Impacts of cold ionospheric ions in magnetic reconnection at the Earth's magnetopause and magnetotail

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November 22, 2022

Abstract

The Earth's magnetosphere is filled by particles from two sources: the solar wind and the ionosphere. Ionospheric ions are initially cold and contain He^+ and O^+, in addition to to H^+. Depending on their initial magnetic latitude and local time, and the state of the magnetosphere, they may contribute to the plasmasphere, the plasma sheet, the ring current, the warm plasma cloak etc. Depending on which path they follow in the magnetosphere, some of these ionospheric ions remain cold when they reach the two key reconnection regions: the Earth's magnetopause and the plasma sheet in the tail. In this presentation, we will first review previous statistical works that quantify the number of cold/ionospheric ions near these two regions. Several works have attempted to quantify these populations, but they are inherently difficult to characterize due to their low energy, often below the spacecraft potential. We will also discuss the impacts they have on the magnetic reconnection process. Ionospheric ions mass-load the regions where reconnection takes place and change the characteristic Alfven speed, resulting in a smaller reconnection electric field. They also take a portion of the energy that is imparted to particles, affecting the energy budget of magnetic reconnection. Finally, they introduce new length and time scales, associated to their gyroradius and gyroperiod. We will discuss what are the implications of these impacts for the evolution of the magnetosphere – solar wind interactions.

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Reviews of Geophysics

REVIEW ARTICLE
10.1029/2020RG000707

Impacts of Ionospheric Ions on Magnetic Reconnection and Earth's Magnetosphere Dynamics

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Key Points:

- Ionospheric plasma contributes a significant part of the magnetospheric density in the regions where magnetic reconnection is most frequent
- Cold and heavy ions of ionospheric origin reduce magnetic reconnection efficiency and modify energy conversion mechanisms
- The presence of ionospheric ions and their effects on reconnection and magnetospheric dynamics are enhanced during geomagnetic storms

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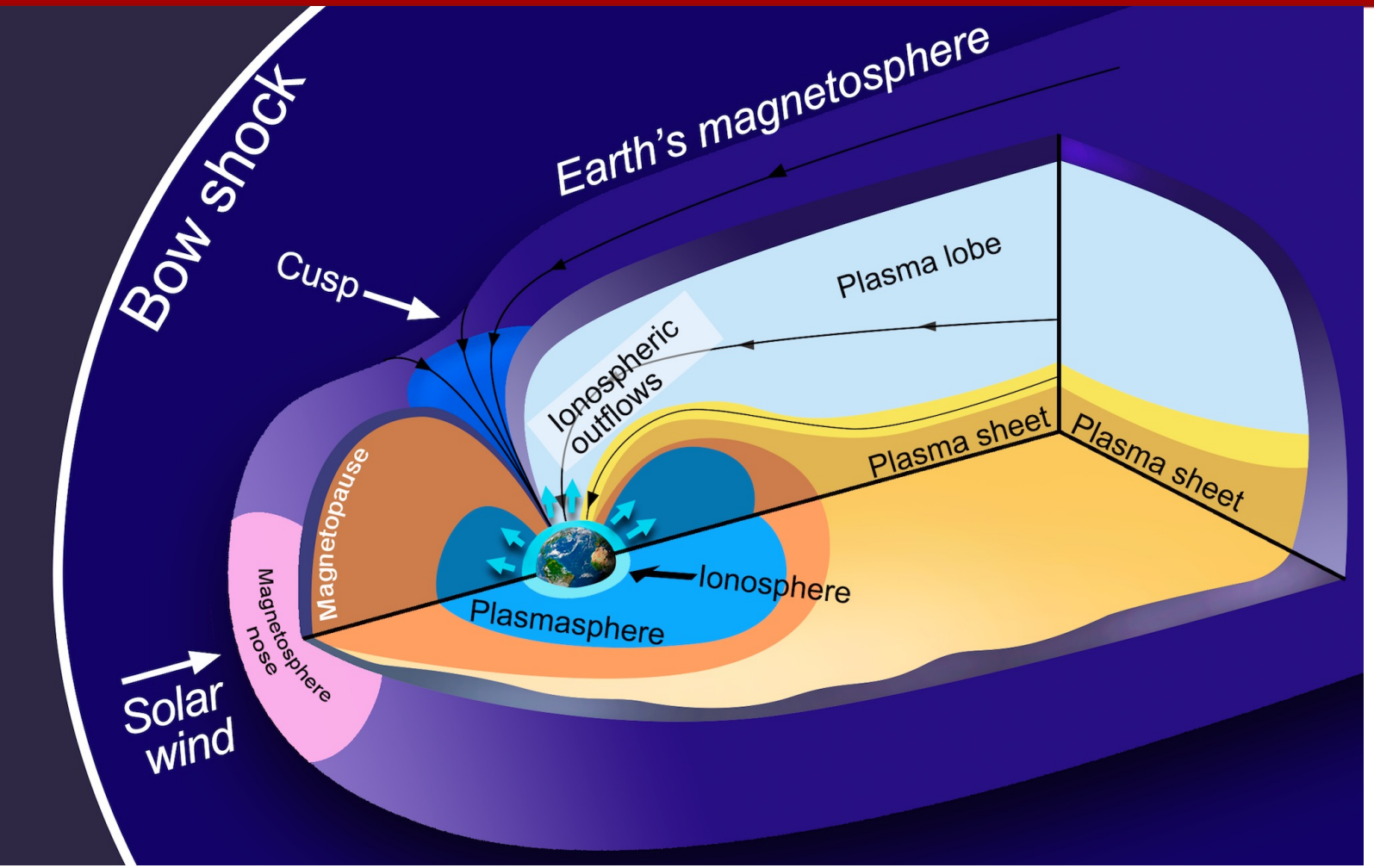
Introduction
Ionospheric-originating ions



Ionospheric-originating (cold) populations in the outer magnetosphere:

1. Detached plasmasphere material (eV)
2. Ionospheric outflows (eV)
3. Warm Plasma Cloak (WPC) (10 – 1keV)

Cold ion and electron VDFs measurement

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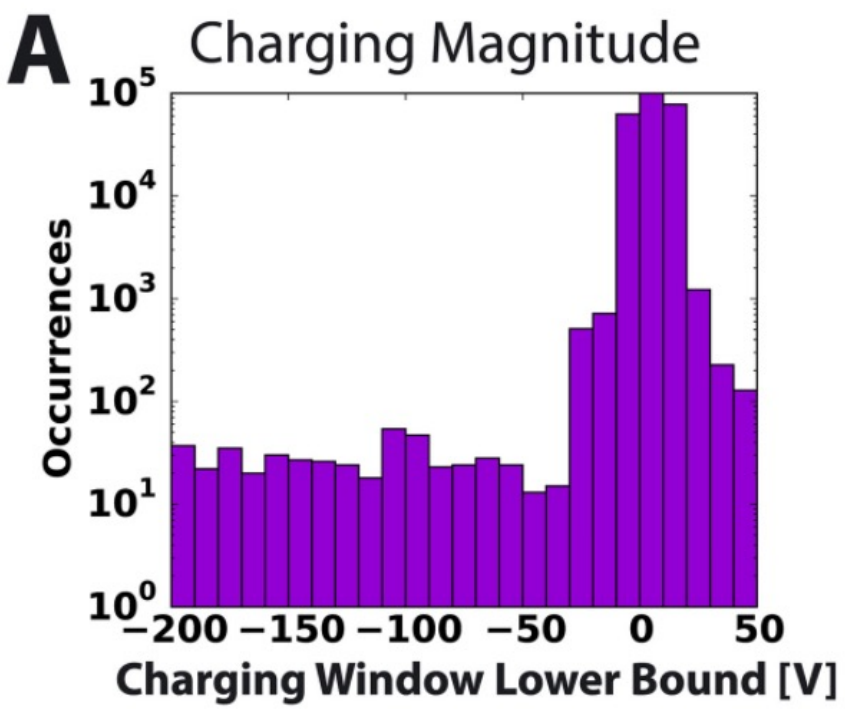
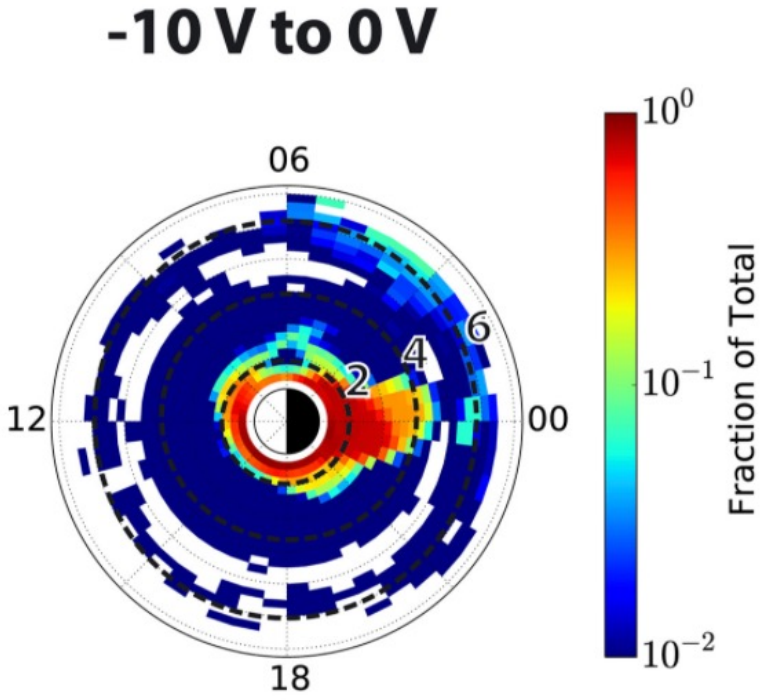
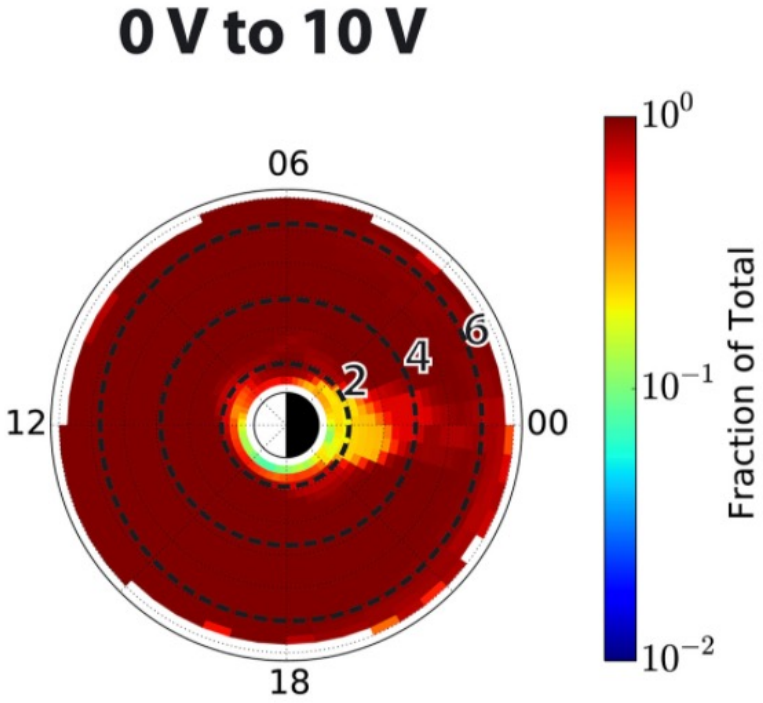




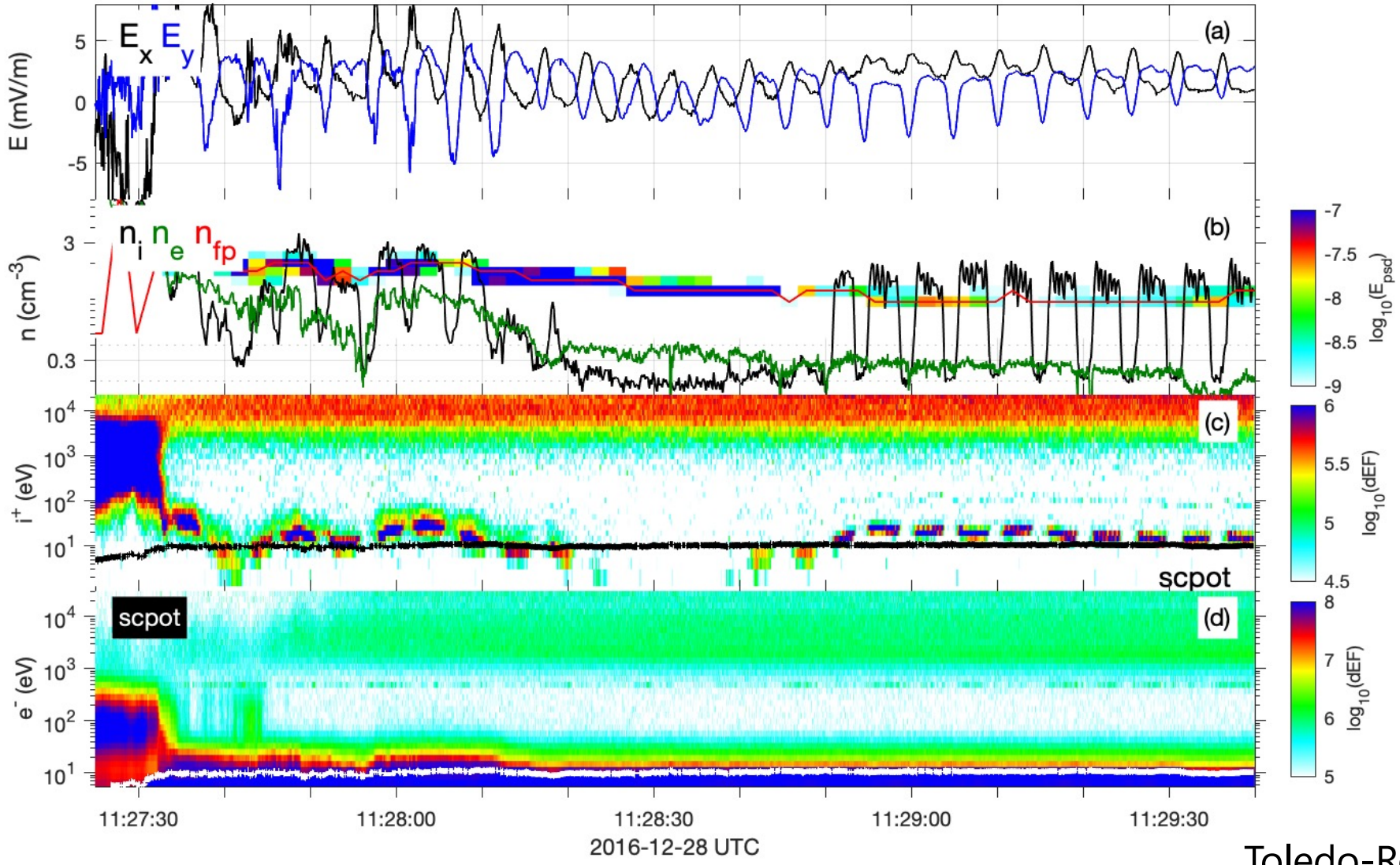


RBSP1+2 SC charging statistics (Feb 2013 – April 2015)

Sarno-Smith et al. (2016)

Spacecraft charging prevents or hinders measurement of cold VDFs

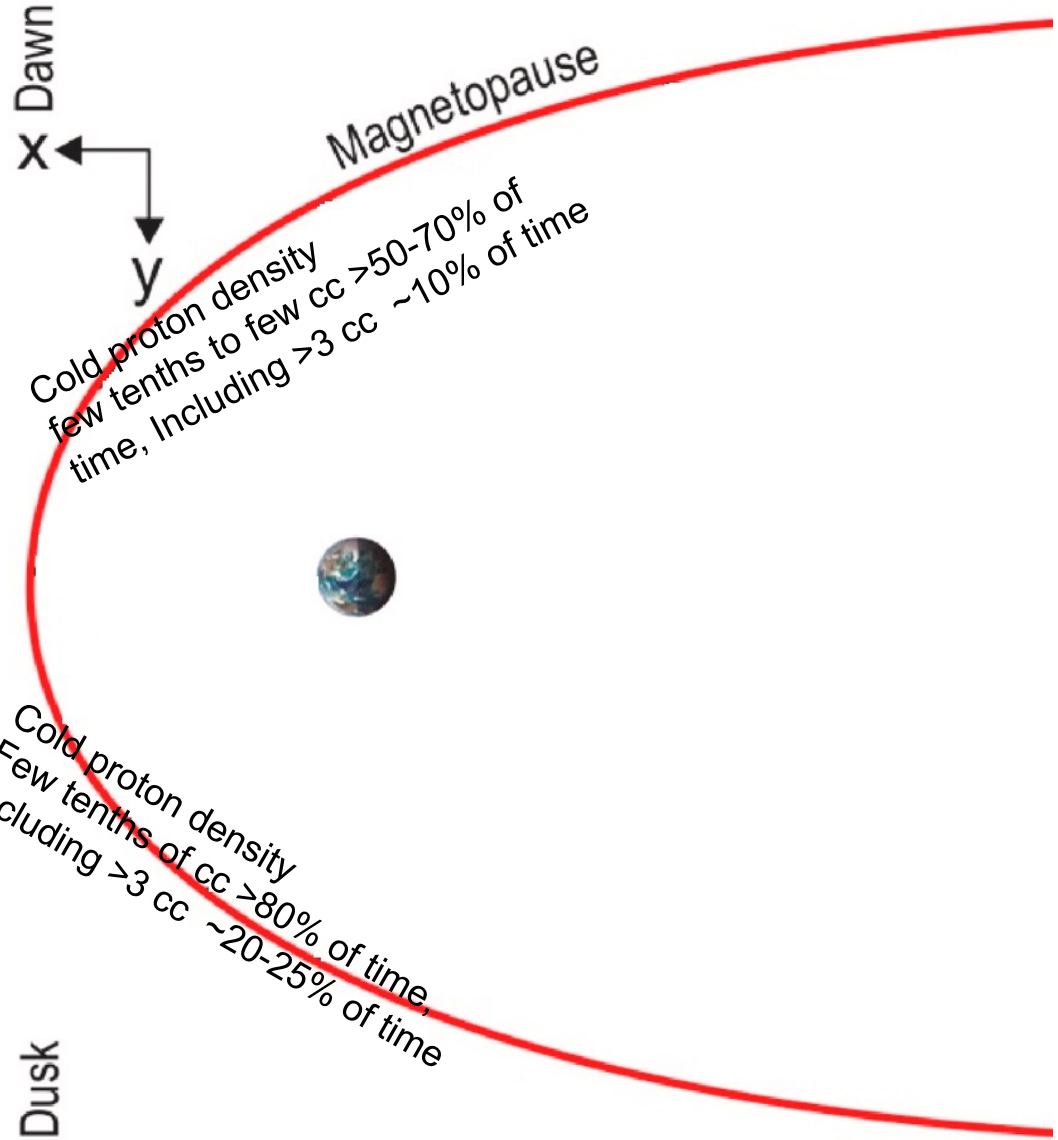
Cold ion and electron VDFs measurement



Toledo-Redondo et al. (2019)

Ionospheric ions at the dayside magnetopause

Review of statistical studies



- Cold ionospheric protons **increase magnetospheric density** near the magnetopause **by a factor 2 or more most of the time**.
- However, the magnetospheric density is usually 1 order of magnitude than magnetosheath density.

Based on 12 independent statistical studies, see Toledo-Redondo et al. (2021)

Ionospheric ions at the magnetotail

Review of statistical studies

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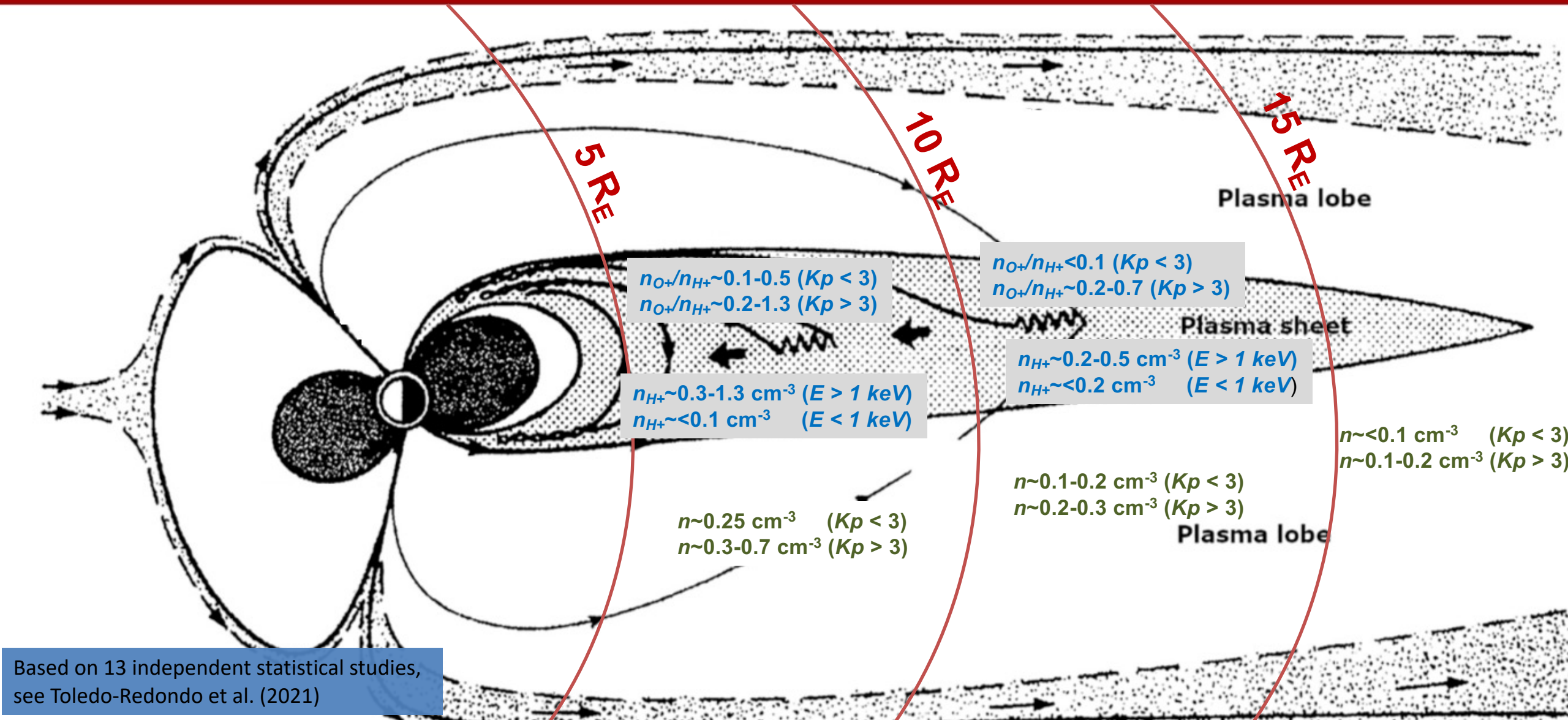

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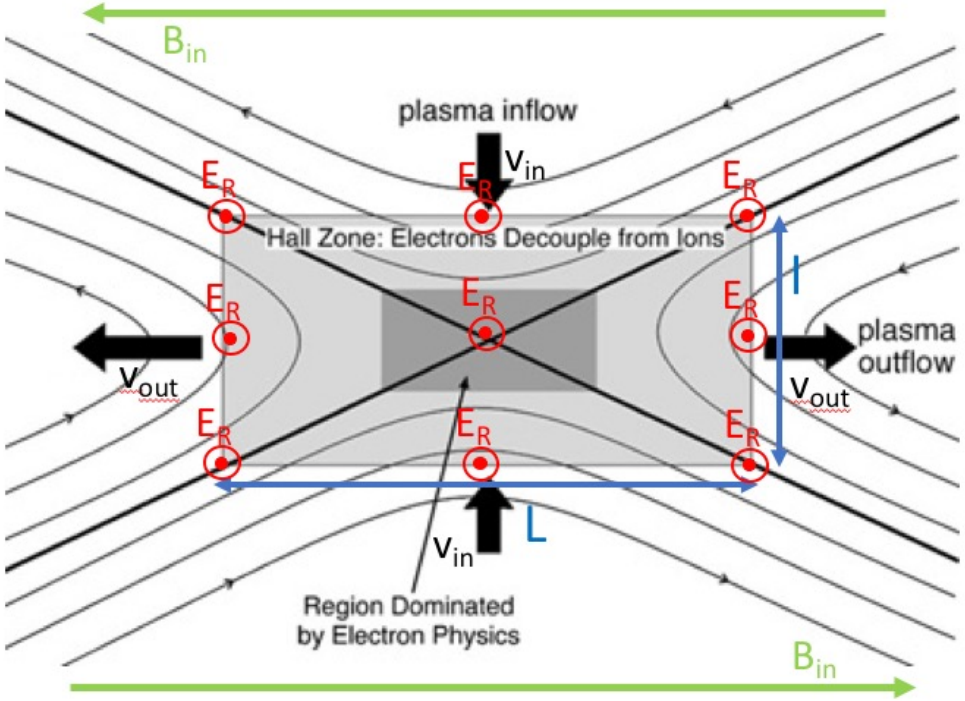
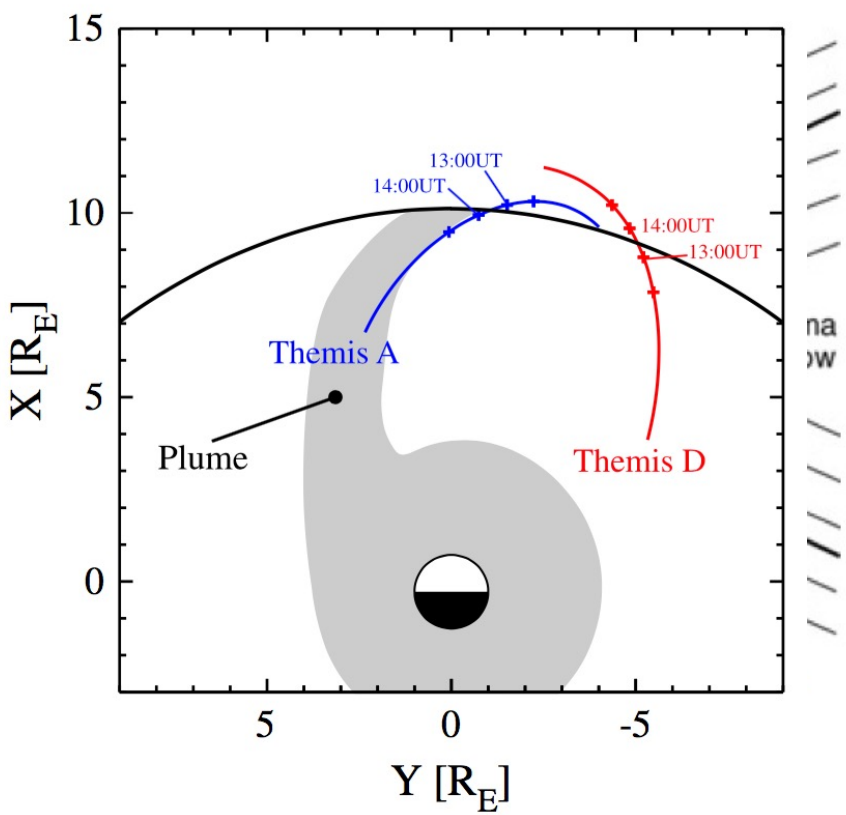
Mass-loading of reconnection



$E_R \sim B_{in}\, v_{out}\, (l/L)$

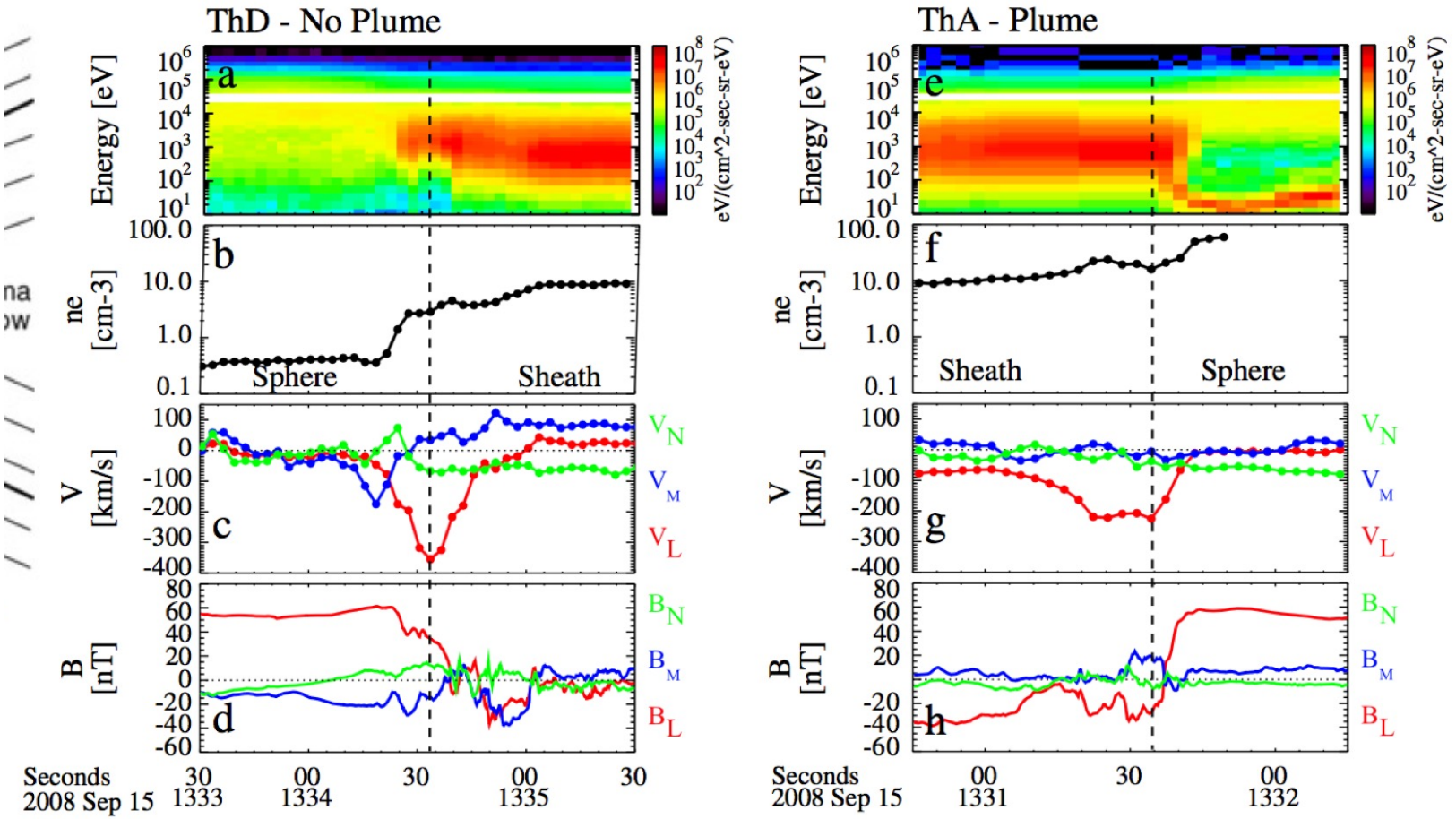
$V_{out} = v_A = B_{out}^2/(\mu_0 \rho_{out})$

Mass-loading of reconnection



$E_R \sim B_{in}\, v_{out}\, (l/L)$

$V_{out} = v_A = B_{out}^2/(\mu_0 \rho_{out})$



Walsh et al. (2013, 2014)

See also Borovsky and Denton (2006), Borovsky (2008), Borovsky et al. (2013)

Ionospheric ions and magnetic reconnection

Mass-loading the magnetopause locally

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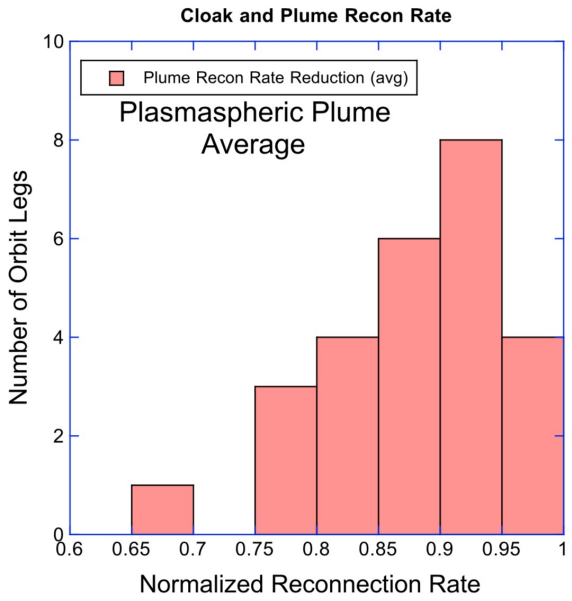
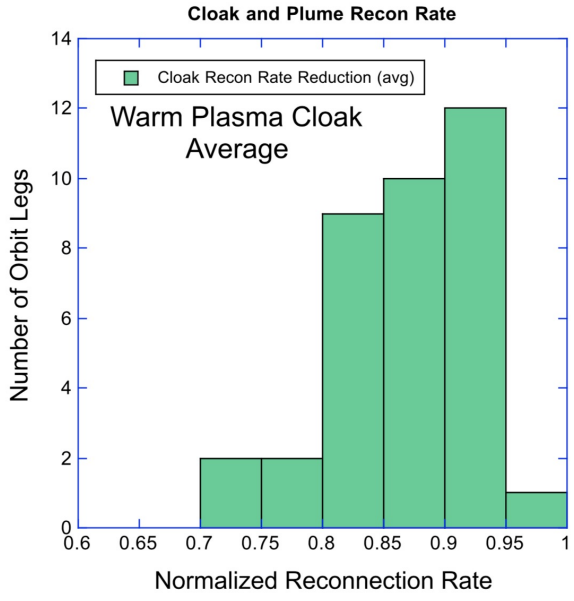
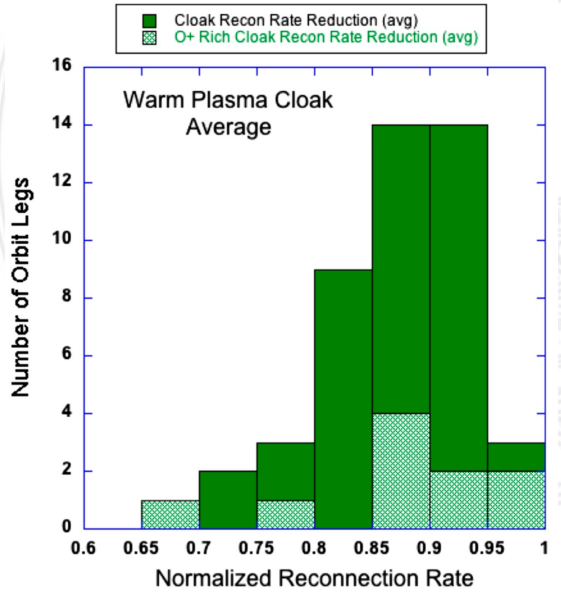
- Reduction in reconnection efficiency by >20% only during <5% of the time (Fuselier et al. 2017, 2019).
- During disturbed magnetospheric times (ie increased O^+), reduction in reconnection efficiency >20% during ~25% of the time.
- Observational evidence (not statistics) of 40% reduction due to plumes (H^+ and He^+)

$$R = \frac{E_{ML}}{E_s} = \frac{1}{\sqrt{1 + \frac{\rho_m B_s}{\rho_s B_m}}}$$

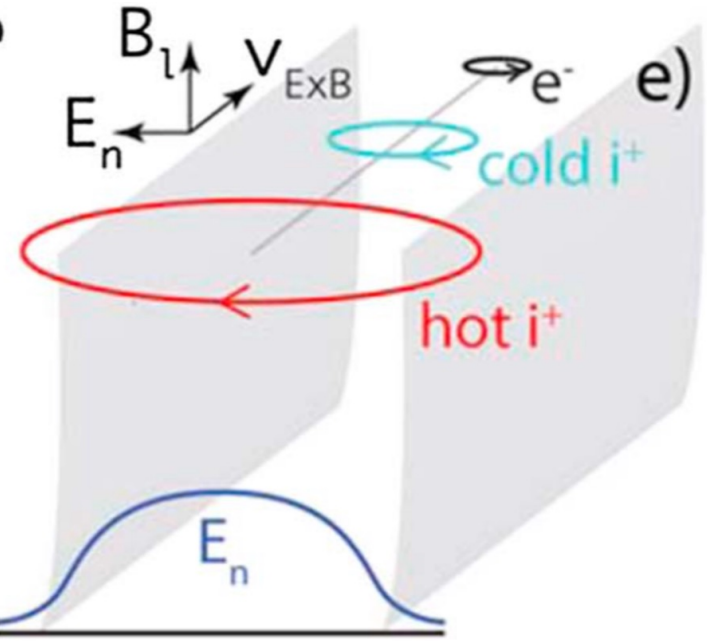






Fuselier et al. (2017, 2019, 2020)

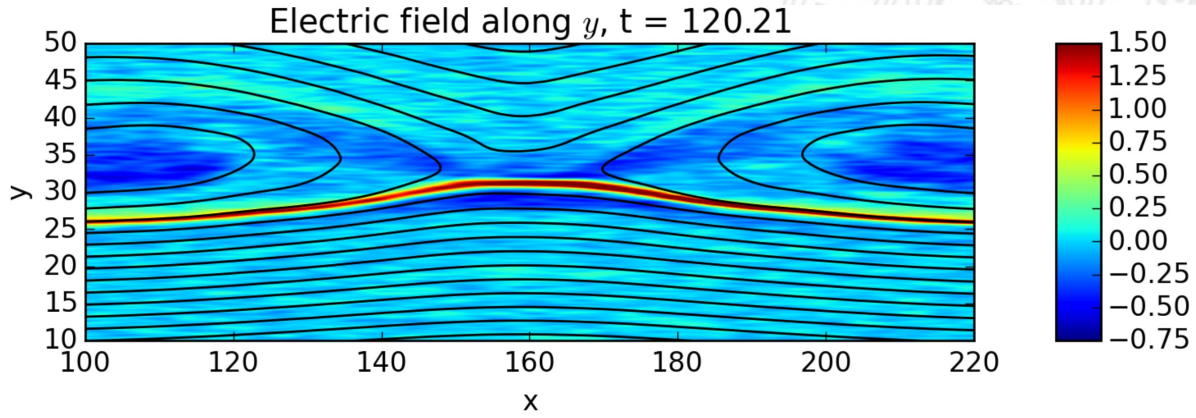
Additional length-scales in kinetic processes



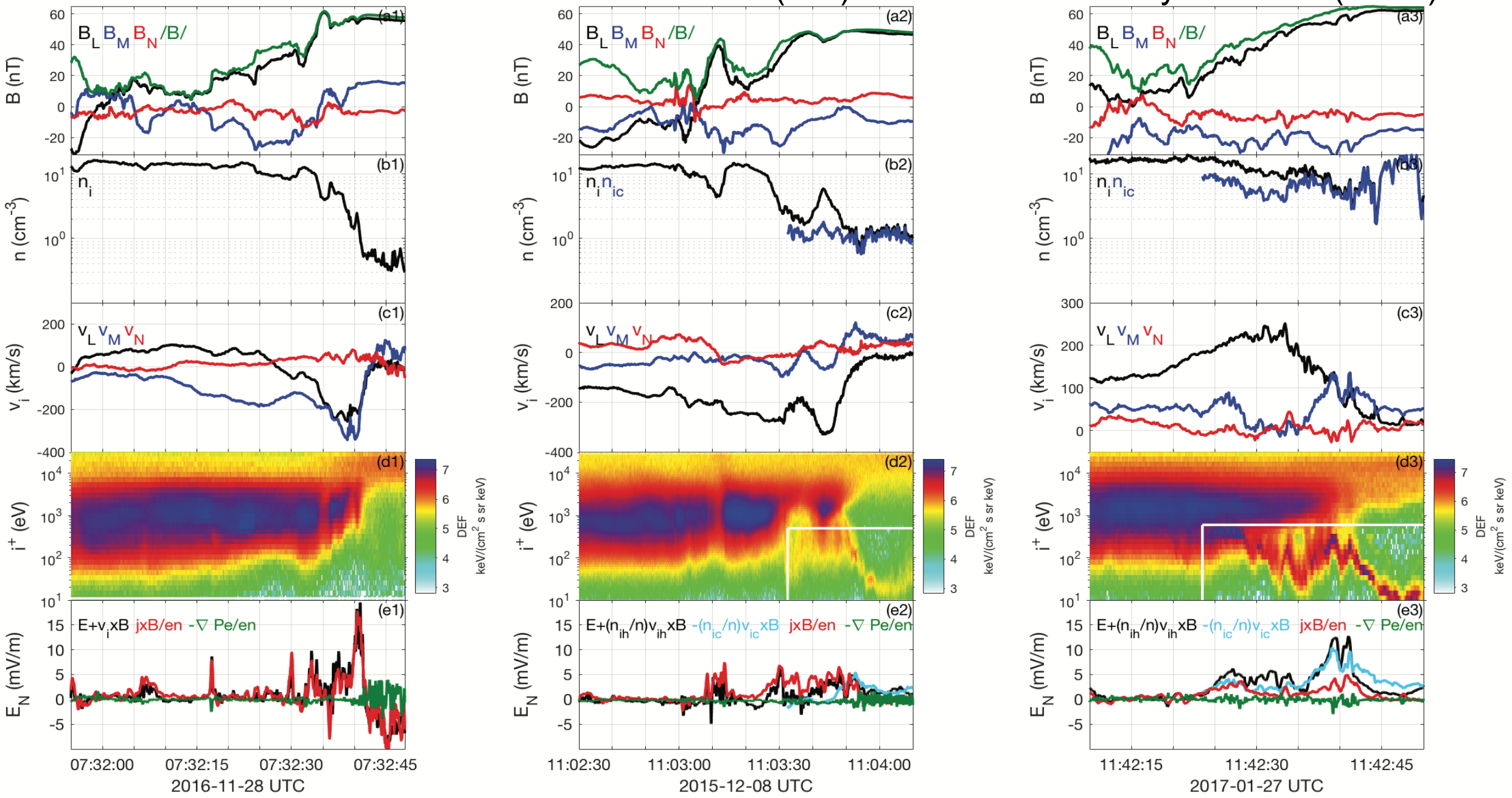
Toledo-Redondo et al. (2015)

$$\vec{E} = -\vec{v} \times \vec{B} + \frac{1}{ne}\vec{J} \times \vec{B} - \frac{1}{ne}\nabla \vec{\vec{P}}_e$$

$$\vec{E} = -\frac{n_h}{n}\vec{v}_h \times \vec{B} - \frac{n_c}{n}\vec{v}_c \times \vec{B} + \frac{1}{ne}\vec{J} \times \vec{B} - \frac{1}{ne}\nabla \vec{\vec{P}}_e$$



"**Cold ions** introduce a **new length-scale** owing to their smaller gyroradius. They can reduce the perpendicular currents at these scales."



André et al. (2016), Toledo-Redondo et al. (2018)

Ionospheric ions and magnetic reconnection

Cold ion diffusion region

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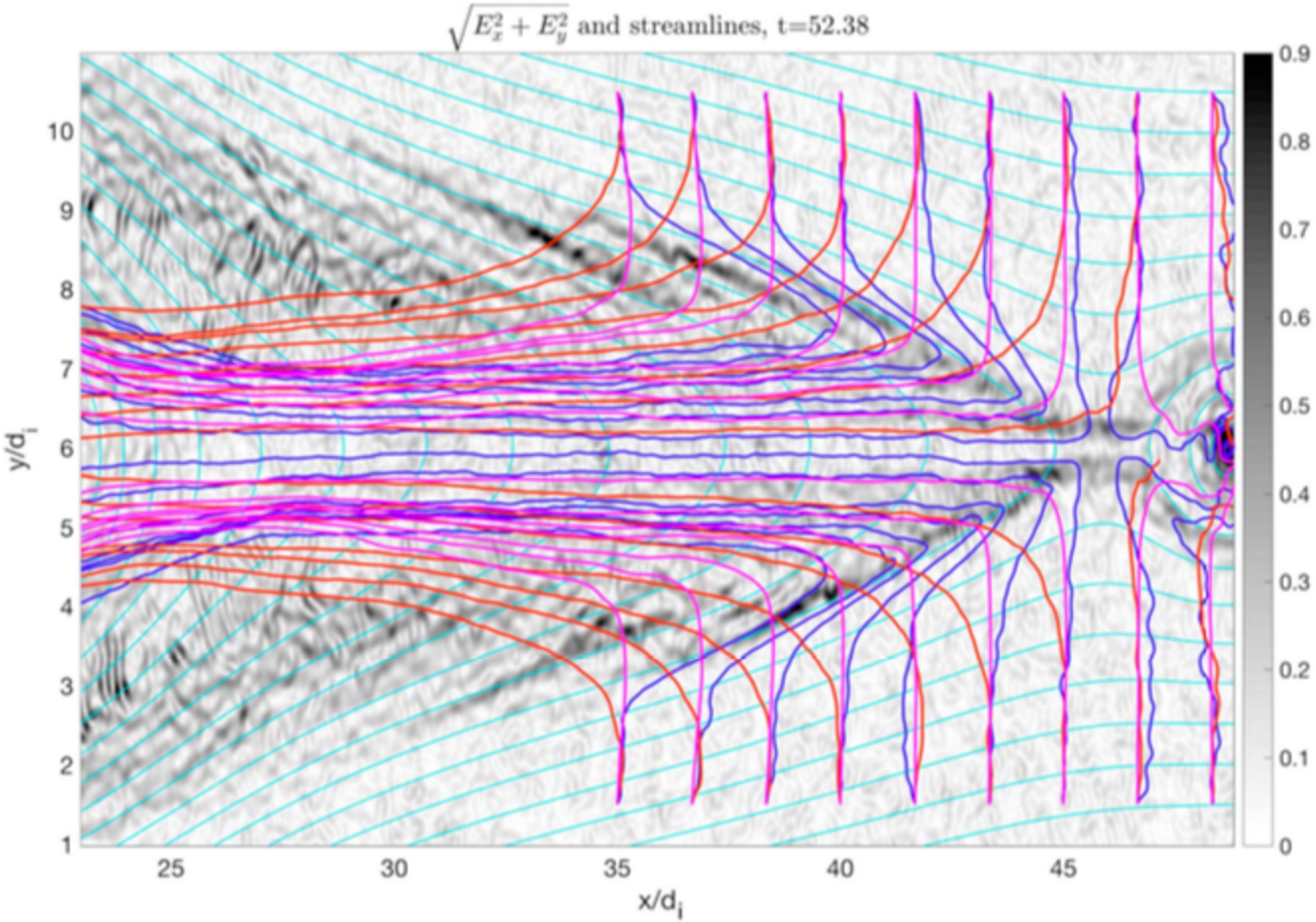
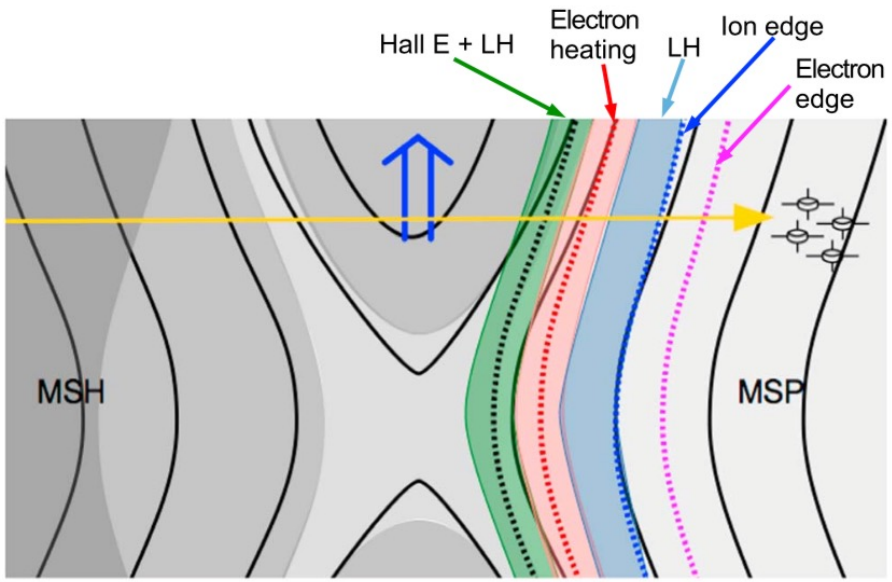
electrons
cold ions
hot ions



Divin et al. (2016)

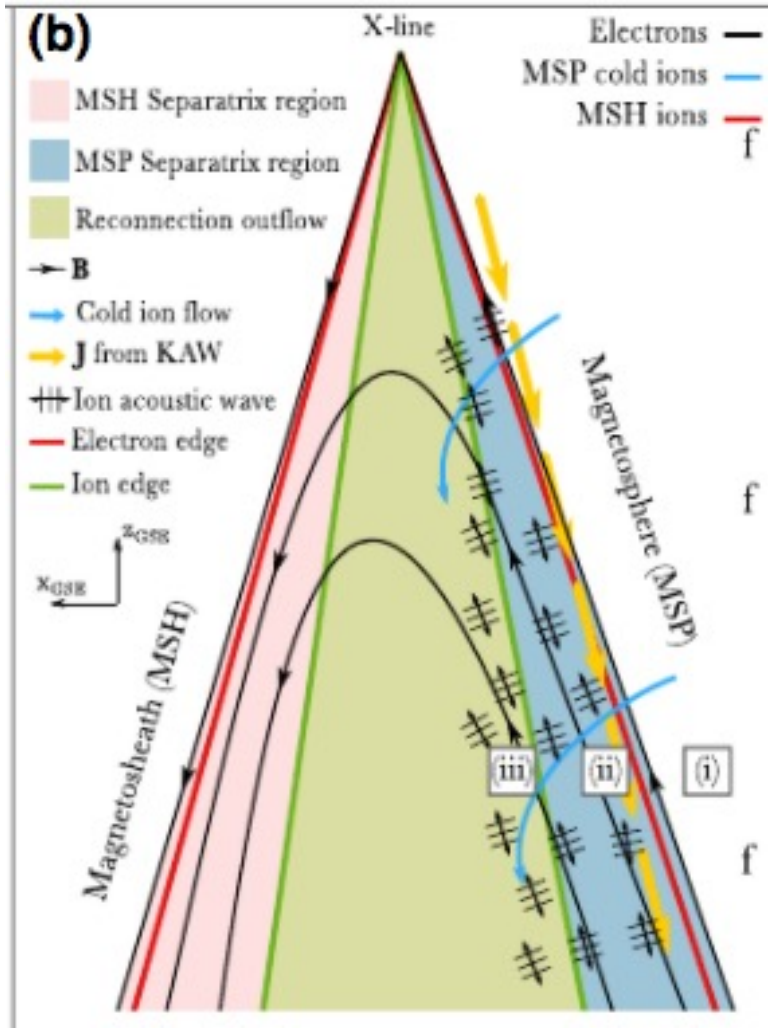
Ionospheric ions and magnetic reconnection

Cold ion heating mechanisms



The relative motion between the magnetized cold ions and the magnetosheath ions favours **an ion – ion drift instability** at the separatrix that generates **lower hybrid drift waves**. These waves can **heat the cold ions** and demagnetize them.

Graham et al. (2017)



Ion acoustic waves are formed in the separatrix and outflow region of dayside reconnection

88% of the IAW observed at the magnetopause during 5 months of MMS data are in association to cold ions ($n_c/n > 0.6$)

Steinvall et al. (2021)

Ionospheric ions and magnetic reconnection

Cold ion heating and energy budget

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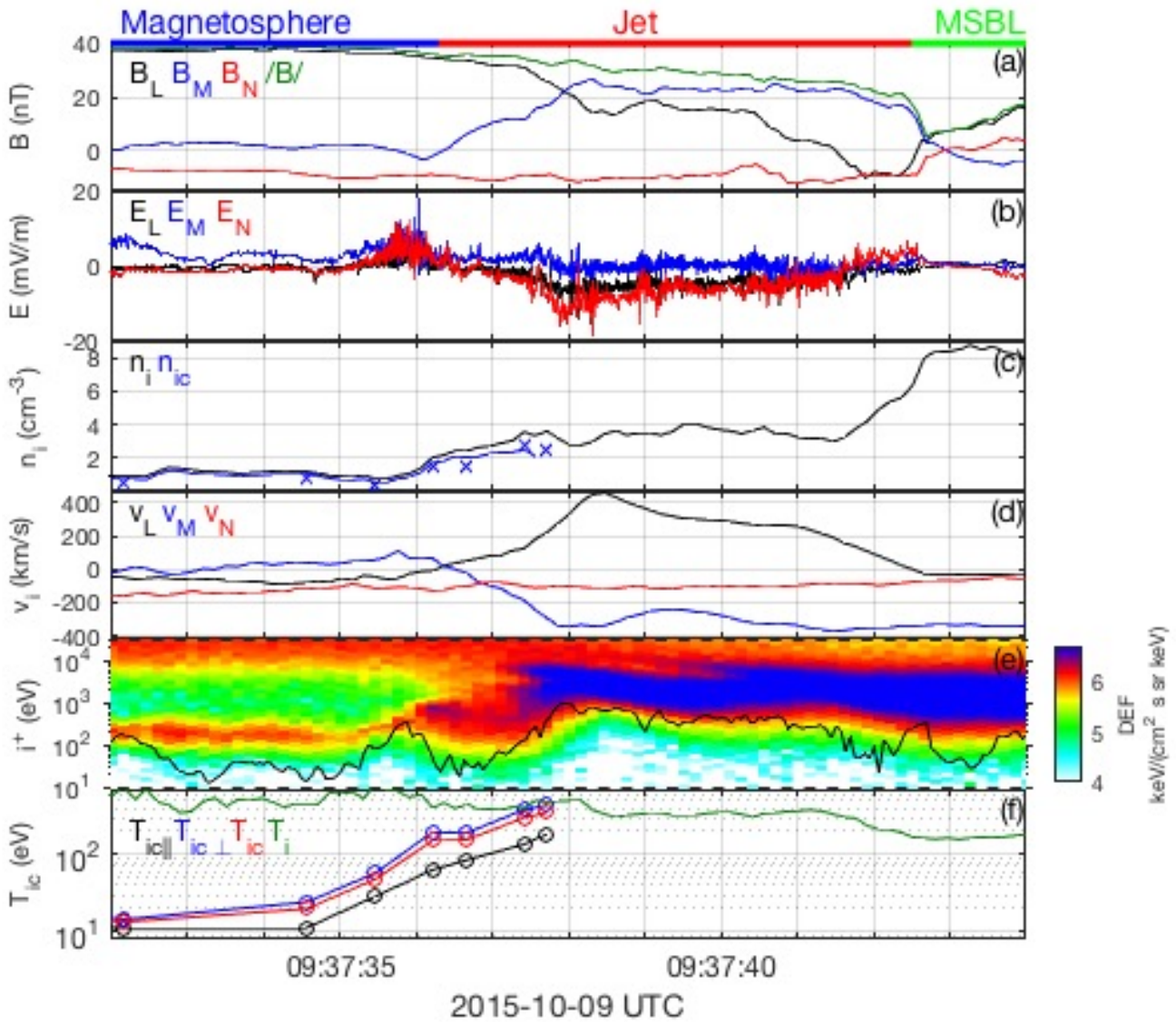

Toledo-Redondo+, GRL, (2016b)
Toledo-Redondo+, JGR, (2017)

Some open questions for the community

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Table 4
Summary of Open Questions in the Role of Ionospheric Ions and Magnetic Reconnection in the Magnetosphere

Global magnetospheric dynamics	What is the relative contribution of solar wind versus ionospheric-originating H^+ to the magnetosphere?
	How is the plasma sheet formed?
	Does the variable magnetospheric density affect the global coupling with the solar wind efficiency?
Kinetic physics of magnetic reconnection	How do the microphysics introduced by multiple ion populations change reconnection at MHD scales?
	Does the WPC alter the suppression of magnetic reconnection?
	Which portion of the reconnection energy is taken by cold and heavy ions?
	What are the effects of cold electrons in magnetic reconnection?
	How ionospheric ions in the plasma sheet condition the onset of magnetic reconnection?

Abbreviation: WPC, warm plasma cloak.

Conclusions

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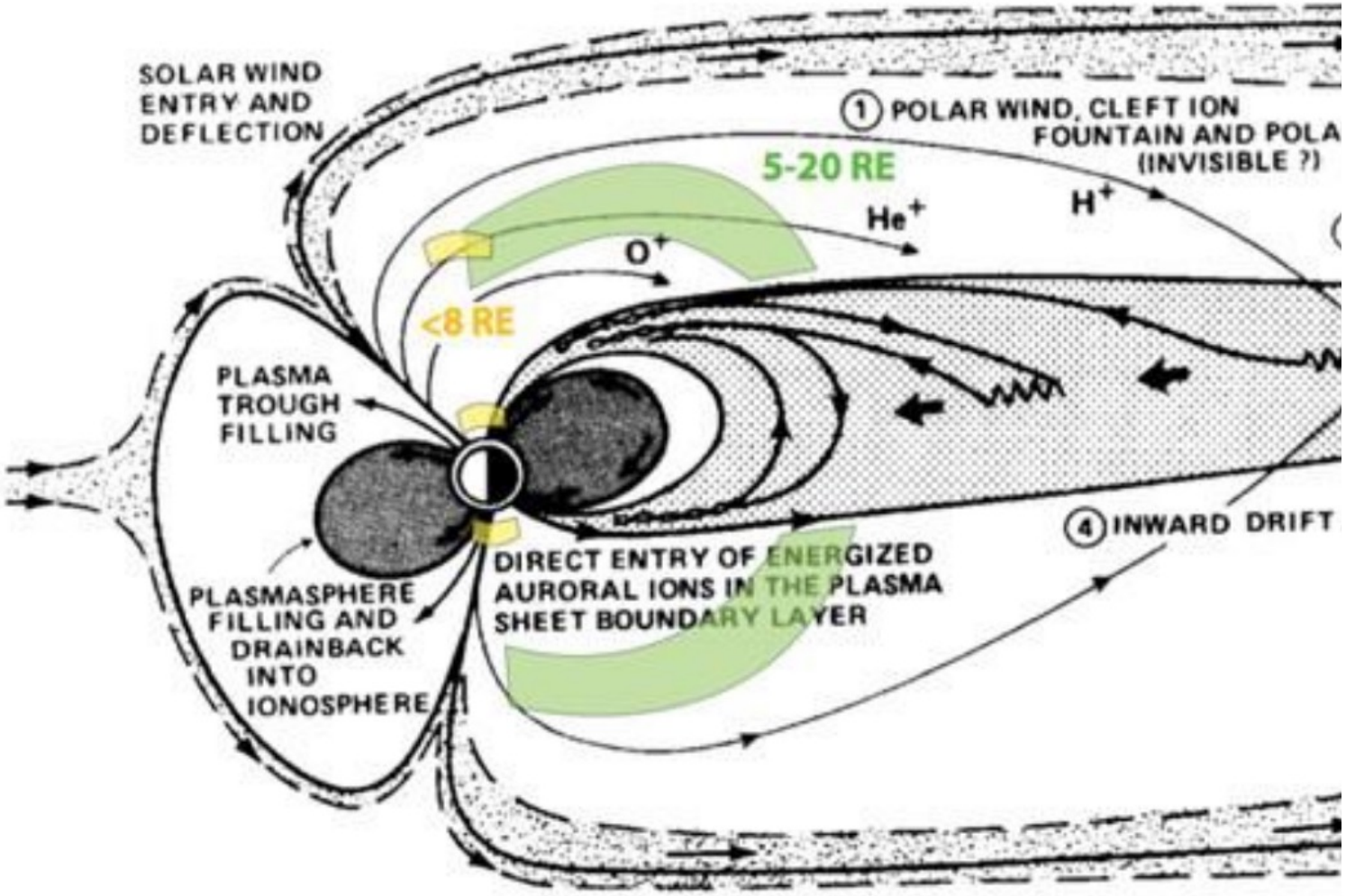
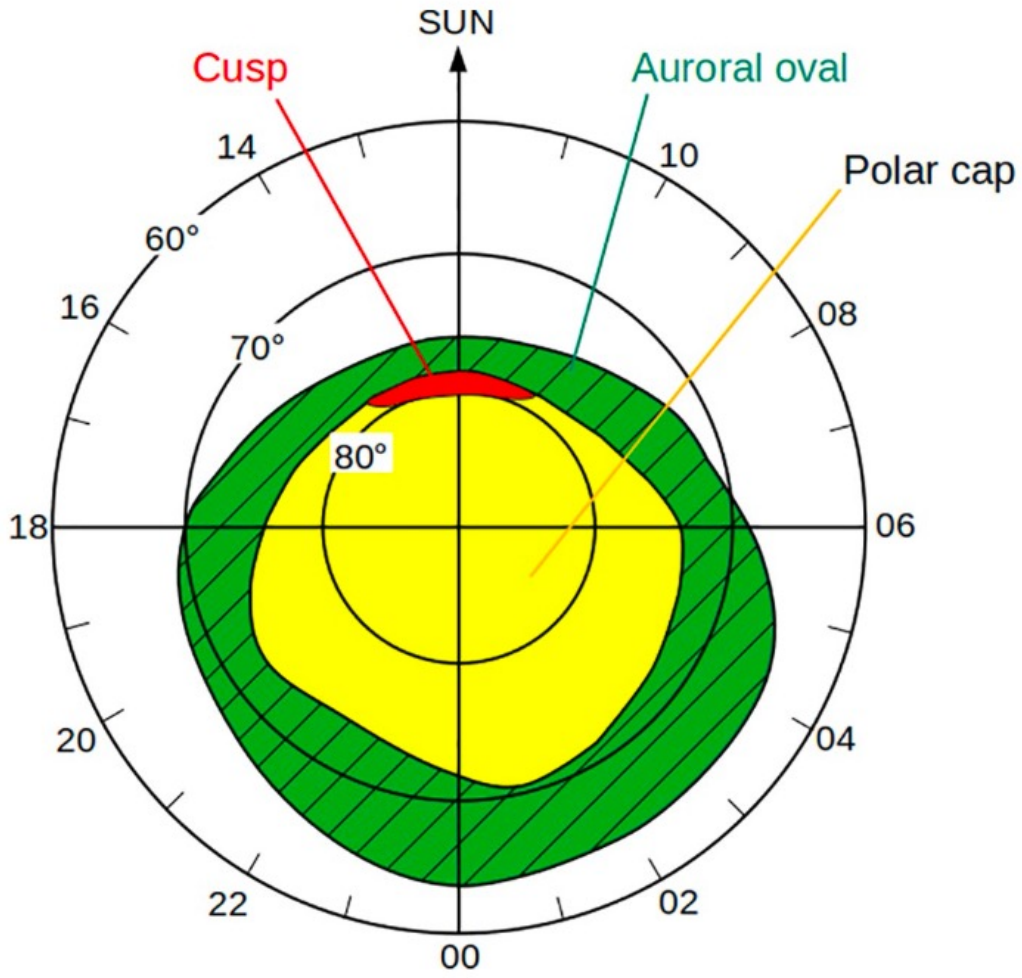
- The **ionosphere** is a **primary supplier** of plasma to the Earth's magnetosphere, together with the solar wind (roughly same order of magnitude)
- Changes in global coupling to SW due to **mass-loading** of the magnetosphere are **significant only during disturbed conditions** of the magnetosphere.
- Ionospheric populations introduce **new time and length-scales** into magnetic reconnection and **modify kinetic processes (reconnection, micro-instabilities)**
- How these **microphysics** changes affect the magnetosphere dynamics on **global scales** remains **unknown**

THANK YOU

Introduction
Ionospheric outflows



Chappell et al. (1987, 2000)



Akasofu (2015)

Cold ion and electron VDFs measurement

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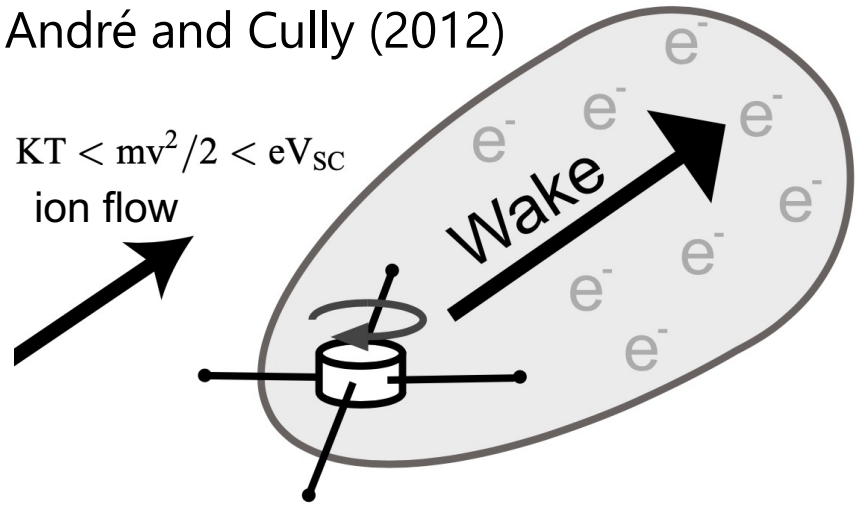
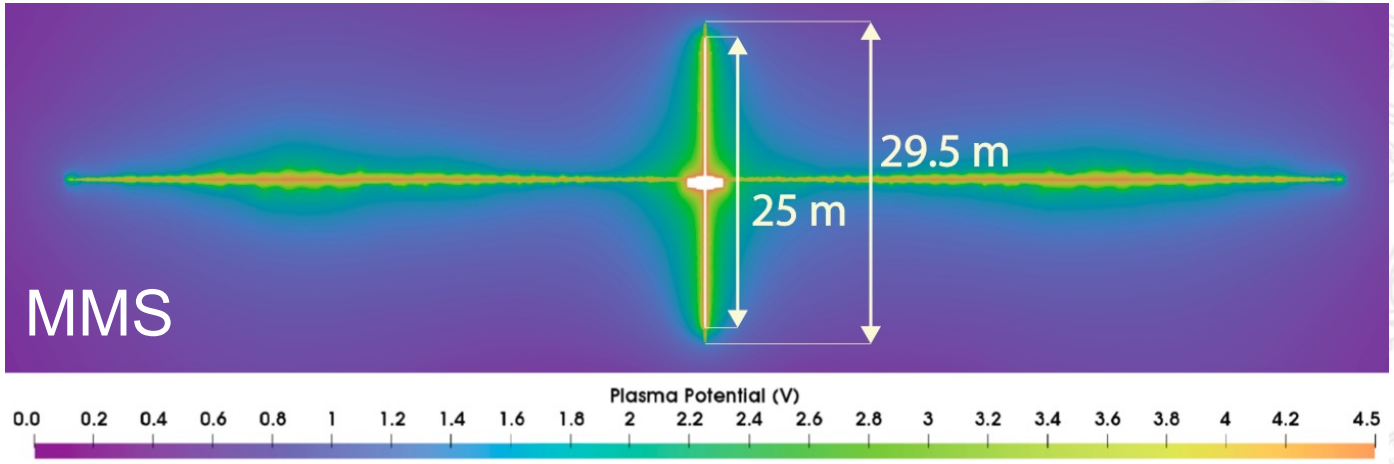
André and Cully (2012)





Toledo-Redondo et al. (2019)

Spacecraft charging prevents or hinders measurement of cold VDFs

Ionospheric ions at the dayside magnetopause

Review of statistical studies

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- Dusk side magnetopause (dominated by detached plasmaspheric material)
  - Cold ionospheric protons are present >80% of the time, with densities of few tenths of cm^{-3}
  - During 20 – 25 % of the time, cold proton density is > 3 cm^{-3} (mainly plumes)

- Dawn side magnetopause (dominated by WPC)
  - Cold ionospheric protons are present 50 – 70 % of the time, with densities of few tenths to few cm^{-3}
  - During ~10 % of the time, cold proton density is > 3 cm^{-3}

- Plasma sheet ions are both of ionospheric and solar wind origin, and have densities of up to ~0.5 cm^{-3} near the magnetopause

Ionospheric ions and magnetic reconnection

O^+ in magnetotail, reconnection onset

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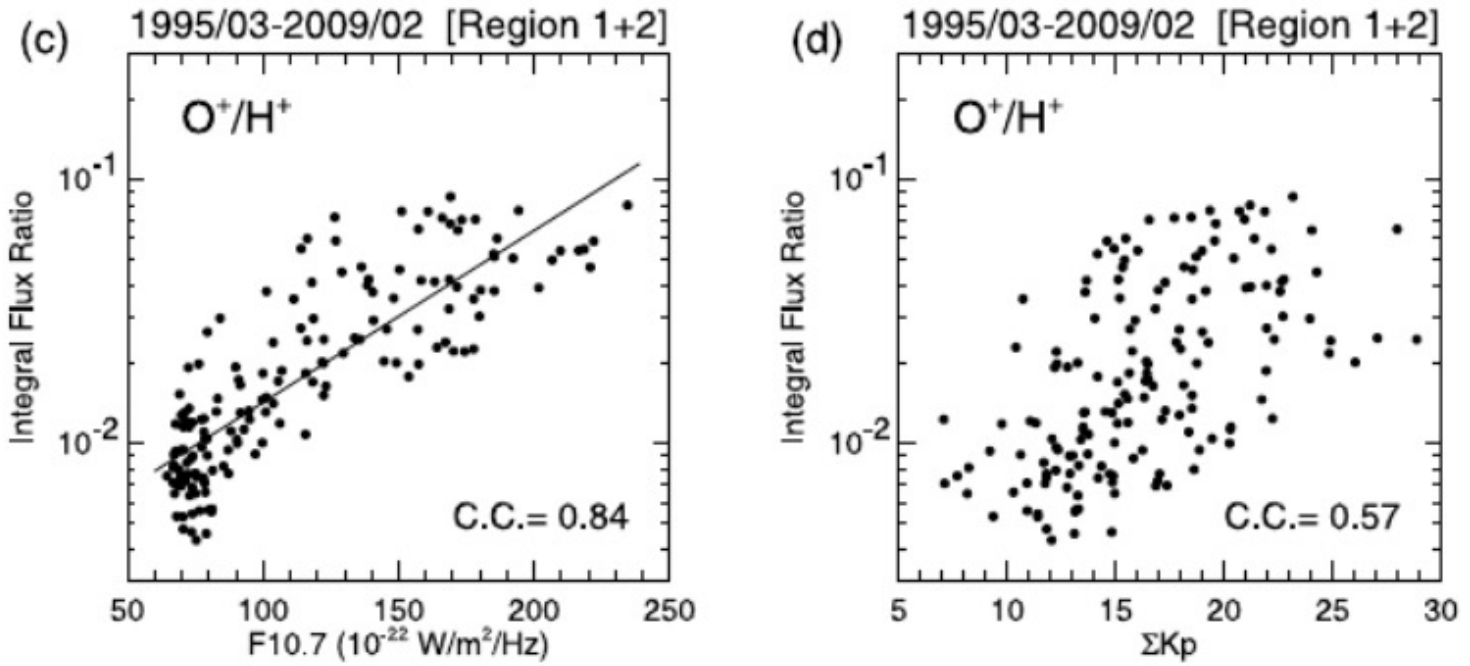
- The presence of O+ should make the tail more unstable to tearing instability (eg Baker et al. 1982)
- Various statistical studies seem to find the opposite (eg Liu et al 2013, Liao et al 2014, Lennartsson et al. 1993, Nosé et al. 2009)



Nosé et al. (2009)

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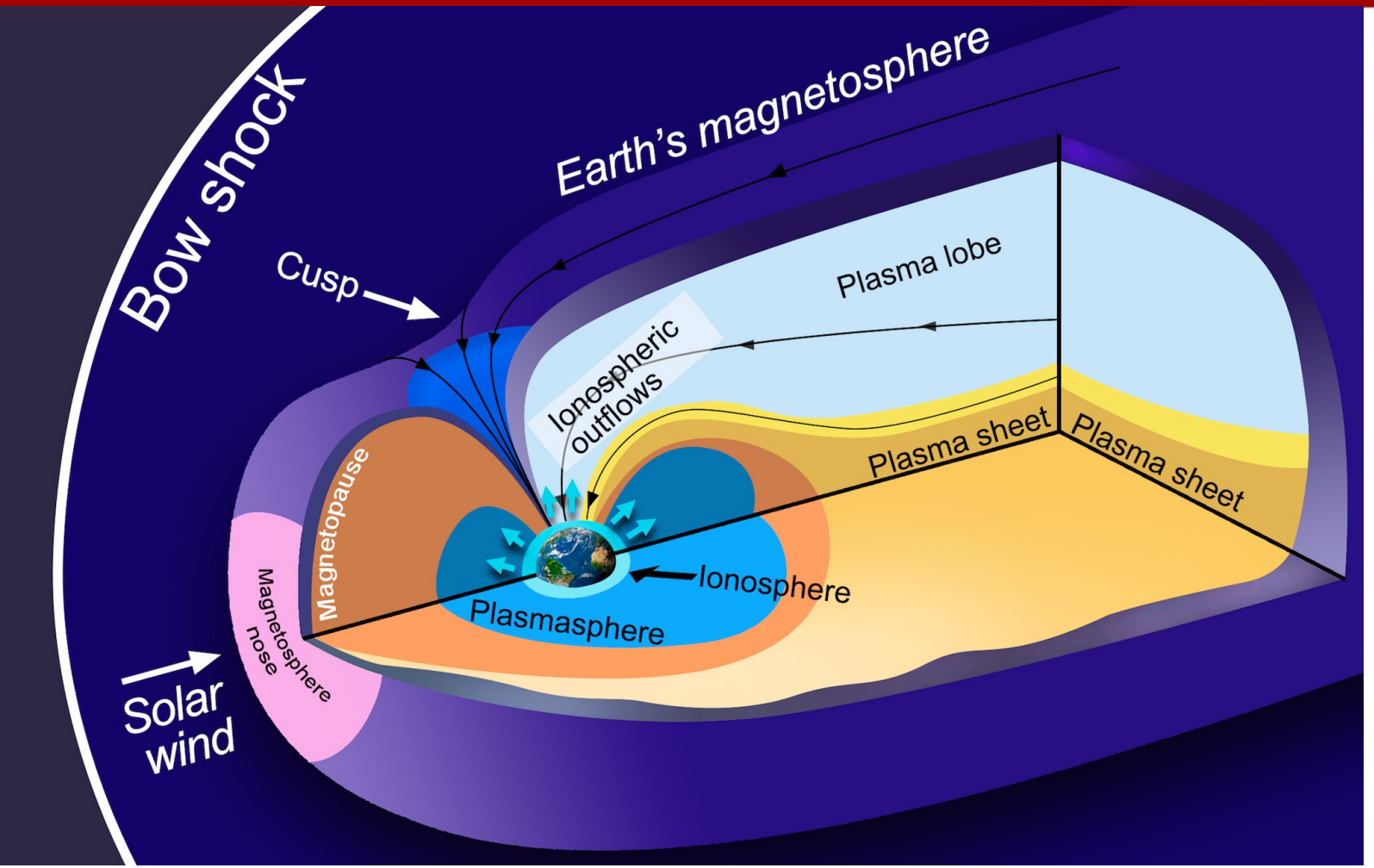

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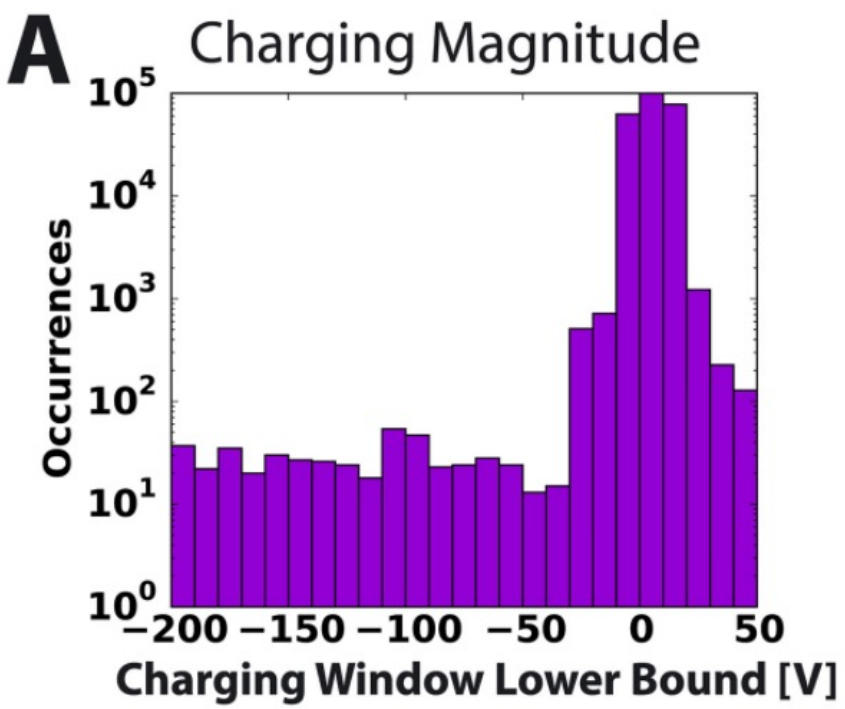
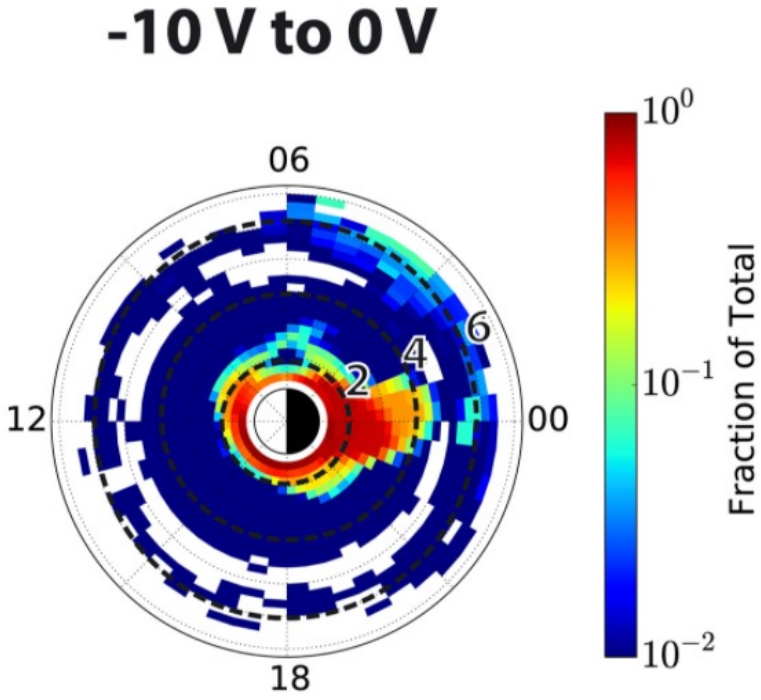
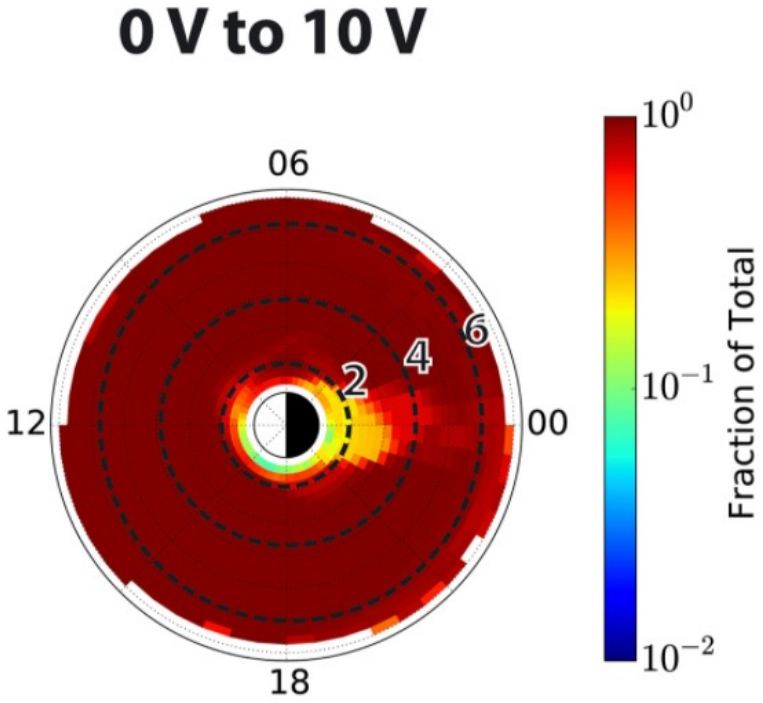




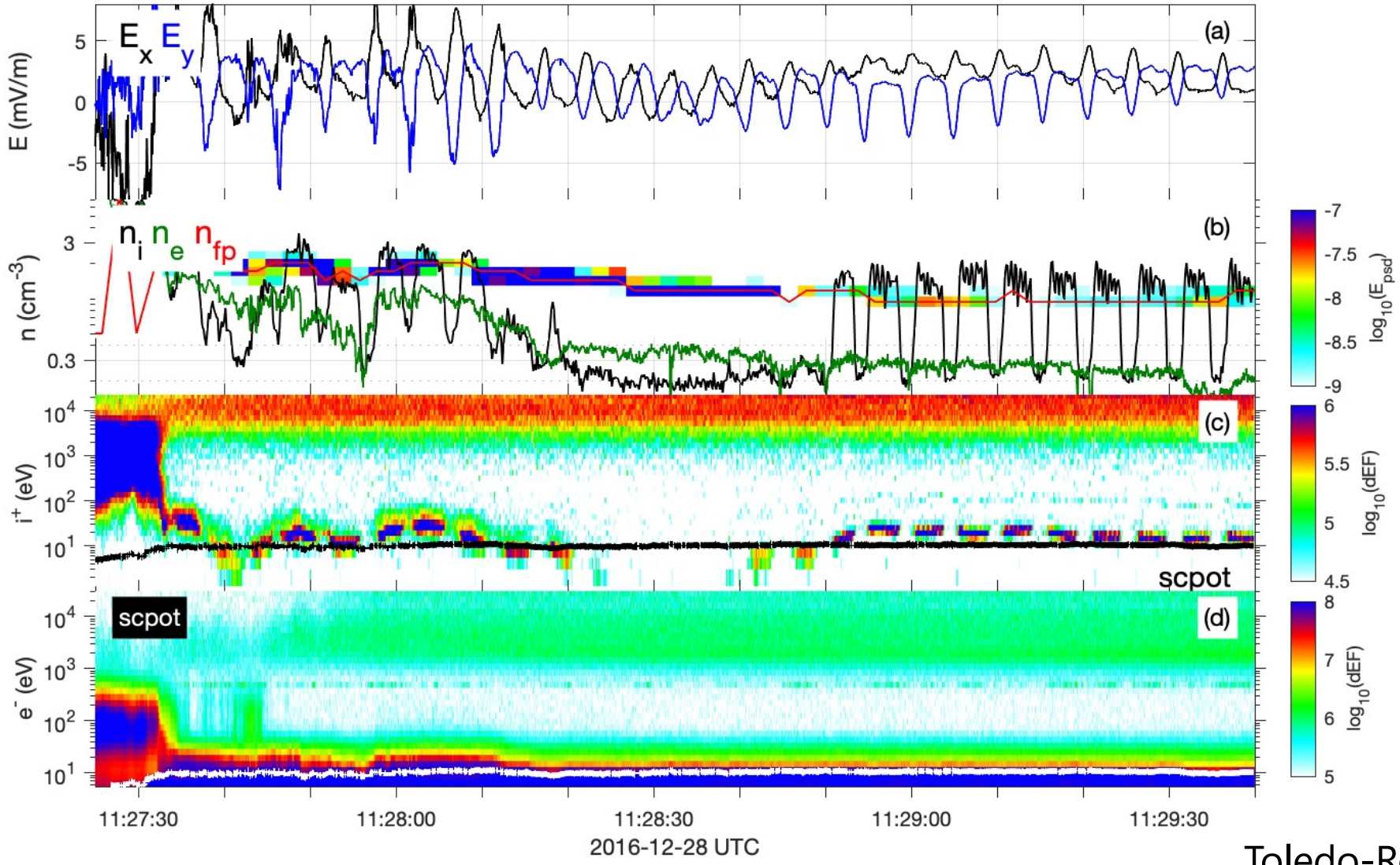


RBSP1+2 SC charging statistics (Feb 2013 – April 2015)

Sarno-Smith et al. (2016)

Spacecraft charging prevents or hinders measurement of cold VDFs

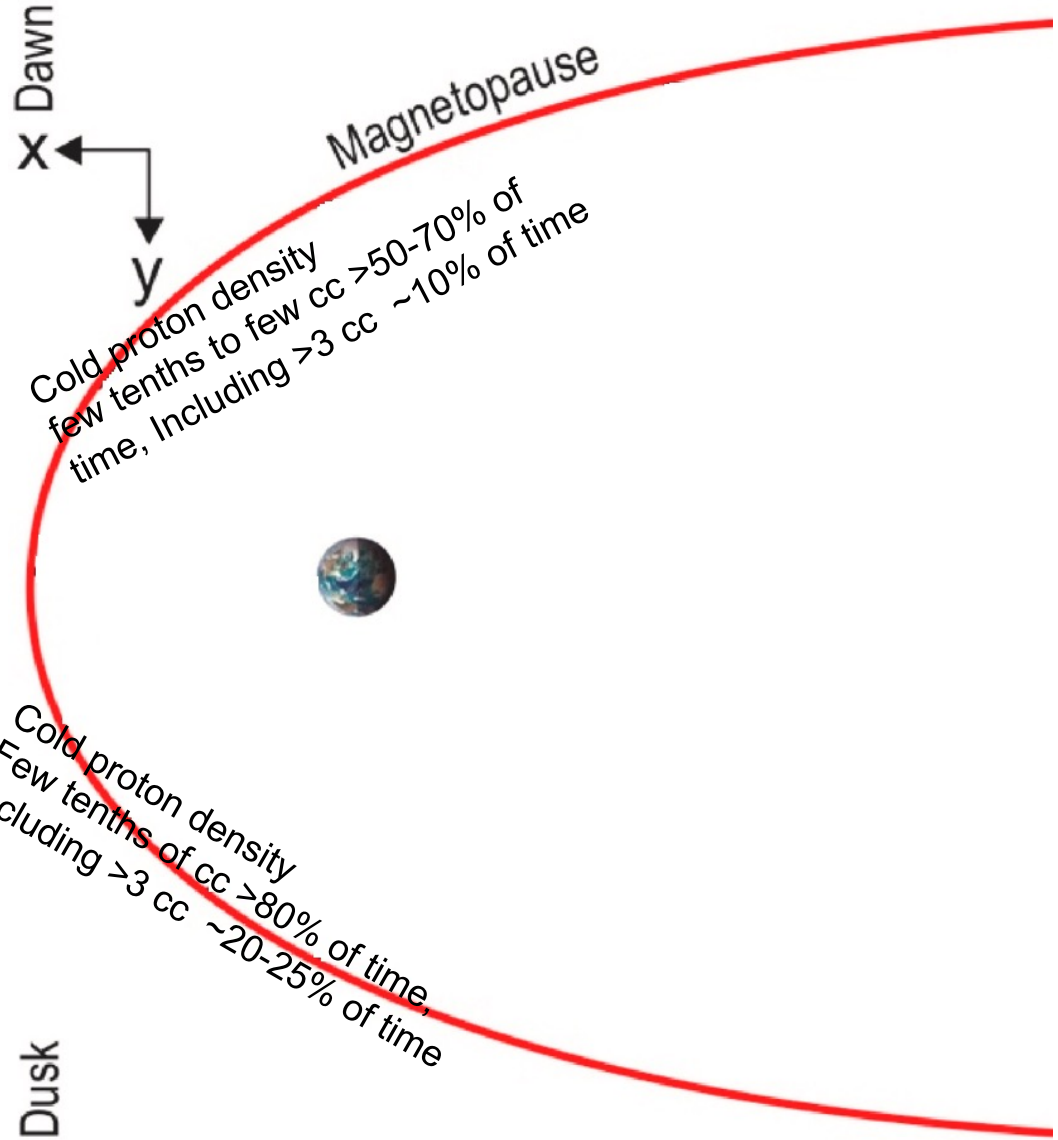
Cold ion and electron VDFs measurement



Toledo-Redondo et al. (2019)

Ionospheric ions at the dayside magnetopause

Review of statistical studies



- Cold ionospheric protons **increase magnetospheric density** near the magnetopause **by a factor 2 or more most of the time**.
- However, the magnetospheric density is usually 1 order of magnitude than magnetosheath density.

Based on 12 independent statistical studies, see Toledo-Redondo et al. (2021)

Ionospheric ions at the magnetotail

Review of statistical studies

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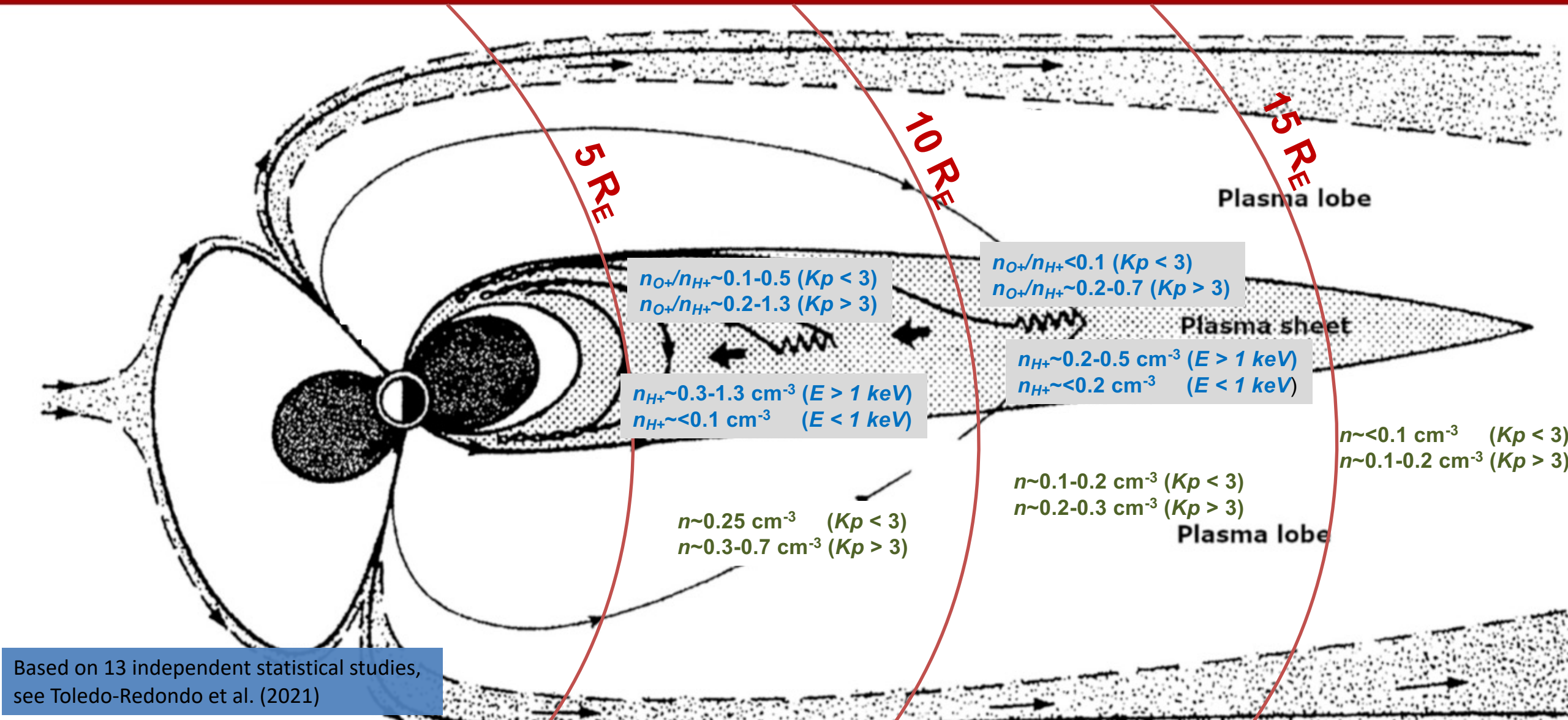
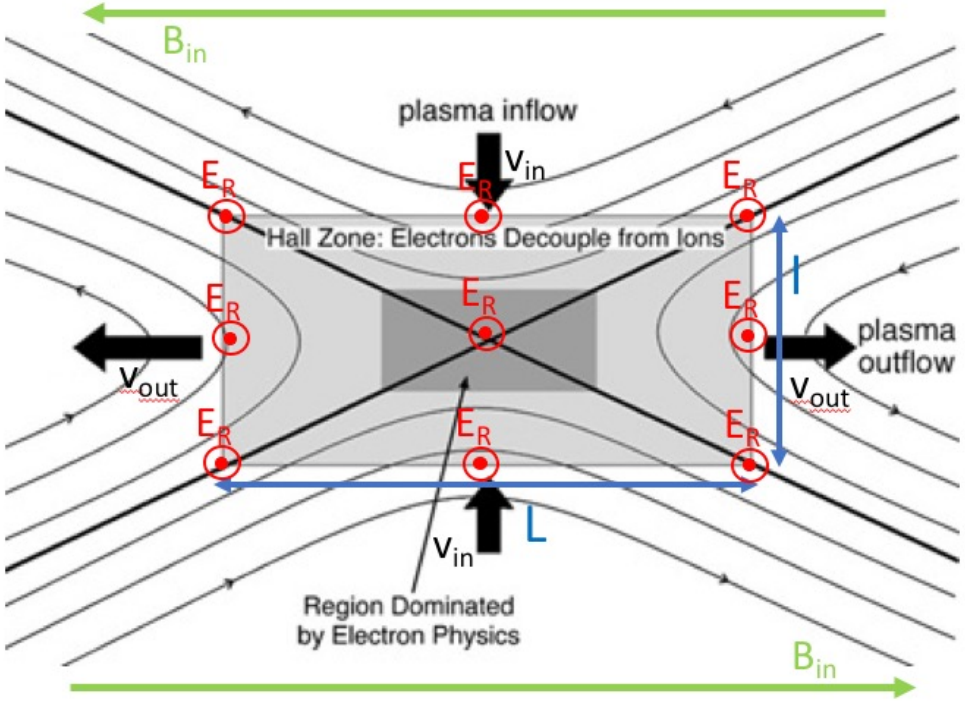


Based on 13 independent statistical studies, see Toledo-Redondo et al. (2021)

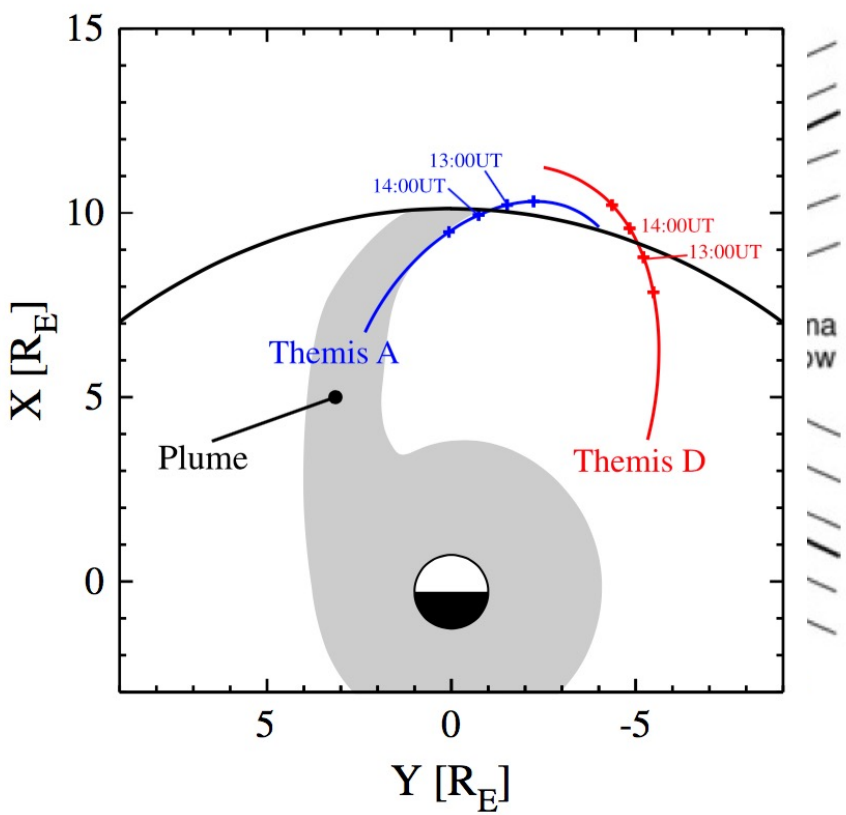
Mass-loading of reconnection



$E_R \sim B_{in}\, v_{out}\, (l/L)$

$V_{out} = v_A = B_{out}^2/(\mu_0 \rho_{out})$

Mass-loading of reconnection



$E_R \sim B_{in}\, v_{out}\, (l/L)$

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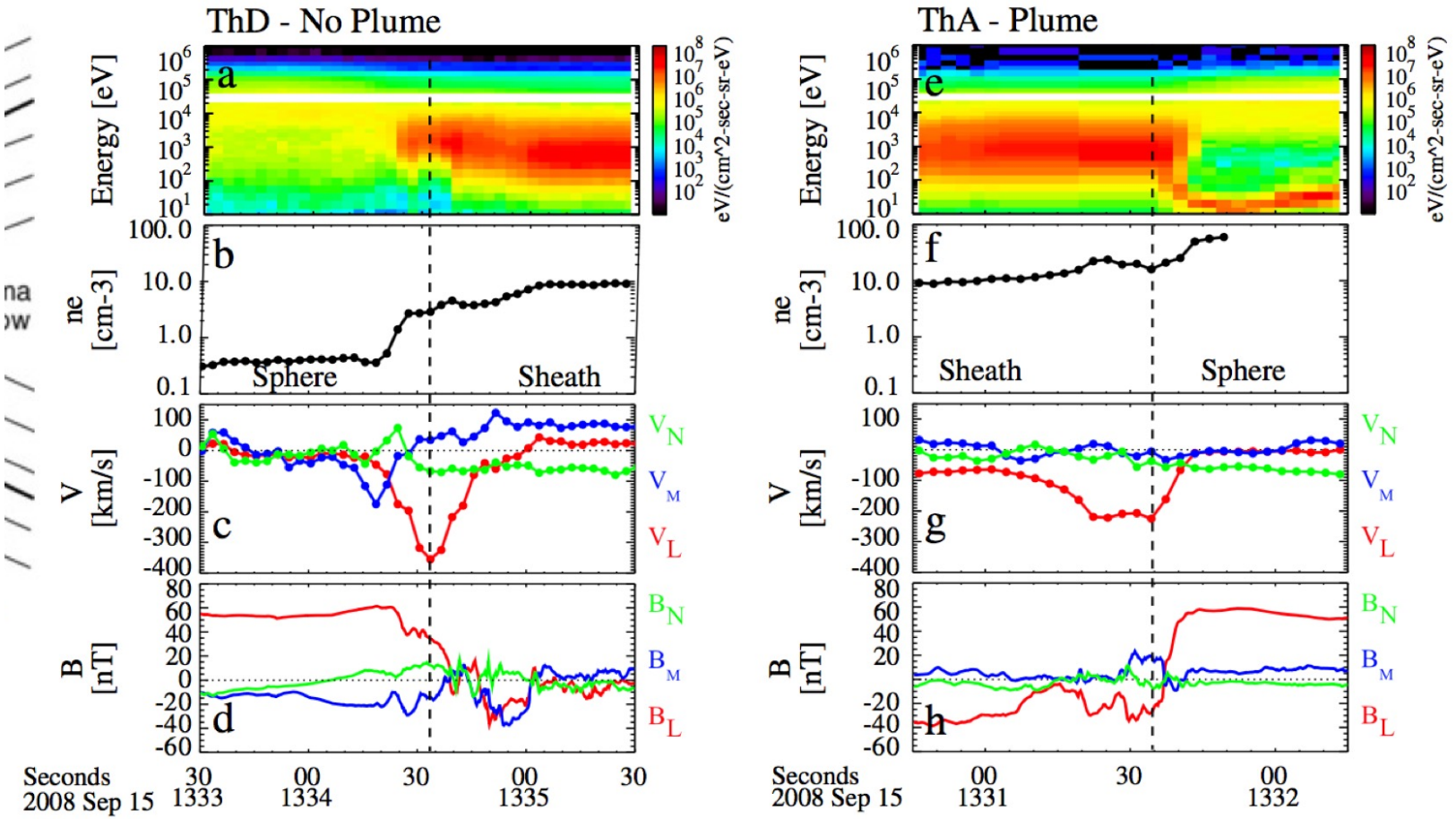

Walsh et al. (2013, 2014)

See also Borovsky and Denton (2006), Borovsky (2008), Borovsky et al. (2013)

Ionospheric ions and magnetic reconnection

Mass-loading the magnetopause locally

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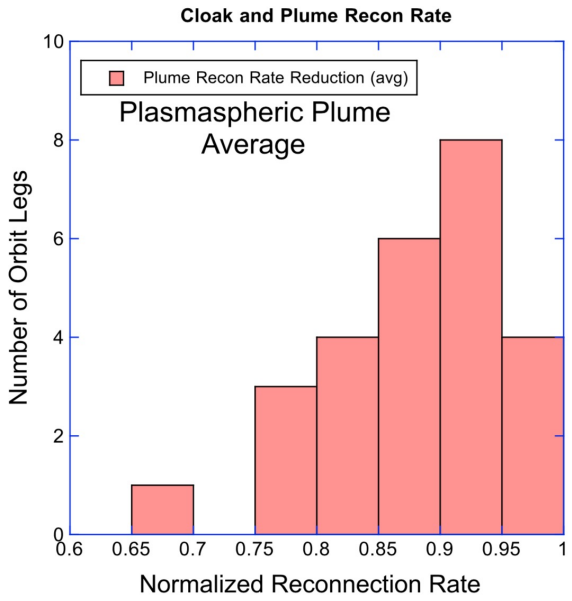
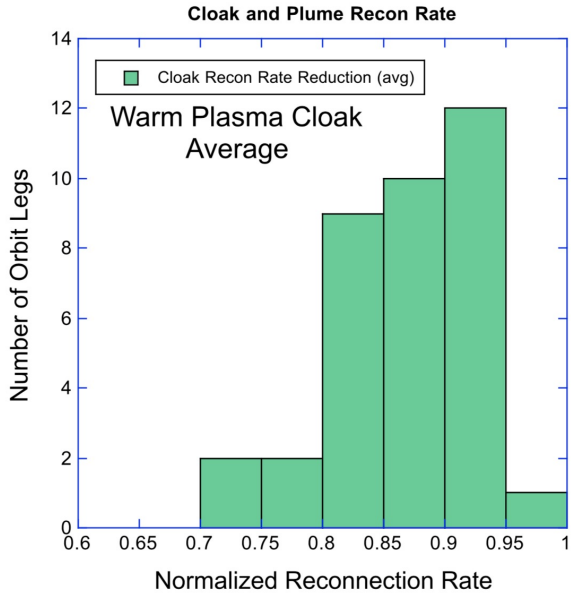
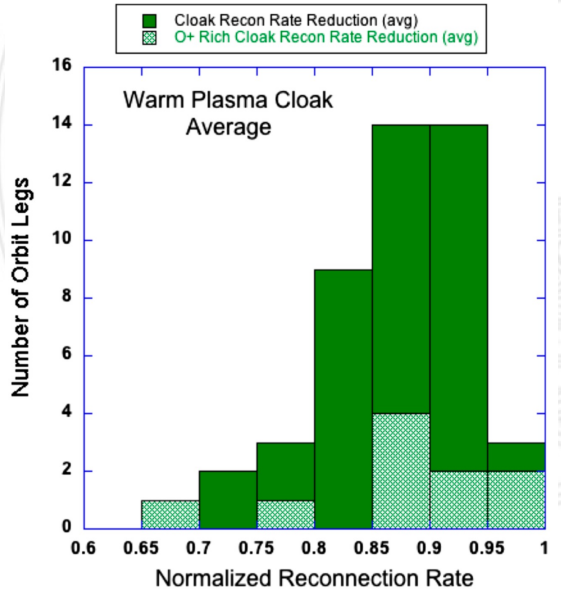
- Reduction in reconnection efficiency by >20% only during <5% of the time (Fuselier et al. 2017, 2019).
- During disturbed magnetospheric times (ie increased O^+), reduction in reconnection efficiency >20% during ~25% of the time.
- Observational evidence (not statistics) of 40% reduction due to plumes (H^+ and He^+)

$$R = \frac{E_{ML}}{E_s} = \frac{1}{\sqrt{1 + \frac{\rho_m B_s}{\rho_s B_m}}}$$

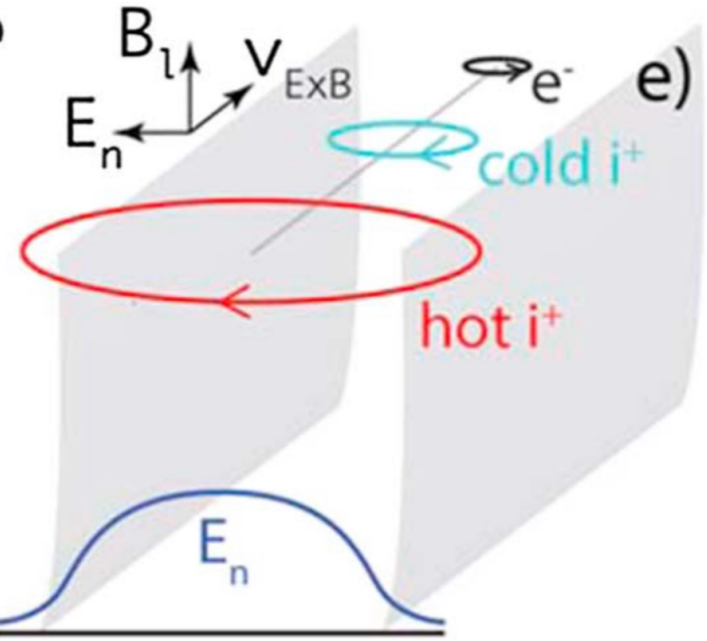






Fuselier et al. (2017, 2019, 2020)

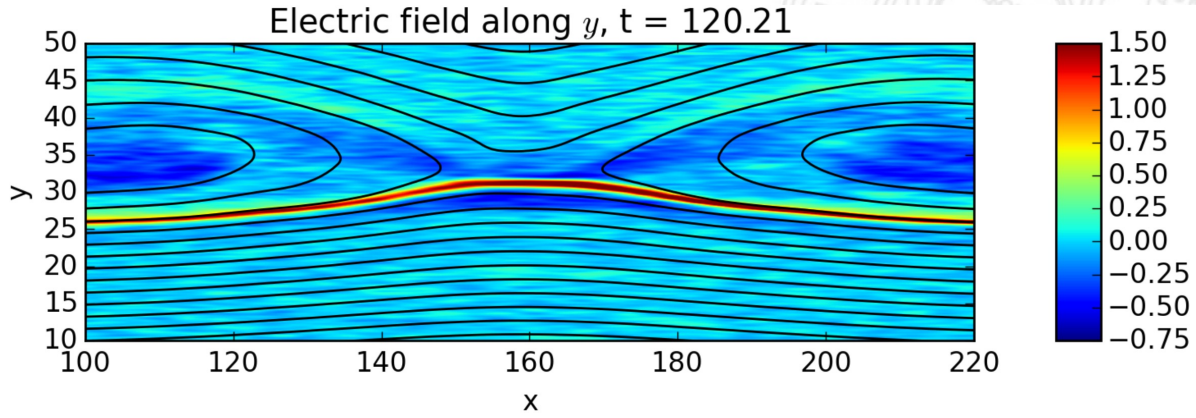
Additional length-scales in kinetic processes



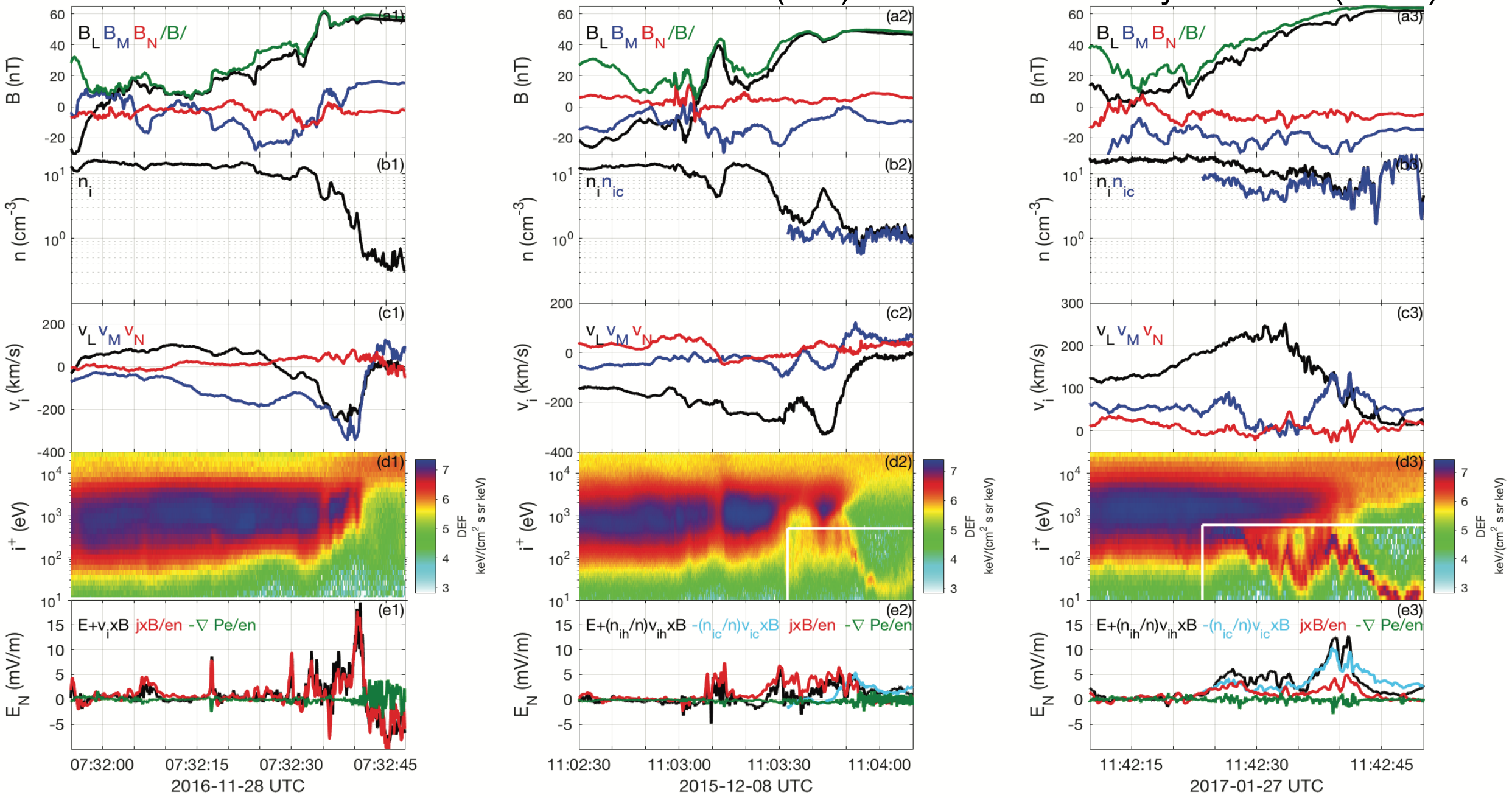
Toledo-Redondo et al. (2015)

$$\vec{E} = -\vec{v} \times \vec{B} + \frac{1}{ne}\vec{J} \times \vec{B} - \frac{1}{ne}\nabla \vec{\vec{P}}_e$$

$$\vec{E} = -\frac{n_h}{n}\vec{v}_h \times \vec{B} - \frac{n_c}{n}\vec{v}_c \times \vec{B} + \frac{1}{ne}\vec{J} \times \vec{B} - \frac{1}{ne}\nabla \vec{\vec{P}}_e$$



"**Cold ions** introduce a **new length-scale** owing to their smaller gyroradius. They can reduce the perpendicular currents at these scales."



André et al. (2016), Toledo-Redondo et al. (2018)

Ionospheric ions and magnetic reconnection

Cold ion diffusion region

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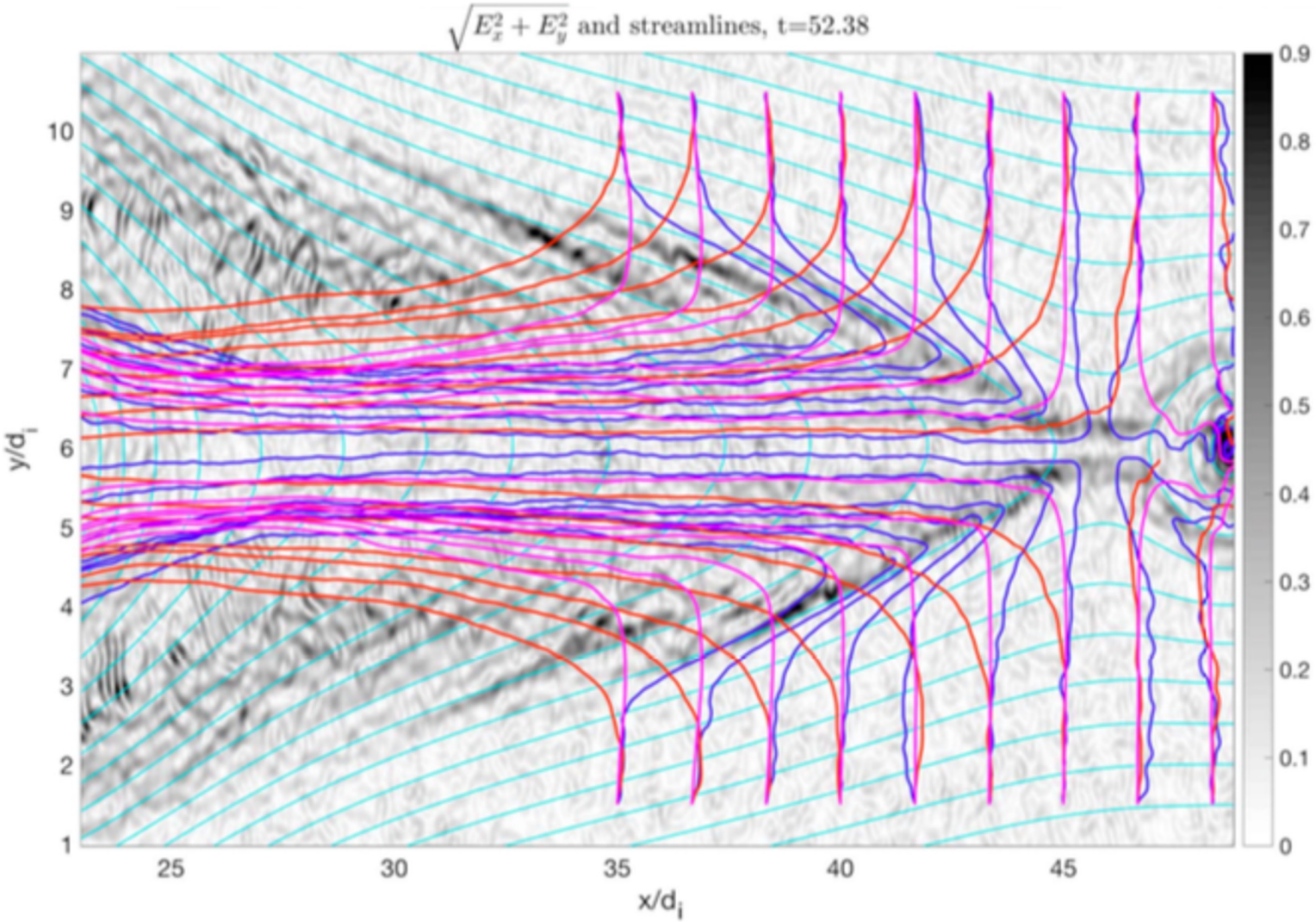
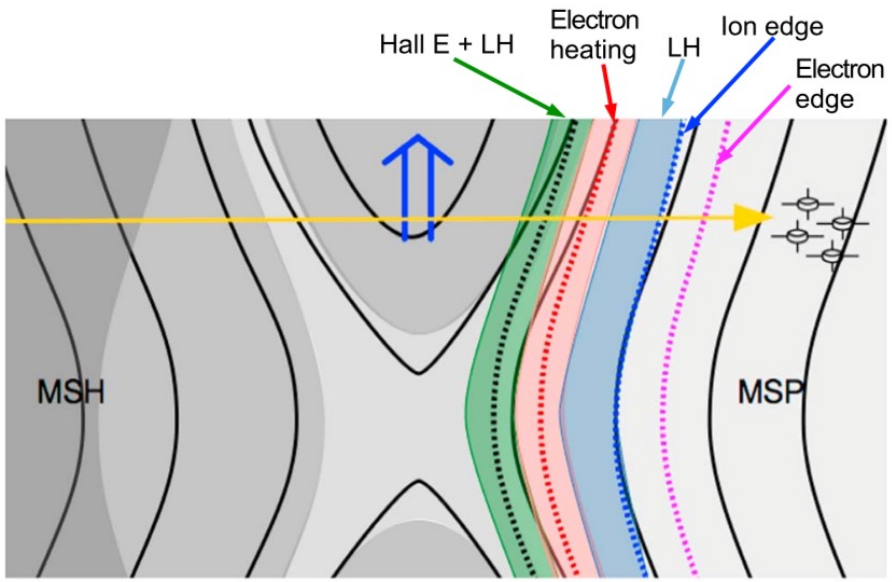
electrons
cold ions
hot ions



Divin et al. (2016)

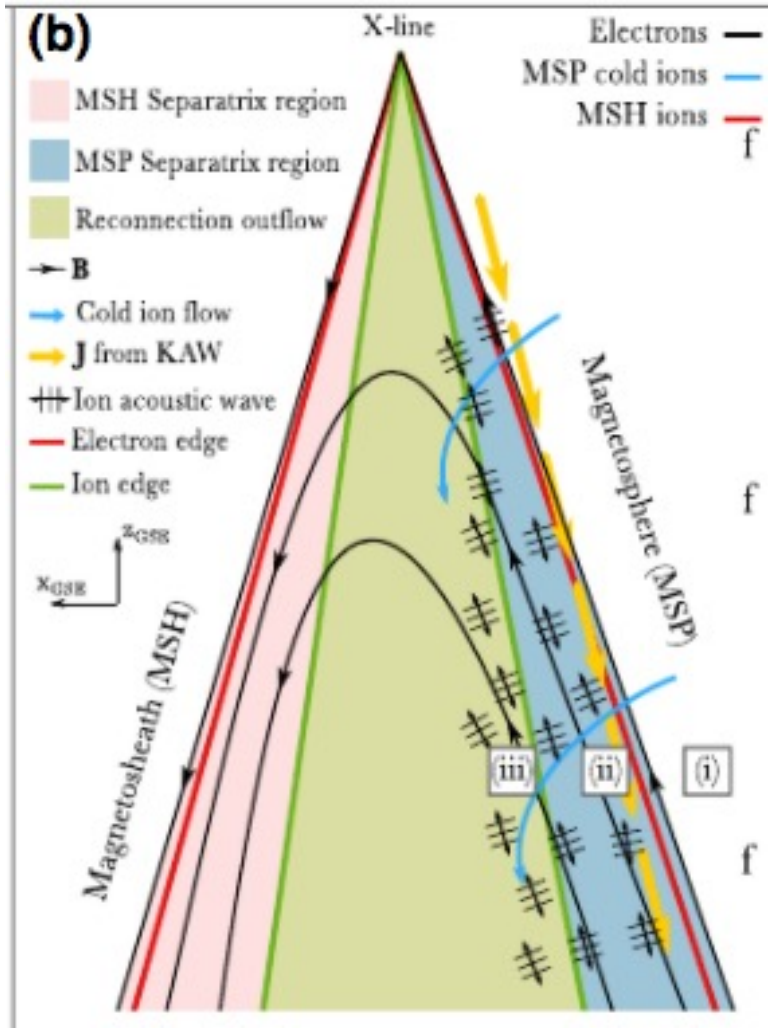
Ionospheric ions and magnetic reconnection

Cold ion heating mechanisms



The relative motion between the magnetized cold ions and the magnetosheath ions favours **an ion – ion drift instability** at the separatrix that generates **lower hybrid drift waves**. These waves can **heat the cold ions** and demagnetize them.

Graham et al. (2017)



Ion acoustic waves are formed in the separatrix and outflow region of dayside reconnection

88% of the IAW observed at the magnetopause during 5 months of MMS data are in association to cold ions ($n_c/n > 0.6$)

Steinvall et al. (2021)

Ionospheric ions and magnetic reconnection

Cold ion heating and energy budget

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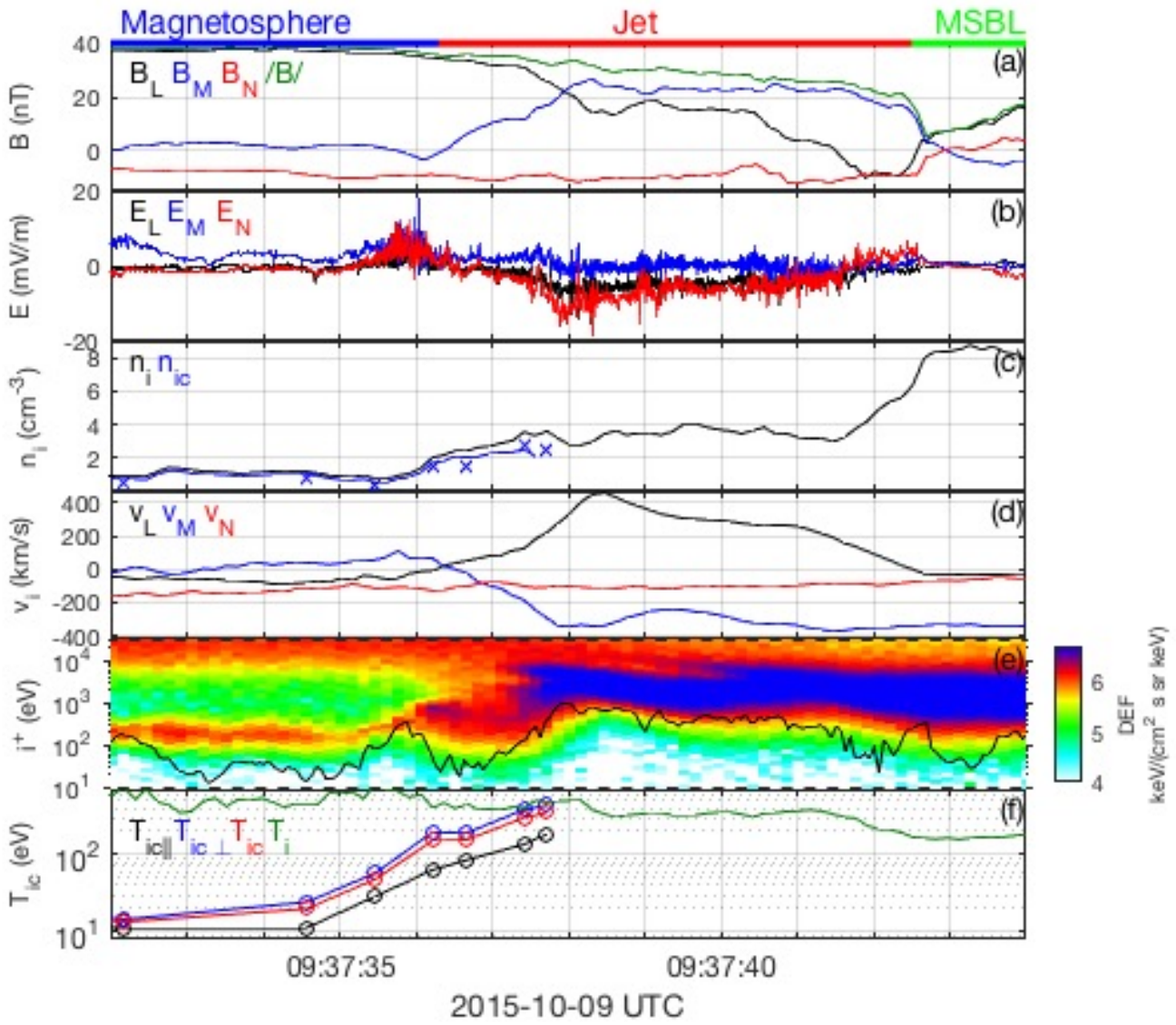

Toledo-Redondo+, GRL, (2016b)
Toledo-Redondo+, JGR, (2017)

Some open questions for the community

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Table 4
Summary of Open Questions in the Role of Ionospheric Ions and Magnetic Reconnection in the Magnetosphere

Global magnetospheric dynamics	What is the relative contribution of solar wind versus ionospheric-originating H^+ to the magnetosphere?
	How is the plasma sheet formed?
	Does the variable magnetospheric density affect the global coupling with the solar wind efficiency?
Kinetic physics of magnetic reconnection	How do the microphysics introduced by multiple ion populations change reconnection at MHD scales?
	Does the WPC alter the suppression of magnetic reconnection?
	Which portion of the reconnection energy is taken by cold and heavy ions?
	What are the effects of cold electrons in magnetic reconnection?
	How ionospheric ions in the plasma sheet condition the onset of magnetic reconnection?

Abbreviation: WPC, warm plasma cloak.

Conclusions

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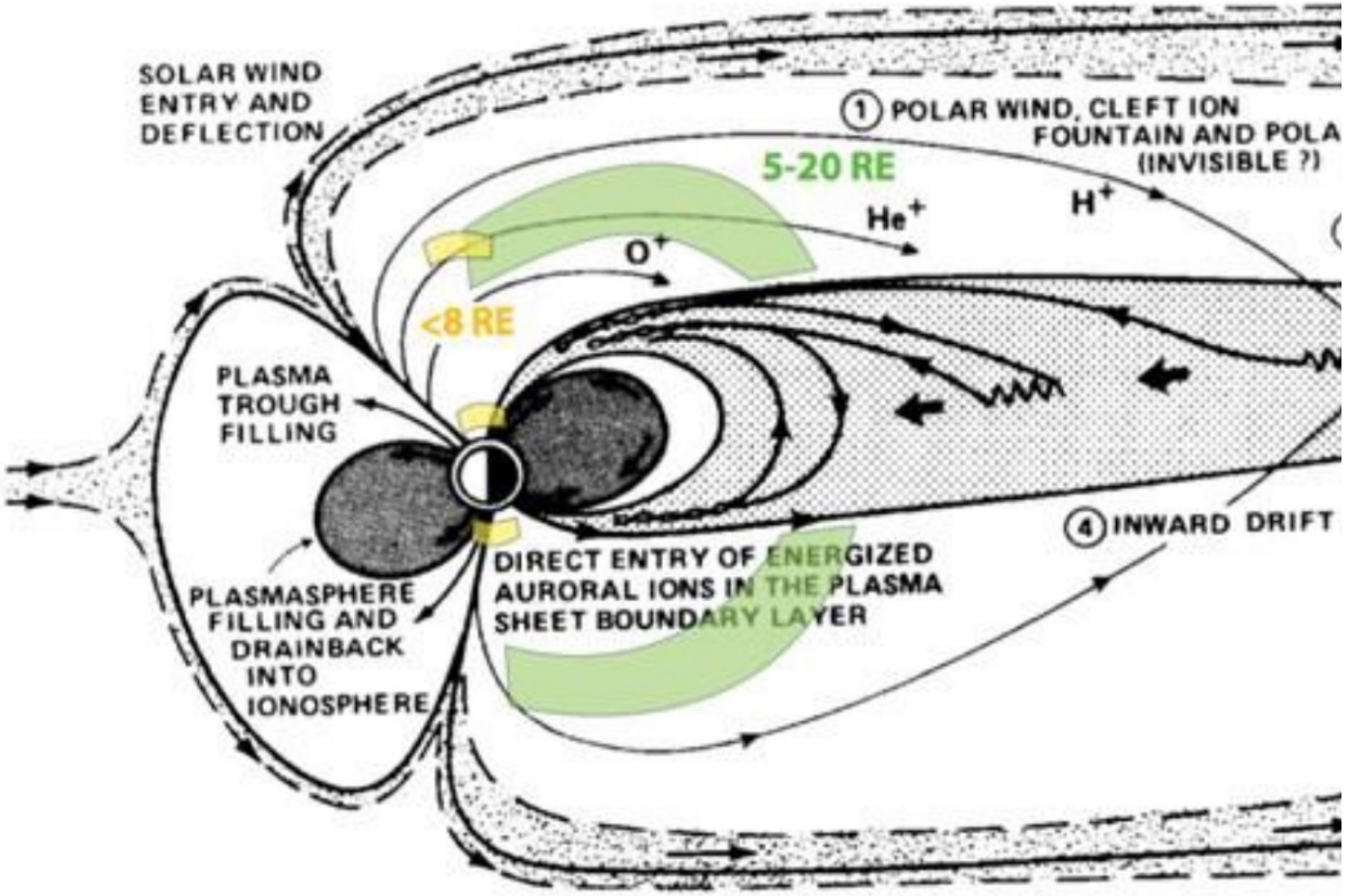
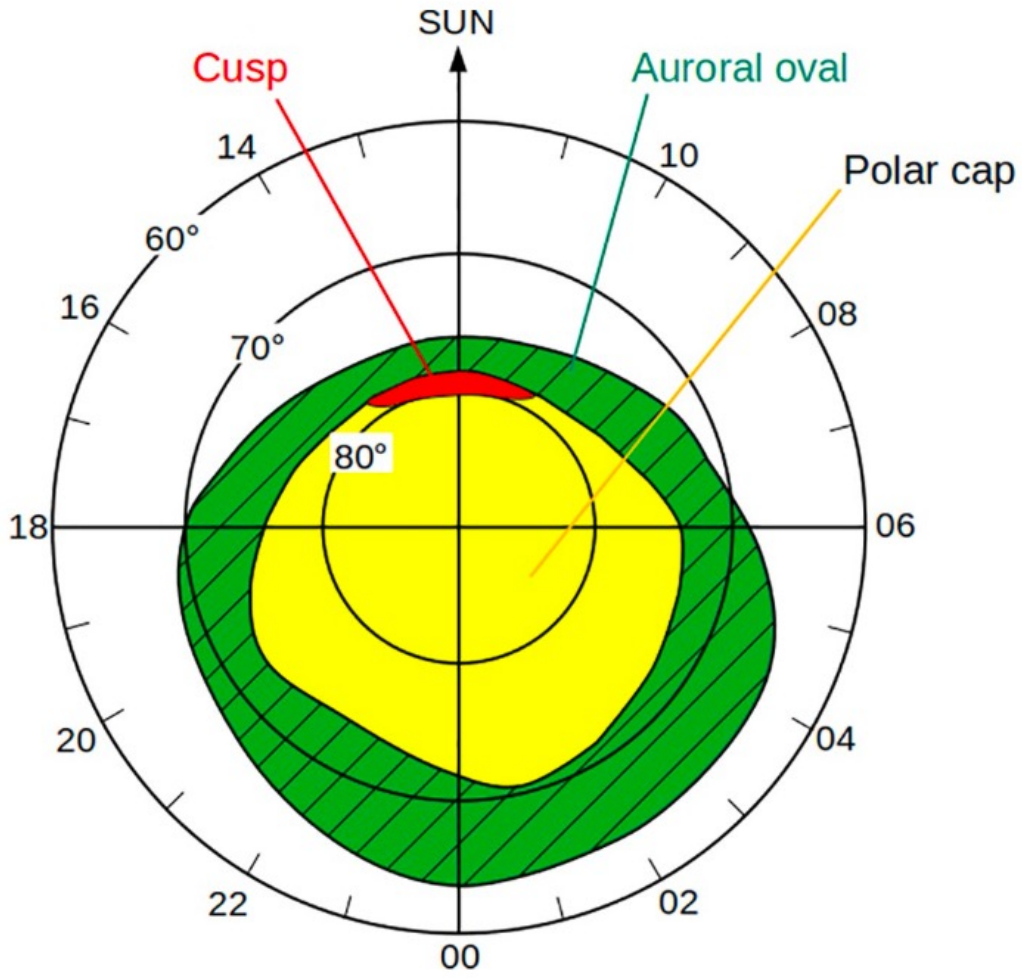
- The **ionosphere** is a **primary supplier** of plasma to the Earth's magnetosphere, together with the solar wind (roughly same order of magnitude)
- Changes in global coupling to SW due to **mass-loading** of the magnetosphere are **significant only during disturbed conditions** of the magnetosphere.
- Ionospheric populations introduce **new time and length-scales** into magnetic reconnection and **modify kinetic processes (reconnection, micro-instabilities)**
- How these **microphysics** changes affect the magnetosphere dynamics on **global scales** remains **unknown**

THANK YOU

Introduction
Ionospheric outflows



Chappell et al. (1987, 2000)



Akasofu (2015)

Cold ion and electron VDFs measurement

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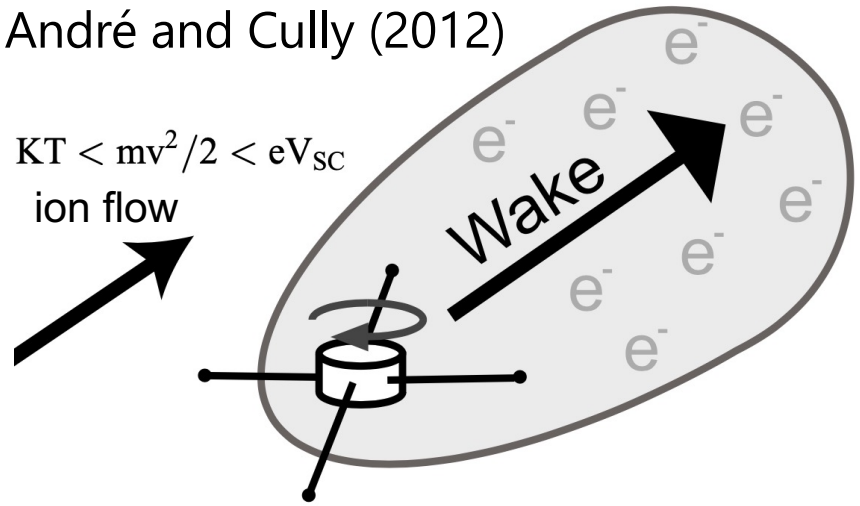
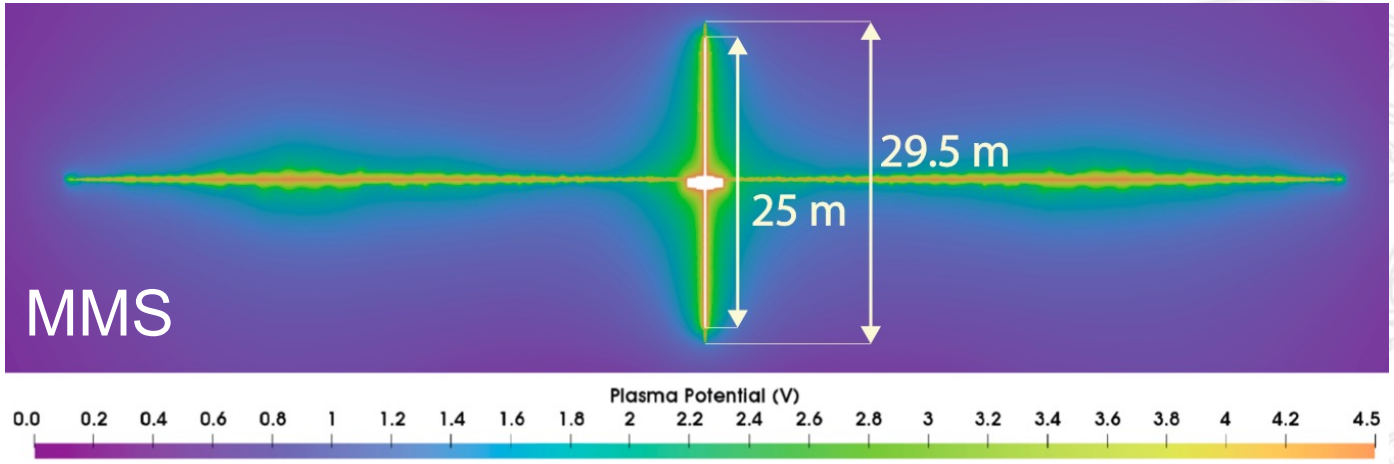
André and Cully (2012)





Toledo-Redondo et al. (2019)

Spacecraft charging prevents or hinders measurement of cold VDFs

Ionospheric ions at the dayside magnetopause

Review of statistical studies

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- Dusk side magnetopause (dominated by detached plasmaspheric material)
  - Cold ionospheric protons are present >80% of the time, with densities of few tenths of cm^{-3}
  - During 20 – 25 % of the time, cold proton density is > 3 cm^{-3} (mainly plumes)

- Dawn side magnetopause (dominated by WPC)
  - Cold ionospheric protons are present 50 – 70 % of the time, with densities of few tenths to few cm^{-3}
  - During ~10 % of the time, cold proton density is > 3 cm^{-3}

- Plasma sheet ions are both of ionospheric and solar wind origin, and have densities of up to ~0.5 cm^{-3} near the magnetopause

Ionospheric ions and magnetic reconnection

O^+ in magnetotail, reconnection onset

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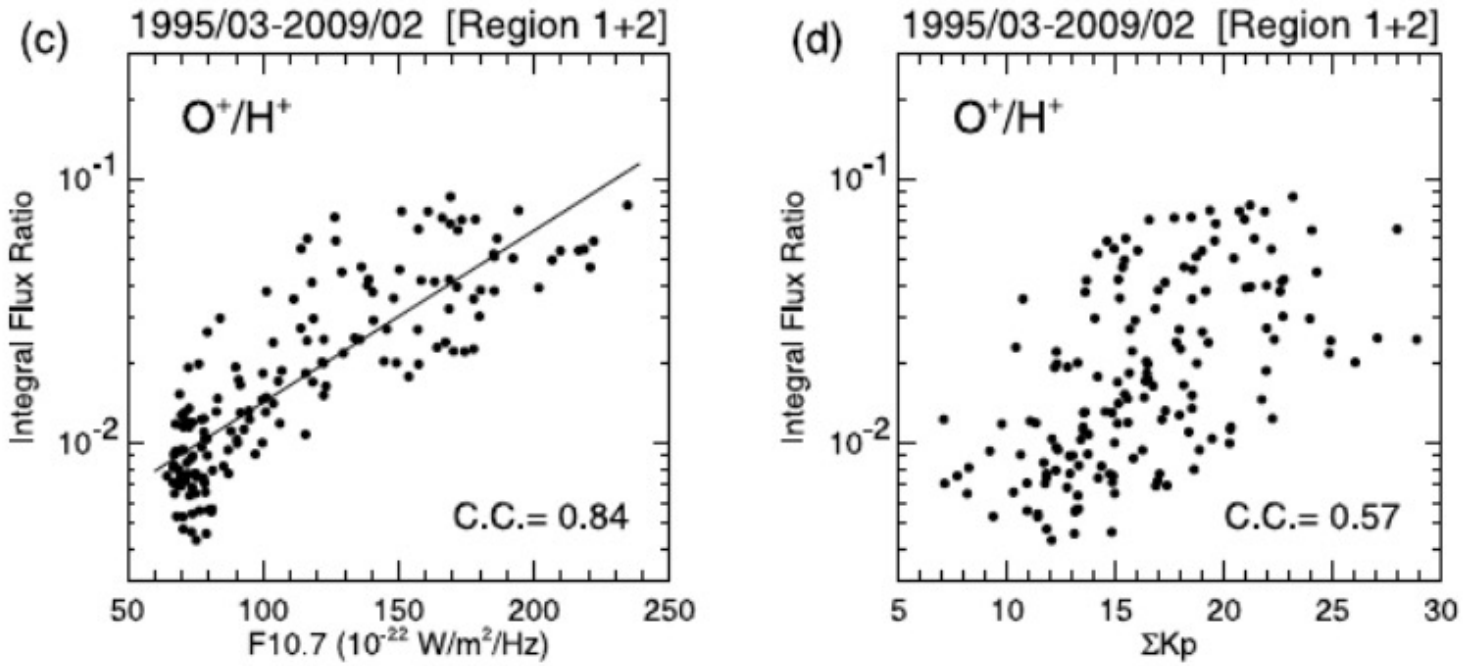
- The presence of O+ should make the tail more unstable to tearing instability (eg Baker et al. 1982)
- Various statistical studies seem to find the opposite (eg Liu et al 2013, Liao et al 2014, Lennartsson et al. 1993, Nosé et al. 2009)



Nosé et al. (2009)