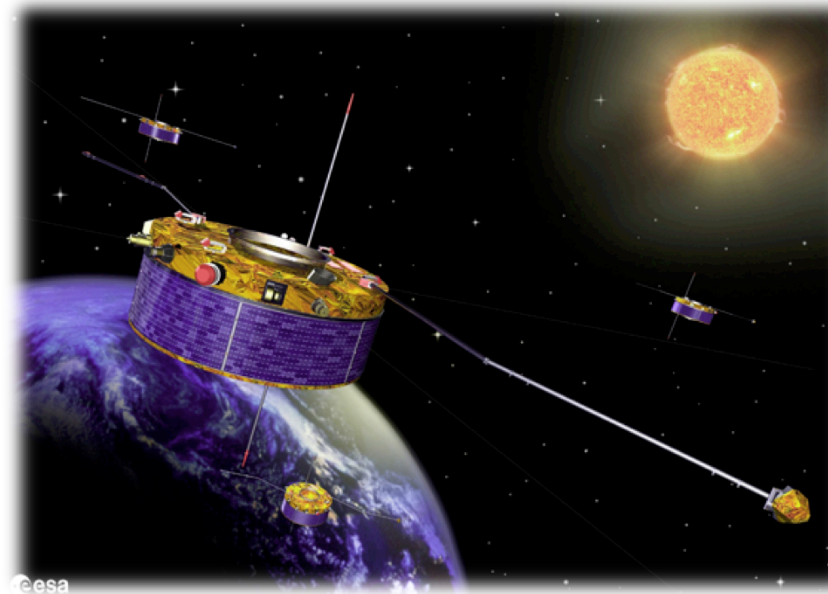
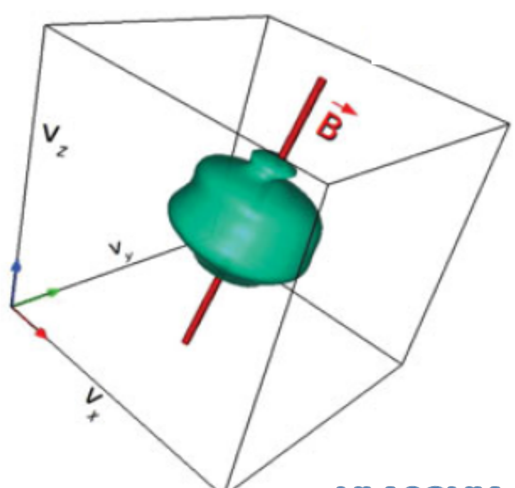
# KINETIC EFFECTS IN SOLAR WIND USING VLASOV SIMULATIONS AND CLUSTER DATA





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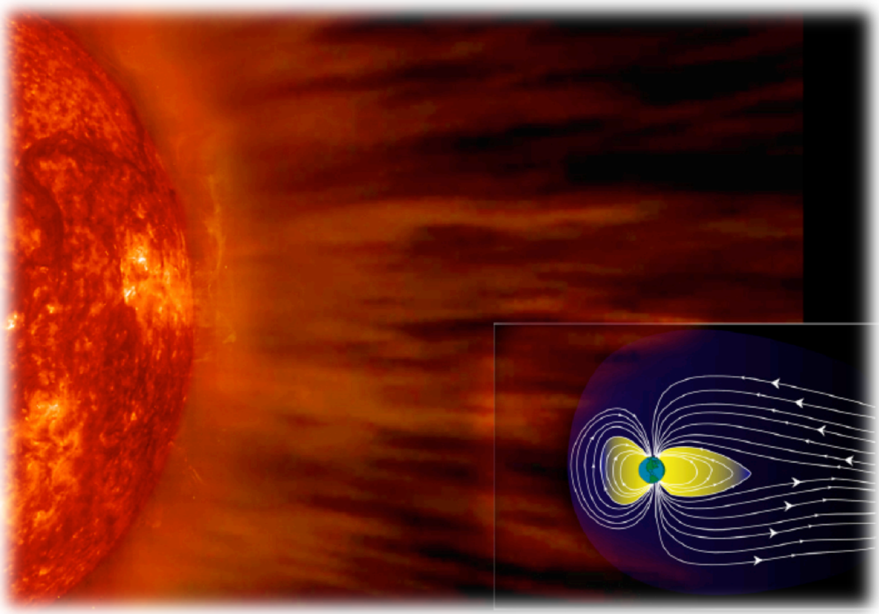
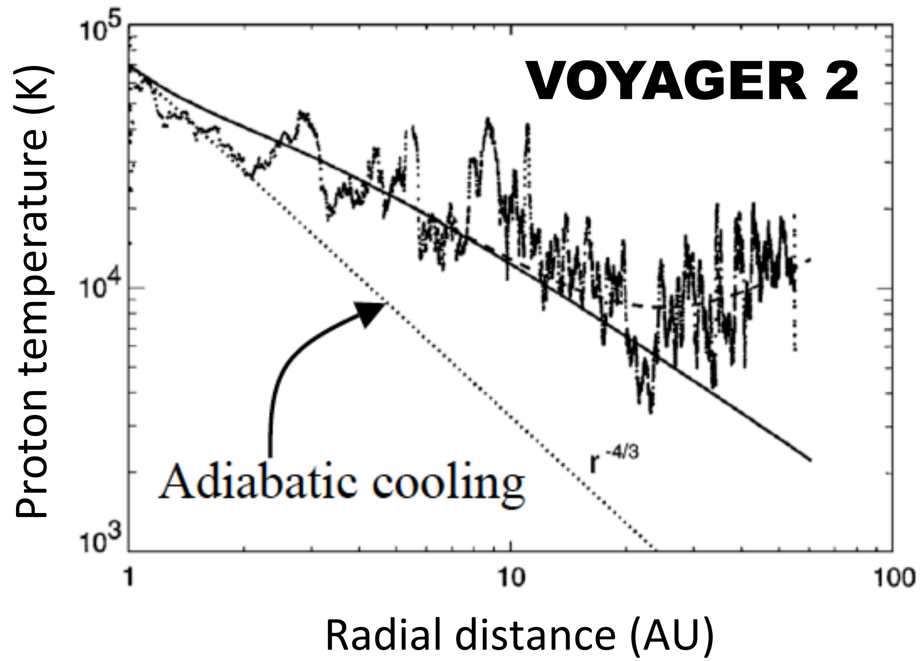
VLASOVIA 2016, COPANELLO – JUNE 2ND, 2016

# PHYSICS OF THE SOLAR WIND

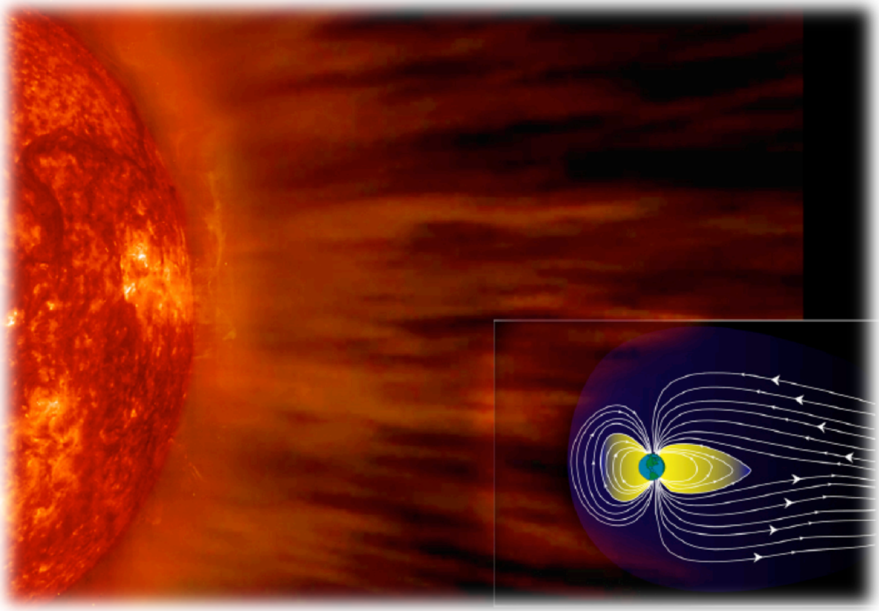
***The solar wind is a turbulent and weakly collisional system…***

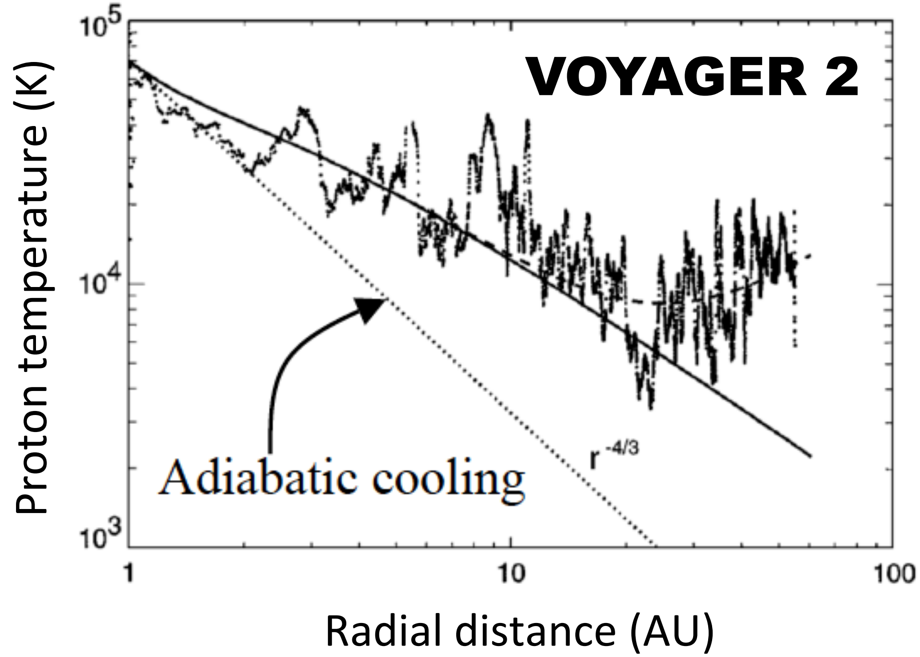





***and it represents the classical paradigm of a collisionless plasma***

***The solar wind is a turbulent and weakly collisional system…***

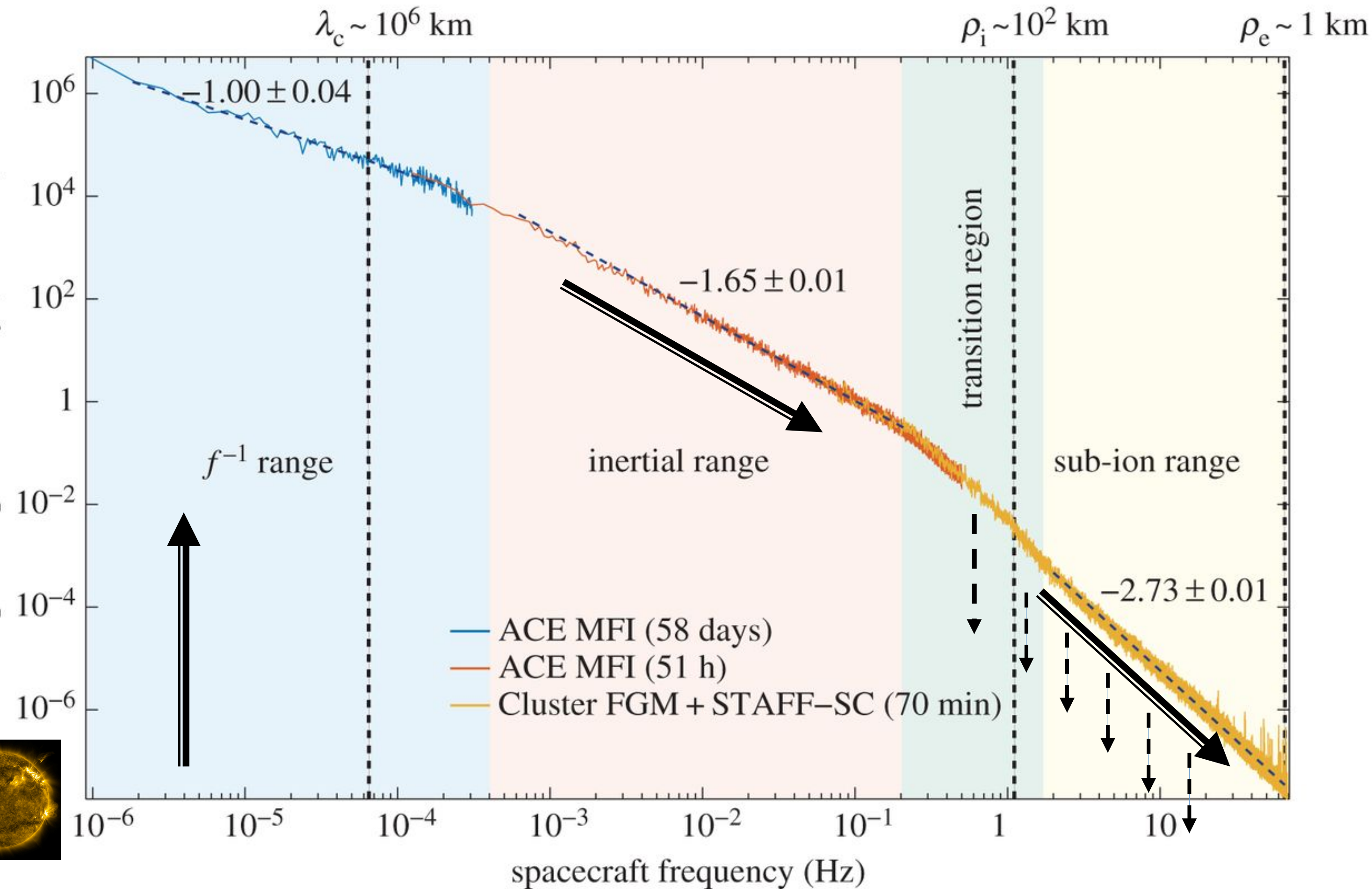


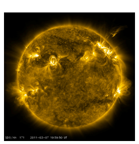



***and it represents the classical paradigm of a collisionless plasma***

**TURBULENCE !**

## Power laws at MHD scales & sub-ion scales

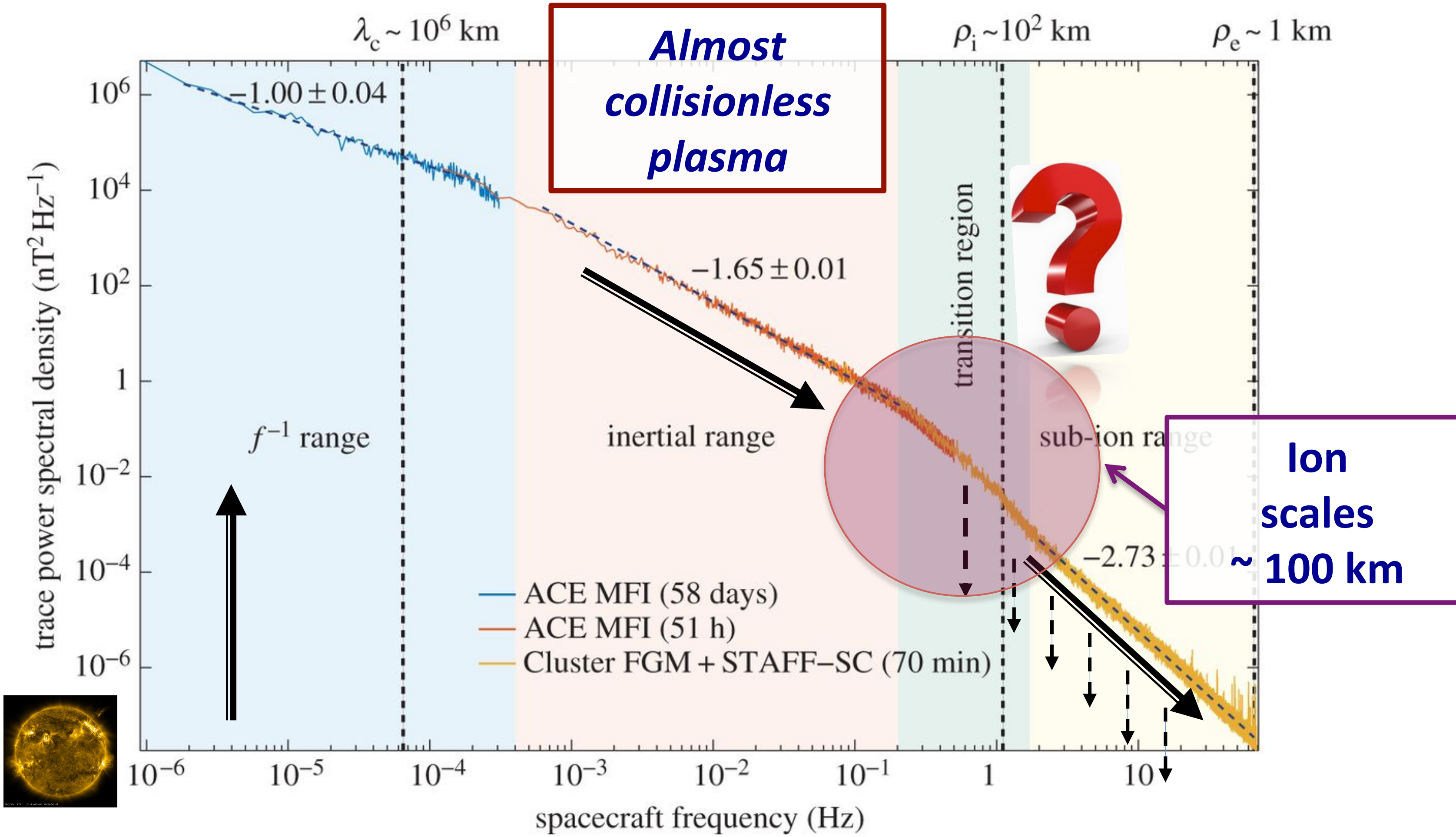


[Kiyani et al., 2015]

# SOLAR WIND TURBULENCE

## Power laws at MHD scales & sub-ion scales



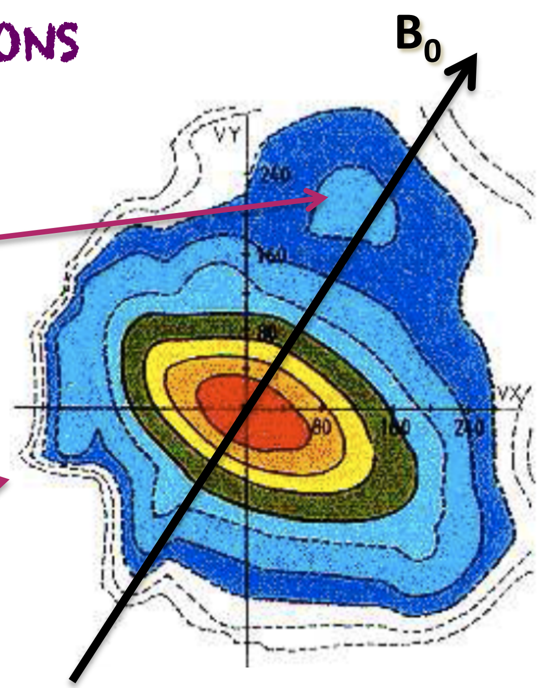

[Kiyani et al., 2015]

# PARTICLE DISTRIBUTION FUNCTIONS

PROTONS

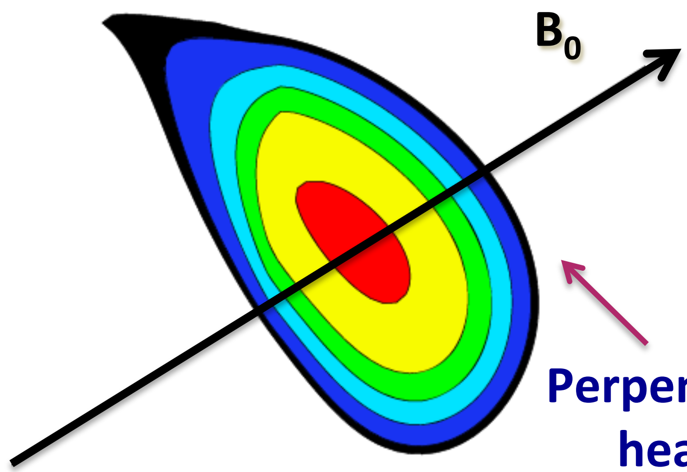
Beam of accelerated particles

Temperature anisotropy




Marsch, 2006

PARTICULES ALPHA




Perpendicular heating

Perrone et al., 2014

STRONG DEFORMATION OF THE ION DISTRIBUTION FUNCTION!!!

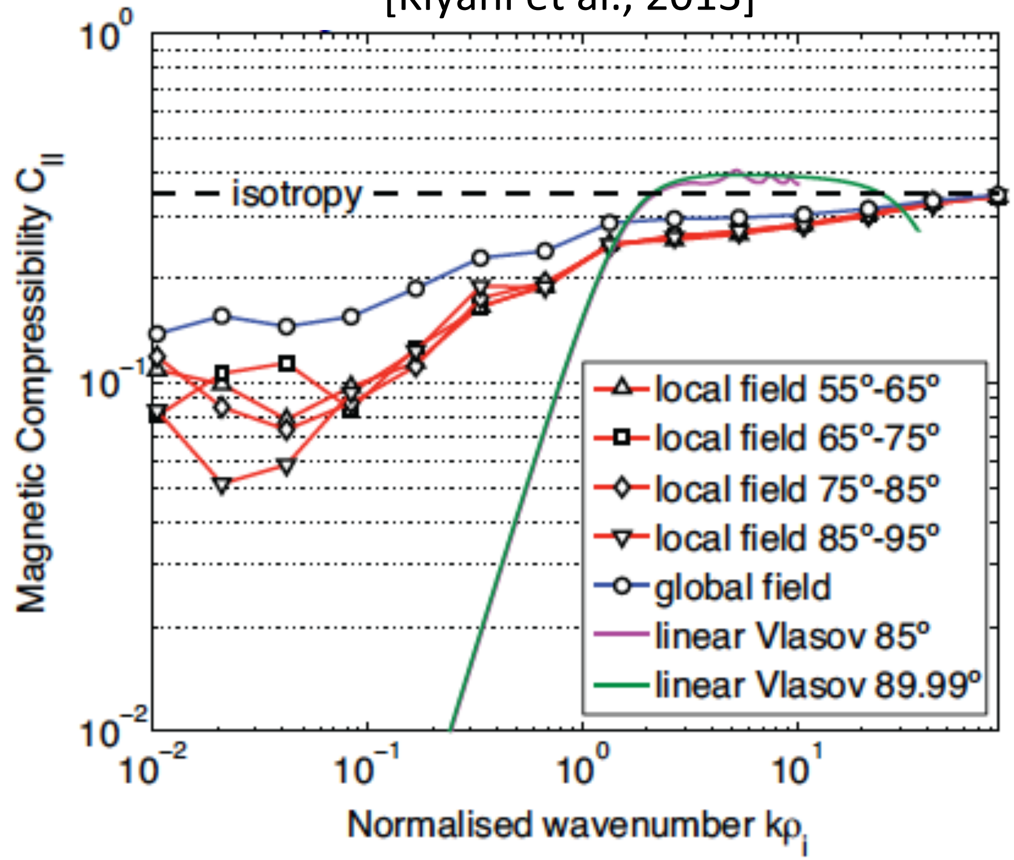
# COMPRESSIBILITY OF MAGNETIC FLUCTUATIONS

## MAGNETIC COMPRESSIBILITY

$$C_{//} = \frac{S_{//}(f)}{S(f)}$$

**The spectrum of compressible fluctuations $S_{//}(f)$ approaches the total spectrum S(f) at ion scales!**

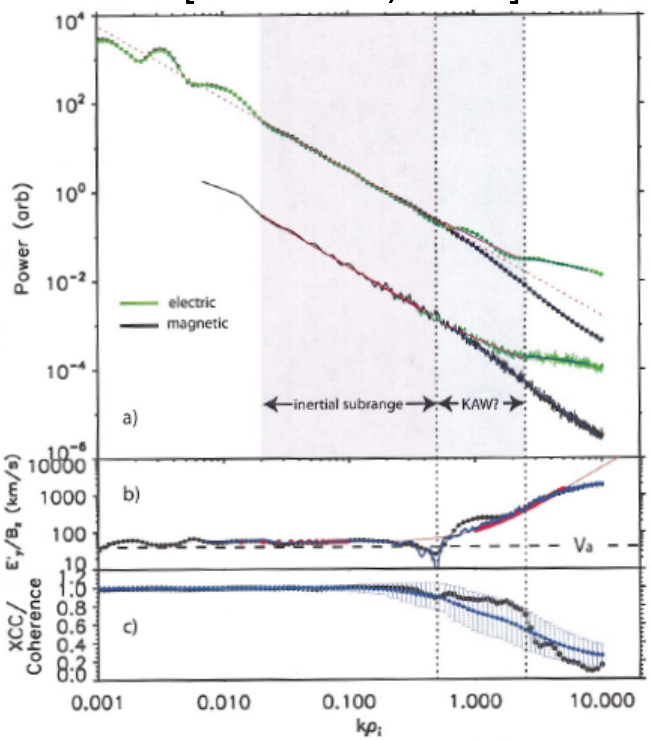
[Kiyani et al., 2013]



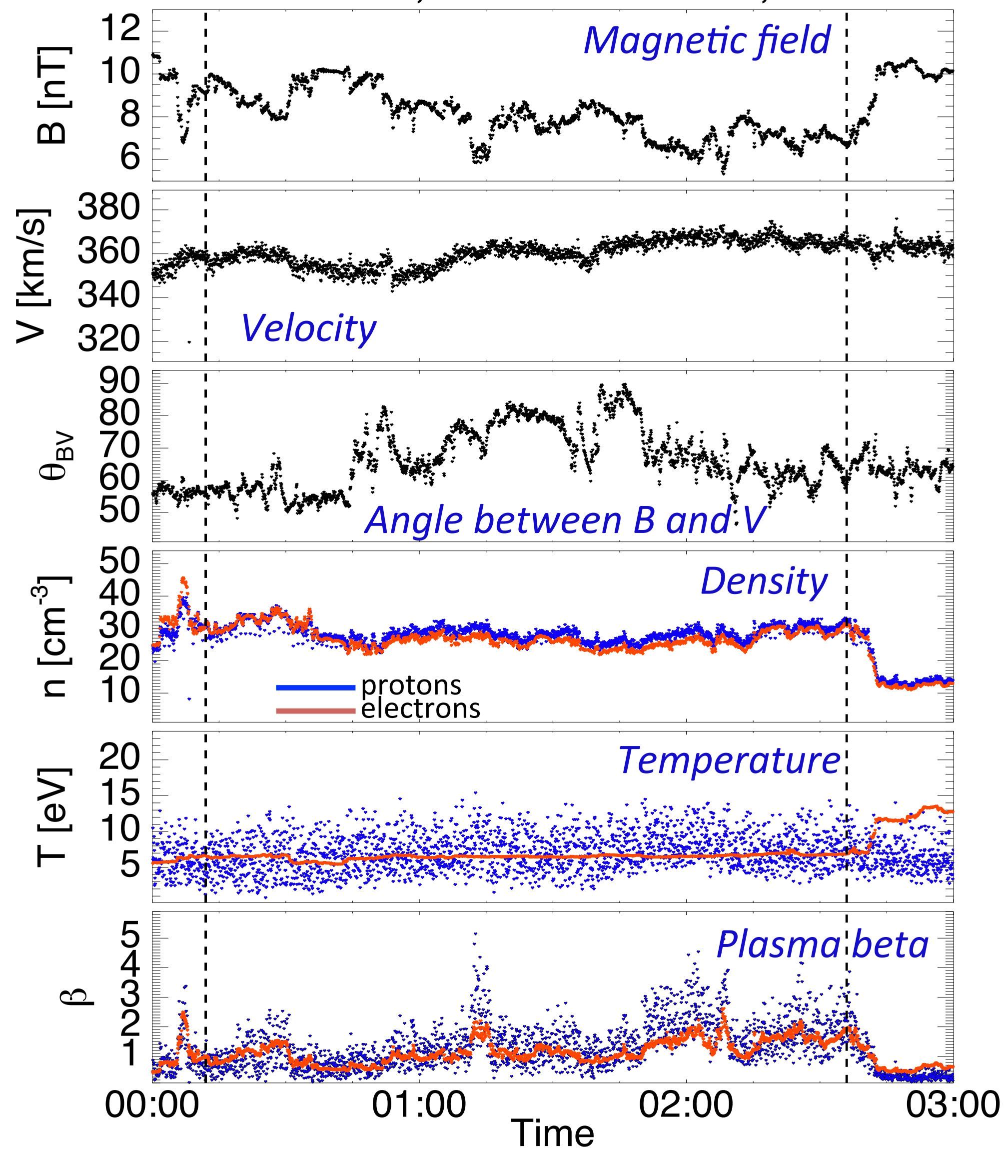

**What is the nature of these compressible fluctuations?**

# SLOW SOLAR WIND

[Bale et al., 2005]




2002-02-19, 00:00-03:00UT, Cluster




$$\langle B \rangle \approx 8nT$$

$$\langle V \rangle \approx 360km/s$$

$$\langle n_p \rangle \approx \langle n_e \rangle \approx 25cm^{-3}$$

$$\langle T_p \rangle \approx \langle T_e \rangle \approx 8eV$$

# WAVELET ANALYSIS

## INTERMITTENCY

**2002-02-19, 00:12-02:36UT, CLUSTER/FGM**

### Morlet wavelet transform

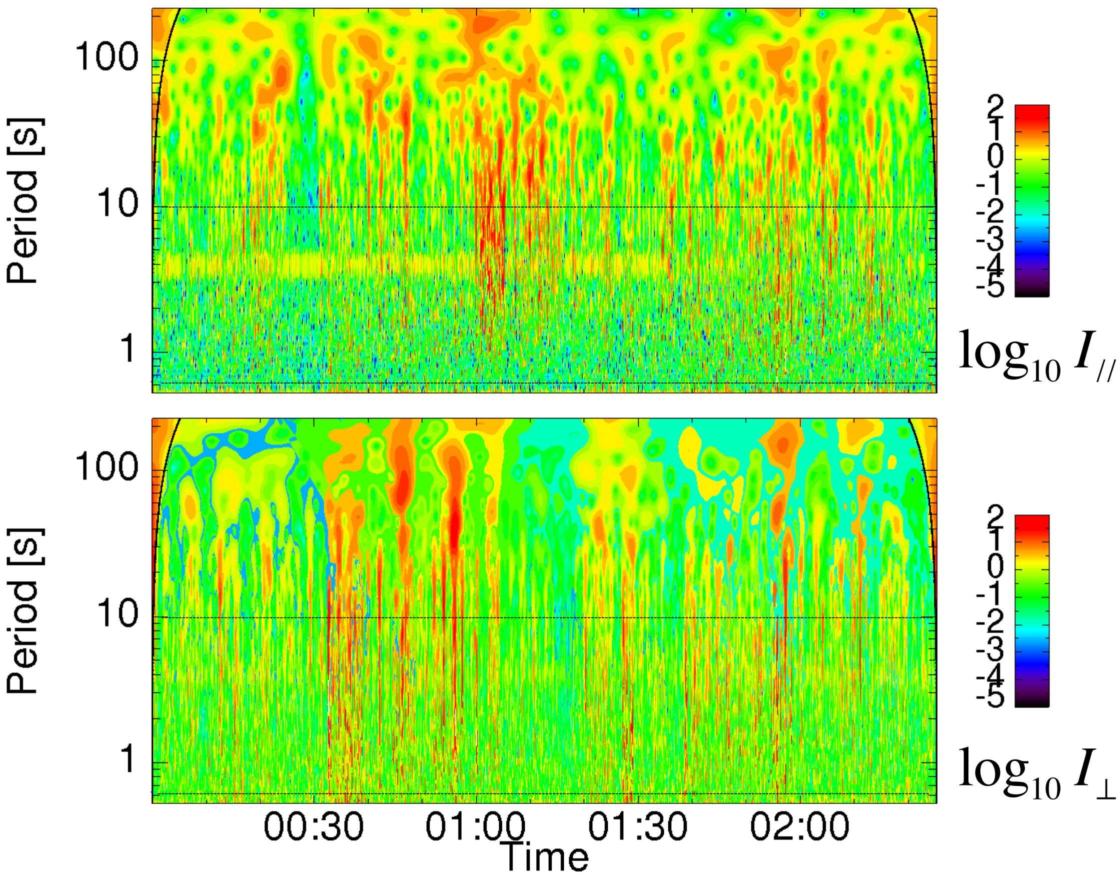
$$W_i(\tau,t) = \sum_{j=0}^{N-1} B_i(t_j)\psi^*\left[(t_j - t)/\tau\right]$$

$$\psi(u) = \pi^{-1/4} e^{-i\omega_0 u} e^{-u^2/2}$$

[Farge, 1992]

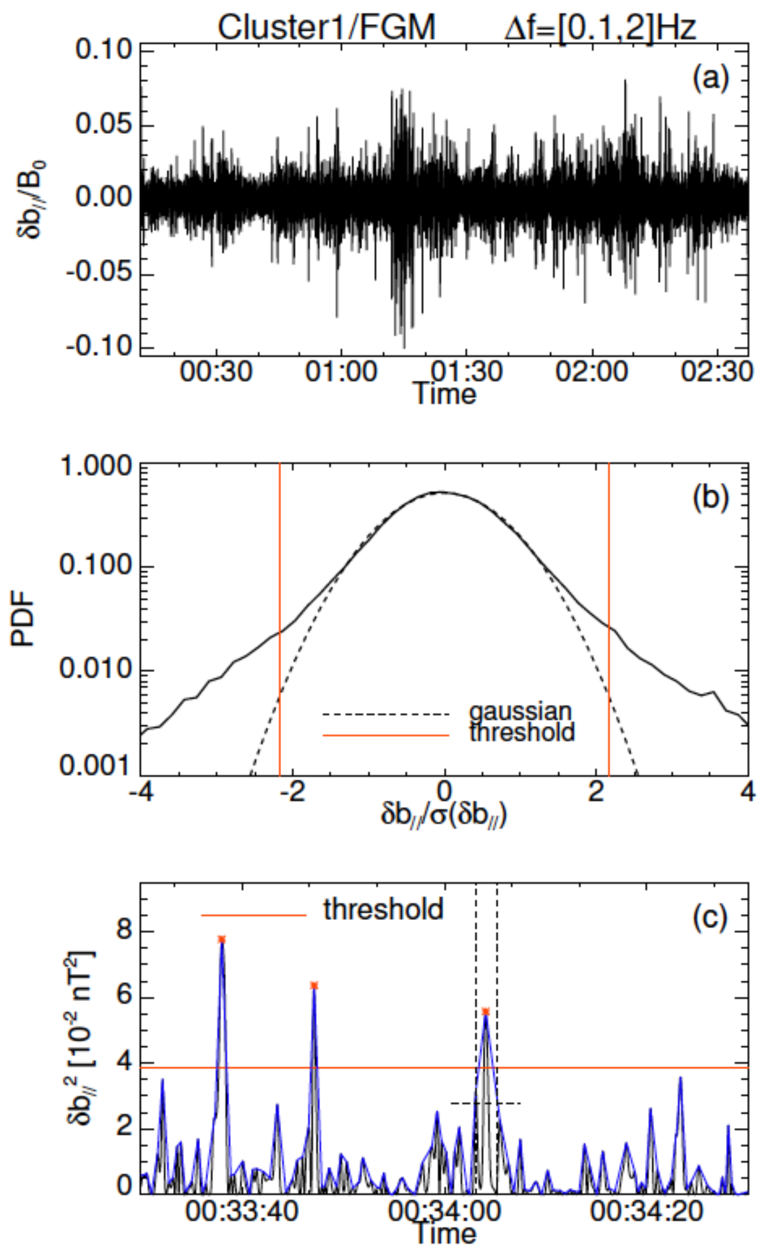
$$I_{//}(\tau,t) = \frac{\left|W_{//}(\tau,t)\right|^2}{\left\langle \left|W_{//}(\tau,t)\right|^2 \right\rangle_t}$$

$$I_{\perp}(\tau,t) = \frac{\left|W_{\mathbf{B}}(\tau,t)\right|^2 - \left|W_{//}(\tau,t)\right|^2}{\left\langle \left|W_{\mathbf{B}}(\tau,t)\right|^2 - \left|W_{//}(\tau,t)\right|^2 \right\rangle_t}$$




- **Local Intermittency Measure I(t,τ)** → **localized events cover a scale range**

# 'DEFINITION' OF COHERENT STRUCTURES




**Reconstruction of the signal in the range [0.1,2] Hz ≈ band pass filter**

Farge, 1992; He et al., 2012

$$\delta b_i(t_n) = \frac{\delta j \delta t^{1/2}}{C_\delta \psi_0(0)} \sum_{j=j_1}^{j_2} \frac{\tilde{W}_i(\tau,t)}{\tau^{1/2}}$$

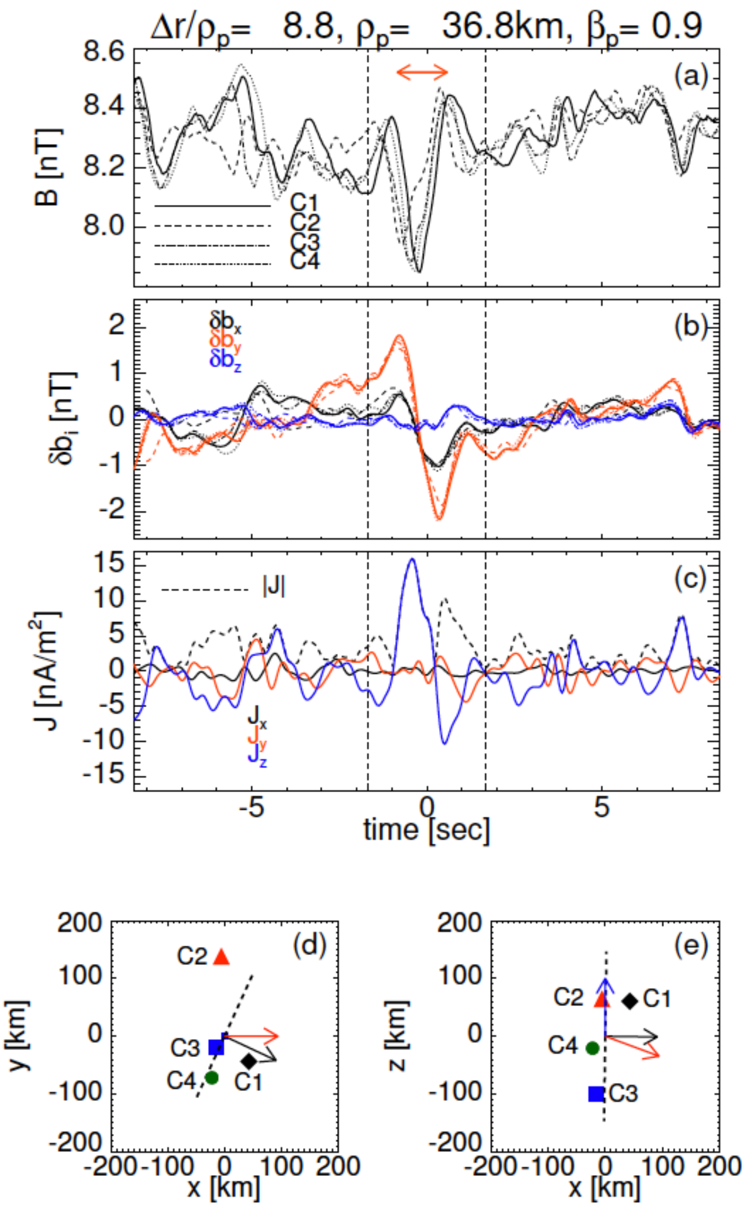
- **The threshold is 3σ of the corresponding Gaussian fit**

↓

- **Heavy tails correspond to ~ 600 intermittent events!**

**What is the nature of these events?**

# ALFVENIC STRUCTURES (I): CURRENT SHEET

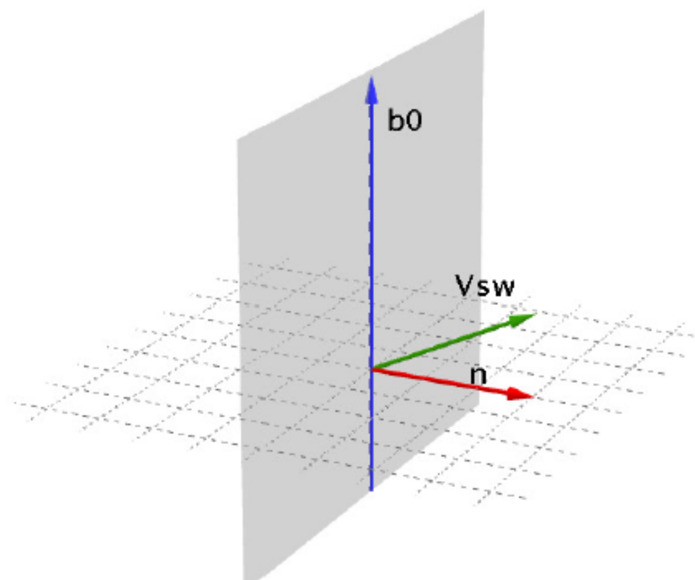



$$\theta_{nB} = 89^\circ \pm 9^\circ$$

$$\theta_{nV_\perp} = 25^\circ \pm 14^\circ$$

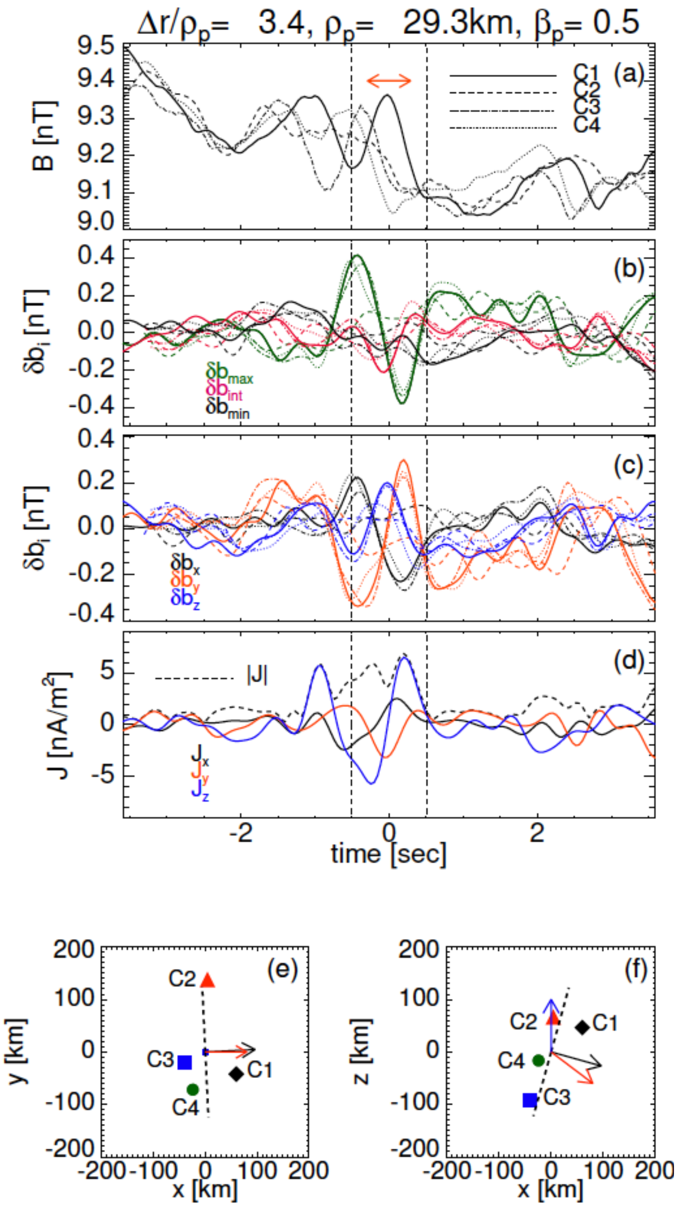
$$\theta_{max} = 89^\circ$$

$$V_0 = (24 \pm 88)km/s$$




[Perrone et al., 2016]

# ALFVENIC STRUCTURES (II): COMPRESSIVE VORTICES



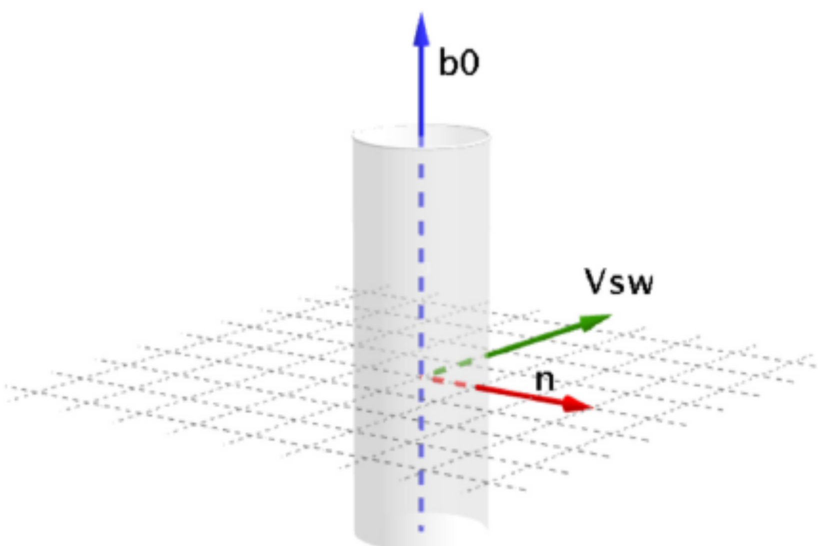

**THE MOST COMMON CASE!!!**

$$\theta_{nB} = 75^\circ \pm 2^\circ$$

$$\theta_{max} = 80^\circ$$

$$\theta_{nV_\perp} = 16^\circ \pm 7^\circ$$

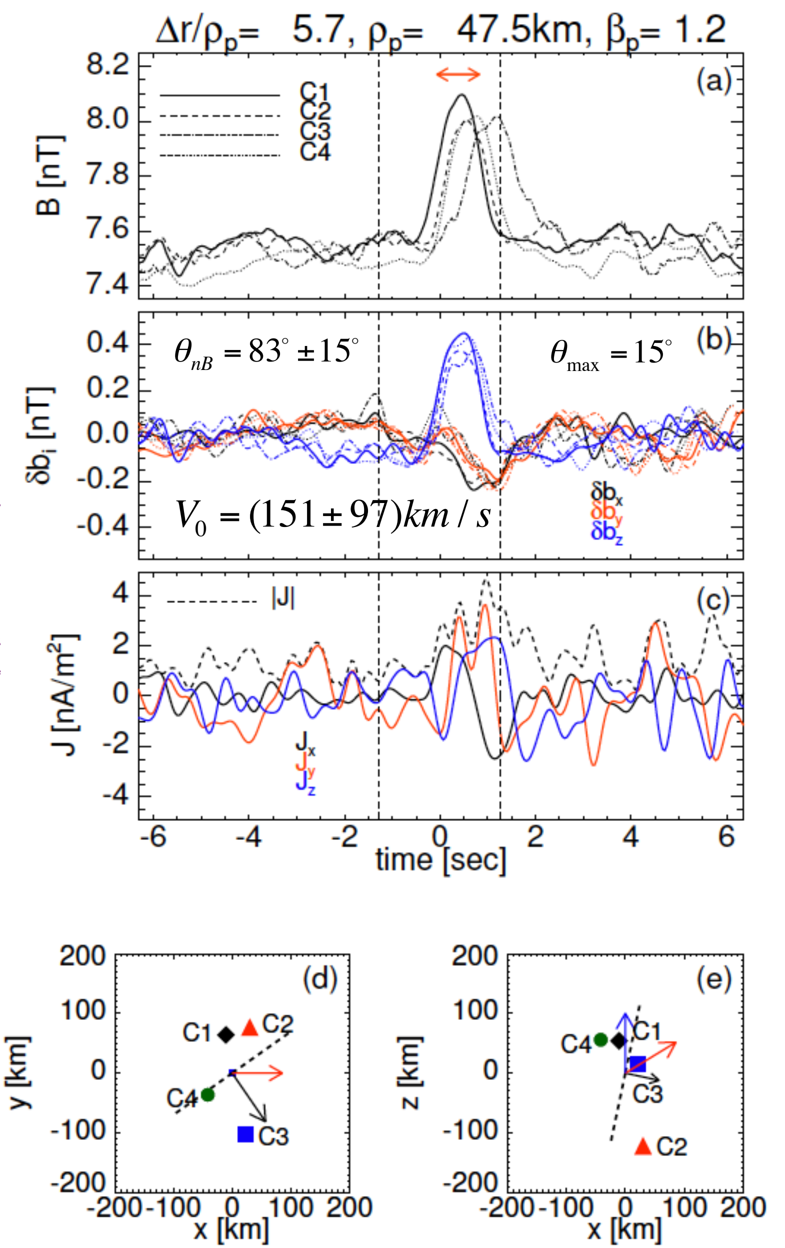
$$V_0 = -(158 \pm 27) km/s$$

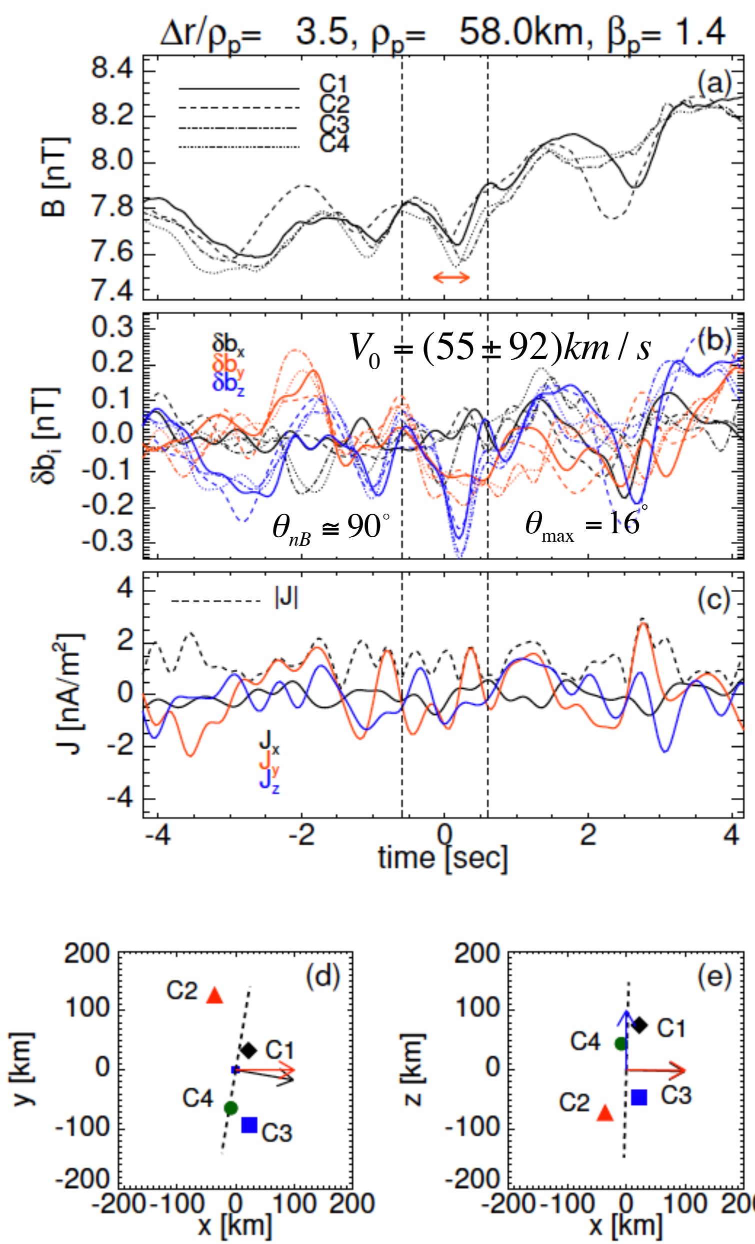



[Perrone et al., 2016]

# COMPRESSIBLE STRUCTURES

SOLITON




MAGNETIC HOLE

# HYBRID VLASOV-MAXWELL (HVM) SIMULATIONS

- Protons and alpha particles as kinetic particles (**Vlasov equation**)
- Fluid electrons (**generalized Ohm's law**)

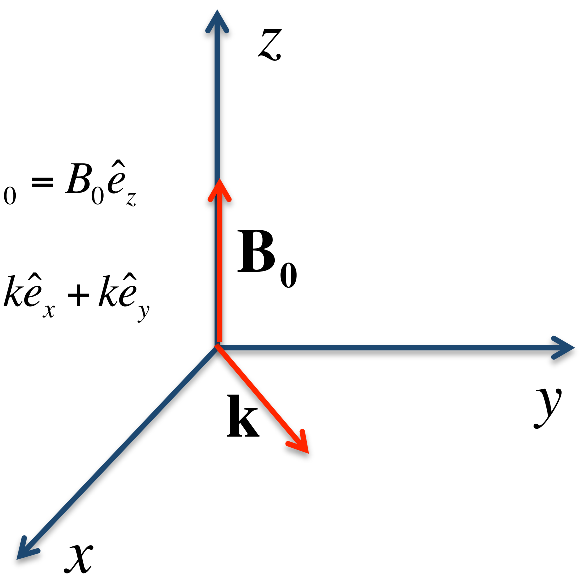
[Valentini et al., 2007; Perrone et al., 2011]

+

Maxwell equations

$\mathbf{B}_0 = B_0 \hat{e}_z$

$\mathbf{k} = k\hat{e}_x + k\hat{e}_y$



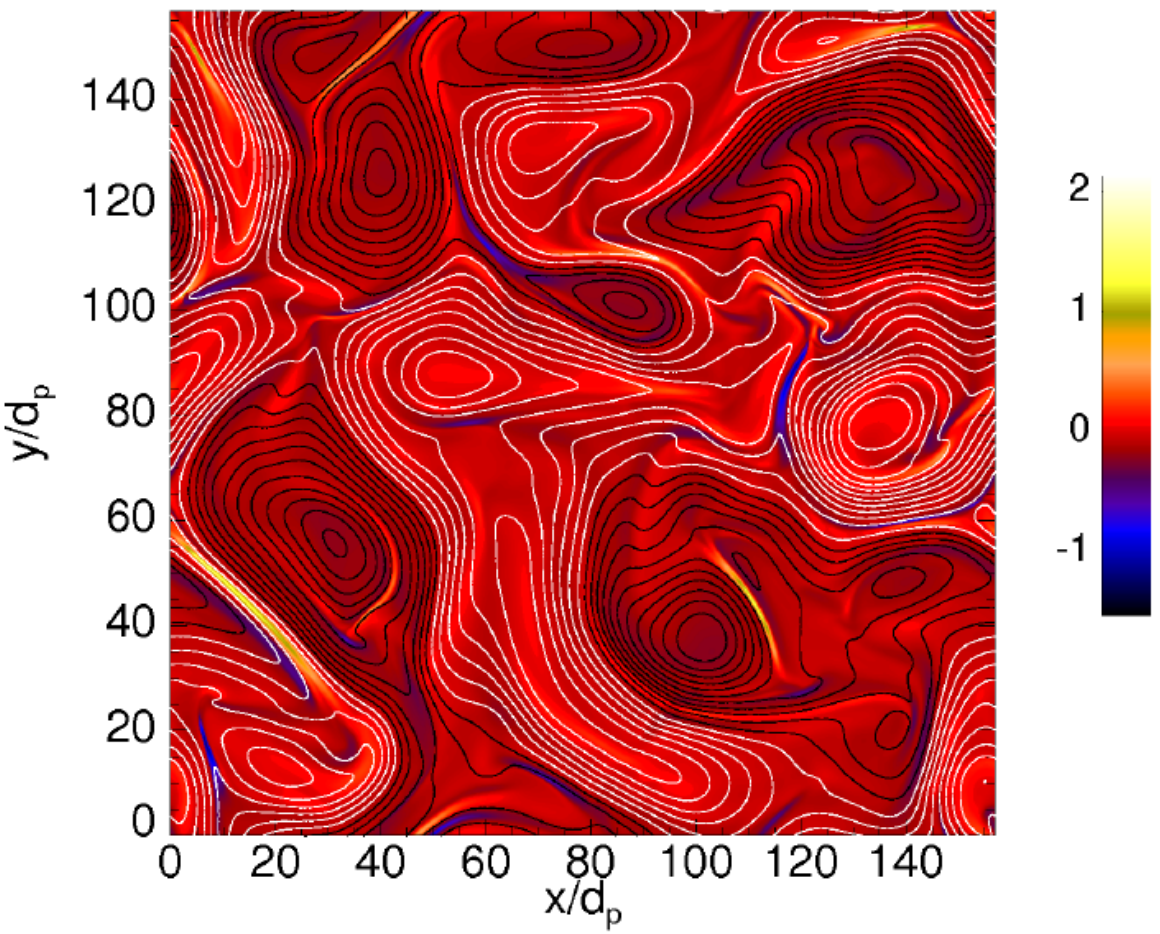

2D3V PHASE SPACE CONFIGURATION

In typical conditions for the solar wind:

$\beta = 1$ $\delta B / B_0 = 0.3$

# KINETIC TURBULENCE

LONGITUDINAL CURRENT DENSITY




INTERMITTENT CHARACTER OF THE MAGNETIC FIELD

# KINETIC TURBULENCE

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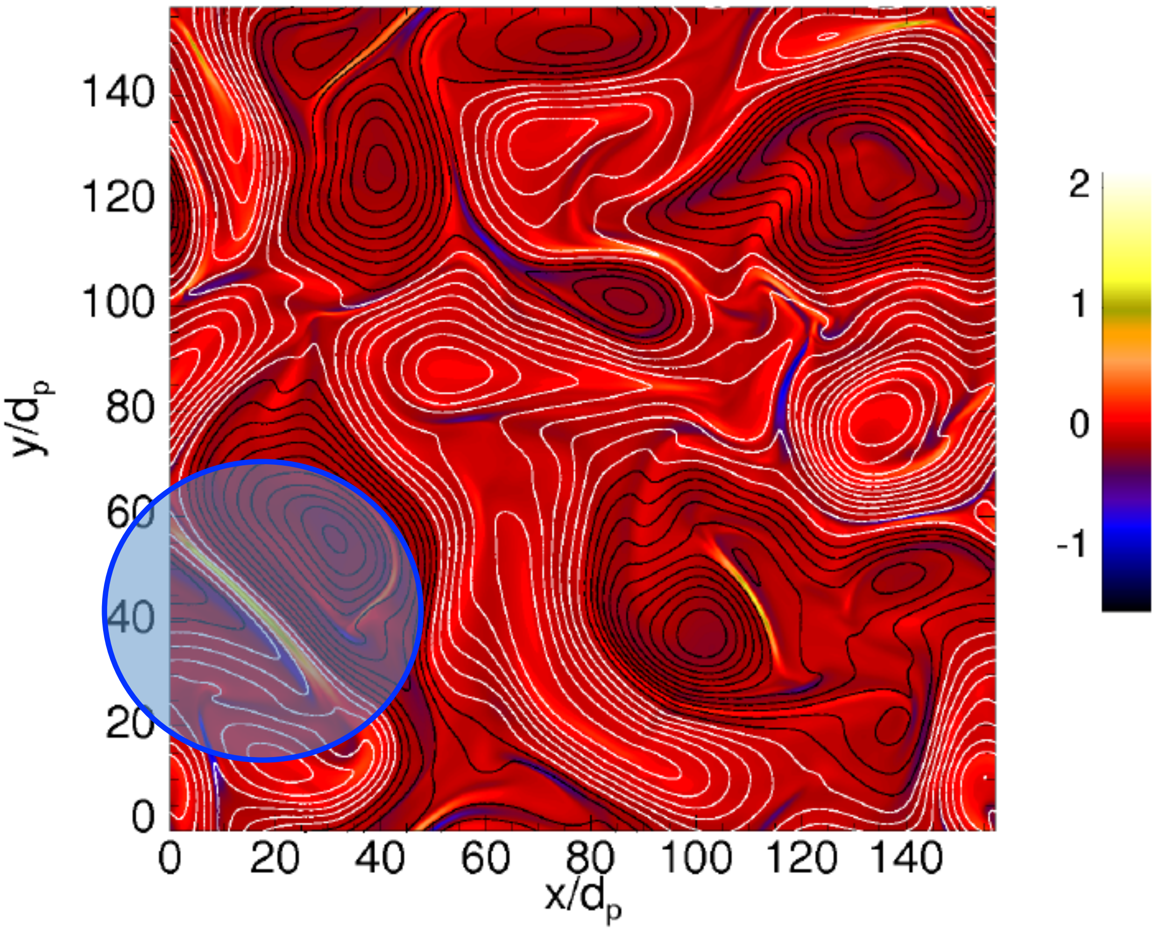


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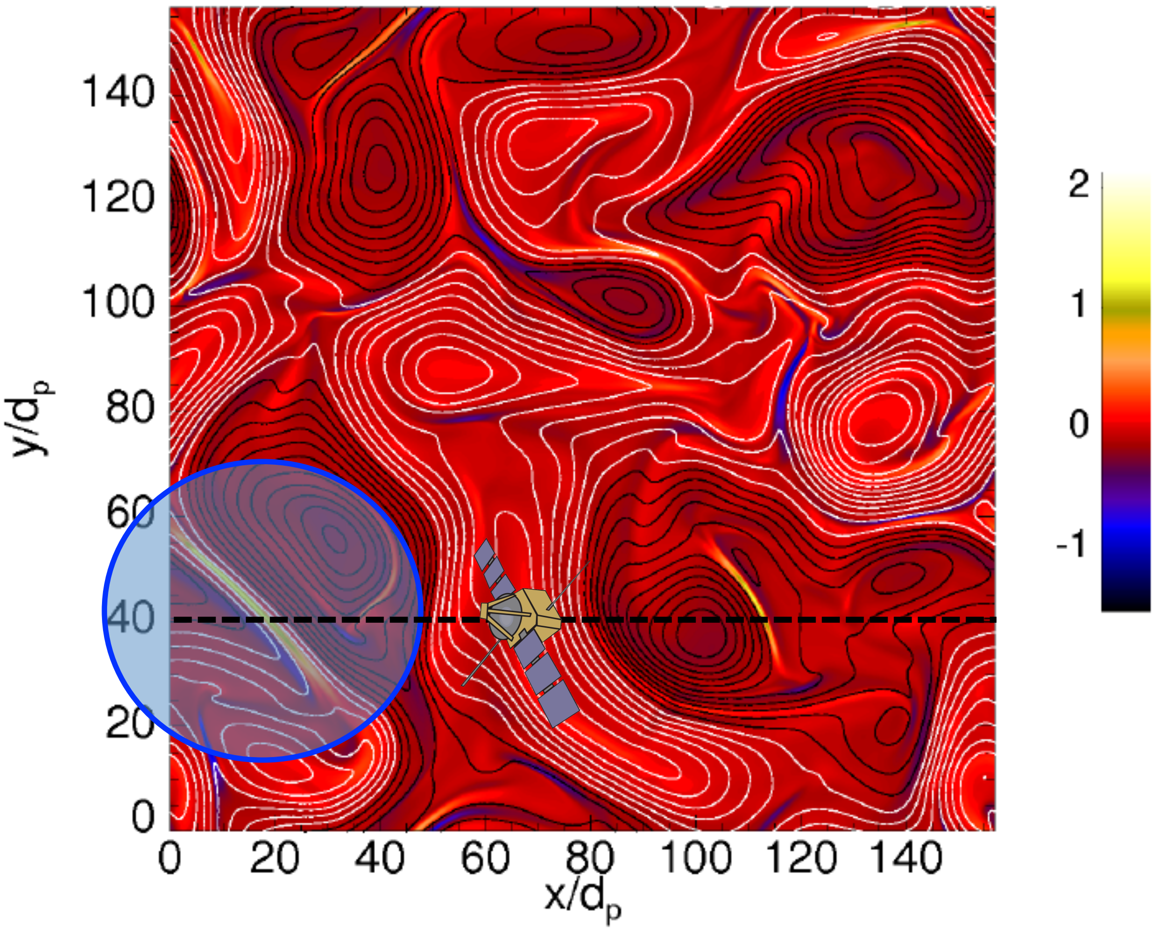


INTERMITTENT CHARACTER OF THE MAGNETIC FIELD

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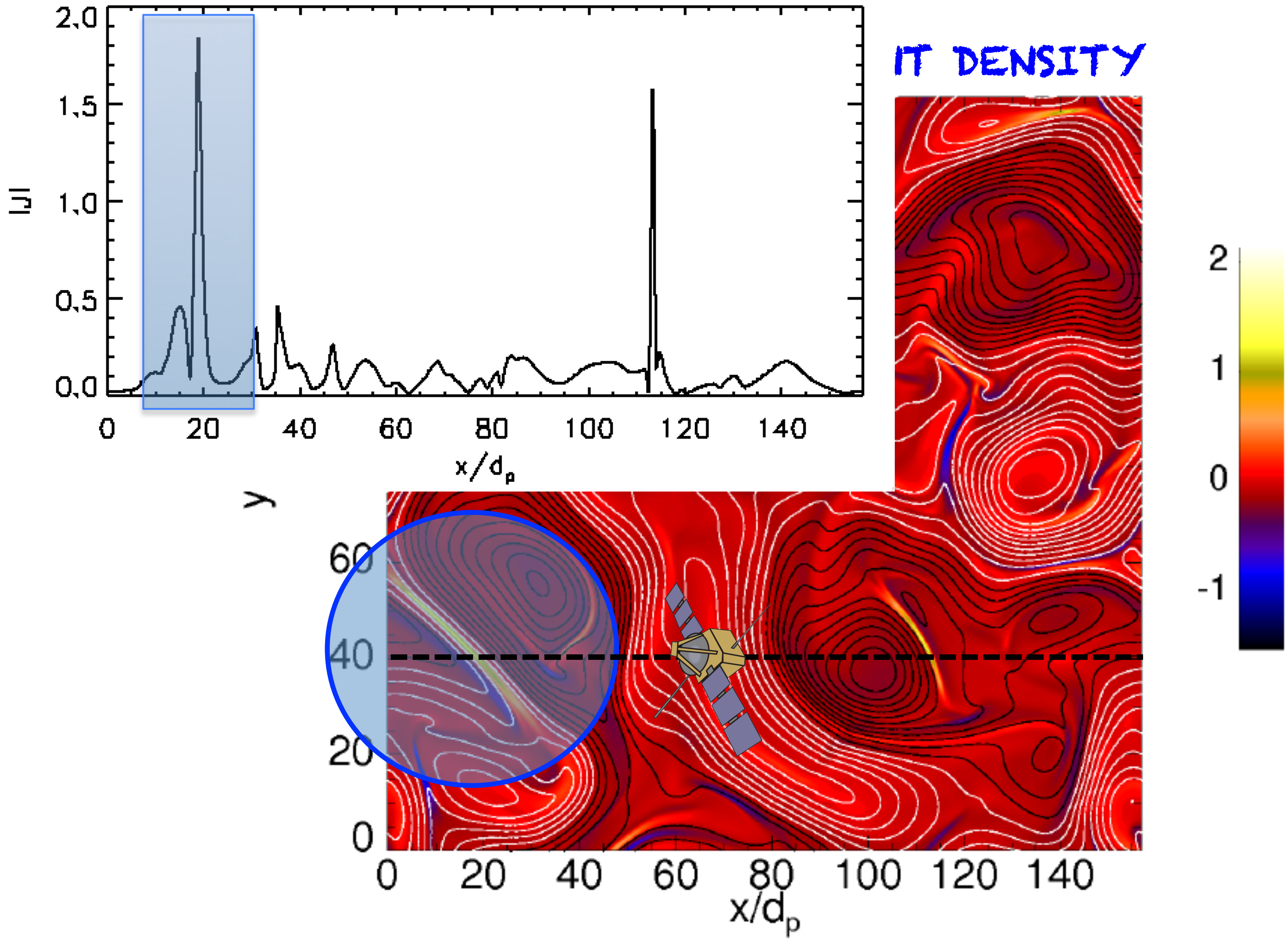
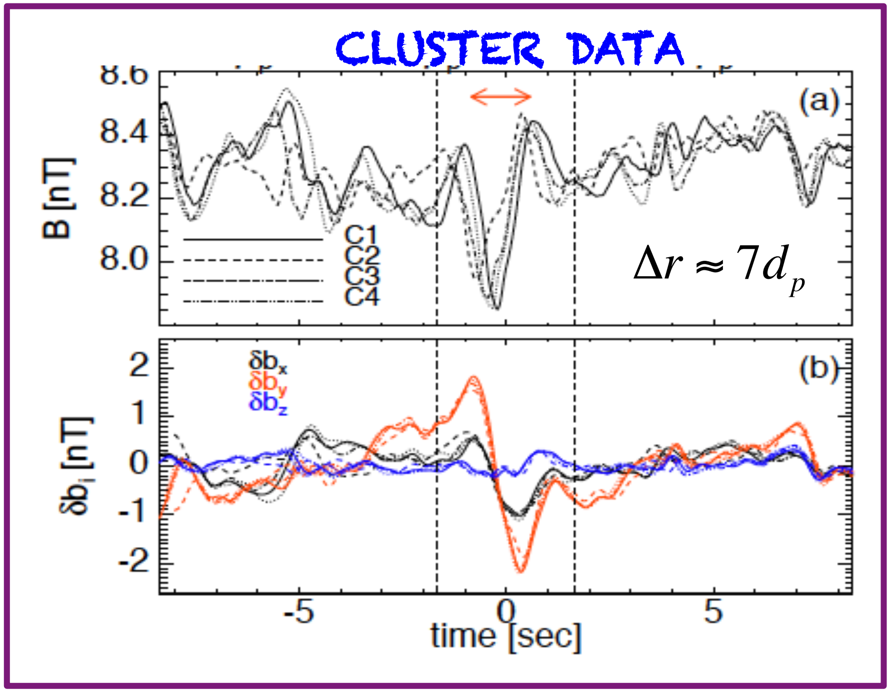
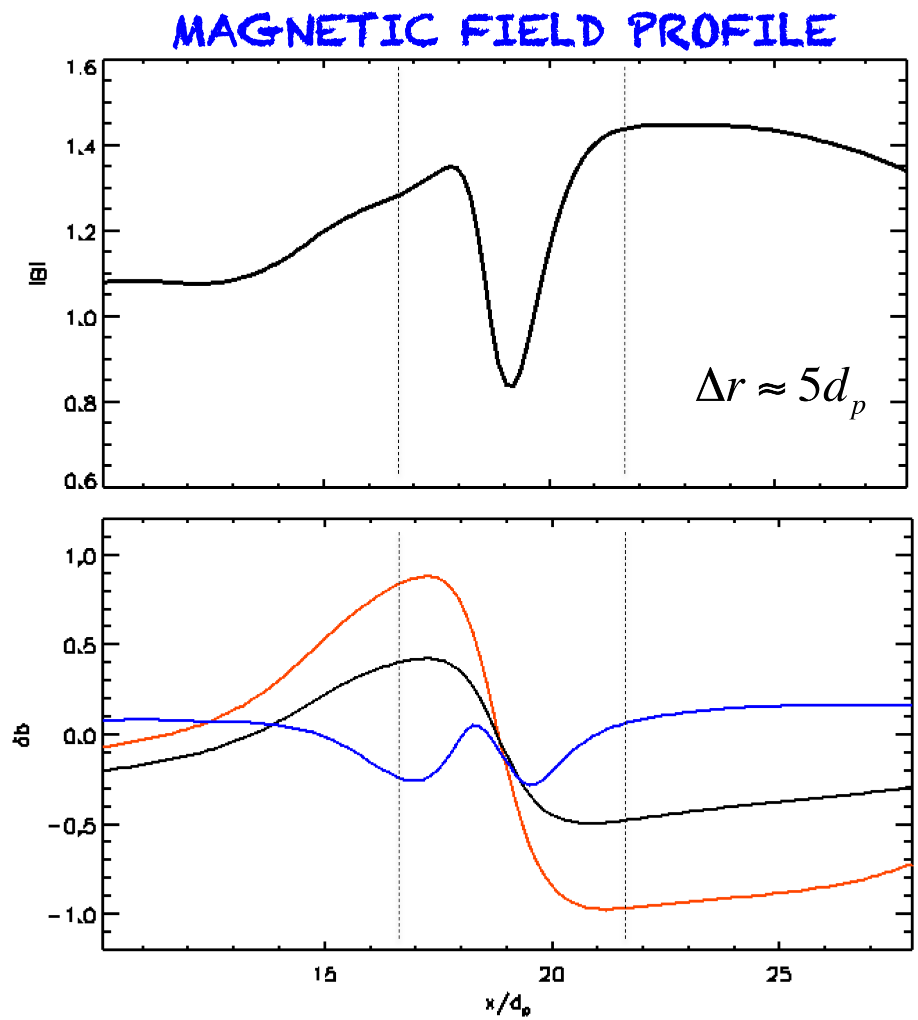
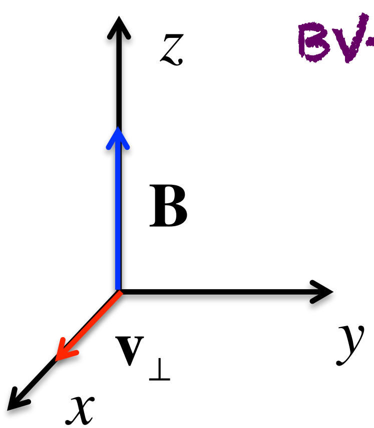



INTERMITTENT CHARACTER OF THE MAGNETIC FIELD

# CURRENT SHEET



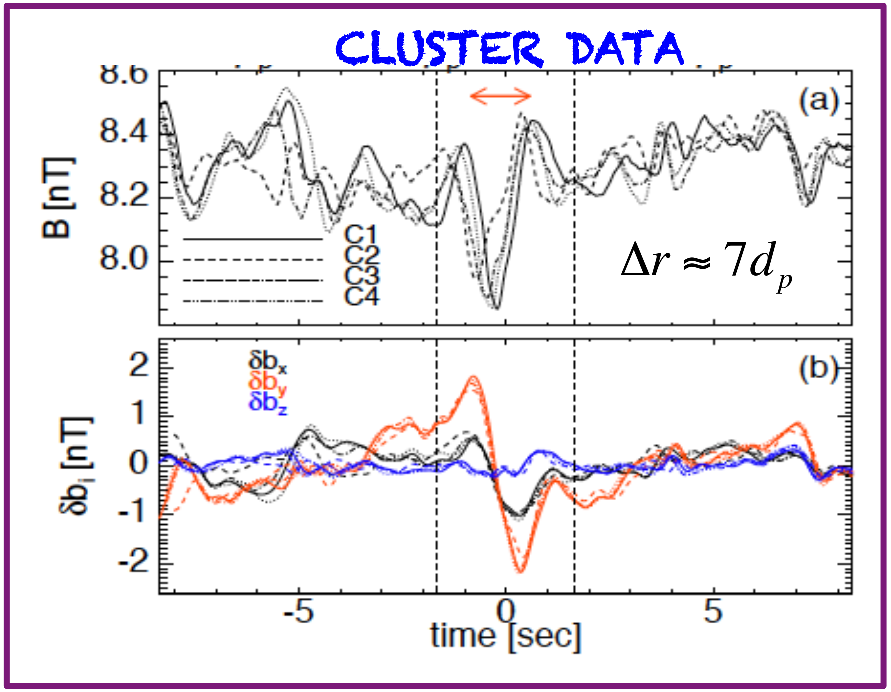

## BV-REFERENCE FRAME

$$\mathbf{e}_x = (\mathbf{e}_b \times \mathbf{e}_v) \times \mathbf{e}_b$$

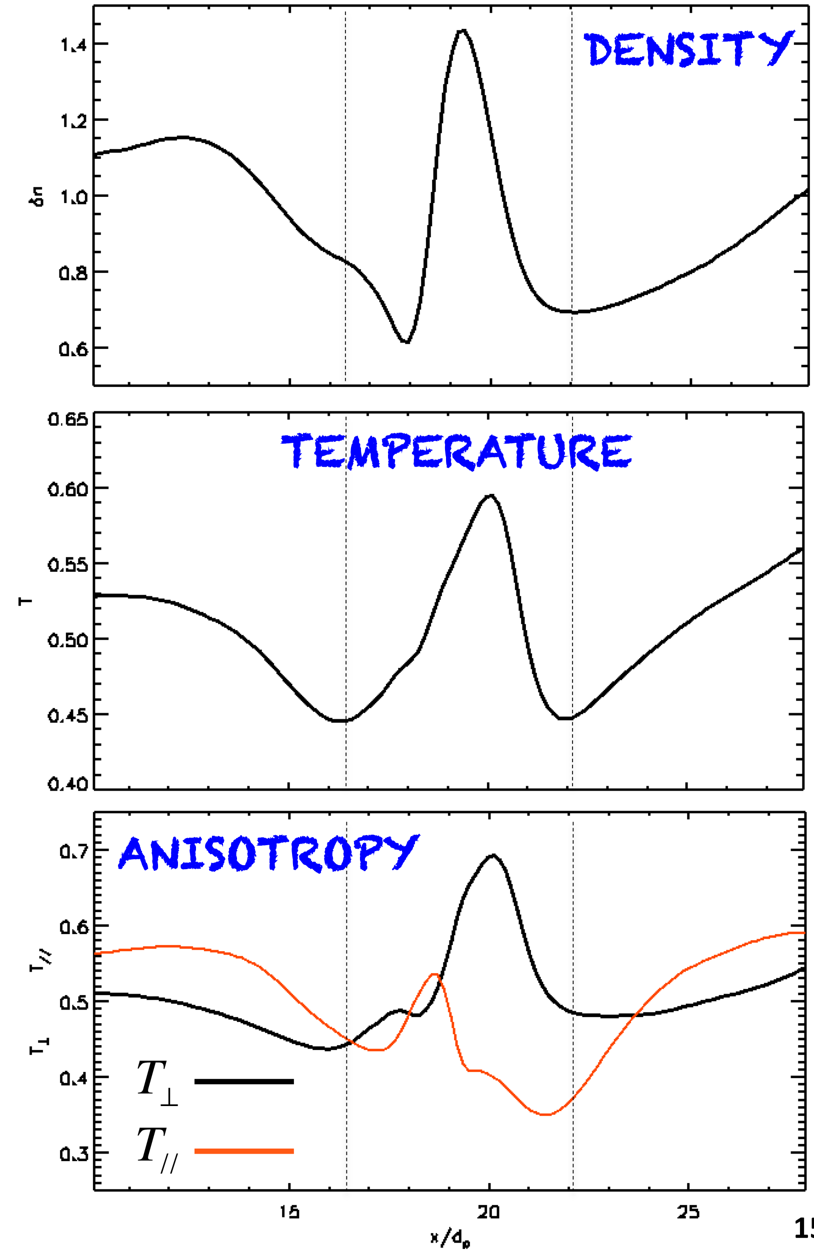
$$\mathbf{e}_y = \mathbf{e}_b \times \mathbf{e}_x$$

$$\mathbf{e}_z = \mathbf{e}_b$$

# PARTICLE MEASUREMENTS




- Increase of density
- Increase of temperature
- Deformation of the ion distribution function



# CONCLUSION

- Turbulence in the solar wind around ion scales is compressible and it is characterized by strong intermittency related to mostly convected coherent structures with k perp to $B_0$
- Unfortunately, the existing particle 'in situ' measurements have several limitations to study kinetic processes

SYNERGY BETWEEN KINETIC SIMULATIONS
AND OBSERVATIONAL DATA!