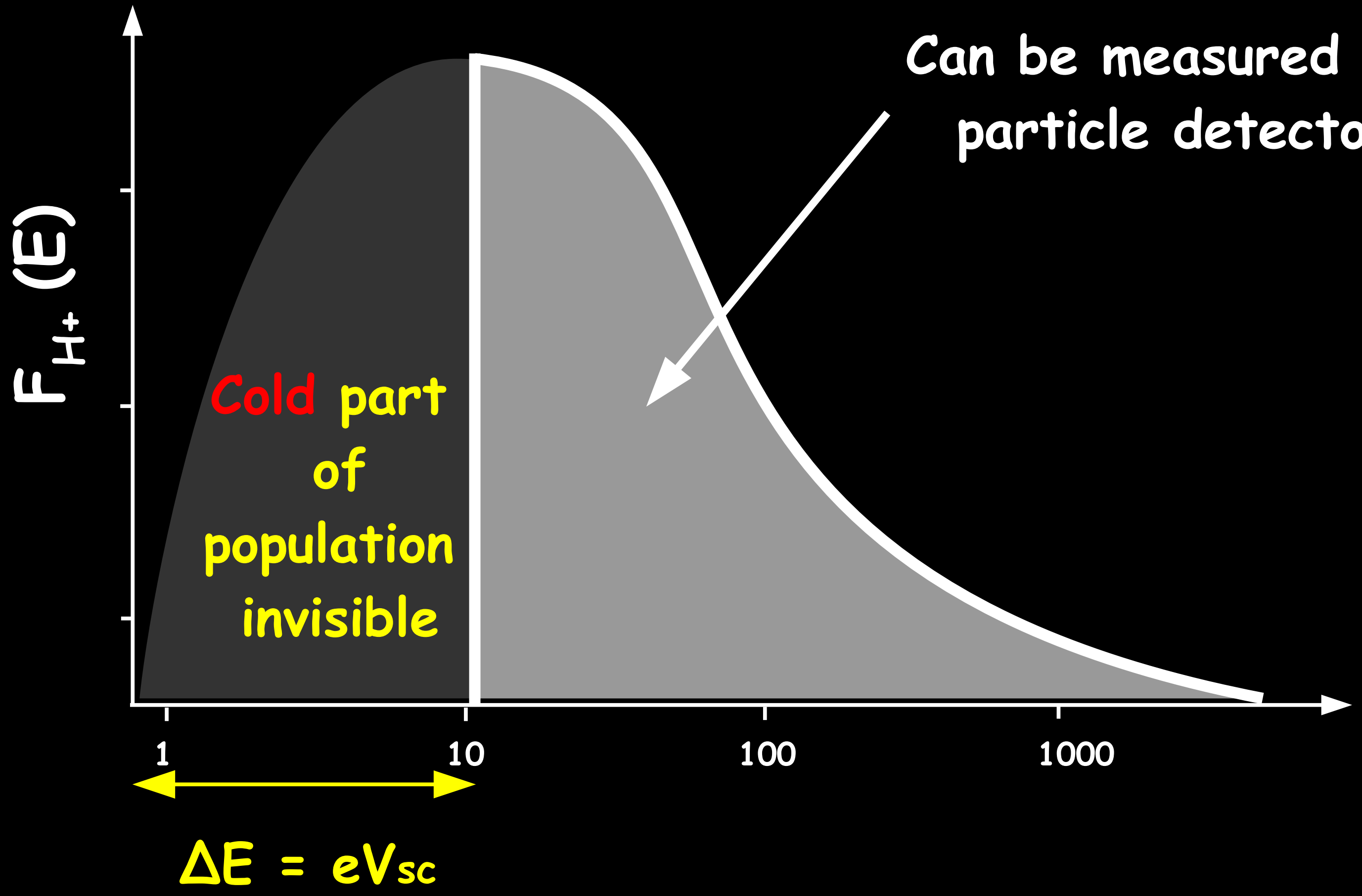
Spacecraft, positive potential

Spacecraft charging



Cold ions shielded from particle sensors...

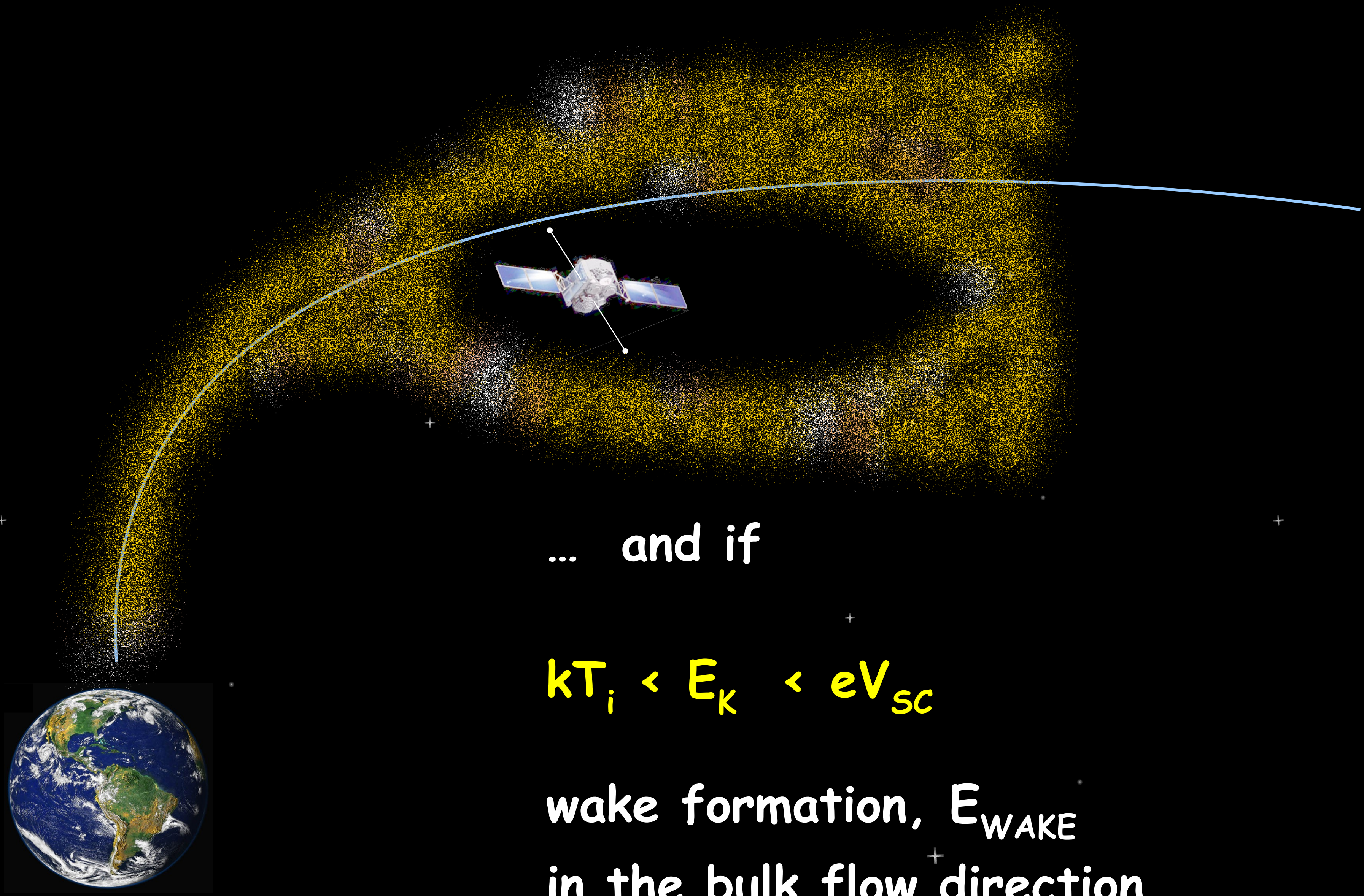
Spacecraft charging



Cold ions can not be measured with particle instruments !

See e.g., Huddleston et al, 2005, Lybekk et al, 2012, Andre et al, 2015

Spacecraft charging



… and if

$kT_i < E_K < eV_{SC}$

wake formation, E_{WAKE}

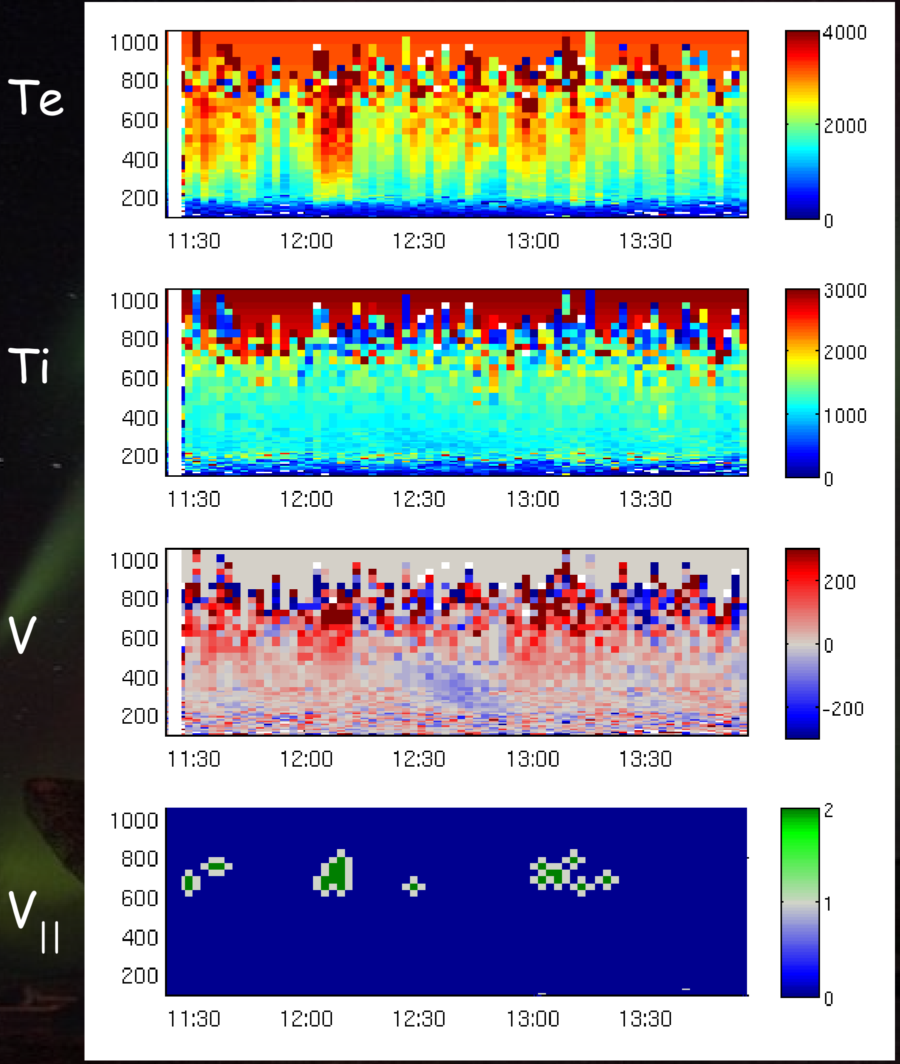
in the bulk flow direction

How to measure low energy outflowing ions ?

1: Ground based studies

e.g., Wahlund et al, 1992, Ogawa et al, 2000, 2003

1: Ground based studies

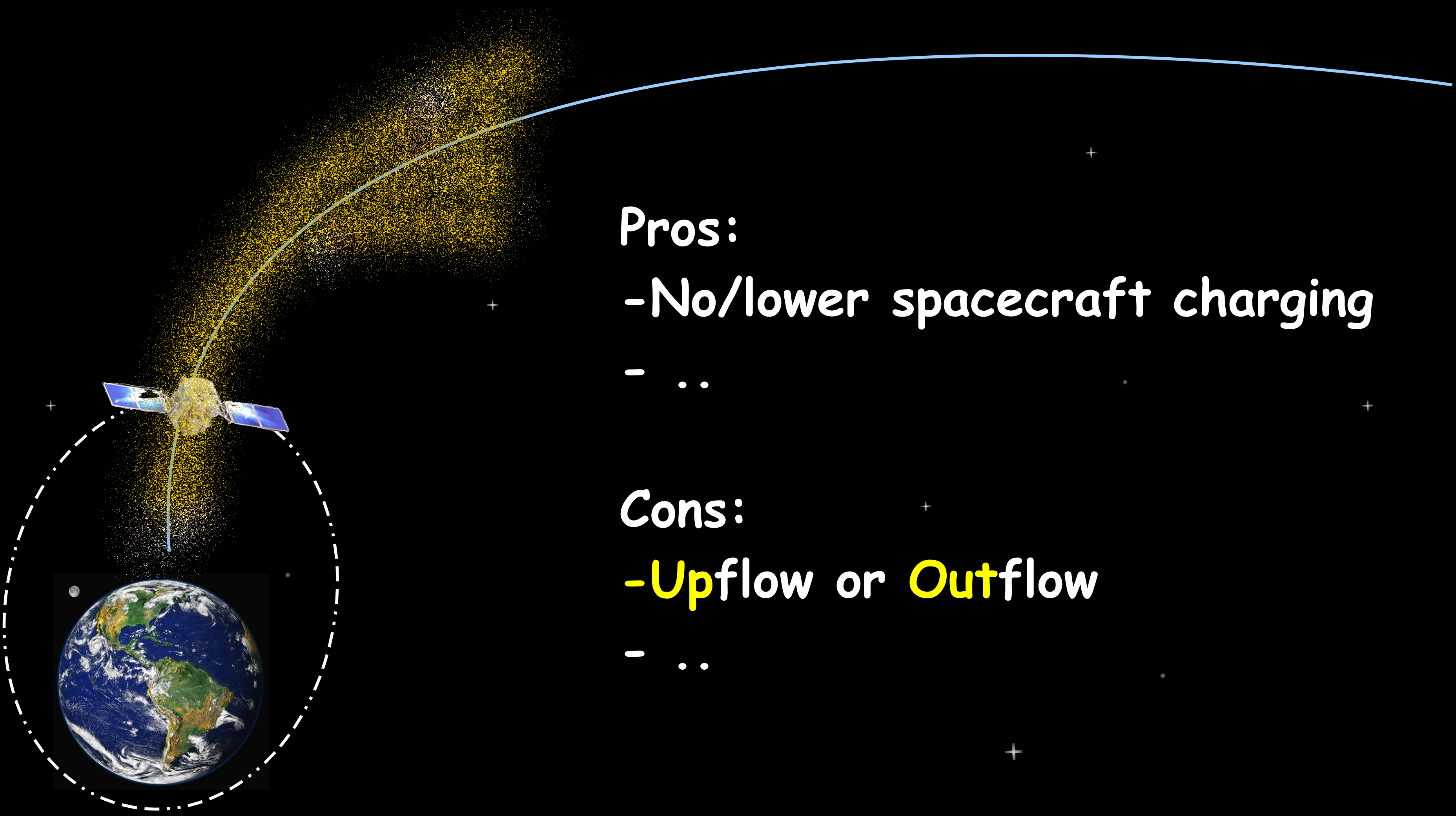


EISCAT Svalbard, 2014
(from Maes et al, 2016)

Cons :

- Max ~1500 km
- UPflow, not OUTflow
- ….

2: Low orbit satellites



Pros:

-No/lower spacecraft charging

- ..

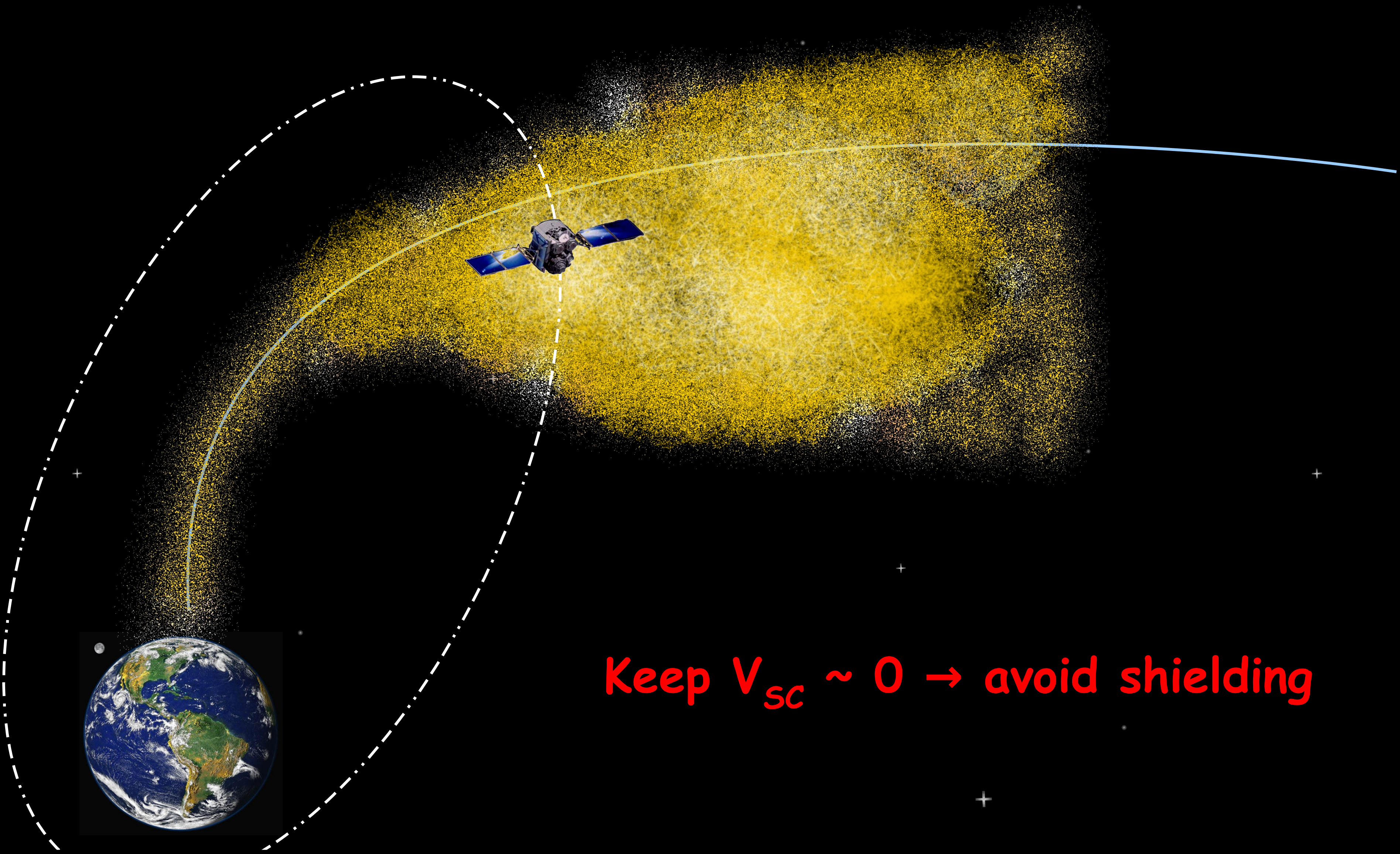
Cons:

-Upflow or Outflow

- ..

e.g., Abe et al, 1993, 1996 (Akebono), Kitamura, 2012,2013,2015 (Akebono, FAST)

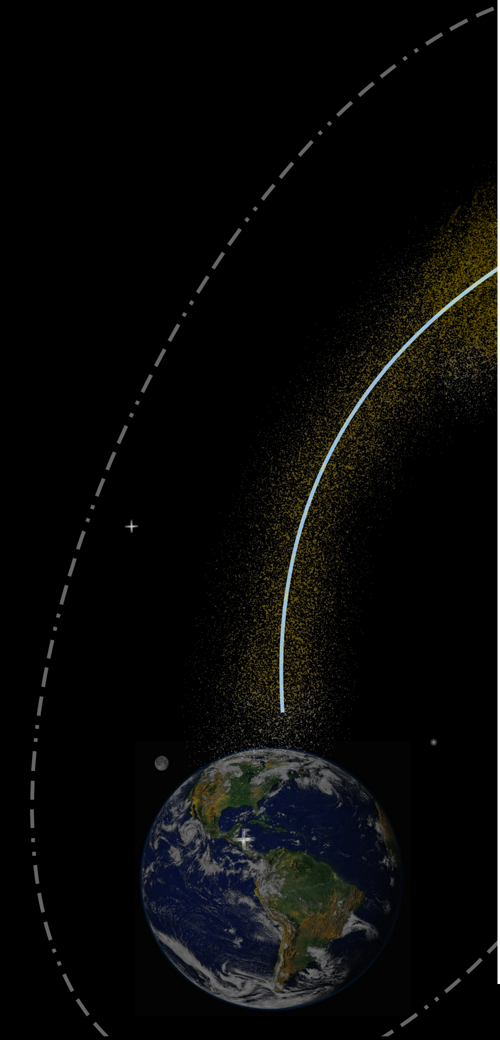
3: Active potential control

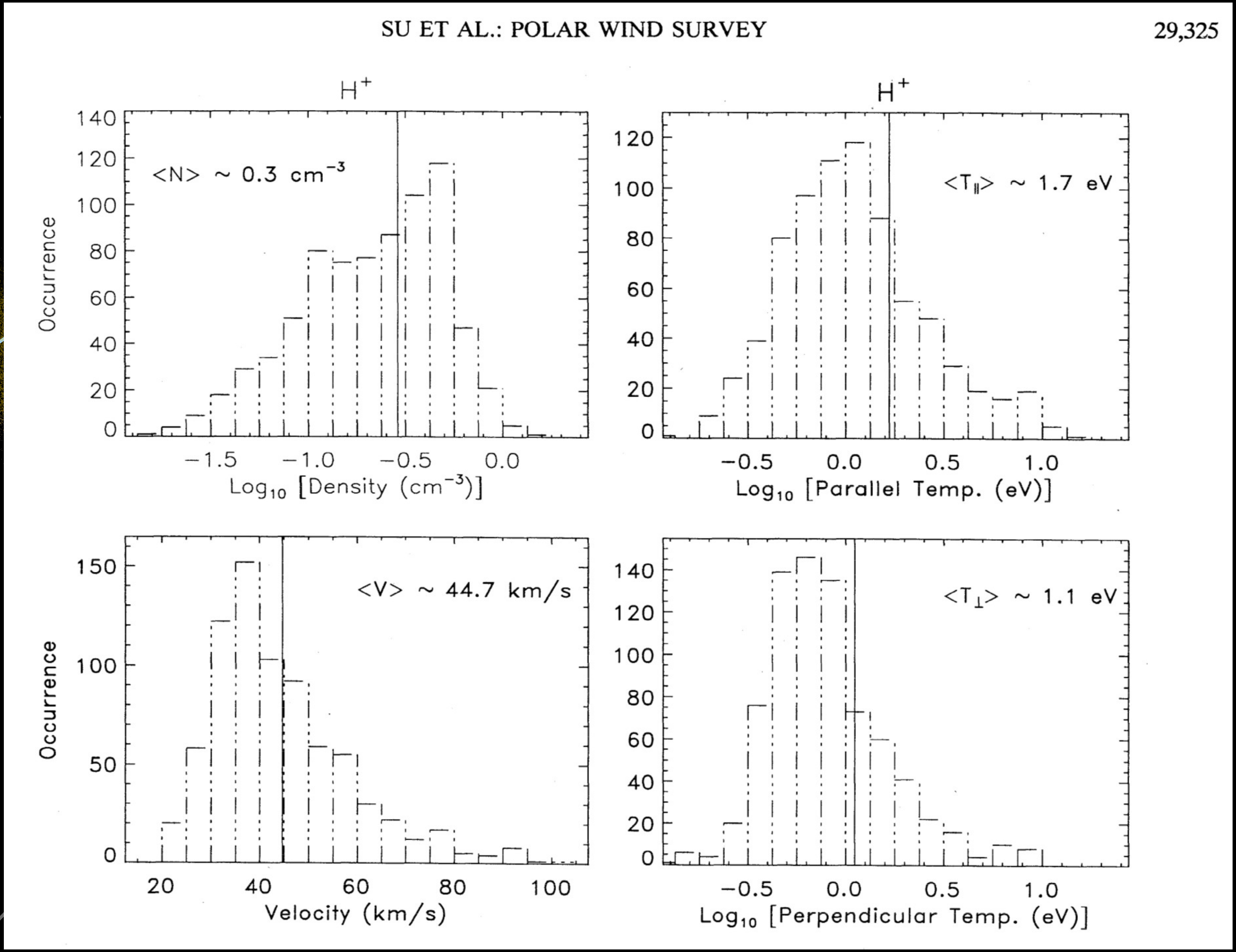


Keep V_{sc} ~ 0 → avoid shielding

e.g., Moore et al, 1997, Su et al, 1998 (using Polar)

3: Active potential control

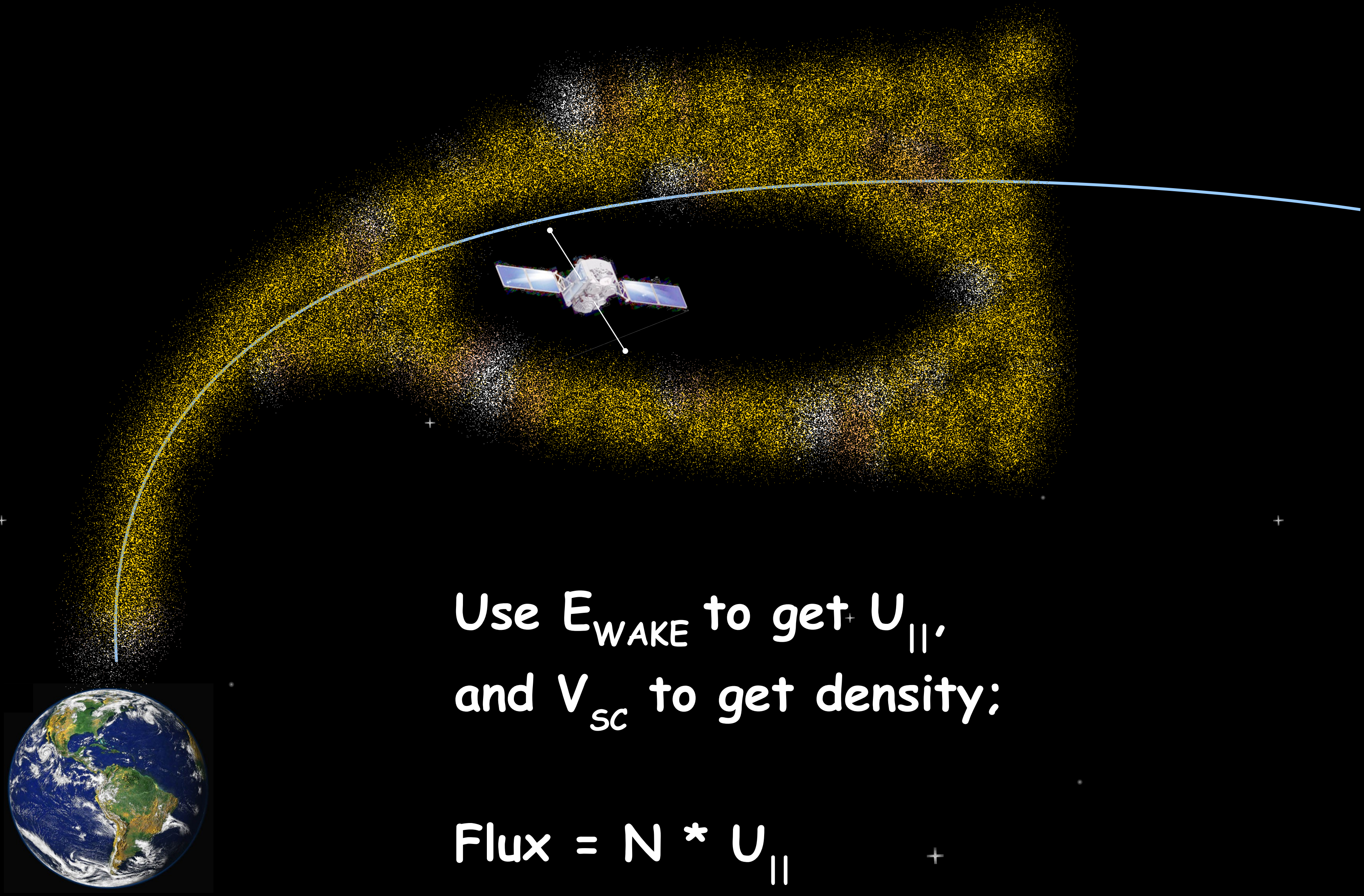




SU ET AL.: POLAR WIND SURVEY 29,325

e.g., Moore et al, 1997, Su et al, 1998 (using 3 orbits from Polar; PSI operating)

4: Utilize spacecraft charging and wake



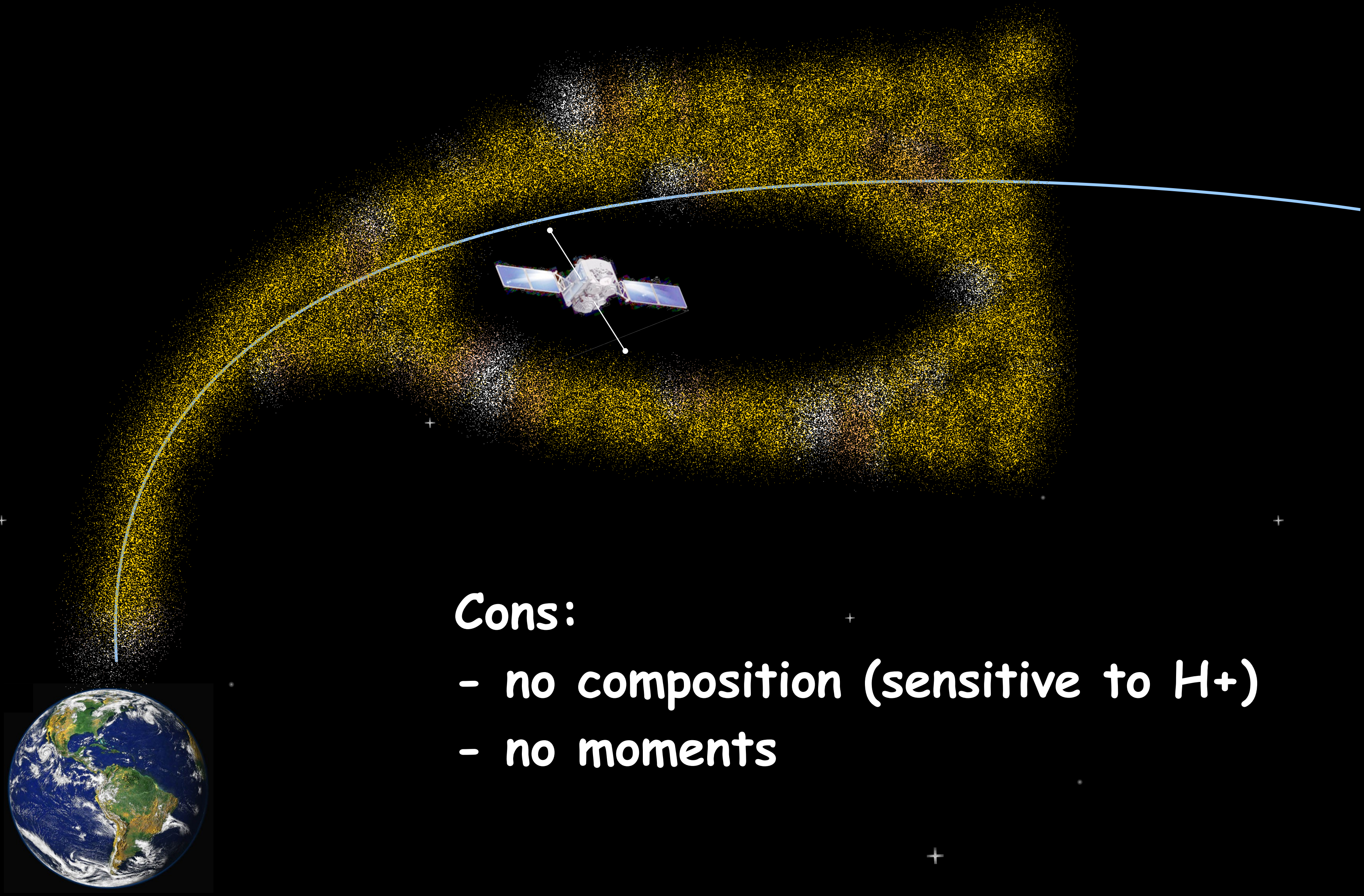
Use E_{WAKE} to get $U_{||}$,

and V_{sc} to get density;

Flux = $N * U_{||}$

Engwall et al, 2009

4: Utilize spacecraft charging and wake



Cons:

- no composition (sensitive to H+)
- no moments

Engwall et al, 2009

Making the invisible visible:

Utilizing Cluster observations

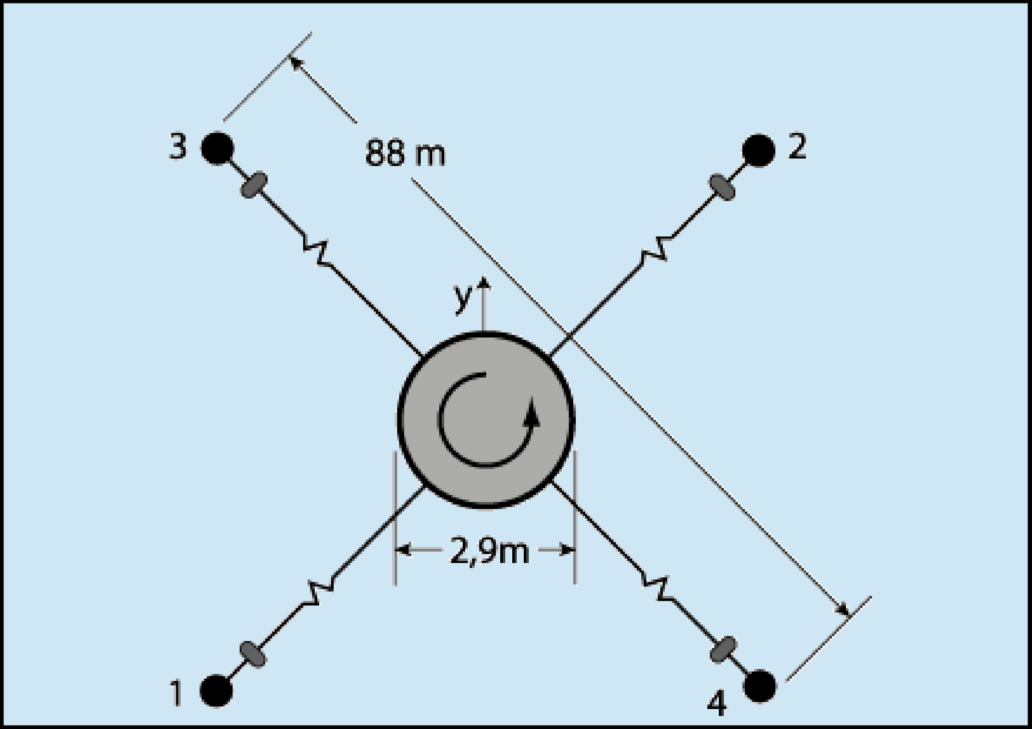
$V_{\|\|}$	[Engwall et al, 2009, Andrė et al, 2015]
N_e	[Lybekk et al, 2012]
E_{CONV}	[Haaland et al, 2009]
PCArea	[Milan, 2009, Milan et al, 2012]

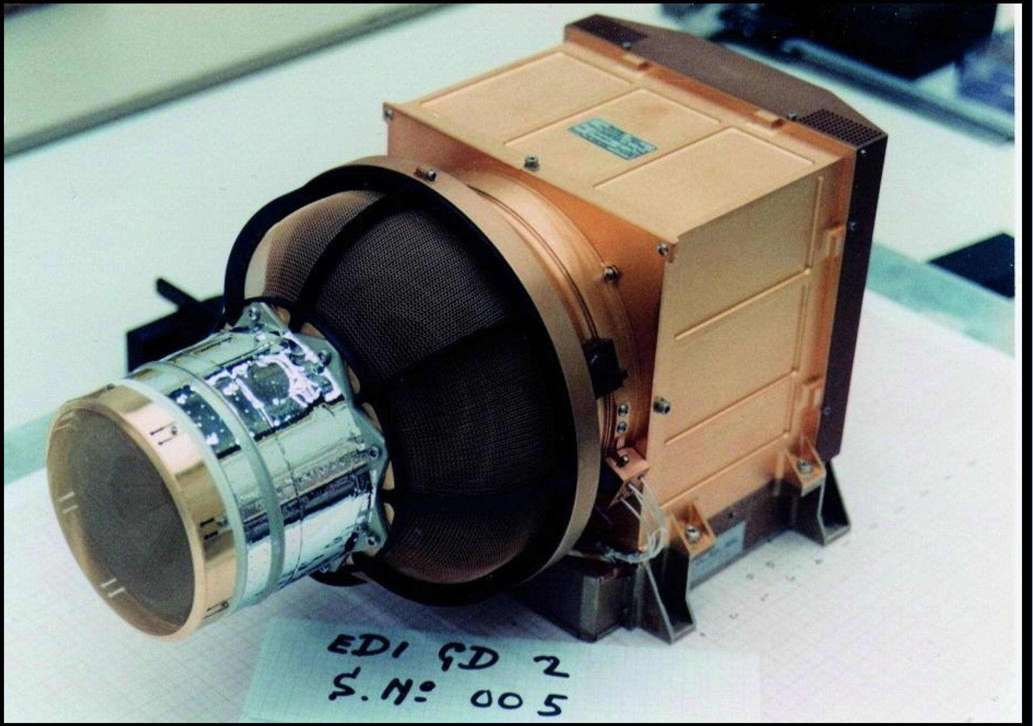
Cluster:

Launch: 2002

4 x 19 Re polar orbit

Key feature: 2 complementary E-field instruments





EFW : measures E_{WAKE}

EDI : measures E_{CONV}

Technique : Use spacecraft charging

1) Derive electron (plasma) density, n

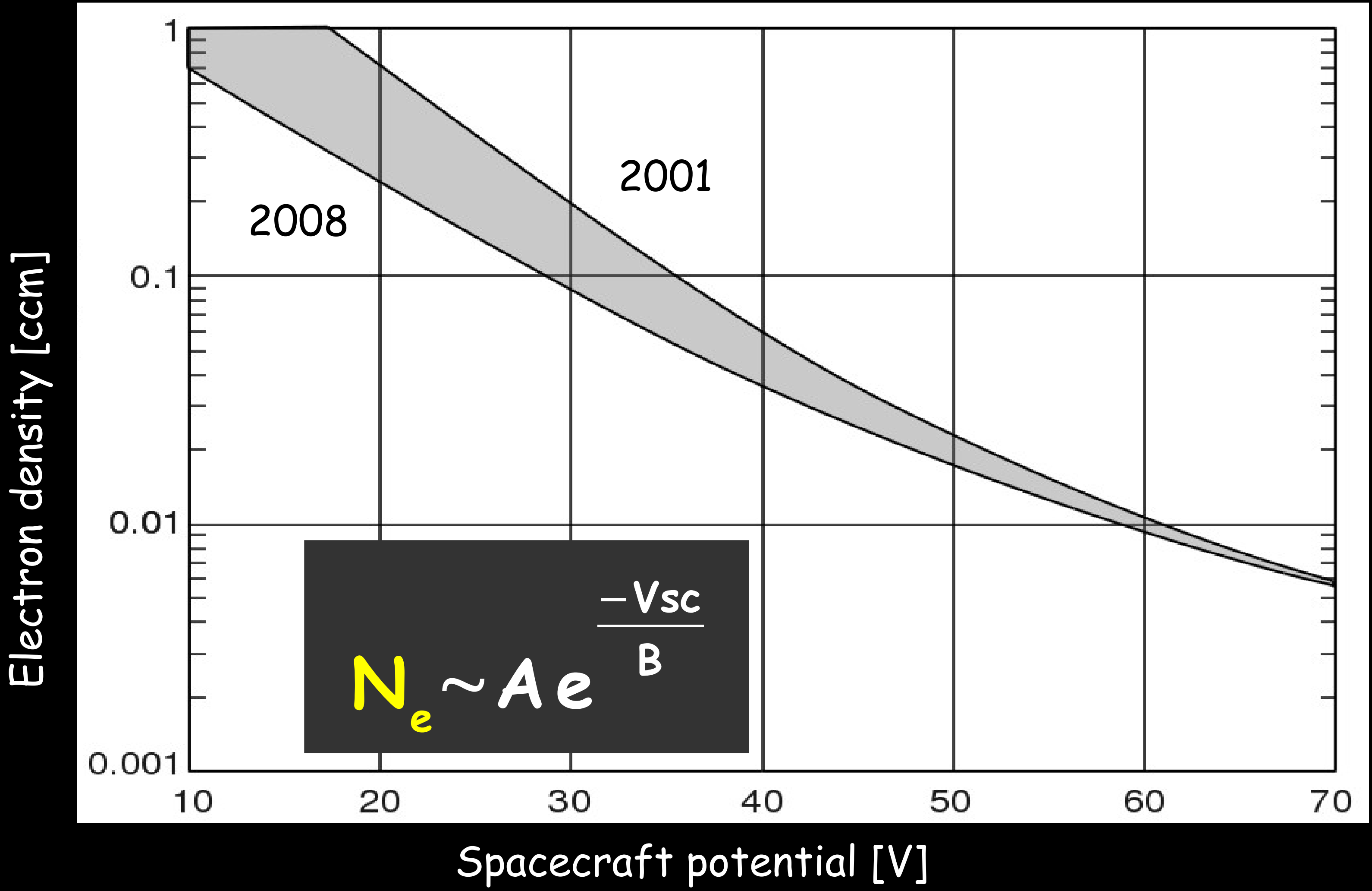
2) Combine E_{WAKE} and E_{CONV} to find $u_{||}$

3) Calculate flux, $f = n * u_{||}$

4) Total outflow = Area * $flux_{1000}$

Pedersen et al, 2008, Lybekk, 2012, Engwall et al, 2009, Haaland et al, 2009, Milan 2009, 2012

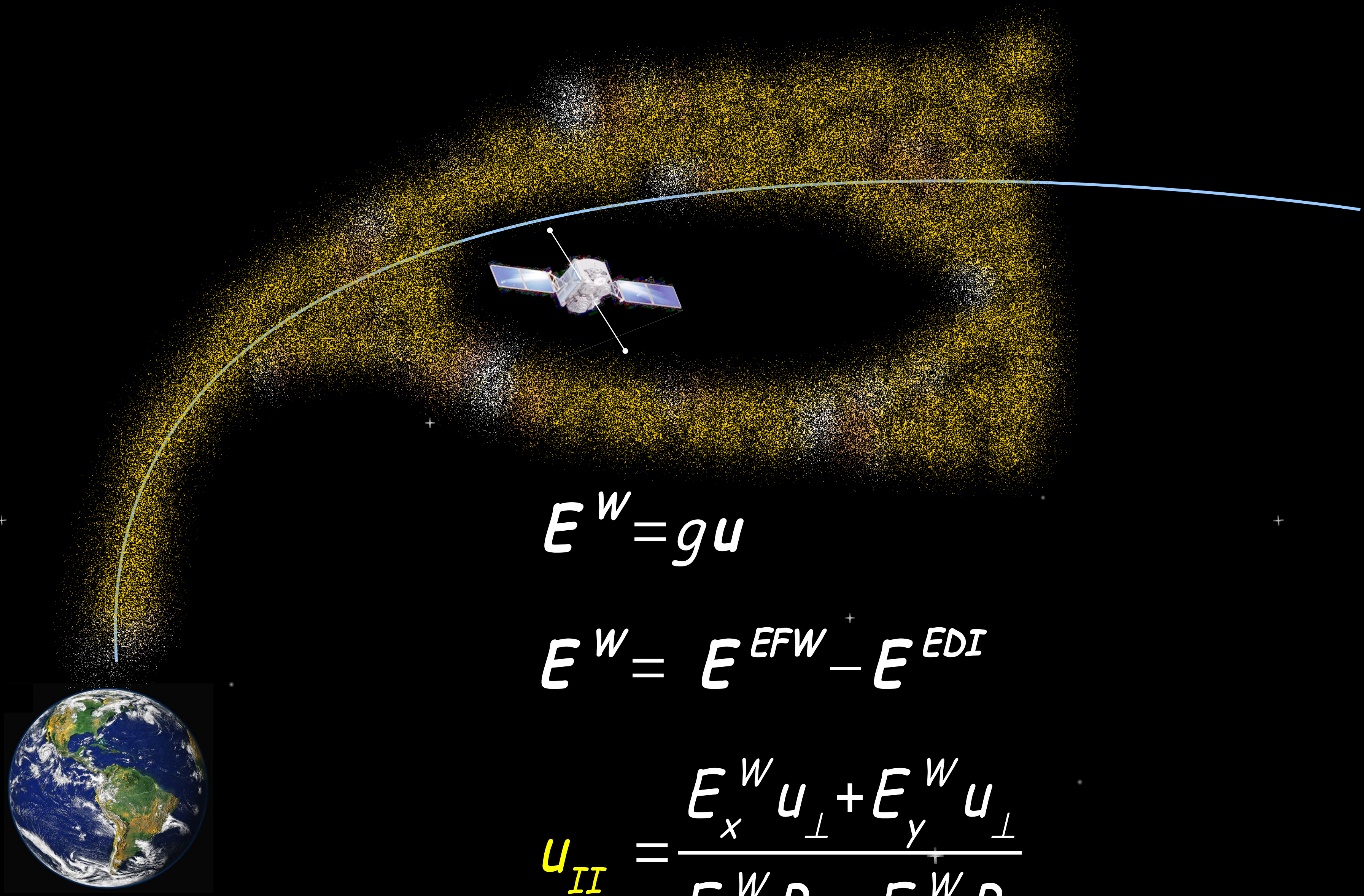
1) Electron density from spacecraft potential



$$N_e \sim A e^{\frac{-Vsc}{B}}$$

e.g., Pedersen et al, 1998, 2001,2008 Lybekk et al, 2012

2: Find $U_{||}$ outflow velocity



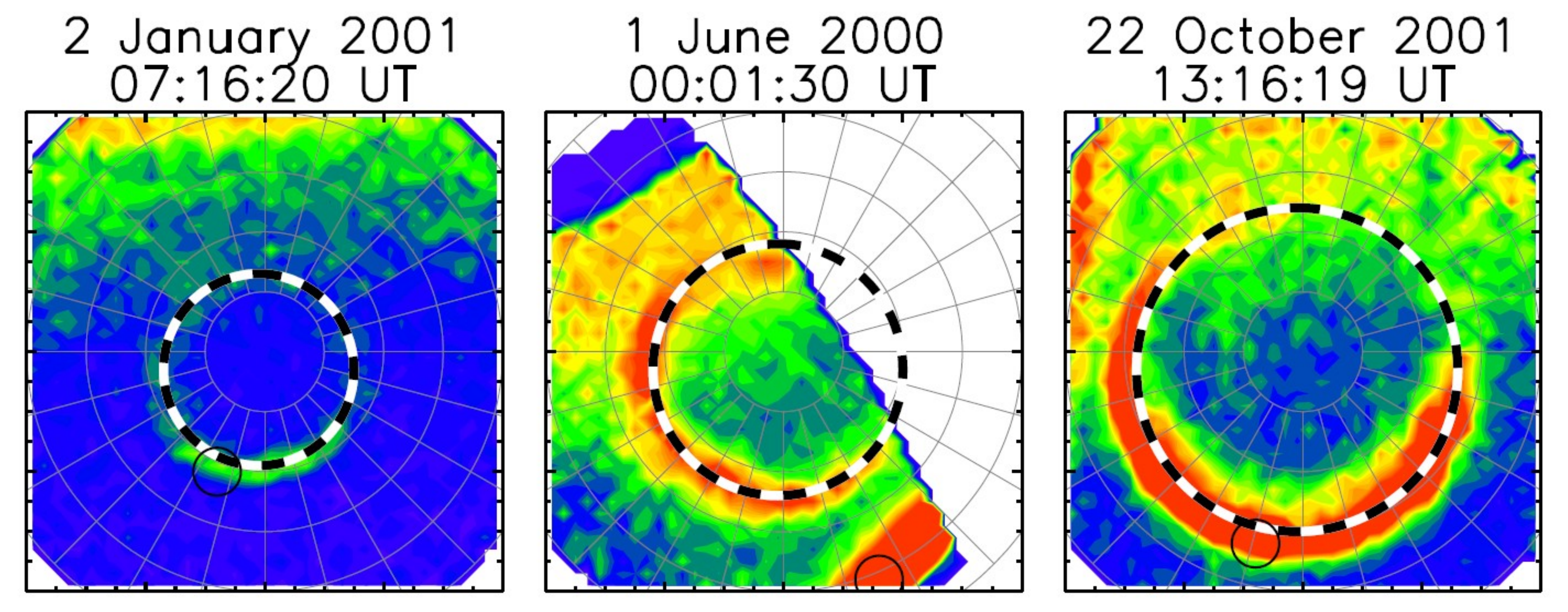
$$E^{W} = g\mathbf{u}$$

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

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

Engwall et al, 2009

Assumption : source area = open polar cap



From Milan et al, 2012

- 40'000 images of auroral oval: find Λ of oval + 2°
- model: parametrize with Θ_D and Dst (open + close)

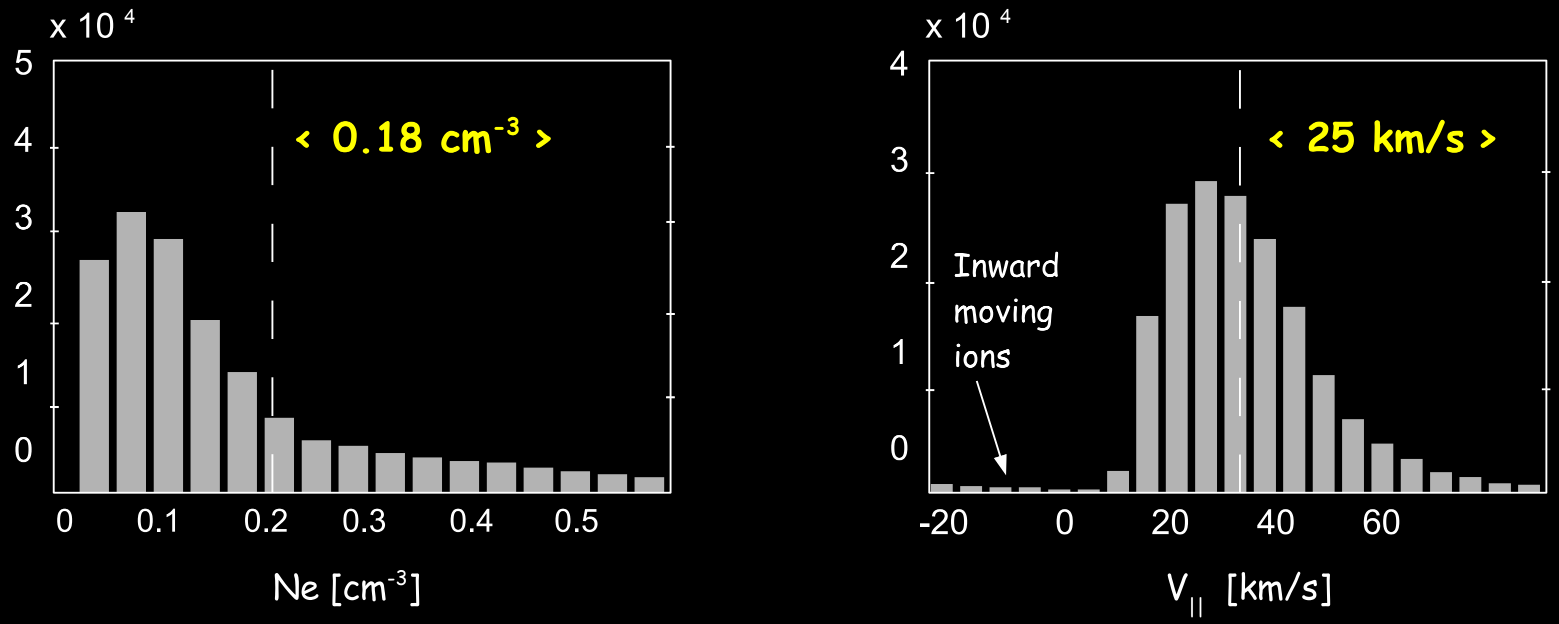
Results :

- Engwall et al, 2009, André et al, 2015:
    - outflow rates

- Li et al, GRL 2012:
    - source of cold ions
    - response to geoactivity

- Haaland et al, 2012a
    - fate of ions

Densities, fluxes and outflow rates

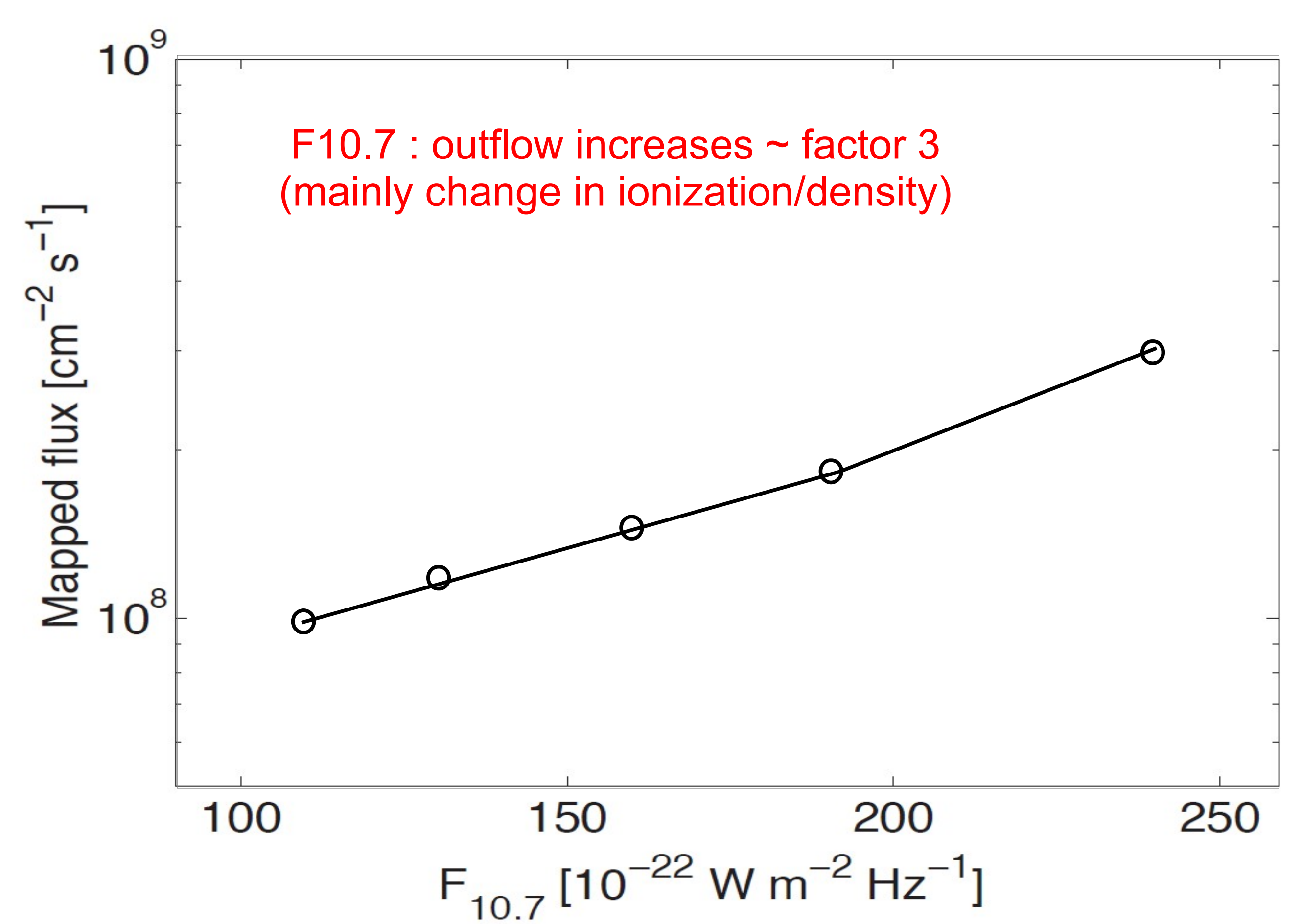


* Ionospheric fluxes ~10^8 cm^{-2} s^{-1}

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

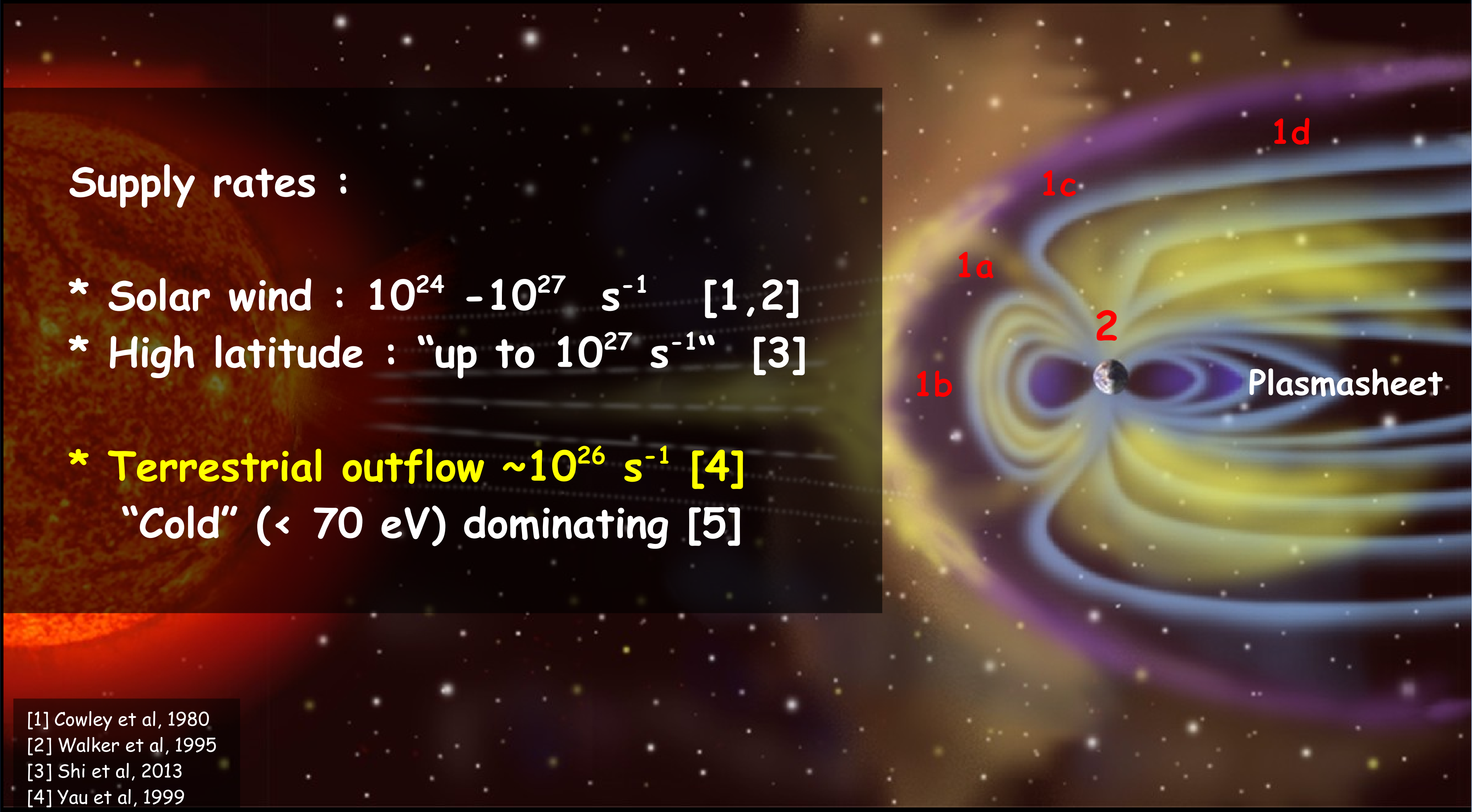
After Engwall et al, 2009, André & Cully, 2012, André et al, 2015

Solar irradiance



F10.7 : outflow increases ~ factor 3
(mainly change in ionization/density)

...for comparison .. other sources



Supply rates :

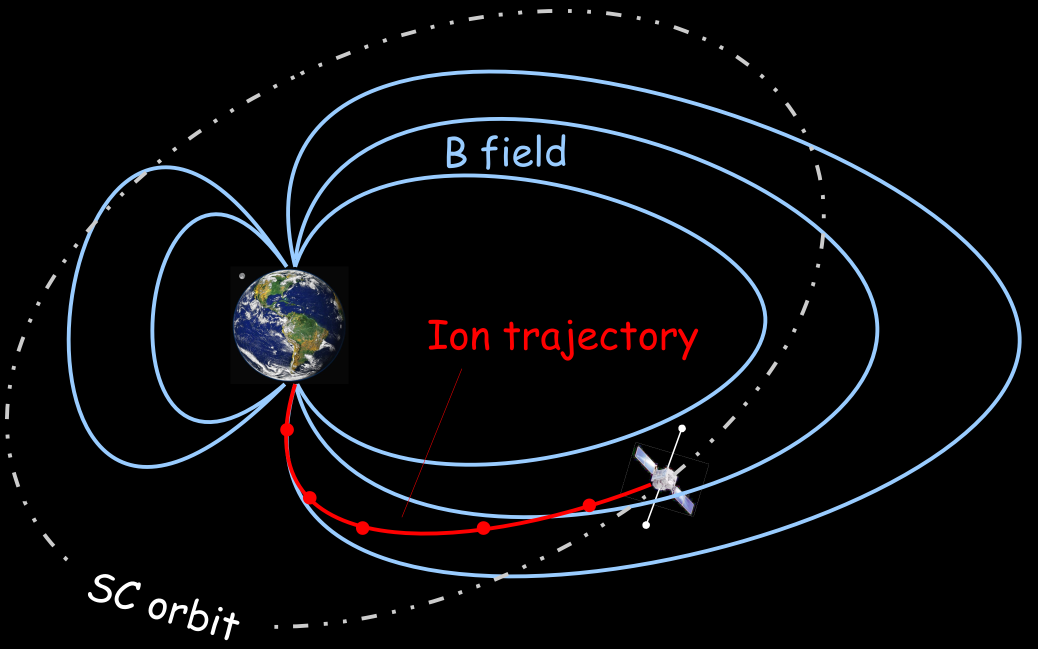
- * Solar wind : 10^{24} -10^{27} s^{-1} [1,2]
- * High latitude : "up to 10^{27} s^{-1}" [3]

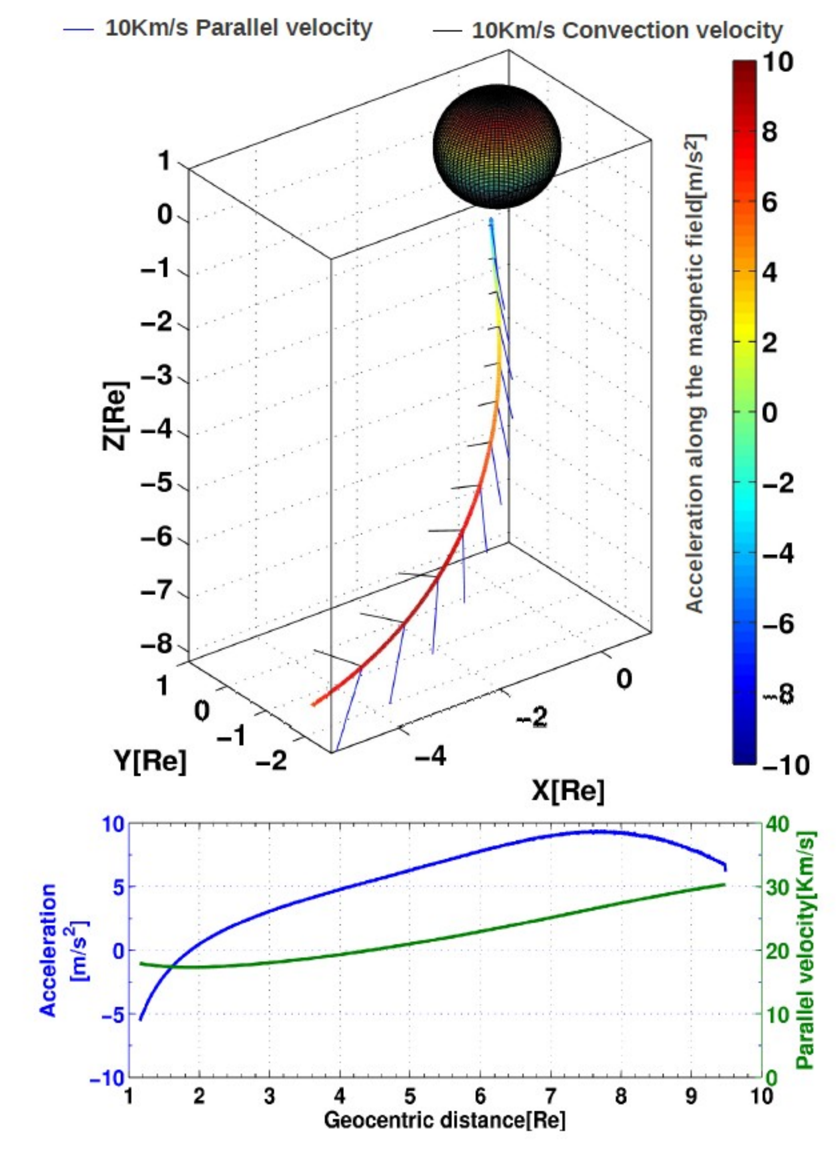
* Terrestrial outflow ~10^{26} s^{-1} [4]
"Cold" (< 70 eV) dominating [5]

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

Source region

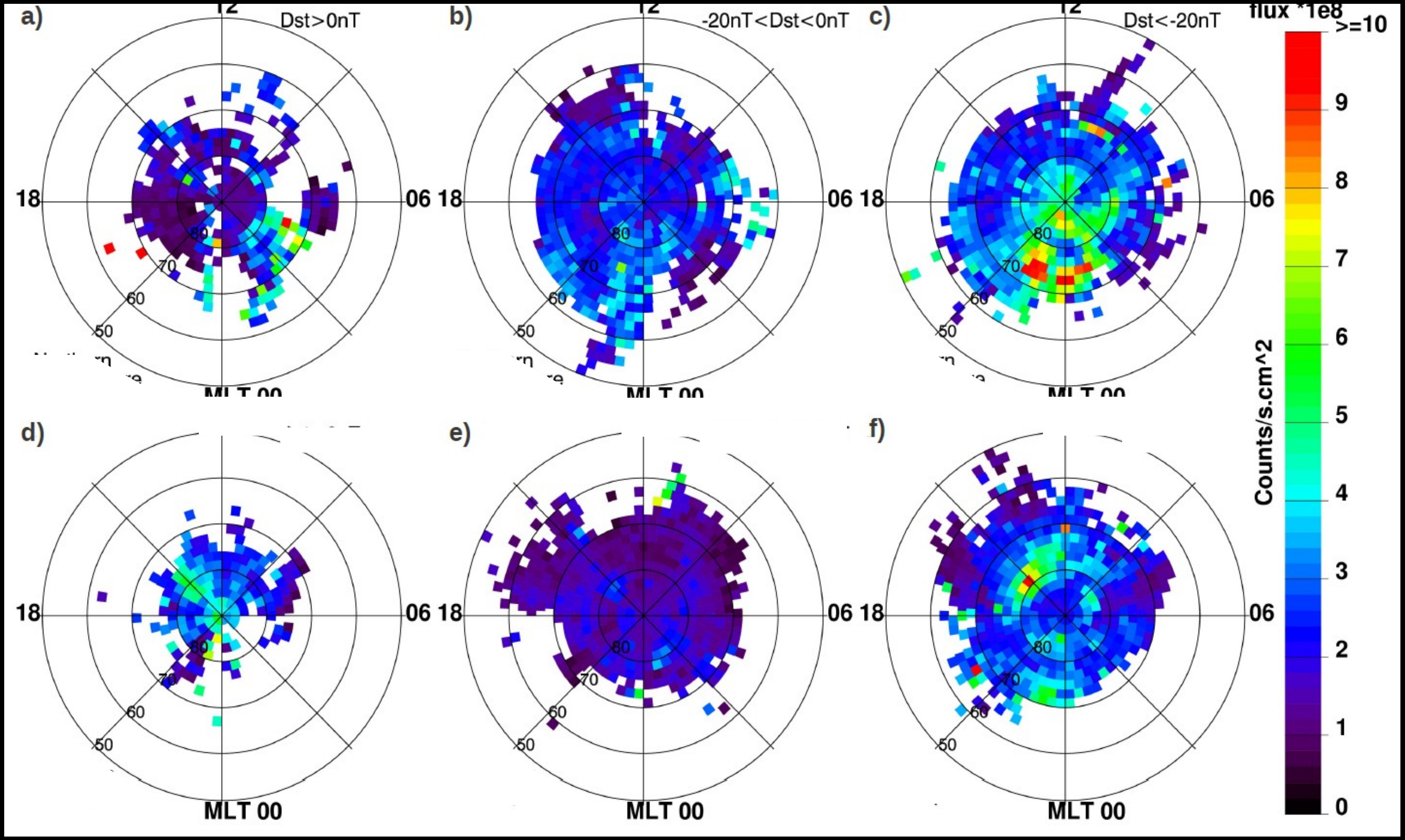
Particle tracing
Li et al , GRL 2012





$$\frac{dv_{||}}{dt} = \vec{v}_E \cdot \frac{d\,\hat{b}}{ds} - \vec{g}_{||}$$

Source region (Li et al, GRL, 2012)

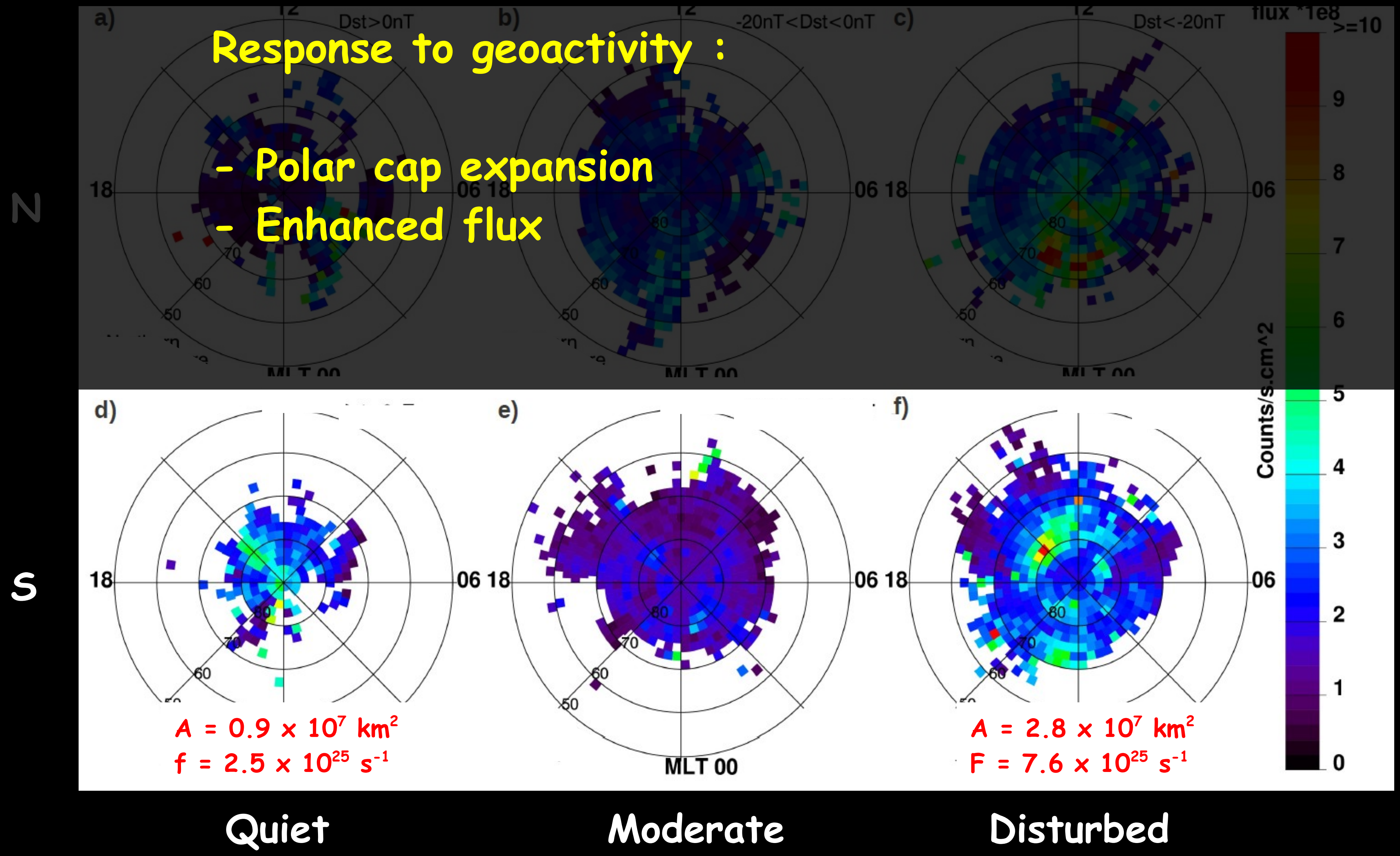


Quiet

Moderate

Disturbed

Source region (Li et al, GRL, 2012)



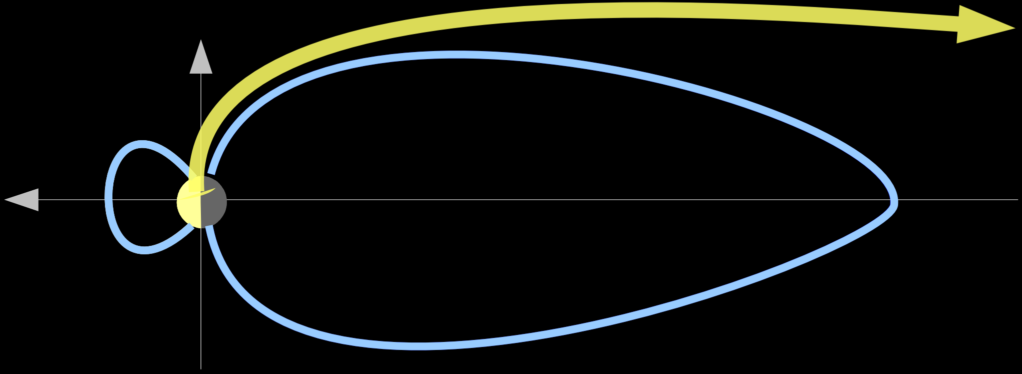
Response to geoactivity :

- Polar cap expansion
- Enhanced flux

$A = 0.9 \times 10^7\ km^2$
$f = 2.5 \times 10^{25}\ s^{-1}$

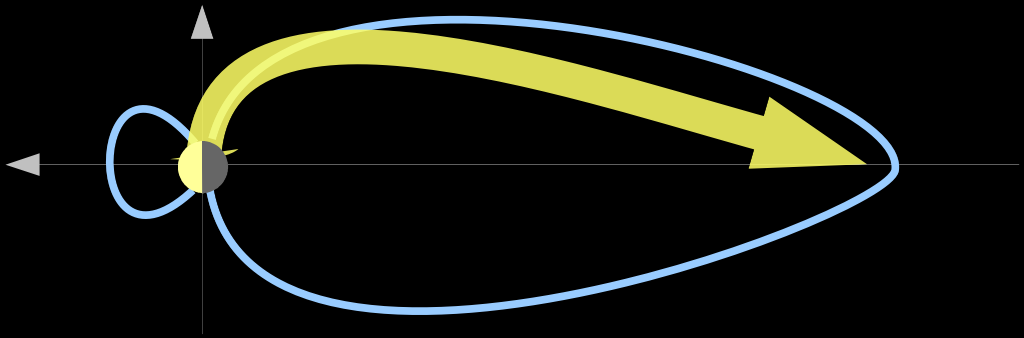
$A = 2.8 \times 10^7\ km^2$
$F = 7.6 \times 10^{25}\ s^{-1}$

Fate of ions (Haaland et al, 2012a,b, Li et al, 2013)



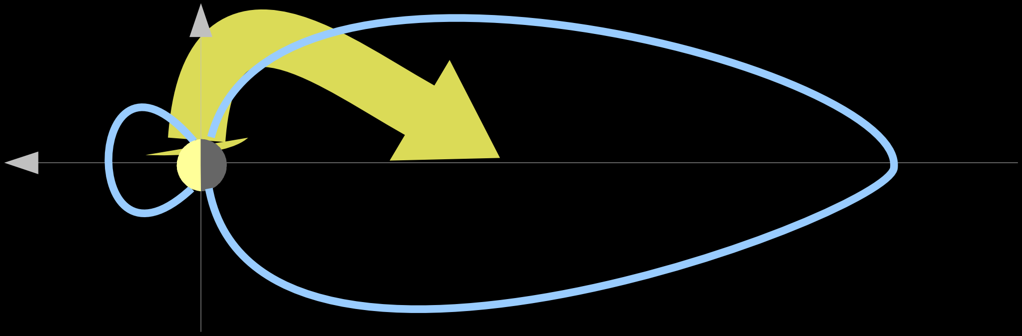
Quiet conditions, stagnant convection

- direct loss downtail



Intermediate geoactivity

- 80-90 % circulation
- supply far downtail



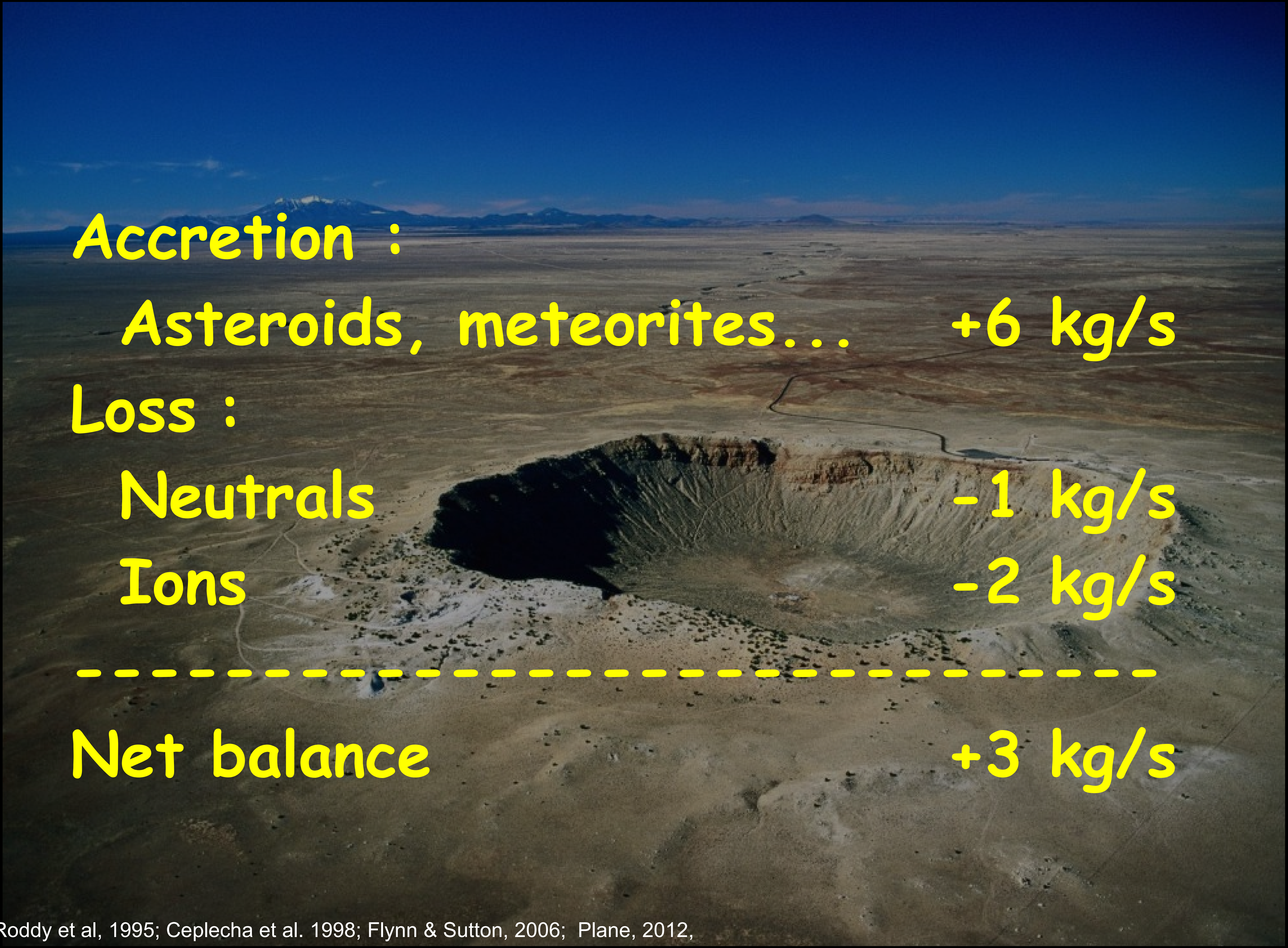
Disturbed conditions, strong convection

- little downtail loss
- supply close to Earth

Global balance ?

© photos.cyberborean.org

www.meteorwatch.com



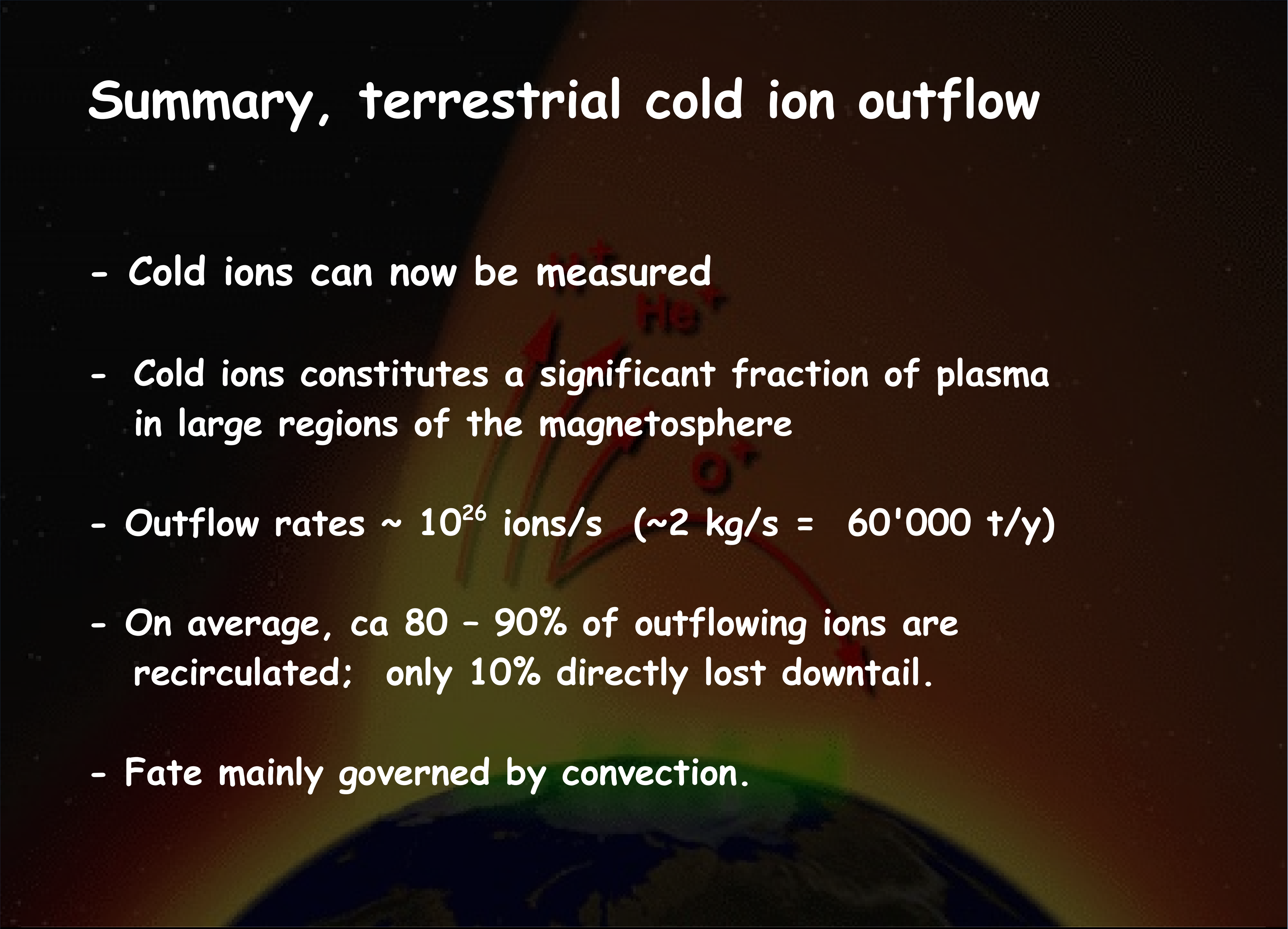
Accretion :	
Asteroids, meteorites...	+6 kg/s
Loss :	
Neutrals	-1 kg/s
Ions	-2 kg/s

Net balance	+3 kg/s

Roddy et al, 1995; Ceplecha et al. 1998; Flynn & Sutton, 2006; Plane, 2012,

	Mars	Earth	Venus
R_M	~ 3390 km	6371 km	6050 km
Ms	~ $0.65 \cdot 10^{24}$ kg	$6.0 \cdot 10^{24}$ kg	$4.9 \cdot 10^{24}$ kg
I_{SUN}	~ 600 W/m^2	1200 W/m^2	2600 W/m^2
$E_{ESC\ H+}$	~ 0.2 eV	0.6 eV	0.5 eV
$E_{ESC\ O+}$	~ 1.9 eV	9.7 eV	8.6 eV
L_{OUT}	~ 10^{24} ions/s	10^{26} ions/s	10^{25} ions/s
	(mostly lost)	(mostly recirculated)	(mostly lost ?)

Summary, terrestrial cold ion outflow



- Cold ions can now be measured
- Cold ions constitutes a significant fraction of plasma in large regions of the magnetosphere
- Outflow rates ~ 10^{26} ions/s (~2 kg/s = 60'000 t/y)
- On average, ca 80 – 90% of outflowing ions are recirculated; only 10% directly lost downtail.
- Fate mainly governed by convection.