The low-latitude boundary layer (LLBL)

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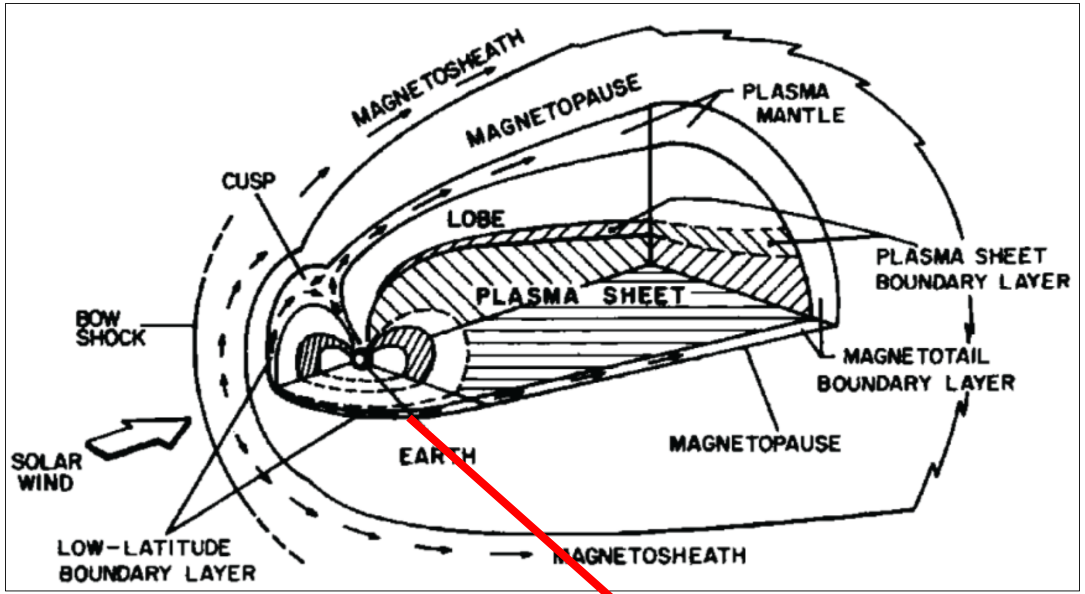

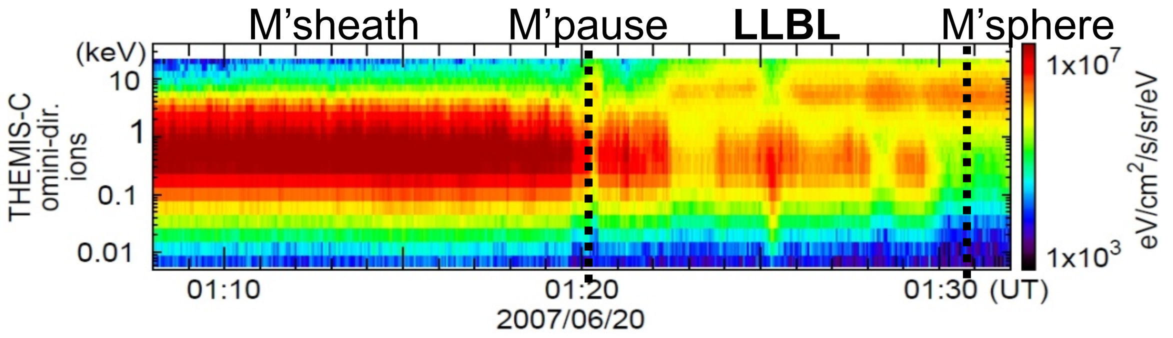

A note of my talk:

My speech is awkward by stuttering disability ☹

But, enjoy my talk!
- the content is not awkward ☺
- science has no borders ☺

Outline

1. Observational features of LLBL

- Basic structures
- IMF dependences
- Local time dependences
- Coupling with ionosphere

2. Candidate formation mechanisms

- Magnetic reconnection
- Kelvin-Helmholtz (KH) instability
- Kinetic Alfvén waves (KAWs)
- Cross-process couplings

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Basic features

"The Plasma Boundary Layer and Magnetopause Layer of the Earth's Magnetosphere"
PhD thesis by Eastman [1979]

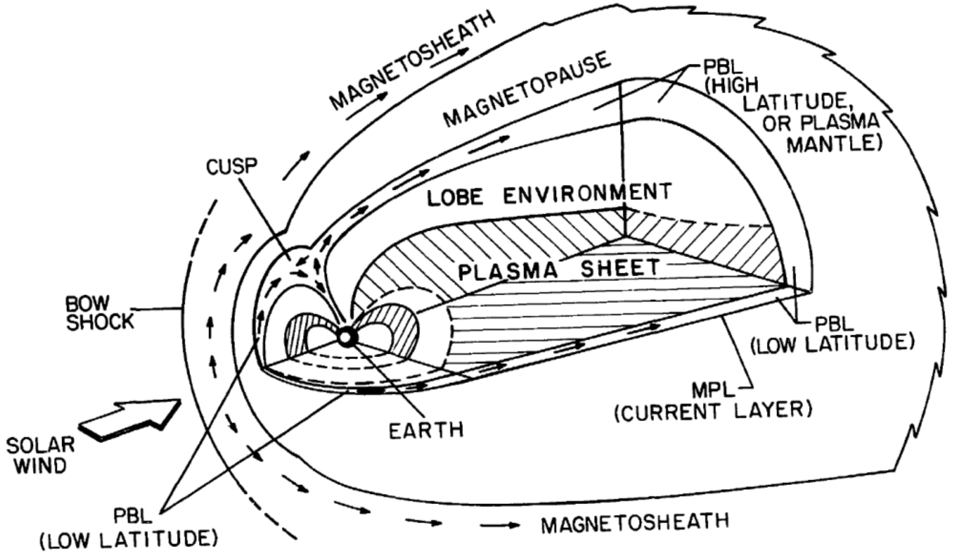


Figure 1.1 A sketch of the earth's magnetosphere showing the plasma boundary layer (PBL) and magnetopause layer (MPL).

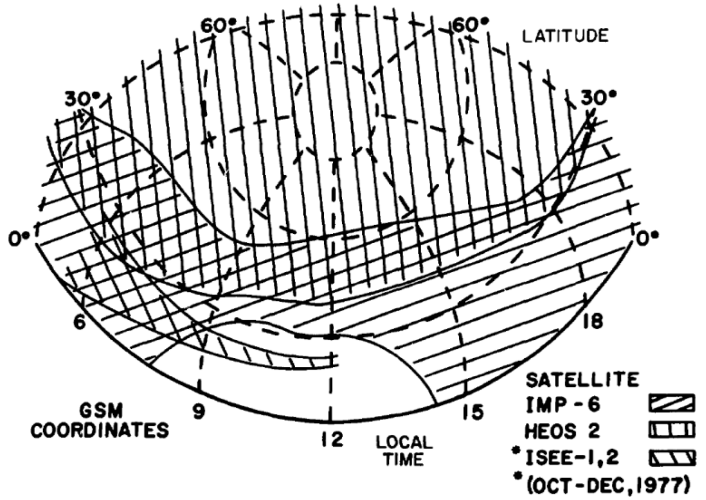


Figure 2.2.2 Satellite coverage of the sunward magnetopause and plasma boundary layer (PBL) for IMP 6, HEOS 2 and the ISEE 1 and ISEE 2 satellite pair. ISEE coverage is given only for October-December, 1977.

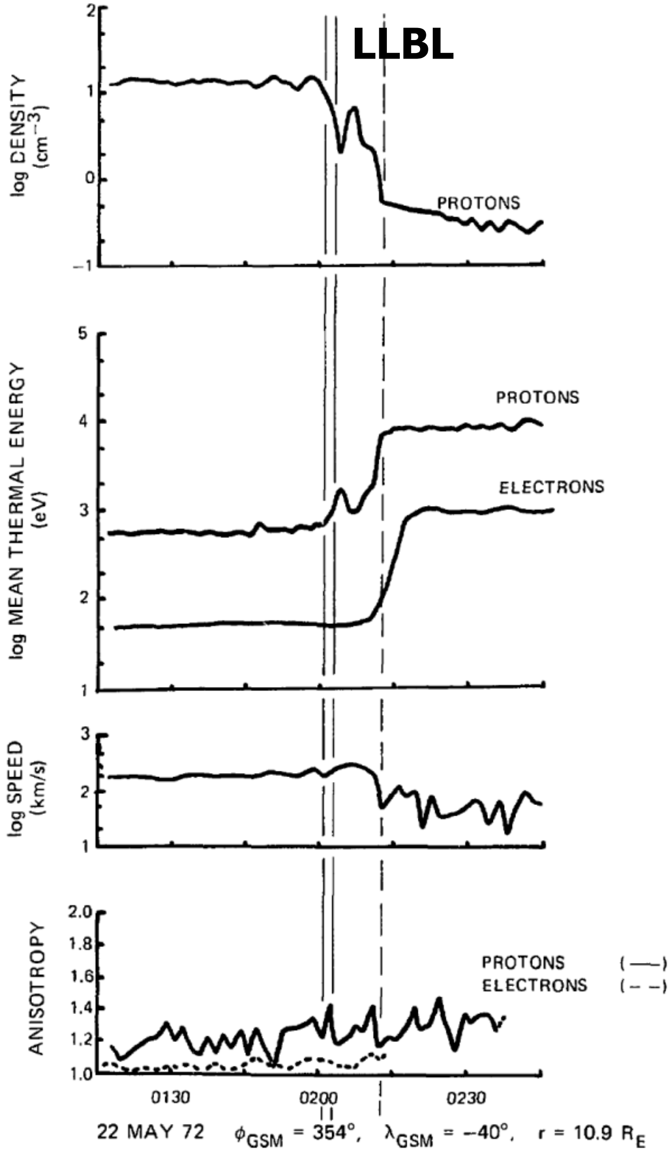


Figure 2.3.6.1 22 May 1972 plasma data.

- In the 1970's, in-situ observations initially explored various boundary layers in the Earth's magnetosphere.

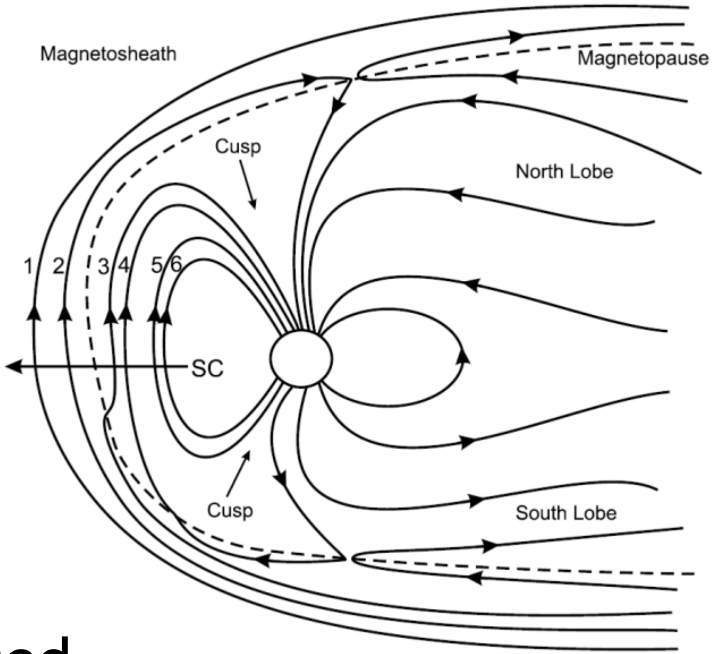
Basic features

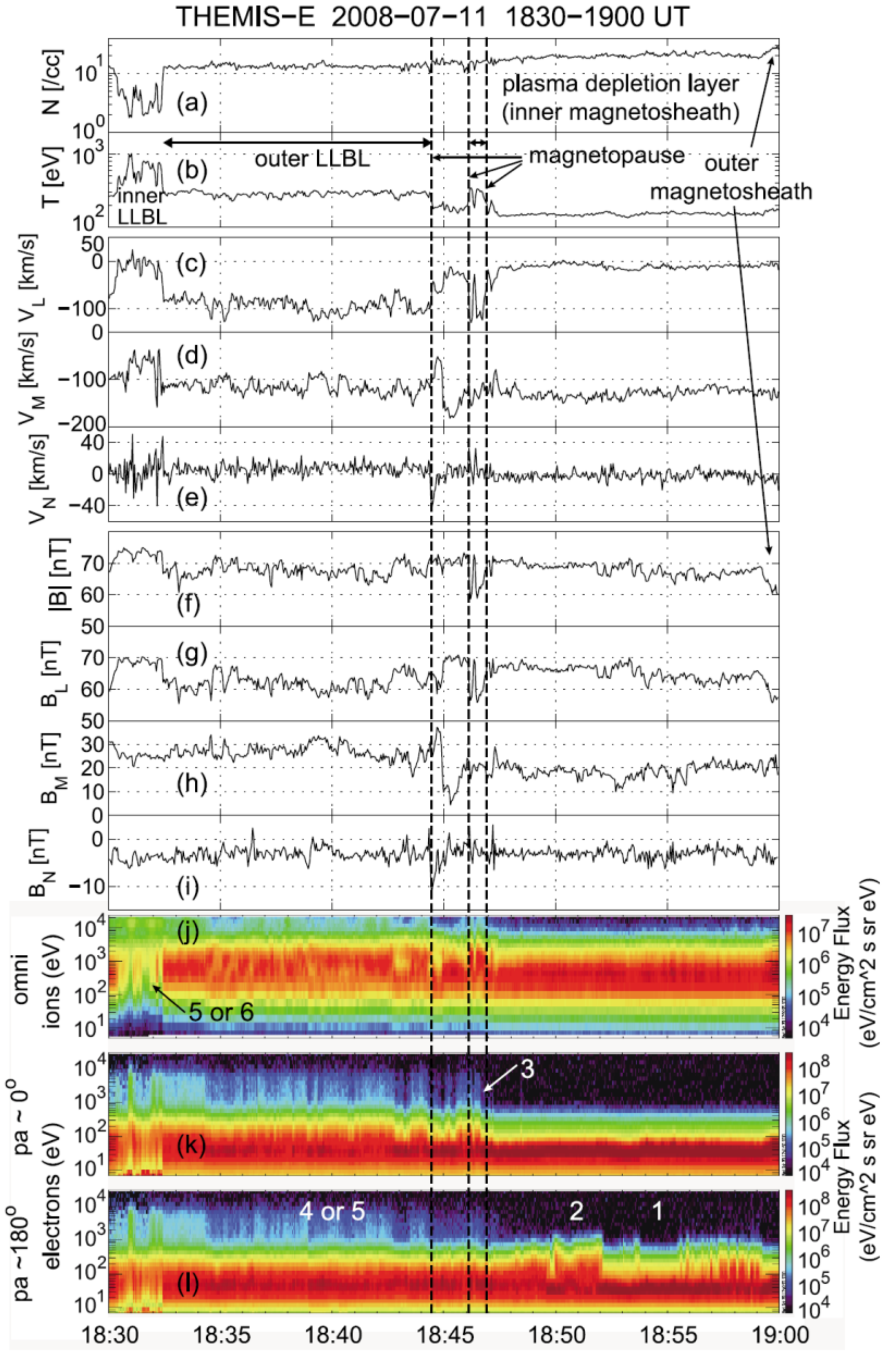
- In the last 50 years, the development of observational techniques/resources enabled to know detailed structure of the LLBL.

- Magnetopause has a multi-layered structure.
  - PDL(1), MSBL(2), LLBL(4-6)

- LLBL has a distinct (at least) two-layered structure.
  - Inner LLBL: closed
  - Outer LLBL: newly closed

Hasegawa [2012]





IMF dependences

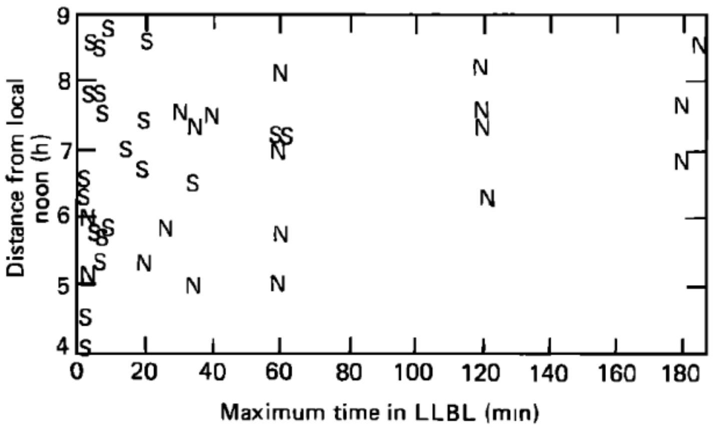
- LLBL tends to be thicker during northward IMF.

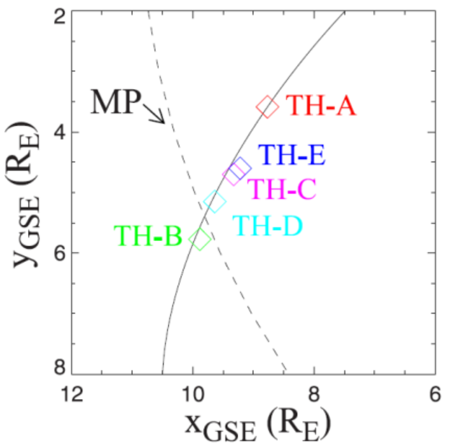
- Multi-spacecraft observations revealed the steady expansion of the LLBL during northward IMF.

Mitchell+ [1987]

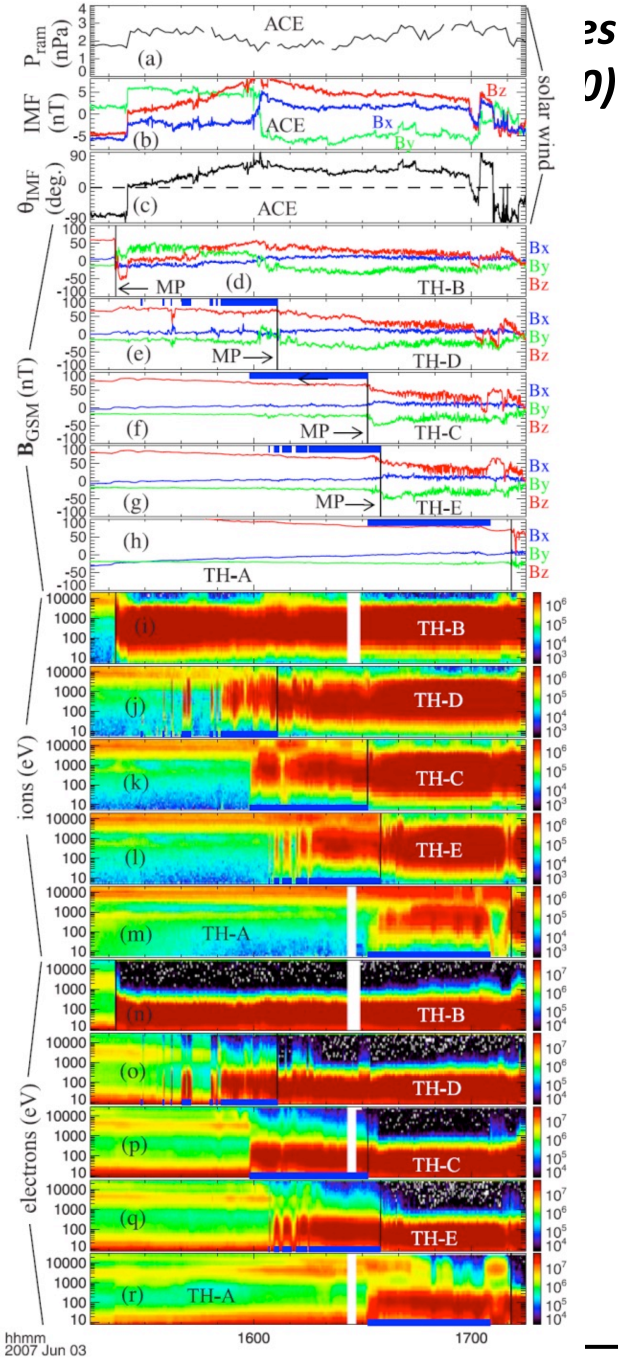
Southward IMF (S)		
Dawn	13 passes	Average = 13.8 minutes Median = 5 minutes
Dusk	8 passes	Average = 15 minutes Median = 7 minutes
Northward IMF (N)		
Dawn	13 passes	Average = 90 minutes Median = 60 minutes
Dusk	6 passes	Average = 46 minutes Median = 38 minutes

(a)





Øieroset+ [2008]

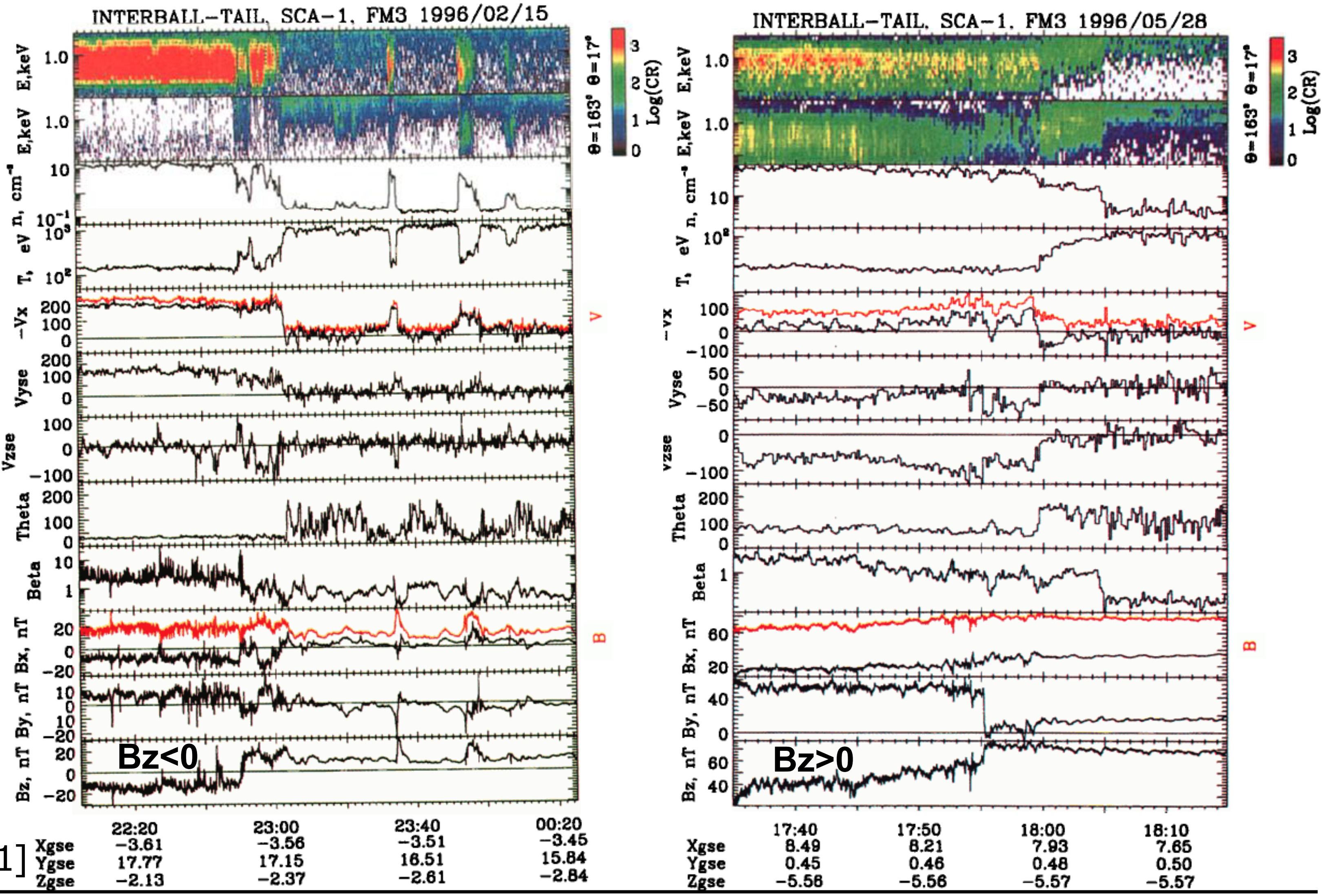


IMF dependences

- When IMF is southward, LLBL tends to be highly-structured, and frequently shows transients such as FTEs.
  →by low-lat. reconnection.

- When IMF is northward, LLBL tends to be weakly-structured.

LLBL is thicker and steady during the northward IMF.



Vaisberg+ [2001]

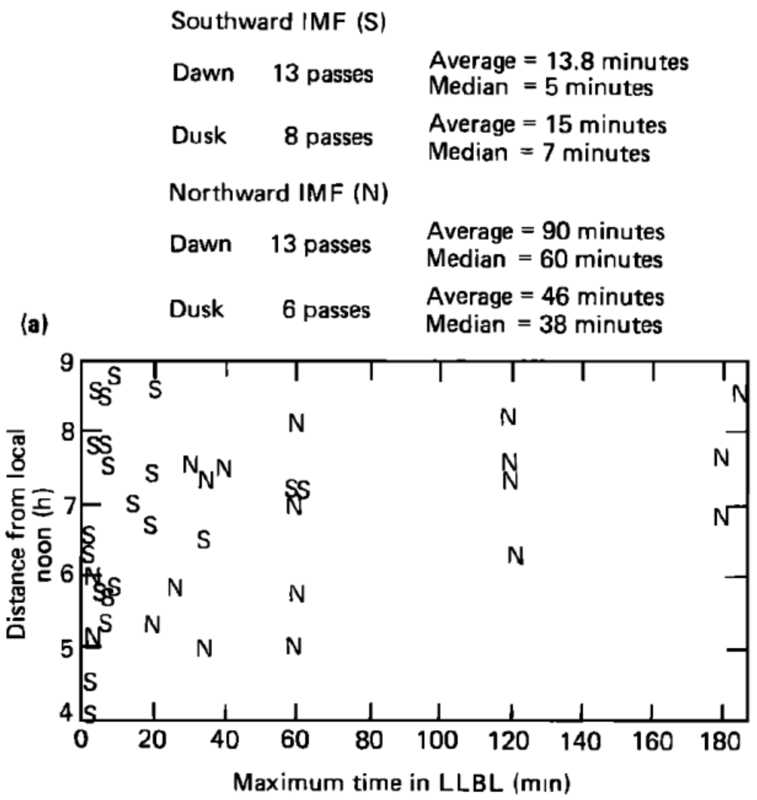
Local time dependences

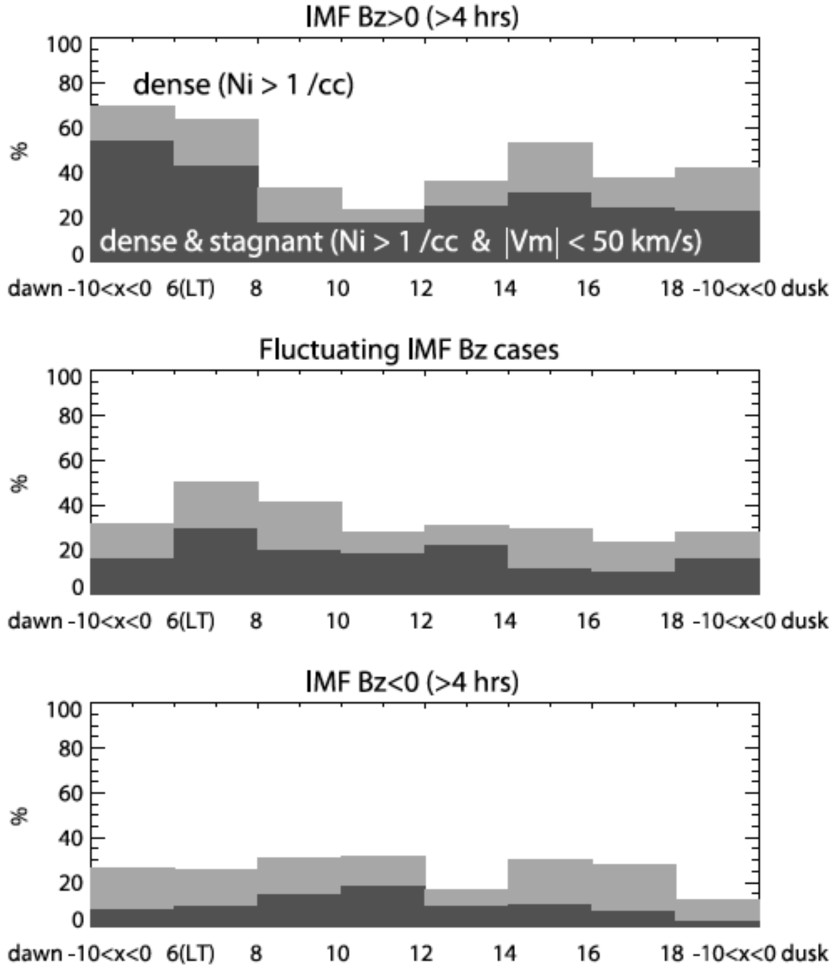
- The LLBL thickness tends to increase with increasing downtail distance.

- The dense & stagnant LLBL often appears in the flank-to-tail region especially on the dawnside.

→ More solar wind entry occurs in a more taiward region on the dawnside?

Mitchell+ [1987]

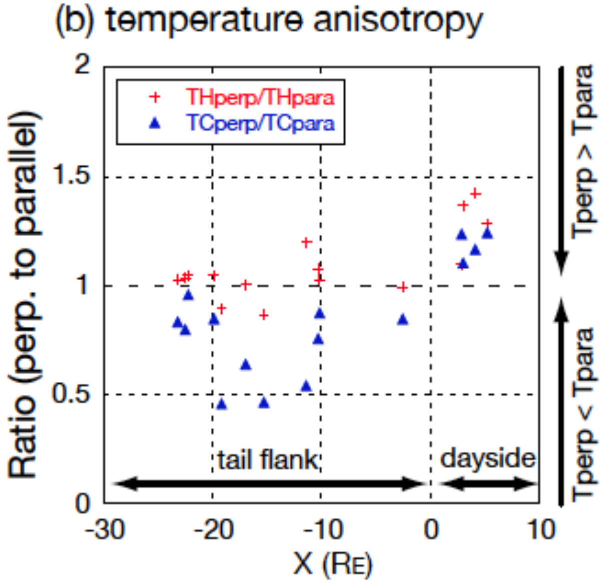




Hasegawa+ [2004a]

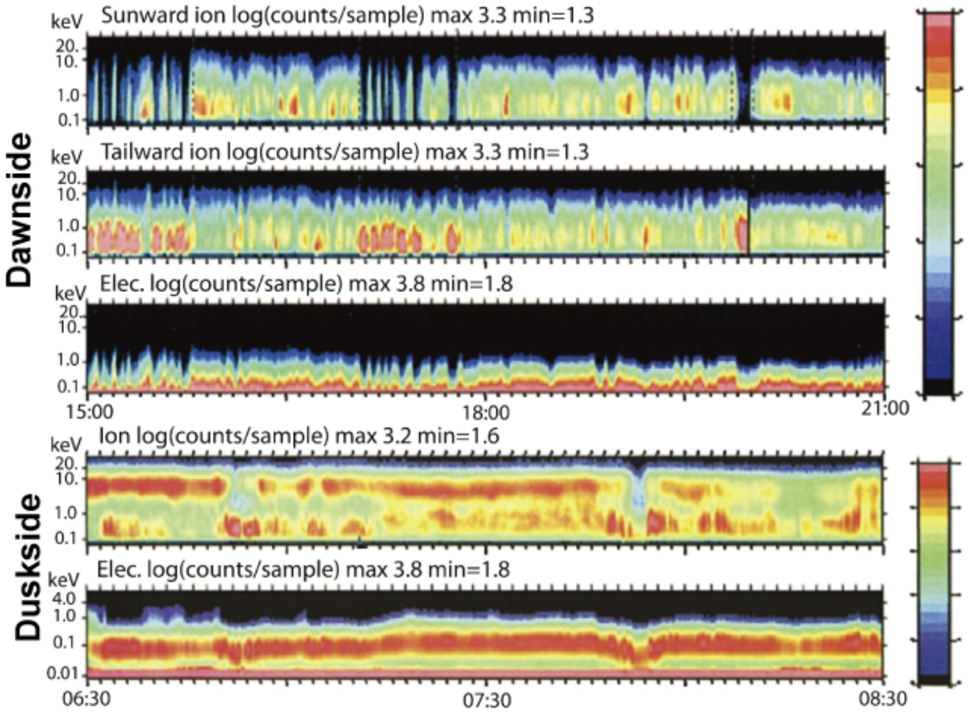
Local time dependences

- $T_{e\perp} < T_{e\parallel}$: whole LLBL
- $T_{i\perp} > T_{i\parallel}$: dayside
- $T_{i\perp} < T_{i\parallel}$: flank-to-tail
- $T_{i\parallel}$ is increasing with increasing distance from the subsolar point.



Nishino+ [2007]

Fujimoto+ [1998]

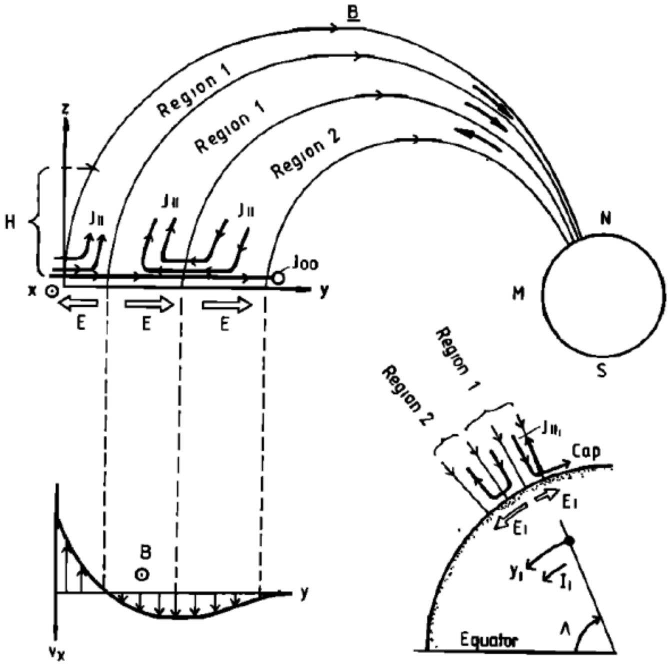


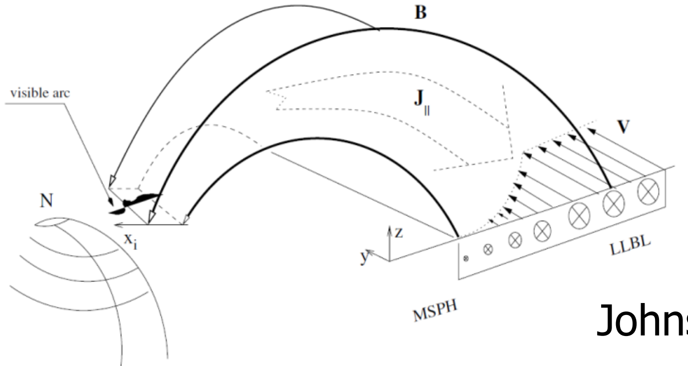
- A clear dawn-dusk asymmetry is seen in the ion energy spectrum in the LLBL.
  - Duskside: two distinct components (M'sphere & M'sheath components)
  - Dawnside: one-component (M'sheath-like low energy component is heated)

Coupling with ionosphere

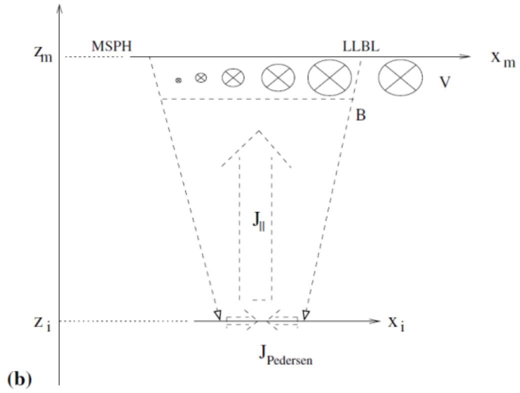
- Velocity shear across the LLBL can drive the field-aligned currents (FACs).
- Theoretical model of the FACs are well consistent with the observed currents.

Sonnerup [1980]

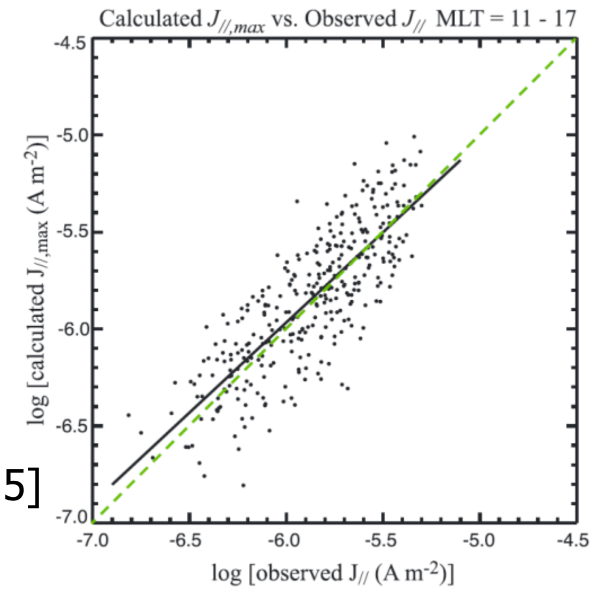




Johnson & Wing [2015]



Wing & Johnson [2015]



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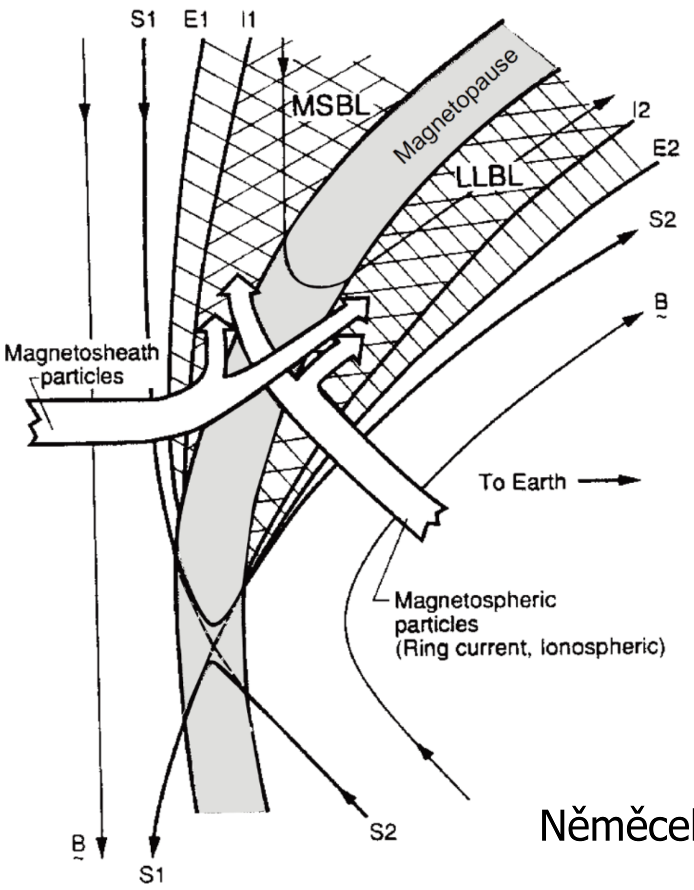
Reconnection

Southward IMF

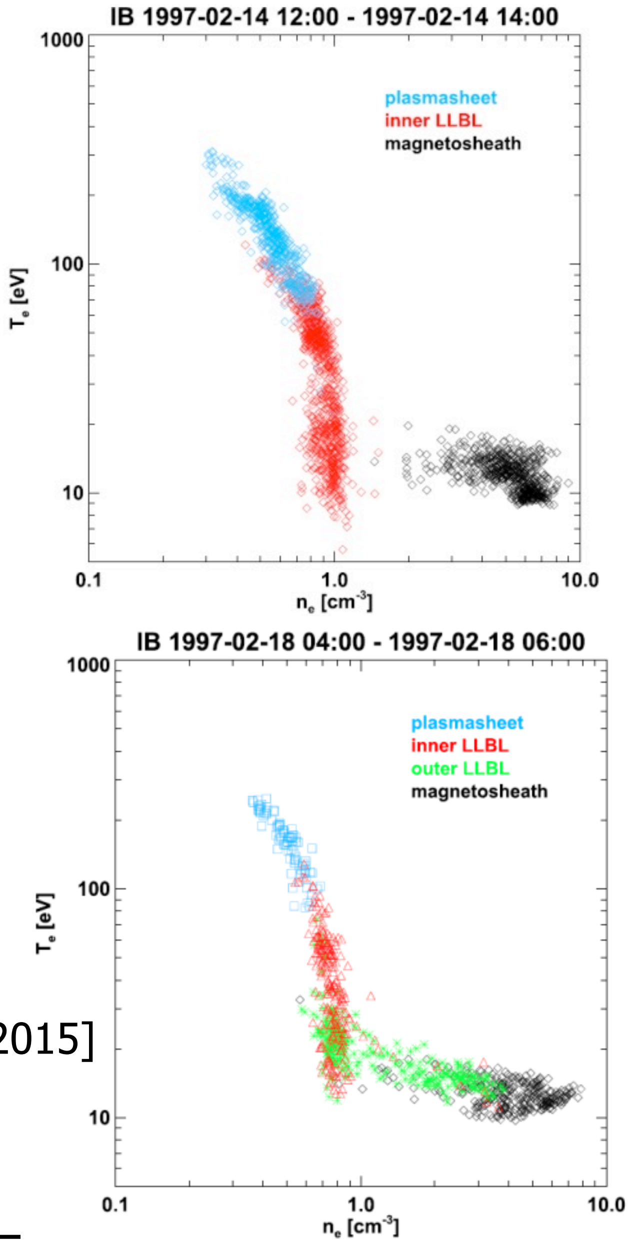
- Reconnection is expected to occur at low-latitude, leading to transient formation of LLBL.

- LLBL can also be peeled away by low-latitude reconnection.

→ may explain why LLBL is thinner and highly-structured during the southward IMF.



Gosling+ [1990]

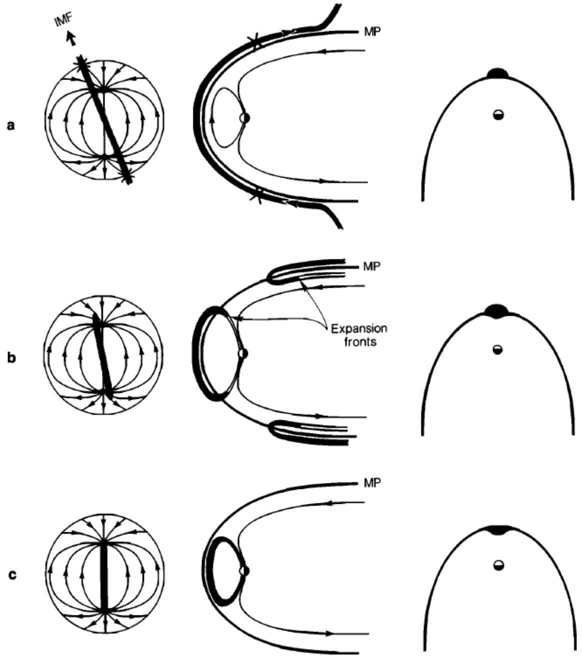


Němeček+ [2015]

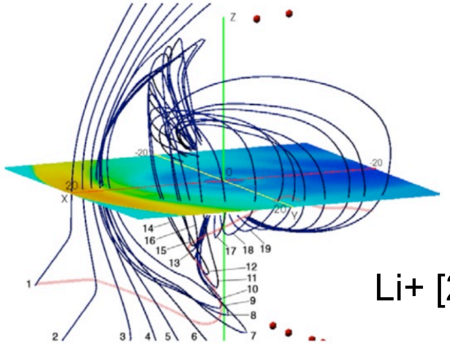
Reconnection

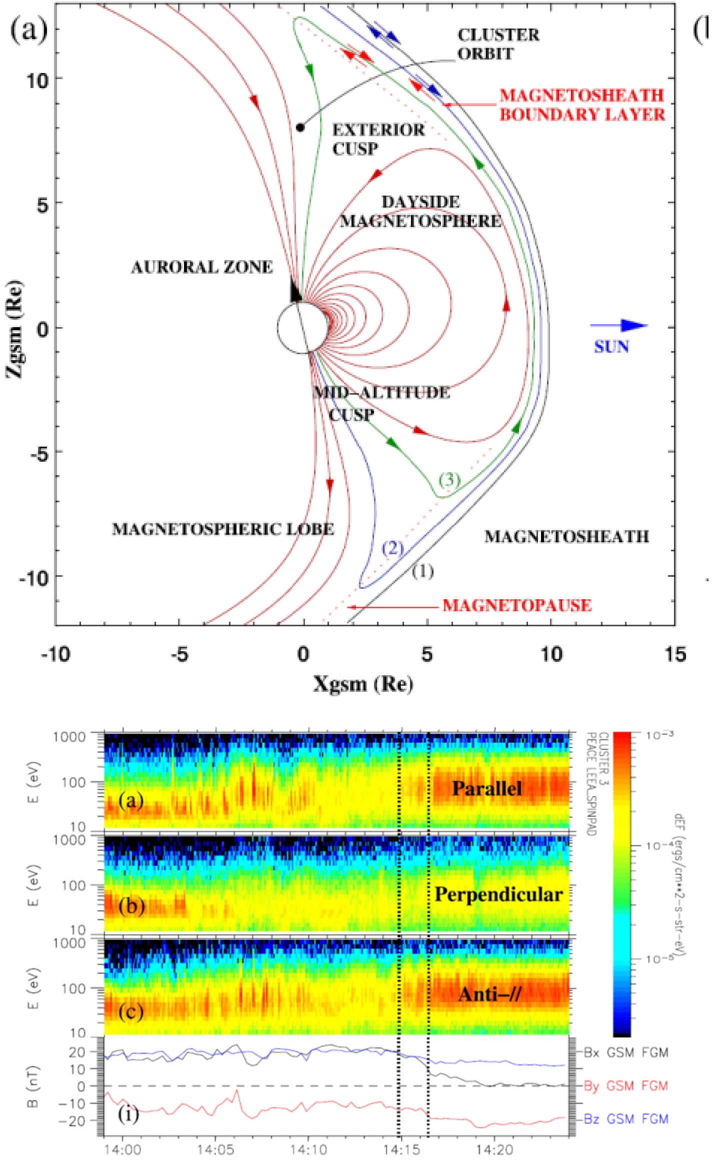
Northward IMF

- Reconnection is expected to occur behind the cusps.
- Double high-latitude reconnection lead to the formation of the dayside LLBL.
- Bi-directional heated electrons confirmed the occurrence of double high-lat. Reconnection.



Song & Russell [1992]


Li+ [2005]



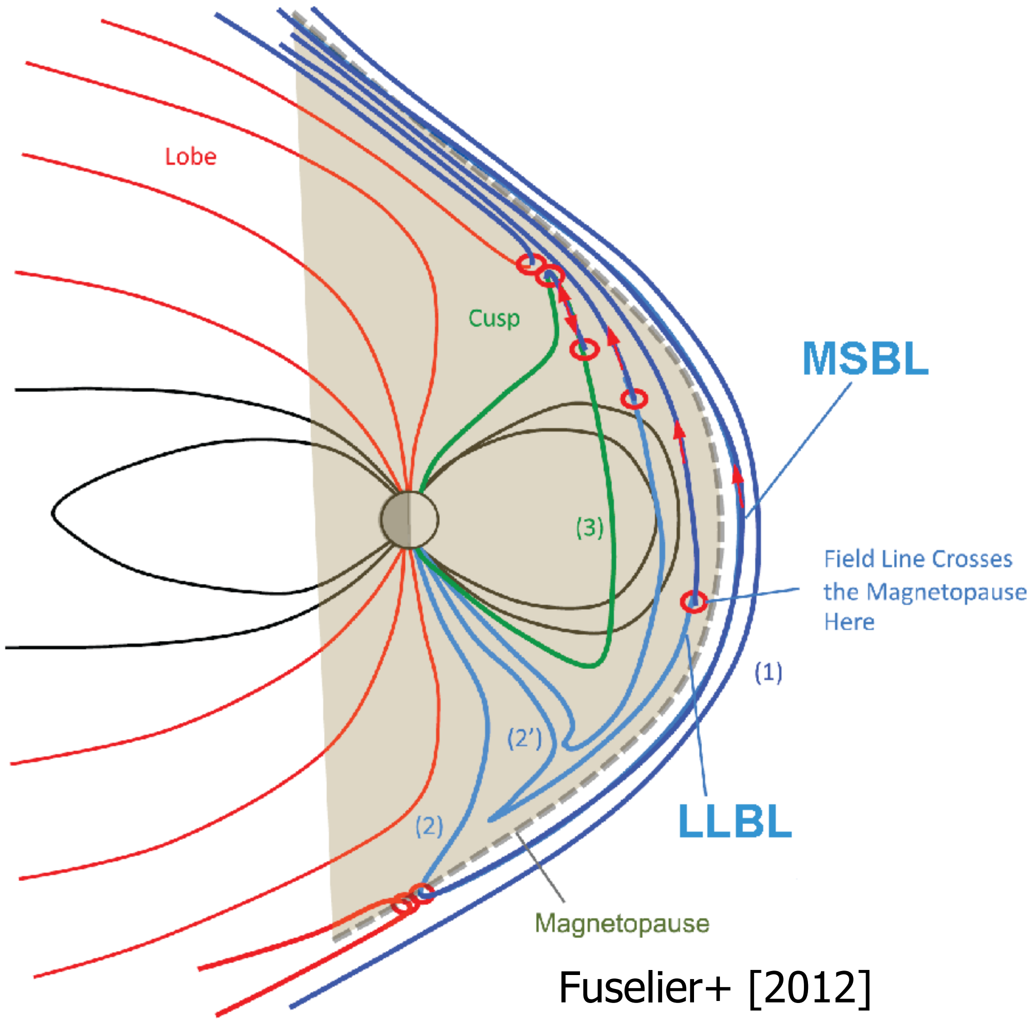
Lavraud+ [2006]

Reconnection

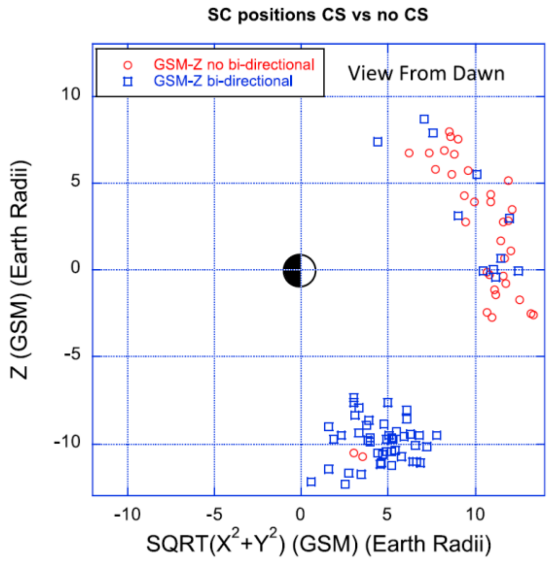
Northward IMF

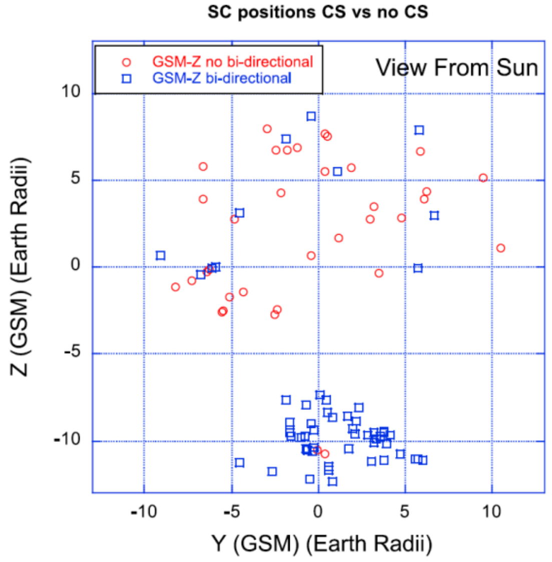
- Considering 3D space, high-latitude reconnection occurs sequentially, and forms the closed LLBL more or less away from the Y=0 plane.

- High-latitude reconnection would form the open/closed LLBL in the dayside-to flank region.



Fuselier+ [2012]

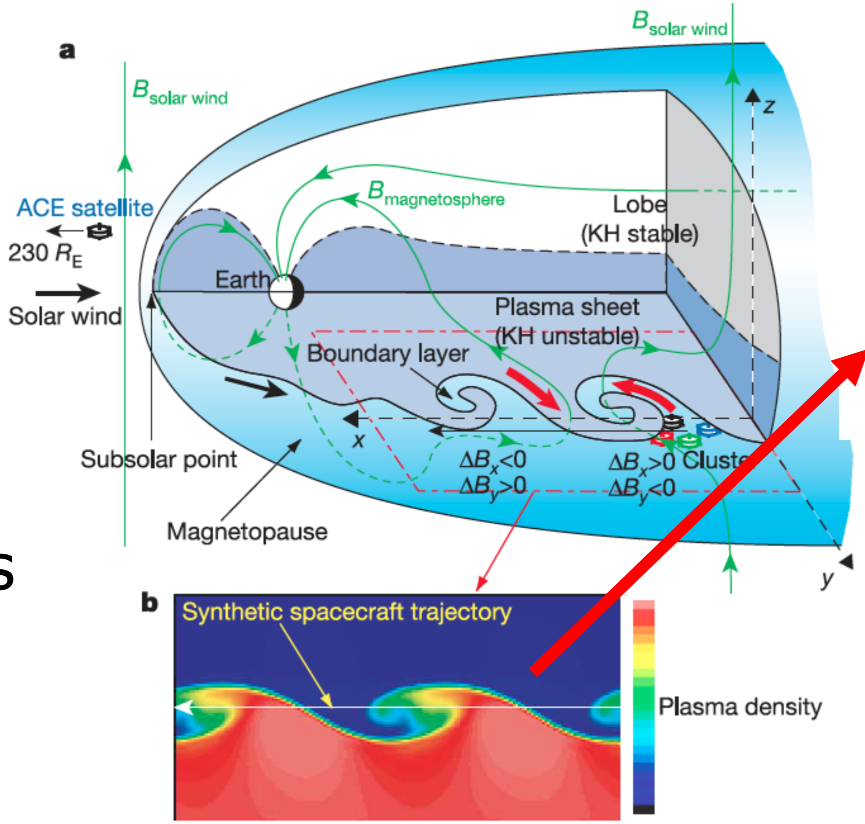




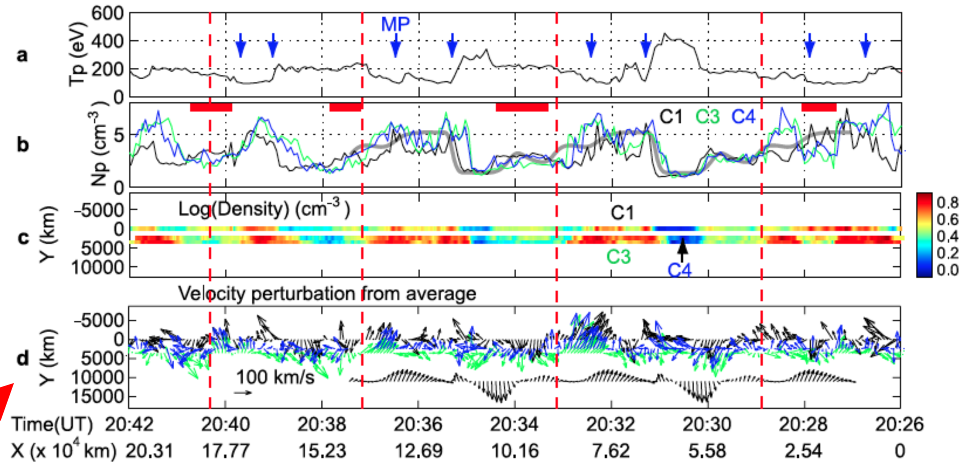
Kelvin-Helmholtz instability

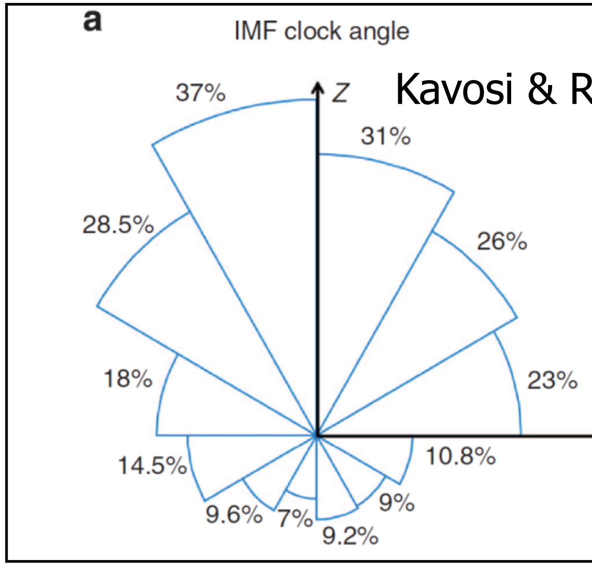
- The velocity shear across the magnetopause can drive the KHI at low-latitudes.

- The KH waves/vortices tends to be observed much more frequently during northward IMF.



Hasegawa+ [2004b]





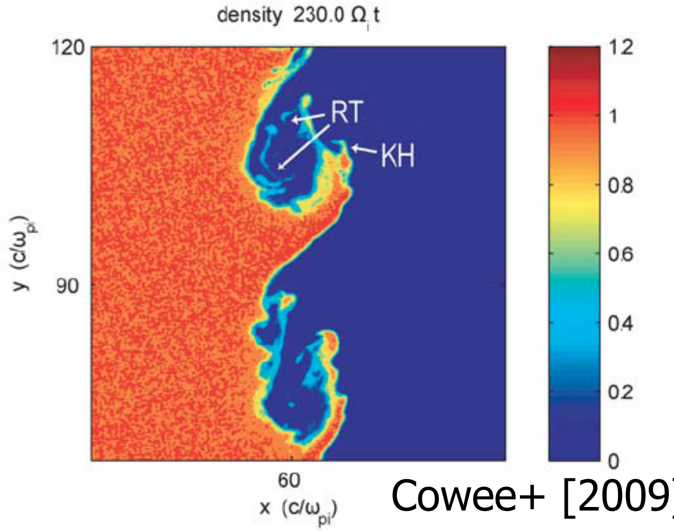
Kavosi & Raeder [2015]

Kelvin-Helmholtz instability

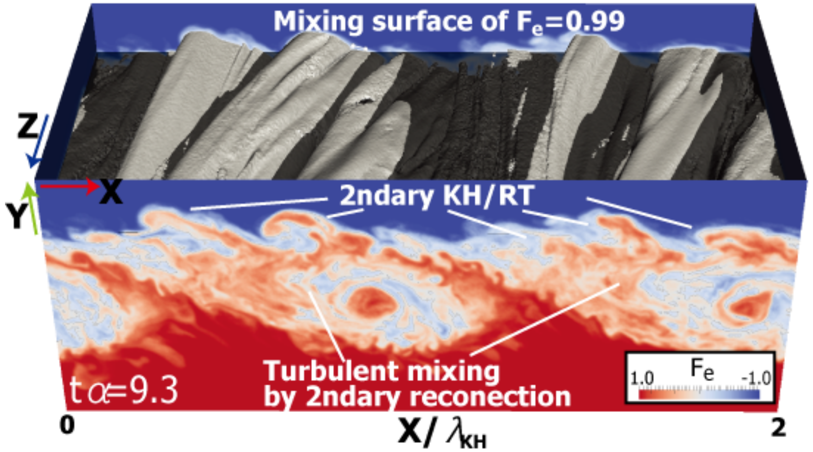
- Theories/simulations predicted that the non-linear vortex flow induces 2ndary KH/RT instabilities and 2ndary reconnection.

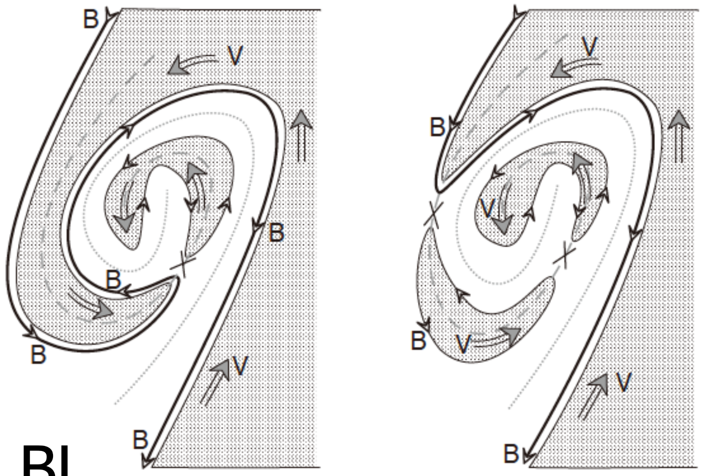
- The 2ndary reconnection causes a rapid expansion of the mixing layer, while the 2ndary KH/RT causes a gradual transport deeper into the magnetosphere.

→ KHI can form the flank-to-tail LLBL.

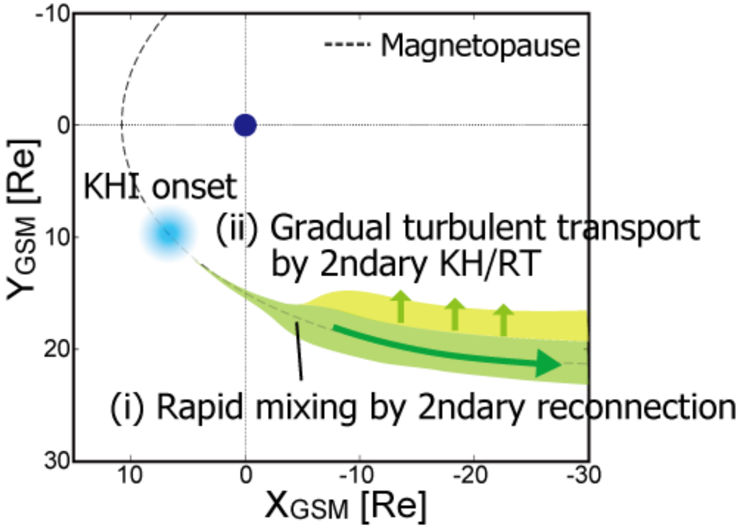


Cowee+ [2009]





Nykyri & Otto [2001]



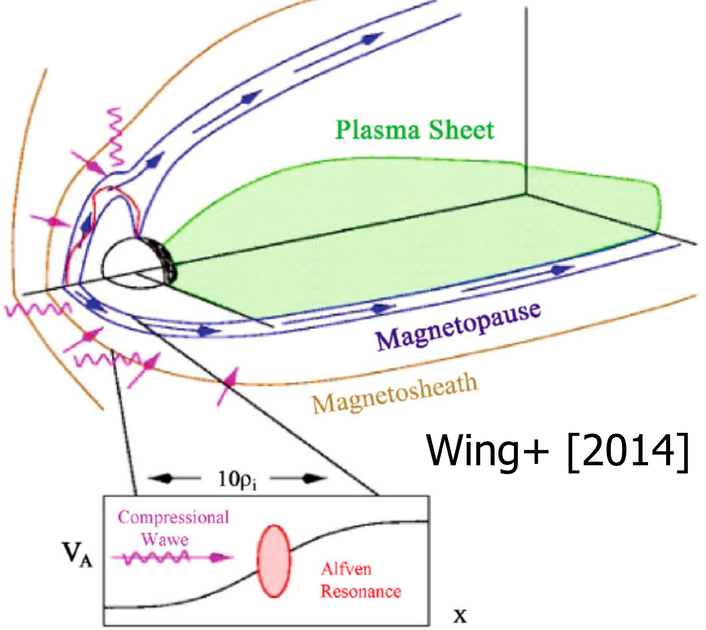
Nakamura & Daughton [2014]

Kinetic Alfvén waves

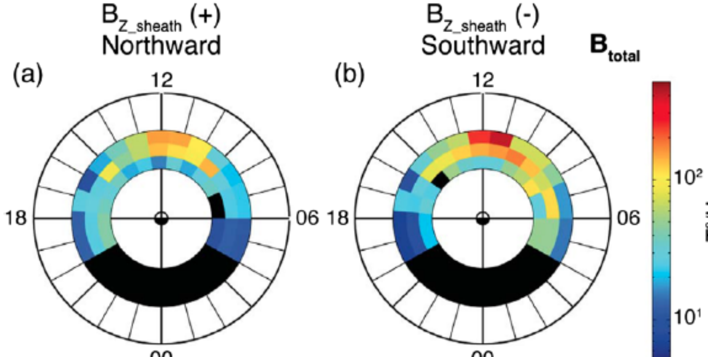
- KAWs can be induced at the magnetopause by coupled with compressional waves in the magnetosheath, and cause diffusive transport.

- KAWs are frequently observed near the flank-to-tail magnetopause, and cause perpendicular ion heating.

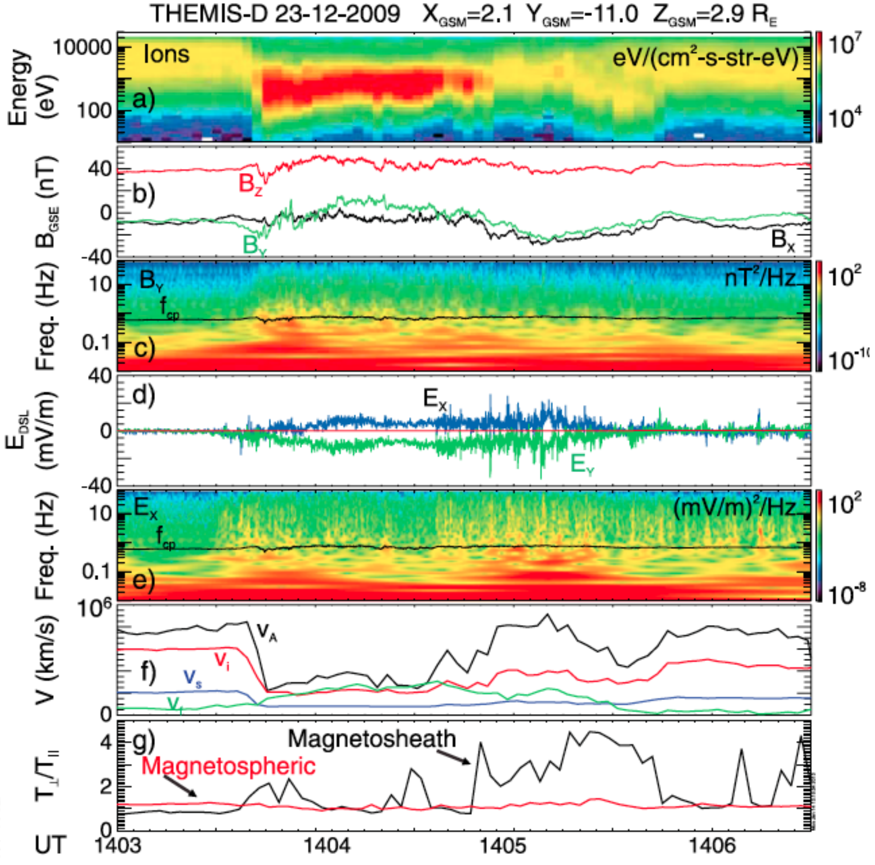
→may explain $T_{i\perp} > T_{i\parallel}$ observed in the dayside LLBL.



Wing+ [2014]



Yao+ [2011]

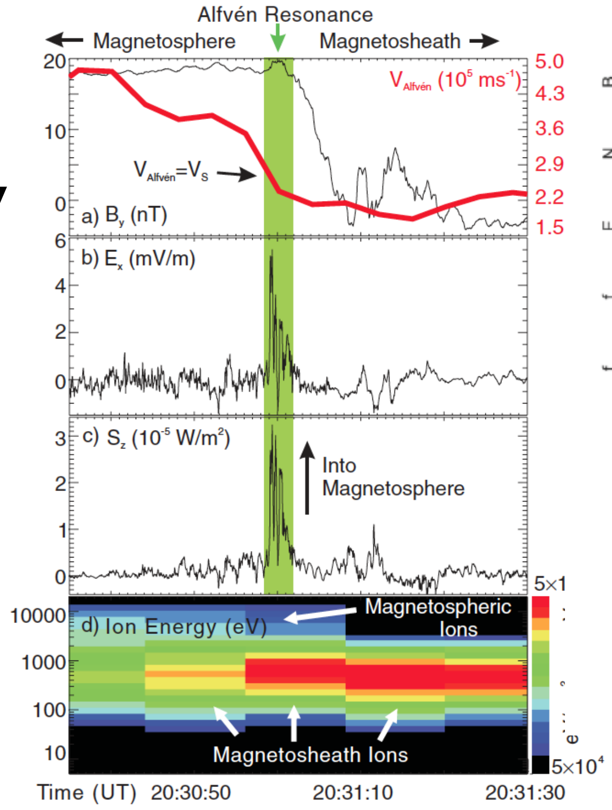


Chaston+ [2013]

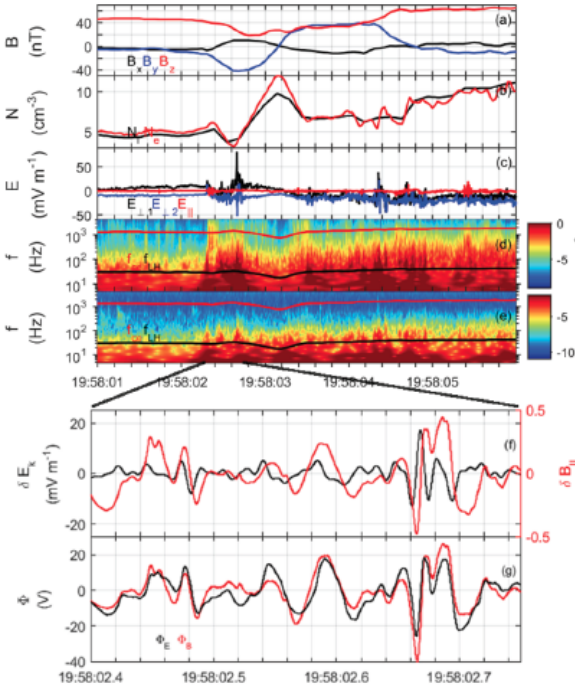
Cross-process couplings

- Local processes often drive other processes, and such a local cross-process coupling can enhance the mixing/transport rate.

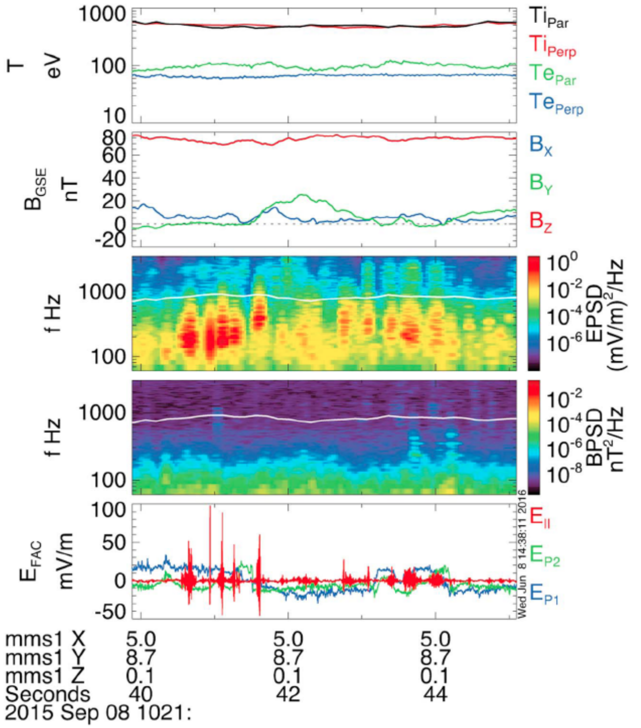
- e.g., KH-induced reconnection, KH/RT and other waves.



KAWs within KH
Chaston+ [2007]



LHWs within KH
Tang+ [2012]



Ion acoustic waves within KH
Wilder+ [2016]

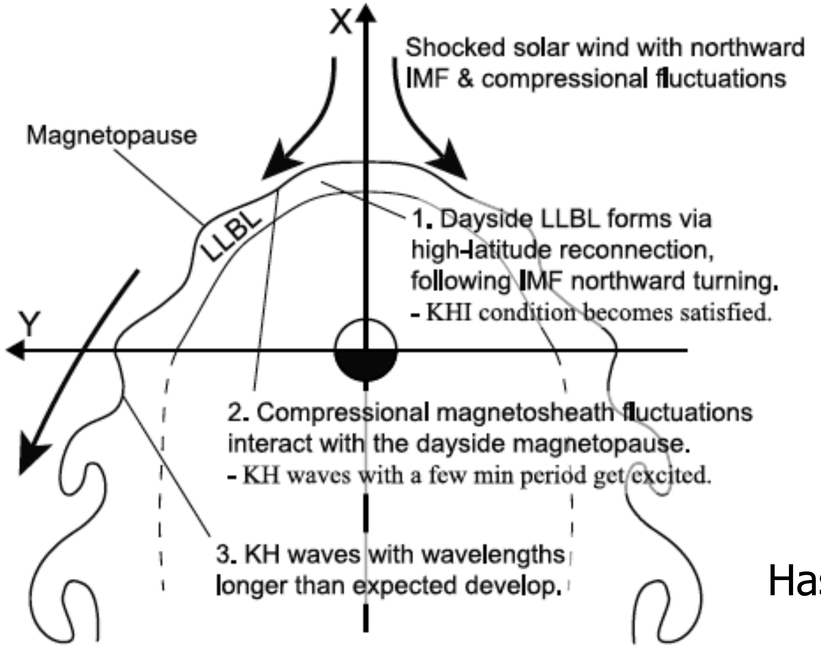
Cross-process couplings

- High-latitude reconnection & low-latitude KHI can be "globally" coupled.

- High-latitude reconnection can form the LLBL and enhance density along the magnetopause, which can excite stronger KHI.

$$\gamma_{KH}^2 = \underbrace{\frac{\rho_1\rho_2}{(\rho_1+\rho_2)^2}[\mathbf{k}\cdot(\mathbf{U}_1-\mathbf{U}_2)]^2}_{A} - \underbrace{\frac{1}{\mu_0(\rho_1+\rho_2)}[(\mathbf{k}\cdot\mathbf{B}_1)^2+(\mathbf{k}\cdot\mathbf{B}_2)^2]}_{B} > 0$$

$$M_A^2 = \frac{A}{B} = \frac{\rho_1\rho_2}{\rho_1+\rho_2}\cdot\frac{[\mathbf{k}\cdot(\mathbf{U}_1-\mathbf{U}_2)]^2}{[(\mathbf{k}\cdot\mathbf{B}_1)^2+(\mathbf{k}\cdot\mathbf{B}_2)^2]/\mu_0} > 1$$



Hasegawa+ [2009]

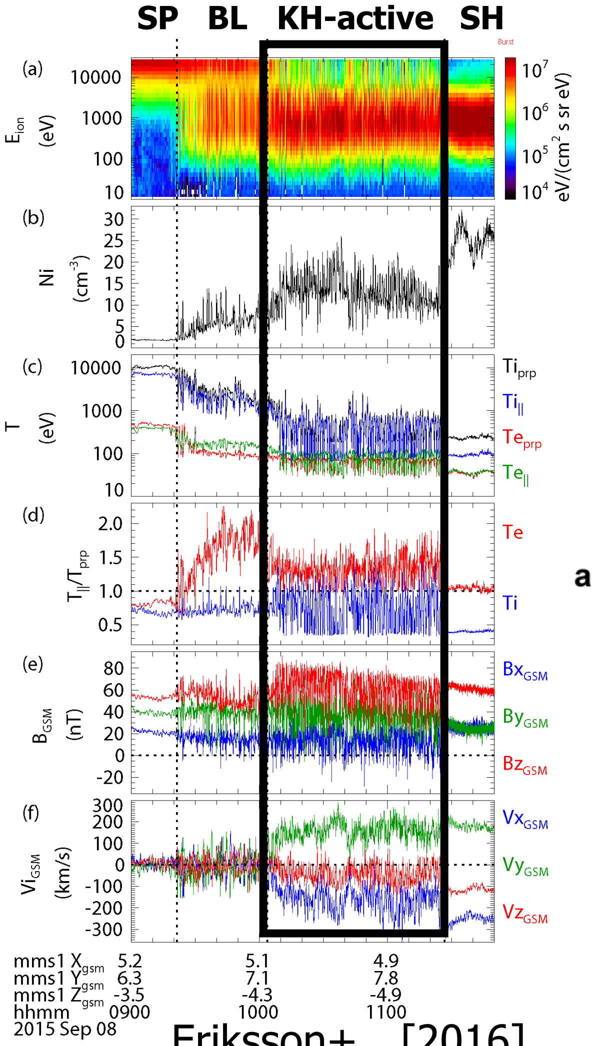
- Unstable condition of KHI [Chandrasekhar, 1961]
- Higher M_A → stronger KH
- Higher density → higher M_A

Cross-process couplings

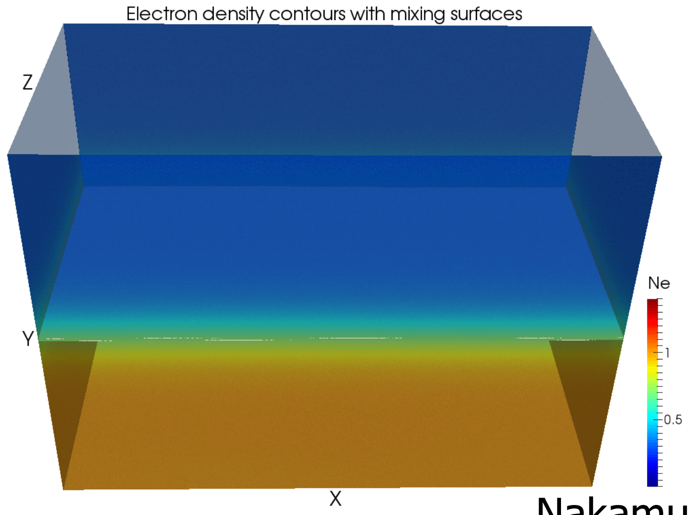
- MMS observed strong KHWs between pre-existing LLBL and magnetosheath.

- 3D Fully kinetic simulation of this event showed efficient mixing/transport.

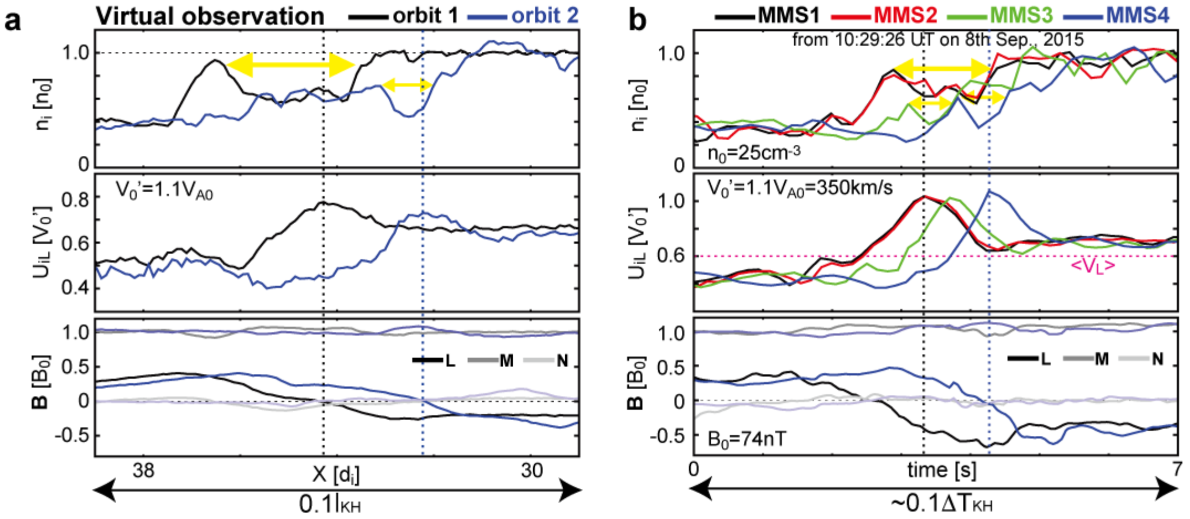
- Simulation data quantitatively agrees with observations.



Eriksson+ [2016]



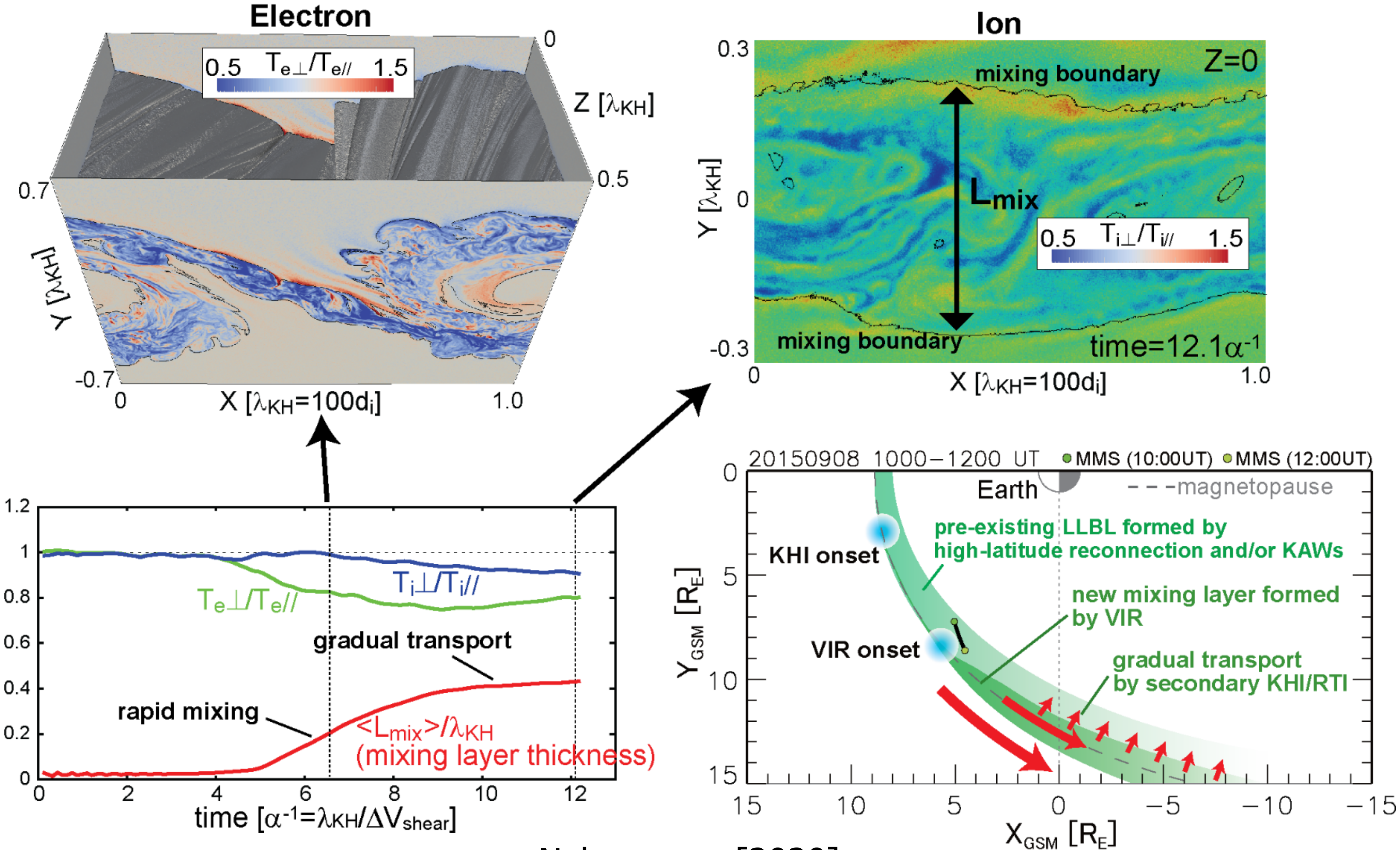
Nakamura+ [2017a, b]



Cross-process couplings

- Parallel electron heating starts just after the onset of reconnection within KHWs.
  → may explain $T_{e\perp} < T_{e\parallel}$ observed in the whole LLBL.

- Parallel ion heating also occurs in the later non-linear KH growth phase.
  → may explain $T_{i\perp} < T_{i\parallel}$ observed in the flank-to-tail LLBL.



Nakamura+ [2020]

Summary

1. Observational features of LLBL

- Basic structures

→ plasma mixing, multi-layered structures

- IMF dependences

→ Thicker & more weakly-structured during northward IMF

- Local time dependences

→ Thicker & larger $T_{i\parallel}$ in flank-to-tail, one-(dawn) or two-(dusk) components

- Coupling with ionosphere

→ via FACs by velocity shear

2. Candidate formation mechanisms

- Magnetic reconnection

→ low- or high-latitude reconnection, dayside-to-flank

- Kelvin-Helmholtz (KH) instability

→ 2ndary instabilities, flank-to-tail

- Kinetic Alfvén waves (KAWs)

→ widely induced in the dayside region

- Cross-process couplings

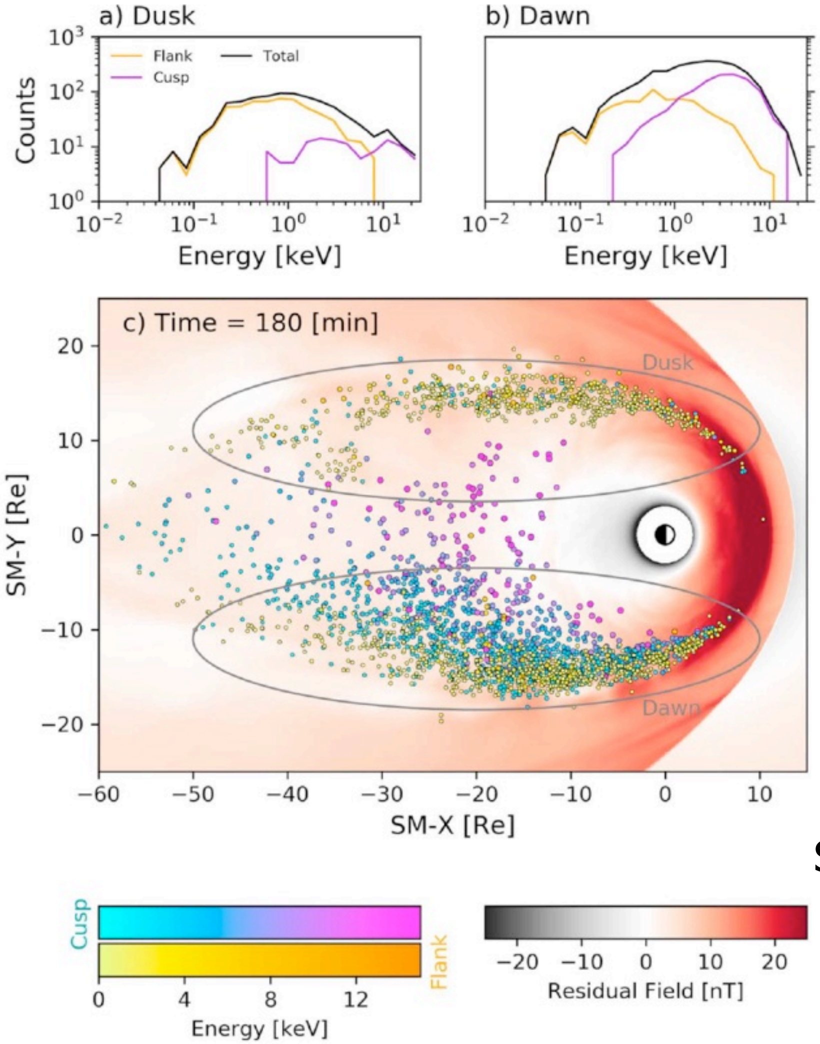
→ local coupling with KAWs/LHDWs, global coupling of reconnection + KH (and KAWs?)

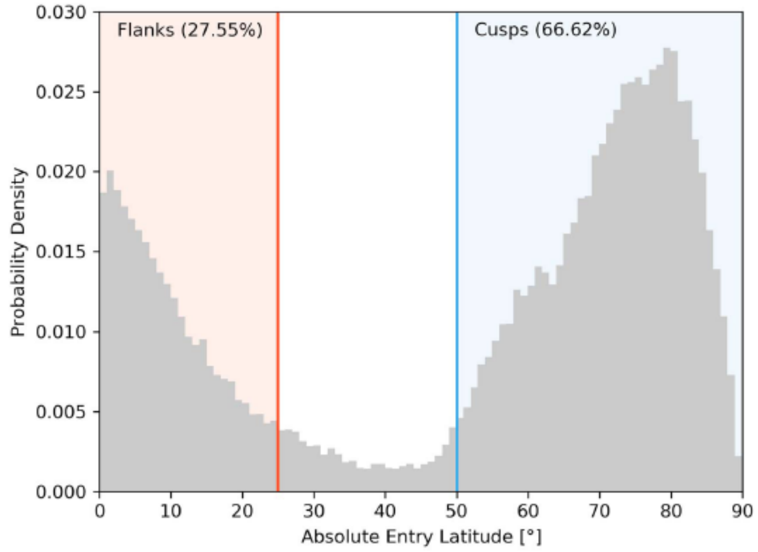
More recent works

- Global MHD simulation for pure northward IMF + test particles (ions).

- Test particle trajectories show (i) more particles enter from the dawnside, and (ii) entered particles being more strongly heated on the dawnside.

→ consistent with observed dawn-dusk asymmetry in ion-energy spectrum.



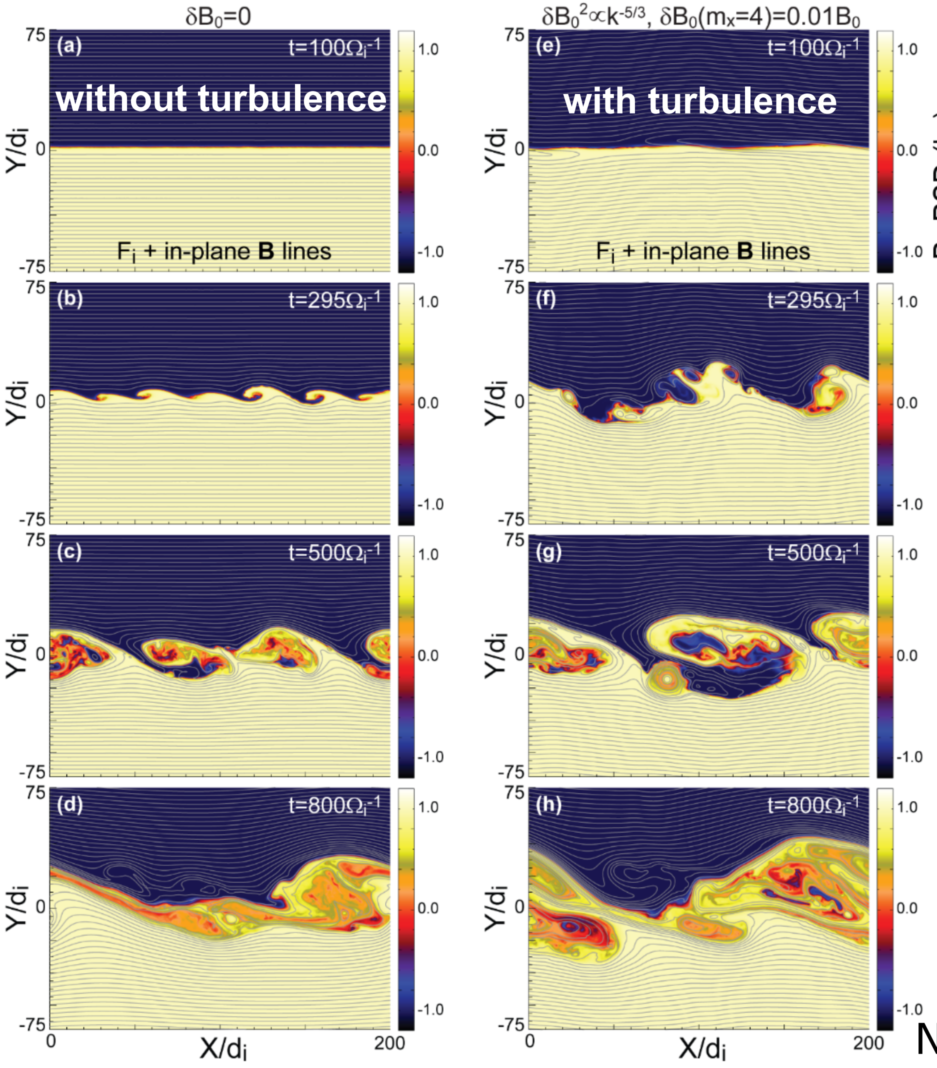


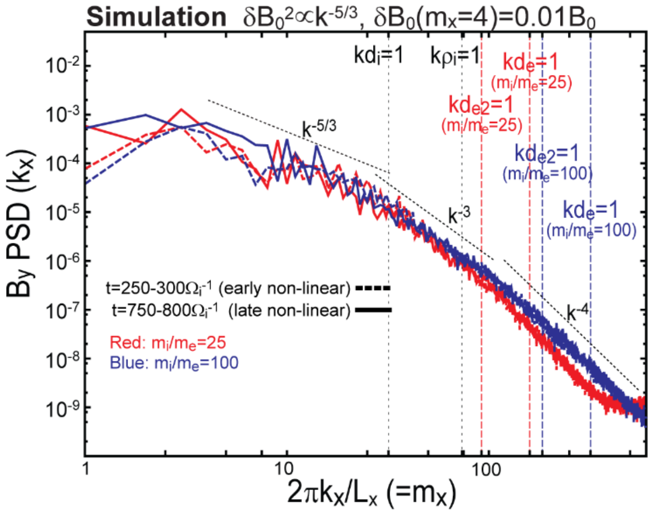
Sorathia+ [2019]

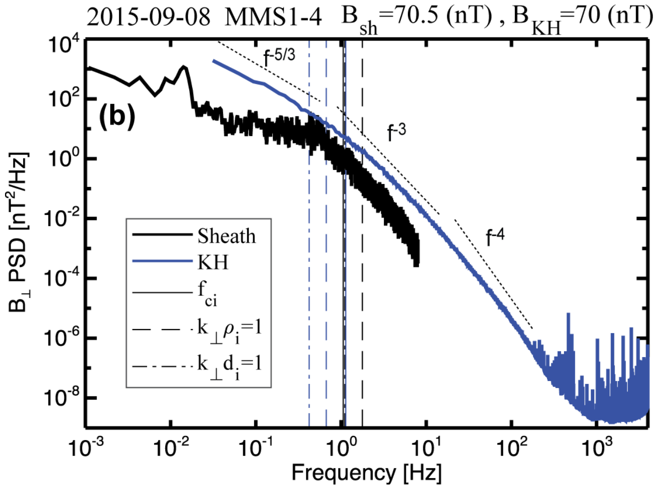
More recent works

- Magnetosheath turbulence can excite the KHI more strongly and enhance the mixing (solar wind entry) rate.

- Simulated turbulent spectrum, whose amplitude is enhanced by the KHI, is well consistent with the observations.





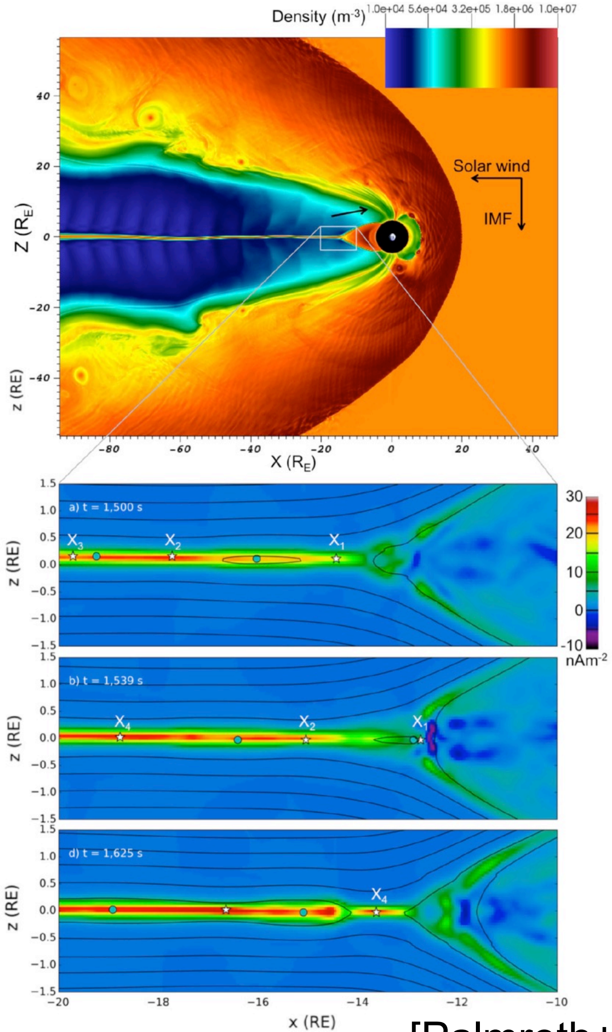


Nakamura+ [2020]

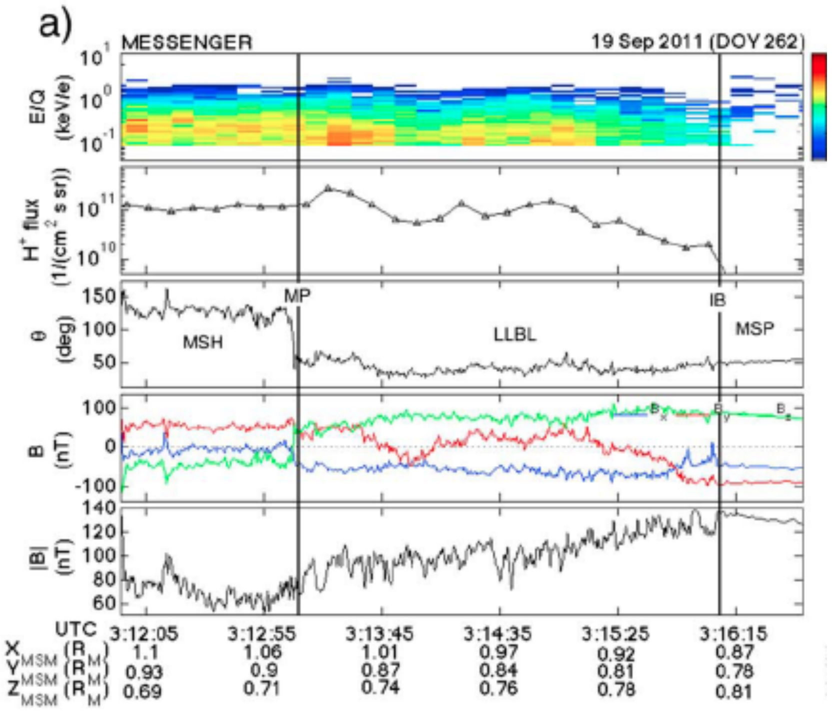
Future perspectives

- Global hybrid simulation of the Earth's magnetosphere is also becoming feasible.
→ would support quantitative understanding of cross-process/region couplings.

- Future missions
  - MMS and beyond: multi-points, conjunction
  - BepiColombo: comparison with Mercury



[Palmroth+, 2018]



[Liljeblad+, 2015]

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