

Mirror instability and structures in the Earth magnetosheath : Cluster observations, simulations and theory

V. Génot, E. Budnik, I. Dandouras
CESR, Toulouse, France

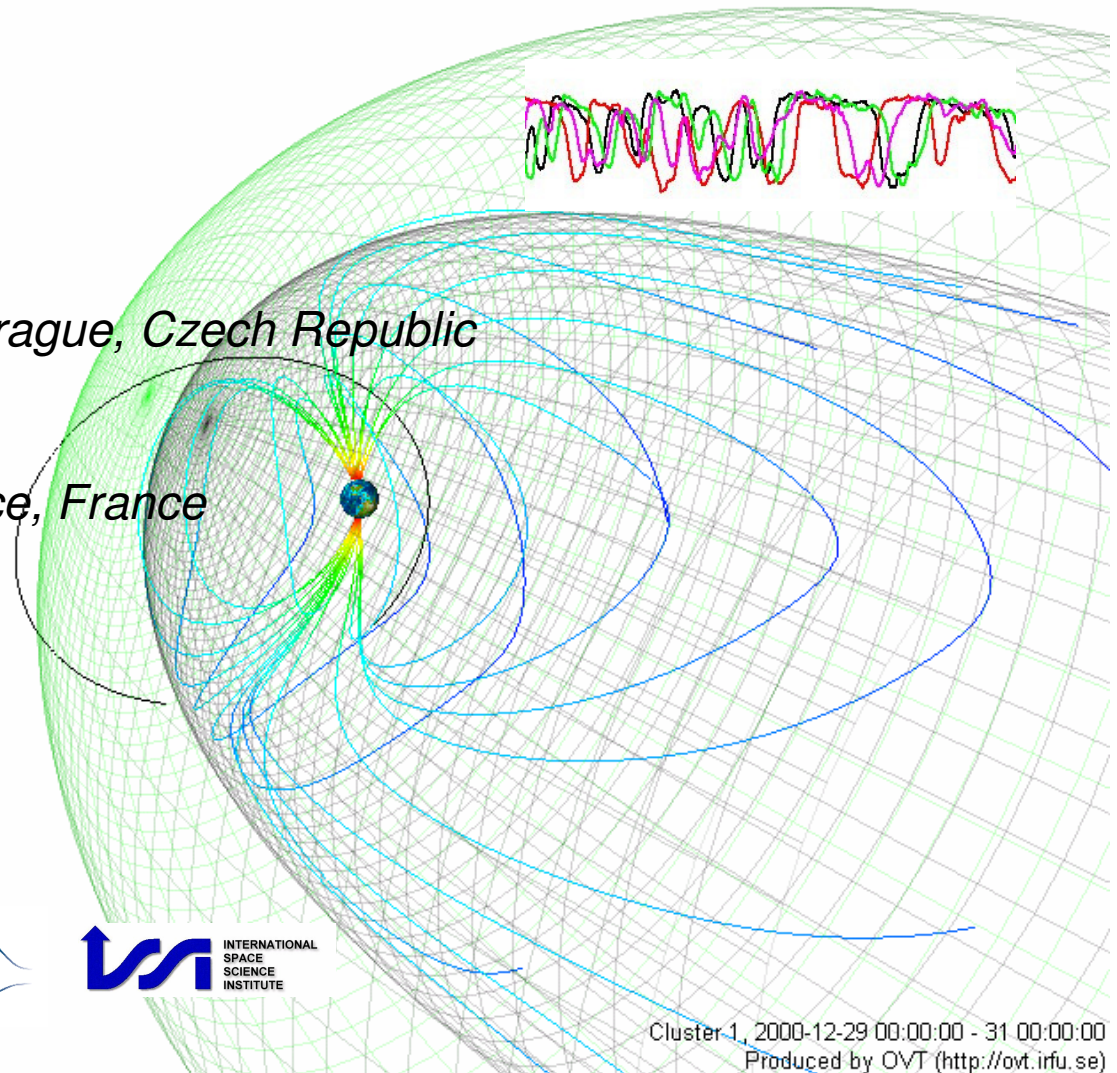
P. Hellinger
Institute of Atmospheric Physics, Prague, Czech Republic

T. Passot
Observatoire de la Côte d'Azur, Nice, France

G. Belmont
CETP, Vélizy, France

E. Lucek
Imperial College, London, UK

CDPP and ISSI 80 teams



Cluster 1, 2000-12-29 00:00:00 - 31 00:00:00
Produced by OVT (<http://ovt.irfu.se>)

General outline

- 1 Obtain the spatial distribution of mirror mode events

- as a function of the normalized distance between the magnetopause and the bow shock
- in relation with conditioning parameters of the solar wind
- compare with previous studies using ISEE-1 data

-2 Investigate mirror-like nonlinear structures (holes & peaks)

- compare with results from hybrid simulations
- compare with results from nonlinear MHD theory

Data : 5 years of CLUSTER observations and associated ACE data

Tools : AMDA/SP at CDPP (visit cdpp.cesr.fr)

Identification methods

Identification of mirror mode events is a long standing problem because :

- Slow modes and mirrors have both anti-correlated B and N signatures
- Mirror mode and ion cyclotron mode both grow on temperature anisotropy

Different methods have been developed and used :

- transport ratio : *Song et al. 1994, Denton et al. 1995, 1998*
- minimum variance analysis : *Tatallyay & Erdos, 2005*
- 2- and 4- satellite methods : *Chisham et al. 1999, Génot et al. 2001, Balikhin et al., 2003, Horbury et al. 2004*
- 90° degree B/Vz phase difference : *Lin et al. 1998*

In our data analysis we shall use:

'B test'

Magnetic field fluctuations are :

- of large amplitude : $\delta B/B > 0.15$
- parallel to B_0 : $\text{angle}(\text{Max. Var.}, B_0) < 20^\circ$

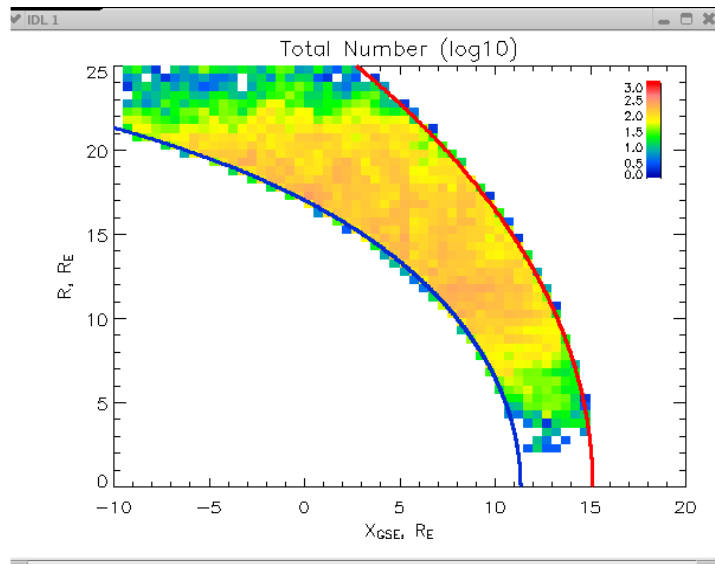


'Plasma test'

Conditions on :

- plasma β
- based on the linear mirror instability threshold

Total number of 5 min magnetosheath crossings



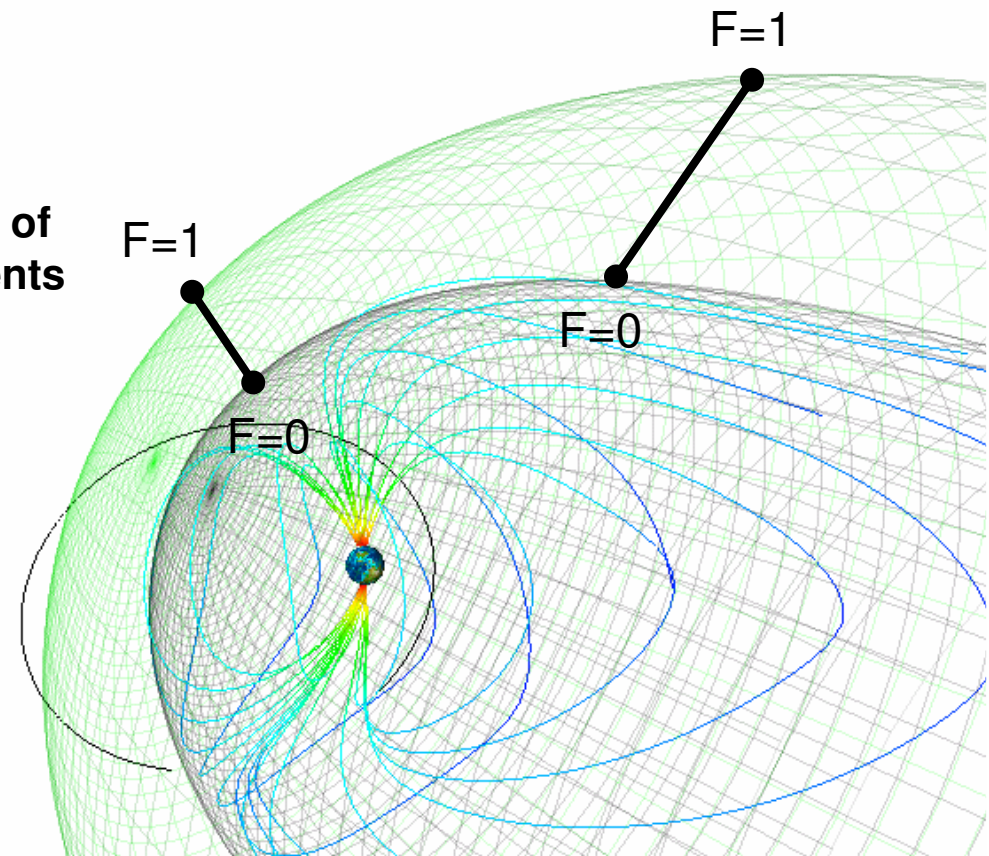
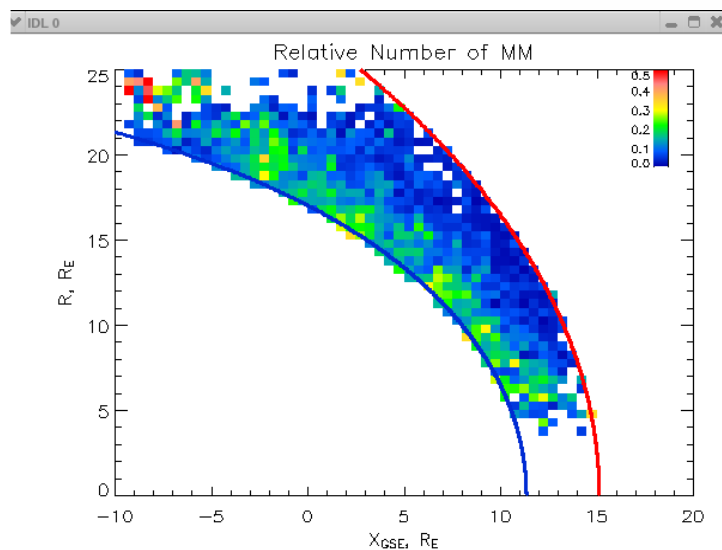
$$F_{\text{mipm}} = \frac{r - r_{\text{MP}}(\vartheta_{\text{mipm}} | \rho V^2, B_z)}{r_{\text{BS}}(\vartheta_{\text{mipm}}, \varphi_{\text{mipm}} | M_a, M_s, \vartheta_{\text{bv}}) - r_{\text{MP}}(\vartheta_{\text{mipm}} | \rho V^2, B_z)}$$

Verigin et al., 2001, 2003, 2006

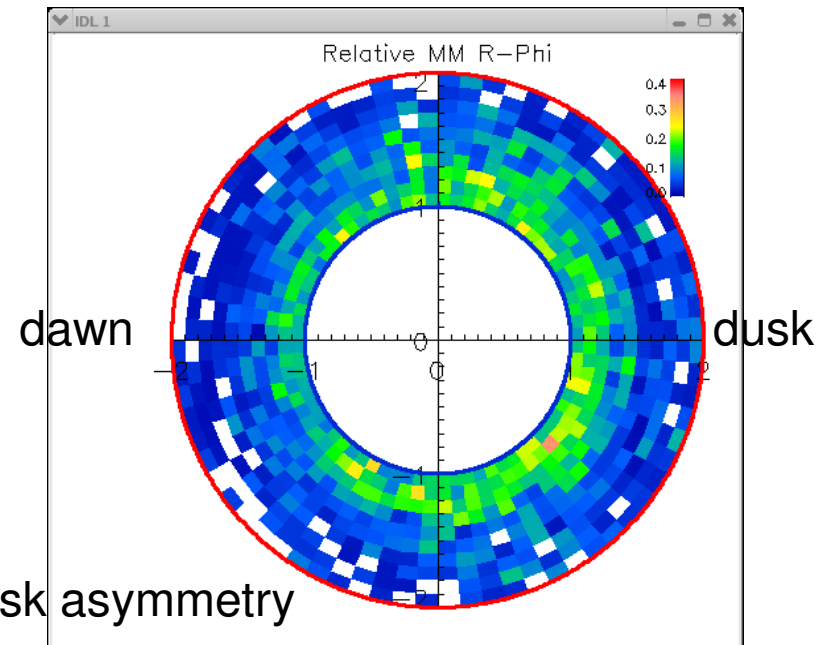
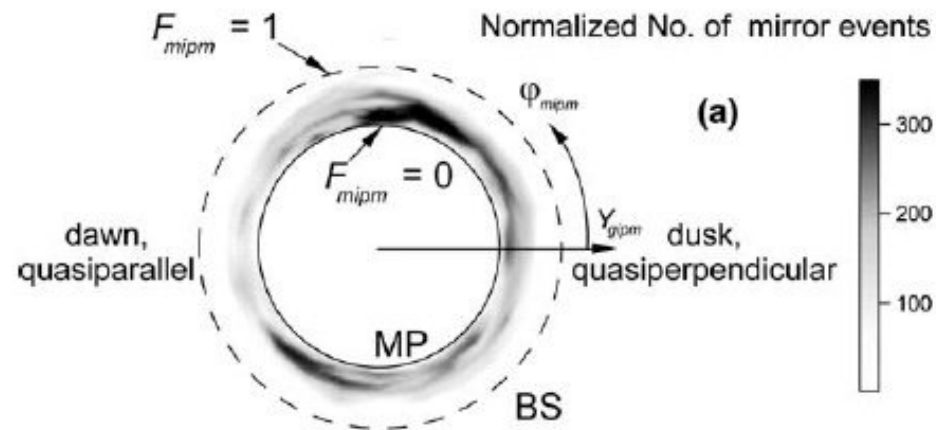
- For a position \mathbf{r} inside the magnetosheath, the fractional distance is between 0 (MP) and 1 (BS)
- ACE data are also used for MP and BS models

'B test' + 'plasma test'

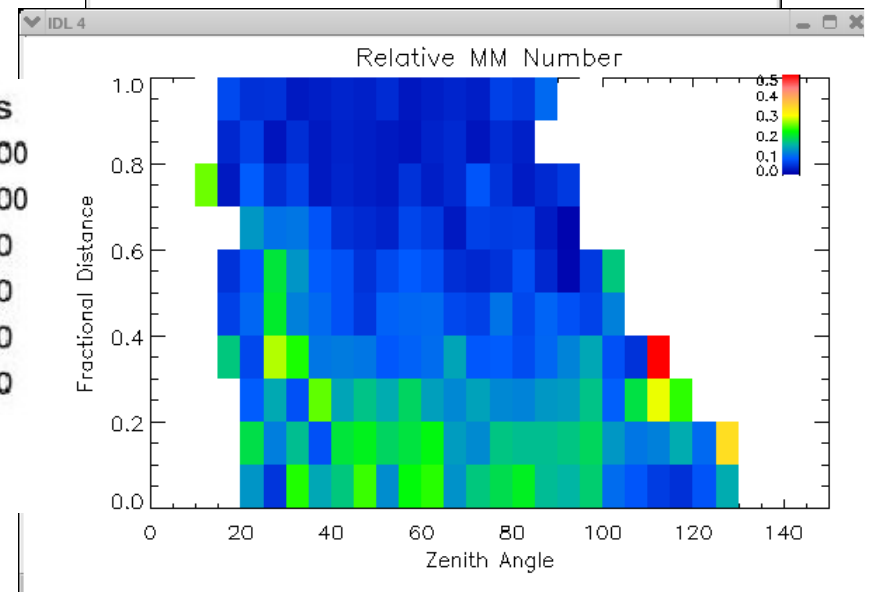
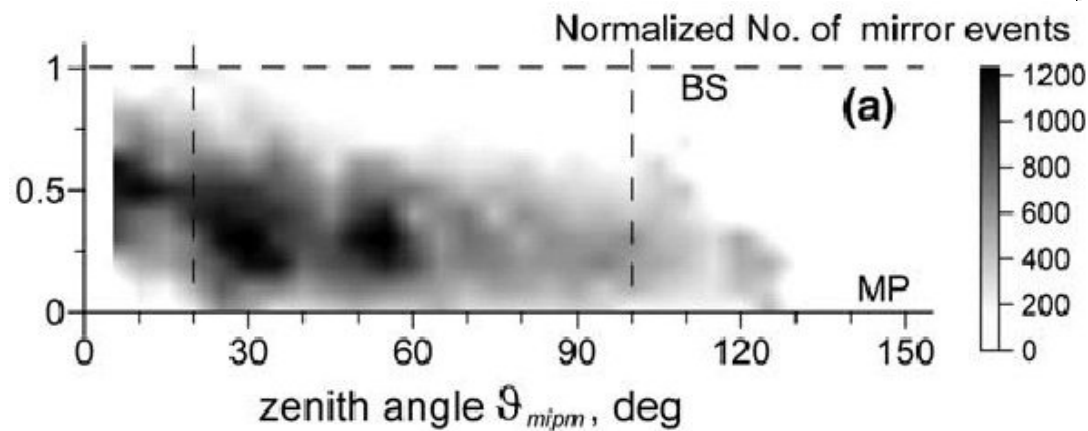
Relative number of mirror mode events



Comparaison CLUSTER / ISEE : occurrence frequency



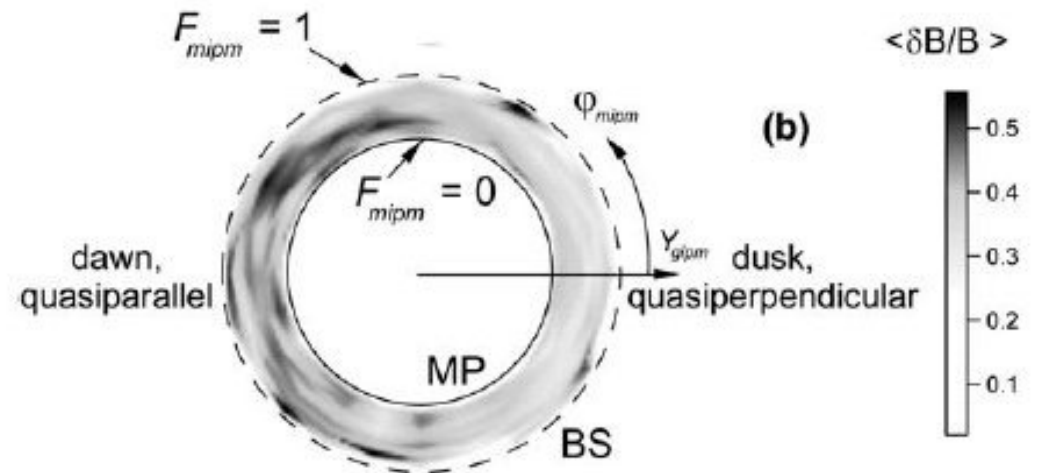
Dawn/dusk asymmetry



Comparaison CLUSTER / ISEE : amplitude distribution

Earth

Mirror modes observed mostly in the inner magnetosheath Region (*Lucek et al., 1999, this study*)

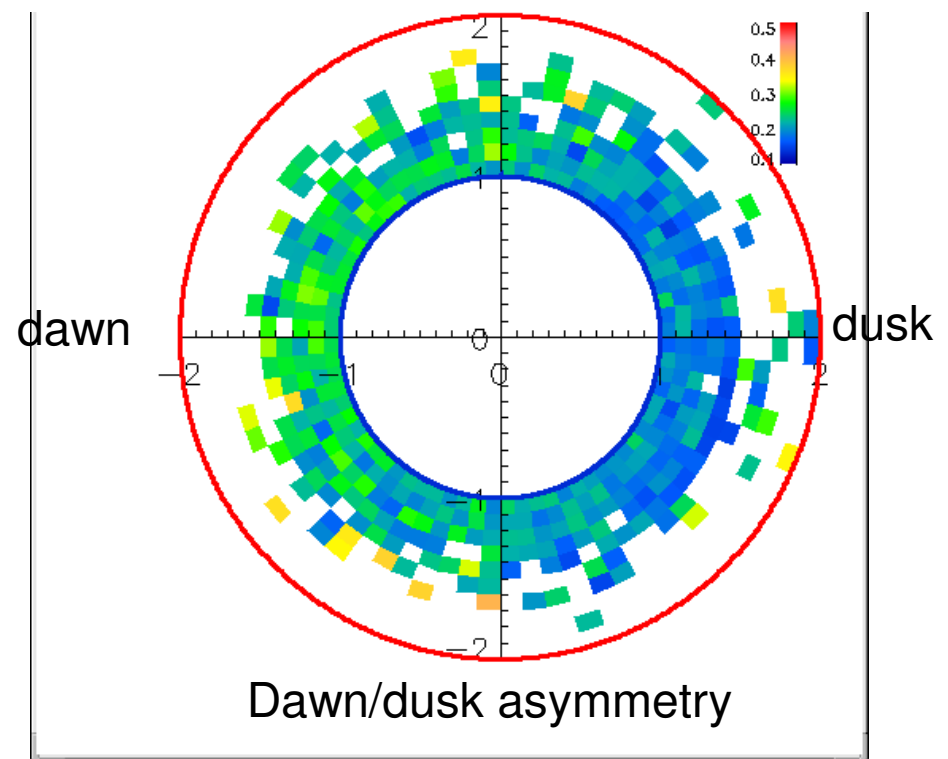


Saturn

Bavassano Cattaneo et al. (1998) found that the amplitude and wavelength of these fluctuations tend to increase with increasing distance from the quasi-perpendicular bow shock, except close to the magnetopause in the plasma depletion layer.

Jupiter

Erdos & Balogh (1996) studied the statistical properties of mirror mode depressions observed by Ulysses and found that the amplitude of the fluctuations was decreasing when approaching the bow shock.

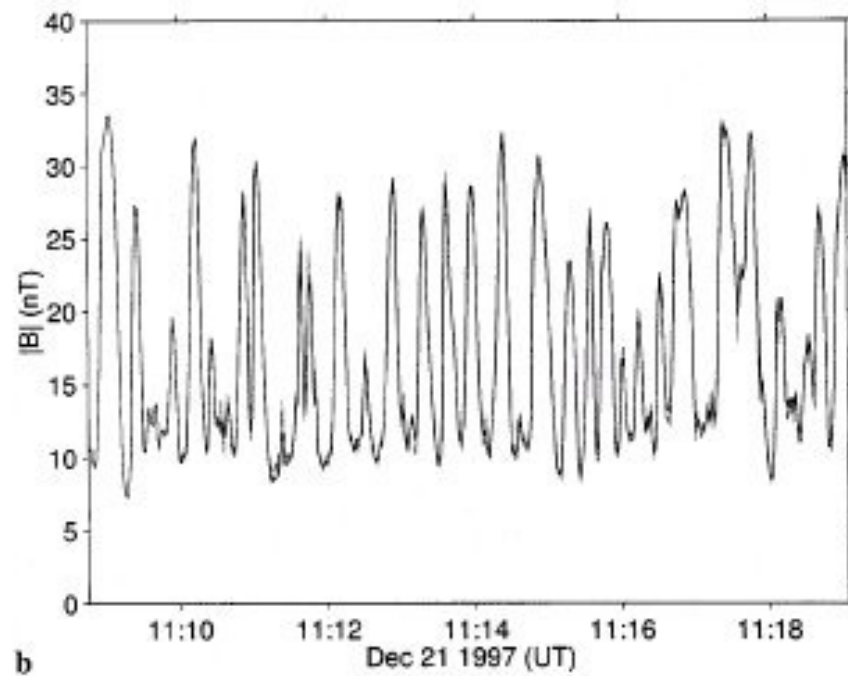


Investigation of mirror-like *peak* and *hole* structures

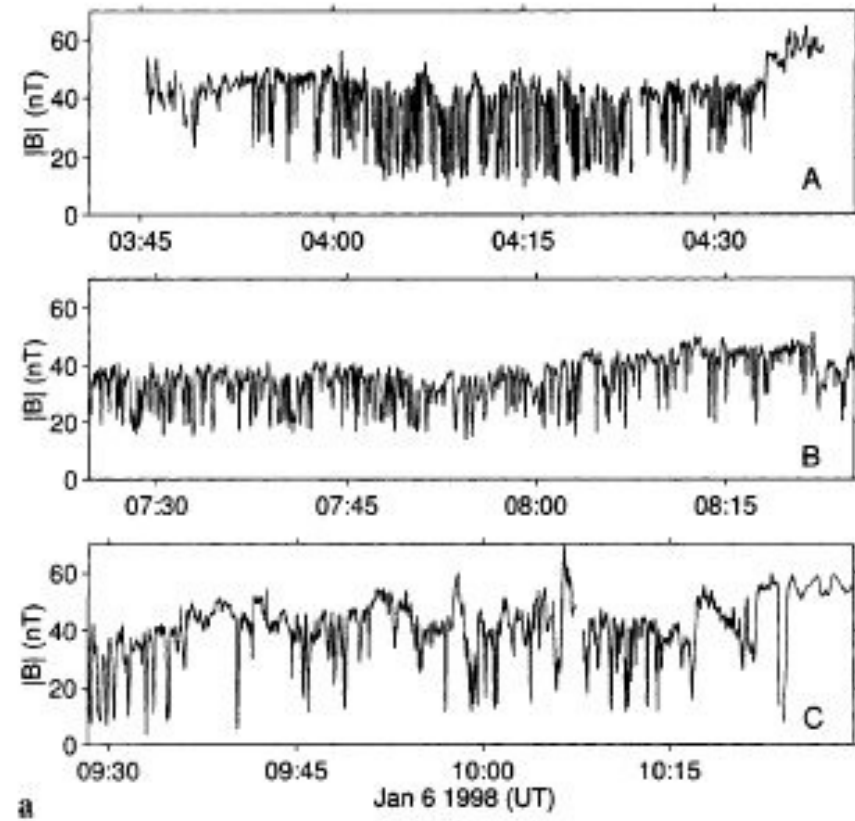
- Observations : statistical analysis of CLUSTER data
- Simulation (*Hellinger et al., 2003 ; Travnicek et al., 2007*)
 - 1D hybrid expanding box simulation
 - Ion = particle
 - Electron = massless (fluid), finite temperature
- Modelisation (*Passot et al., 2006*)
 - MHD model (with uniform T_{\perp})
 - Derivation of equation of state in the quasi-static regime
 - Minimization of a potential energy

Equator-S data

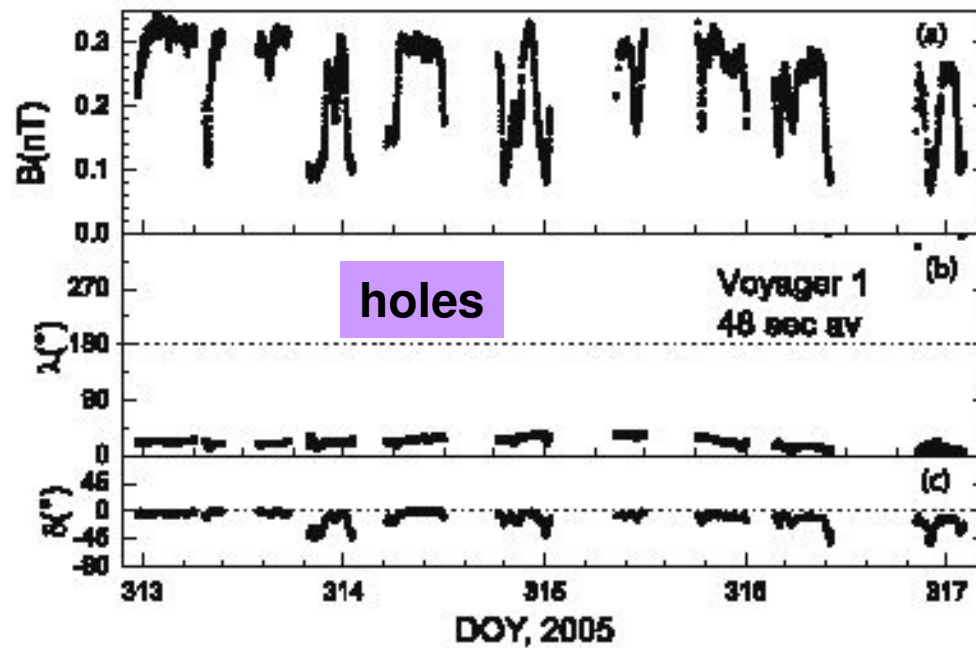
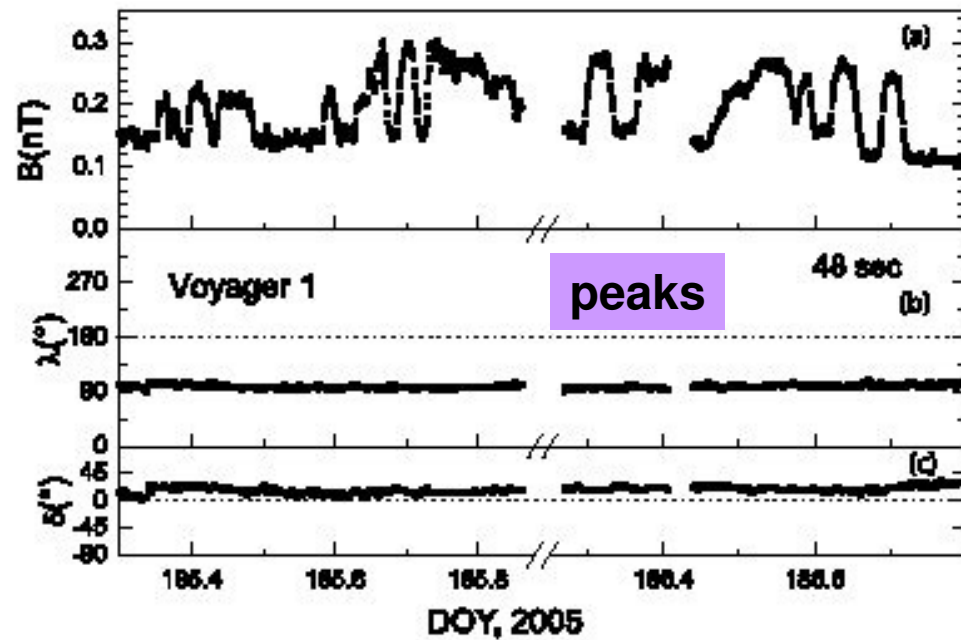
peaks



holes



Lucek et al., 1999

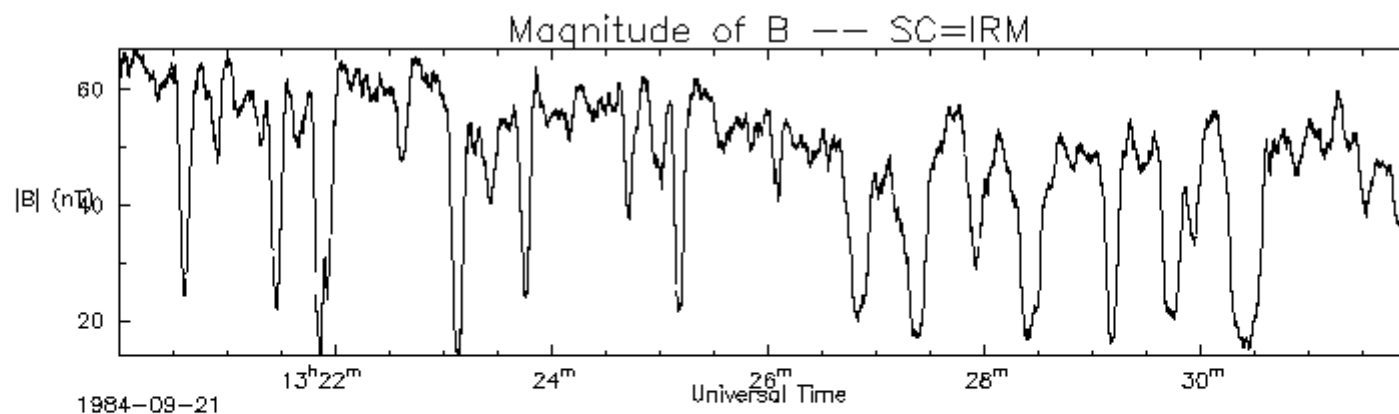


Trains of magnetic holes and
magnetic humps in the
heliosheath observed by
Ulysses

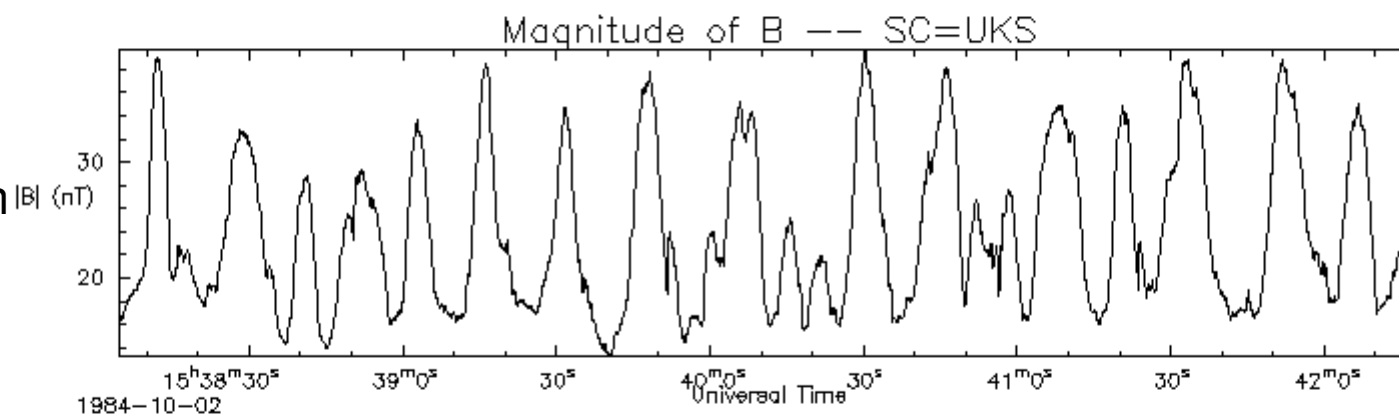
Burlaga et al., 2006

IRM
UKS

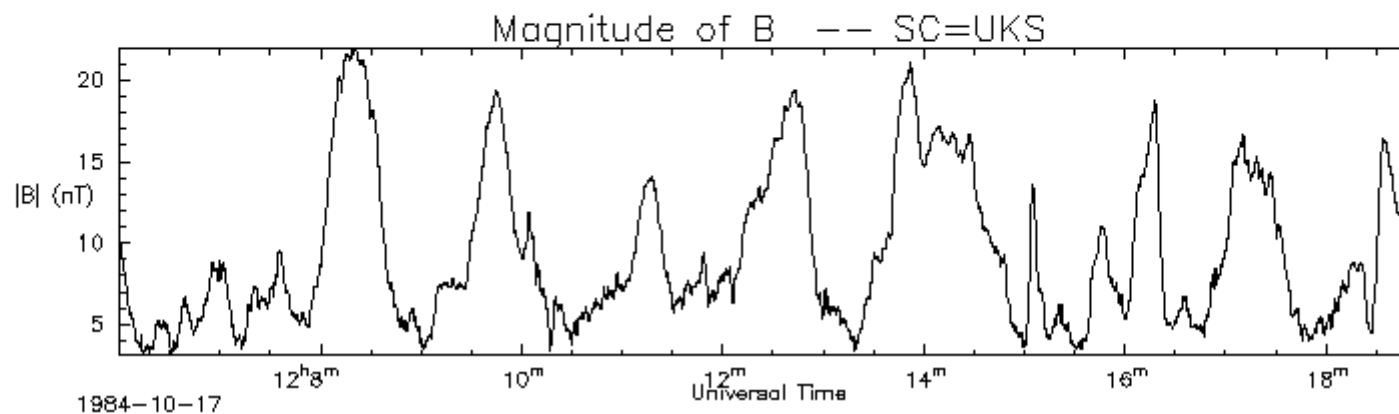
12min

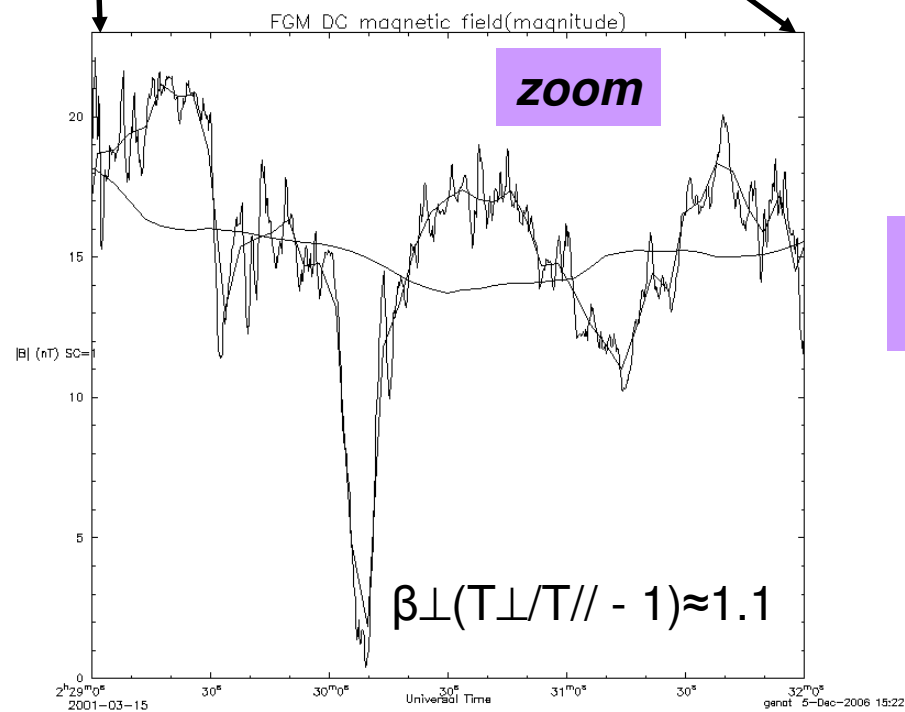
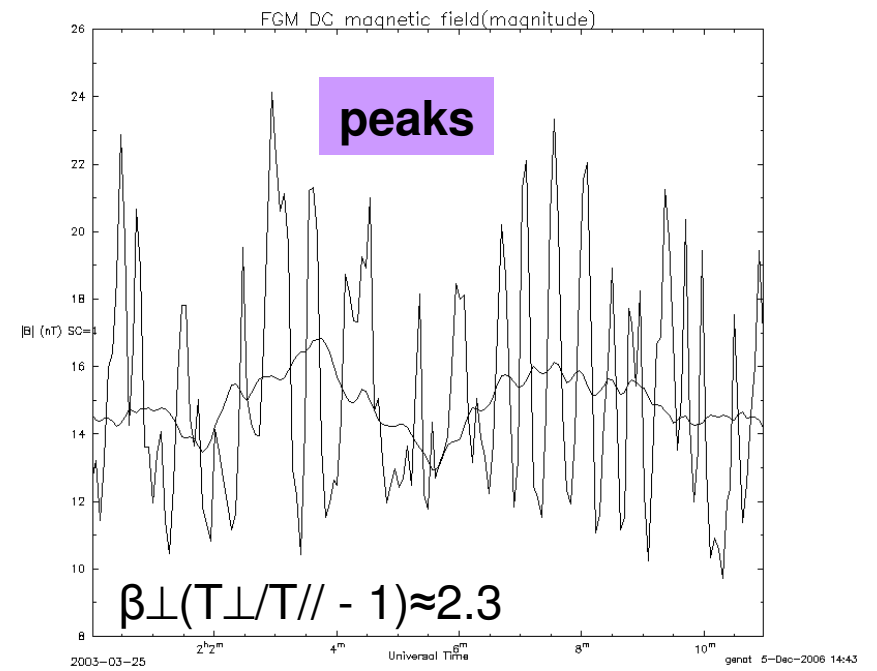
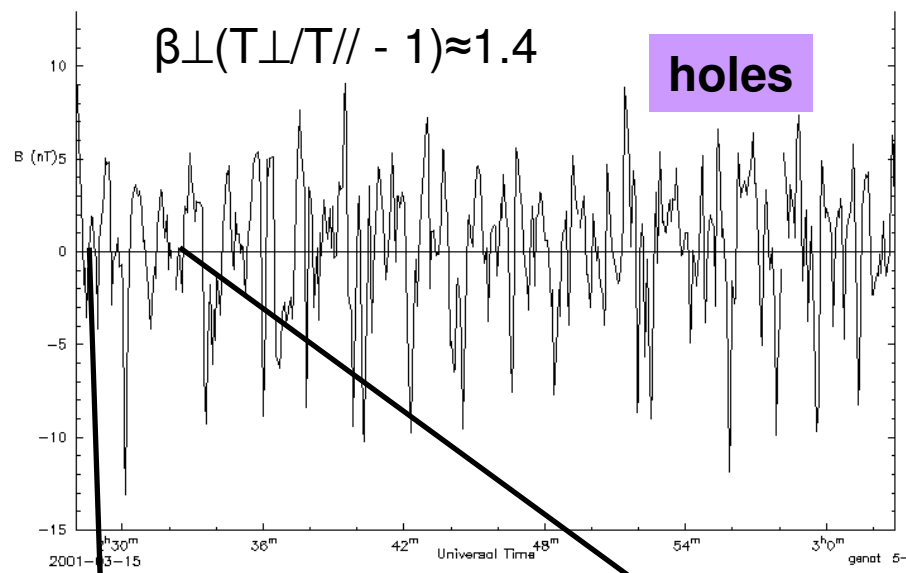


4.5min

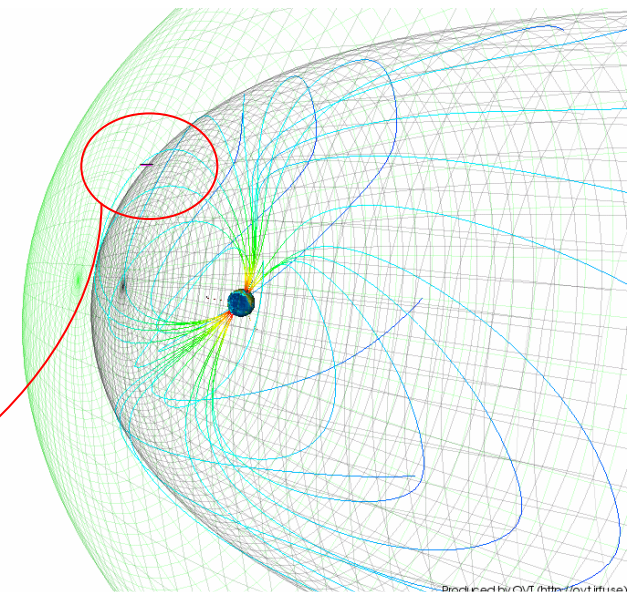


12.5min





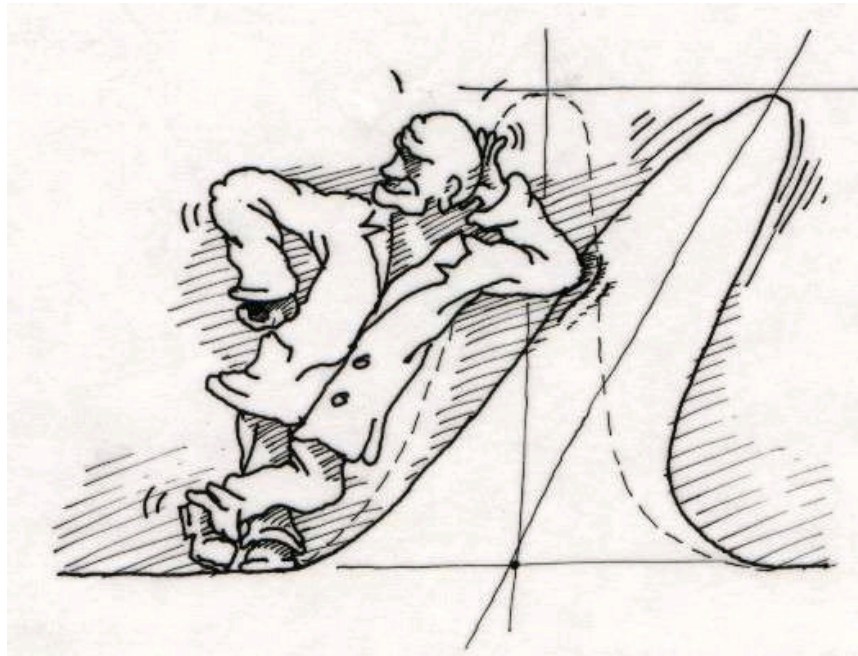
CLUSTER
observations



Questions on holes & peaks

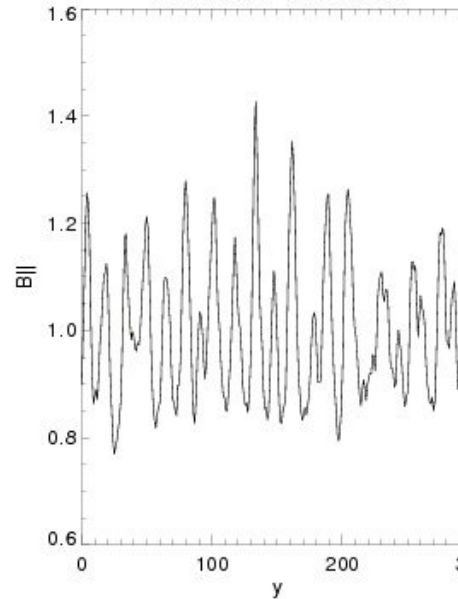
- Where are they localized in the sheath ?
- How are they constrained by local/in situ parameters ?
- Are they present close or far from mirror threshold ?
- Are they *at all* related to mirror instability ?
- What can theory and simulations tell us about their nature ?
- ... *do we have a unified understanding* ?

Skewness of the amplitude distribution of magnetic field fluctuations



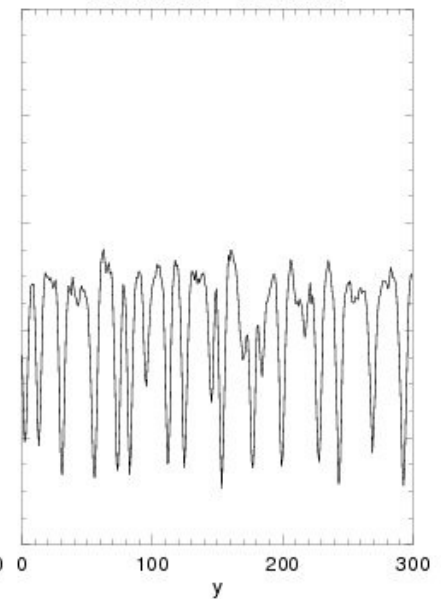
peaks

skewness= 0.652273



holes

skewness= -0.851854



$B - \langle B \rangle$

holes

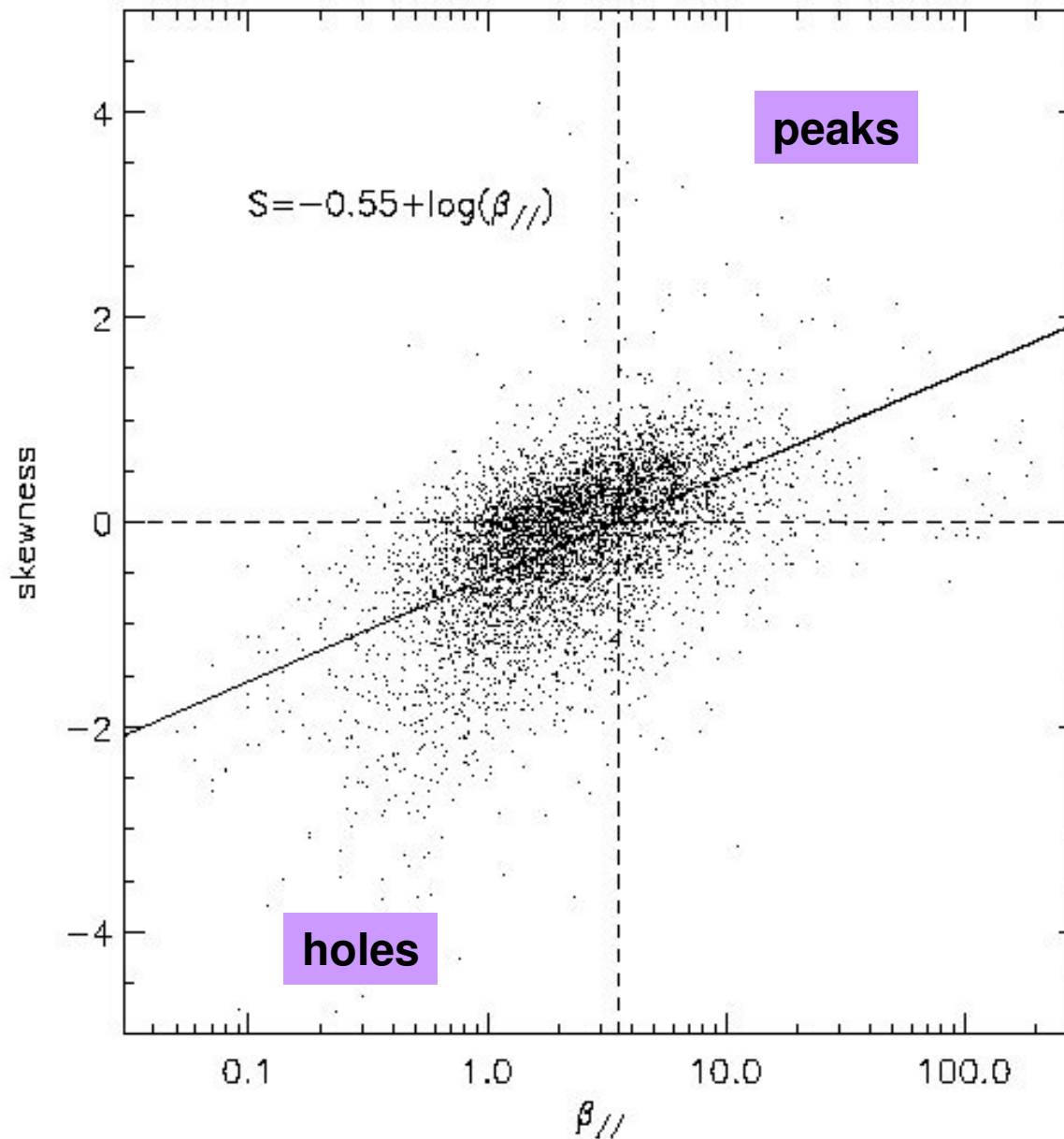


sinusoidal
distribution

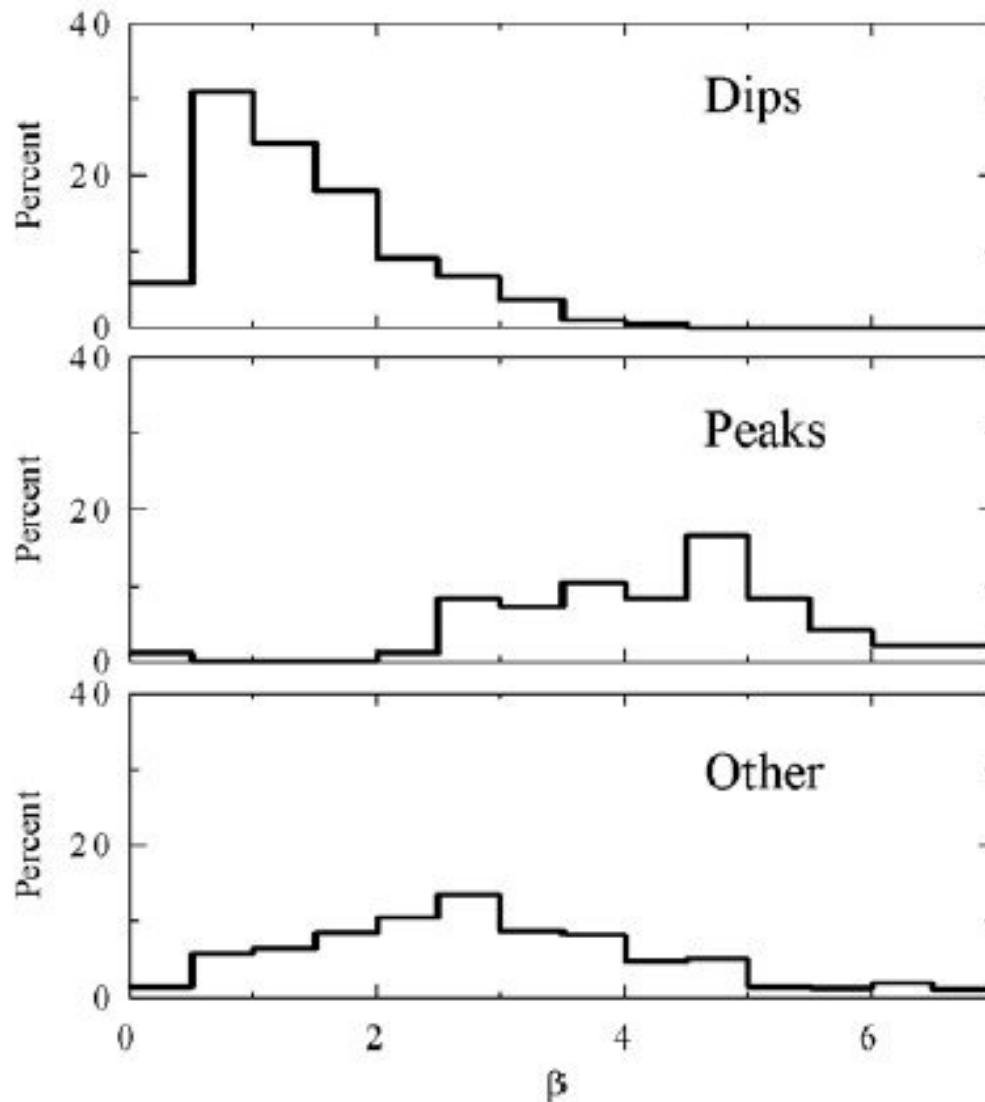


peaks

Cluster observations : 'B test' magnetosheath events



The skewness of the magnetic field distribution is calculated in each 5min window where the 'B test' is positive



Joy et al., 2006

On Jupiter :

- Dips are primarily observed in relatively low (<3) β plasma

- Peaks are observed when β is higher (3–6).

In his model, *Pantellini [1998]* showed that dips form preferentially when β is relatively small (>1) and peaks form when the anisotropy and β are relatively high ($T_{\perp}/T_{\parallel} < 0.5$, $\beta_{\parallel} > 10$).

Linear mirror mode instability threshold

In the low frequency, long wavelength limit of the Vlasov-Maxwell equation

$$\beta_{p\perp} \left(\frac{T_{p\perp}}{T_{p\parallel}} - 1 \right) + \beta_{e\perp} \left(\frac{T_{e\perp}}{T_{e\parallel}} - 1 \right) > 1 + \frac{\left(\frac{T_{p\perp}}{T_{p\parallel}} - \frac{T_{e\perp}}{T_{e\parallel}} \right)^2}{2 \left(\frac{1}{\beta_{p\parallel}} + \frac{1}{\beta_{e\parallel}} \right)}$$

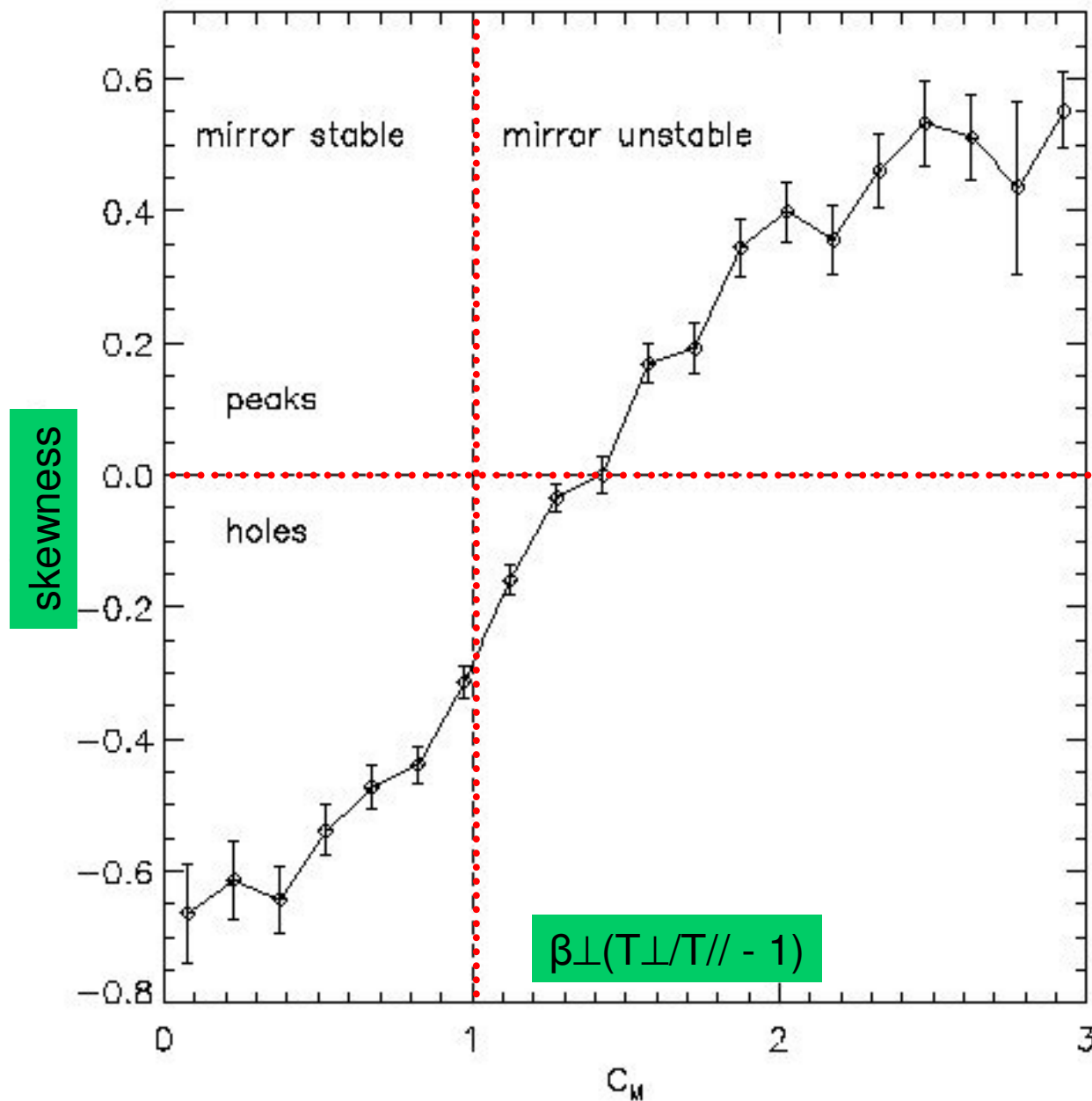
Stix, 1962
Hall, 1979

For isotropic cold electrons ($T_{e\perp}=T_{e\parallel}$, $\beta_e \rightarrow 0$)

$$C_M = \beta_{p\perp} \left(\frac{T_{p\perp}}{T_{p\parallel}} - 1 \right) > 1$$

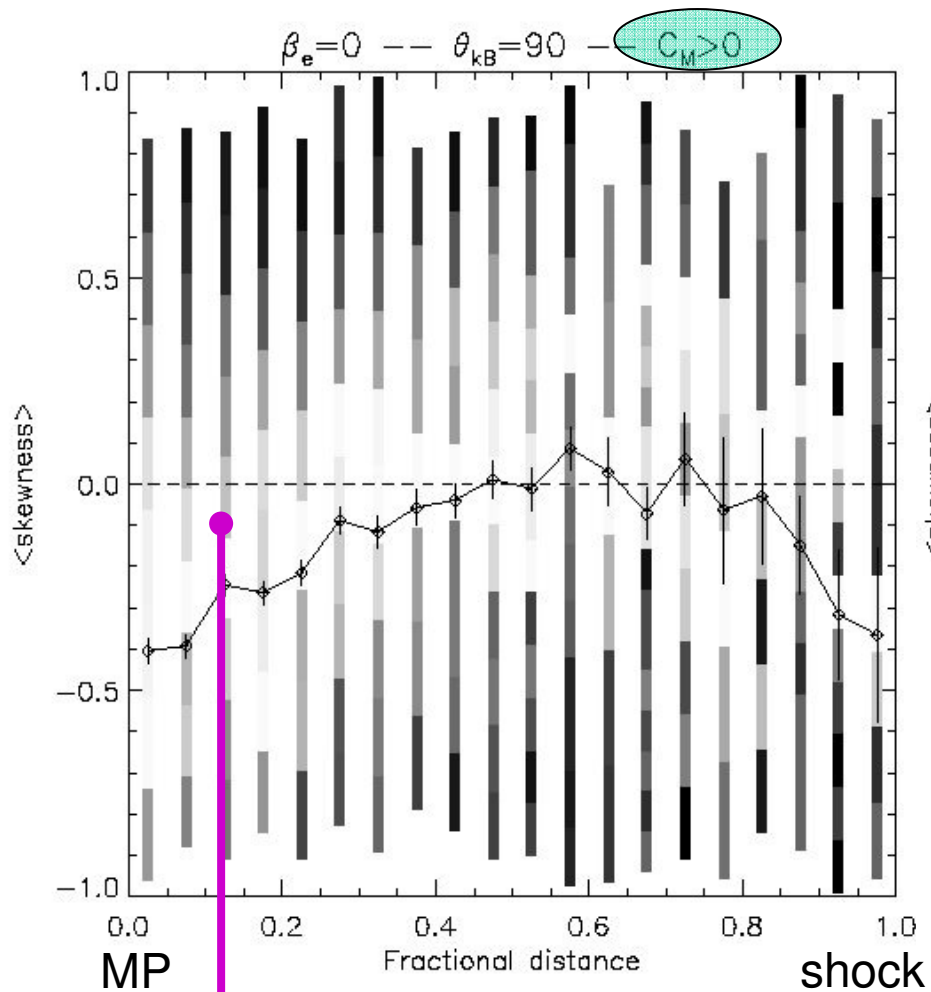
Typical magnetosheath regime is such that $C_M > 0$

Cluster observations : 'B test' magnetosheath events

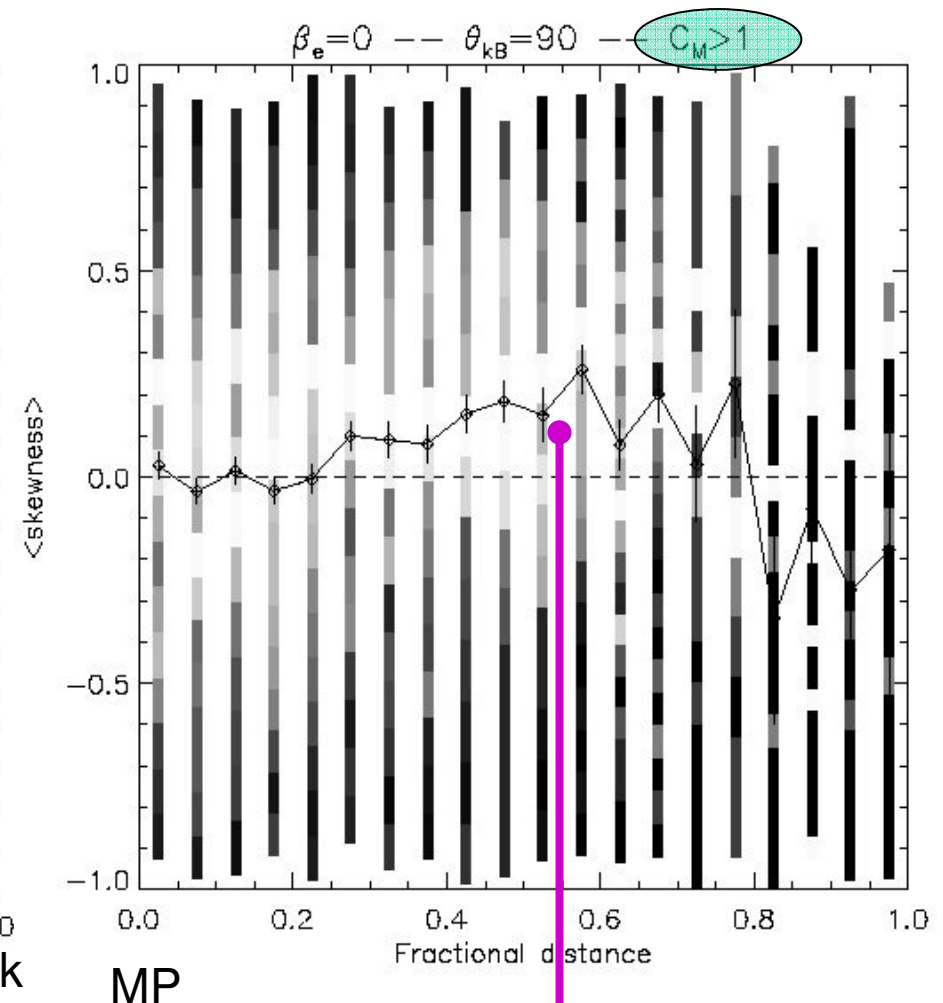


The average skewness is calculated in each C_M bin

Structures localization in the magnetosheath



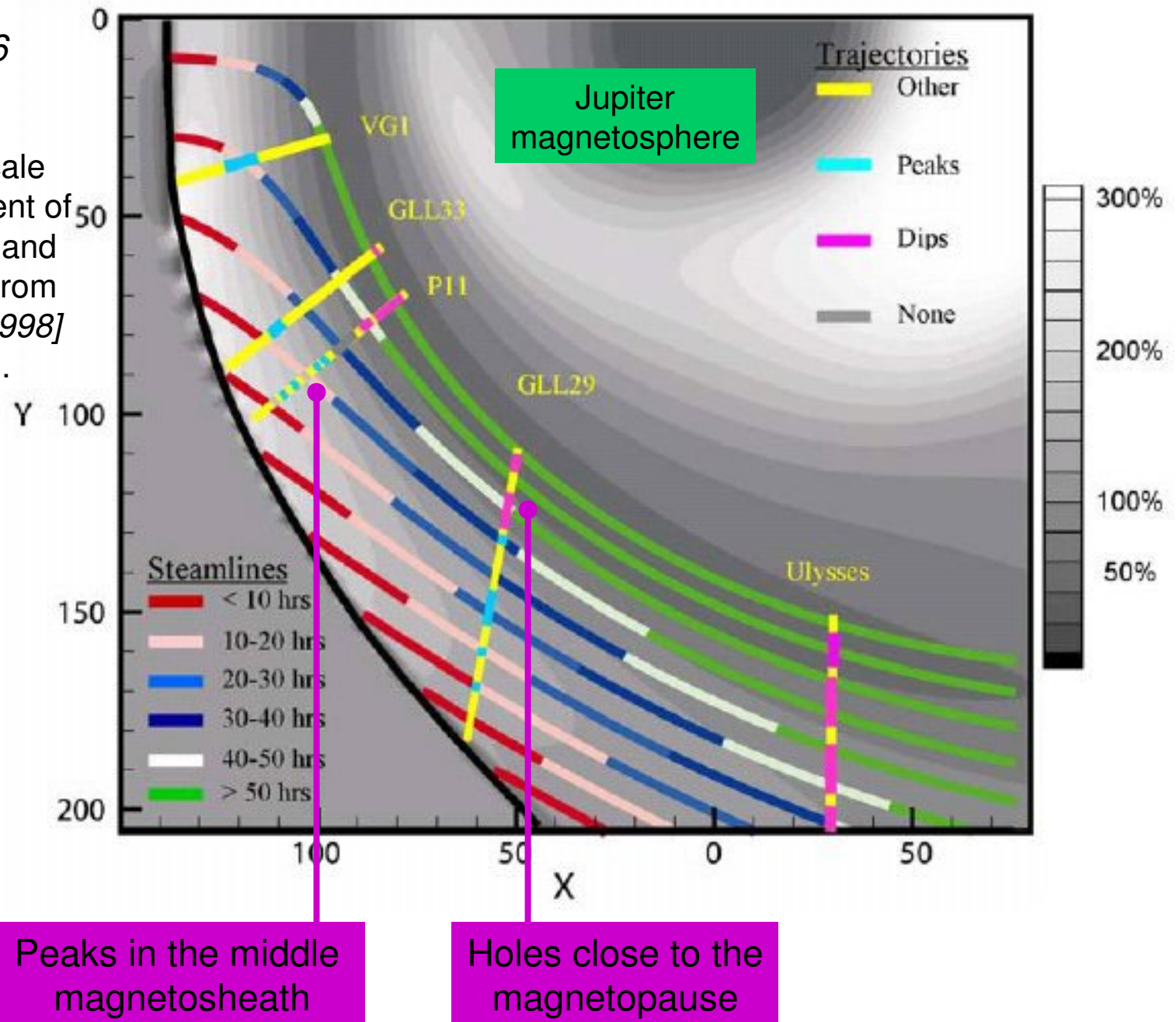
NL hole structures in a mirror stable plasma



'peaked' unstable mirror modes

Joy et al., 2006

Plasma β (grayscale contours as percent of solar wind value) and flow streamlines from an Ogino et al. [1998] Jupiter simulation.



Piece-wise nonlinear solutions

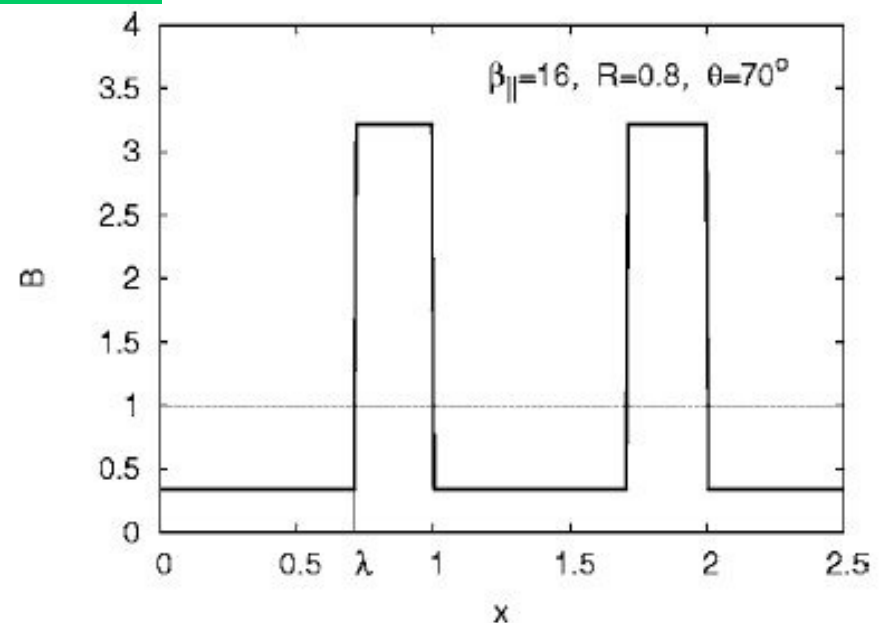
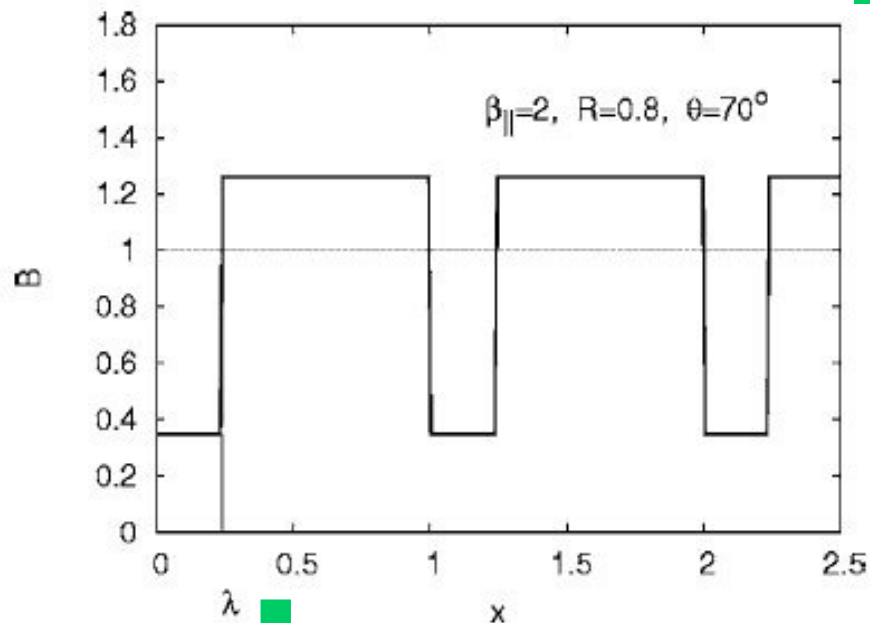
From the fluid model of *Passot et al., 2006*

- Equation of state in the quasi-static regime : $T_{\parallel} = \text{cst}$ and $T_{\perp}/T_{\perp 0} = \frac{B/B_0}{(A+1)B/B_0 - A}$
- Potential energy minimization
- Constraints = particle conservation + frozen-in magnetic field $A = T_{\perp 0}/T_{\parallel 0} - 1$

Small β , $C_M=0.625$ --- holes

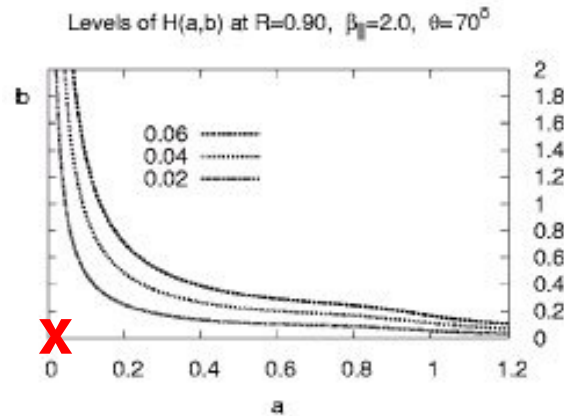
Strong β , $C_M=5$ --- peaks

$T_{\perp}/T_{\parallel}=1.25$

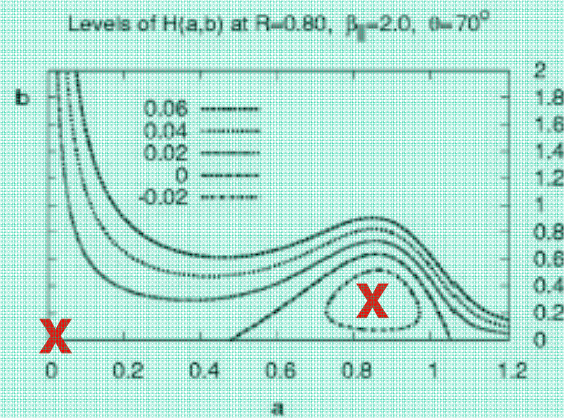


bistability regime

Fluid model : solutions .vs. anisotropy

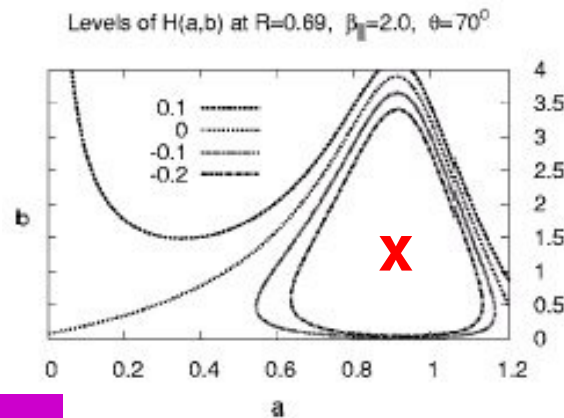


Linearly stable



Bistability regime

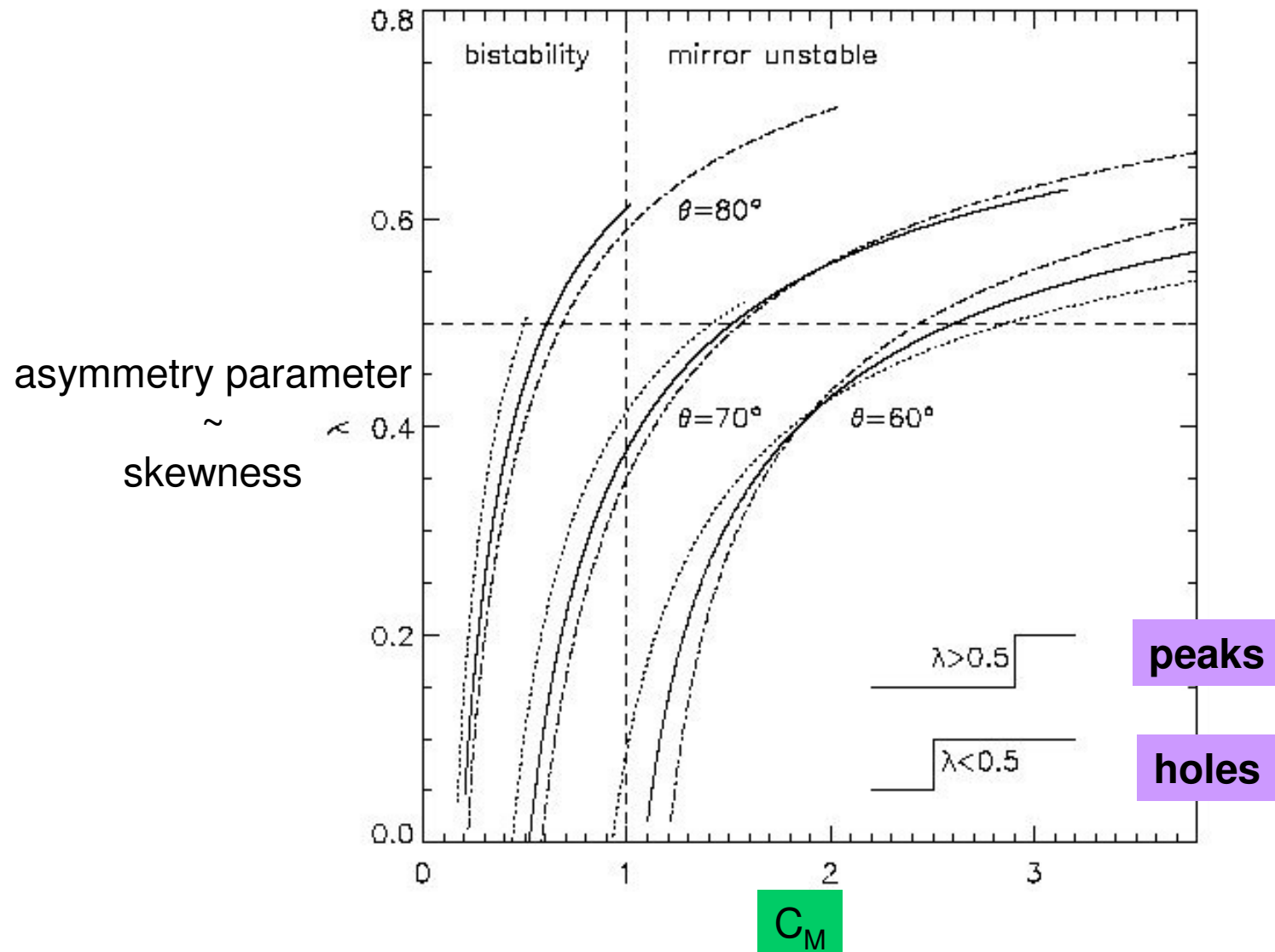
Linearly stable / nonlinear structure



Linearly unstable / nonlinear structure

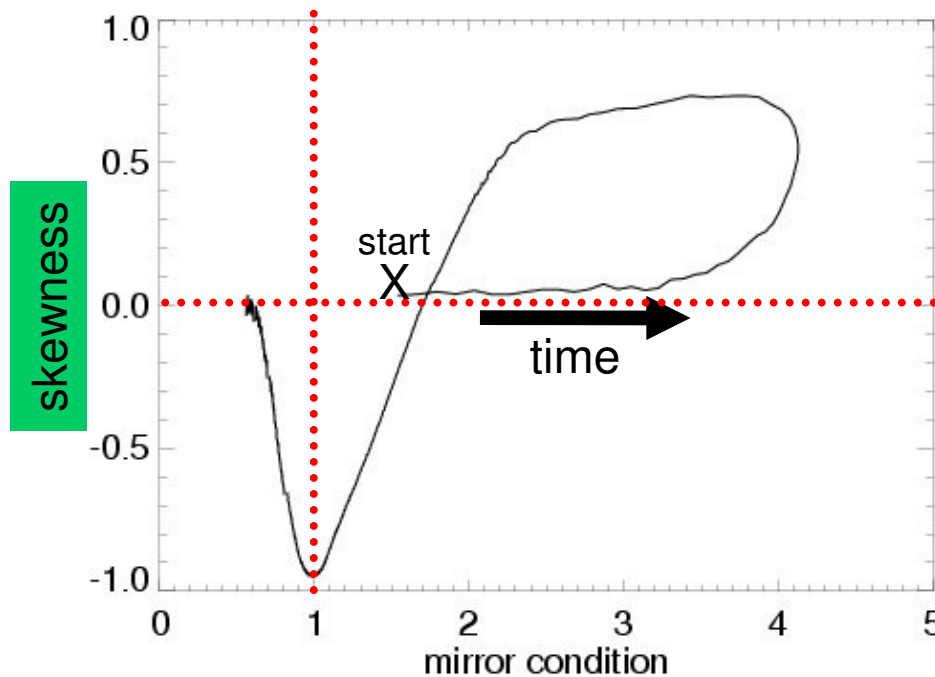
anisotropy

Fluid model : asymmetry .vs. C_M



2D Hybrid expanding box simulations : a dynamical perspective

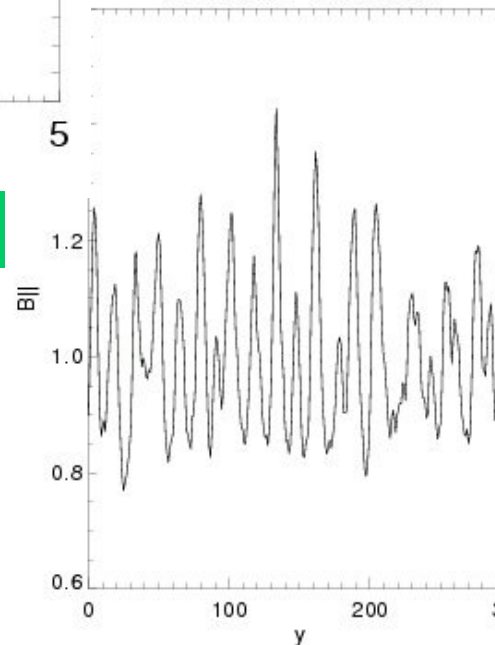
Hellinger et al., 2003
Travnicek et al., 2007



$\beta_{\perp}(T_{\perp}/T_{\parallel} - 1)$ -electron term

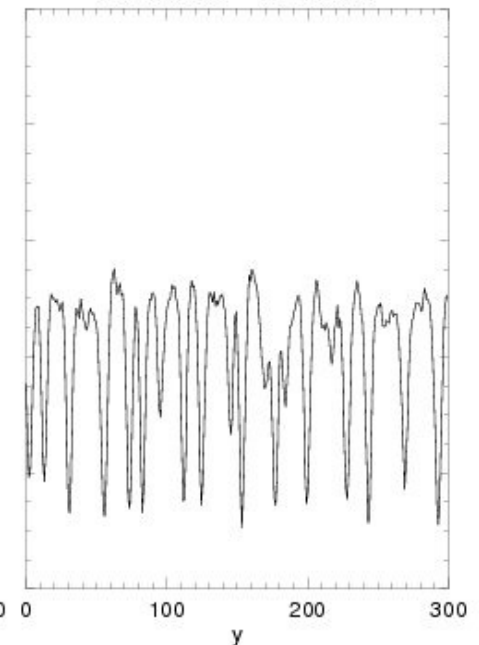
peaks

skewness= 0.652273



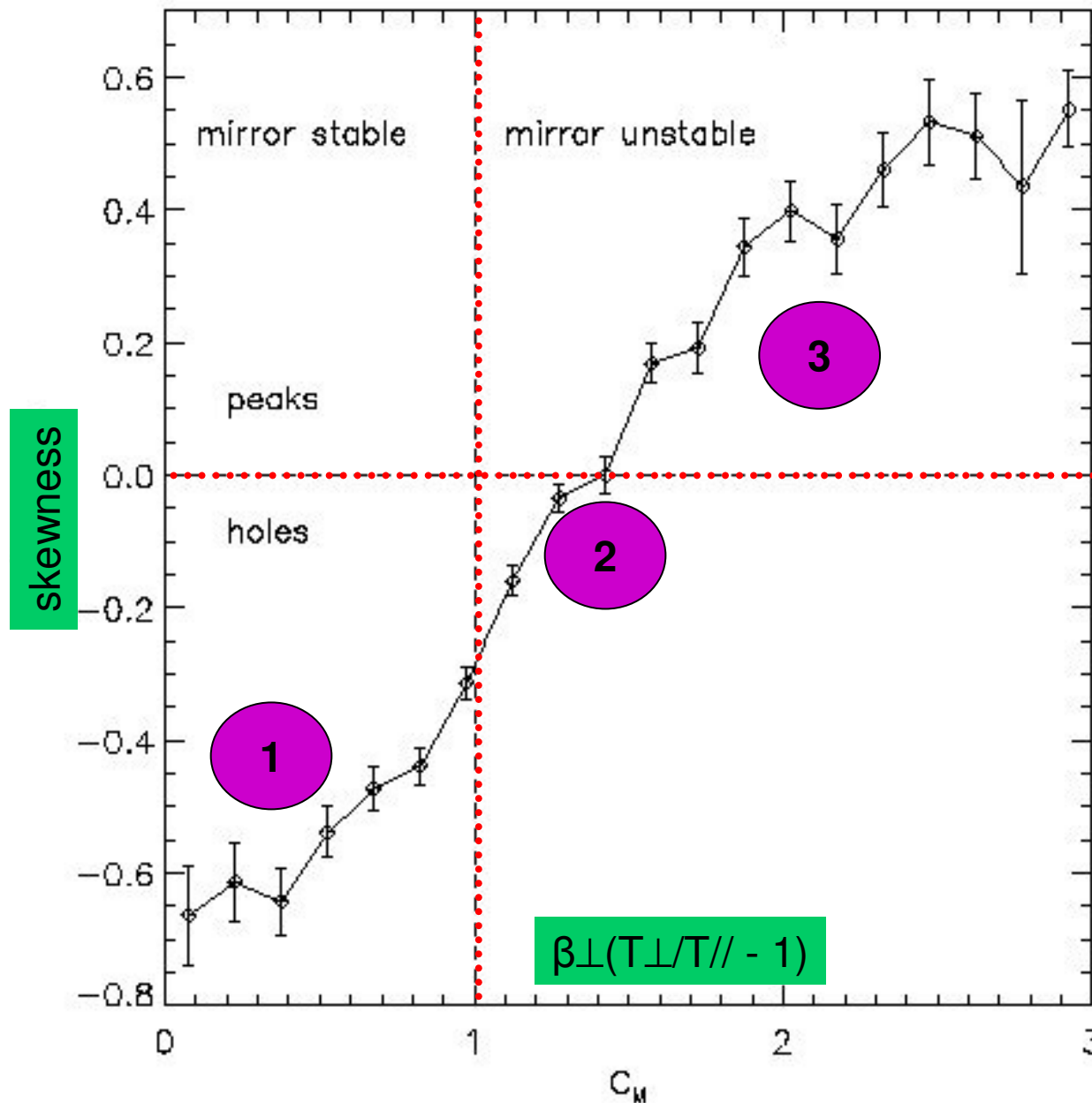
holes

skewness= -0.851854



Expanding box, $\beta_e=1$, $\theta=90^\circ$

Cluster observations : 'B test' magnetosheath events



1

- holes in small beta region
- linearly stable nonlinear structures in the *bistability* region
- corresponds to evolved peaks in the late simulation phase

2

- linear mirror mode
- 'classical' sinusoidal shape

3

- peaks in large or moderate beta region
- corresponds to the saturation phase of the hybrid simulations

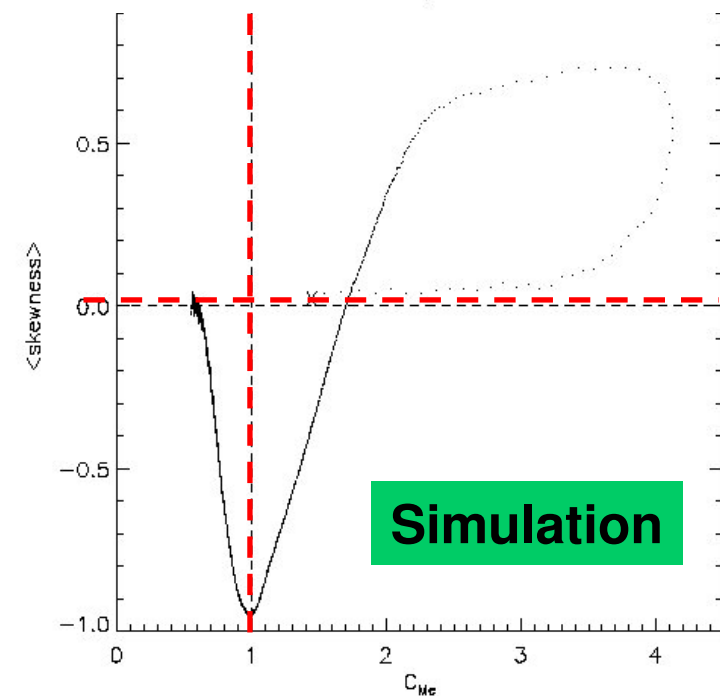
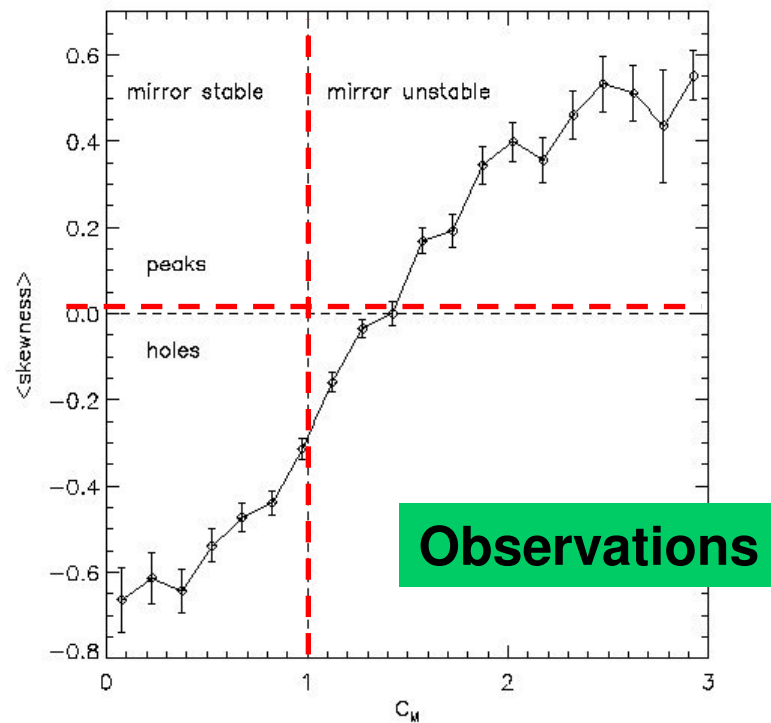
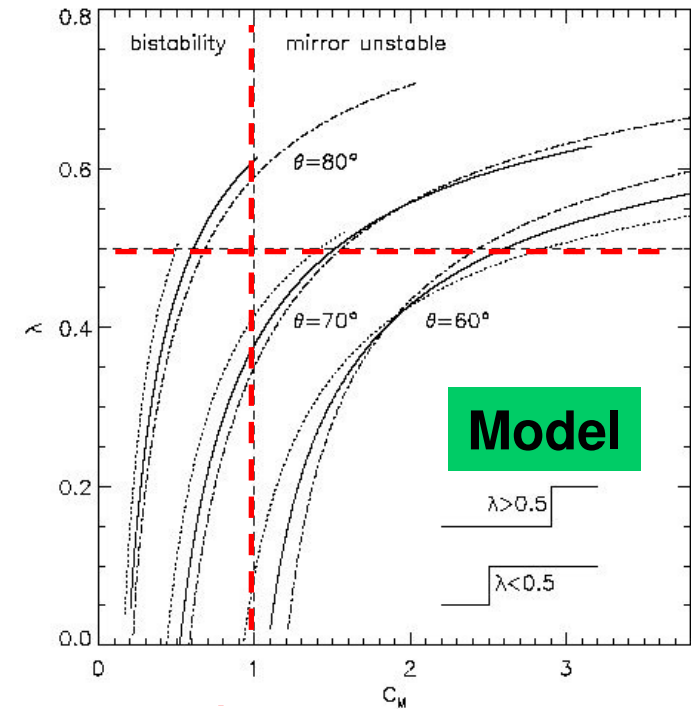
3 complementary approaches

model : $T_e=0$, fixed β , varying anisotropy

simulation : $\theta=90^\circ$, finite T_e

observations : $T_e=0$

- similar general trend : skewness=0 for $C_M \sim 1.5$
- isolated holes and grouped peaks



Conclusions

Below threshold, only holes are predicted by theory and simulations and are effectively observed by CLUSTER.

The transition hole/peak with distance to threshold is consistent within the three approaches.

Magnetic holes do not result from direct nonlinear saturation of the mirror instability which rather leads to magnetic peaks.

Simulations suggest that the long time evolution of magnetic peaks, resulting from the mirror instability far enough from threshold, may eventually lead to magnetic holes.

Magnetic holes are also stable solutions of the Vlasov-Maxwell equations, above and below threshold. This is the reason why they may appear more isolated than peaks.

The bistability phenomenon may explain the presence of mirror-like structures in the data, below the linear threshold. It is an alternative to convection which is usually invoked.