NORDITA

Magnetic Reconnection in Plasmas

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Magnetic Reconnection in Plasma Turbulence: from MHD to Vlasov Models

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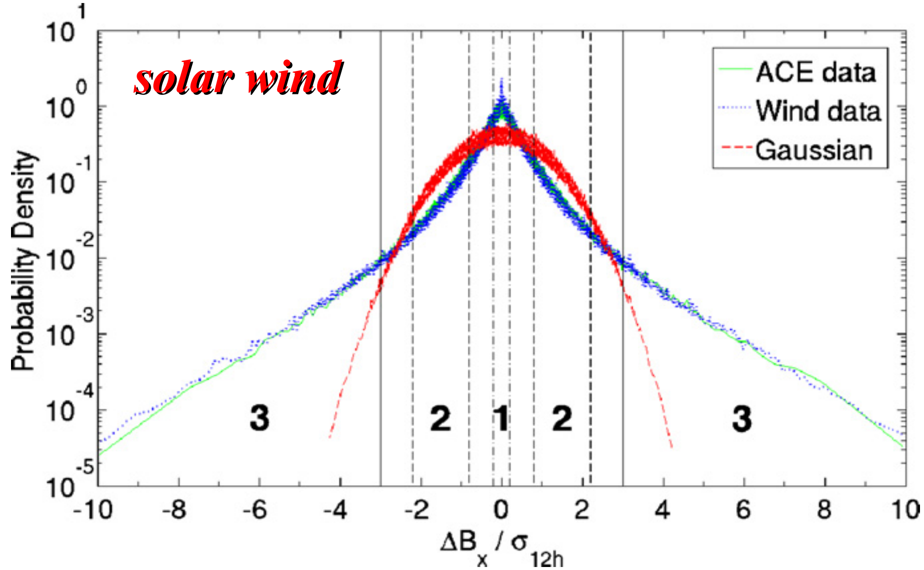
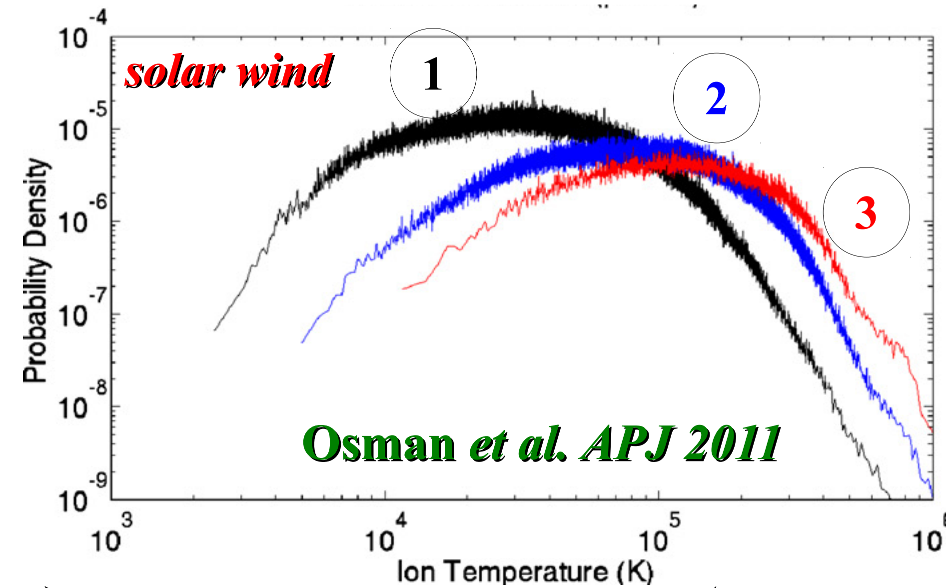
Outline

- Common features in space plasmas: turbulence, intermittent magnetic structures & kinetic effects
- Reconnection in MHD turbulence
- From fluid to plasma models: reconnection in Vlasov turbulence
- 6D Vlasov

• Discontinuities & heating in the solar wind





Sorriso-Valvo *et al.*, GRL (1999)
Sundkvist *et al.*, PRL (2007)
Retinò *et al.*, Nature Physics (2007)
Gosling & Szabo JGR (2008)
Greco *et al.* GRL (2008), APJ (2009)
Wang *et al.*, APJL (2013)

Intermittent magnetic gradients, that may be local reconnection events, are sites of enhanced heating

PRL **112,** 215002 (2014) PHYSICAL REVIEW LETTERS week ending 30 MAY 2014

Magnetic Reconnection and Intermittent Turbulence in the Solar Wind

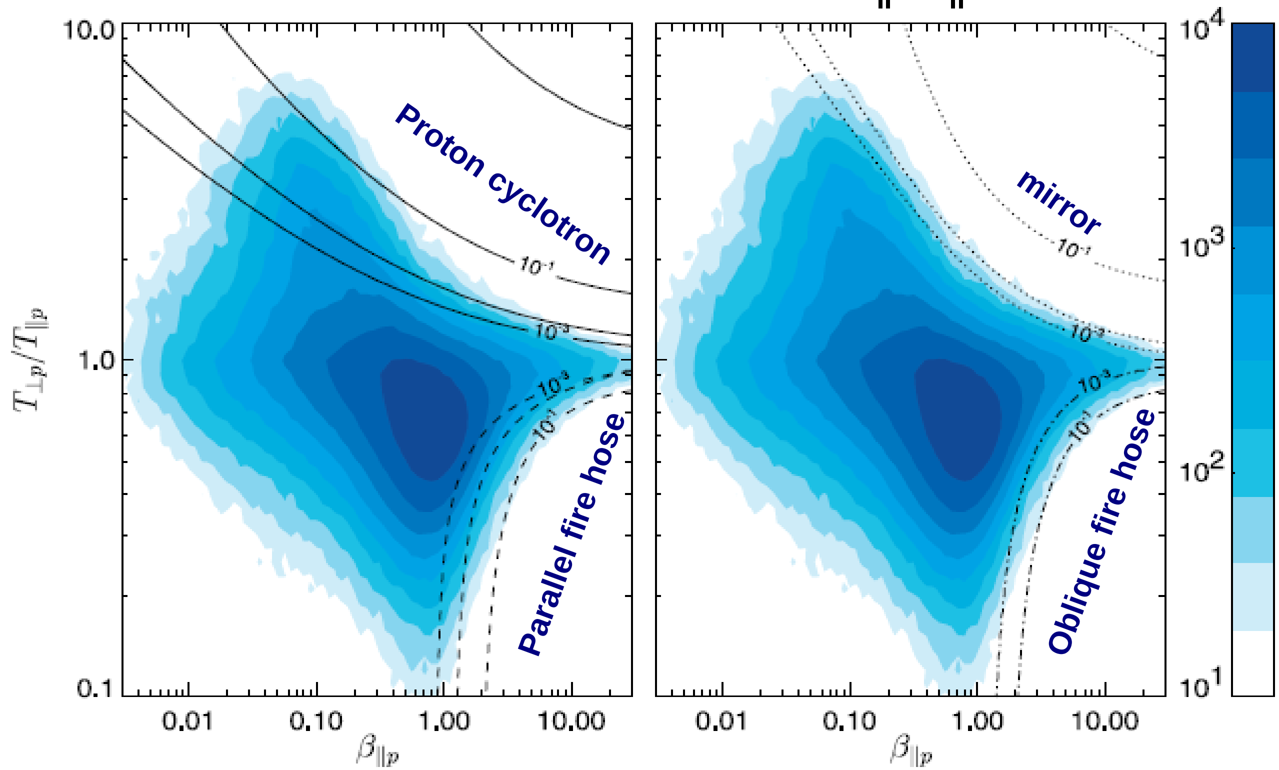
K. T. Osman,[1,*] W. H. Matthaeus,[2] J. T. Gosling,[3] A. Greco,[4] S. Servidio,[4] B. Hnat,[1] S. C. Chapman,[1,5,6] and T. D. Phan[7]

Kinetic effects in the solar wind

$T_{||}$ and $T_{\perp} \equiv$
parallel and perpendicular proton temperatures with respect to the ambient B

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

Distribution PDF($T_{\perp}/T_{||}$, $\beta_{||}$)

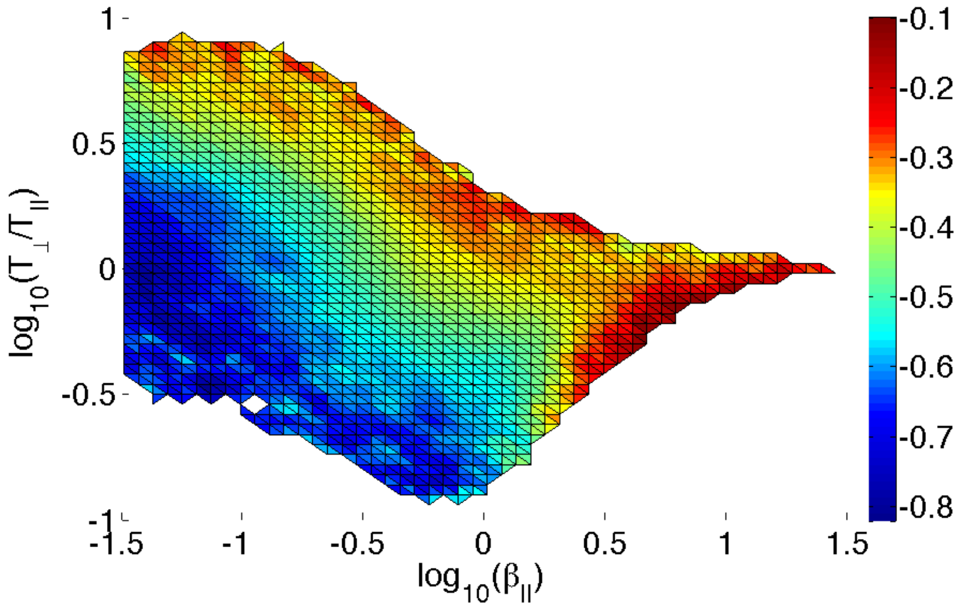


Kinetic instabilities influence the solar wind

nonlinear kinetic processes may locally occur in turbulence!

Kinetic effects & intermittency

$$PVI = \frac{|\Delta \boldsymbol{B}|}{\sqrt{\langle |\Delta \boldsymbol{B}|^2 \rangle}}$$ on $(\beta_{||}, T_\perp/T_{||})$



Osman *et al.*, PRL 2012

(I) Solar wind is turbulent;
(II) Kinetic instabilities influence the solar wind;
(III) The solar wind near the thresholds is hotter, with a lot of "current sheets" and (possibly) reconnection

reconnection & kinetic processes may locally occur in turbulence!

Standard description

The *orthodox* procedure

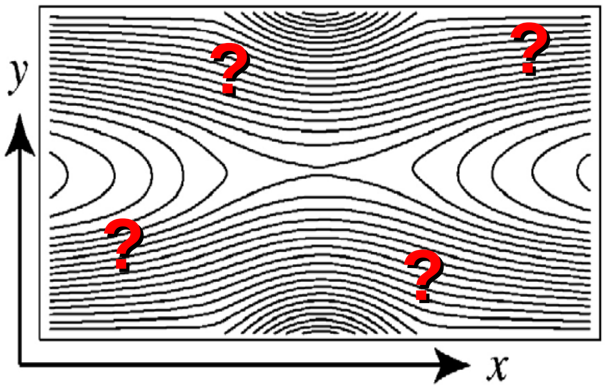
* Initially highly ordered, large scale magnetic field

* Special well-known boundary conditions

* The process can be driven by mechanical pressure supplied by open boundaries, or magnetic flux injected from a conducting wall

* Small initial perturbation in the center of the box, with *the right k*-vector

* The nonlinear regime is then achieved -> well-known growth rates



* very limited dynamic

* rarely observed in nature since plasma is generally turbulent

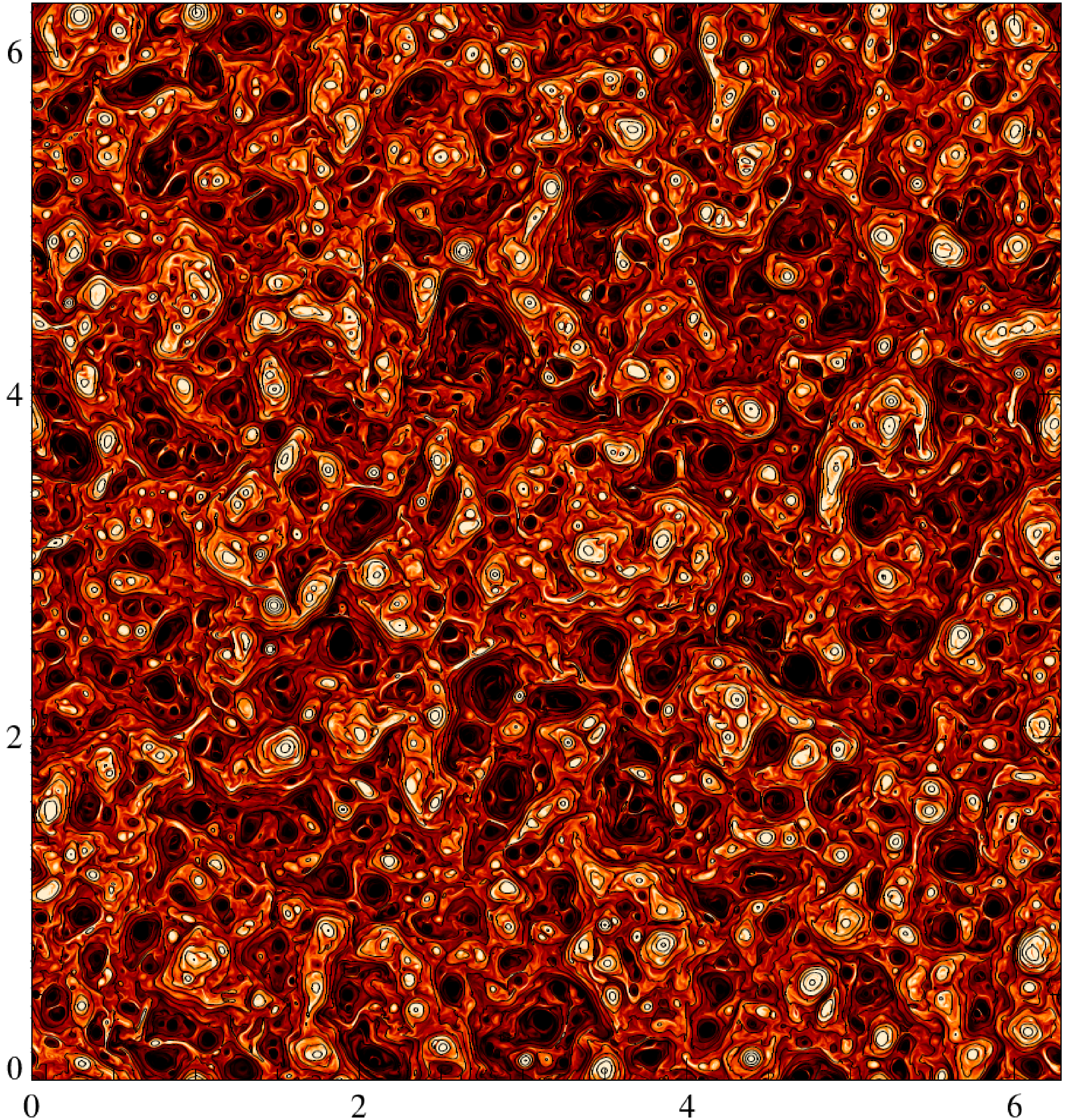
• An alternative description ...

*** Turbulence**

Matthaeus & Montgomery, *Ann. N.Y. Acad. Sci.* (1980);
Carbone *et al.*, *Phys. Fluids* (1990);
Frisch *et al.*, *Journal de Mecanique Theorique et Appliquee* (1983);
Matthaeus & Lamkin, Phys. Fluids (1986);
Lazarian & Vishniac, APJ (1999);
Retinò *et al.*, Nature Physics (2007).

Is possible that reconnection develops in turbulence? If yes, which are the statistical properties of reconnection in turbulence?

2D MHD



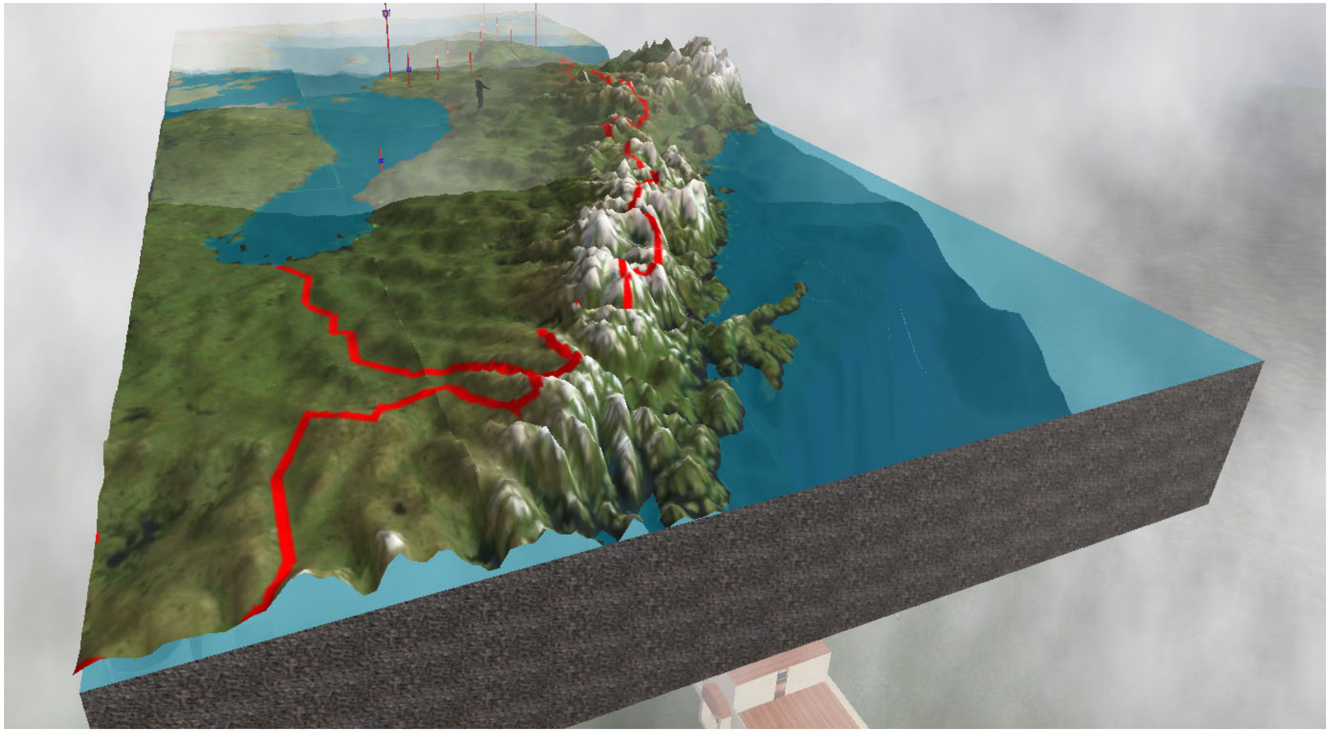
$$\frac{\partial \omega}{\partial t} = -(\boldsymbol{v}\cdot\nabla)\omega + (\boldsymbol{b}\cdot\nabla)\, j + R_\nu^{-1}\nabla^2\omega$$

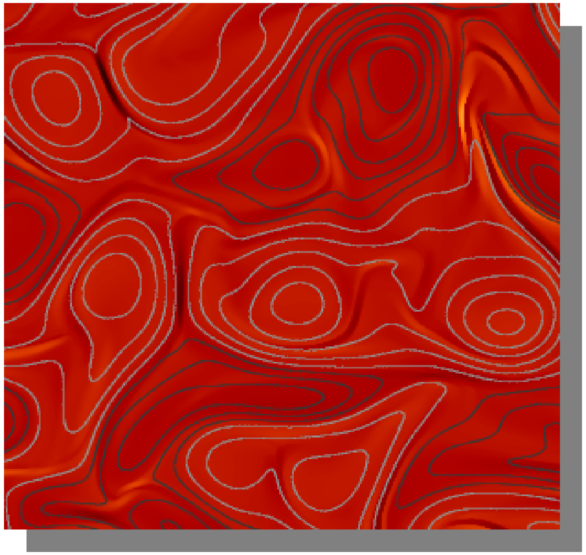
$$\frac{\partial a}{\partial t} = -(\boldsymbol{v}\cdot\nabla)\, a + R_\mu^{-1}\nabla^2 a$$

- **dealiased pseudo-spectral code**
- **16384^2 mesh points**
- **$R_\nu = R_\mu = 10000$**

Where is reconnection?

Some "topography"...



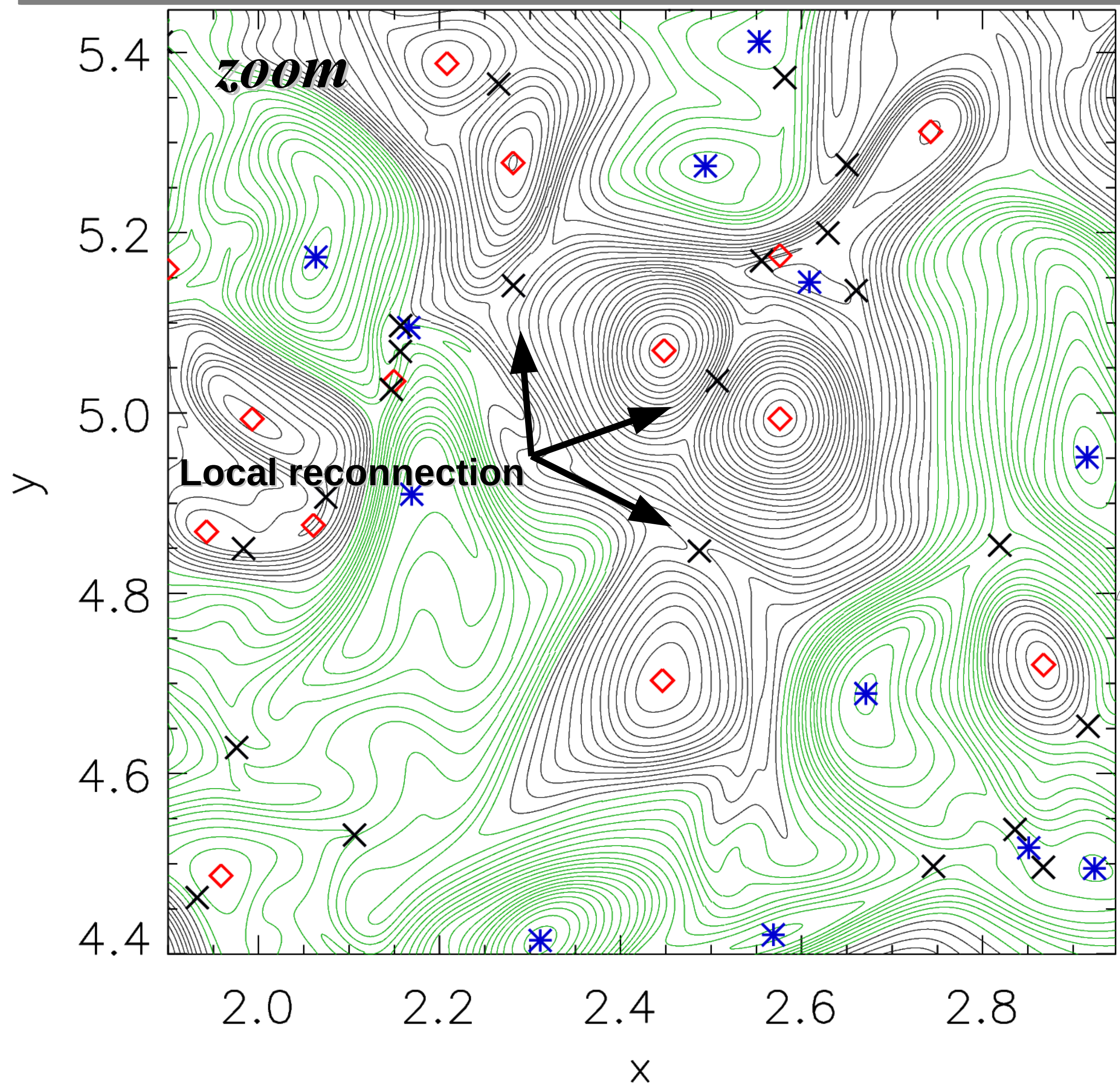


Critical points of the magnetic potential "*a*" →

$$H_{ij}^{[a]}(\boldsymbol{x}) = \frac{\partial_{ij}^2 a}{\partial x_i \partial x_j},$$

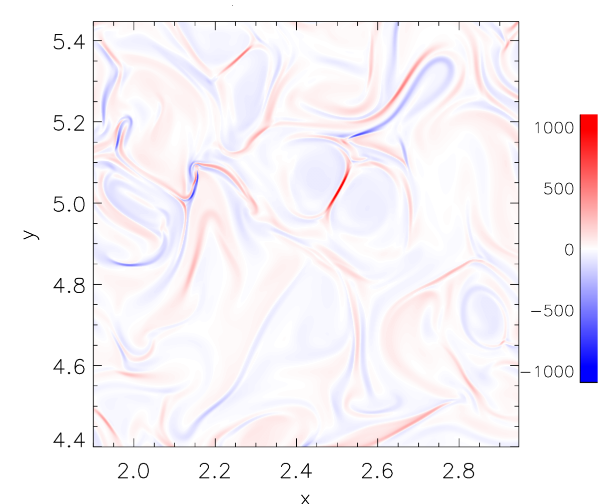
$$\text{where} \quad \nabla a = \mathbf{0}$$

Critical points in turbulence



Magnetic potential *a* and critical points

a > 0 — green line
a < 0 — black line
maximum ✳
minimum ◇
X-point ✕

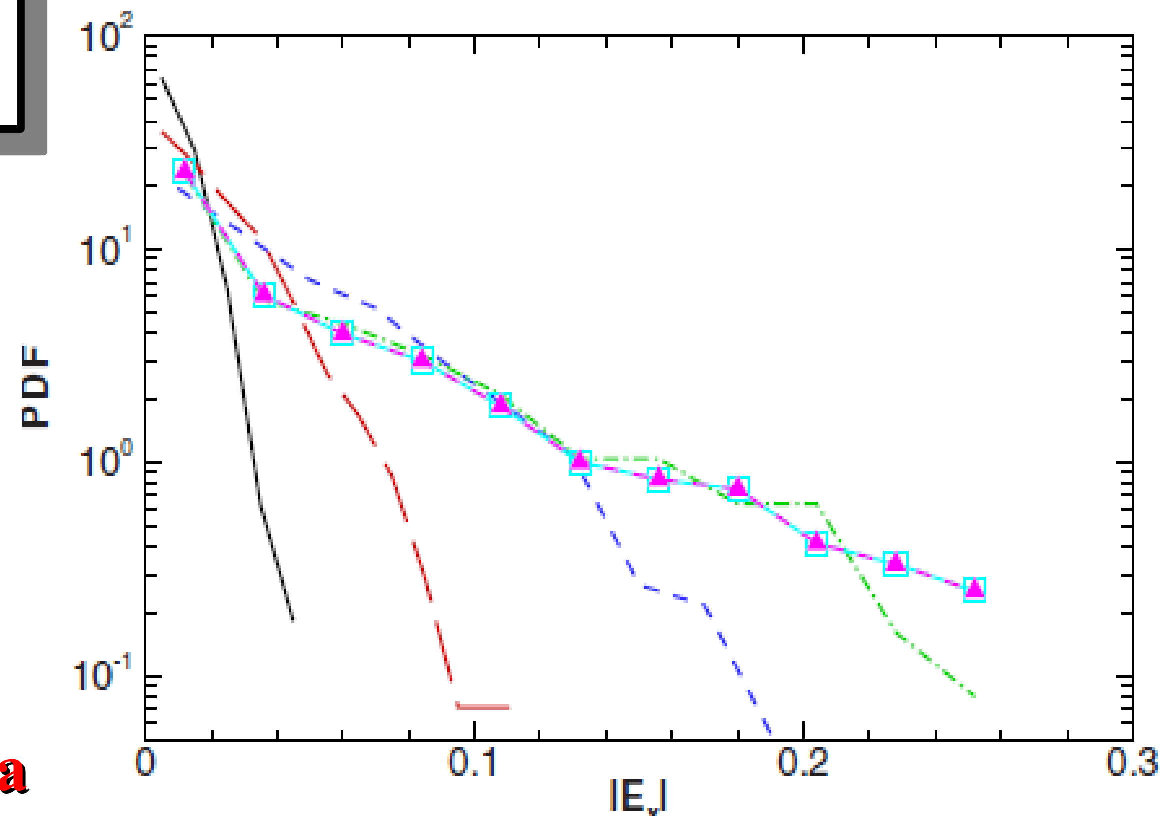


***j* is intermittently intense**

Distribution of reconnection rates

Rate of change of the magnetic flux:

$$\dot{a} = R_{\mu}^{-1} \nabla^2 a \,|_{\times - point} = -E_{\times}$$



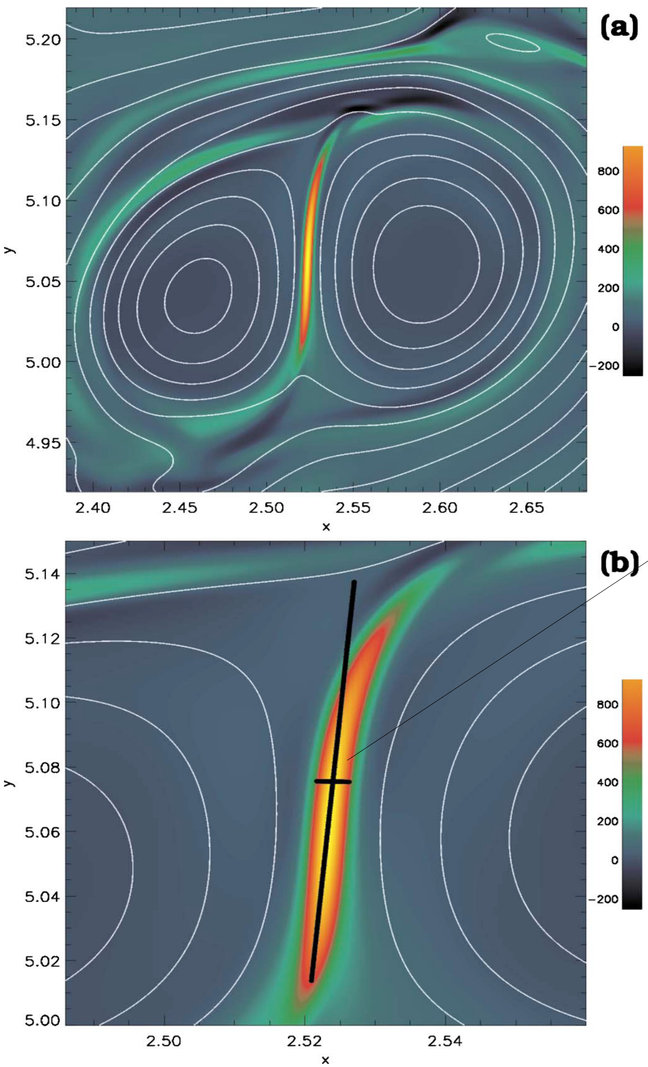
Reconnection rates are broadly distributed

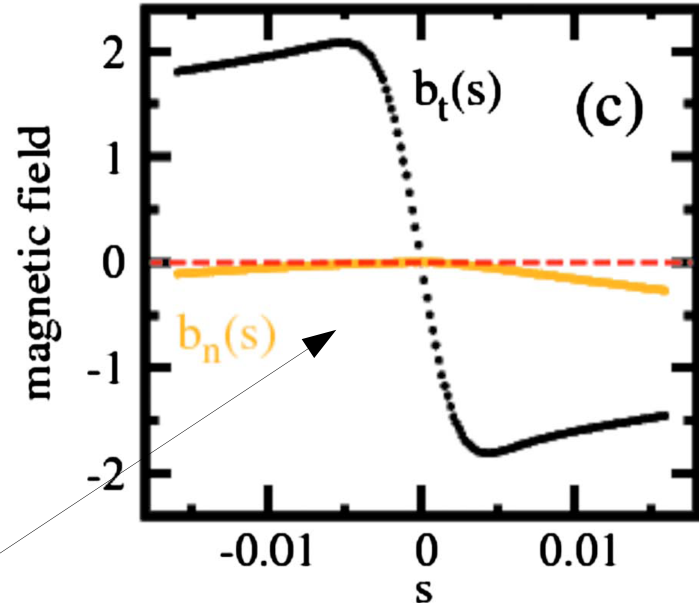
Turbulence can be viewed as a sea of reconnecting islands with different reconnection rates

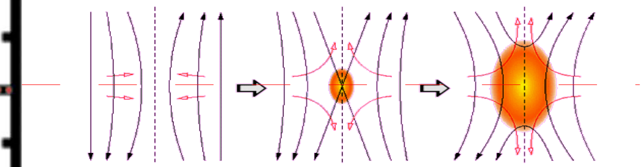
reconnection rates up to ~0.3

Diffusion region

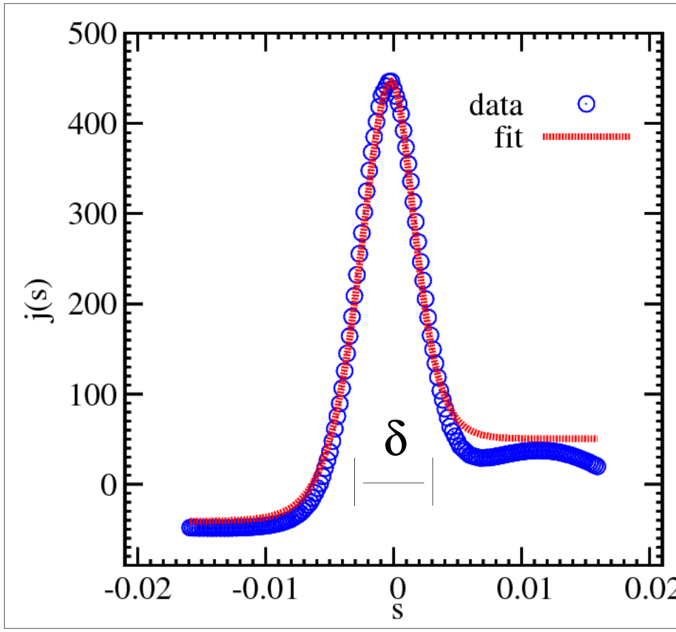
Another zoom-in







characteristic lengths

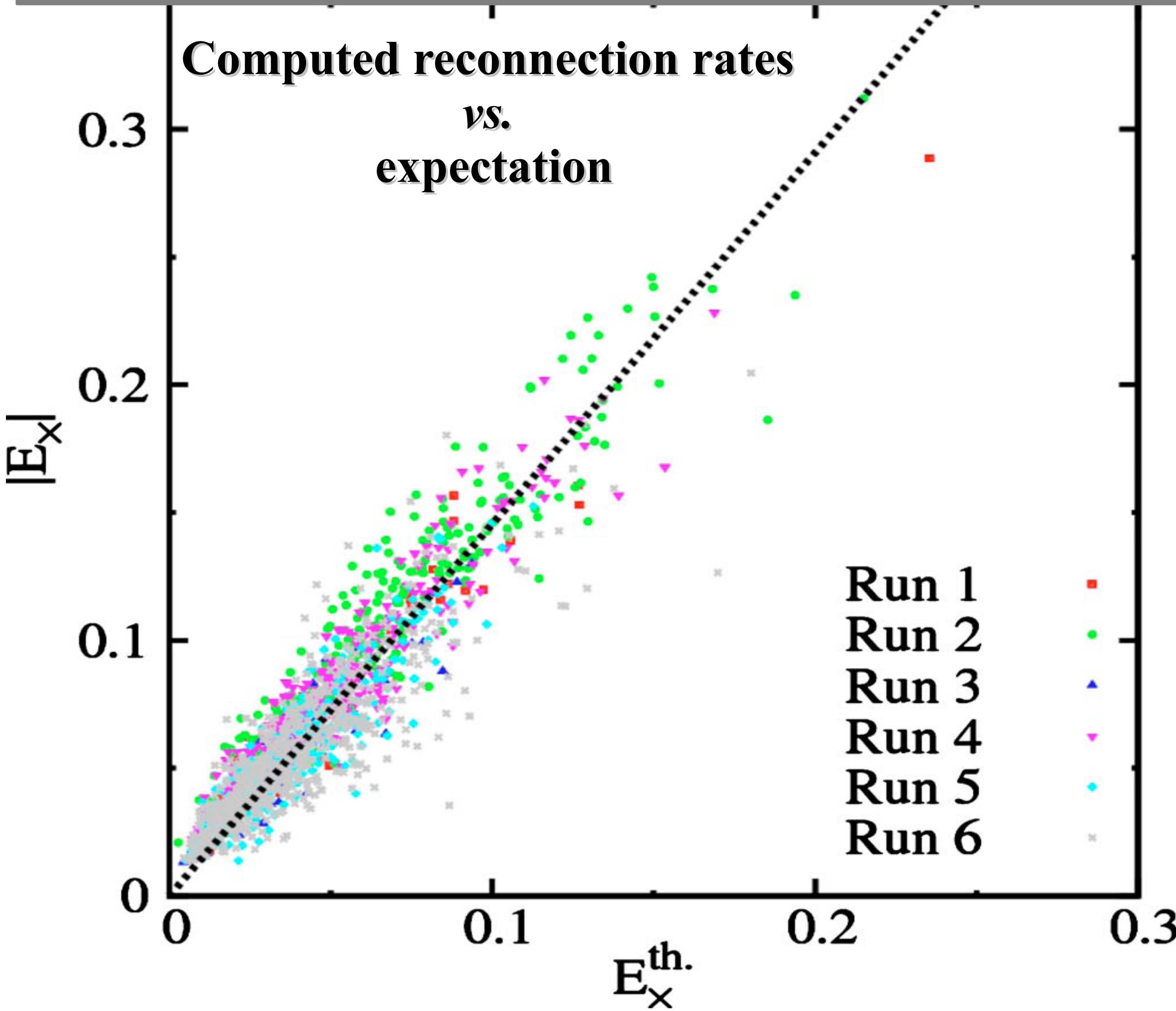


$$fit \rightarrow \delta$$

$$\ell \simeq \delta \sqrt{\frac{\lambda_{max}}{\lambda_{min}}}$$

See for SW analysis:
Sundkvist *et al.*, PRL (2007)

Reconnection rate in turbulence



Asymmetric reconnection

$$E_\times^{th.} = \sqrt{\frac{b_1^{3/2}\, b_2^{3/2}}{R_\mu\, \ell}} \qquad b_i \equiv upstream\ fields$$

P. Cassak & M. Shay, Phys. Plasmas 2007;Borovsky & Hesse, Phys. Plasmas (2007); Birn *et al.*, Phys Plasmas (2008); Pritchett, JGR (2008).

Reconnection rates are consistent with a modified Sweet-Parker model

Turbulence provides locally the parameters that determine the Sweet Parker reconnection rate: the lengths and local magnetic field strengths.

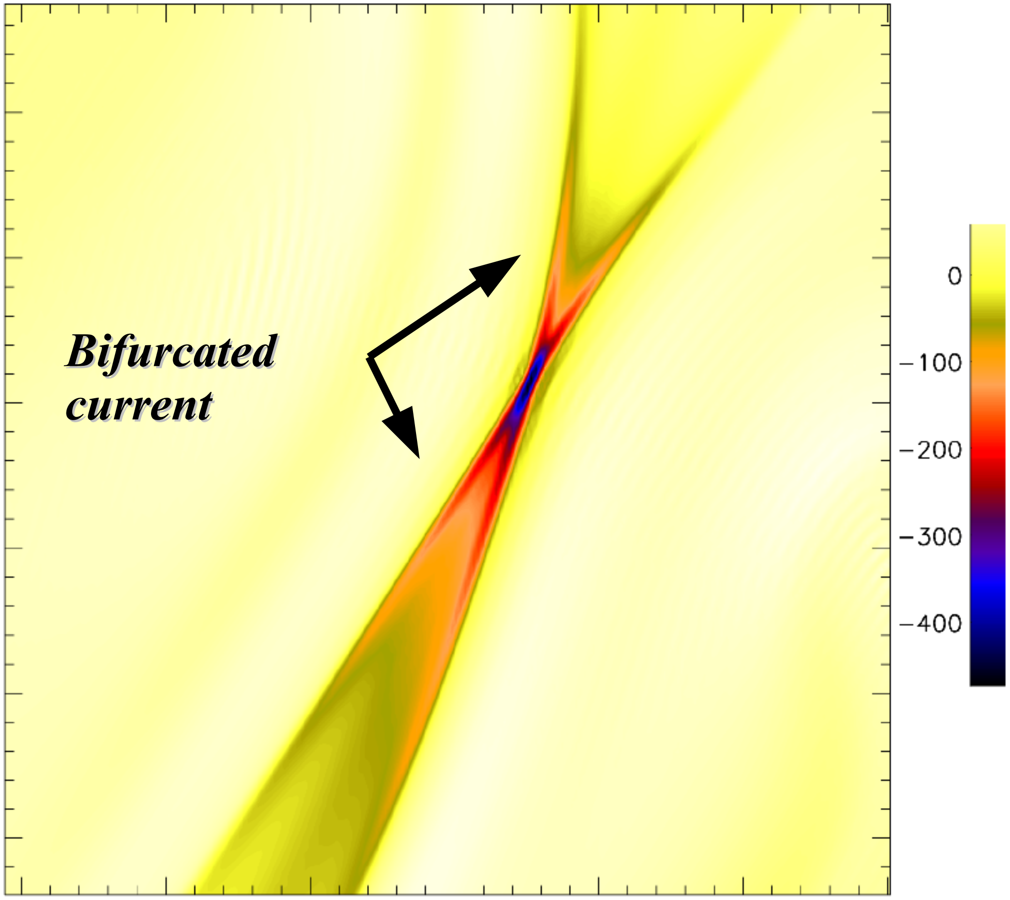
Servidio *et al.*, Phys Rev. Lett. (2009).

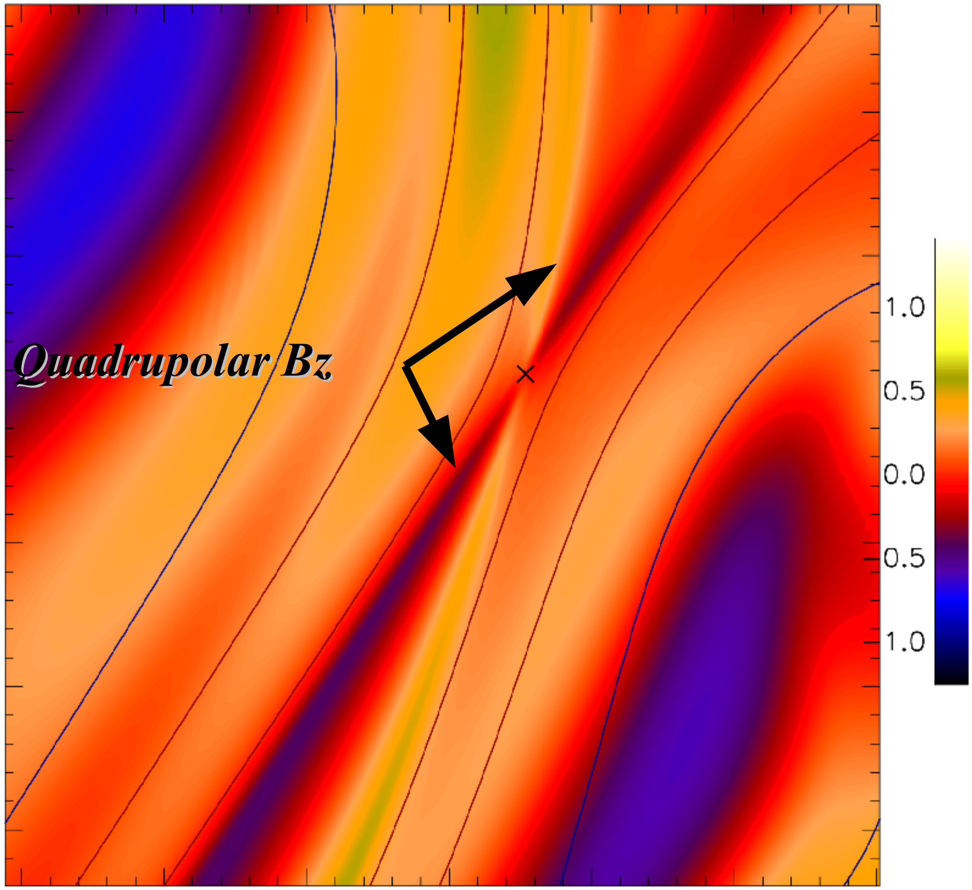
Hall Magnetohydrodynamics

$$\frac{\partial \boldsymbol{v}}{\partial t} = -(\boldsymbol{v}\cdot\nabla)\boldsymbol{v} + \boldsymbol{j}\times\boldsymbol{b} - \nabla P + R_\nu^{-1}\nabla^2\boldsymbol{v}$$

$$\frac{\partial \boldsymbol{b}}{\partial t} = \nabla\times(\boldsymbol{v}\times\boldsymbol{b}) + \epsilon_H\nabla\times(\boldsymbol{j}\times\boldsymbol{b}) + R_\mu^{-1}\nabla^2\boldsymbol{b}$$

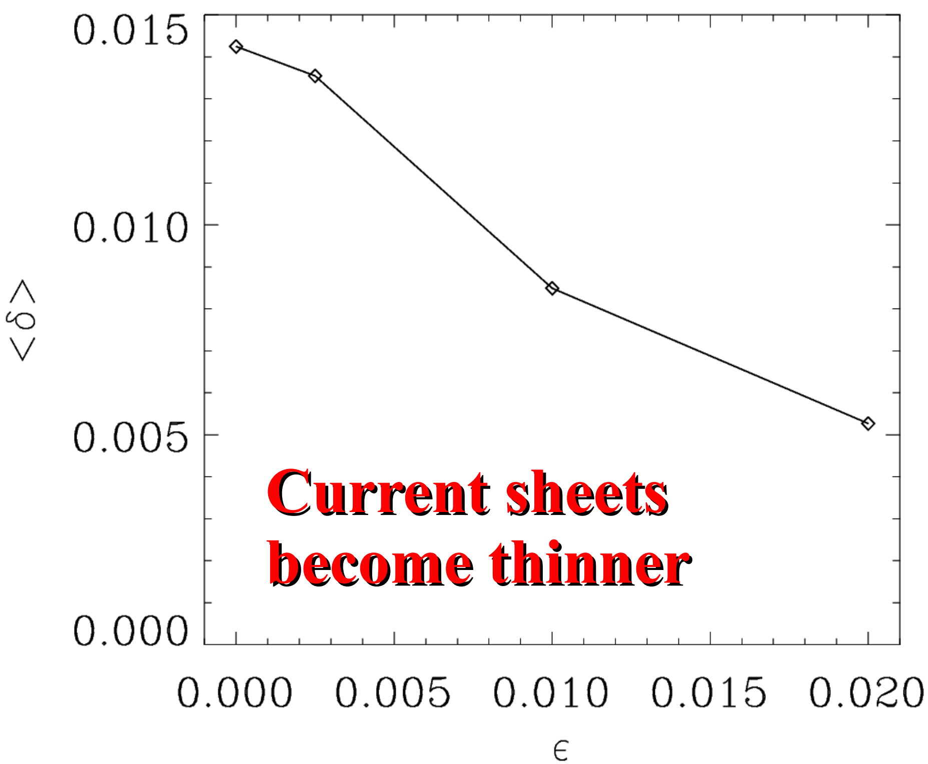
- *pseudo-spectral*
- *2.5D*
- *8192^2*
- $R_\nu = R_\mu = 2000$

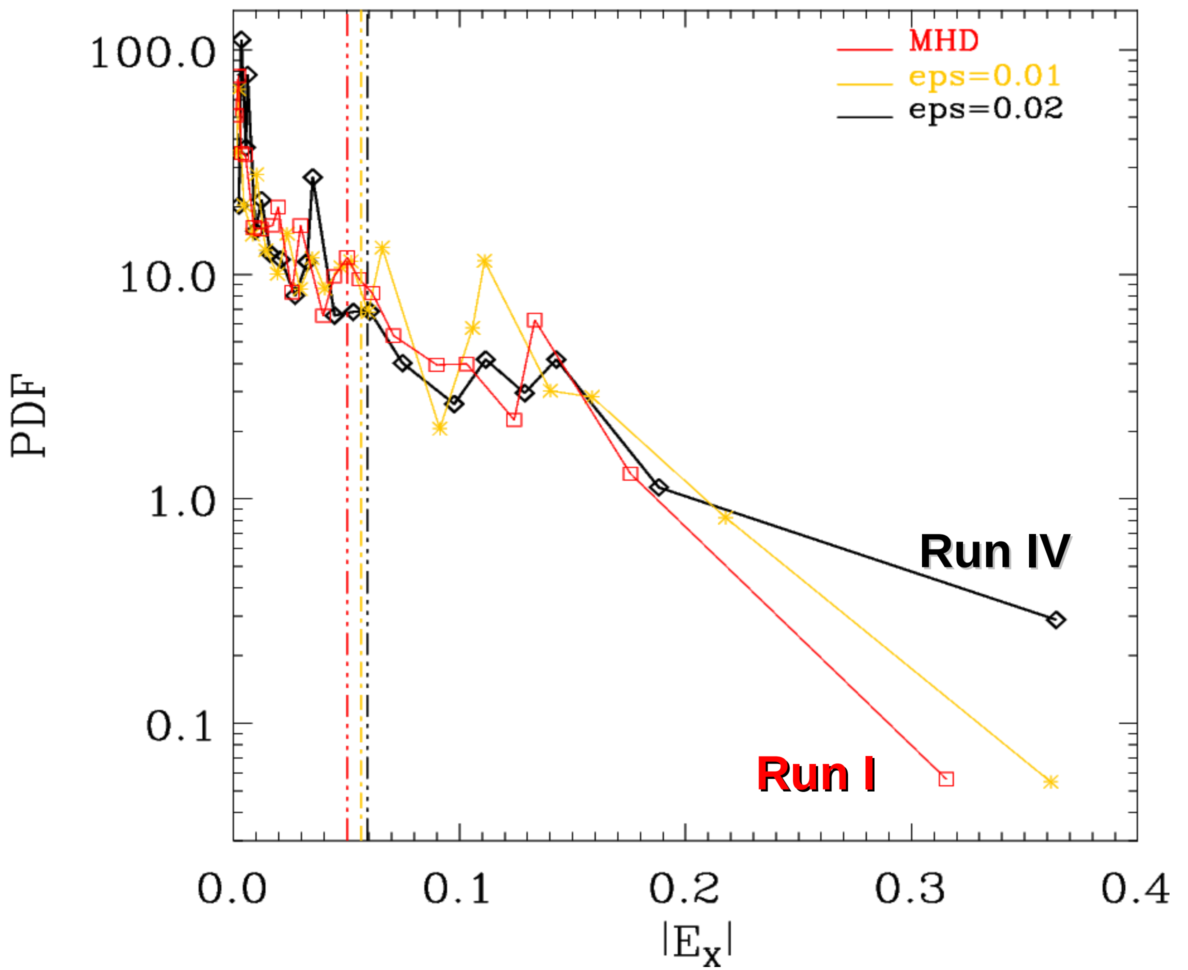




Reconnection in Hall MHD turbulence

Run	ϵ_H
I	0.0 (*MHD*)
II	0.0025
III	0.01
IV	0.02





The Hall electric field increases the reconnection rate in turbulence

Donato *et al.*, Phys. Plasmas (2012); JGR (2013).

...and from fluid-like models of a plasma we explore now “Vlasov turbulence”

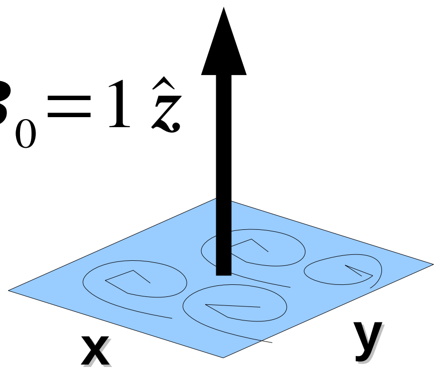
Hybrid Vlasov-Maxwell

$$f(\boldsymbol{x},\boldsymbol{v}) = f(x, y, v_x, v_y, v_z)$$ ***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, 2011)

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

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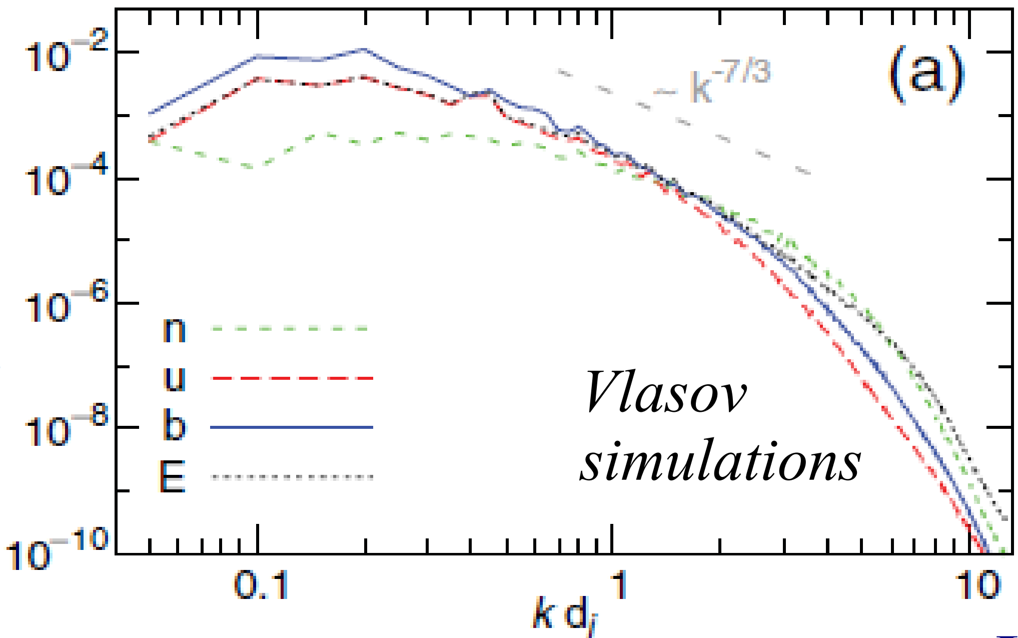
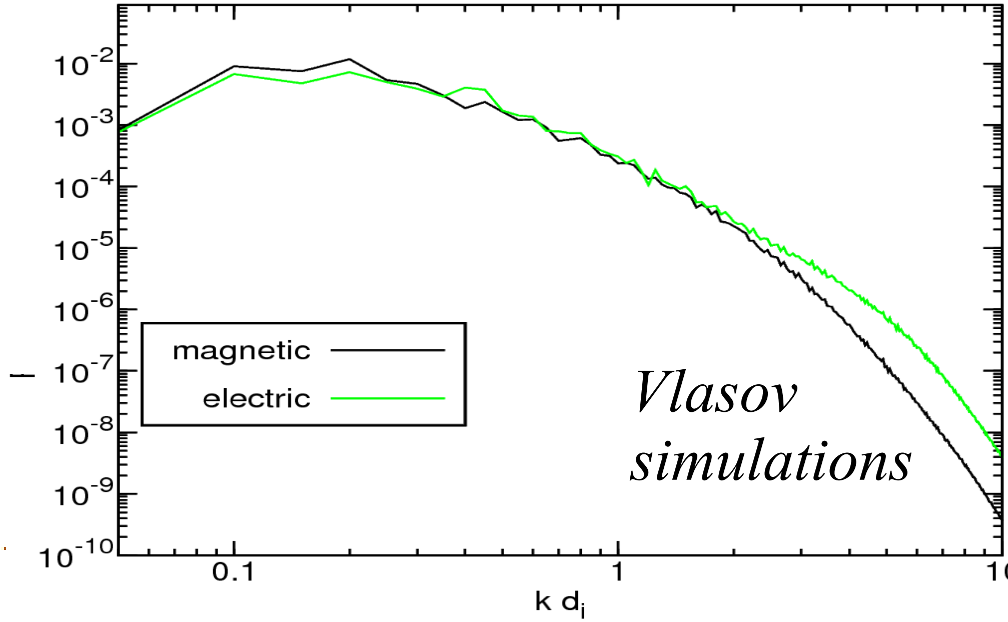
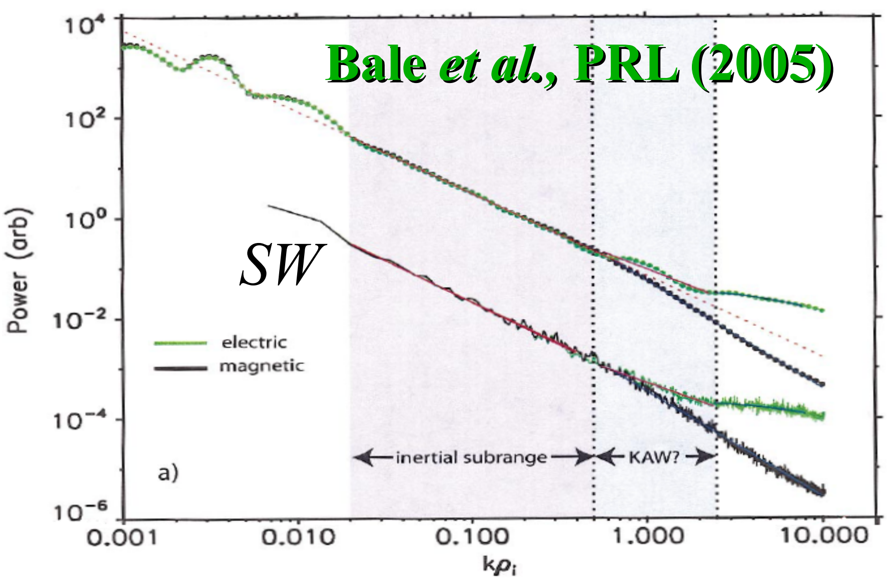
• Spectral features of turbulence ...





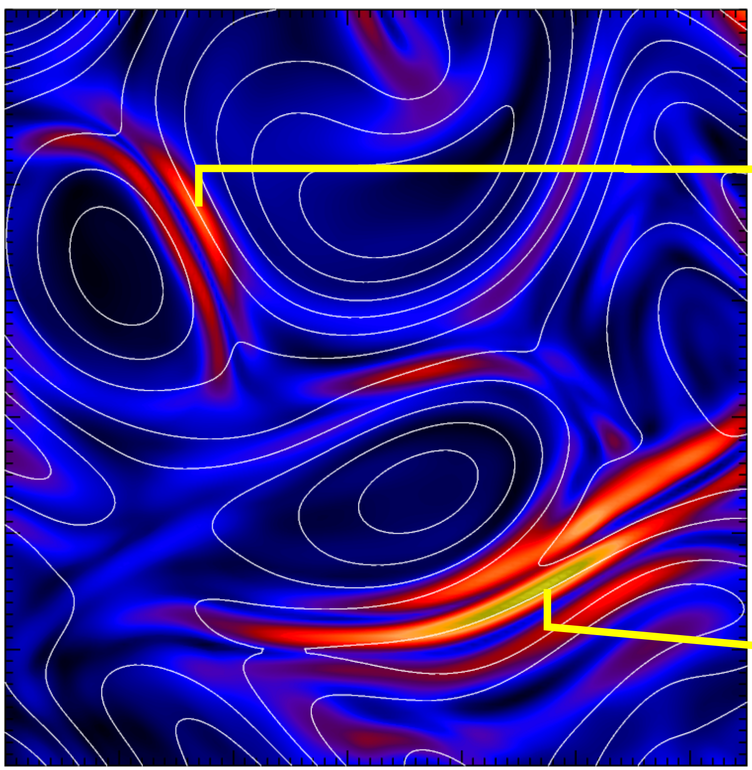


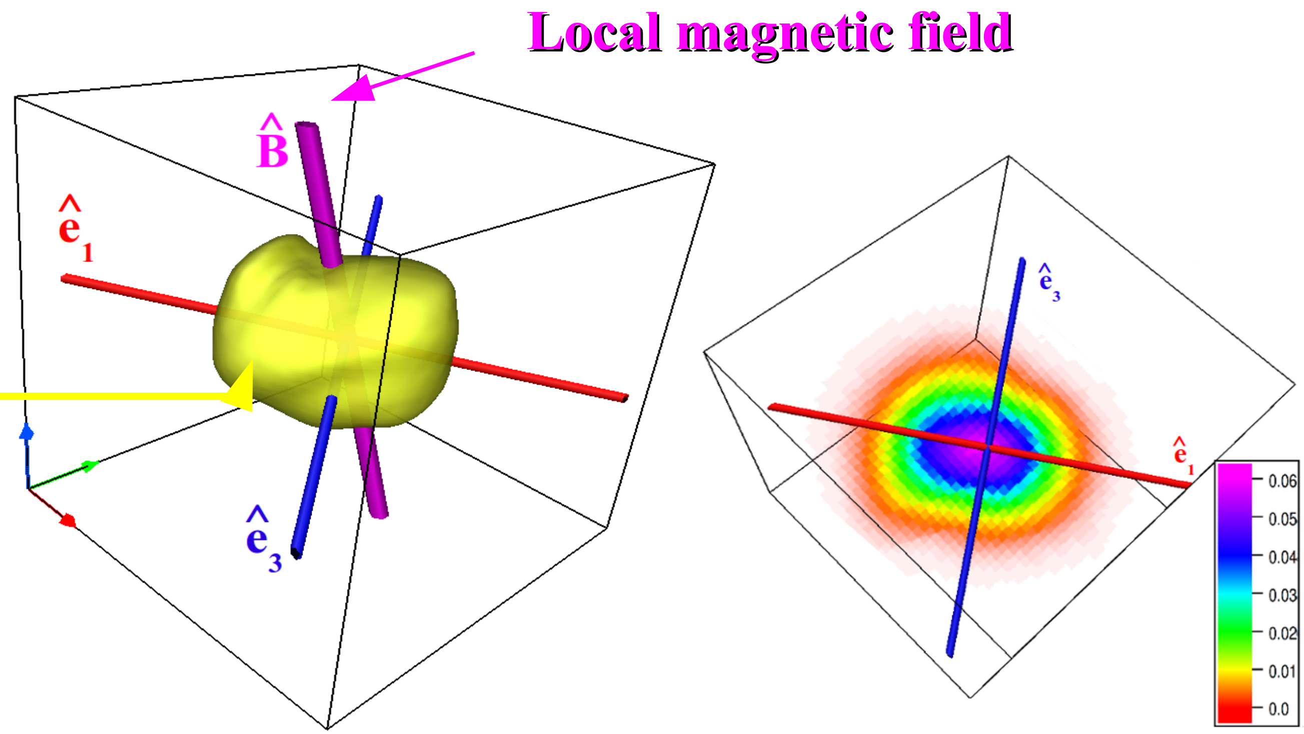
- **Large scale Alfvenic correlations**
- **Intense electric activity at small scales**
- **Steepening of the magnetic spectrum at $kd_p \sim 1$**

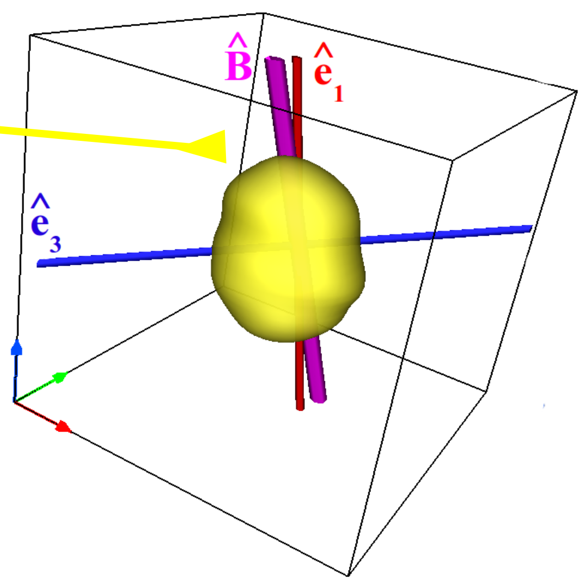
Schekochihin *et al.*, APJ SS (2009), Servidio *et al.*, PSS (2007), Howes *et al.*, PRL (2008); Sahraoui *et al.*, PRL (2009); Alexandrova *et al.*, PRL (2009)

...several features commonly observed in space plasmas!

Distribution functions in turbulence



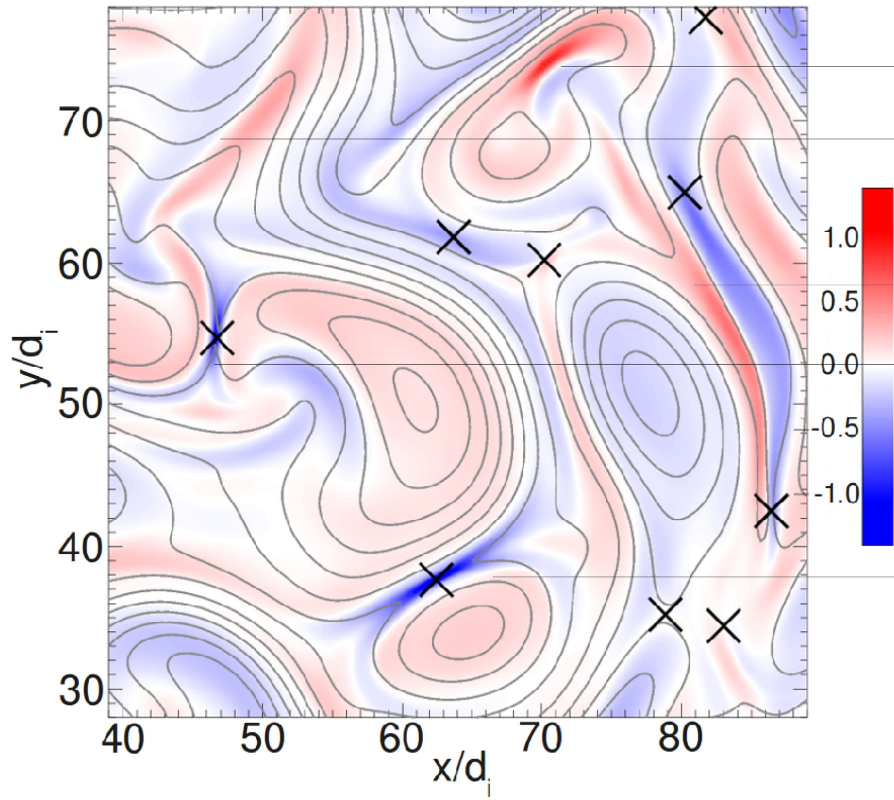


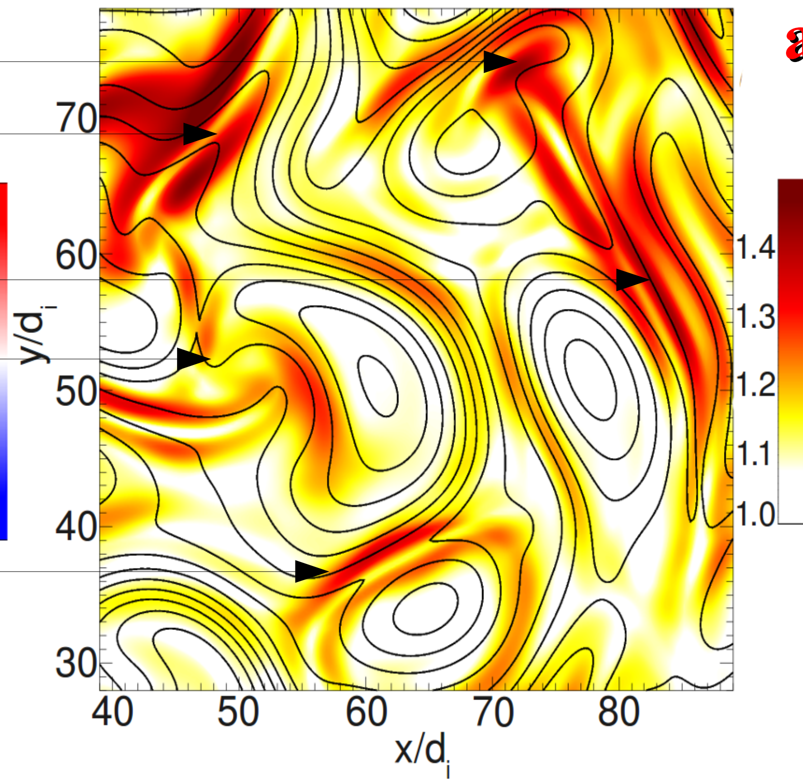


the DF is strongly affected by turbulence, resembling an elongated potato-like structure

Servidio *et al.*, PRL (2012)
Drake *et al.*, APJ (2010)

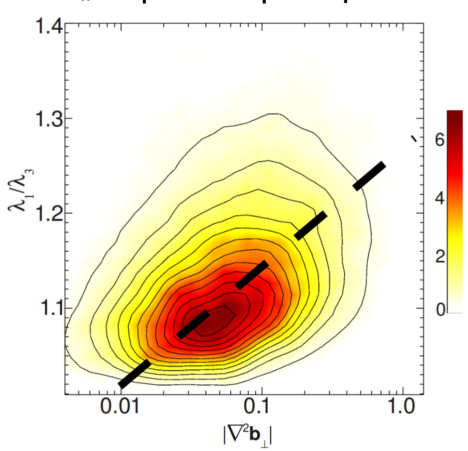
Turbulence, reconnection & kinetic effects





anisotropy

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

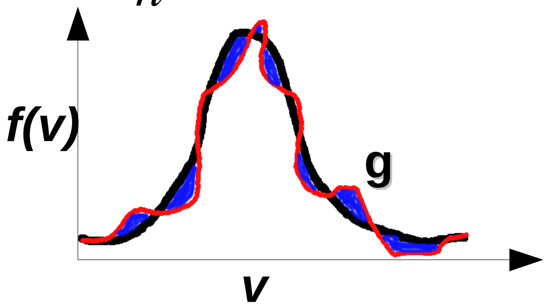


streams of kinetic effects (anisotropy, skewness and kurtosis) are adjacent to reconnecting current sheets.
In a fluid model these would correspond to regions where collisional dissipation takes place. Here cyclotron and/or Landau resonances may be at work.

Servidio *et al*, PRL 2012

“Multiple” kinetic effects

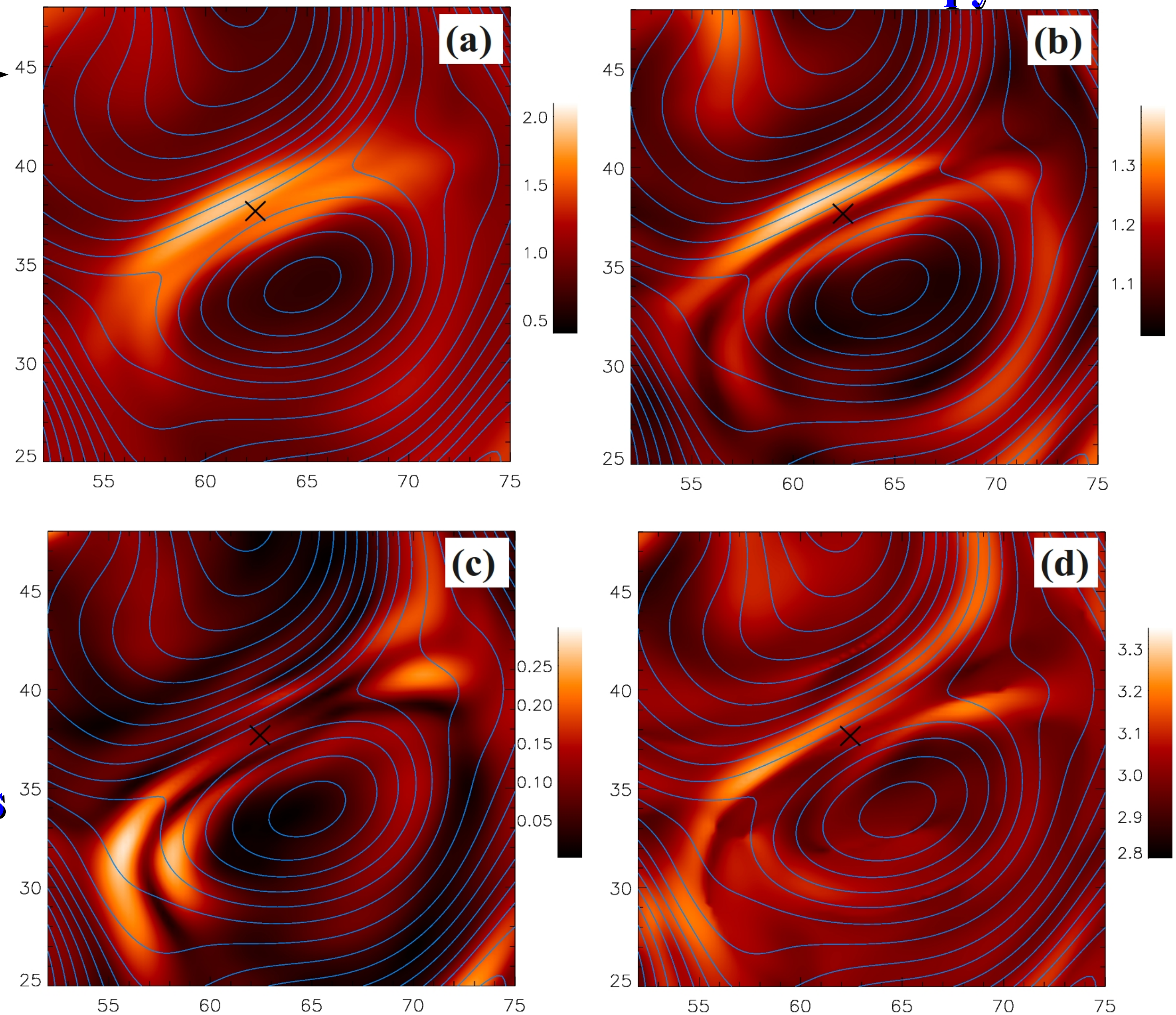
$$\epsilon(x)=\frac{1}{n}\sqrt{\int (f-g)^2 d^3v}$$



g is the Maxwellian associated to *f*

Anisotropy

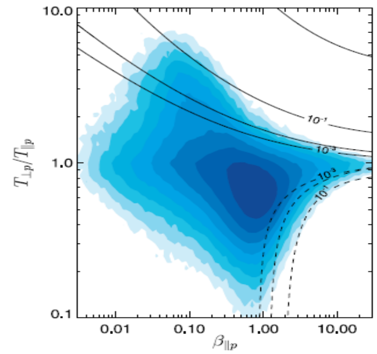
Skewness



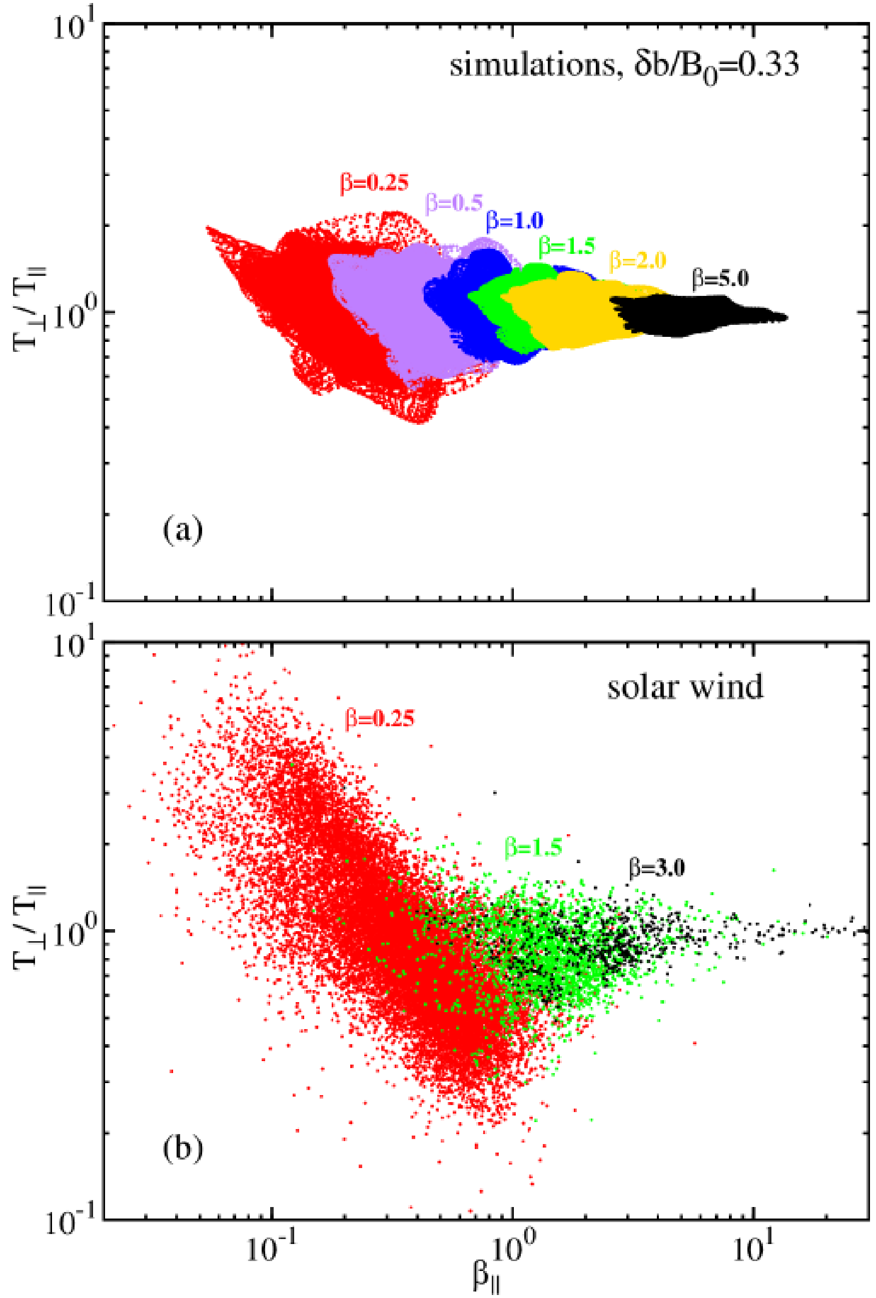
Kurtosis

Greco *el al.*, PRE (2012)

Can we describe the solar wind?



Back to the solar wind



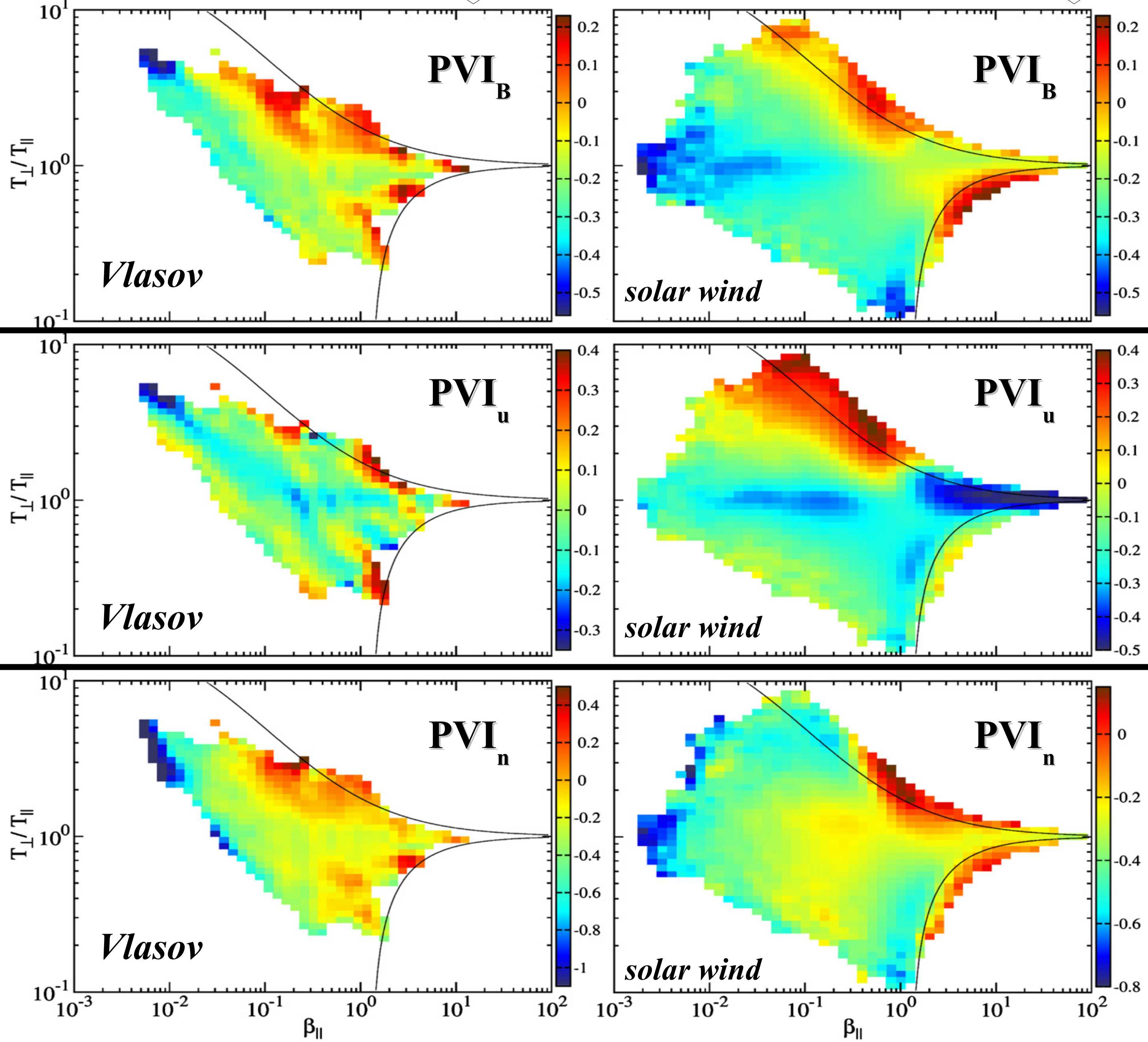
Solar wind: high variability

↓ ↓ ↓

Different Vlasov simulations, varying global parameters

Vlasov *vs.* solar wind

Ensemble of simulations **10 years of solar wind**



Magnetic intermittent structures

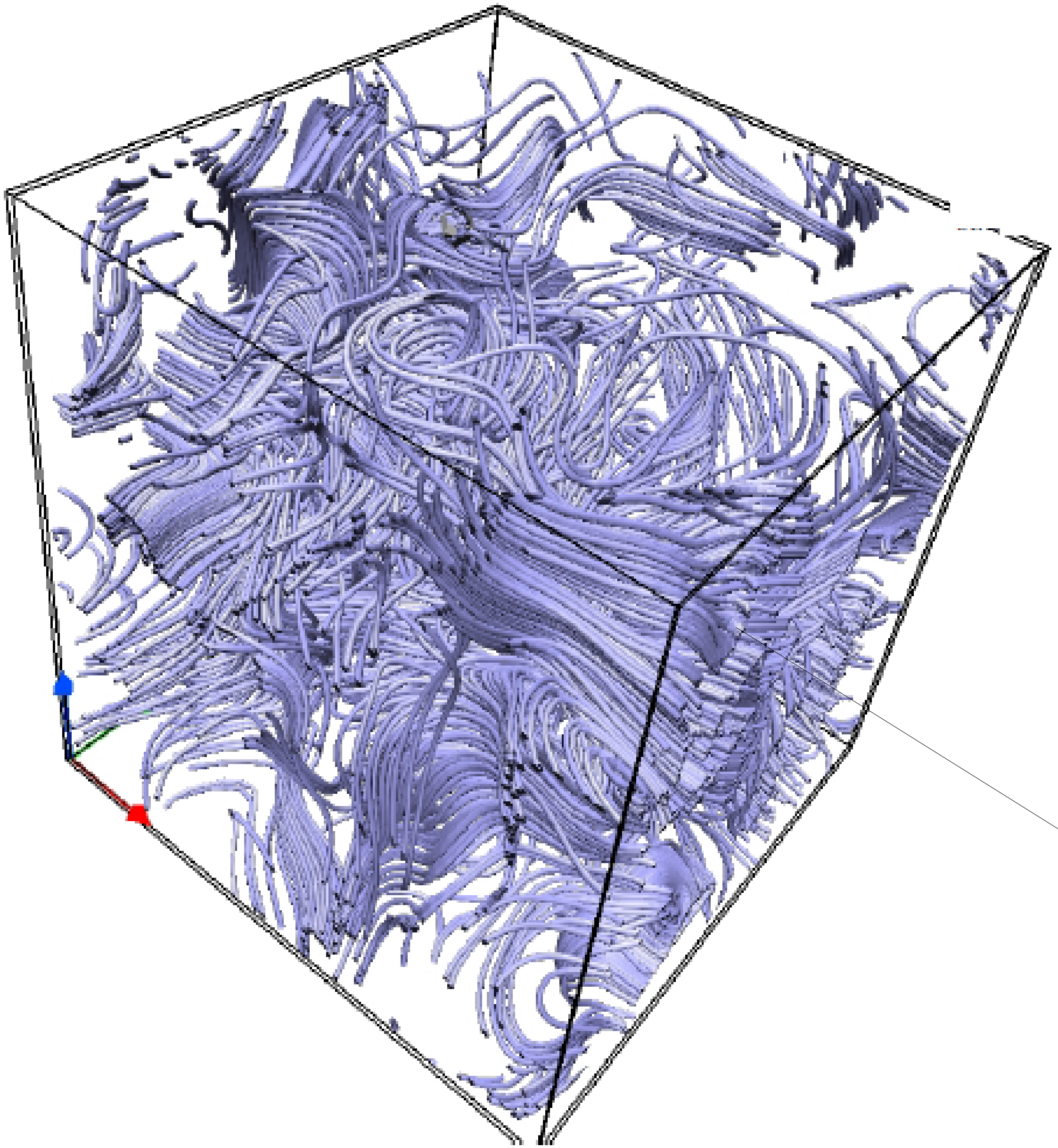
(Reconnection?)

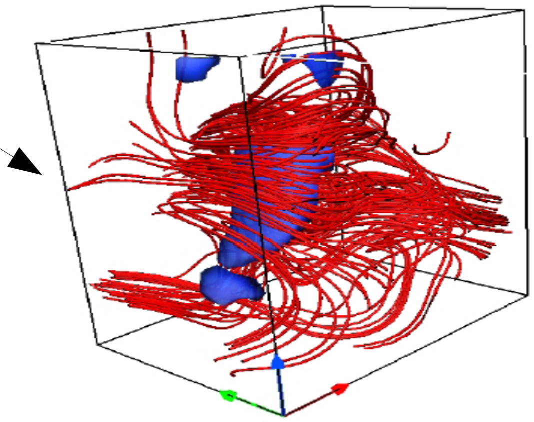
velocity intermittent structures

density intermittent structures

Servidio *et al.*, APJL (2014)

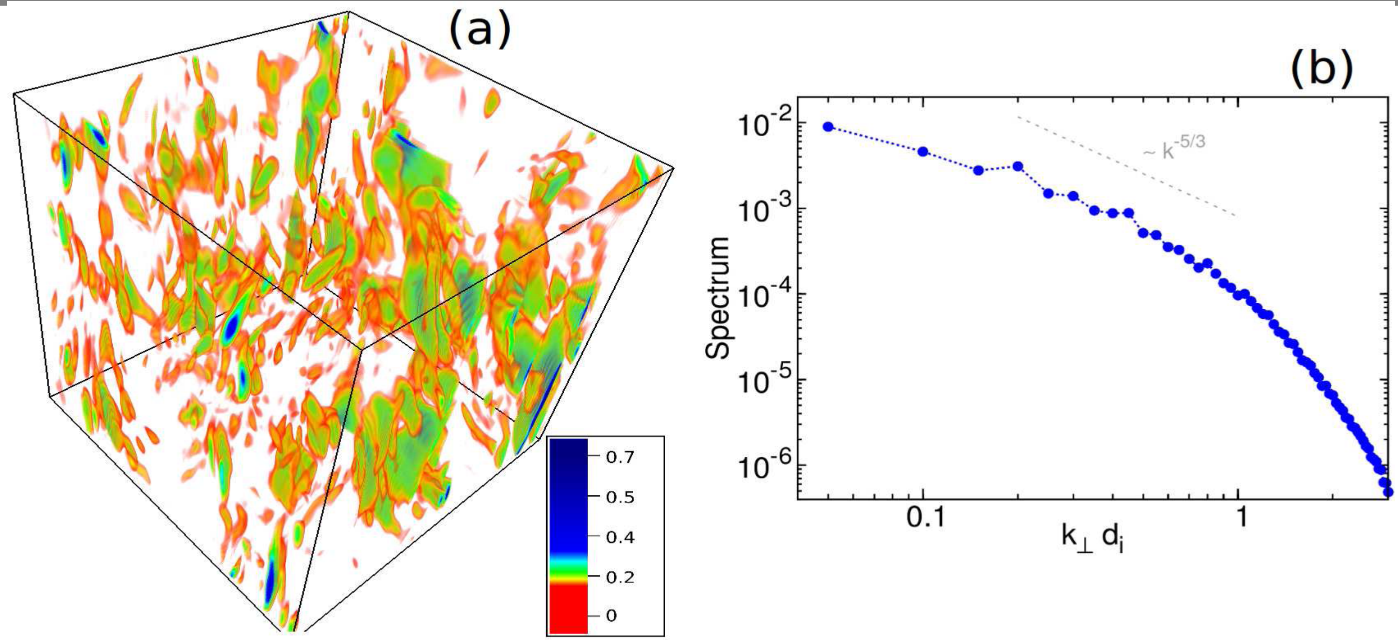
• "6D" Vlasov

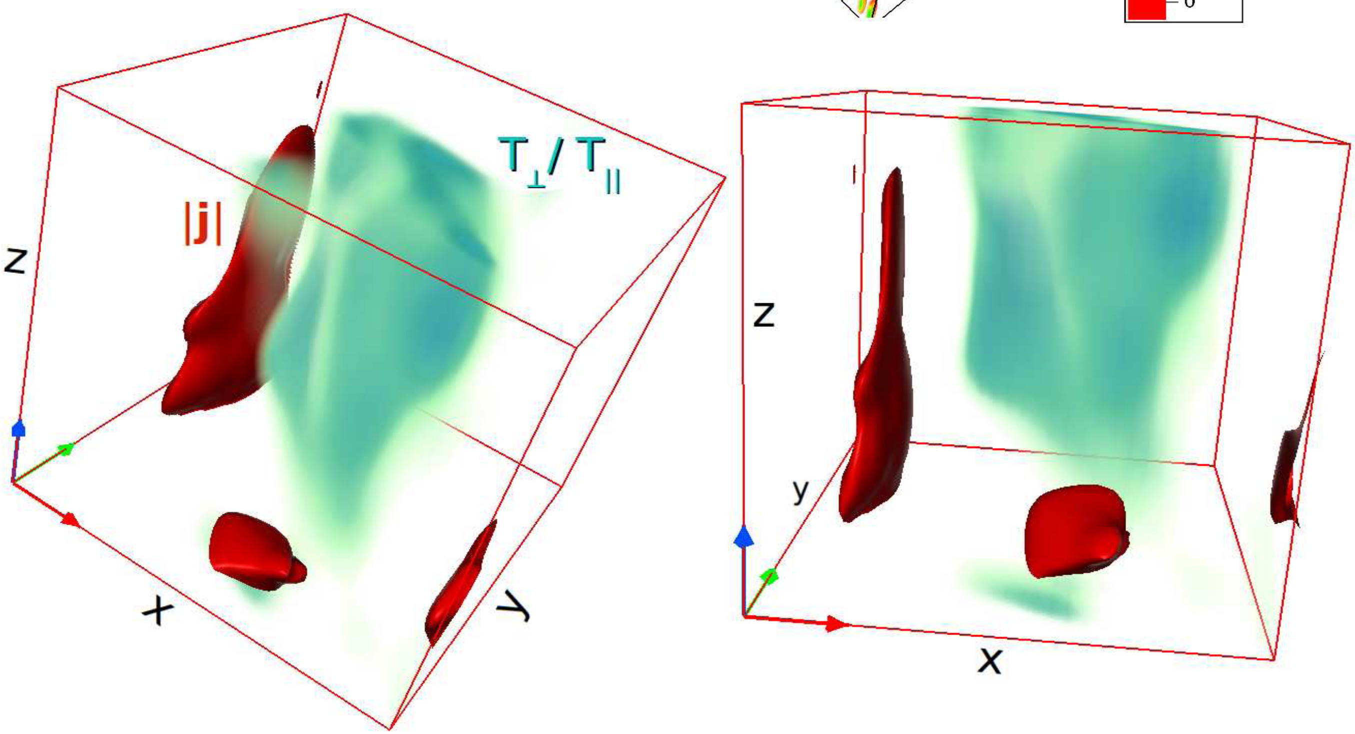




“6D” Vlasov turbulence

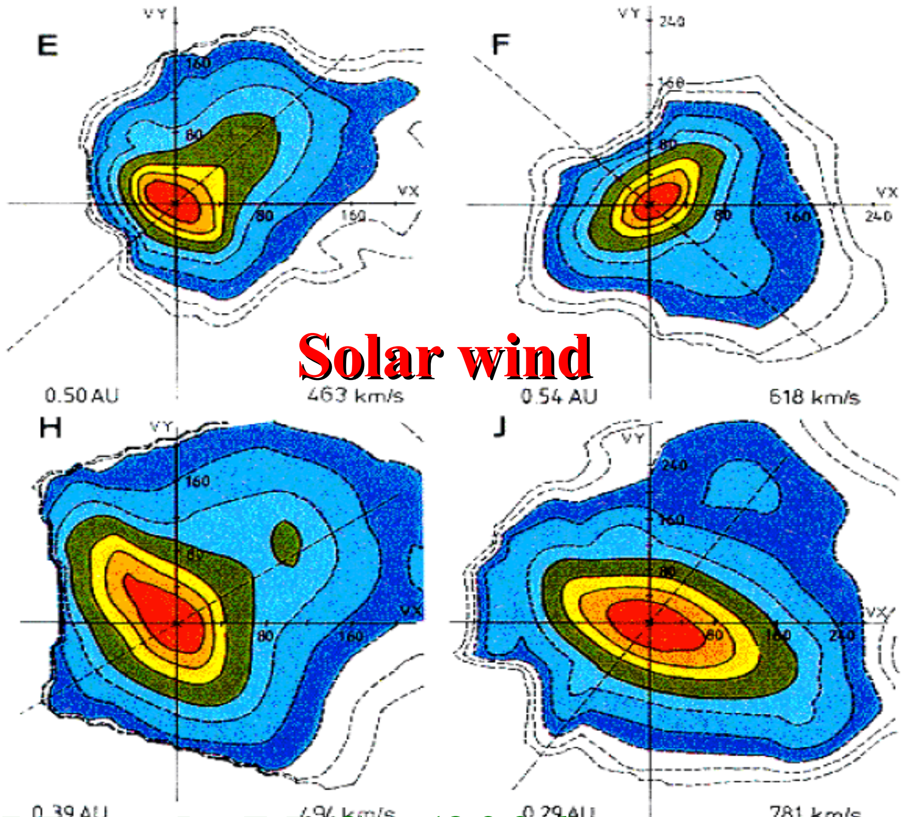
Intermittent, anisotropic Vlasov turbulence...





Patterns of temperature anisotropy are near current sheets

6D Vlasov: more kinetic effects!

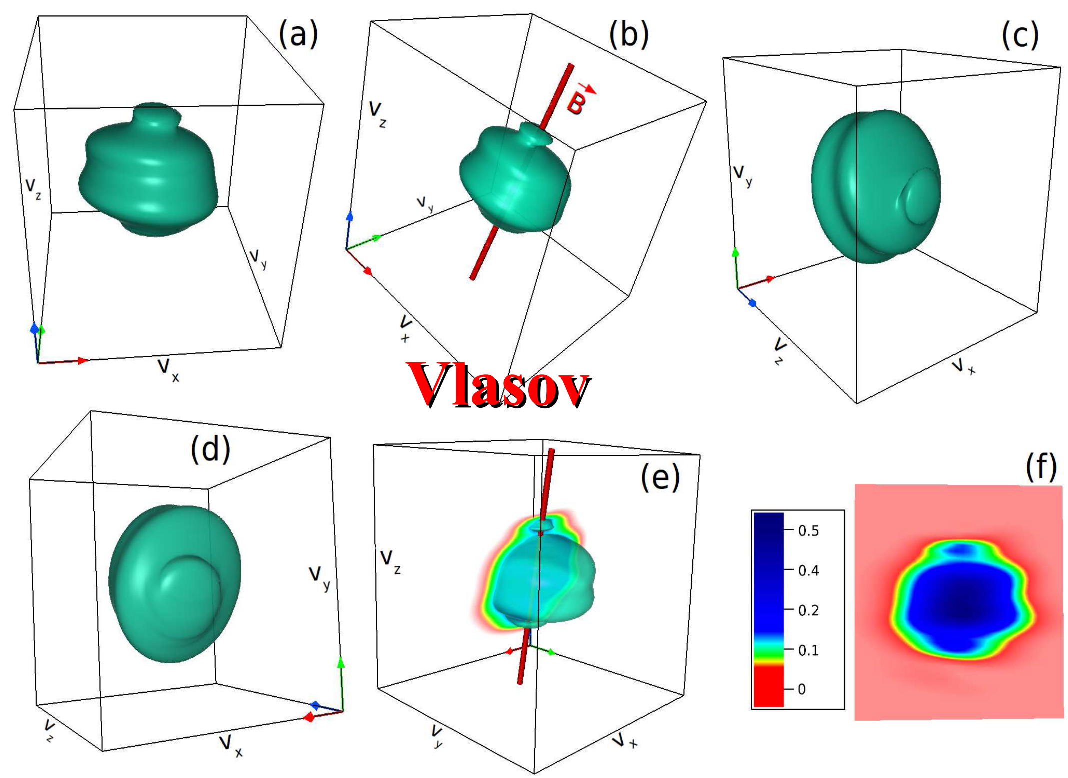


Solar wind

Marsch, LRSP (2006)

beams, anisotropy, and strong non-gyrotropic modulations

Servidio *et al.*, JPP (2014)

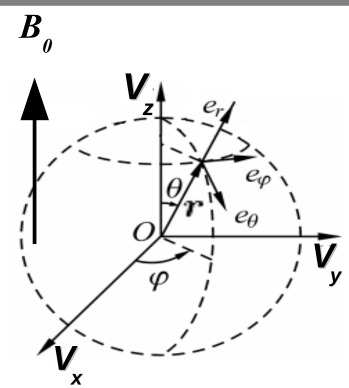


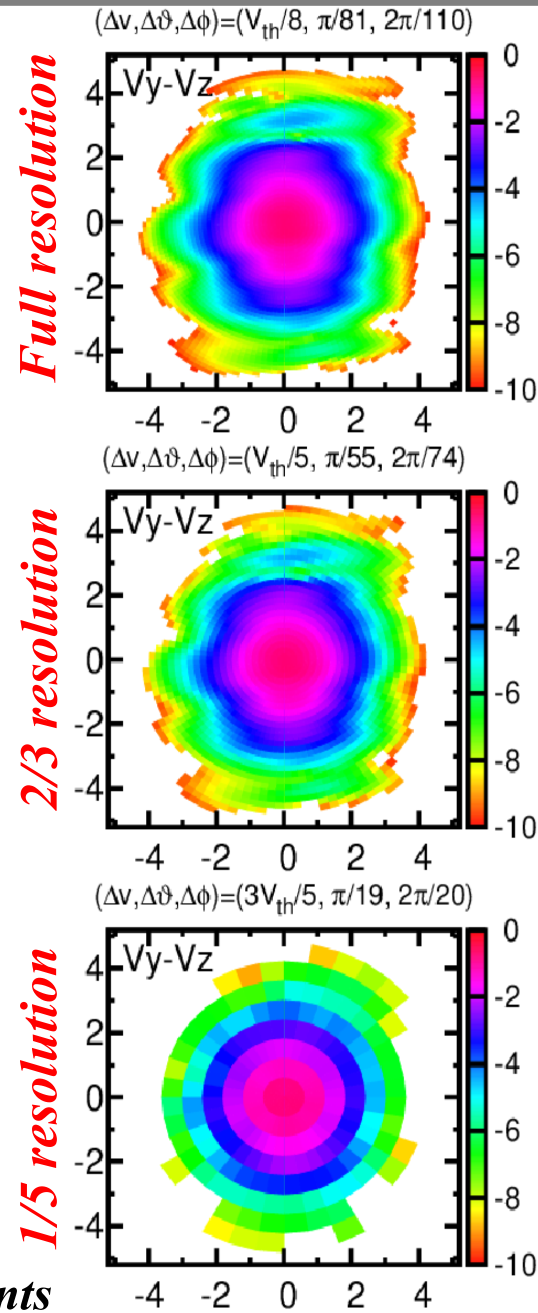
Vlasov

Landau resonances can be locally excited:

$$\omega - k_{\parallel} v_{\parallel} - n\Omega_{ci} = 0$$

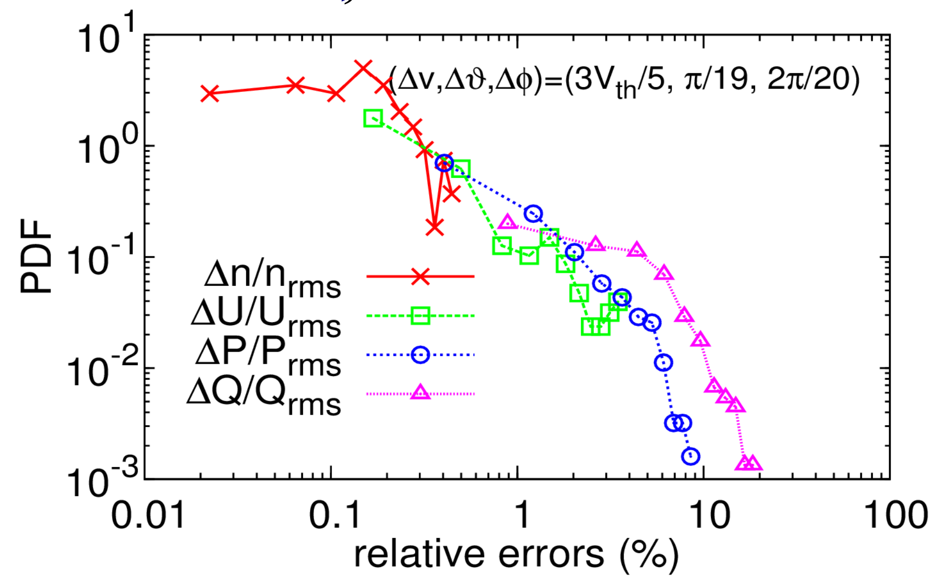
High resolution measurements in the SW?





Modern measurements

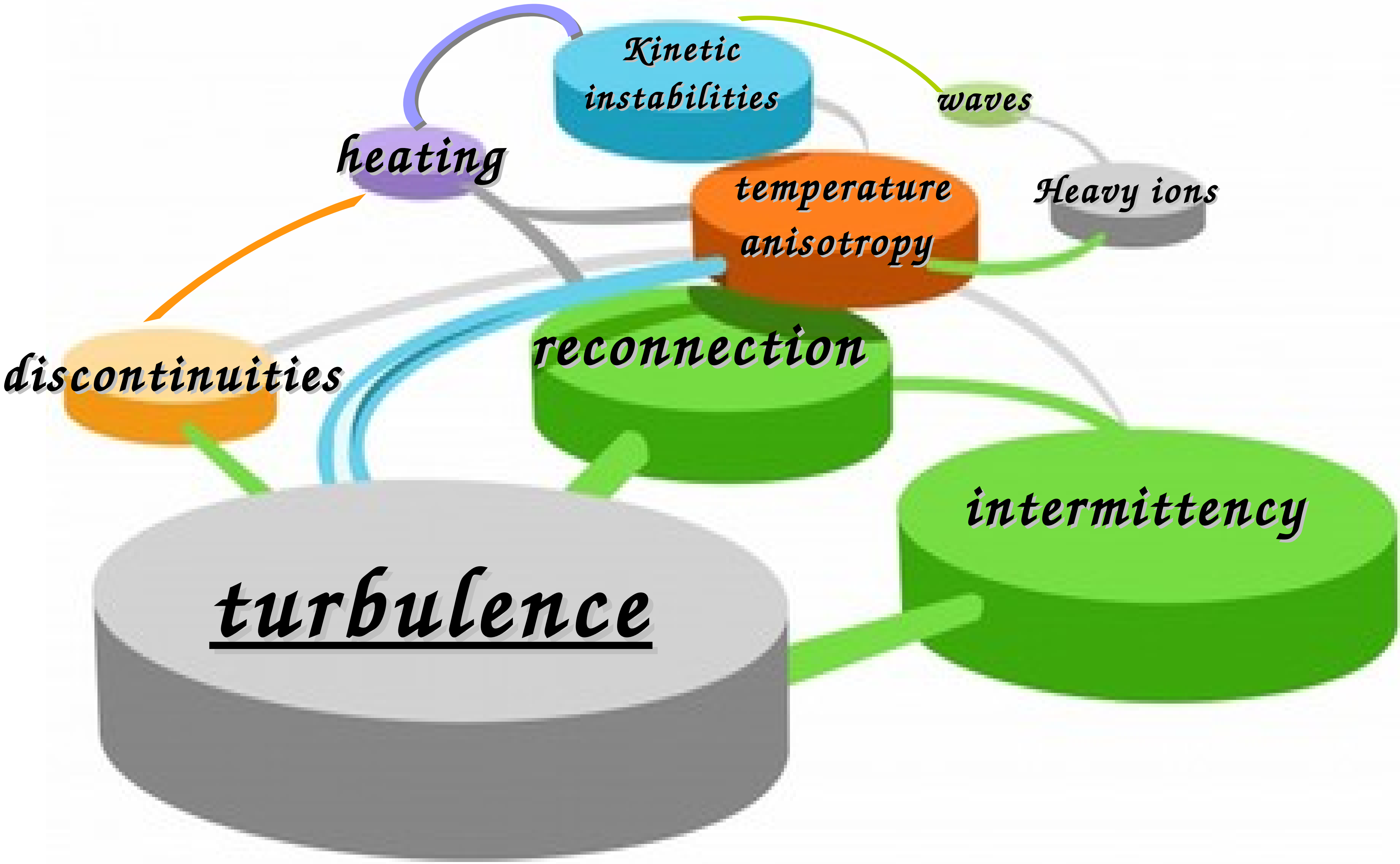
Errors with respect the full resolution, for several moments



We need higher precision measurements

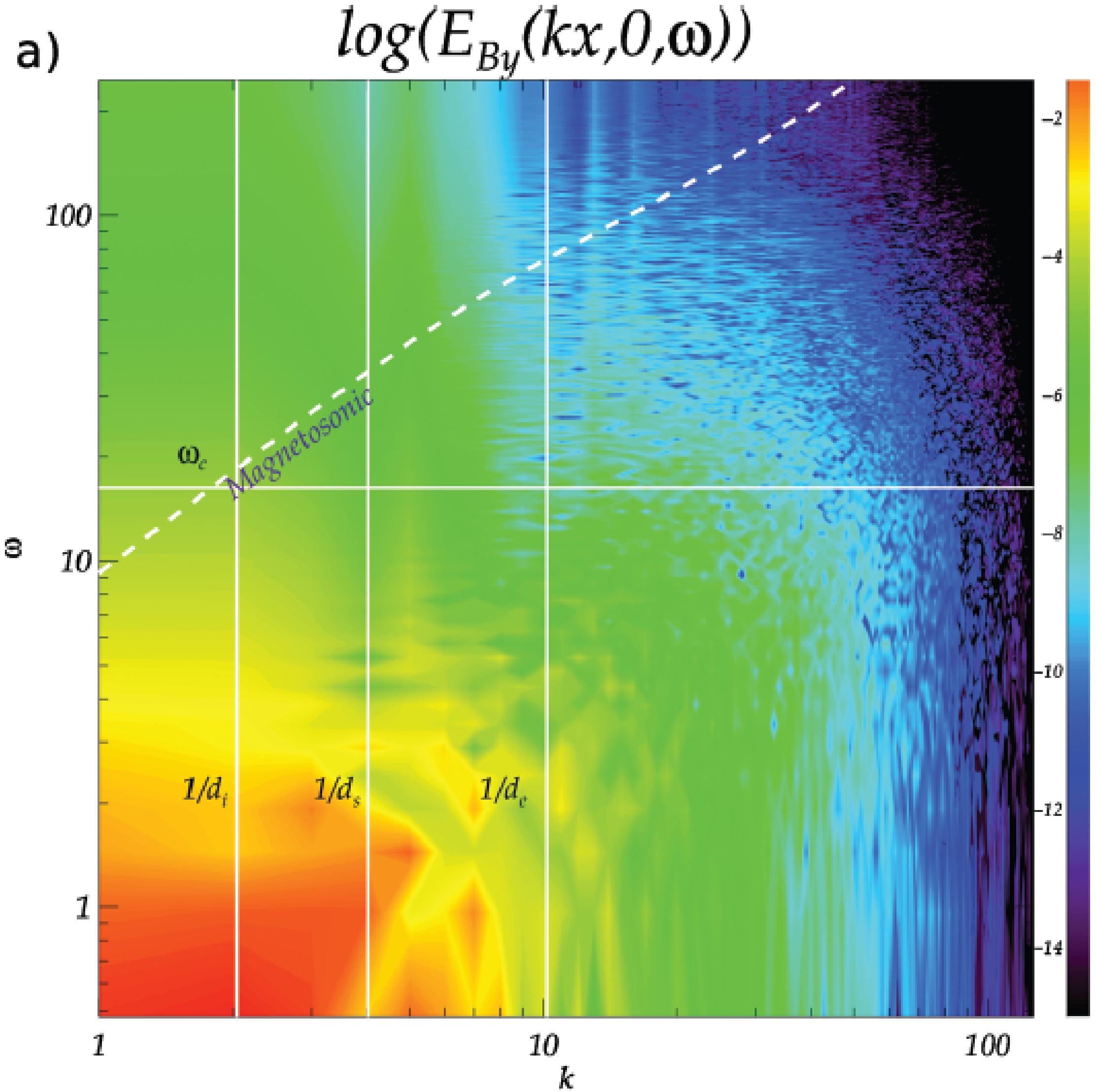
THOR

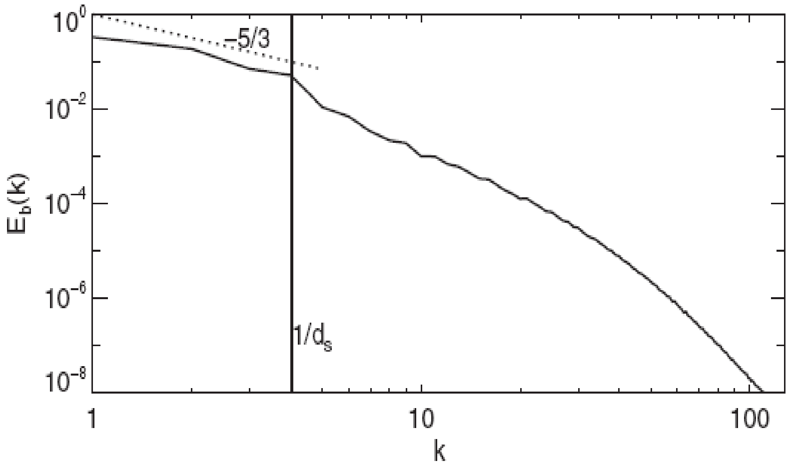
A “simple” sketch



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)

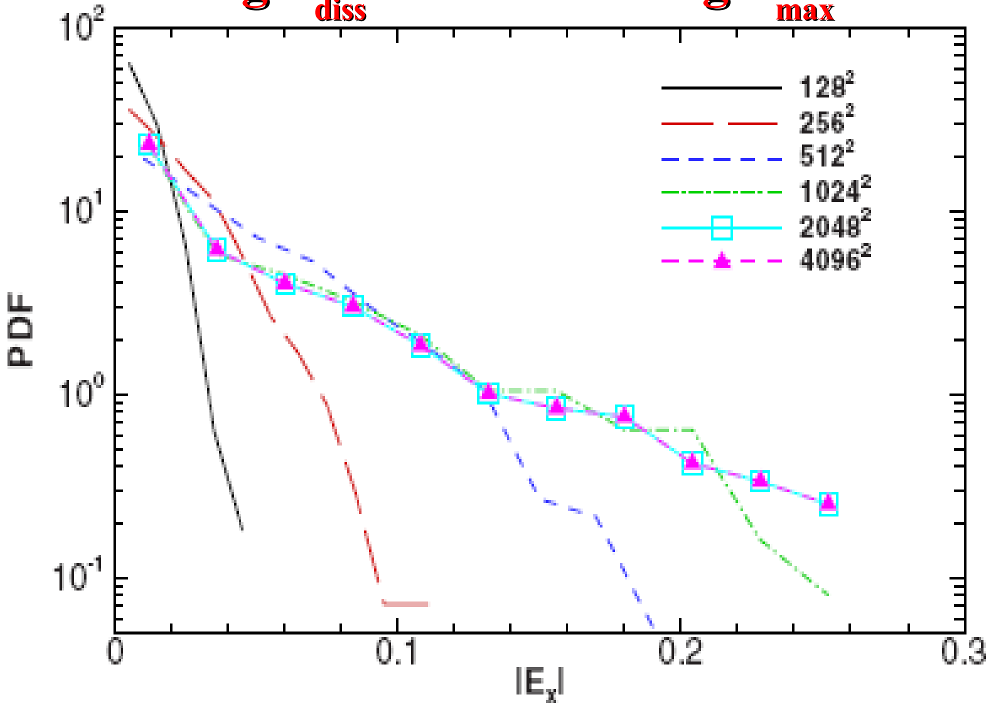
Extra slide

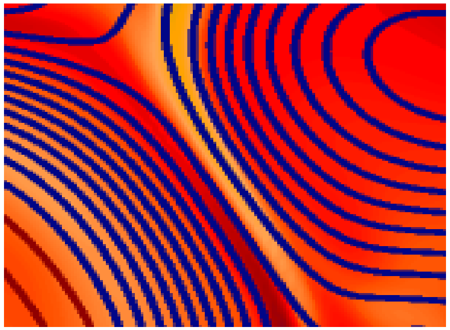
• Note on the numerics

Generally simulators, tempted by the “high Reynolds number dream”, may use too low resistivity...

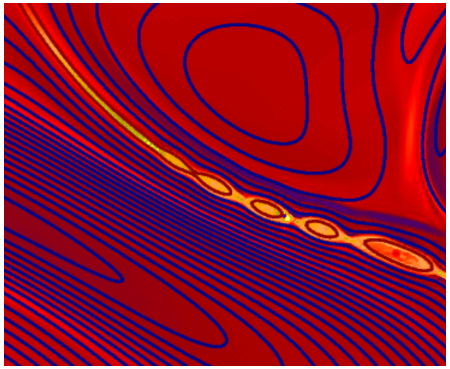
$$k_{max} \sim N_{mesh\ points}$$
$$k_{diss} \sim \eta^{-1/2}$$

Fixing k_{diss} and increasing k_{max} ...





$k_{max}/k_{diss} > 3$



$k_{max}/k_{diss} < 1$

Reconnection events in turbulent regime are strongly affected by “Gaussianization” of small scales!!!

Wan *et al.*, Phys. Plasmas (2009, 2010)

Extra slide

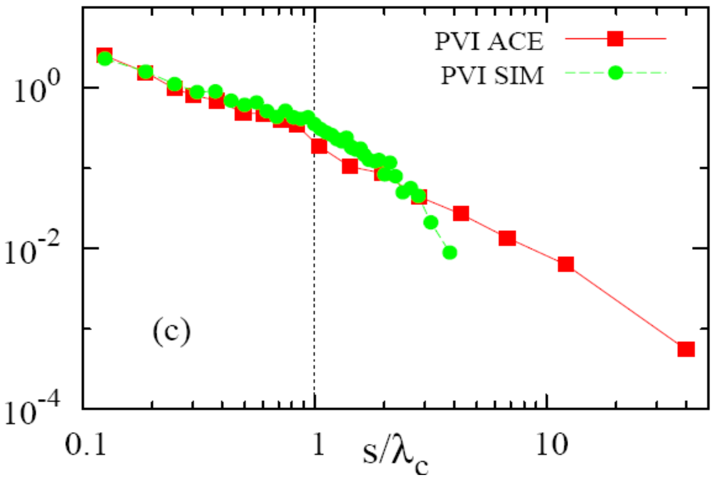
A method to identify discontinuities

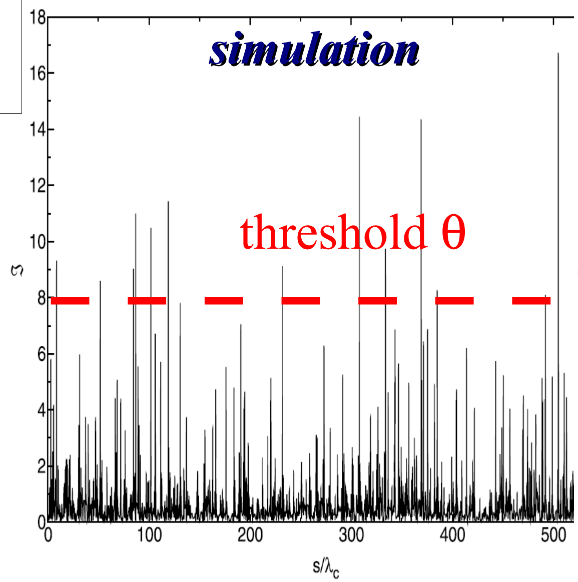
The Partial Variance of Increments (PVI)

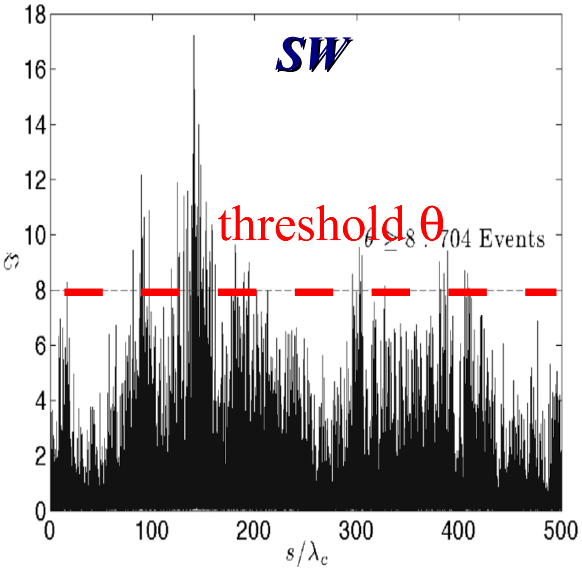
$$\Delta \mathbf{B}(s, \Delta s) = \mathbf{B}(s + \Delta s) - \mathbf{B}(s)$$

$$\Im(\Delta s, \ell, s) = \frac{|\Delta \mathbf{B}(s, \Delta s)|}{\sqrt{\left\langle |\Delta \boldsymbol{B}(s, \Delta s)|^2 \right\rangle_\ell}}$$

Greco *et al.*, GRL (2008), APJ (2009)





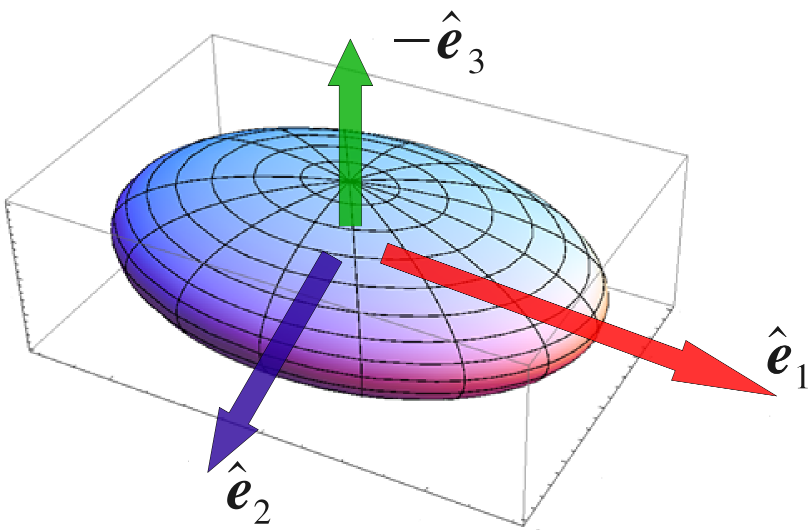


For each threshold θ, a number of discontinuities can be localized and "counted"

A measure of temperature-anisotropy

The velocity distribution function *f* may exhibit strong deformations in the velocity space → **How to properly measure these distortions?**

Assuming *f* as an ellipsoid:



Minimum Variance Frame (MVF)

$$A_{ij}(\boldsymbol{x}) = \frac{1}{n}\int (v_i - \langle v_i \rangle)(v_j - \langle v_j \rangle) f \, d^3 v$$

Eigenvalues (temperatures) $\lambda_1 > \lambda_2 > \lambda_3$

Eigenvectors $\hat{e}_1 \quad \hat{e}_2 \quad \hat{e}_3$

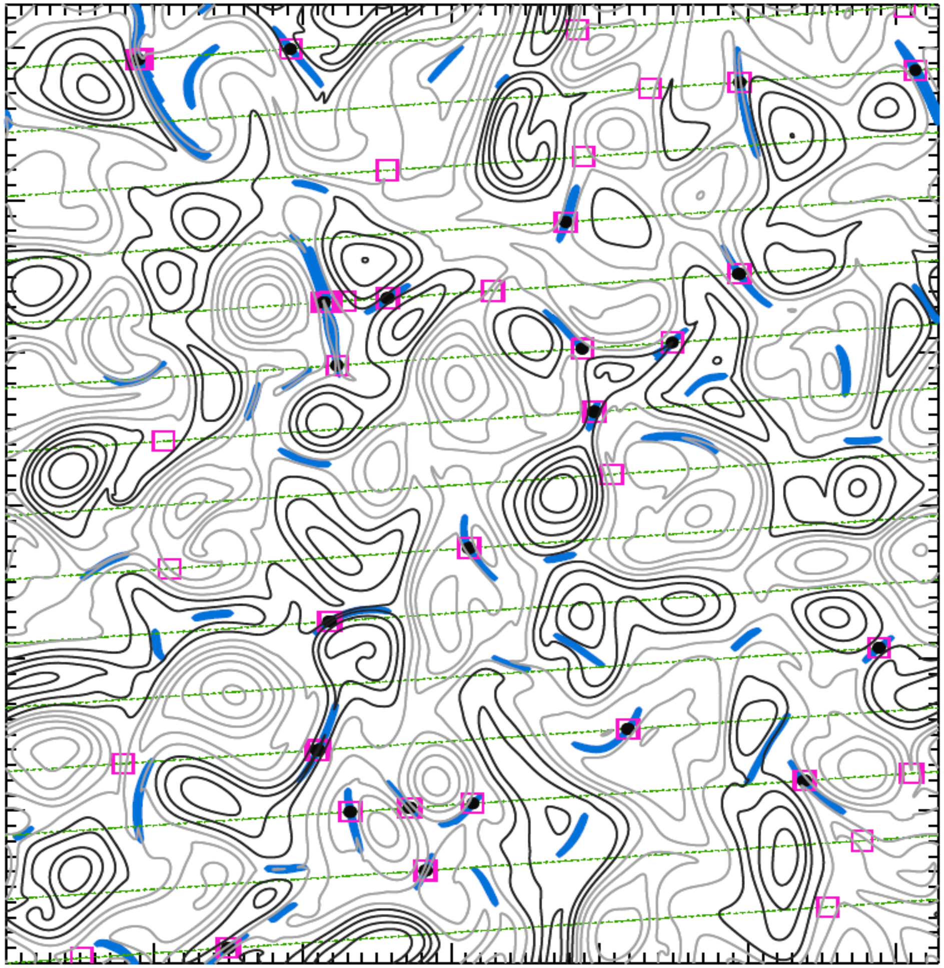
Note: for a Maxwellian $\lambda_1 = \lambda_2 = \lambda_3 = 1$

(Maximum) Temperature anisotropy ≡ λ_1 / λ_3

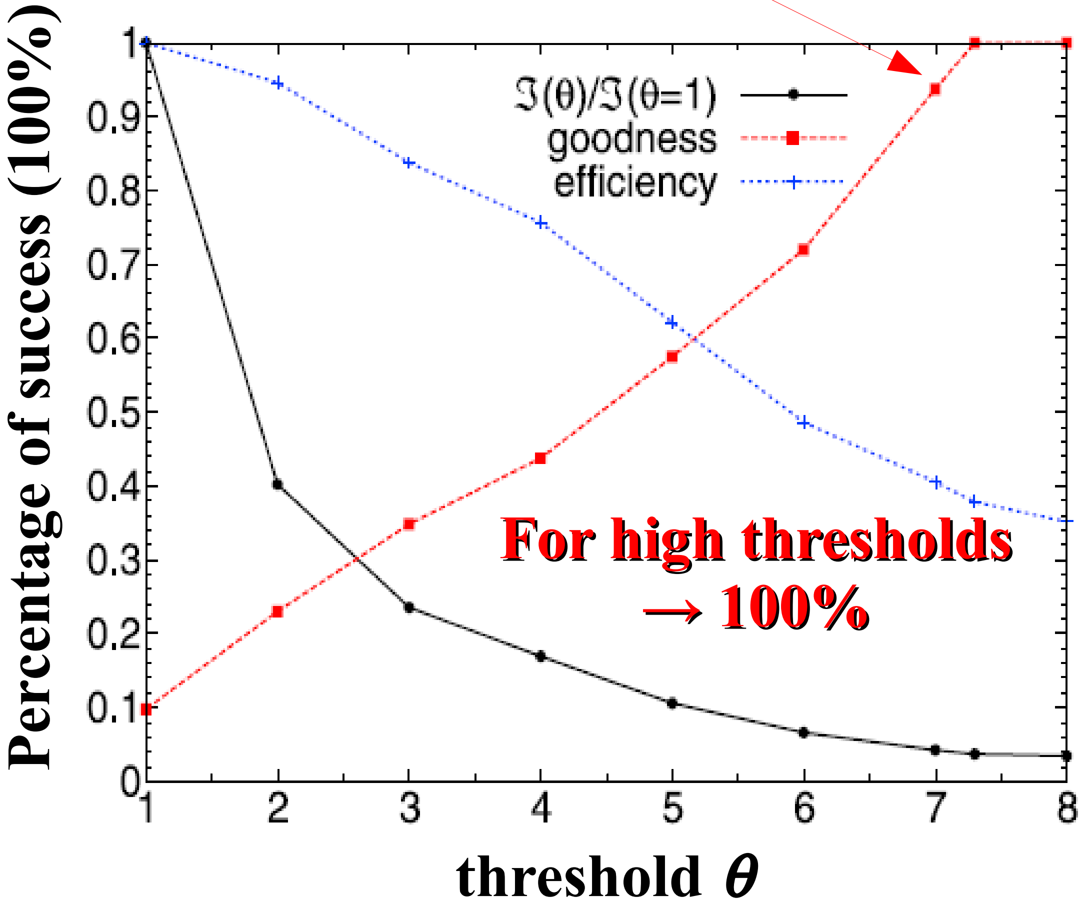
Extra slide

Discontinuities & reconnection

- magnetic potential
- satellite path
- reconnection regions
- PVI technique, with θ =5
- discontinuities=reconnection



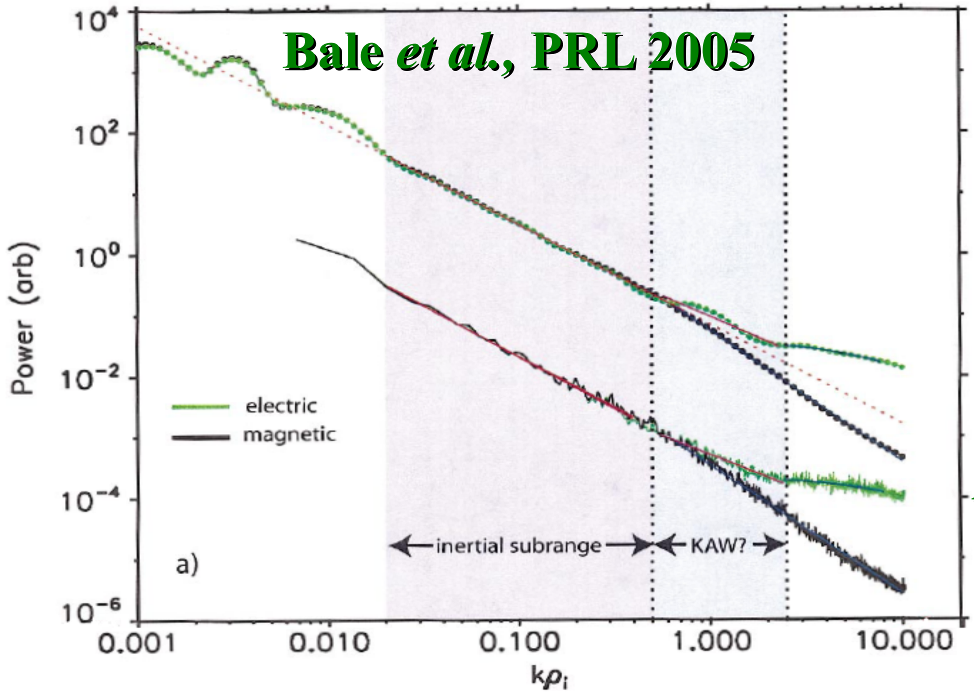
#reconnection events/#discontinuities



Strongest discontinuities are reconnection events

S. Servidio *et al.*, JGR (2011)

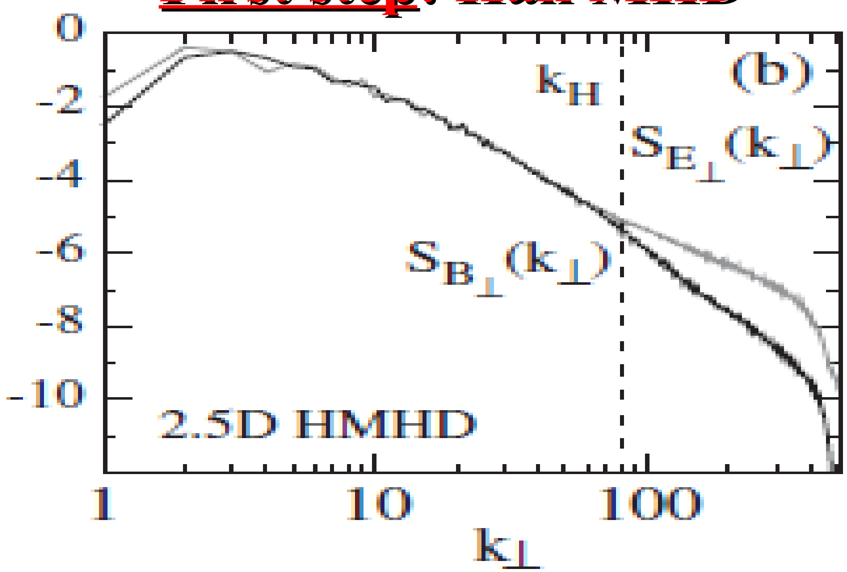
Turbulence in the solar wind



At small scales, the nature of the cascade changes

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

First step: Hall MHD

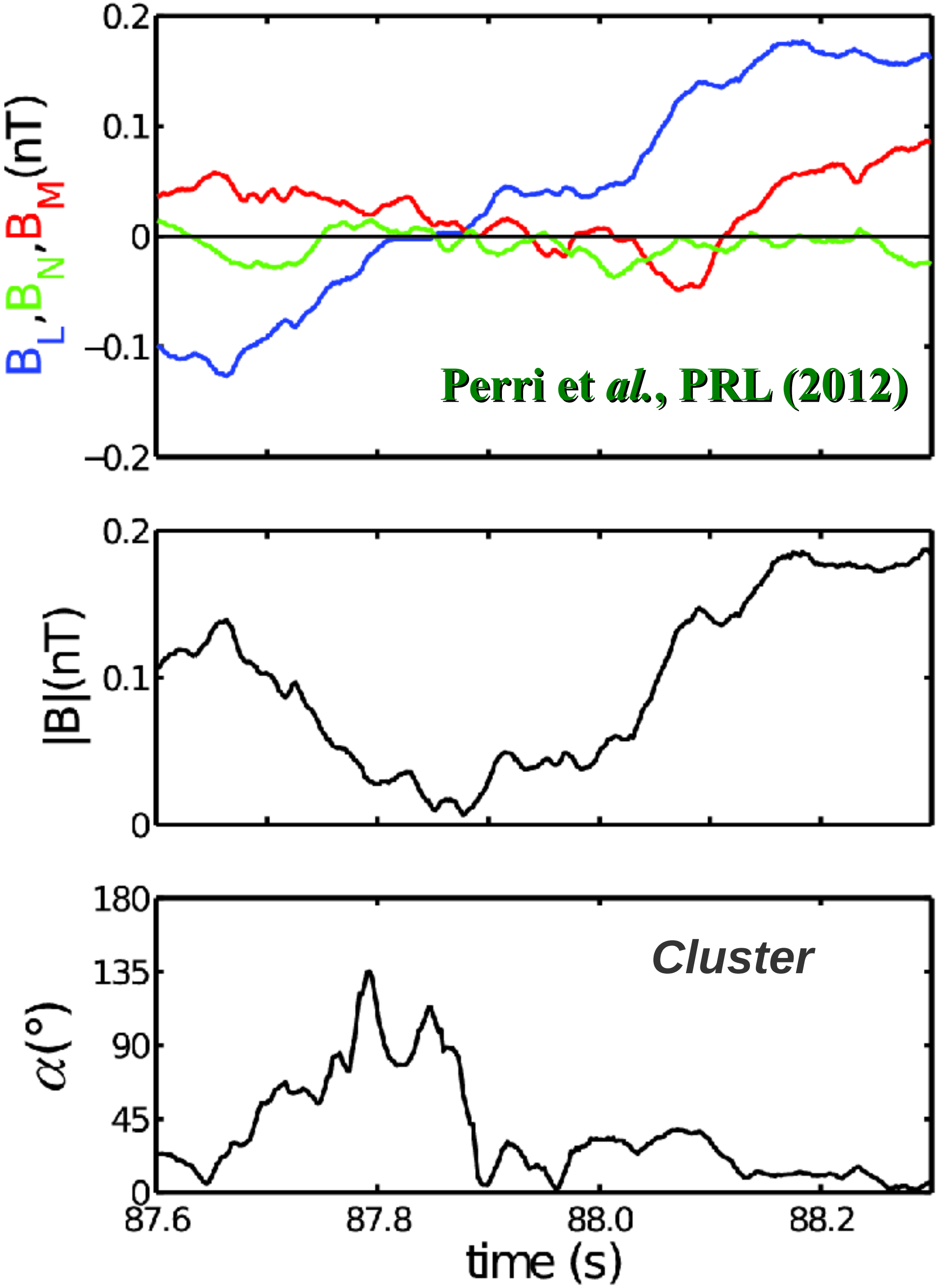


To investigate kinetic physics

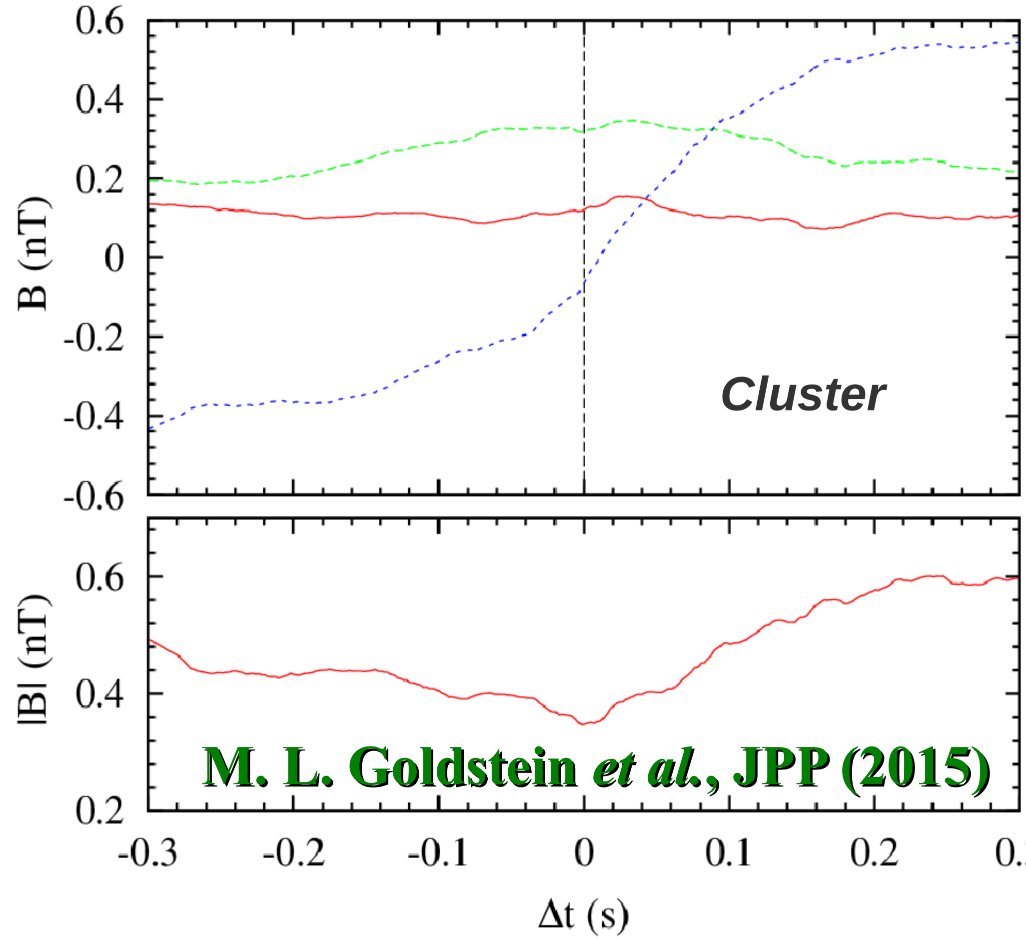
Matthaeus *et al.*, PRL (2008); Howes *et al.*, PRL (2008)

Next step: Vlasov

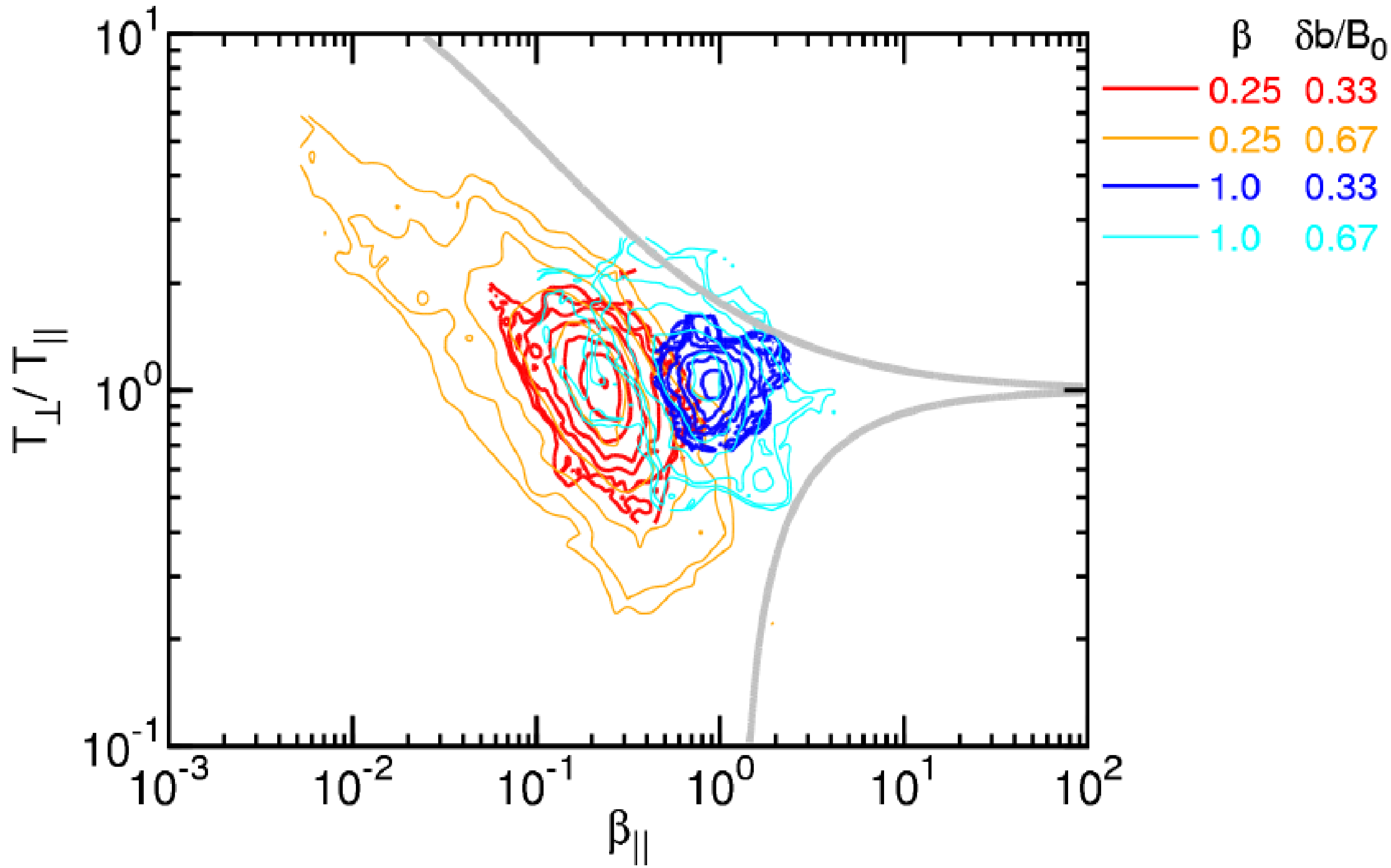
Some sub-proton discontinuities



Spatial scales 40-50 *km* (~ 0.5 ρ_i)



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