Dissipation of Magnetofluid Turbulence as Observed on the Scale of the Proton Larmor Radius (and smaller)

Melvyn L. Goldstein (NASA/GSFC)

and
Fouad Sahraoui (CNRS), Silvia Perri (U. Calabria/GSFC),
Haihong Che and Peter Hunana (NPP/GSFC)

OUTLINE

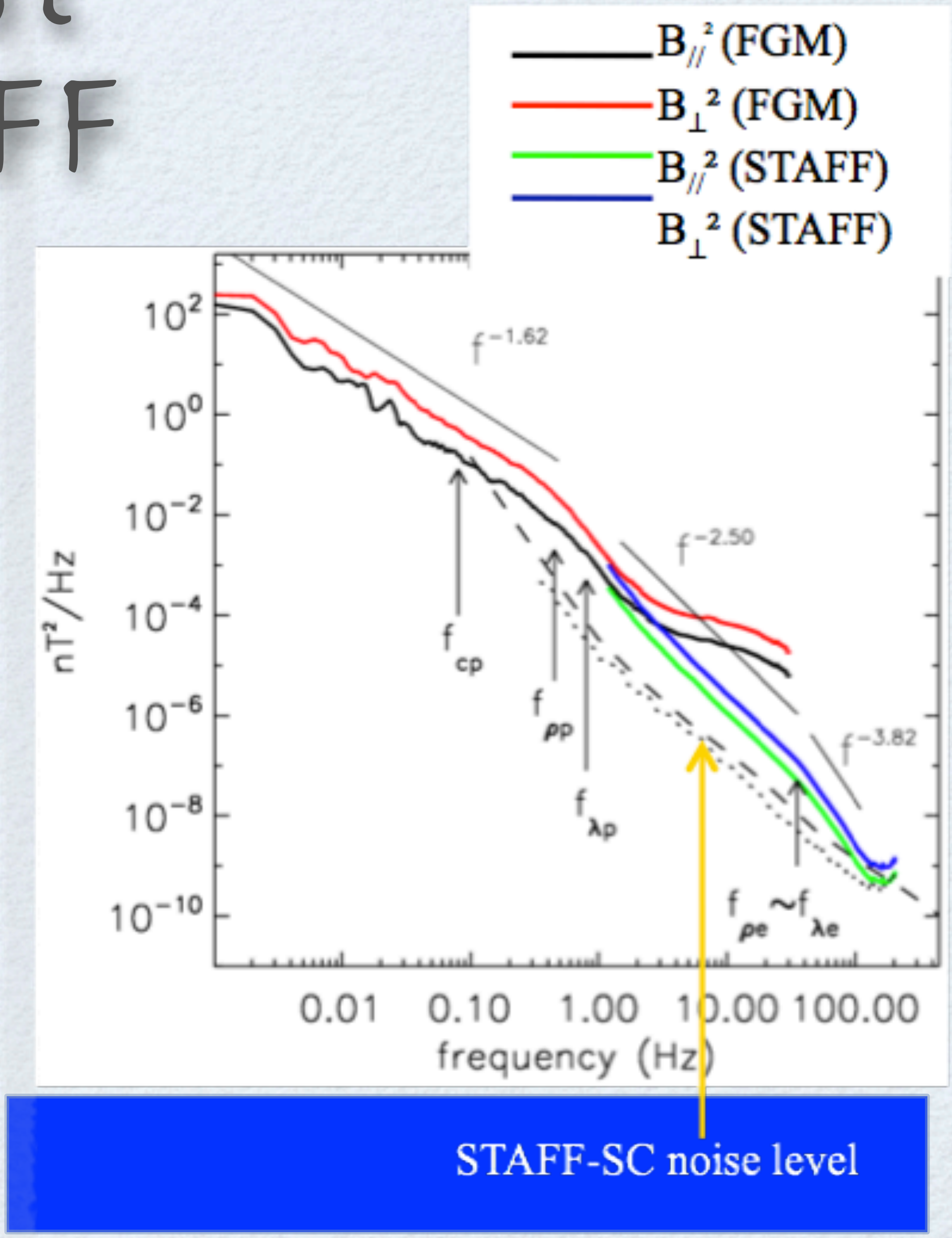
- Magnetofluid turbulence:
  - What happens to it?
    - High resolution observations between the ion gyroscale and the electron inertial length from the Cluster search coil magnetometer (STAFF)
  - What does it look like in the dissipation range at scales approaching the electron inertial length?
    - *k-filtering*
    - Current sheets and other discontinuities

Out to the electron scale: Cluster burst mode: FGM and STAFF

There's the breakpoint near the proton *Larmor radius* where the spectrum steepens to ~ –2.5 (seen by Leamon *et al.* and others).

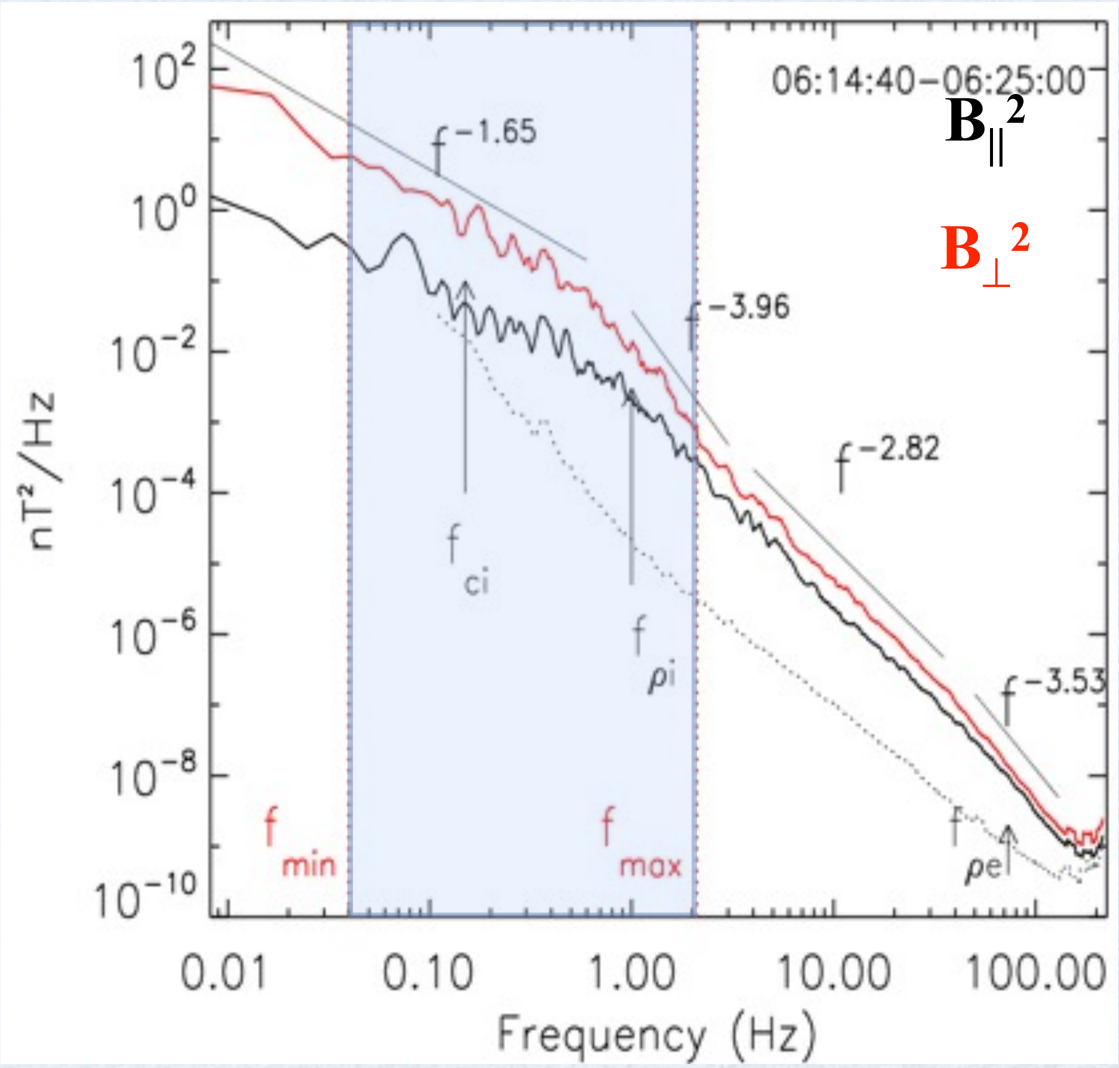
This spectral slope is consistent with Hall-MHD, whistler turbulence, or kinetic Alfvénic turbulence and gyrokinetic theory at scales smaller than the proton Larmor scale ($V_{thermal}/\Omega_{cp}$).

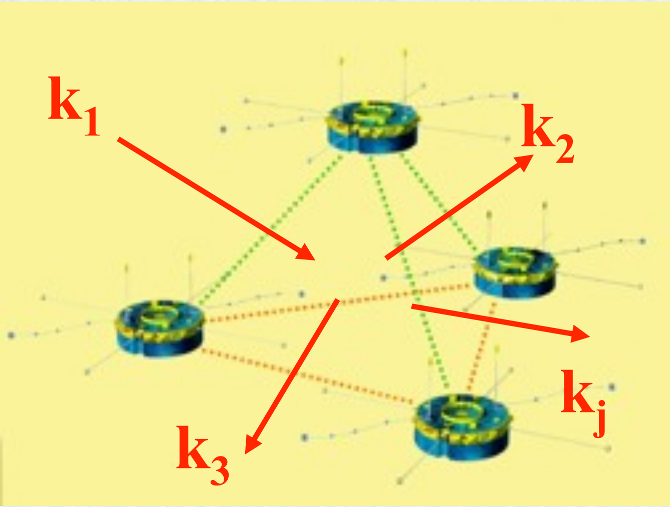
Near the electron Larmor radius there's evidence of a dissipation range where the spectrum steepens to ~ –4.



January 10, 2004
3D k-Spectra

k-filtering technique was used to estimate the 4-dimensional magnetic energy density, *$P(\omega,\mathbf{k})$*, from of $B_j(\mathbf{r}_j,t)$ [*Pincon & Lefeuvre; Sahraoui et al., 2010; Narita et al.,* 2010].





In calculating *$P(\omega,\mathbf{k})$* one must minimize spatial aliasing and the tetrahedral configuration must be "regular".

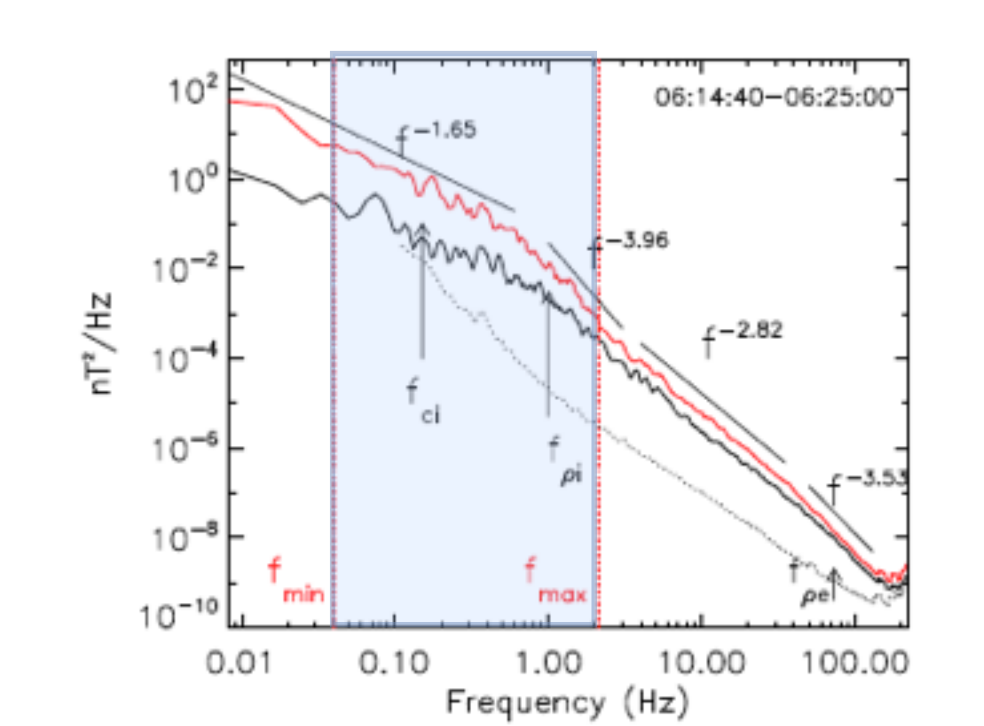
Then using the Doppler shift with very good solar wind velocity data, one can calculate $P(\mathbf{k})$ and obtain the wave-vector spectrum in the plasma frame of reference.

Strong evidence for Kinetic Alfvénic Turbulence

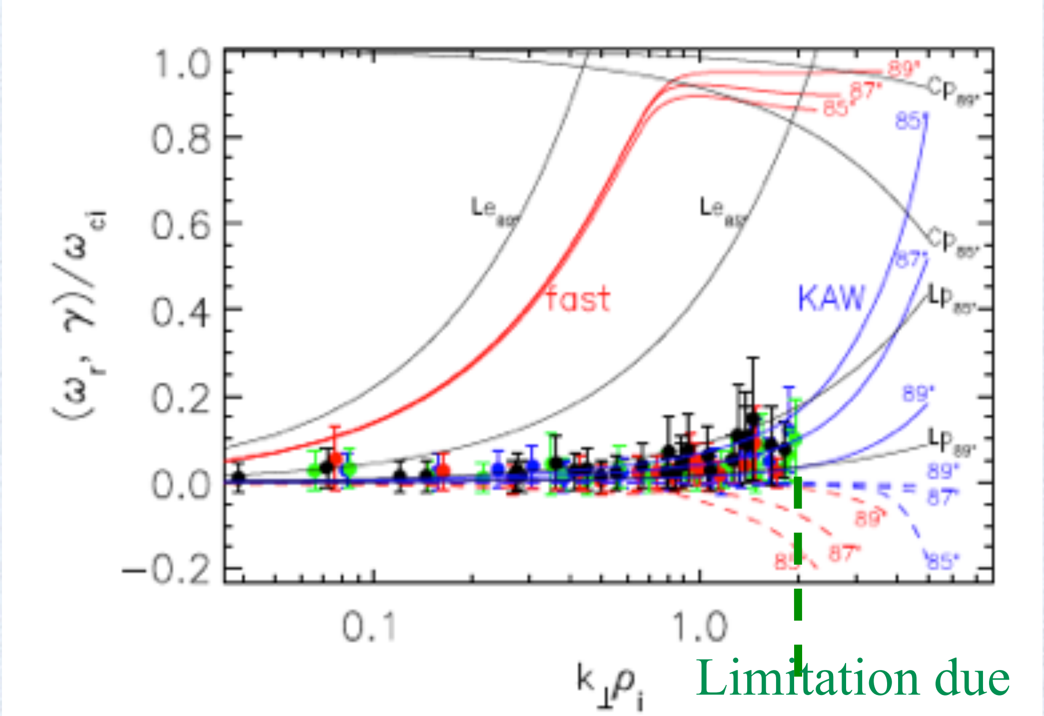
10 January 2004, ~200 km separation in the solar wind, and a nearly perfect tetrahedron we obtained the following ω–**k dispersion** curve.

The magnetic field was stationary, therefore, the *local* magnetic field is well-defined.

Note that the fluctuations have $\omega_{\text{plasma frame}}$ ~0, *i.e.*, broadband turbulence (the error bars are a consequence of uncertainties in the CIS determination of $\mathbf{V}_{sw}$)



Parallel and perpendicular power spectra from FGM & STAFF-SC on C2. Vertical arrows are f_{ci}, and the "Doppler-shifted" proton and electron gyro radii.



Observed dispersion relations (dots), compared with linear solutions of Maxwell-Vlasov for three angles. Black curves are the proton and electron Landau resonances $\omega = k_{\|} V_{thi,e}$ ($L_{p,e}$) and the proton cyclotron resonance $\omega = \Omega_{ci} - k_{\|} V_{thi}$ (C_p)

Limitation due to the 200 km Cluster separation

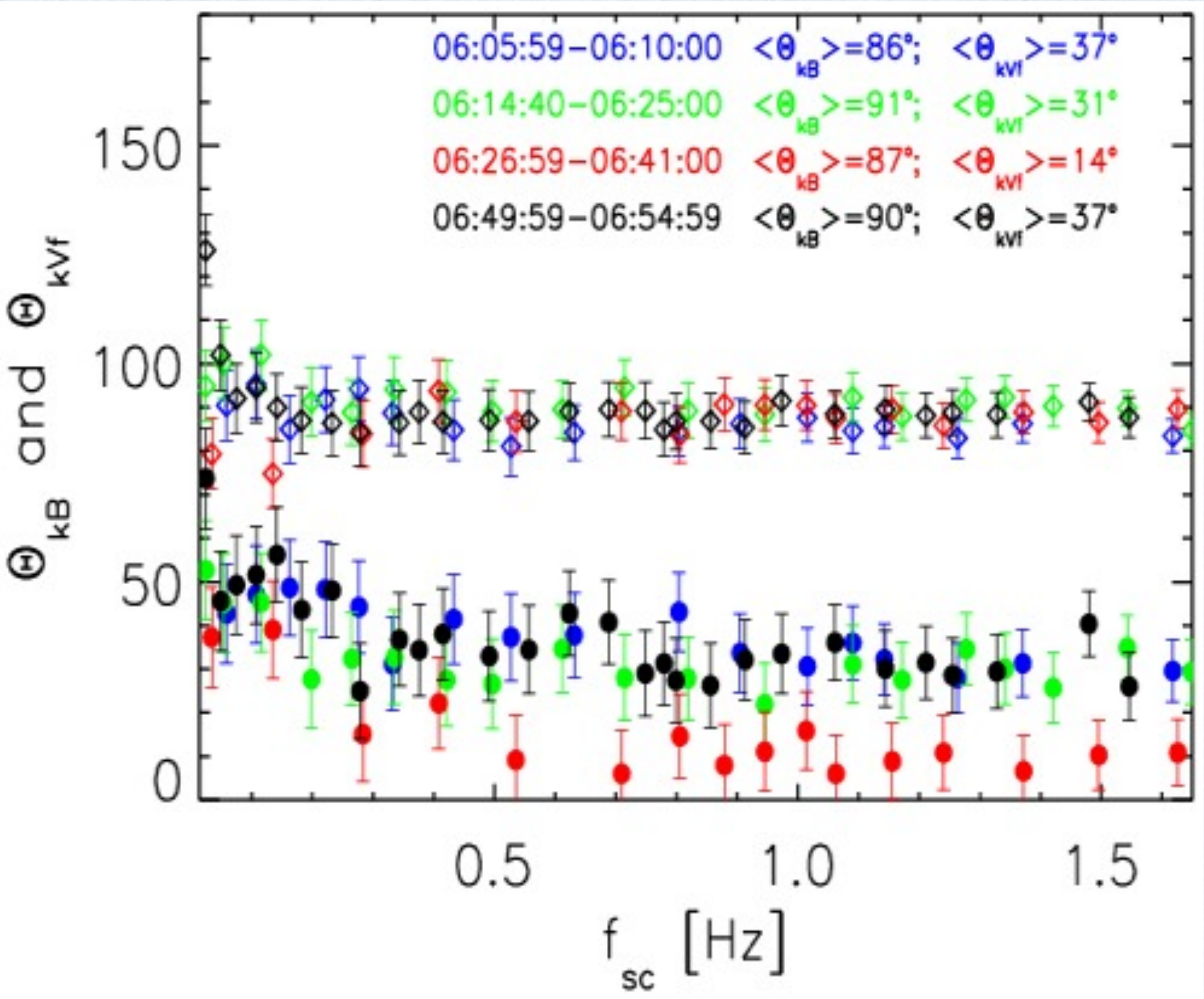
Sahraoui et al., *Phys. Rev. Lett.*, 2010

Angles between k and magnetic field and velocity

The turbulence is highly oblique to **B**

To the extent that these results can be interpreted as kinetic Alfvénic fluctuations, there will be $E_{\|}$ that, presumably, can be in Landau resonance with thermal protons and electrons.

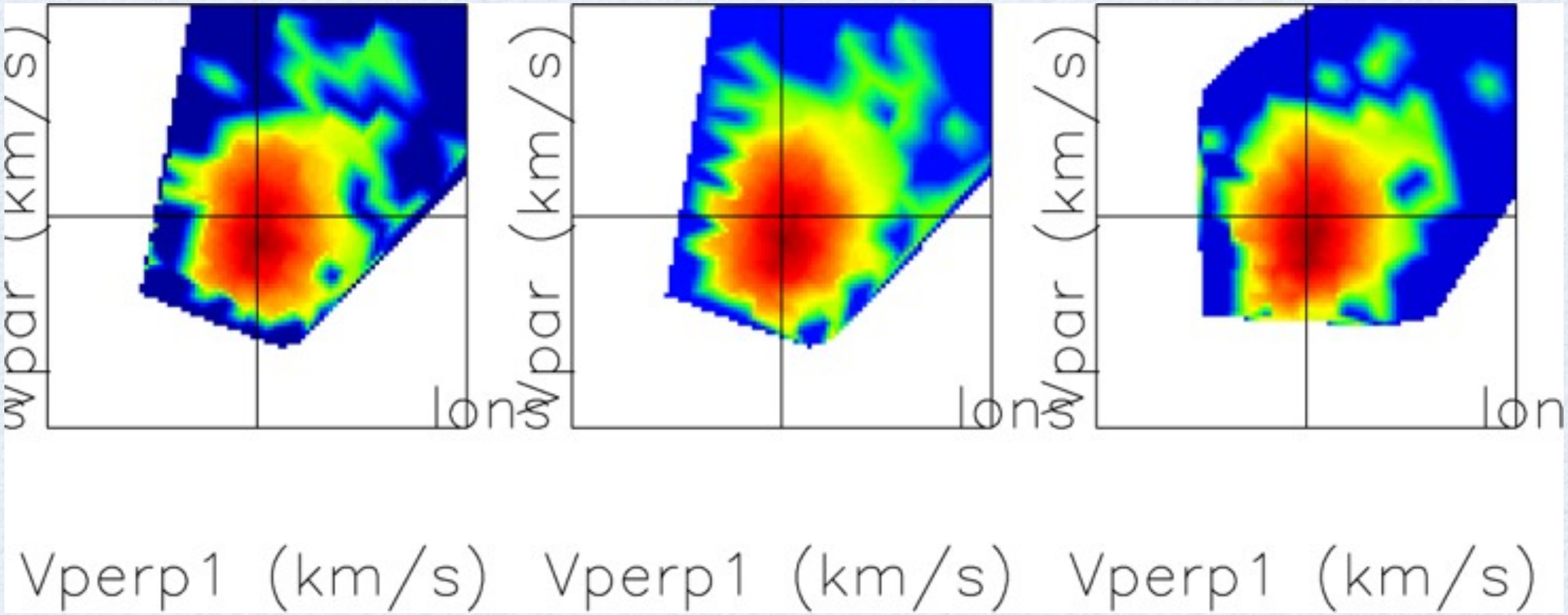
That interaction, first with protons and then with electrons, can damp the fluctuations and heat the solar wind. As the fluctuations become more oblique, higher phase speeds are needed for effective Landau damping and the interaction will move to the solar wind core/halo/strahl population.



Sahraoui et al., *Phys. Rev. Lett.*, 2010

Supporting evidence from Cluster (thermal protons)

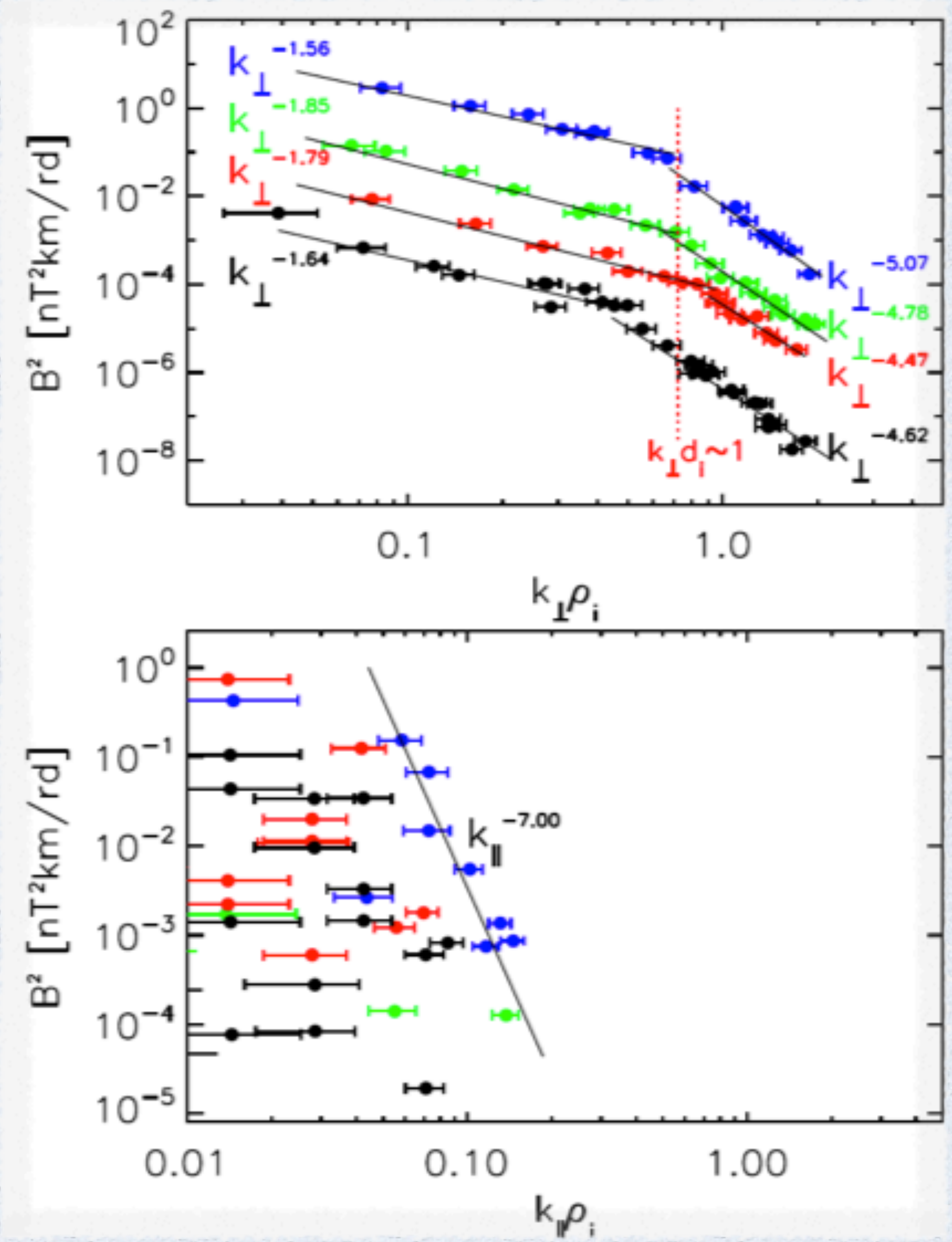
Heating from Landau damping implies that $T_{\parallel} > T_{\perp}$



Data from George Parks and Iannis Dandouras

Integration over ω leads to a wave-number spectrum

- Power in $k_\perp$ is *Kolmogorov* to $k_\perp \rho_i \sim 1$. First direct determination of a breakpoint at the proton gyroscale in *k*-space
  - No Taylor-frozen-in-flow approximation—Doppler shift was used
- There is strong steepening of the spectra at scales smaller than the proton inertial length (steeper than Hall MHD or Gyrokinetic expectations, which are -7/3).
- Power in $k_\parallel$ is almost nonexistent at the smallest scales—this is 2D turbulence.



Possible Relationship to the Electron Strahl...

- *Shay et al.*, 2011: KAW will have an associated Poynting Flux that is parallel to the background magnetic field.
- In the solar wind, if the fluctuations *are* KAW, there should be a Poynting Flux parallel to the background solar wind magnetic field.
- But the *strahl* is a relatively cold beam that is flowing along that magnetic field in contrast to the thermal core/halo that is flowing radially outward from the sun.
- ***Conjecture:*** The ***strahl*** will interact with the KAW turbulence via Landau damping, as was suggested by the linear Vlasov analysis shown previously.

Possible Relationship to the Electron Strahl...

Start with: $k_\perp \rho_i \simeq 2, \ \varpi \simeq 0.2 \ \Omega_{cp}$

$$\rho_i = \frac{V_{thermal}}{\Omega_{cp}} \simeq 60 \ \text{km}$$

Then:

$$\frac{\varpi}{k_\parallel} = \left(\frac{\varpi}{\Omega_{cp}} \right) \left(\frac{\rho_i}{k_\parallel \rho_i} \right) \Omega_{cp}$$

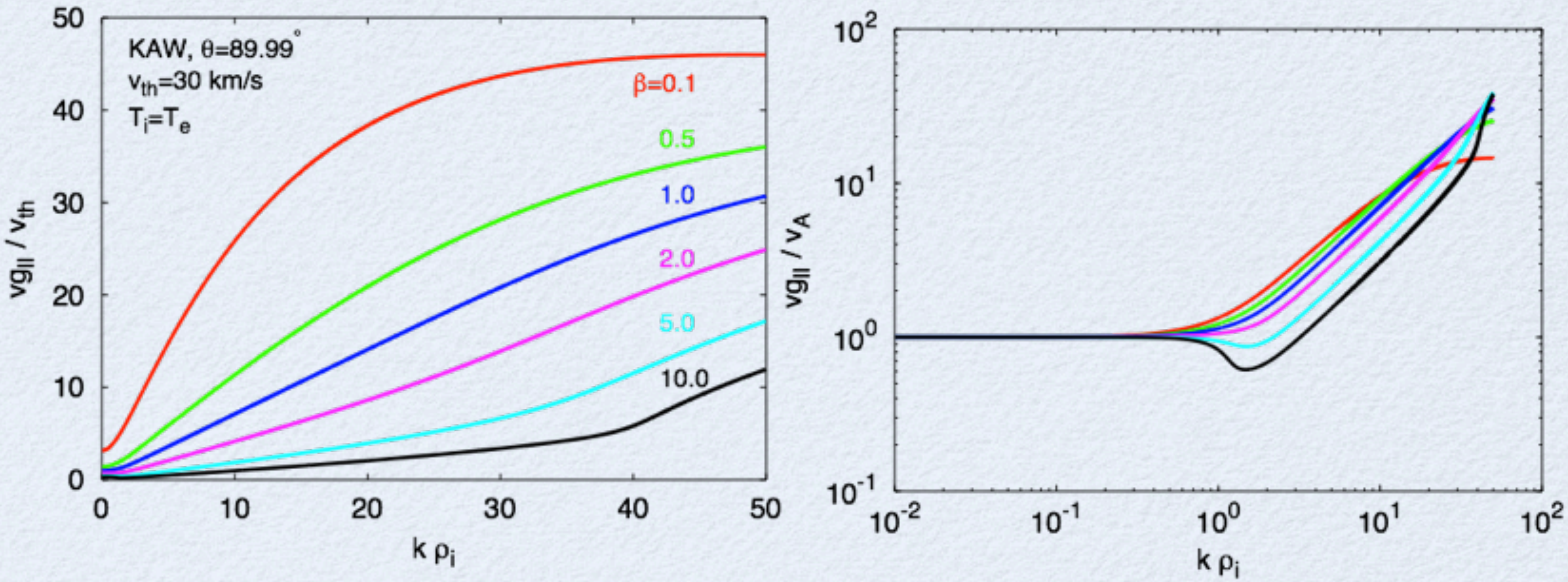
$$\simeq \frac{0.2 V_{thermal}}{k \rho_i \cos\theta}$$

The halo/strahl boundary is at ~87eV ~5000 km/s ~ 80 V_{thermal} which implies that θ ≳89.9°

It is possible, as shown recently by Peter Hunana, to achieve ~20 V_{thermal}

Group speed of KAW

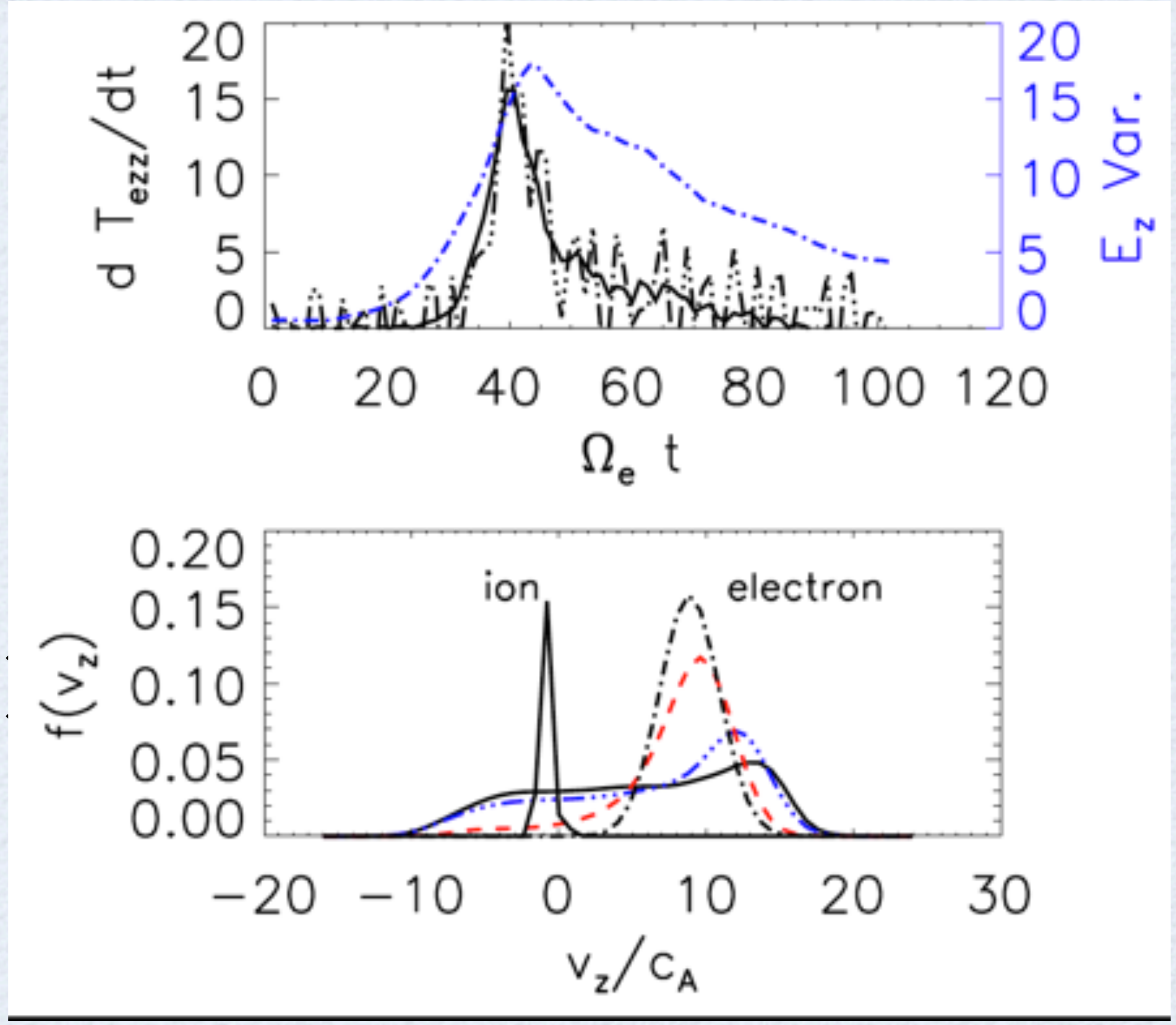
Group and phase speeds are along **B**



Electron Landau Damping in a 3D PIC Simulation of a Current Driven Instability

(courtesy of Haihong Che)

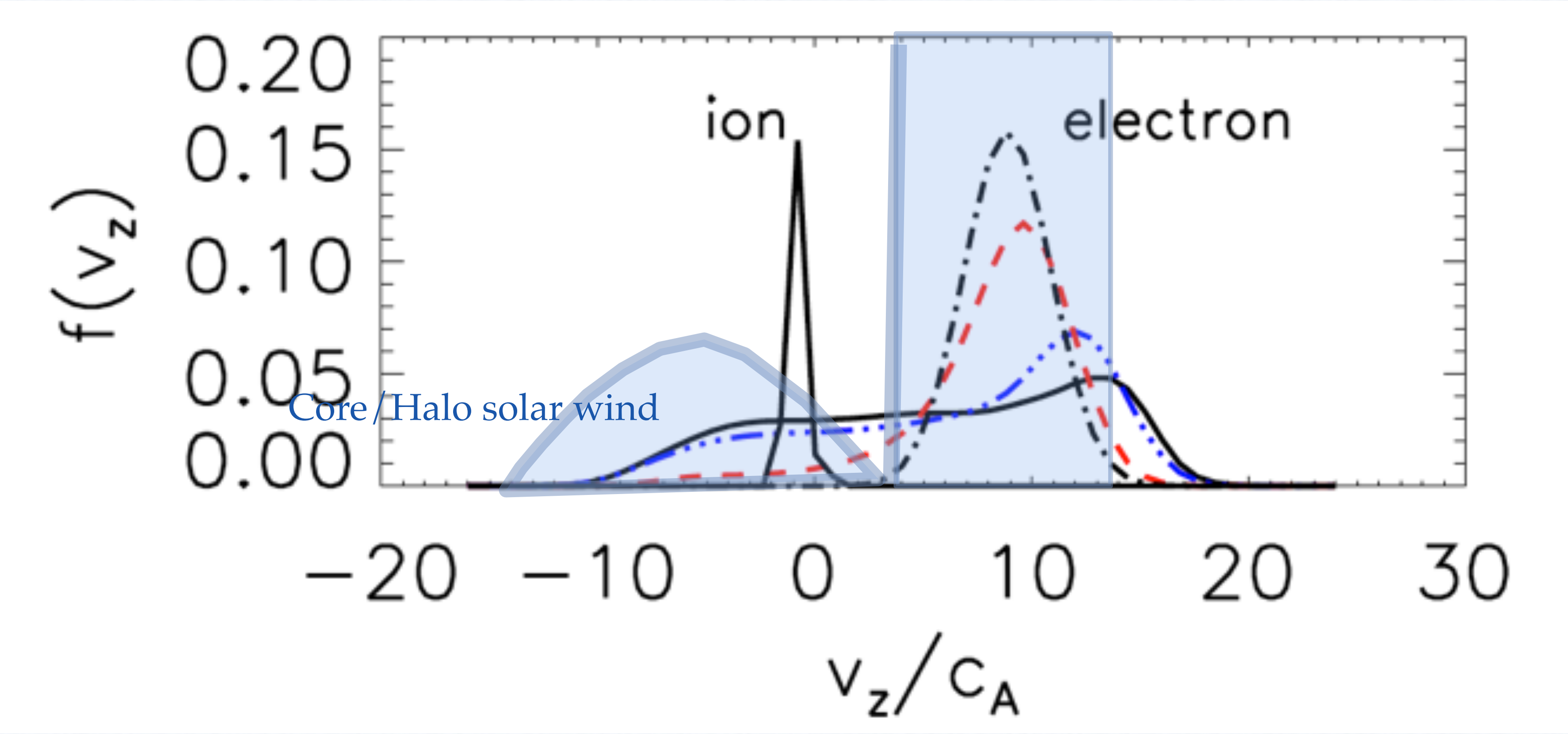
- In this situation T_a *decreases* but this schematic is not representative of the solar wind electron distribution where the core and halo have a density approximately equal to that of the protons and the *strahl/beam* is only a few %.



Possible relationship to the electron strahl...

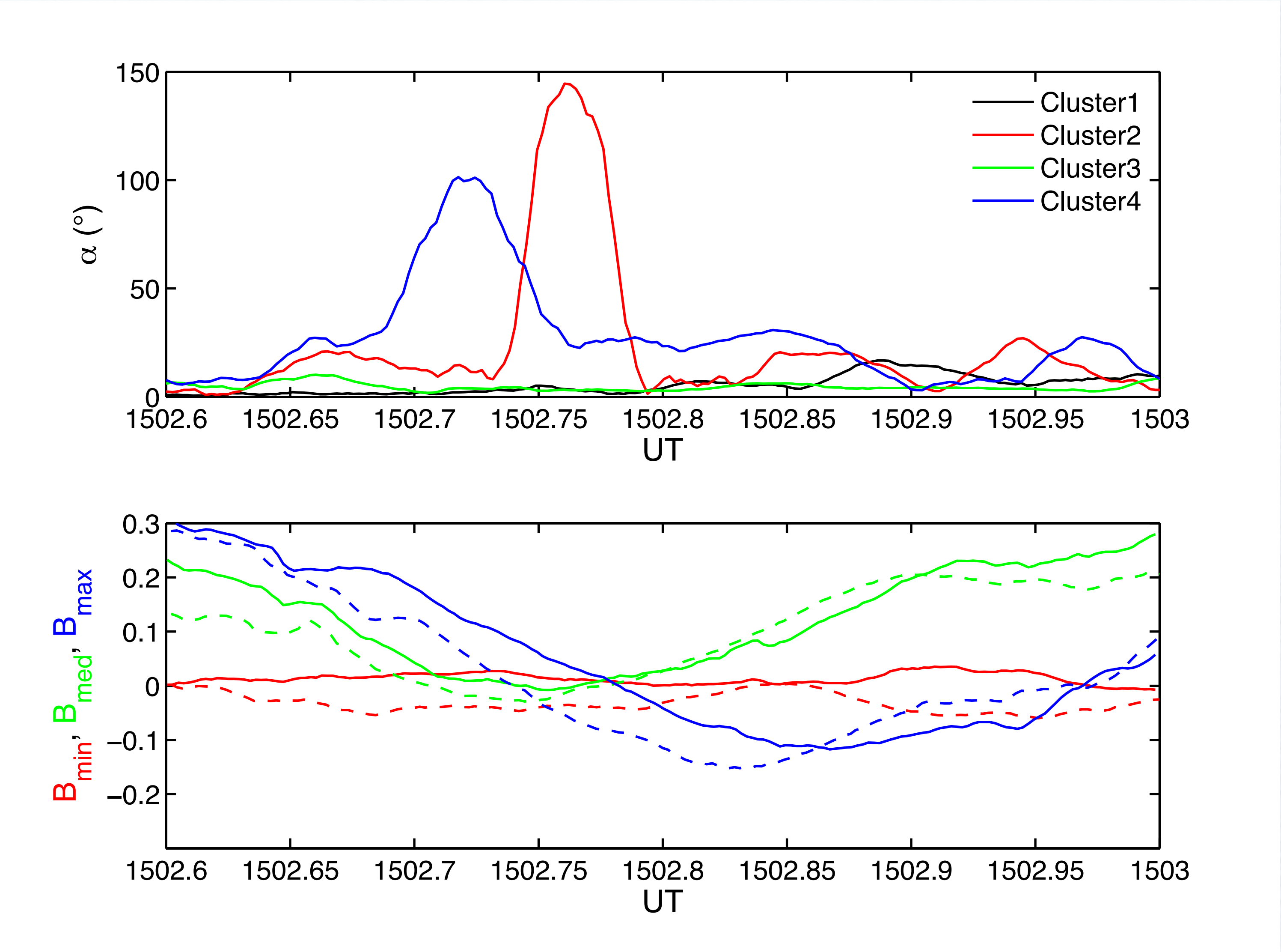
Conjecture:

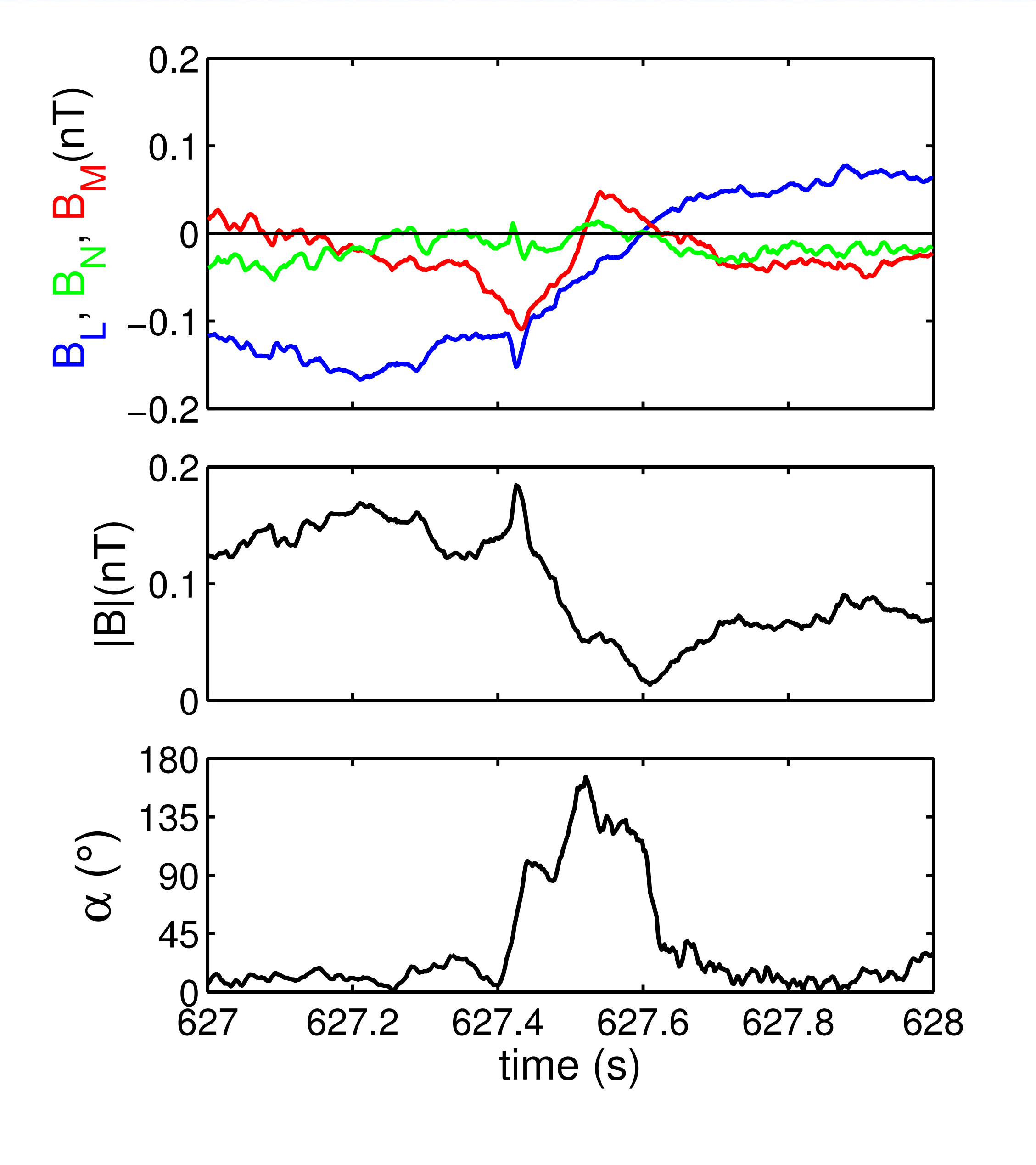
The strahl/wave interaction slows the strahl electrons, which then merge into the halo. Consequently, the moment calculation for $V_{\|}$ doesn't include those halo particles and T_a appears to be > 1.



What do the fields look like in configuration space?

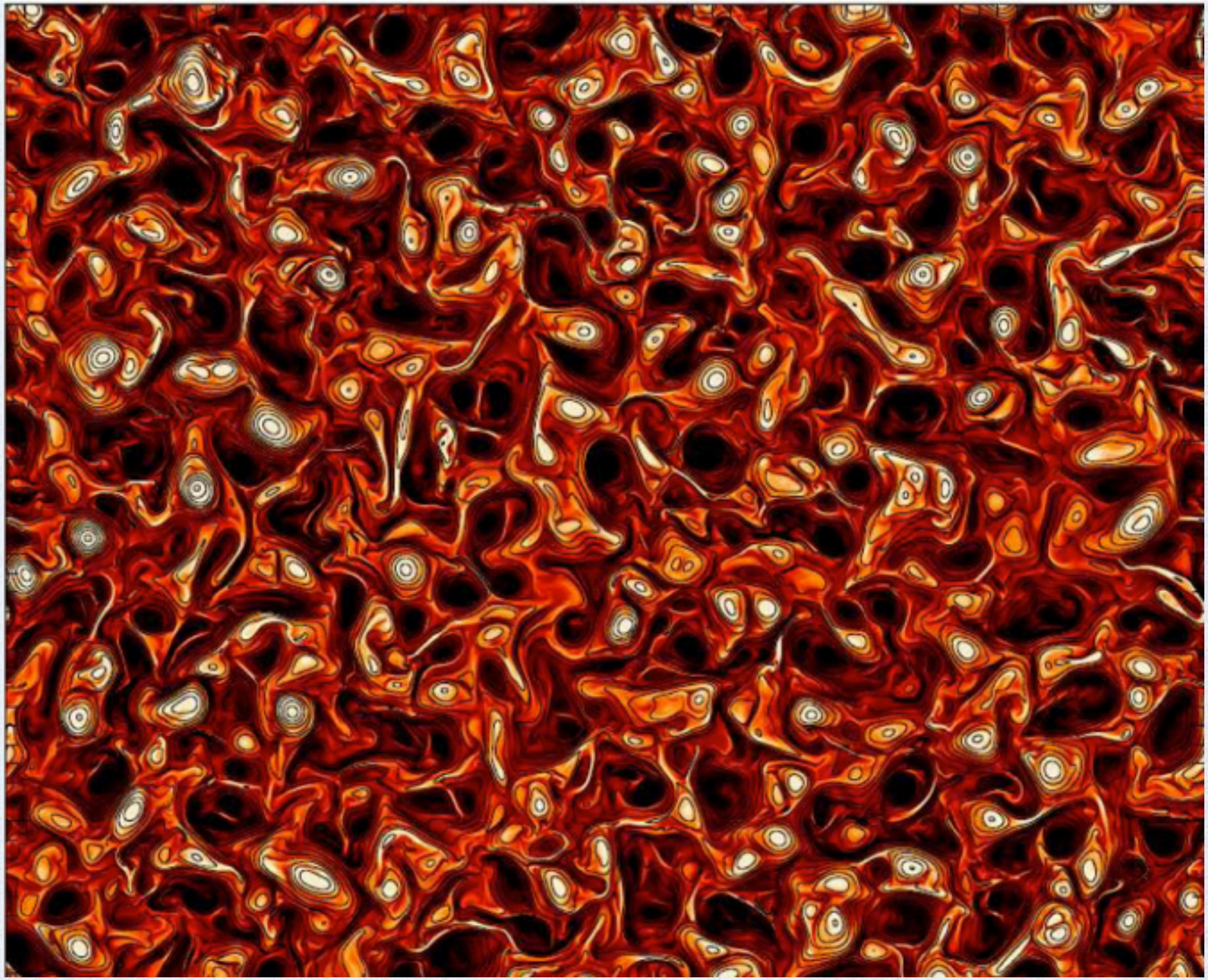
- STAFF data for two of the intervals analyzed spectrally with *k-filtering*





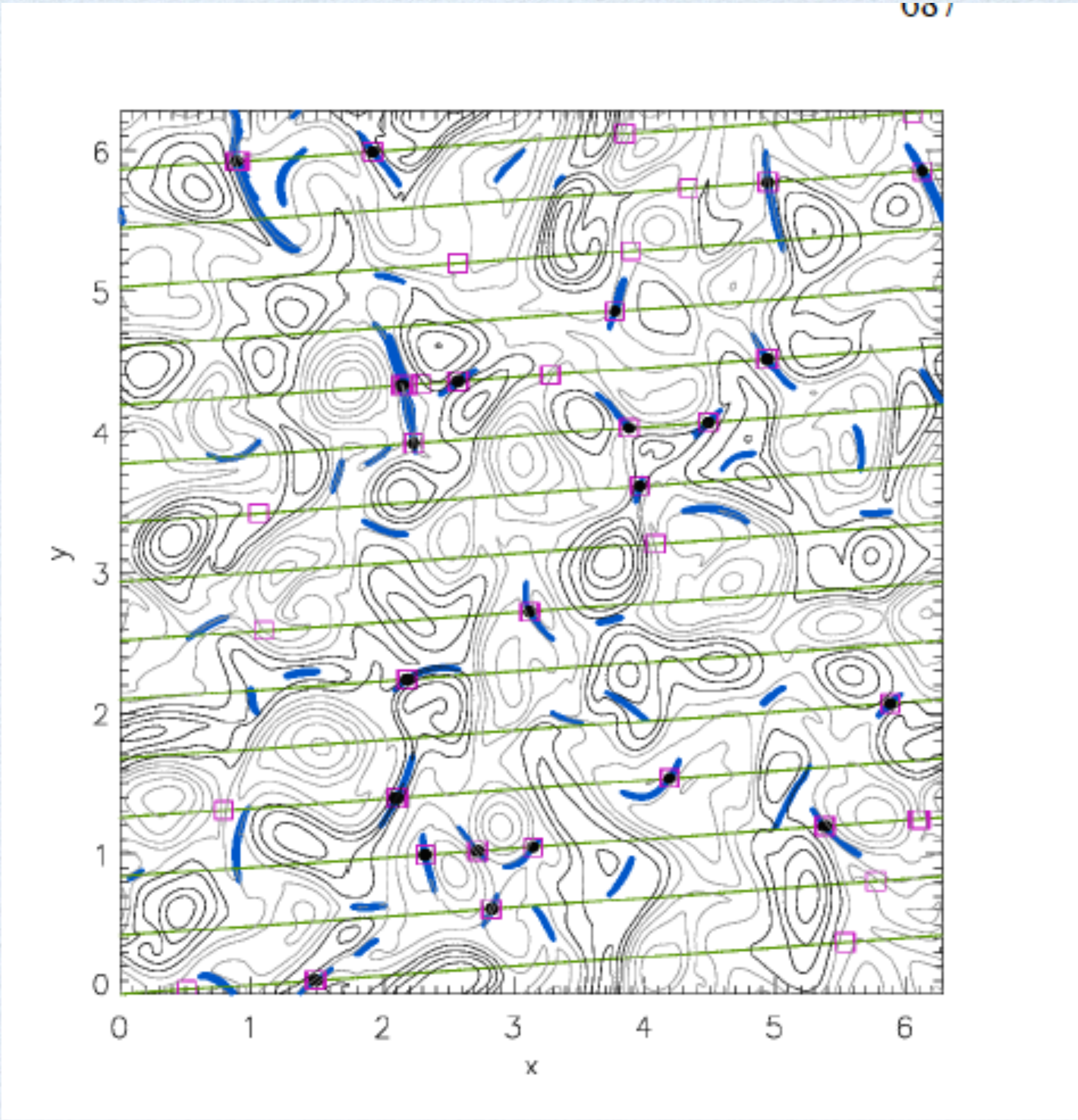
Turbulence cascade as seen in (MHD) simulations

Current Density *j* and magnetic potential, from Servidio, Dmitruk, Greco, Wan, Donato, Cassak, Shay, Carbone, Matthaeus, *Nonlin. Processes Geophys.,18,* 675–695, 2011



Turbulence cascade as seen in (Hall-MHD) simulations

Contours of magnetic field, diffusion regions (blue), discontinuities and reconnection sites, from Servidio, Dmitruk, Greco, Wan, Donato, Cassak, Shay, Carbone, Matthaeus, *Nonlin. Processes Geophys.,18*, 675–695, 2011



Summary

- The turbulent cascade continues below the ion Larmor scale, ρ_i, down to ρ_e
- The small-scale plasma turbulence appears to consist of very oblique *kinetic Alfvénic fluctuations* and *small-scale current sheets*
  - These current sheets and discontinuities are probably the sources of small-scale intermittency
- At least four spacecraft are required to determine the power and direction of propagation of fluctuations at the scale of the proton Larmor radius.
- *There is no indication at these scales of ion cyclotron or whistler turbulence.*
- The electron strahl may interact with these oblique fluctuations, causing them to merge into the halo population.
  - The kinetic interaction appears to enhance the tendency of the fluctuations to become increasingly two-dimensional.
- Determining the relative importance of kinetic interactions and current sheets in dissipating solar wind turbulence is an on-going study.