Field-aligned and gyrating ion beams in the Earth's foreshock

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"A collaborative Effort to Study the Production and Transport of 1-30 keV Upstream ions"

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Outline

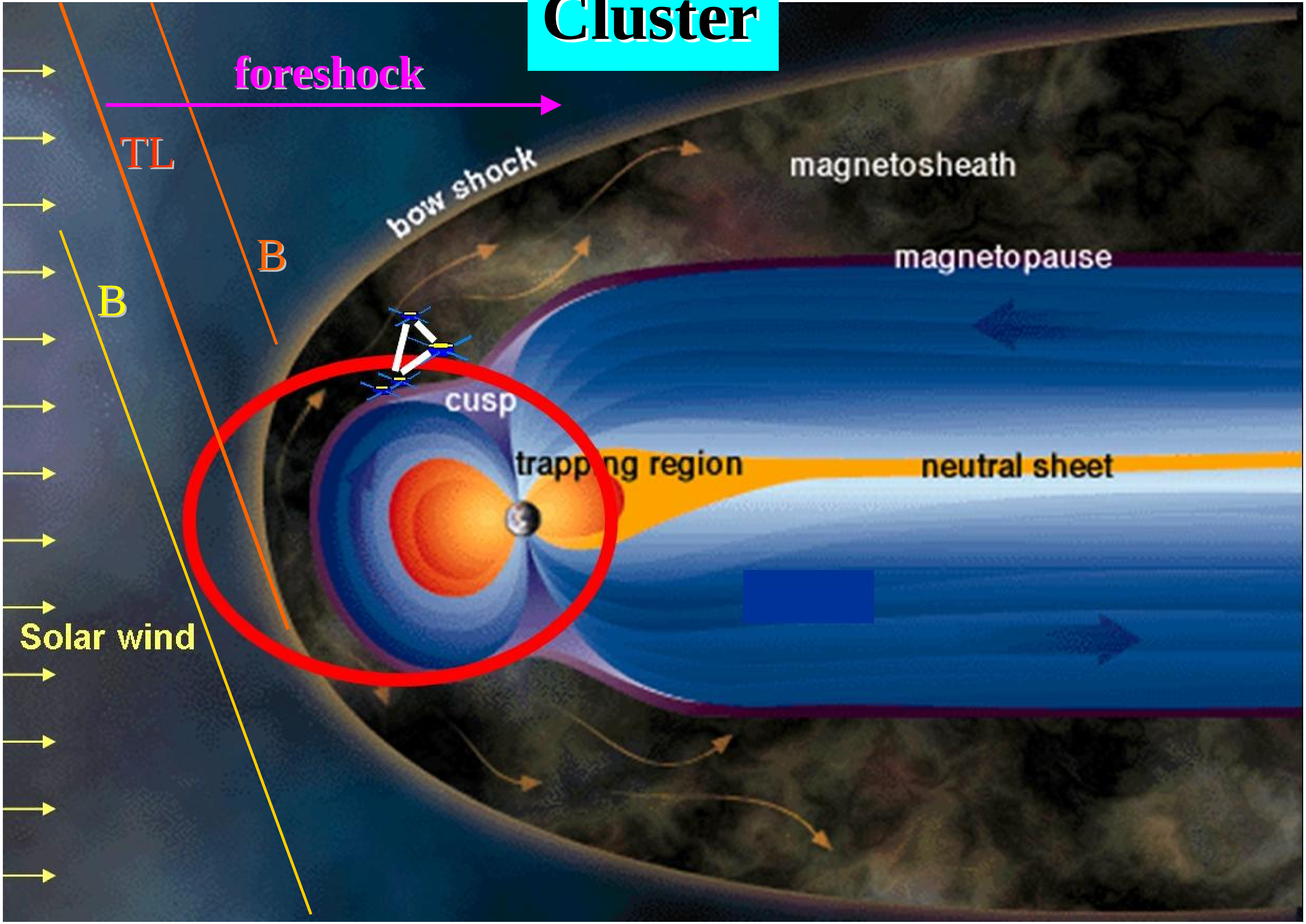
1- Gyrophase-bunched ion distributions in the ion foreshock

2- Low Frequency wave properties

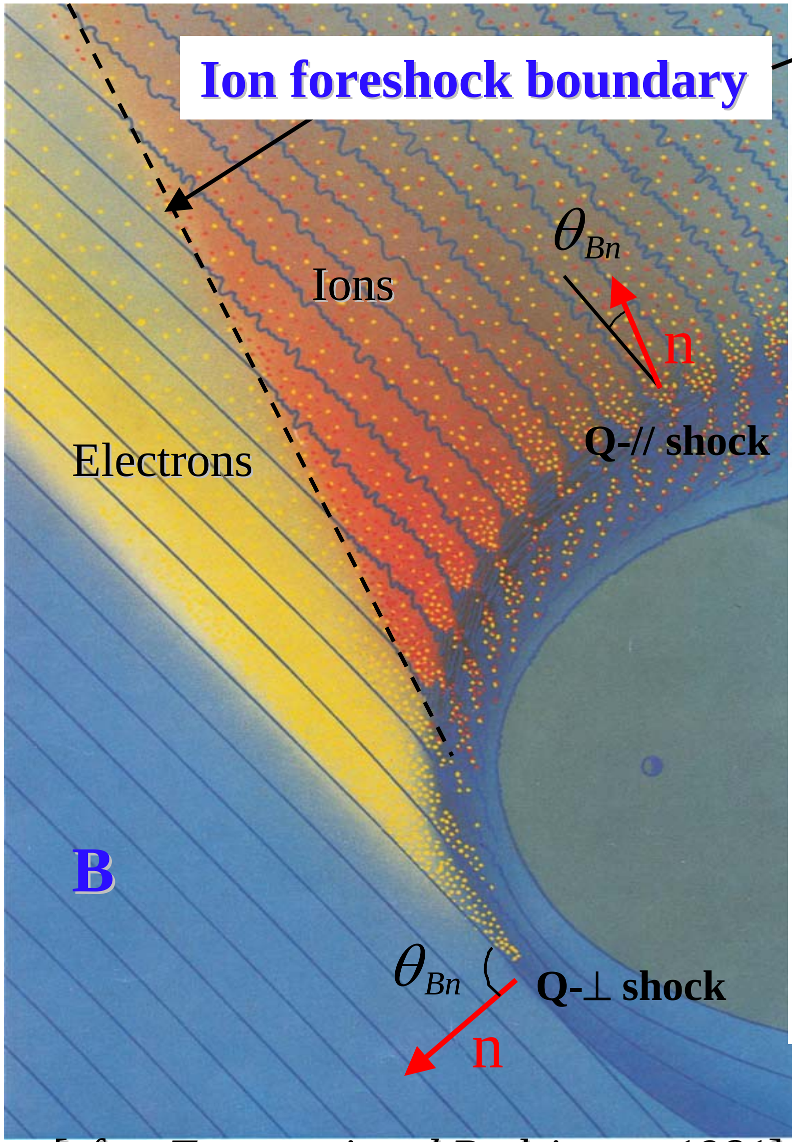
3- Wave excitation: linear theory
Cyclotron resonance

4- Nonlinear coherent wave-particle interaction

Cluster

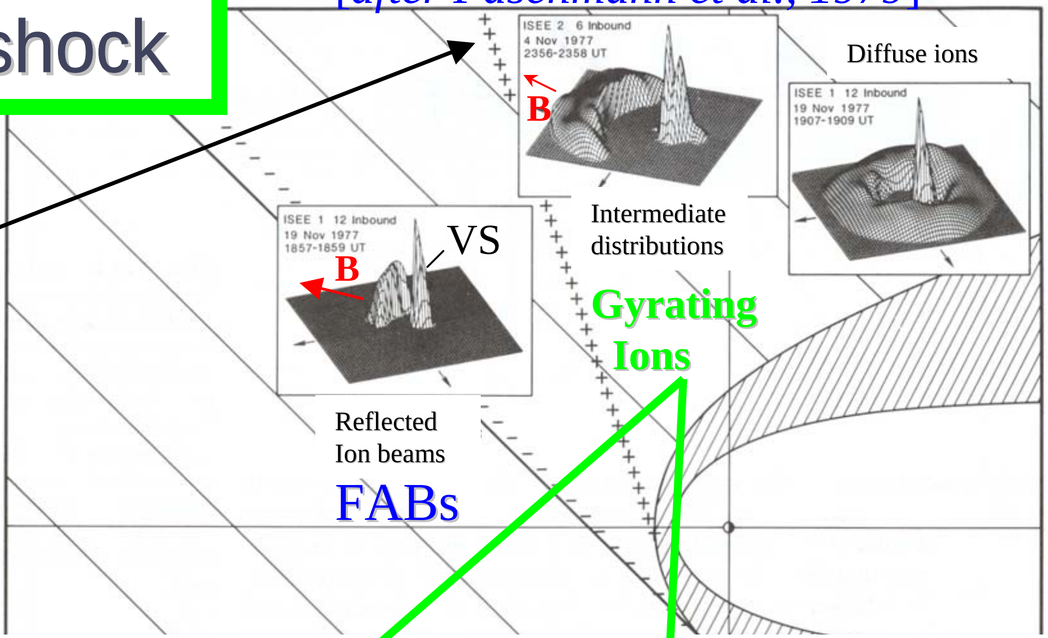

foreshock
TL
B
B
bow shock
magnetosheath
magnetopause
cusp
trapping region
neutral sheet
Solar wind

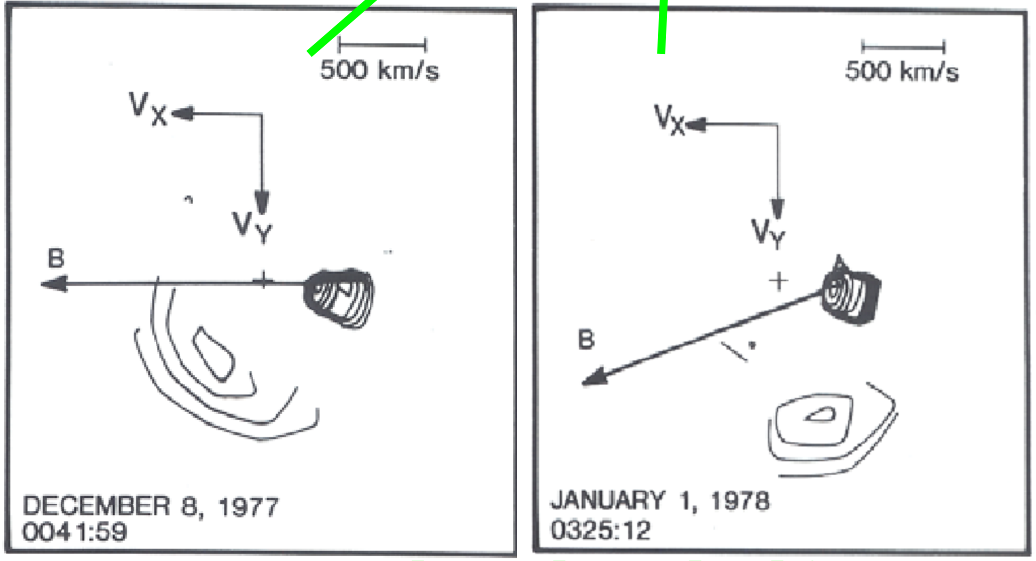
Planetary Foreshock



[after *Tsurutani and Rodriguez, 1981*]

[*after Paschmann et al., 1979*]

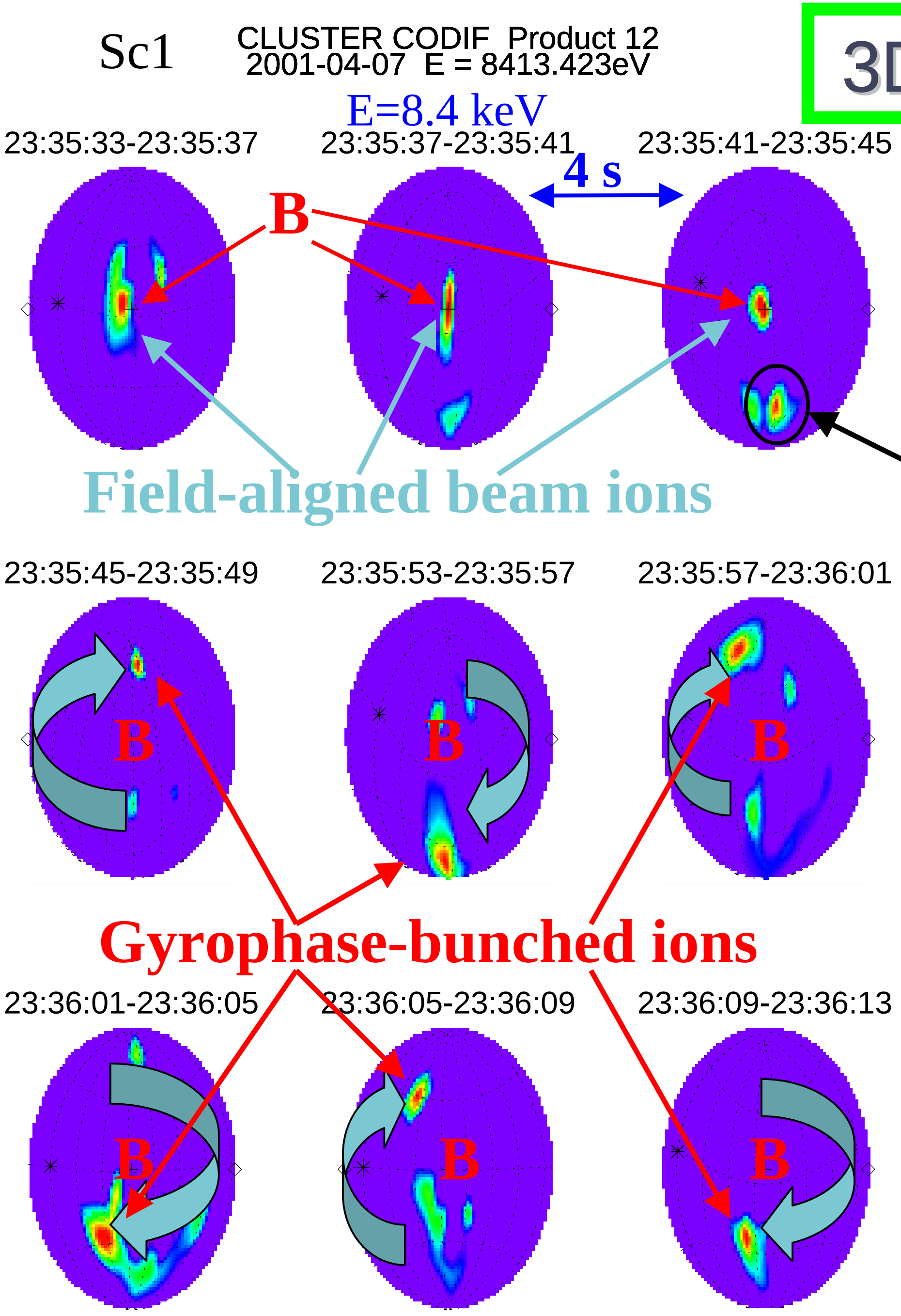




Gyrophase-bunched ions

[*Thomsen et al., 1985*]

3D angular distributions (H^+)



Field-aligned beam ions

Gyrophase-bunched ions

Projection of the normalized distribution function on a constant energy sphere **in the solar wind frame**

Centered on the background field B (averaged on the observation interval)

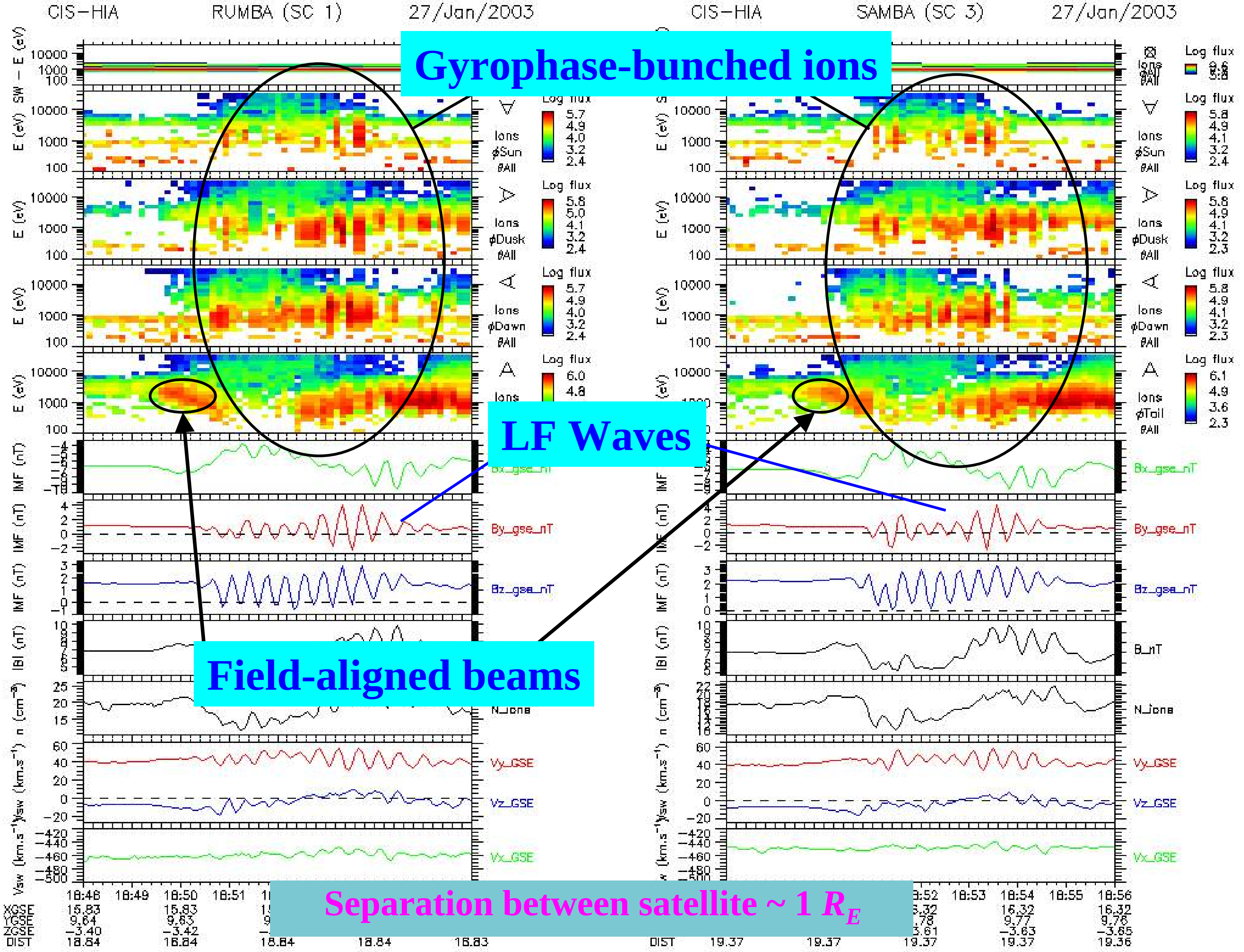
Subsequent distributions for the energy level of maximum flux (~8 keV)

Accumulation time : 4 s
Cyclotron period : 7 s

Modification of the distribution

Large pitch-angles (~60°) in SW frame
Distributions highly **non gyrotropic**

[*Mazelle, et al., Planet Sp. Sci., 2003*]



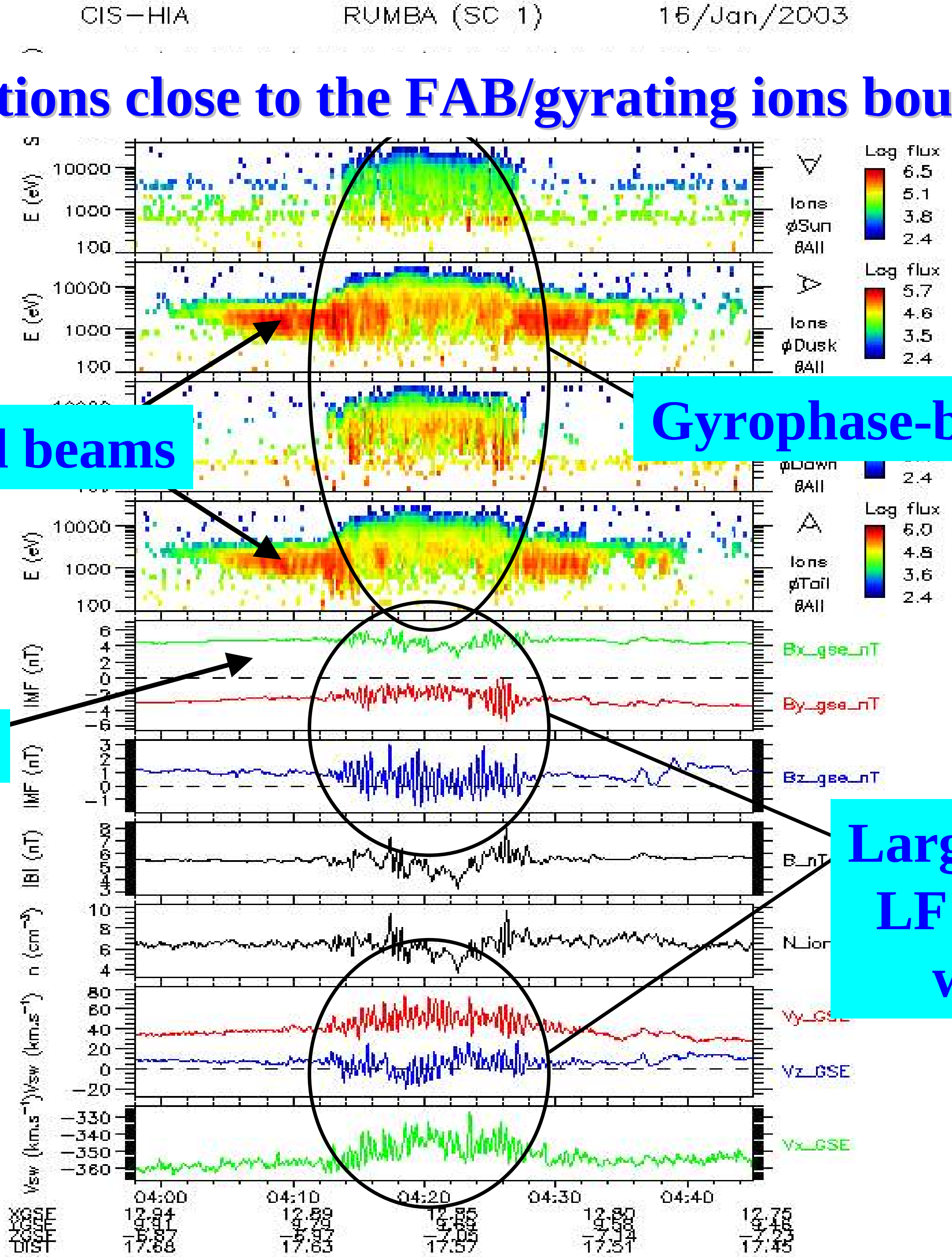
Gyrophase-bunched ions

LF Waves

Field-aligned beams

Separation between satellite ~ 1 R_E

Observations close to the FAB/gyrating ions boundary



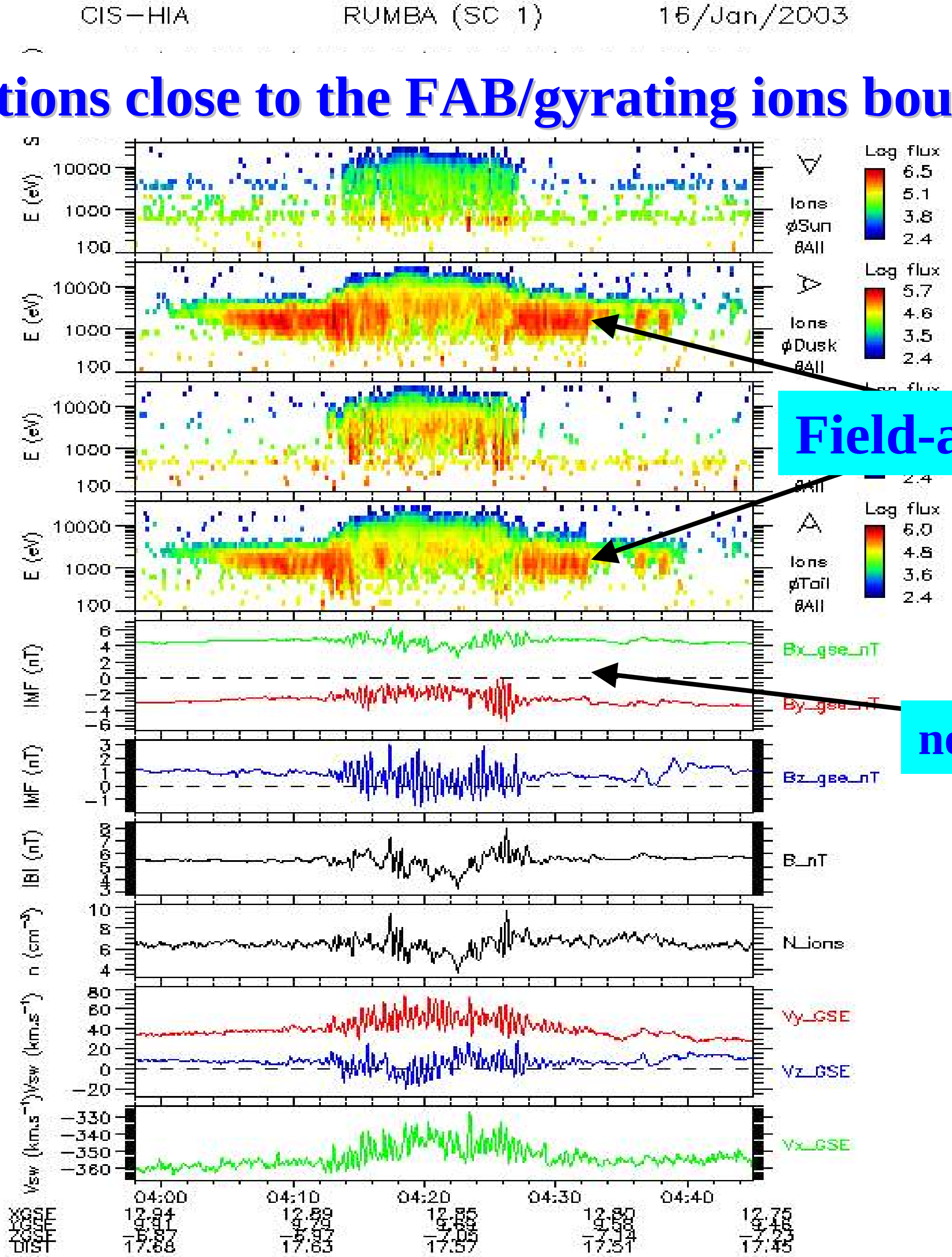
Field-aligned beams

no obvious wave

Gyrophase-bunched ions

Large amplitude LF coherent waves

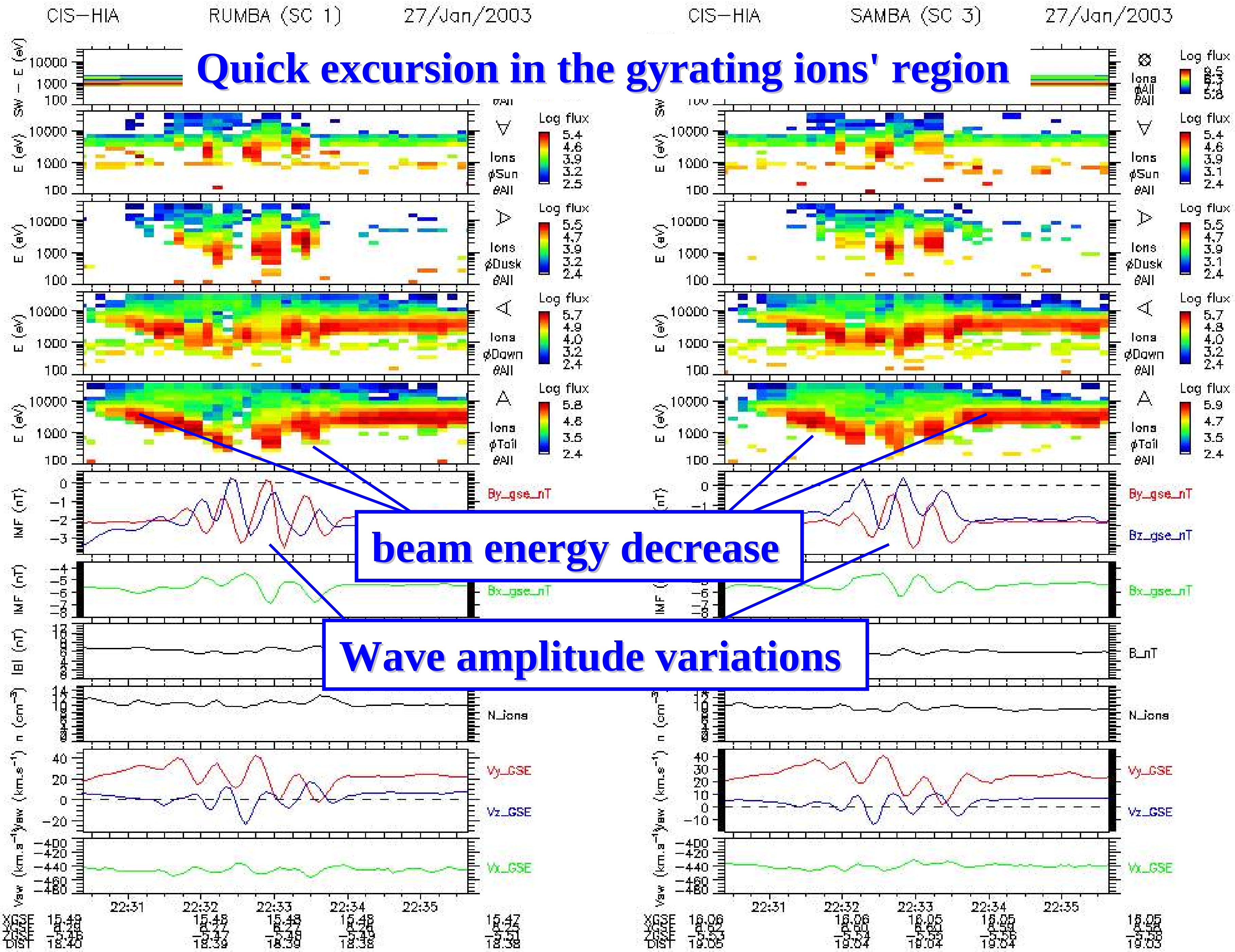
Observations close to the FAB/gyrating ions boundary



Field-aligned beams

no obvious wave

Quick excursion in the gyrating ions' region

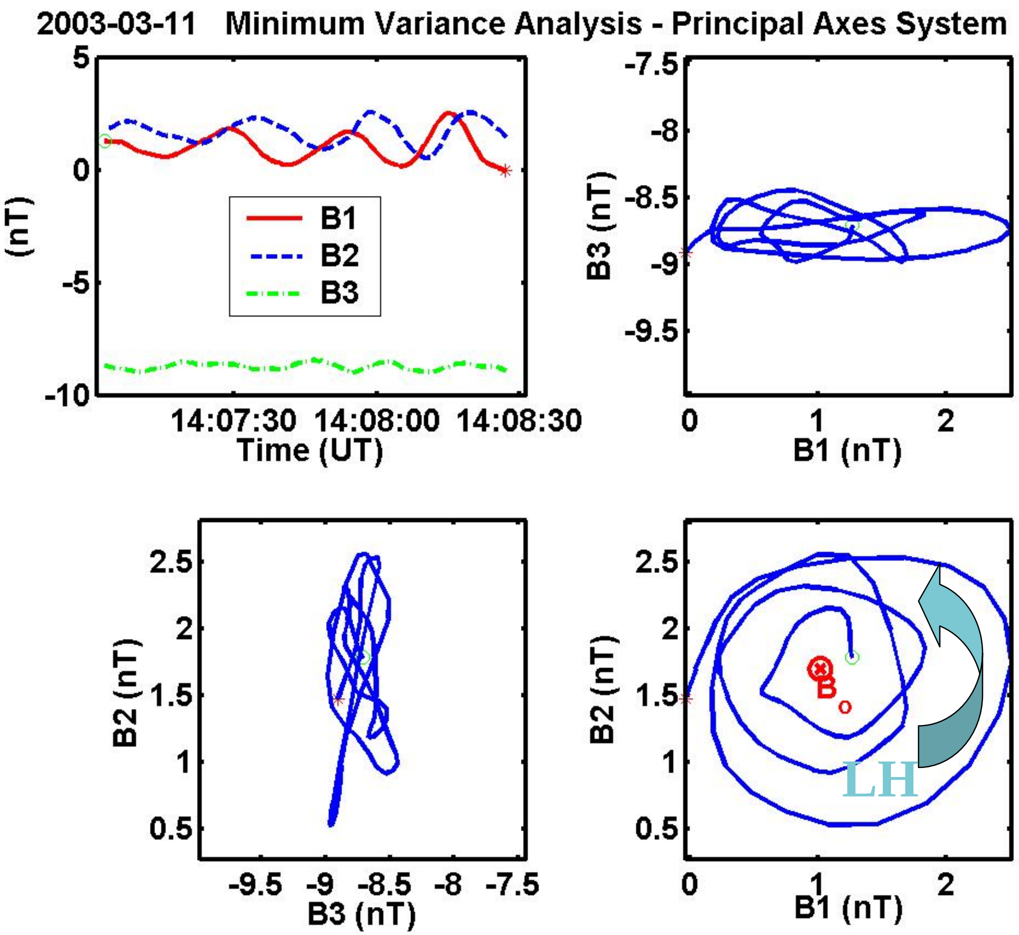


beam energy decrease

Wave amplitude variations

Low Frequency wave properties:

Minimum Variance Analysis



$T \sim 23$ sec

$T_{cyclotron} = 7$ sec

$\lambda_1/\lambda_2 = 1.3 \quad \lambda_2/\lambda_3 = 40.1$

$\theta_{kB} = 12 \pm 2°$

$|\delta B|/B_0 \sim 0.2 \quad \delta|B|/B_0 \sim 0.05$

Left-hand polarized in s/c frame

but $\theta_{kV} = 140°$

→ upstream propagation in SW frame

with $V_{phase} \cong V_{Alfven} << V_{SW}$

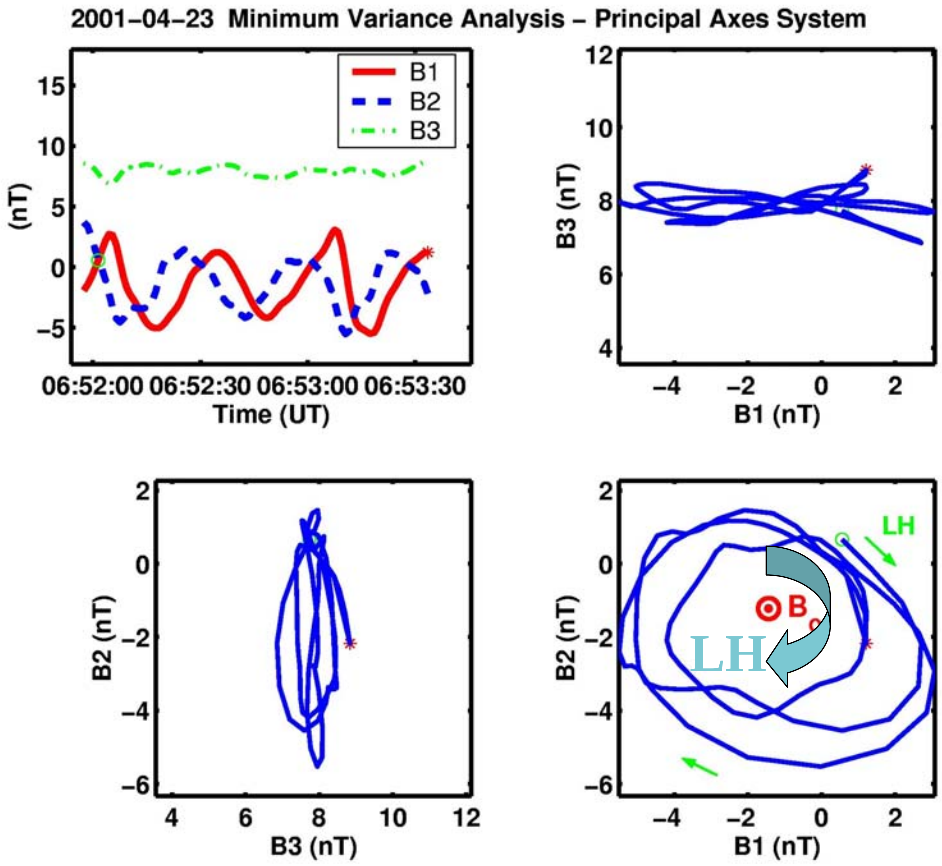
anomalous Doppler shift

→ **Right-Hand mode waves** in plasma frame

Low Frequency wave properties:

large amplitude waves

Minimum Variance Analysis



$T \sim 30$ sec

$T_{cyclotron} = 8$ sec

$\lambda_1/\lambda_2 = 1.1$ $\lambda_2/\lambda_3 = 48.0$

$\theta_{kB} = 15 \pm 1°$

$|\delta B| / B_0 \sim 0.63$

$\delta |B| / B_0 \sim 0.24$

Left-hand polarized in s/c frame

upstream propagation in SW frame

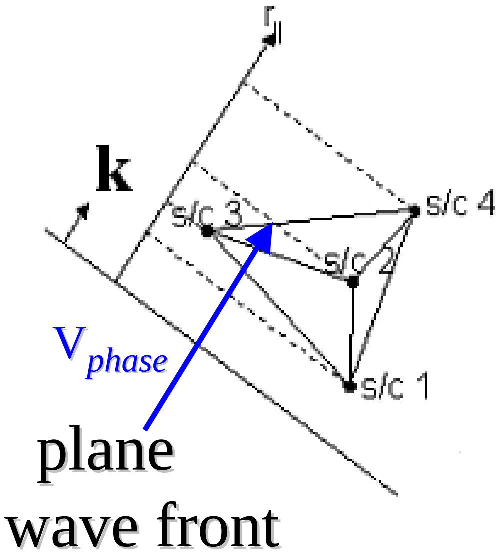
with $\theta_{kV} = 135°$

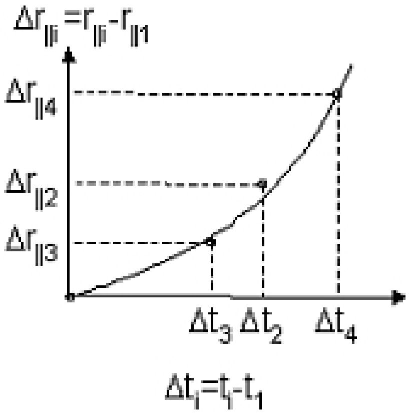
again Right-Hand mode waves

Similar properties

Low frequency multi-spacecraft wave analysis

- Minimum variance analysis for each individual spacecraft: polarization analysis and k direction
- Multi-spacecraft analysis: determination of the wave phase velocity and plasma frame frequency without ambiguity





Wave front timing method

→ $\omega, \mathbf{k}$

Confirms the right-hand polarization in plasma frame

possibility of cyclotron resonant wave generation

Field-aligned beams: observed just before the gyrating distributions appear in cyclotron resonance with the ULF RH mode waves:

$$\boxed{\omega - k_{//} V_{//} + \Omega_p = 0}$$

$$\omega' = \omega + \mathbf{k} \cdot \mathbf{V}_{sw} \approx k_{||} V_{sw} \frac{\cos \theta_{kV}}{\cos \theta_{kB}}$$

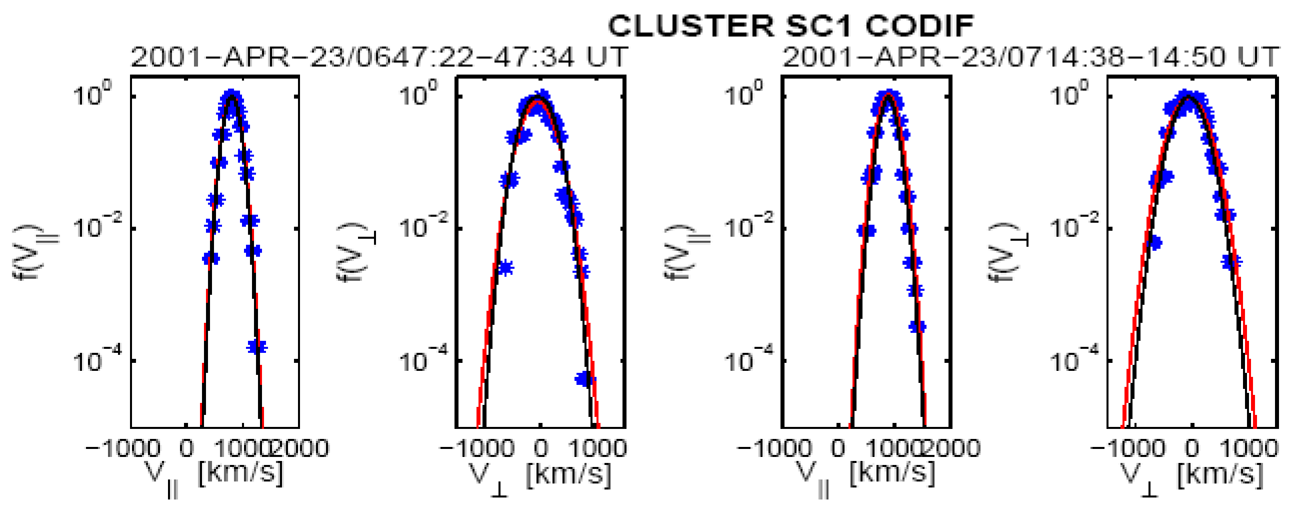
frame s/c sw

and $T_{pred} = {}^{2\pi}/_{\omega'}$

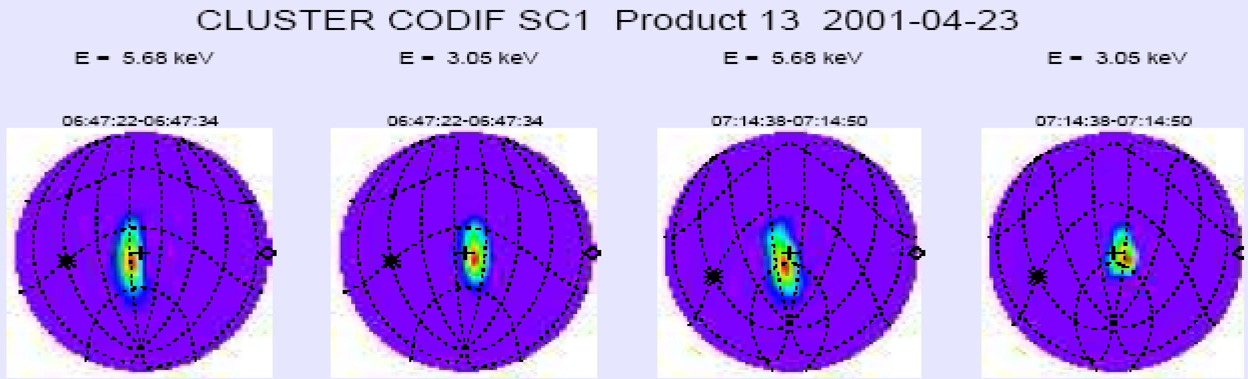
$(= T_{obs}$ if resonance$)$

Need for an acurate determination of Vbeam

FABs properties (solar wind frame)



Maxwellian
FABs



Angular
Distribution

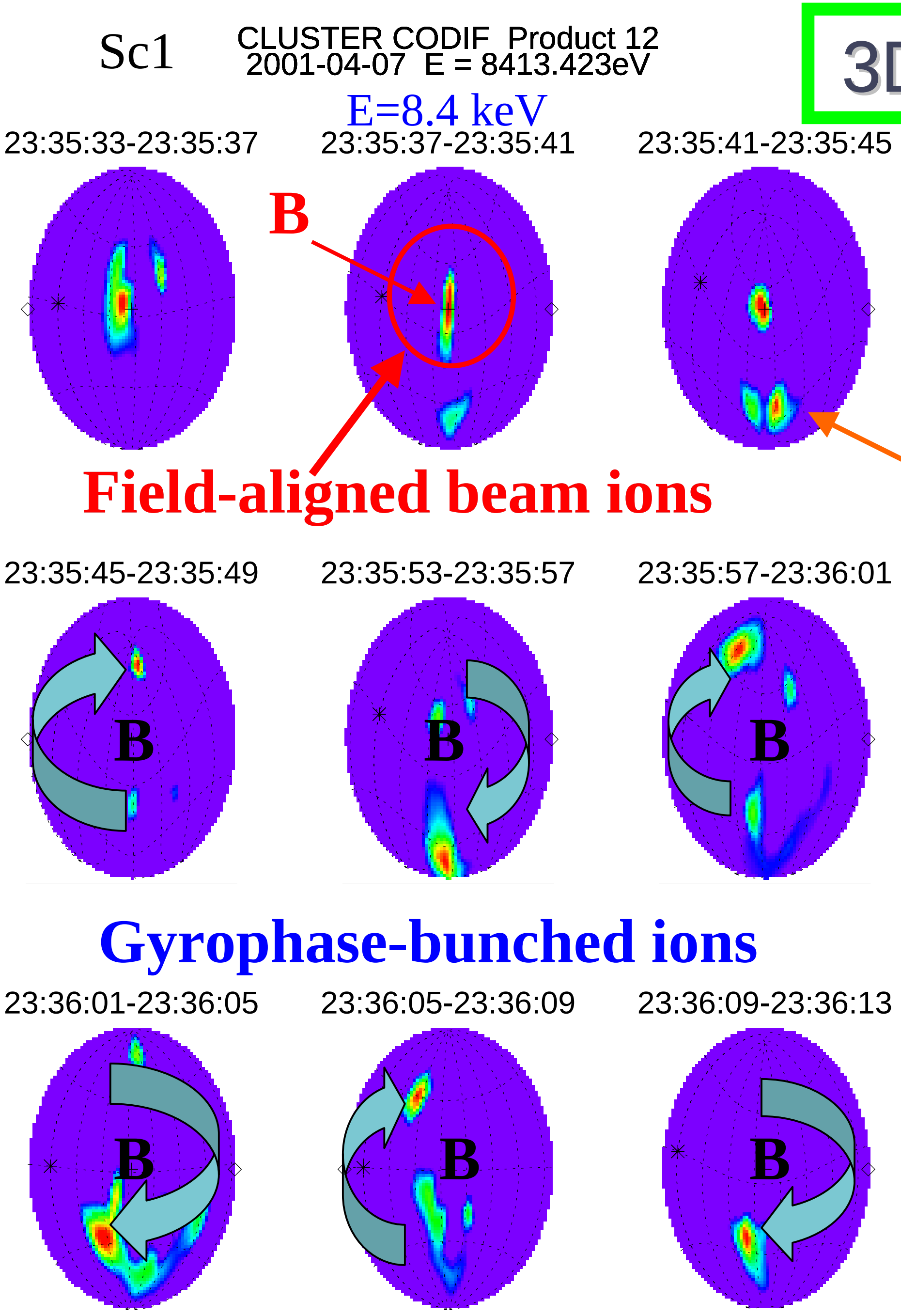
(+=Bo)

[*Meziane et al, 2005*]

→ Determination of beam velocity

See poster **P2.6** by K. Meziane et al.

3D angular distributions (H^+)



Field-aligned beam ions

Gyrophase-bunched ions

Modification of the distribution at the onset of LF waves

possibility of cyclotron resonant wave generation

Field-aligned beams: observed just before the gyrating distributions appear in cyclotron resonance with the ULF RH mode waves:

$$\boxed{\omega - k_{//} V_{//} + \Omega_p = 0}$$

$$\omega' = \omega + \mathbf{k} \cdot \mathbf{V}_{sw} \approx k_{\|} V_{sw} \frac{\cos\theta_{kV}}{\cos\theta_{kB}} \quad \text{and} \quad T_{pred} = {}^{2\pi}/_{\omega'}$$

frame s/c sw

$(= T_{obs}$ if resonance)

e.g. for 2001 04 07 at 2335:37 UT $V_{//} = 1060 \pm 50$ km/s

⇒ $T_{pred} = 25.4$ s while $T_{obs} = 25 \pm 2.0$ s !!

Parallel wavelength: $\lambda_{//}\big|_{\exp} = 7{,}000 \pm 300$ km

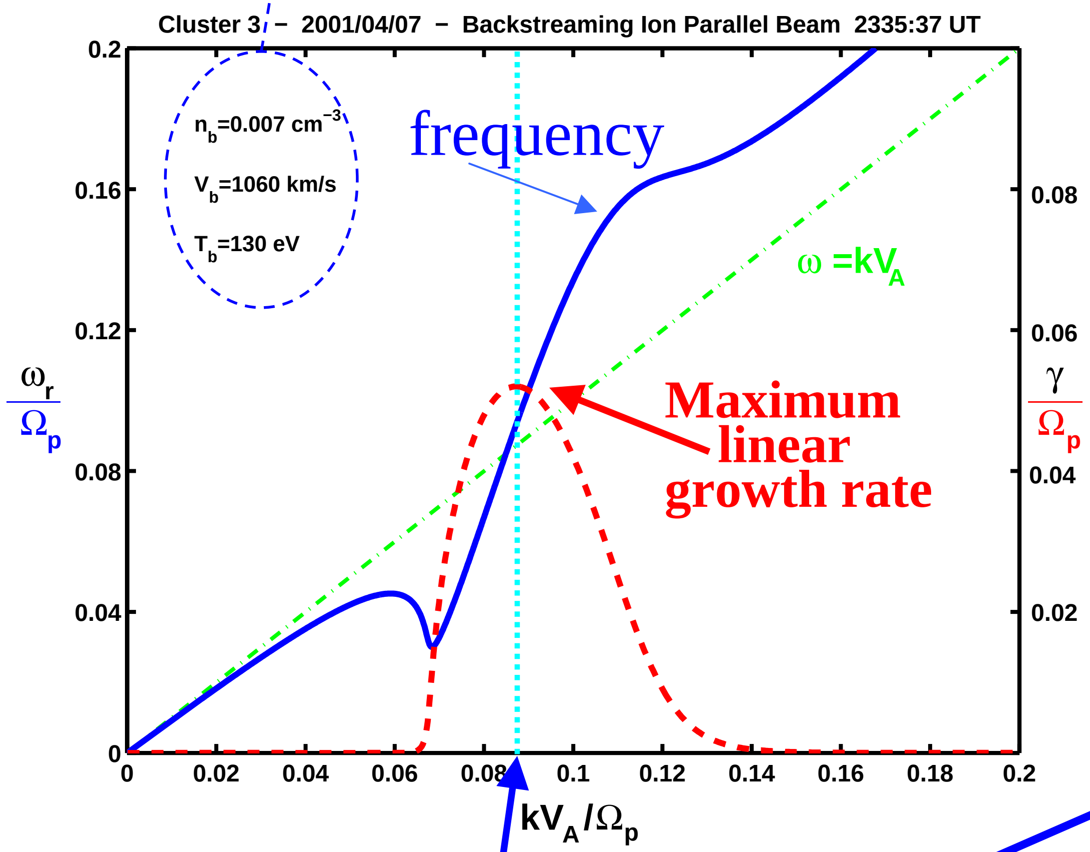
while $\lambda_{//}\big|_{reson} = {}^{2\pi V_{//}}/_{\omega + \Omega p} = 6{,}700$ km

→ **generation from the ion/ion resonant RH beam instability?**

Wave dispersion analysis

Solution of Maxwell-Vlasov dispersion relation: linear theory

Obtained for the observed parameters



Wavenumber associated to the excited mode

[Mazelle, et al., PSS, 2003]

Real frequency (solid line) and linear growth rate (dashed line)
right-hand ion/ion instability :

$$\omega_r/\Omega_p|_{max} = 0.1$$

$$\gamma/\Omega_p|_{max} = 0.05$$

Ω_p : cyclotron frequency

$$V_{phase}^{theory} = 1.1\, V_{Alfvén} \cong V_{phase}^{obs}$$

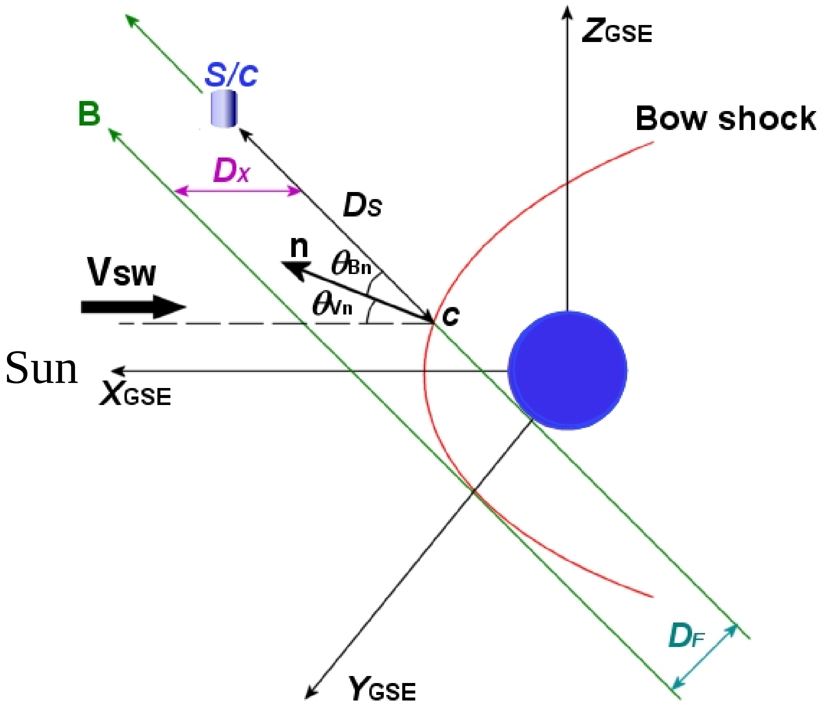
$$\lambda_{//}|_{max} = 6670 \text{ km}$$

$$\lambda_{//}|_{res} = 6700 \text{ km}$$

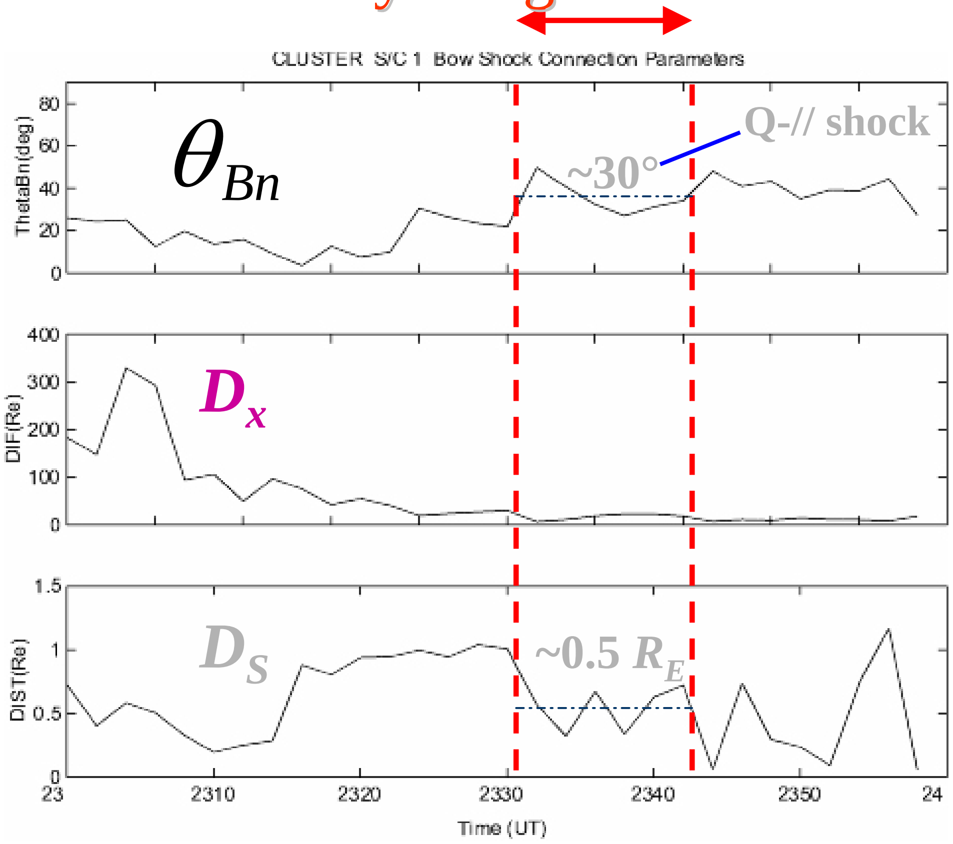
$$\lambda_{//}|_{exp} = 7000 \pm 300 \text{ km}$$

Remote study of shock geometry

Use of a bow shock model
[Cairns *et al.*, 1995]



Gyrating ions interval



Cluster sc 1 April 7, 2001

Interpretation of the observations for these gyrating ion events:

Gyrating ion distributions:

(1) Properties inconsistent with direct production from the reflection mechanism at the shock surface:

1. observed pitch-angle α_{exp} larger than 45° and different from θ_{Bn} as expected *e.g*. from a specular reflection where α_{exp} must be $< 39°$

   [*Schwartz et al*., 1983]

2. ions observed at distances from the shock larger than their gyroradius

   $\Rightarrow$ **need for a local production mechanism (no remote finite Larmor radius effect)**.

(2) Predicted periods (T_{pred}) in the spacecraft frame for cyclotron resonance with right-hand mode waves using the parallel velocity of the gyrating ions very close to observed periods

$\Rightarrow$ **possibility of wave-particle interaction**

$\rightarrow$ **Wave generation from the ion beam instability and subsequent nonlinear beam disruption by the wave to produce the gyrating distributions?**

Non linear wave-particle interaction: wave trapping

Invariants of motion of an ion with velocity **v** in a frame moving // to $\mathbf{B_0}$ at wave speed V_{phase} (**E**=0):

$T = w_{//}^2 + w_\perp^2 = C_1$ (normalized kinetic energy)

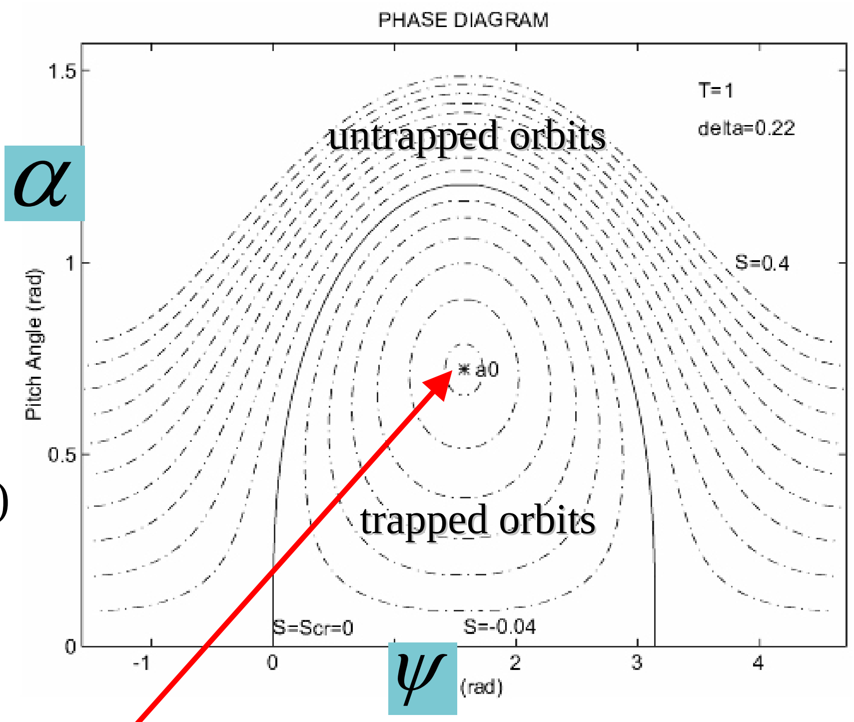
$S = (w_{//} - 1)^2 - 2\frac{\Omega_1}{\Omega_0} w_\perp \sin\psi = C_2$ (// & ⊥ exchange)

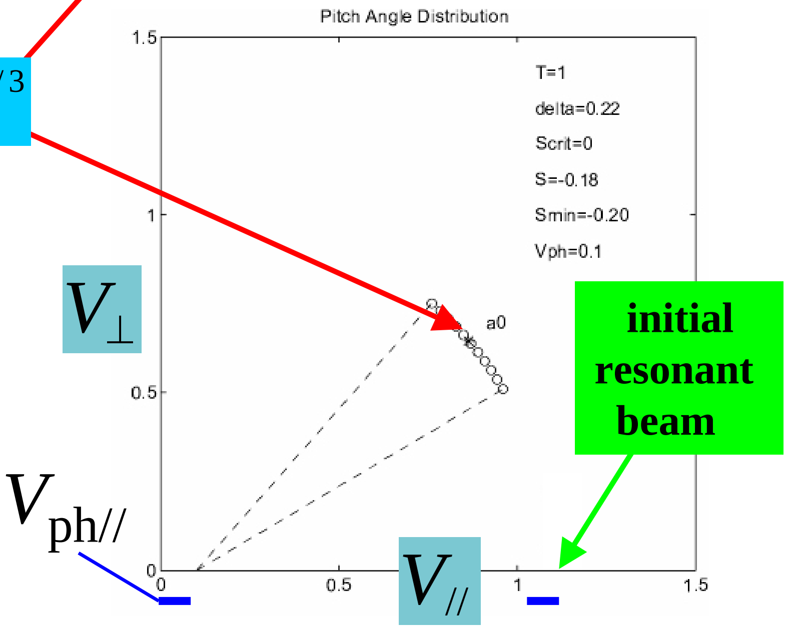
$\mathbf{w} = \frac{k_{//}}{\Omega_0}\mathbf{v}$ $\psi = \varphi + k_{//} z$ gyrophase $\Omega_{0,1} = \frac{qB_{0,1}}{m}$ $\frac{\Omega_1}{\Omega_0} = \frac{\delta B_\perp}{B_0}$

Hamiltonian $S(\alpha,\psi)$ with $\tan\alpha = w_\perp / w_{//}$

Singularity: $\psi_0 = \pi/2$ and $\alpha_0 \approx \left(2\,\delta B_\perp / B_0\right)^{1/3}$ for small α_o

[*Mazelle et al., Nonlinear Processes in Geophysics, 2000*]



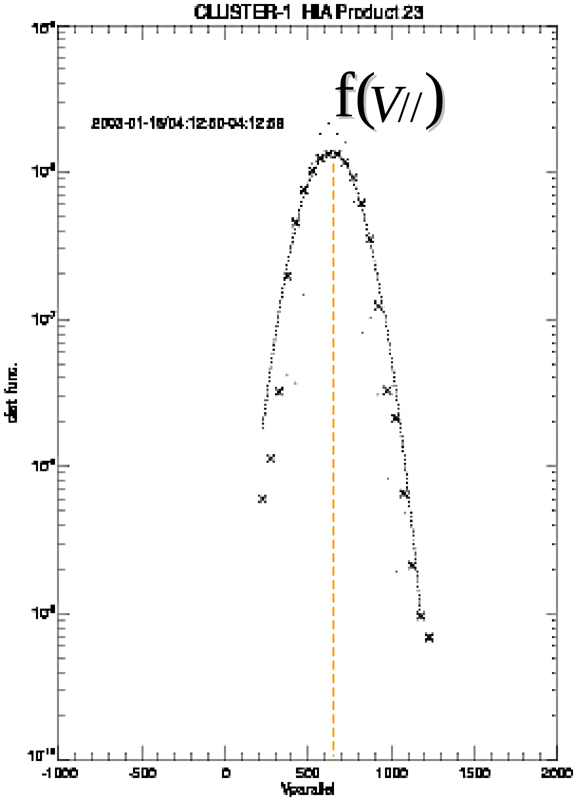


Determination of ion properties (SW frame)

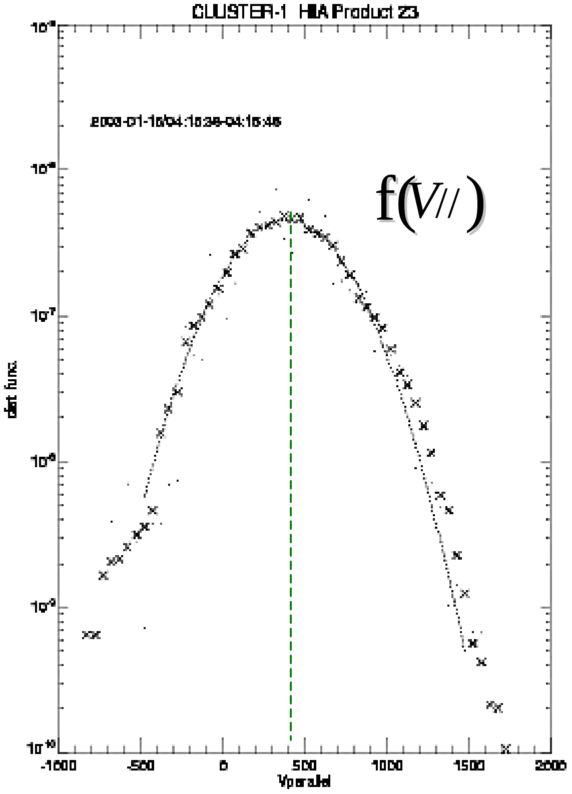
Fits of reduced distribution functions

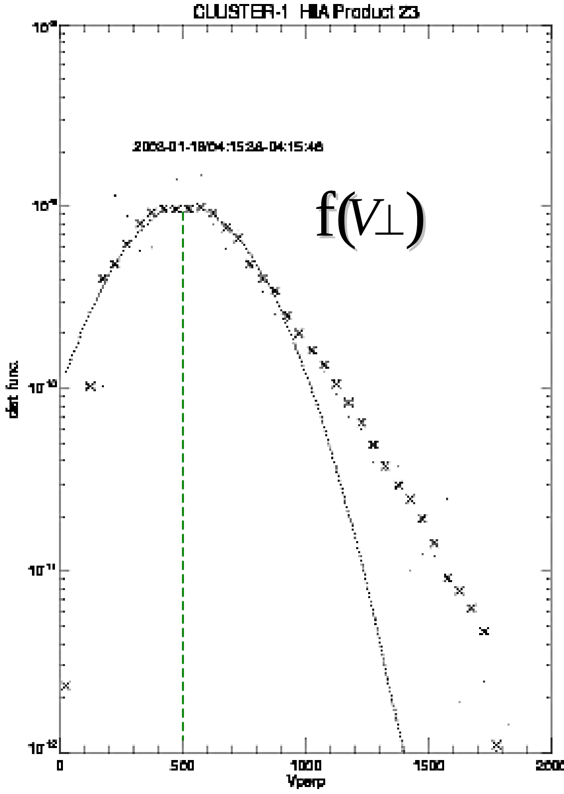
Field-aligned Beam

Gyrating ions



→ beam velocity





→ $V_{//}$ $V_\perp$

[*Meziane et al, 2005*]

Comparison with observations (1)

Gyrating ions

Time 2001-04-07	$V_{//}\left(km/s\right)$	$V_{\perp}\left(km/s\right)$	$\alpha_{\exp}$
23:38:09 UT	500	910	66°
23:38:13 UT	600	855	60°
23:38:25 UT	650	815	56°
23:38:29 UT	700	1060	60°
23:38:45 UT	600	845	59°

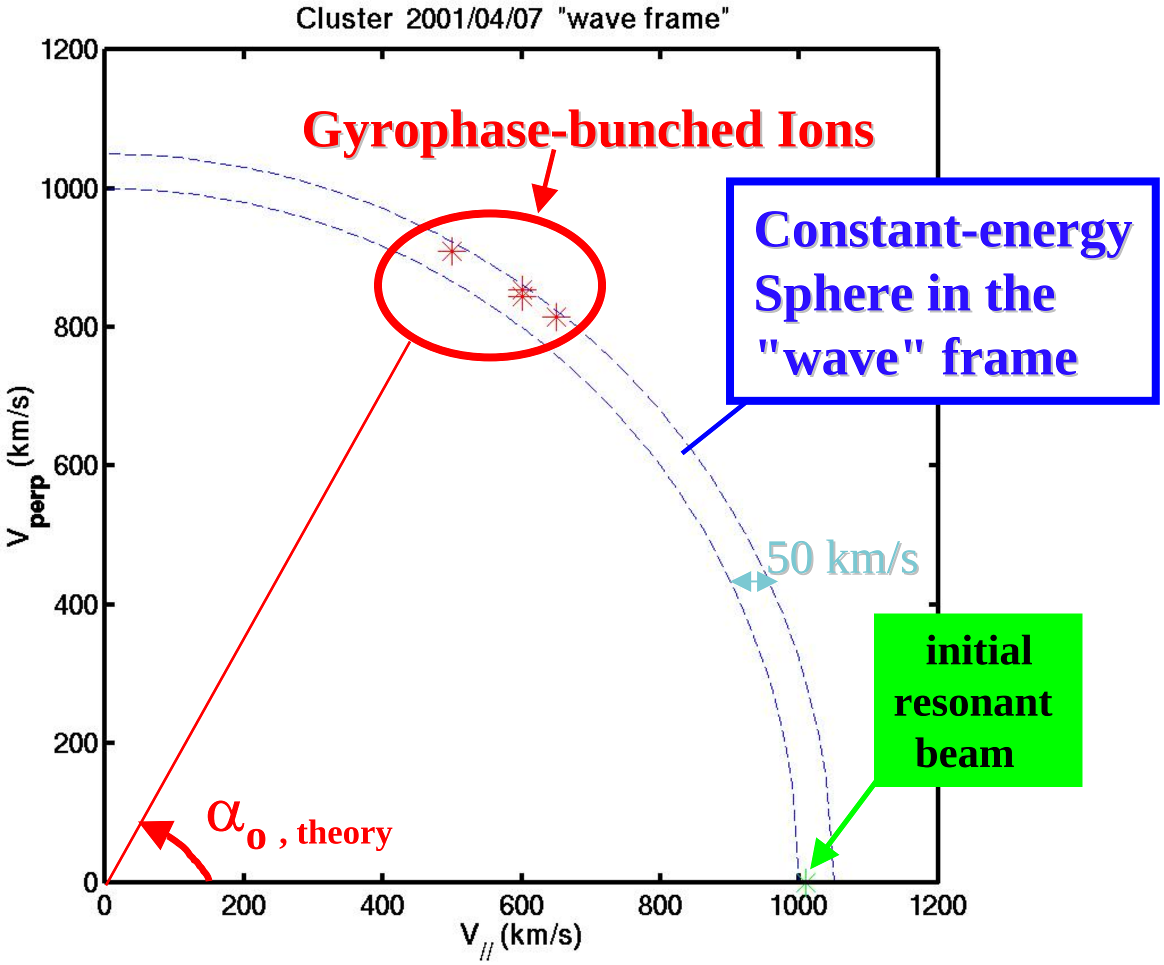
[*Mazelle et al., PSS, 2003*]

$\alpha_{otheor} = 59.8°$ for $\delta B_{\perp}/B = 0.85$

very good agreement

Comparison with observations (2)

Pitch-angle distribution in the "wave" frame



Gyrophase-bunched Ions

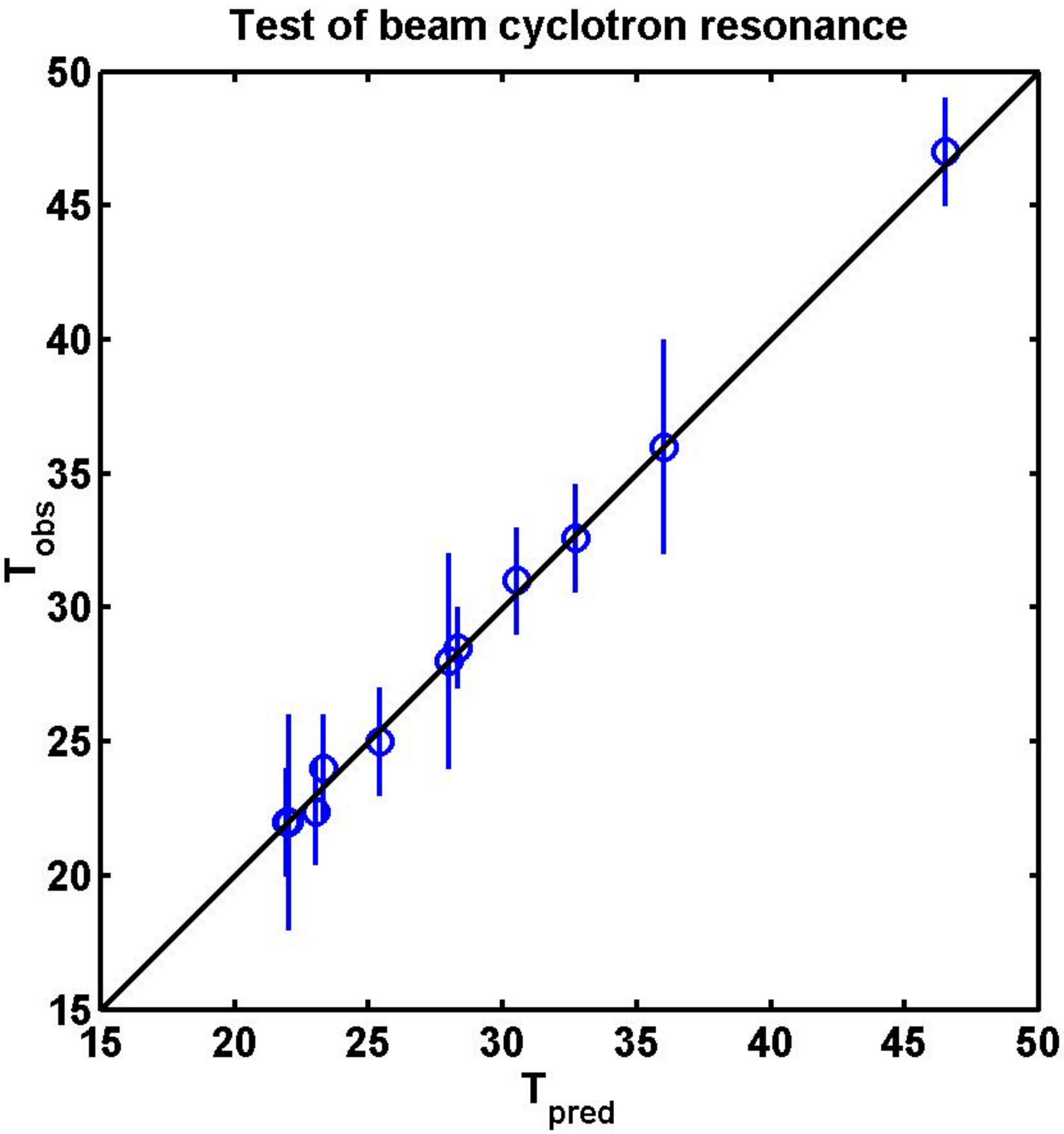
Constant-energy Sphere in the "wave" frame

initial resonant beam

Consistent with theory (energy conservation)

Check of cyclotron resonance

Observed wave period versus Predicted (using Tcy, $V_{//}$, ω and **k**)



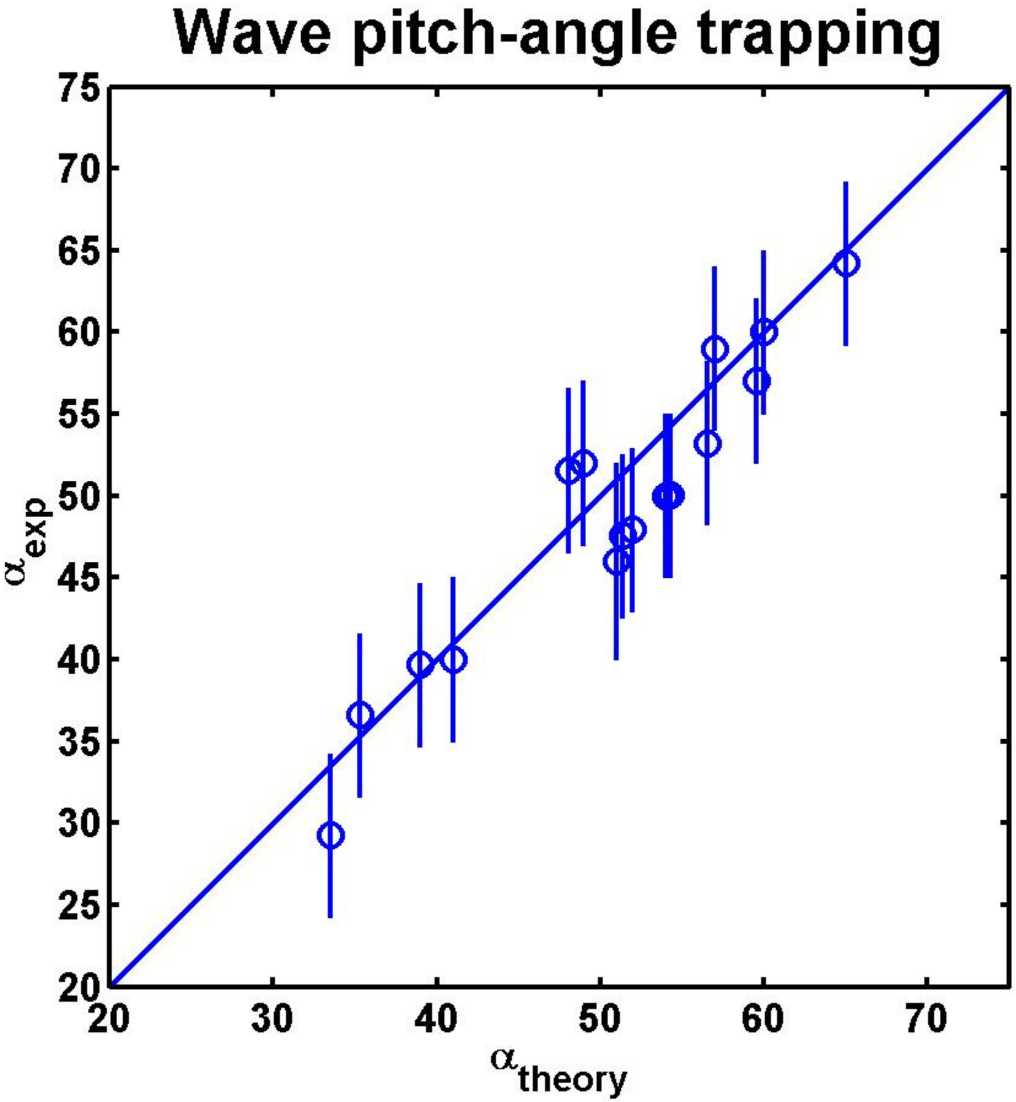
12 different events

very good agreement

first **quantitative** demonstration of the cyclotron resonance in the foreshock

Check of 1-wave trapping theory

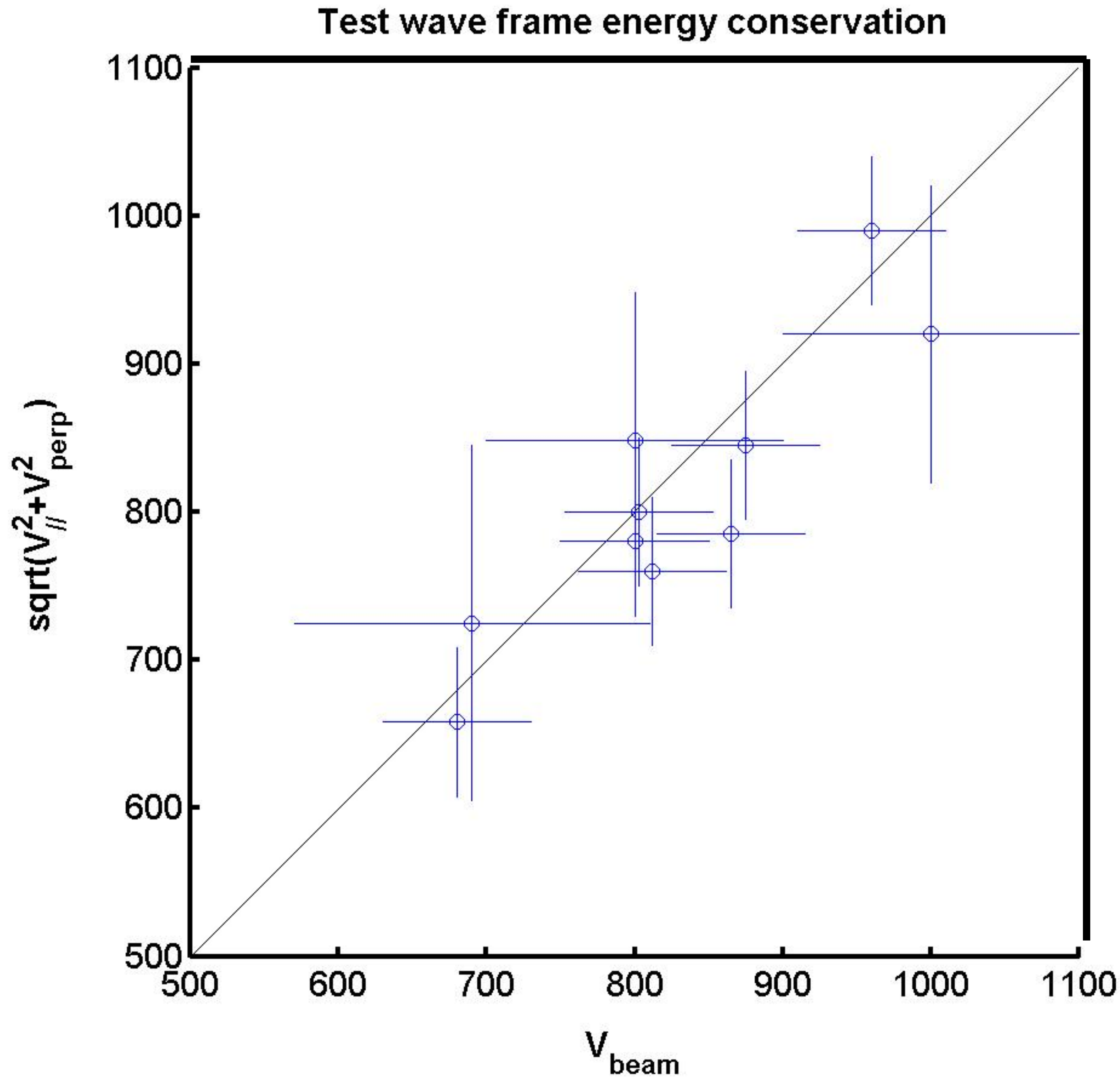
α_0 (theory) depends only on the wave amplitude $\delta B_\perp / B$



16 intervals

good agreement

Check of wave frame energy conservation



good agreement

Conclusion: foreshock FABs and gyrating ions

- ❑ Observations of well-defined gyrophase-bunched backstreaming ion distributions in the Earth’s foreshock.
- ❑ Association with quasi-monochromatic, large amplitude, low frequency right-hand mode waves.
- ❑ Possibility of resonantly driving these waves unstable from the electromagnetic ion/ion beam instability: good quantitative agreement with the observed field-aligned ion beams.
- ❑ The angular distribution of the gyrophase-bunched ions is peaked at a pitch angle in good agreement with nonlinear single wave phase-trapping orbit theory.
- ❑ These results have implications on the understanding of a planetary foreshock and show the possibility to study some plasma microphysics with Cluster (while not designed for it).

END