Turbulence: major results from Cluster and input to the future space missions

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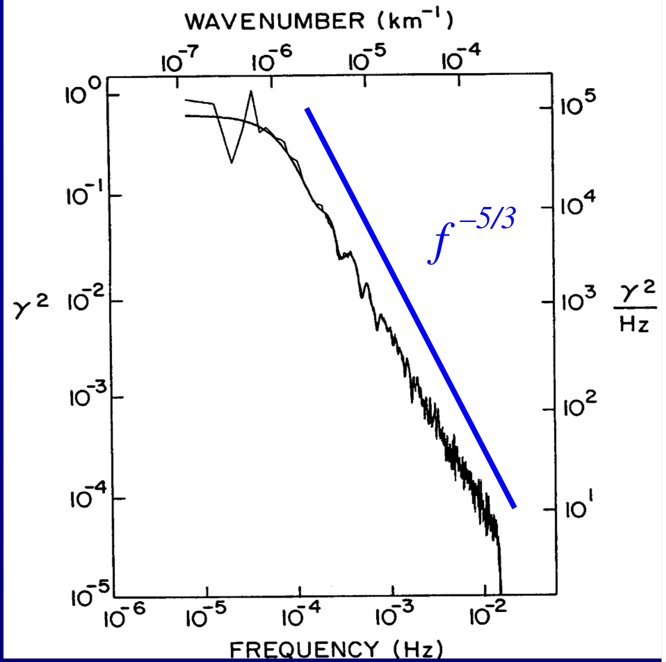
Outline

- Introduction
- Apport de Cluster à l'étude de la turbulence
  1. Analyses multi-points: identifications de la nature et des anisotropies de la turbulence
  2. Données haute résolution: importantes résultats sur la turbulence/chauffage à petite échelle dans le vent solaire
- Quelques limitations et projections futures (MMS, Cross-Scale/ Eidoscope)
- Un peu de théorie?
- Conclusions

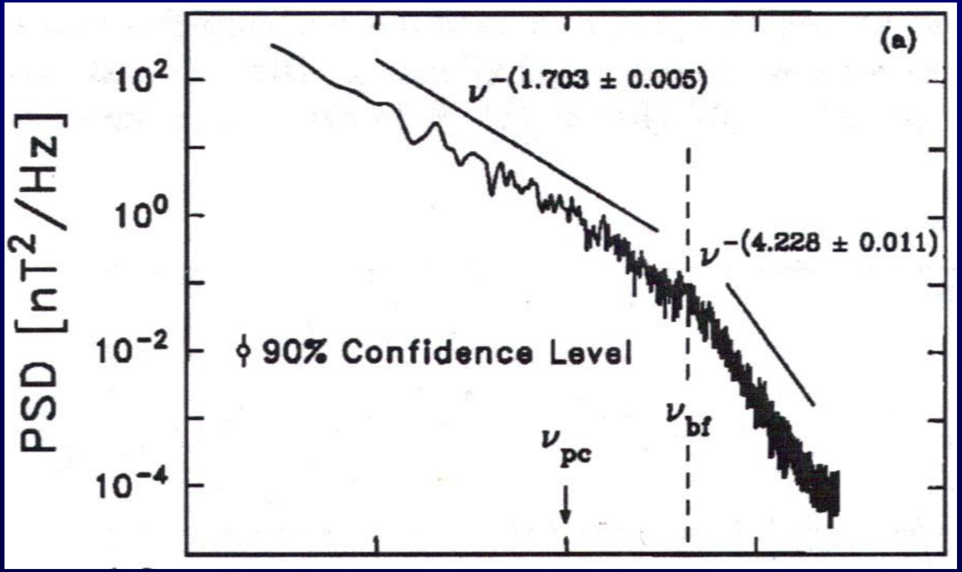
Solar wind turbulence

Matthaeus & Goldstein, 82



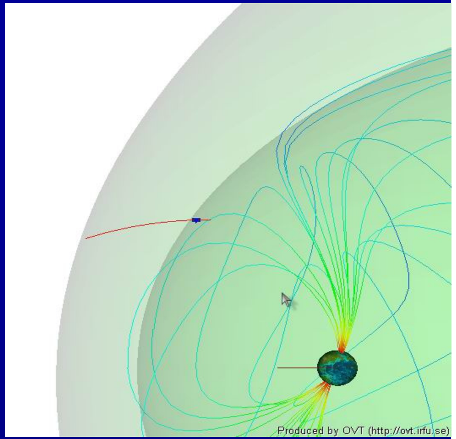
Typical power spectrum of magnetic energy at 1 AU

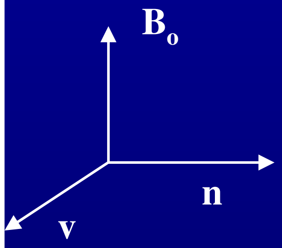
1. Nature of turbulence in k-space: 2D? Slab?
2. **dissipation or a new cascade** below the ion scale ρ_i (not f_{ci})?



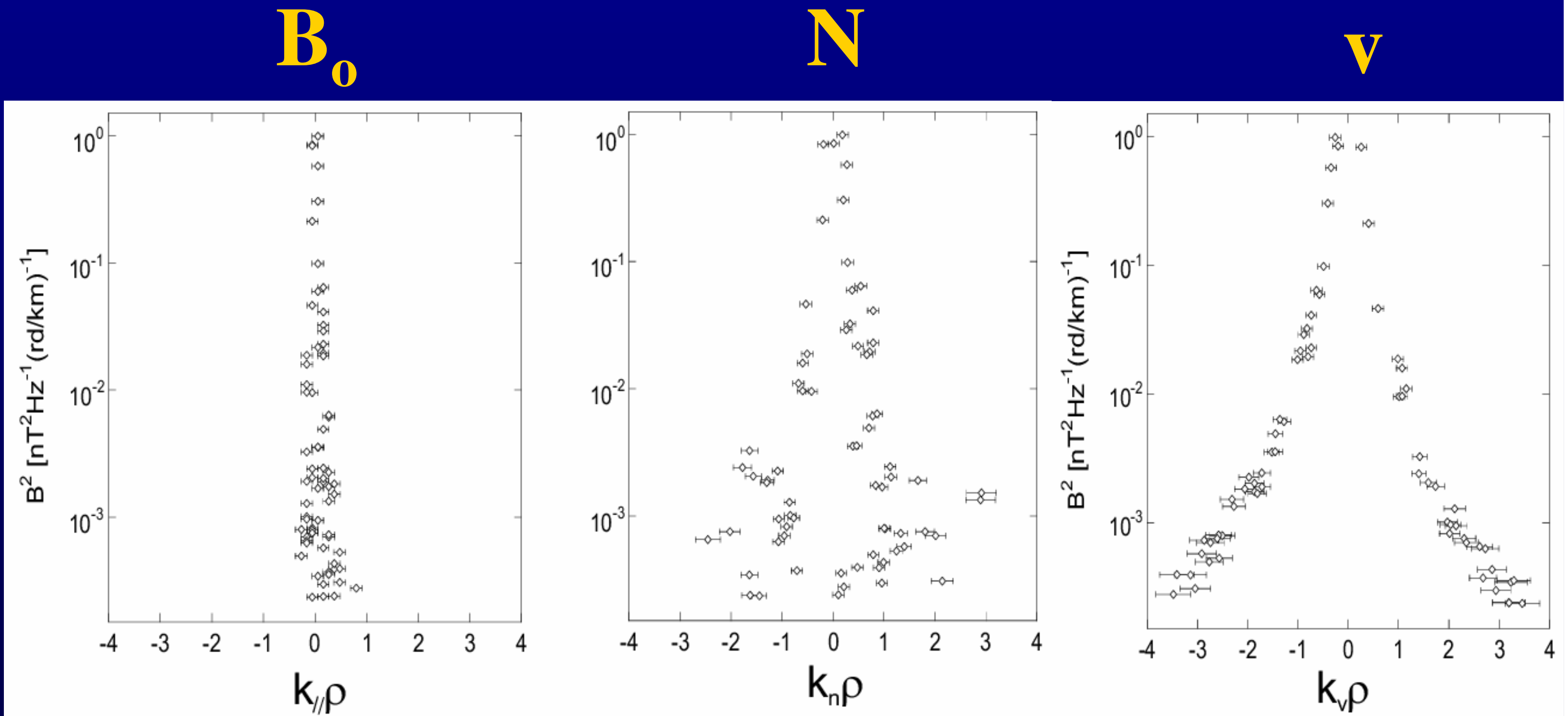
Leamon *et al.* 98; Goldstein *et al.* JGR, 94

Magnetosheath Turbulence: anisotropies along B and N





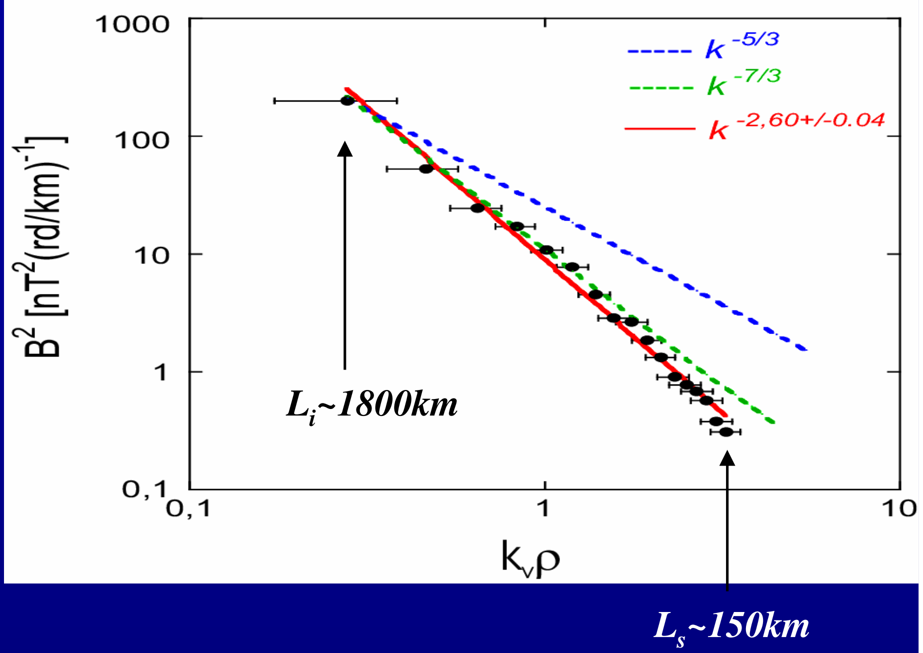
(v,n) ~ 104°
(v,B_o) ~ 110°
(n,B_o) ~ 81°



Strong anistropies along B_o and the magnetopause normal **N**

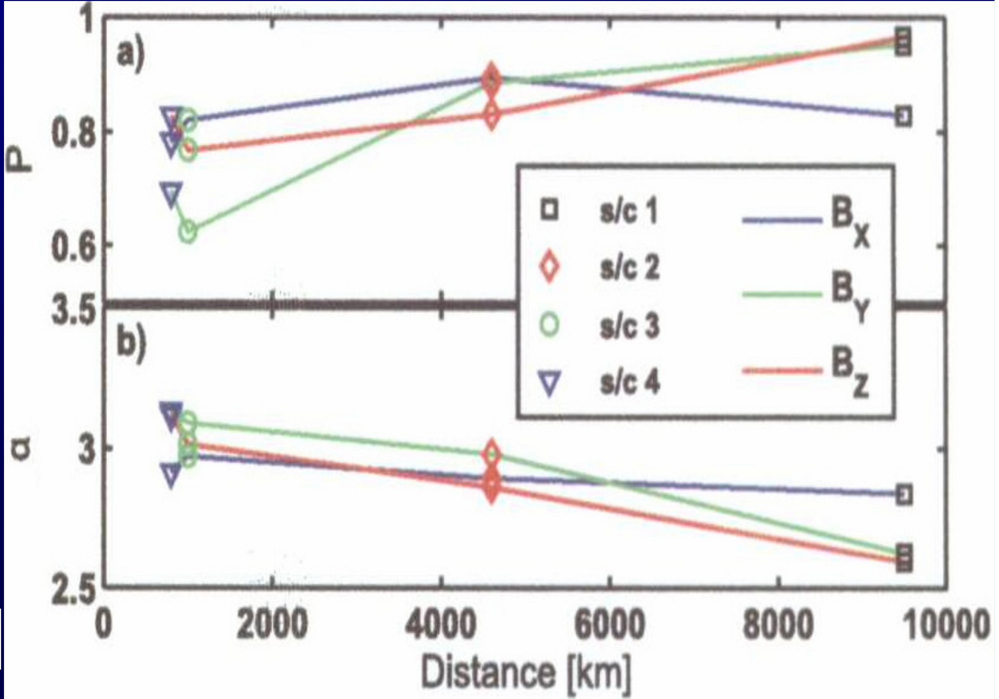
⇒ Evidence of a power law spectrum along v: $B^2 \sim k_v^{-8/3}$

[Sahraoui et al., PRL., 2006]



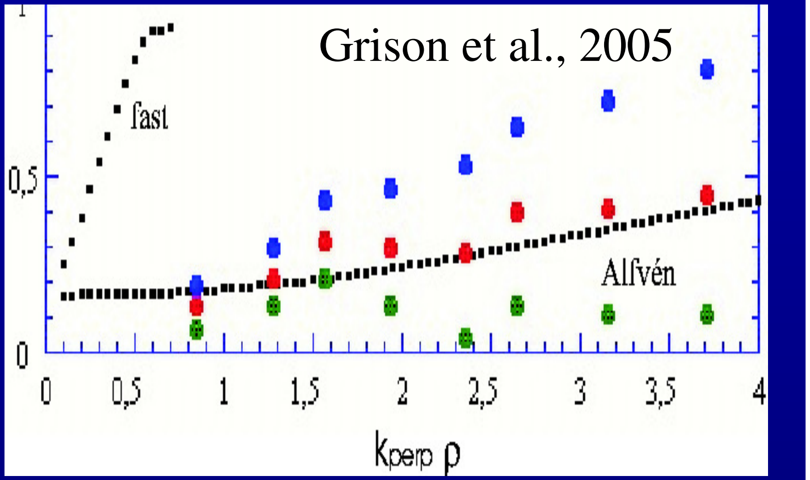
Similar anisotropy caused by the normal to the bow shock (BS): more intermittent and less-steeper power spectra away from the BS

[Yordanova et al., PRL, 2008]

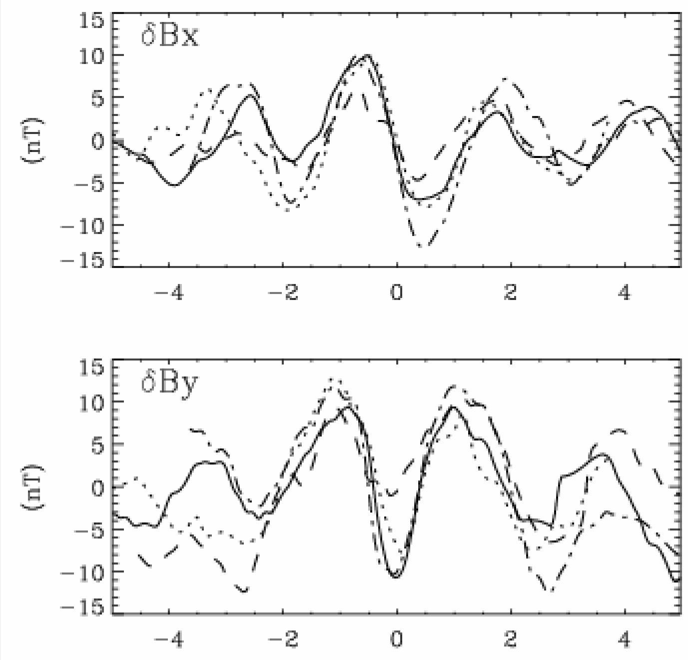


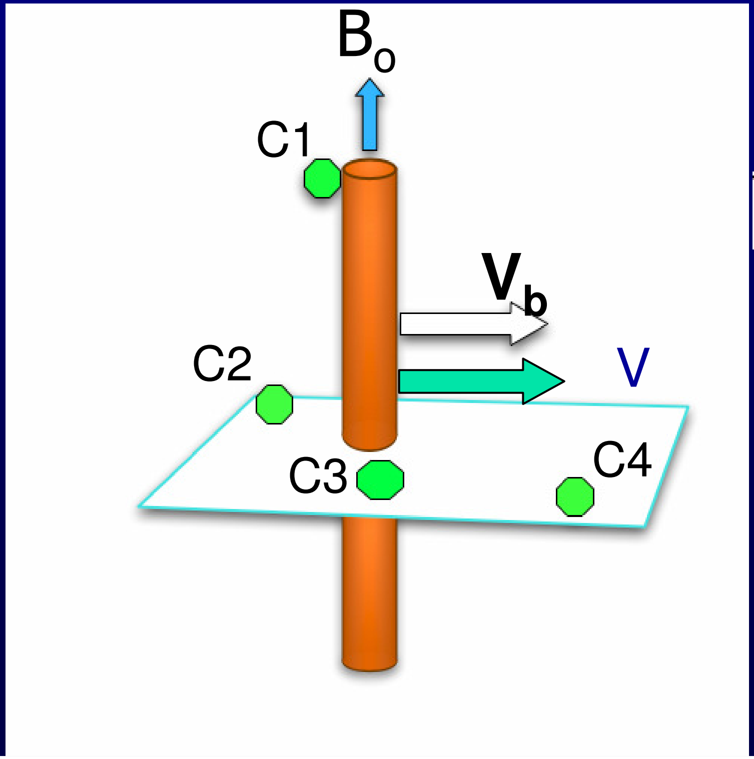
Alfvenic turbulence in the magnetsophere

⇒ **2D Alfvénic structures/vortices in the Cusp** **$k_\perp >> k_{//}$** [Sundkvist et al., Nature, 2005; Grison et al., 2005]


Grison et al., 2005

Similar Alfvenic vortices in the magnetosheath





In plasma frame:

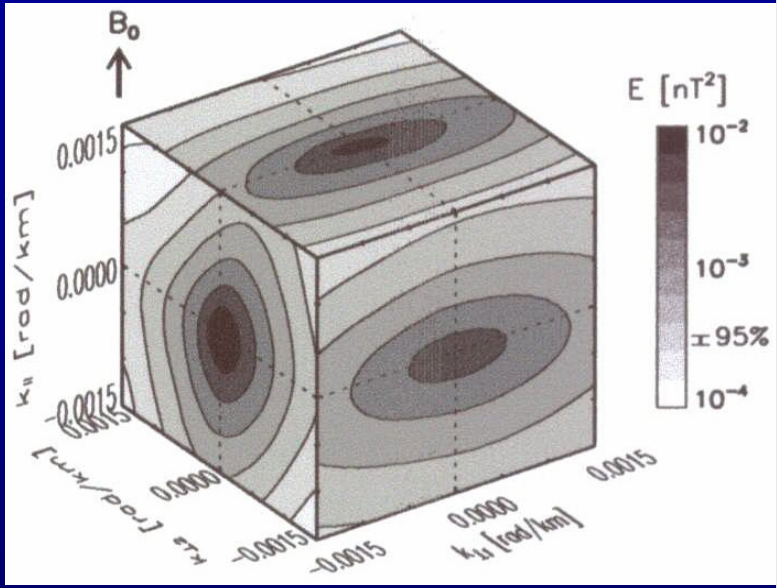
$$V \sim [0, 0.3] V_A$$

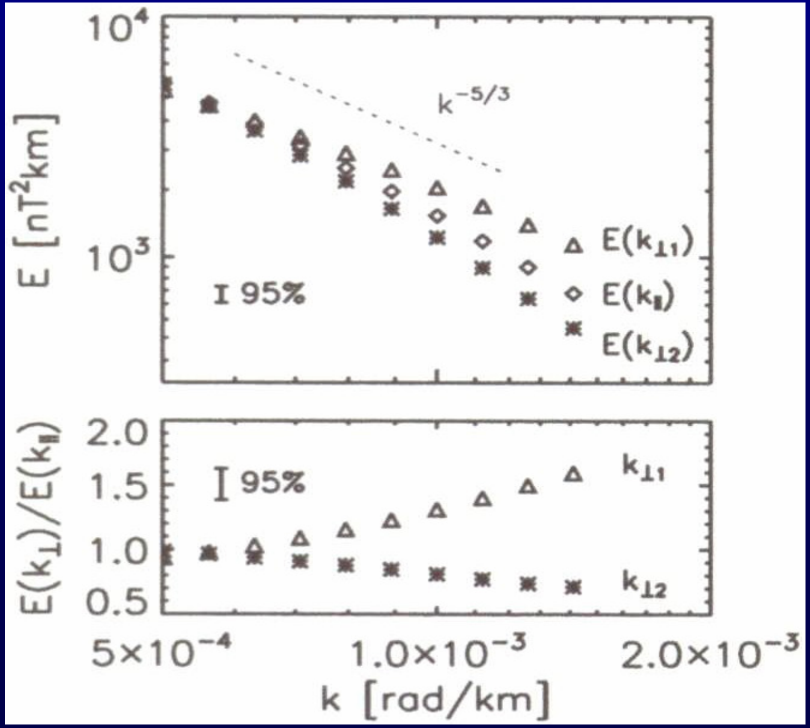
$$d_\perp \sim 10 c/\omega_{pi}$$

[Alexandrova et al., JGR, 2006]

Solar Wind turbulence: Anisotropy along B and V_{sw}

Turbulence is not axisymmetric (around B) [Narita et al. , PRL, 2010]





The anisotropy ($\perp$ B) is correlated with V_{sw} → Expansion effect [Saur & Bieber, JGR, 1999]?

Anisotropy and the critical balance conjecture

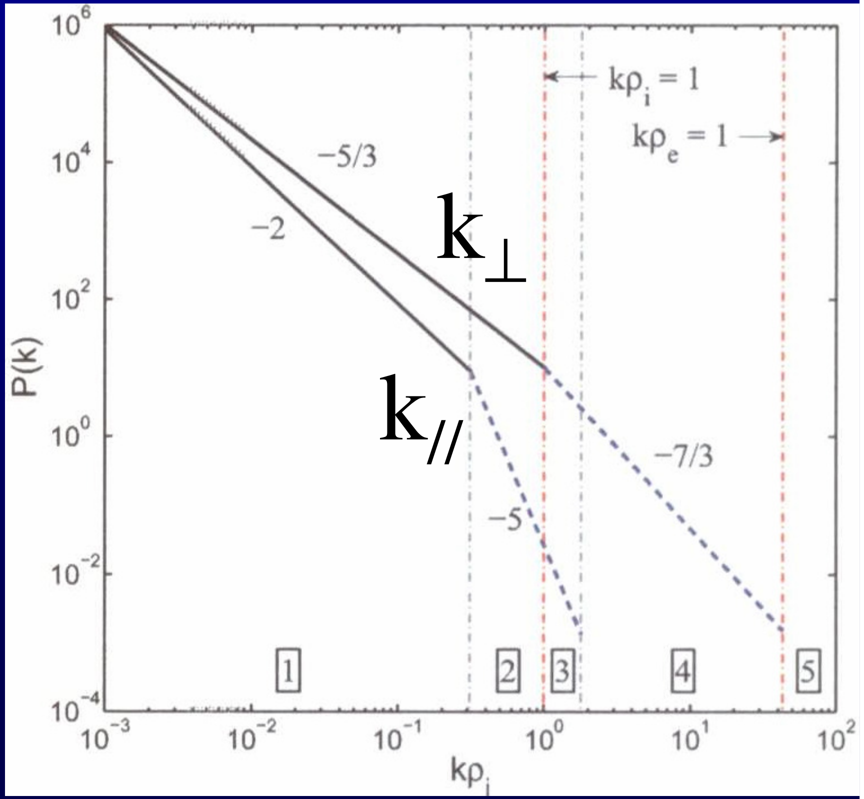
The critical balance conjecture [Goldreich & Sridhar, 1995]:

Linear (Alfvén) time ~ nonlinear (turnover) time

$\Rightarrow \omega \sim k_{//} V_A \sim k_{\perp} u_{\perp}$

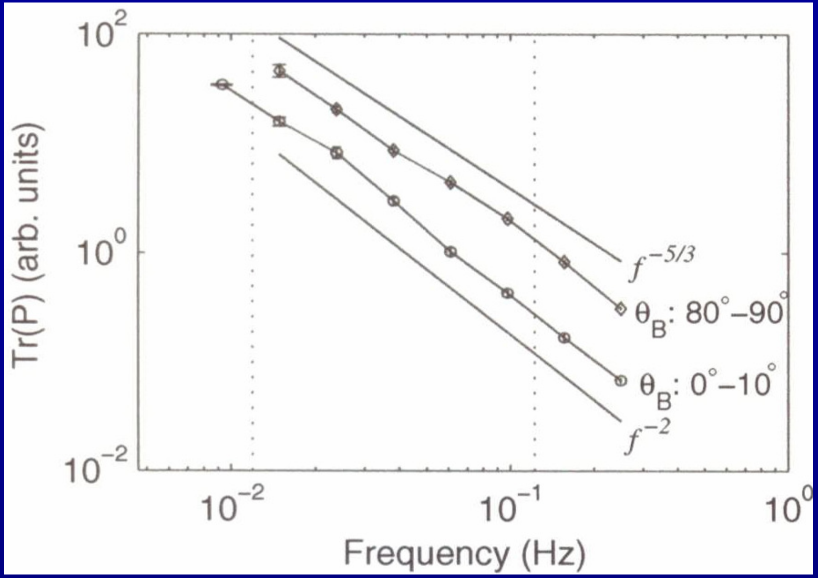
$\Rightarrow k_{//} \sim k_{\perp}^{2/3}$

See also [Boldyrev, ApJ, 2005] and [Galtier et al., Phys. Plasmas, 2005]



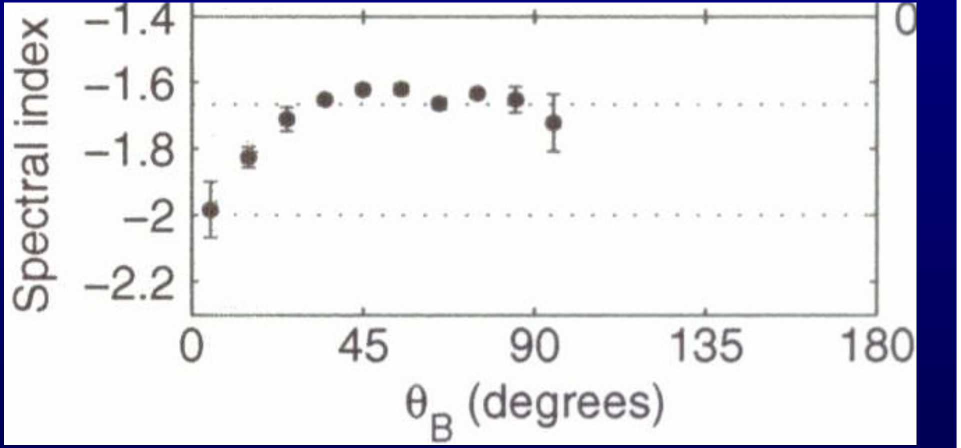
[Chen et al., ApJ, 2010]

Single satellite analysis→ use of the Taylor assumption: $\omega_{sc}\sim\mathbf{k.V}_{sw}\sim k_v V_{sw}$



$V//B \rightarrow k_v=k_{//}$

$V\perp B \rightarrow k_v=k_\perp$

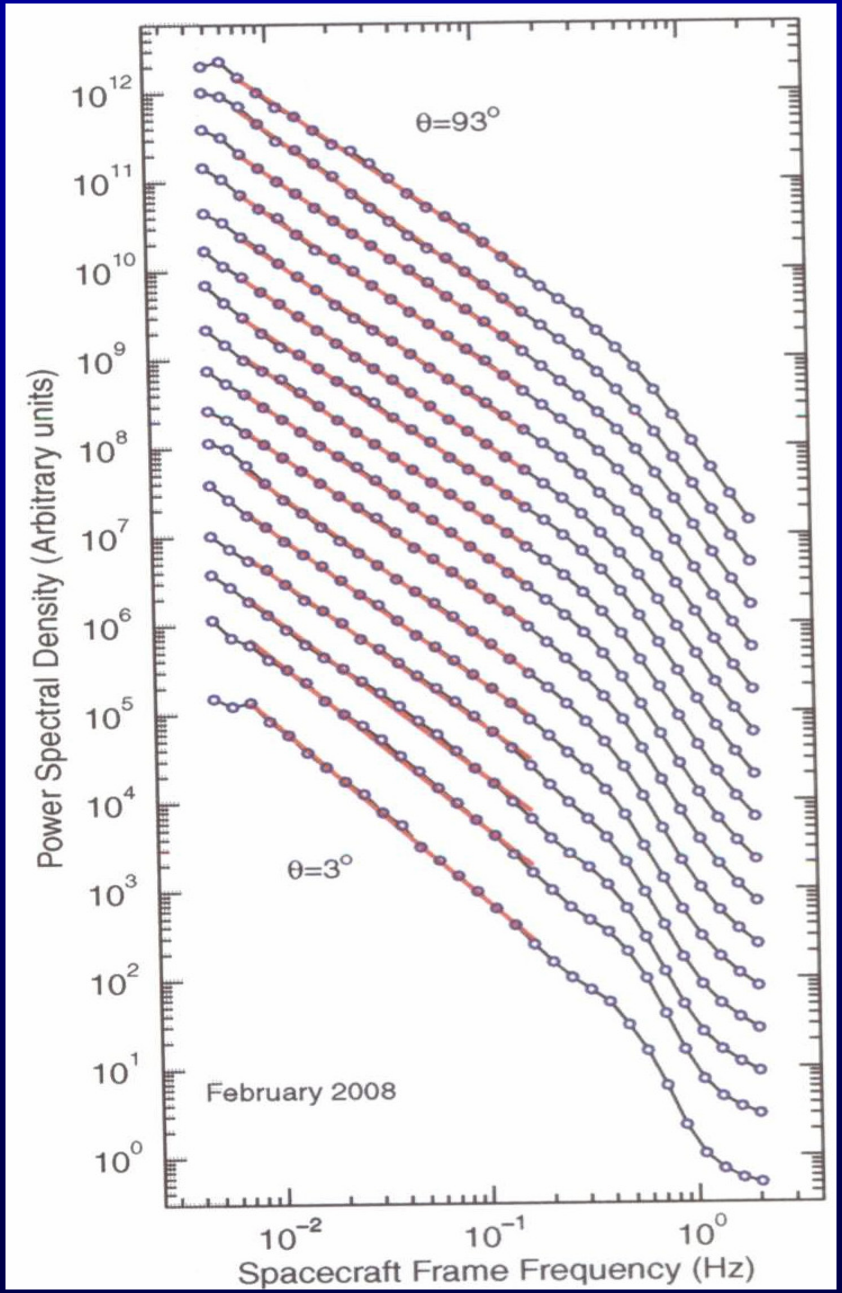


Assumes axisymmetry around B

$\Theta_{BV}\rightarrow 0 \Rightarrow B^2 \sim k_{//}^{-2} \Rightarrow$ Evidence of the critical balance [Horbury et al., PRL, 2008]

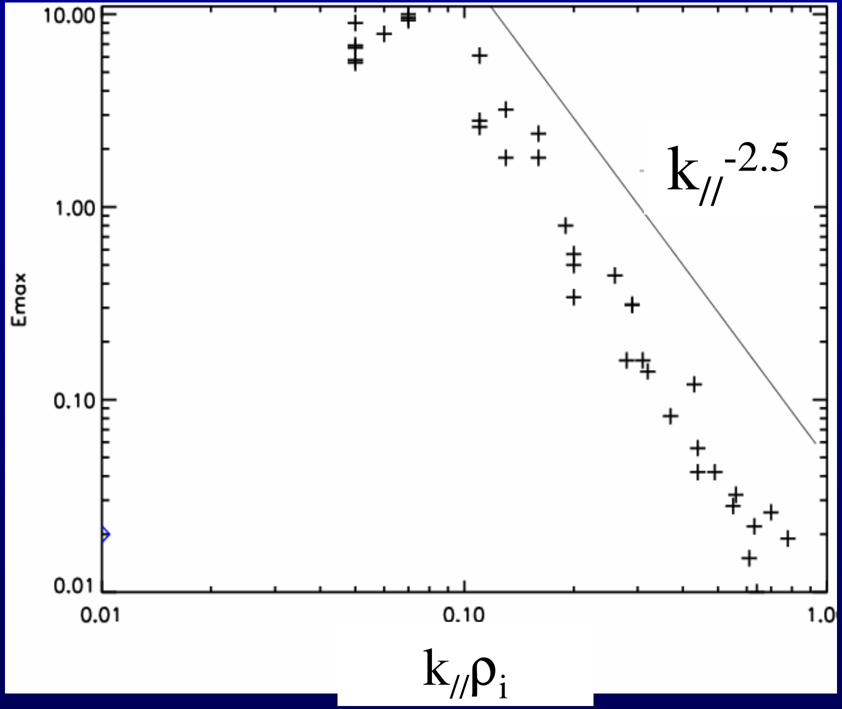
Results confirmed by Podesta, ApJ, 2009

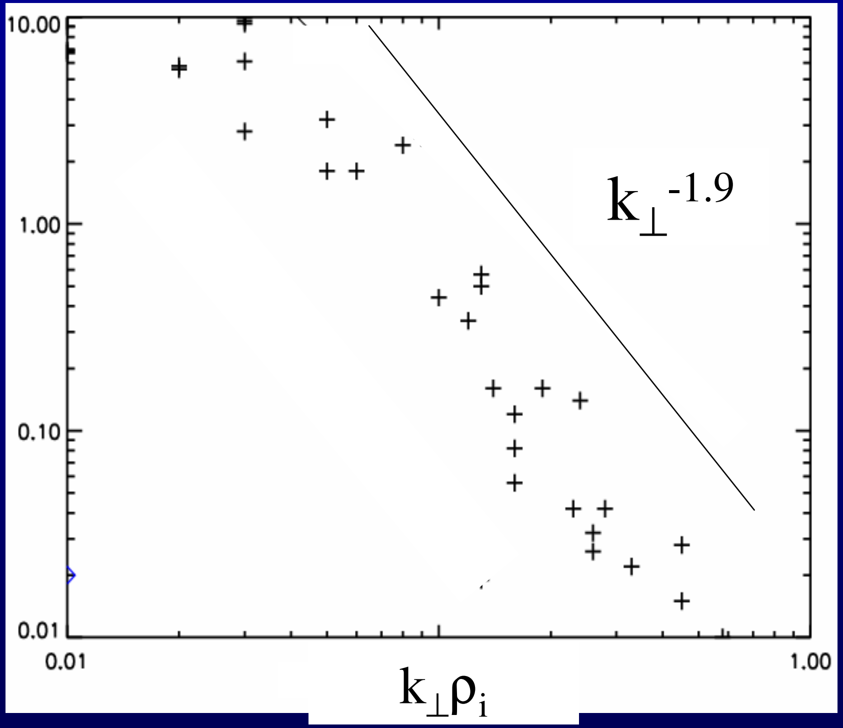
See also Chen et al., PRL, 2010



Testing the critical balance using the k-filtering technique

Mar. 2005





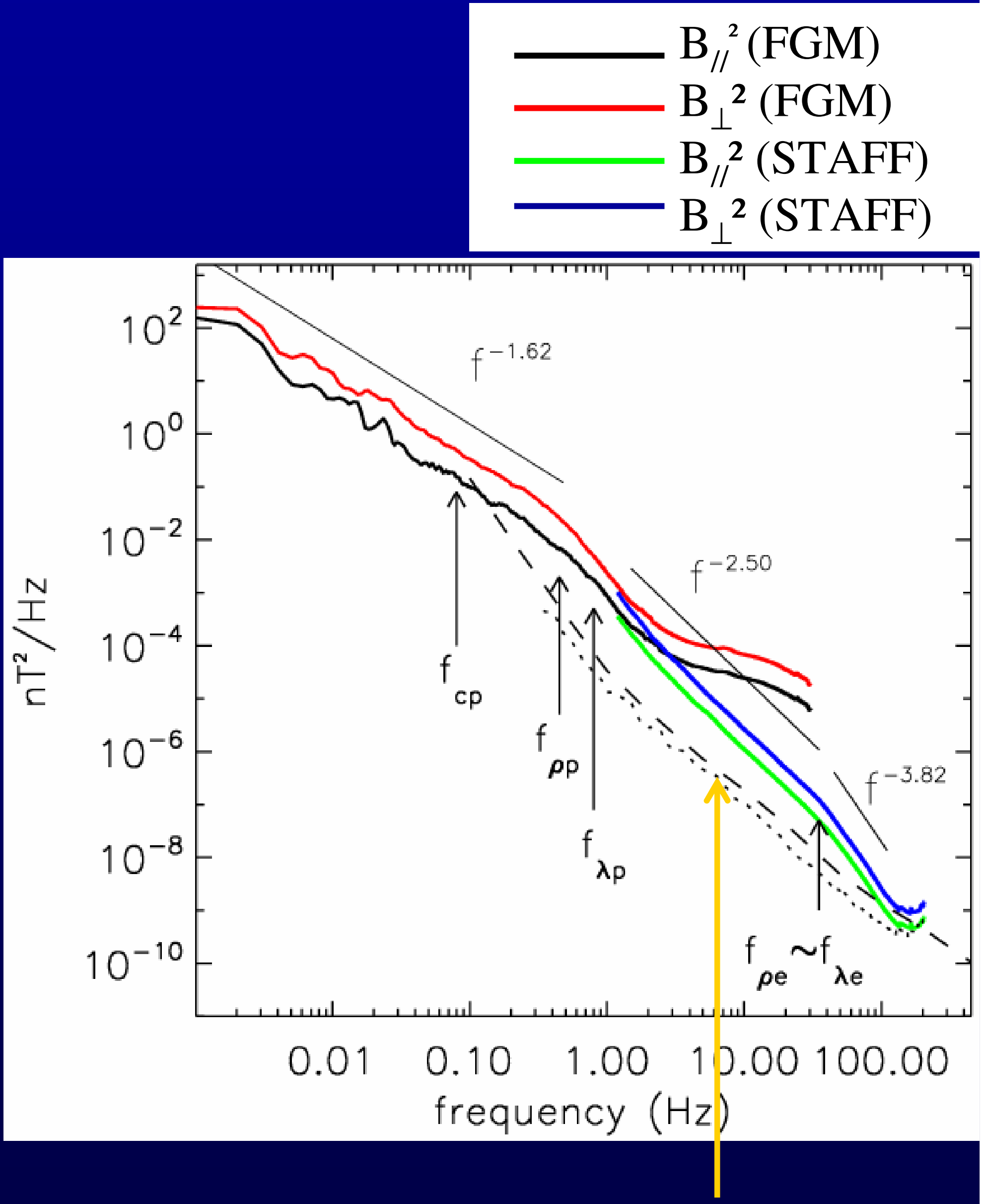
First *direct* verification of the critical balance !

[Sahraoui et al., in prep.]

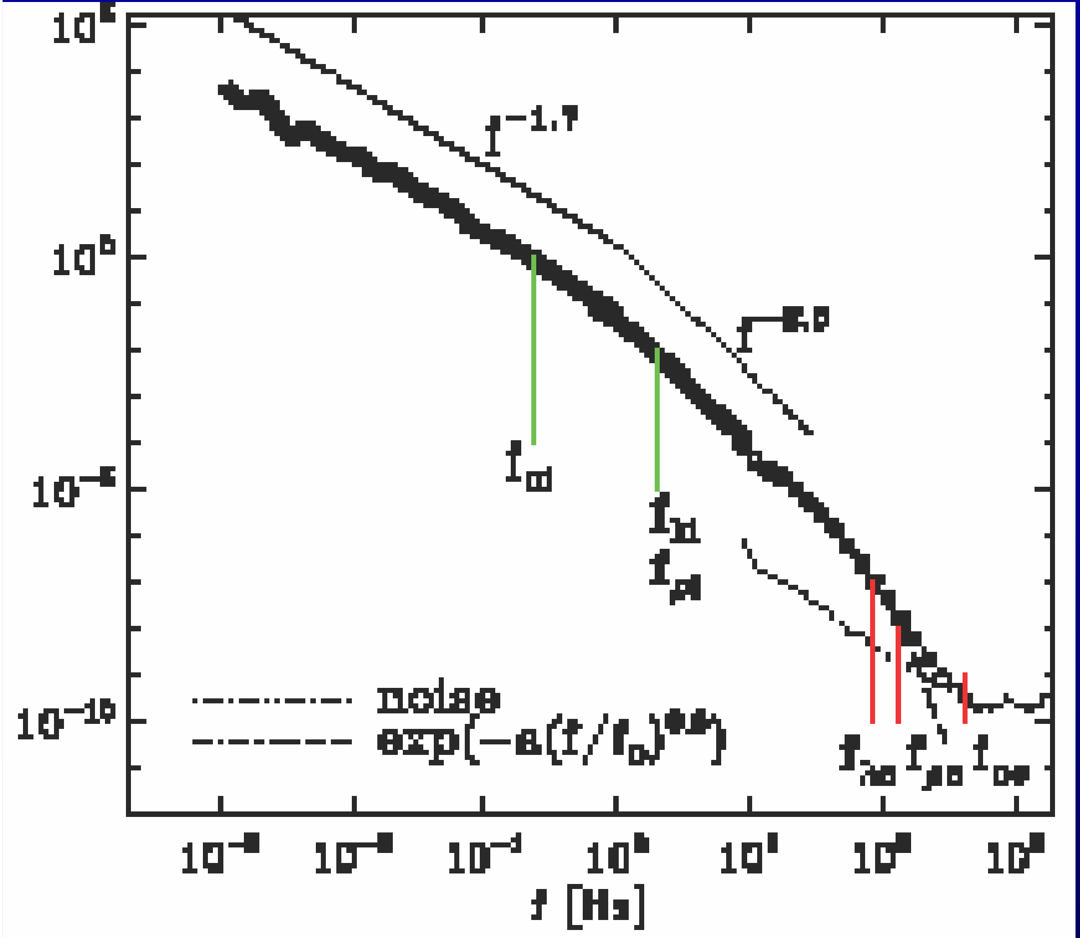
Small scale SW turbulence

1. Two breakpoints corresponding to ρ_i and ρ_e are observed.
2. A clear evidence of a new inertial range ~ $f^{-2.5}$ below ρ_i
3. ***First evidence of a dissipation range ~ f^{-4} near the electron scale ρ_e***

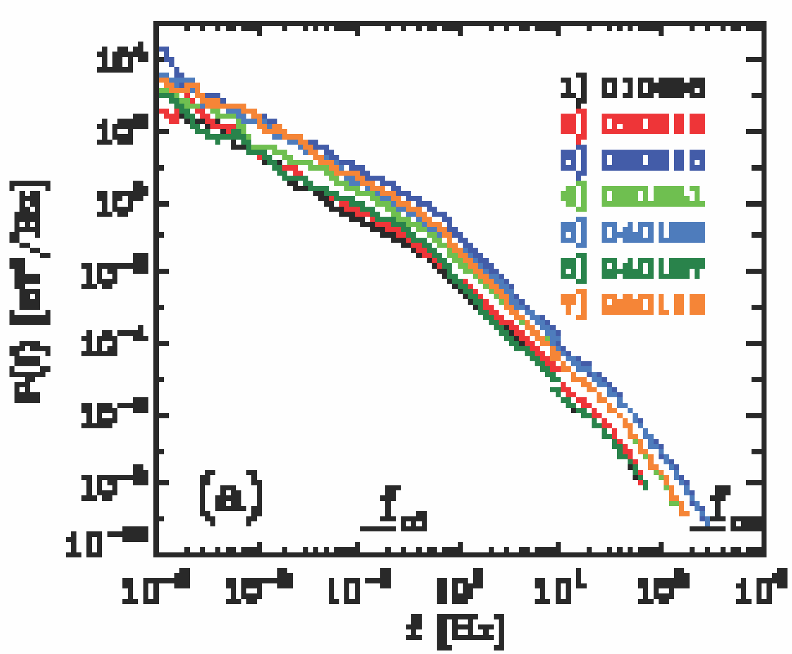
[Sahraoui et al., PRL, 2009]



STAFF-SC sensitivity floor



Similar observations from STAFF-SA data [Alexandrova et al., PRL, 2009]



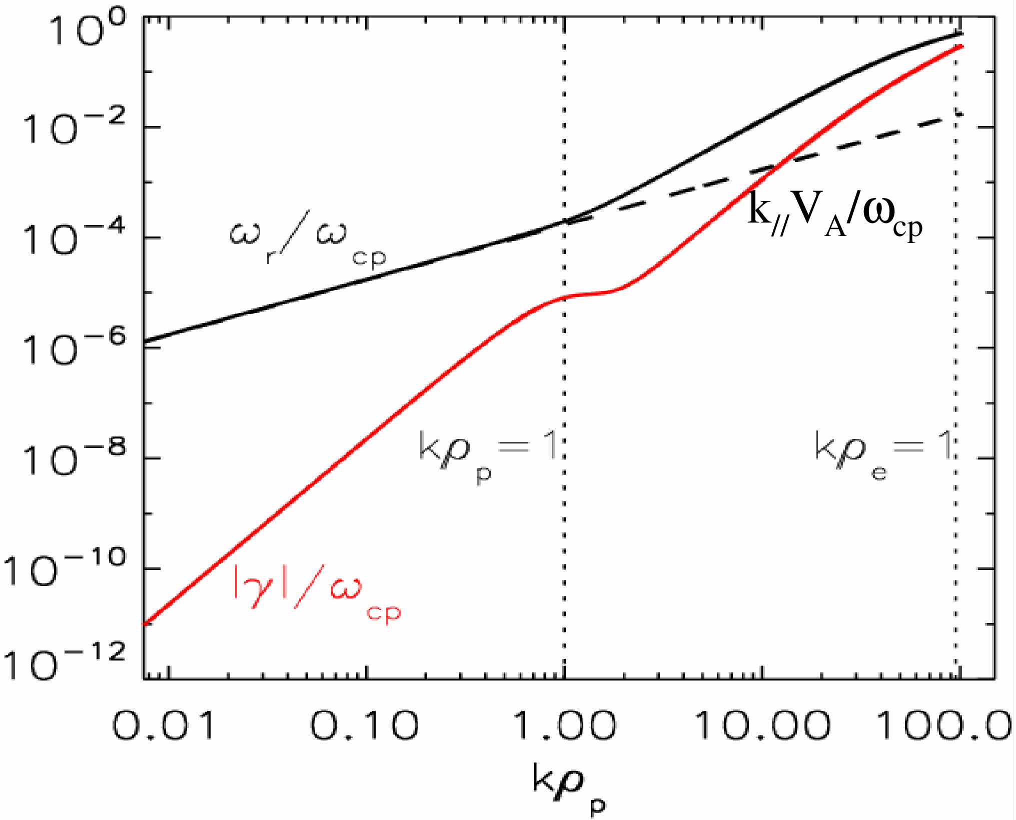
Theoretical interpretation : KAW turbulence

Linear Maxwell-Vlasov solutions: Θ_{kB}~ 90°, β_i~2.5, T_i/T_e~4

The Kinetic Alfvén Wave solution extends **down to kρ_e~1** with **$\omega_r < \omega_{ci}$**

→ **Rules out the cyclotron heating**

→ **Heating by p-Landau and e-Landau damping**



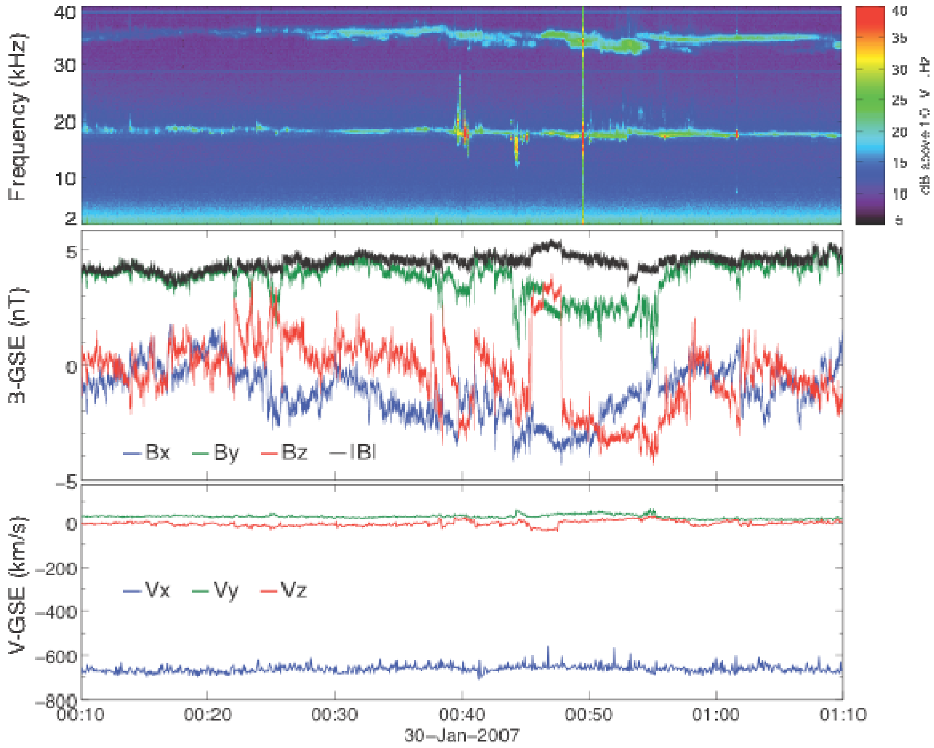
See also [Podesta, ApJ, 2010]

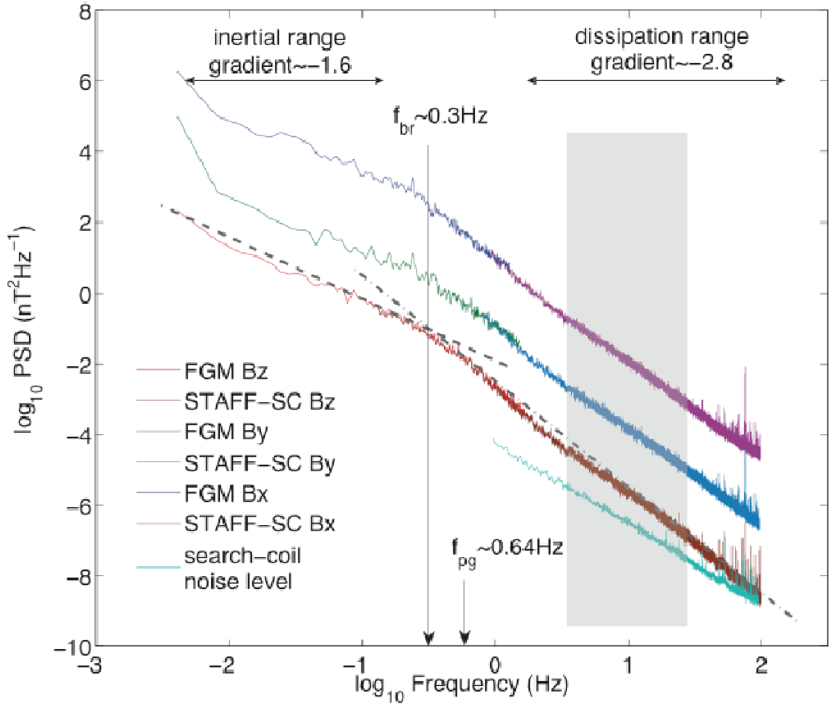
Evidence of self-similarity in the dispersive range

$n_e \sim 4\ \mathrm{cm}^{-3}$ ion $\beta \sim 2$

$V_A \sim 50\ \mathrm{km\ s}^{-1}$

Ti ~ 103 eV |B|~4 nT

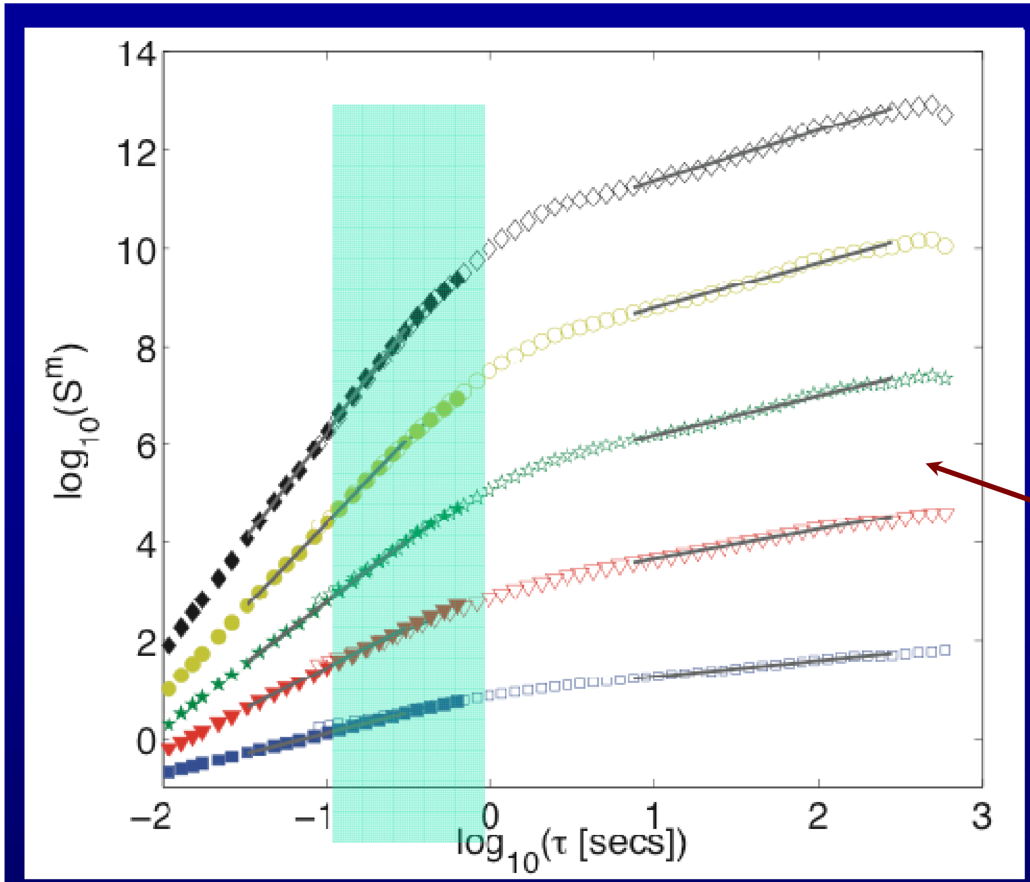


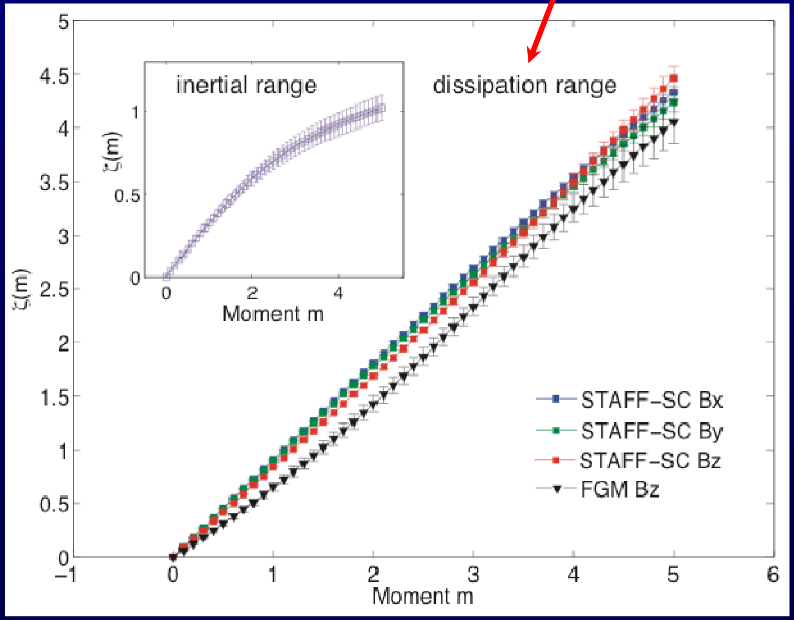


[Kiyani et al., PRL, 2009]

Structure functions scaling

$$S^m(\tau) = S^m(1)\tau^{\zeta(m)}$$





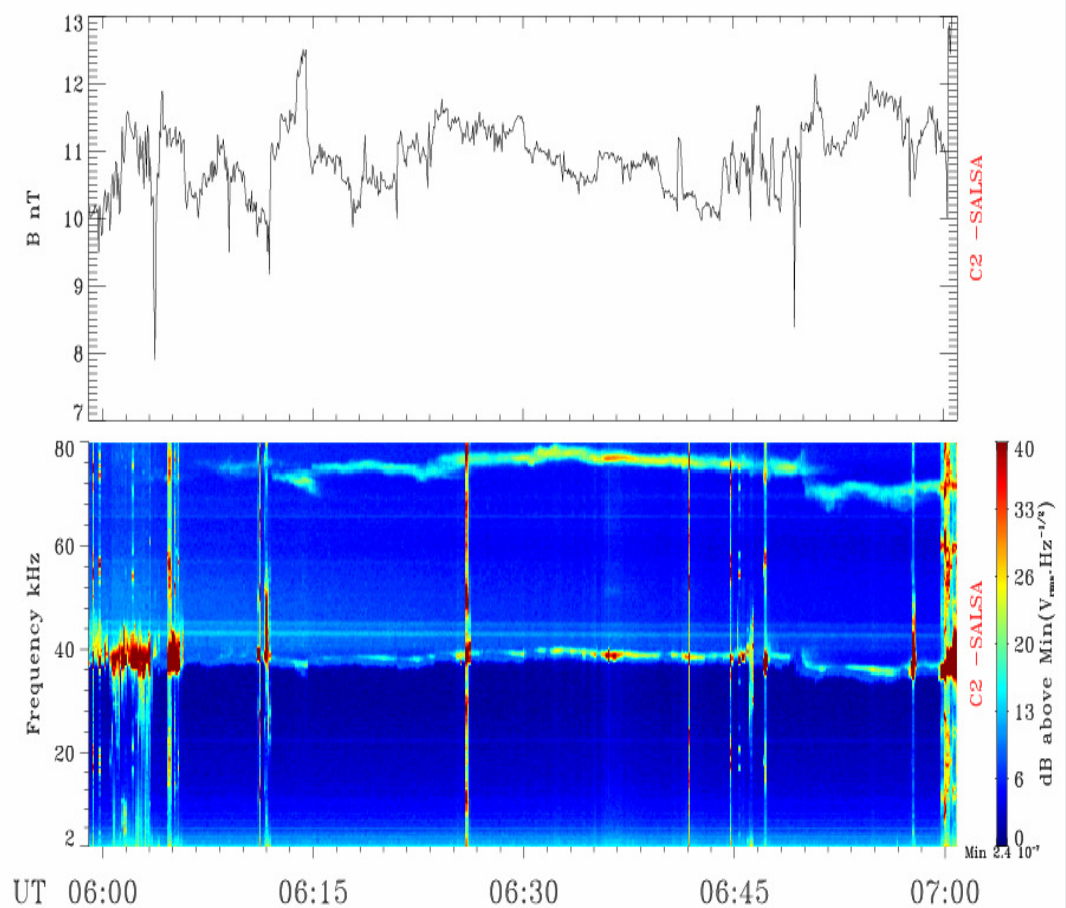
Evidence of monofractality (self-similarity) at small/electron - scales, while MHD-scales are multifractal (intermittent)

First 3D analysis of sub-proton scales of SW turbulence with Cluster data

Conditions required:

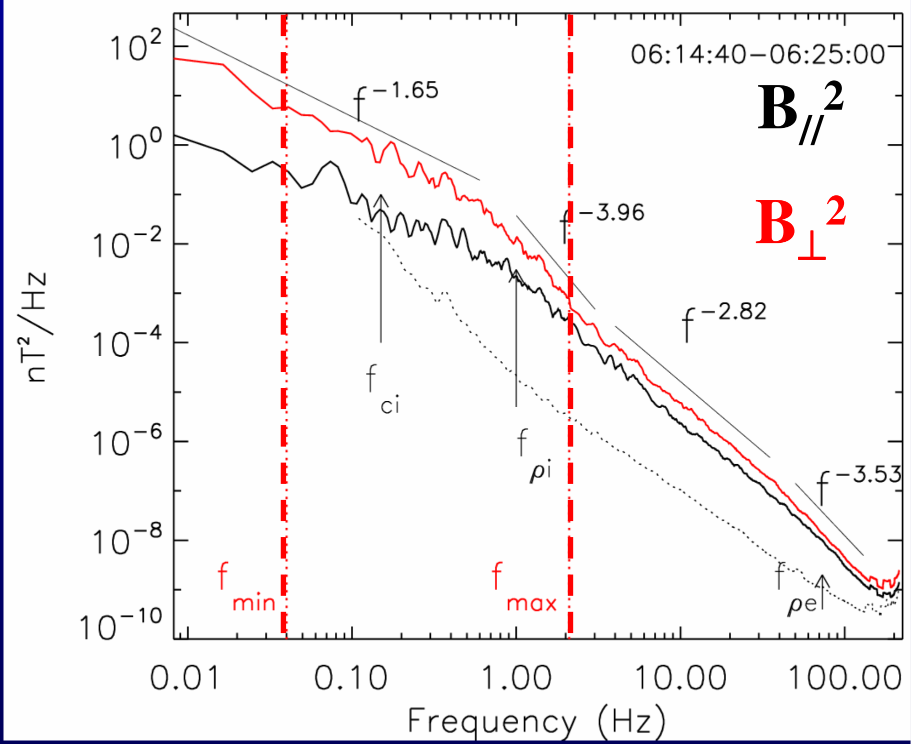
1. Quiet SW: NO electron foreshock effects
2. Shorter Cluster separations (~100km) to analyze sub-proton scales
3. Regular tetrahedron to infer actual 3D *k*-spectra [Sahraoui et al., JGR, 2010]
4. High SNR of the STAFF data to analyse HF (>10Hz) SW turbulence.

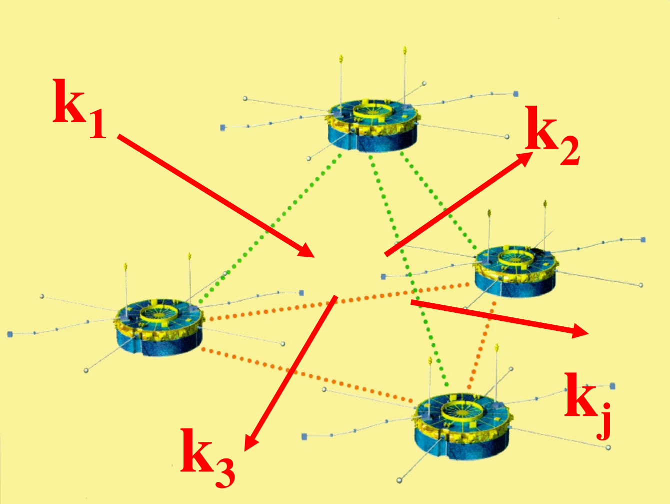
20040110, 06h05-06h55

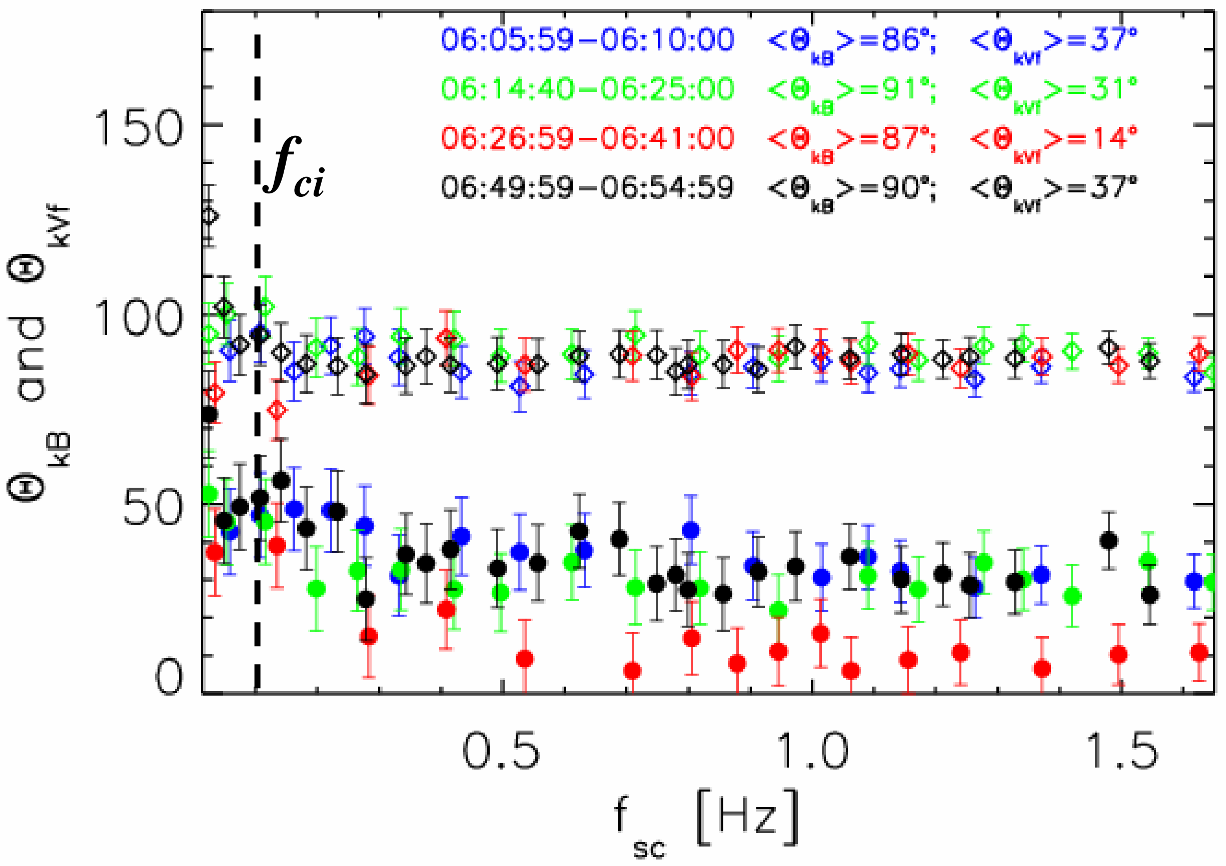


Kinetic cascade and dissipation at sub-proton scales

We use the *k*-filtering technique to estimate the 4D spectral energy density $P(\omega,k)$ from measurements of $B_j(\mathbf{r_i},t)$ [Pinçon & Lefeuvre; Sahraoui et al., 03, 04, 06, 10; Narita et al., 03, 06,09]







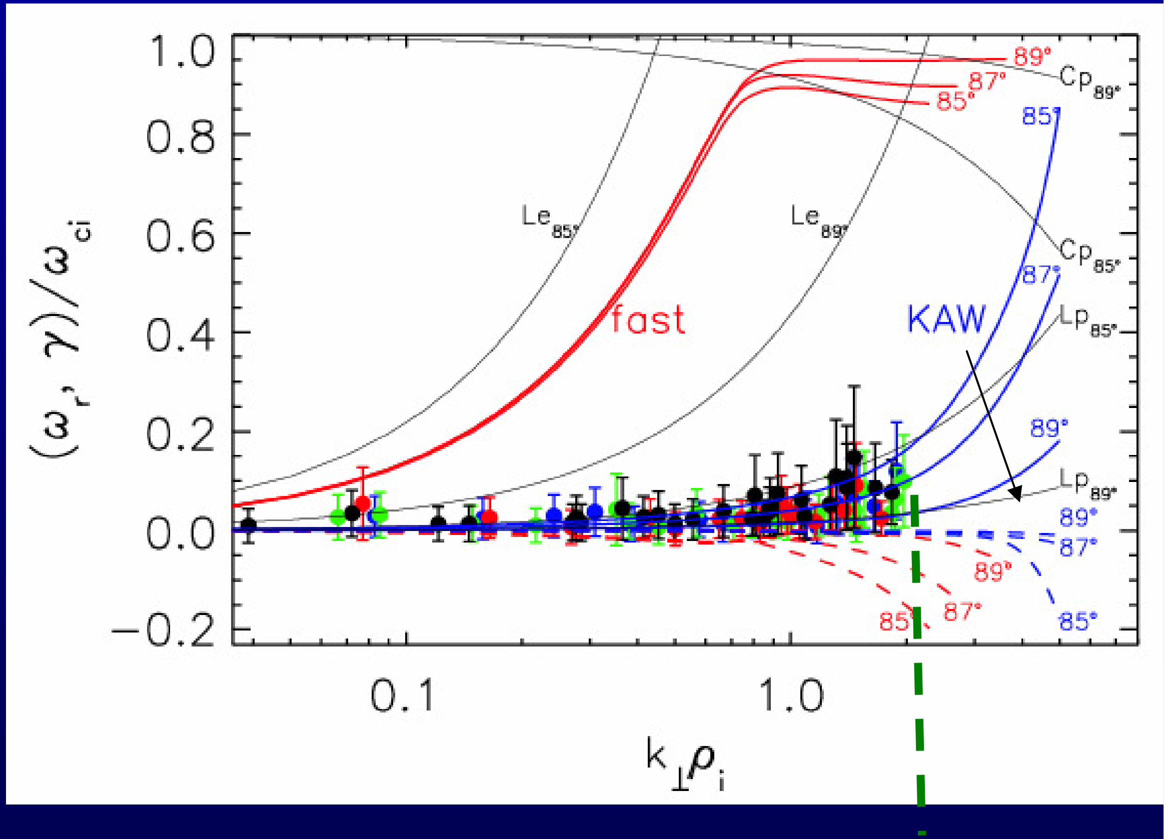
Turbulence is

- $\perp B_0$ *but non axisymmetric*
- Quasi-stationnary ($\omega_{plas} \sim 0$)

Comparison with the Vlasov theory

$\beta_i \sim 2$ $T_i/T_e=3$ $85° < \Theta_{kB} < 89°$

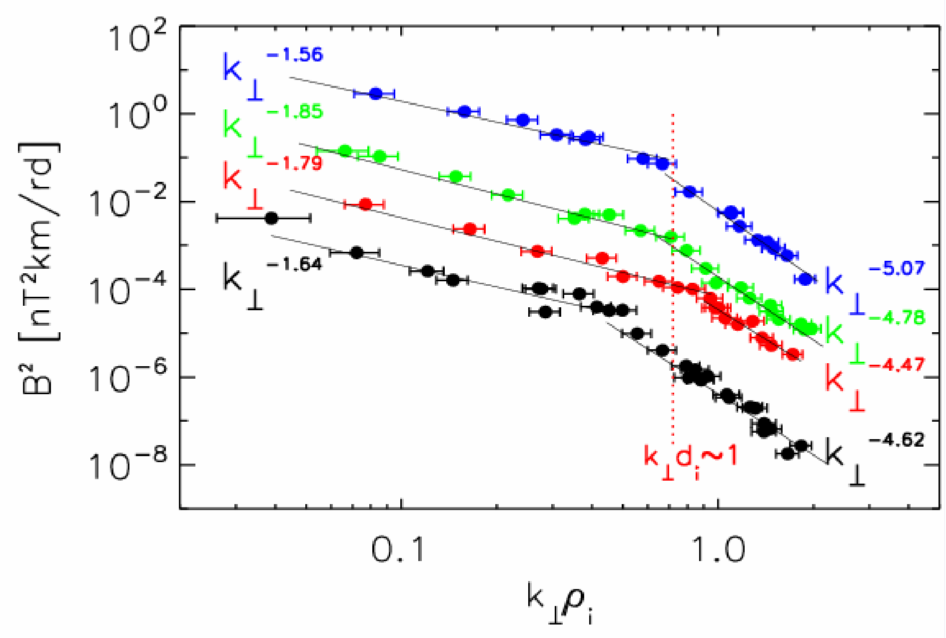
Turbulence develops following the Kinetic Alfvén mode (KAW) as proposed in Sahraoui et al., PRL, 2009



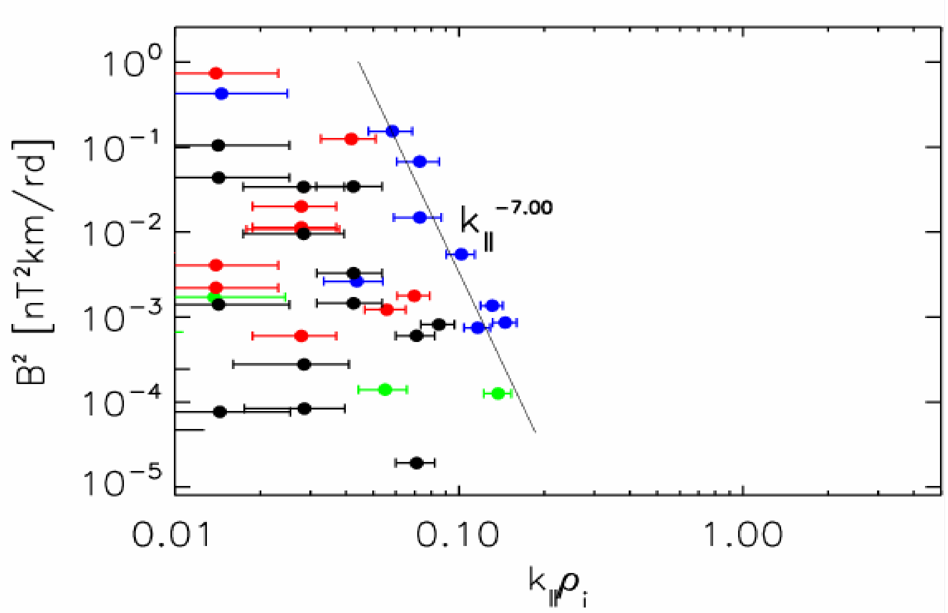
[Sahraoui et al., PRL, 2010]

Limitation due to the Cluster separation

First *k*-spectra at sub-proton scales



1. First *direct* evidence of the breakpoint at the proton gyroscale in k-space (***no additional assumption, e.g. Taylor hypothesis, is used***).

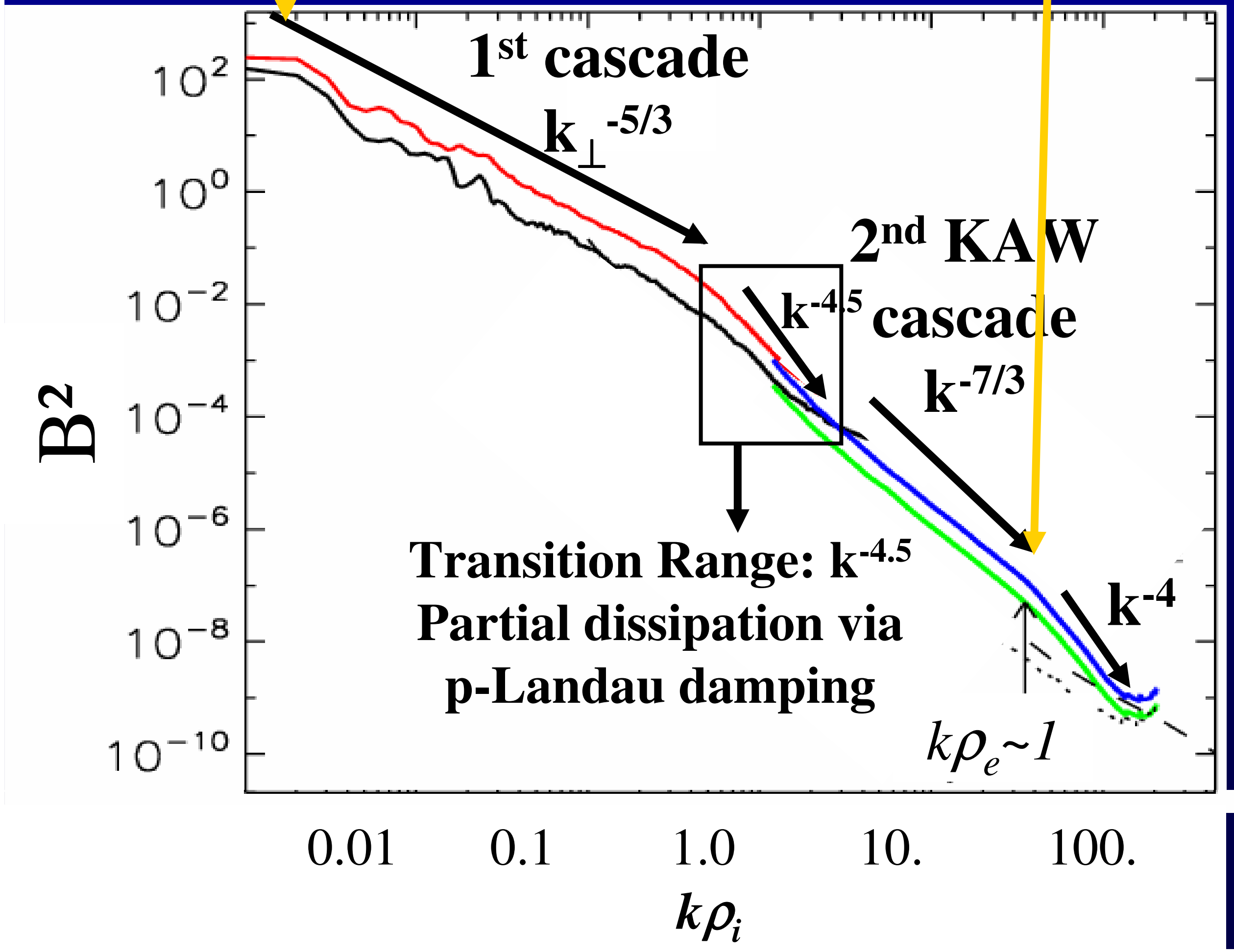


2. Strong steepening of the spectra below ri → A ***Transition Range*** to dispersive/electron cascade

Journey of the energy through scales: 2D cascade

Injection

Complete dissipation
e-Landau damping



1^{st} cascade
$k_\perp^{-5/3}$

2^{nd} KAW cascade
$k^{-7/3}$

$k^{-4.5}$

k^{-4}

Transition Range: $k^{-4.5}$
Partial dissipation via
p-Landau damping

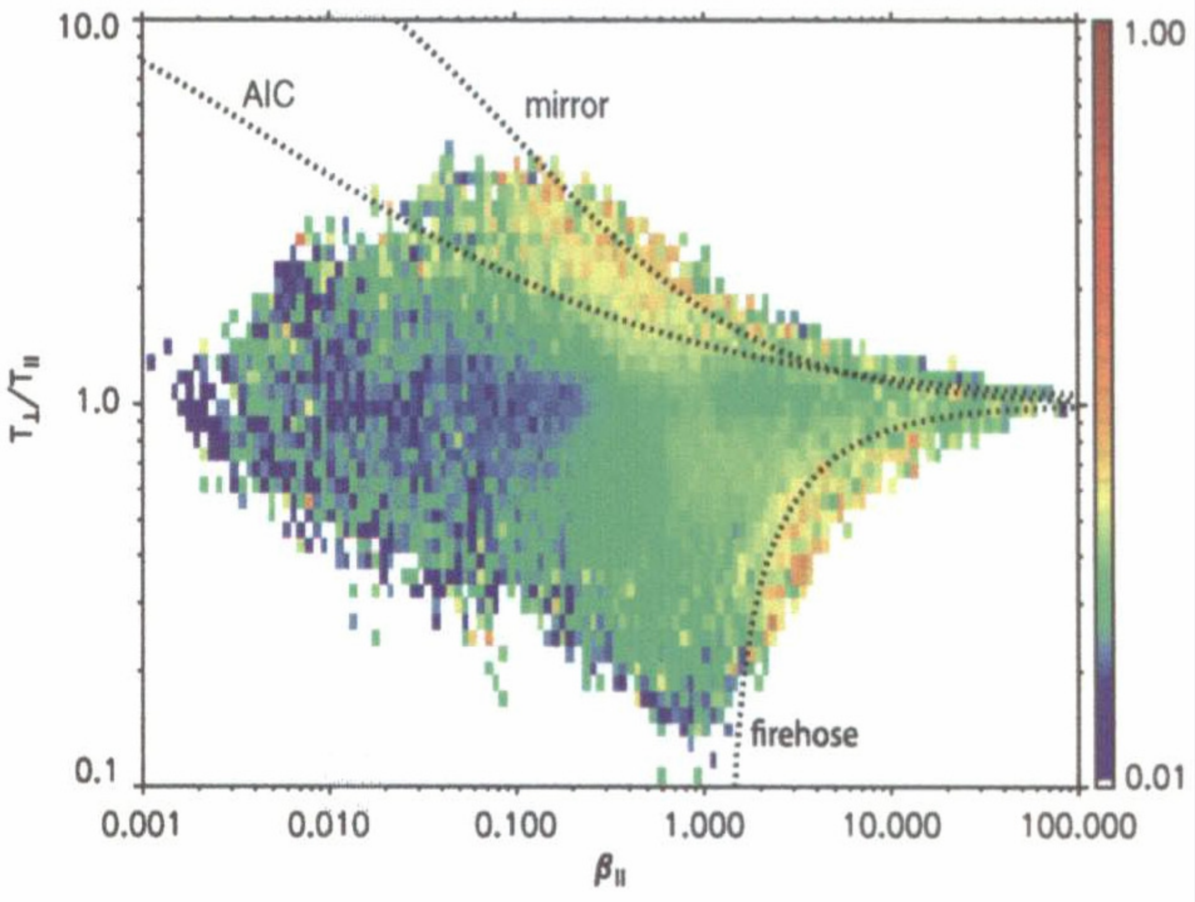
Dissipation
range

1. Turbulence
2. e-Acceleration & Heating
3. Reconnection

Importance of the kinetic effects in SW turbulence

Bale et al., PRL, 2010

How linear kinetic instabilities fit into the whole picture of turbulence in the SW?

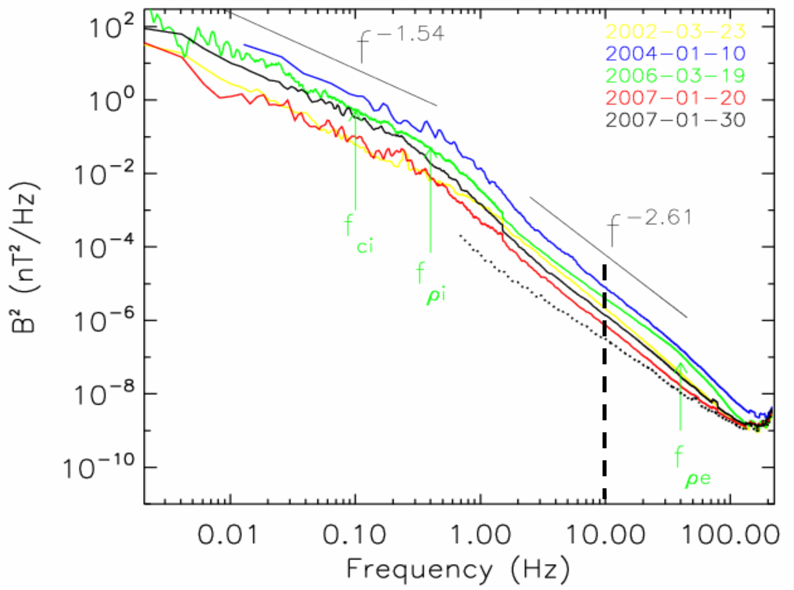


Is the energy injected by large scale driving or by local kinetic instability?

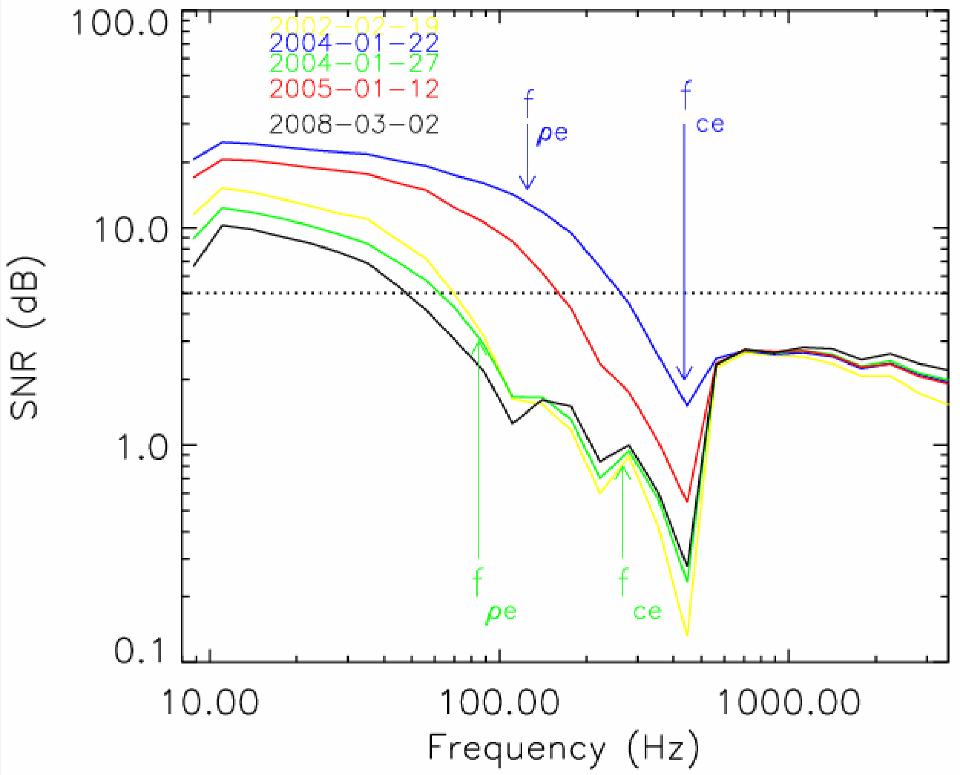
See also [Hellinger et al., 2006]

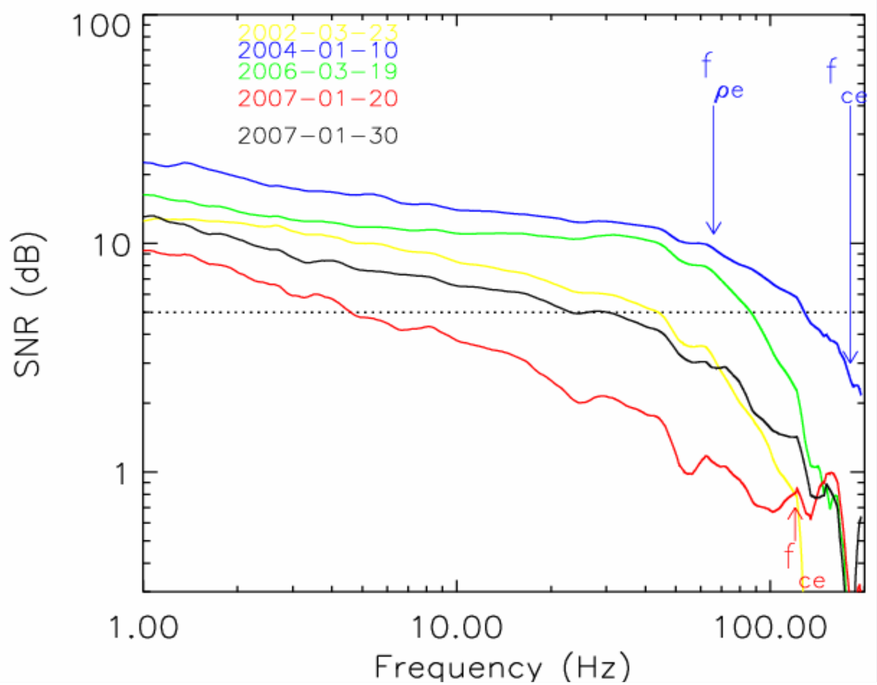
The SCM sensitivity and e-physics in the SW

Cluster SCM Noise level on Cluster:
0.76 pT/Hz$^{1/2}$ @ 10Hz



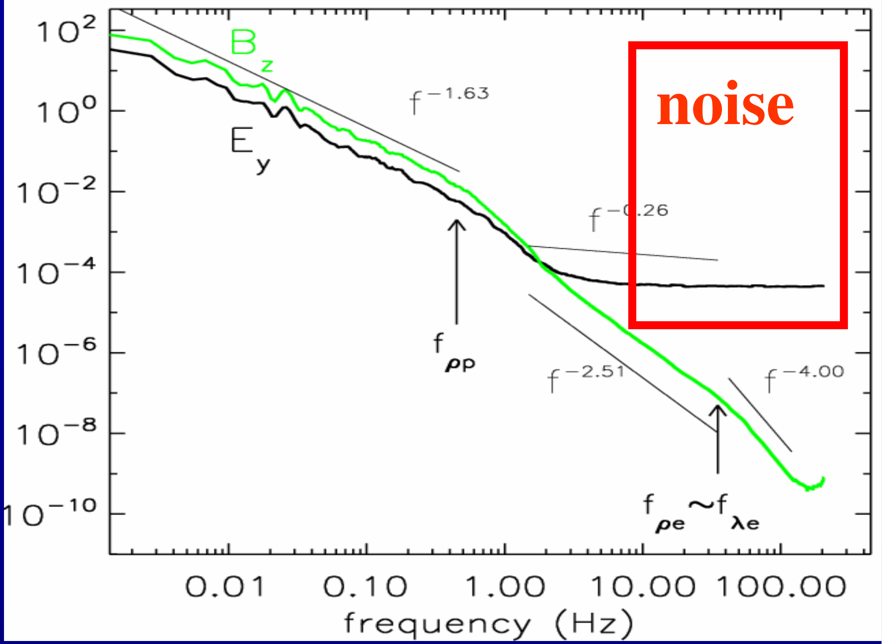
STAFF-SA data [8, 1000]Hz

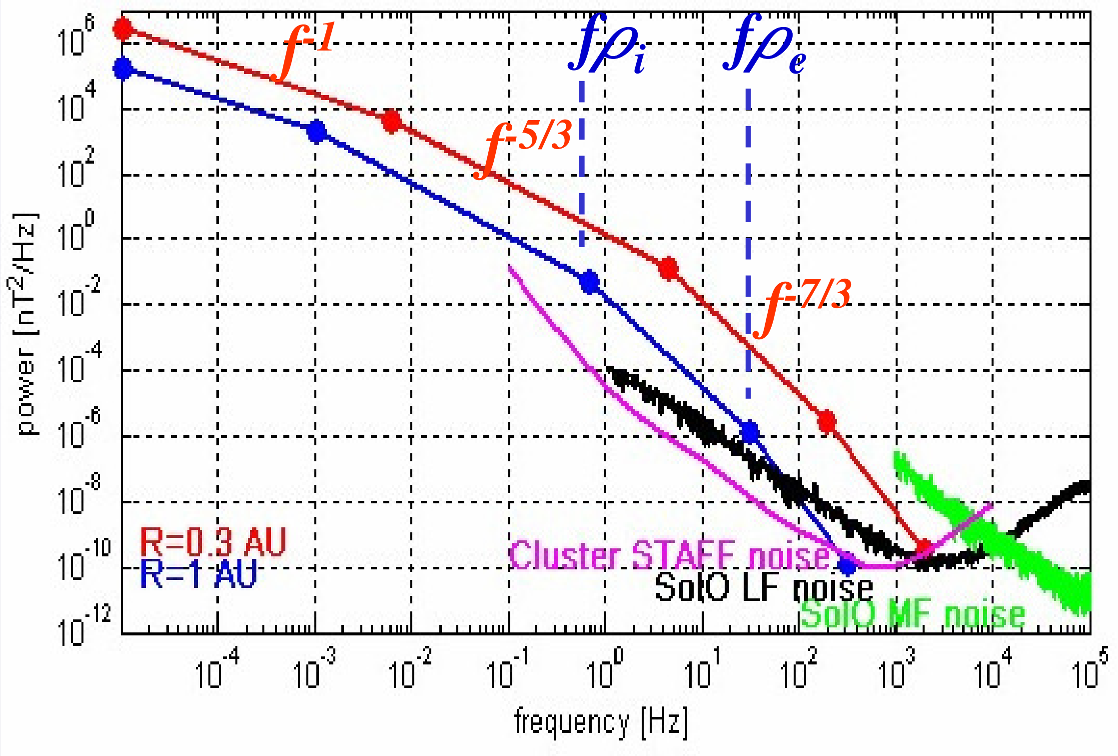




A similar noise issue in the EFW data in the SW

The SCM on Themis and MMS have a lower sensitivity than on Cluster !





Expected sensitivity on SO: slightly better than Cluster but not good enough to always resolve $f_{\rho e}$ and f_{ce}

⇒Eidoscope

The k-filtering and Xscale/Eidoscope

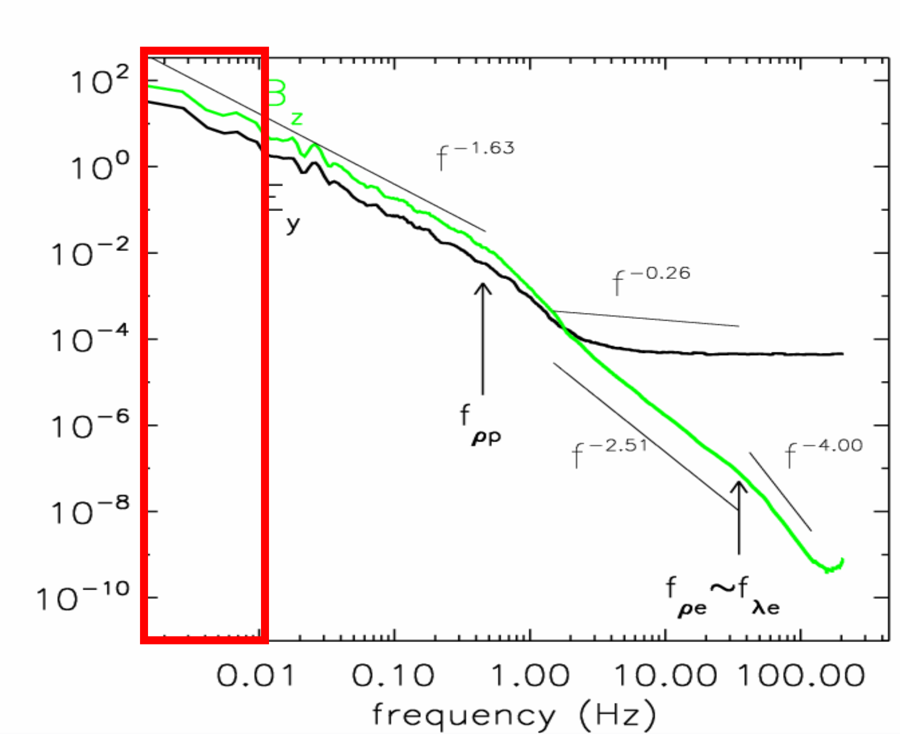
Given a separation *d* between 4 spacecraft ⇒ only one decade of scales $2d < \lambda < 30d$ can be correctly determined using interferometric methods (e.g., k-filtering, wave telescope).

- $\lambda_{min} \simeq 2d$, otherwise aliasing occurs.
- $\lambda_{max} \simeq 30d$, because larger scales are subject to important uncertainties

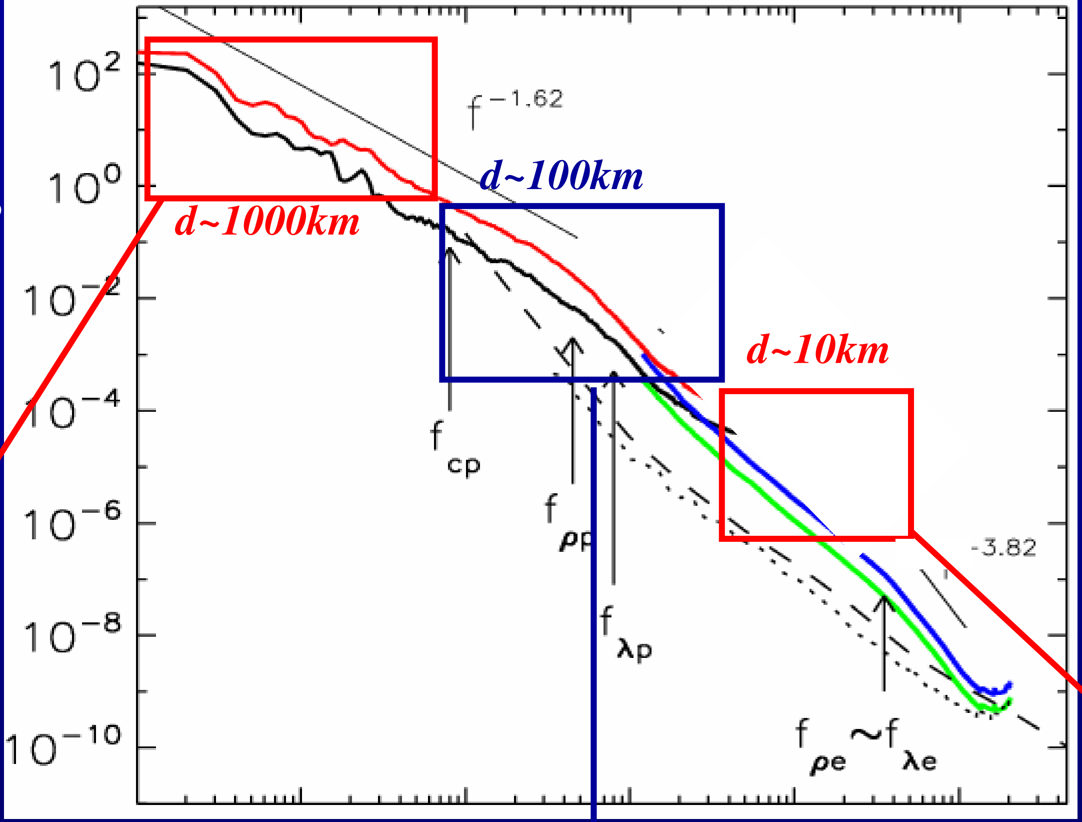
$\omega_{sat} \sim kV \Rightarrow f_{max} \sim k_{max} V/\lambda_{min}$

Here d~10^4 km and V~500km/s

$\Rightarrow \; 10^{-3}$ Hz $< f < 10^{-2}$ Hz



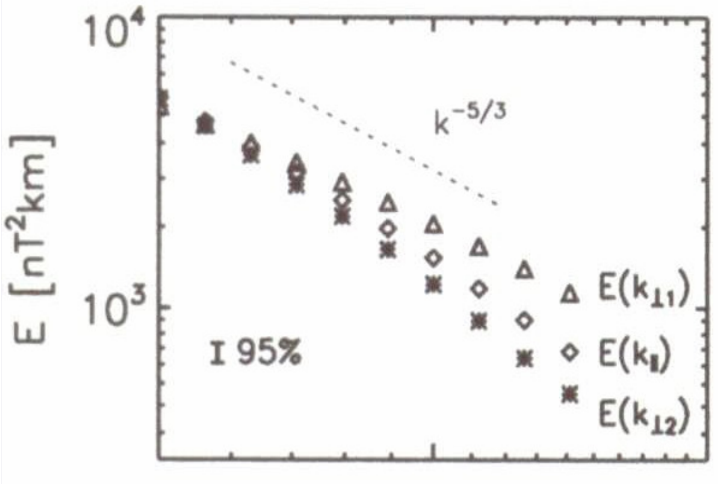
⇒ Need of multi-scale measurements ***with appropriate spacecraft separations***

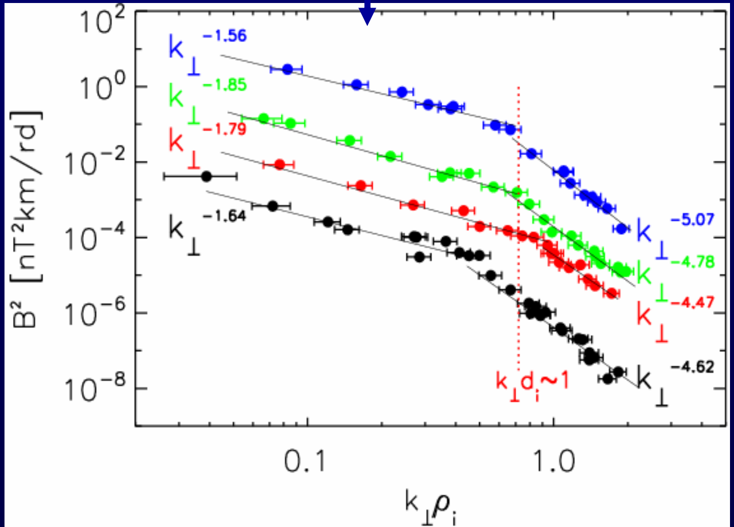


MMS

2014

Narita *et al.* PRL, 2010



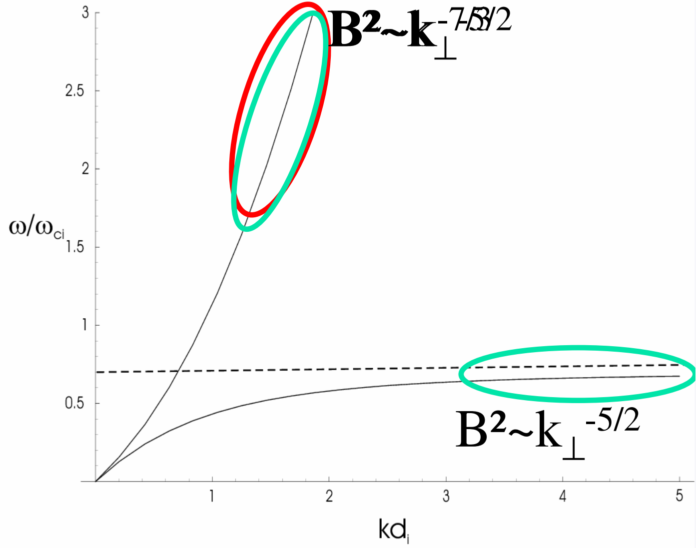


Sahraoui *et al.* PRL, 2010

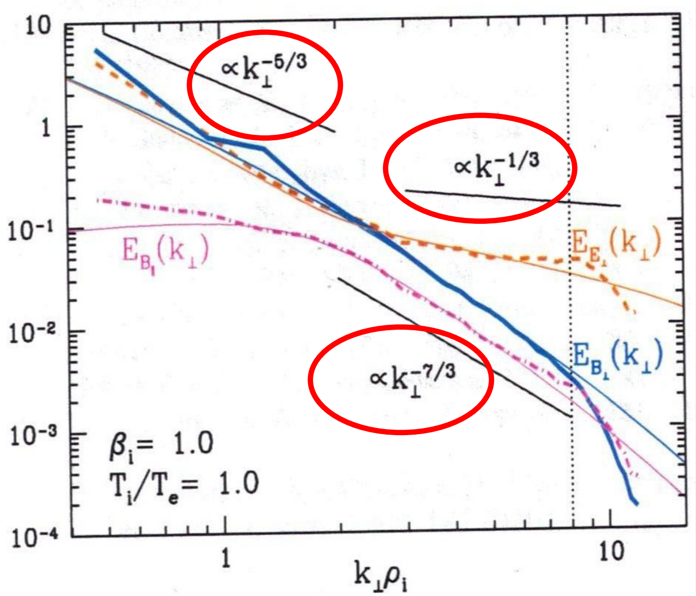
Theoretical predictions on small scale turbulence

$$\mathbf{E}+\mathbf{V}\times\mathbf{B}=\frac{1}{en}\mathbf{J}\times\mathbf{B}-\frac{\nabla P_e}{en}+\ldots$$

1. Fluid models (Hall-MHD)
   - Whistler turbulence (E-MHD): (Biskamp *et al.*, 99, Galtier, 08)
   - Weak Turbulence of Hall-MHD (Galtier, 06; Sahraoui et al., 07)



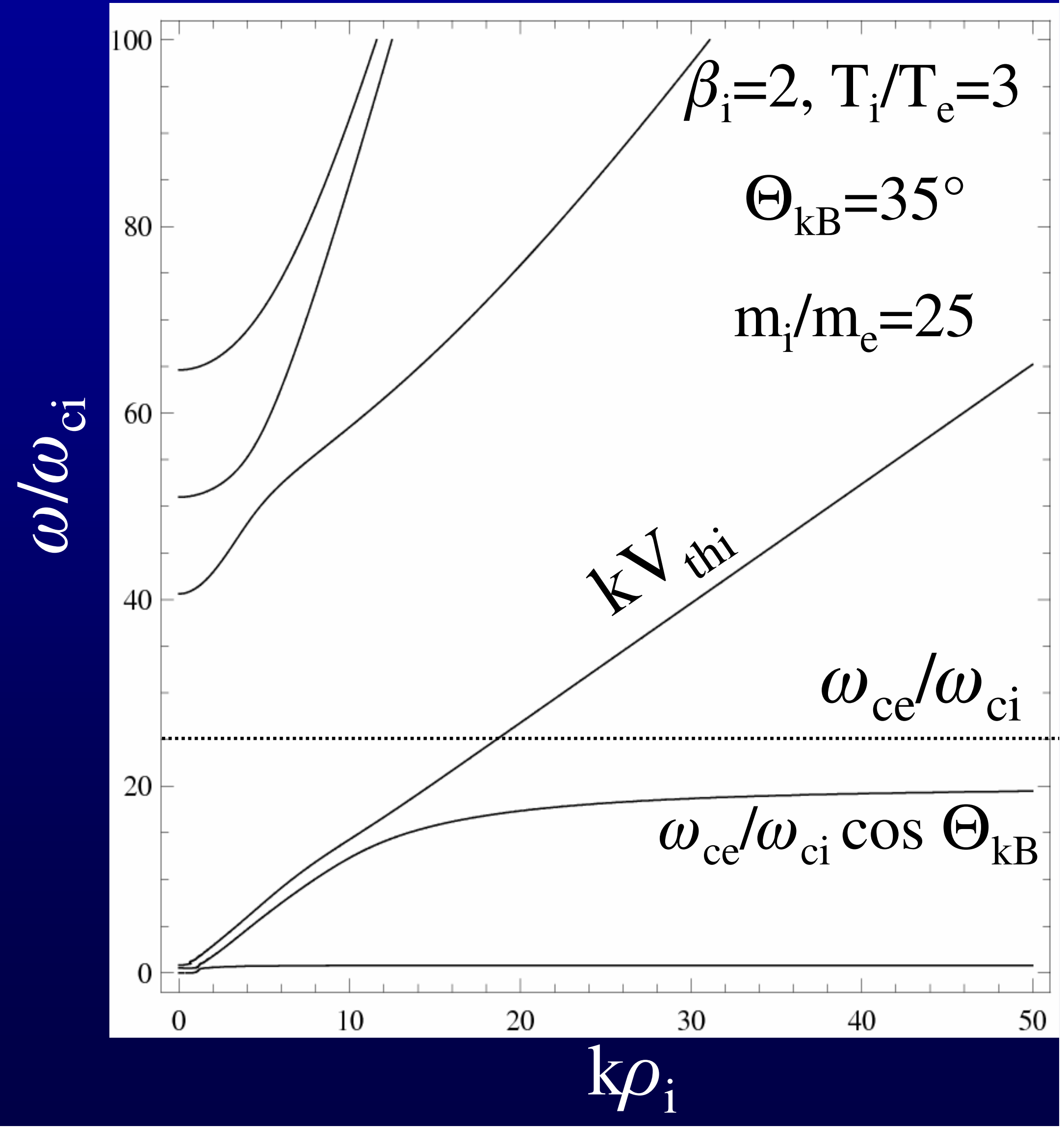
2. Gyrokinetic theory: $k_{//} \ll k_\perp$ and $\omega \ll \omega_{ci}$ (Schekochihin *et al.* 06; Howes *et al.*, 08)

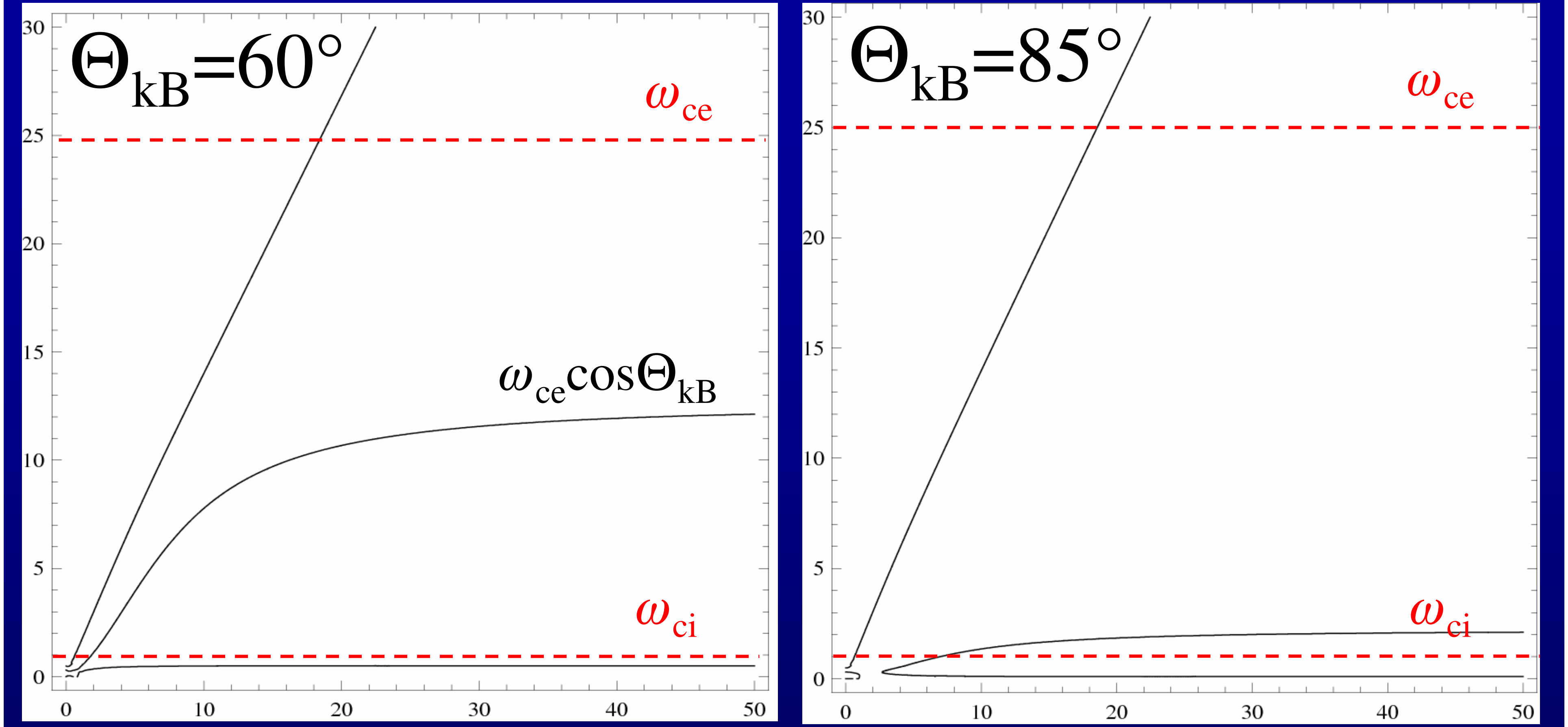


Why the Whistler mode Cannot acount for small scale HOT Solar Wind?

1. **Hot two fluid theory:**

The whistler mode is connected at LF ($\omega<\omega_{ci}$) to the Alfvén mode and NOT to the fast magnetosonic mode !



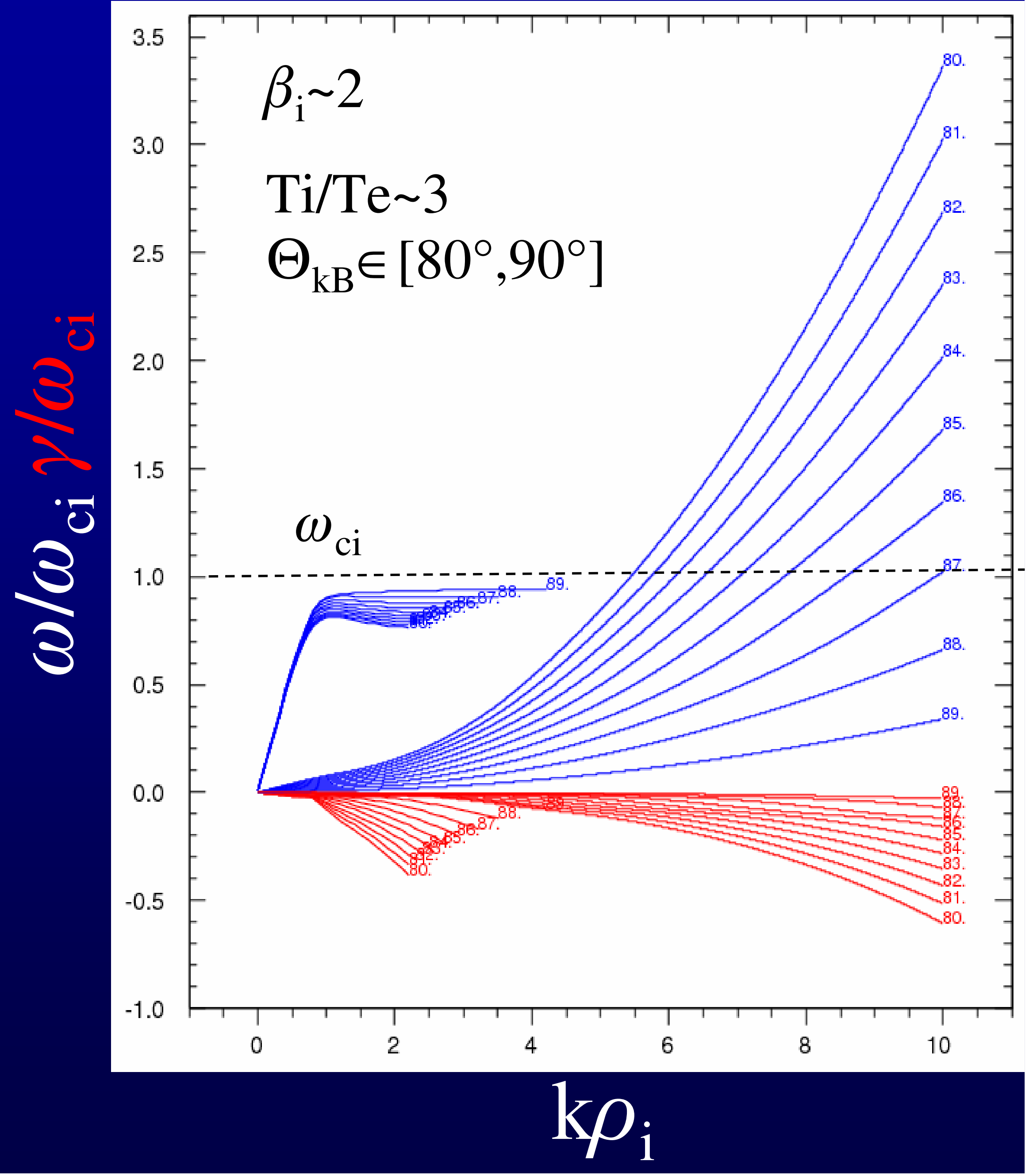


- As Θ_{kB} →90° the asymptote of the Whistler mode $\omega_{ce}\cos\Theta_{kB} \rightarrow \omega_{ci}$

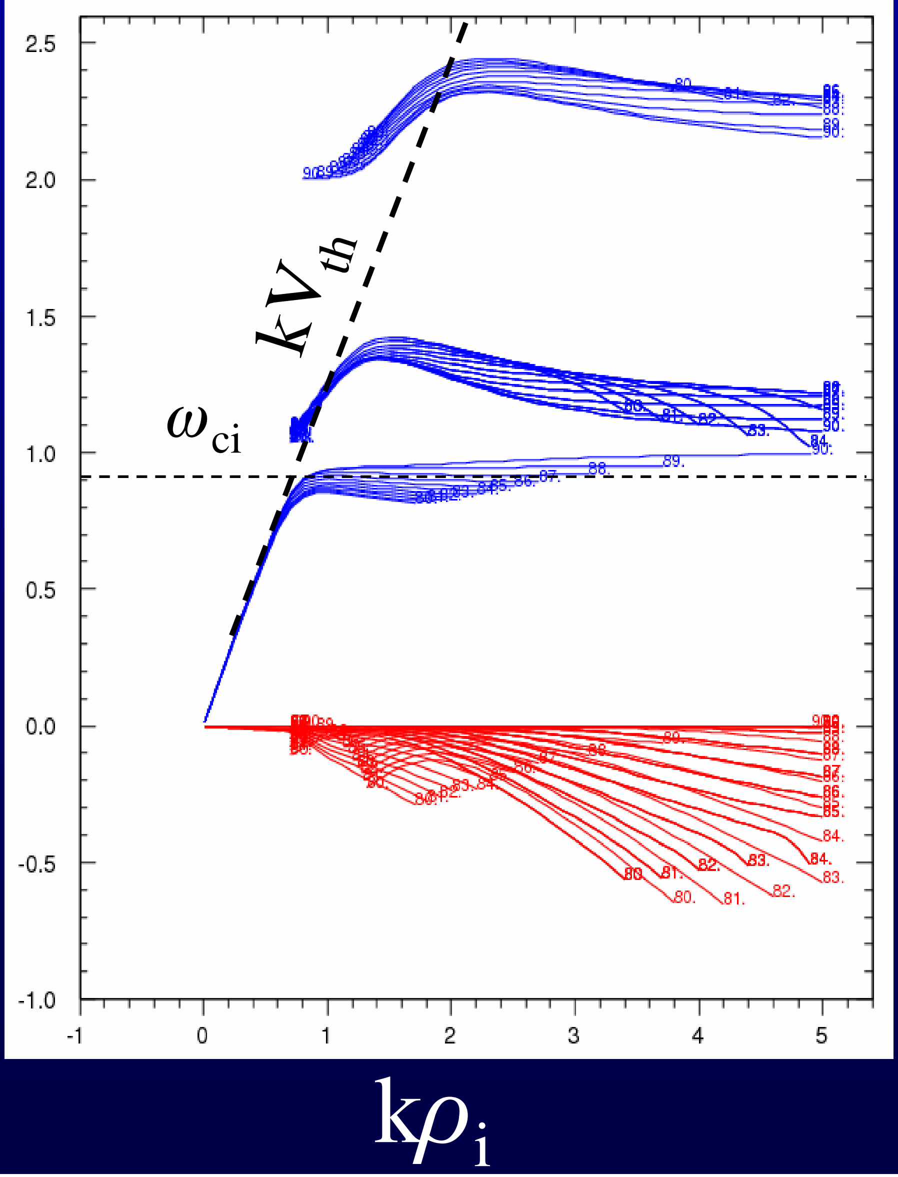
- $\text{Cos}\Theta_{kB} < m_e/m_i \Rightarrow$ The whistler mode ‘‘becomes’’ a KAW (i.e., $\omega < \omega_{ci}$)!

2. Maxwell-Vlasov linear theory [*Sahraoui et al., submitted]*

1. The slow magnetosonic mode is highly Landau-damped (not observable)
2. The fast magnetosonic modes splits up into Bernstein modes for $\omega>\omega_{ci}$
3. The high oblique KAWs are only weakly damped



1. **The fast magnetosonic modes splits up into Bernstein modes for $\omega > \omega_{ci}$**



2. **The highly oblique KAWs are only weakly damped**