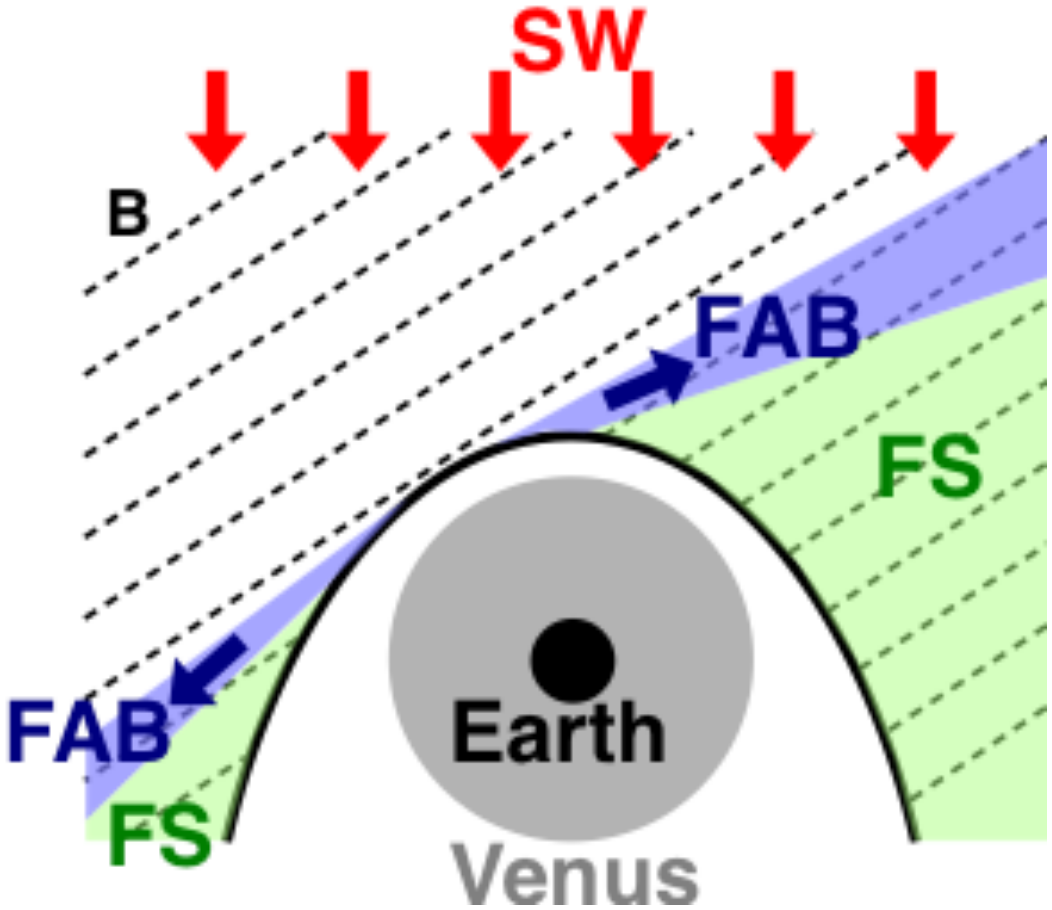
Foreshock studies by MEX and VEX

M. Yamauchi et al.



FAB: field-aligned beam

FAB + FS: foreshock

Shock = Fluid nature

Foreshock = Particle nature

Important parameters

(1) Alfvén Mach number (M_A)

x ⇒ (2) Gyroradius (r_g) / Bow-shock radius (R_S)

(3) Inertia length (c/ω_{pi}) / Bow-shock size (R_S)

SW parameter	R_S (BS radius)	M_A ($\propto n^{1/2}V/B$)	c/ω_{pi} ($\propto n^{-1/2}$) & $c/\omega_{pi}R_S$	r_g ($\propto V/B$) & r_g/R_S
Venus	**1**	**1**	**1** & **1**	**1** & **1**
Earth	**~ 5**	**~ 1.2**	**~ 1.7** & **~ 0.3**	**~ 2** & **~ 0.4**
Mars	**~ 0.5**	**~ 1.4**	**~ 3** & **~ 5**	**~ 4** & **~ 8**

For Mars: **R_S ~ 5000 km** for Martian Subsolar

2 keV H^+ under 6 nT ⇒ **r_g = 1000 km**

5/cm^3 H^+ ⇒ **c/ω_{pi} = 100 km**

Venus-Mars difference: (2) cold H+

(1) Gravity: **Venus > Mars**

⇓

(2) Exosphere: **Venus < Mars**

⇓

(3) newly born H+: **Venus << Mars**

(This is clear from the difference in “ring distribution”)

⇓

(4) cold H+ at Bow shock: **Venus << Mars**

(High density cold H+ is observed only for Mars)

Venus - Mars difference (summary)

(1) Alfvén Mach number (M_A)

(2) Gyroradius (r_g) / Bow-shock radius (R_S)

(3) Inertia length (c/ω_{pi}) / Bow-shock size (R_S)

(4) Cold ion inside Bow-shock

parameter	R_S	M_A	$c/\omega_{pi}R_S$	r_g/R_S	cold H+ at BS
Venus	**1**	**1**	**1**	**1**	**very little**
Mars	**~ 0.5**	**~ 1.4**	**~ 5**	**~ 8**	**a lot**

⇑ ? ⇑ ?

Ending (add Earth)

(1) Alfvén Mach number (M_A)

(2) Gyroradius (r_g) / Bow-shock radius (R_S)

(3) Inertia length (c/ω_{pi}) / Bow-shock size (R_S)

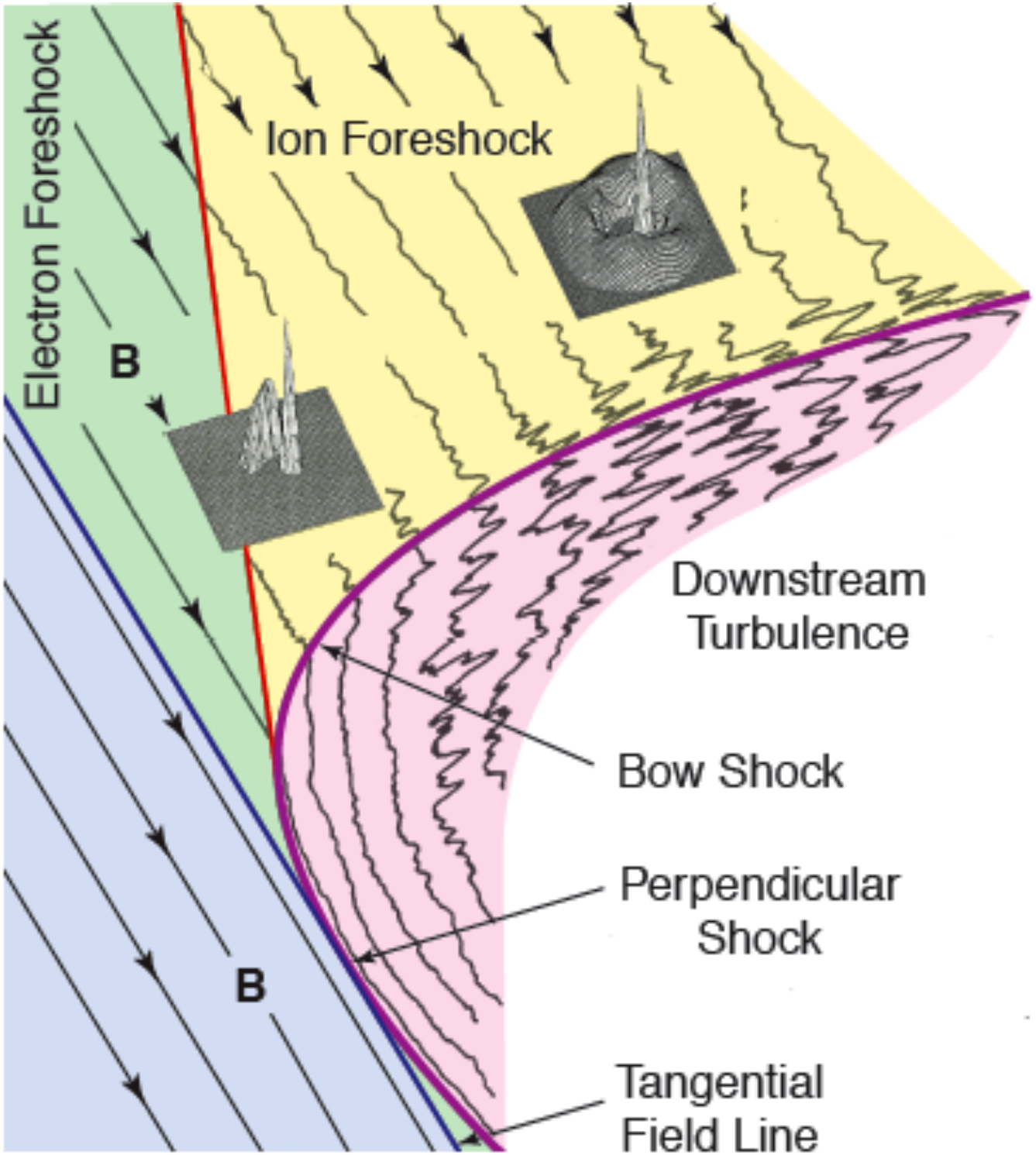
(4) Cold ion inside Bow-shock

parameter	R_S	M_A	$c/\omega_{pi}R_S$	r_g/R_S	cold H+ at BS
Earth	**5**	**~ 1.2**	**~ 0.3**	**~ 0.4**	**no**
Venus	**1**	**1**	**1**	**1**	**very little**
Mars	**~ 0.5**	**~ 1.4**	**~ 5**	**~ 8**	**a lot**

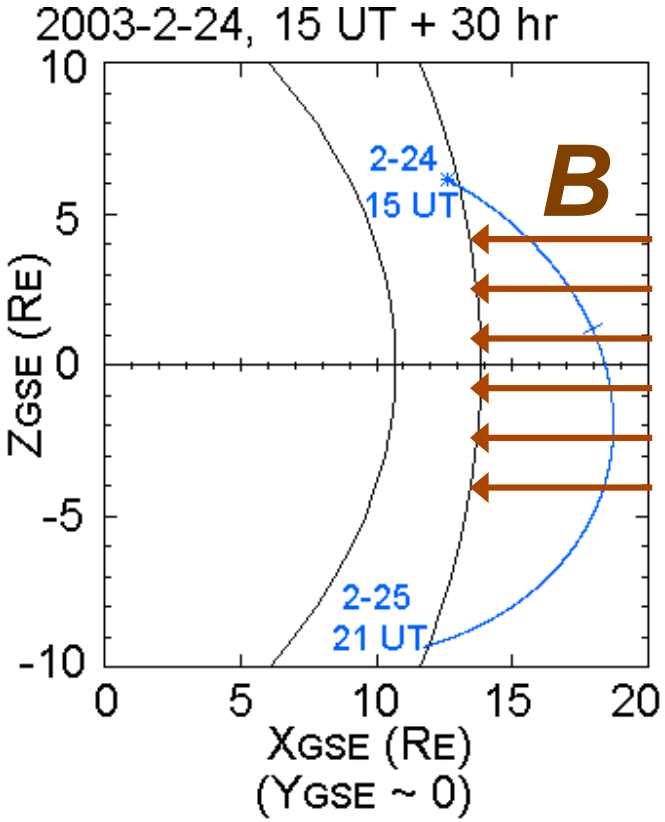
⇑ ? ⇑ ?

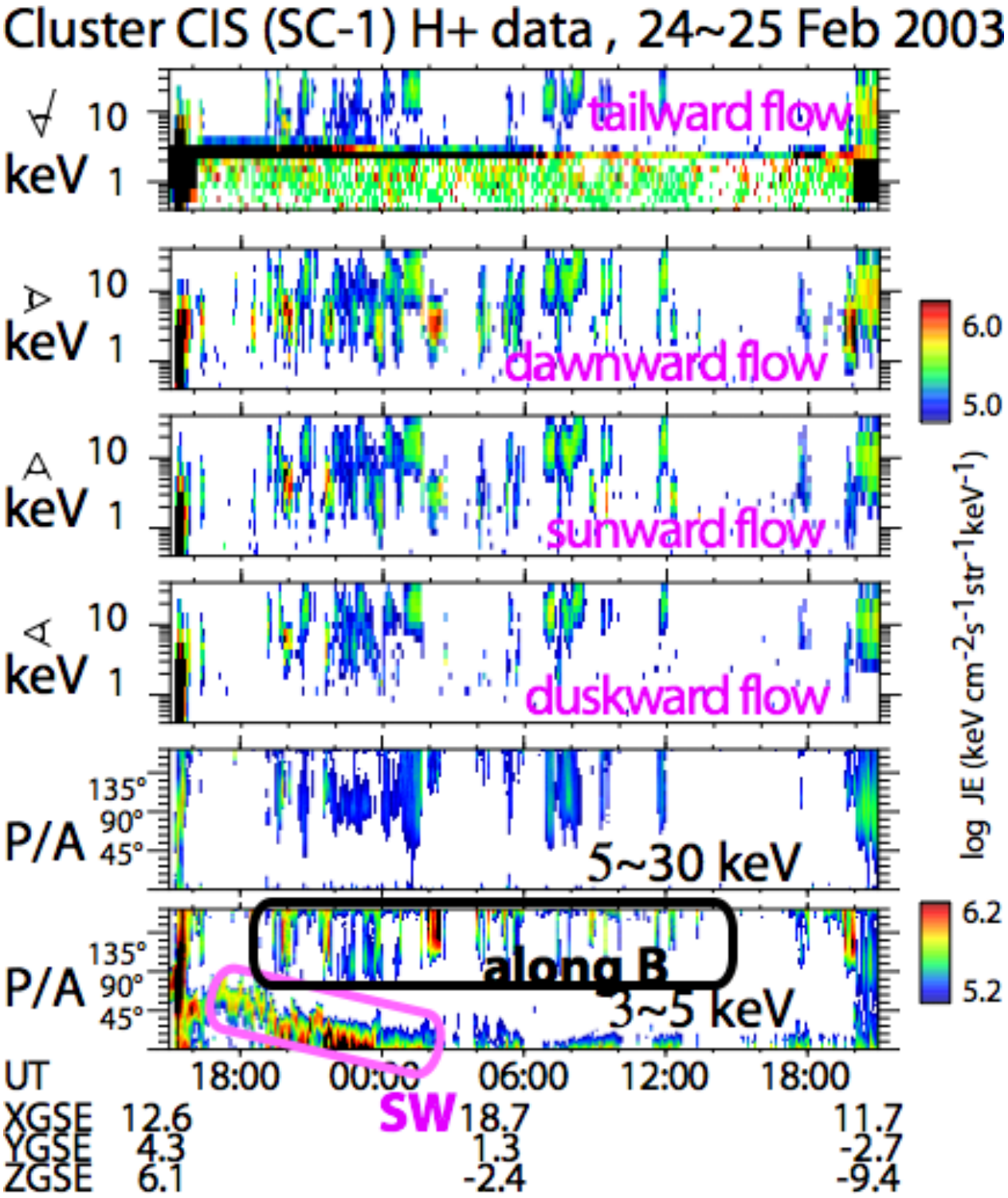
Outline

1. **Introduction**: ion motion
2. **Introduction**: Earth's knowledge
3. **Venus** (similar to Earth)
4. **Mars** (Different from Venus/Earth)


Electron Foreshock
Ion Foreshock
B
Downstream
Turbulence
Bow Shock
Perpendicular
Shock
B
Tangential
Field Line

Earth's case
= since 1970's

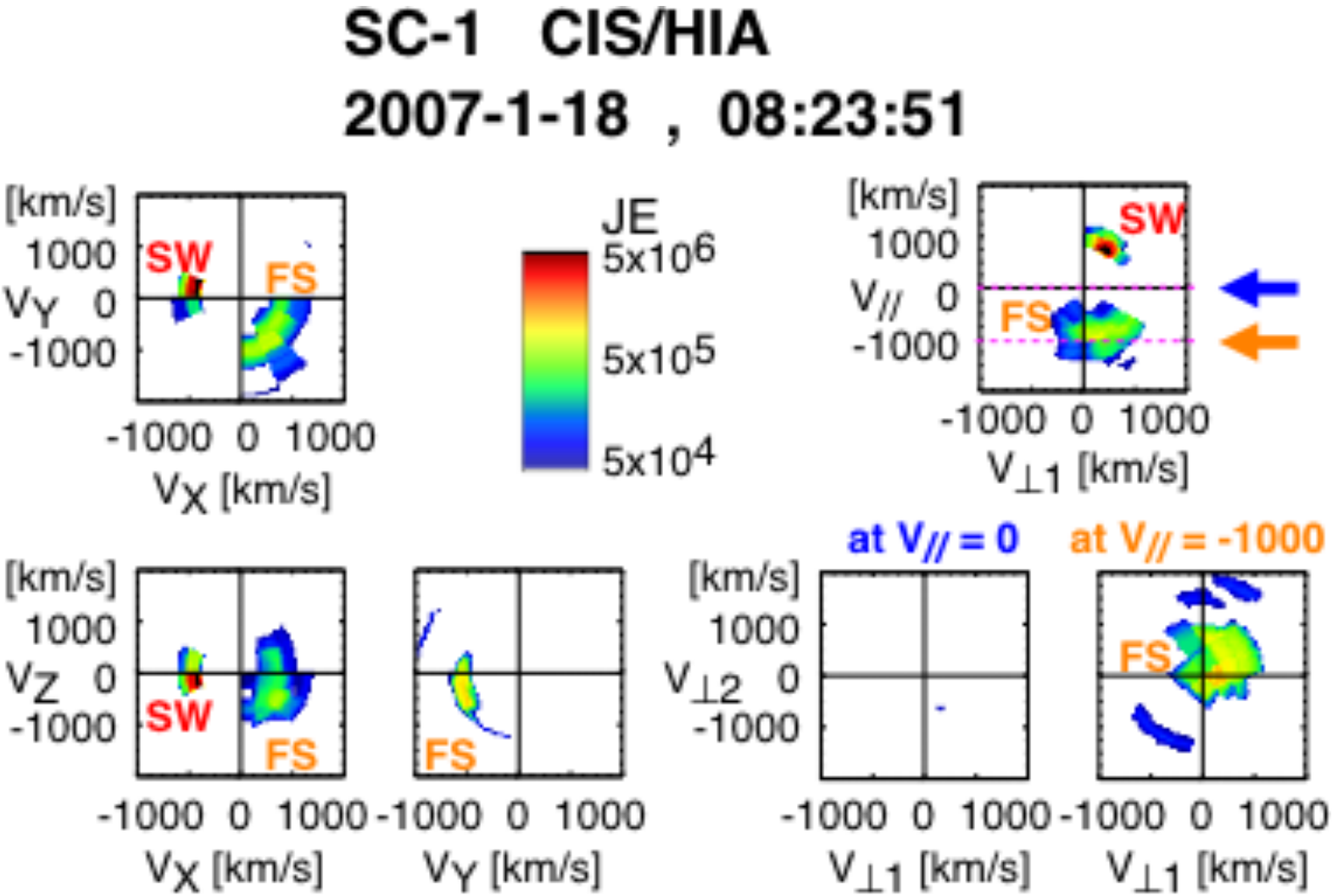




* Upstream region

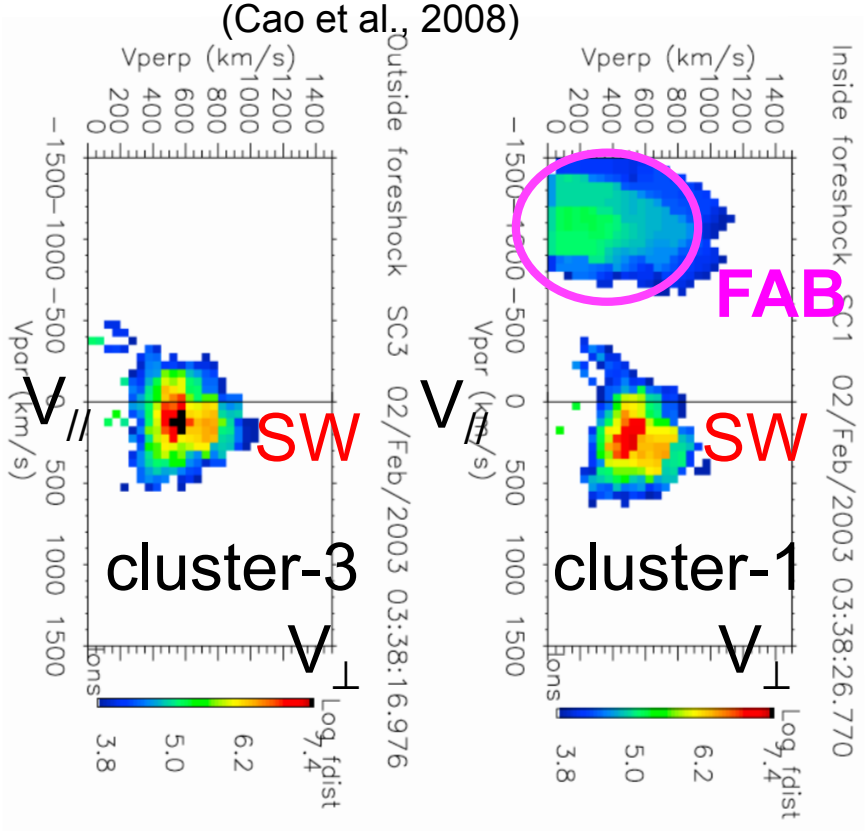
* Large $V_{//}$ (& sunward)

* Energized (> E_{sw})



* Localized (< few 100km)

(Cao et al., 2008)



Ion motion in B (and E)

Lorenz transform

$\boldsymbol{B'} = \boldsymbol{B}$

$\boldsymbol{E'} = \boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B}$

Lorenz force on ion

$\boldsymbol{F} = q(\boldsymbol{E'} + q\boldsymbol{v} \times \boldsymbol{B'})$

where

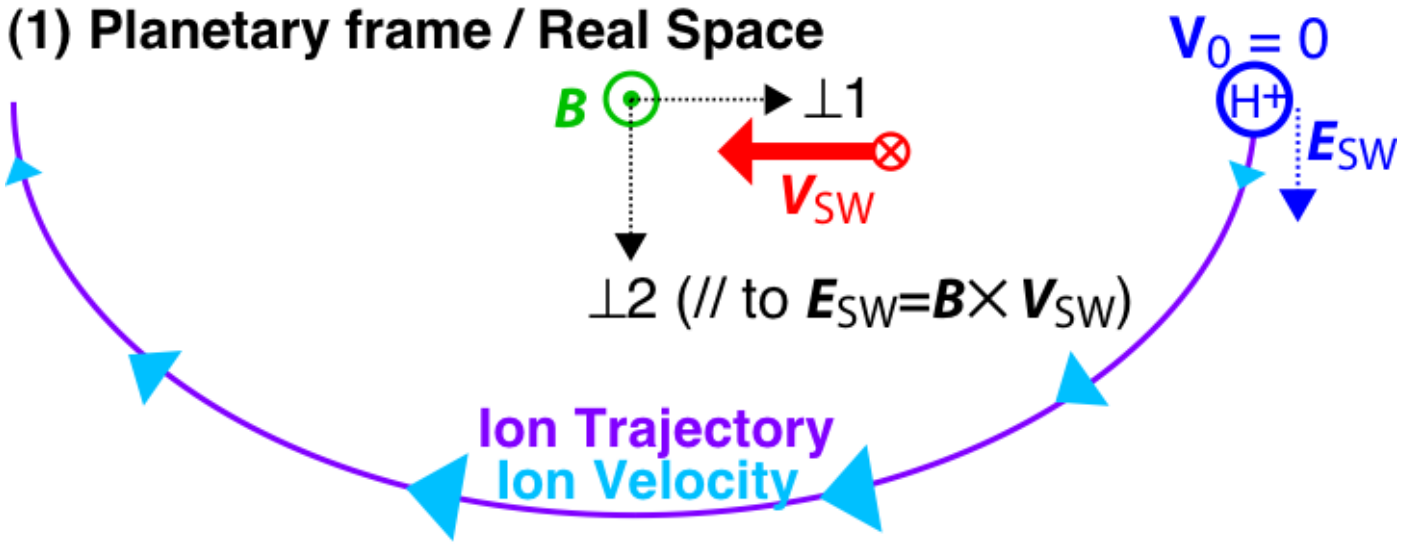
$\boldsymbol{V}$: velocity of frame

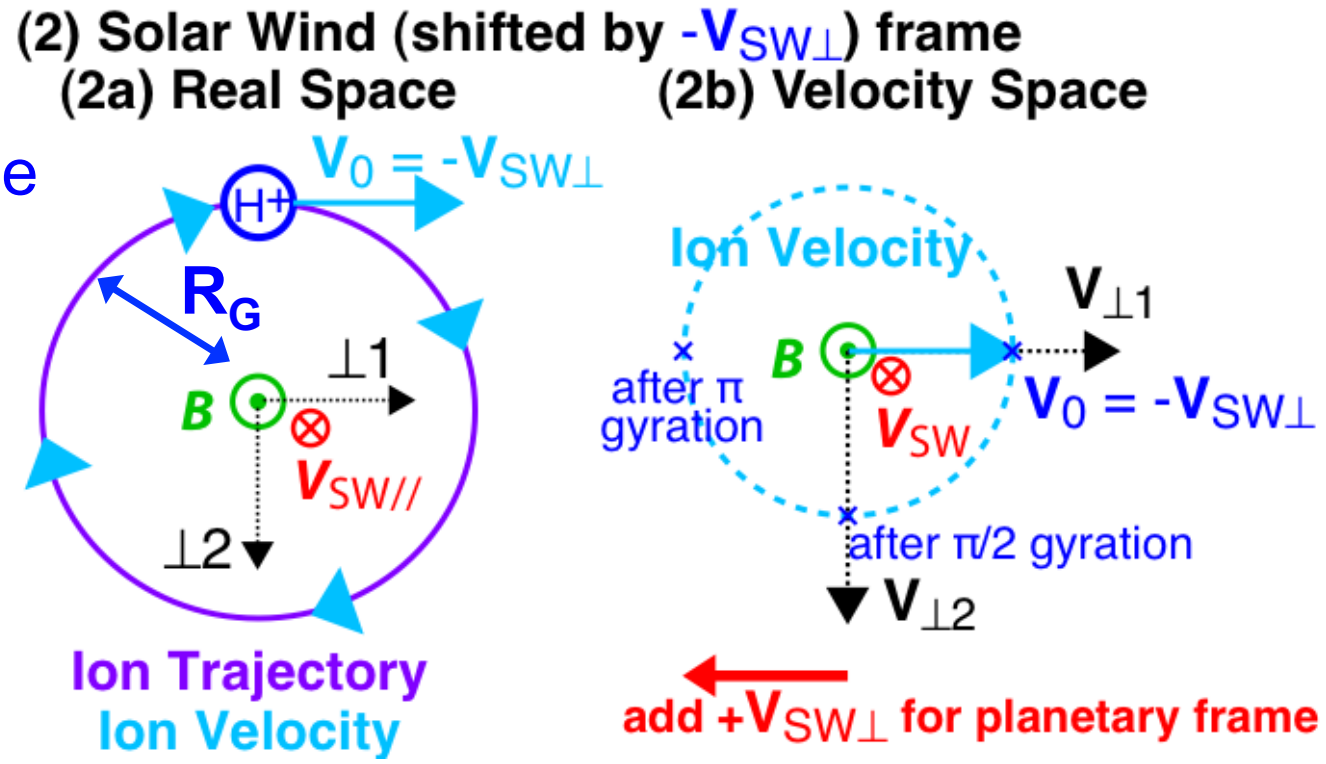
$\mathbf{v}$: velocity of ion

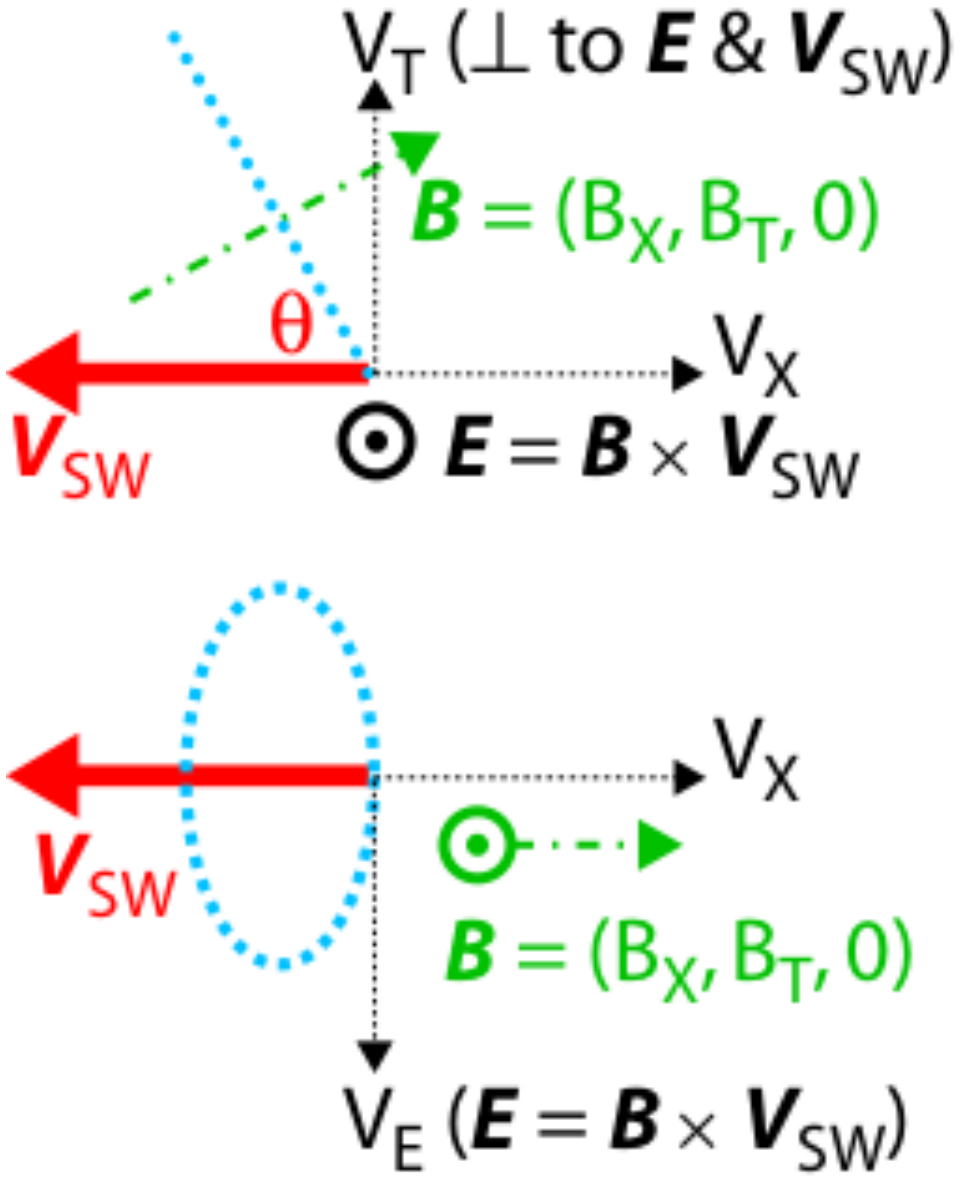
q: charge of ion

and

$R_G = mv_\perp/qB$



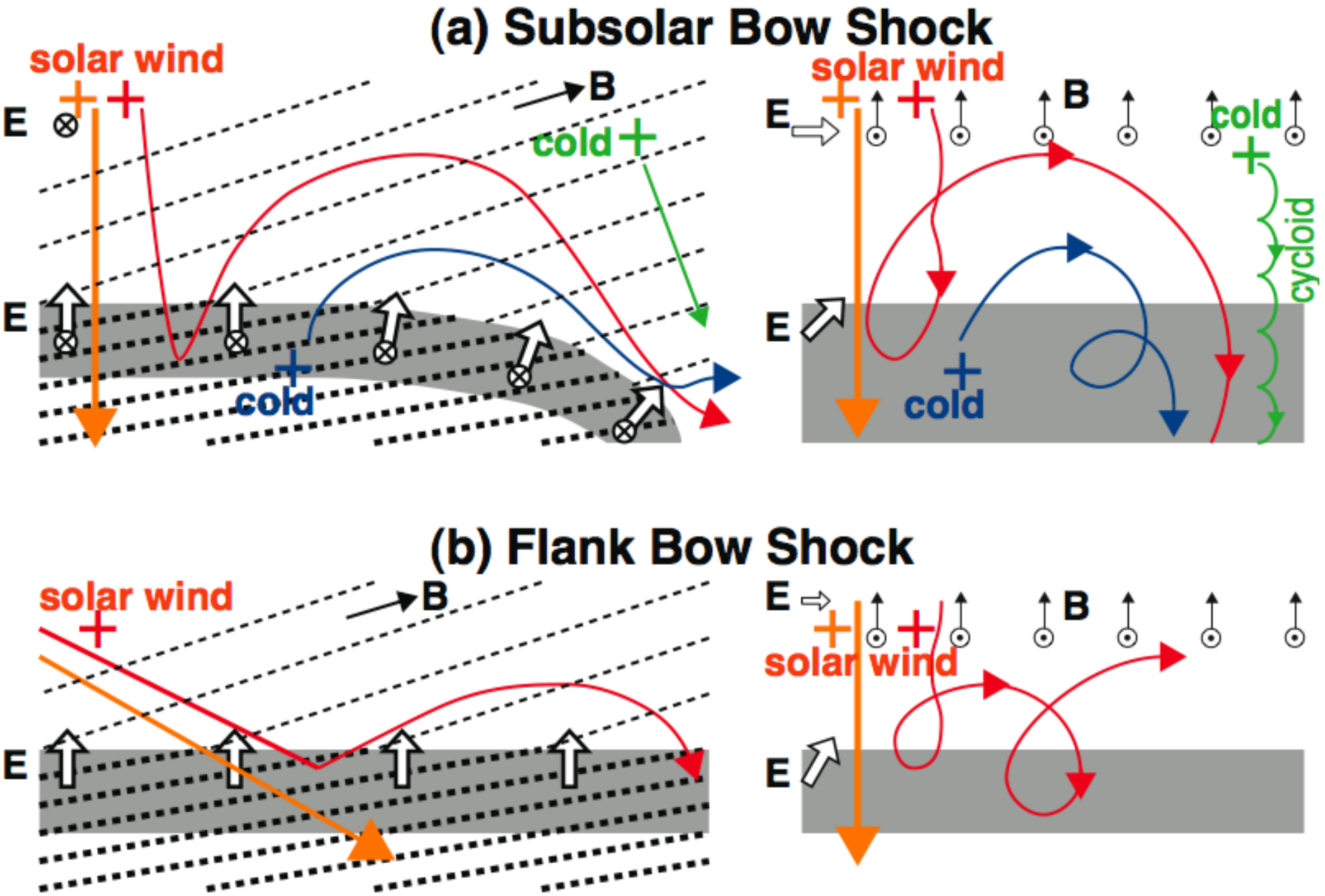




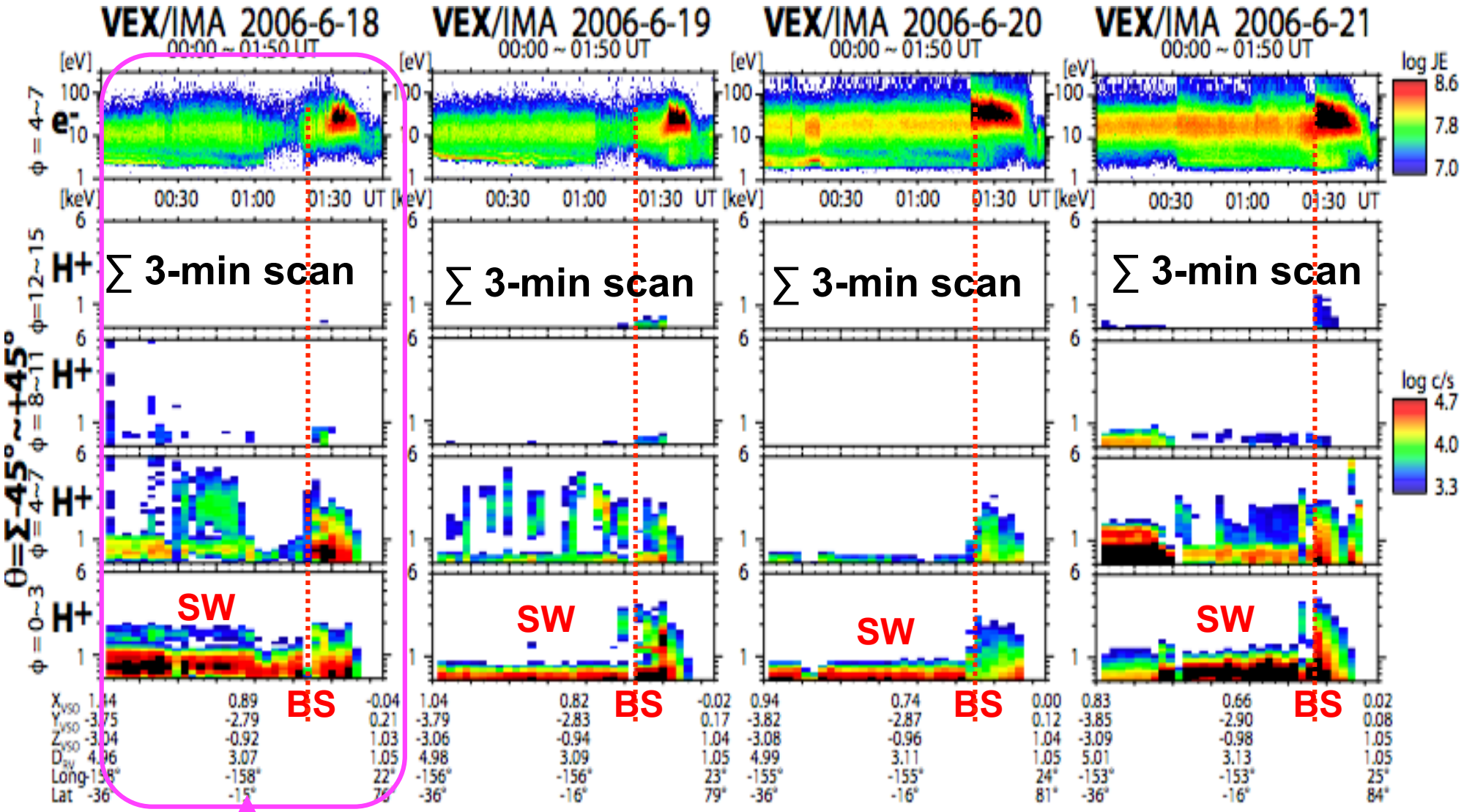
Long Radius = $|\boldsymbol{V}_{SW} \times \boldsymbol{b}|$

Short radius = $|\boldsymbol{V}_{SW} \times \boldsymbol{b}|\cos(\theta)$

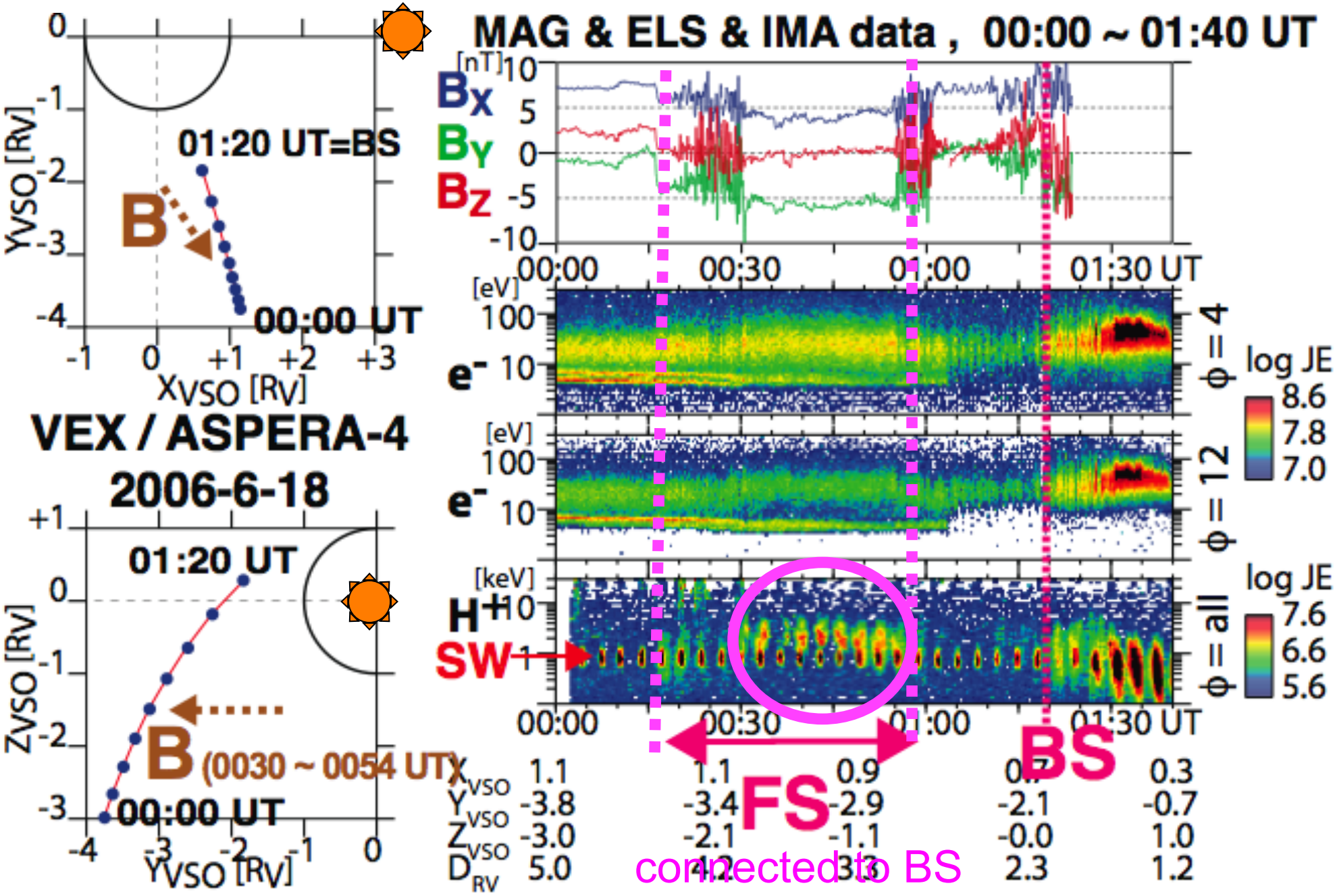
1. solar wind, 2. newly born ion, 3. bow-shock cold ion

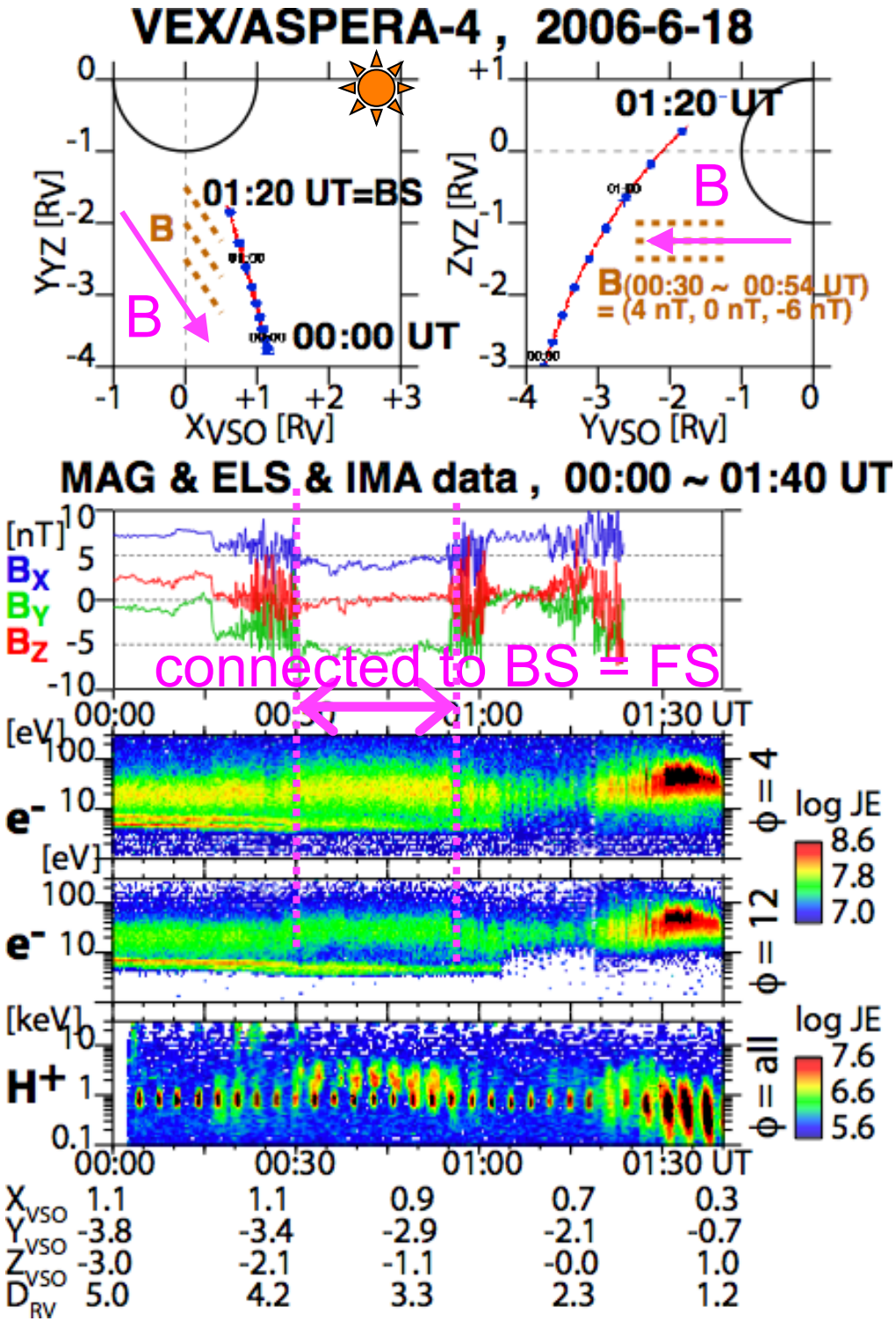


Venus (Venus Express)

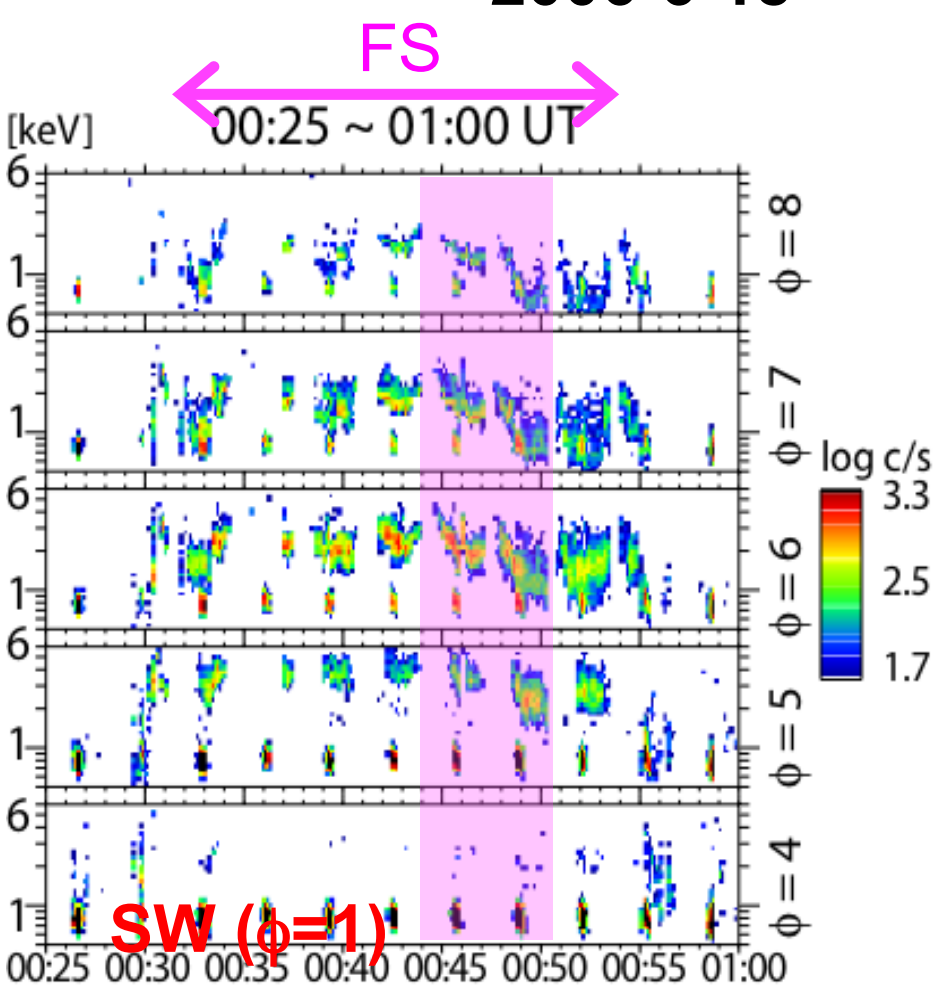


Venus (VEX)

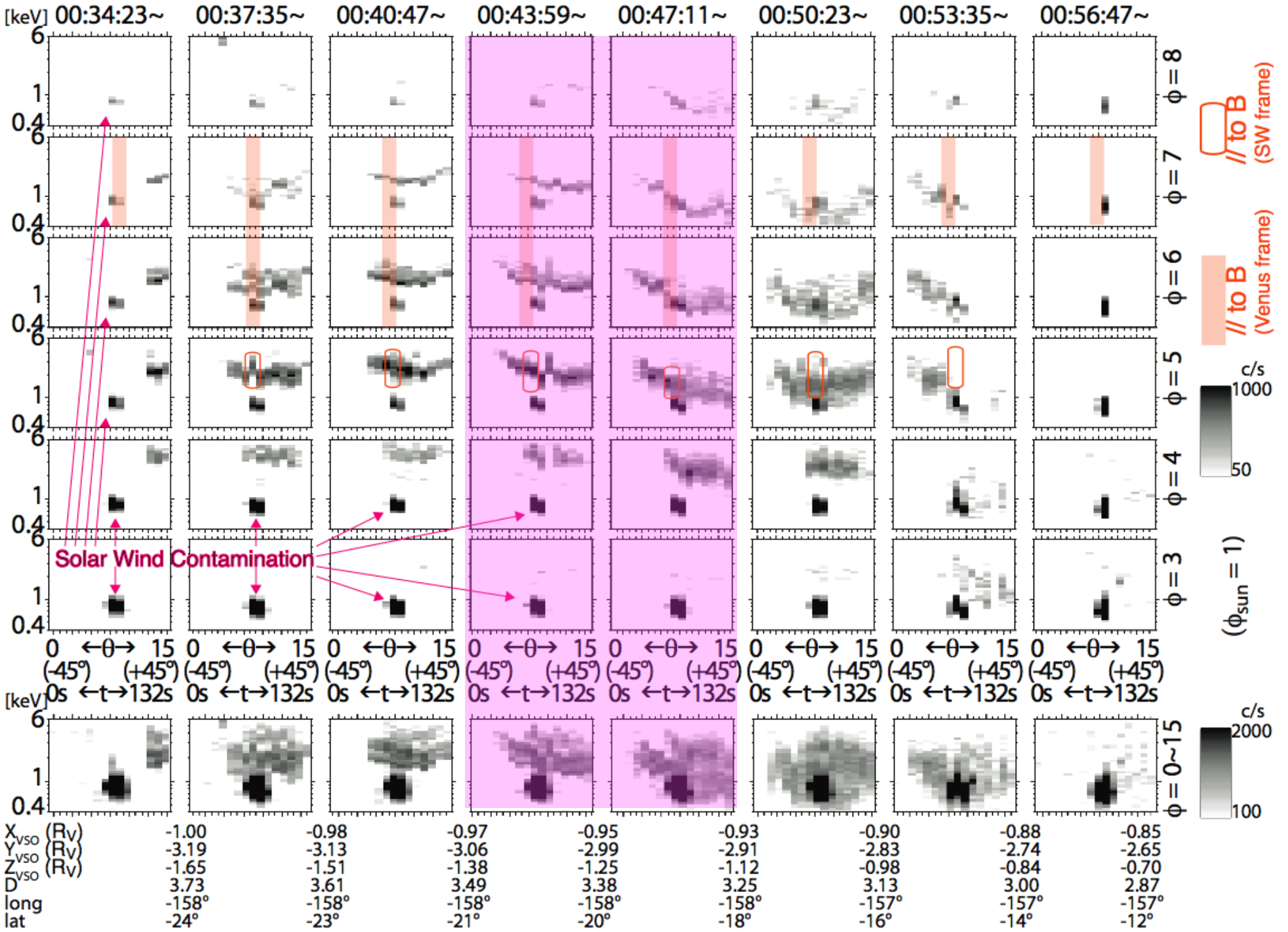

01:20 UT=BS
B
00:00 UT
YVSO [RV]
XVSO [RV]
VEX / ASPERA-4
2006-6-18
01:20 UT
B (0030 ~ 0054 UT)
00:00 UT
ZVSO [RV]
YVSO [RV]
MAG & ELS & IMA data , 00:00 ~ 01:40 UT
[nT]
Bx
By
Bz
00:00
00:30
01:00
01:30 UT
[eV]
e-
φ = 4
log JE
8.6
7.8
7.0
φ = 12
φ = all
7.6
6.6
5.6
[keV]
H+
SW
FS
BS
connected to BS
XVSO 1.1 1.1 0.9 0.7 0.3
YVSO -3.8 -3.4 -2.9 -2.1 -0.7
ZVSO -3.0 -2.1 -1.1 -0.0 1.0
DRV 5.0 4.2 3.3 2.3 1.2



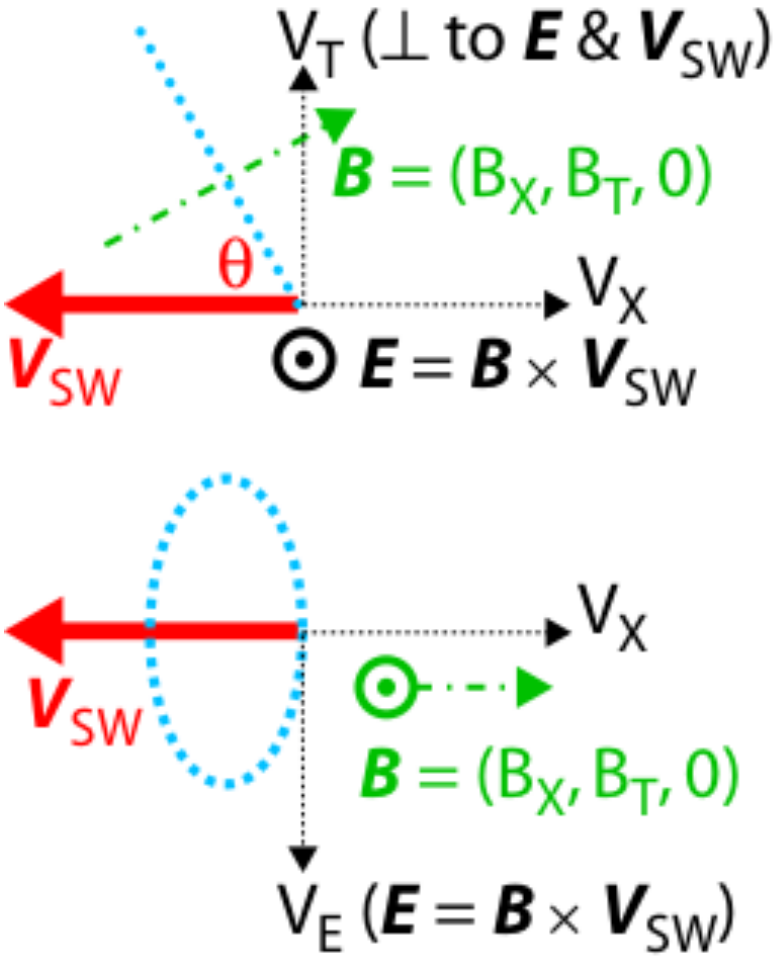
Venus ≈ Earth



Scanning over -45°~+45°

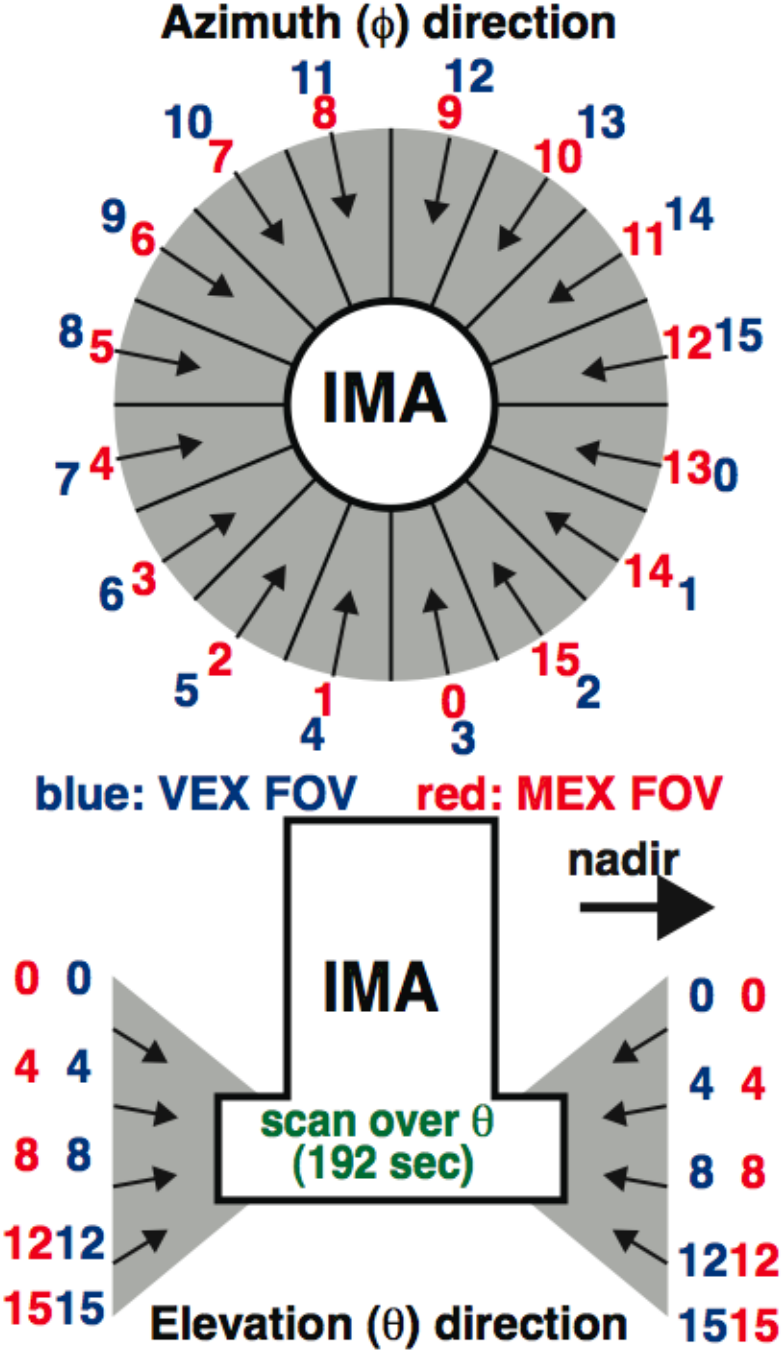

VEX/IMA H+ data (0.4~6 keV), 2006-6-18
[keV]
00:34:23~
00:37:35~
00:40:47~
00:43:59~
00:47:11~
00:50:23~
00:53:35~
00:56:47~
Solar Wind Contamination
// to B (SW frame)
// to B (Venus frame)
c/s
1000
50
(φsun = 1)
0 ←θ→ 15
(-45°) (+45°)
0s ←t→132s
c/s
2000
100
φ = 0~15
Xvso (RV)
Yvso (RV)
Zvso (RV)
D
long
lat
-1.00 -3.19 -1.65 3.73 -158° -24°
-0.98 -3.13 -1.51 3.61 -158° -23°
-0.97 -3.06 -1.38 3.49 -158° -21°
-0.95 -2.99 -1.25 3.38 -158° -20°
-0.93 -2.91 -1.12 3.25 -158° -18°
-0.90 -2.83 -0.98 3.13 -157° -16°
-0.88 -2.74 -0.84 3.00 -157° -14°
-0.85 -2.65 -0.70 2.87 -157° -12°

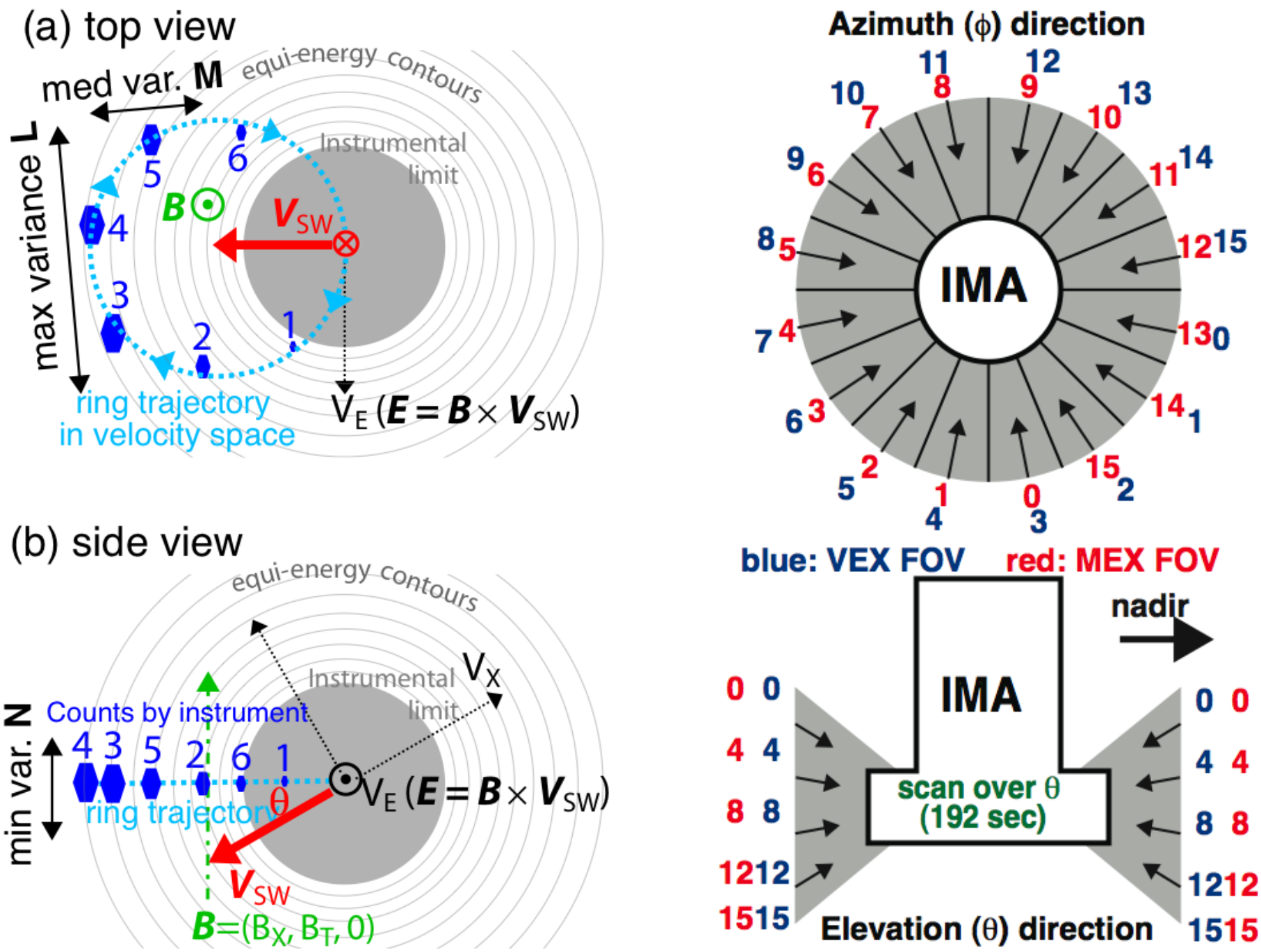
gyrotropic ion @ IMA Instrument

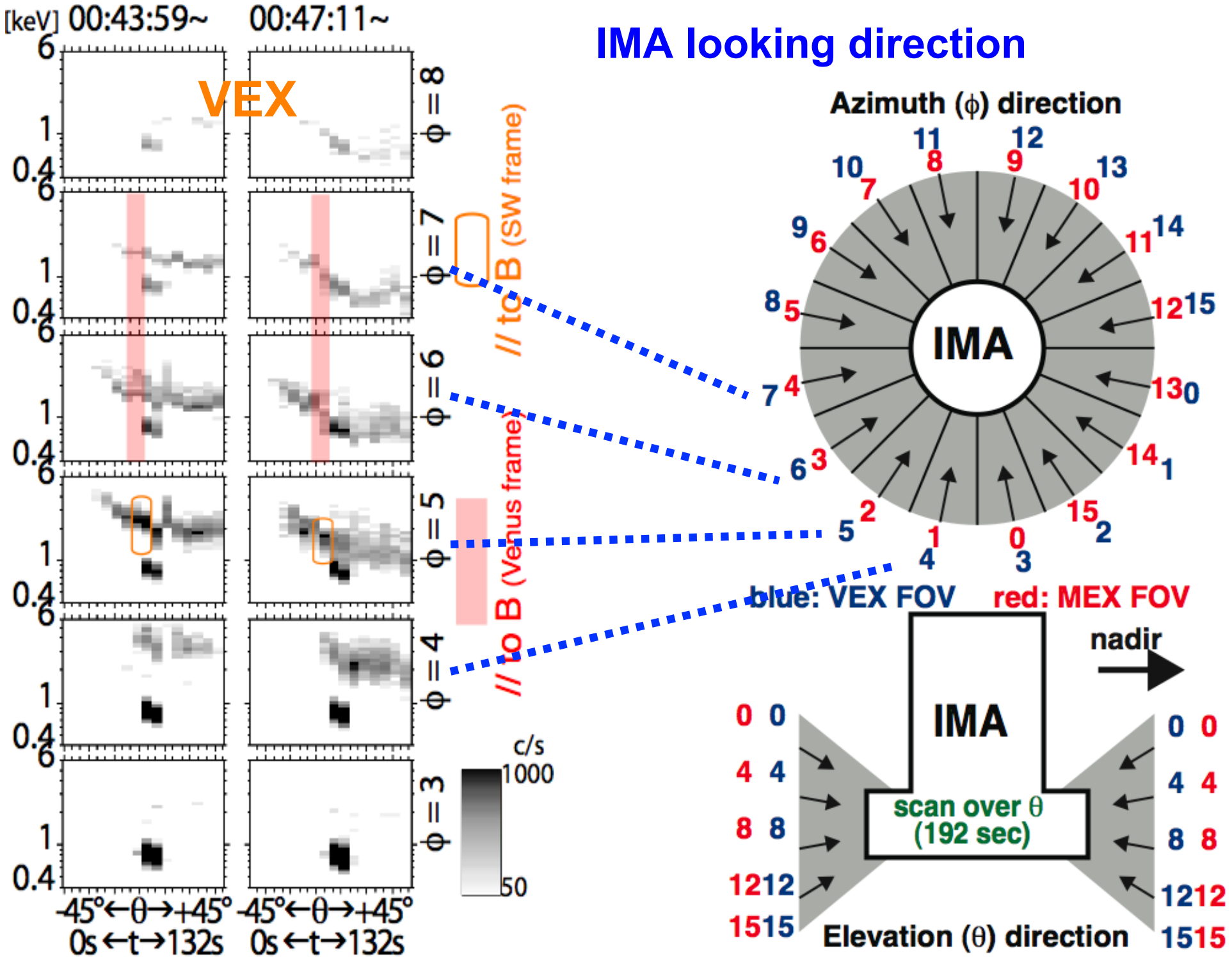


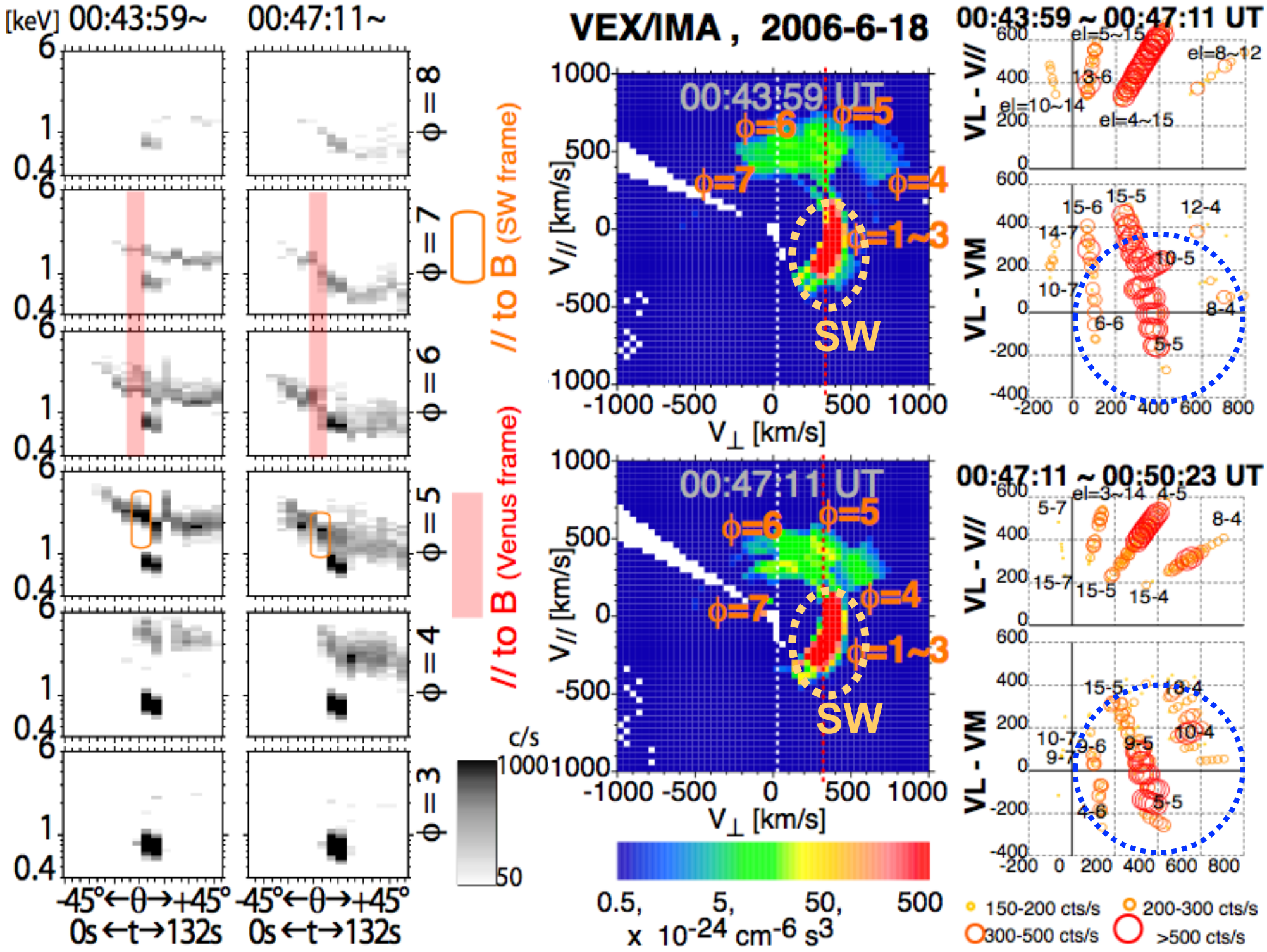
Long Radius = $|\boldsymbol{V}_{SW} \times \boldsymbol{b}|$

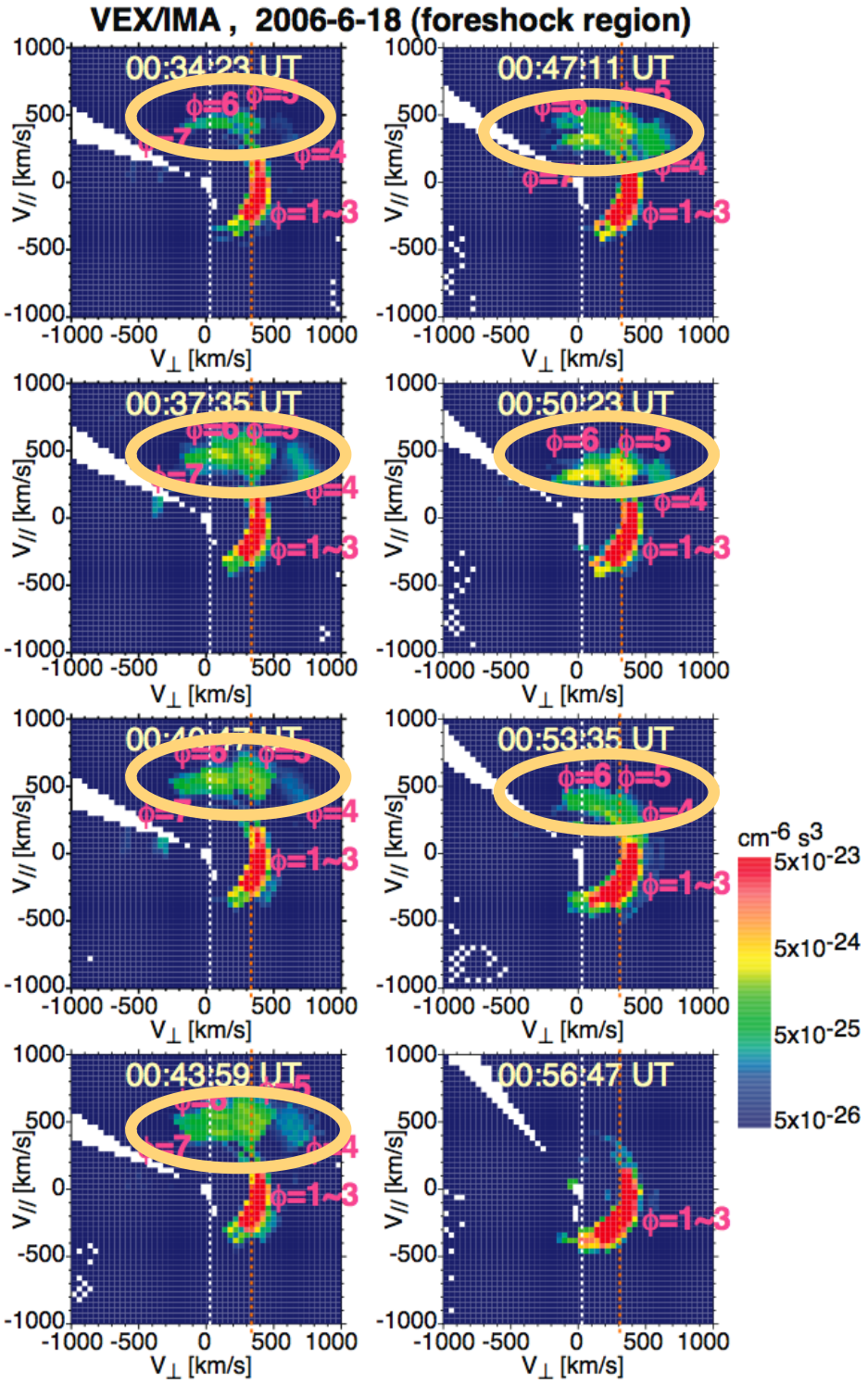
Short radius = $|\boldsymbol{V}_{SW} \times \boldsymbol{b}|\cos(\theta)$




(a) top view
med var. M
max variance L
equi-energy contours
Instrumental limit
B
V_SW
ring trajectory in velocity space
V_E (E = B × V_SW)
(b) side view
equi-energy contours
Instrumental limit
V_X
Counts by instrument
min var. N
ring trajectory
θ
V_E (E = B × V_SW)
V_SW
B=(B_X, B_T, 0)
Azimuth (ϕ) direction
IMA
blue: VEX FOV
red: MEX FOV
nadir
IMA
scan over θ (192 sec)
Elevation (θ) direction


[keV] 00:43:59~ 00:47:11~
VEX
φ = 8
φ = 7
φ = 6
φ = 5
φ = 4
φ = 3
// to B (SW frame)
// to B (Venus frame)
c/s
1000
50
-45°←θ→+45°
0s←t→132s
IMA looking direction
Azimuth (φ) direction
IMA
blue: VEX FOV
red: MEX FOV
nadir
scan over θ
(192 sec)
Elevation (θ) direction


[keV] 00:43:59~
00:47:11~
ϕ=8
ϕ=7
ϕ=6
ϕ=5
ϕ=4
ϕ=3
// to B (SW frame)
// to B (Venus frame)
c/s
1000
50
-45°←θ→+45°
0s←t→132s
VEX/IMA , 2006-6-18
00:43:59 UT
00:47:11 UT
V// [km/s]
V⊥ [km/s]
SW
0.5, 5, 50, 500
x 10-24 cm-6 s3
00:43:59 ~ 00:47:11 UT
00:47:11 ~ 00:50:23 UT
VL - V//
VL - VM
150-200 cts/s
200-300 cts/s
300-500 cts/s
>500 cts/s



Two populations (same as Earth)

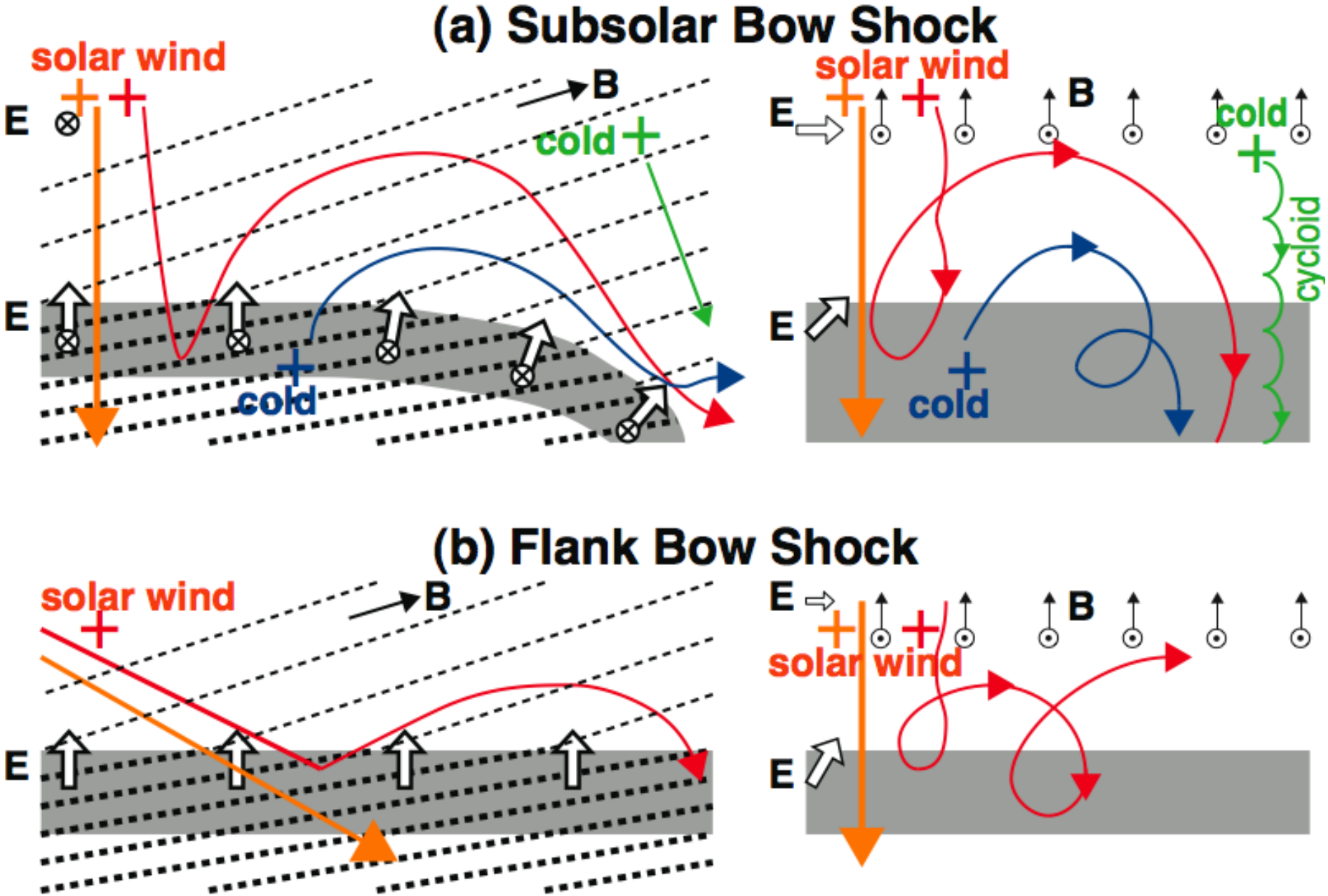
1. Field-aligned H^+.

2. Gyrating H^+ with large $V_{//}$.

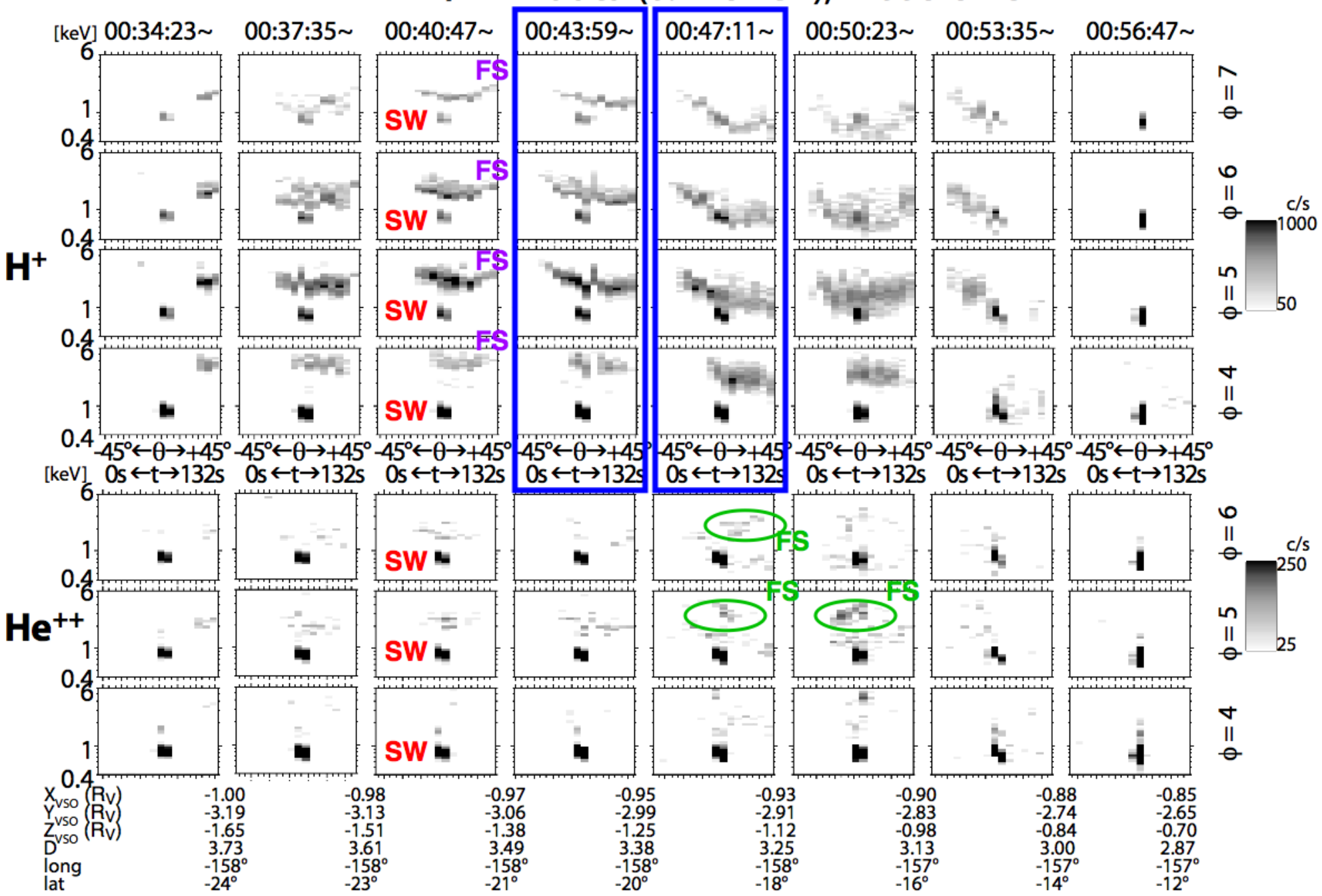
Both types are $\Delta V_{//} << V_{//}$,

1. solar wind, 2&3. bow-shock cold ion, 4. sneak out

$\Delta V_{//} << V_{//}$ (yes), $\Delta V_{//} << V_{//}$ (yes), $\Delta V_{//} \sim V_{//}$ (no),



He++ and H+ show different behavior (future work)



Venus ≈ Earth

No internal magnetic field.

Planet is the same size as the Earth

⇓

Smaller bow shock size than the Earth, yet MHD regime.

Effect of cod ions in the bow shock can be ignored.

Mars ≠ Earth

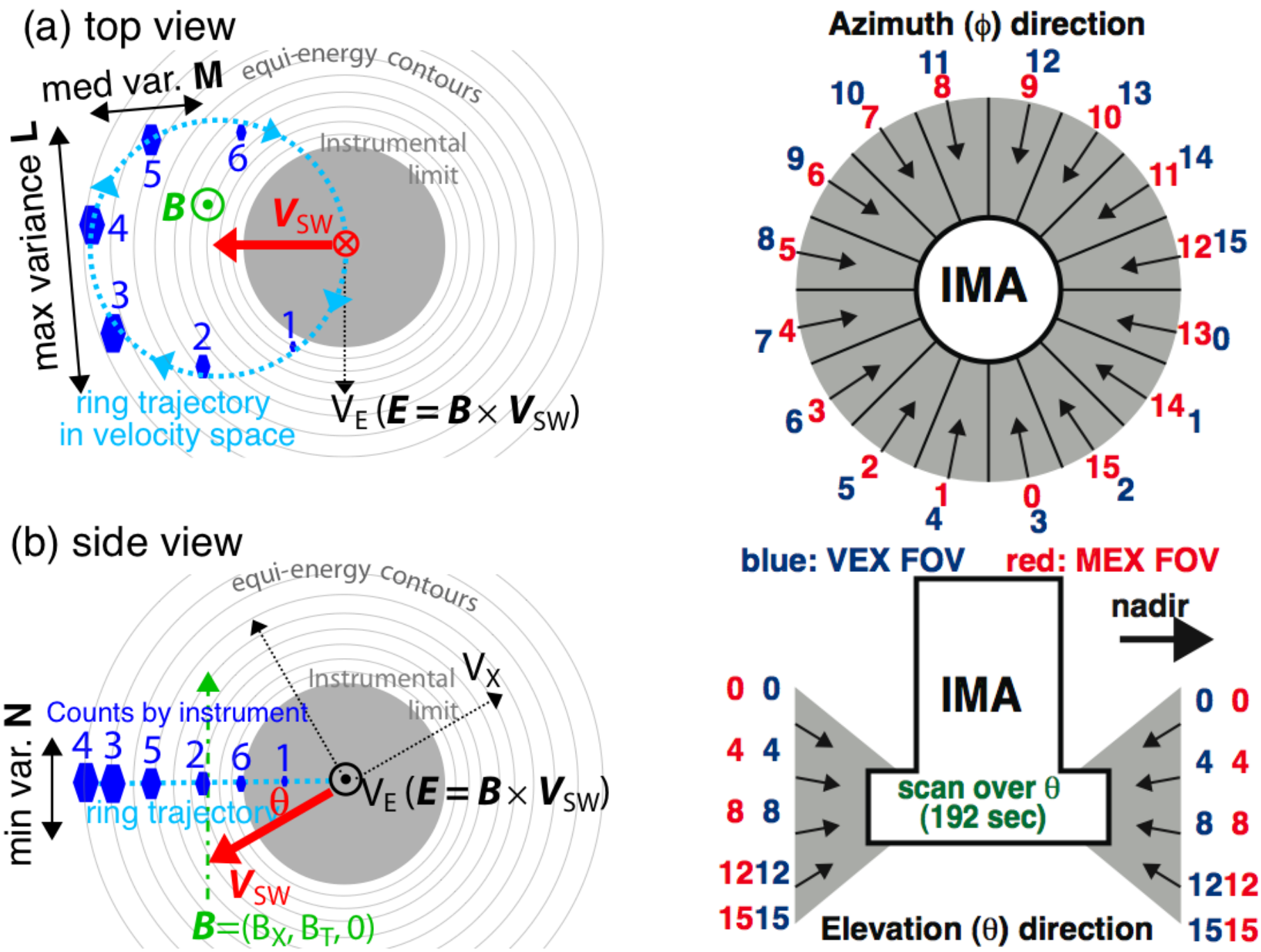
No internal magnetic field.

Planet is smaller than the Earth.

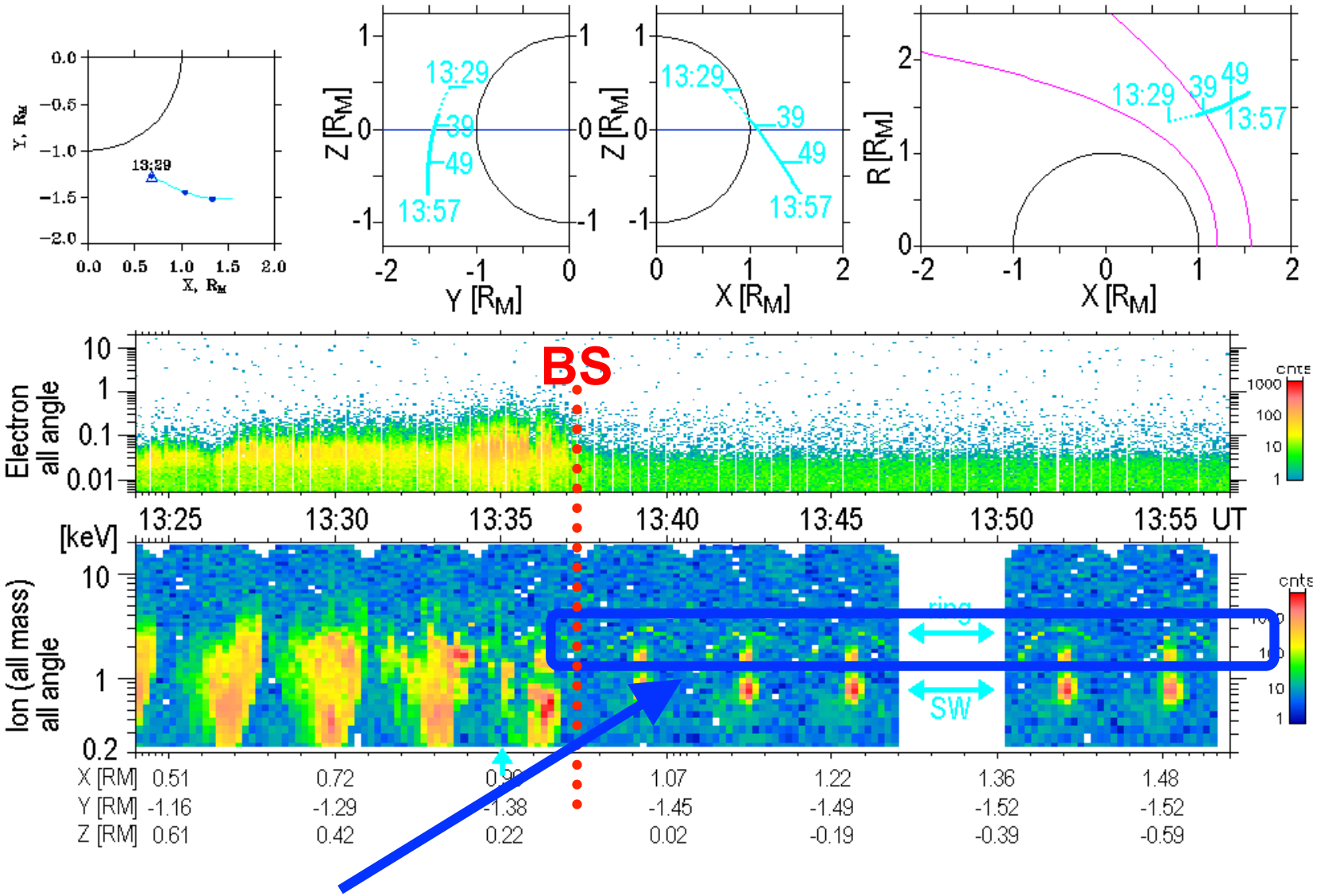
⇓

The bow shock size is too small to treat with MHD.

Effect of cod ions in the bow shock cannot be ignored.


(a) top view
med var. M
max variance L
equi-energy contours
Instrumental limit
B
V_SW
ring trajectory in velocity space
V_E (E = B × V_SW)
(b) side view
equi-energy contours
Instrumental limit
V_X
Counts by instrument
min var. N
ring trajectory
θ
V_E (E = B × V_SW)
V_SW
B=(B_X, B_T, 0)
Azimuth (ϕ) direction
IMA
blue: VEX FOV
red: MEX FOV
nadir
IMA
scan over θ (192 sec)
Elevation (θ) direction

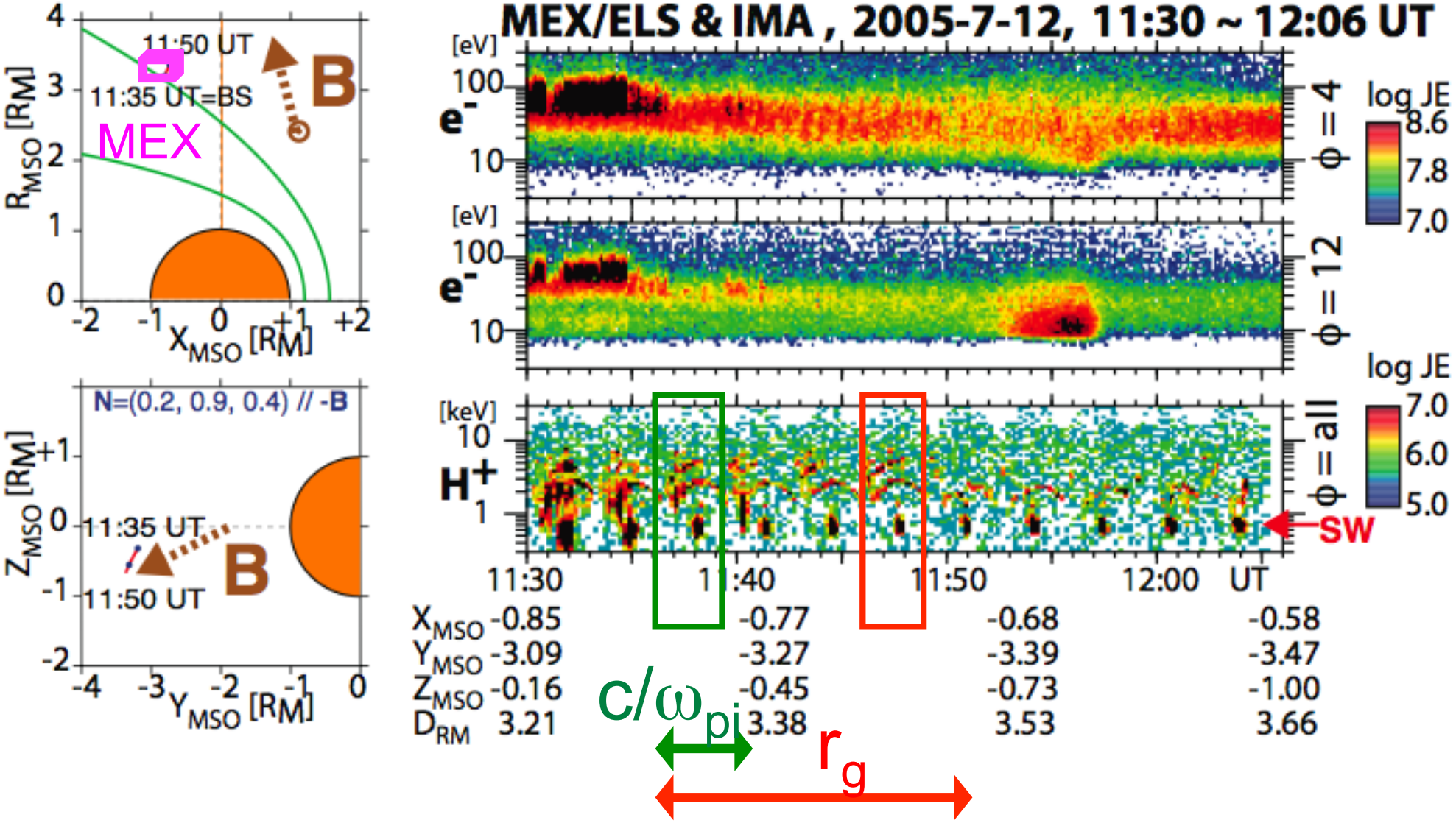
Quite different from Venus:



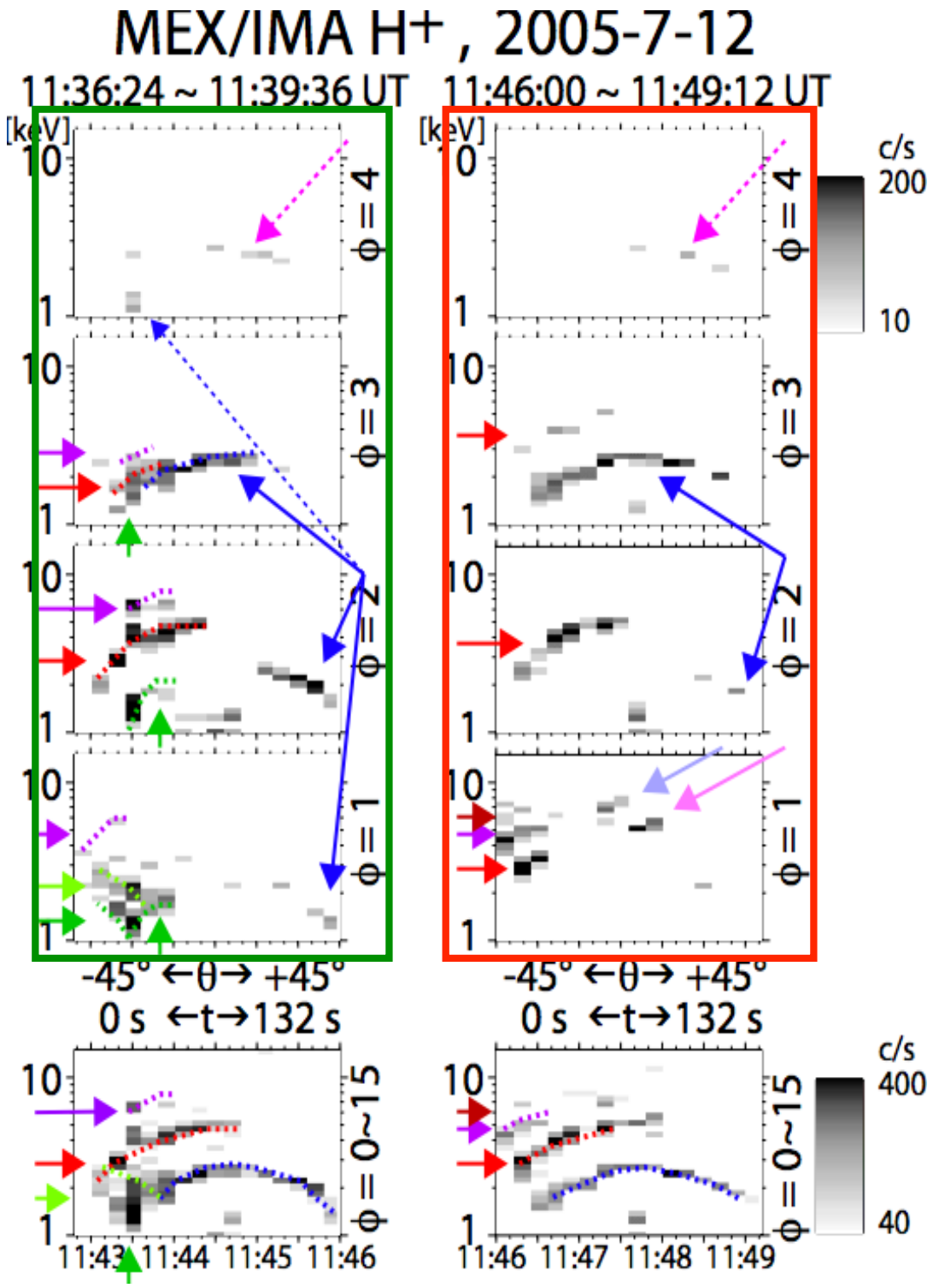
(1) only "ring" distribution

(2) no "foreshock" signature (examined ~ 500 traversals)

Examine close to the Bow Shock



We sometimes observed “multiple-ring” structure.

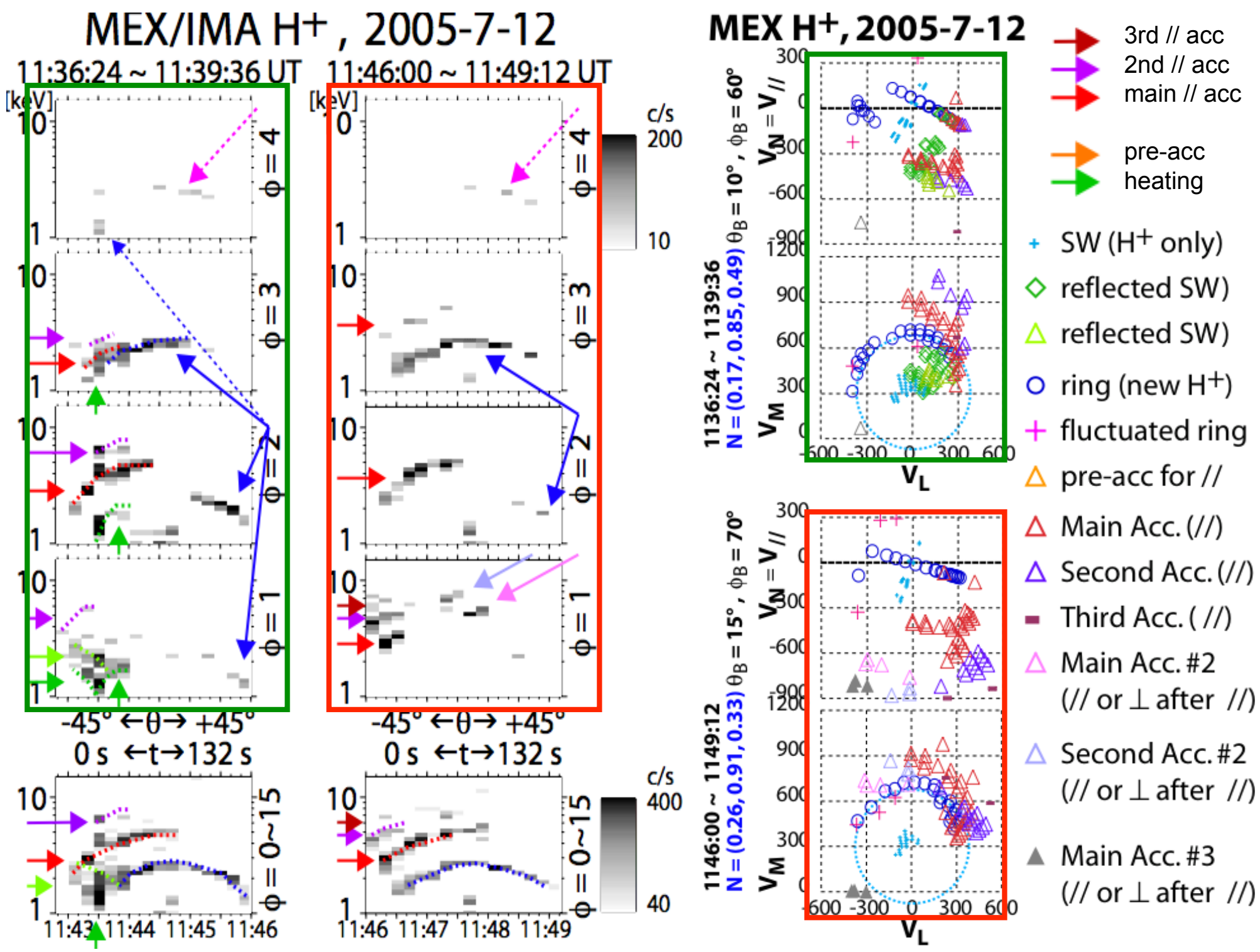


Three types of accelerated ions

beyond r_g
= pickup ions
⇒obtain B direction

beyond c/ω_{pi}
within r_g
= reflected ions

within c/ω_{pi}
= foot ions

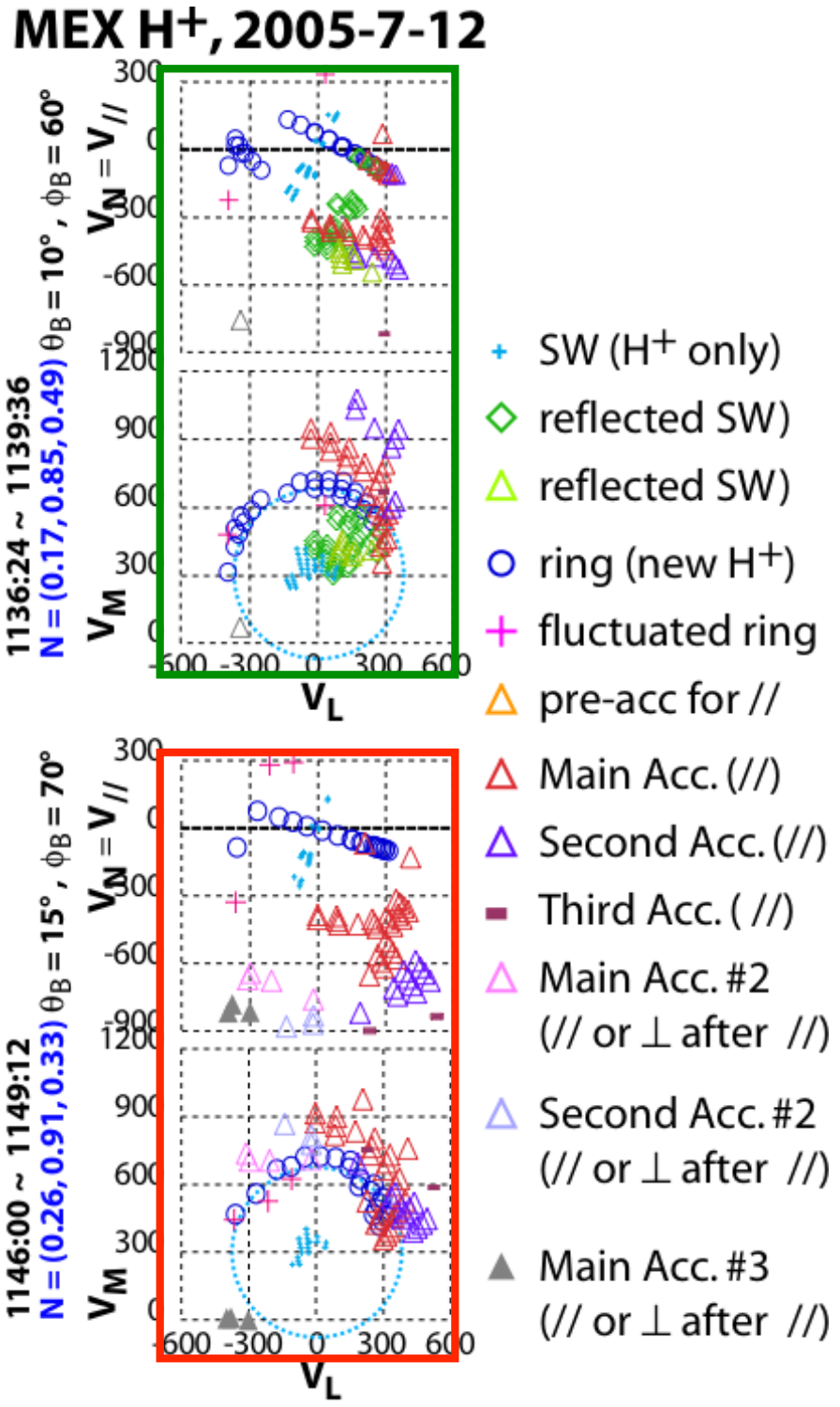

MEX/IMA H+ , 2005-7-12
11:36:24 ~ 11:39:36 UT
11:46:00 ~ 11:49:12 UT
[keV]
c/s
200
10
400
40
φ = 4
φ = 3
φ = 2
φ = 1
φ = 0~15
-45° ←θ→ +45°
0 s ←t→132 s
11:43 11:44 11:45 11:46
11:46 11:47 11:48 11:49
MEX H+, 2005-7-12
1136:24 ~ 1139:36
N = (0.17, 0.85, 0.49) θB = 10° , φB = 60°
1146:00 ~ 1149:12
N = (0.26, 0.91, 0.33) θB = 15° , φB = 70°
VM = V//
VM
VL
3rd // acc
2nd // acc
main // acc
pre-acc
heating
SW (H+ only)
reflected SW)
reflected SW)
ring (new H+)
fluctuated ring
pre-acc for //
Main Acc. (//)
Second Acc. (//)
Third Acc. (//)
Main Acc. #2
(// or ⊥ after //)
Second Acc. #2
(// or ⊥ after //)
Main Acc. #3
(// or ⊥ after //)

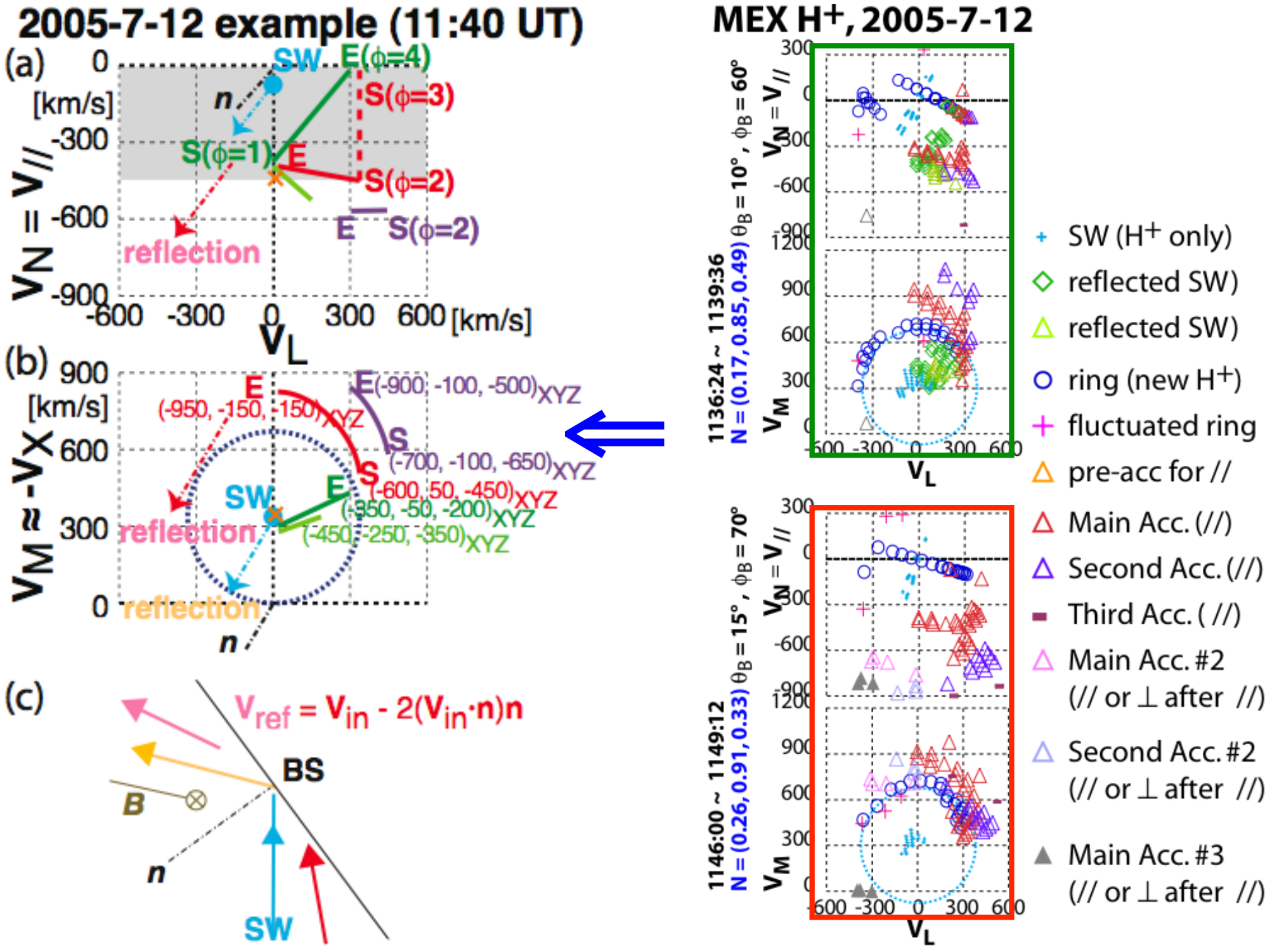
Multiple acceleration

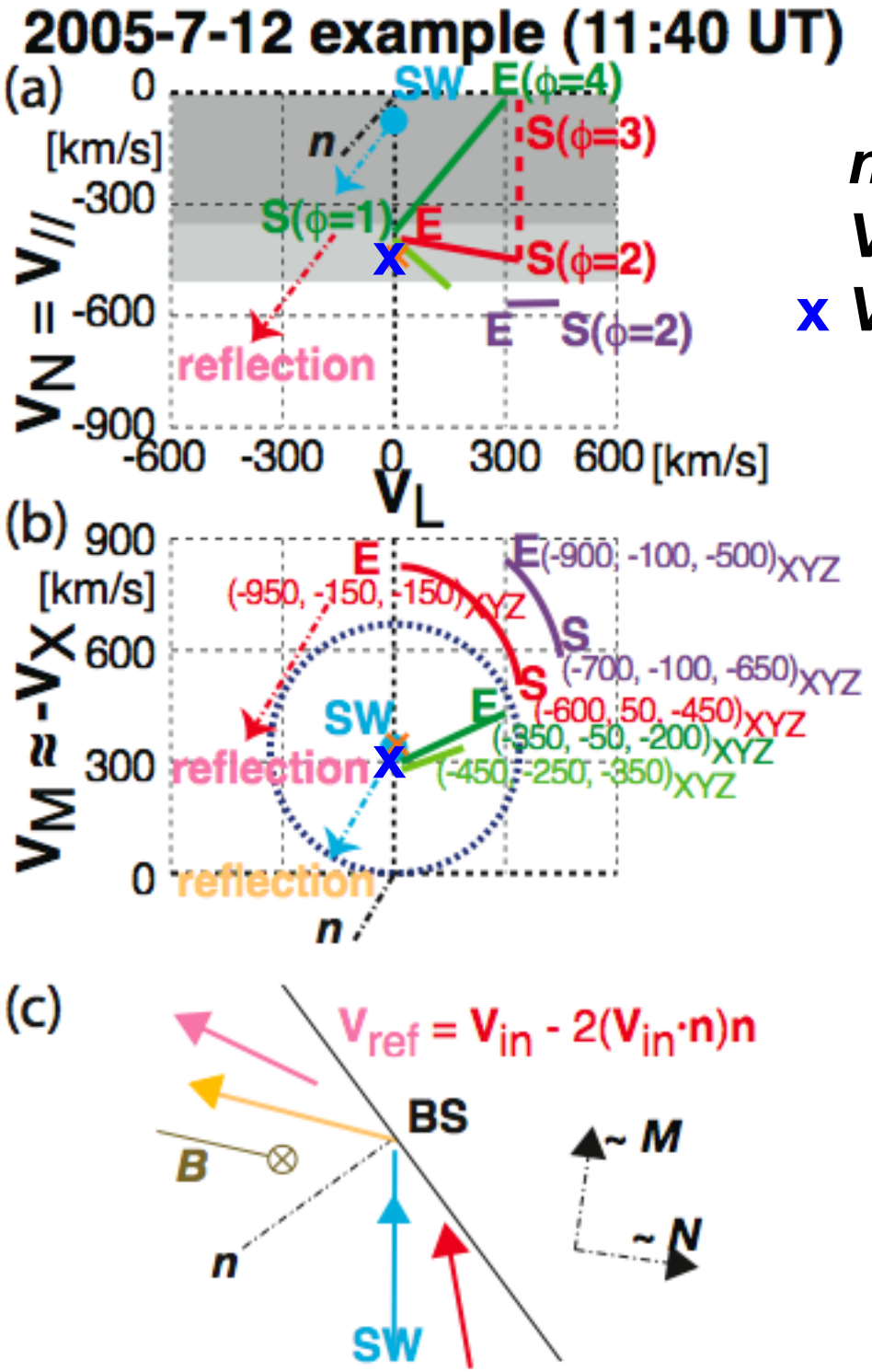
green: foot
blue: primary ring
red: 1st branch
purple: 2nd branch
brown: 3rd branch

Gyro-phase bunching

red: half gyro
purple: one third gyro




2005-7-12 example (11:40 UT)
(a)
SW
E(ϕ=4)
S(ϕ=3)
n
S(ϕ=1)
E
S(ϕ=2)
E
S(ϕ=2)
reflection
[km/s]
0
-300
-600
-900
$V_{//}$
V_N
-600 -300 0 300 600 [km/s]
V_L
(b)
900
[km/s]
600
300
0
V_M
$-V_X$
E
(-950, -150, -150)XYZ
E(-900, -100, -500)XYZ
S
(-700, -100, -650)XYZ
S
(-600, 50, -450)XYZ
E
(-350, -50, -200)XYZ
(-450, -250, -350)XYZ
SW
reflection
reflection
n
(c)
$V_{ref} = V_{in} - 2(V_{in}\cdot n)n$
BS
B
n
SW
MEX H+, 2005-7-12
1136:24 ~ 1139:36
N = (0.17, 0.85, 0.49) θB = 10°, ϕB = 60°
1146:00 ~ 1149:12
N = (0.26, 0.91, 0.33) θB = 15°, ϕB = 70°
$V_N = V_{//}$
V_M
V_L
SW (H+ only)
reflected SW)
reflected SW)
ring (new H+)
fluctuated ring
pre-acc for //
Main Acc. (//)
Second Acc. (//)
Third Acc. (//)
Main Acc. #2
(// or ⊥ after //)
Second Acc. #2
(// or ⊥ after //)
Main Acc. #3
(// or ⊥ after //)



Multiple-Reflection

n: shock normal

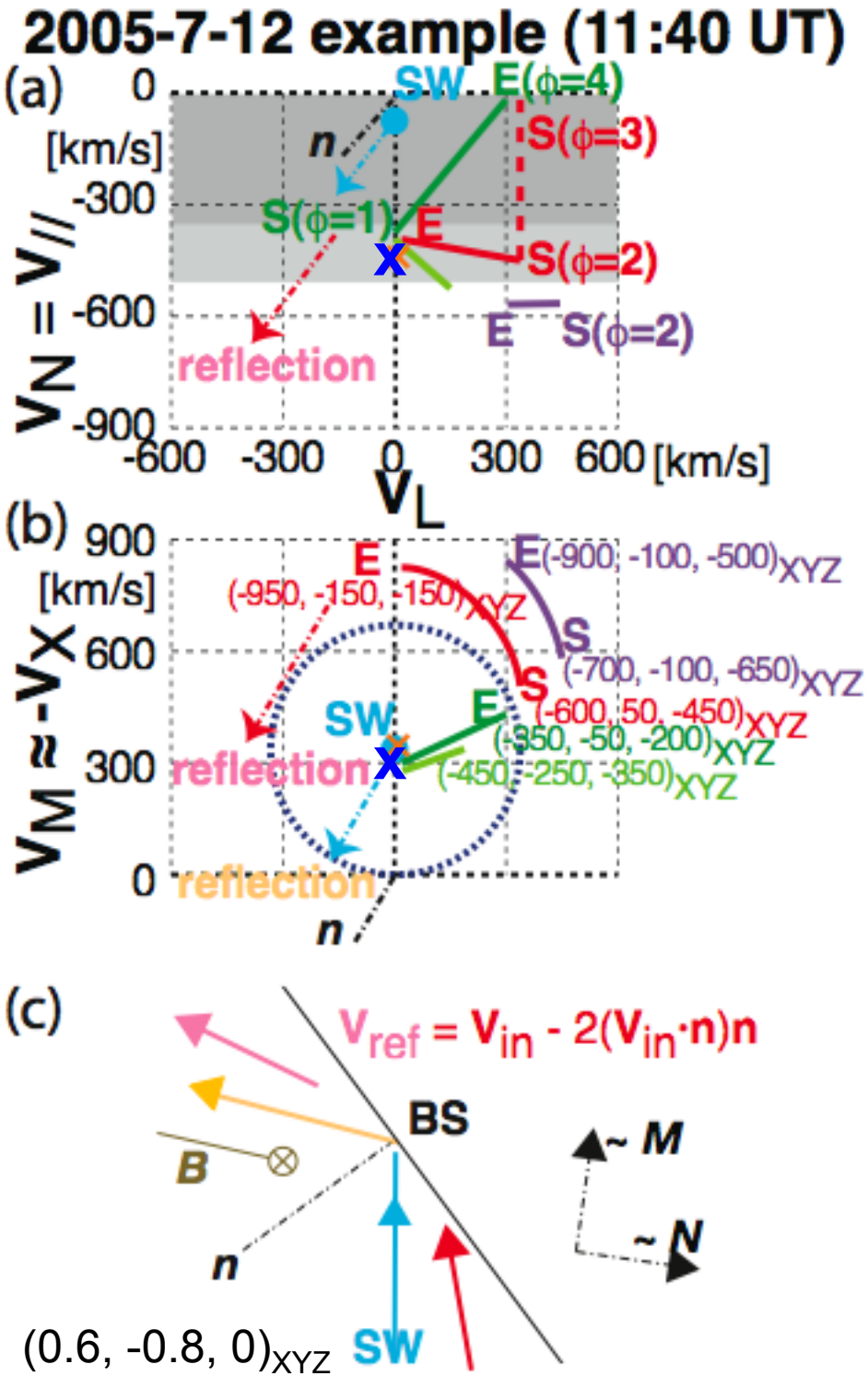
$\boldsymbol{V}_R$: specularly reflected SW

x $\boldsymbol{V}_{HT}$: de Hoffman Teller ($\boldsymbol{V'}_{SW}$ // ***B***)

e.g., 11:40 UT

L	~ (0, 0.6, -0.8)_XYZ
M	(-1.0, 0.2, 0.1)_XYZ
N=-***B***/B	(0.2, 0.8, 0.6)_XYZ

n	(-0.5, -0.7, -0.5)_LMN ±(0.05, 0.05, 0.05)
$\boldsymbol{V}_{SW}/V_{SW}$	(0.0, 1.0, 0.2)_LMN
$\boldsymbol{V}_R/V_{SW}$	(-0.6, 0.1, -0.8)_LMN ±(0, 0.2, 0)
$\boldsymbol{V}_{HT}/V_{SW}$	(0., 1.0, -1.4)_LMN ±(0, 0, 0.3)



Multiple-Reflection

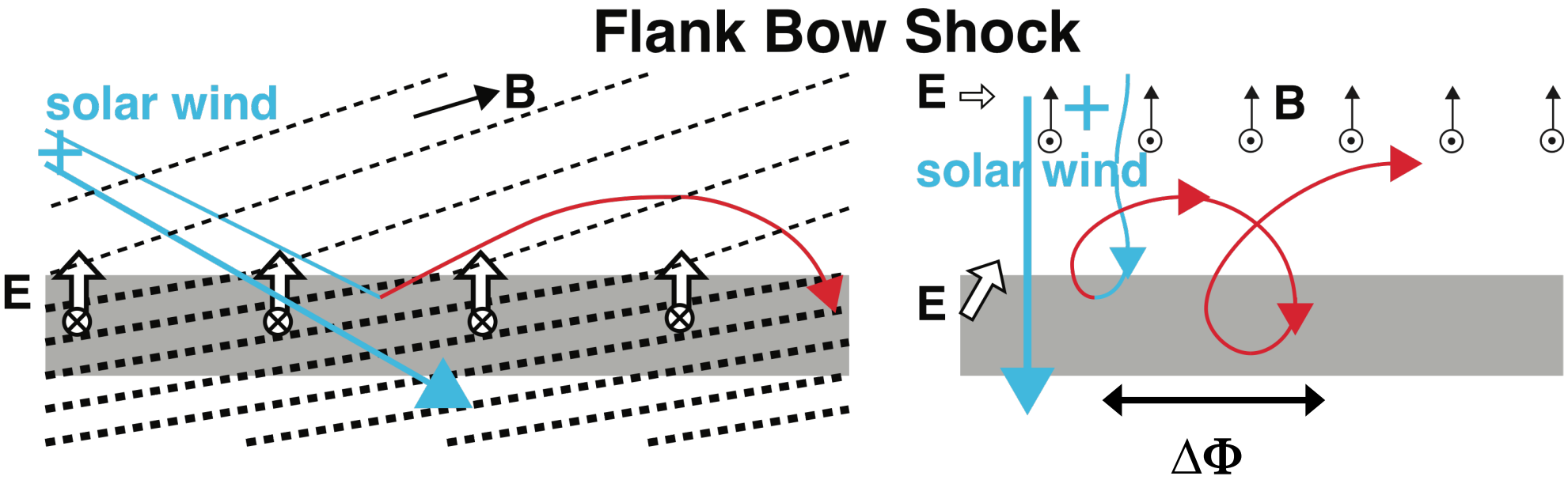
S E → S: toward BS from left
E: toward BS from right

S E → S&E: toward BS from left

S E → S ~ V_{HT} = along BS
E: along BS

S E → S: along BS
E: toward BS

SW Reflection ⇒ convert $V_{\perp}$ to $V_{//}$ in SW frame



The observed multiple ring structure is well explained by multiple specular reflection.

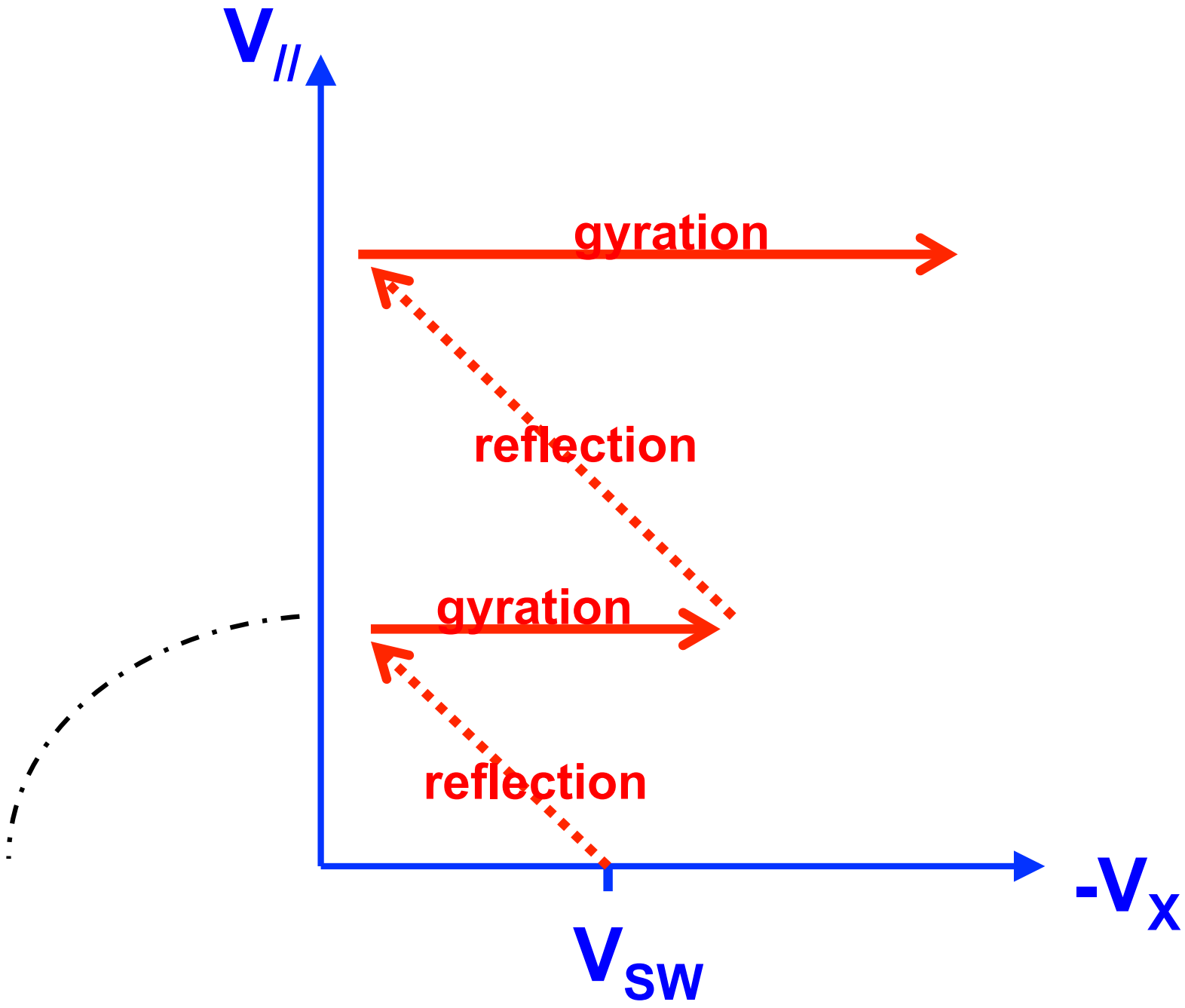
But, **why is it observed outside the foot region?**

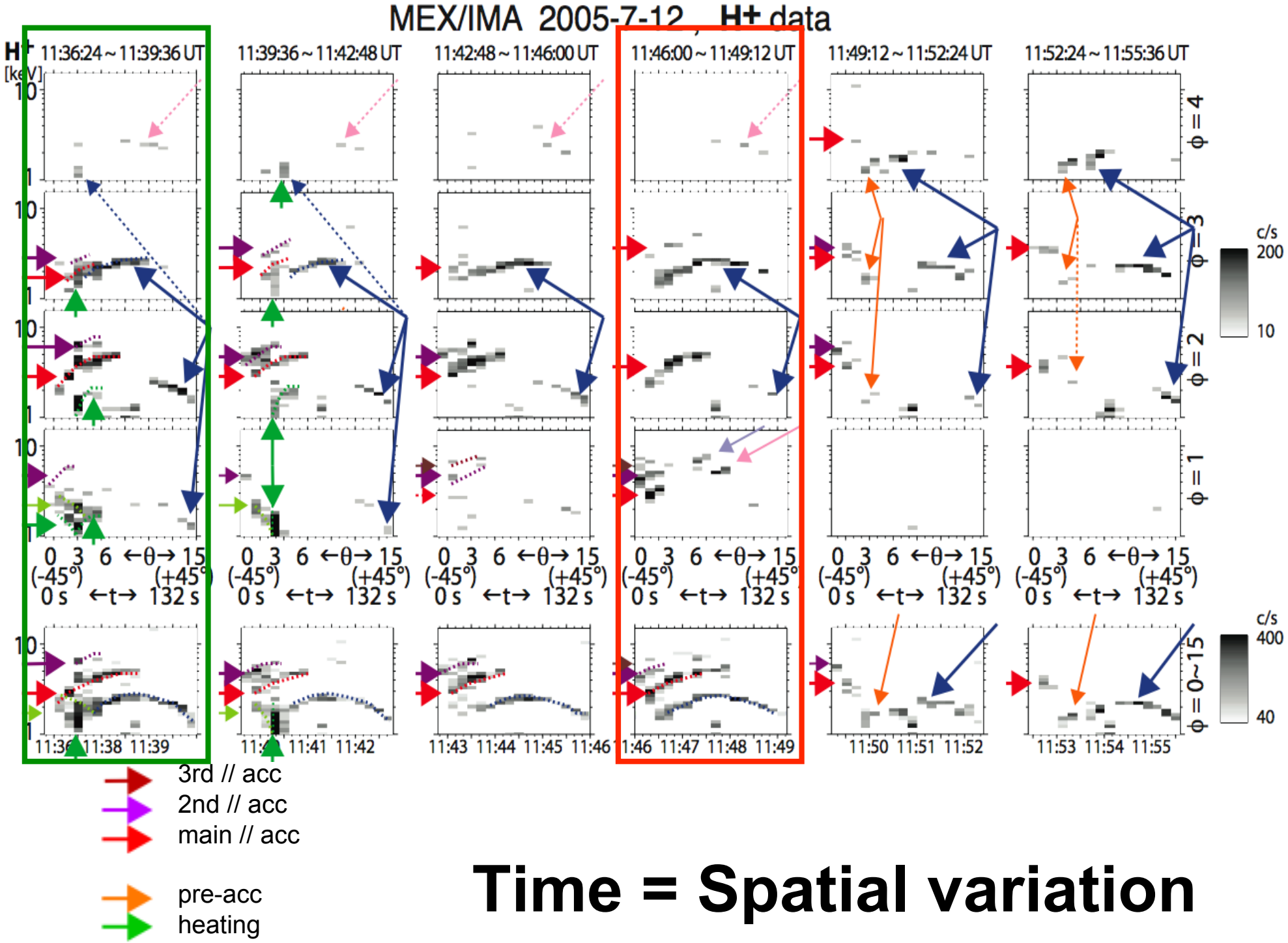
⇓

no : Finite bow shock size compared to r_g.

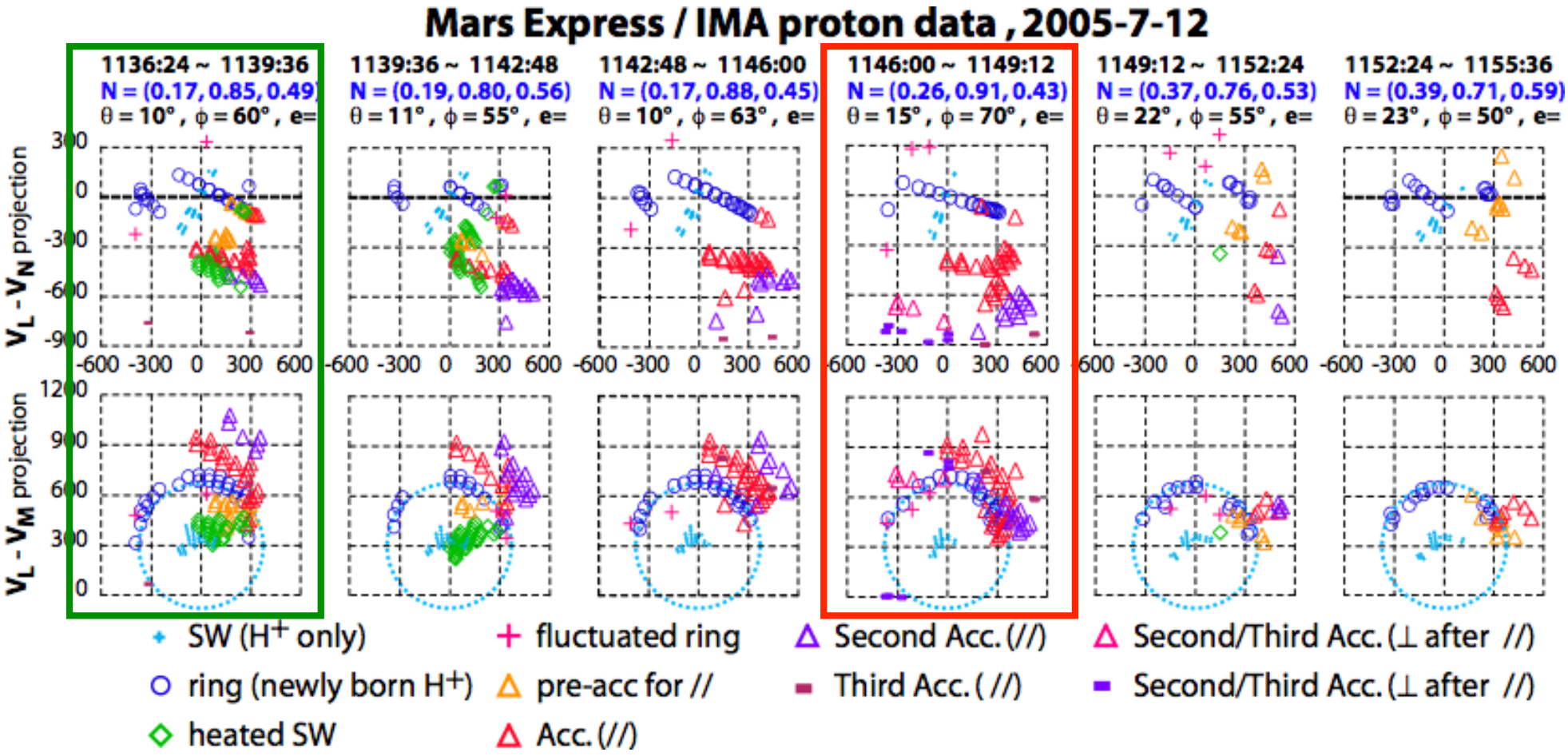
yes: Cold ion in the bow shock

⇒ This may explain “non-specular reflection” at subsolar.


V//
gyration
reflection
gyration
reflection
-Vx
Vsw


MEX/IMA 2005-7-12, H+ data
H+
[keV]
11:36:24 ~ 11:39:36 UT
11:39:36 ~ 11:42:48 UT
11:42:48 ~ 11:46:00 UT
11:46:00 ~ 11:49:12 UT
11:49:12 ~ 11:52:24 UT
11:52:24 ~ 11:55:36 UT
10
1
0 3 6 ←θ→ 15
(-45°) (+45°)
0 s ←t→ 132 s
ϕ = 4
ϕ = 3
ϕ = 2
ϕ = 1
ϕ = 0~15
c/s
200
10
400
40
11:36 11:38 11:39
11:41 11:42
11:43 11:44 11:45 11:46
11:46 11:47 11:48 11:49
11:50 11:51 11:52
11:53 11:54 11:55
3rd // acc
2nd // acc
main // acc
pre-acc
heating
Time = Spatial variation

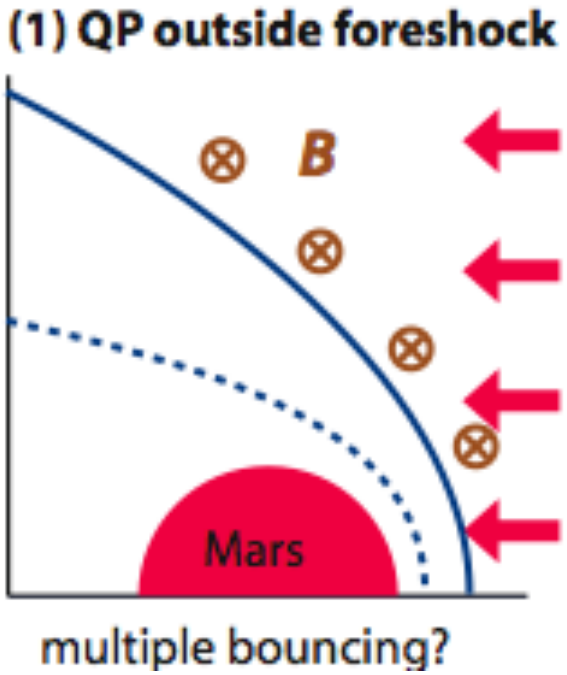
Classifying counts in // and ⊥ directions



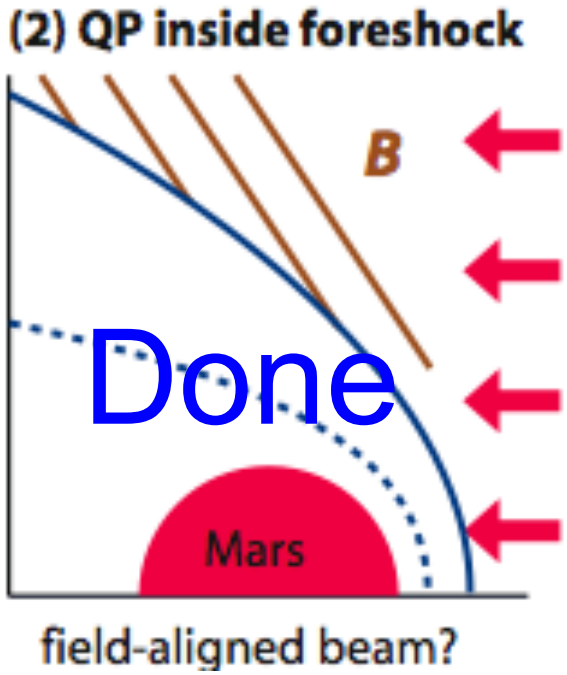
B (N-direction) is estimated from minimum variance method applied to the ring distribution

Time = Spatial variation

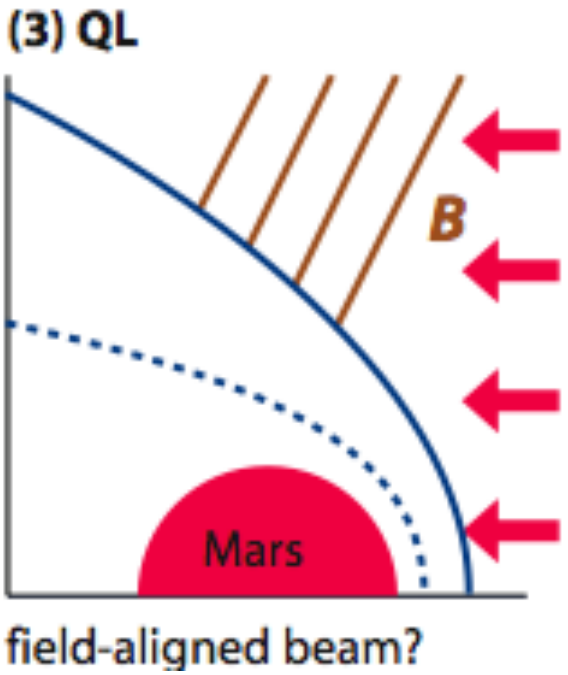
Three configurations (on-going work)



2005-7-29
2005-8-3



2005-7-12



2005-8-5

Special features for Mars

- Energy is stepping (due to reflection?)
- Gyro-bunching effect (due to short distance?) with gradual $\perp$ acceleration (why?)
- Two different scale length
- No specular reflection near the bow shock (need to confirm)

Summary

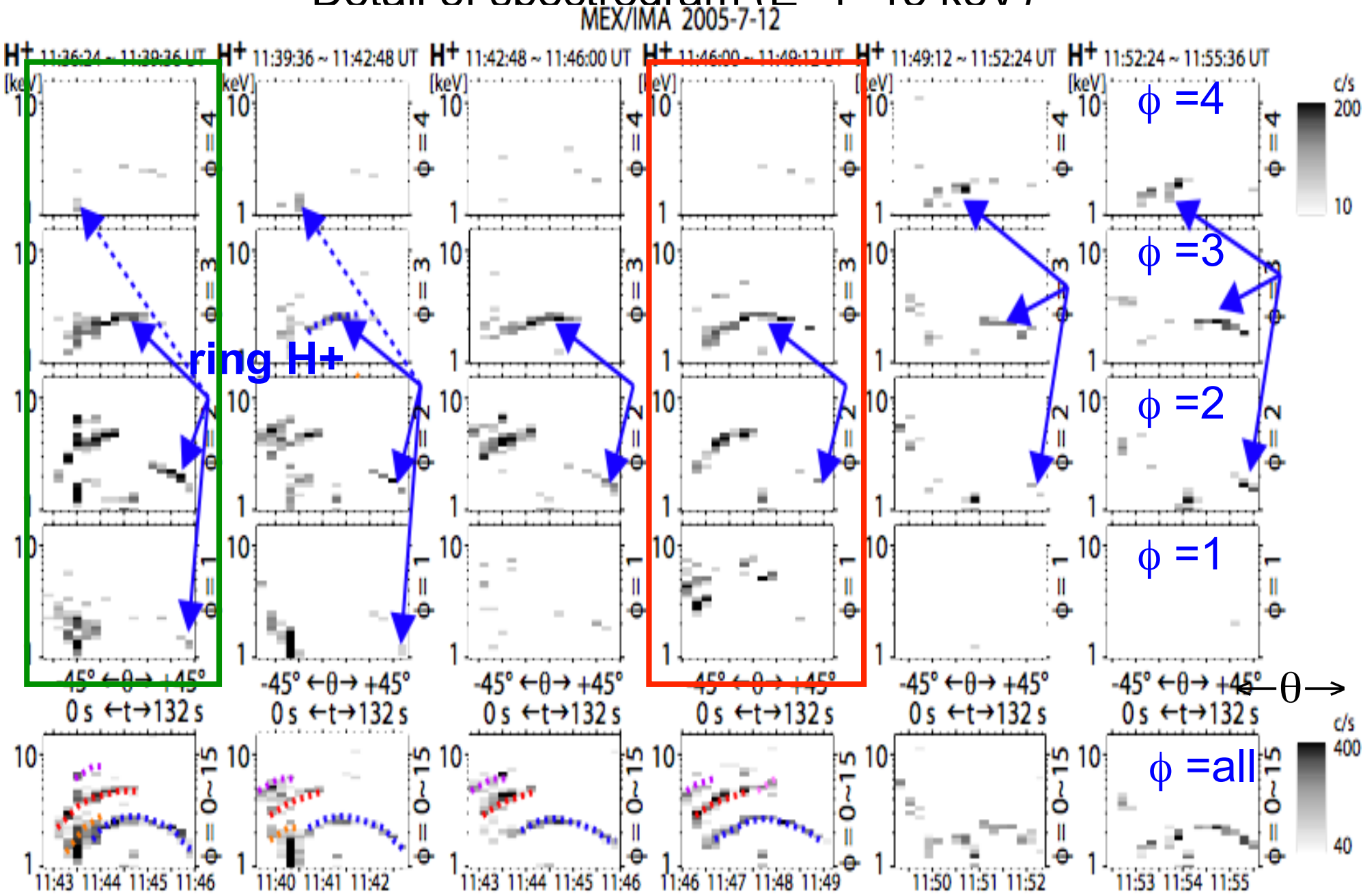
Venus Express / ASPERA-4 often observes back-streaming H^+ in the foreshock region of Venus, in a similar ways as the Terrestrial foreshock, i.e., field-aligned component, and intermediate (gyrating) component

Mars Express / ASPERA-3 (same instrumentation as VEX) did not observe similar ions in the Martian foreshock region beyond the foot region. Instead, it shows different type of acceleration in the foot region, indicating the ion trajectory (history) during its gyromotion.

The finite gyroradius effect makes Mars a perfect laboratory to study acceleration processes.

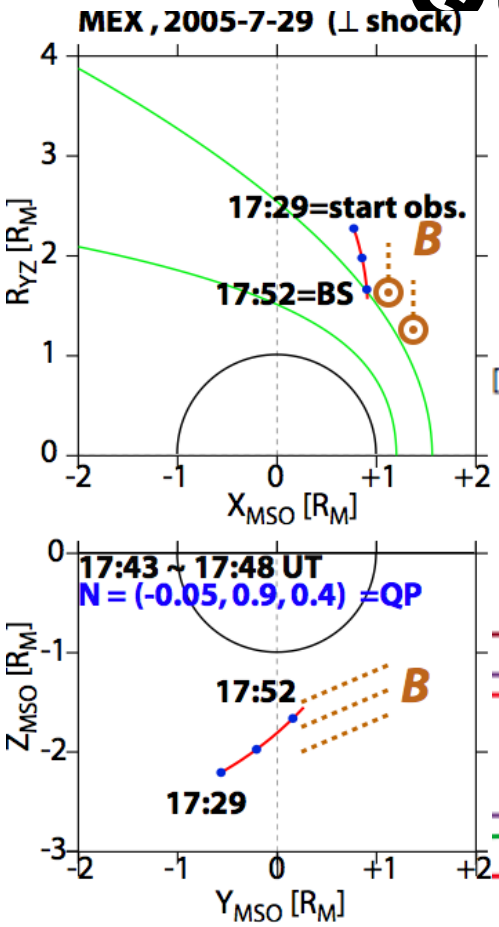
End

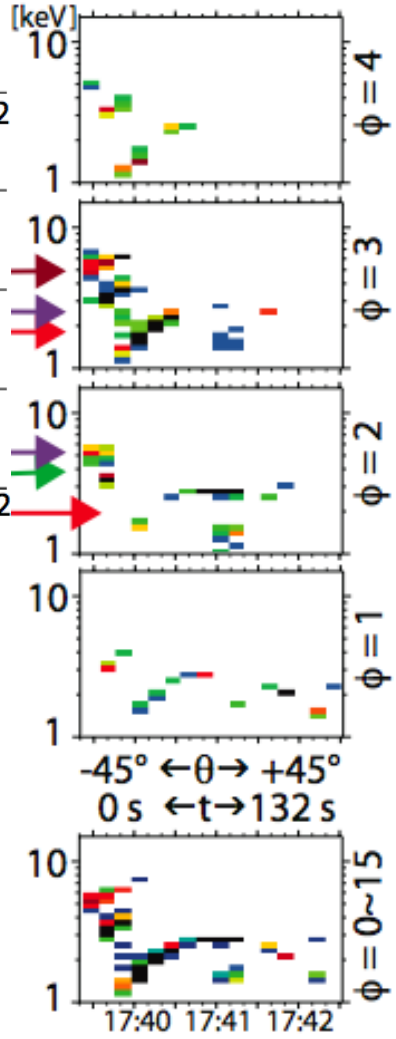
Detail of spectrogram (E=1~15 keV)

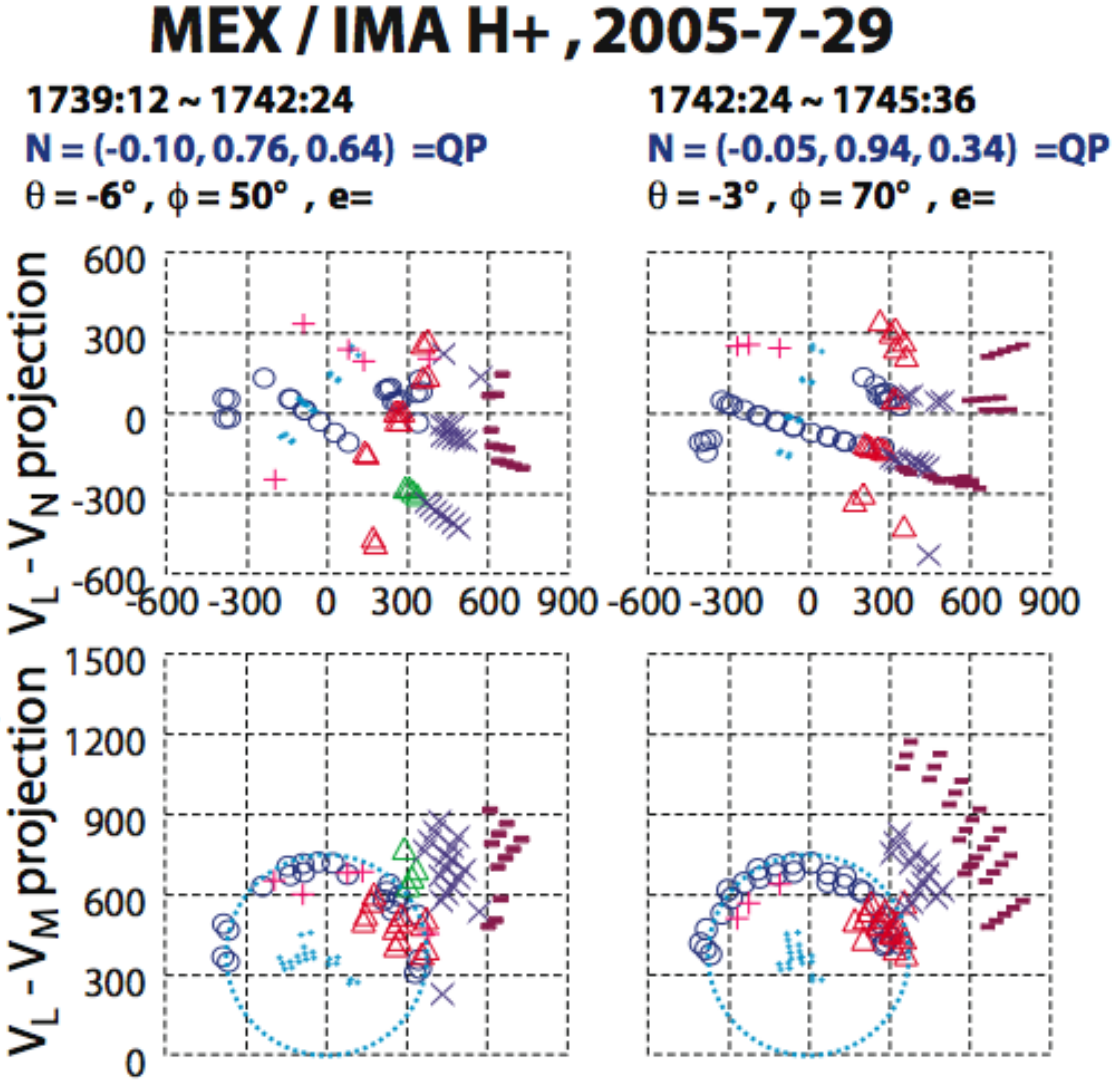


Mixture of accelerated ion (H+) components

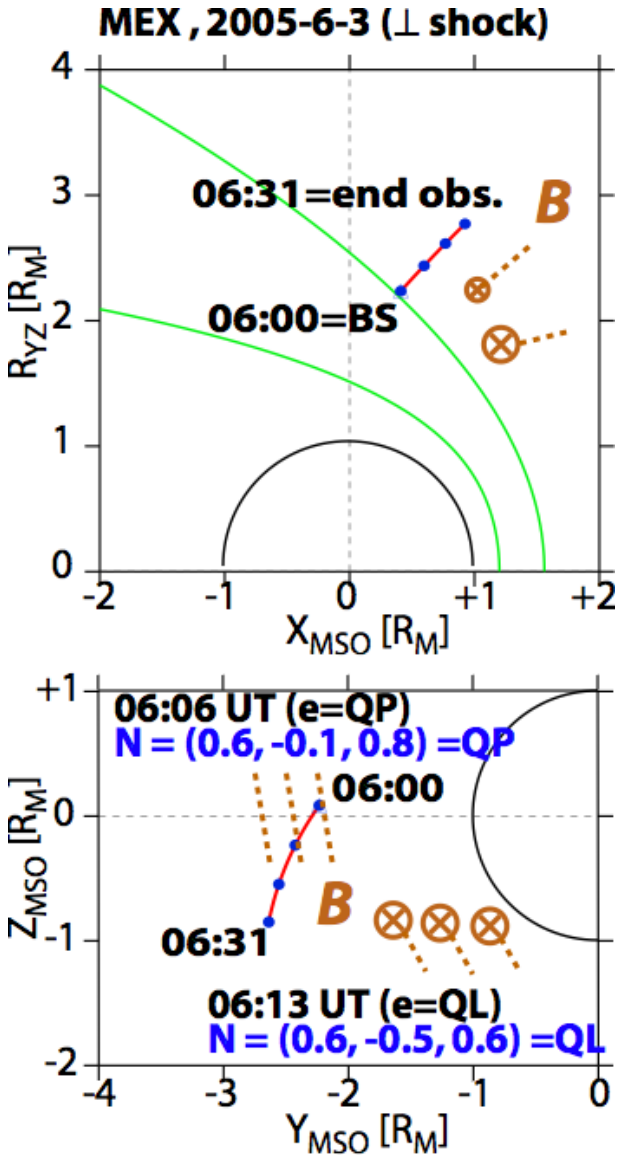
Quasi-⊥ shock (case 1)

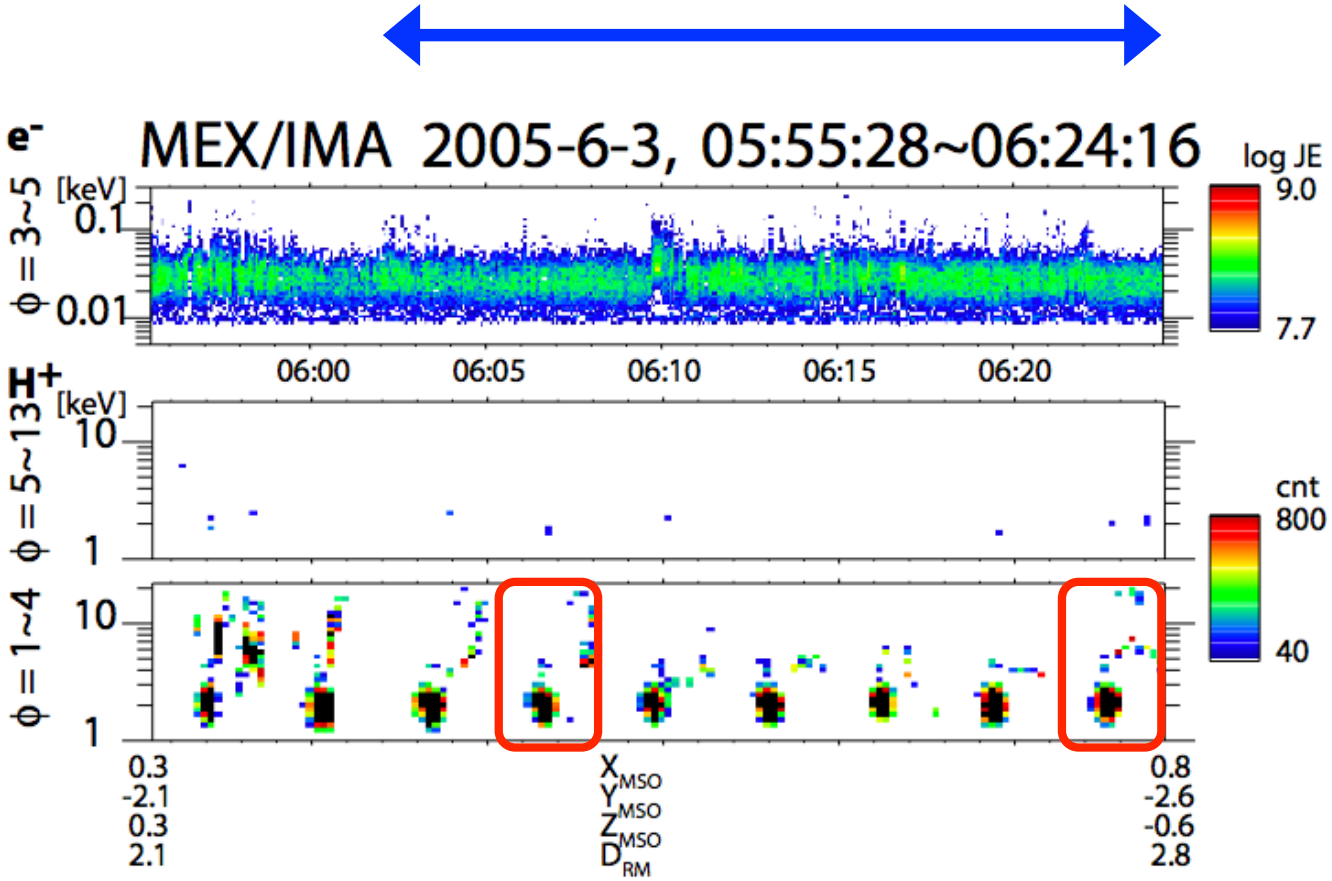


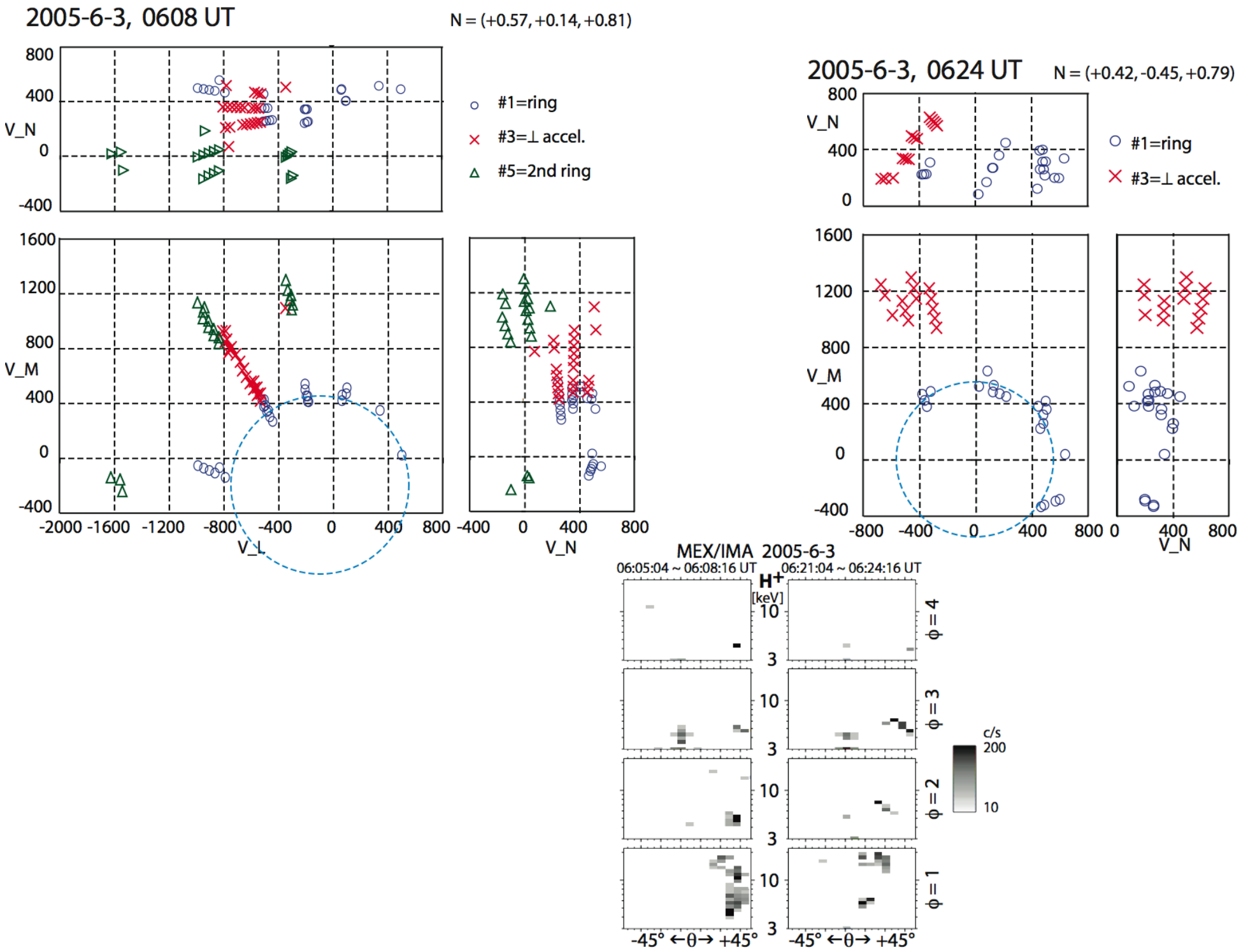




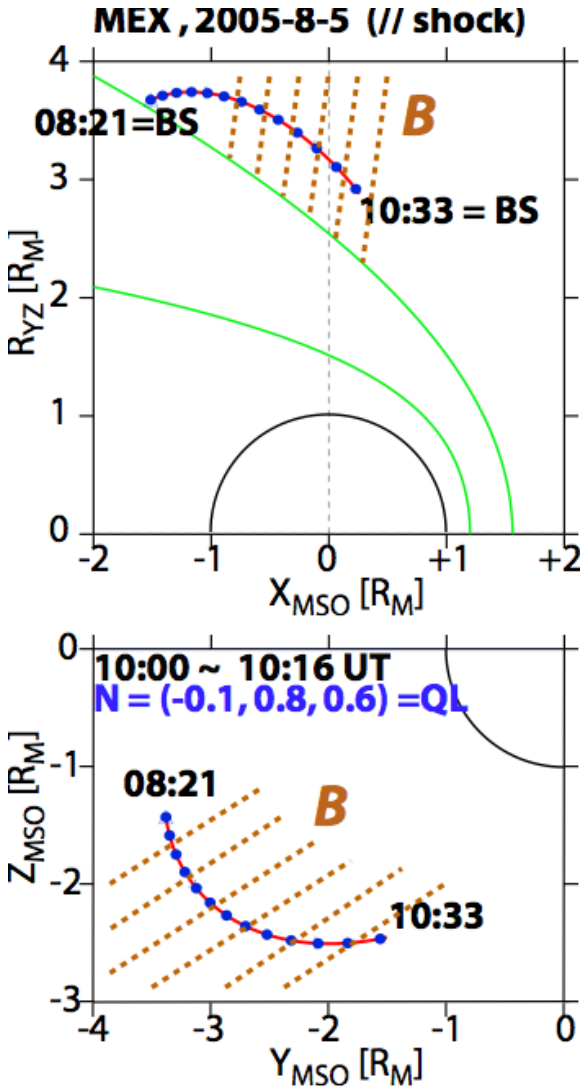
Quasi-⊥ and // (case 1+3)

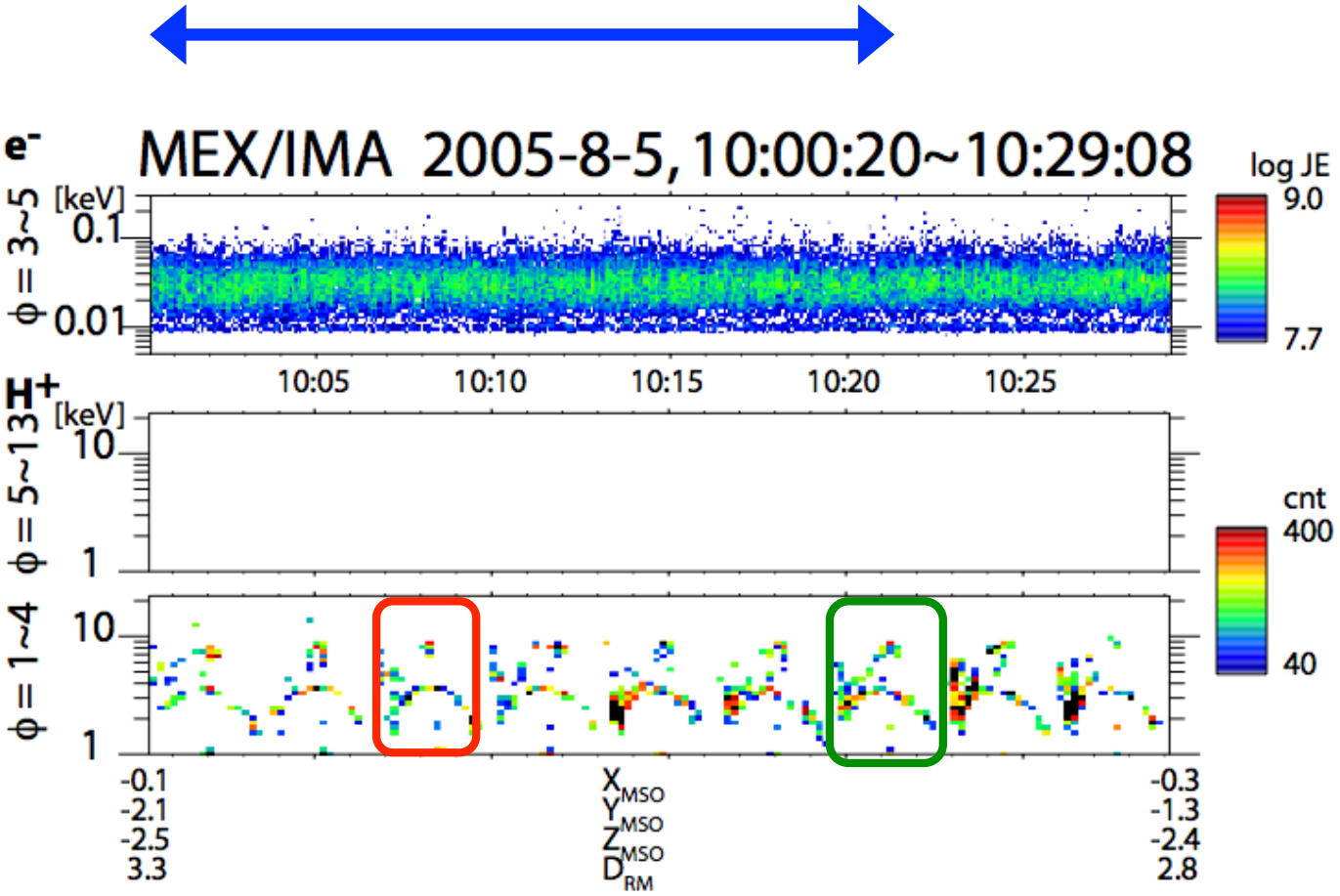


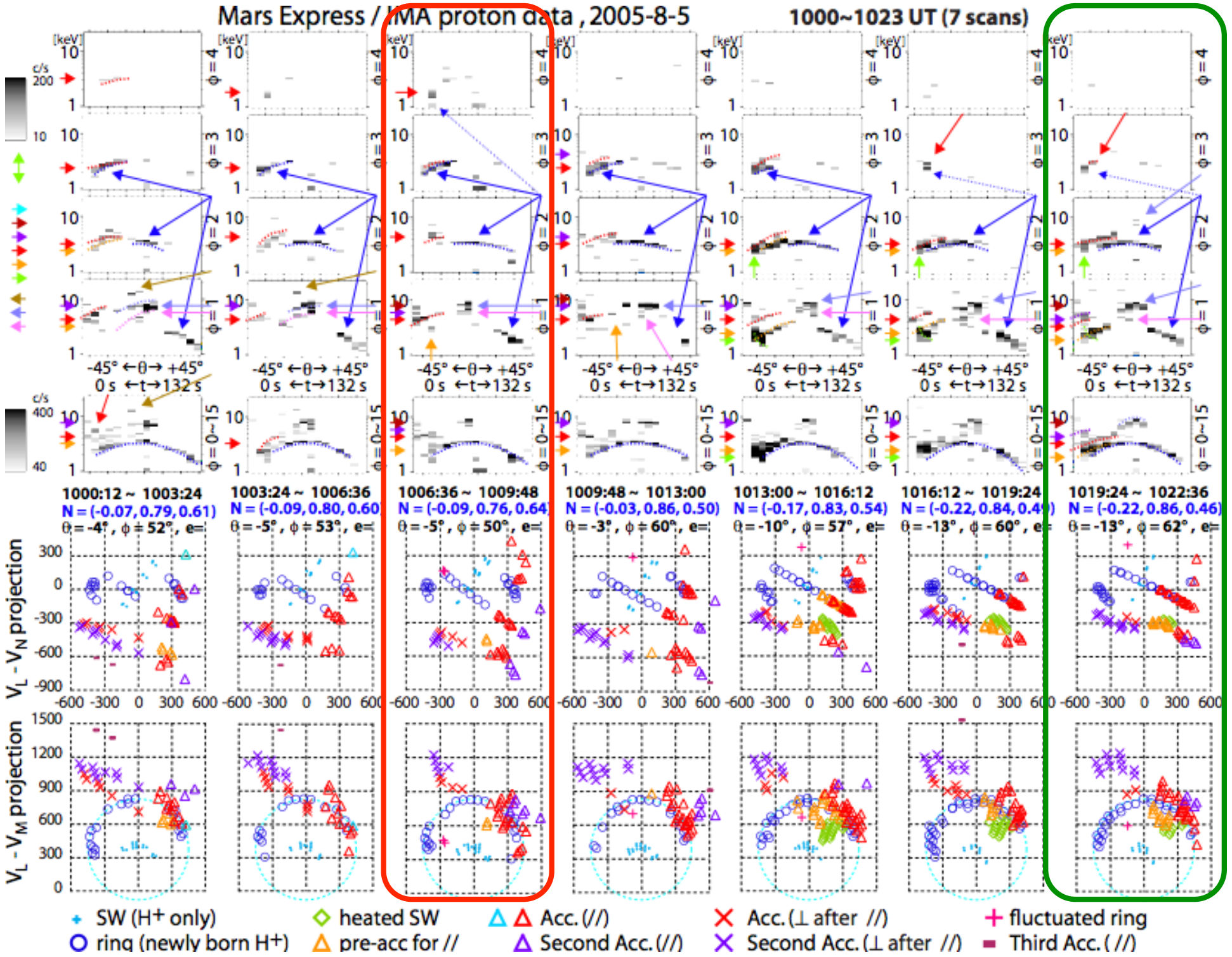



2005-6-3, 0608 UT
N = (+0.57, +0.14, +0.81)
#1=ring
#3=⊥ accel.
#5=2nd ring
V_N
V_M
V_L
2005-6-3, 0624 UT
N = (+0.42, -0.45, +0.79)
MEX/IMA 2005-6-3
06:05:04 ~ 06:08:16 UT
06:21:04 ~ 06:24:16 UT
H+
[keV]
c/s
200
10
-45° ←θ→ +45°

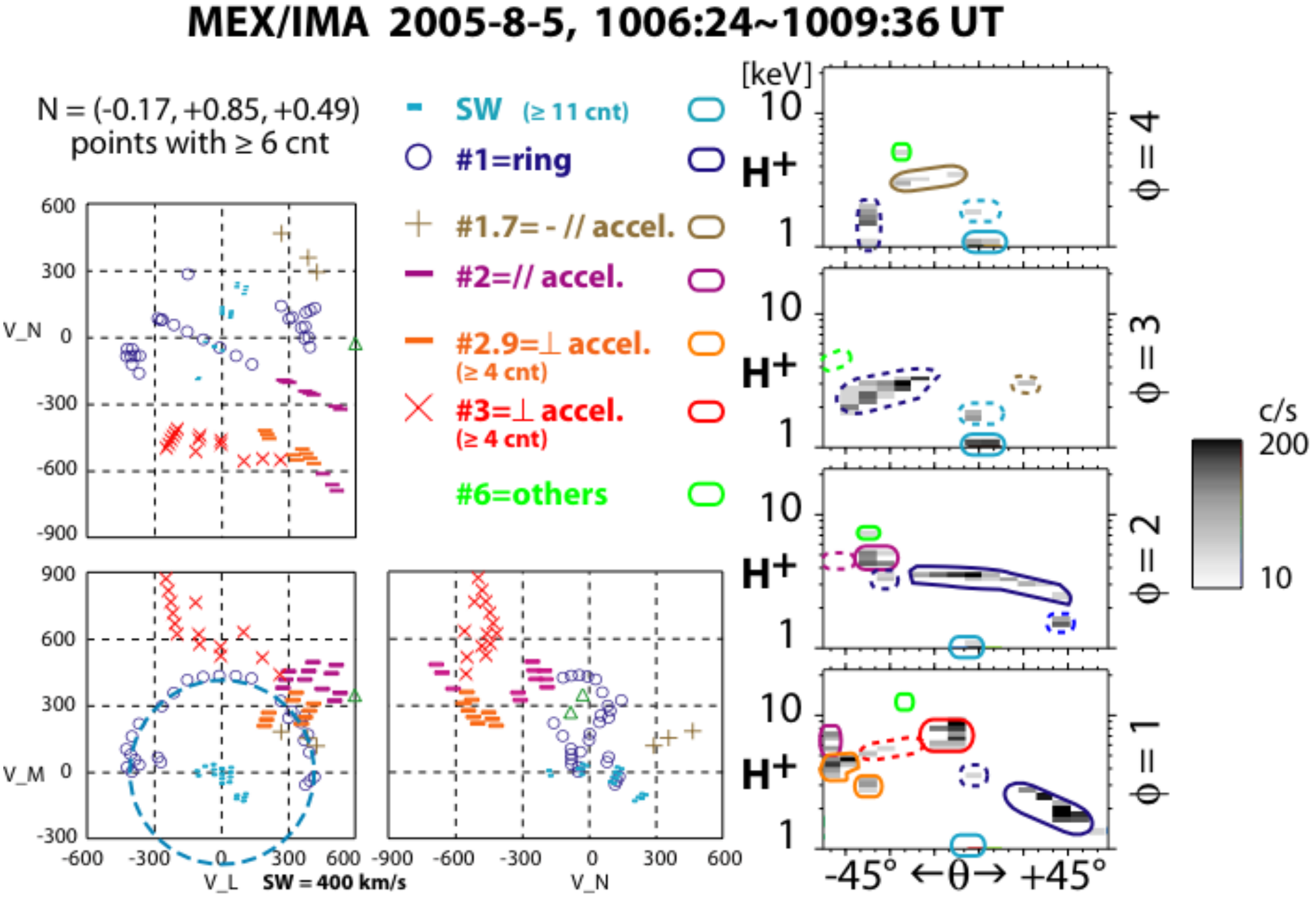
Quasi-// (case 3)


MEX , 2005-8-5 (// shock)
08:21=BS
B
10:33 = BS
R_{YZ} [R_M]
X_{MSO} [R_M]
10:00 ~ 10:16 UT
N = (-0.1, 0.8, 0.6) =QL
08:21
B
10:33
Z_{MSO} [R_M]
Y_{MSO} [R_M]

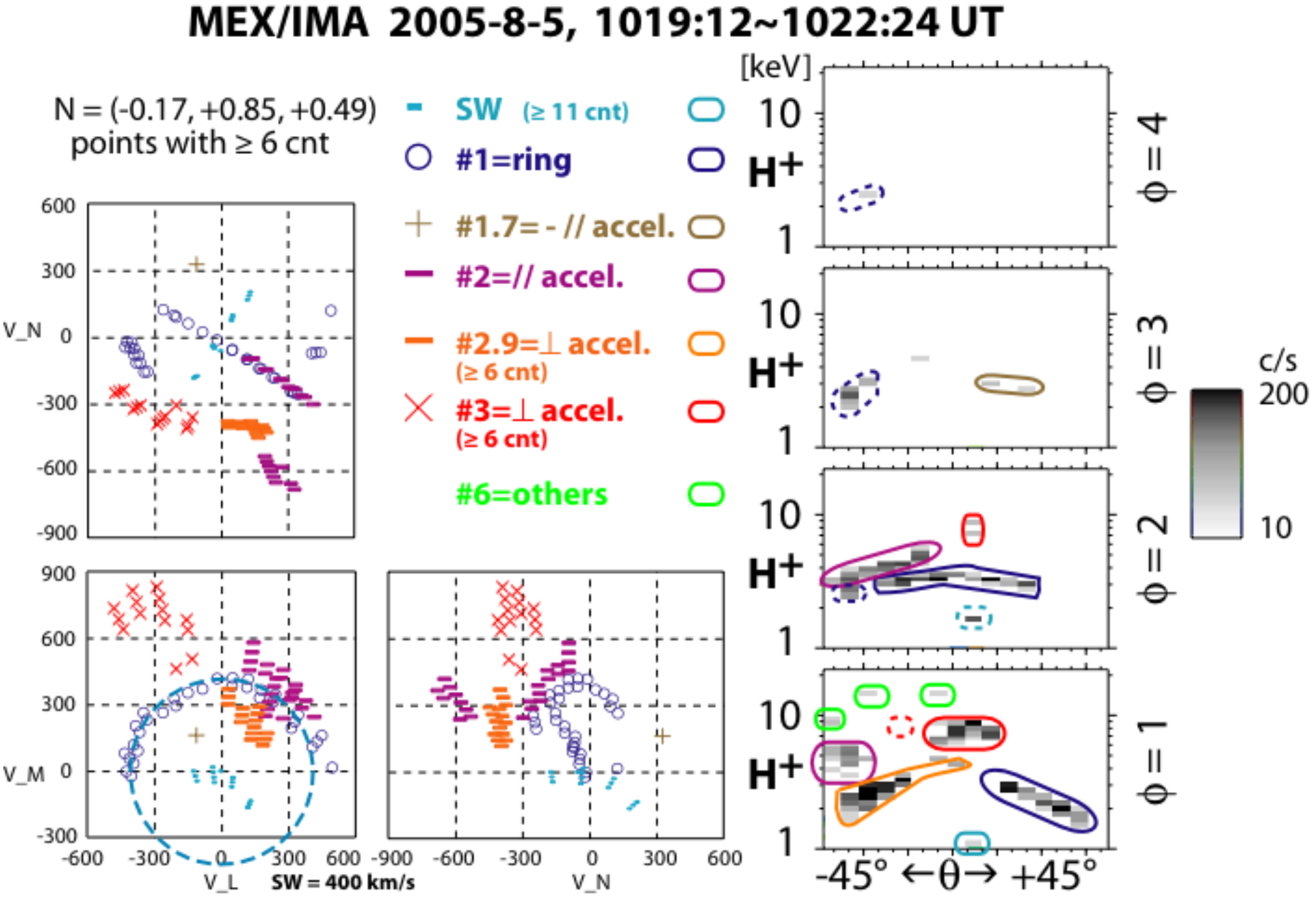

MEX/IMA 2005-8-5, 10:00:20~10:29:08
e⁻
ϕ = 3~5
[keV]
0.1
0.01
10:05
10:10
10:15
10:20
10:25
log JE
9.0
7.7
H⁺
ϕ = 5~13
ϕ = 1~4
[keV]
10
1
10
1
cnt
400
40
-0.1
-2.1
-2.5
3.3
X_{MSO}
Y_{MSO}
Z_{MSO}
D_{RM}
-0.3
-1.3
-2.4
2.8


Mars Express / IMA proton data , 2005-8-5
1000~1023 UT (7 scans)
[keV]
c/s
200
10
400
40
φ = 4
φ = 3
φ = 2
φ = 1
φ = 0~15
-45° ←θ→ +45°
0 s ←t→ 132 s
1000:12 ~ 1003:24
N = (-0.07, 0.79, 0.61)
θ = -4°, φ = 52°, e=
1003:24 ~ 1006:36
N = (-0.09, 0.80, 0.60
θ = -5°, φ = 53°, e=
1006:36 ~ 1009:48
N = (-0.09, 0.76, 0.64
θ = -5°, φ = 50°, e=
1009:48 ~ 1013:00
N = (-0.03, 0.86, 0.50)
θ = -3°, φ = 60°, e=
1013:00 ~ 1016:12
N = (-0.17, 0.83, 0.54)
θ = -10°, φ = 57°, e=
1016:12 ~ 1019:24
N = (-0.22, 0.84, 0.4
θ = -13°, φ = 60°, e=
1019:24 ~ 1022:36
N = (-0.22, 0.86, 0.46)
θ = -13°, φ = 62°, e=
V_L - V_N projection
V_L - V_M projection
SW (H+ only)
ring (newly born H+)
heated SW
pre-acc for //
Acc. (//)
Second Acc. (//)
Acc. (⊥ after //)
Second Acc. (⊥ after //)
fluctuated ring
Third Acc. (//)

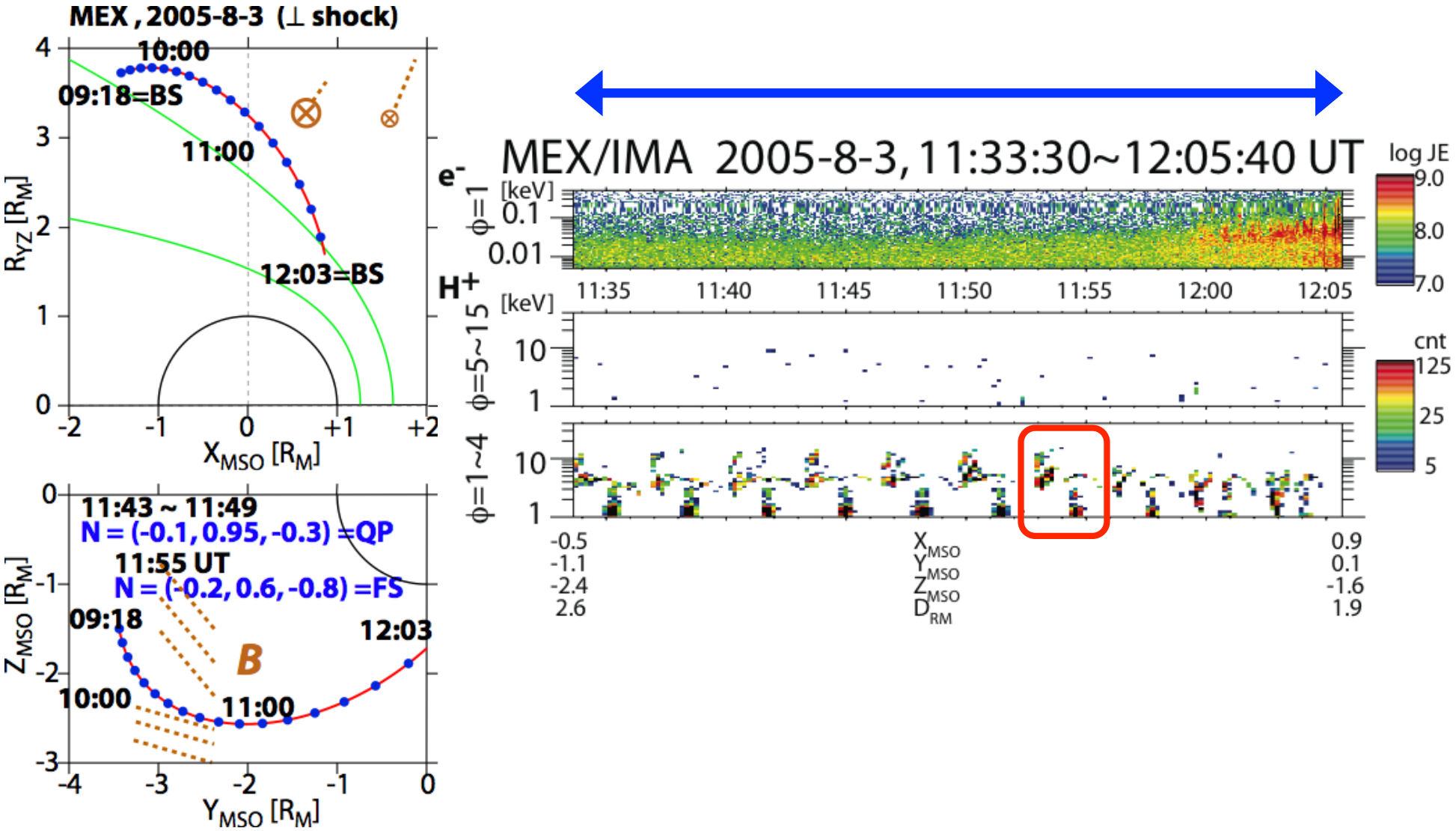
case 3a


MEX/IMA 2005-8-5, 1006:24~1009:36 UT
N = (-0.17, +0.85, +0.49)
points with ≥ 6 cnt
SW (≥ 11 cnt)
#1=ring
#1.7= - // accel.
#2=// accel.
#2.9=⊥ accel.
(≥ 4 cnt)
#3=⊥ accel.
(≥ 4 cnt)
#6=others
V_N
V_M
V_L
SW = 400 km/s
[keV]
H+
ϕ = 4
ϕ = 3
ϕ = 2
ϕ = 1
c/s
200
10
-45° ←θ→ +45°

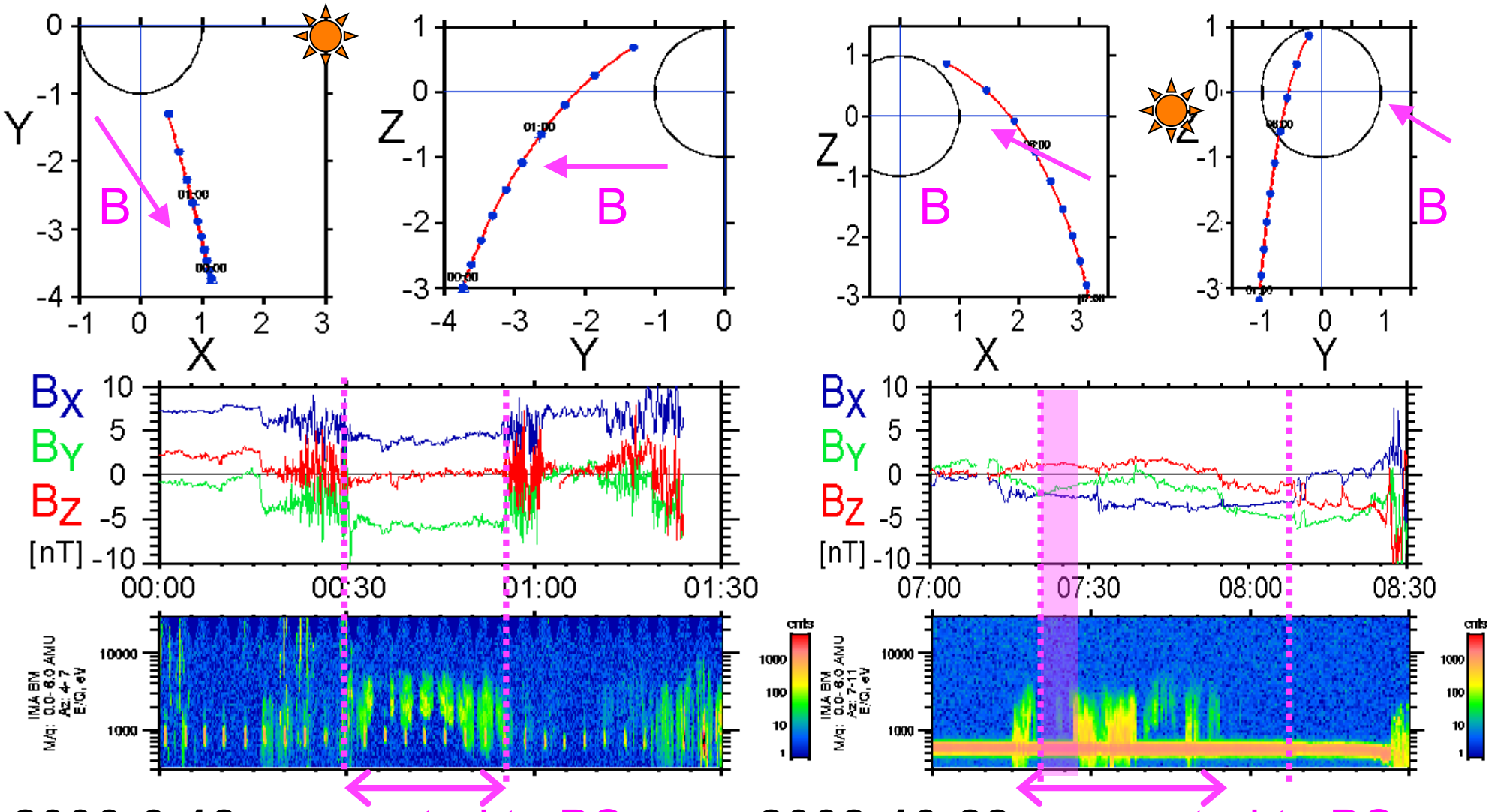
case 3b


MEX/IMA 2005-8-5, 1019:12~1022:24 UT
N = (-0.17, +0.85, +0.49)
points with ≥ 6 cnt
SW (≥ 11 cnt)
#1=ring
#1.7= - // accel.
#2=// accel.
#2.9=⊥ accel.
(≥ 6 cnt)
#3=⊥ accel.
(≥ 6 cnt)
#6=others
V_N
V_M
V_L
SW = 400 km/s
[keV]
H+
ϕ = 4
ϕ = 3
ϕ = 2
ϕ = 1
c/s
200
10
-45° ←θ→ +45°

Quasi-⊥ (case 1+3)



Venus ≈ Earth

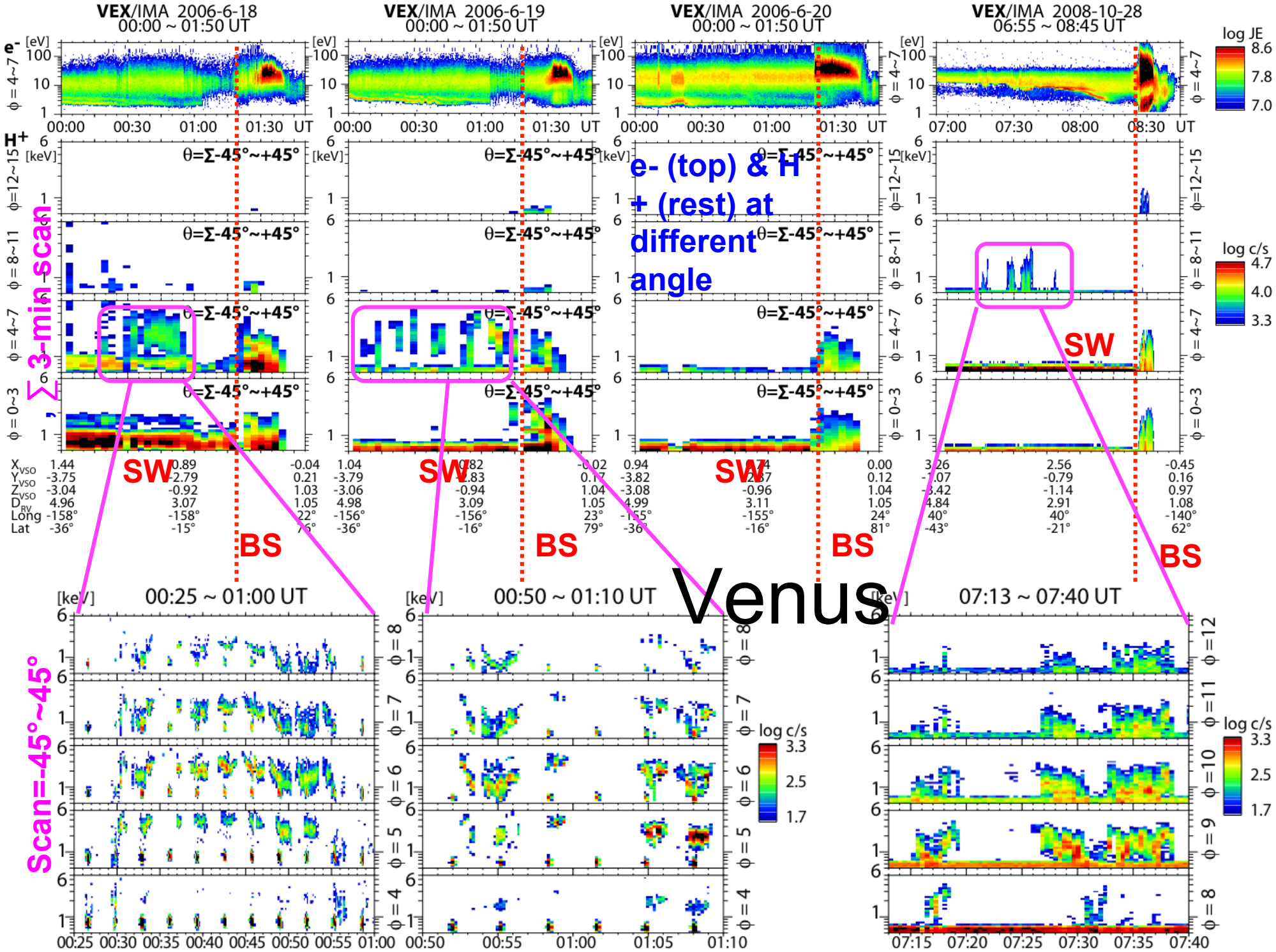


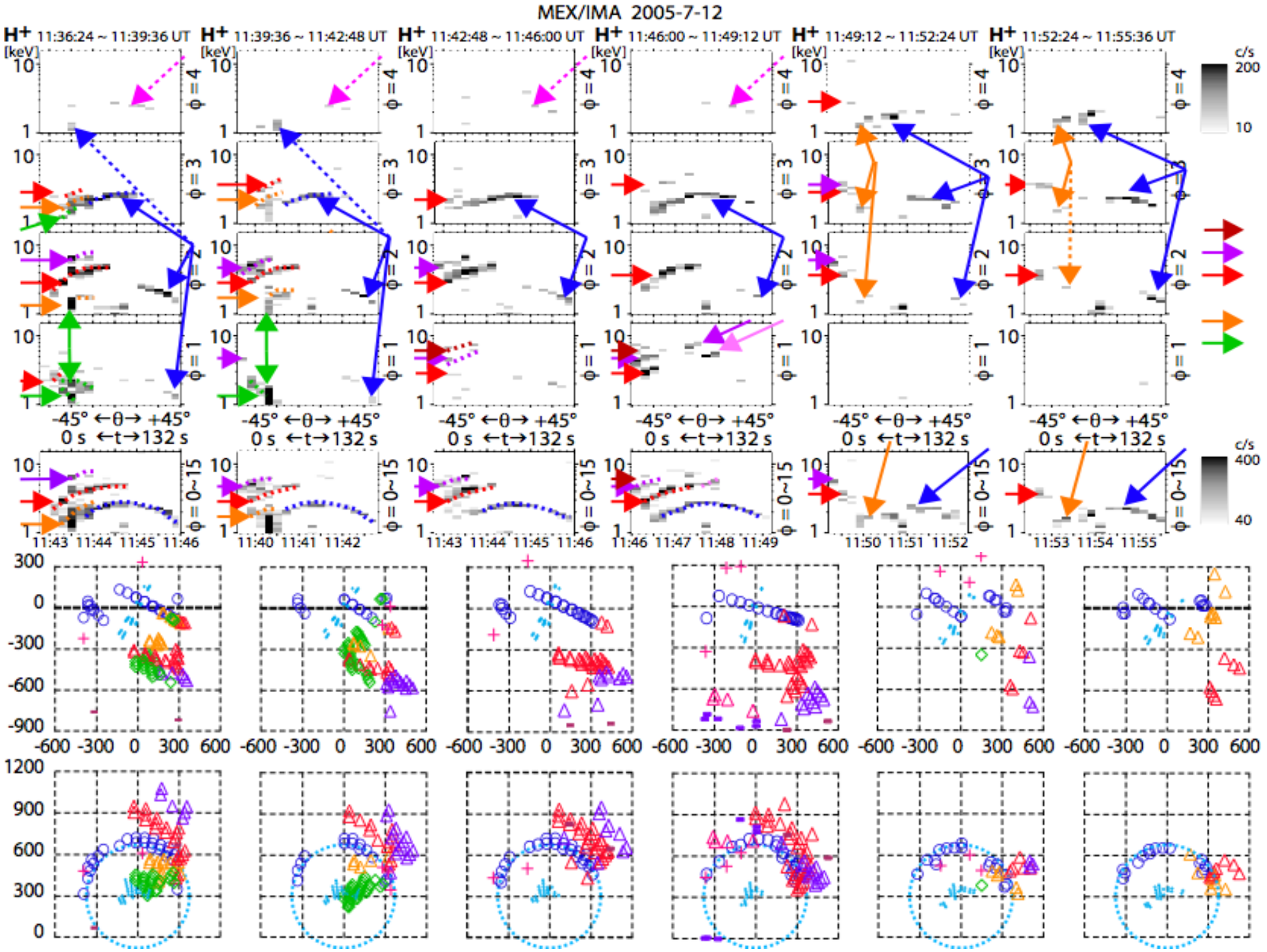
2006-6-18 connected to BS

Beam = foreshock

2008-10-28 connected to BS

Sometimes no beam in foreshock


VEX/IMA 2006-6-18
00:00 ~ 01:50 UT
VEX/IMA 2006-6-19
00:00 ~ 01:50 UT
VEX/IMA 2006-6-20
00:00 ~ 01:50 UT
VEX/IMA 2008-10-28
06:55 ~ 08:45 UT
e-
H+
log JE
log c/s
θ=Σ-45°~+45°
e- (top) & H+ (rest) at different angle
∑3-min scan
SW
BS
Venus
Scan=-45°~45°
00:25 ~ 01:00 UT
00:50 ~ 01:10 UT
07:13 ~ 07:40 UT


MEX/IMA 2005-7-12
H+ 11:36:24 ~ 11:39:36 UT
H+ 11:39:36 ~ 11:42:48 UT
H+ 11:42:48 ~ 11:46:00 UT
H+ 11:46:00 ~ 11:49:12 UT
H+ 11:49:12 ~ 11:52:24 UT
H+ 11:52:24 ~ 11:55:36 UT
[keV]
c/s
200
10
400
40
φ = 4
φ = 3
φ = 2
φ = 1
φ = 0~15
-45° ←θ→ +45°
0 s ←t→ 132 s
11:43 11:44 11:45 11:46
11:40 11:41 11:42
11:43 11:44 11:45 11:46
11:46 11:47 11:48 11:49
11:50 11:51 11:52
11:53 11:54 11:55

5th Alfvén Conference

on **"Plasma Interaction with Non-magnetized Planets/Moons and its Influence on Planetary Evolution"**

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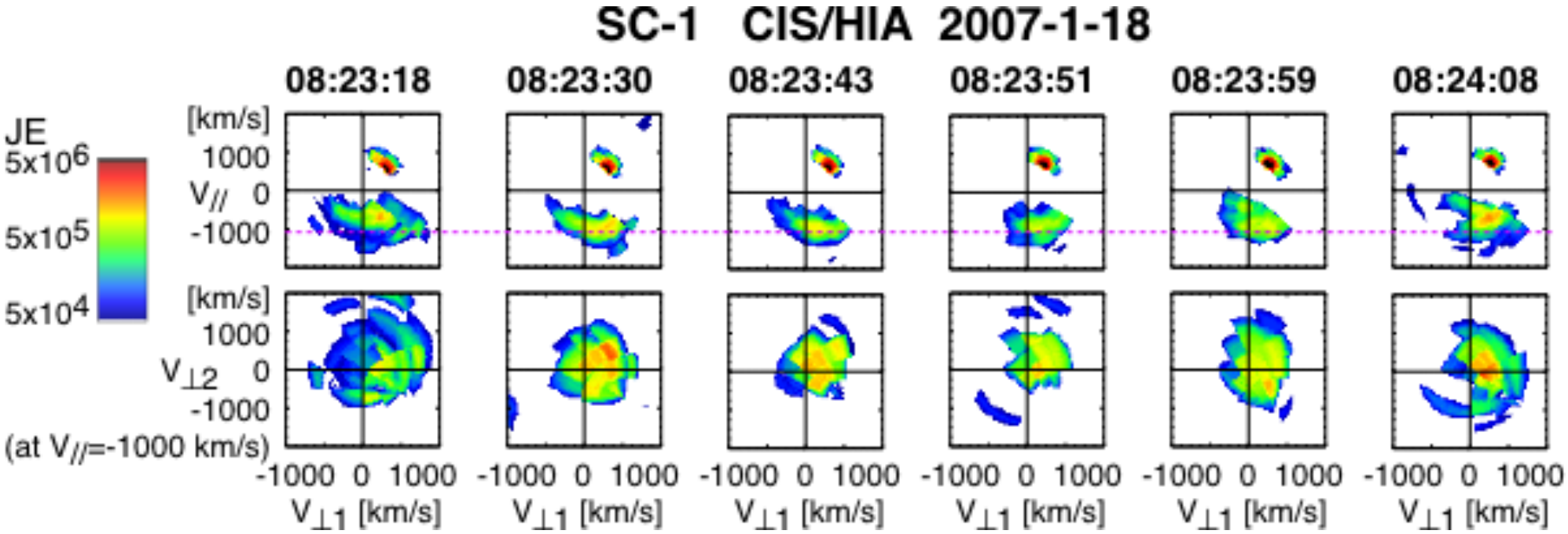
4-8 October, 2010
Sapporo, Japan

Mars, Venus, The Moon, and Jovian/Saturnian satellites


SC-1 CIS/HIA 2007-1-18
08:23:18
08:23:30
08:23:43
08:23:51
08:23:59
08:24:08
JE
5x10^6
5x10^5
5x10^4
[km/s]
1000
V// 0
-1000
[km/s]
1000
V⊥2 0
-1000
(at V//=-1000 km/s)
-1000 0 1000
V⊥1 [km/s]