Transport and energization of planetary ions in the magnetospheric flanks of Mercury

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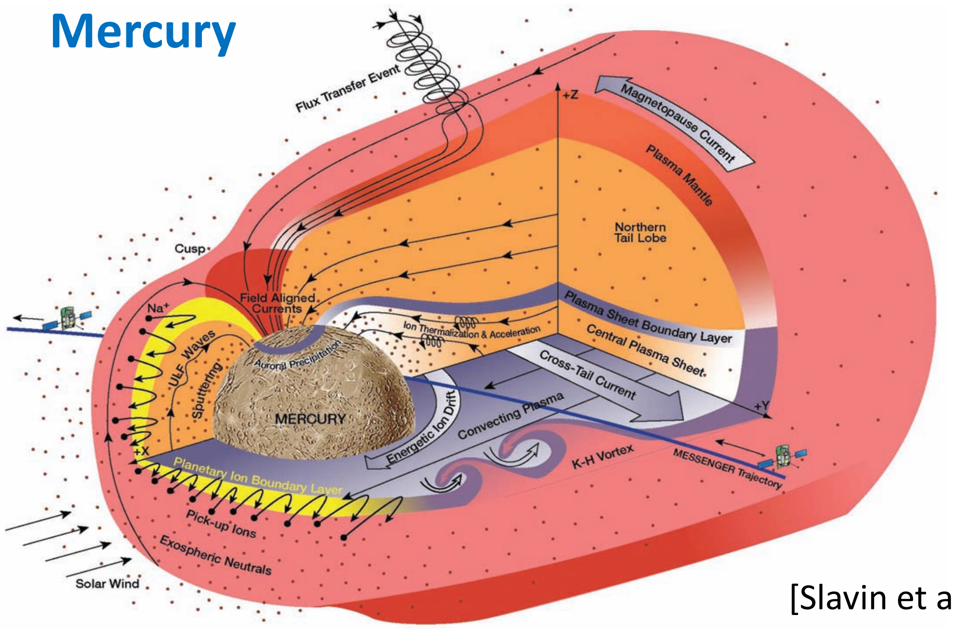
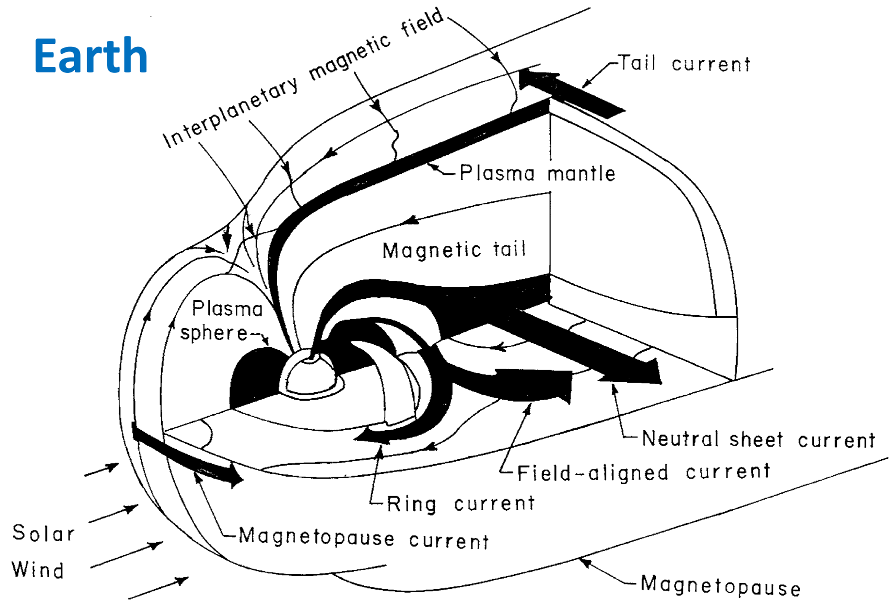
Mercury’s magnetosphere

Mercury



[Slavin et al., 2008]

Earth



[Singh et al., 2004]

Characteristics of Mercury’s magnetosphere :

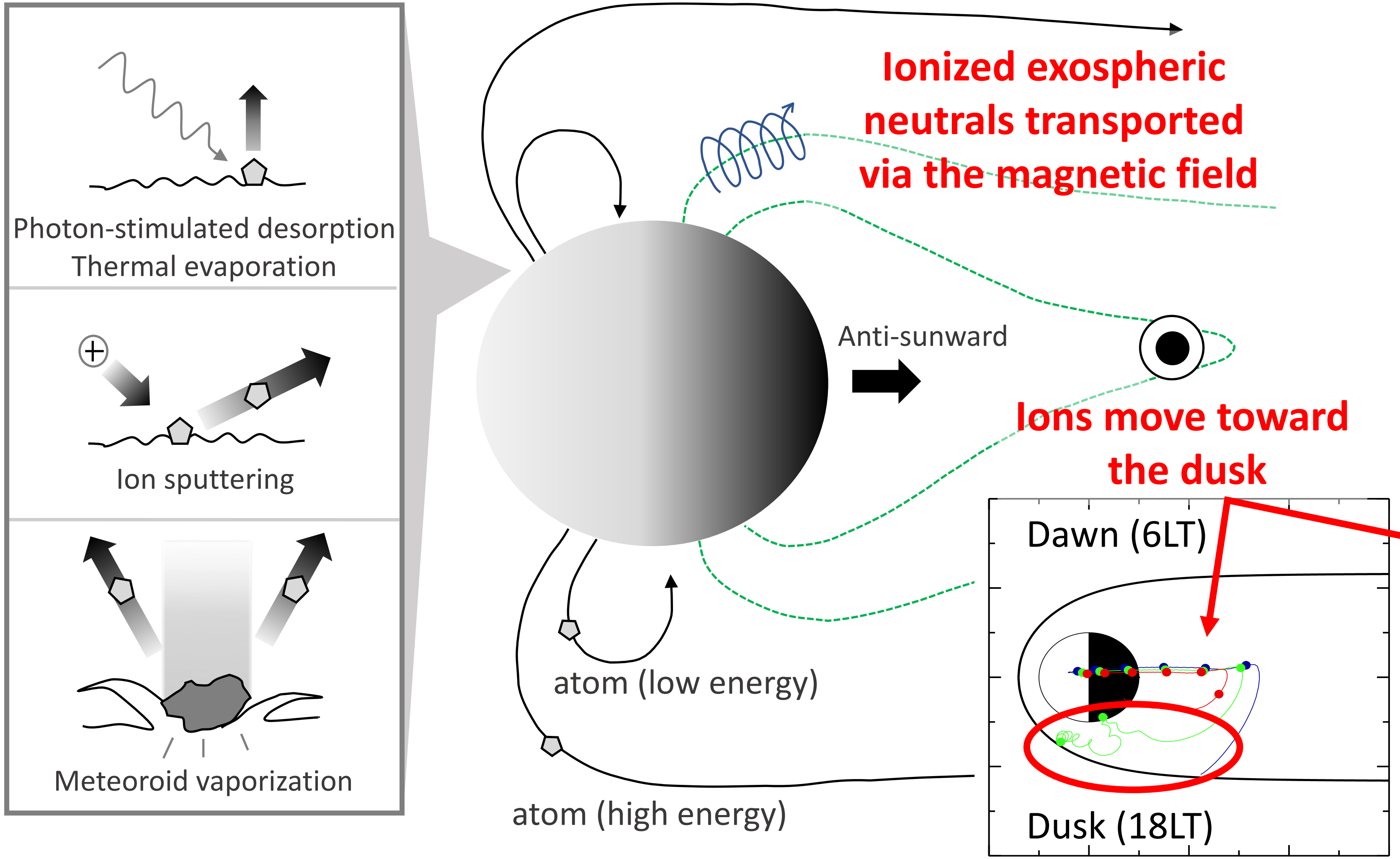
■ Small (size: 5% of Earth’s magnetosphere)
- Temporally (～1:8), spatially (～1:50)

■ Different boundary condition (no thick ionosphere)
- Extended thin atmosphere (exosphere) with O, Na, He, K, H, Ca (heavy species)

In the case of Mercury :
- Different coupling system (Surface – Exosphere – Magnetosphere – Solar wind)
- More dynamical plasma processes

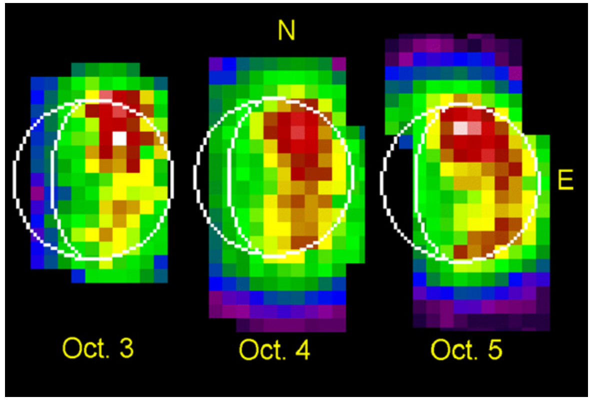
Particle transport in the Hermean magnetosphere

Source processes



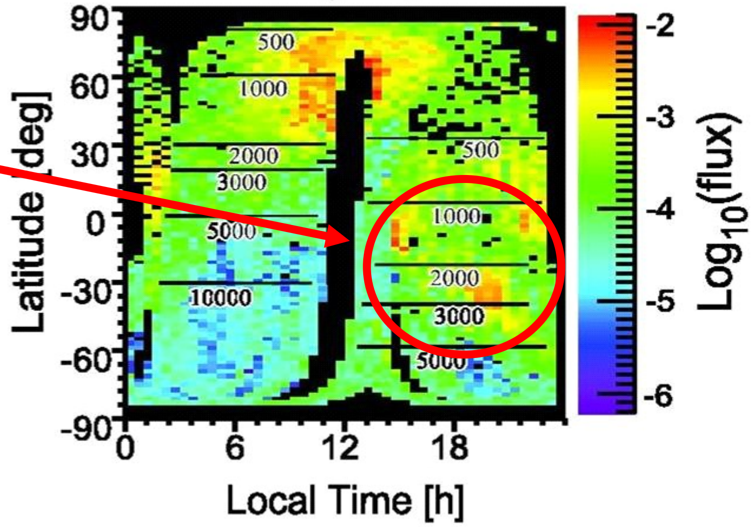
[Delcourt et al., 2003]

Exosphere (Na population)



[Potter and Killen, 2008]

Magnetosphere (Na^+ population)



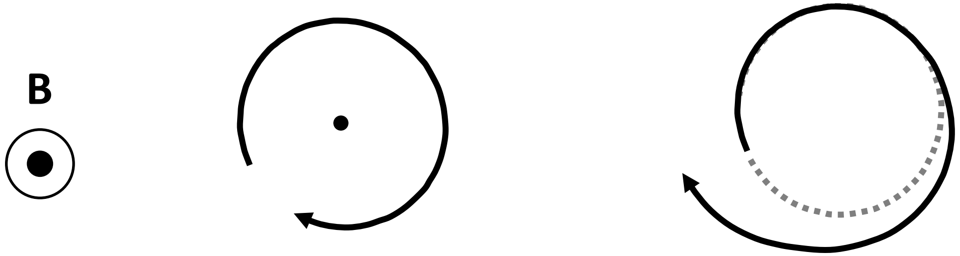
[Zurbuchen et al., 2011]

Non-adiabatic energization (1/2)

Key parameter :
the particle magnetic moment $\mu = \frac{\frac{1}{2} m v_\perp^2}{B}$

Adiabatic **($t_{field} \gg \tau_{gyro}$)**

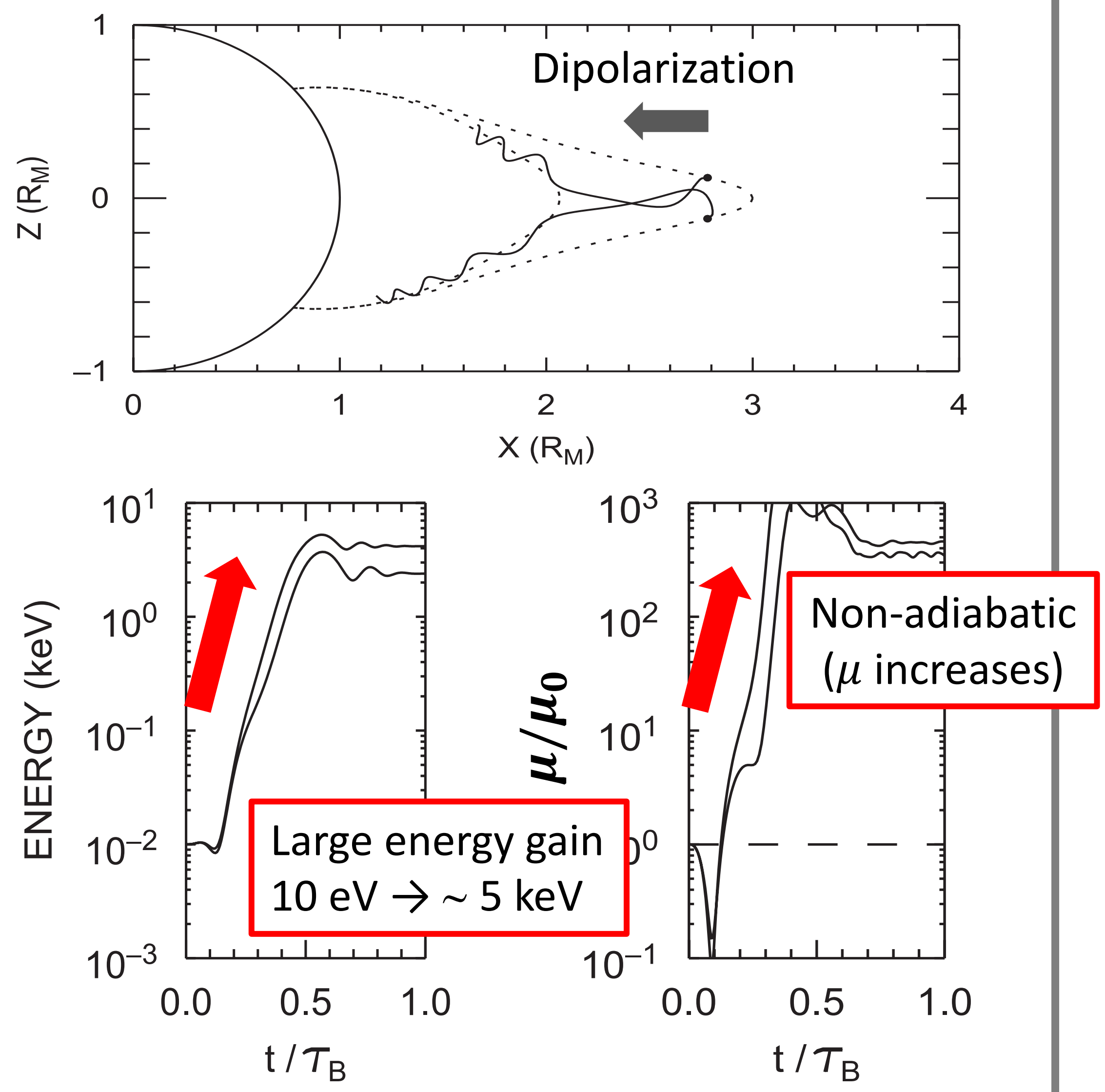
Non-adiabatic **($t_{field} \leq \tau_{gyro}$)**



orbit	closed	open / closed
μ	conserved	conserved or not ?

Previous studies :
(magnetotail region)

Speiser [1965]
Chen and Palmadesso [1986]
Büchner and Zelenyi [1989]
Delcourt and Martin [1994]

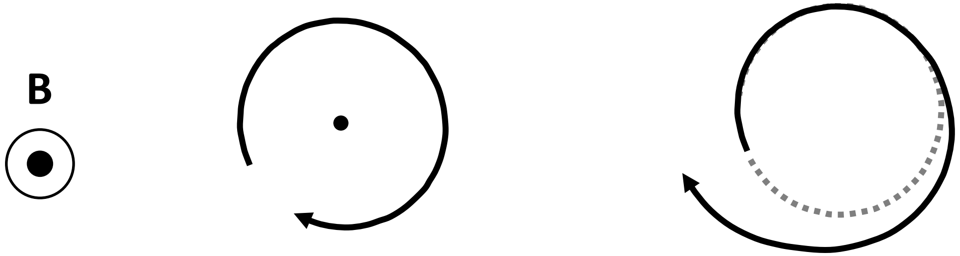


[Delcourt et al., 2007]

Non-adiabatic energization (2/2)

Key parameter :
the magnetic moment of particle $\mu = \frac{\frac{1}{2} m v_{\perp}^{2}}{B}$

Adiabatic ($t_{field} >> \tau_{gyro}$) **Non-adiabatic** ($t_{field} \leq \tau_{gyro}$)

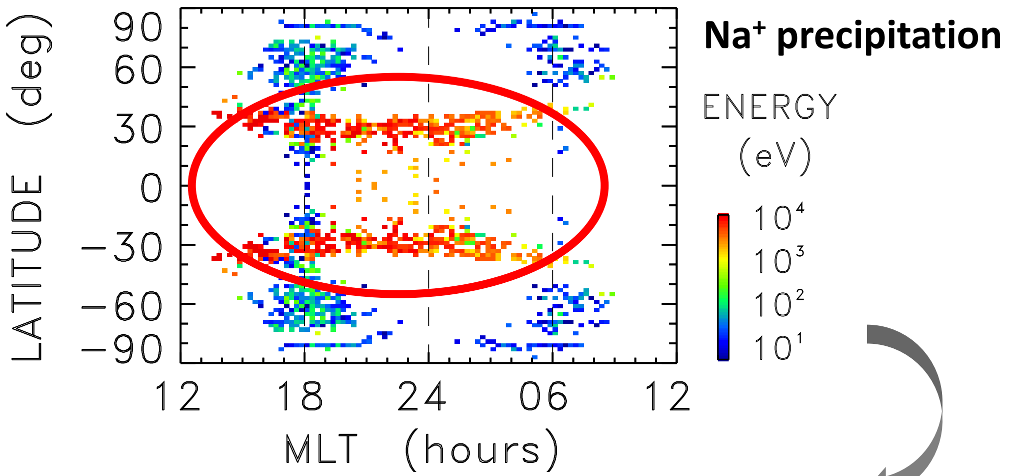


orbit	close	open / closed
μ	conserved	conserved or not ?

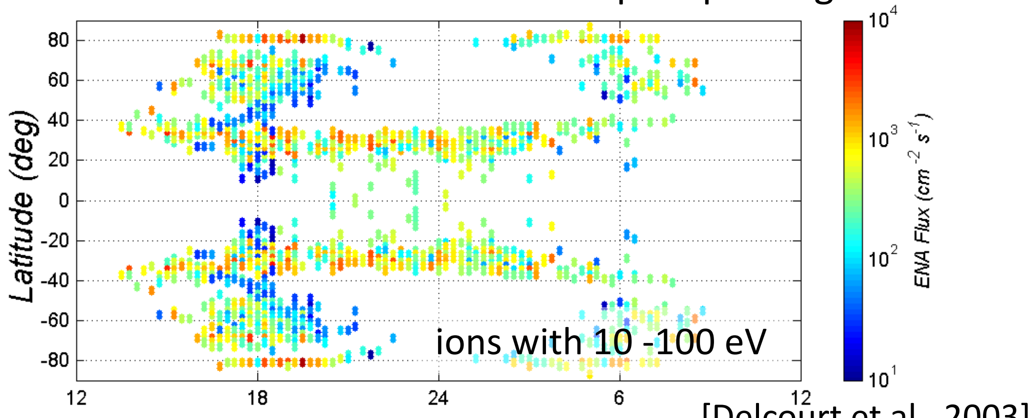
Non-adiabatic energization and transport contribute to the Hermean environment !

Non-adiabatic energized ions :

- Escape from the magnetosphere (loss)
- Sputter the surface (produce neutrals)

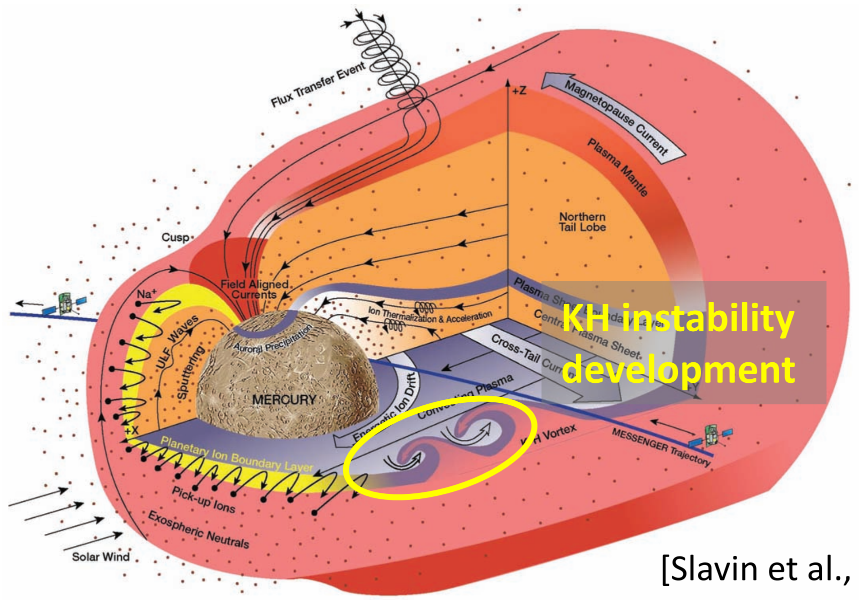


Flux of Na atoms due to the ion precipitating

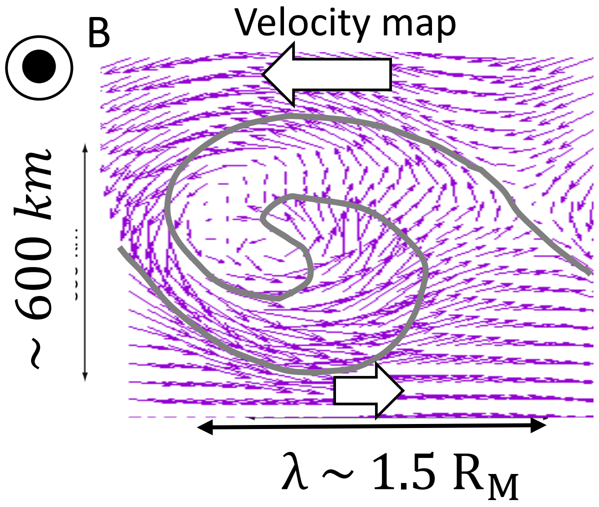


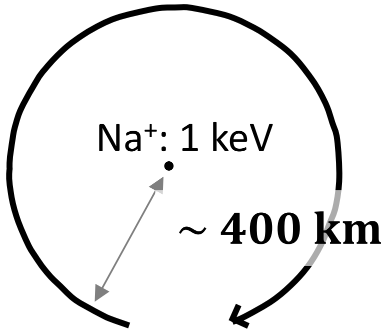
[Delcourt et al., 2003]

Kelvin-Helmholtz (KH) observations around Mercury



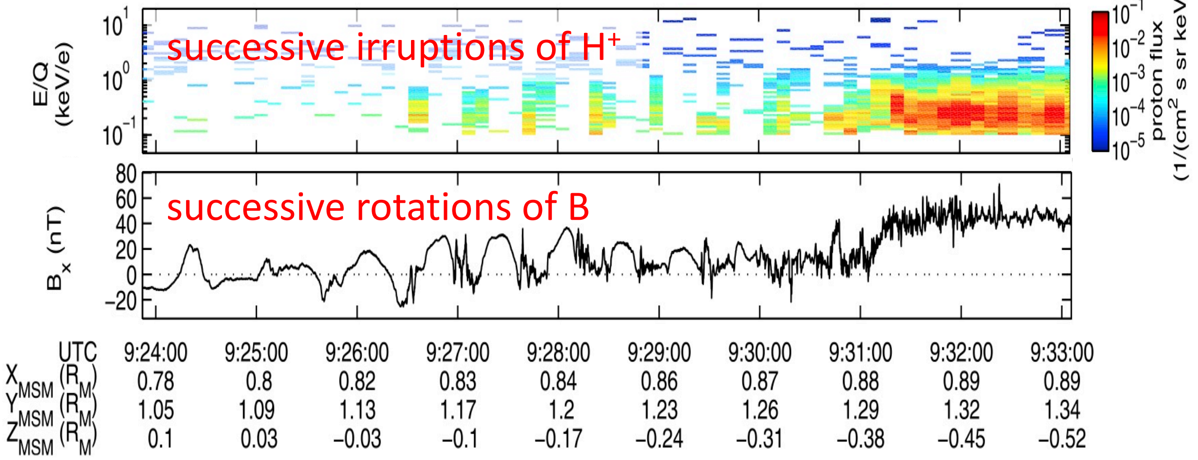
[Slavin et al., 2008]





Non-adiabatic motion can be expected
[Rothwell et al., 1984]

MESSENGER 15 May 2011



[Sundberg et al., 2012]

Questions :

- How are ions affected by the electric field from the KH development ?
- How are magnetospheric ions transported by KH vortices?

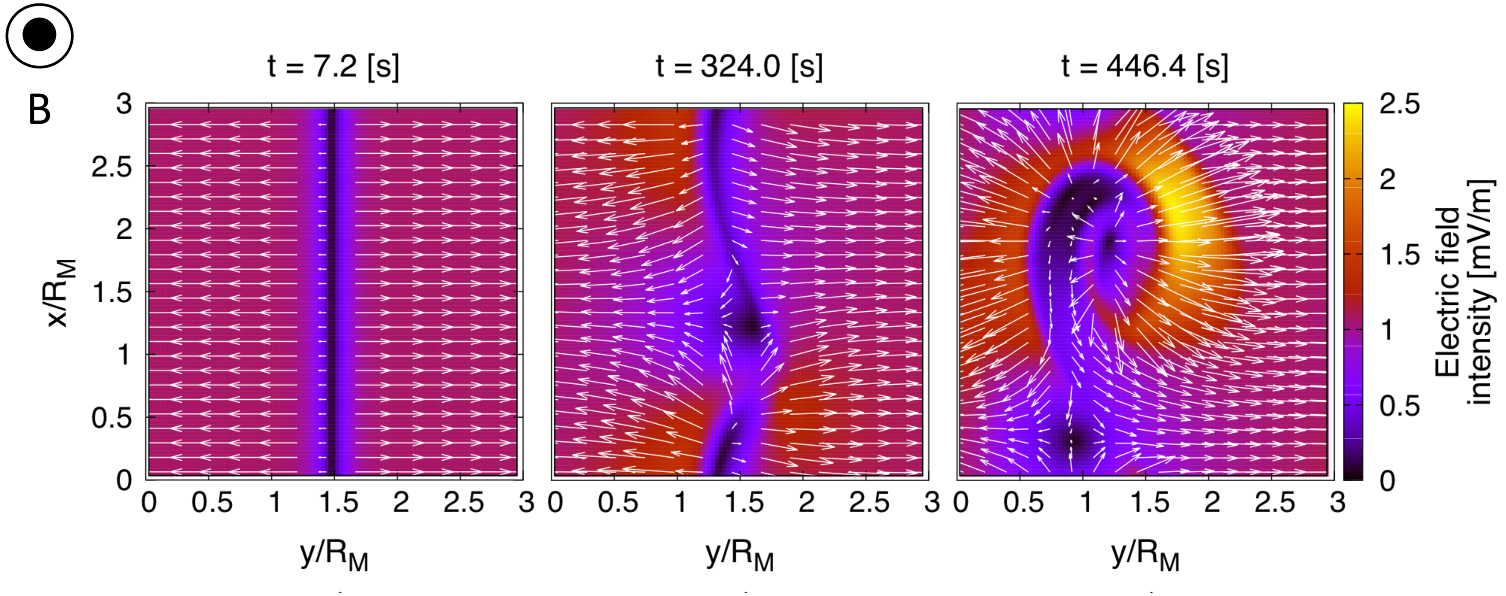
Modeling approach

KH fields : MHD simulation (Treated as a fluid)

+ Ion behavior : Test particle tracing technique (Tracing individual ions)

[e.g., Large-Scale Kinetics by Ashour-Abdalla et al., 1994]

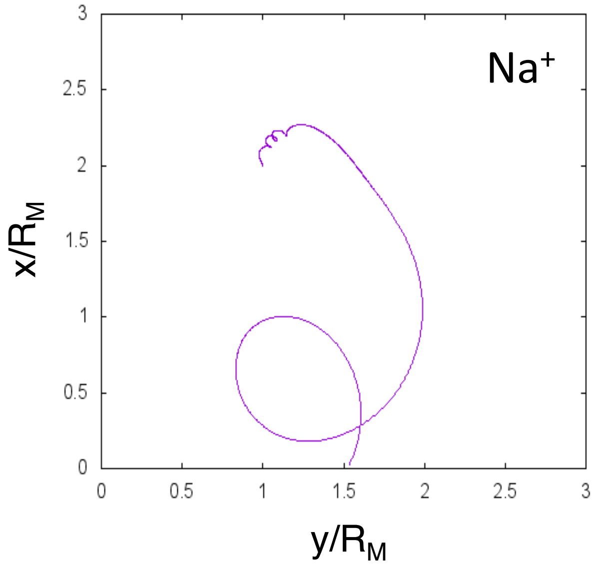
MHD (background : proton dominant)



- Magnetic field
- Electric field ($\boldsymbol{E} = -\boldsymbol{V}\times\boldsymbol{B}$)

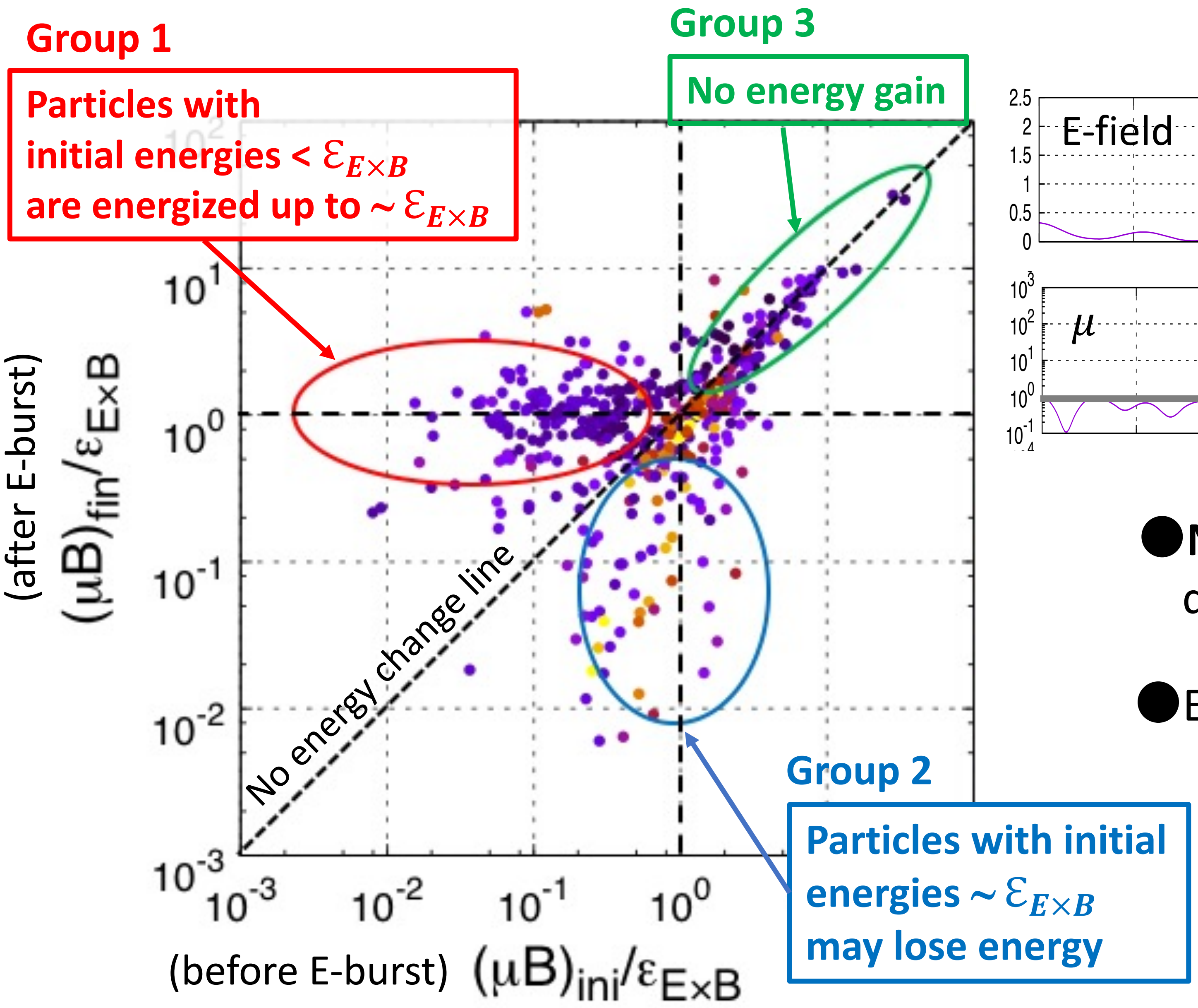
\+

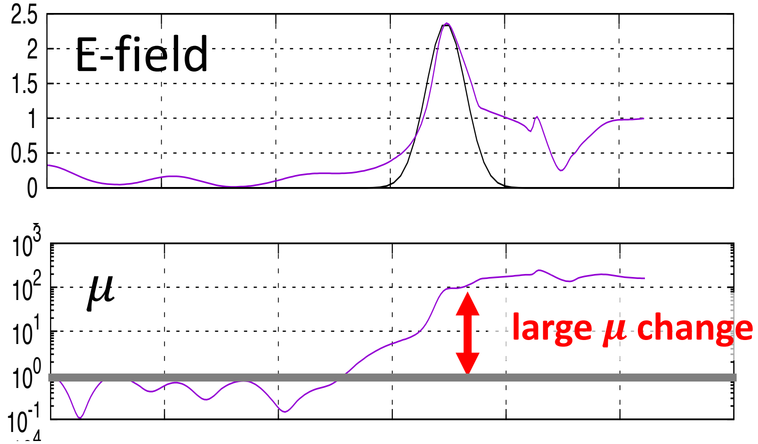
Test particle tracing

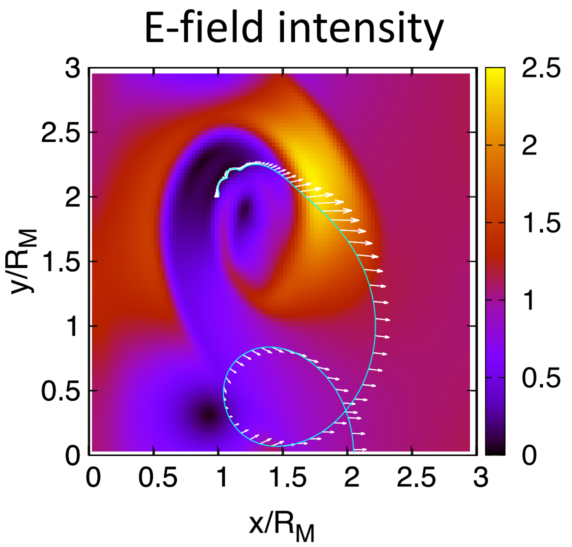


$$m\frac{d\boldsymbol{v}(t)}{dt} = \mathrm{q}(\boldsymbol{E}(\mathrm{r},\mathrm{t}) + \boldsymbol{v}(\mathrm{t})\times\boldsymbol{B}(r,t))$$

General features of ion dynamics







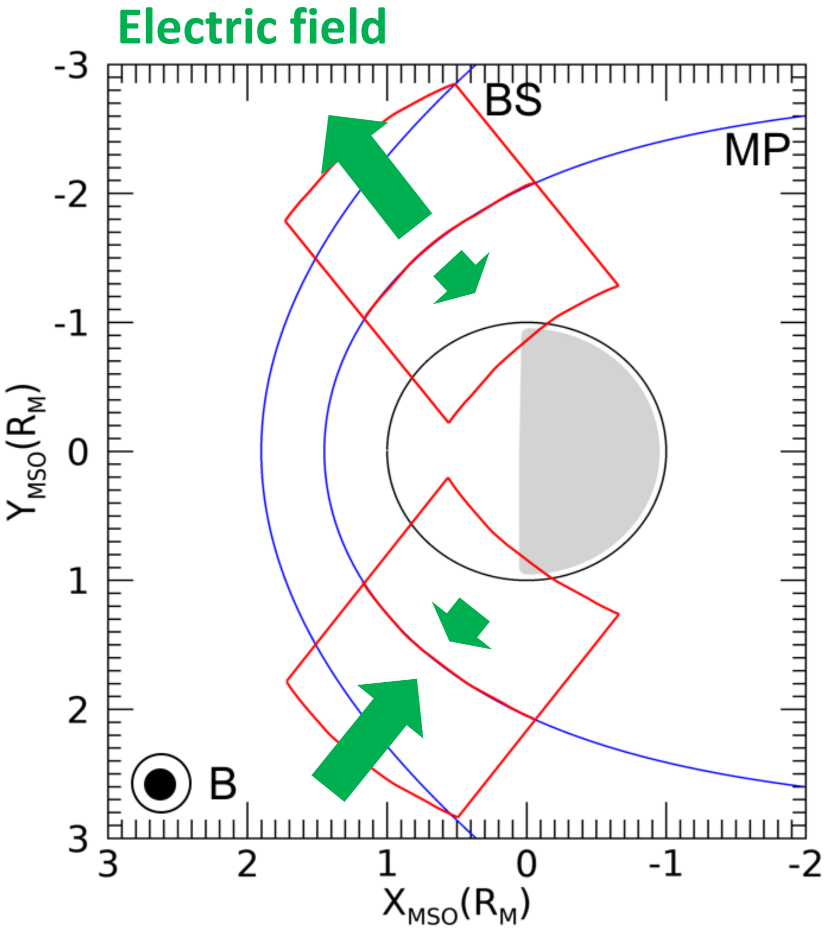
- **Non-adiabatic energization** occurs due to the electric field variation (***E***-burst)
- Energization is controlled by the field:

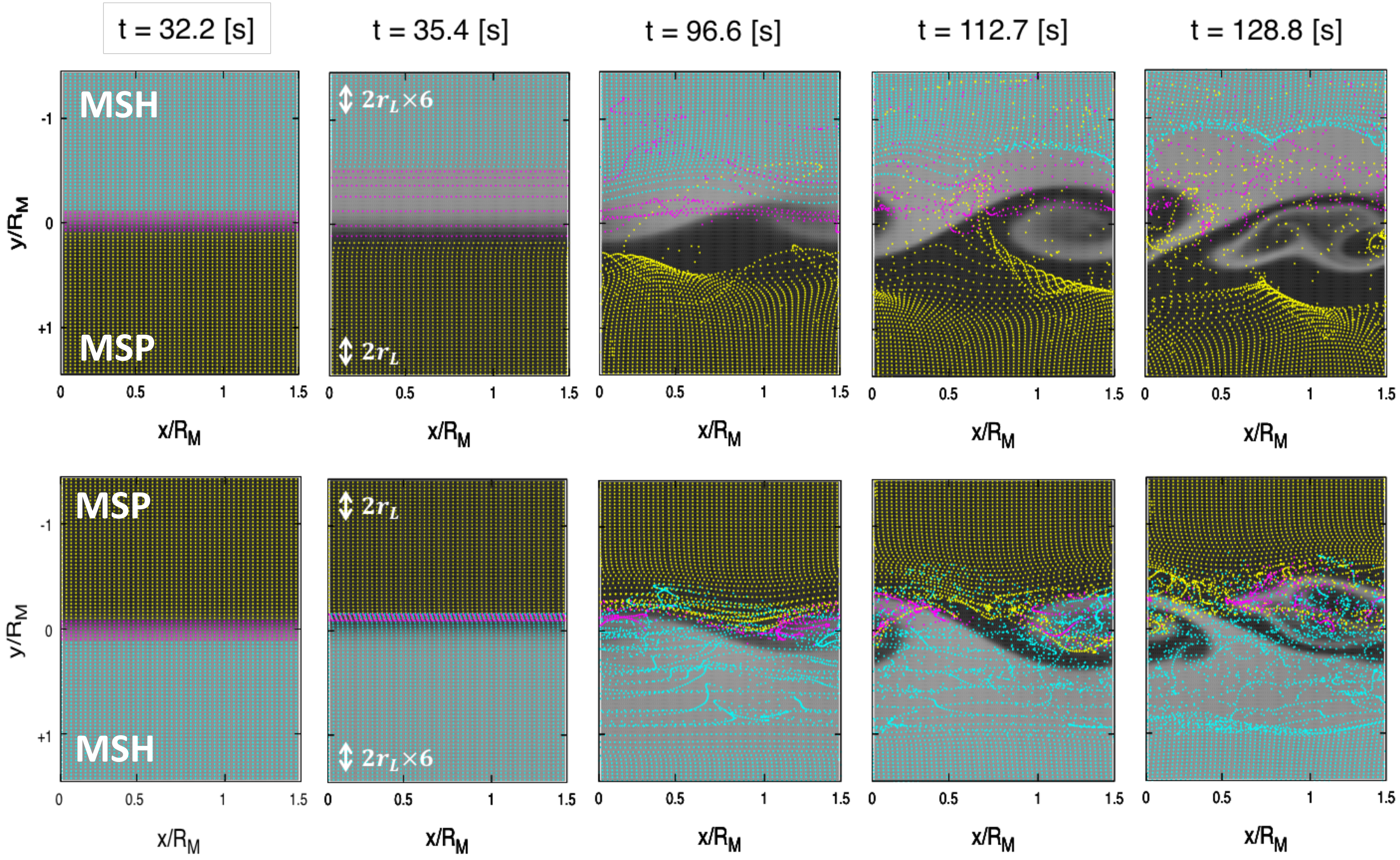
$$\mathcal{E}_{E\times B} = \frac{1}{2} m \left(\frac{E_{max}}{B}\right)^2$$

[Aizawa et al., 2018]

Overview of Na^+ behavior in realistic configurations

【Northward IMF case】





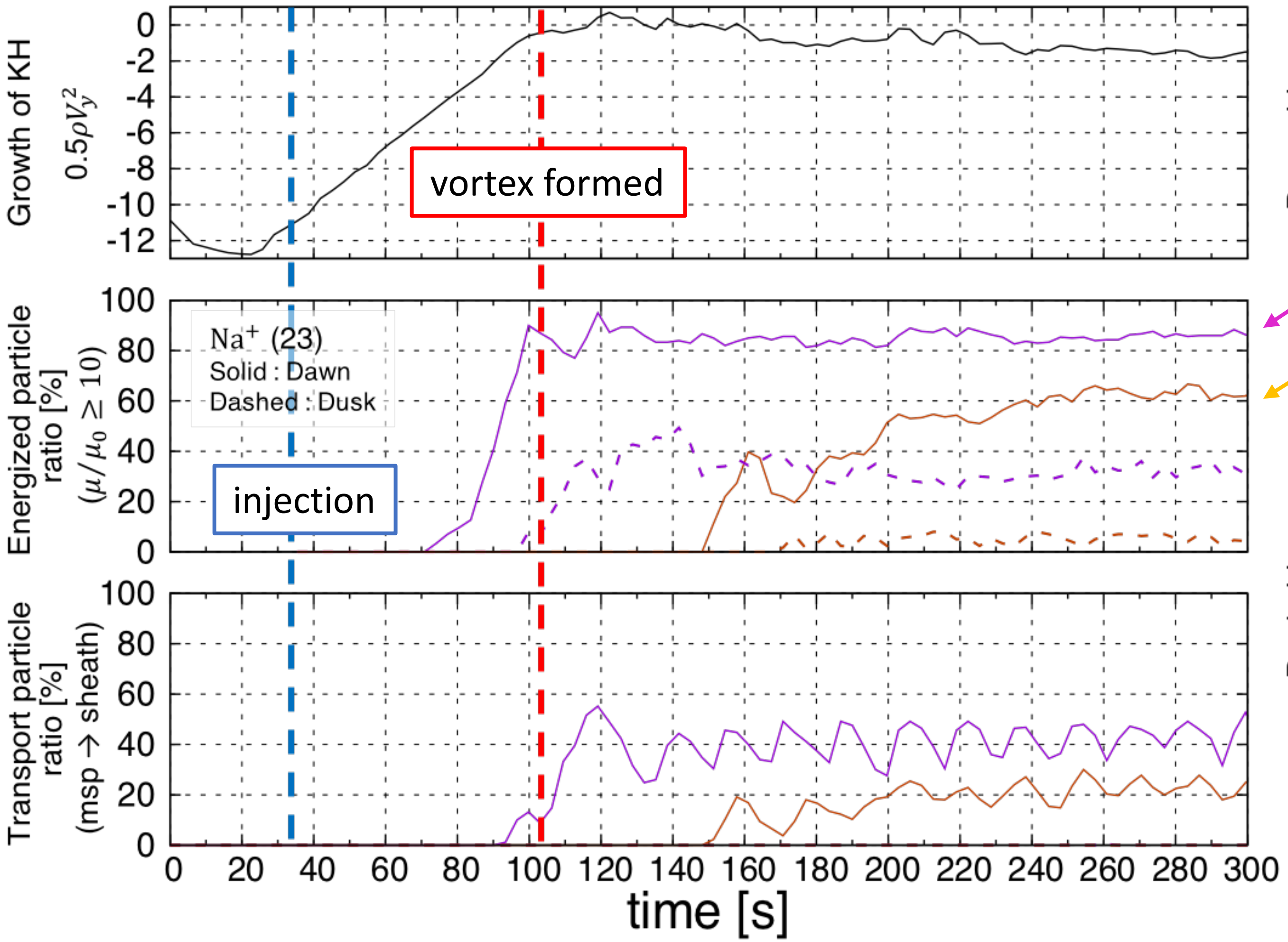
BS: Bow Shock
MP: Magnetopause
MSH: Magnetosheath
MSP: Magnetosphere

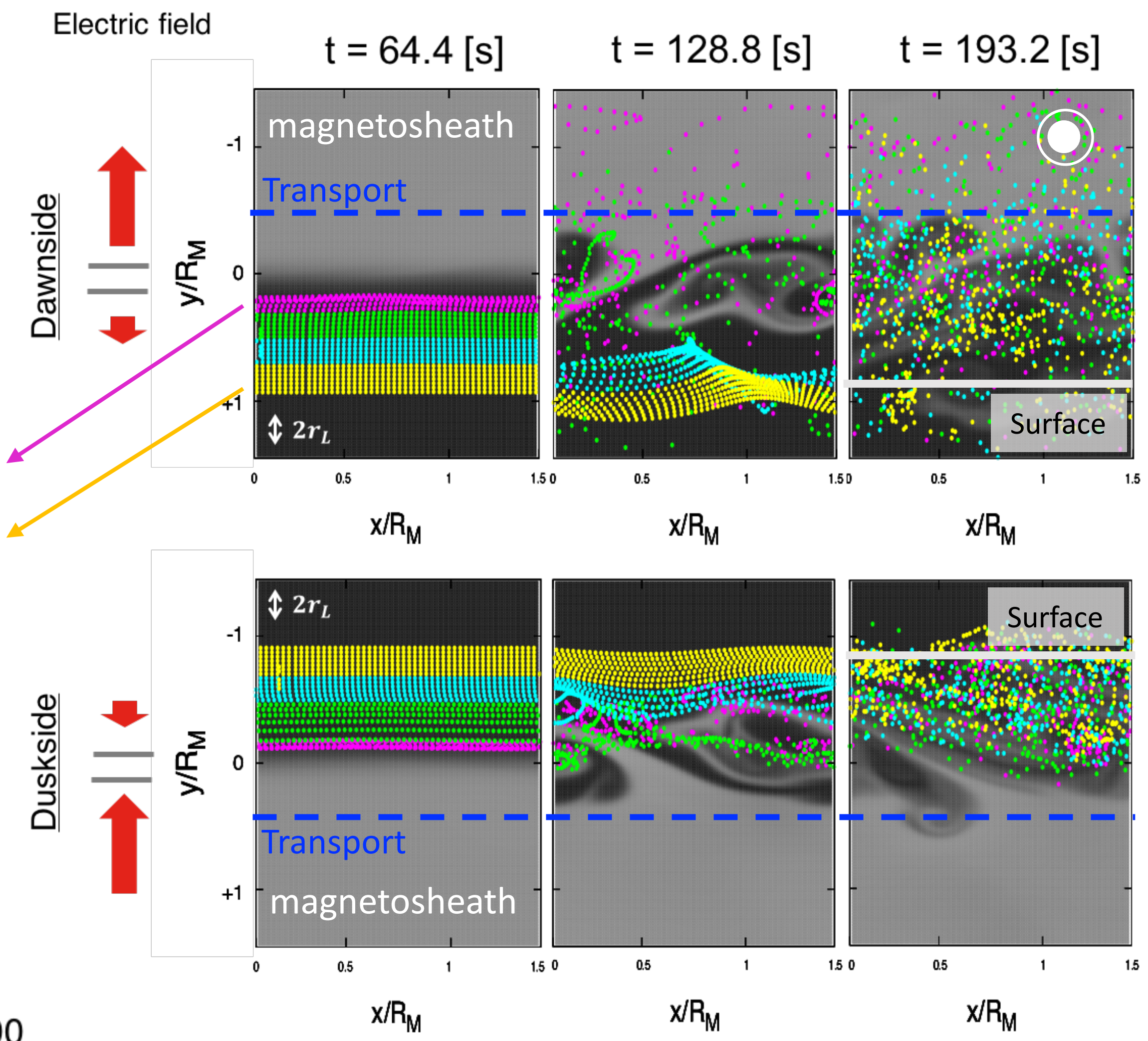
Gray : number density of background proton

Na^+ behavior [Northward IMF]

Acceleration : Dawn > Dusk

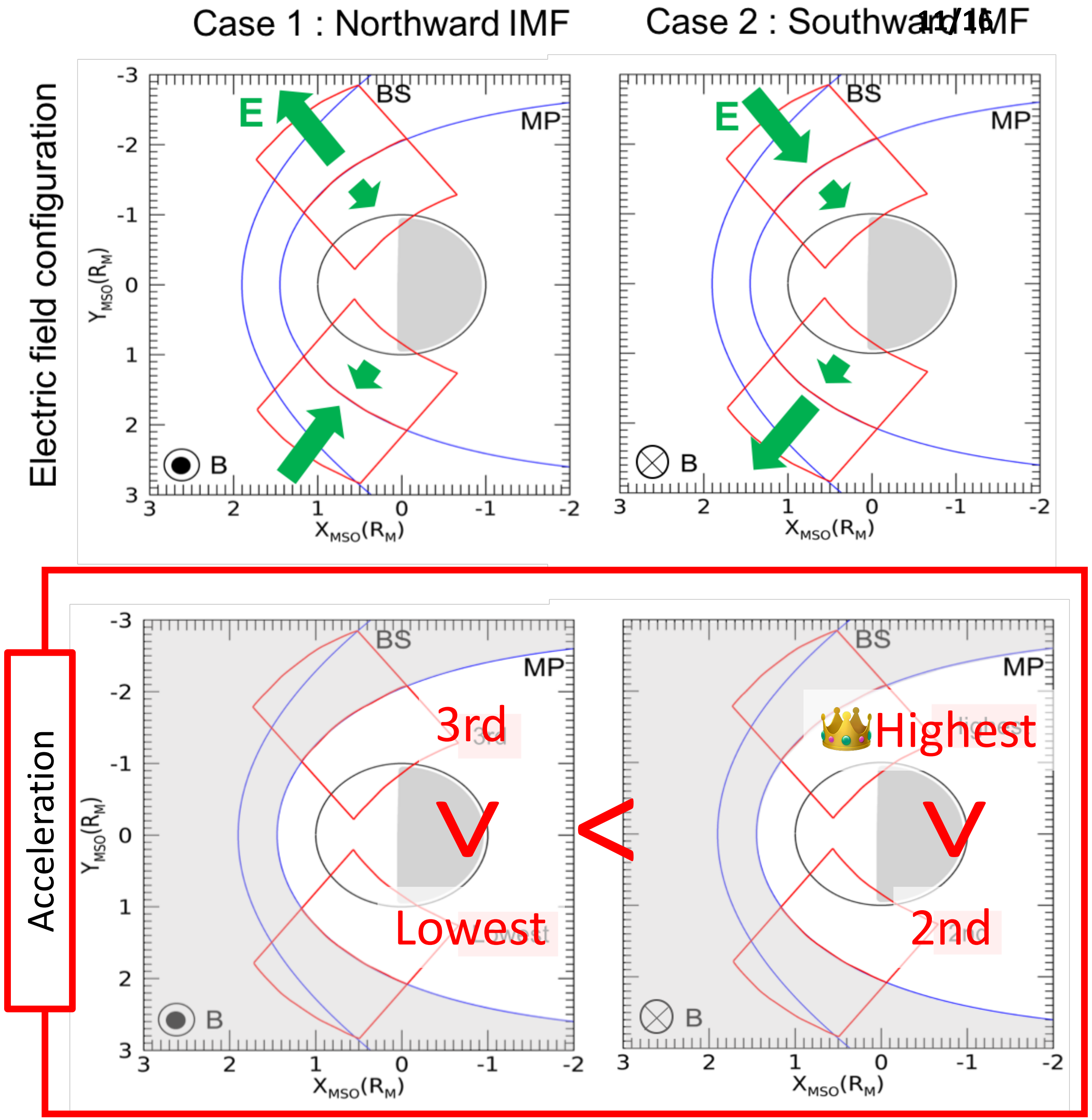
Transport : Seen in Dawnside only





Gray : number density of background proton

Role of magnetosheath electric field orientation : Acceleration



Ions of planetary origin (H^+, H_2^+, O^+, Na^+, K^+)

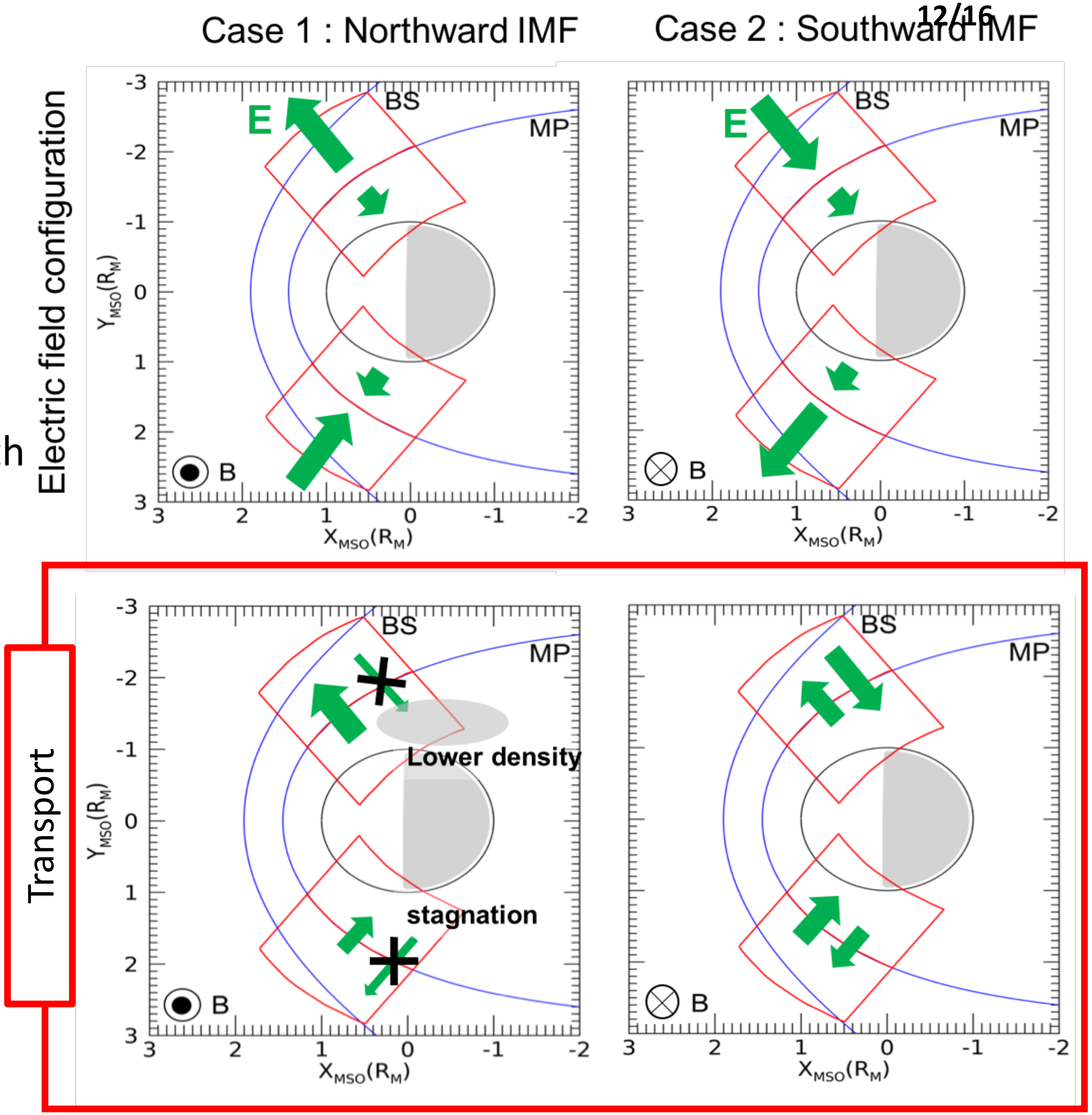
Picked up in

- Magnetosphere : all ions are accelerated
- Magnetosheath : lighter ions are accelerated

Solar wind plasma (H^+, He^{++} in magnetosheath)

Fewer ions are accelerated

Role of magnetosheath electric field orientation : Transport

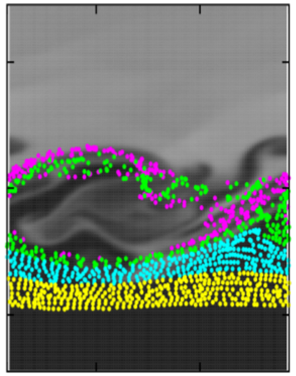


Ions of planetary origin (H^+, H_2^+, O^+, Na^+, K^+)

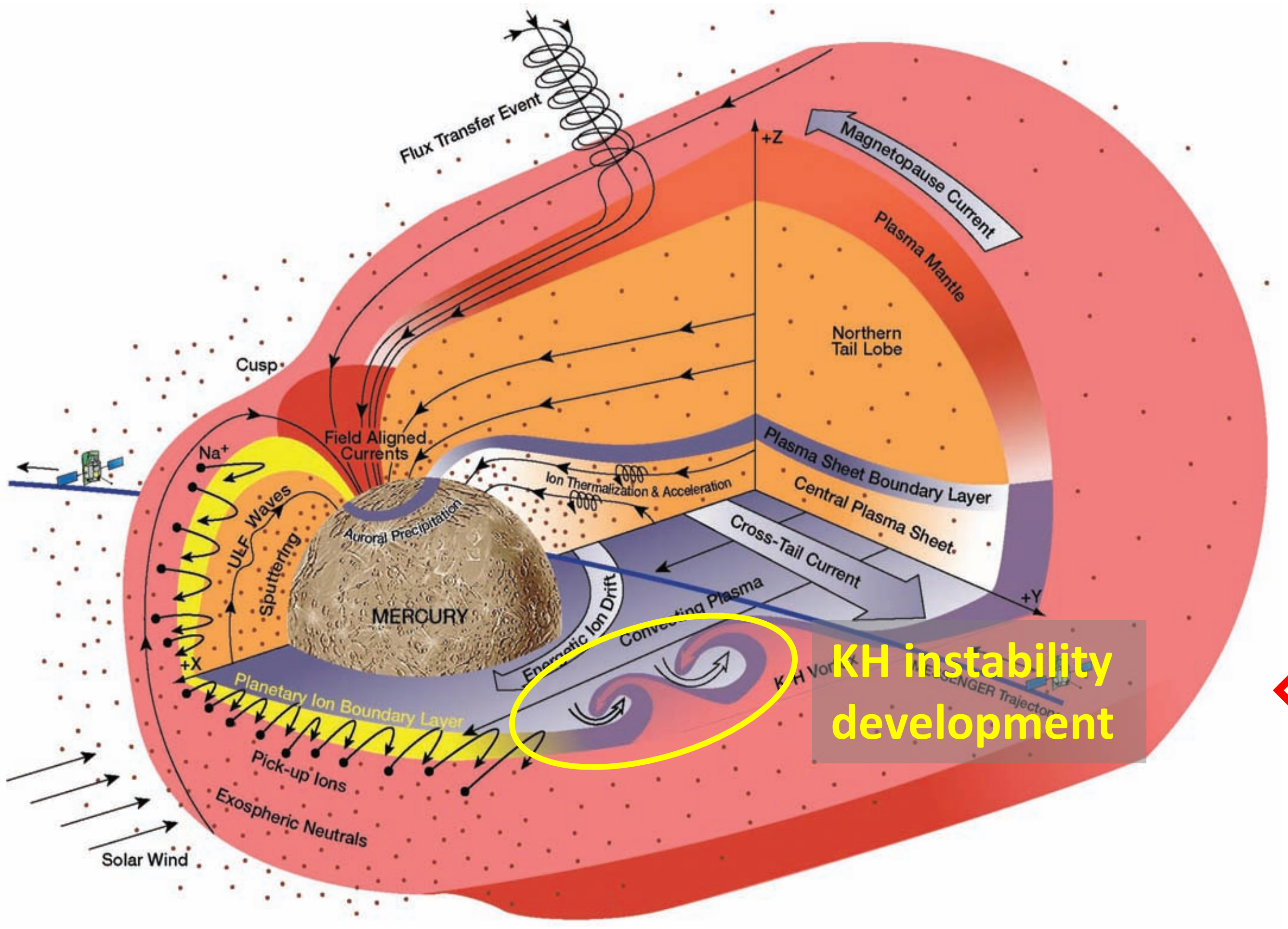
- Northward IMF
  - Dawnside : All ions move towards magnetosheath
  - Duskside : Ions stagnate in magnetosphere
- Southward IMF
  Ions can cross the magnetopause

Solar wind plasma (H^+, He^{++} in magnetosheath)

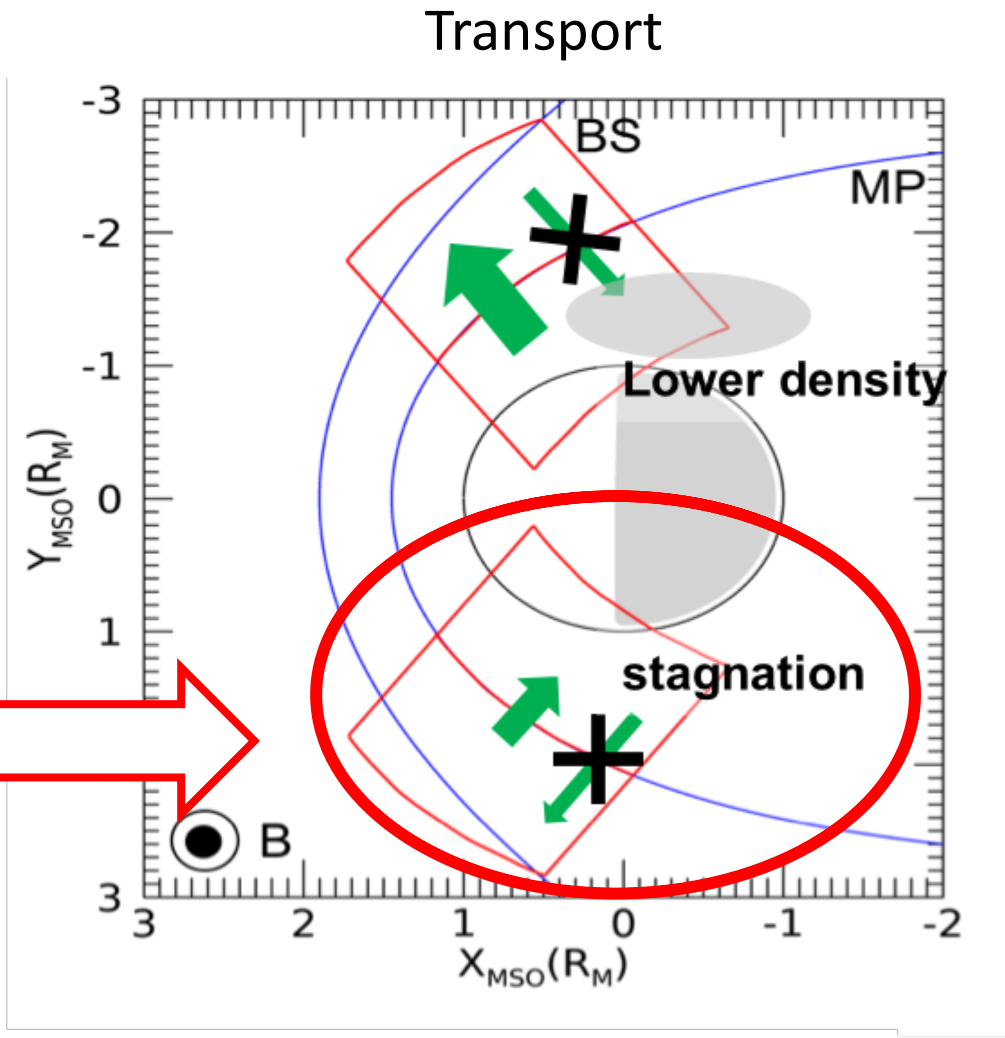
Penetrate into the magnetosphere
(MHD-like behavior)



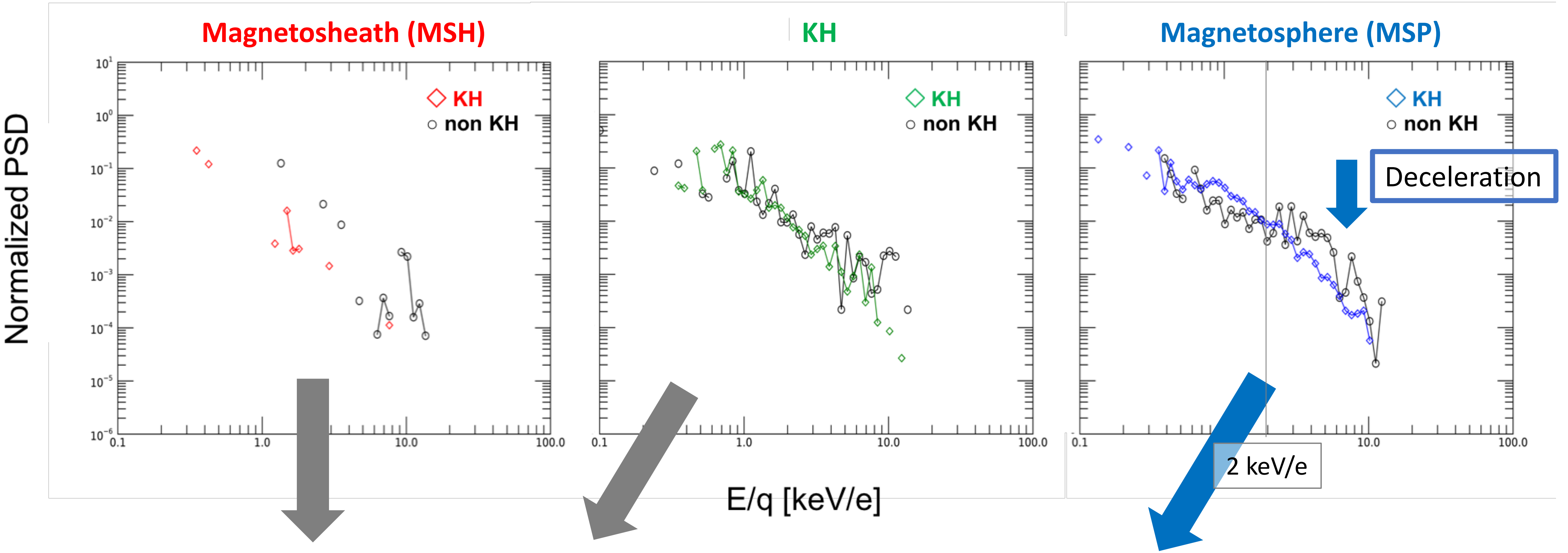
Does MESSENGER show similar features ?



[Slavin et al., 2008]



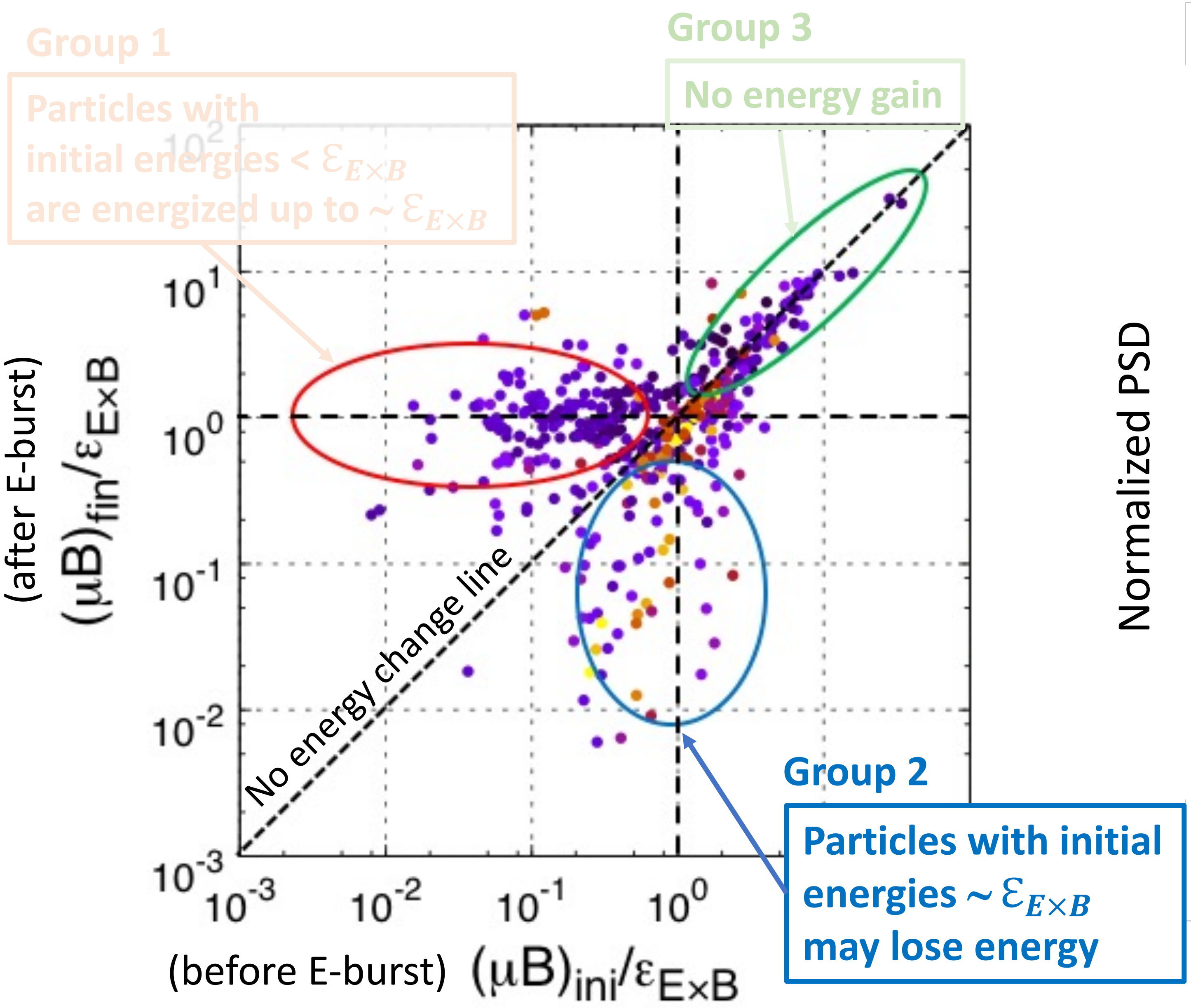
Na^+ PSD behavior (statistical study)

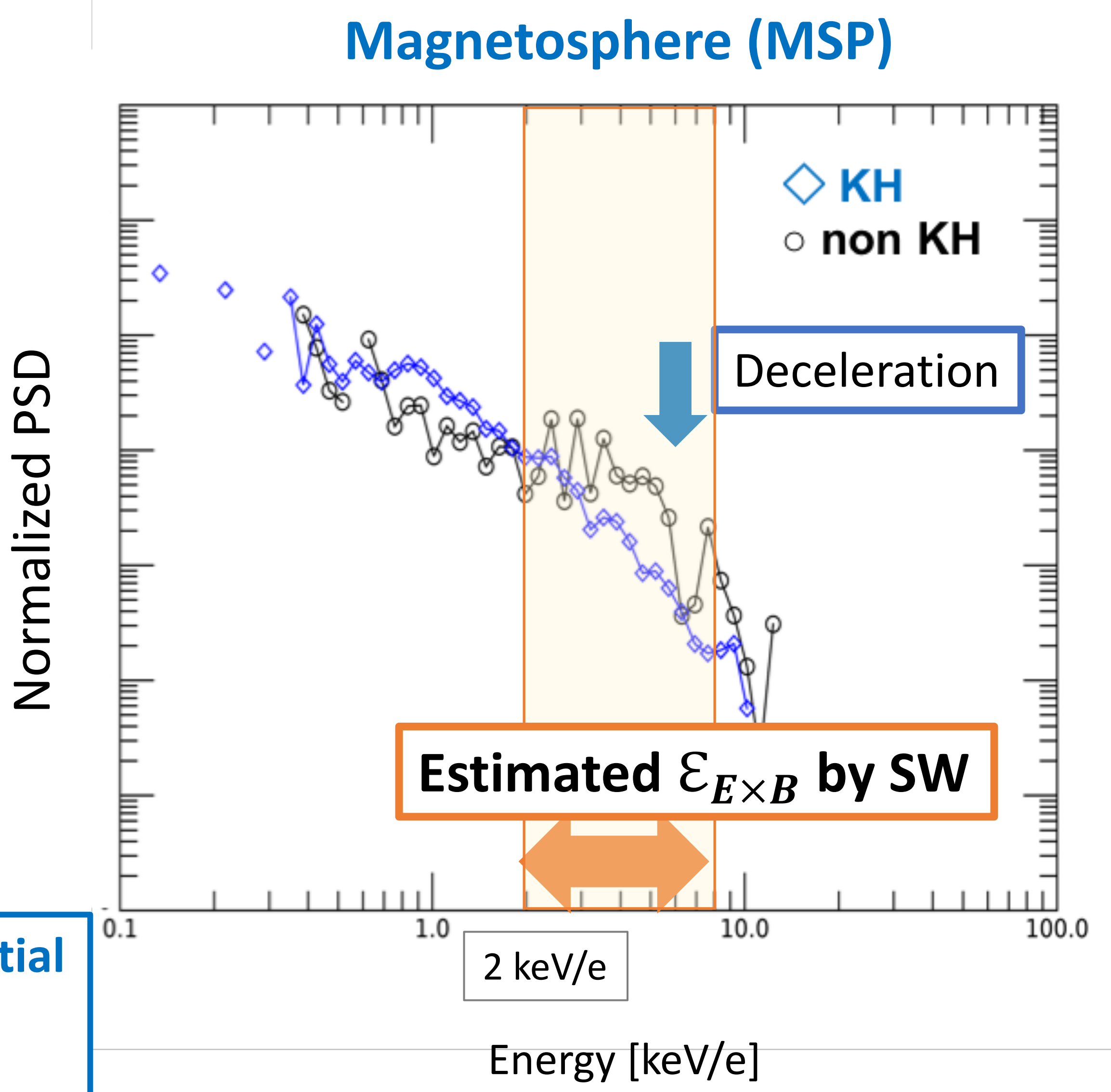


MSH & KH region :
No difference in PSD behavior
Larger Na^+ counts in presence of KH vortices

MSP region :
> 2 keV : PSD behavior shows "Deceleration" in KH case
< 2 keV : Small acceleration and larger Na^+ counts in KH case

Na^+ PSD behavior (statistical study)





Summary

■ Non-adiabatic energization is caused by the electric field variation generated from KH development. Energization occurs systematically.

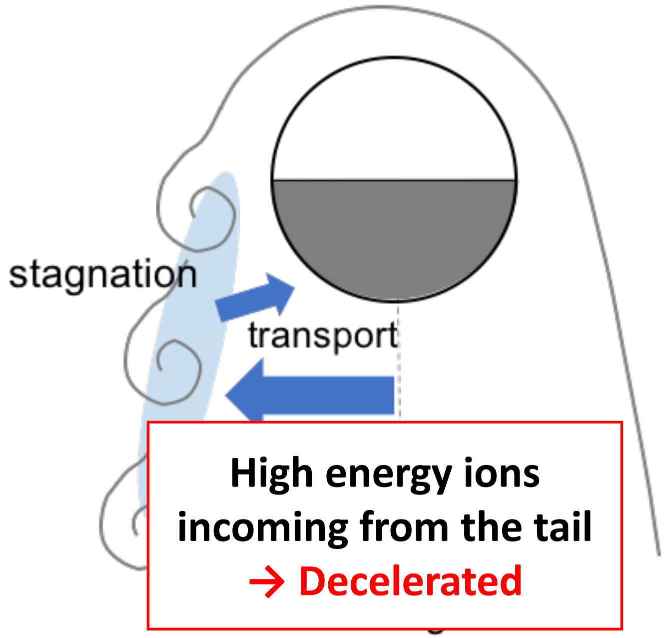
■ Transport of planetary ions is controlled by the electric field in the magnetosheath region
- Duskside : stagnation
  - **→ FIPS/MESSENGER counts of Na-group increase in the presence of KH vortices**
- Dawnside : Lower ion density (northward IMF)

■ Ions are decelerated in dusk-night magnetopause by KH vortices.

■ No significant differences in PSD behavior for ion acceleration.

⟹ Limited Field of View and energy range

→ future BepiColombo observations!
- Energy range (MSA + MIA/MIO) : a few eV/q to ~35 keV/q
  FIPS : 100eV/q – 13keV/q
- Three-dimensional information

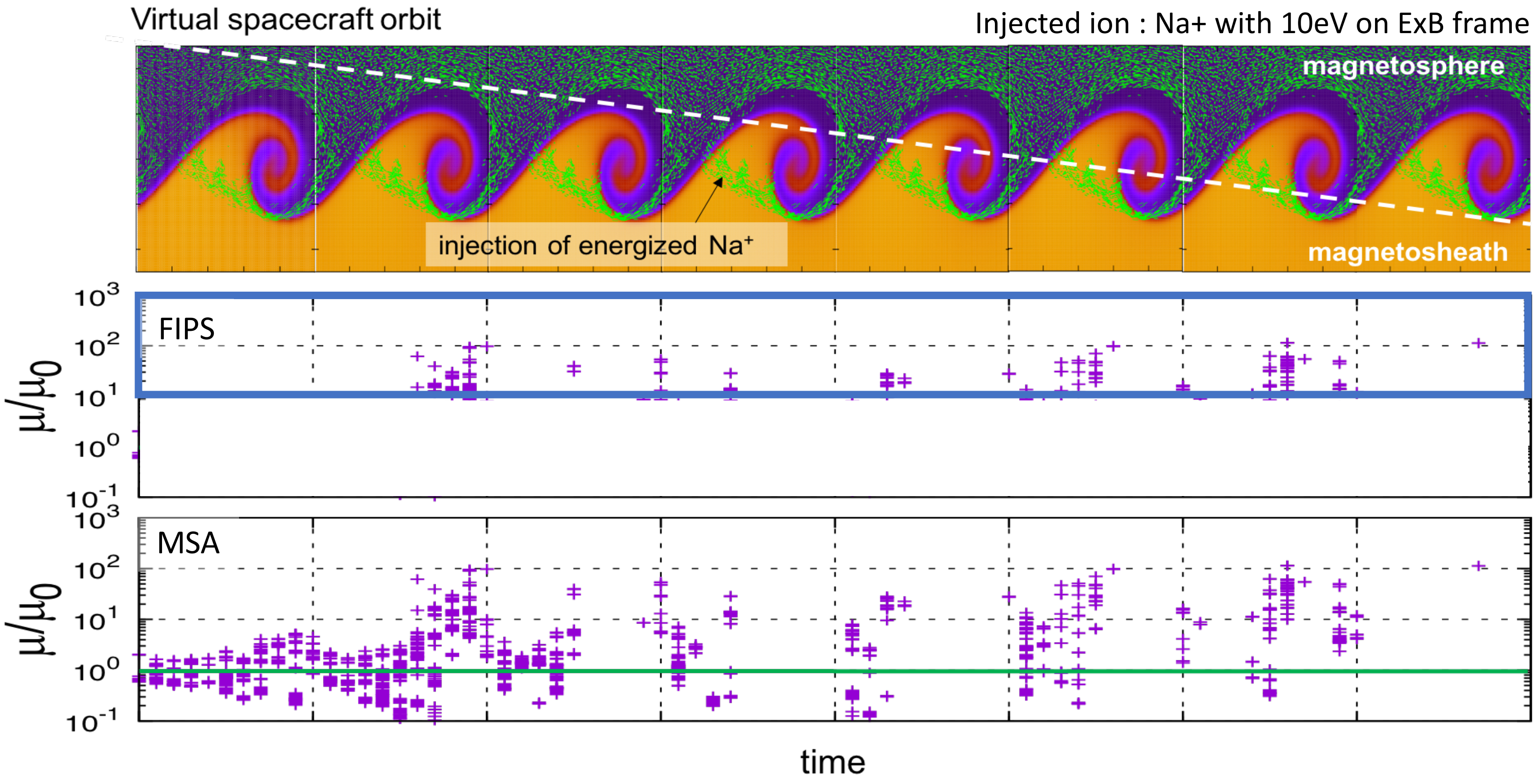


ESA/JAXA BepiColombo mission

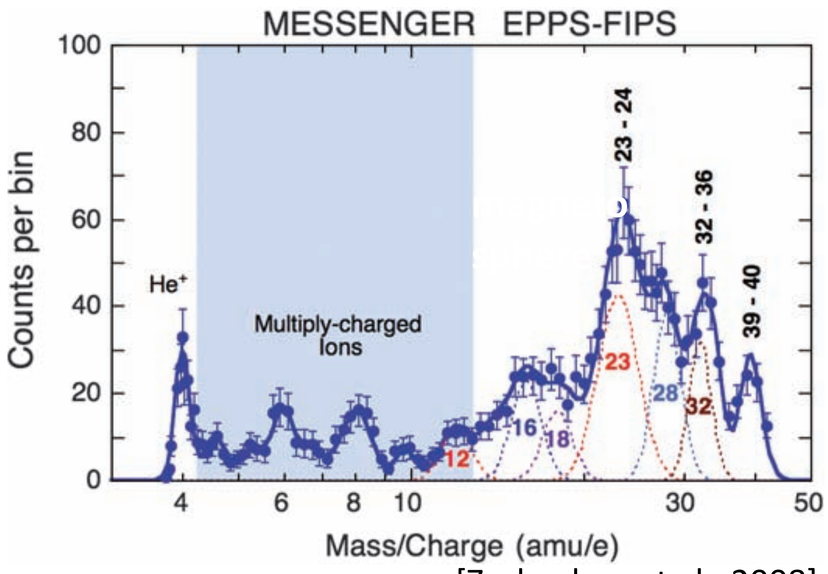
- Arrival : Dec. 2025
- mission : 1 year nominal (+ 1 year extended ?)
- Instruments for ions on MIO (MPPE consortium) :

MIA, MSA (Ion composition information)

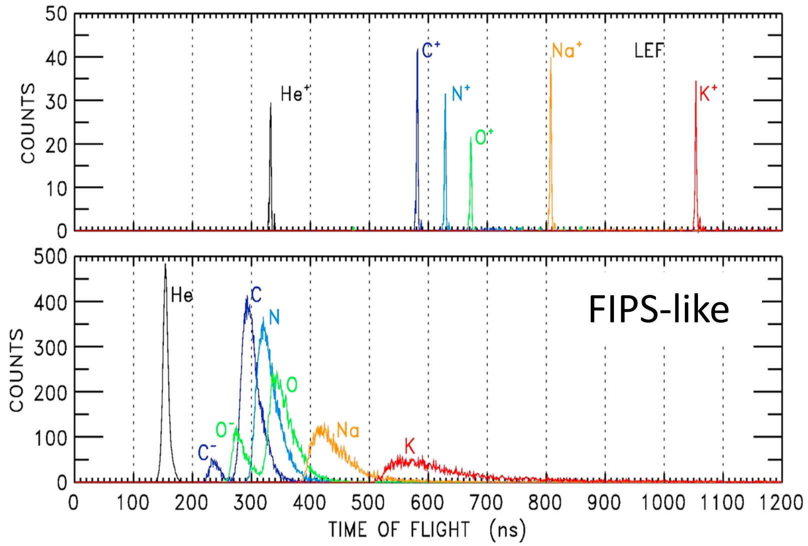
Energy range : a few eV/q to ~35 keV/q (FIPS : 100eV/q – 13keV/q)



m/q resolution comparison



[Zurbuchen et al., 2008]



[Delcourt et al., 2016]

Realistic Mercury configurations (2/2)

	Magnetosheath region	Magnetosphere region
Background H^+ number density	100 ions/cc	10 ions/cc
Flow velocity (MSO)	- 300 km/s	$+$ 50 km/s
Injected planetary ion species (m/q)	H^+ (1), H_2^+ (2), O^+ (16), **Na^+ (23)**, K^+ (39)	
Solar wind ions on ExB frame (m/q)	H^+ (1), He^{++} (2)	
Initial ion energy	H^+(1), H_2^+(2) : 0.047 eV (540K) in Mercury frame	
	O^+ (16), **Na^+ (23)**, K^+ (39) : 1 eV in Mercury frame	
	H^+ (1), He^{++} (2) : 10 eV in ExB frame	
Injection time	32.2 s, 80.5 s, 128.8 s	
Magnetic field (B_z)	$\pm$ 48.7 nT	$+$ 48.7 nT

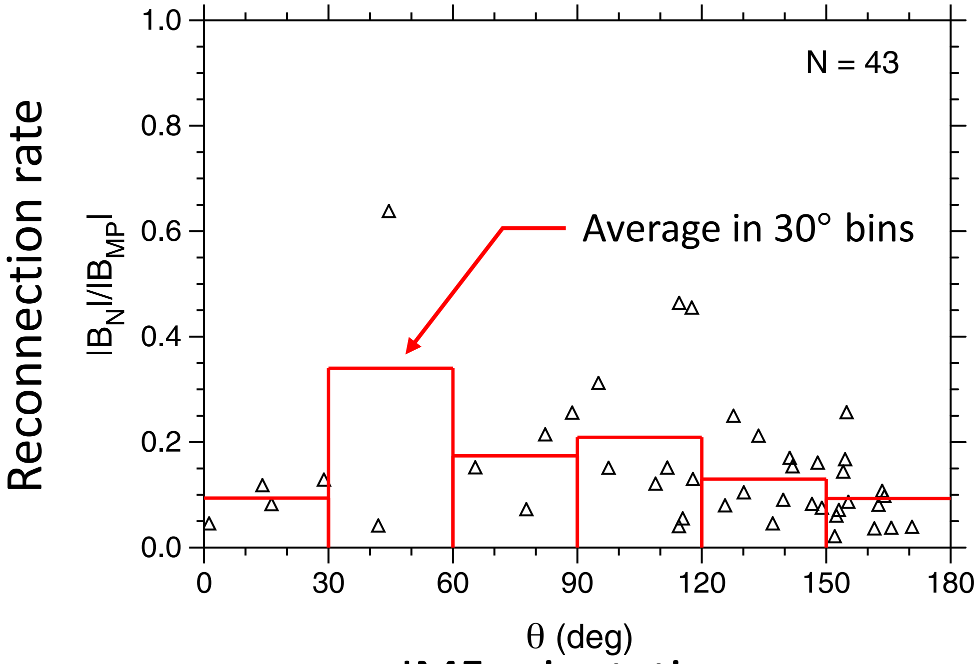
Highly dynamic physical phenomena around Mercury

(Ex. 1) Frontside magnetic reconnection

Earth : No reconnection under northward IMF

Mercury : Reconnection under wider range of IMF orientations

[DiBraccio et al., 2013]



IMF orientation

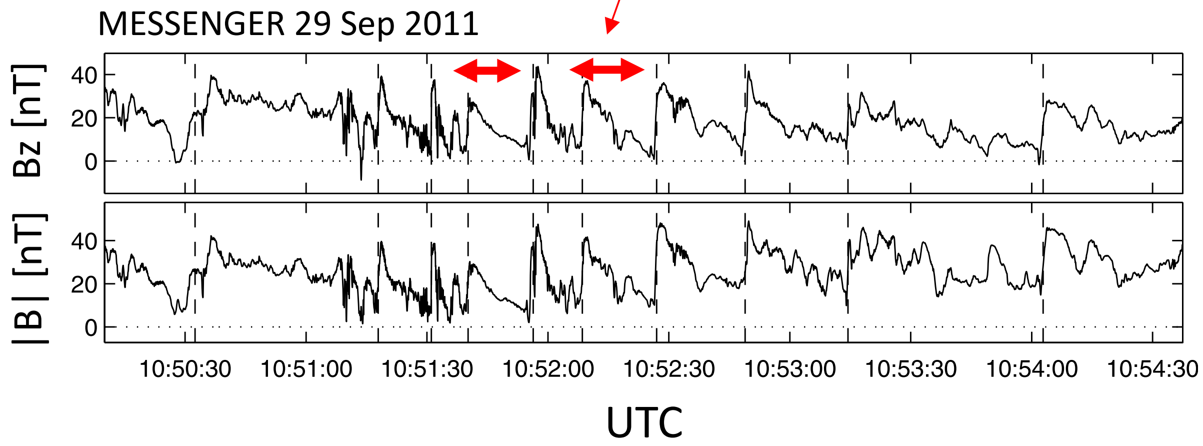
(← northward southward →)

(Ex. 2) Dipolarization in the magnetotail

Earth : Time scale of a few minutes

Mercury : Time scale in **~10 s**

[Sundberg et al., 2012]



Estimated gyroperiod

Electron : ~ 1 ms

Proton : **~1 s**

Heavy ions (Na^+, K^+…) : **a few 10 s**

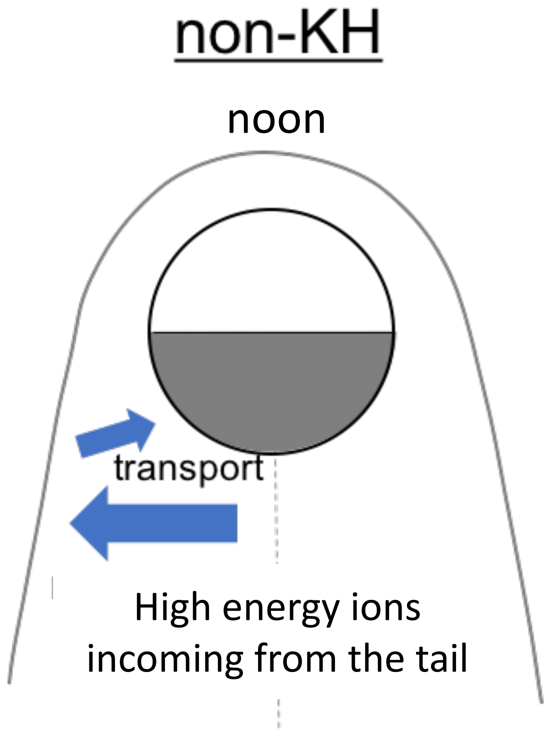
Non-adiabatic energization is expected!

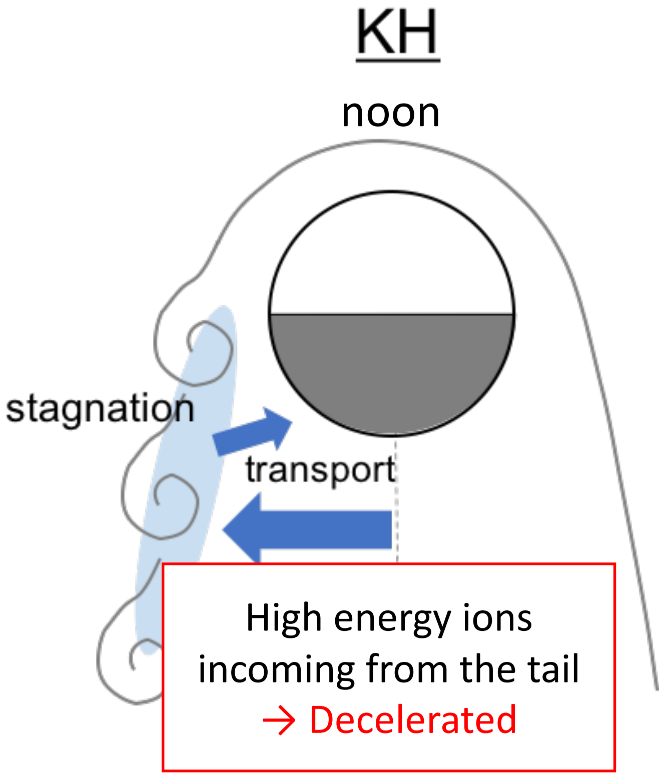
Possible mechanism (duskside + northward IMF)

Numerical results (Chap. 4 & 5)
- Energization : Weak
- Transport : Stagnation

Relationship ?

Results of data analysis (Chap. 6)
- Na^+ PSD behavior : Deceleration (> 2 keV)
- Na^+ counts : Large in KH and MSP region (< 2 keV)





Energization

- Large Na^+ population incoming from the tail
  → They are decelerated
- Picked up ions are not dominant
  → Energized ions but no PSD changes

Transport

- Stagnation because of the convection E-field
- Large Na+ population may lead to efficient development of KH instability

MESSENGER: MAG, FIPS observations (3/3)

Questions :

- Are there any differences in the Phase Space Density (PSD) measurements between KH and non-KH events? (energization)
- Do we have similar signature of stagnation as our previous numerical results show? (transport)

Data selection

■KH events

1. clear signature of KH waves
2. enough FIPS counts
3. FIPS clock angle (180 – 270°)

→ 16 KH events

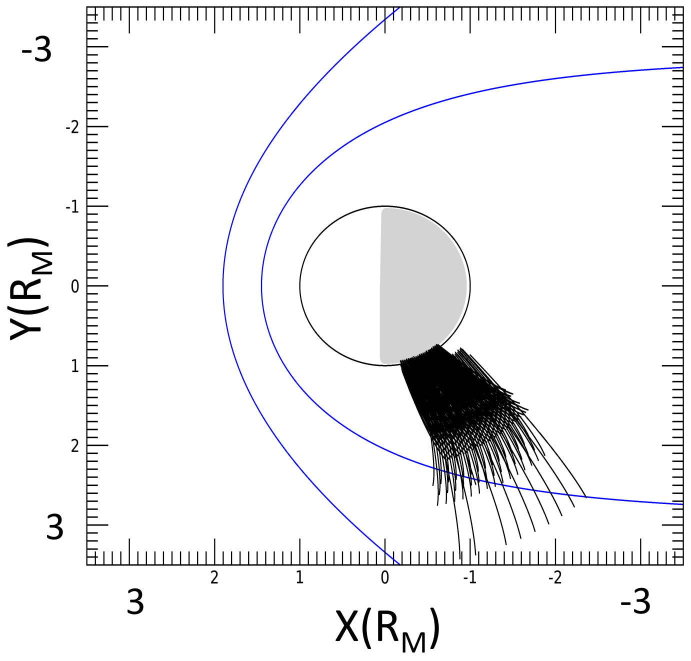
✓ Previously reported KH events
[e.g., Sundberg et al. 2012, Gershman et al., 2015]

✓ Nightside magnetopause crossing event (19 – 21LT)

■Non-KH events

Adjacent orbits of KH events

All magnetopause crossing orbit in 2012



MESSENGER: MAG, FIPS observations