

# Observations sur les chocs: où en sommes-nous et vers où allons-nous?

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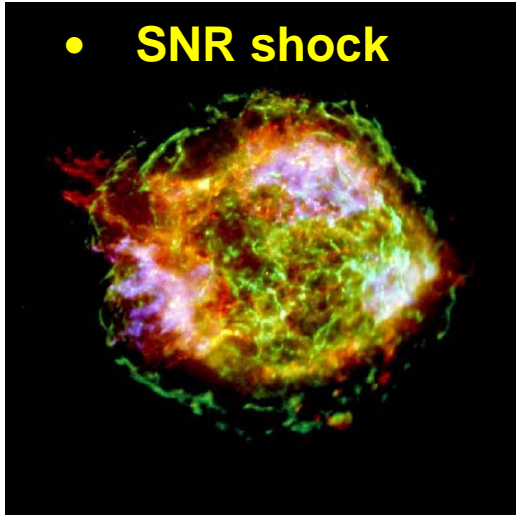
**Vladimir Krasnoselskikh**

LPC2E, Orléans

**Bertrand Lembège**

LATMOS, UVSQ, Guyancourt

# Astrophysique

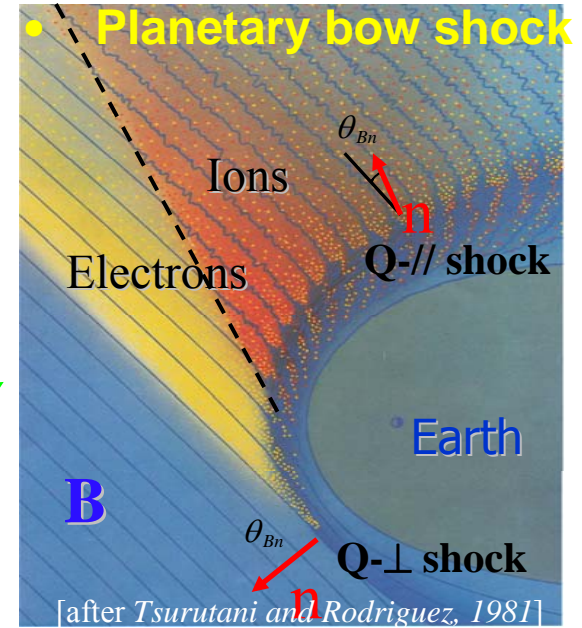


# Shocks

(*collisional* shocks).  
fluid shocks, etc.

(*collisionless* shocks).  
SNR shock ,  
interstellar bow shock,  
planetary bow shock,  
cometary bow shocks  
termination shock,  
CME-driven shock etc.

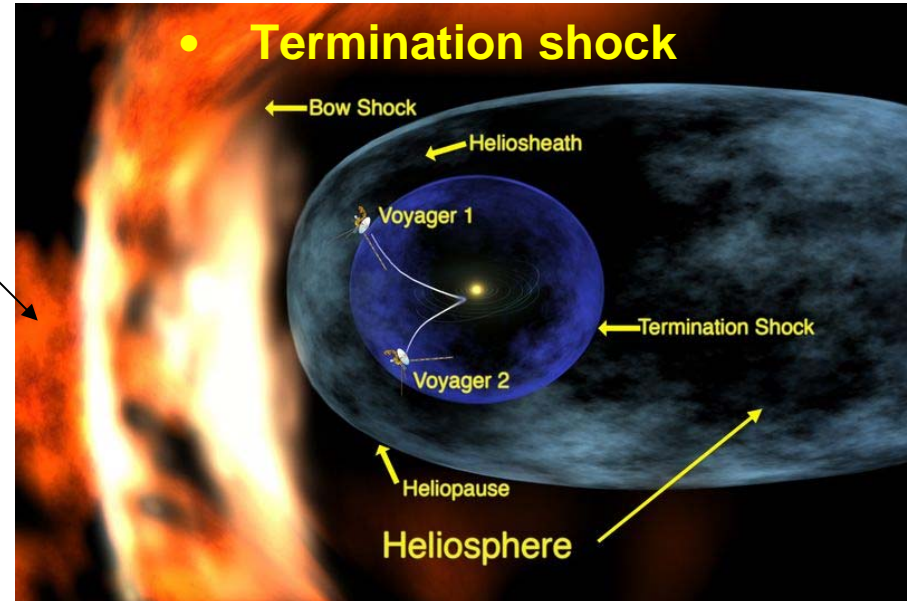
# Heliosphere



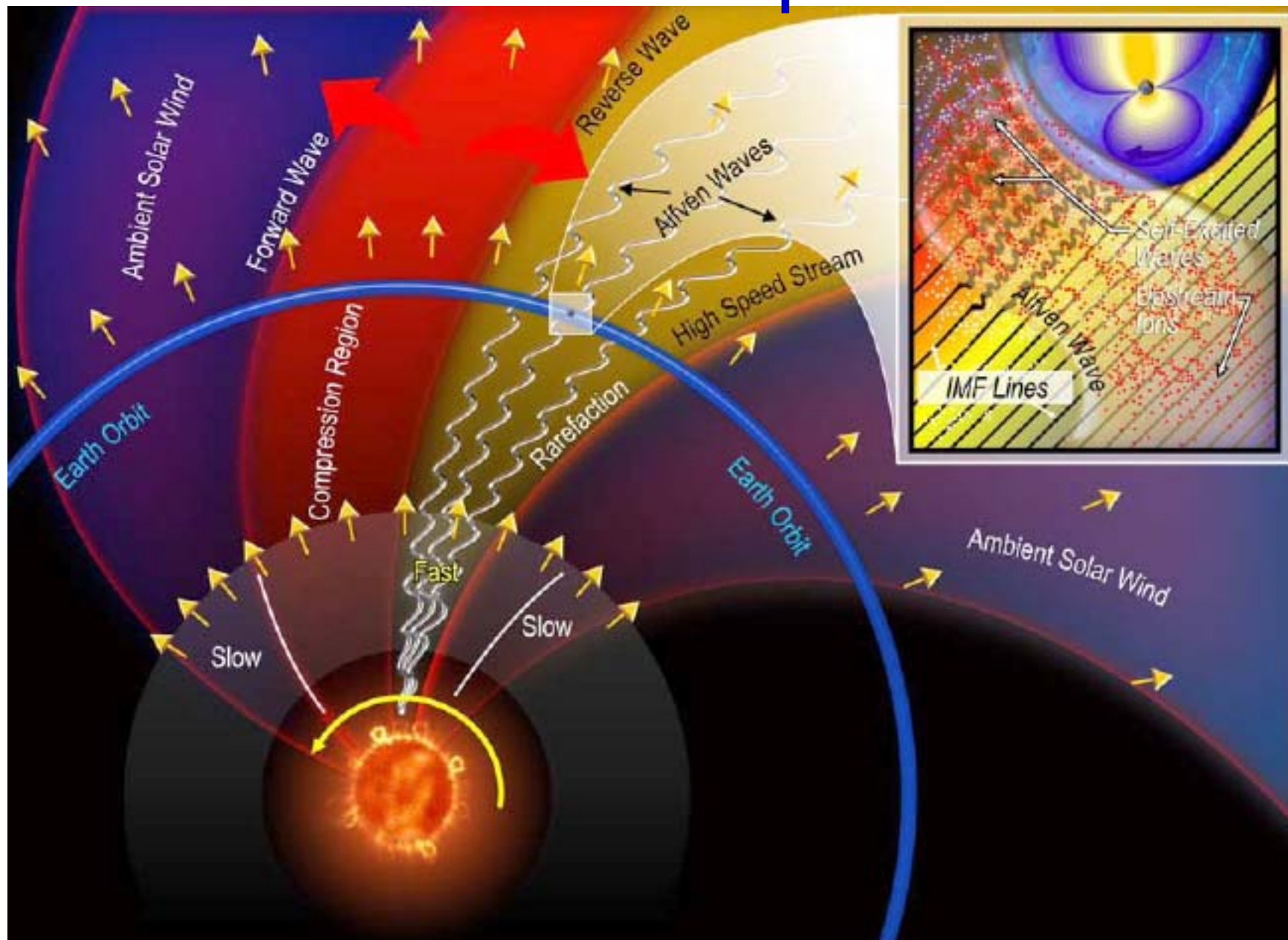
- Interstellar bow shock:
- about half a light-year across



LISM

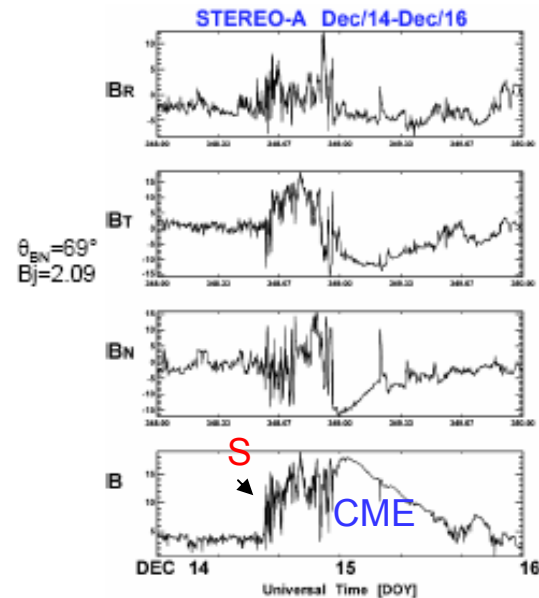
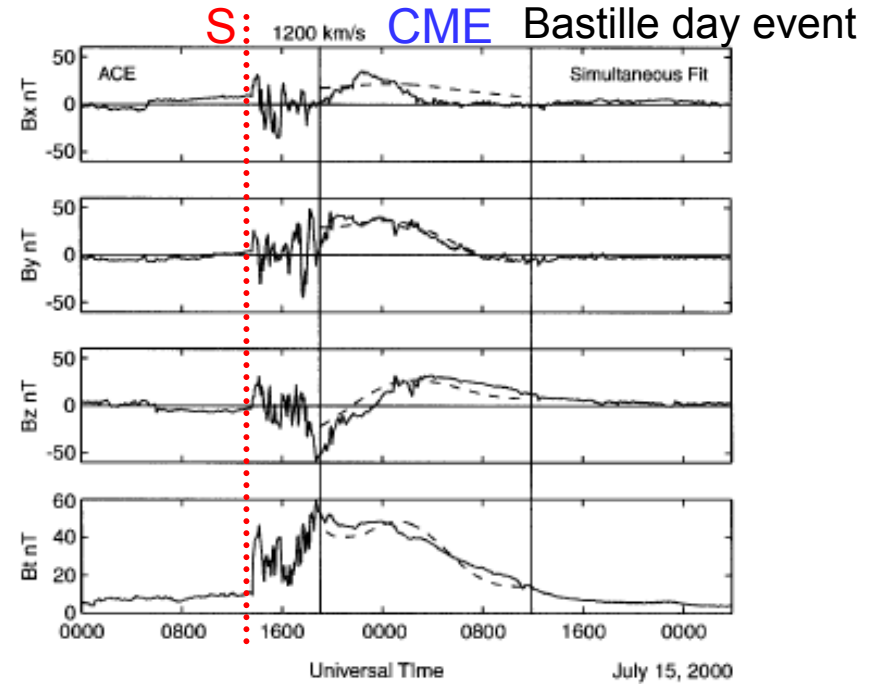
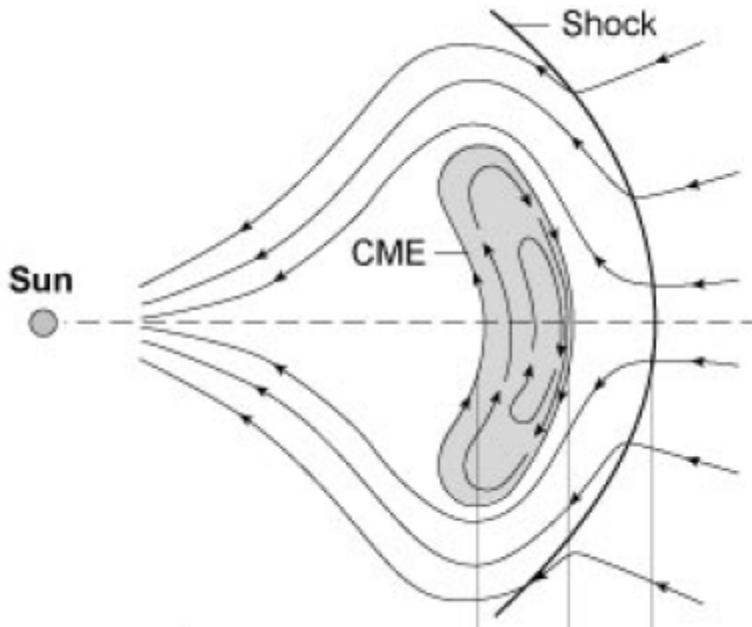


# Inner Heliosphere

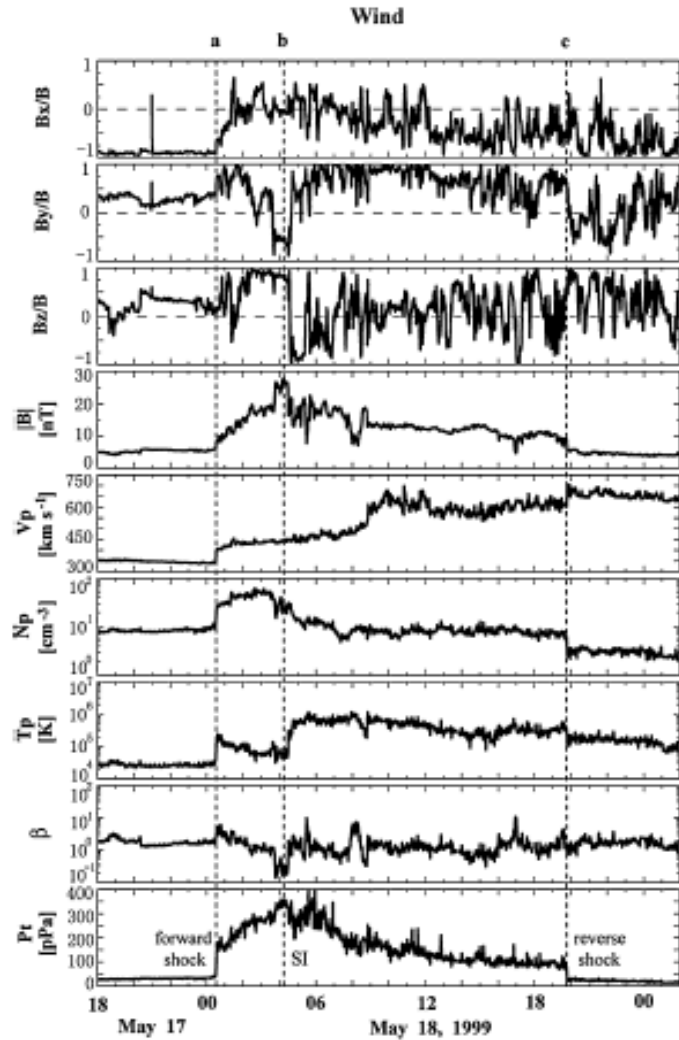


# Interplanetary shocks I

- Fast CMEs

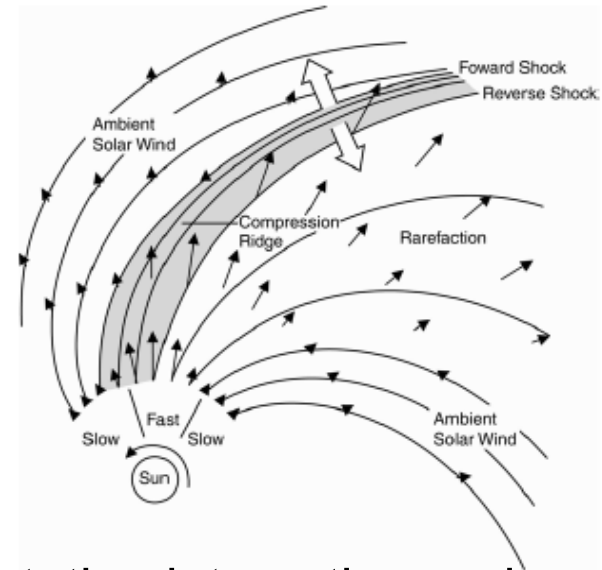


# Interplanetary shocks II



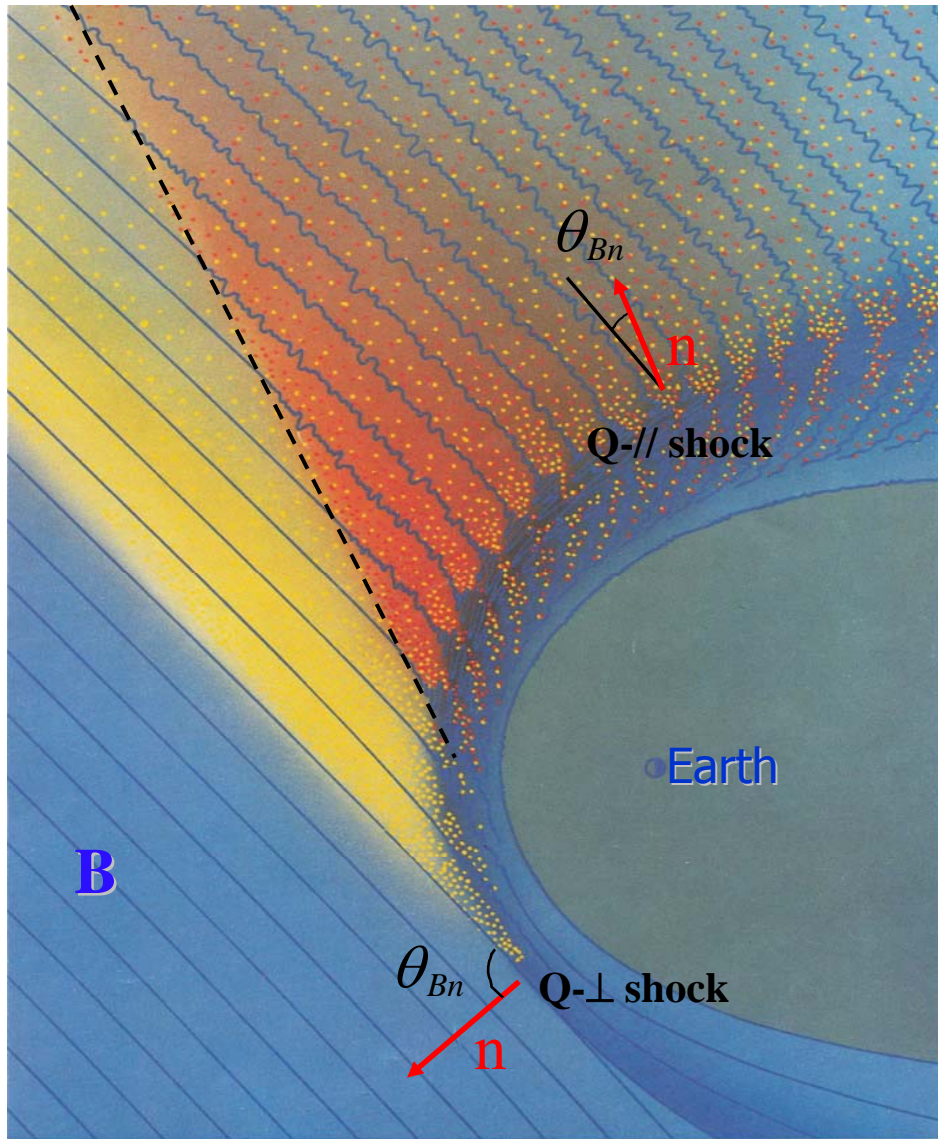
Universal Time  
Jian et al., 2006

- Fast/slow solar wind interactions

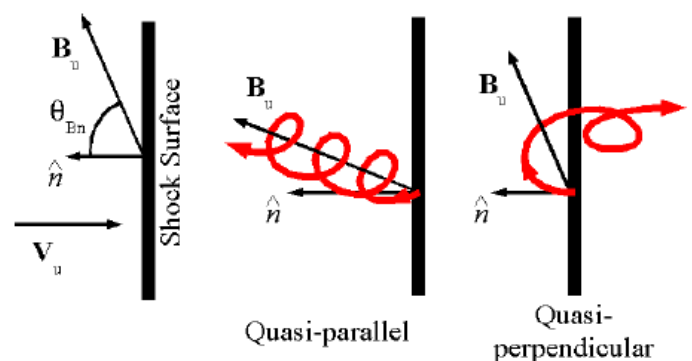
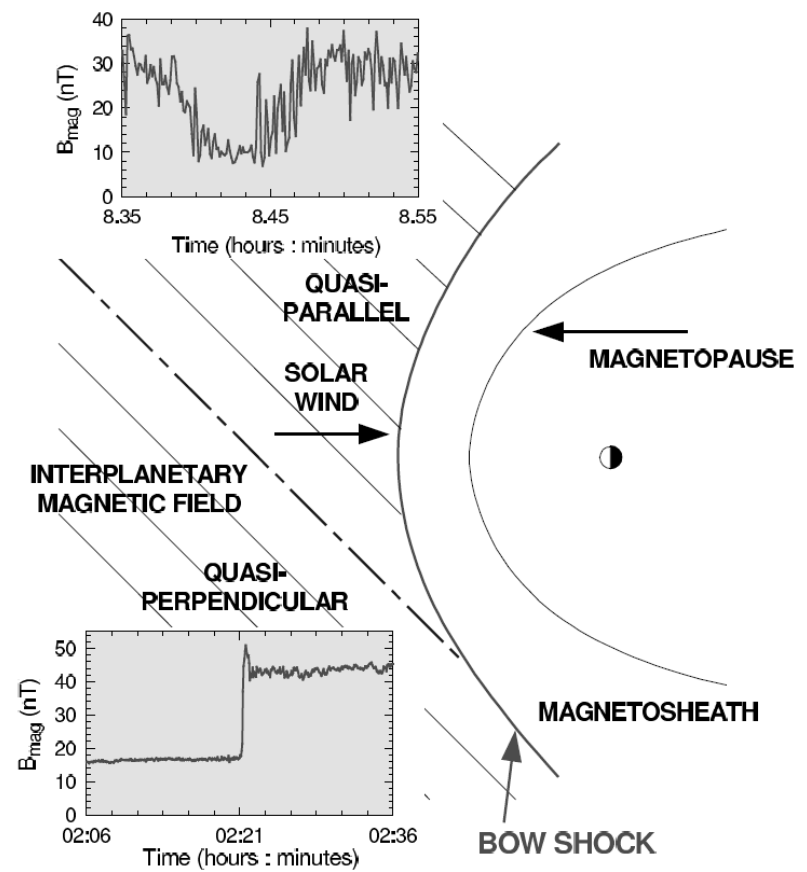


- Corrotating interaction regions (CIRs)
- Stream interaction regions (SIRs)
- Forward and Reverse shock

# Choc Planétaire et Pré-Choc



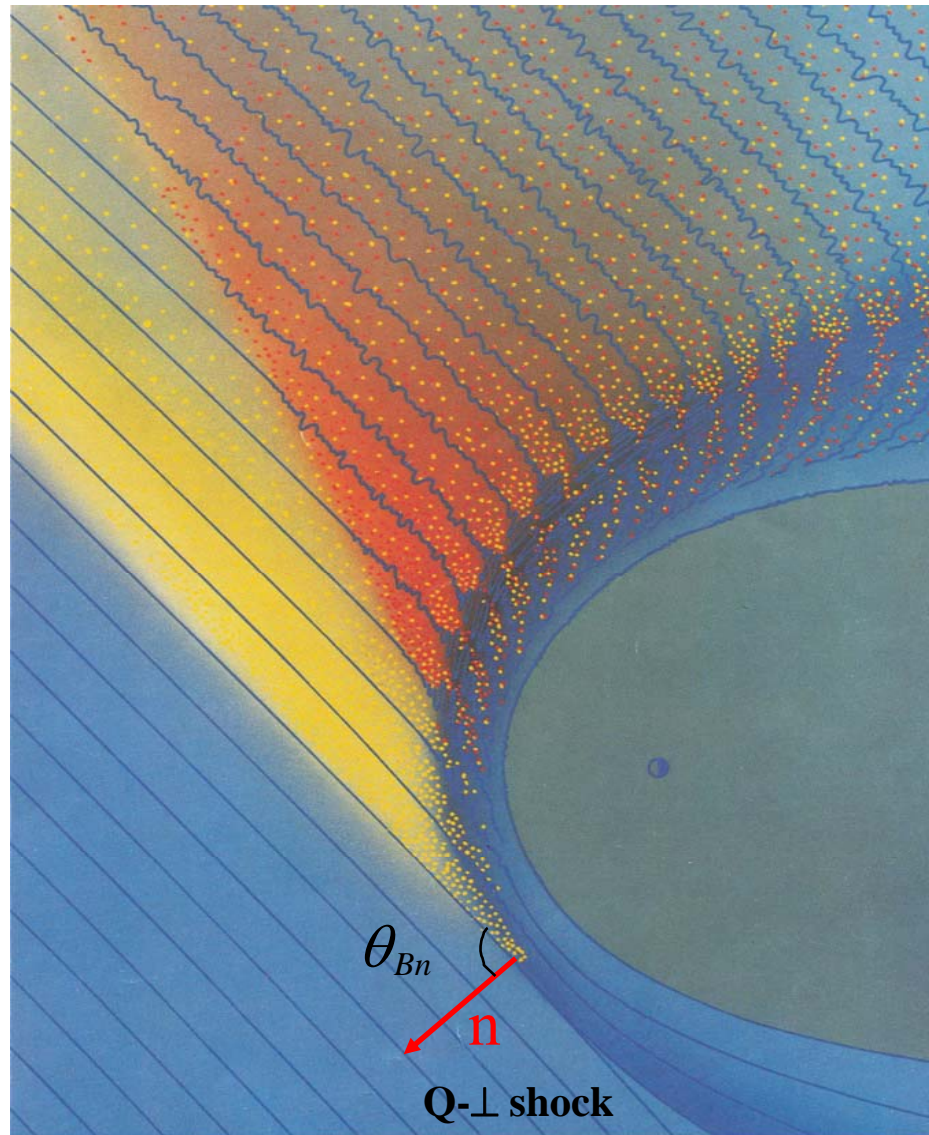
[après Tsurutani and Rodriguez, 1981]



# Apport de CLUSTER: Chocs et pré-chocs

- Possibilité pour la première fois de déterminer sans ambiguïté à la fois la normale au choc et sa vitesse de propagation locale:
  - Nouvelles méthodes d'analyse multi-sat. (analyse de timing). Amélioration de la précision. [e.g. travaux de T. Horbury].
  - Mise en évidence du mouvement à grande échelle du choc [Maksimovic *et al.*, 2003]. Influence des variations du vent solaire (pression dynamique et perturbations). Ondes de surface sur le front [Moullard *et al.*, 2006].
  - **Possibilité d'étude des échelles du choc**: fondamental pour étudier la dynamique intrinsèque du choc (**non stationnarité**) et la **dissipation**.
  - Analyse des normales d'ondes et des vitesses de phase sans ambiguïté (en particulier ondes ULF dans le pré-choc).
  
- Instrumentation plus performante (exemple: précision angulaire des spectromètres d'ions,...):
  - Analyse détaillées des distributions 3D des ions.
  - possibilité d'étude de microphysique (dans le pré-choc surtout): interaction ondes-particules. Résonance cyclotron. Piègeage dynamique.

# Choc Q-perp





# Study of Quasi-perpendicular Shock

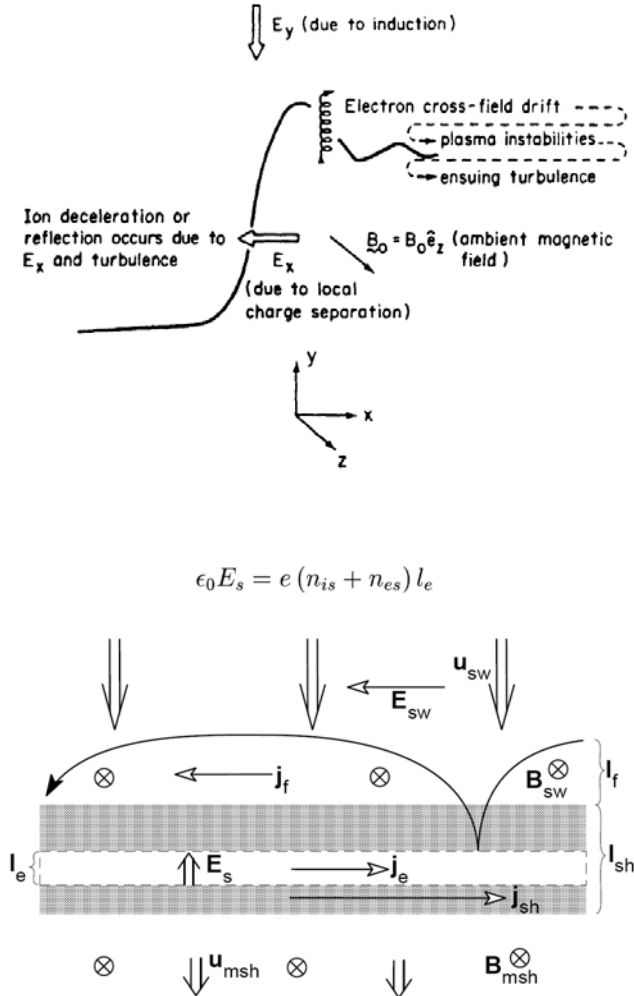
The spatial scales over which the shock dissipates energy, and slows the incoming flow, are thought to be related to the nature of the dissipation mechanism itself. Hence, knowing these scales and their dependence on macroscopic plasma parameters is tantamount to knowing the dissipation physics at the shock. Quasiperpendicular shocks have been traditionally targeted for dissipation scale studies, including aspects such as:

1. the role/interpretation of competing dissipation mechanisms within more classical frameworks (anomalous resistivity, viscosity, Hall physics);
2. differing scales for the transition of different bulk parameters (magnetic field, density, velocity);
3. Ohm's law, including contributions from electron inertia and departures from isotropy;
4. the role of stationary (DC) fields in the dissipation processes (electron kinetics, ion reflection);
5. the role of non-stationary fields in scattering and shaping the particle distributions at, and downstream of, the main shock transition;
6. the competition between dissipation and dispersion in effecting and limiting the steepening of the shock profile.

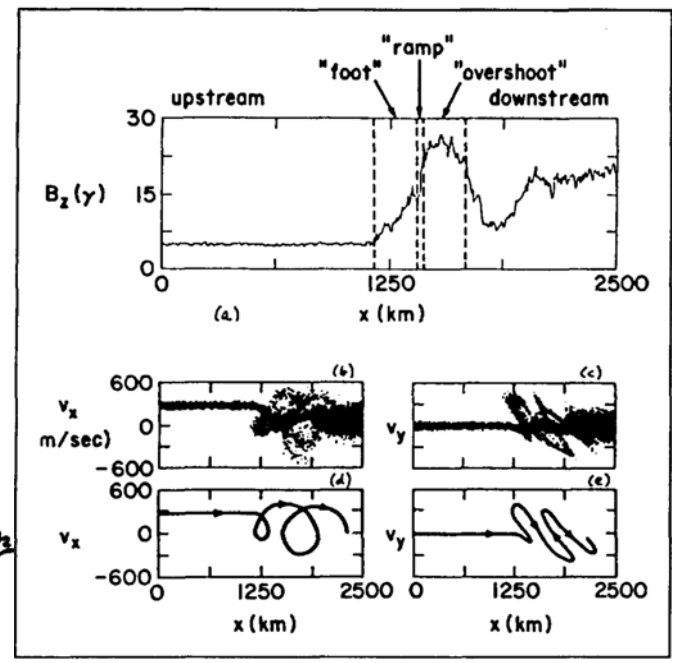
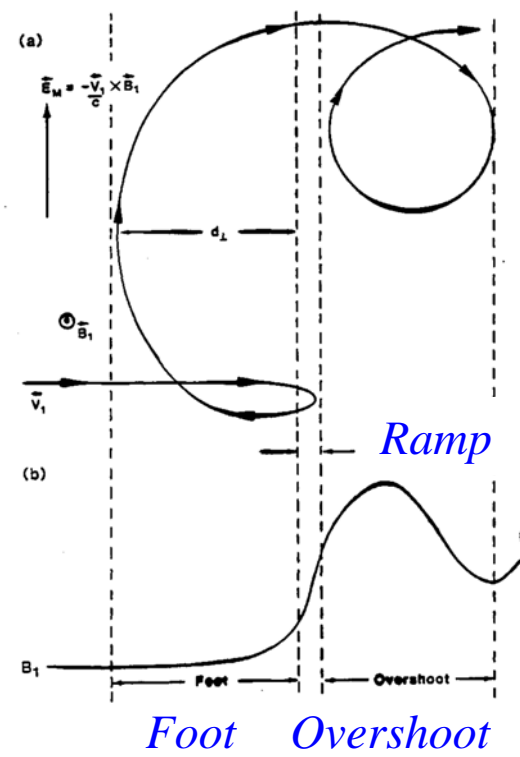
# Physical characteristics of supercritical quasi-perpendicular shock

Above a critical value of  $M_{Ar}$  dispersion as well as "resistive anomalous" dissipation are not sufficient to balance steepening: other dissipation process by reflected ions mandatory

→ characteristics substructures:

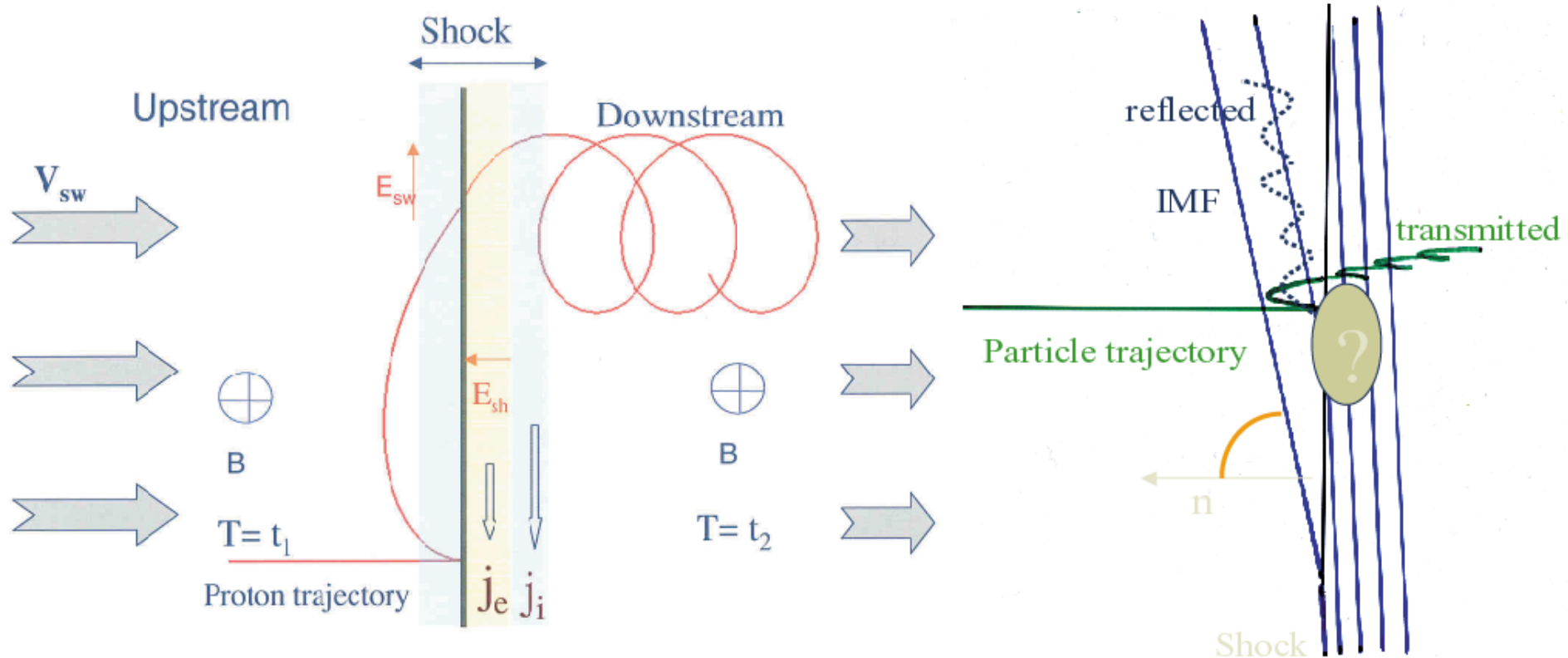


reflected gyrating ion



[Leroy, 1981]

# Transmitted and reflected ions

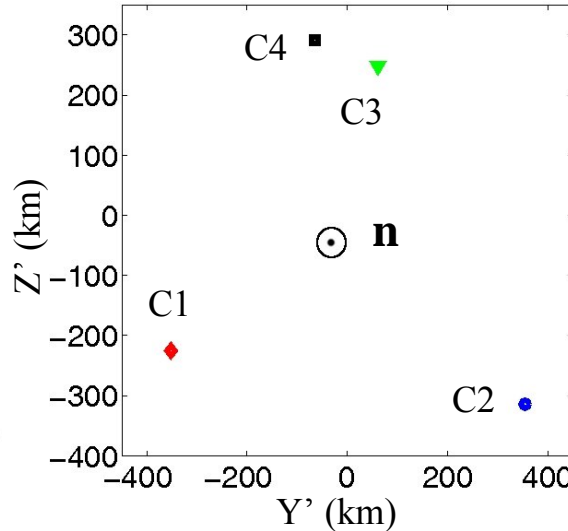
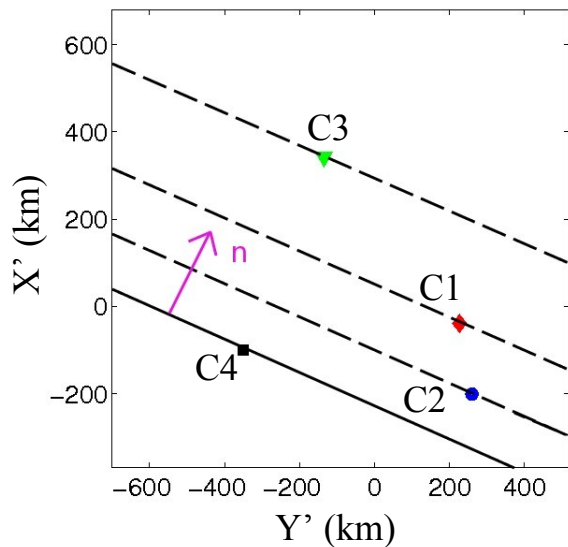


- The different motion of the ions and electrons create a cross shock potential.
- This potential is oriented along the shock normal direction.

# Echelles et non stationarité: Cluster

$$\theta_{Bn} = 89^\circ \pm 2^\circ$$

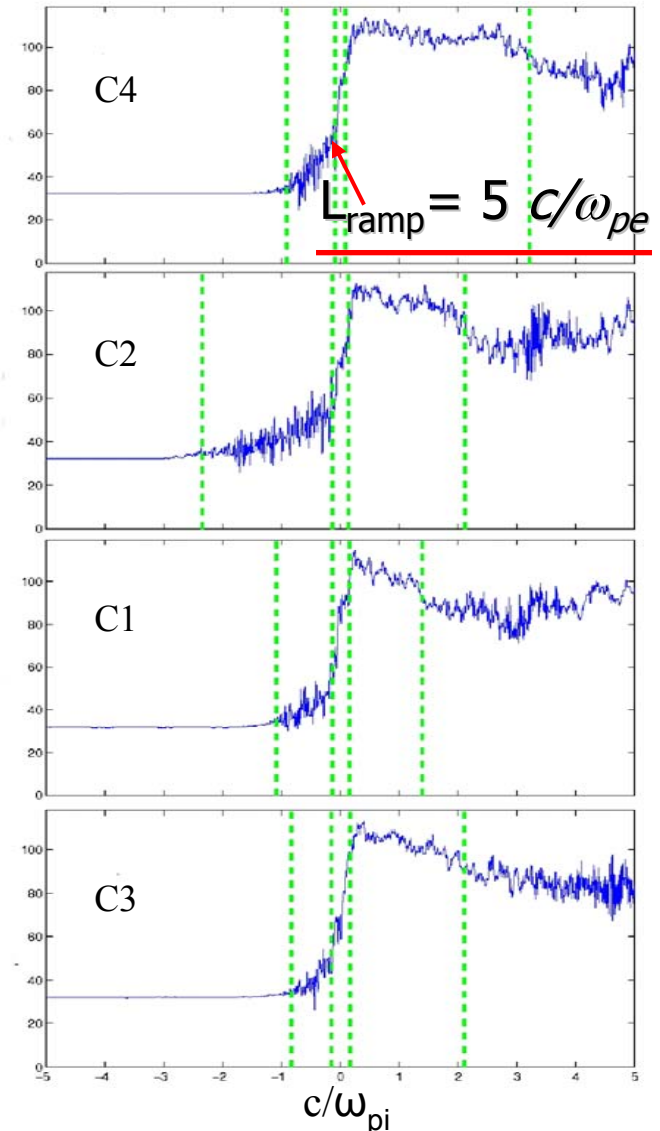
$$M_A = 4.1 \quad \beta_i = 0.05$$



Positions des 4 sat. dans les plans ( $X_{GSE}, \mathbf{n}$ ) et perp. à  $\mathbf{n}$  au temps de référence (milieu rampe du sat. 4)

- **Rampes très étroites:** qqes longueurs inertielles des **electrons (pas à l'échelle ionique)**
  - Variabilité des épaisseurs du pied ionique, de la rampe et de la survalueur (overshoot)
- évidence de la non stationarité du choc et apparait en accord avec l'**auto-reformation**

|B|



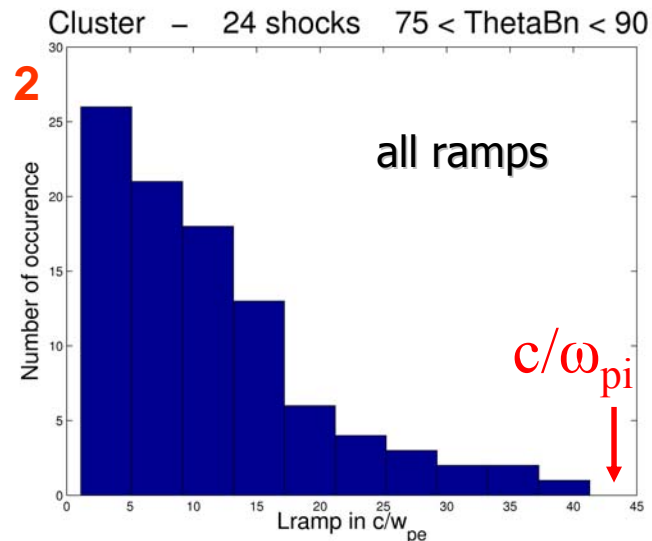
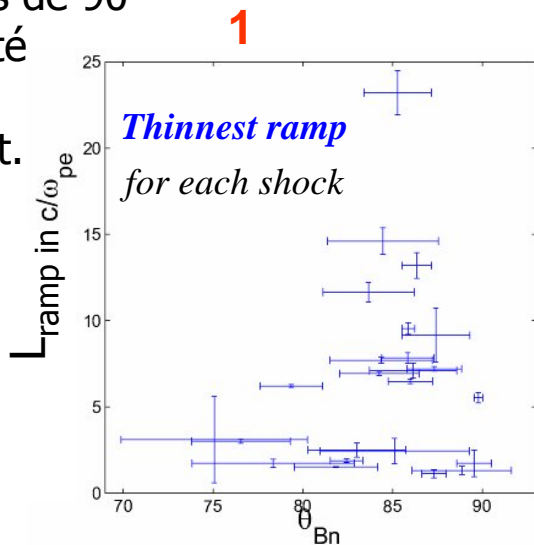
Séquence de l'ordre des traversées

[Mazelle et al., 2009]

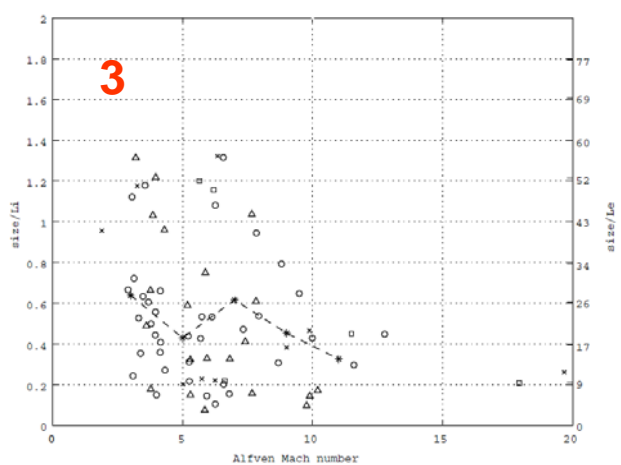
# Echelles du choc Q-perp: statistiques

magnetic ramps: [Mazelle *et al.*, 2010]

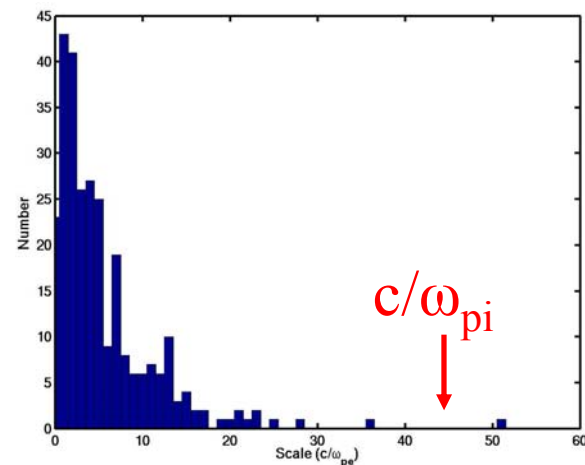
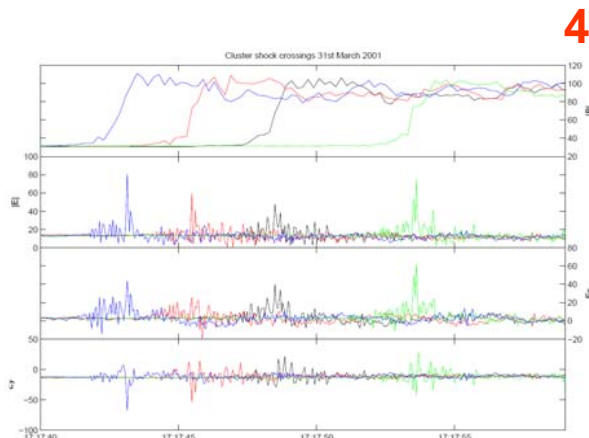
1. Rampes tendent à décroître près de 90°
2. PDF des rampes: forte probabilité de rencontrer des rampes fines. Echelle ionique comme majorant.
3. Largeurs tendent à décroître avec le nombre de Mach.
4. Statistique d'échelle très similaire pour les « spikes » de champ électrique au niveau des rampes magnétiques mais échelles plus fines: *compatible avec sous-structures de la rampe?*



E-field spikes: [Walker *et al.*, 2004]



[Hobara *et al.*, 2010]

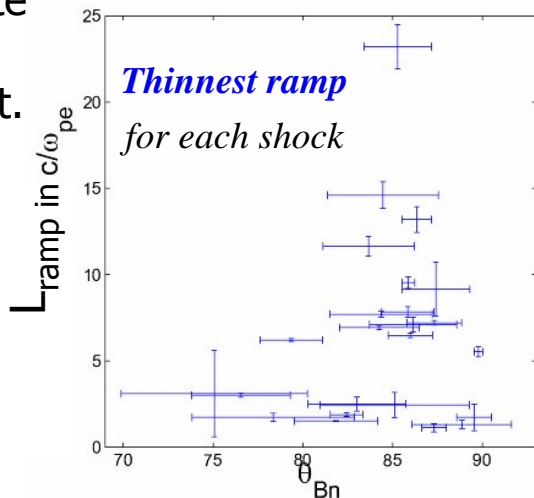


*Contribution au saut de potentiel du choc?*

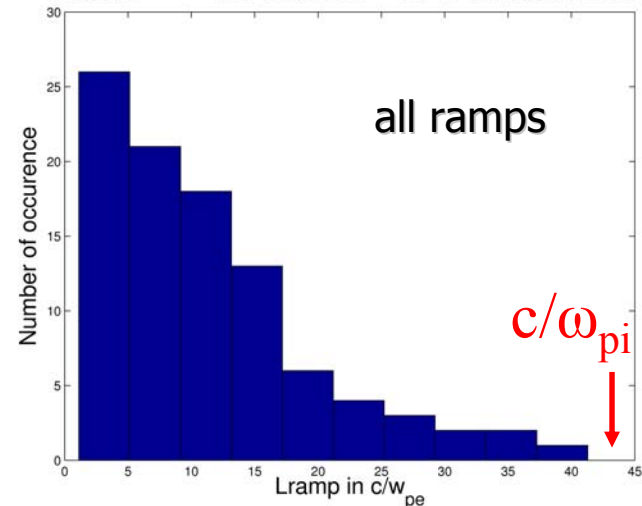
# Echelles du choc Q-perp: statistiques

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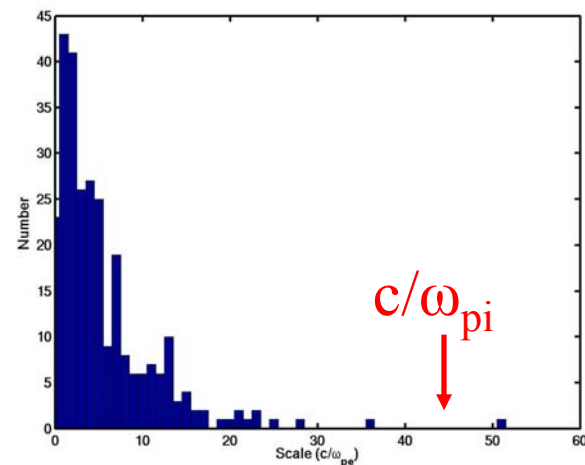
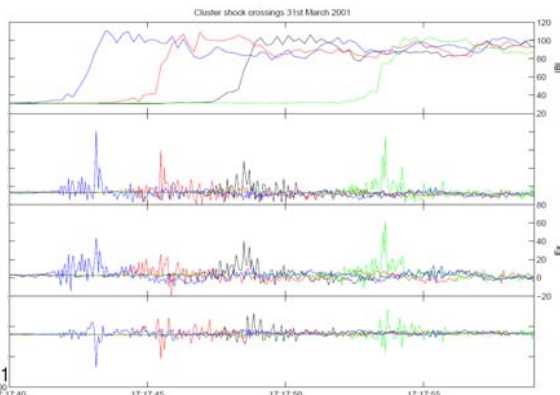
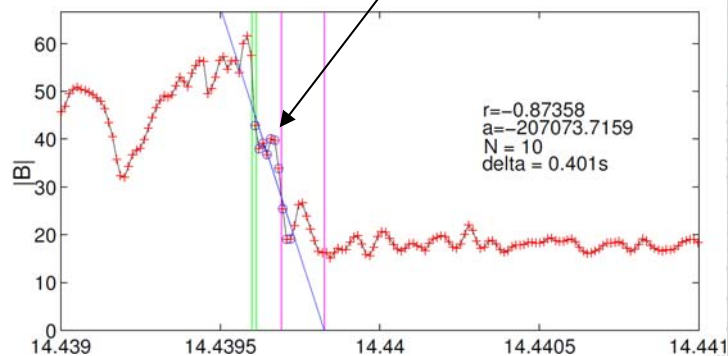
magnetic ramps: [Mazelle *et al.*, 2010]



Cluster - 24 shocks  $75 < \theta_{Bn} < 90$



E-field spikes: [Walker *et al.*, 2004]



*Contribution au saut de potentiel du choc?*

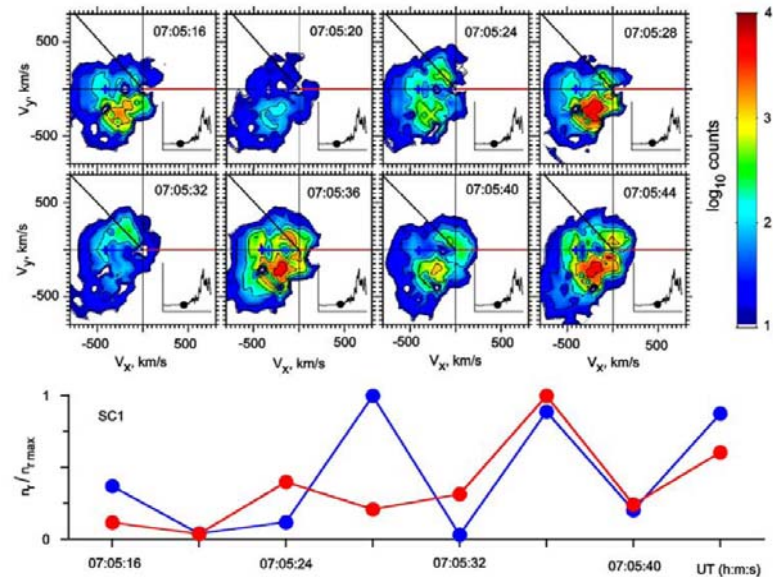
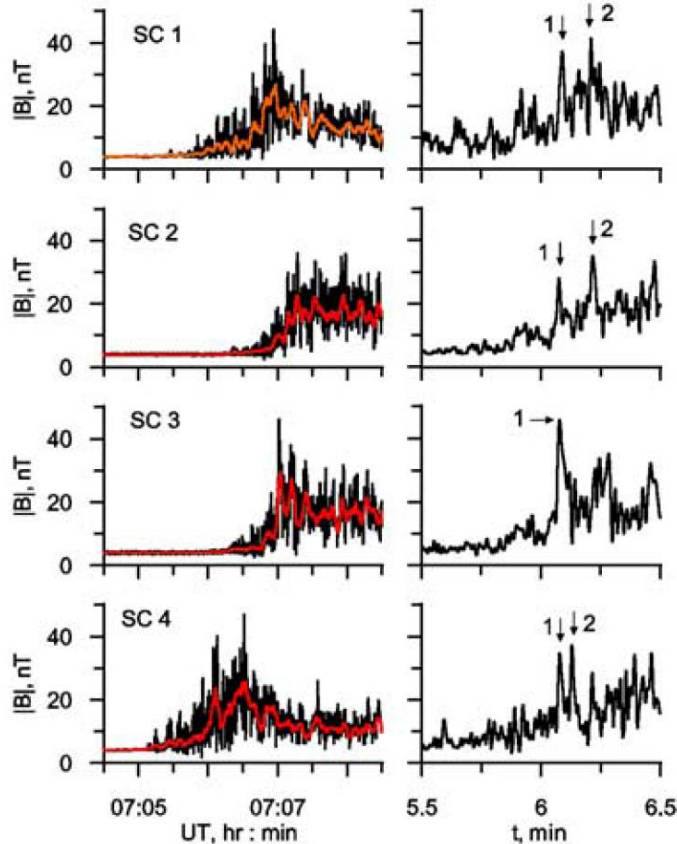
# Shock nonstationarity with Cluster

one case study: highly supercritical Q-perp shock

[Lobzin *et al.*, GRL, 2007]

$$\theta_{Bn} = 81^\circ \quad M_A = 10 \quad \beta_i = 0.6$$

Variability of the shock front with embedded nonlinear whistler wave trains and "bursty" quasi-periodic production of reflected ions proposed as experimental evidence of non stationarity and self-reformation as described in Krasnoselskikh *et al.* [2002]



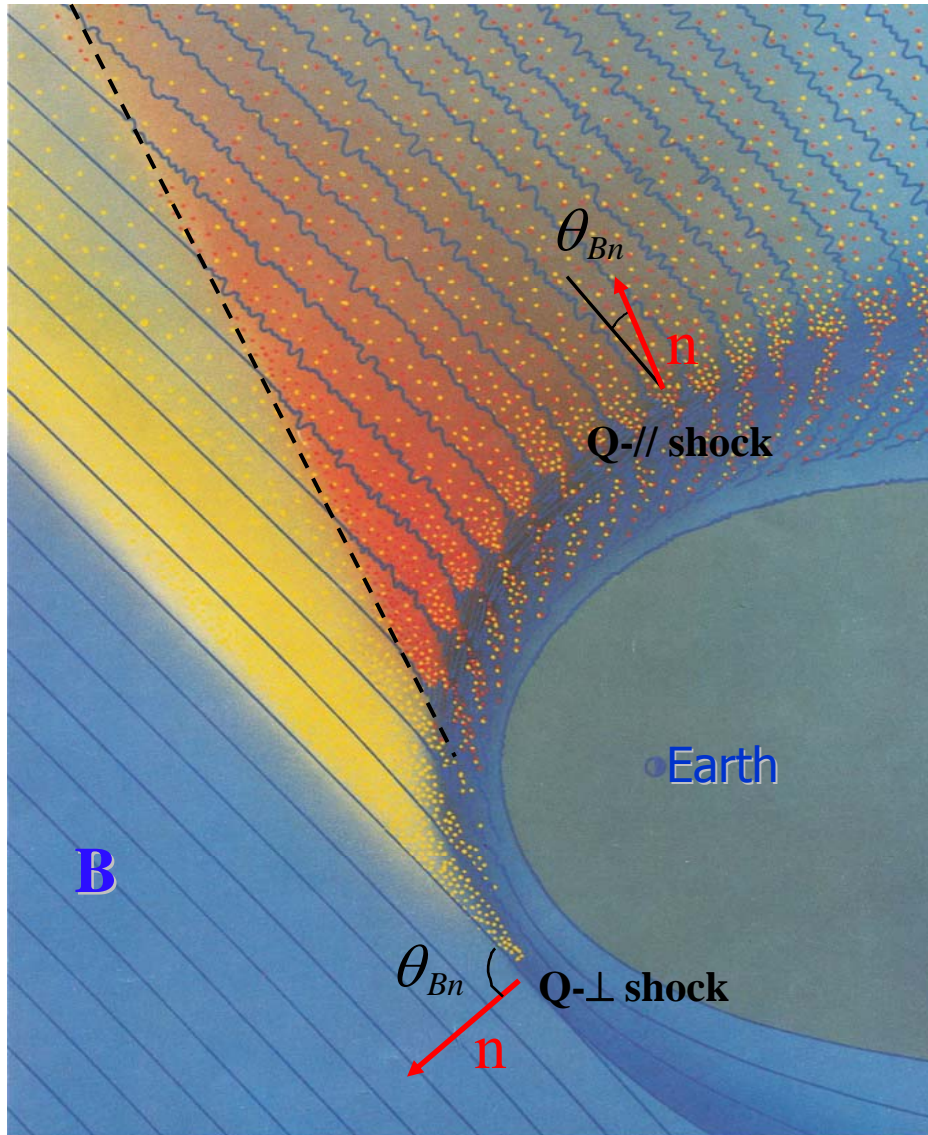
# Questions ouvertes sur chocs Q-perp

- Comment les différentes échelles du choc (ioniques et électroniques) sont-elles couplées?
- A quelle(s) échelle(s) la dissipation est-elle la plus efficace? (ionique et/ou électronique?)
- Quel(s) mécanismes de non stationnarité le plus en accord avec les observations?
- Quels effets de la non stationnarité sur l'accélération des particules au niveau du choc?
- Pb de l'injection. Quel mécanisme pour créer la population énergétique (« seed ») nécessaire pour que puissent opérer les mécanismes d'accélération comme Shock Drift Acceleration et Shock Surfing Acceleration (comment maintenir les particules suffisamment longtemps au voisinage du choc)?



# Choc oblique et pré-choc ionique

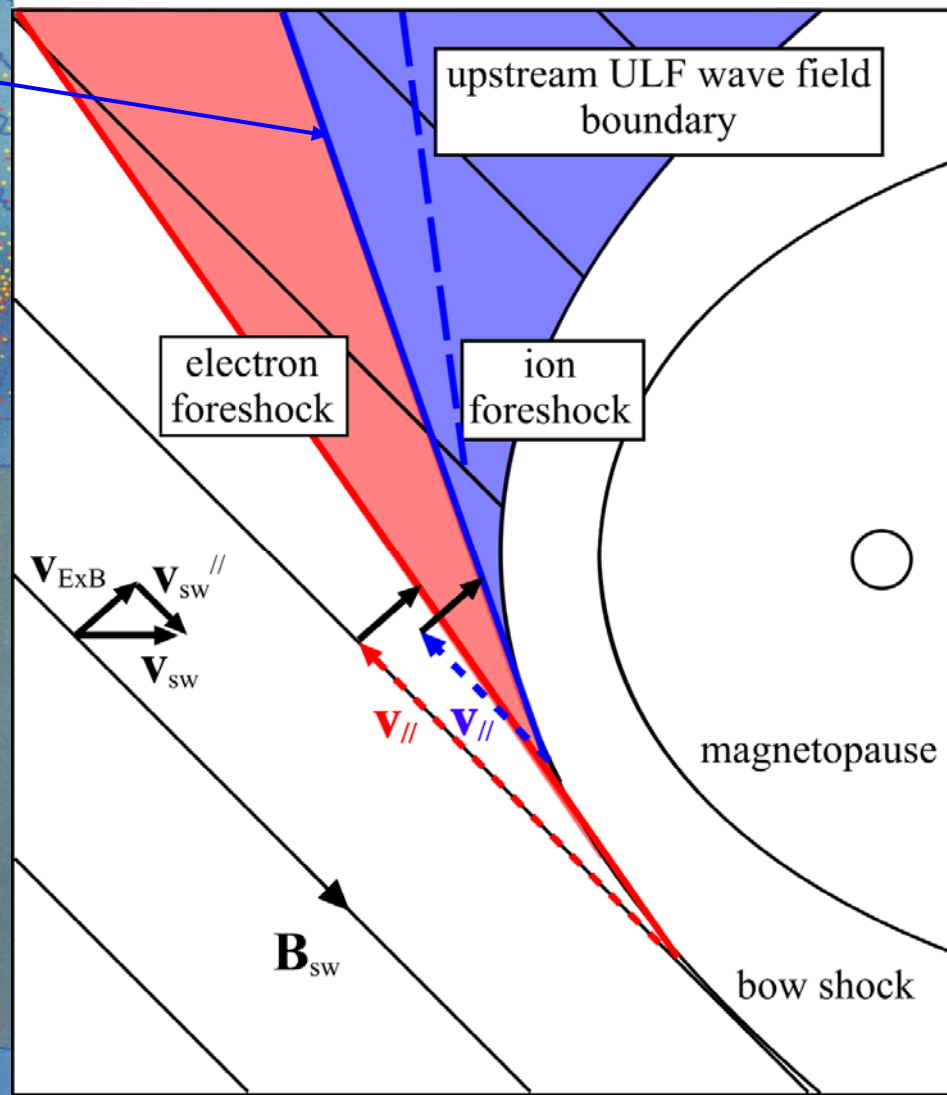
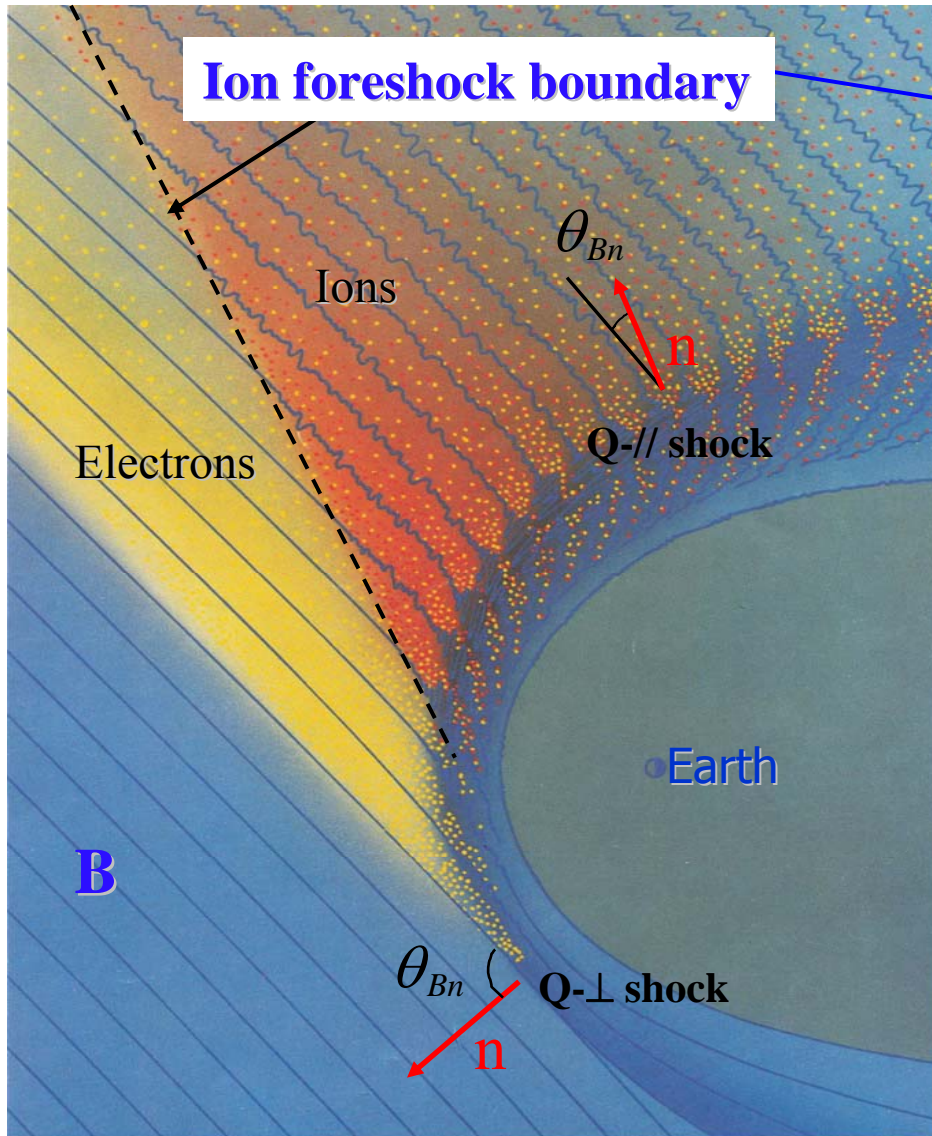
# Planetary Foreshock



The Earth's foreshock is the region upstream from the bow shock where the interplanetary magnetic field intersects the bow shock. It is characterized by backstreaming electrons and ions, as well as associated electrostatic and electromagnetic waves over a wide frequency range.

[after Tsurutani and Rodriguez, 1981]

# Planetary Foreshock Structure

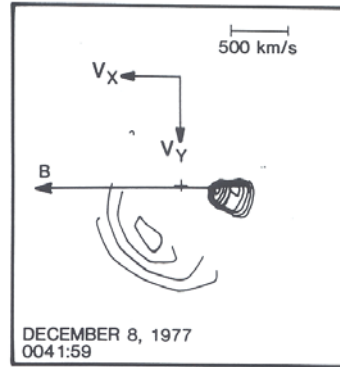


[after Tsurutani and Rodriguez, 1981]

$$\mathbf{v}_{ExB} = \mathbf{ExB}/B^2$$

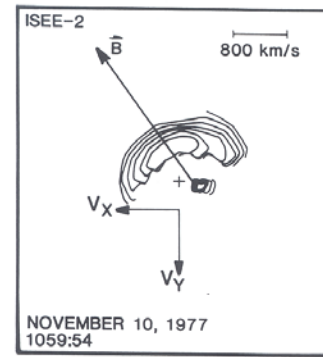
# « Zoology » of foreshock ion distributions

## Gyrophase-bunched



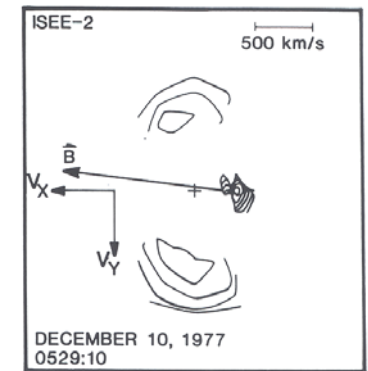
Quasi-perpendicular

## Intermediate distribution

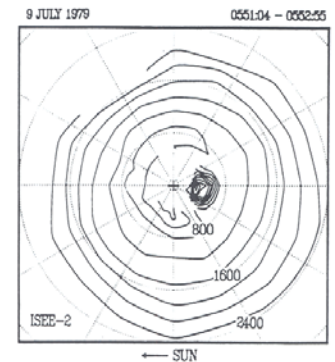


Quasi-parallel

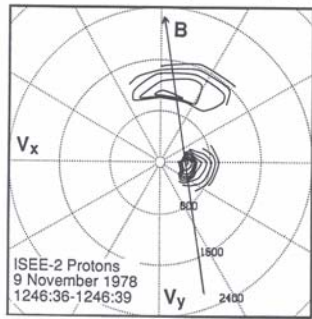
## Gyrotropic distribution



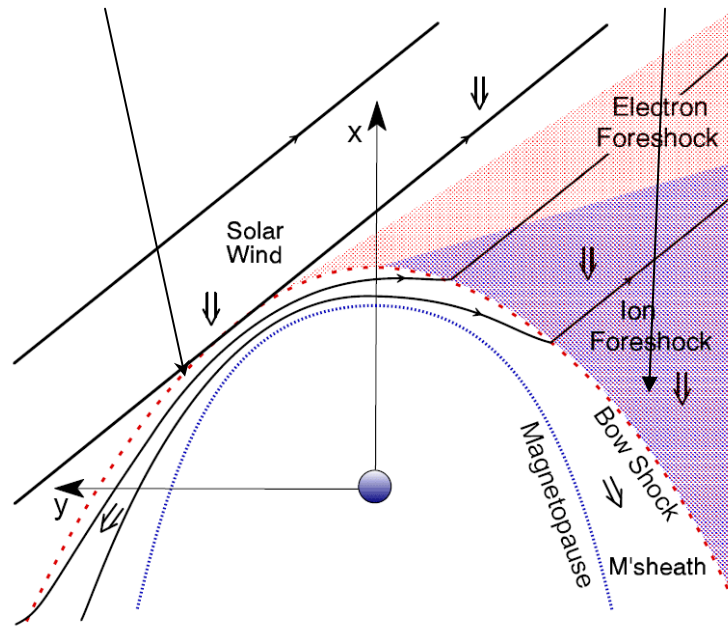
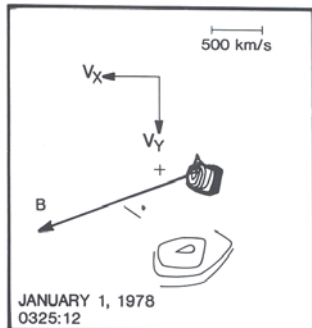
## diffuse distribution



## Field-aligned beam



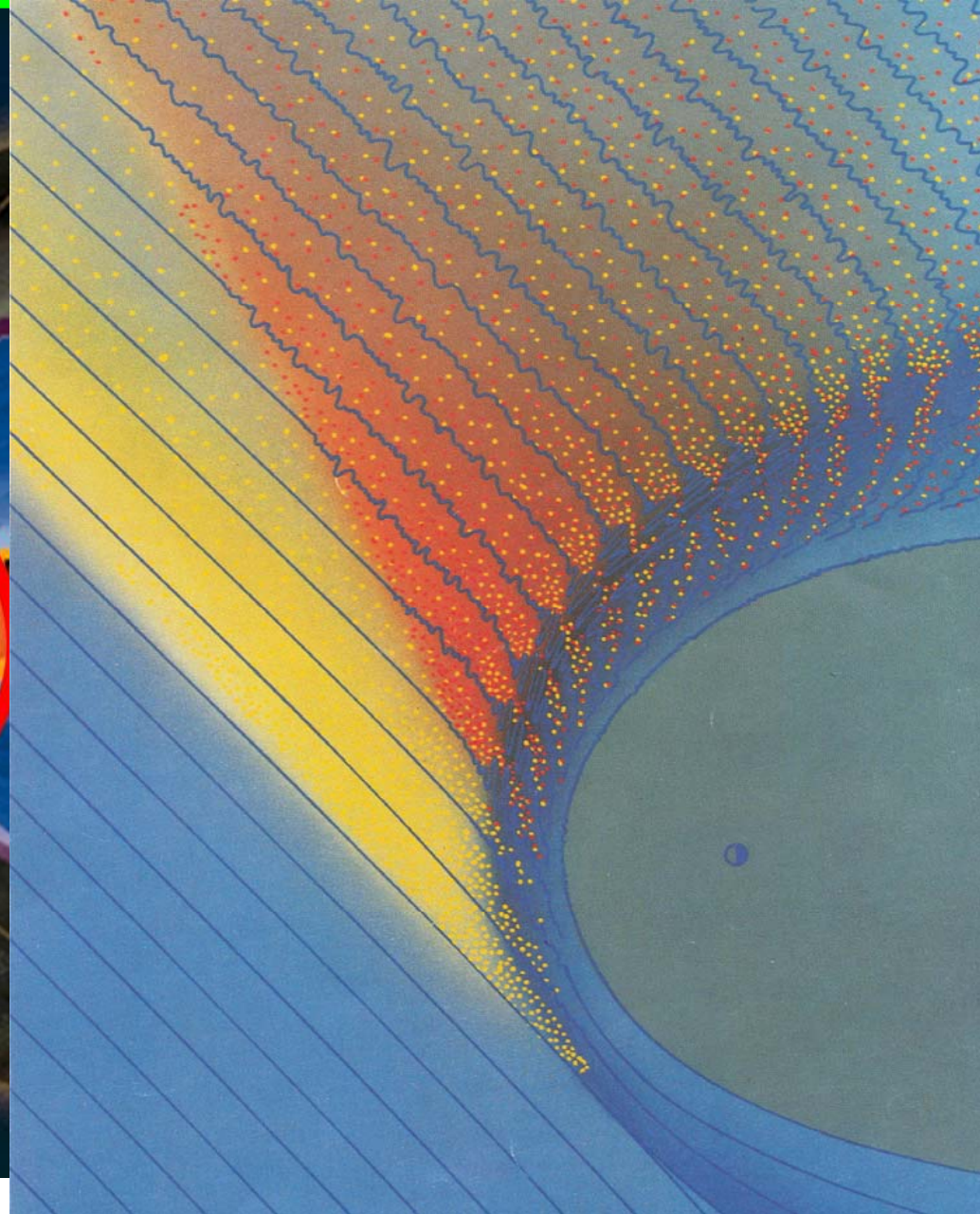
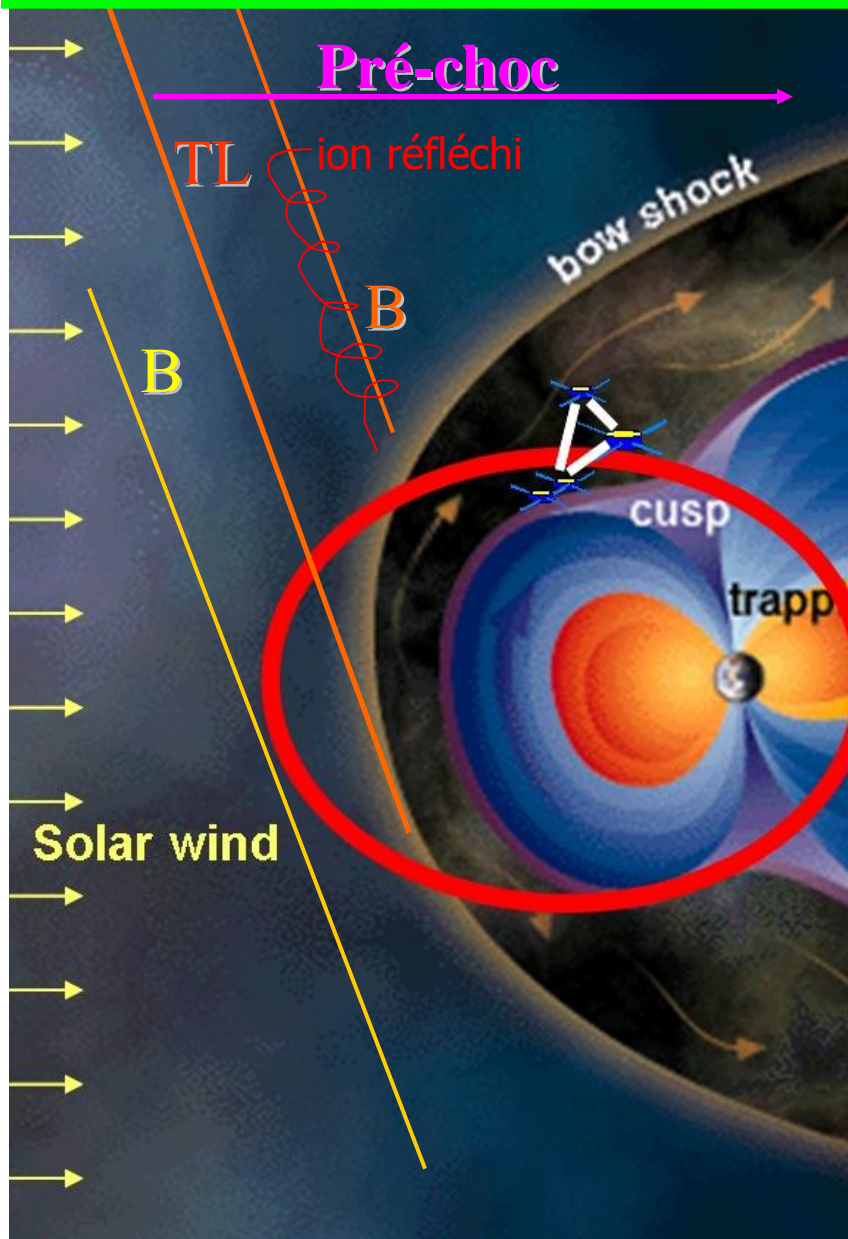
## Specularly reflected ions



Before CLUSTER (ISEE mainly + AMPTE, WIND)

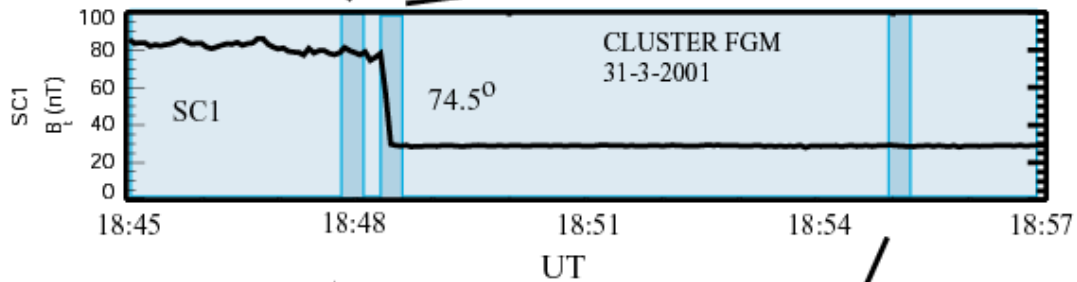
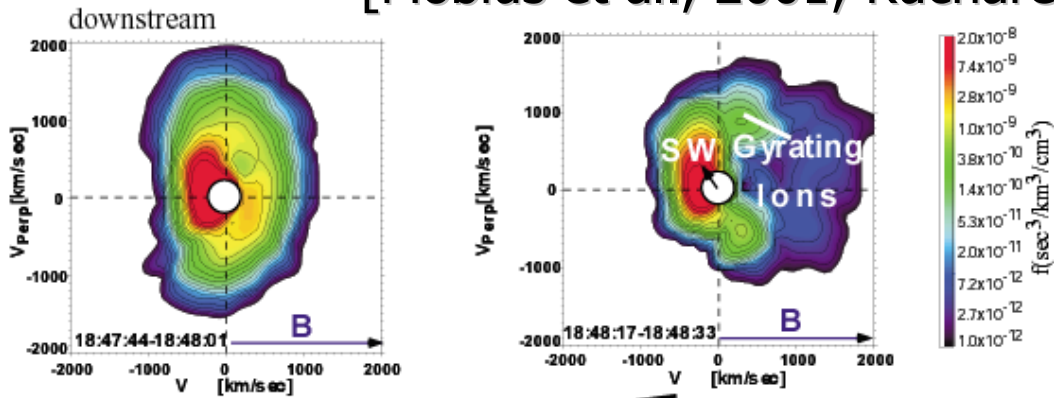
# Choc et pré-choc planétaire

Cluster

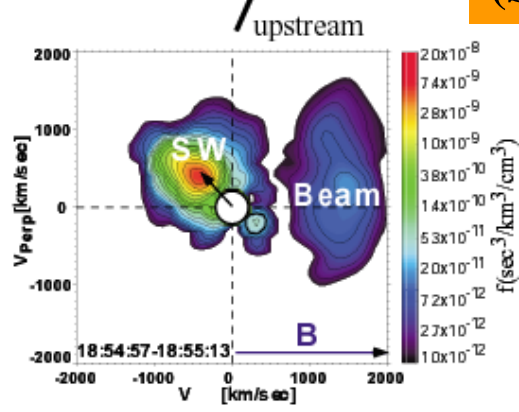
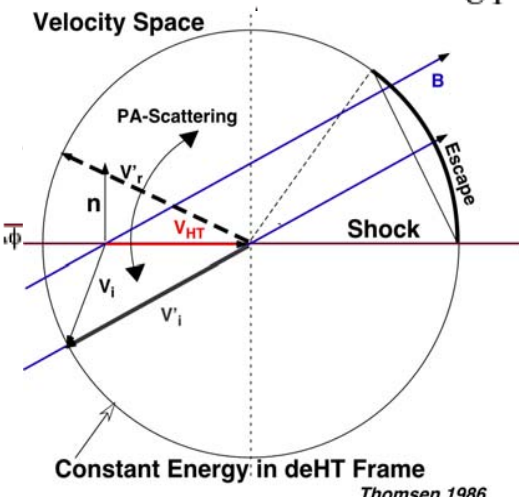


# Origin of the FABs

[Mobius et al., 2001; Kucharek et al., 2004; 2008]



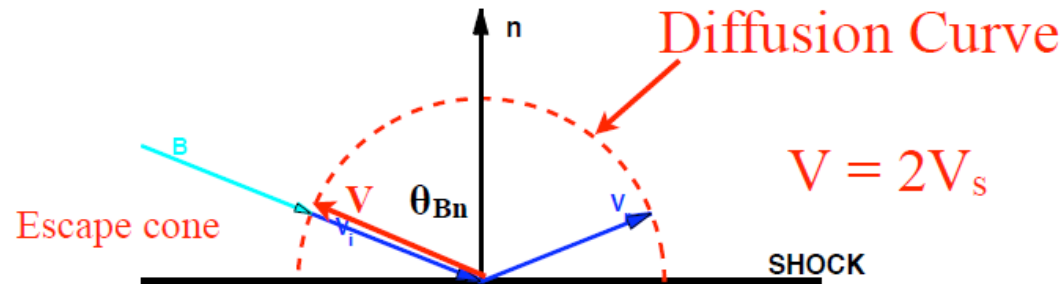
**Reflection in ramp and immediate scattering by Alfvén waves;  
Ions ||B can escape along B  
(Scattering depends on  $M_A$ )**



## ● Mechanisms

### Pitch-Angle Diffusion of Gyrating Ions

[Möbius *et al.*, 2001; Kucharek *et al.*, 2004]

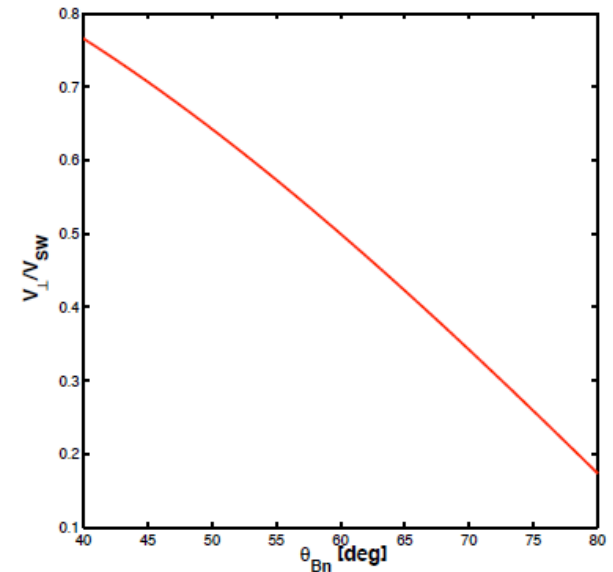


$$\frac{\partial f(\mu)}{\partial t} = \frac{\partial}{\partial \mu} \left( D_{\mu} \frac{\partial f(\mu)}{\partial \mu} \right) = \frac{\partial}{\partial \mu} \left( \frac{1 - \mu^2}{\tau} \frac{\partial f(\mu)}{\partial \mu} \right)$$

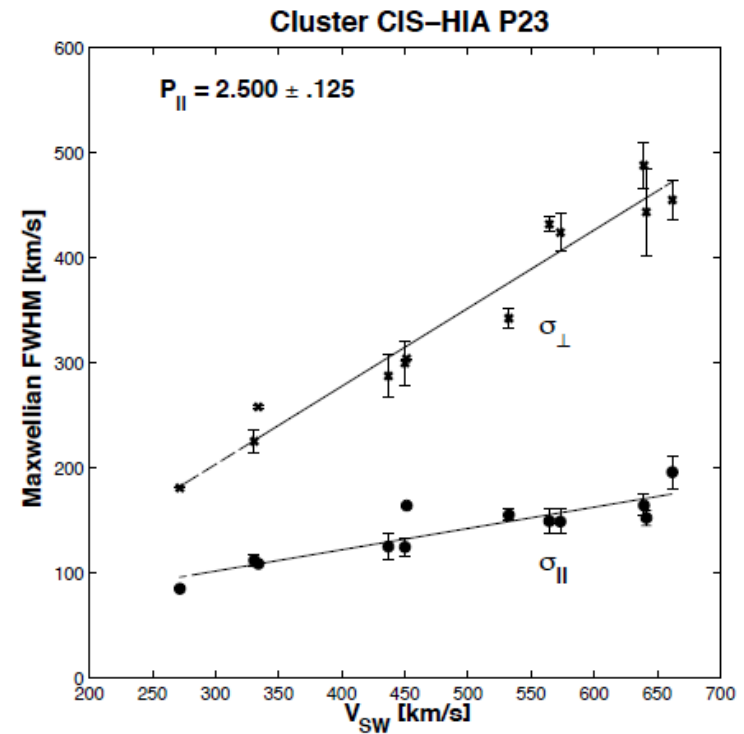
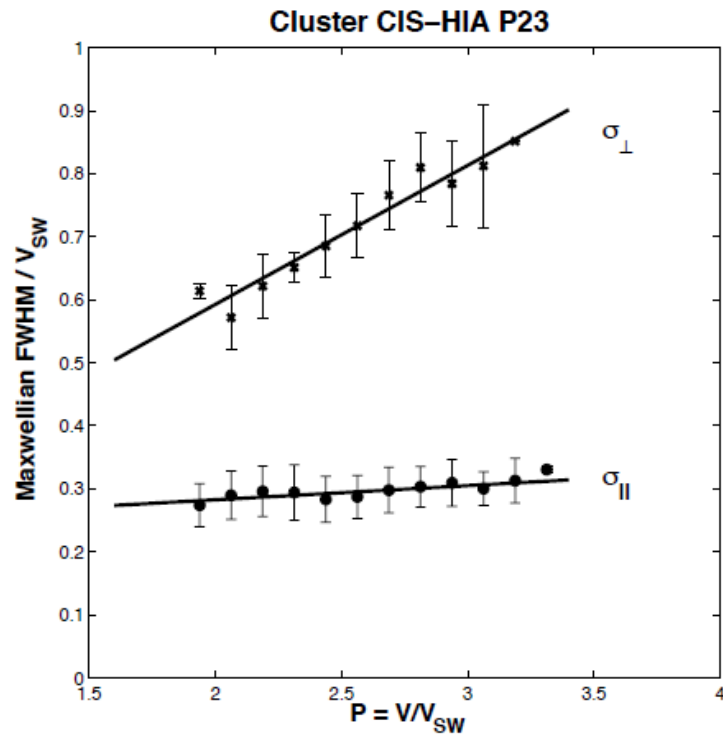
Ion-Cyclotron waves [Zank *et al.*, 2004]

$\tau$ : Very large

$T_{\perp}$ : Strongly  $\theta_{Bn}$ -Dependence



# ● FAB Thermal Energy



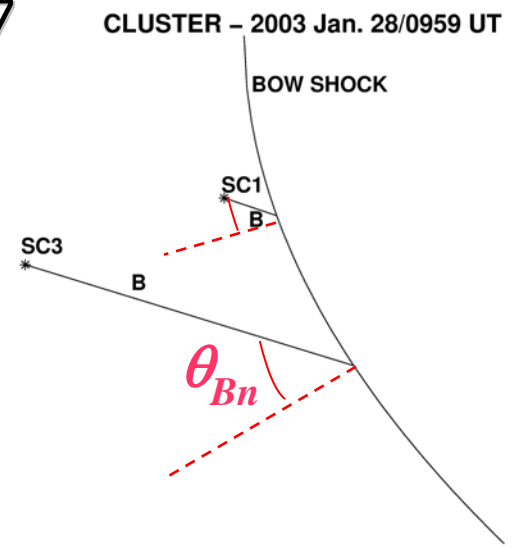
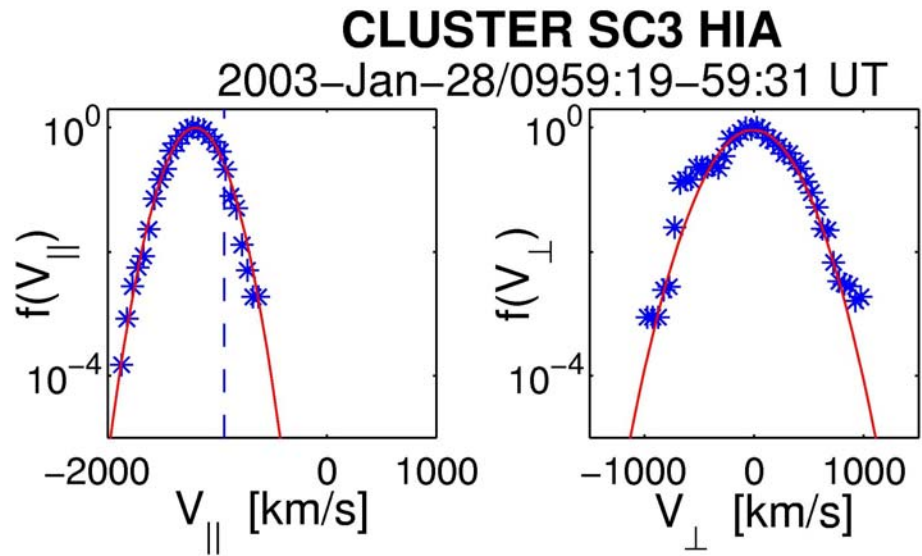
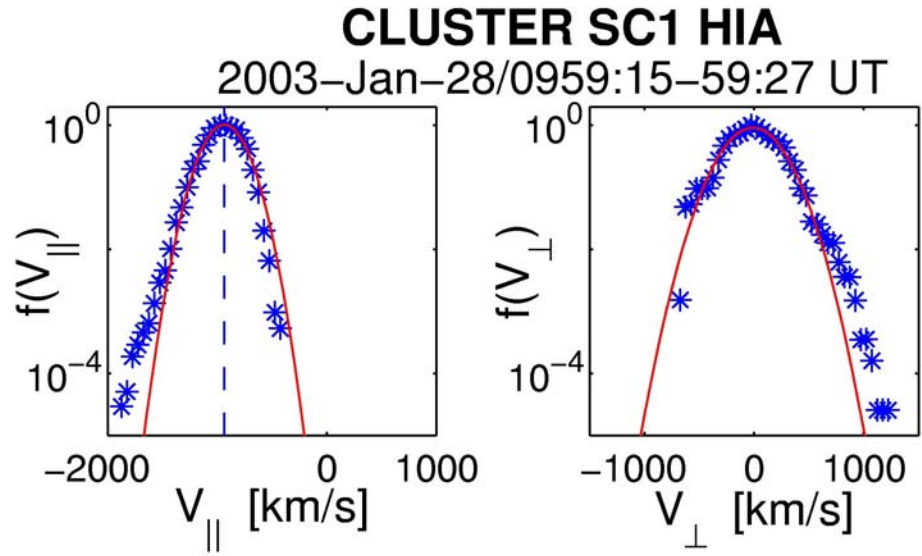
Parallel Heating: Constant  
Perpendicular Heating:  $\theta_{Bn}$  dependent

[Meziane *et al.*, 2010]



# New class of FABs

Meziane et al., 2007



**SC# 1 Downstream from SC#3**

$$\Delta V_{\parallel} = V3_{\parallel} - V1_{\parallel}$$

$$= 260 \text{ km/s}$$

[consistent with geometry]

**Maxwellian FABs**

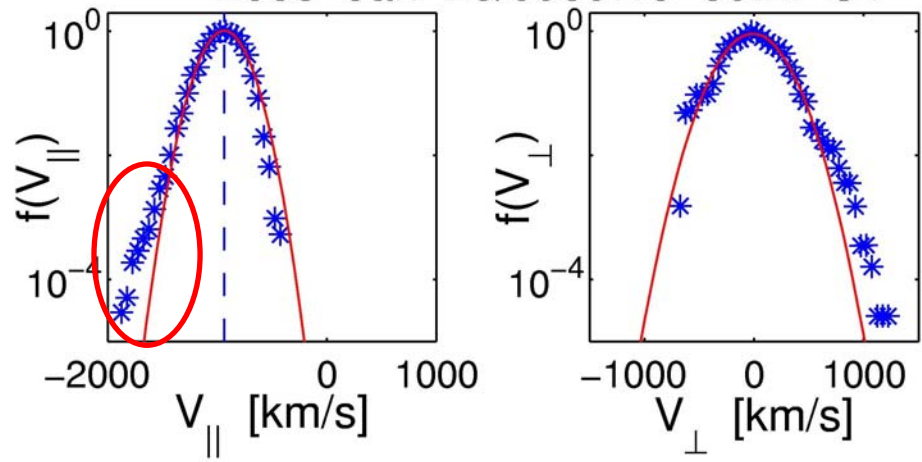
**ALWAYS** upstream of FABs with tail

# New class of FABs

Meziane et al., 2007

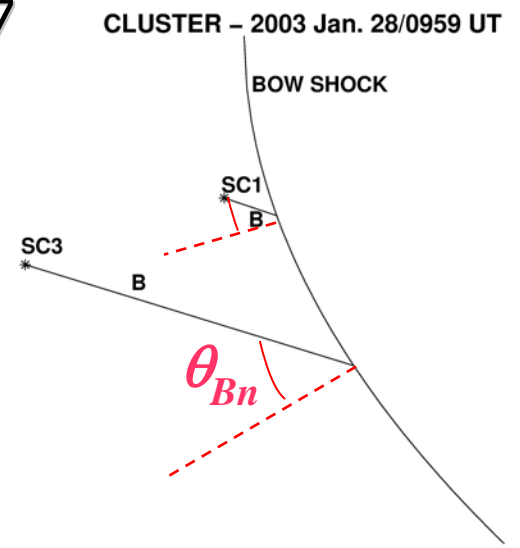
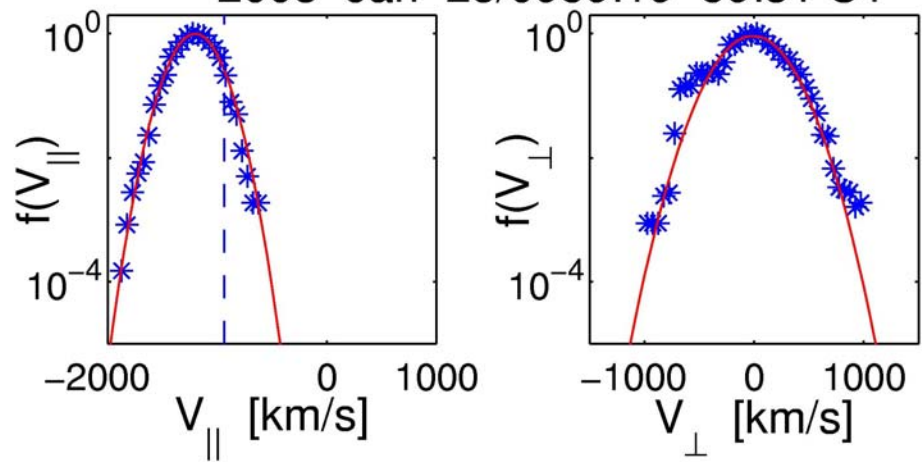
## CLUSTER SC1 HIA

2003-Jan-28/0959:15-59:27 UT



## CLUSTER SC3 HIA

2003-Jan-28/0959:19-59:31 UT



**SC# 1 Downstream from SC#3**

$$\Delta V_{\parallel} = V3_{\parallel} - V1_{\parallel}$$

$$= 260 \text{ km/s}$$

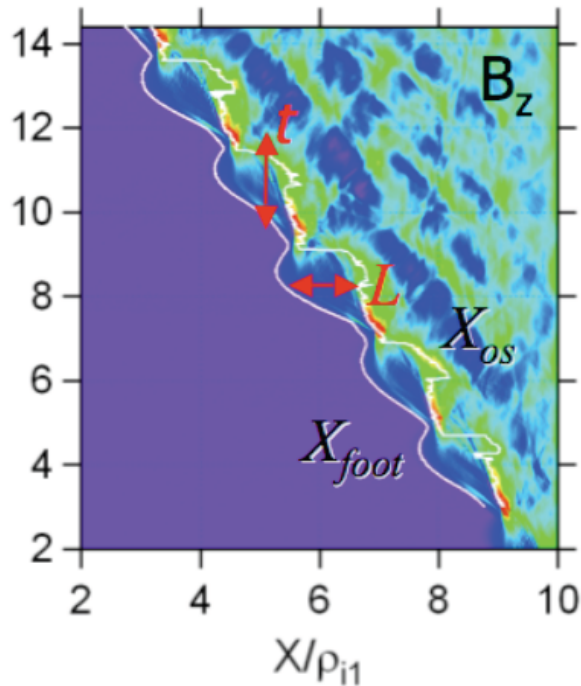
[consistent with geometry]

**Maxwellian FABs**

**ALWAYS** upstream of FABs with tail

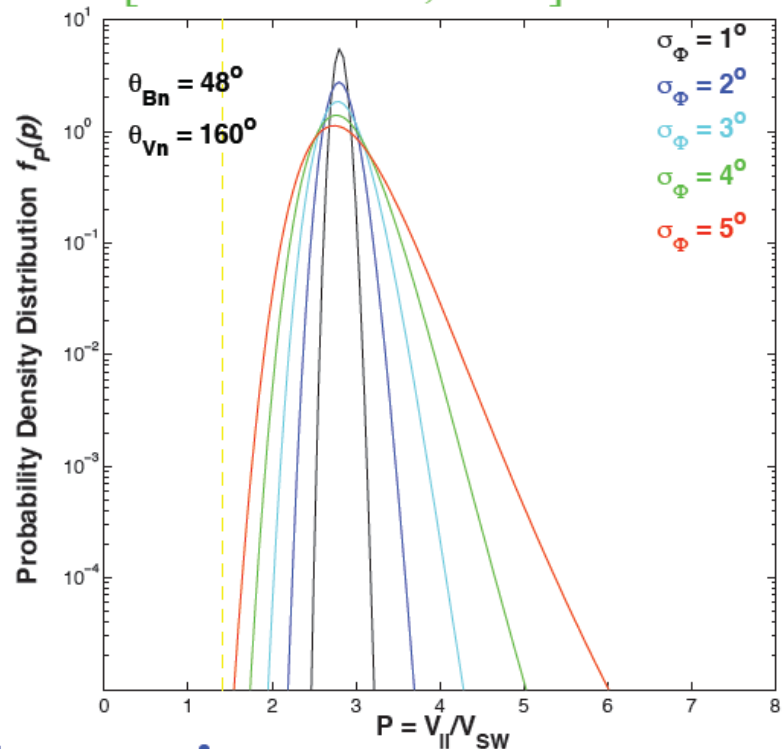
# Origin of FABs tails

## ● What Role for Turbulence?



**$\rho_i$ -scale surface fluctuations**

[Meziane *et al.*, 2010]



$$P = -(1 + \delta) \frac{\cos(\theta_{Vn0} - \Phi)}{\cos(\theta_{Bn0} - \Phi)}$$

$$f_\Phi(\phi) = \frac{2}{\sigma_\Phi \sqrt{2\pi}} \frac{\exp\left(-\frac{\phi^2}{2\sigma_\Phi^2}\right)}{\operatorname{erfc}\left(-\frac{\pi}{\sigma_\Phi \sqrt{2}}\right) - \operatorname{erfc}\left(\frac{\pi}{\sigma_\Phi \sqrt{2}}\right)}$$

$$f_P(p) = \frac{2\Delta}{\sigma_\Phi \sqrt{2\pi}} \frac{|\sin(\theta_{Vn0} - \theta_{Bn0})|}{\operatorname{erfc}\left(\frac{\pi}{\sigma_\Phi \sqrt{2}}\right) - \operatorname{erfc}\left(-\frac{\pi}{\sigma_\Phi \sqrt{2}}\right)} \times \frac{e^{-\left[\frac{1}{\sqrt{2}\sigma_\Phi} \tan^{-1}\left(\frac{p \cos \theta_{Bn0} - \Delta \cos \theta_{Vn0}}{p \sin \theta_{Bn0} - \Delta \sin \theta_{Vn0}}\right)\right]^2}}{\Delta^2 + p^2 - 2p\Delta \cos(\theta_{Vn0} - \theta_{Bn0})}$$

where  $\Delta = 1 + \delta$ .

# Choc et pré-choc planétaire

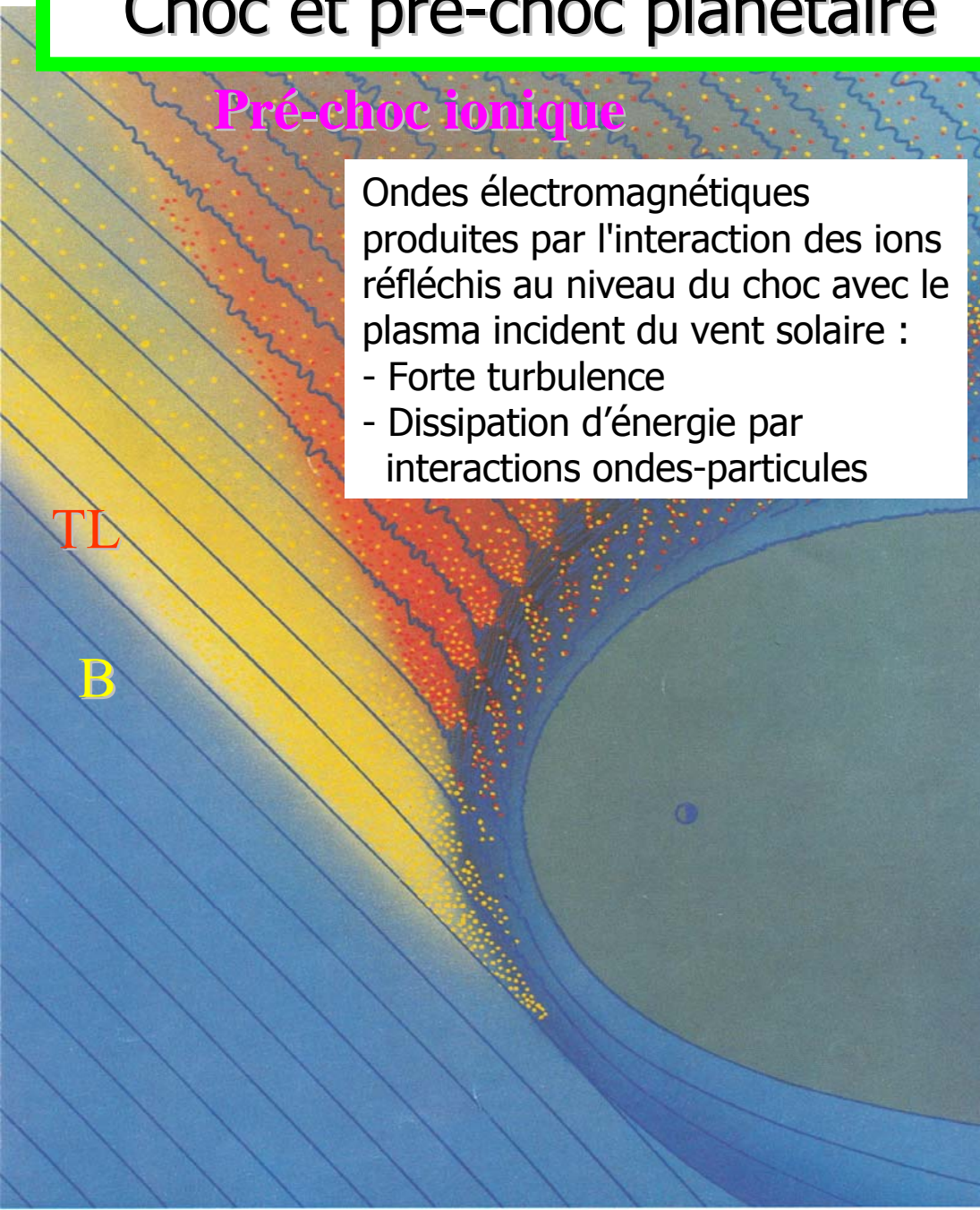
## Pré-choc ionique

Ondes électromagnétiques produites par l'interaction des ions réfléchis au niveau du choc avec le plasma incident du vent solaire :

- Forte turbulence
- Dissipation d'énergie par interactions ondes-particules

TL

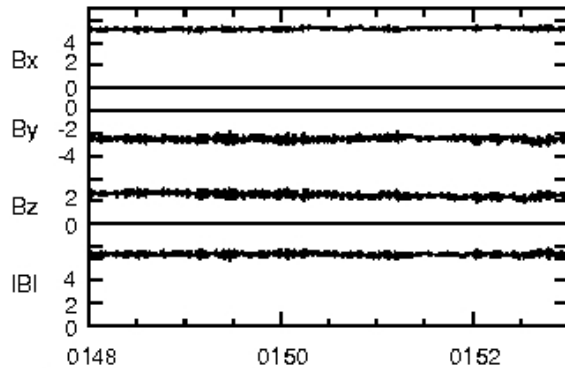
B



# Different types of Foreshock ULF waves

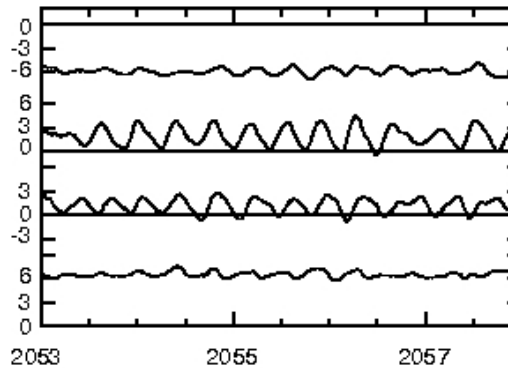
## Upstream ULF Waves - ISEE Observations

One-Hz Waves



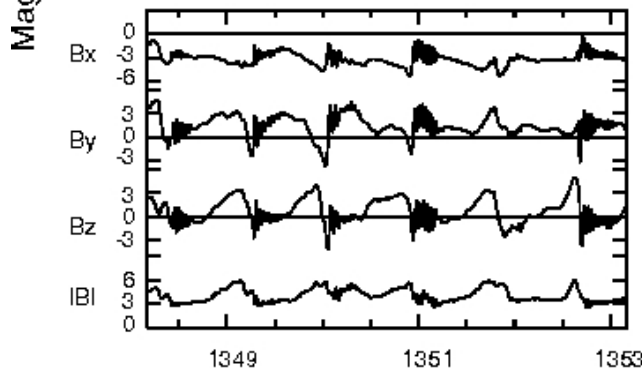
(a) October 8, 1978

Sinusoidal Waves



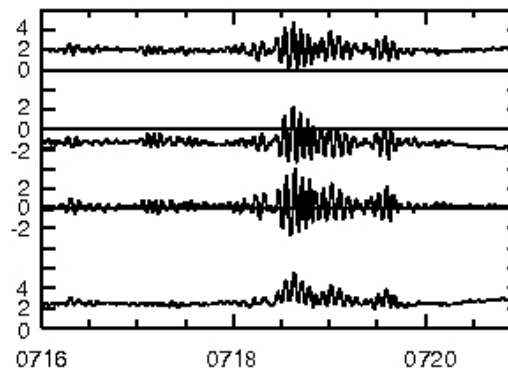
(b) September 11, 1978

Shocklets and Discrete Wave Packets



(c) December 28, 1986

Three-Second Waves



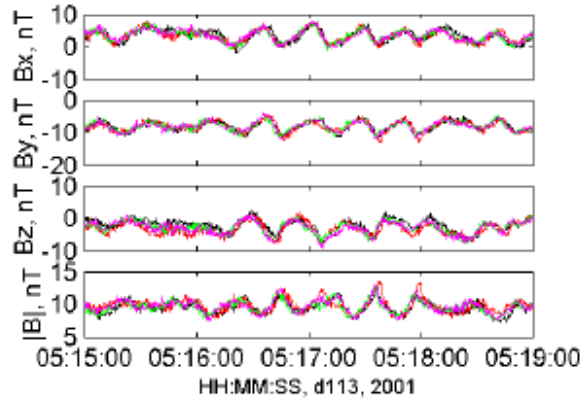
(d) November 4, 1979

[Greenstadt *et al.*, 1995]

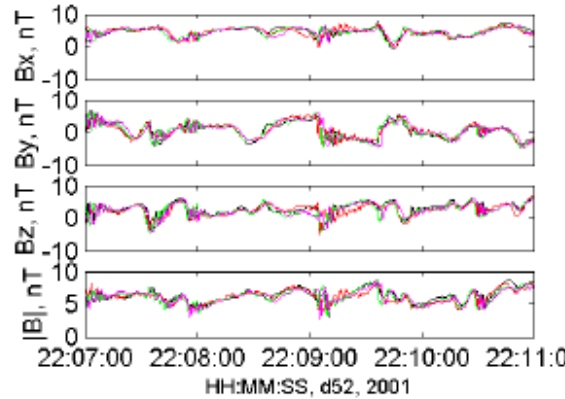
# Different types of Foreshock ULF waves

## Upstream ULF Waves - Cluster FGM Observations

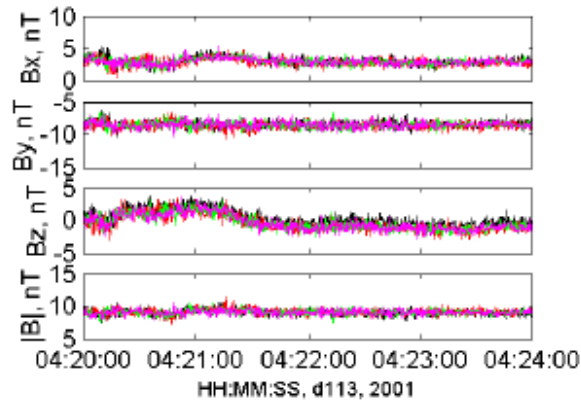
30s Waves



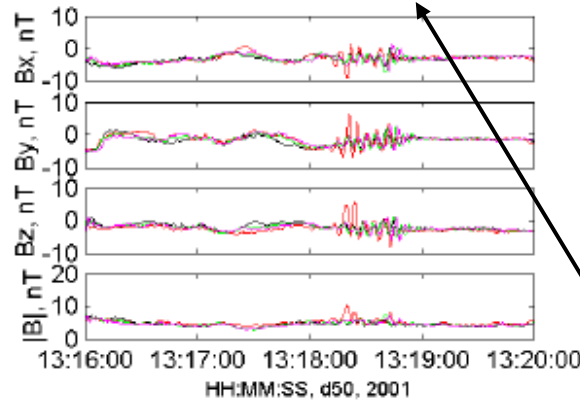
Shocklets and Discrete Wave Packets



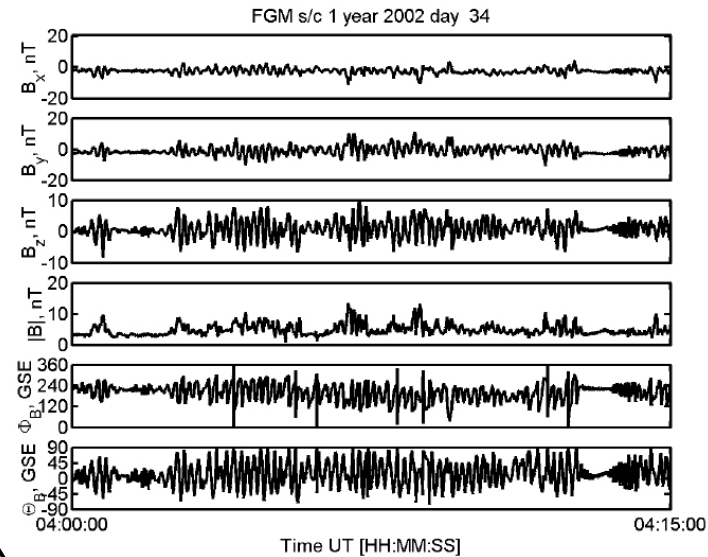
One-Hz Waves



Three Second Waves



New result from Cluster  
+ Left-Hand Alfvén Waves



[Eastwood *et al.*, 2003]

*Still no satisfactory explanation for their origin*

# Choc et pré-choc planétaire

## Pré-choc ionique

Ondes électromagnétiques produites par l'interaction des ions réfléchis au niveau du choc avec le plasma incident du vent solaire :

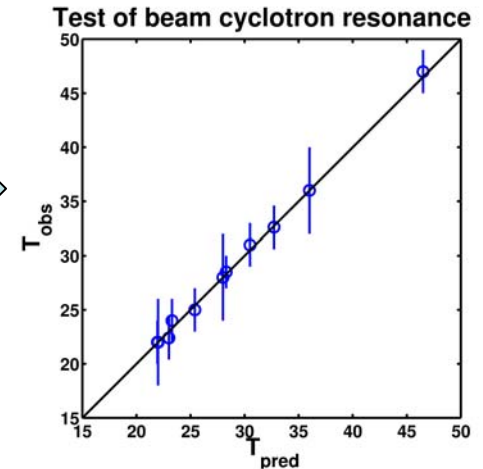
- Forte turbulence
- Dissipation d'énergie par interactions ondes-particules

TL

B

## Interaction Ondes-Particules

- Première démonstration quantitative résonance cyclotron dans le pré-choc



[Mazelle, *et al.*, 2003, 2006]

# Choc et pré-choc planétaire

## Pré-choc ionique

Ondes électromagnétiques produites par l'interaction des ions réfléchis au niveau du choc avec le plasma incident du vent solaire :

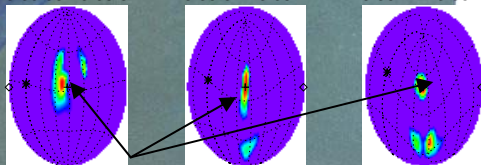
- Forte turbulence
- Dissipation d'énergie par interactions ondes-particules

TL

B

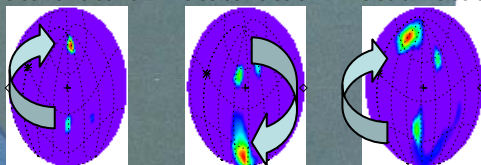
CLUSTER CODIF Product 12  
2001-04-07 E = 8413.423eV

23:35:33-23:35:37    23:35:37-23:35:41    23:35:41-23:35:45



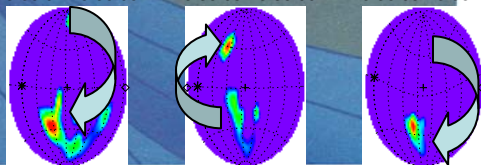
FABS

23:35:45-23:35:49    23:35:53-23:35:57    23:35:57-23:36:01



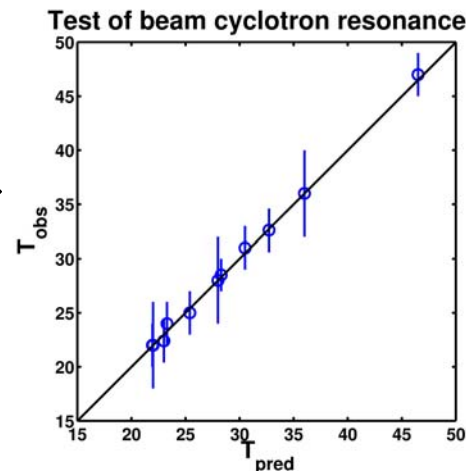
**Gyrophase-bunched ions**

23:36:01-23:36:05    23:36:05-23:36:09    23:36:09-23:36:13



## Interaction Ondes-Particules

- Première démonstration quantitative résonance cyclotron dans le pré-choc



[Mazelle, *et al.*, 2003, 2006]

- Première démonstration quantitative du piègeage dynamique des ions

Ions observés avec les ondes

[Mazelle, *et al.*, 2000; 2003; 2006; 2007]



# Choc et pré-choc planétaire

## Pré-choc ionique

Ondes électromagnétiques produites par l'interaction des ions réfléchis au niveau du choc avec le plasma incident du vent solaire :

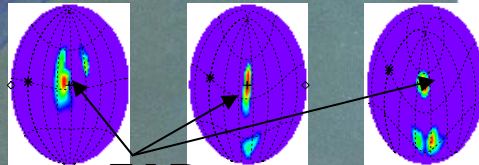
- Forte turbulence
- Dissipation d'énergie par interactions ondes-particules

TL

B

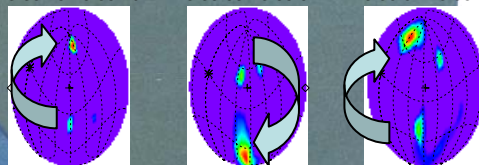
CLUSTER CODIF Product 12  
2001-04-07 E = 8413.423eV

23:35:33-23:35:37    23:35:37-23:35:41    23:35:41-23:35:45



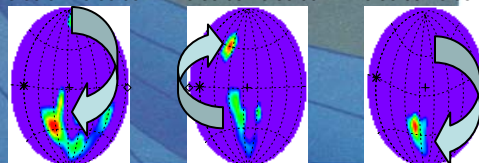
FABS

23:35:45-23:35:49    23:35:53-23:35:57    23:35:57-23:36:01



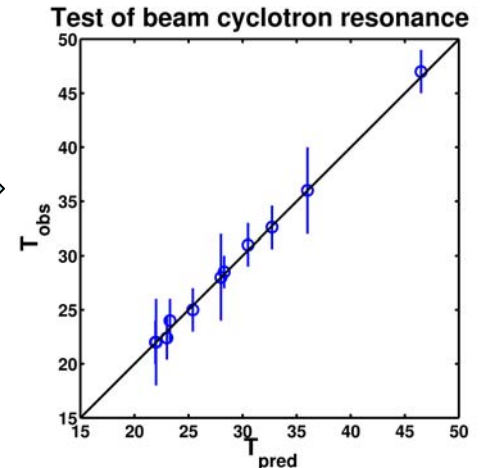
Gyrophase-bunched ions

23:36:01-23:36:05    23:36:05-23:36:09    23:36:09-23:36:13



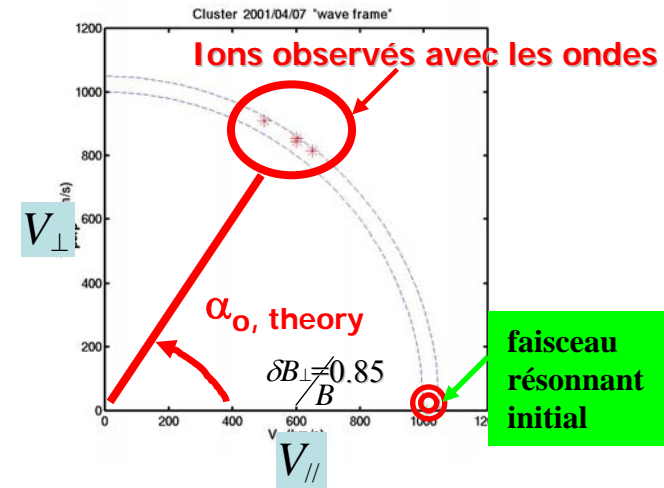
## Interaction Ondes-Particules

- Première démonstration quantitative résonance cyclotron dans le pré-choc



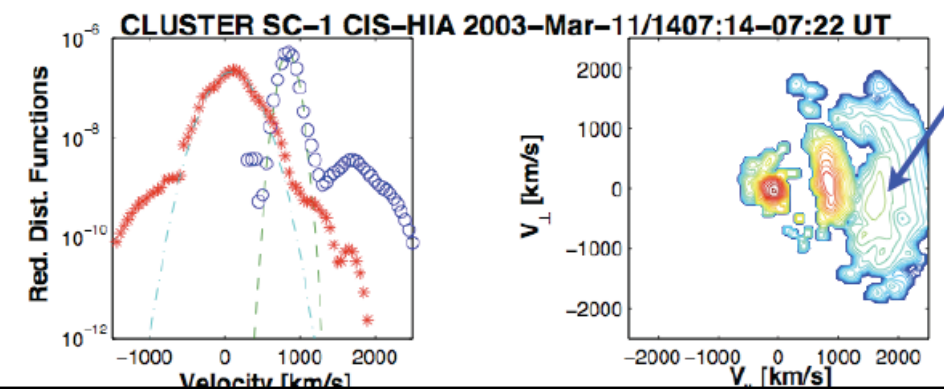
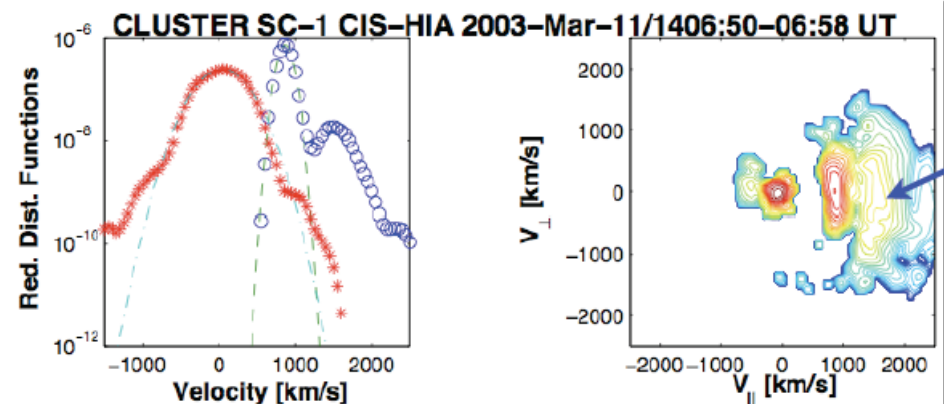
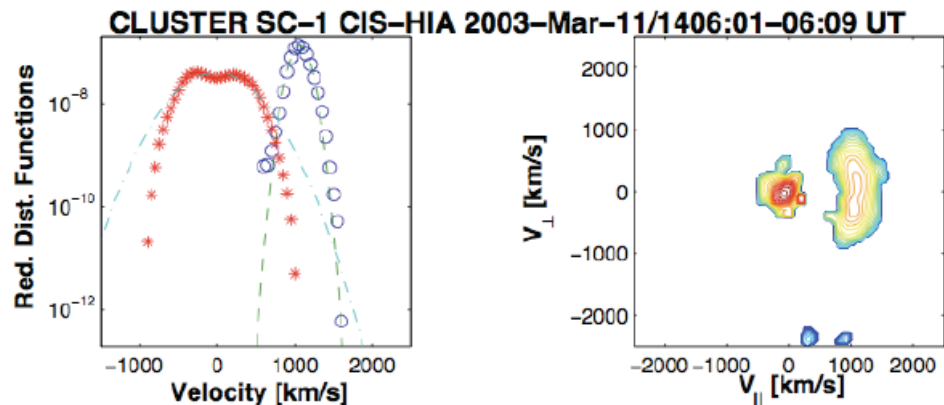
[Mazelle, *et al.*, 2003, 2006]

- Première démonstration quantitative du piégeage dynamique des ions

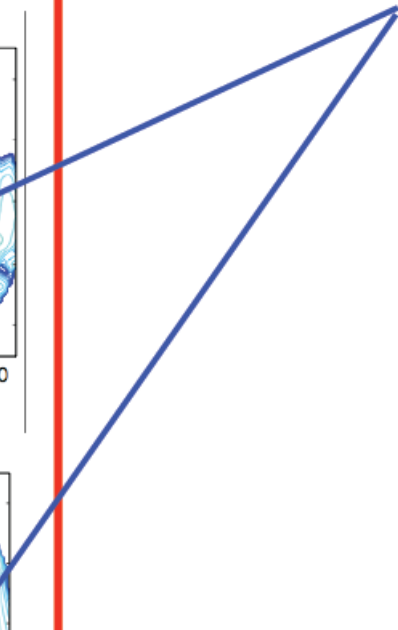


[Mazelle, *et al.*, 2000; 2003; 2006; 2007]

# ● Double FABs [Meziane *et al.*, in preparation]



A secondary FAB?



# Questions ouvertes pour le pré-choc ionique

- Origine des faisceaux alignés toujours pas expliquée de manière satisfaisante.
  - mécanismes de réflexion (pas spéculaire ni adiabatique!)?
  - Cause de la largeur thermique des faisceaux et de leur anisotropie de température?
  - origine des queues à grande vitesse de certains faisceaux? PDF non gaussiennes. Turbulence?
  - origine des doubles faisceaux? Incompatibles avec description « standard ».
  - **problème de l'injection** au niveau du choc Q-perp, relation avec même problème dans d'autres contextes (choc terminal, chocs astros non relativistes).

**Quantification de la réflexion des ions?**

**Capacité accélératrice des chocs?**

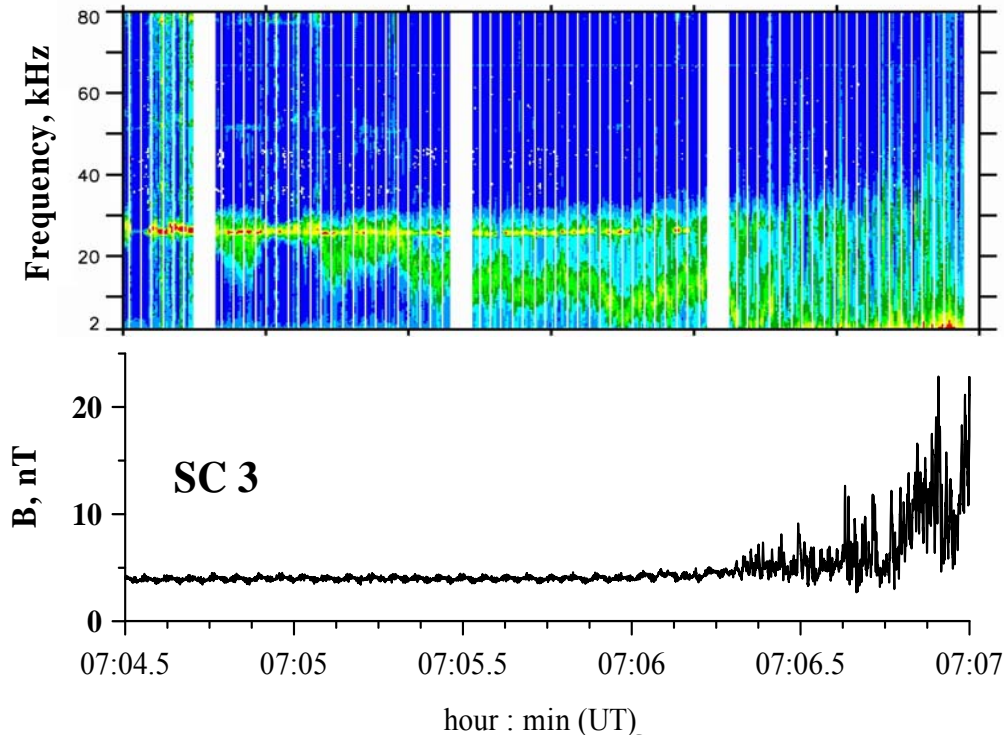
**Phase initiale d'un mécanisme de type Fermi (Accélération diffusive)?**

**Role des interactions choc/choc?**

- Importance quantitative des interactions ondes-particules dans l'énergisation des populations de particules? Liée aussi au problème de l'injection.
  - rôle du piégeage dynamique des ions (résonance cyclotron) par les ondes ULF?
  - origine des ondes d'Alfvén identifiées pour la première fois avec Cluster?
  - origine des structures cohérentes?

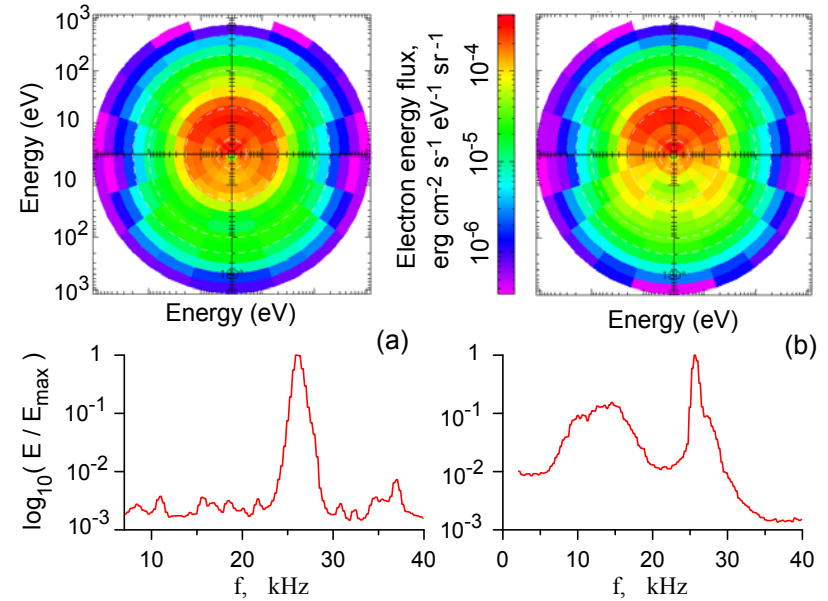
# Pré-choc électronique

# The generation of downshifted oscillations in the electron foreshock: bump-on-tail versus loss-cone instability



Frequency-time spectrogram for the Earth's bow shock crossing on January 24, 2001.

[Lobzin *et al.*, 2005]



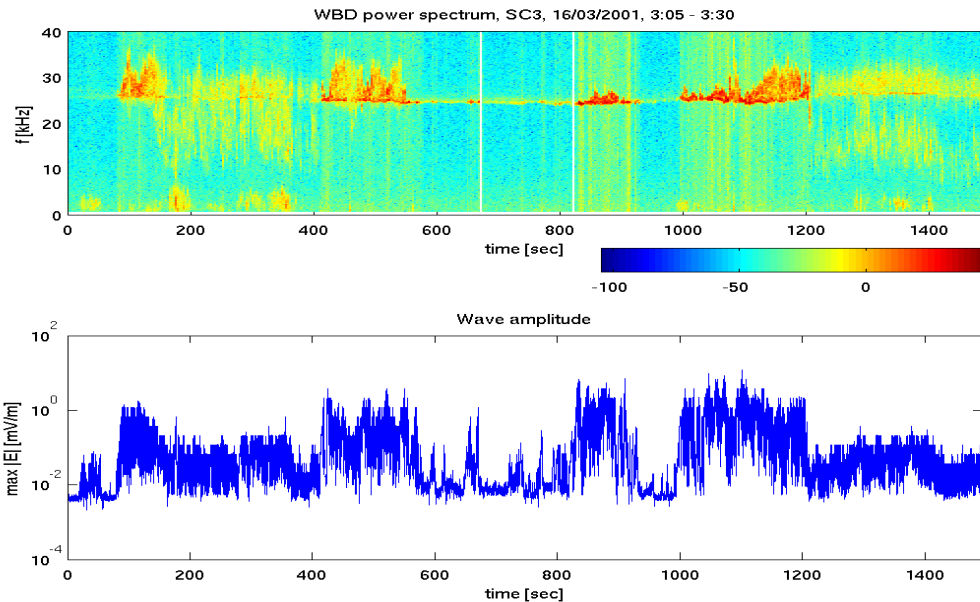
Electron differential energy flux versus energy and pitch angle and the corresponding electric field spectra (a) near the forward edge of the electron foreshock, at 07:04:29-07:04:33 UT, and (b) deeper, at 07:05:13-07:05:17 UT.

The observed loss-cone feature is always accompanied by electrostatic waves with frequencies well below the local plasma frequency.

The downshifted oscillations can result from a loss-cone instability of electron cyclotron modes rather than a beam instability of the Langmuir and/or beam modes

# Beam-plasma interaction in randomly inhomogeneous plasmas

[Krasnoselskikh *et al.*, 2007]



- CLUSTER in the Earth's foreshock (Diff = 0 .. - 6  $R_E$ )
- Observed wave amplitudes up to 5 mV/m

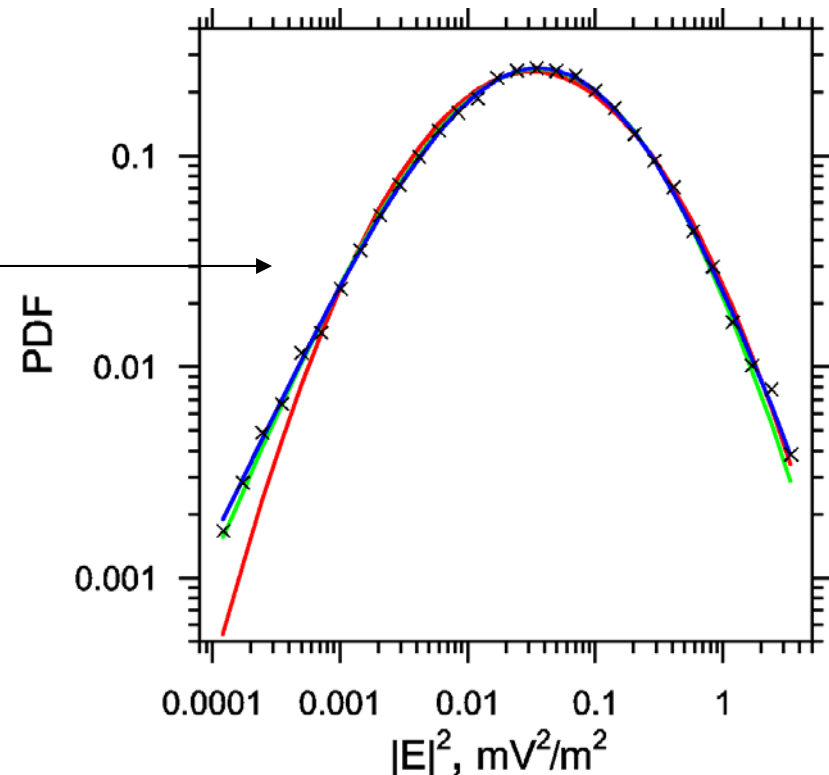
PDF for Langmuir wave energy density

x – experiment

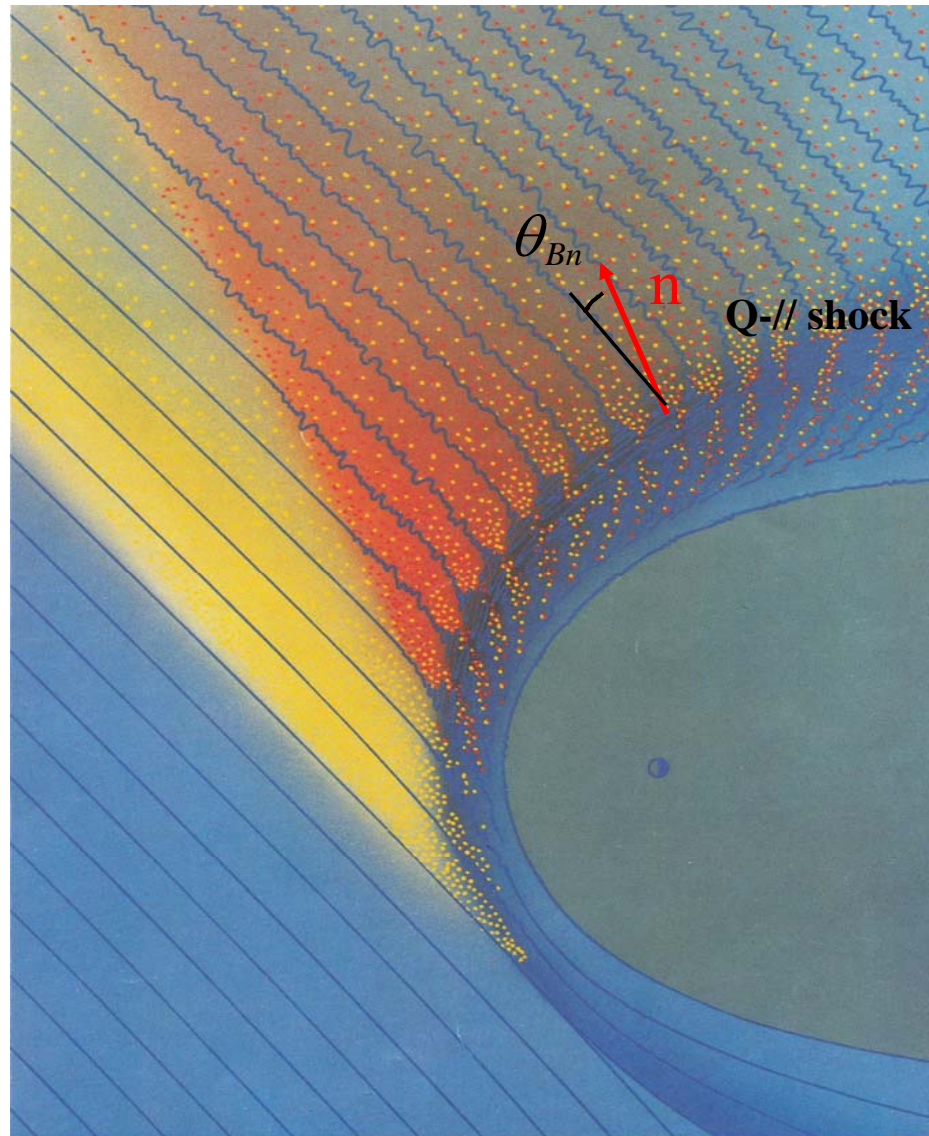
— maximum likelihood fit of a log-normal distribution

— fit of Pearson class IV distribution obtained by maximum likelihood method

— fit of Pearson class IV distribution with parameters derived from estimates of moments

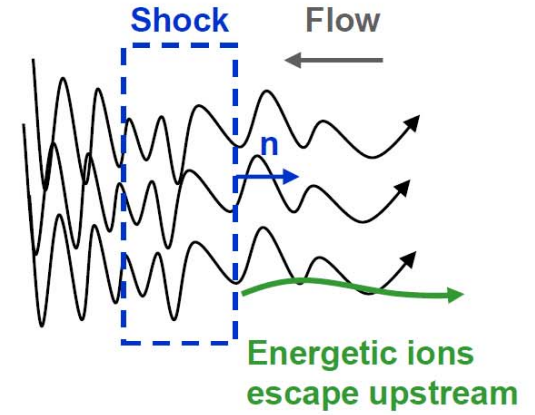


# Choc Q-parallel

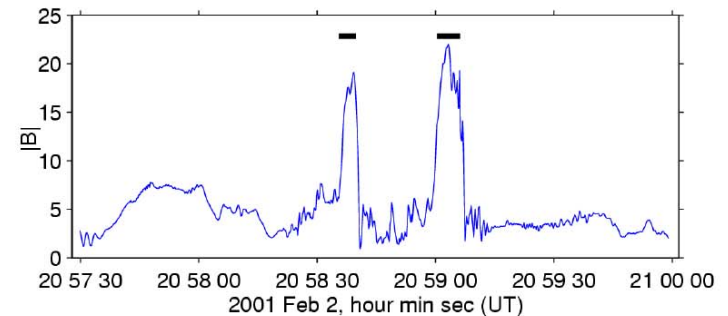
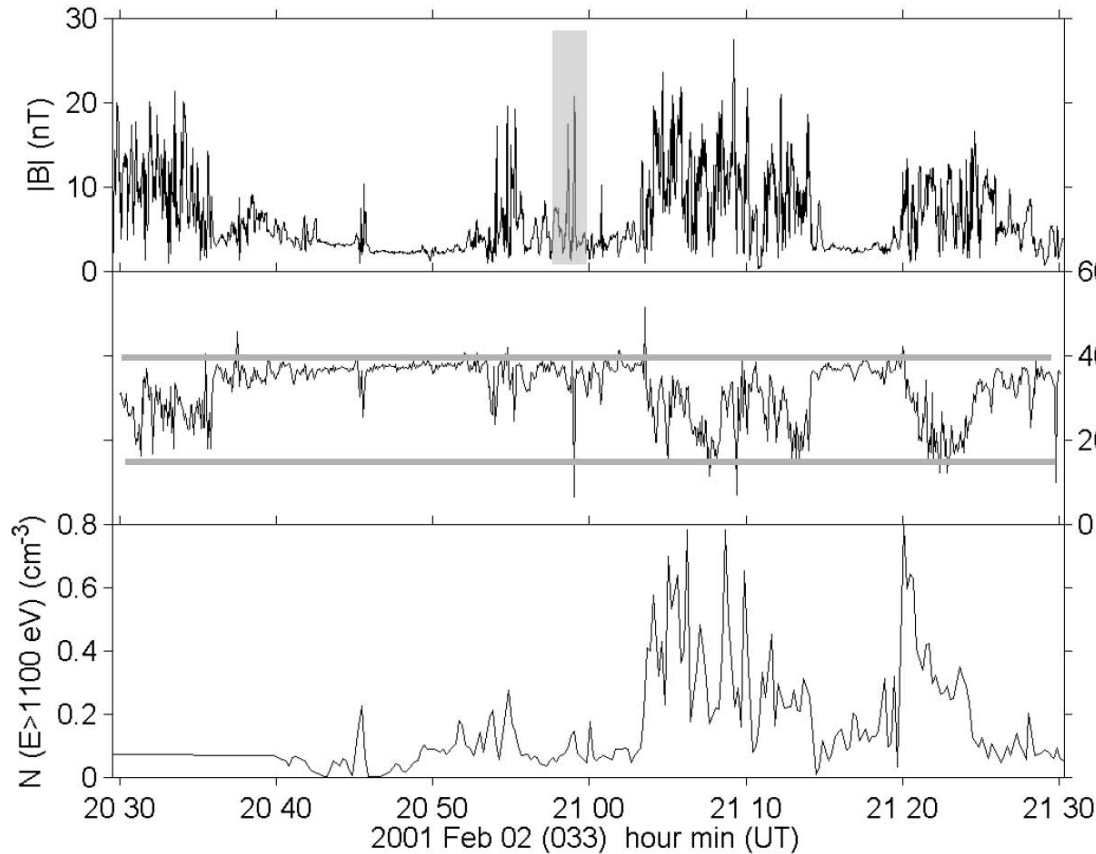


# Quasi-parallel shocks: $\theta_{Bn} \sim 0$ ( $\beta \geq 1$ )

- Magnetic field  $\sim$  parallel to shock normal
  - Significant flux threads shock surface
- Disturbed transition in  $\mathbf{B}$ : not shock motion
  - **Extended spatial transition**



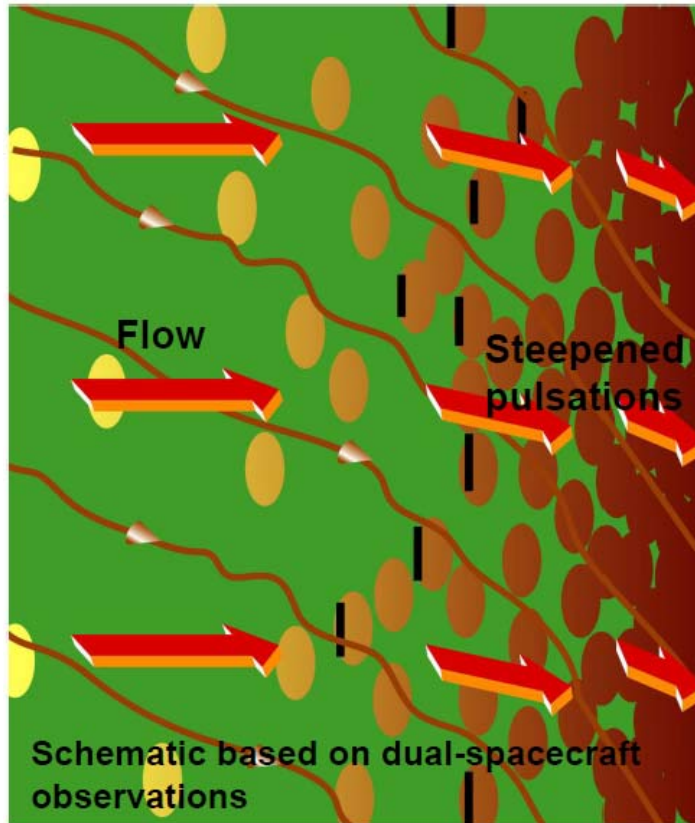
- Particles escape upstream
  - Generate ULF waves
  - Waves carried back to shock
- Pulsations (SLAMS) grow by interacting with hot ions
  - **Shock intrinsically time varying**



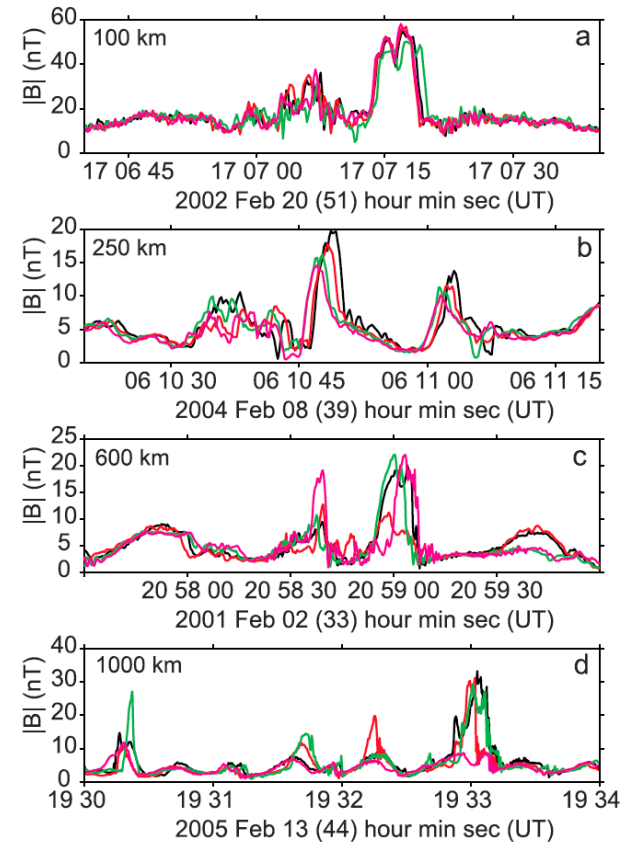
[Lucek *et al.* 2002]



# SLAMS Growth: A Simple Picture?



[Schwartz and Burgess, 1991]



[Lucek *et al.*, 2008]

$$\left( V_{SW} - \frac{B_S}{B_0} V_{A0} \right) \frac{d}{dz} (B_S^2) = C (B_S - B_0) \exp\left(\frac{z}{L}\right)$$

[Martin Lee, work in progress, private communication]

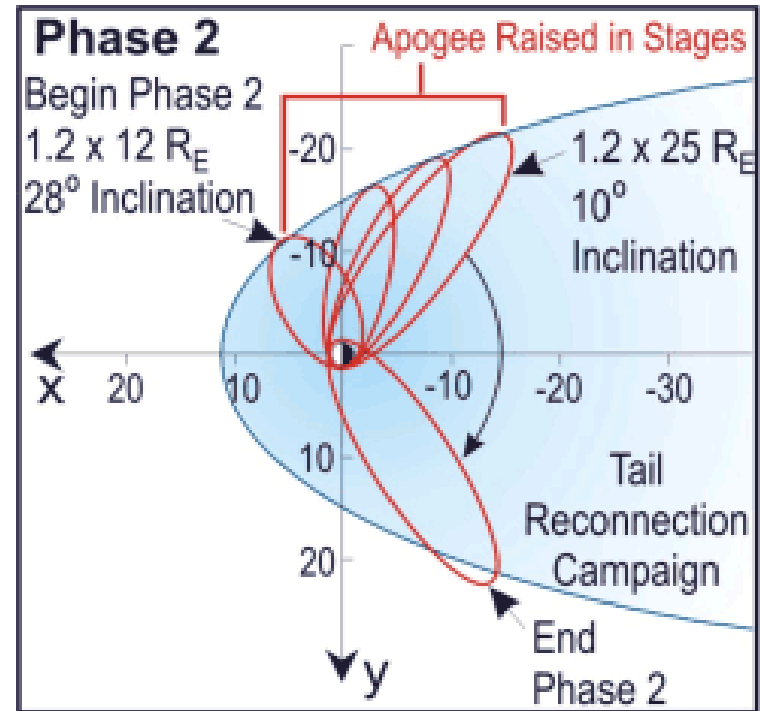
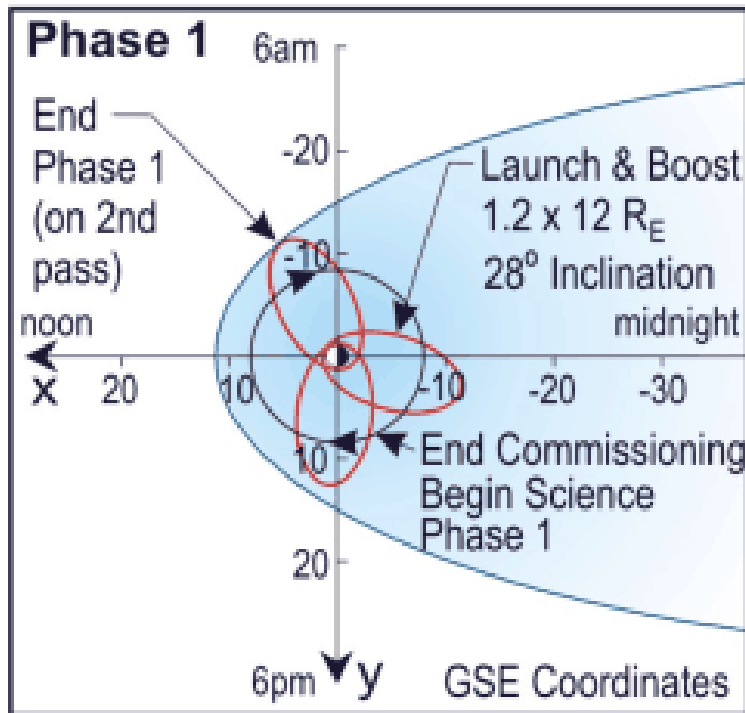
## Open questions for Q-// shocks: origin of a SLAMS?

- Why is length of SLAMS so short? Expect 10,000 km
- How does  $|\mathbf{B}|$  increase? (particle scattering, steepening,  $B^2L = \text{const}$ )
- Nonlinear Schroedinger Equation pulse?
- Polarization of a SLAMS? (Is particle interaction resonant or non-resonant?)
- Does phase speed of a SLAMS increase with  $|\mathbf{B}|$ ?
- Does a SLAMS scatter incoming solar wind?
- Certainly particles from the shock lose energy in the plasma frame to growth of the SLAMS
- Can a SLAMS reform the Q-// shock?

# Futur: MMS

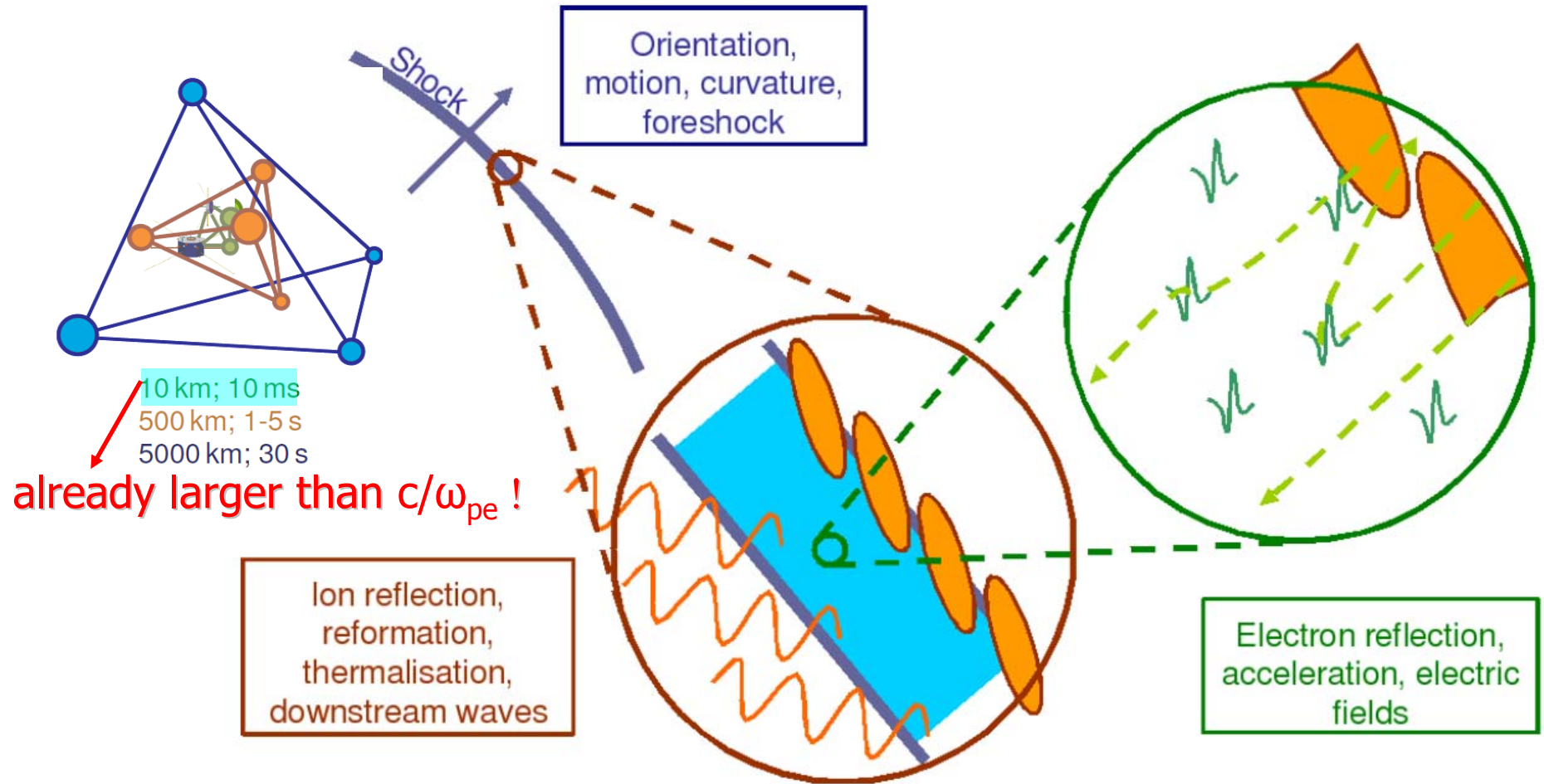
Petites échelles couvertes: jusqu'à qqes km

Mais orbites peu adaptées à l'étude du choc



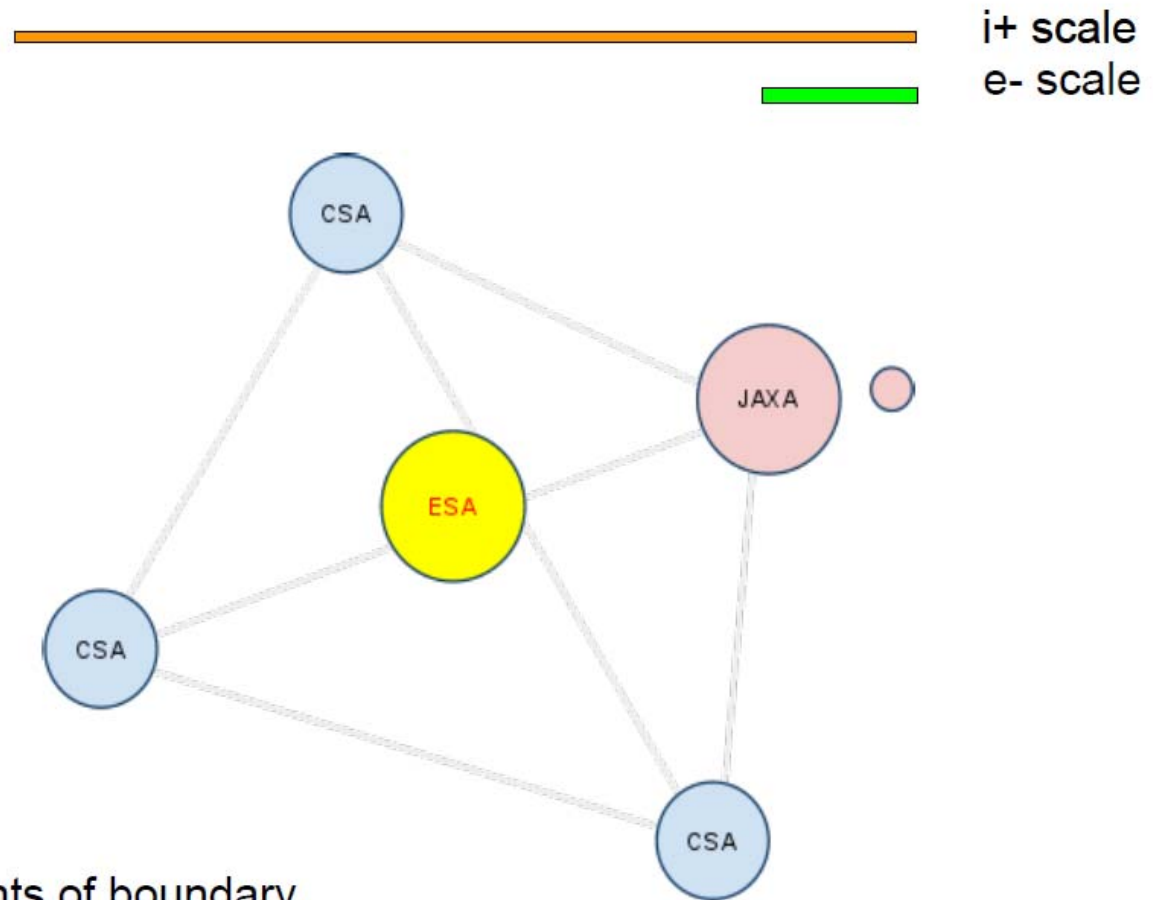
# Implication for future multi-spacecraft missions

## Cross-Scale Coupling at Shocks



# EidoScope

Electron ion dynamics observatory in SCOPE

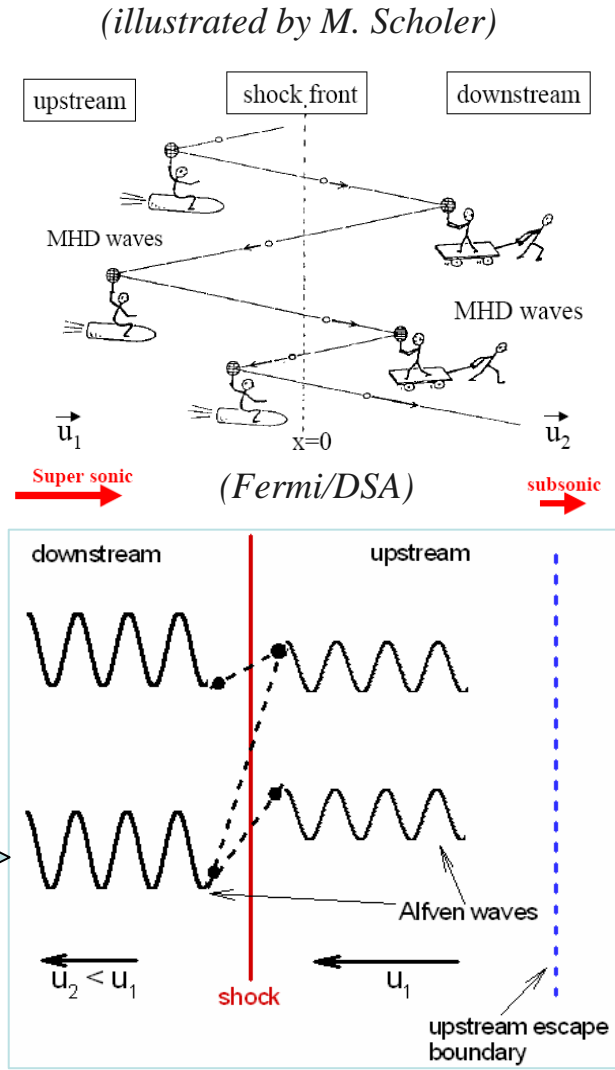
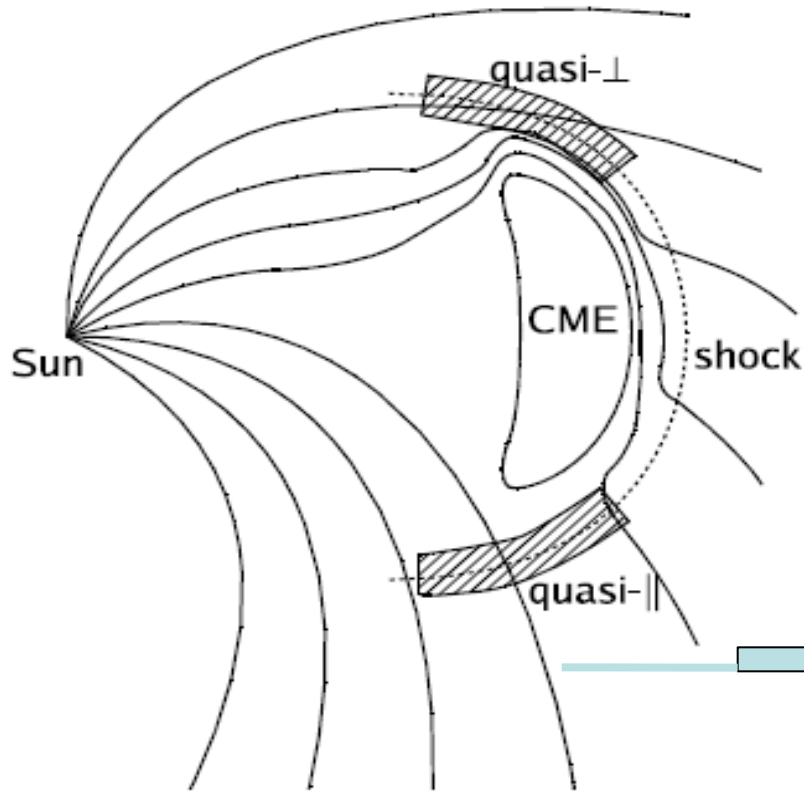


i+ scale  
e- scale

local measurements of boundary  
acceleration/deceleration

**Et Maintenant Simulons!**

# Shock acceleration



(Courtesy of Gang Li)

Schematic of a CME driven shock [From Zank et al., JGR, 2006]. For quasi-perpendicular shock, DSA seems to have some difficulties.