

The Earth's magnetospheric cusps

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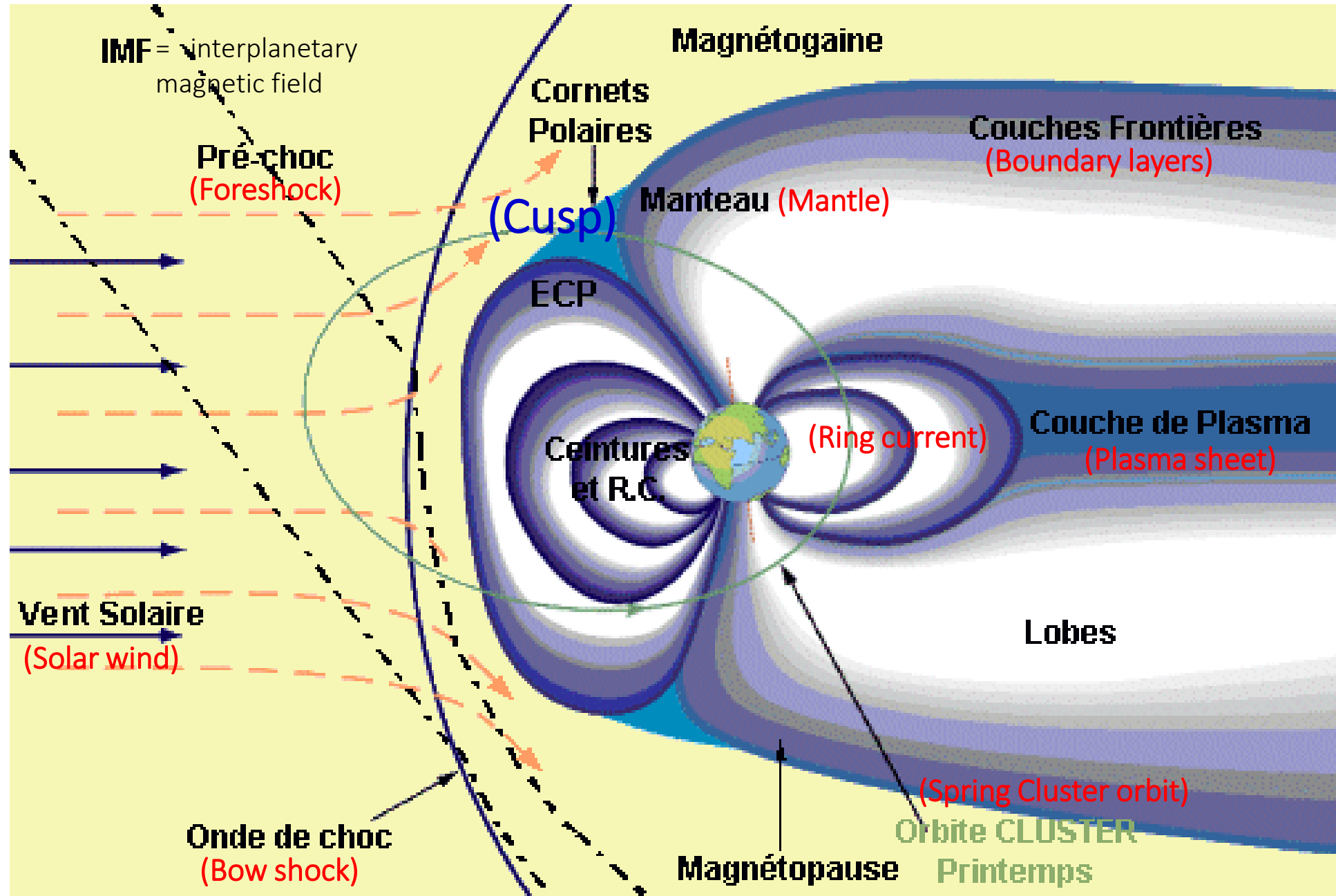
Outline

- Introduction: magnetosphere and cusps
- The polar cusps at mid-to-low altitudes
 - reconnection and convection
 - spatial vs temporal features
- The polar cusps at high altitudes
 - a small scale view
 - a large scale view
 - global modelling
 - waves and heating
- Conclusions & future prospects

Introduction

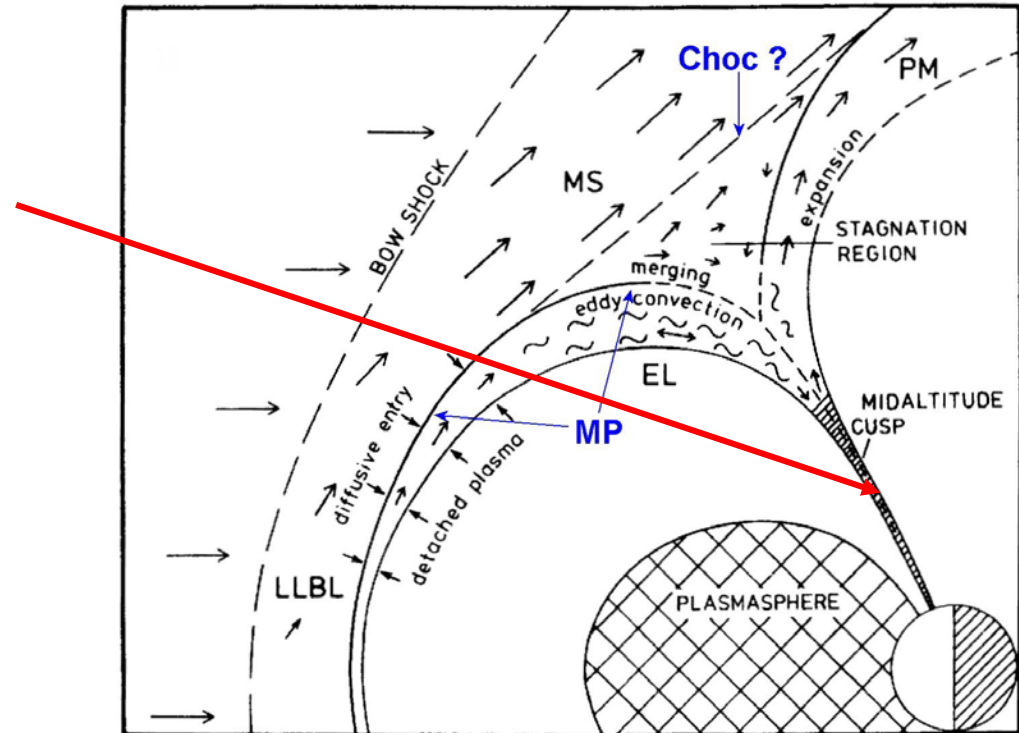
- The magnetosphere:
 - open/closed magnetosphere
 - magnetic reconnection
 - Dungey cycle
 - role of IMF

The Earth's magnetosphere



The **closed** magnetosphere: pre-Cluster conjectures

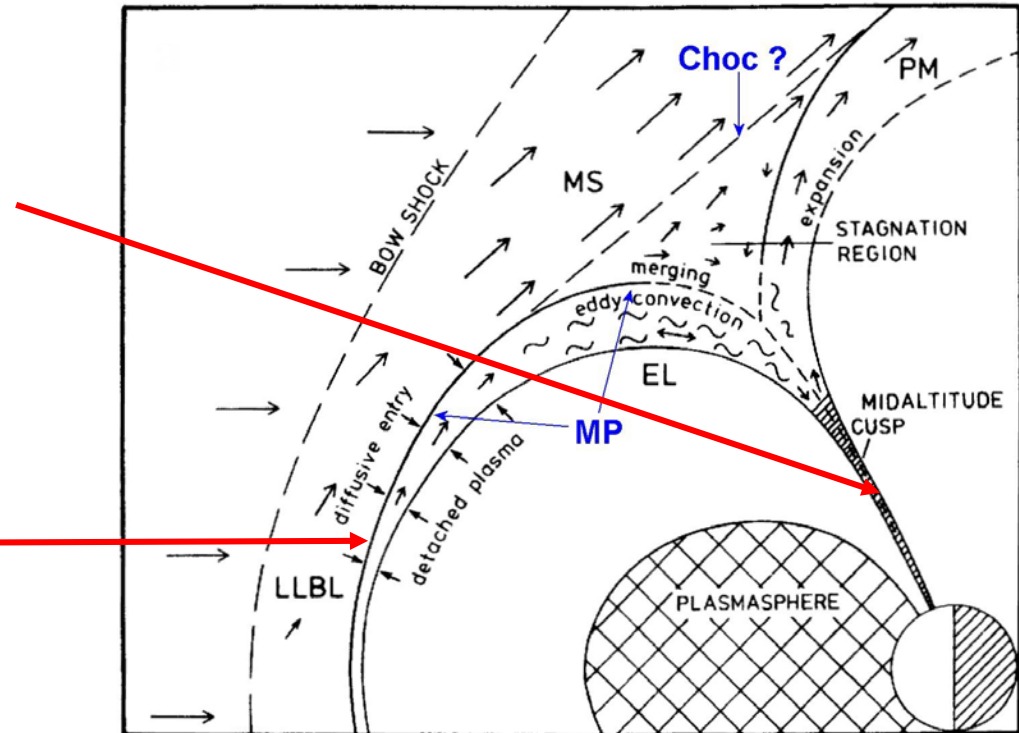
- Cusp discovered from observation of solar wind plasma at low polar altitudes [Heikkila and Winningham, 1971; Frank, 1971]



Adapted from *Haerendel et al.* [1978]

The closed magnetosphere: pre-Cluster conjectures

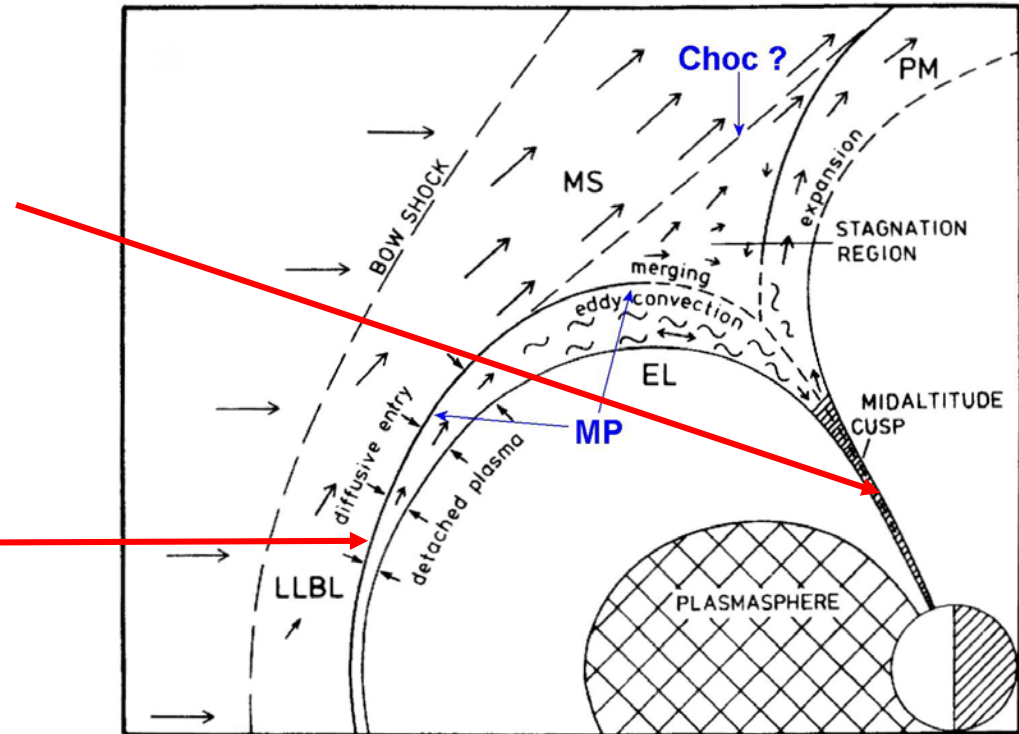
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- The magnetosphere is confined by the solar wind pressure
→ Magnetopause [Chapman and Ferraro, 1931]



Adapted from Haerendel et al. [1978]

The closed magnetosphere: pre-Cluster conjectures

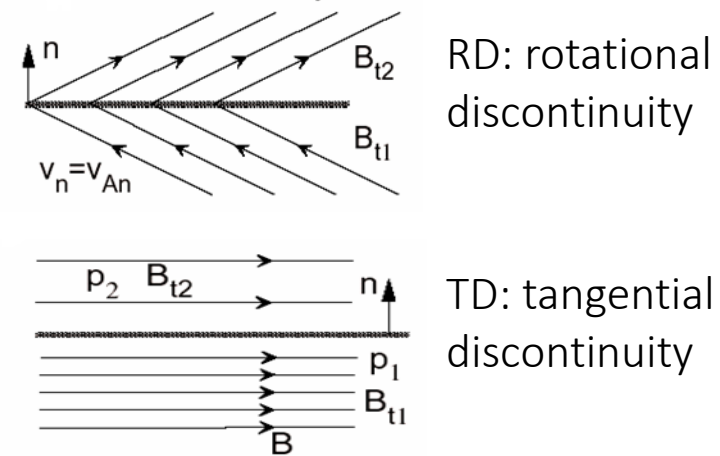
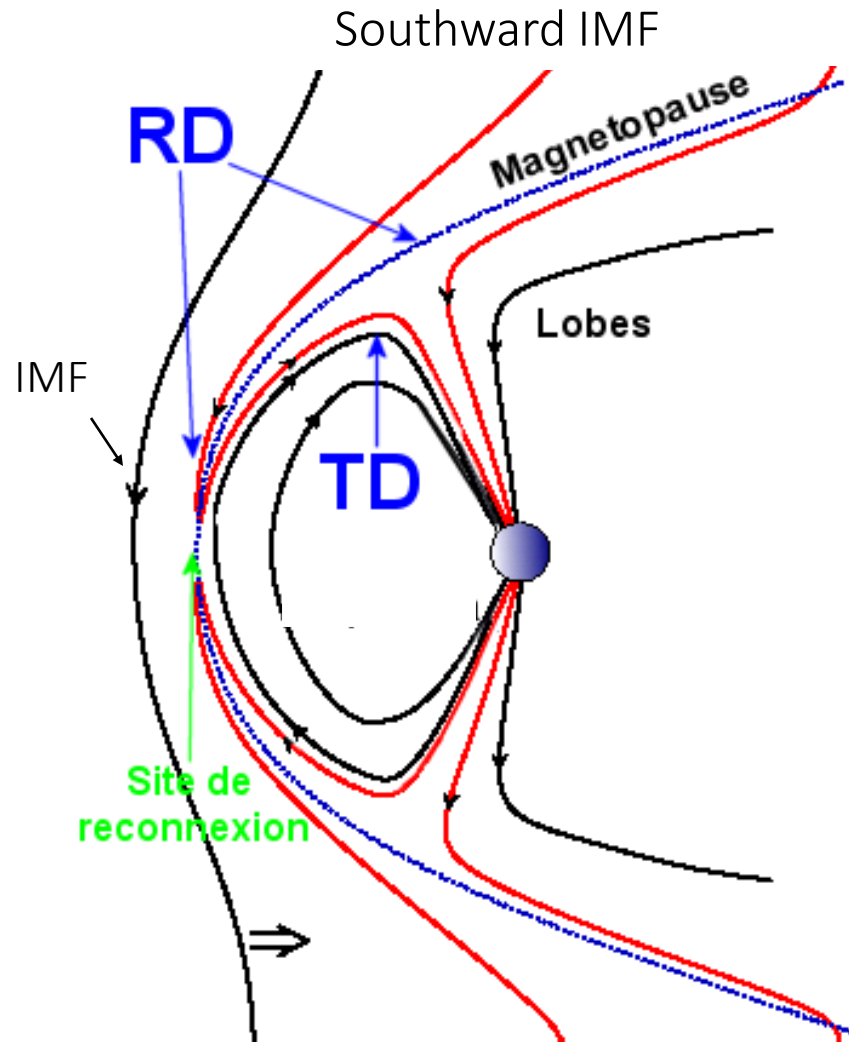
- Cusp discovered from observation of **solar wind plasma at low polar altitudes**
[Heikkila and Winningham, 1971; Frank, 1971]
- The **magnetosphere is confined** by the solar wind pressure
→ **Magnetopause**
[Chapman and Ferraro, 1931]



Adapted from Haerendel et al. [1978]

- Solar wind pressure suggests the presence of **an indentation** at the cusps
→ a **shock?** [Walters, 1966; Cargill, 1999]
- Penetration may occur via **diffusive processes at the boundaries**
[e.g. Haerendel, 1978; Savin et al., 2003]

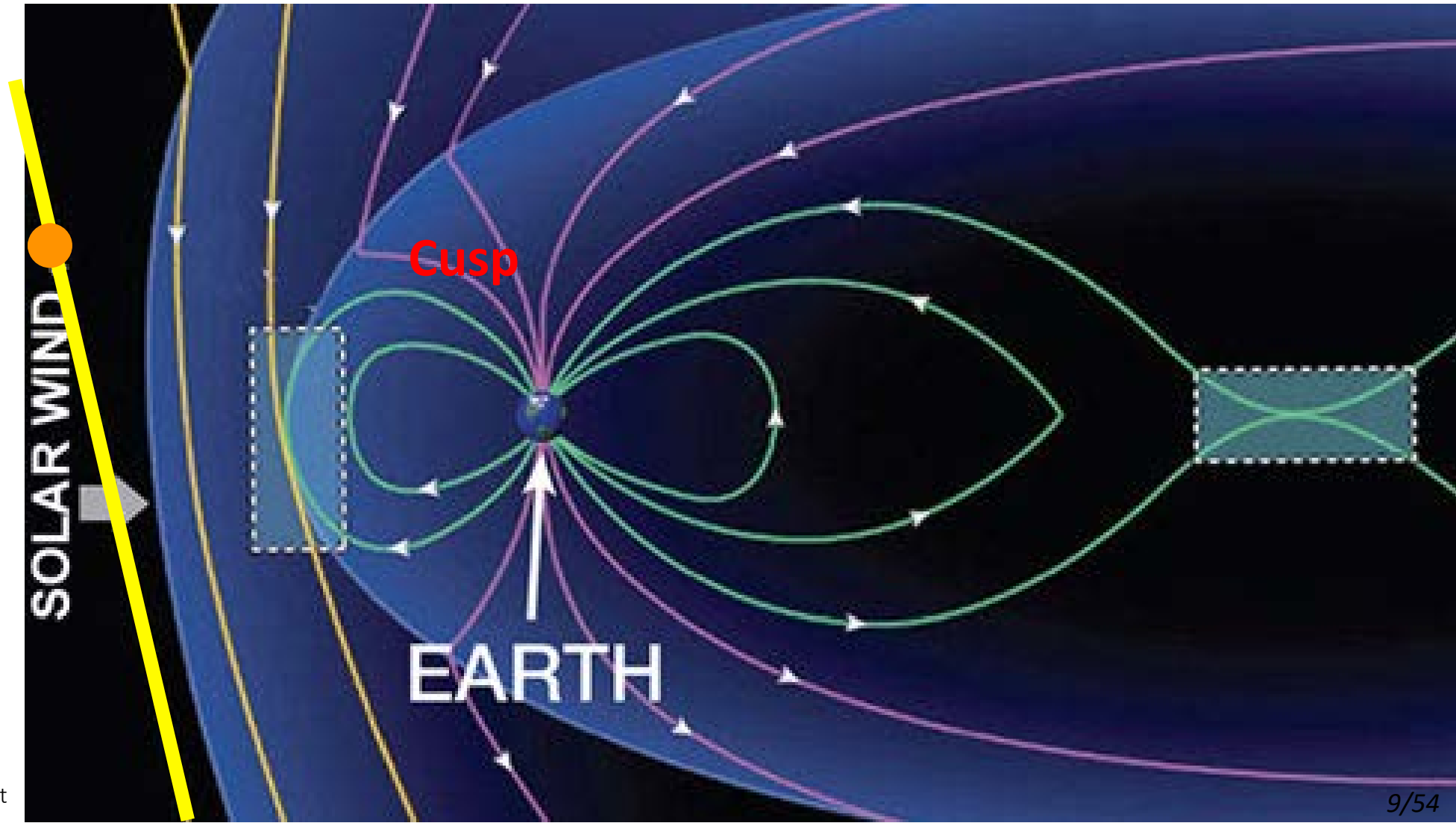
The open magnetosphere



- Assumes the occurrence of magnetic reconnection
[Dungey, 1961]
- Generation of a RD at the outer cusp boundary
[Vasyliunas, 1995]
→ solar wind plasma enters the magnetosphere

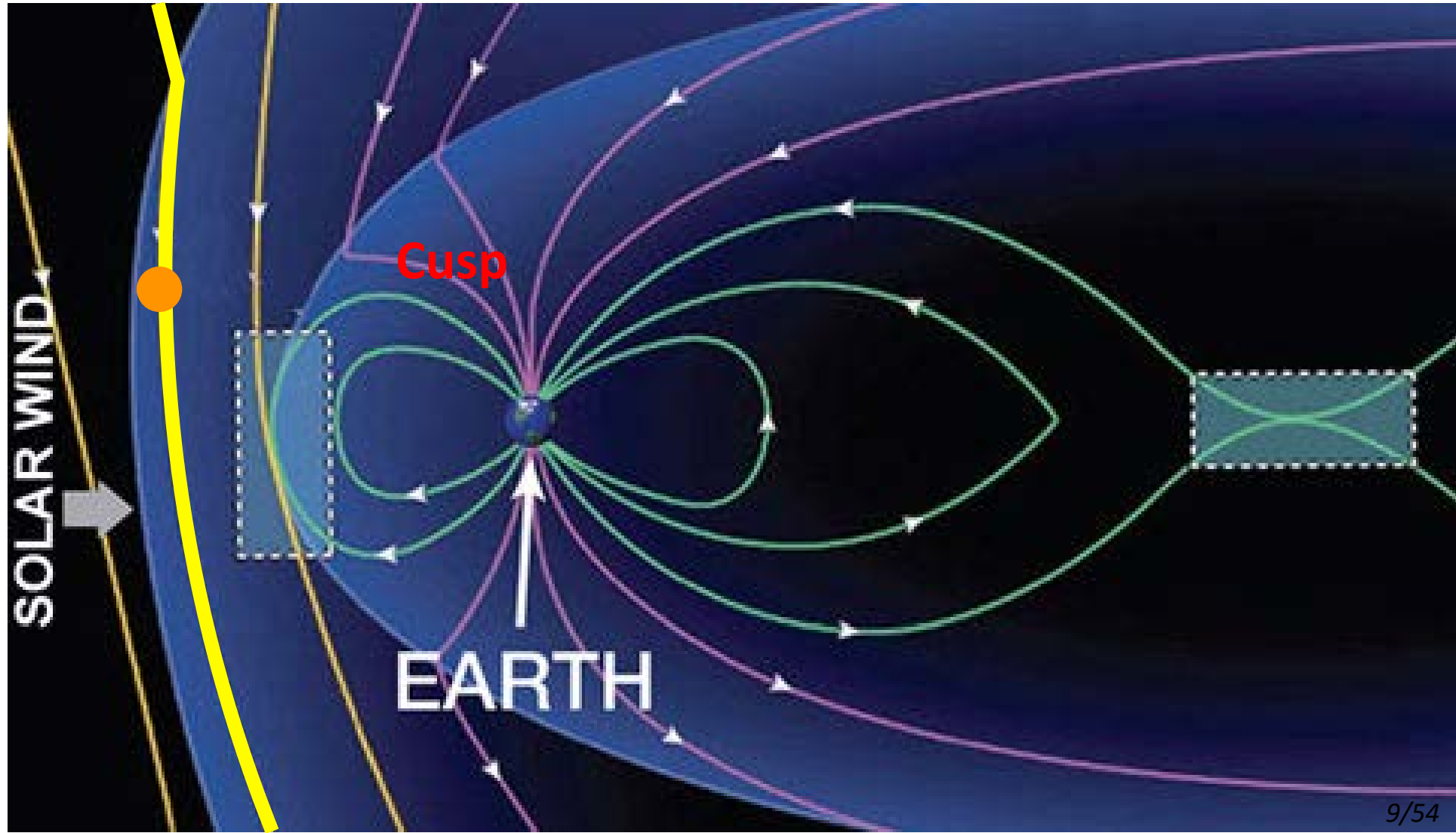
Earth's magnetosphere and magnetic reconnection

The Dungey cycle (JGR, 1961)



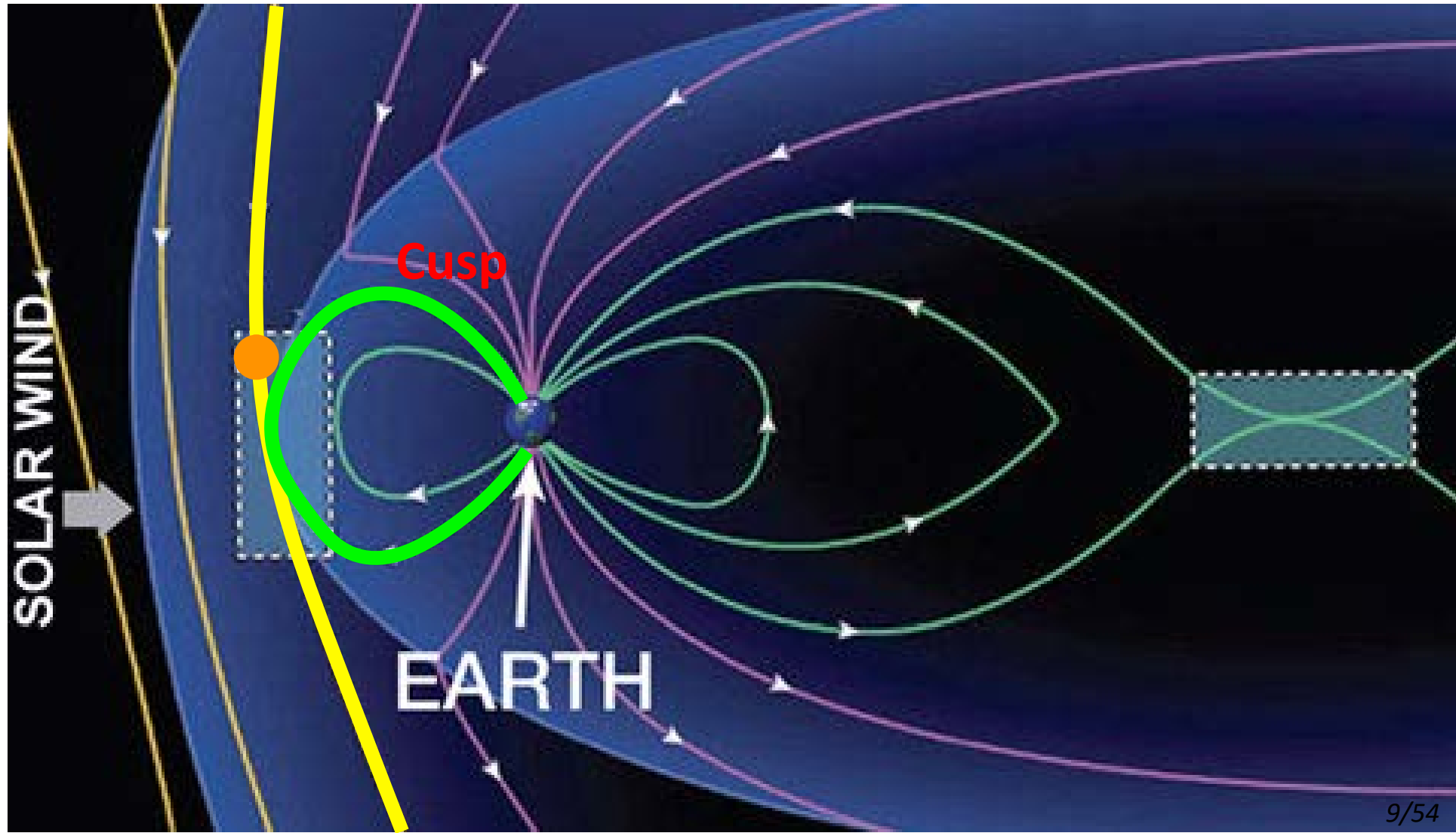
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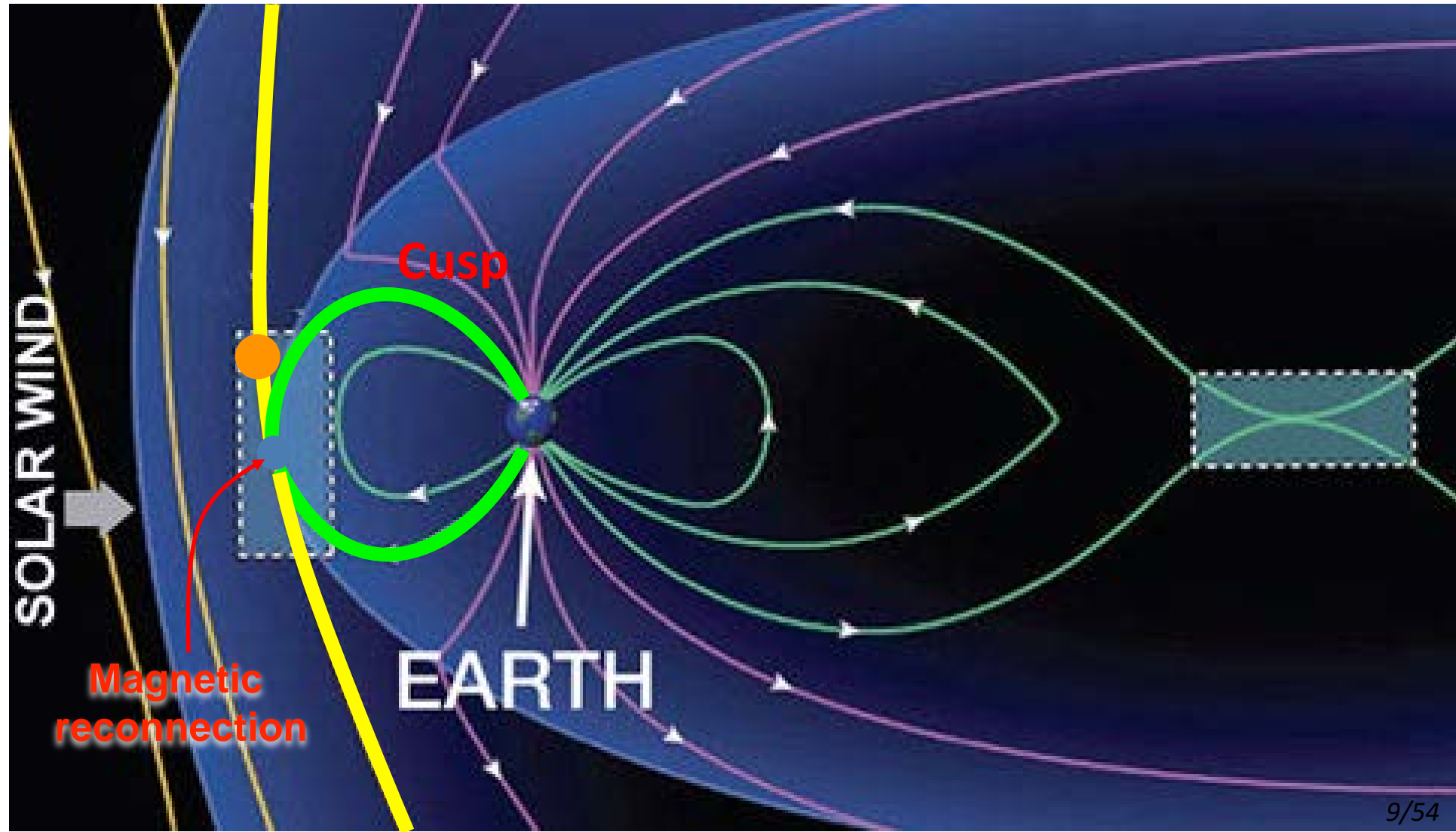
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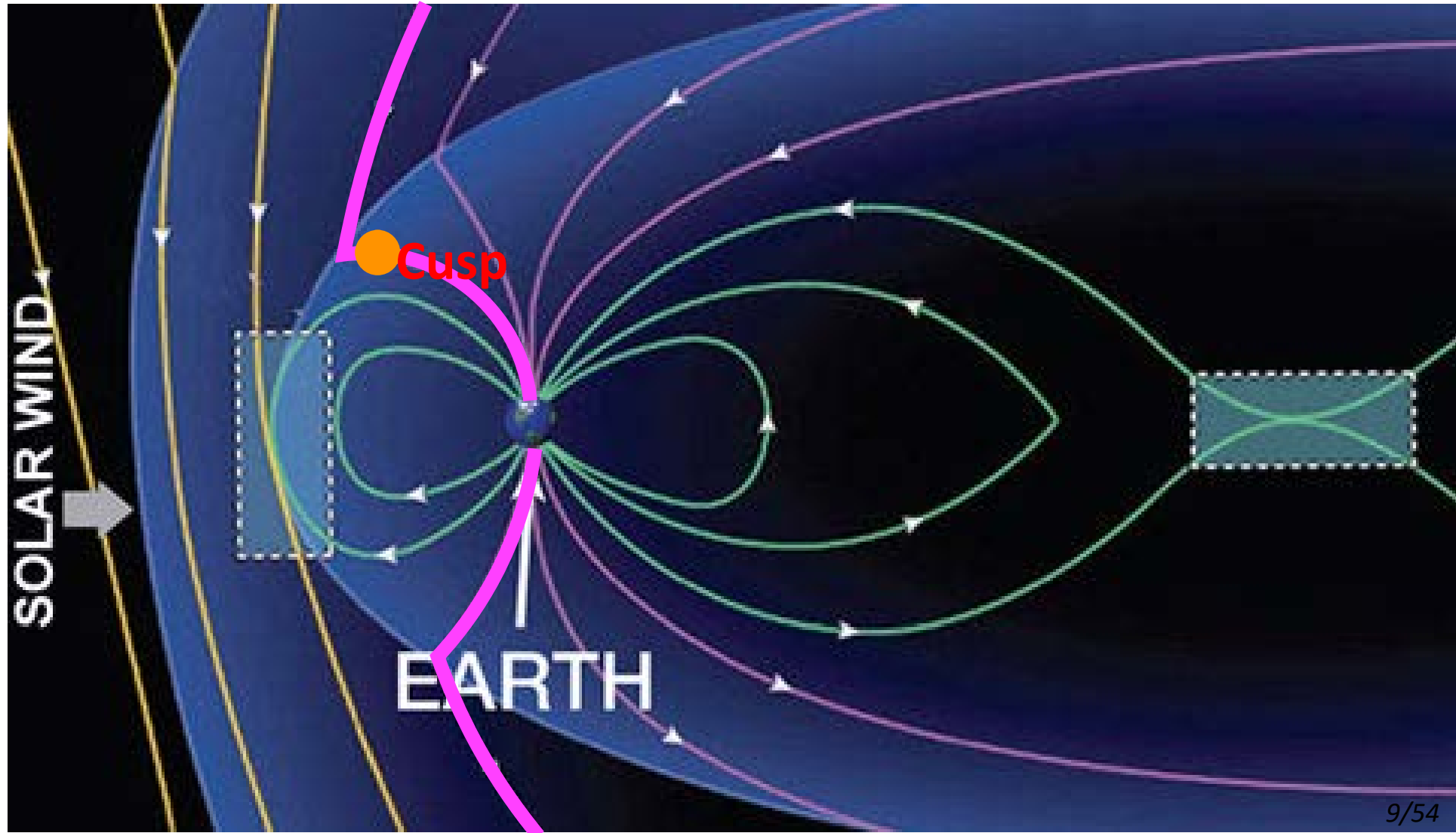
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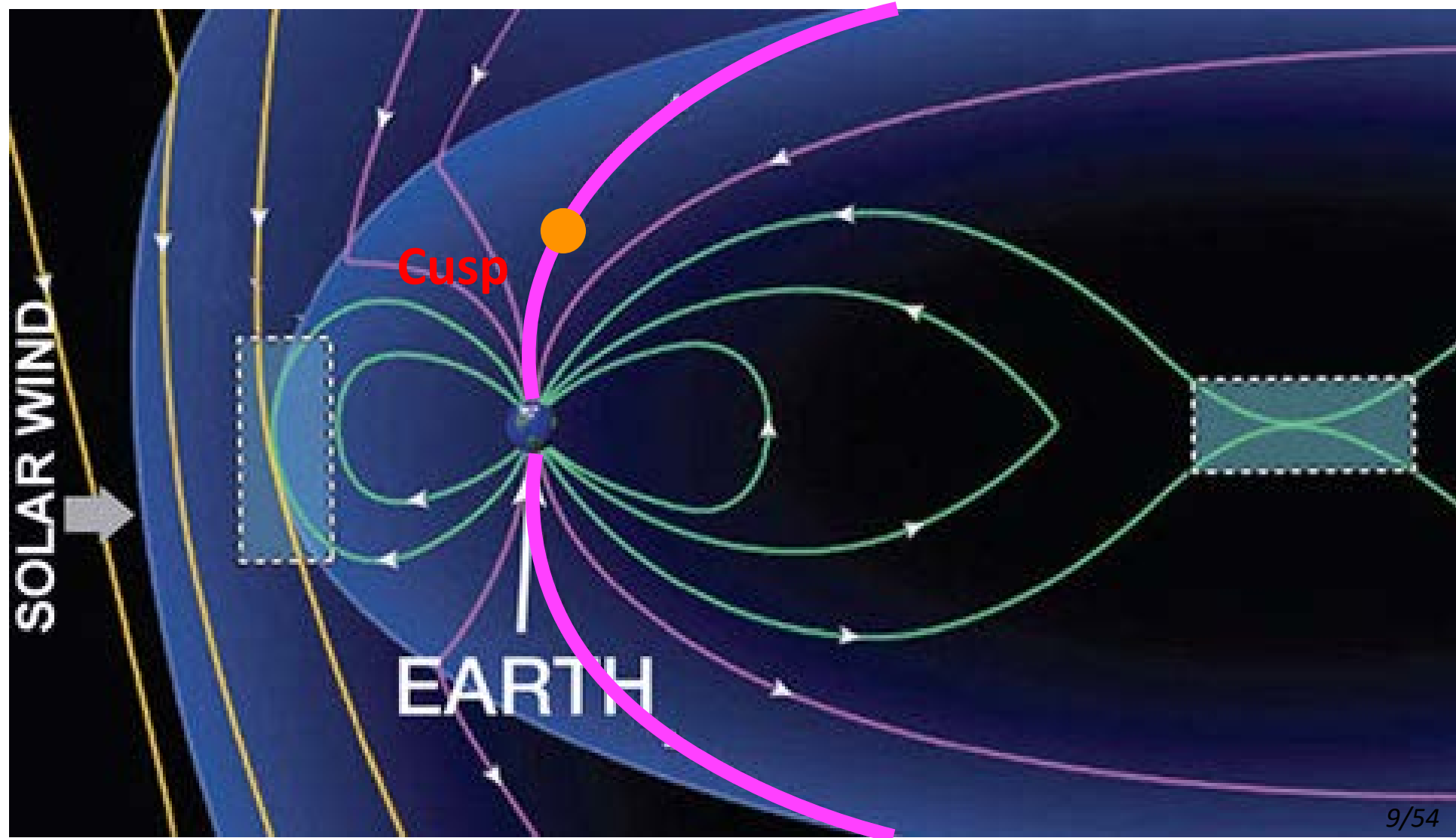
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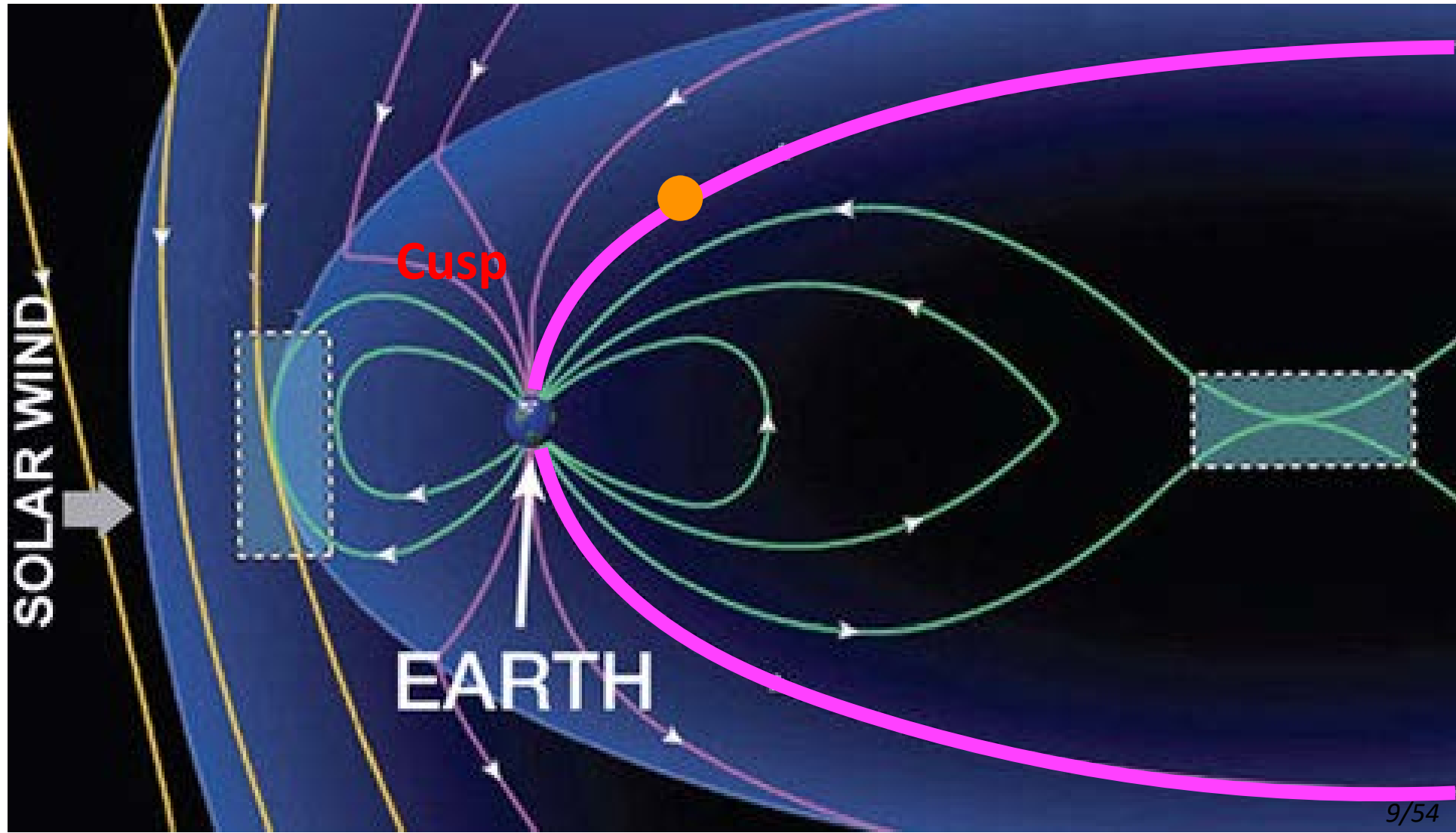
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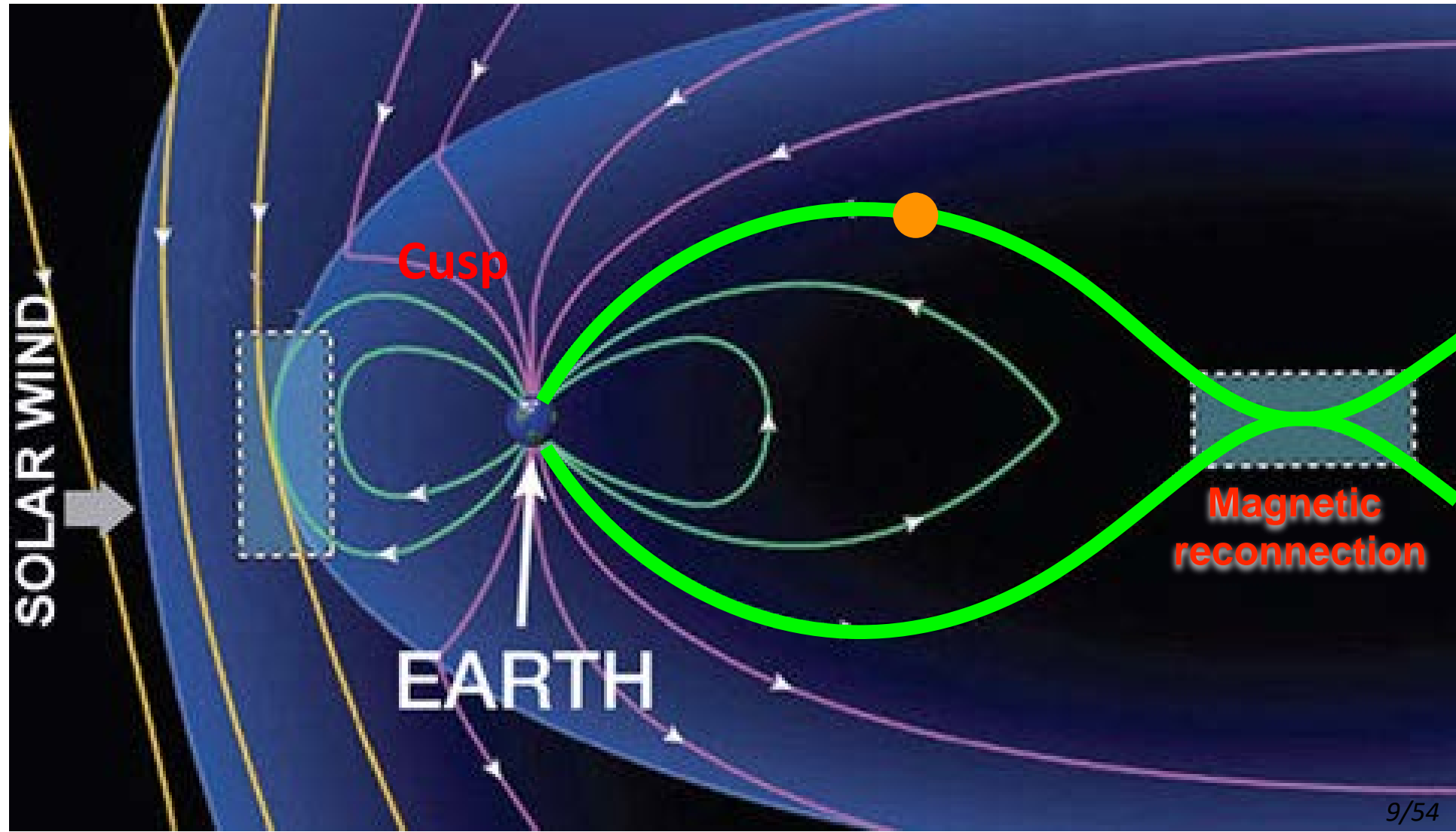
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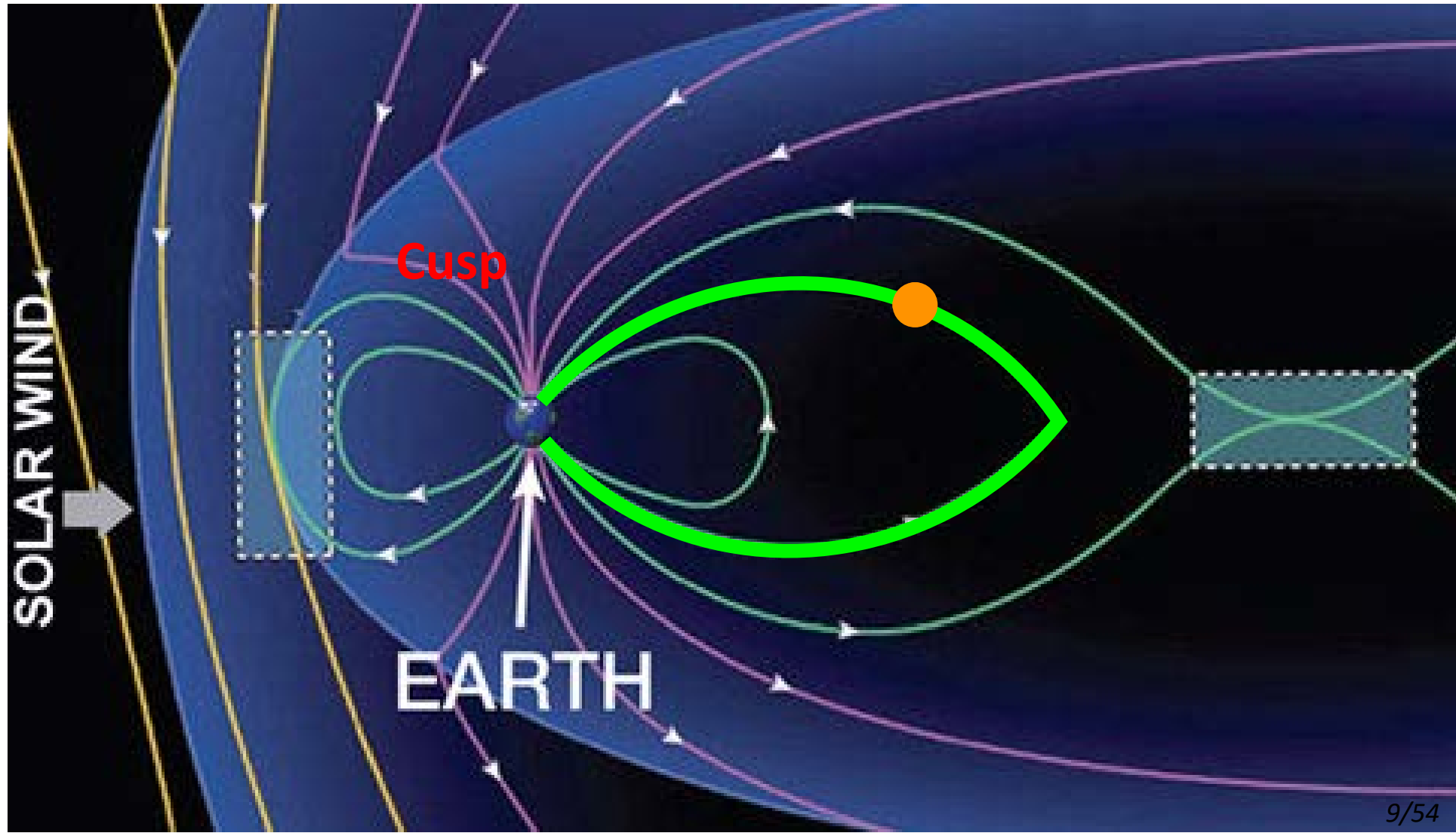
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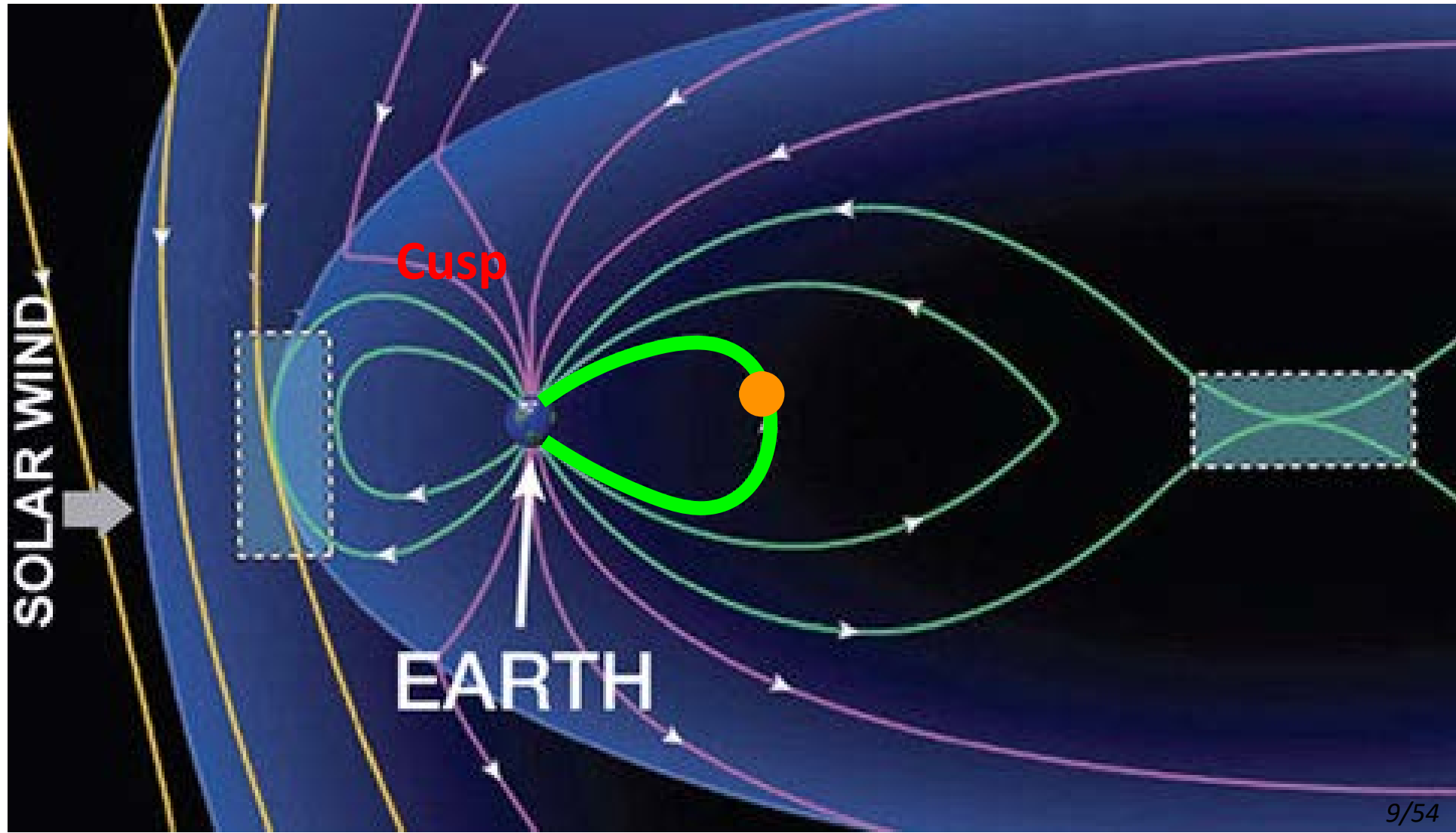
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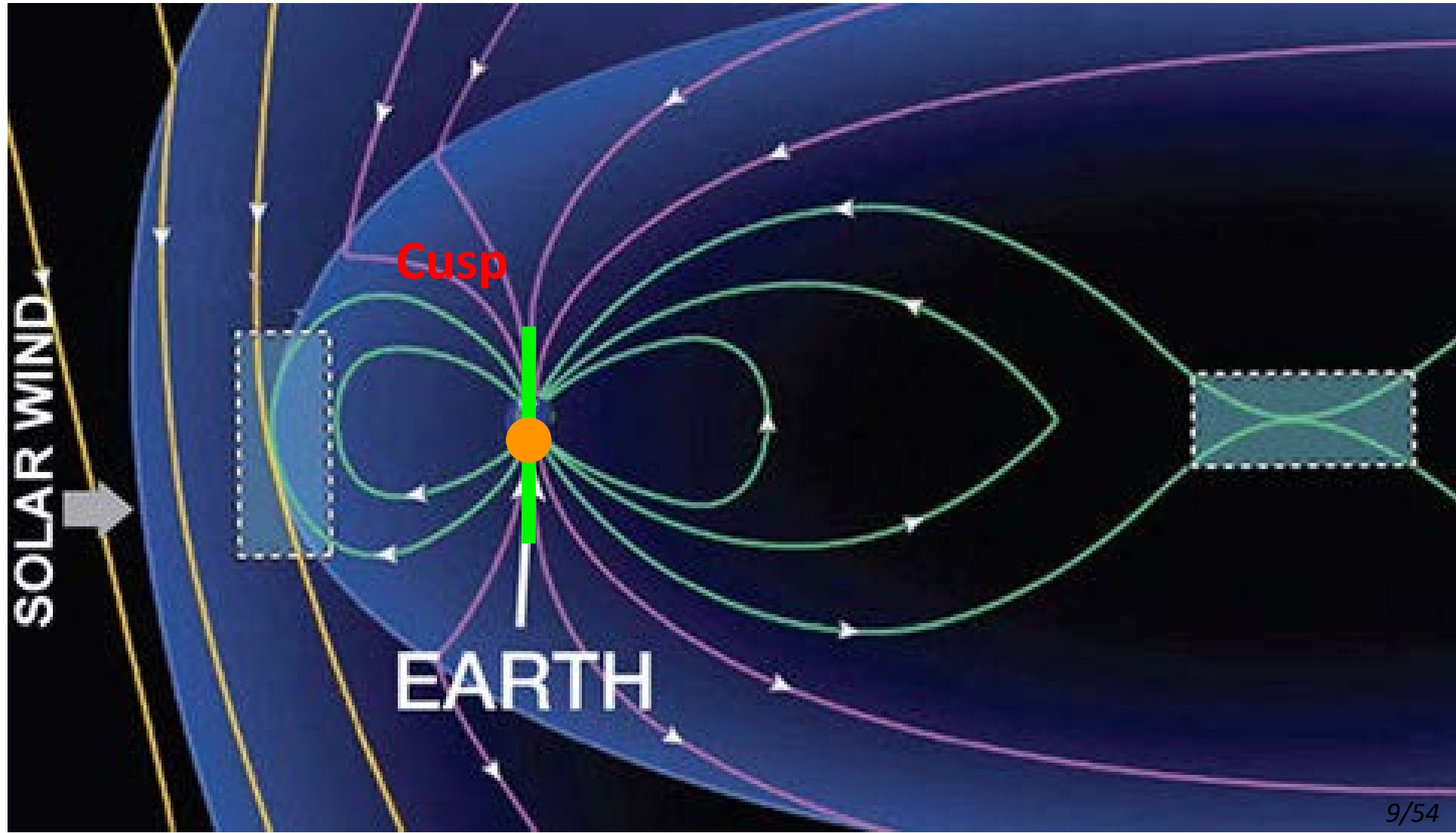
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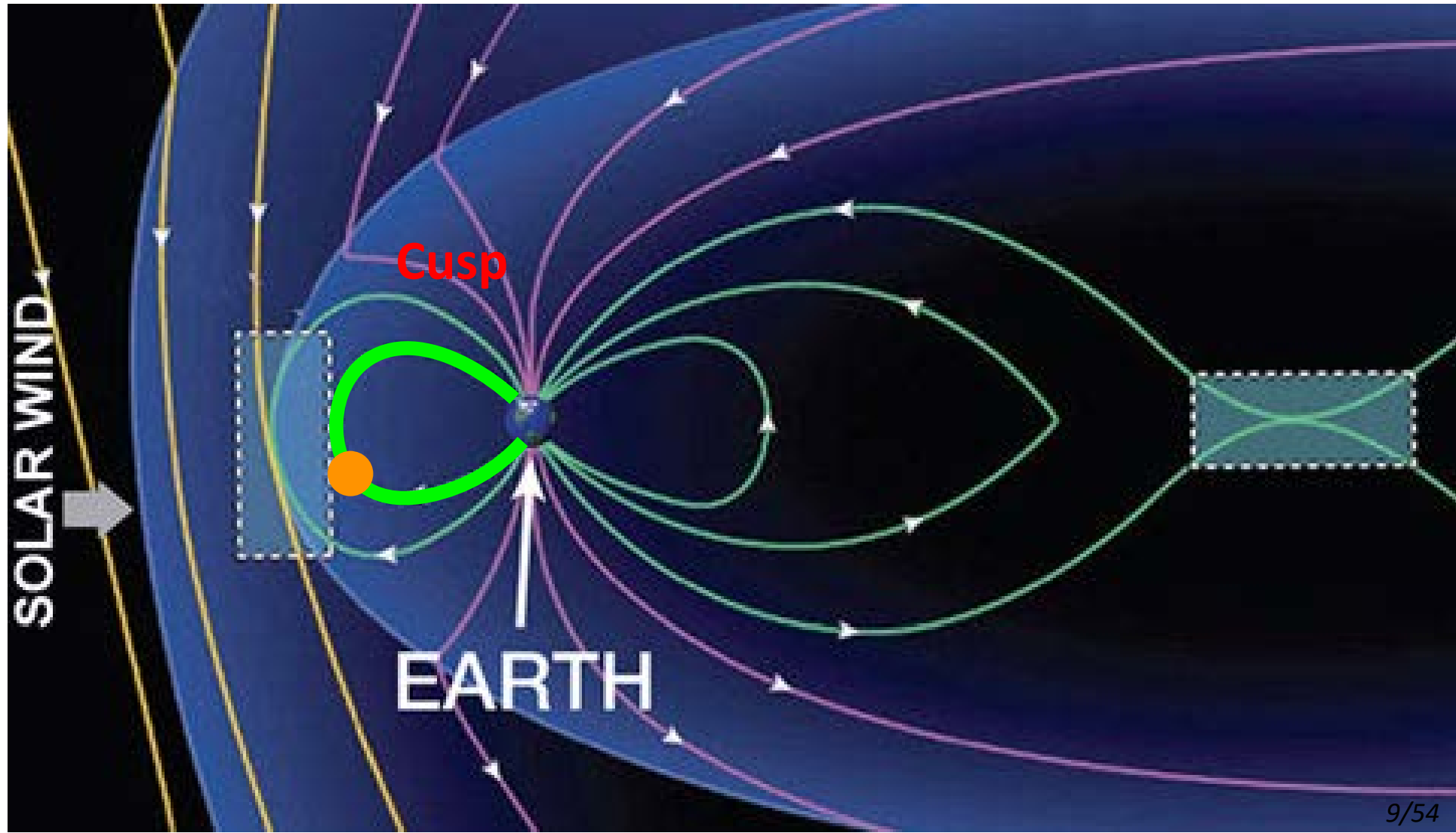
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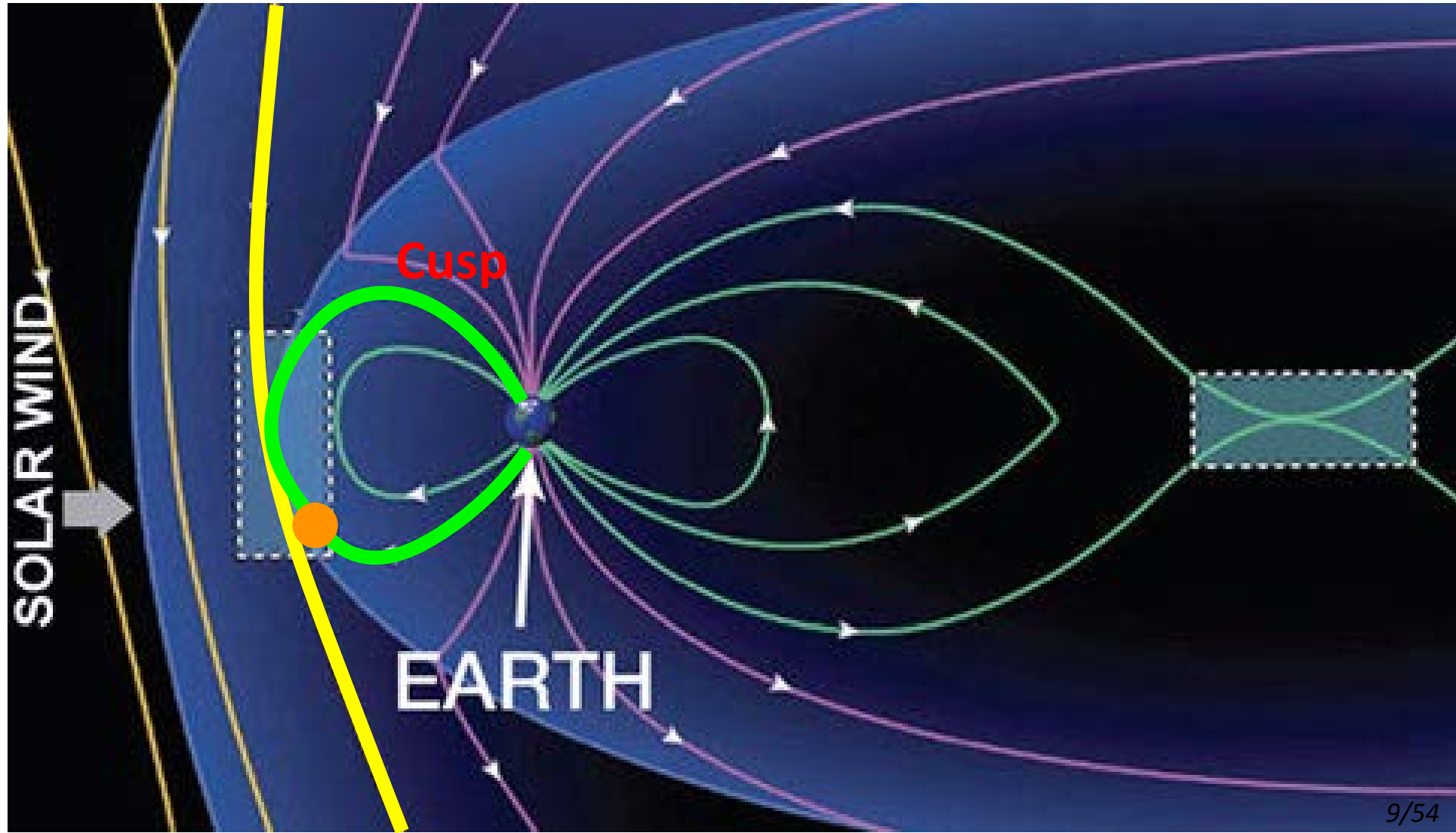
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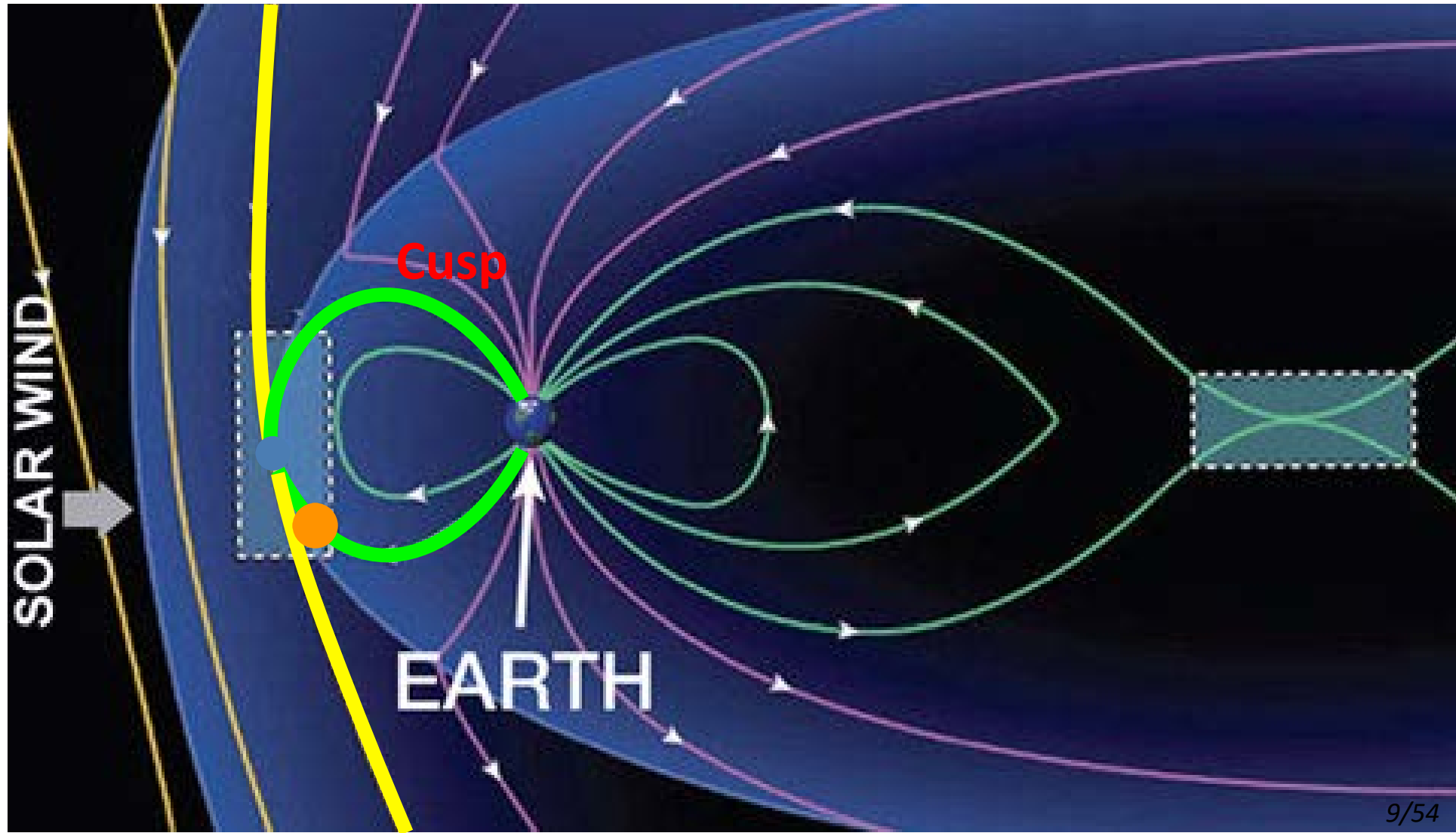
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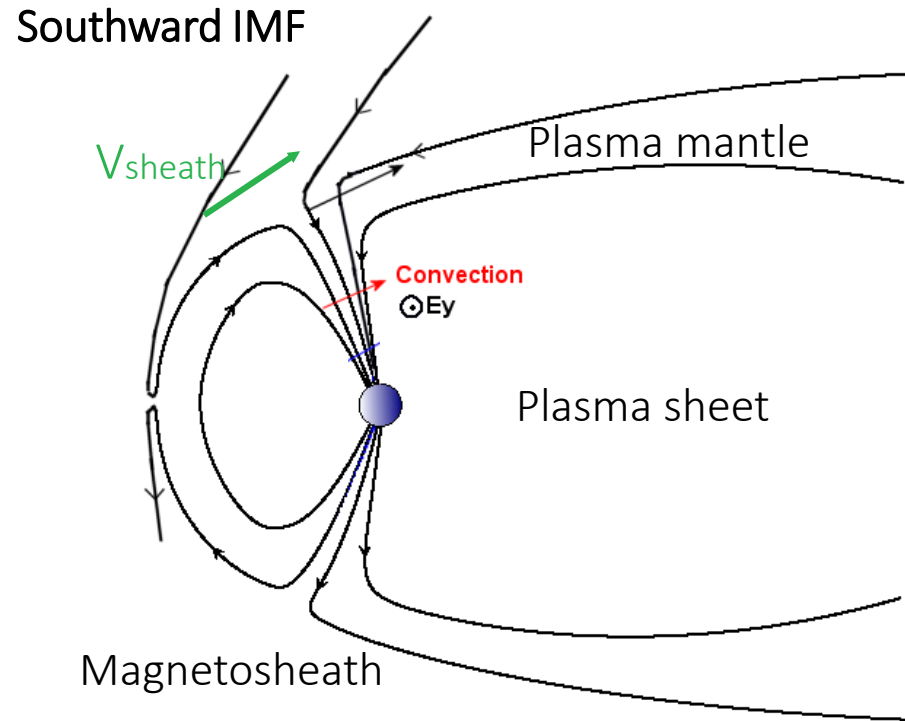


Earth's magnetosphere and magnetic reconnection

The Dungey cycle (JGR, 1961)



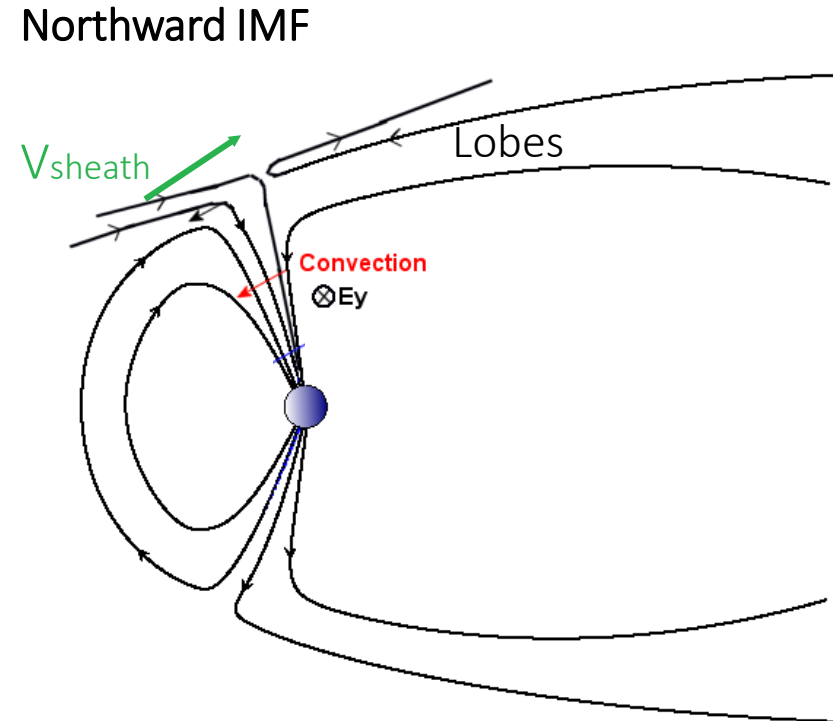
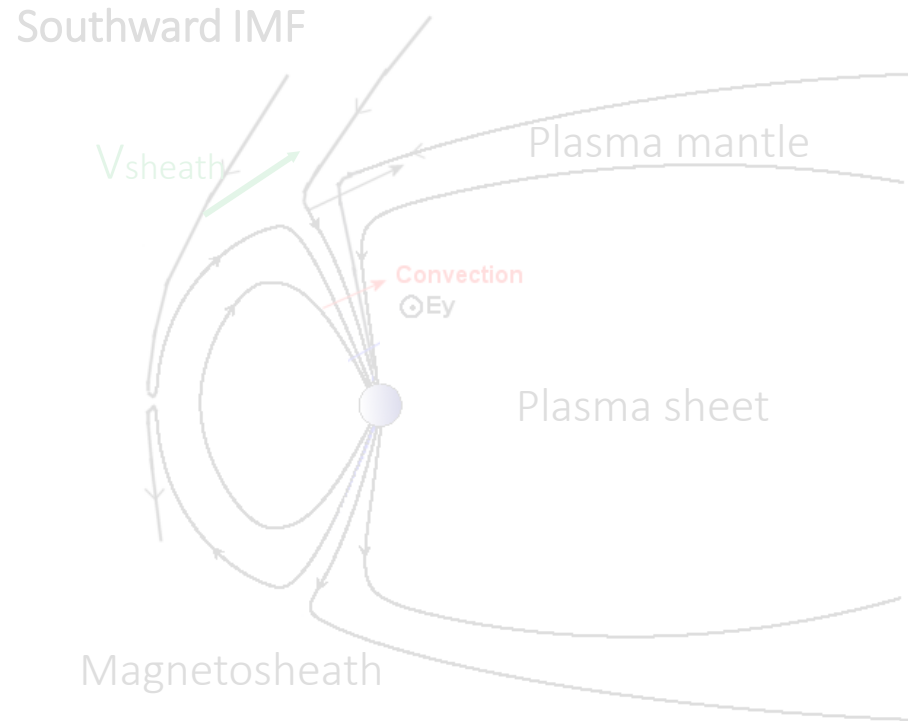
The open magnetosphere (2): role of IMF



For **Southward** IMF:

- Reconnection may occur at **low-latitude**
- Cusp and polar cap **convection is tailward**
- The outer cusp boundary is **open: a rotational discontinuity (RD)**
- **Presence** of a plasma mantle at high latitude

The open magnetosphere (2): role of IMF



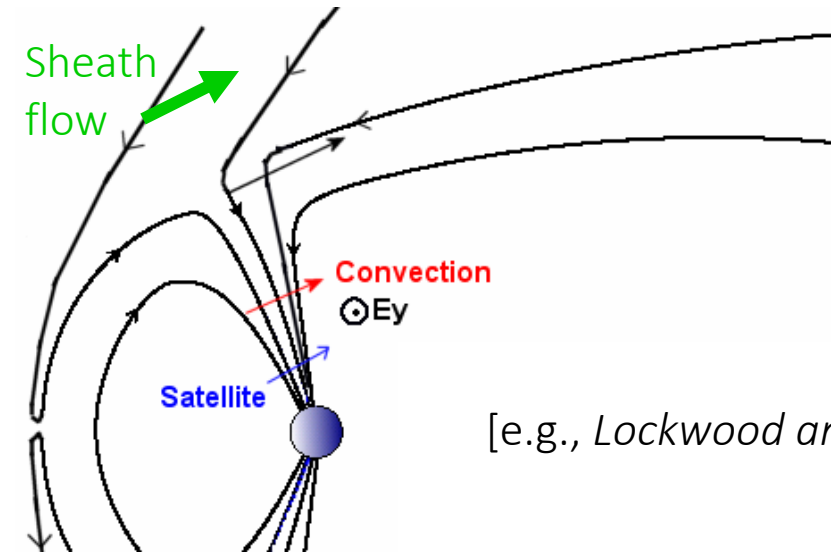
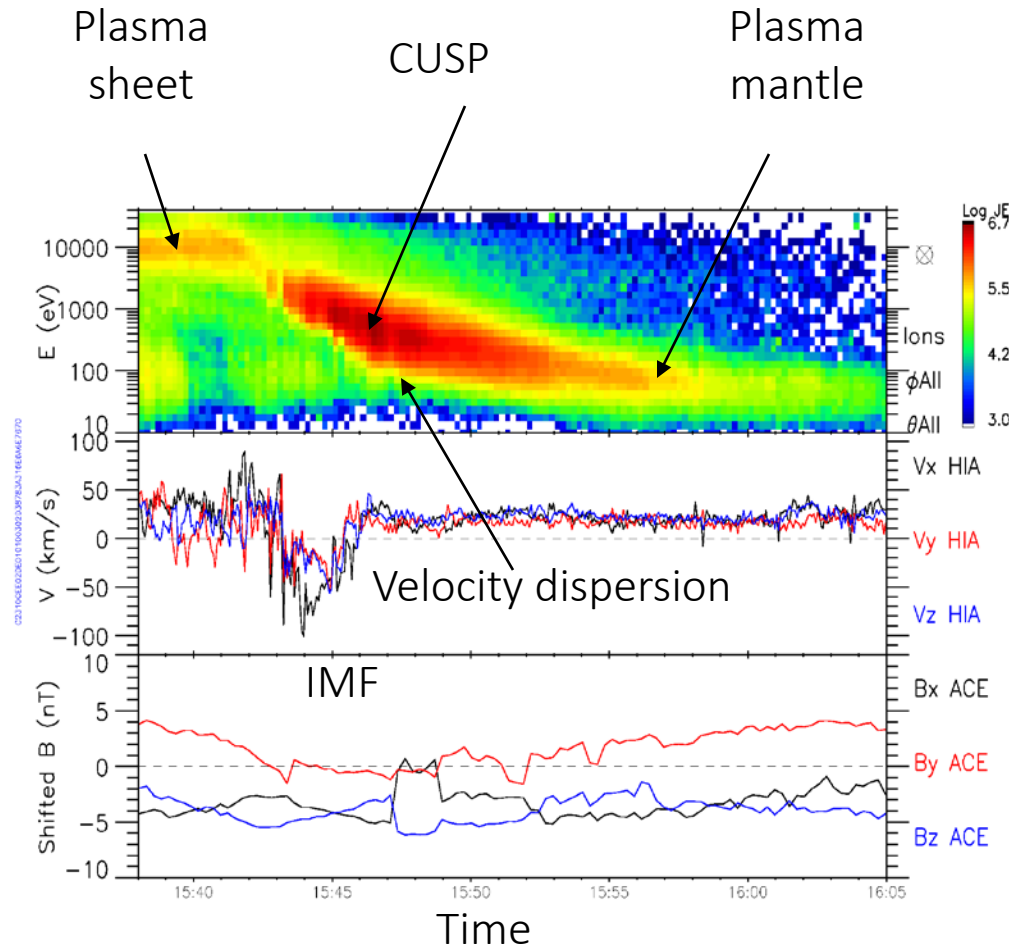
For Northward IMF:

- Reconnection may occur at high-latitude
- Cusp and polar cap convection is sunward
- The outer cusp boundary is open: a rotational discontinuity (RD)
- Absence of a plasma mantle at high latitude

The polar cusps at mid-to-low altitude: Reconnection and convection

- Plasma precipitation:
 - southward IMF
 - northward IMF

The polar cusps at mid-altitude for Southward IMF

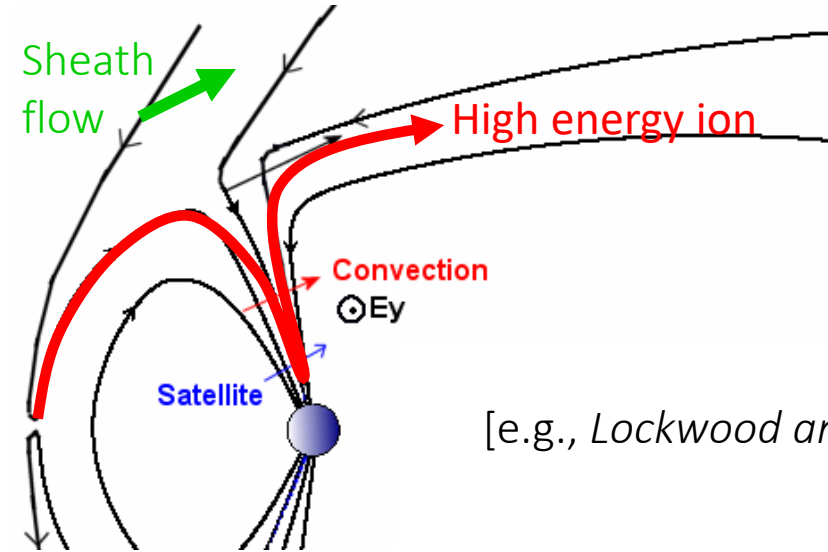
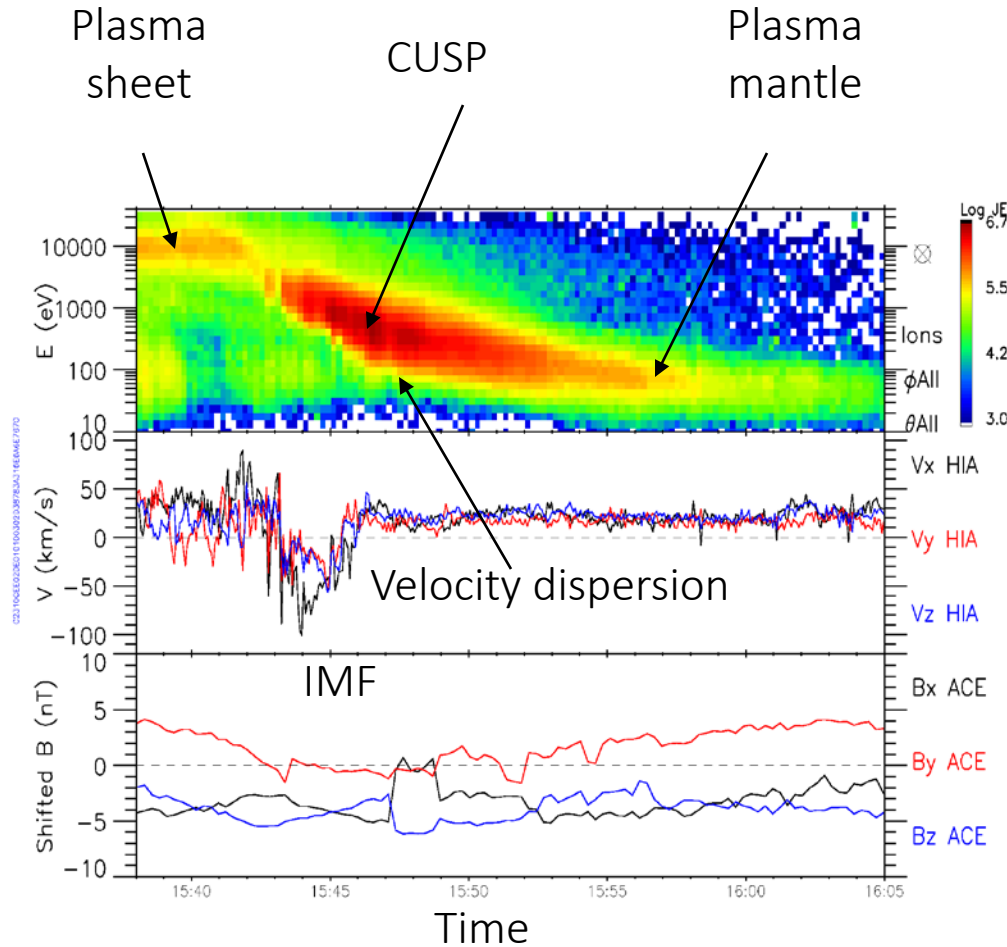


[e.g., Lockwood and Smith, 1993]

Cusp properties for S. IMF:

- Precipitation at low latitude
- Tailward convection/dispersion

The polar cusps at mid-altitude for Southward IMF



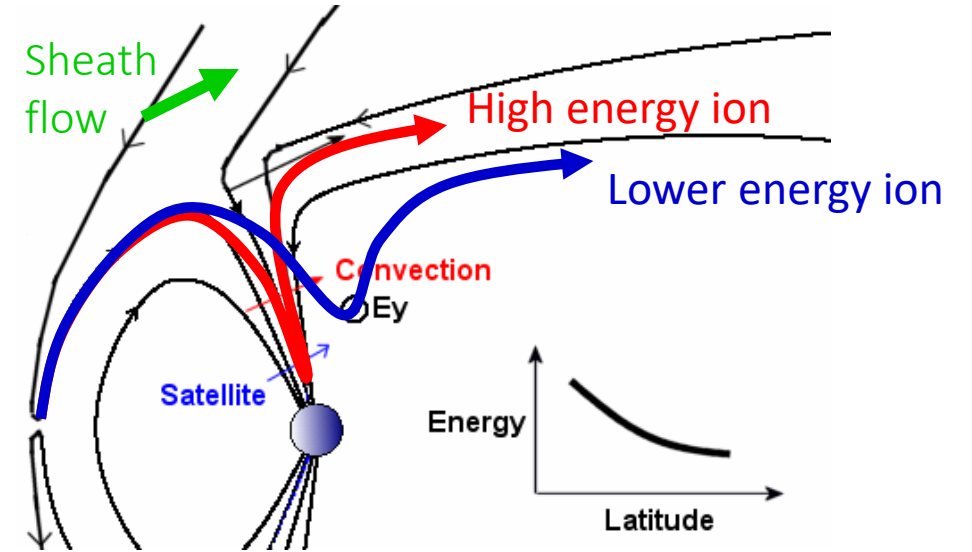
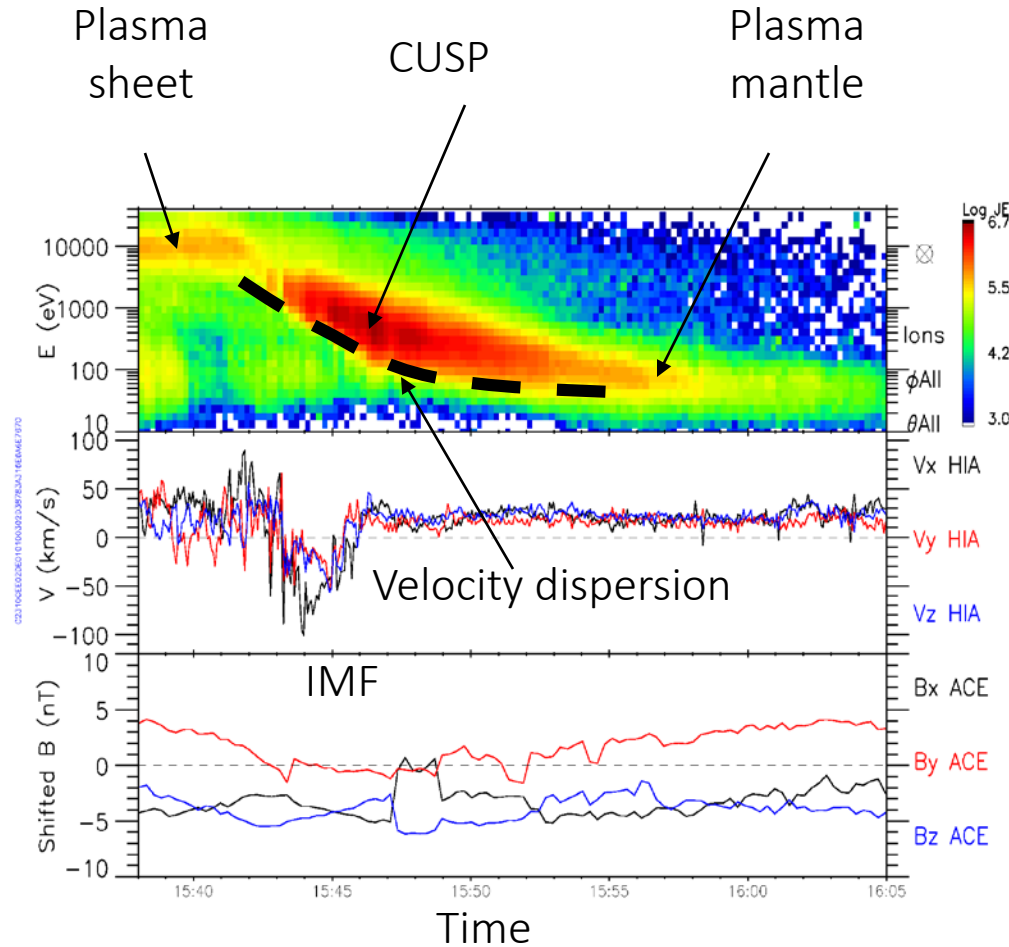
[e.g., Lockwood and Smith, 1993]

Cusp properties for S. IMF:

- Precipitation at low latitude
- Tailward convection/dispersion

→ Solar wind plasma penetrates deep inside the magnetosphere

The polar cusps at mid-altitude for Southward IMF

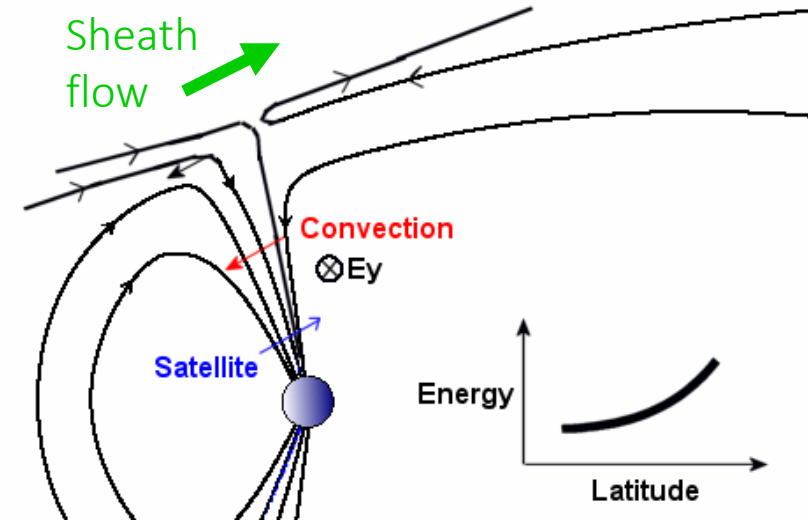
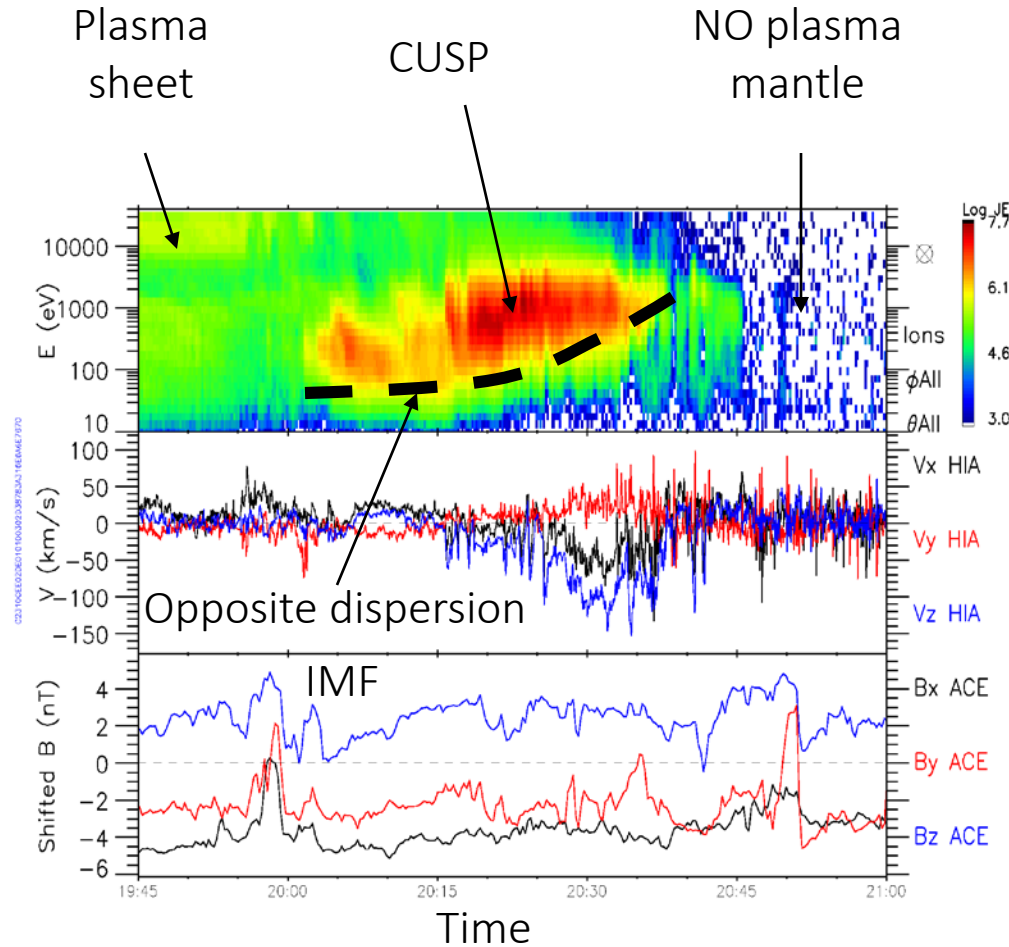


Cusp properties for S. IMF:

- Precipitation at low latitude
- Tailward convection/dispersion

→ Solar wind plasma penetrates deep inside the magnetosphere

The polar cusps at mid-altitude for Northward IMF



Cusp properties for N. IMF:

- Precipitation at high latitude
- Sunward convection/dispersion

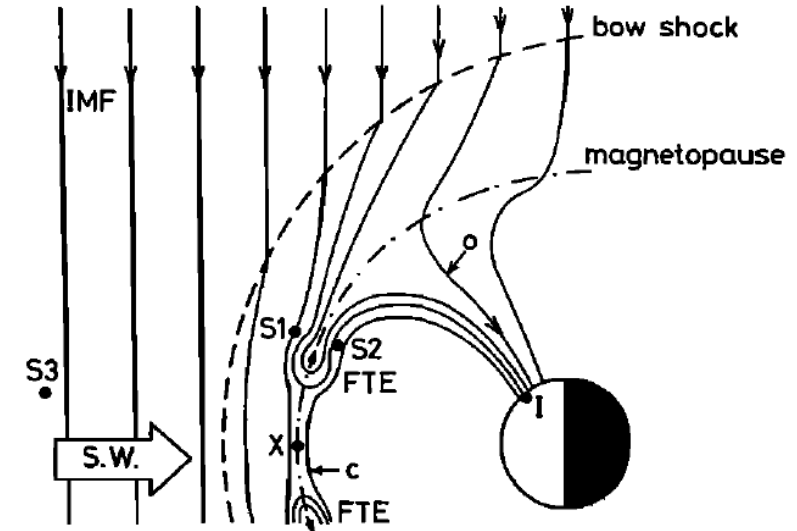
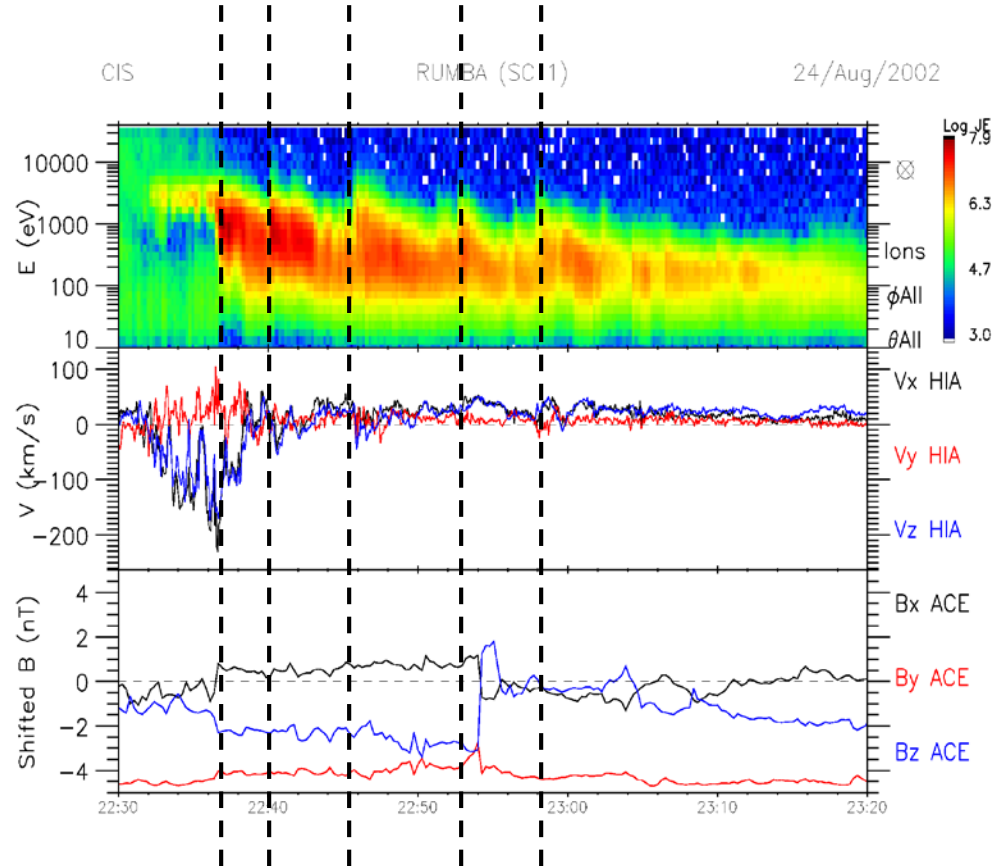
→ Solar wind plasma also penetrates deep, but precipitation and convection differ

The polar cusps at mid-to-low altitude: Spatial vs. temporal features

- Plasma structuring:
 - Patchy/intermittent reconnection
 - Convection patterns

Variability of the polar cusps at mid-altitude

Recurrent discontinuities



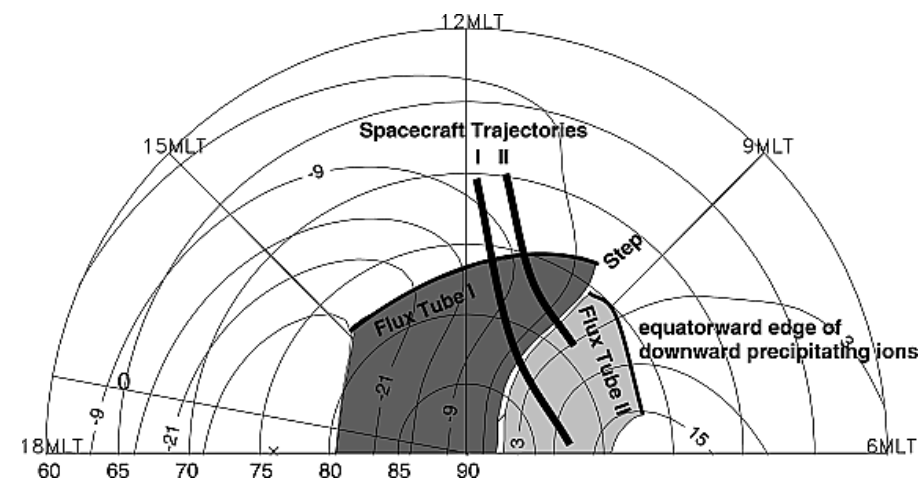
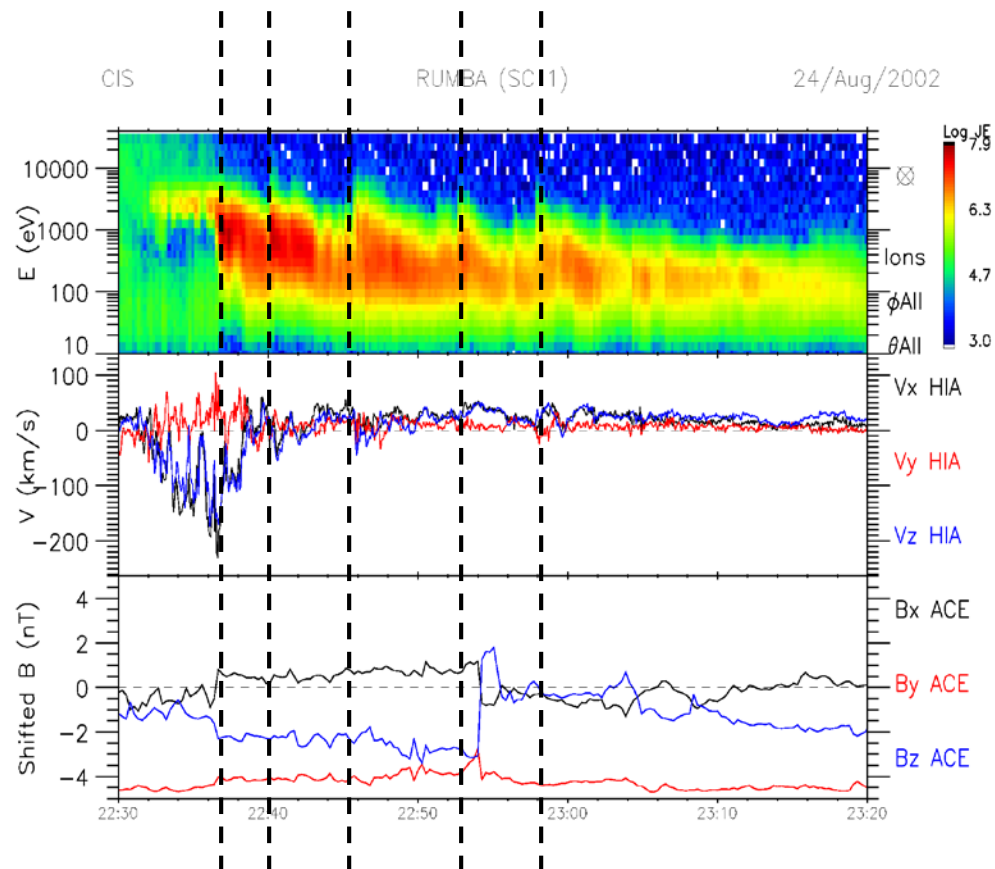
[Lockwood and Wild, 1993]

Explanation 1: Patchy -
intermittent reconnection
[Lockwood and Smith, 1992;
Escoubet et al., 1992]

→ The variability of the cusp pattern may stem from
the **intermittence of the reconnection** process itself

Variability of the polar cusps at mid-altitude

Recurrent discontinuities

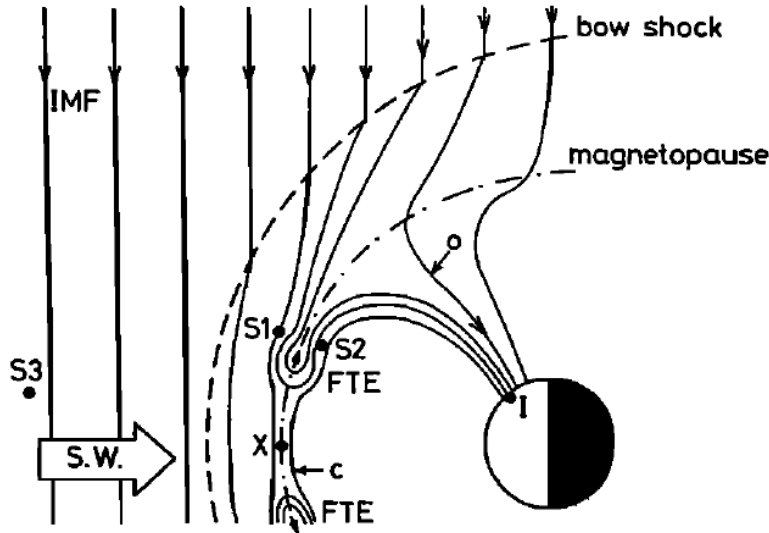


[Trattner et al., 2002]

Explanation 2: Structured reconnection X-line and convection patterns
[e.g., Trattner et al., 2008; 2012]

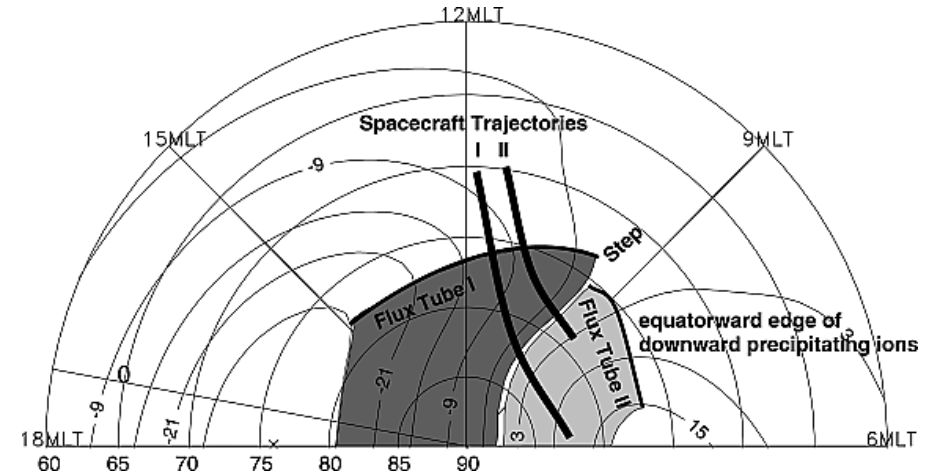
→ The variability of the cusp pattern may stem from
a structured convection pattern / several X lines

Variability of the polar cusps at mid-altitude



[Lockwood and Wild, 1993]

[cf. also Connor et al., 2015]



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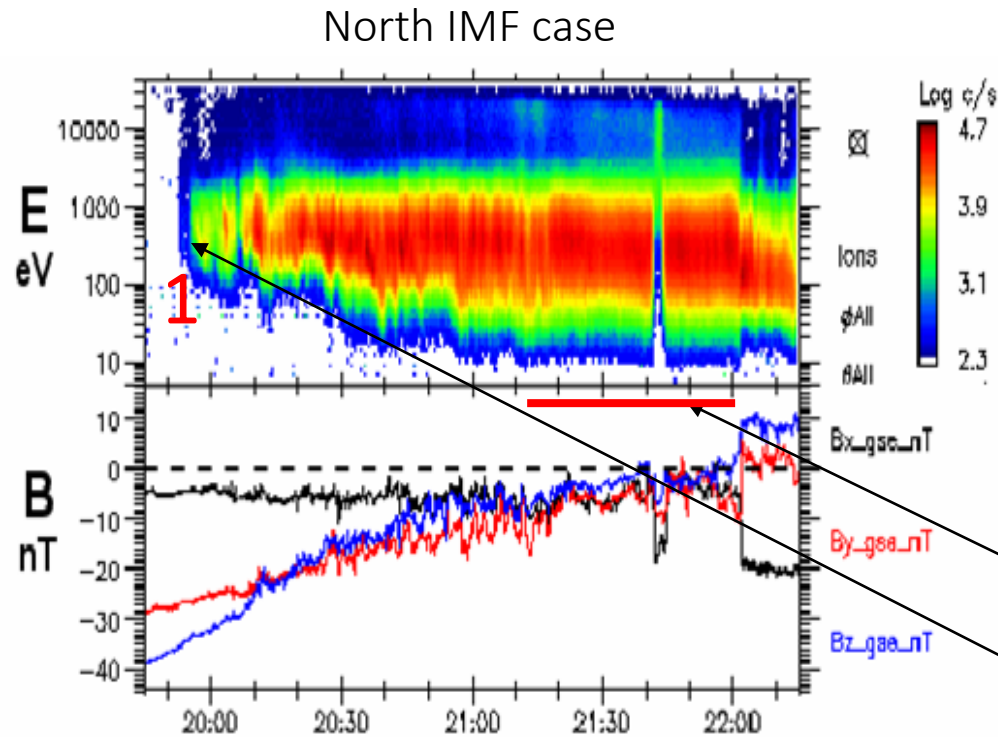
➔ See future NASA TRACERS and ESA/CNSA SMILE missions

The polar cusps at high altitude:

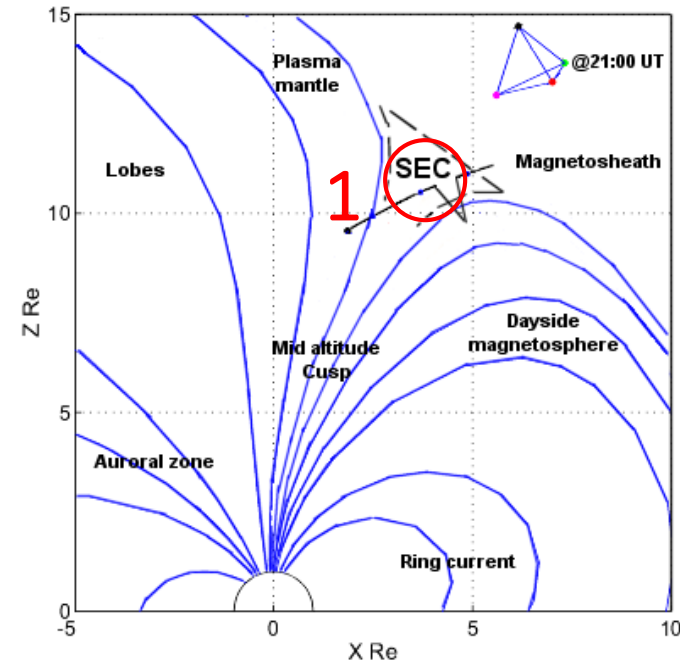
Small-scale view

- Plasma boundaries:
 - location
 - nature
 - plasma entry

The high-altitude cusp and surrounding boundaries

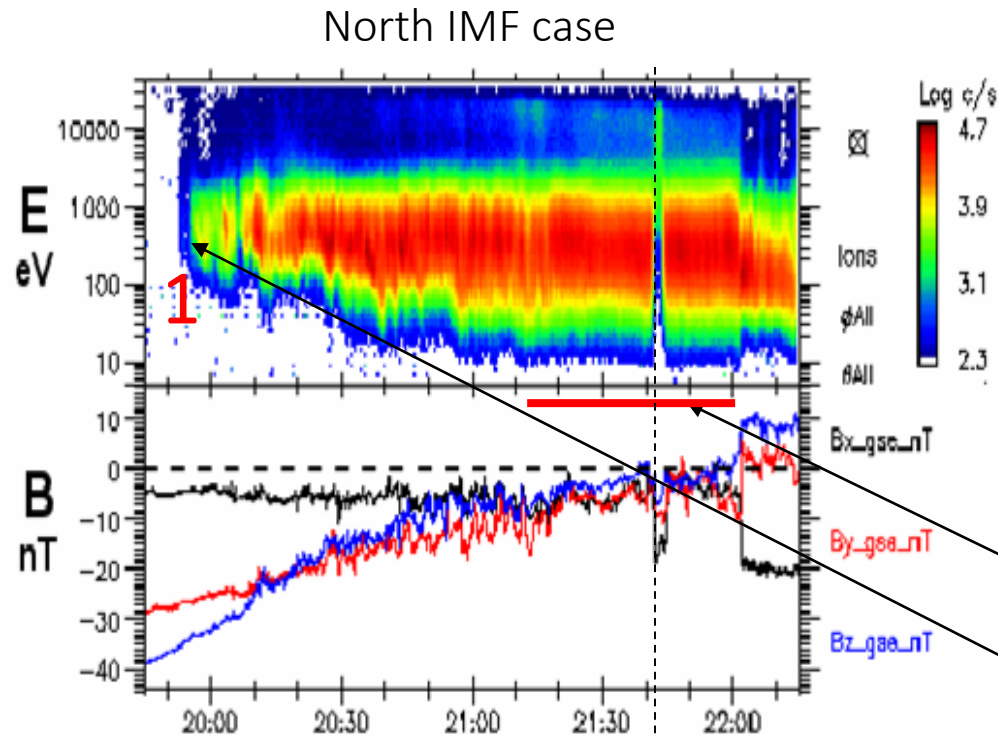


[Lavraud et al., 2002]

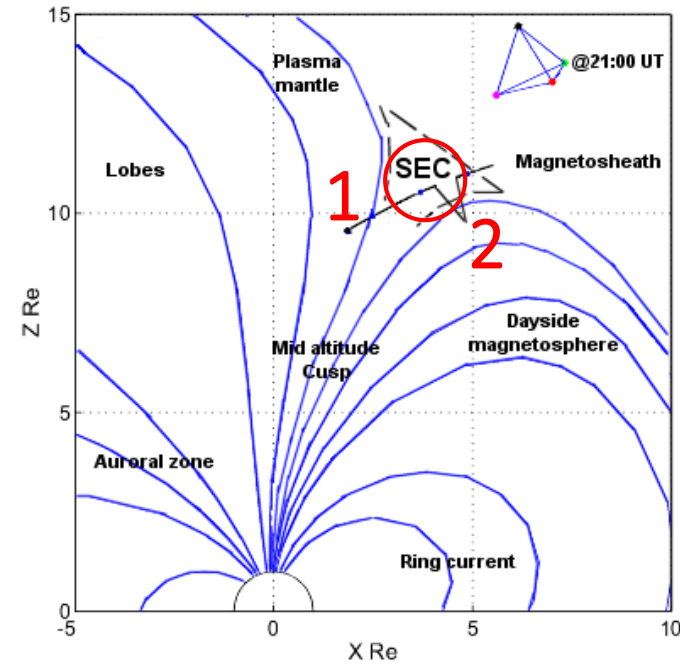


- The **high-altitude cusp** shows a low magnetic field
- It is surrounded by **three distinct boundaries** with:
→ 1: lobes

The high-altitude cusp and surrounding boundaries

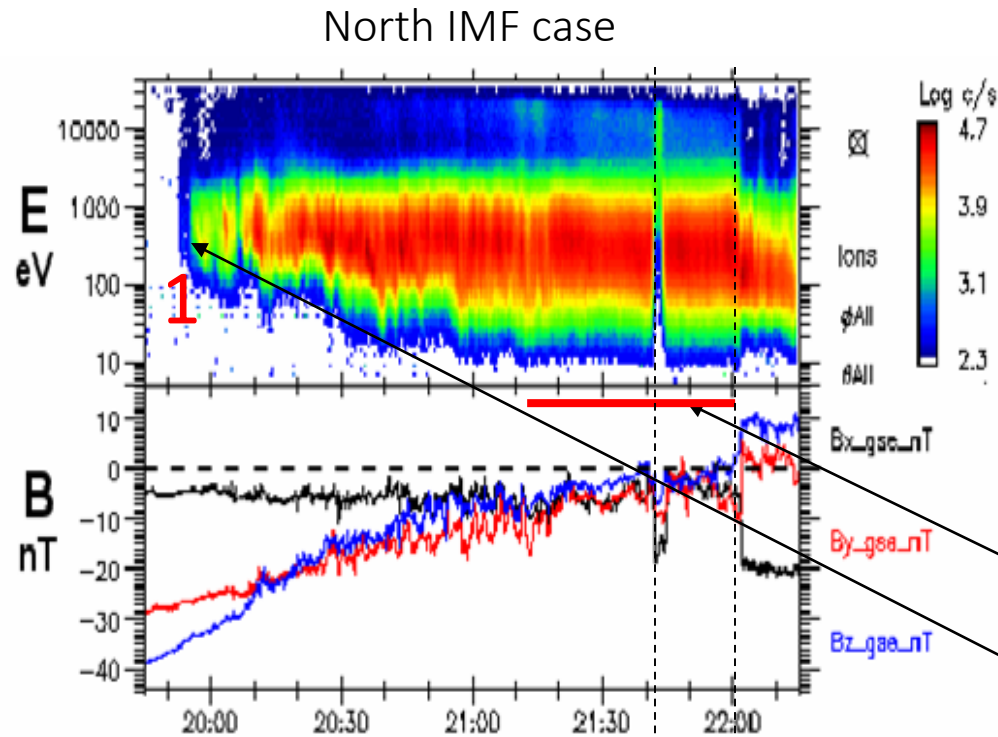


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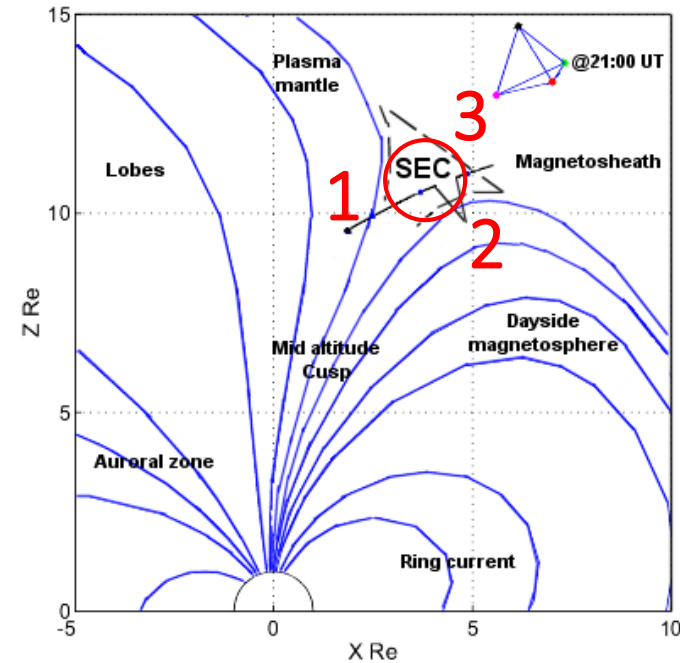
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 - 2: dayside plasma sheet

The high-altitude cusp and surrounding boundaries



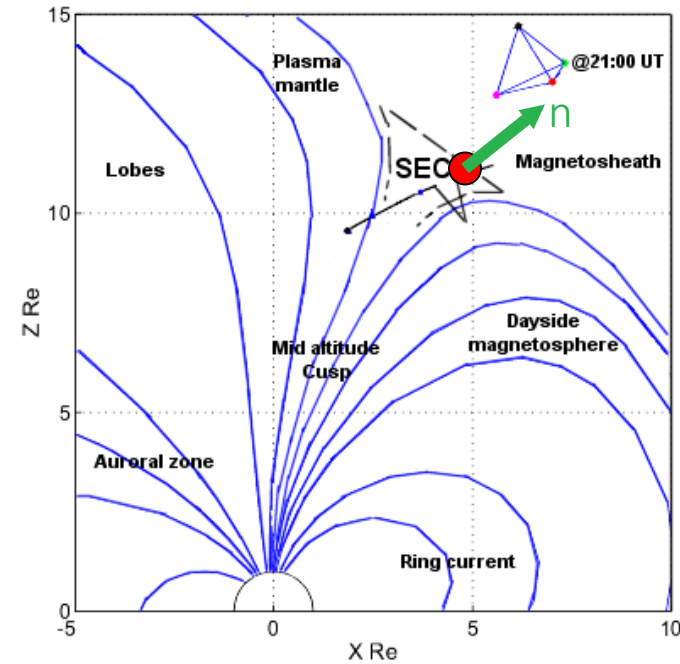
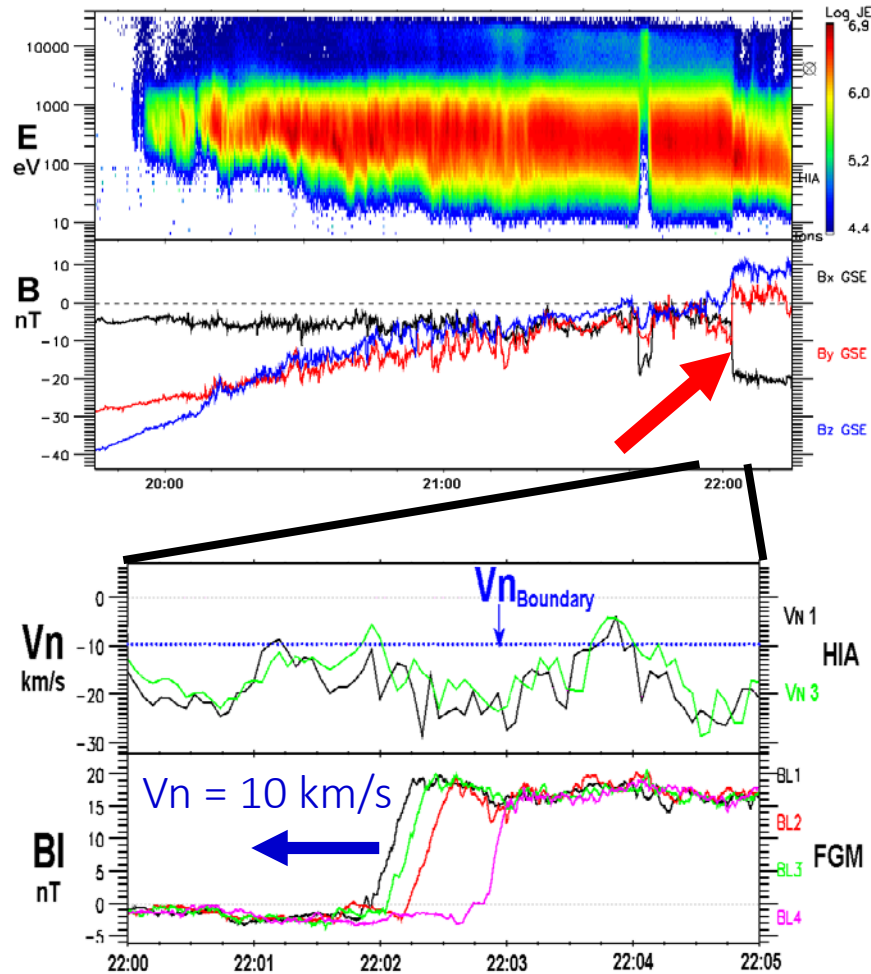
[Lavraud et al., 2002]

The magnetopause



- The **high-altitude cusp** shows a low magnetic field
- It is surrounded by **three distinct boundaries** with:
 - 1: lobes
 - 2: dayside plasma sheet
 - 3: magnetosheath

Multi-spacecraft boundary analysis



- Multi-spacecraft determination of normal plasma flow
→ Plasma penetration
- Boundary nature still unclear

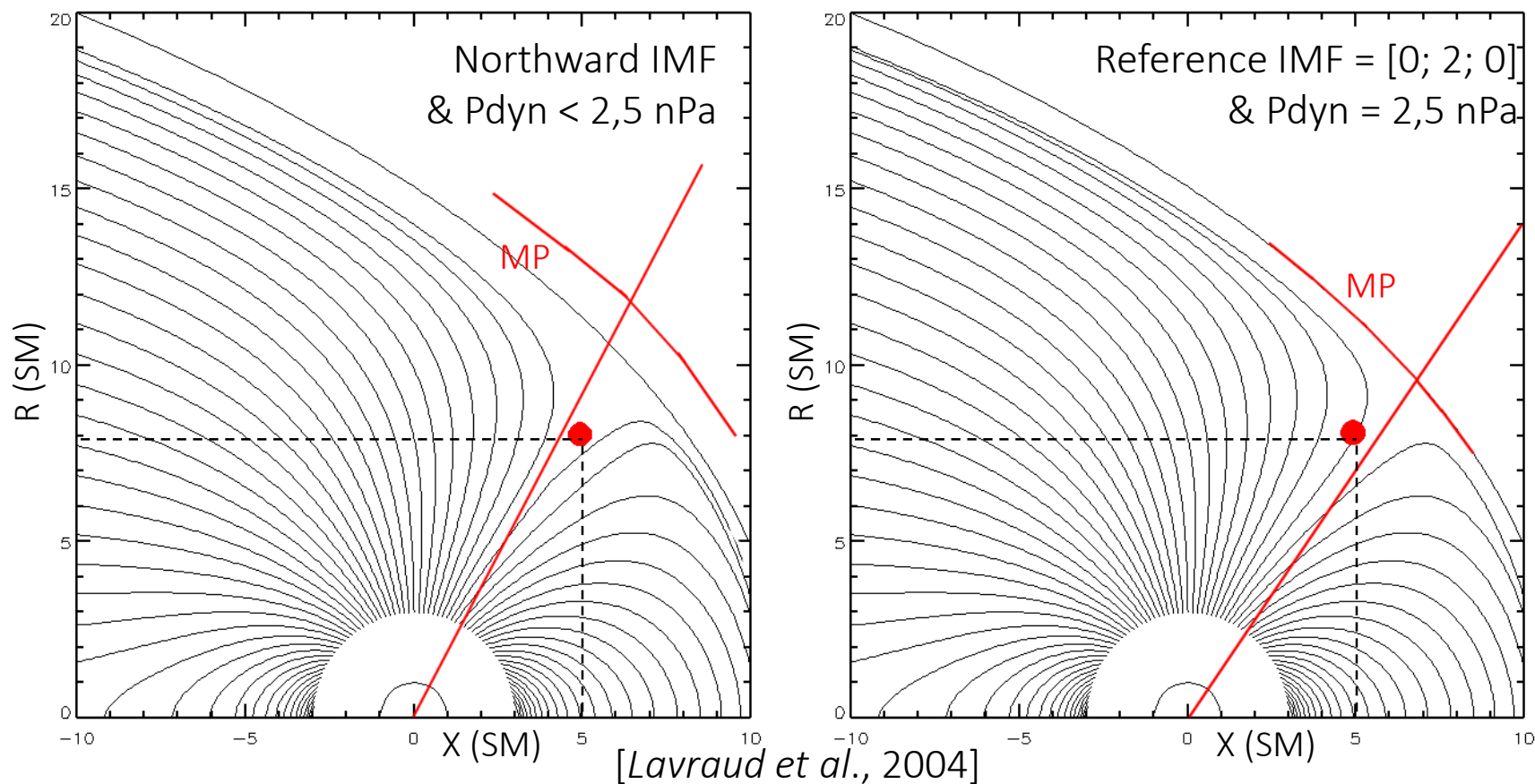
→ Magnetopause allows permanent plasma entry: it is open!

The polar cusps at high altitude:

Large scale view

- Statistical picture:
 - method
 - global properties
 - flows/plasma entry

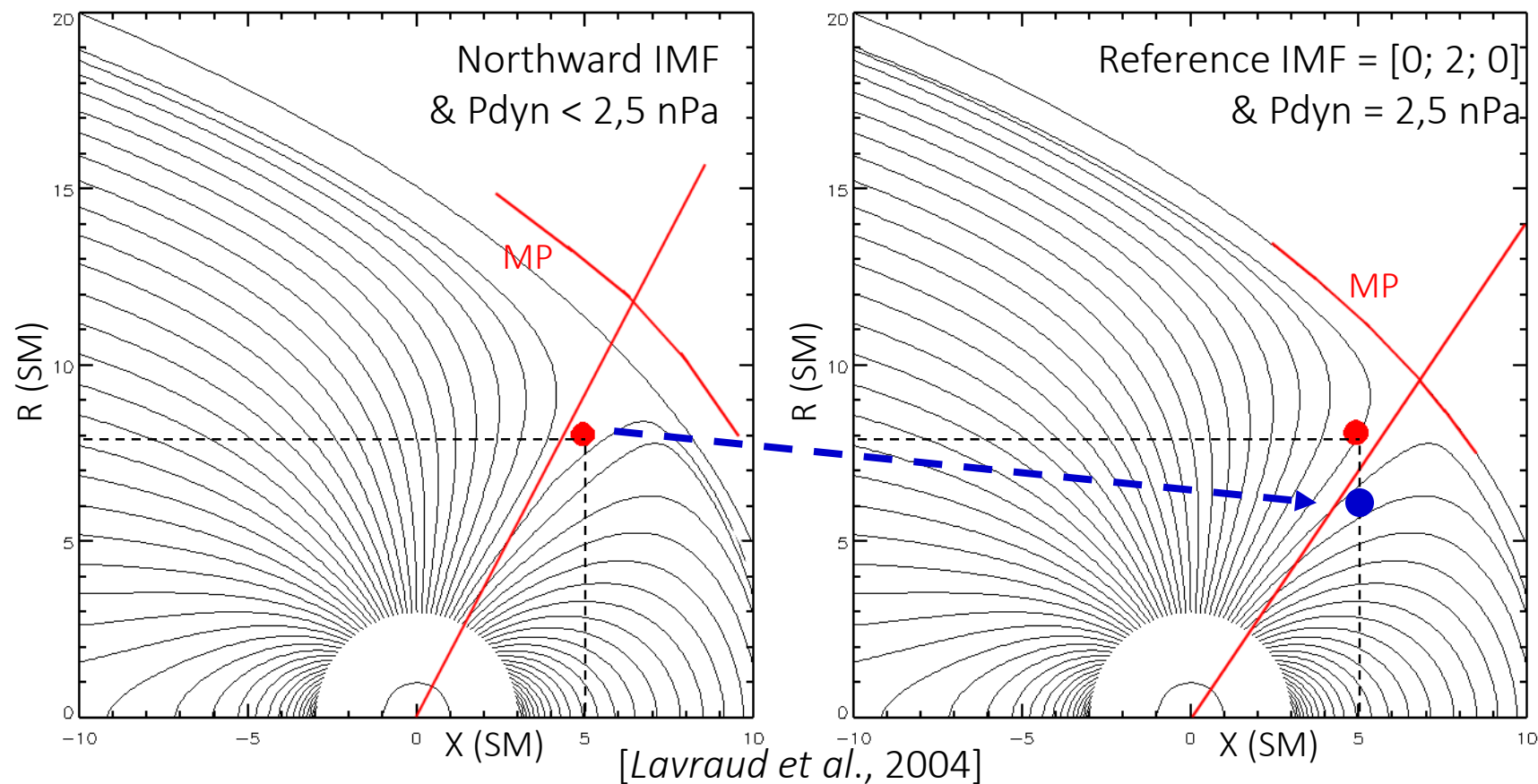
The high-altitude cusp: statistical method



- Data are **folded into a plane**: Y-Z radius vs. X in SM coordinates
- **Cusp latitude** modeled with T96, **MP position** with Shue97

→ Data can be ordered with respect to, e.g., solar wind

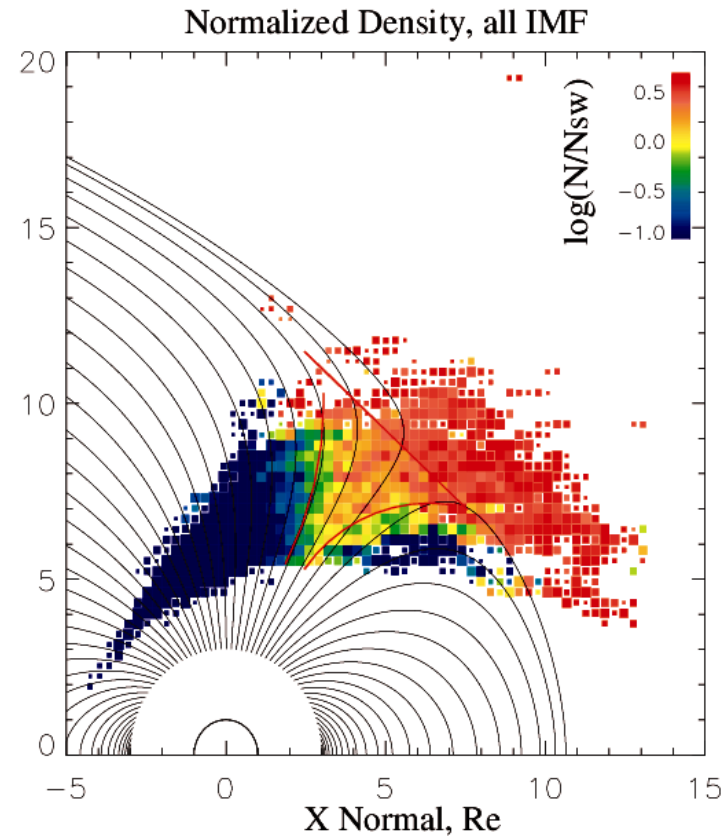
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The high-altitude cusp for all IMF conditions

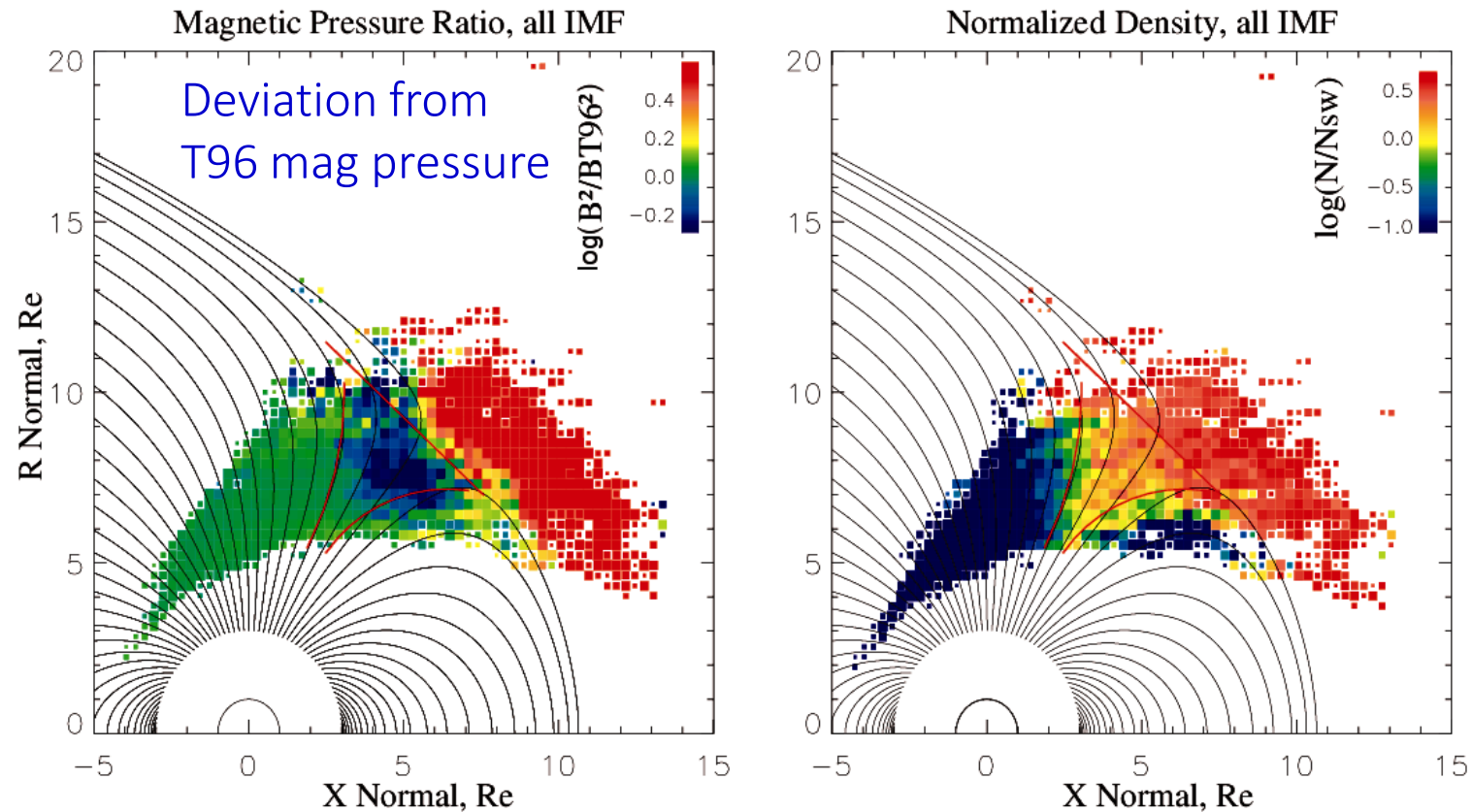


[Lavraud et al., 2004; Tsyganenko and Andreeva, 2018]

- Depressed magnetic field but enhanced densities compared to magnetosphere
- Distinct boundaries with the lobes, dayside plasma sheet and sheath

→ The high-altitude cusp is a diamagnetic cavity

The high-altitude cusp for all IMF conditions

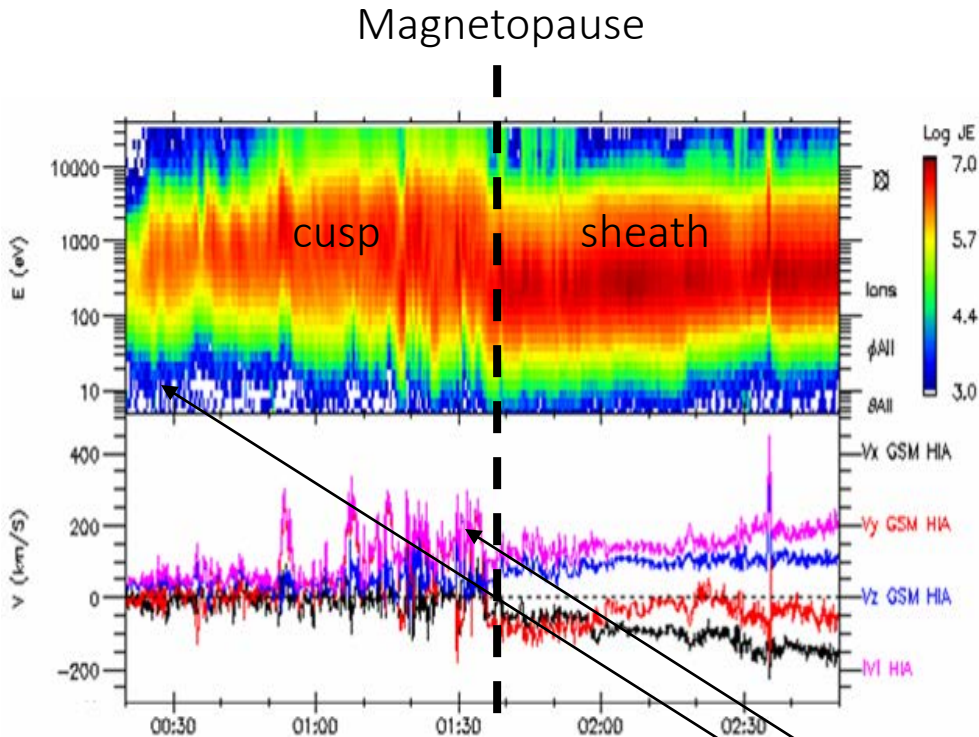


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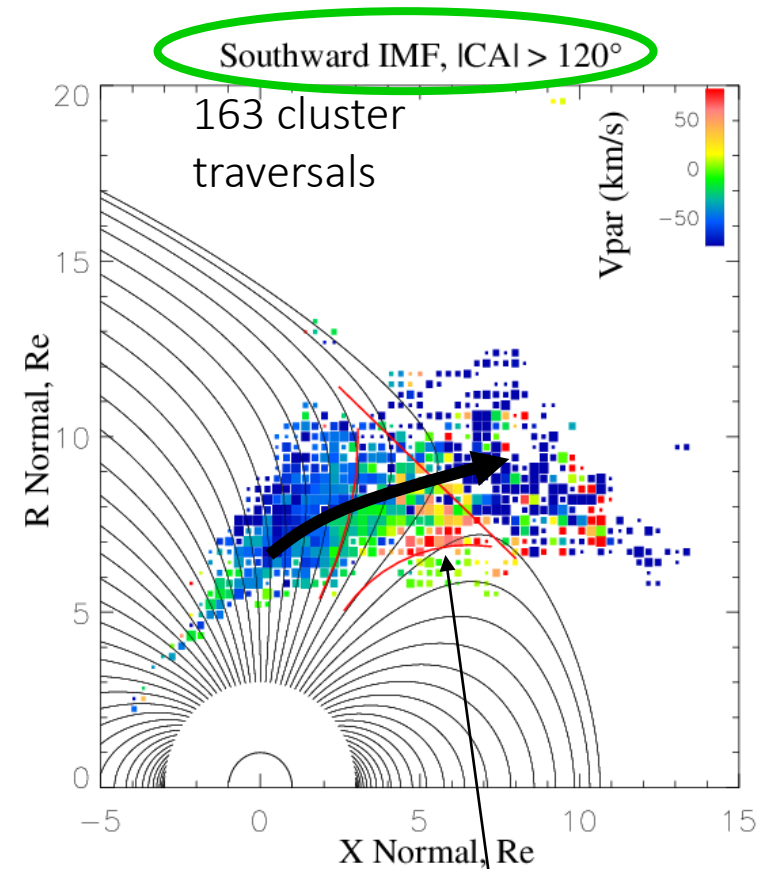
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The high-altitude cusp under Southward IMF



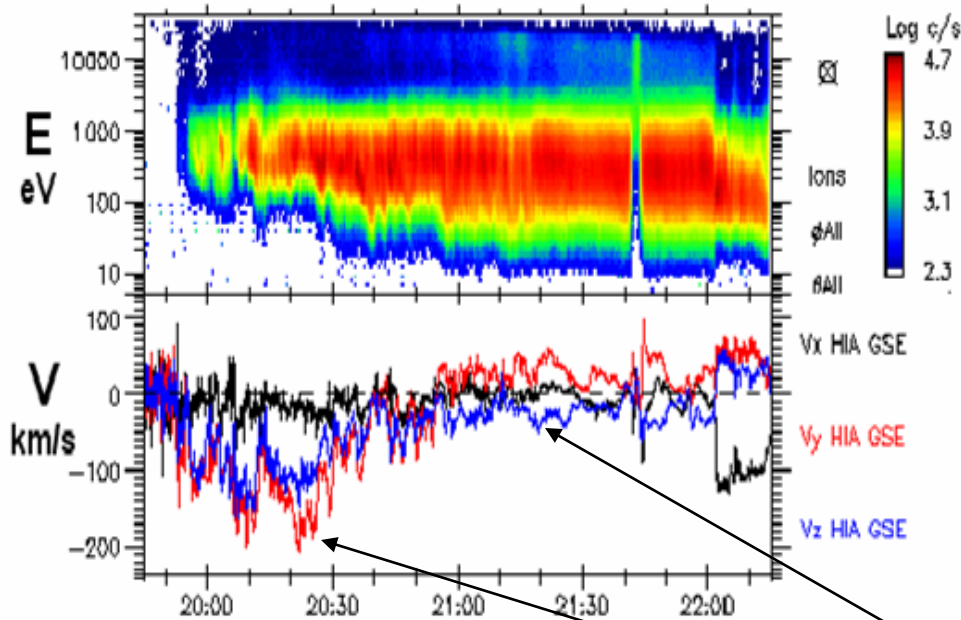
[Lavraud et al., 2005]



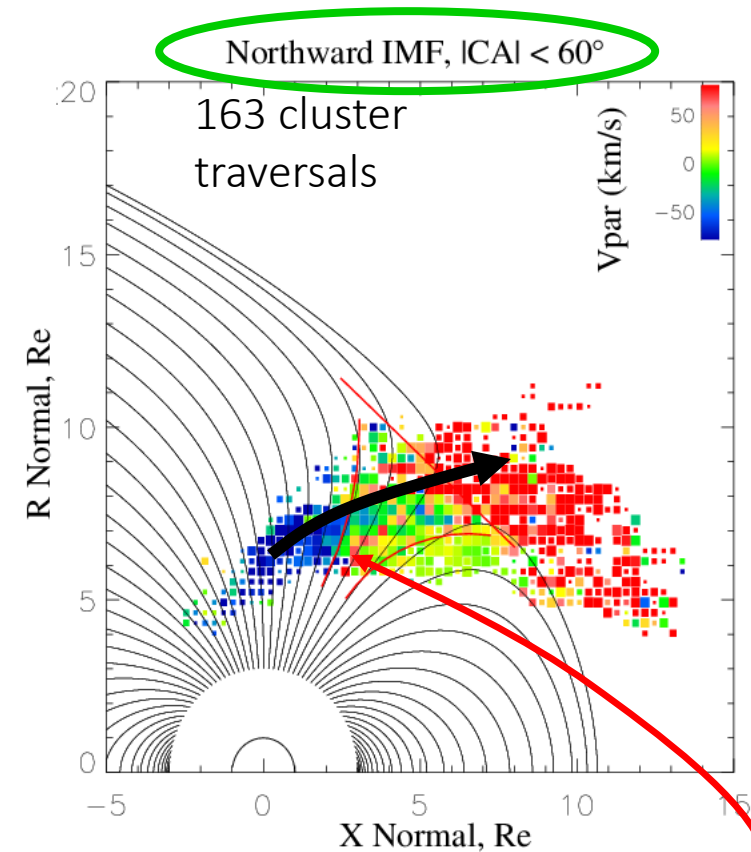
- Precipitation at low latitude
- Large flows in cusp
- Presence of a plasma mantle

→ Precipitation at low latitude and large tailward convection

The high-altitude cusp under Northward IMF



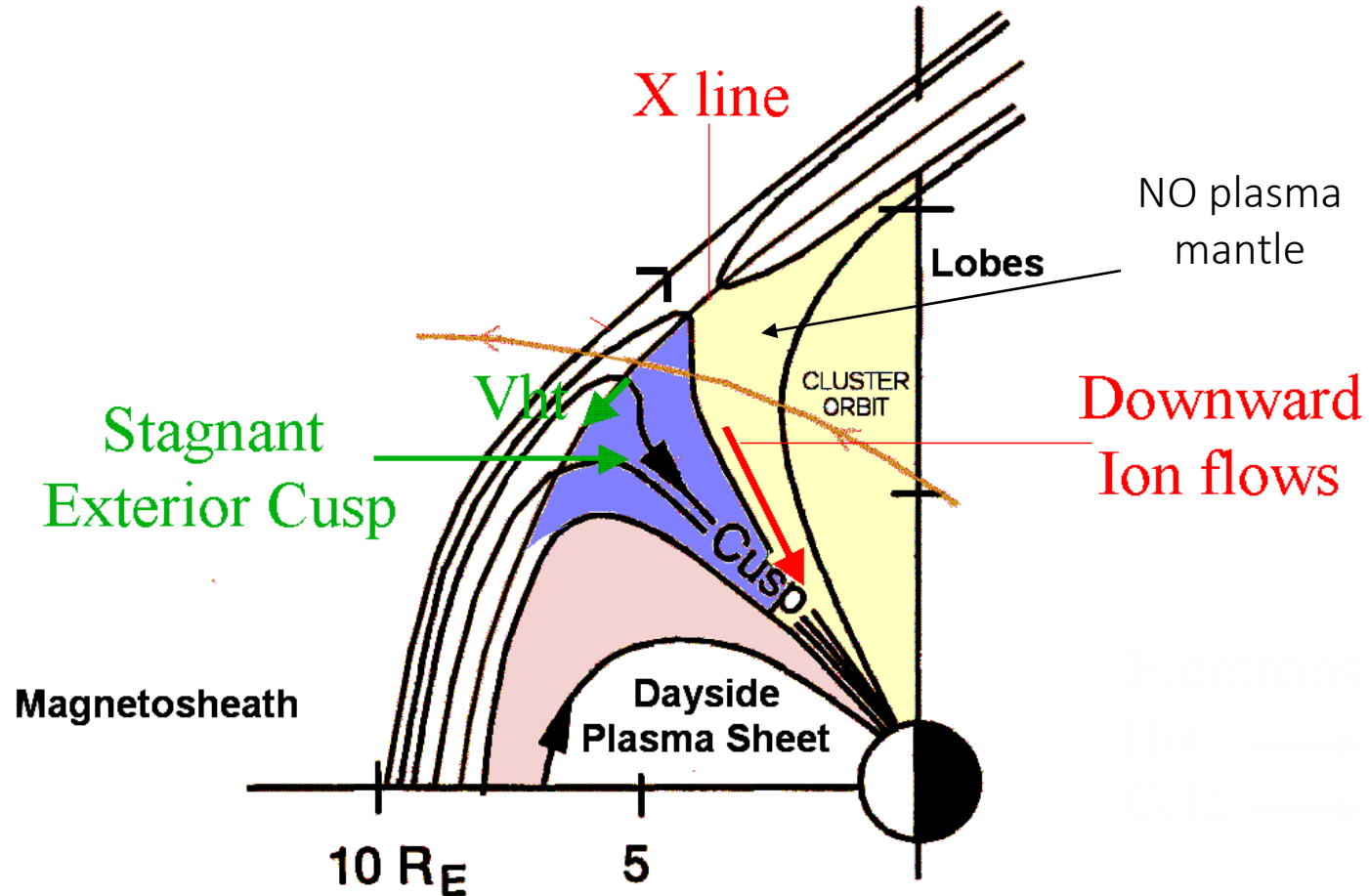
[Lavraud et al., 2005]



- Low sunward flows in cusp
- Precipitation at high latitudes
- Absence of a plasma mantle

→ Precipitation at high latitude and low sunward convection

The high-altitude cusp under Northward IMF



→ Structure consistent with high-latitude reconnection

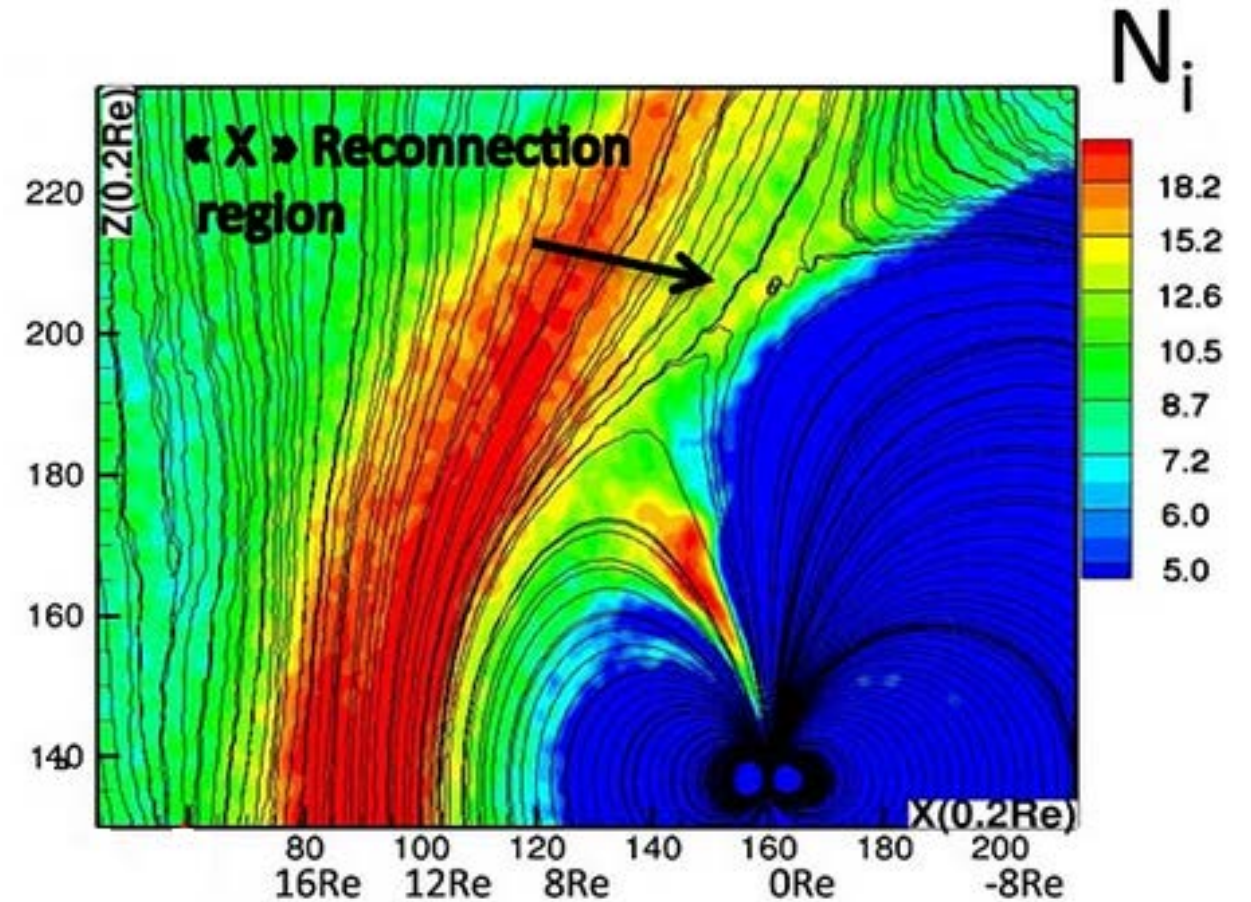
The polar cusps at high altitude:

Global modelling

- Modelling:
 - Numerical simulations
 - The famous indentation

Global simulations of the cusps

- Three main approaches to global numerical modeling:
 - Early global MHD modeling
[e.g., Raeder et al. 1995, Palmroth et al., 2001]
 - Global Hybrid simulations
[e.g., Omid et al., XXX]
 - Global full-kinetic simulations
[e.g., Cai et al., 2015; Esmaili and Kalaei, 2017]

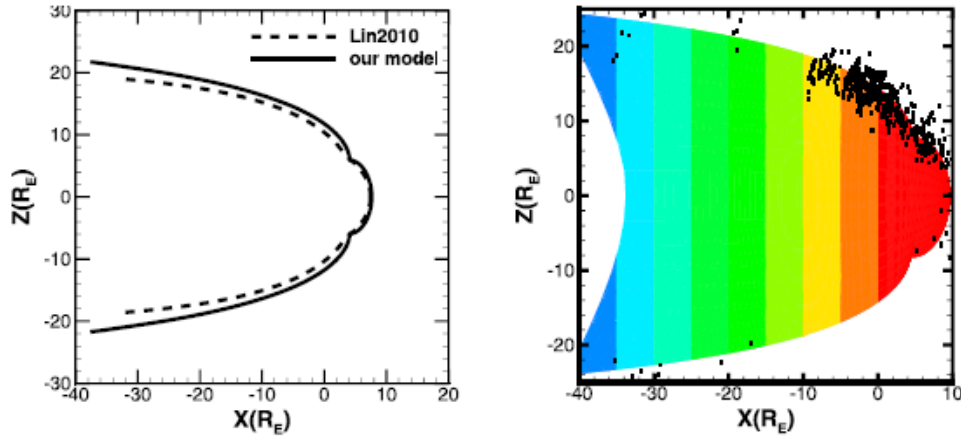


[Cai et al., 2015]

→ Global simulations confirm the pivotal role of the cusps in dynamics

Magnetopause modelling and the cusp indentation

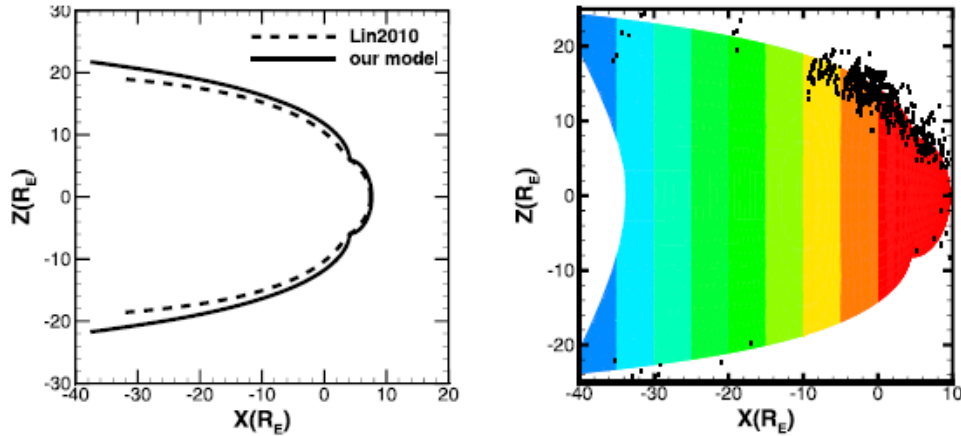
[Liu et al., 2014]



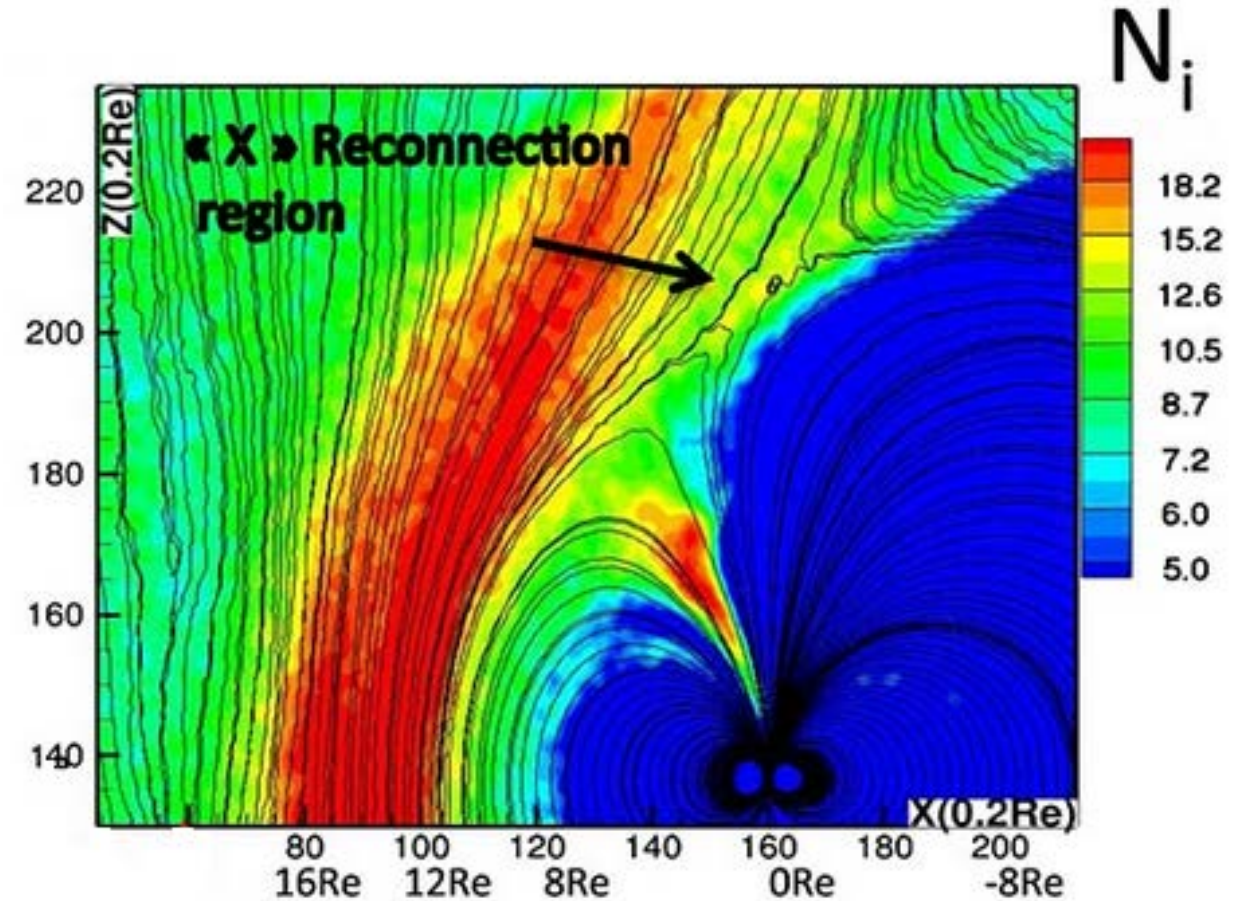
- Some statistical fitting models suggest **magnetopause indentation** at cusps:
[Lin et al., 2010; Wang et al., 2013; Liu et al., 2014]
- But possibly **wrong MP identification**
[Lavraud et al., 2002; 2005, etc.]

Magnetopause modelling and the cusp indentation

[Liu et al., 2014]



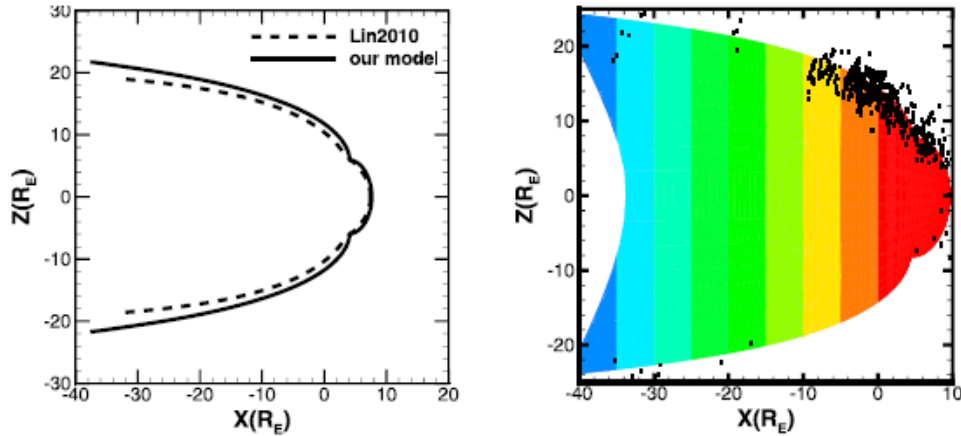
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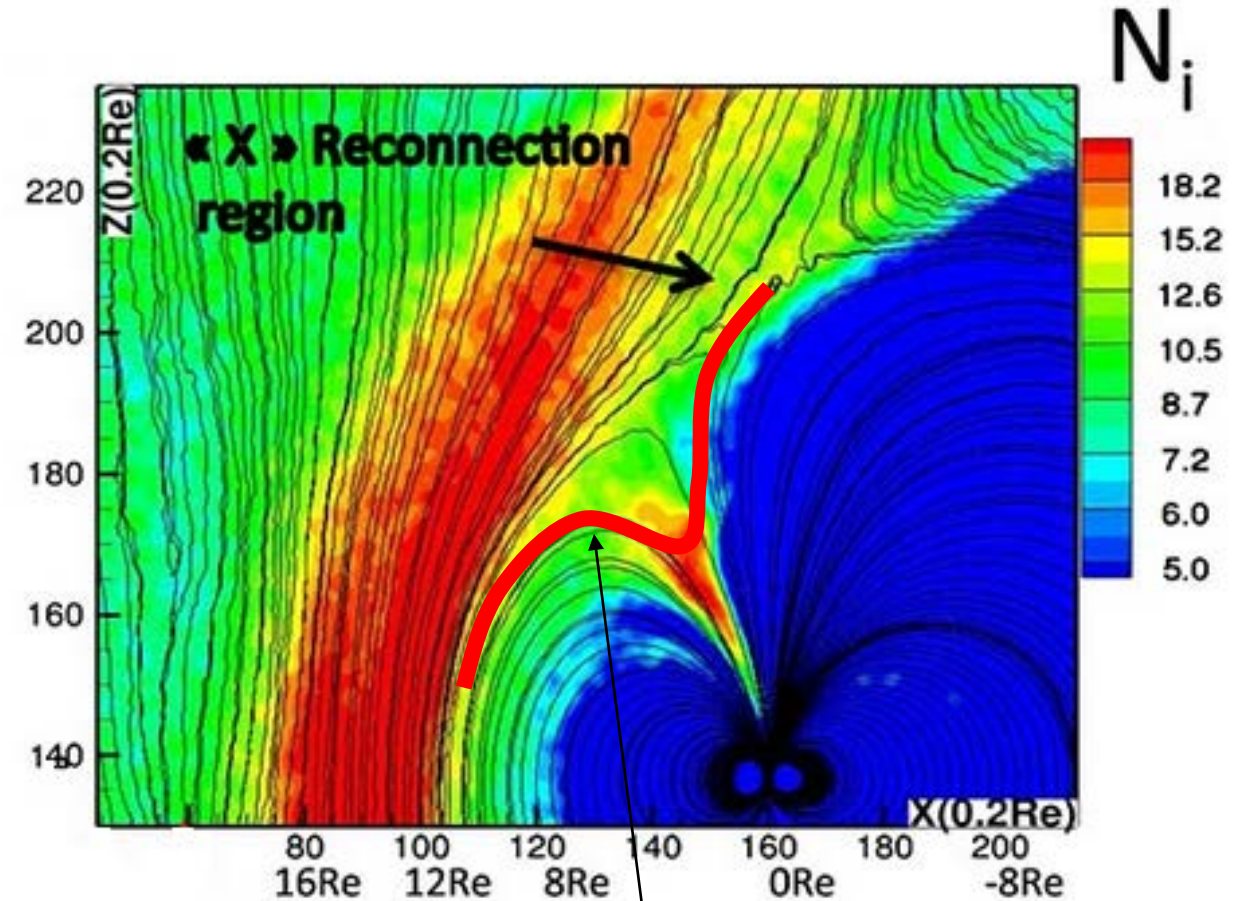
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Magnetopause modelling and the cusp indentation

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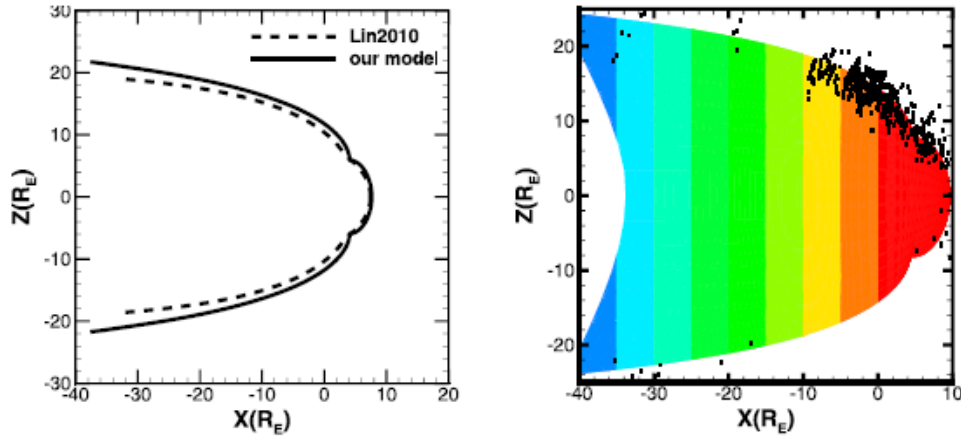


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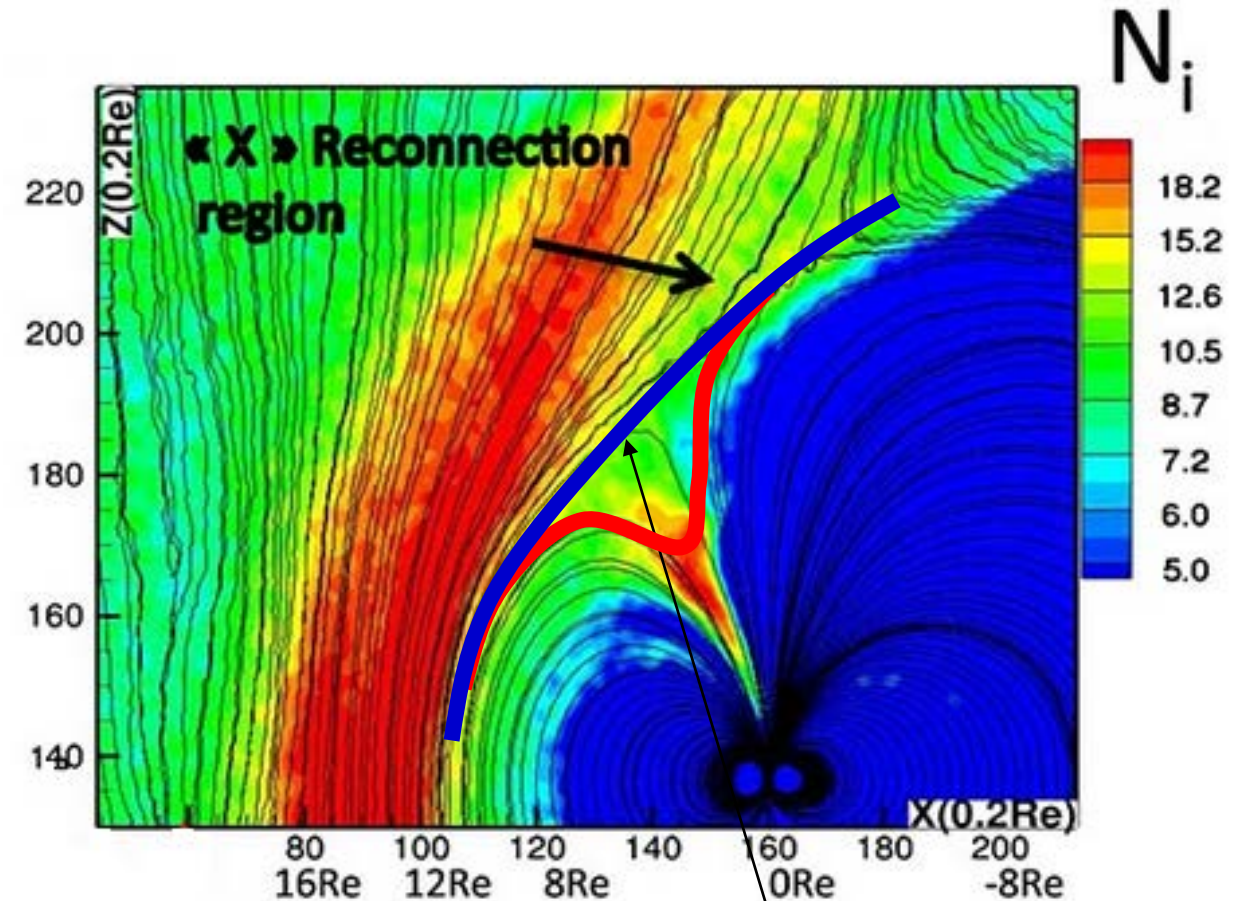
CUSP INDENTATION

Magnetopause modelling and the cusp indentation

[Liu et al., 2014]



- Some statistical fitting models suggest **magnetopause indentation** at cusps: [Lin et al., 2010; Wang et al., 2013; Liu et al., 2014]
- But possibly **wrong MP identification** [Lavraud et al., 2002; 2005, etc.]

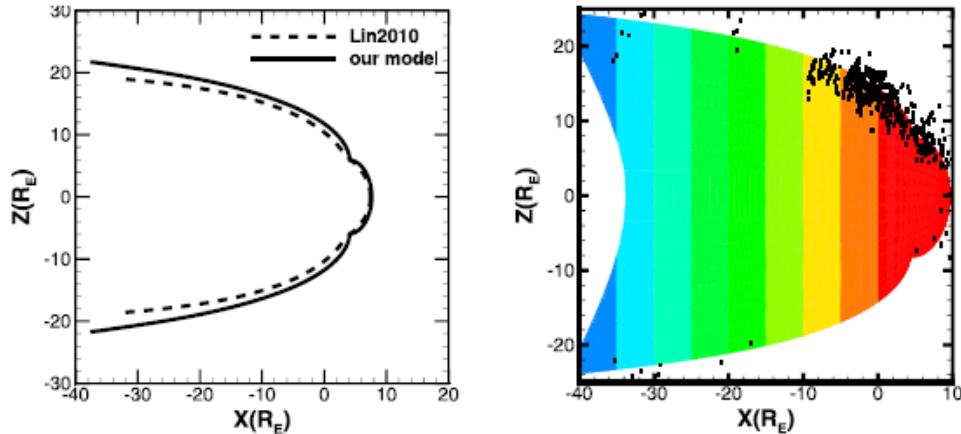


[Cai et al., 2015]

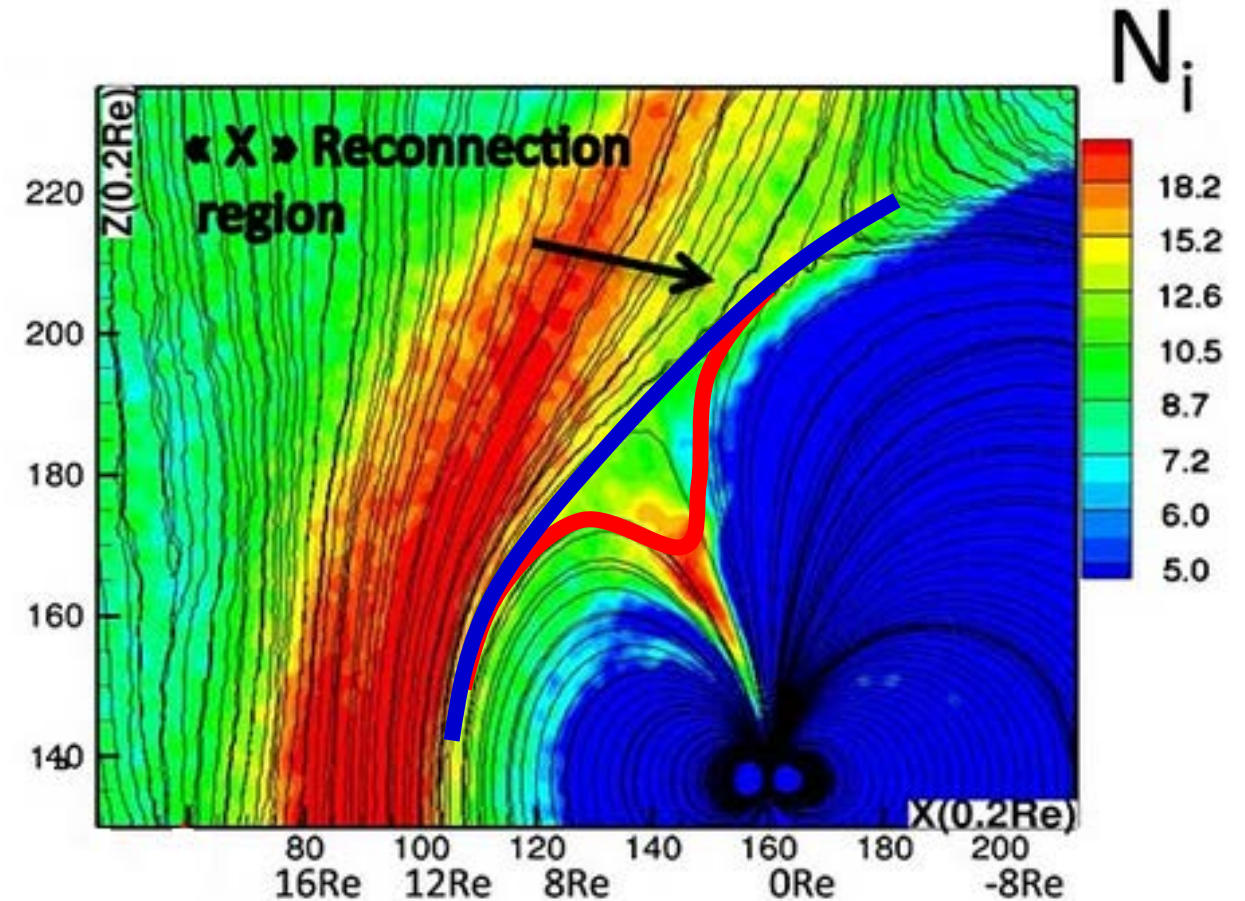
TRUE MAGNETOPAUSE

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[Cai et al., 2015]

Is there a cusp indentation? **Yes, the inner boundaries**

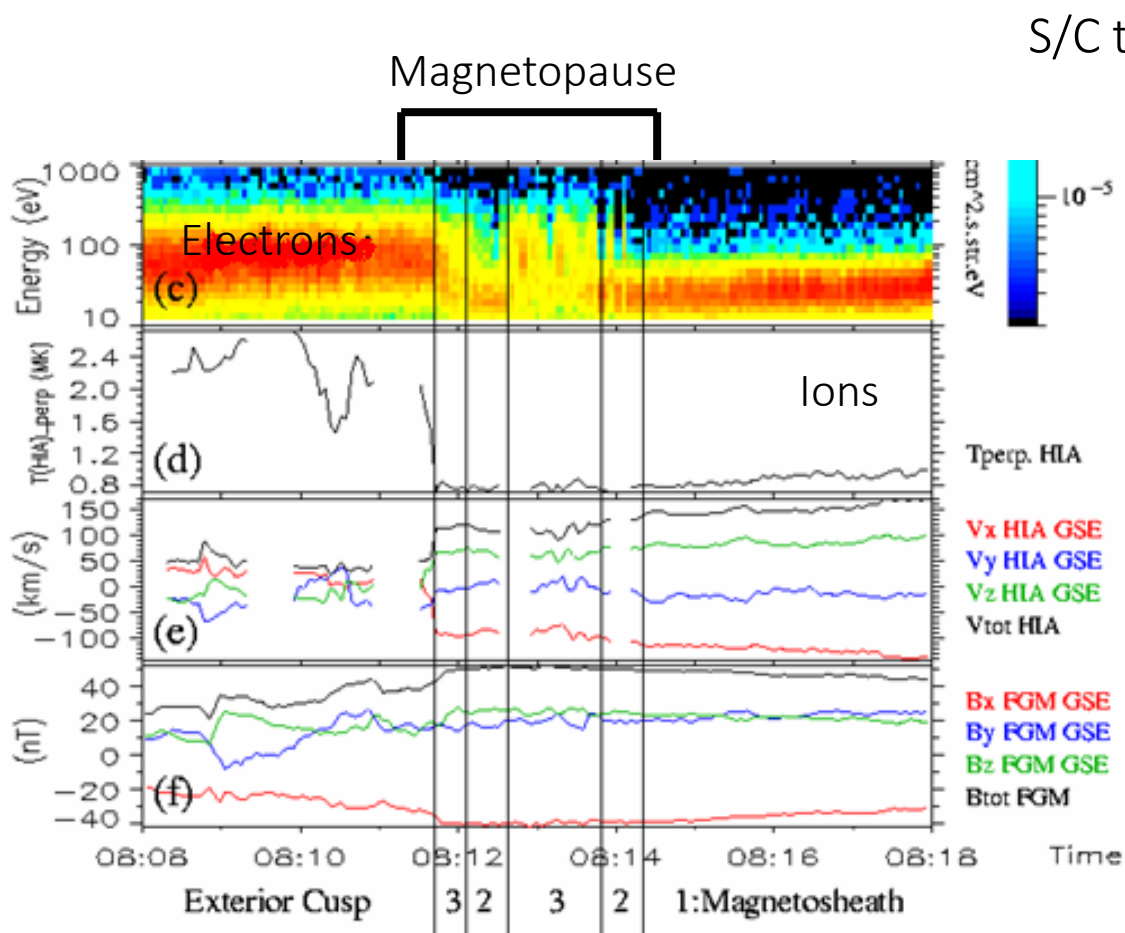
Is there a magnetopause indentation? **No evidence and no obvious reason**

The polar cusps at high altitude:

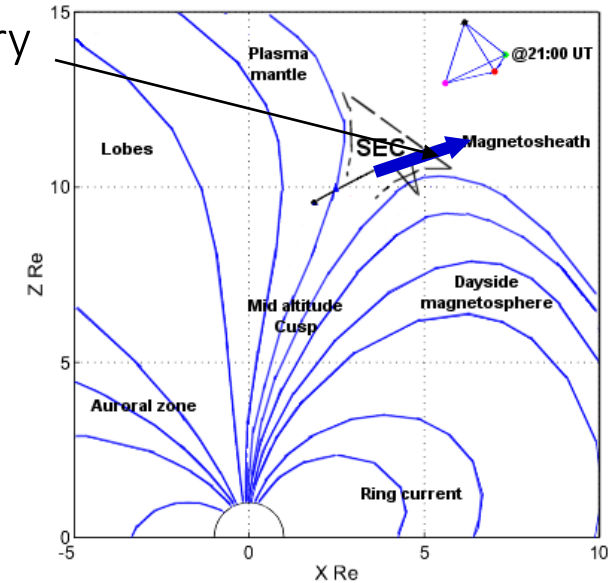
Waves and heating

- Role of waves:
 - heating
 - waves
 - energetic particles

Heating at the magnetopause above the cusps



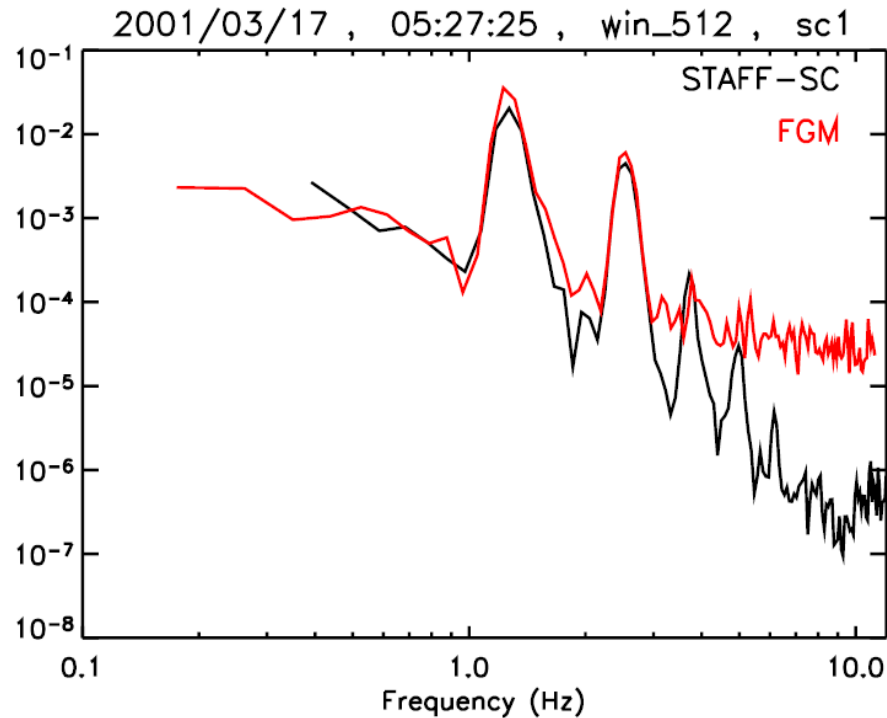
S/C trajectory



- Strong heating already occurs at the MP for:
 - both ions and electrons
 - all IMF orientations

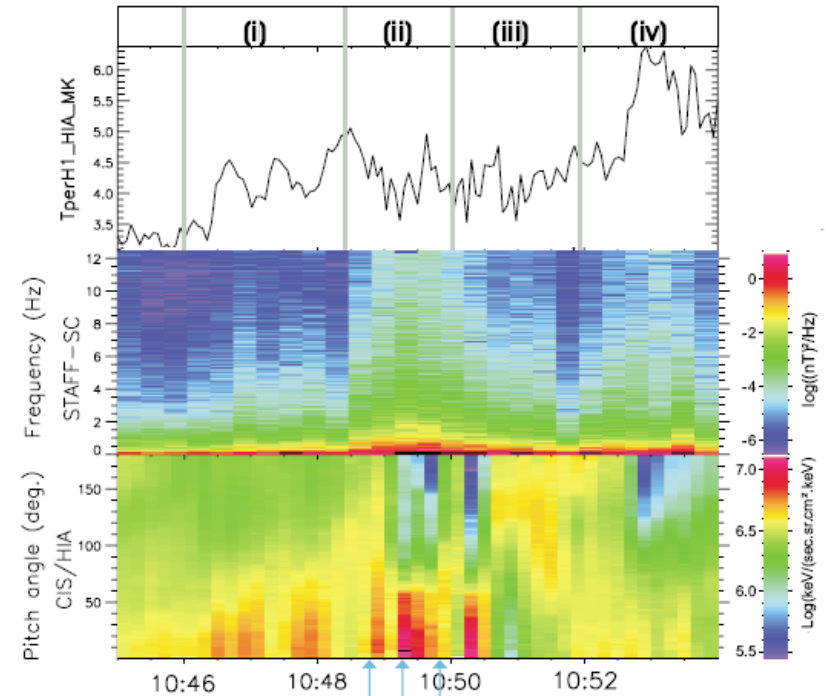
→ Is an additional, substantial heating occurring in the cusps?

Waves and heating in the polar cusps



[Nykyri et al., 2006]

[see also Slapak et al., 2017]



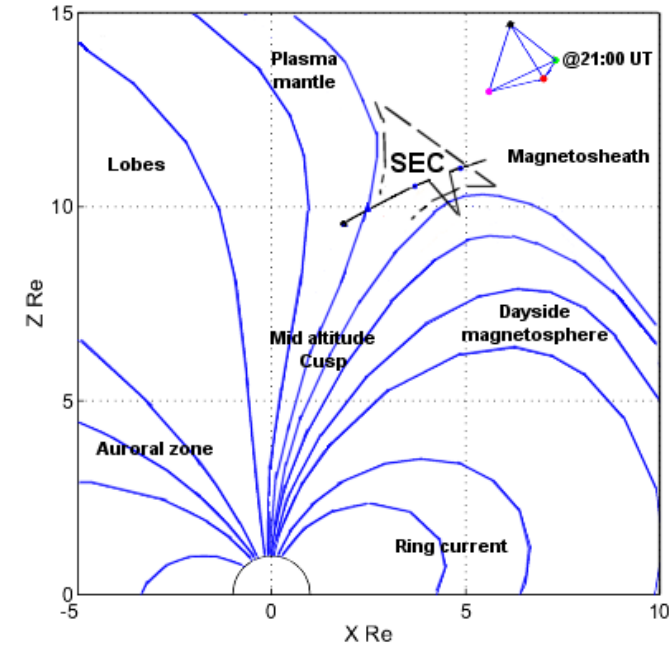
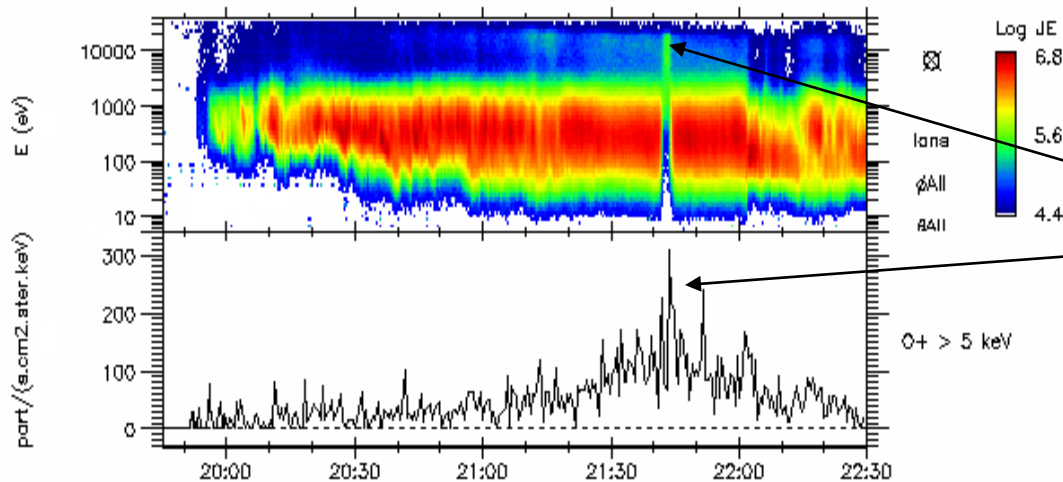
[Grison et al., 2005]

- Harmonics suggest **wave-particle interaction** processes
- But **correlations between waves and heating** is hard to establish

→ A whole zoo of waves is present in the cusps: heating?

Particle acceleration in the cusps

- 3 main explanations for observation of energetic ions (> 40 keV):
 - leakage from nearby plasma sheet
 - [Delcourt and Sauvaud, 1998; Duan et al., 2019]
 - production at bow shock
 - [Chang et al., 2000; Trattner et al., 2001]
 - local wave-particle interaction
 - [Chen and Fritz, 1998; Fritz et al., 2003]



- Few notes:
 - O^+ not from solar wind
 - nearby plasma sheet always as higher fluxes
 - no clear theory for local acceleration

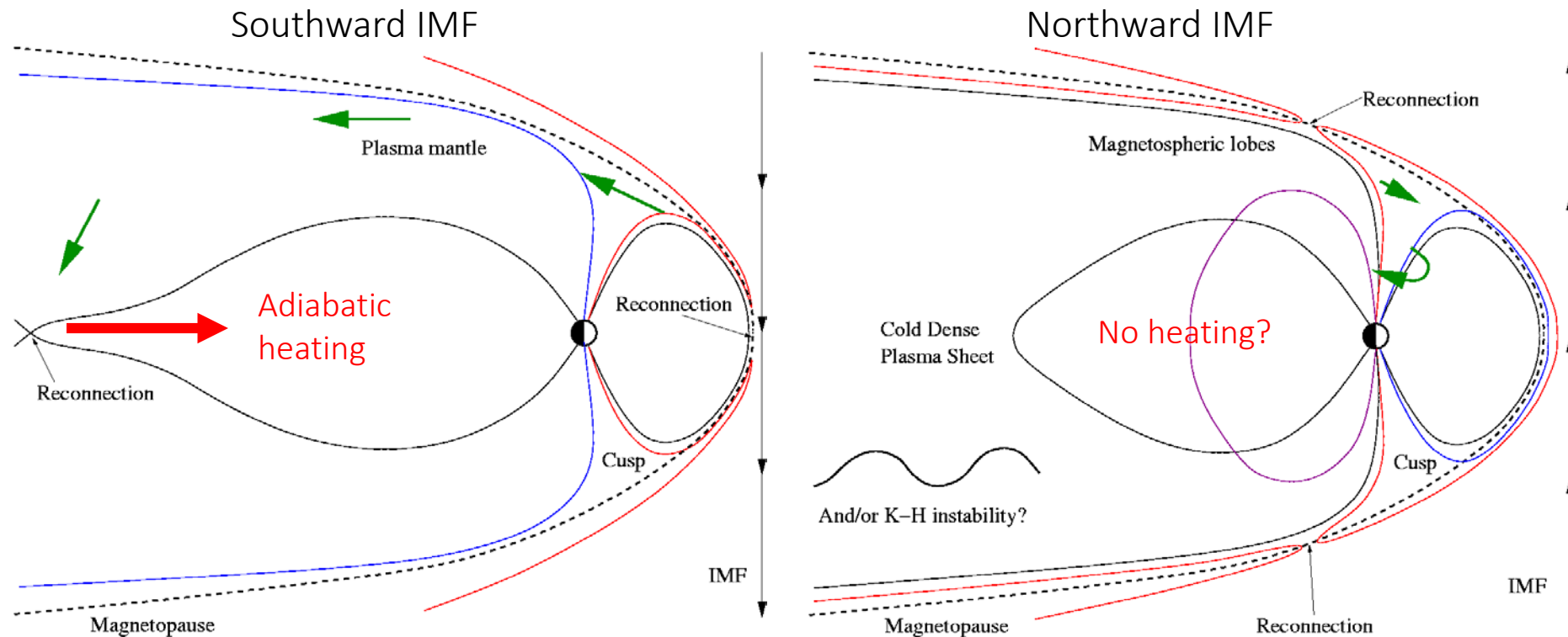
→ Is particle acceleration occurring locally in the cusps?

Conclusions & future prospects

Conclusion: magnetopause and cusps

- The cusps are **diamagnetic cavities** forming **transition regions** between magnetosheath and magnetosphere
 - The **outer boundary** is **open**, as the result of reconnection **elsewhere on the magnetopause**
 - Cusp plasma **precipitation and convection** (and subsequent circulation) are consistent with **low (high)** latitude reconnection for **southward (northward)** IMF
 - No obvious identification, or reasons, **for an indentation**
- Structured, at large scales, by magnetic reconnection

Formation of boundary layers and plasma sheet: simplified picture



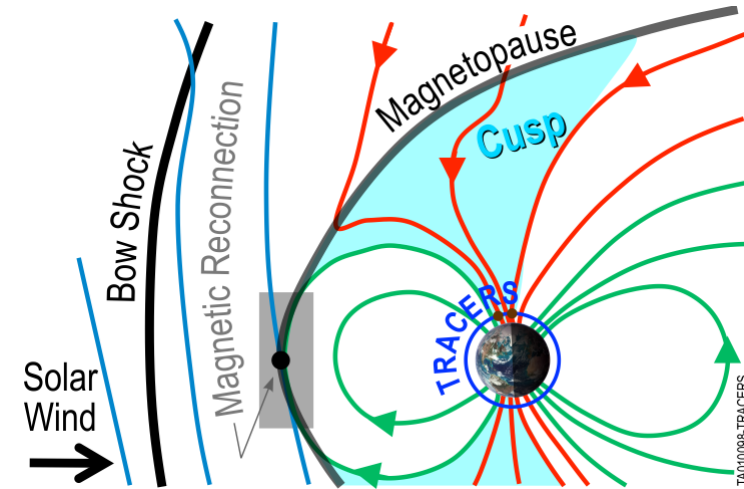
Southward IMF: Plasma sheet
is **hot and tenuous**
 $N < \sim 0.7 \text{ cm}^{-3}$ [Borovsky et al., 1997]

Northward IMF: **Cold and dense**
Plasma sheet (CDPS):
 $N > \sim 1-2 \text{ cm}^{-3}$ [Terasawa et al., 1997]

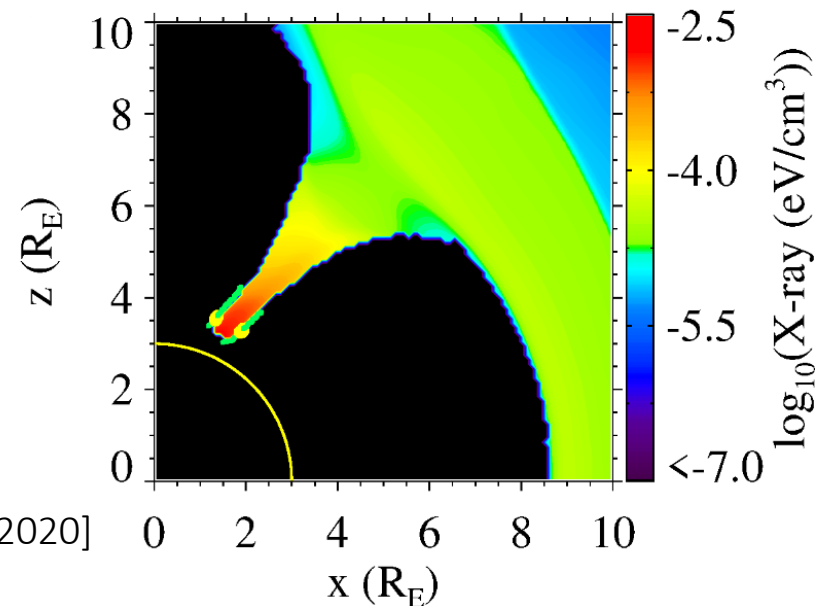
→ The cusps play a pivotal role for plasma circulation

Future prospects: space missions

- **NASA's TRACERS mission:**
Tandem Reconnection and Cusp Electrodynamics
Reconnaissance Satellites
multi-spacecraft study of dynamics
for launch in 2023
[Kletzing *et al.*, 2019]



- **ESA & CNSA's SMILE mission:**
Solar wind-Magnetosphere-Ionosphere Link Explorer
X-ray imaging of the magnetosphere
for launch in 2023
[e.g., Branduardi-Raymond *et al.*, Voyage 2050
ESA White paper 2020]



[Sun *et al.*, 2020]

Some open questions on the cusps

- Is reconnection at the magnetopause **intrinsically patchy/intermittent** (TRACERS mission)?
- What role do **waves/turbulence** play in the cusp?
- heating? acceleration? diffusion? else?
- What is the nature of the **cusp/sheath boundary**?
- Under **southward IMF**, is plasma circulation above the cusp/polar cap sufficient, or is **flank transport needed**?
- Under **northward IMF**, what are the **relative efficiencies** of double high-latitude reconnection vs. K-H instability?

...

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and others...