Comparative Planetary Foreshocks: Results from recent studies

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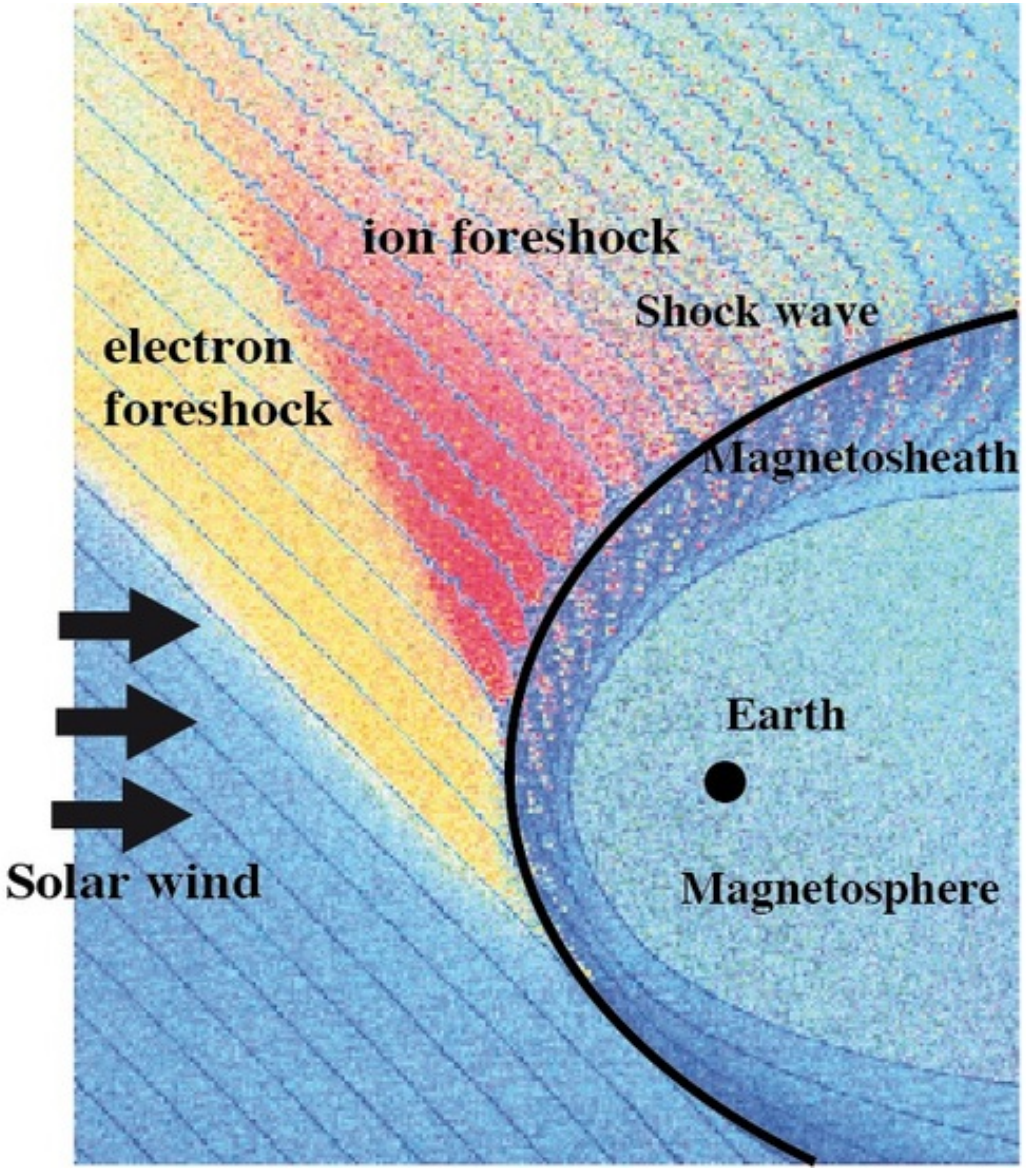
Outline

- **Motivation**
- **Bow shock curvature**
- **New results from MAVEN**
- **Venus' similarity with Earth**
- **Quasi-parallel structures**
- **Conclusion**

The Foreshock



Motivation

- Availability of critical data collection from various planets presenting different physical contexts
- In depth understanding of foreshock formation
- Insights on shocks

Mariner	4	(1965)	Flyby
	6, 7	(1969)	Flyby
	9	(1971)	
Mars	2, 3	(1971)	
Viking	1, 2	(1975)	
MGS		(1996)	
Mars Odyssey		(2001)	
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ExoMars T. G.		(2016)	

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Galileo		(1990)	Flyby
Cassini		(1998)	Flyby
Messenger		(2006)	Flyby
Venus EXpress		(2006)	
Akatsuki		(2015 → Now)	

Bow shock scale & Particle orbit

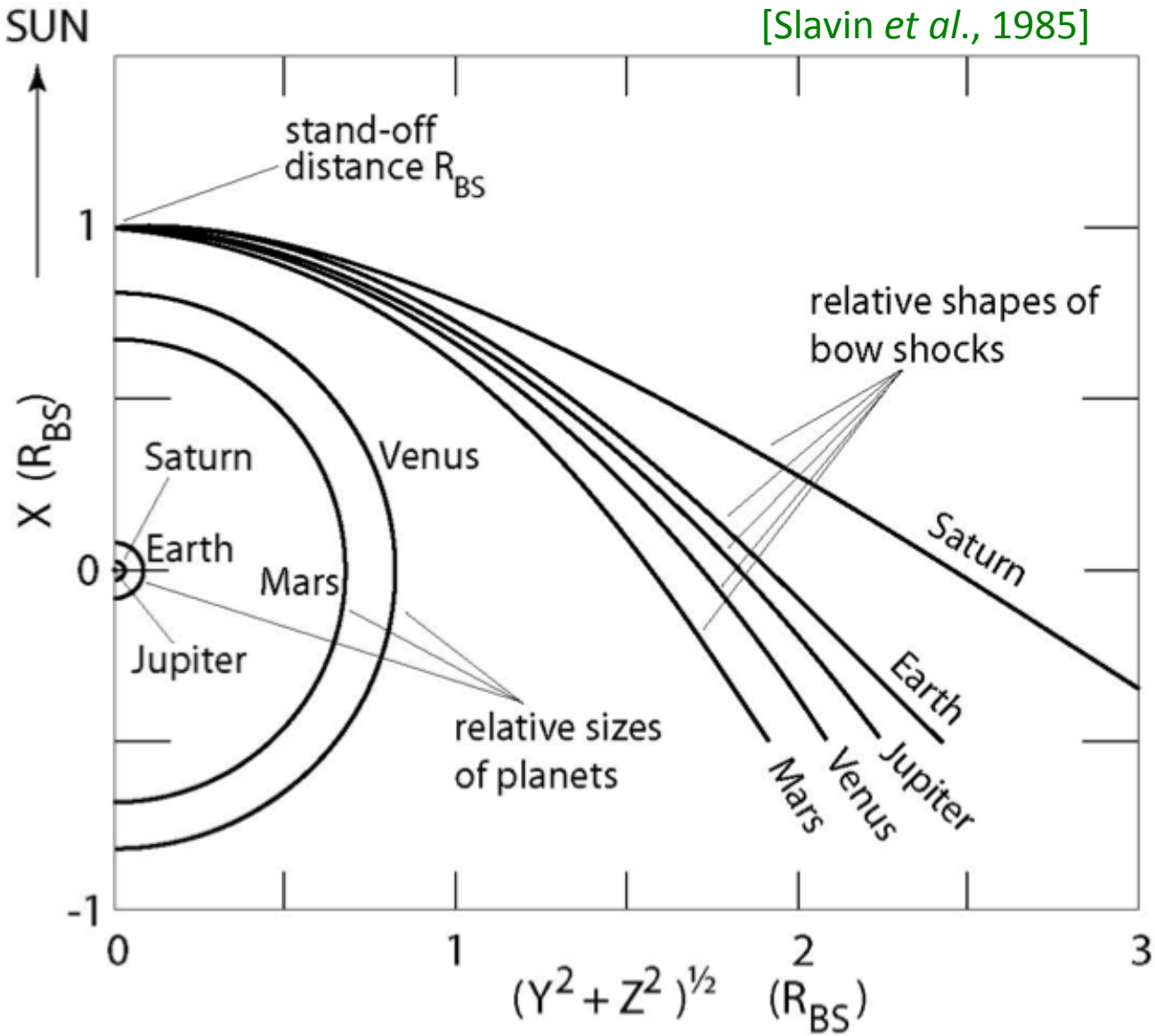
	Planet Radius R_P/R_E	Standoff/ Scale H.	IMF B/B_E	Parker IMF θ_{BX}	Radius Curvature/ρ_i	θ_{Bn}= 90° Drift Length η_{90}
Earth	1	13.5	1	45°	222	1
Venus	0.95	1.4	1.7	36°	25	0.13
Mars	0.63	1.6	0.4	57°	4 [O^+: 0.25]	0.02
Saturn	9.1	26	0.04	84°	224	1.2

Venus & Mars: Bow shock inside H−exosphere

Guiding center approximation (for ions) NOT valid in case of Mars

Bow shock scale

[Slavin *et al.*, 1985]



Maximum Particle Energization

Electric field tangent to the shock

$$\mathcal{E}_t = BV\sin\theta_{BX}$$

Particle energization while drifting for a distance l

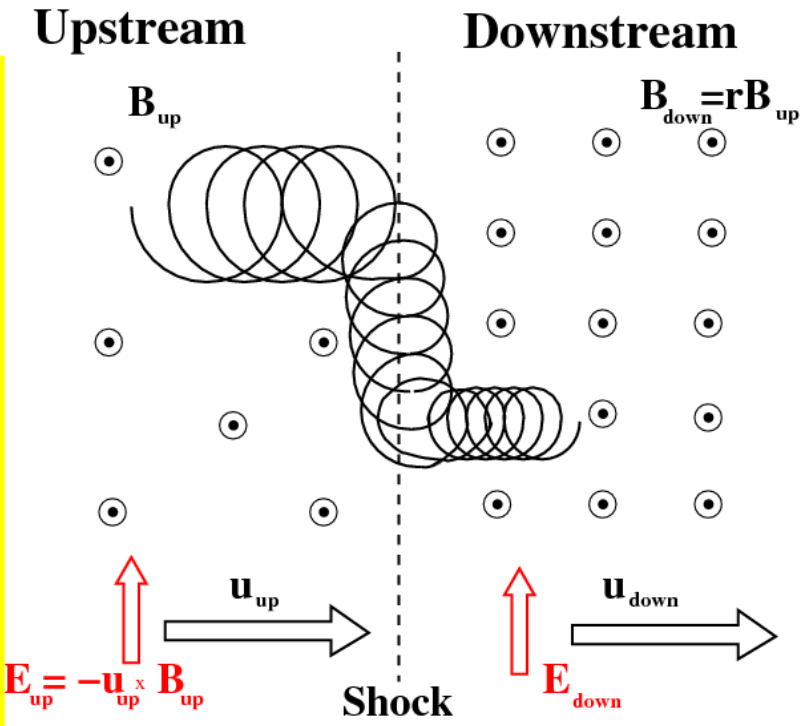
$$\Delta E = q\mathcal{E}_t l = qBVl\sin\theta_{BX}$$

For a nearly perpendicular drift

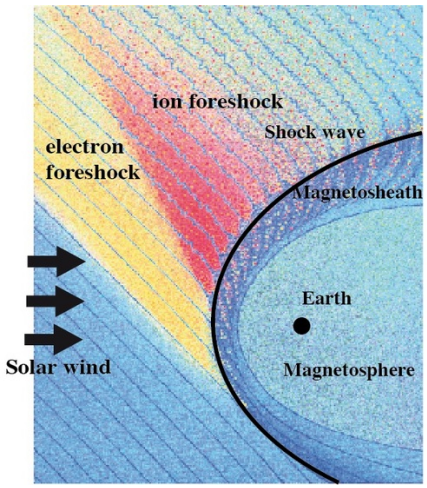
$$l \sim L\sqrt{1+\frac{X_0}{L}}, \quad L = \text{semilatus}, X_0 = \text{conic section focus}$$

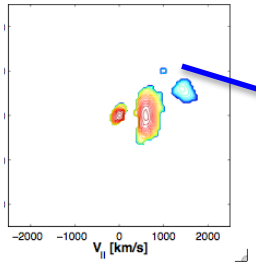
Comparison with Earth bow shock

$$\eta_{90} = \frac{(\Delta E)_{Planet}}{(\Delta E)_{Earth}} \sim \frac{\left[B\sin\theta_{BX}L\sqrt{1+2X_0/L}\right]_{Planet}}{\left[B\sin\theta_{BX}L\sqrt{1+2X_0/L}\right]_{Earth}} \times \frac{R_P}{R_E}$$



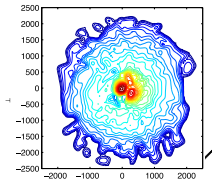
The terrestrial foreshock prototype

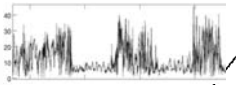




Gyrophase-bunched ions

FABs Region





(P_{GC}=2)

Except for FABs, One-to-One Association Backstreaming ions-ULF Waves

S

B

ULF Wave Boundary

Electrons Spikes up to ~ 100 keV

[Skadron & Lee, 1988]
[Le & Russell, 1992]
[Meziane *et al.*, 2004]

Mars

Mariner	4	(1965)	Flyby
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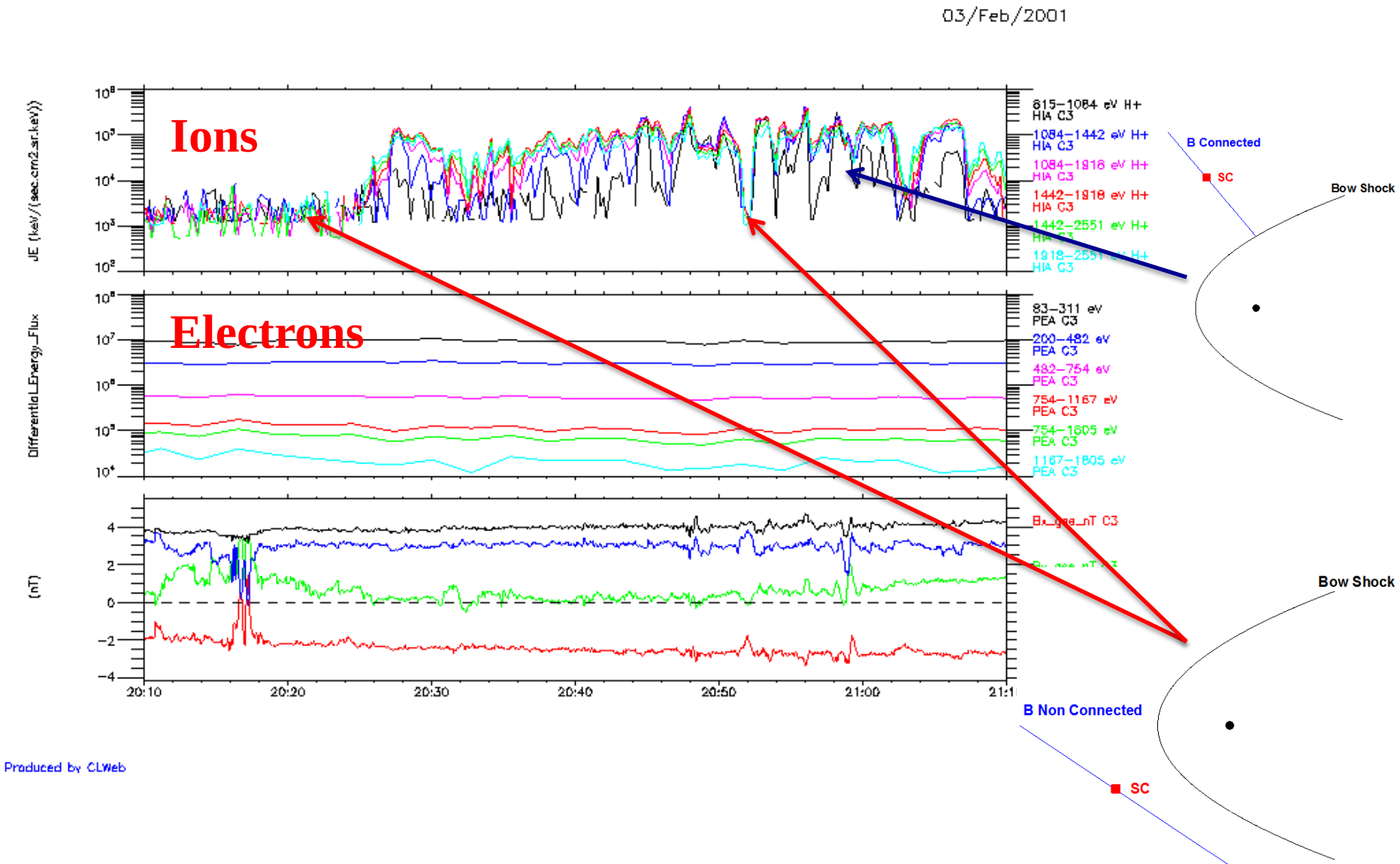
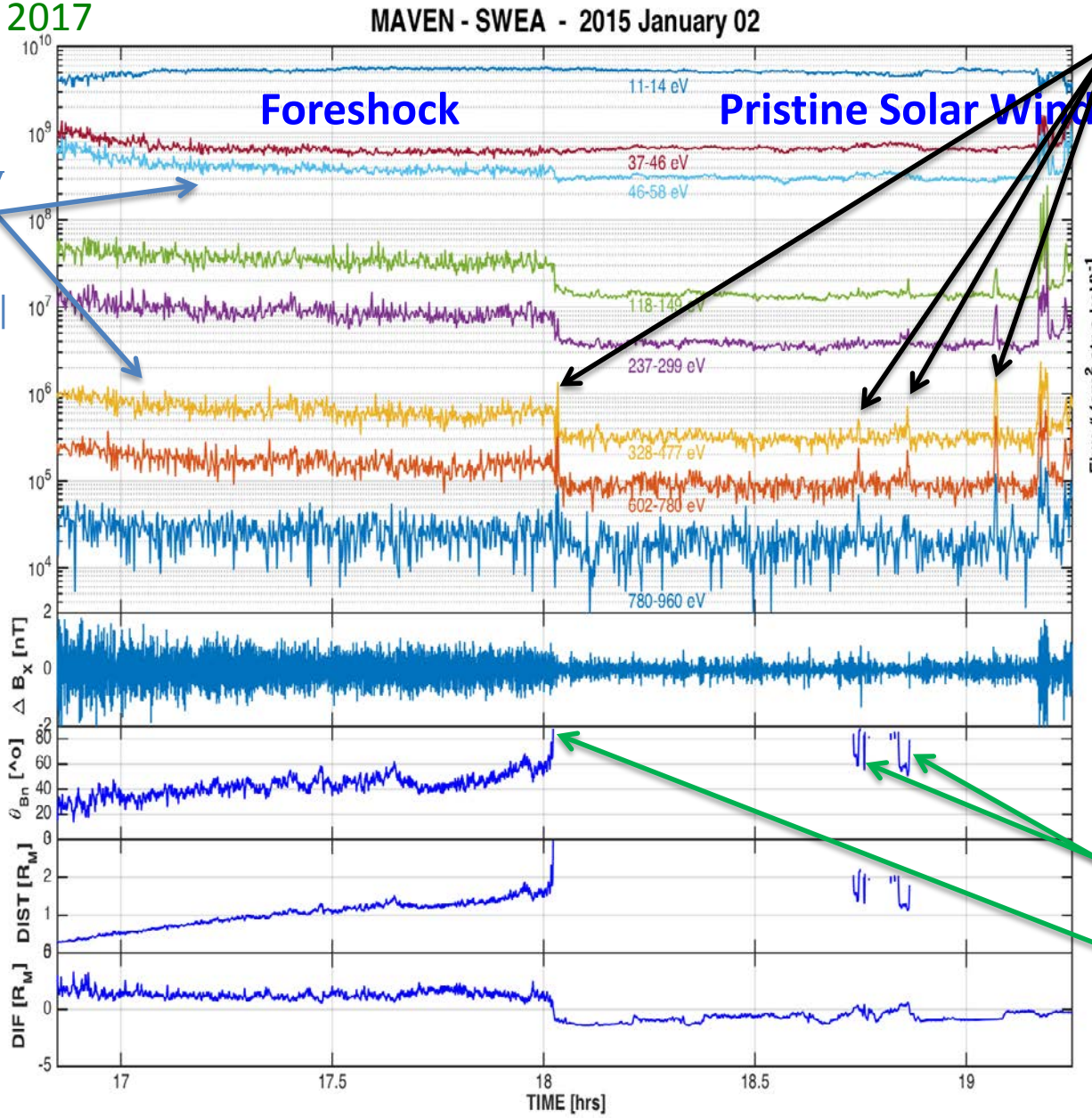
Ions as a proxy for magnetic connection
For the terrestrial foreshock



Two Foreshock Electron Populations

Meziane *et al.*, 2017



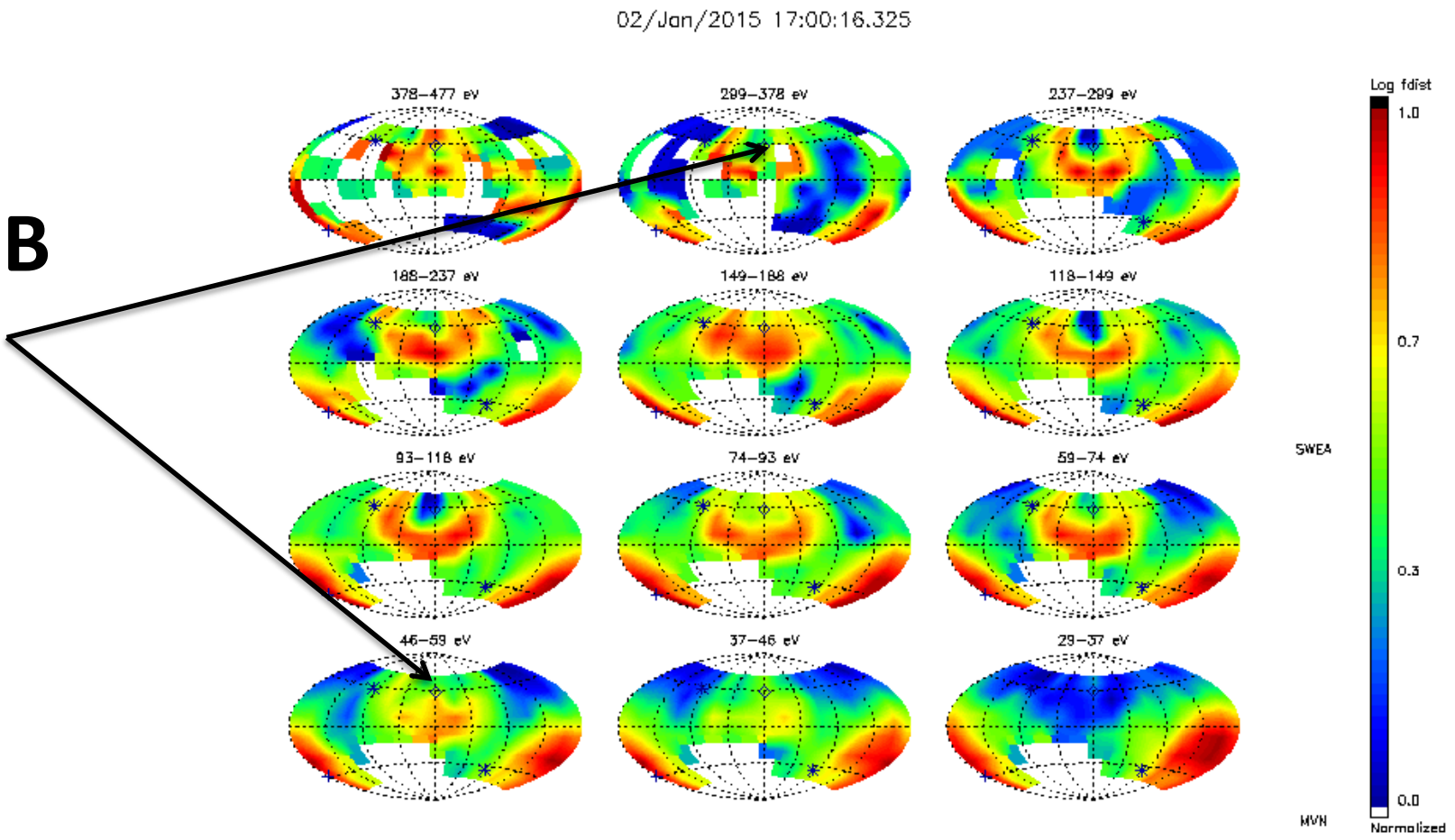
Monotonically decreasing fluxes from $Q_{||}$ to $Q_{\perp}$

Spikes at θ_{Bn}

Sporadic connections

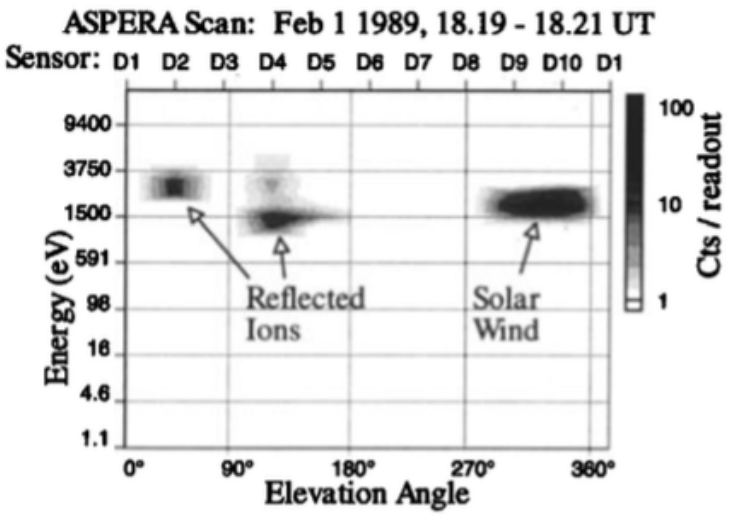
Disconnection

Ring beam distributions indicate a coherent reflection of solar wind electrons



Foreshock ions

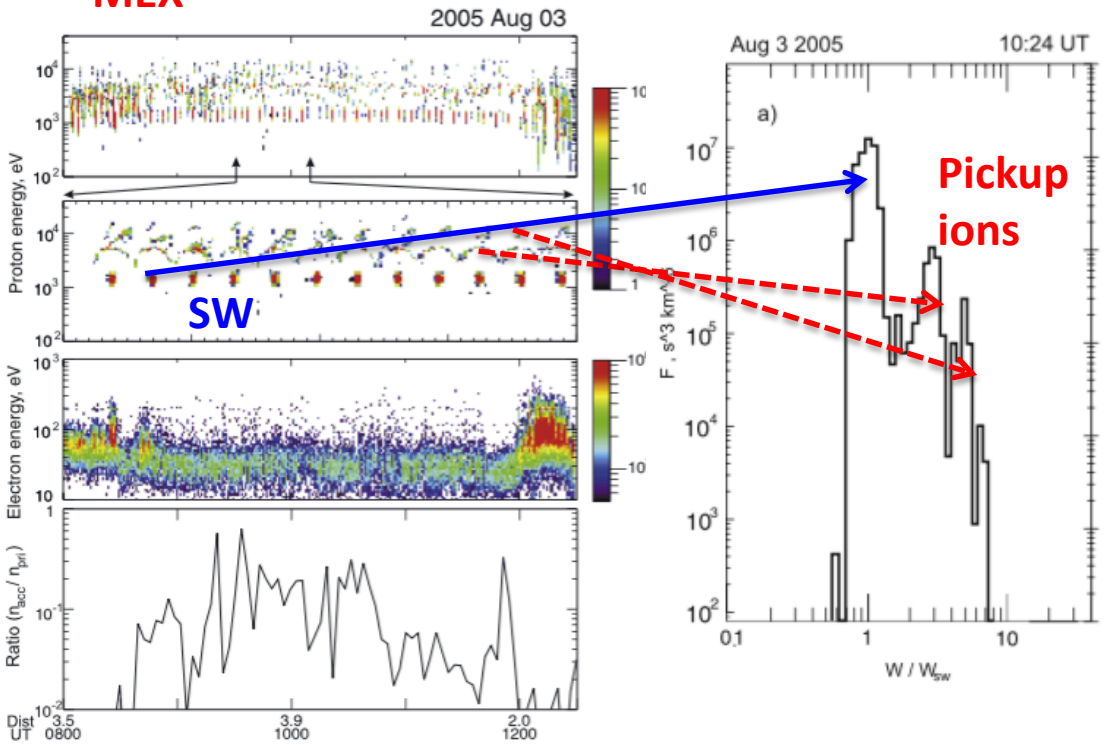
Phobos-2



[Barabash & Lundin, 1993]

MEX

[Dubinin *et al.*, 2006]

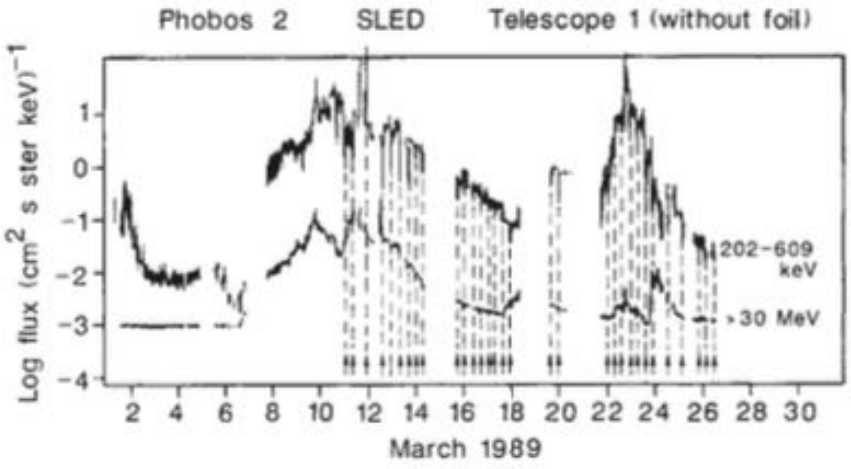


Solar wind direct interaction with the Martian exosphere.

Newly-ionized neutrals are picked up by the IMF

→ Energy source for PCWs

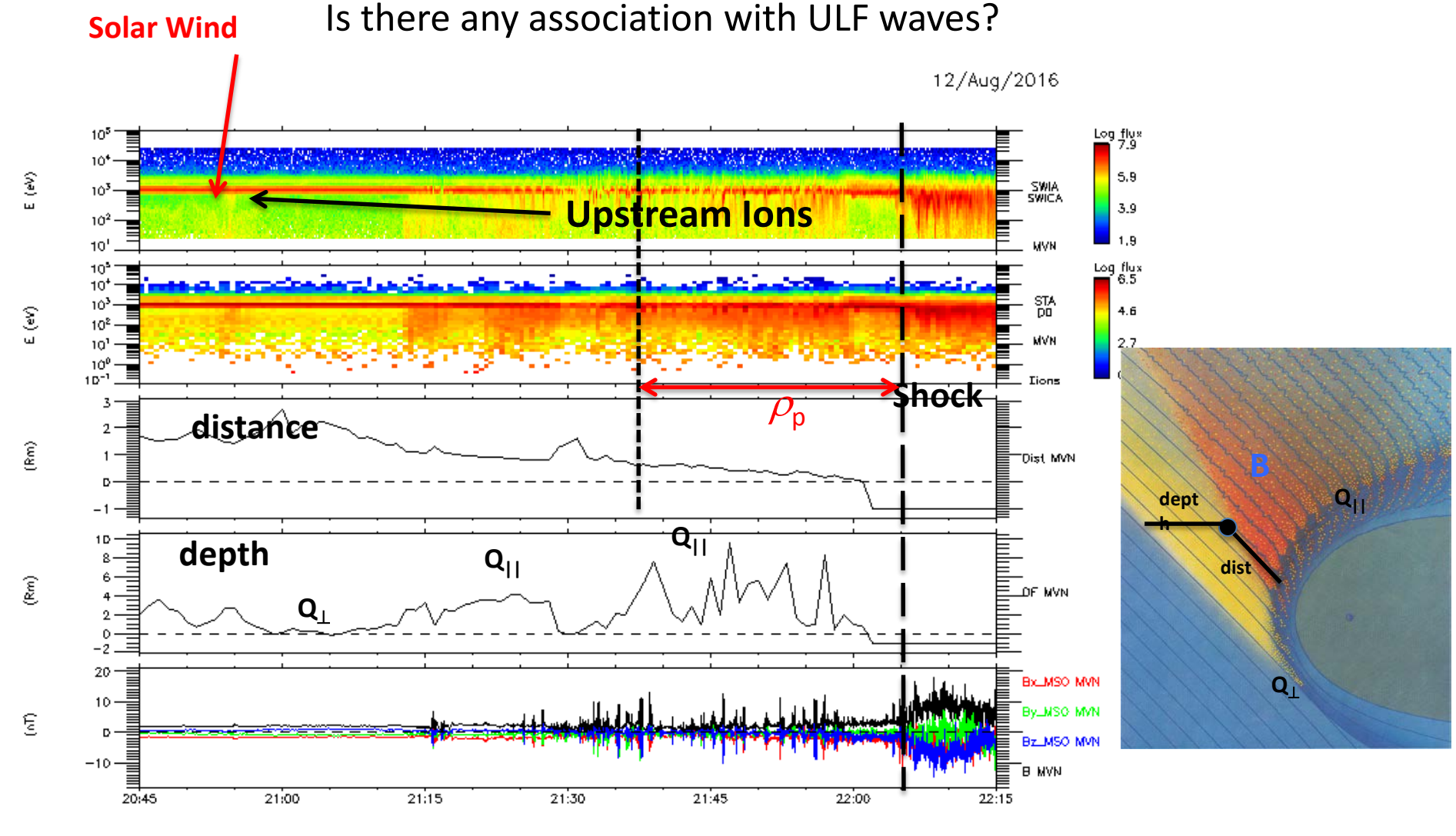
Pickup ions as "seed population" for a coherent acceleration (SDA and/or shock surfing)



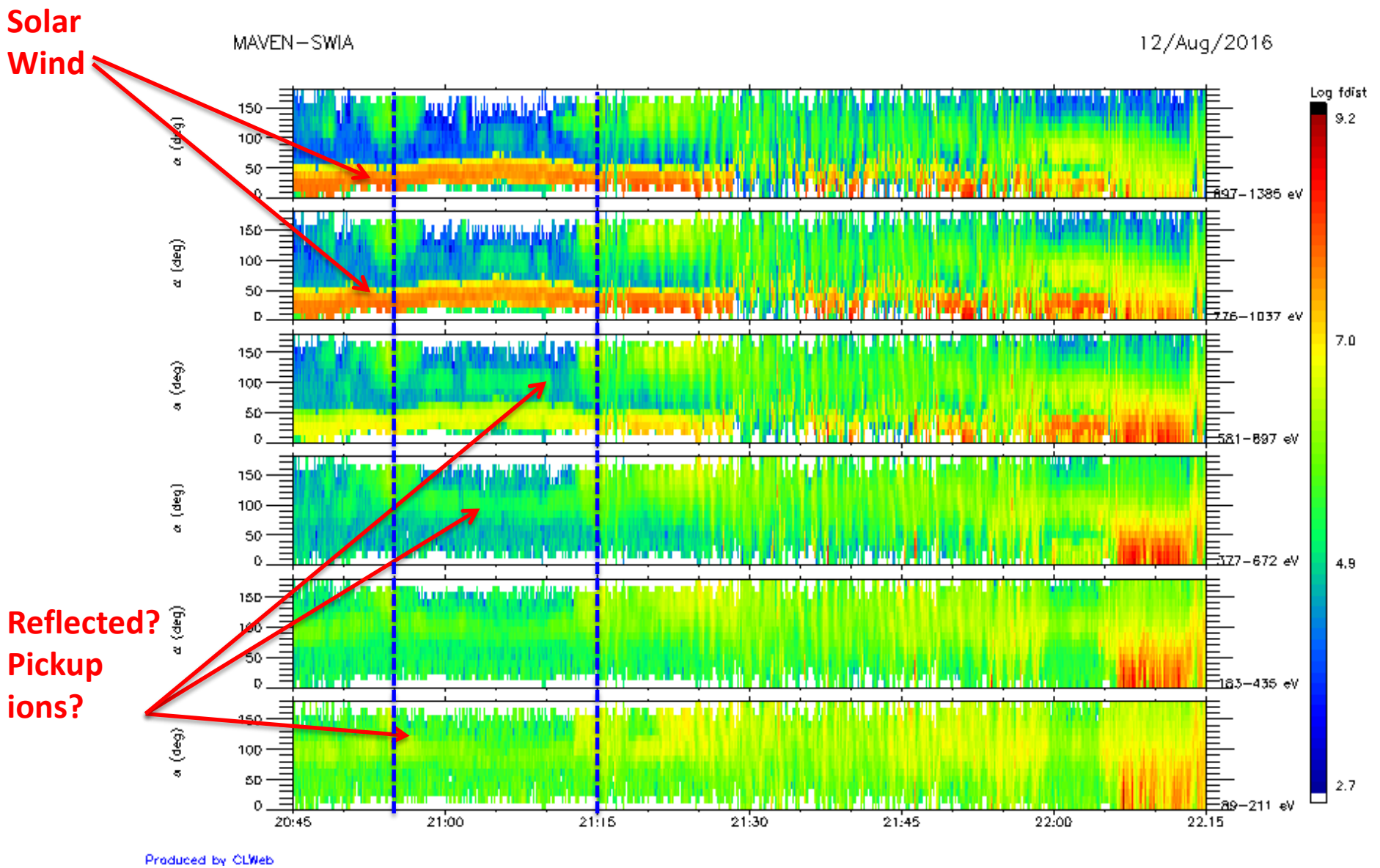
[Afonin *et al.*, Nature, 1989]

MAVEN Foreshock Ions

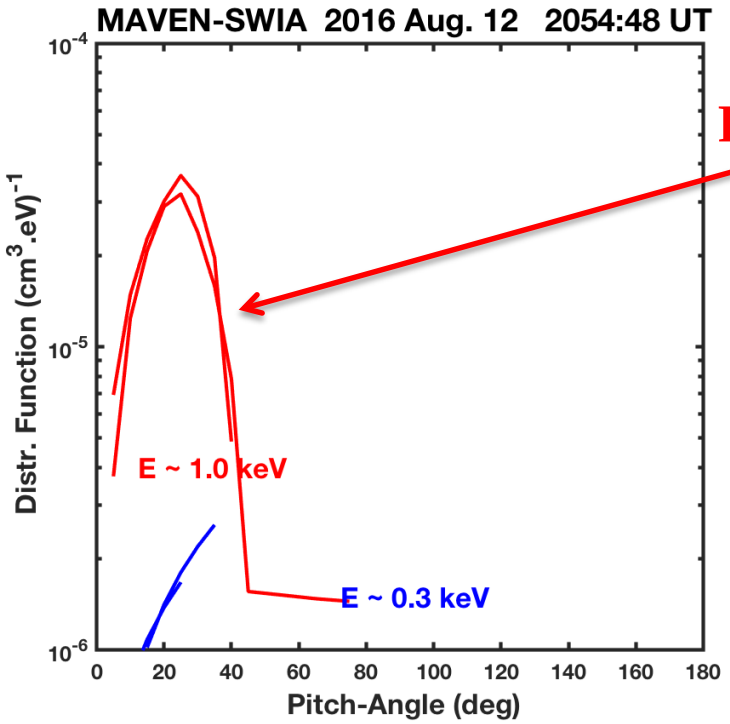
Do ions escape upstream?
Shock geometry & nature of distribution functions?
Is there any association with ULF waves?



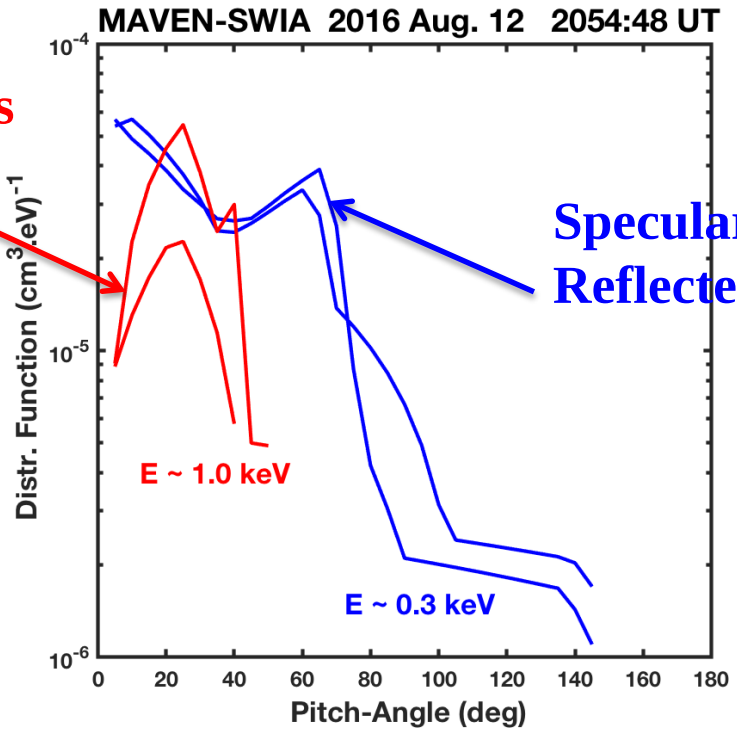
MAVEN Foreshock Ions



Pickup ions & Reflected?



Pickup ions



Specularly Reflected?

In the solar wind Frame of reference

$E \sim E_{SW}$
Pitch-Angle ~ θ_{BV}

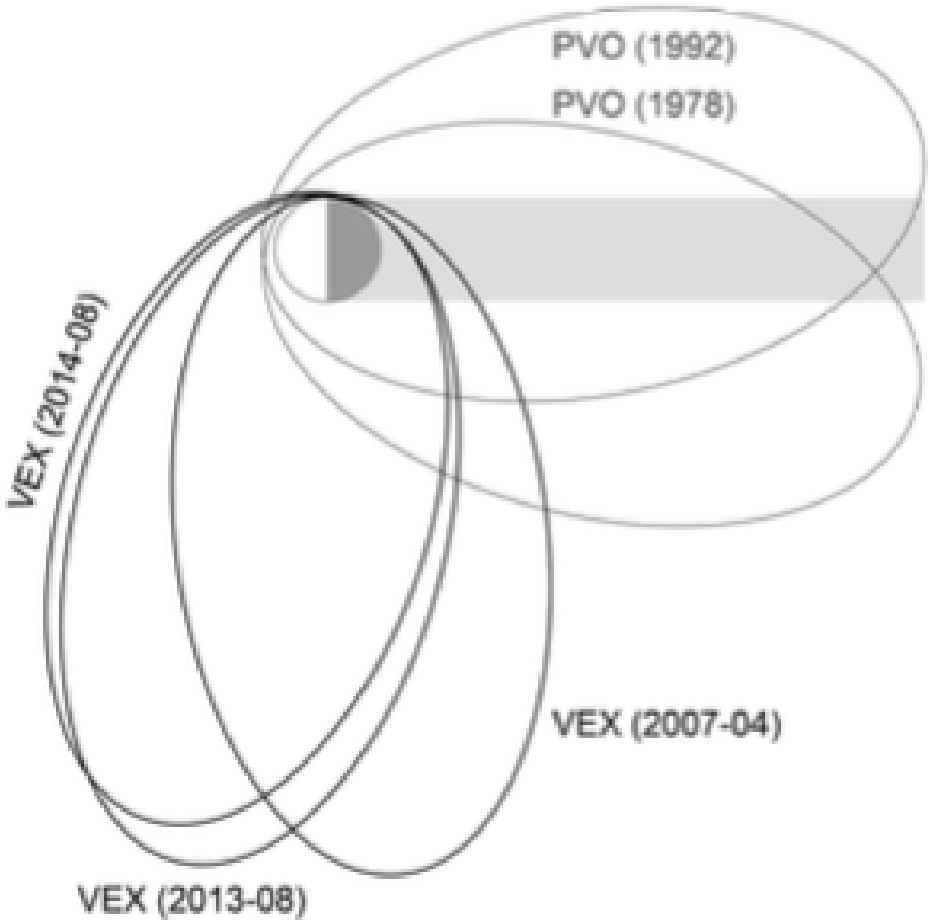
Pitch-angle ~ θ_{Bn}
Do not escape Upstream

Martian foreshock

- **Electrons**
  - Entire shock as a source of backstreaming electrons
  - Two populations
    - Spikes at $\theta_{Bn} \sim 90^{o}$ [similar to Earth]
    - Broad source
  - Spikes maximum energy $E \sim \eta_{90} \times 100$ keV ~ 2 keV
  - Contribute to the pickup ion production
- **Ions**
  - **An assessment (velocity distribution, shock geometry, maximum acceleration, …) and a comprehensive understanding [no planer kinetic analysis] are needed.**
  - **Association with ULF waves?**
  - **Shock Pickup ion acceleration**
  - **The impact of the shock foot (no longer microscopic)**

Venus

[Futanaa *et al*., 2017]



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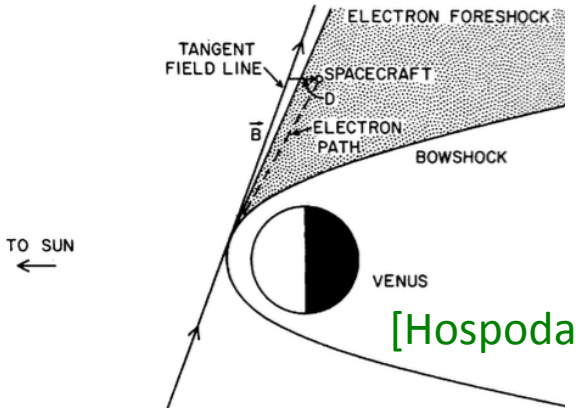
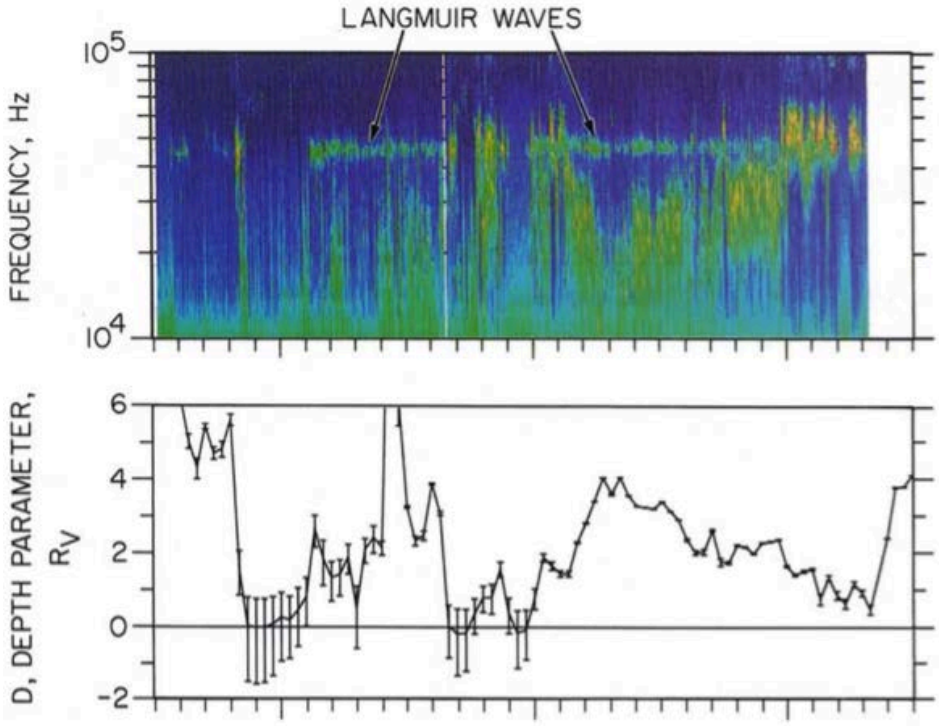
Electron Foreshock

Galileo flyby, 1990 Feb. 10



[Hospodarsky *et al.*, 1994]



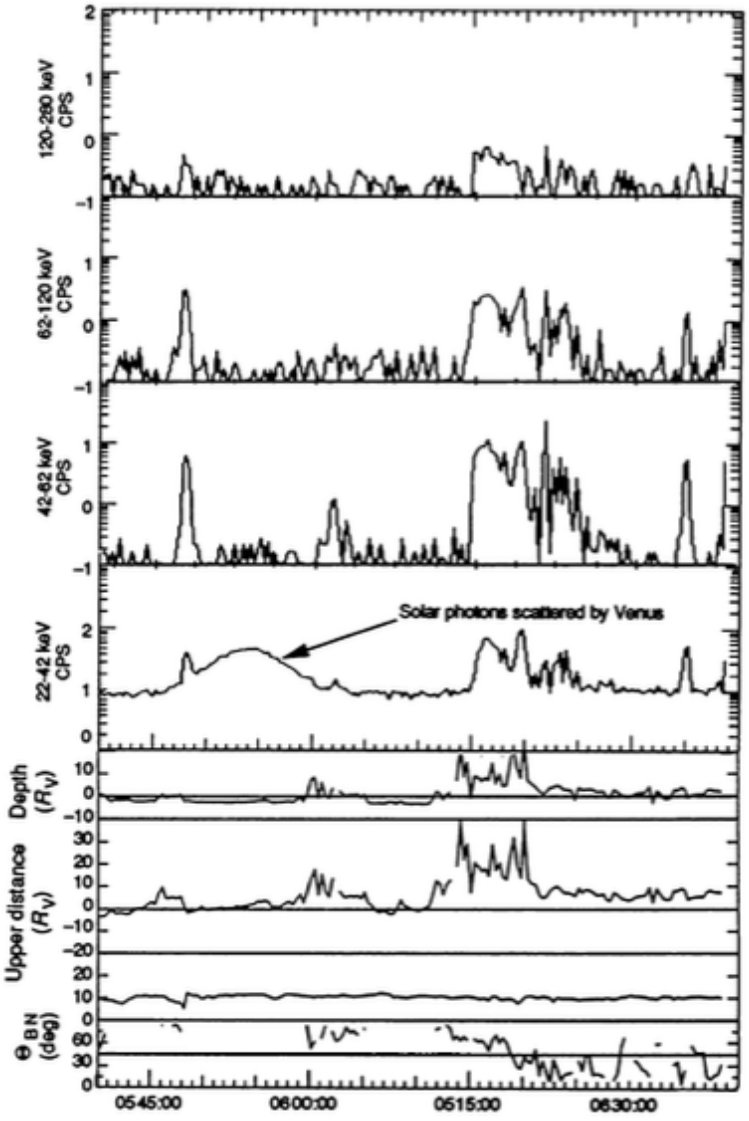
Strong similarity with the Terrestrial foreshock.

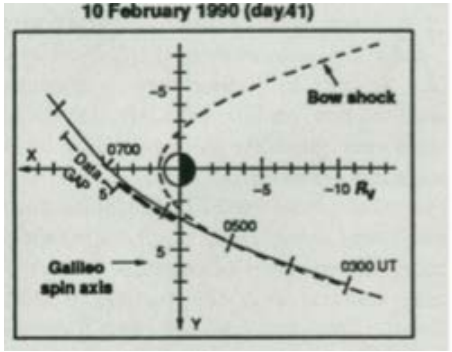
Pioneer Venus Orbiter [Crawford *et al.*, 1993] Plasma waves emission produced by electron beam propagation.

A natural laboratory for nonlinear processes (structures at various spatio-temporal scales).

Ubiquitous energetic ions?

Galileo flyby, 1990 Feb. 10





[Williams *et al.*, 1991]

Antisolar hemisphere 120-280 keV ions during a quite time (SW)

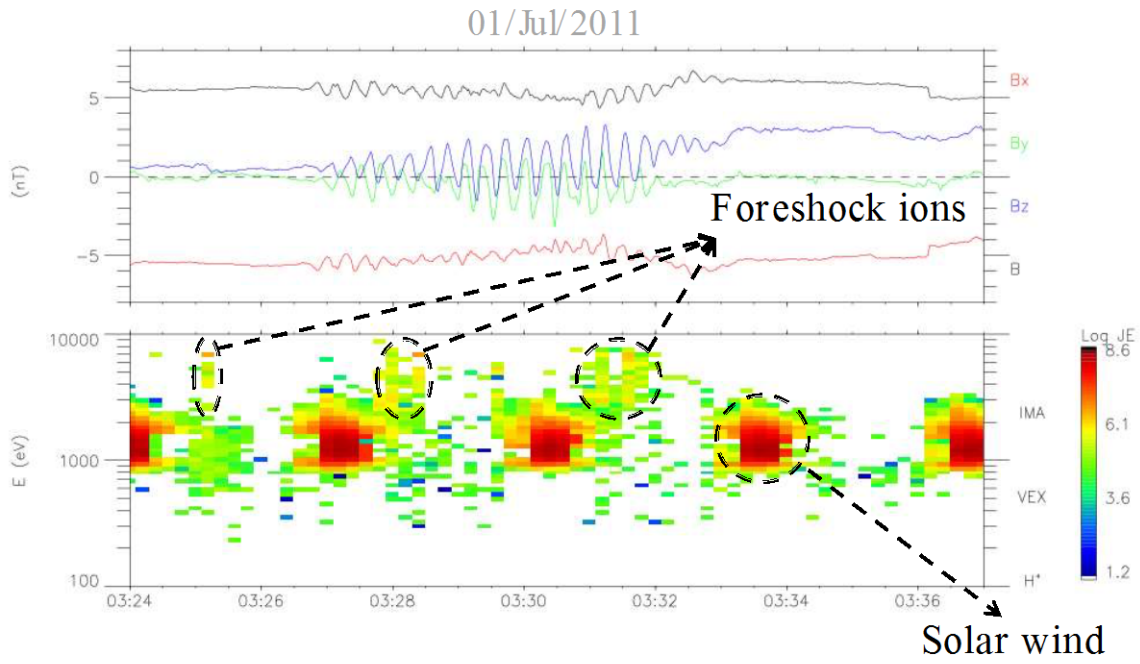
Coming from Venus-foreshock direction with $\theta_{Bn} > 45^o$

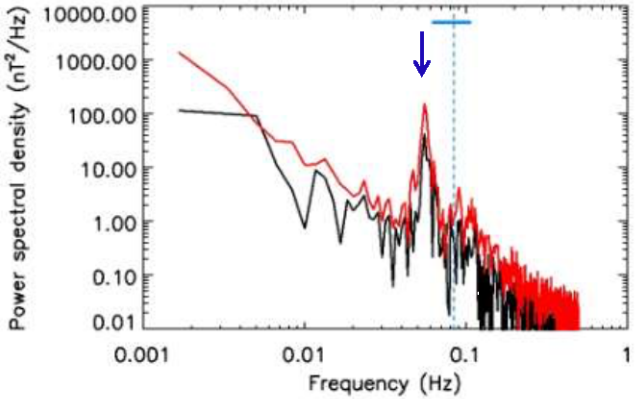
Power law spectrum → SDA rather than Fermi (exponential spectrum)

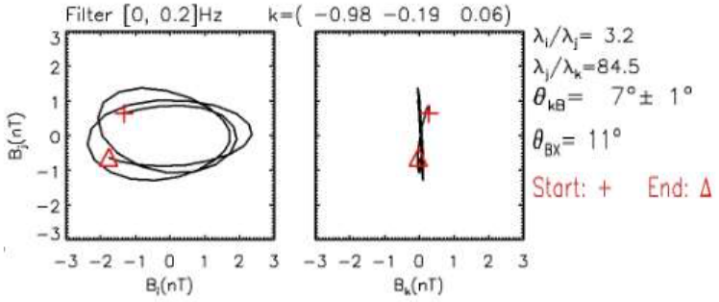
Pickup ions as only possible seed

Energetic ions must be ubiquitous?

Quasi-monochromatic ULF waves at Venus





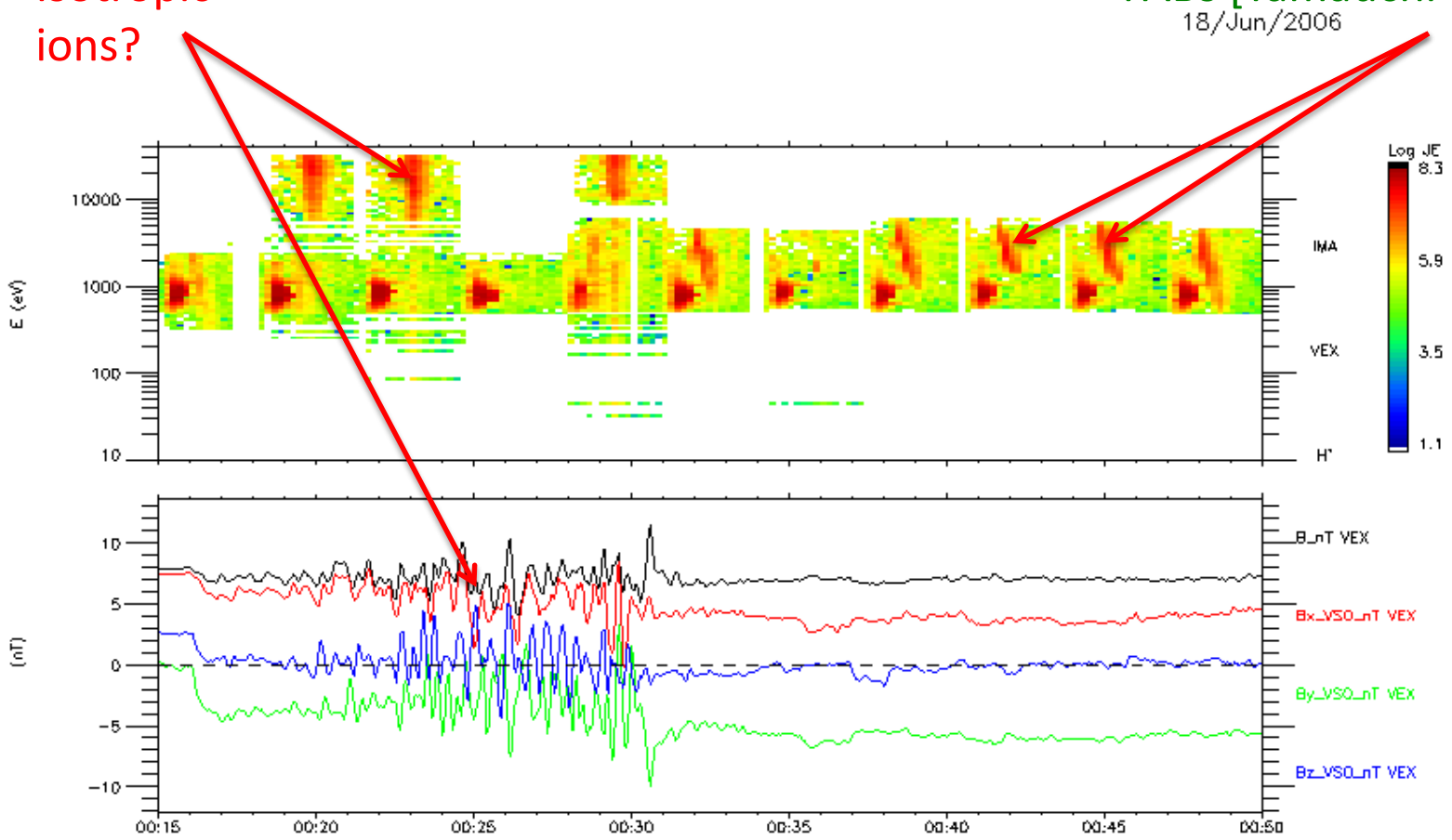


- The periods of the waves shown are 18.1± 1 s, while the local proton cyclotron periods is 12.1 s.
- The transverse part always dominates the power spectrum.
- Wave propagation direction is nearly along x_{VSO} (Venus-Sun line) and B.
- This waves present left-handed polarization with respect to background field.
- Backstreaming foreshock ions are associated with the waves.

Backstreaming Populations & ULF Waves

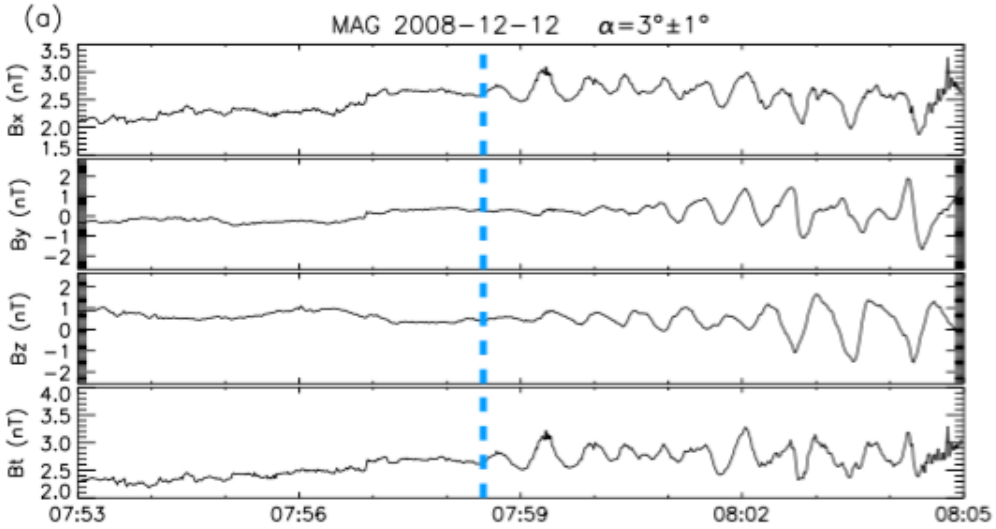
Isotropic ions?

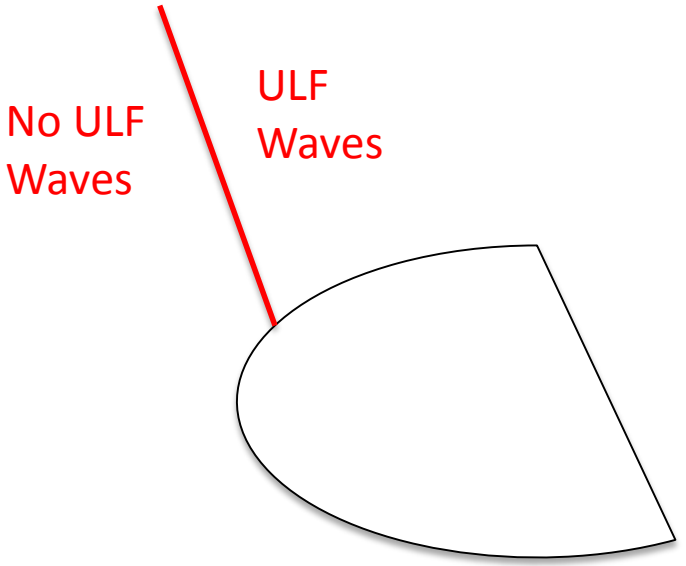
FABs [Yamauchi *et al.*, 2011]



Venus' similarity with Earth: The existence of the ULF wave foreshock boundary

[Lican *et al.*, 2018]

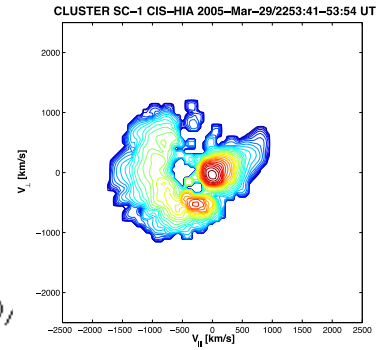




	IMF θ_{BX}	ULF-Wave boundary slope	Ion Vel. Along boundary (VSW)
Earth	**45°**	**78°**	**1.68**
Venus	**45°**	**77°**	**1.23**

Specularly reflected

Source of Field-Aligned Beams?



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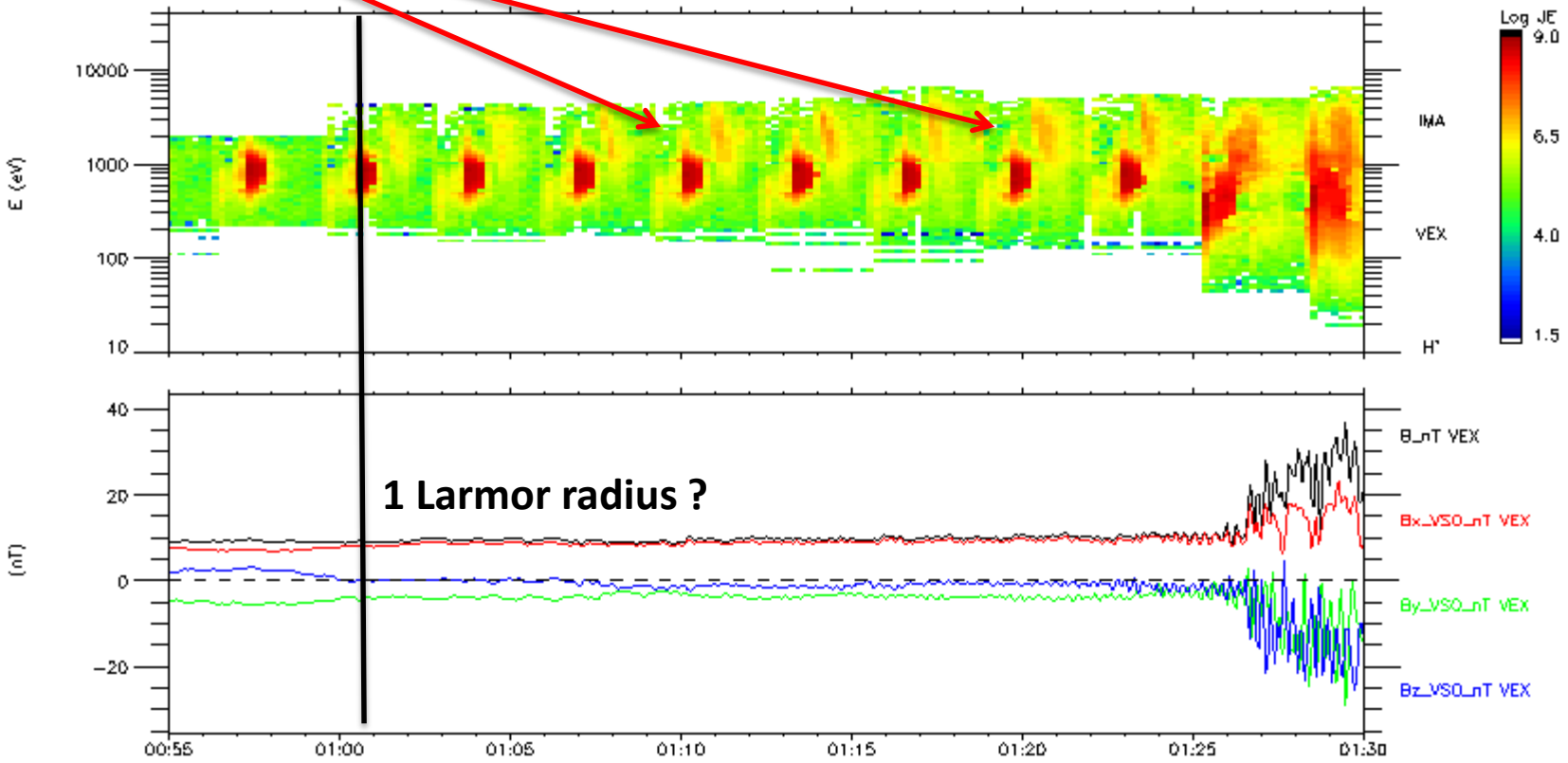
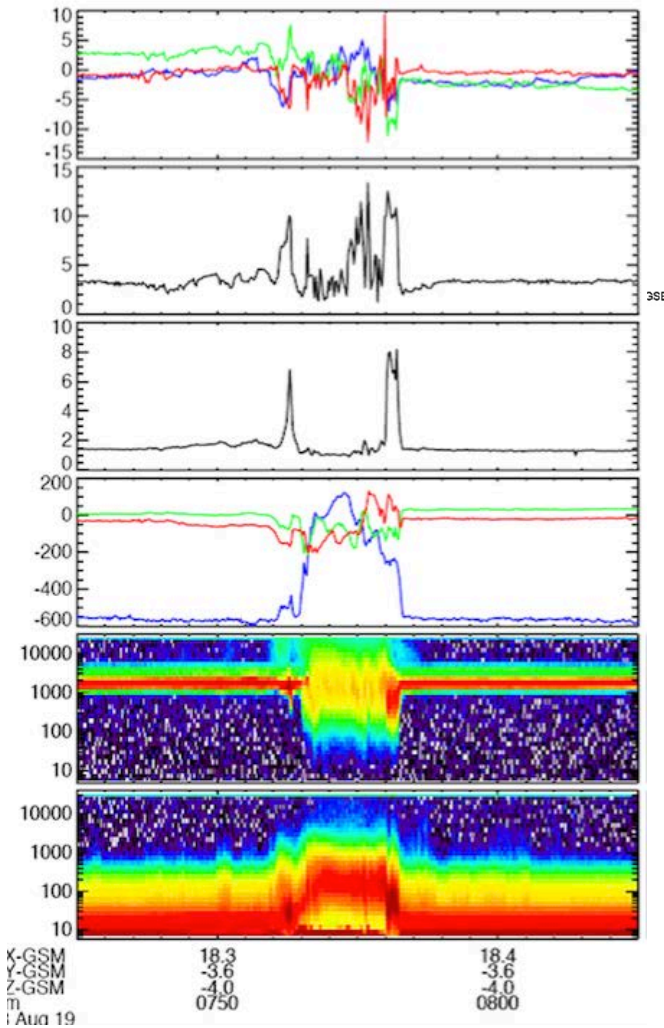


Produced by CLWeb

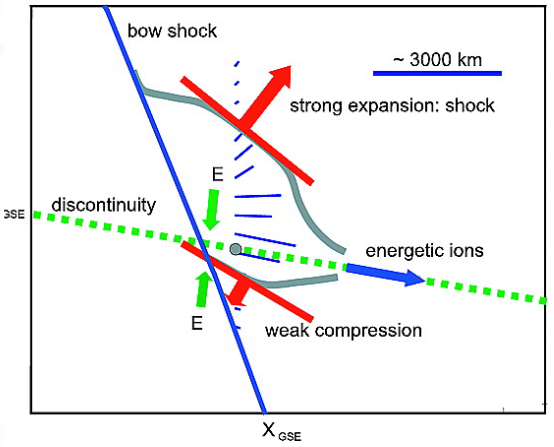
Venusian Foreshock

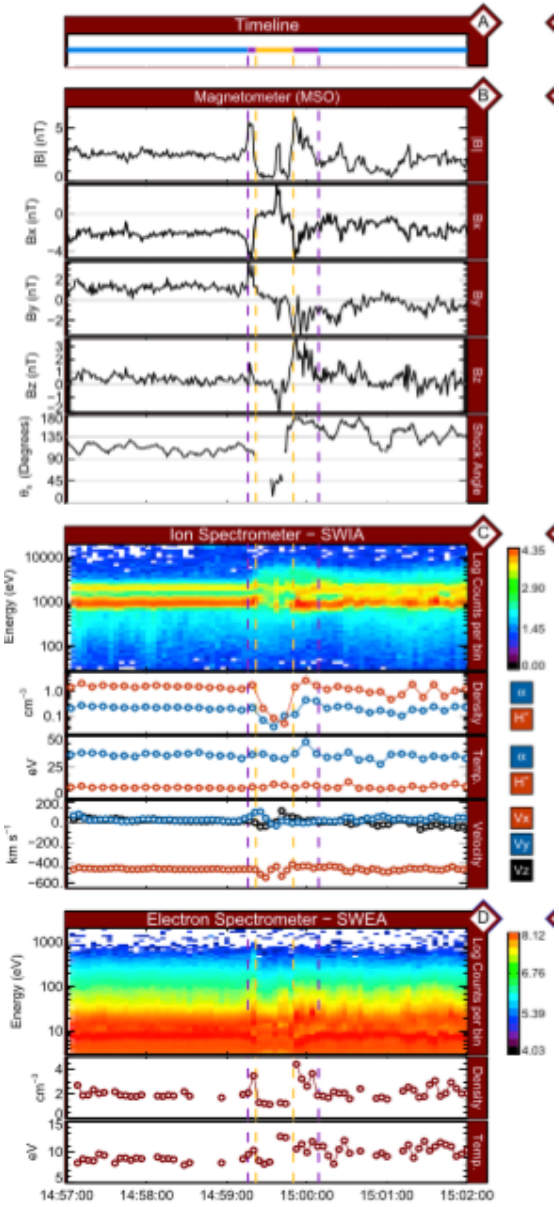
- Similarities
  - Electron foreshock
  - ULF Boundary
- Investigations, quantitative in nature remain to be addressed
  - Ion velocity & shock geometry
  - Associations with ULF waves
  - Populations assessment
- Pickup ions as an ubiquitous seed for coherent particle-shock interaction (SDA , Surfing)

FORESHOCK STRUCTURES



THEMIS





MAVEN

[Collinson *et al.*, 2015]