VLASOVIA 2016

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Vlasov simulations of plasma turbulence

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Outline

- **Common features in space plasmas:**
  - ***turbulence***
  - ***small scale structures & intermittency***
  - ***temperature anisotropy***
- **Vlasov turbulence in 5 and 6 dimensions**
- **THOR**
- **Conclusions**

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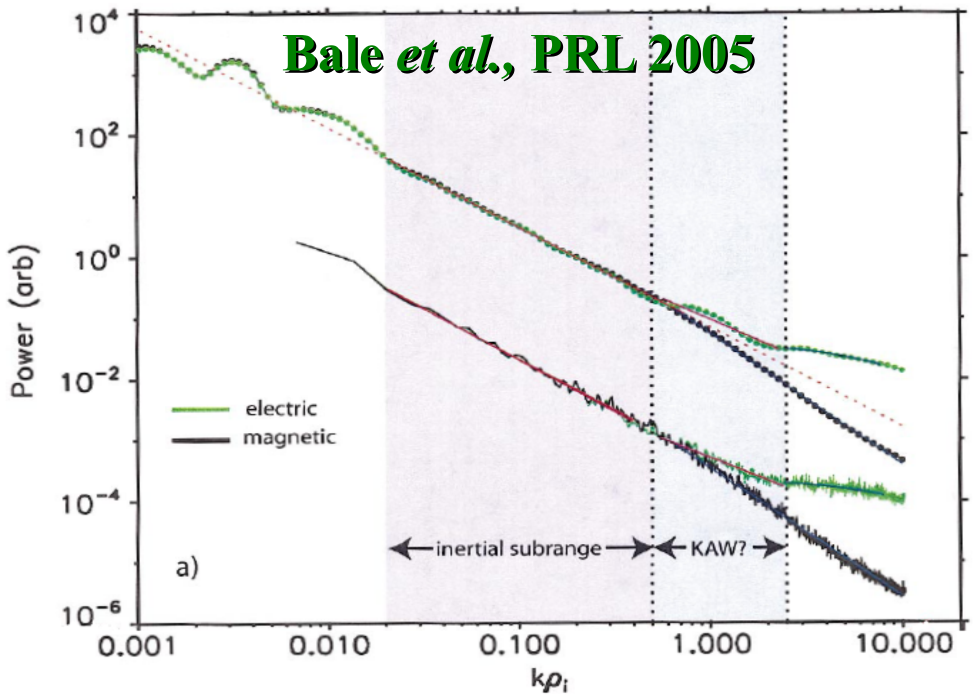
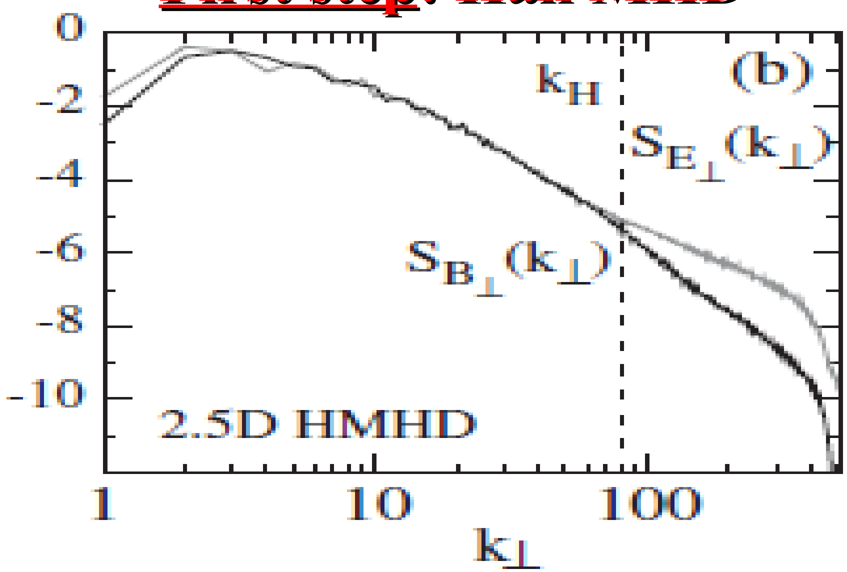
Turbulence in the solar wind



At small scales, the nature of the cascade changes

Sahraoui *et al.*, PRL (2009); Alexandrova *et al.*, PRL (2009)

First step: Hall MHD



To investigate kinetic physics

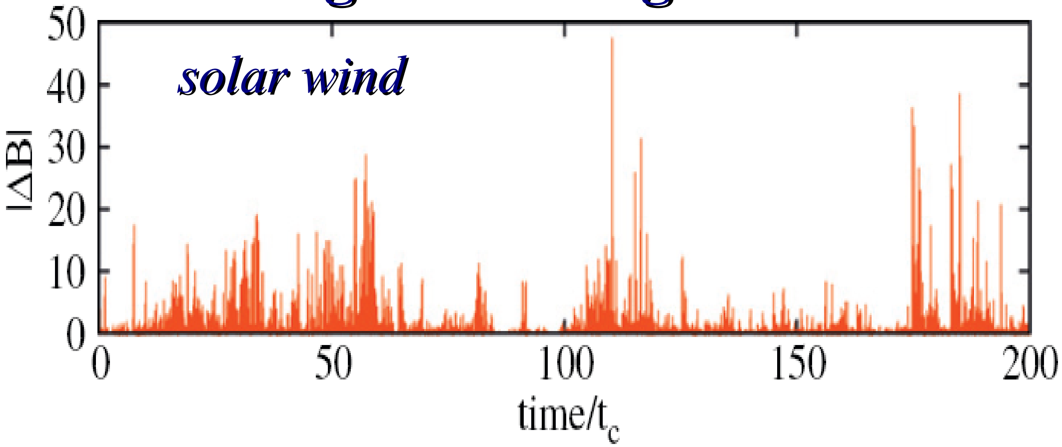
Howes *et al.*, PRL (2008);

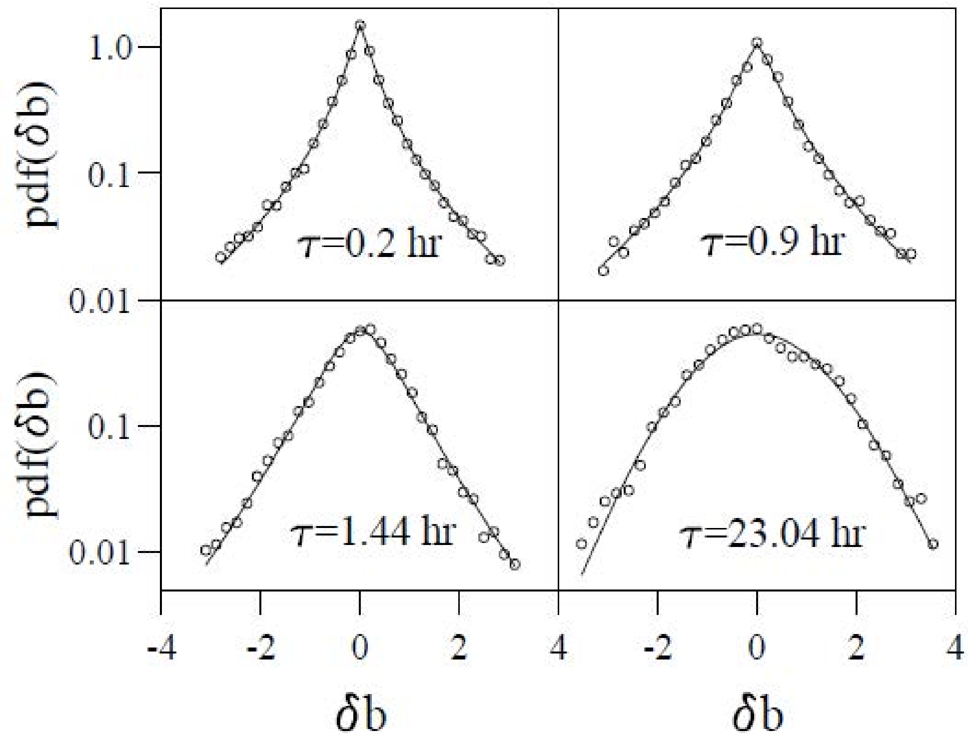
Matthaeus *et al.*, PRL (2008)

Next step: Vlasov

Intermittency in the solar wind

Magnetic field gradients





Burlaga *et al.*, JGR (1991);
Horbury *et al.*, (1997);
Sorriso-Valvo *et al.*, GRL (1999);
Bruno & Carbone, LRSP (2005);
Greco *et al.*, GRL (2008), APJ (2009);
Kiyani *et al.*, PRL (2009);
S. Servidio *et al.* JGR (2011);

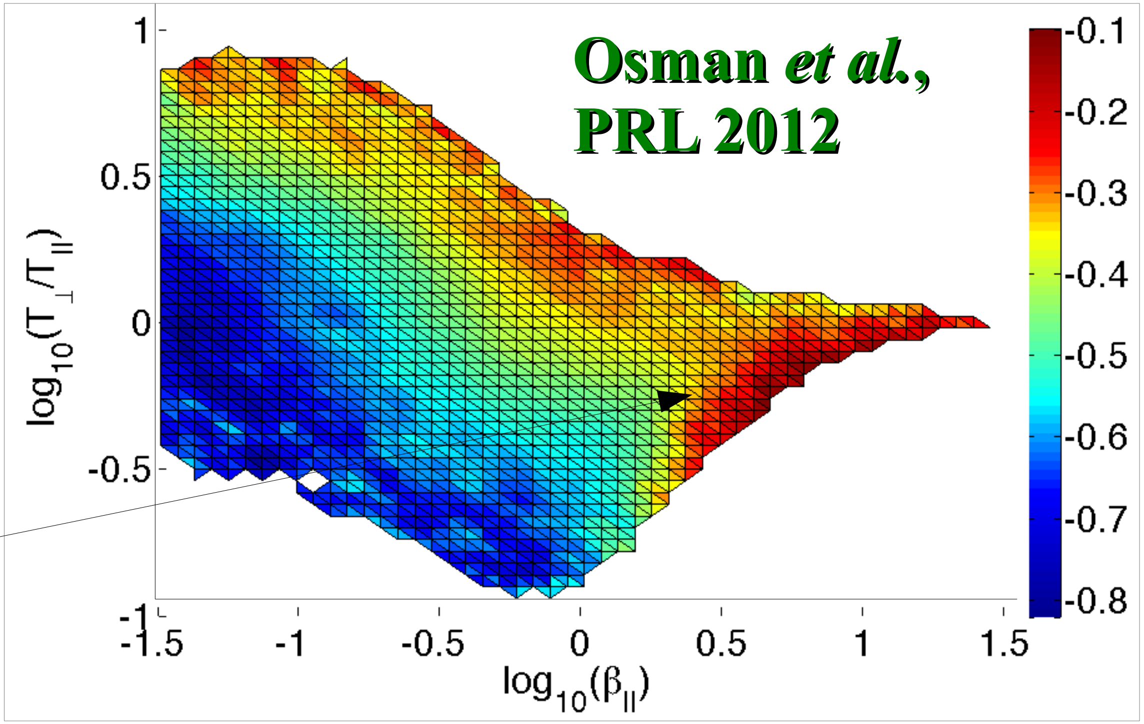
Intermittent magnetic gradients are ubiquitous in space plasmas

... & turbulent reconnection: **Retinò *et al.*, Nature Physics (2007)**

Inhomogeneous kinetic effects

Kinetic instabilities influence the solar wind

Kasper *et al.*, JGR (2006);
Kasper *et al.*, (2002)



The solar wind near the thresholds is hotter, and shows higher concentrations of current sheets

Ingredients:

- Turbulence
- Intermittency
- Magnetic discontinuities
- Magnetic reconnection
- Sub-proton skin depth physics
- Kinetic effects

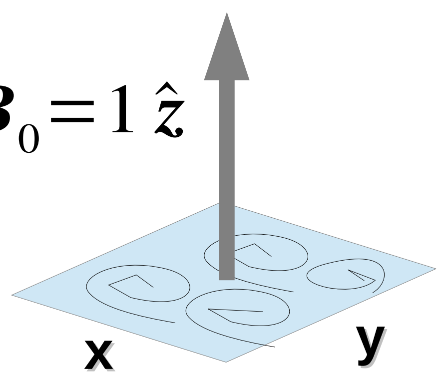
Hybrid Vlasov-Maxwell (HVM)

$$f(\boldsymbol{x},\boldsymbol{v}) = f(x, y, v_x, v_y, v_z)$$ ***proton velocity distribution function***

$$\frac{\partial f}{\partial t} + \boldsymbol{v}\cdot\nabla f + (\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B})\cdot\nabla_v f = 0$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla\times\boldsymbol{E} \longrightarrow \boldsymbol{E} = -\boldsymbol{u}\times\boldsymbol{B} + \frac{1}{n}\boldsymbol{j}\times\boldsymbol{B} - \frac{1}{n}\nabla P_e + \eta\,\boldsymbol{j}$$

$$\boldsymbol{B}_0 = 1\,\hat{z}$$



NOISE–FREE!

Valentini *et al.*, JCP (2007); PRL (2010), PRL (2011)

Some parameters ...

$$L_0 = 2\pi\alpha\, d_i,\ B_0 = 1\,\hat{e}_z,\ T_e/T_i = 1,$$
$$\eta = 1.7\times 10^{-2},\ v_{max} = \pm 5\, v_{ti},$$
$$N_X = N_Y = 512^2,\ N_v = 81^3 \rightarrow 3.5\times 10^{10}\ \textit{points}$$

- ***Kinetic ions, fluid electrons***
- ***Eulerian model***
- ***2D in space + 3V in the velocity space***

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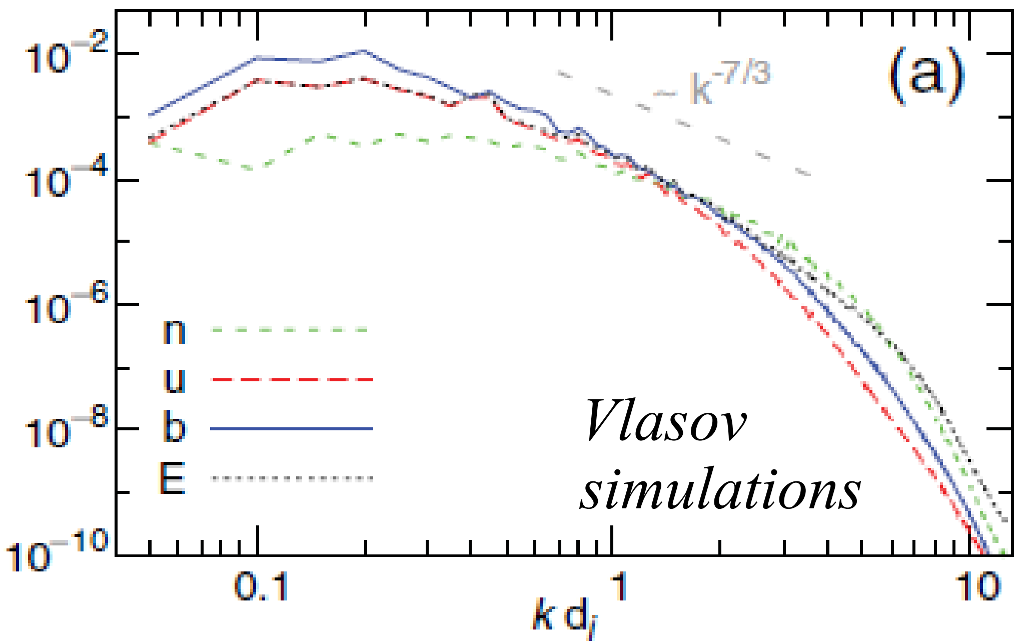
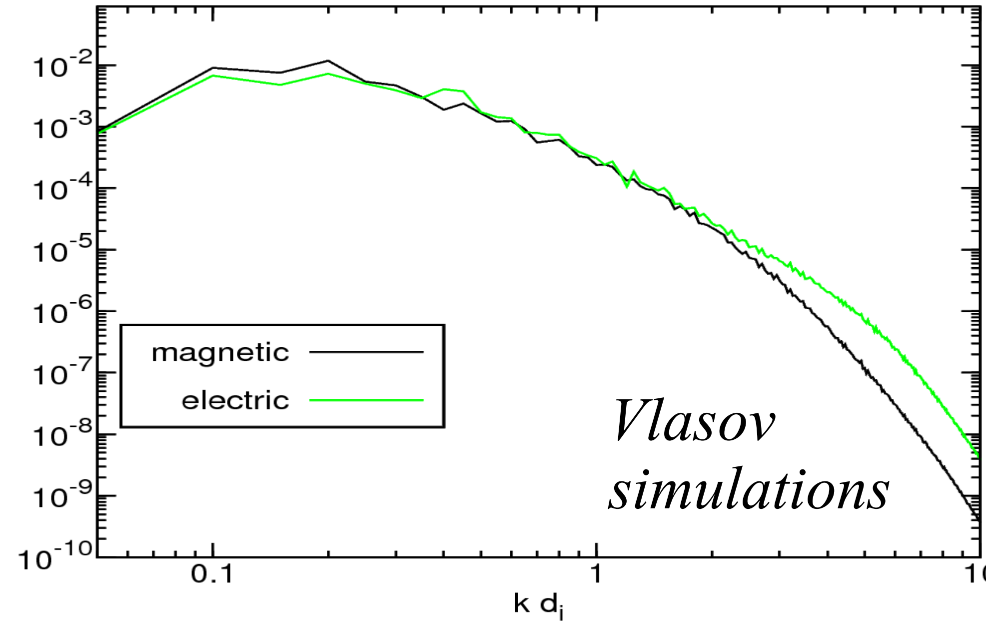
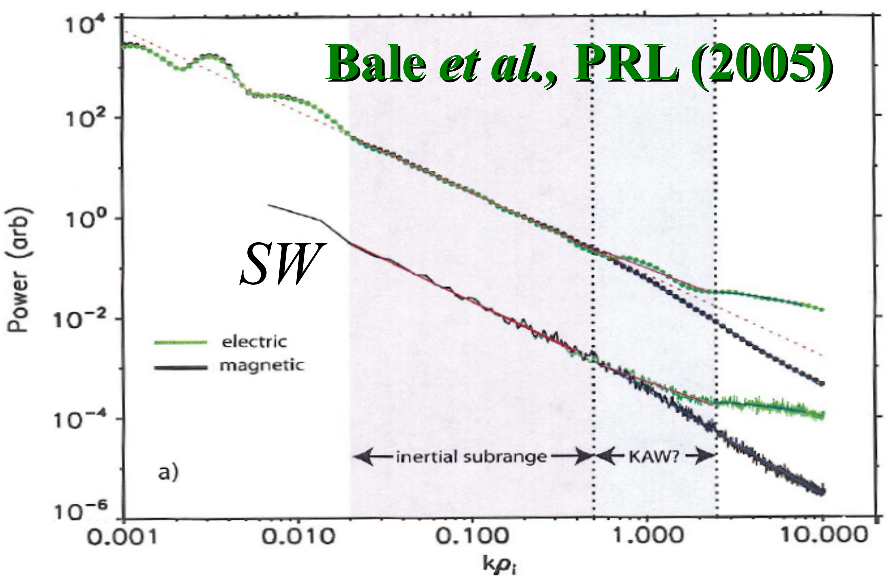
Spectral features of turbulence ...





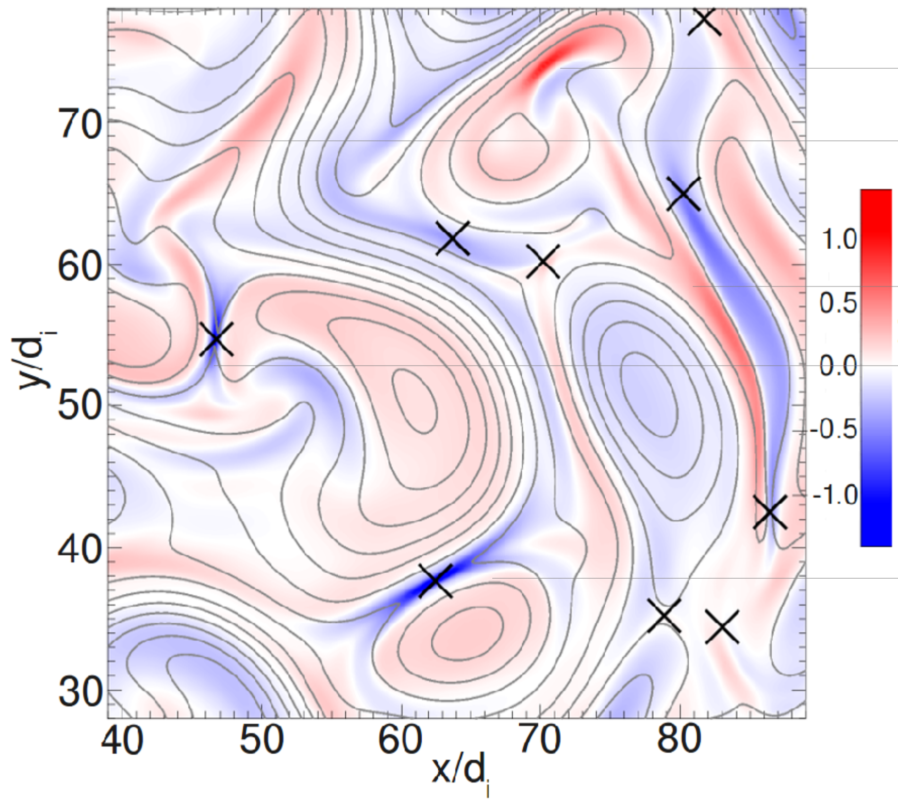


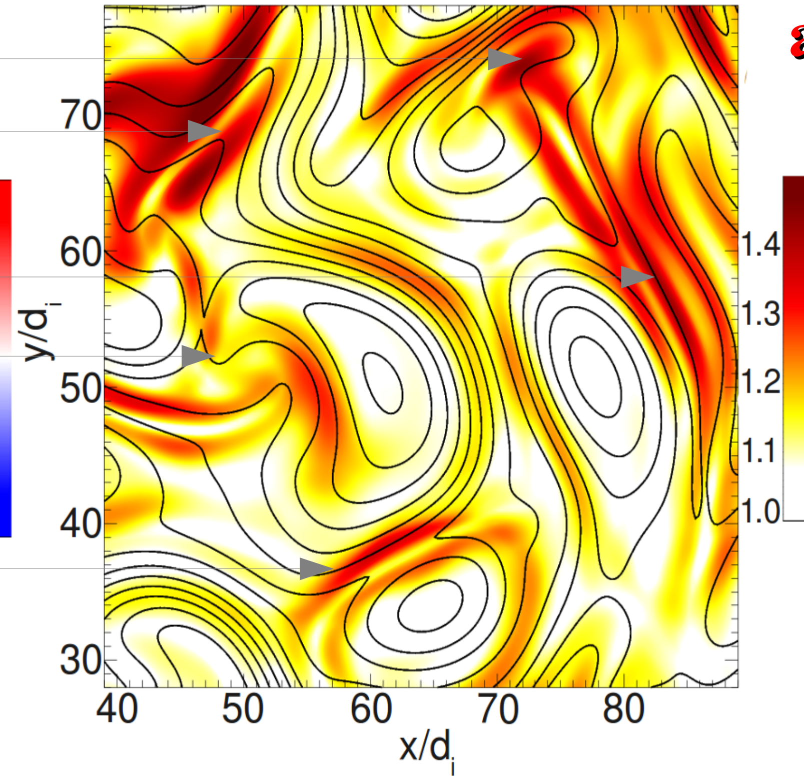
- **Large scale Alfvenic correlations**
- **Intense electric activity at small scales**
- **Steepening of the magnetic spectrum at $kd_p \sim 1$**

Schekochihin *et al.*, APJ SS (2009), Servidio *et al.*, PSS (2007); Sahraoui *et al.*, PRL (2009); Alexandrova *et al.*, PRL (2009)

...several features commonly observed in space plasmas!

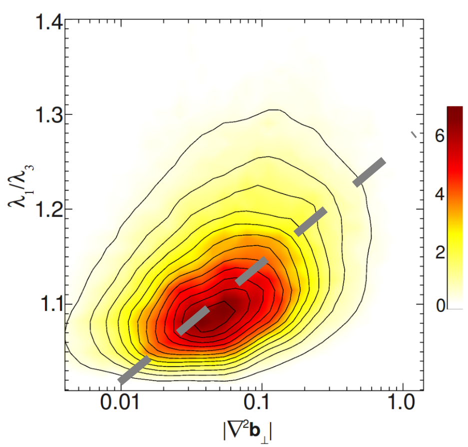
Turbulence, structures & kinetic effects





anisotropy

$$T_{\perp}/T_{\parallel} \propto \left|\nabla j_z\right| \left(\equiv \left|\nabla^2 \boldsymbol{b}_{\perp}\right|\right)$$

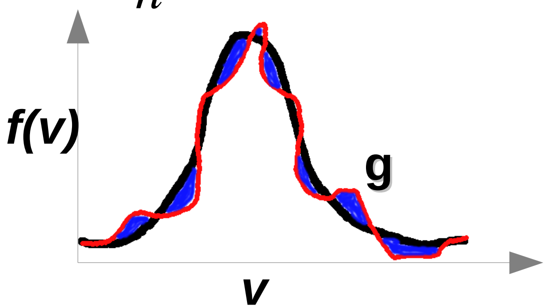


streams of kinetic effects (anisotropy, skewness and kurtosis) are adjacent to reconnecting current sheets.
In a fluid model these would correspond to regions where collisional dissipation takes place. Here cyclotron and/or Landau resonances may be at work.

Servidio *et al*, PRL 2012

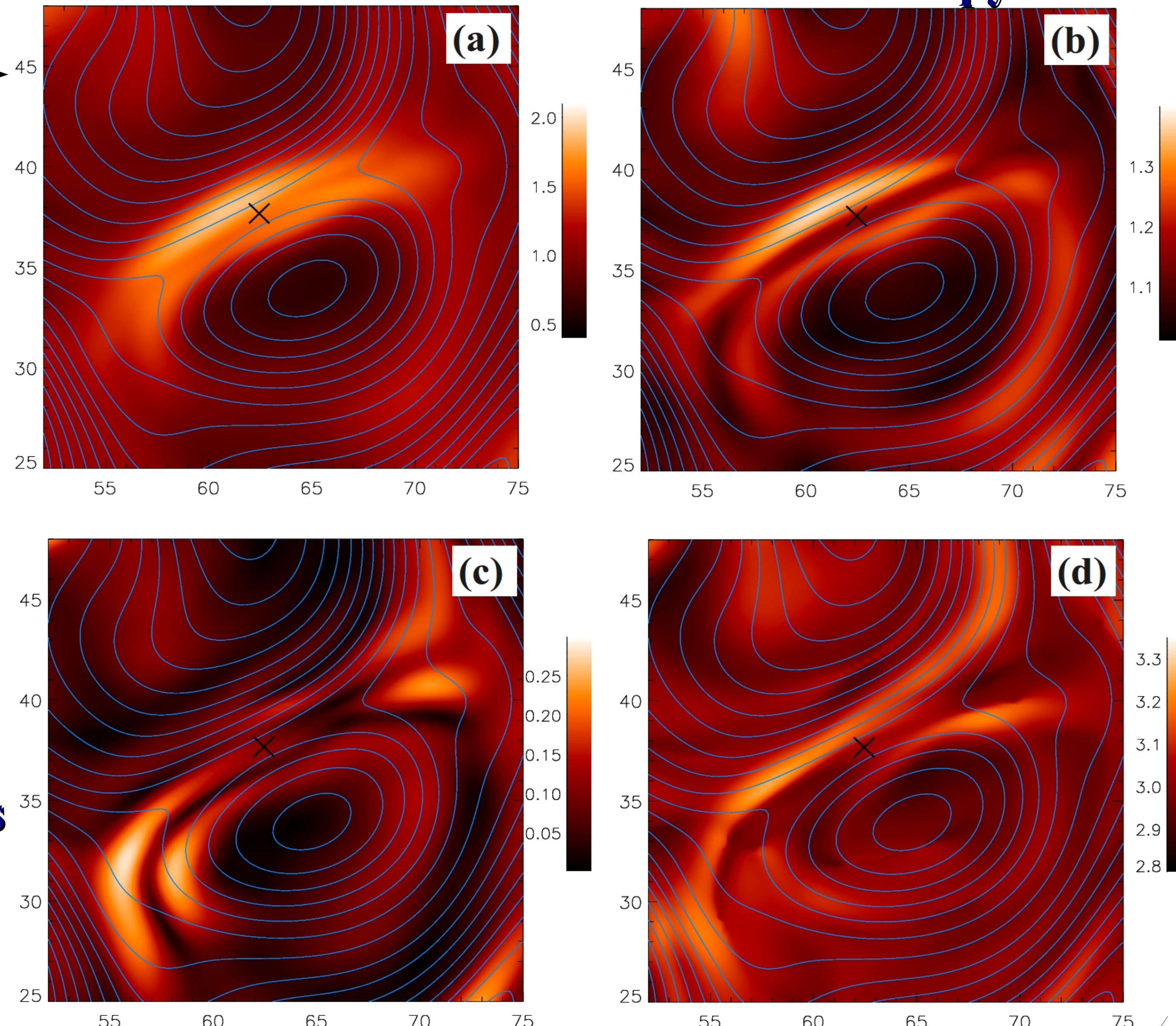
Multiple kinetic effects

$$\epsilon(\boldsymbol{x}) = \frac{1}{n}\sqrt{\int (f-g)^2 d^3v}$$



g is the Maxwellian associated to f

Anisotropy



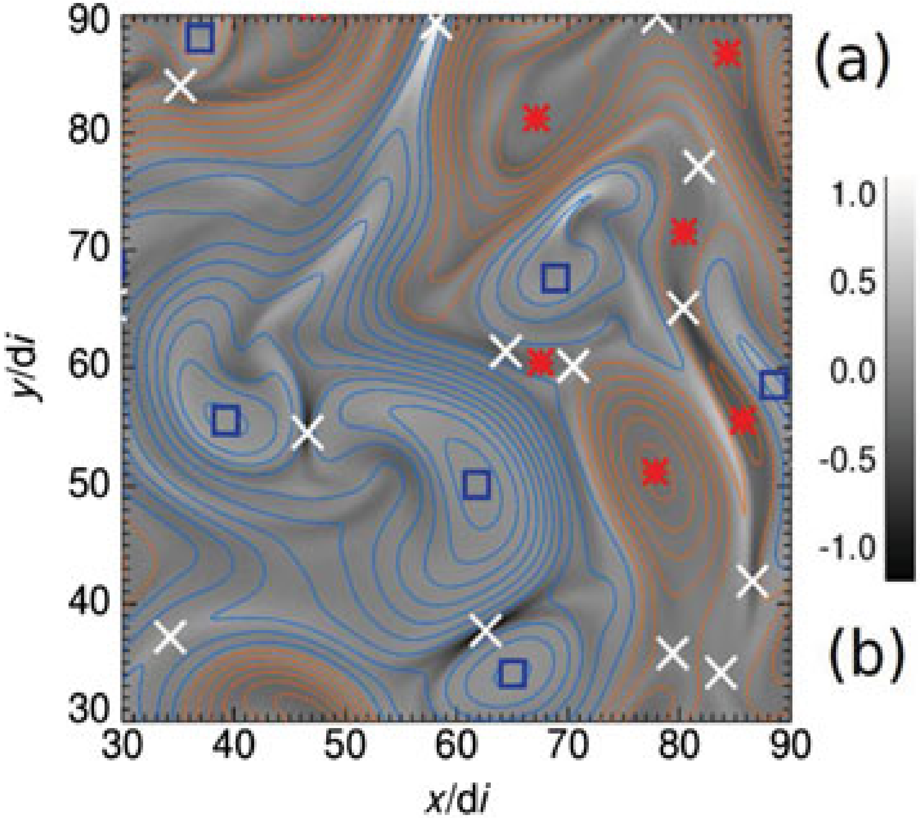
Skewness

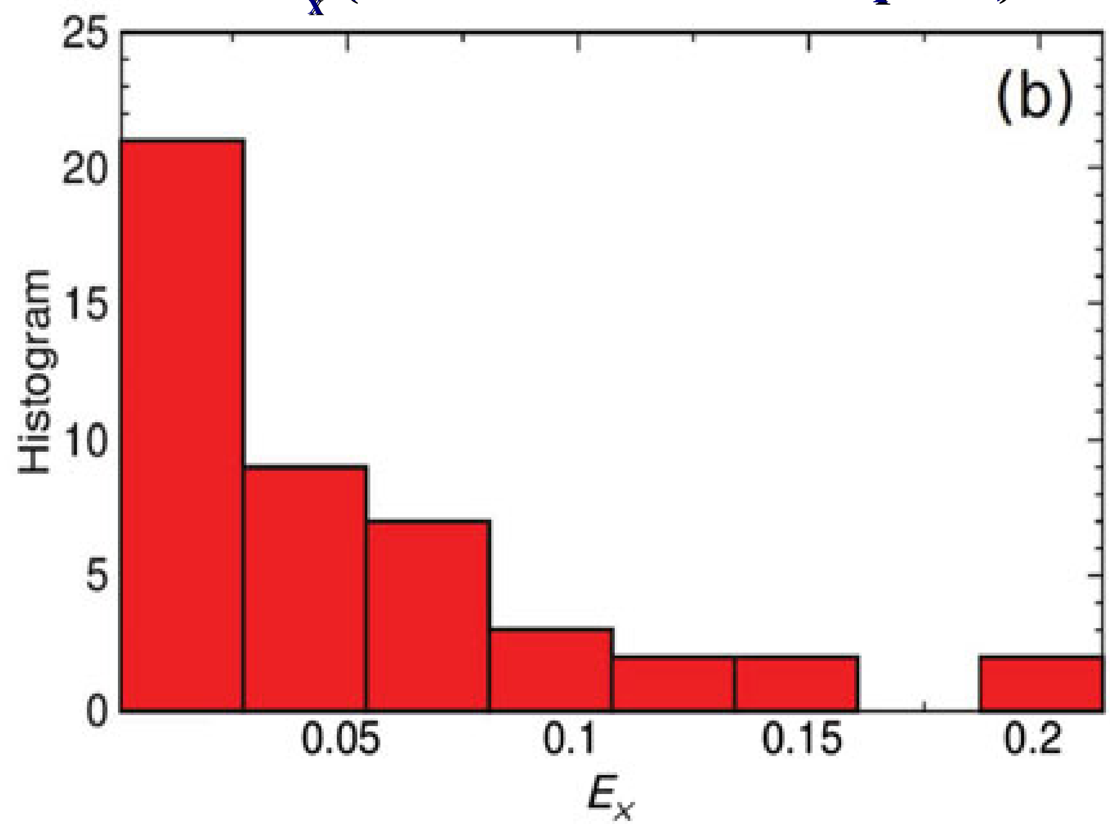
Kurtosis

Greco *el al.*, *PRE* (2012)

Magnetic reconnection in Vlasov turbulence

Reconnection rate =
E_x (electric field at the X-point)





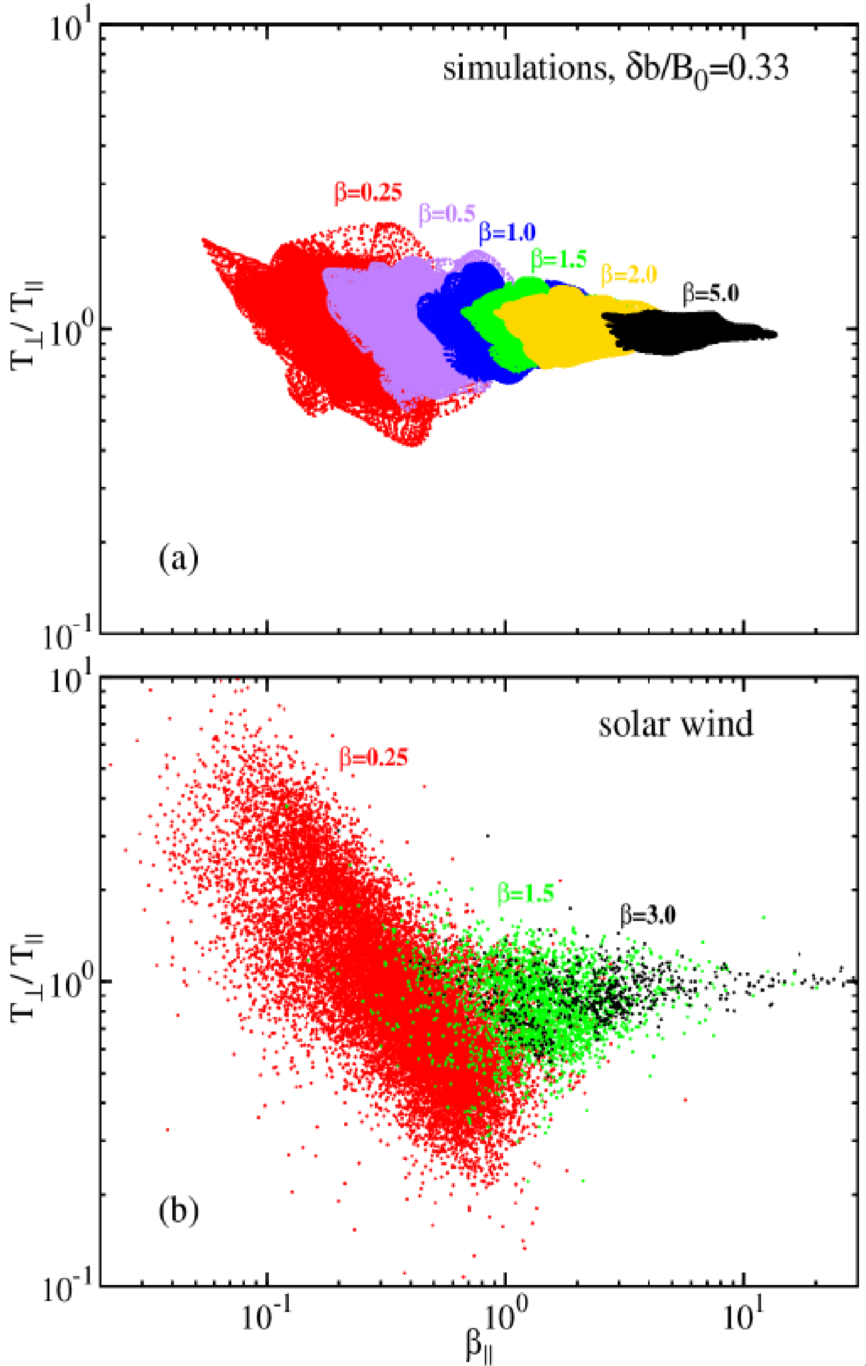
As in 2D MHD, in Vlasov turbulence there is a network of reconnecting sites, with reconnection rated broadly distributed

Ensemble of Vlasov simulations

Can we describe the solar wind?

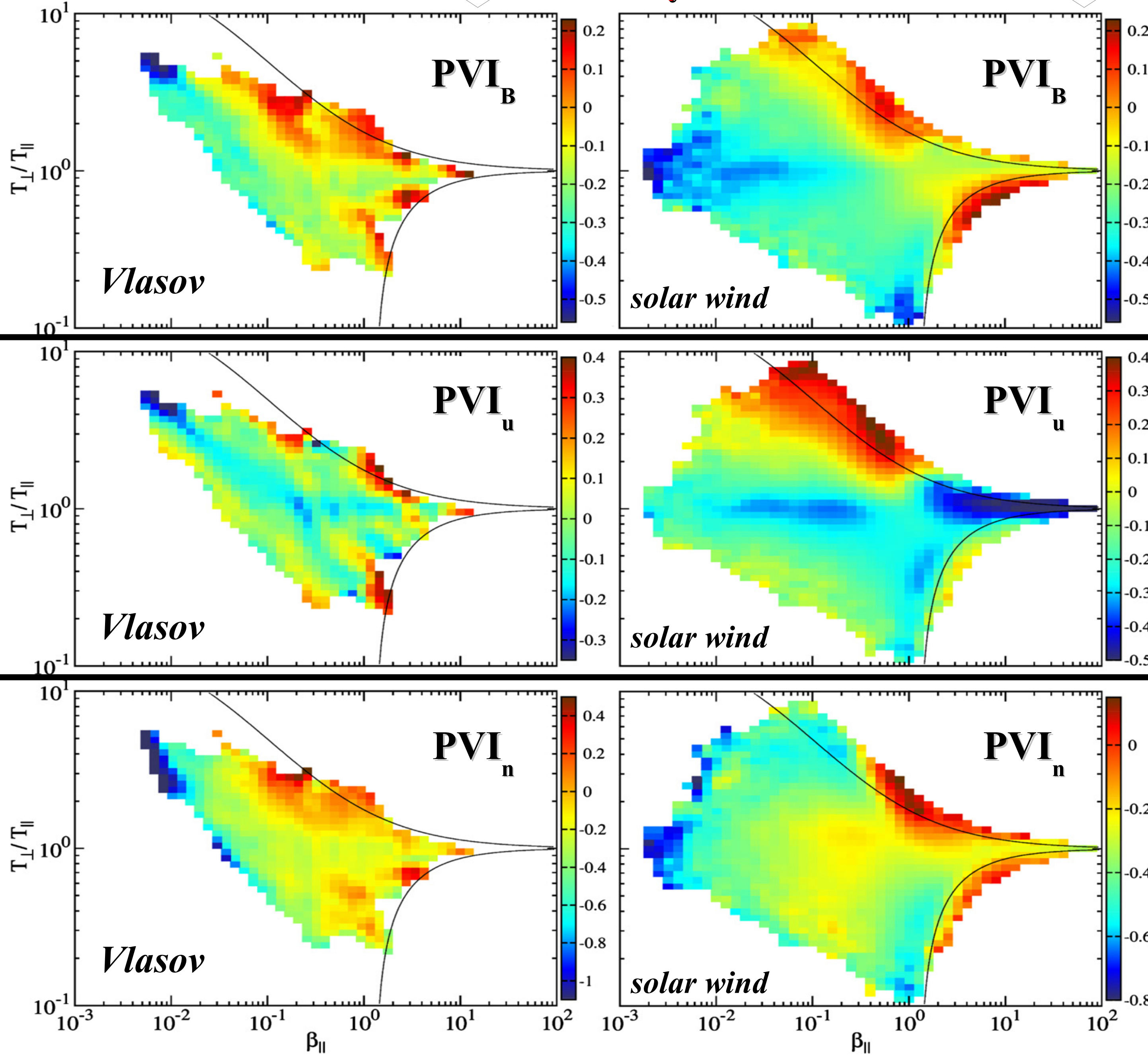
Solar wind: high variability

Different Vlasov simulations, varying global parameters



Vlasov *vs.* solar wind

Ensemble of simulations | **10 years of solar wind** | **Servidio *et al.*, APJL (2014)**



Magnetic intermittent structures

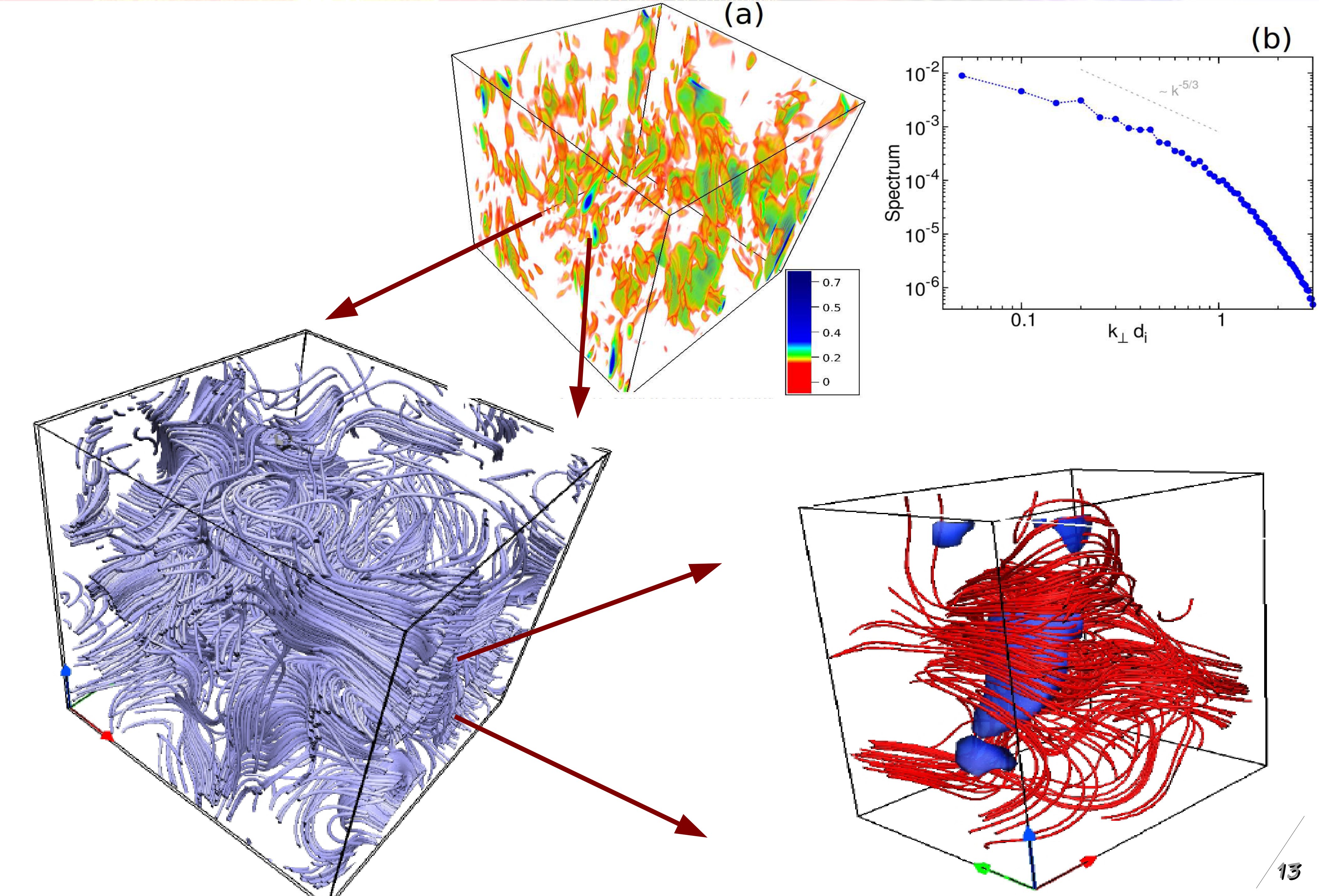
(Reconnection?)

velocity intermittent structures

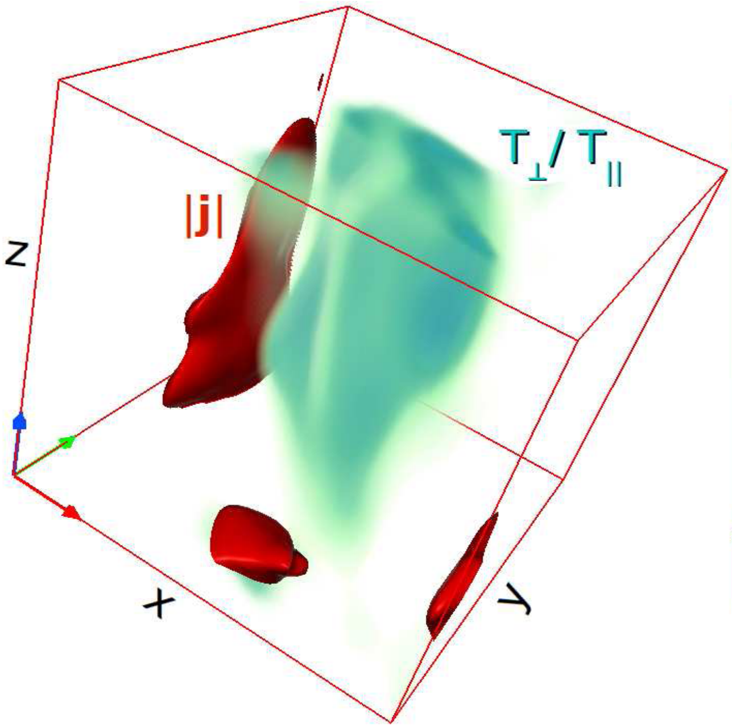
Del Sarto *et al.*, PRE (2016)

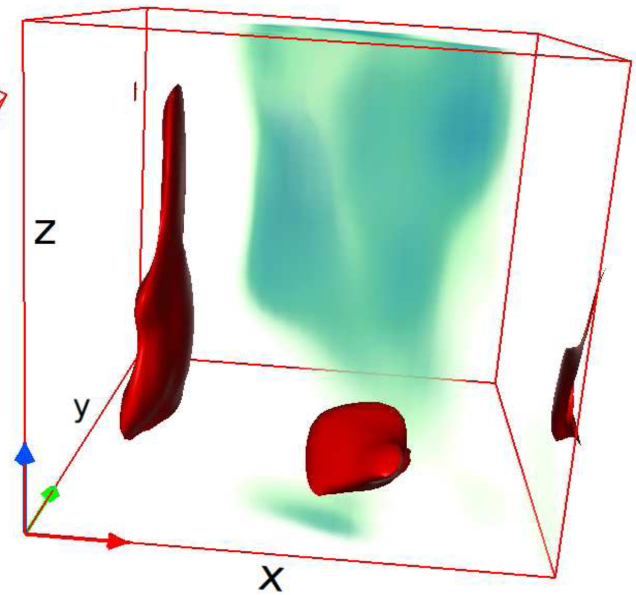
density intermittent structures

“6D” Vlasov

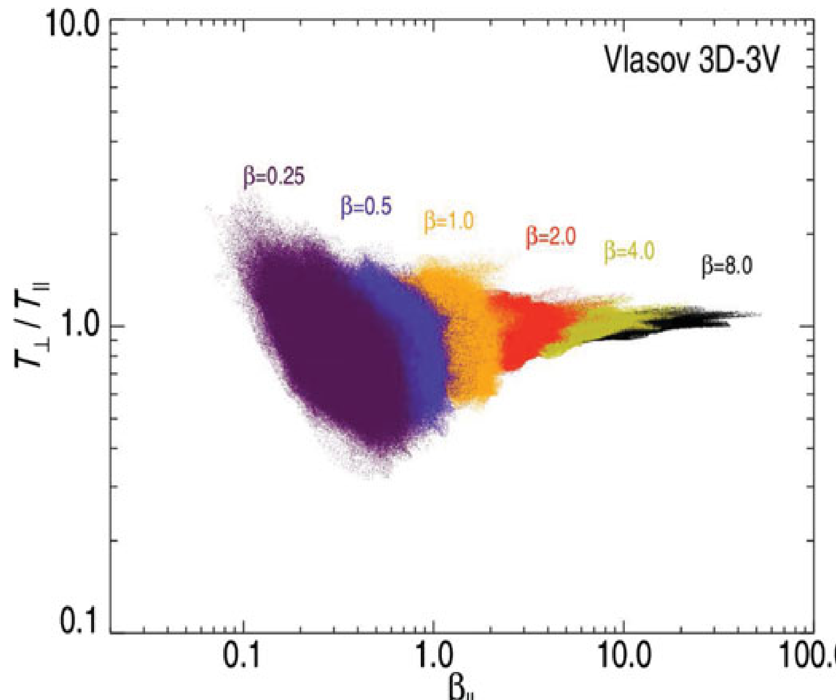


“6D” Vlasov turbulence



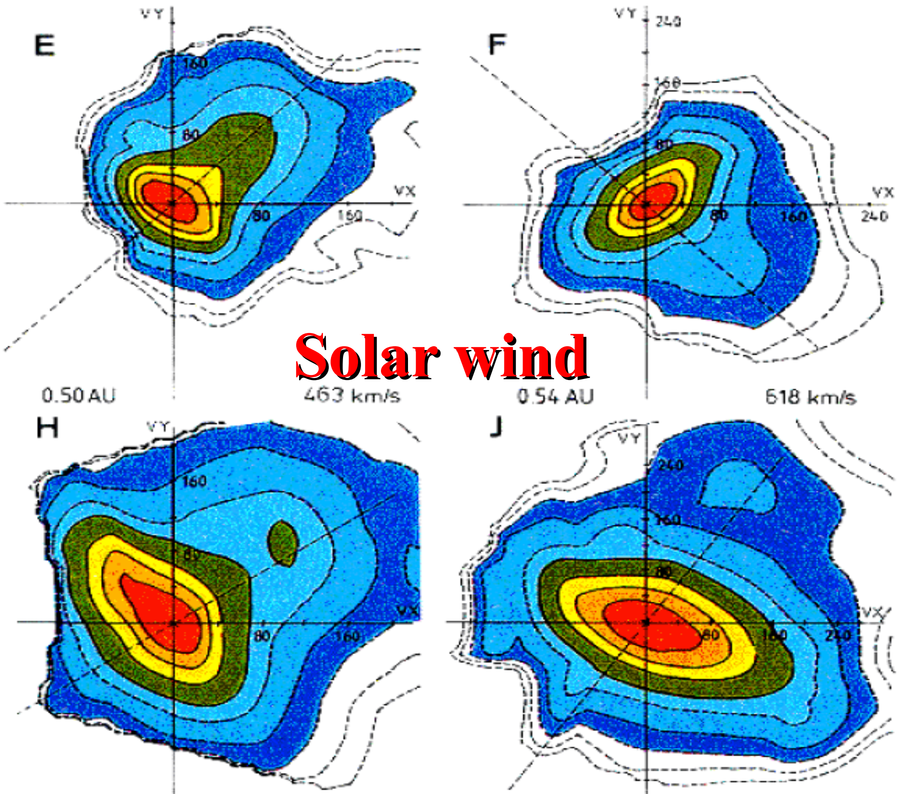


Patterns of temperature anisotropy are near current sheets



Results consistent with 2D

6D Vlasov: more non-thermal effects!

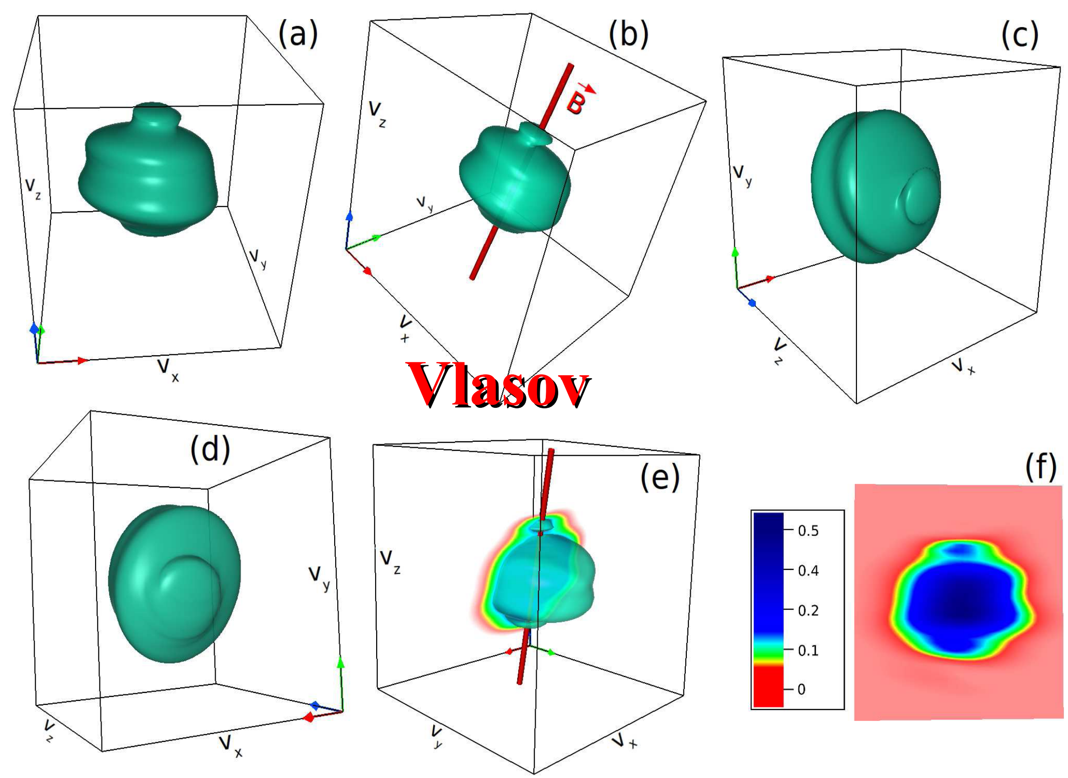


Solar wind

Marsch, LRSP (2006)

beams, anisotropy, and strong non-gyrotropic modulations

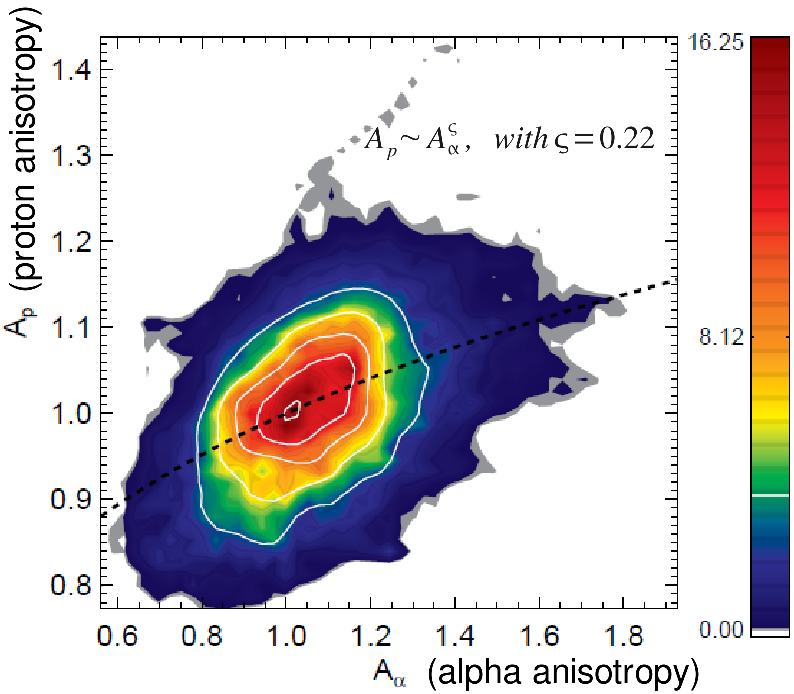
Servidio *et al.*, JPP (2015)



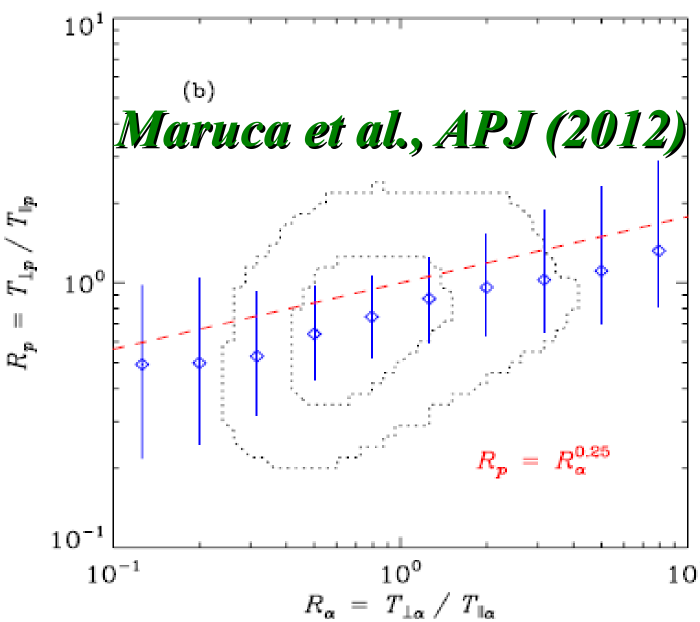
Vlasov

Landau resonances can be locally excited

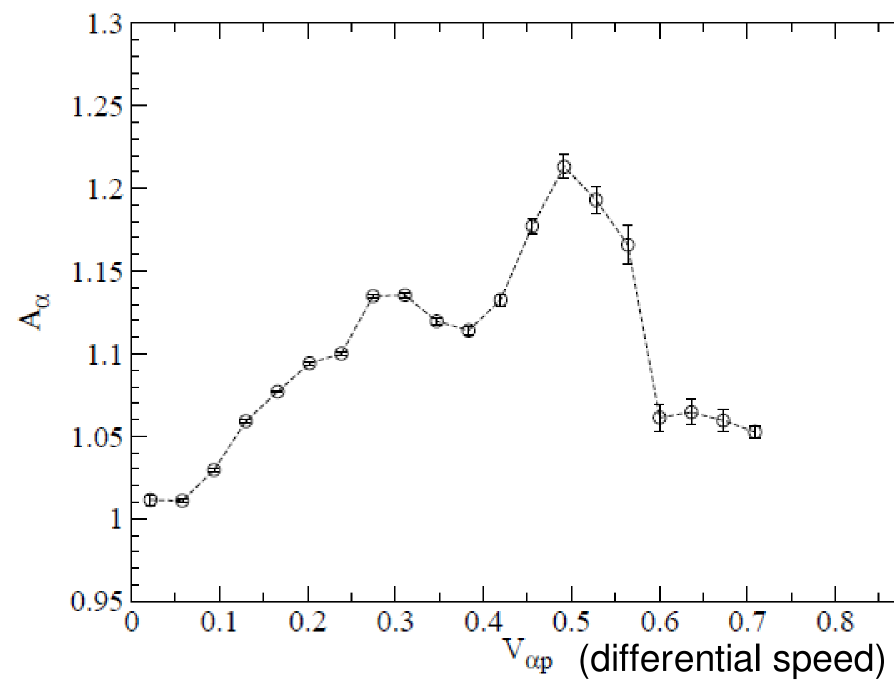
“alpha turbulence”



- **Temperature anisotropy for alpha particles is correlated to proton anisotropy**
- **Alpha anisotropy is correlated also to the differential flow (velocity between bulk protons and alpha particles)**



Maruca et al., APJ (2012)



D. Perrone *el al.*, APJ (2013)

High resolution measurements in the SW?

We need high precision measurements

Turbulence Heating ObserveR

http://thor.irfu.se

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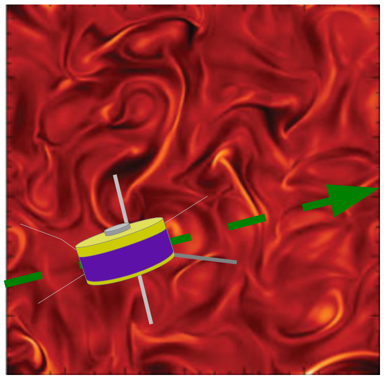
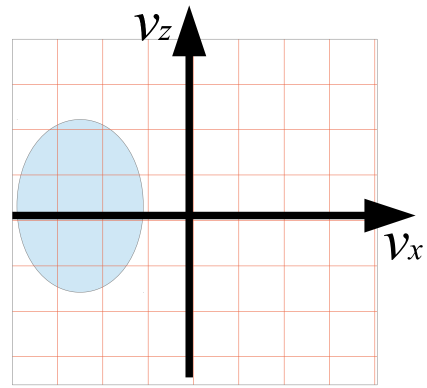
THOR

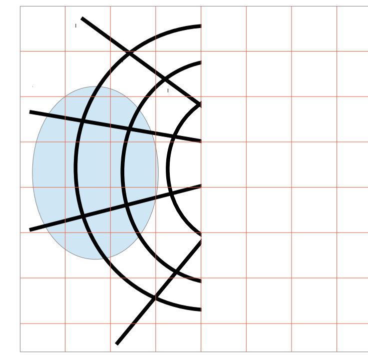
1) Virtual satellite

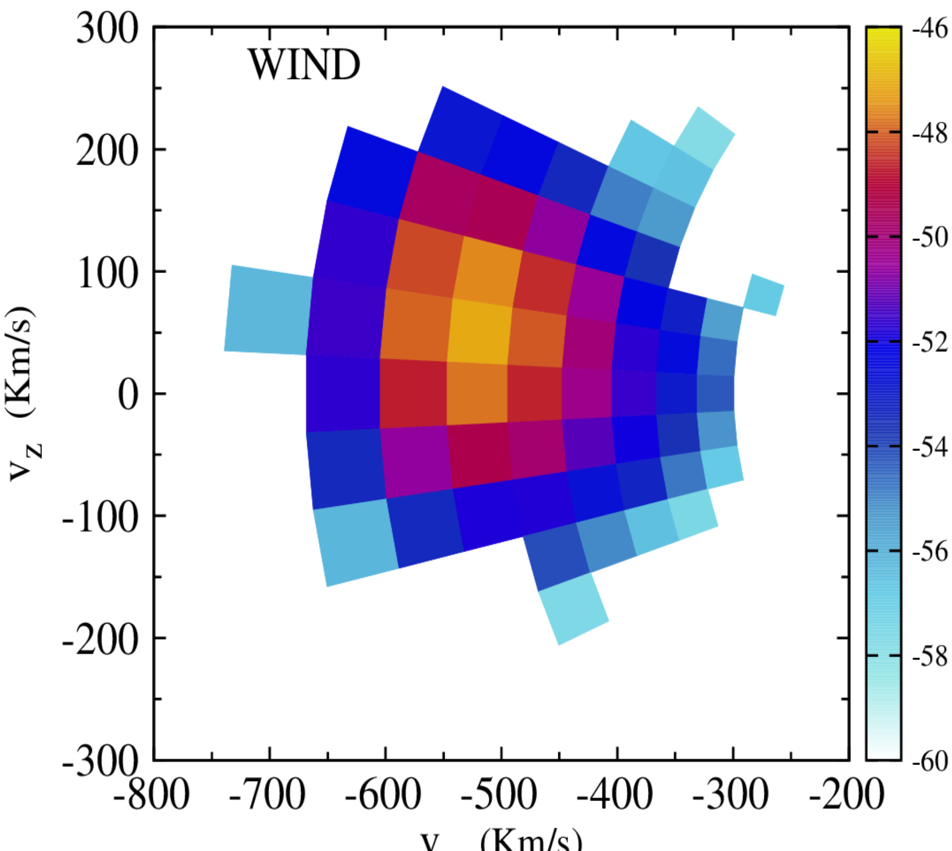


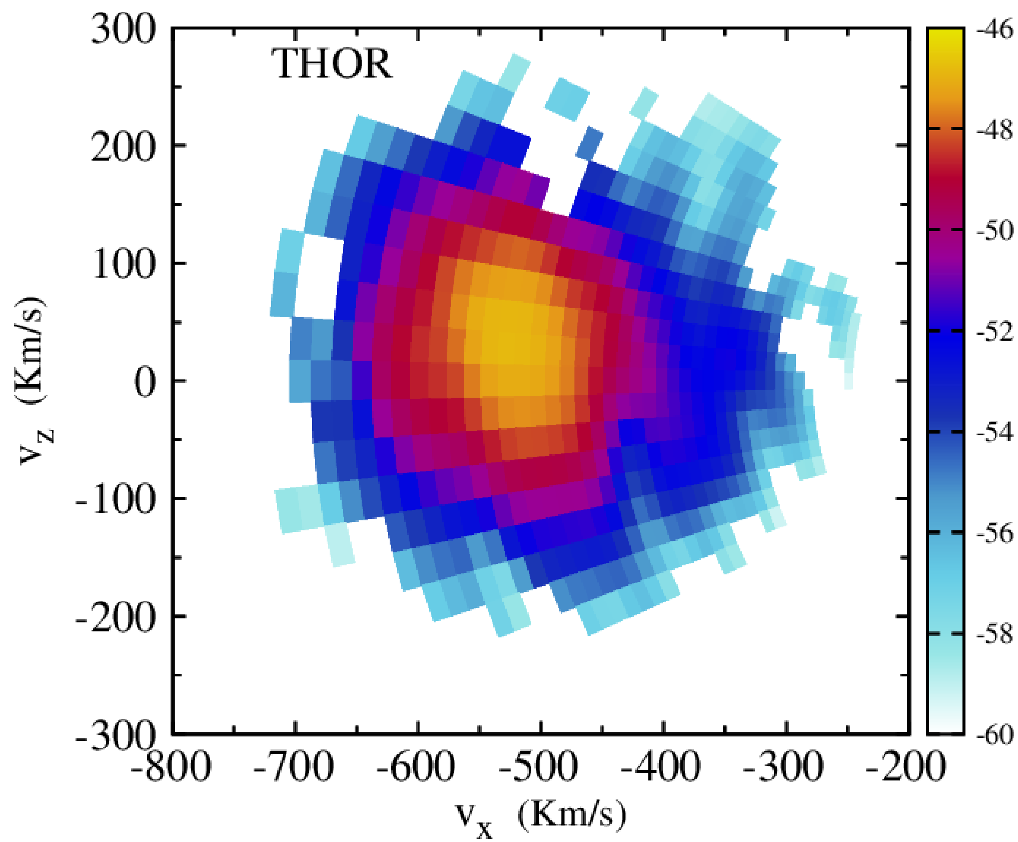
2) Add SW speed



3) From Cartesian to spherical



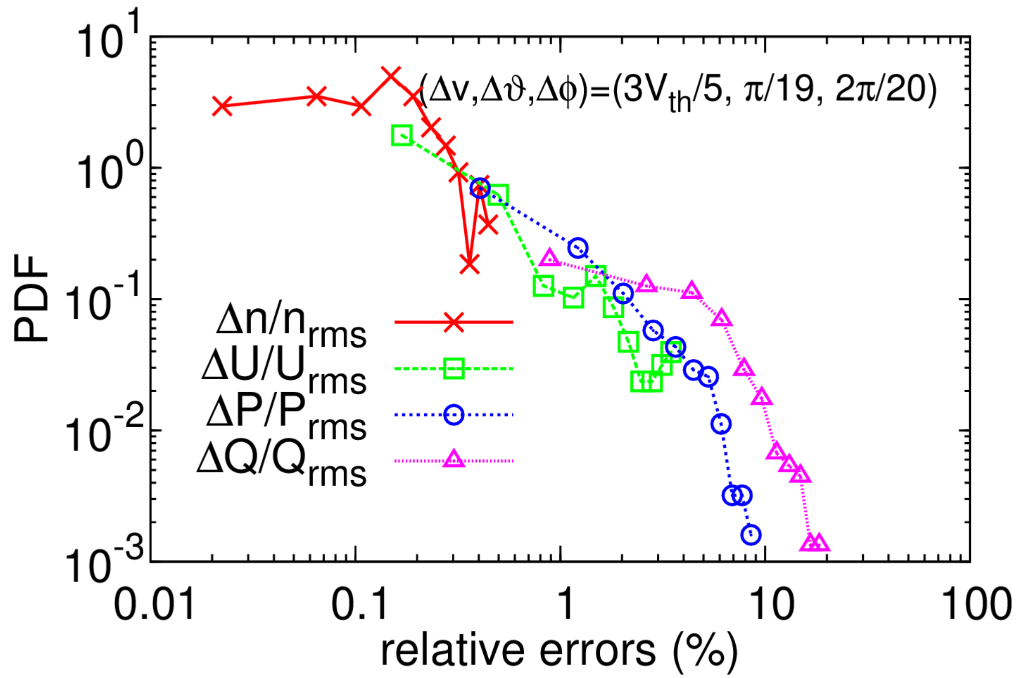




THOR flying through a (numerical) plasma

"Errors"

Comparison among satellites (resolutions)



	Energy res.	Angle res.	Sampling time	Err. *Uj*	Err. *T*	Err. *ε*
SolO	4.8%	6°	150 ms	0.04%	3%	11%
THOR	5%	3°	4 s	0.04%	0.7%	3%

R. De Marco *et al.*, *Conference proceedings of "4th International Conference Frontiers in Diagnostic Technologies"*, submitted

Fundamental questions

Plasma turbulence →

- **heating**
- **acceleration**
- **diffusion**
- **mixing**
- **dispersion**

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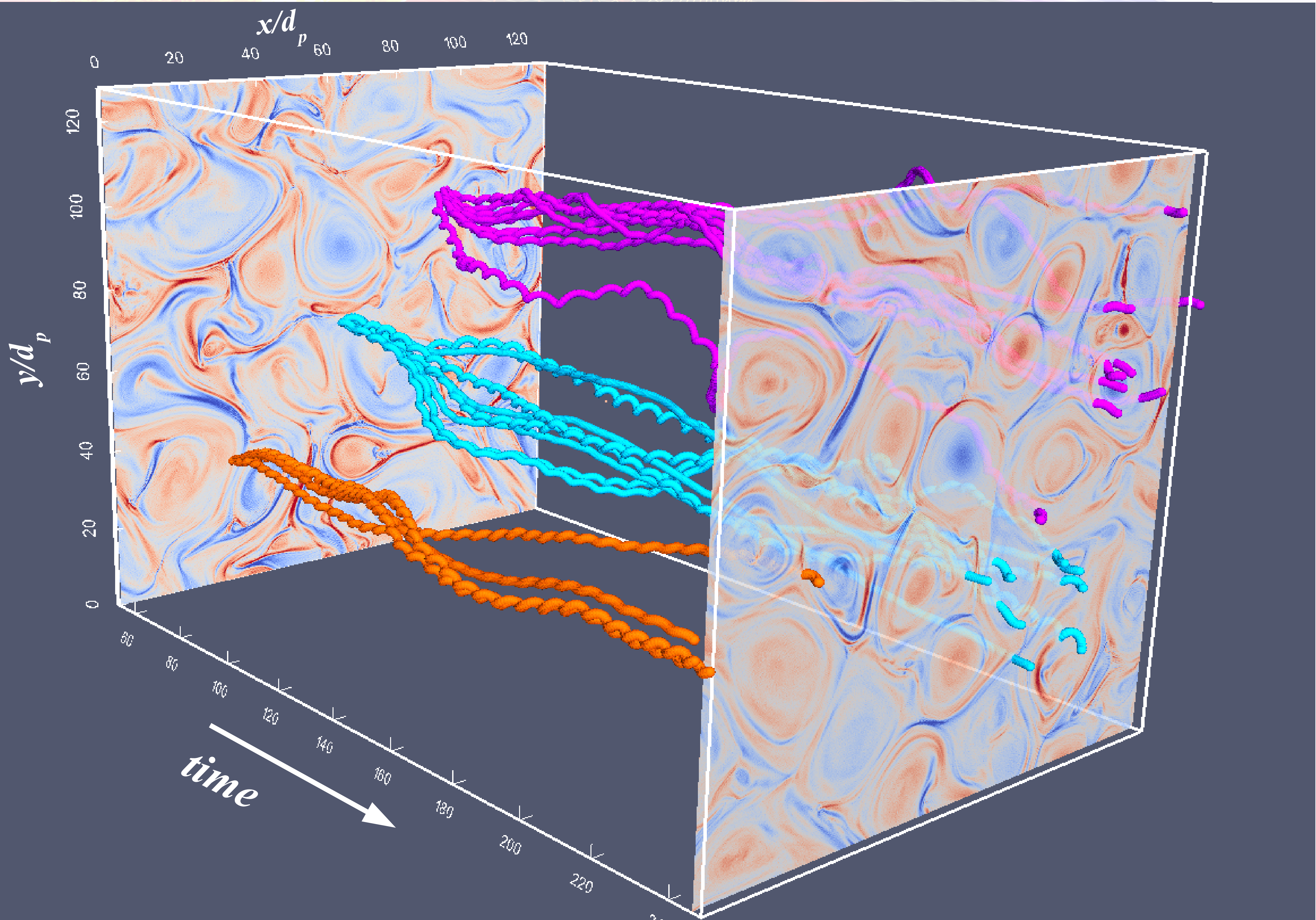
Particles in turbulence



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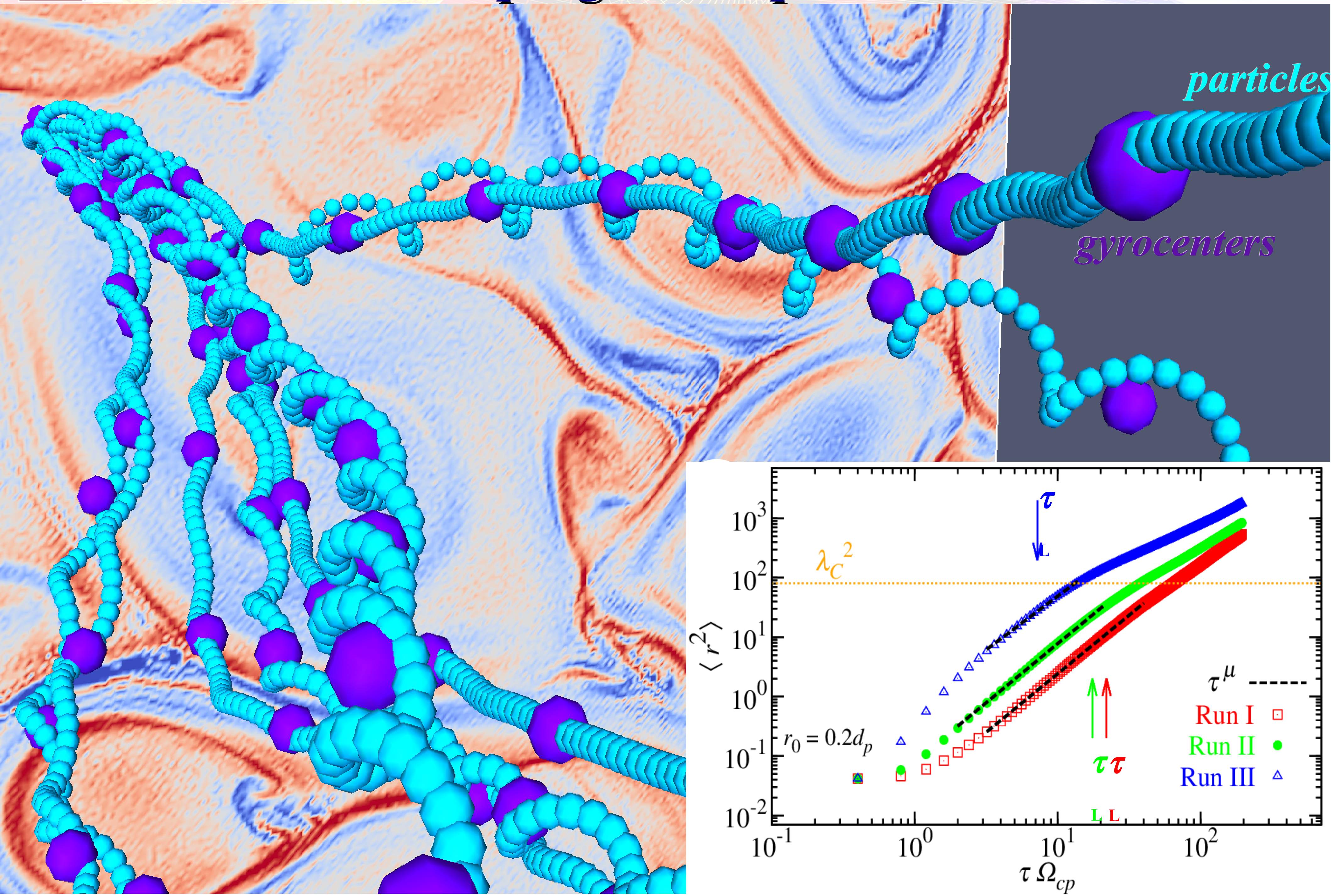
Jumping into a plasma



The termination of the cascade

Many other groups working on these subjects!

Franci *et al.*, APJ 2015

What happens at electron scales in Vlasov turbulence?

Simulations:

Haynes *et al.*, ApJ (2014)
Lapenta *et al.*, Nature Phys. (2015)
Krimabadi *et al.*, PoP (2013)

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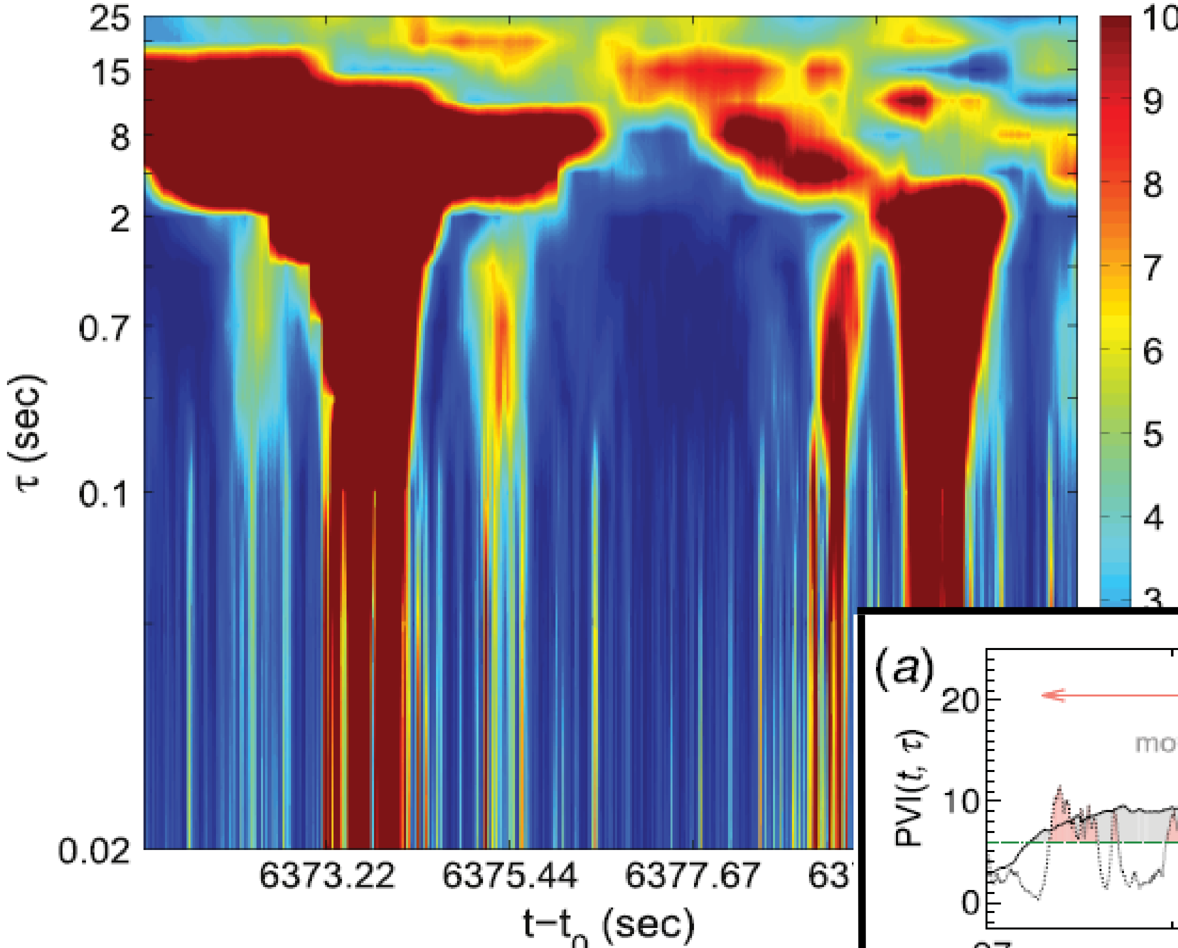
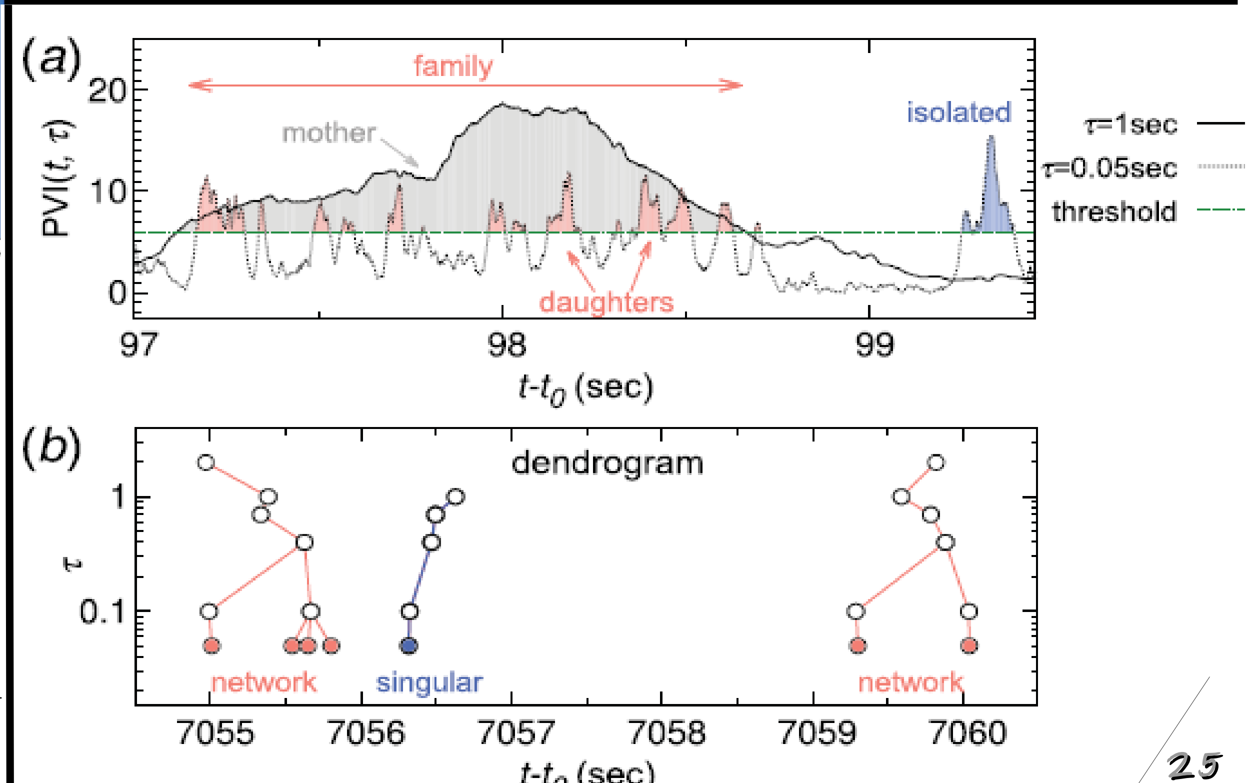
The smallest scales



Solar wind data

$$\mathrm{PVI}(t,\tau)=\frac{|\Delta \boldsymbol{B}(t,\tau)|}{\sqrt{\langle|\Delta \boldsymbol{B}(t,\tau)|^2\rangle}}$$



The smallest scales (~de) are characterized by fragmenting current sheets.
The ideas of "reconnection in turbulence" and "turbulent reconnection" are finally reconciled

Greco *et al.*, APJ Letters, 2016

Conclusions

- Turbulence provides a "network" of reconnection events & intermittent structures

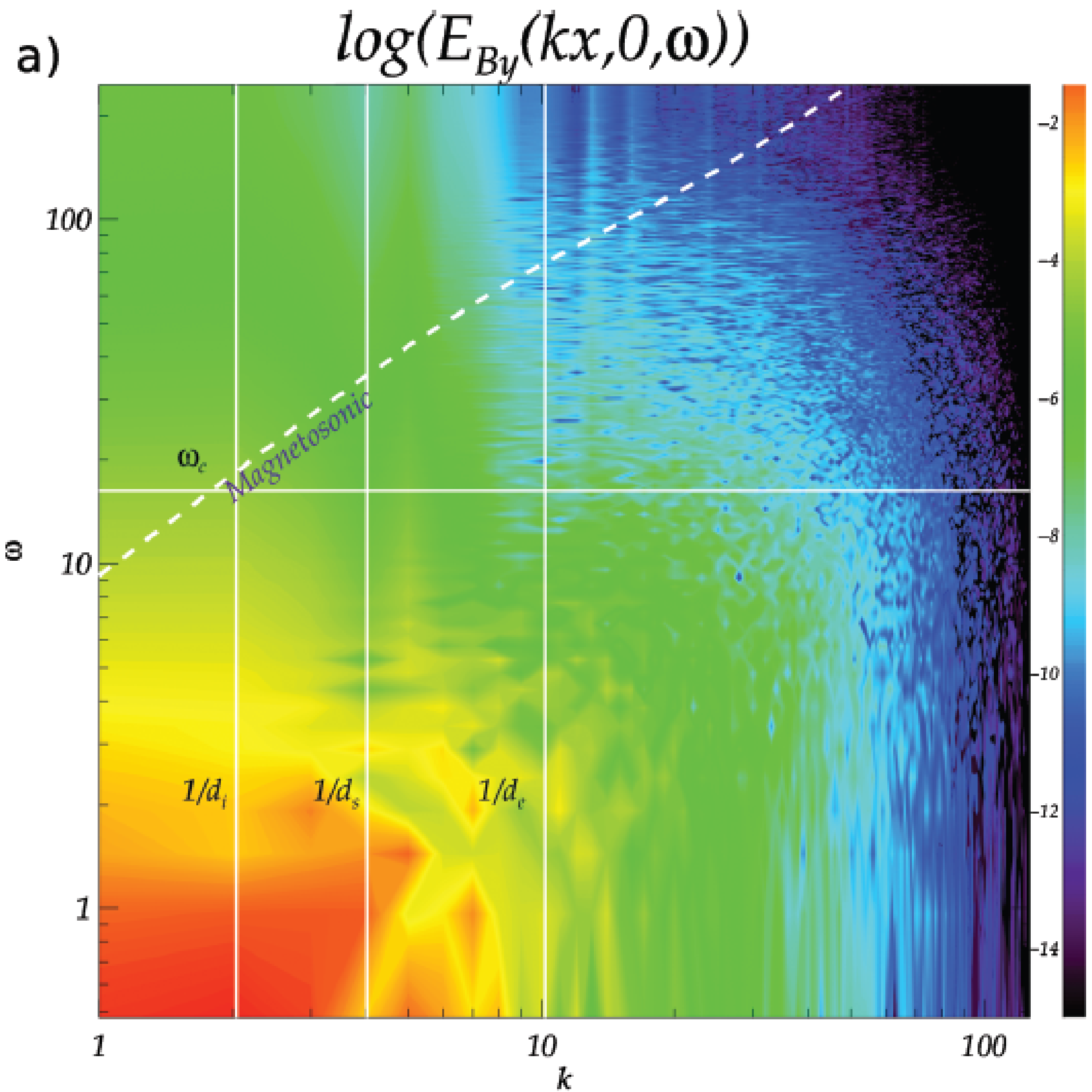
- Hybrid-Vlasov simulations show that kinetic effects are stronger nearby reconnection events;

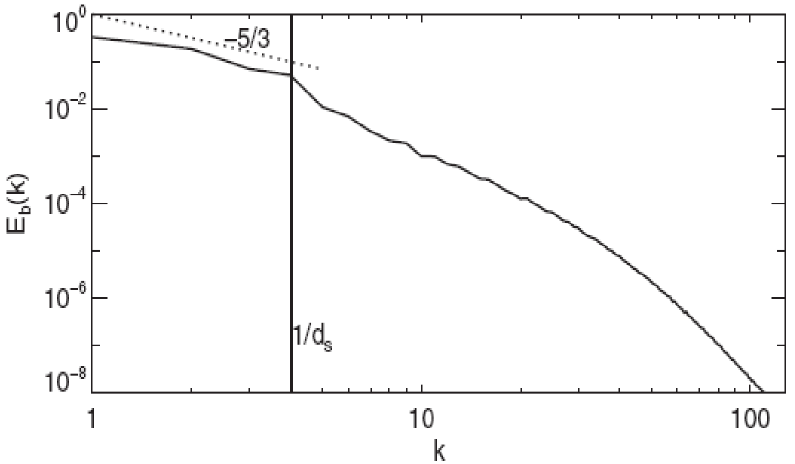
- Temperature anisotropy is higher in regions of strong magnetic stress, and in velocity and density gradients;

- THOR mission can "capture" this physics

Waves in turbulence?

Driven simulations of kinetic turbulence using Hybrid PIC code



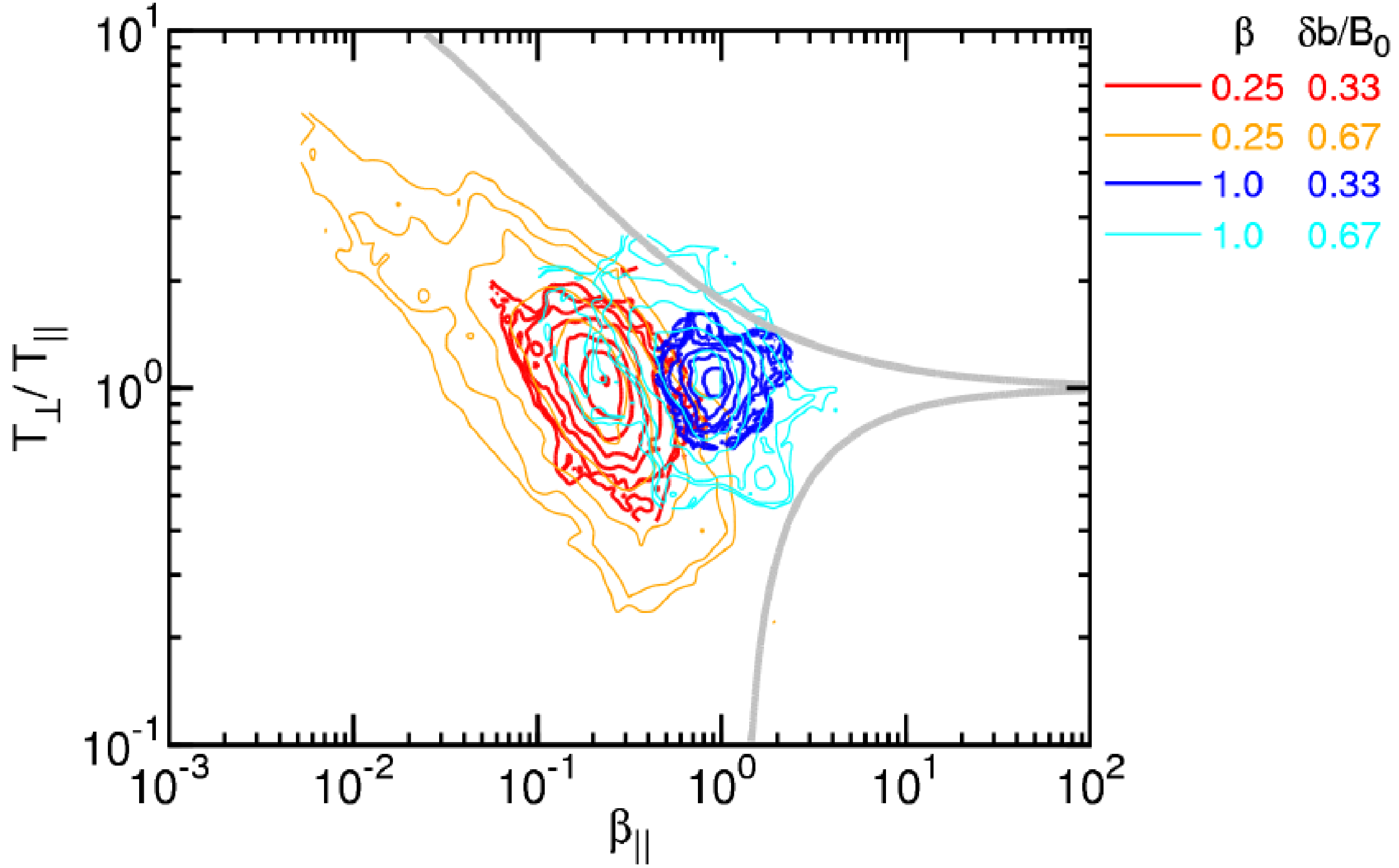


The k-omega spectra show a complete absence of waves in turbulence

Parashar *et al*. Phys. Plasmas (2010, 2011)

Extra slide

Vlasov simulation(s)



By varying parameters such as the level of fluctuations and the average plasma beta, Vlasov simulations "explore" distinct regions of anisotropy plane