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Observatoire de la CÔTE d'AZUR

UNIVERSITÀ DELLA CALABRIA

Intermittent magnetic structures in plasmas: from MHD to Vlasov turbulence

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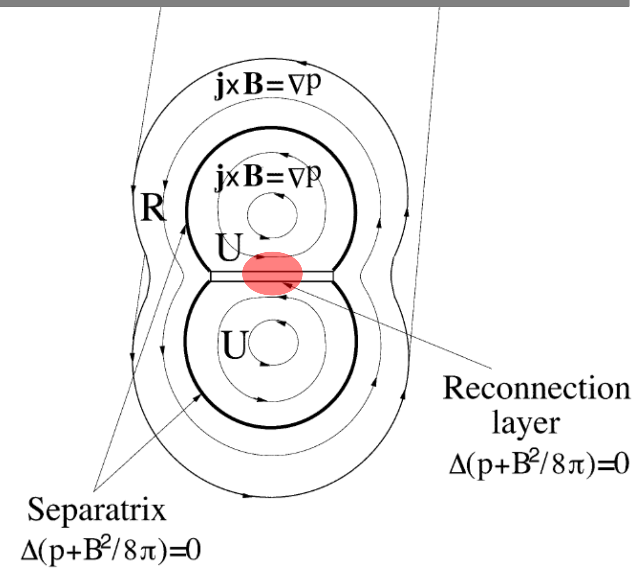
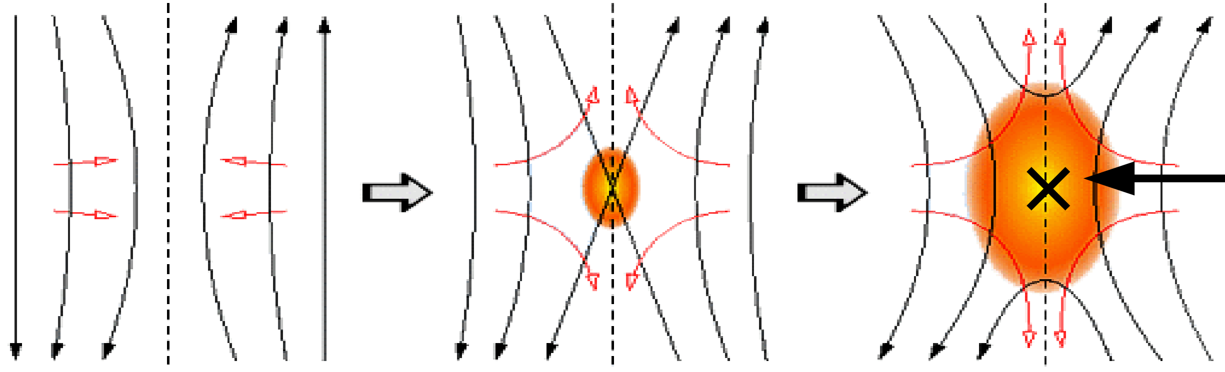
Outline

- Magnetic reconnection & 2D MHD turbulence
- From fluid to plasma models
- Some “applications”
- 6D Vlasov simulations

Classical Picture of Magnetic Reconnection

- Two bipolar regions come together
- The field flattens “analogous to the flattering of a motor tyre when loaded”
- “...a *thin collision layer of gas is formed*” at the neutral point





Reconnection region at the X-point

ℓ system size
δ thickness
$v_{in(out)}$ in(out)flow velocity
E reconnection rate
B upstream magnetic field
η resistivity

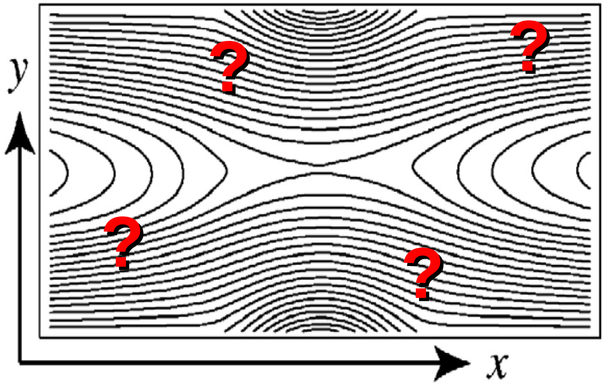
$$\frac{v_{in}}{v_{out}} \sim \frac{\delta}{\ell} \quad \& \quad E \sim \sqrt{\frac{\eta B^3}{\ell}}$$

P. A. Sweet (1958);
E. N. Parker (1957)

Standard Description of Reconnection

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**

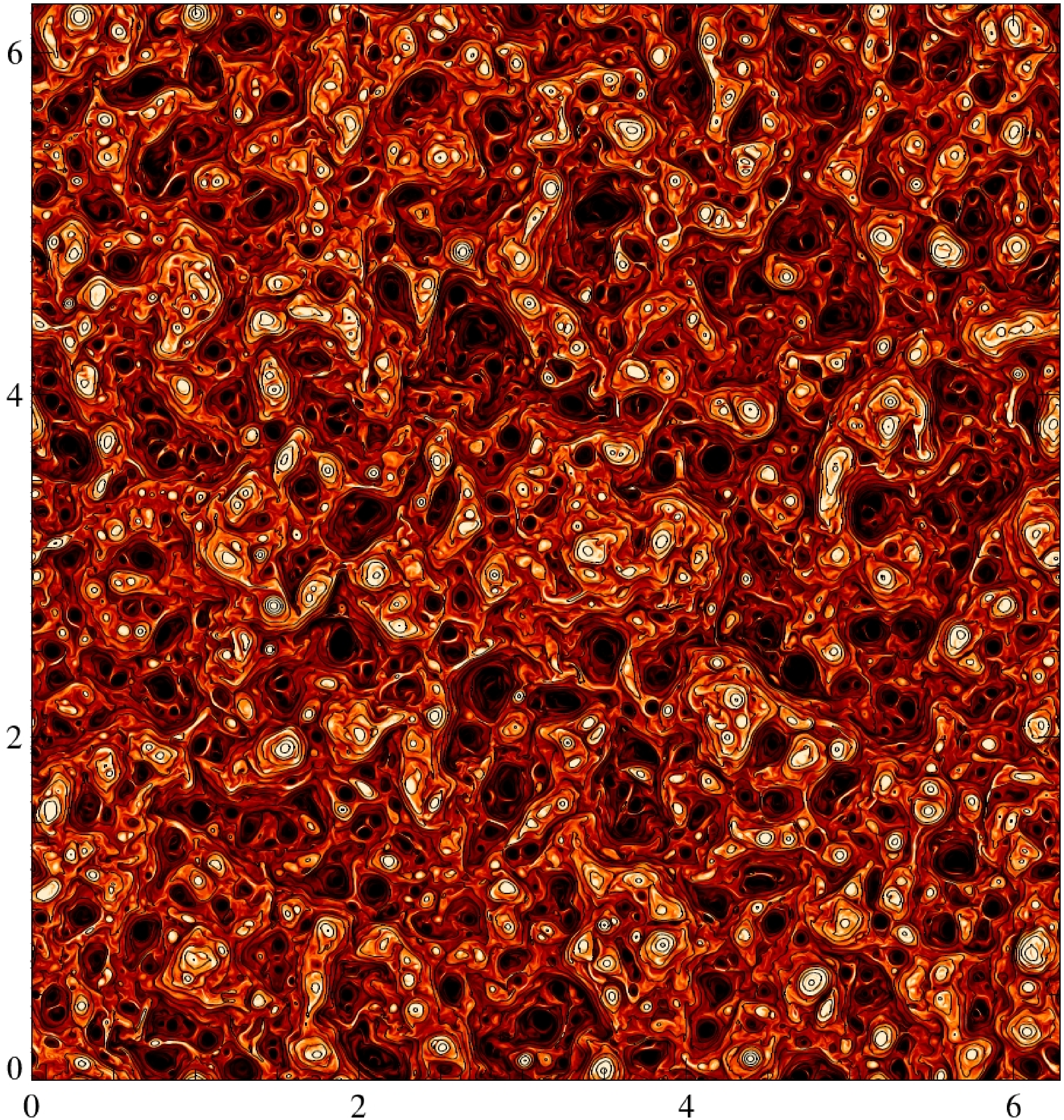
Matthaeus & Montgomery, *Ann. N.Y. Acad. Sci.* (1980);
V. Carbone *et al.*, *Phys. Fluids* (1990)

U. Frisch, A. Pouquet, P.-L. Sulem and M. Meneguzzi,
Journal de Mecanique Theorique et Appliquee (1983)

Figure 6. Contours of current j at $t = 0.7$ for the O-T vortex ($\nu = \eta = 0$). Resolution 512^2. Figure obtained by patching 16 individual figures each of which uses 128^2 points.

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

2D MHD



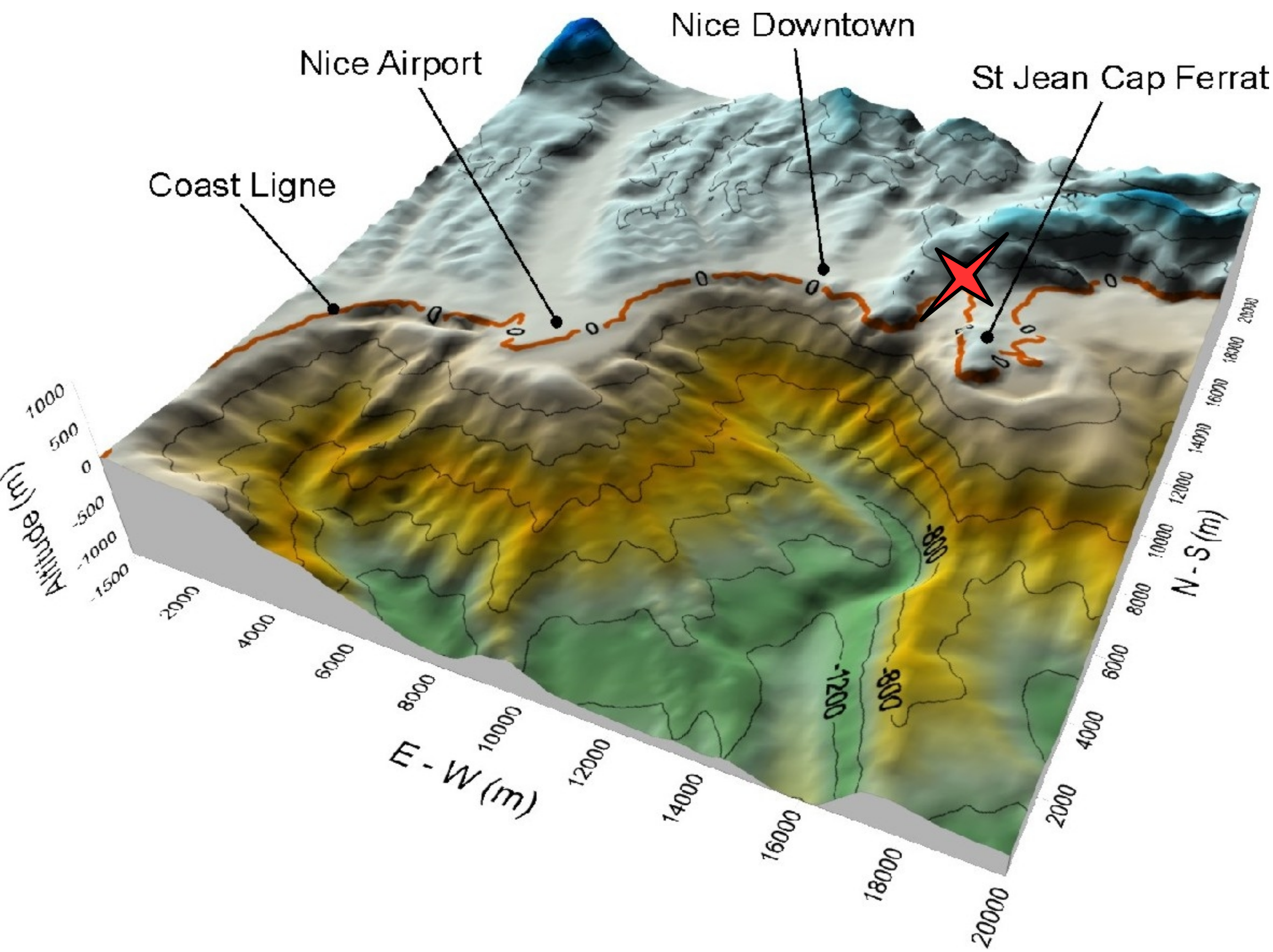
$$\frac{\partial \omega}{\partial t} = -(\boldsymbol{v}\cdot\nabla)\omega + (\boldsymbol{b}\cdot\nabla)j + R_\nu^{-1}\nabla^2\omega$$

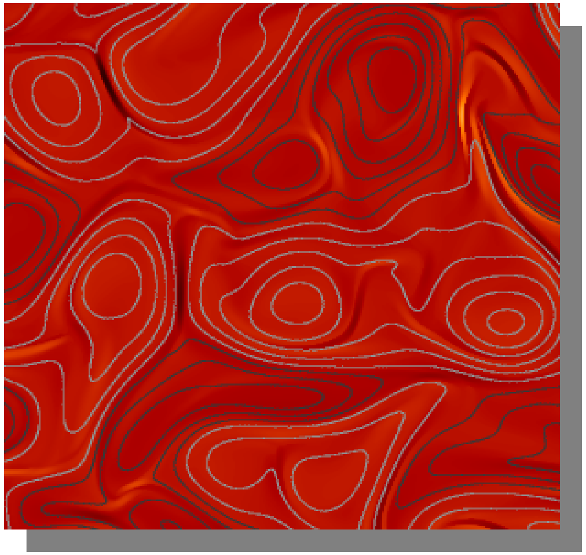
$$\frac{\partial a}{\partial t} = -(\boldsymbol{v}\cdot\nabla)a + R_\mu^{-1}\nabla^2 a$$

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

Where is reconnection?

Some "topography"...

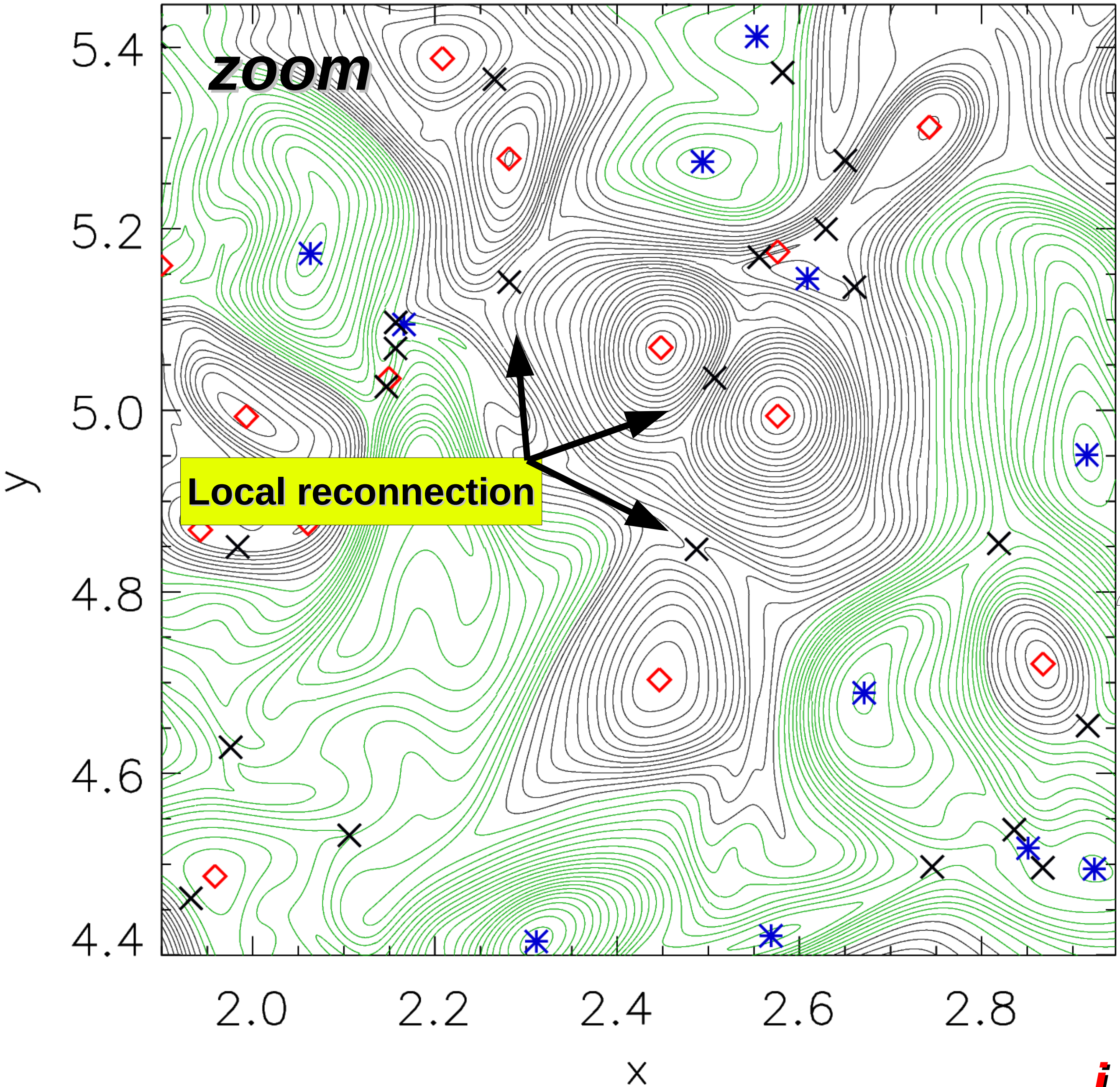




Critical points of the magnetic potential "*a*" →

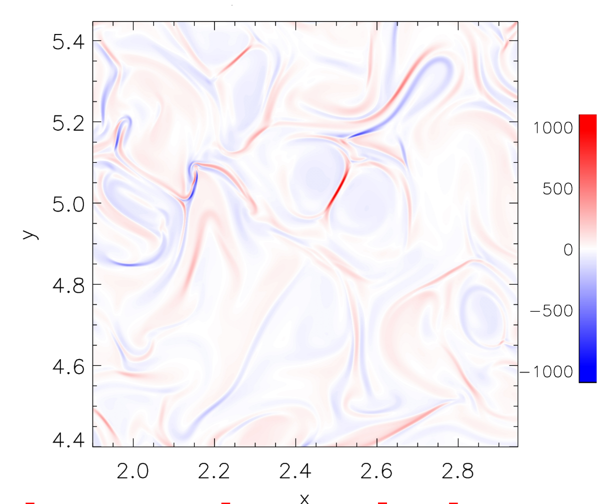
$$H_{ij}^{[a]}(\boldsymbol{x}) = \frac{\partial_{ij}^2 a}{\partial x_i \partial x_j}, \quad \text{where} \quad \nabla a = \mathbf{0}$$

Critical Points in Turbulence



Magnetic potential *a* and critical points

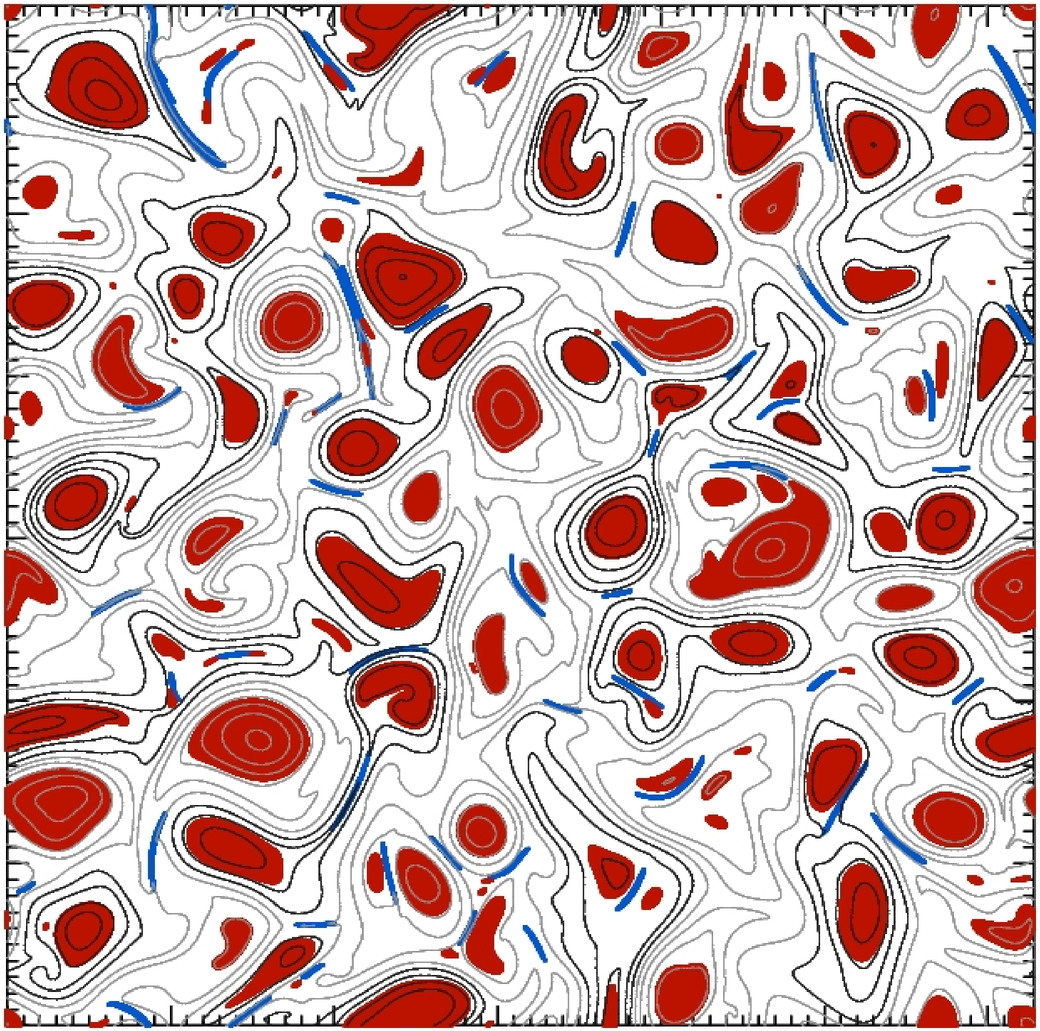
a > 0	green line
a < 0	black line
maximum	✳
minimum	◇
X-point	X



***j* is intermittently intense**

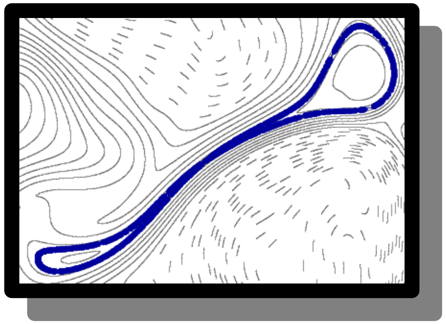
Islands & Sheets

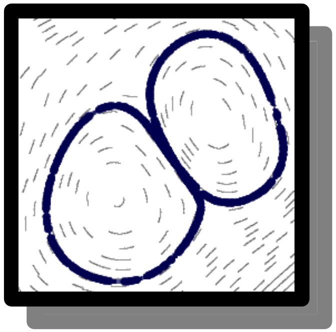
current sheets = BLUE regions
magnetic islands = RED regions

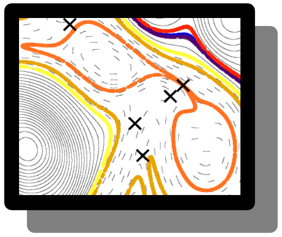


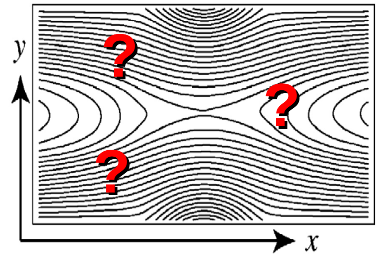
automated algorithm

Boundary conditions?
Symmetry?









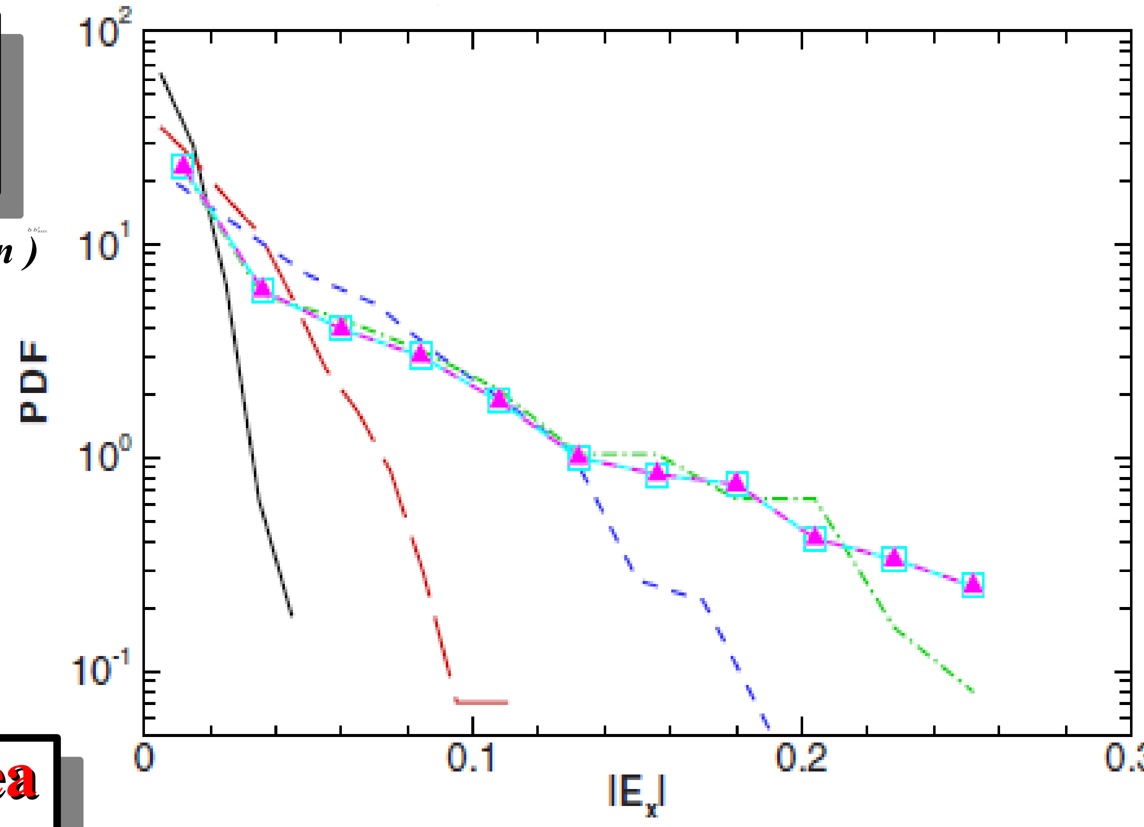
Reconnecting islands are different in size and energy: asymmetric reconnection?

Distribution of Reconnection Rates

Rate of change of the magnetic flux:

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

(normalized to the root mean-square magnetic fluctuation)



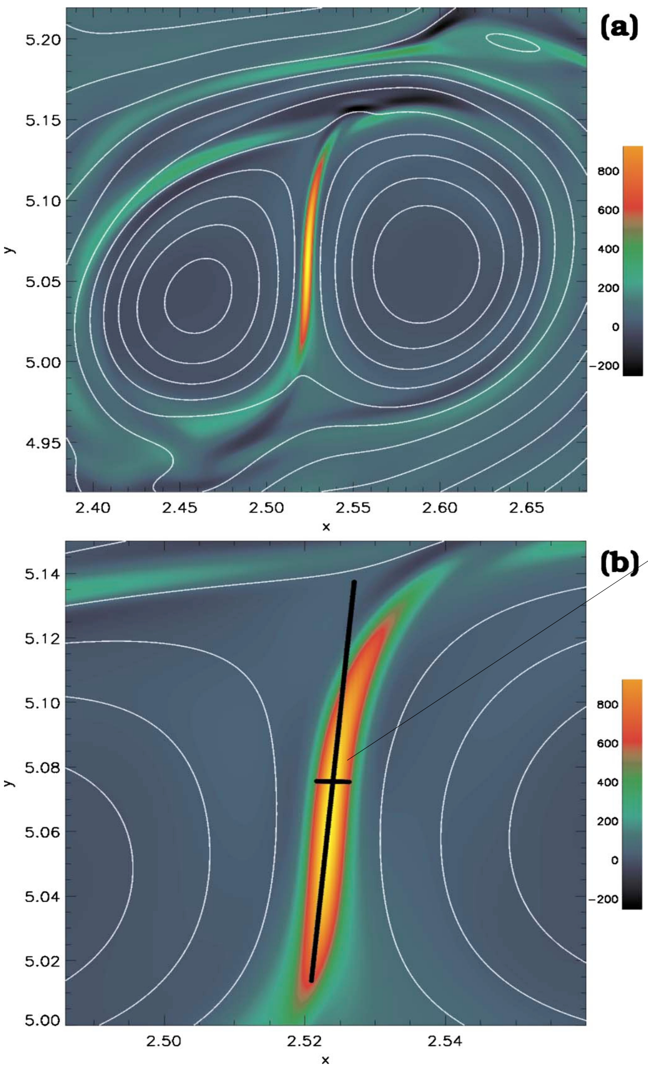
Reconnection rates are broadly distributed

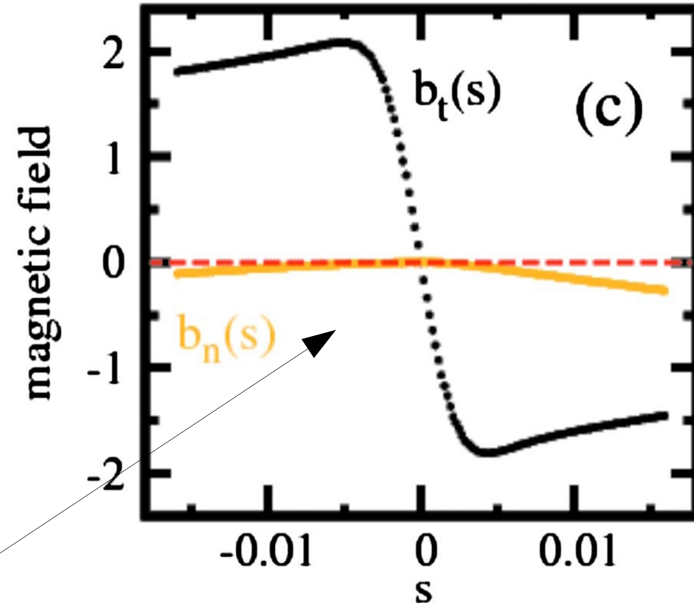
Turbulence can be viewed as a sea of reconnecting islands with different reconnection rates

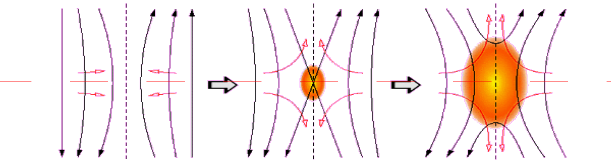
reconnection rates up to ~0.3

Dimensions of the Diffusion Region

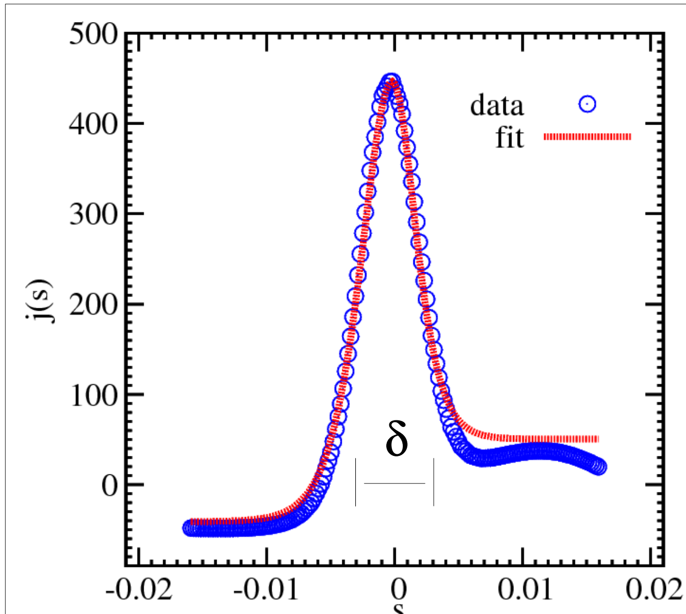
Another zoom-in







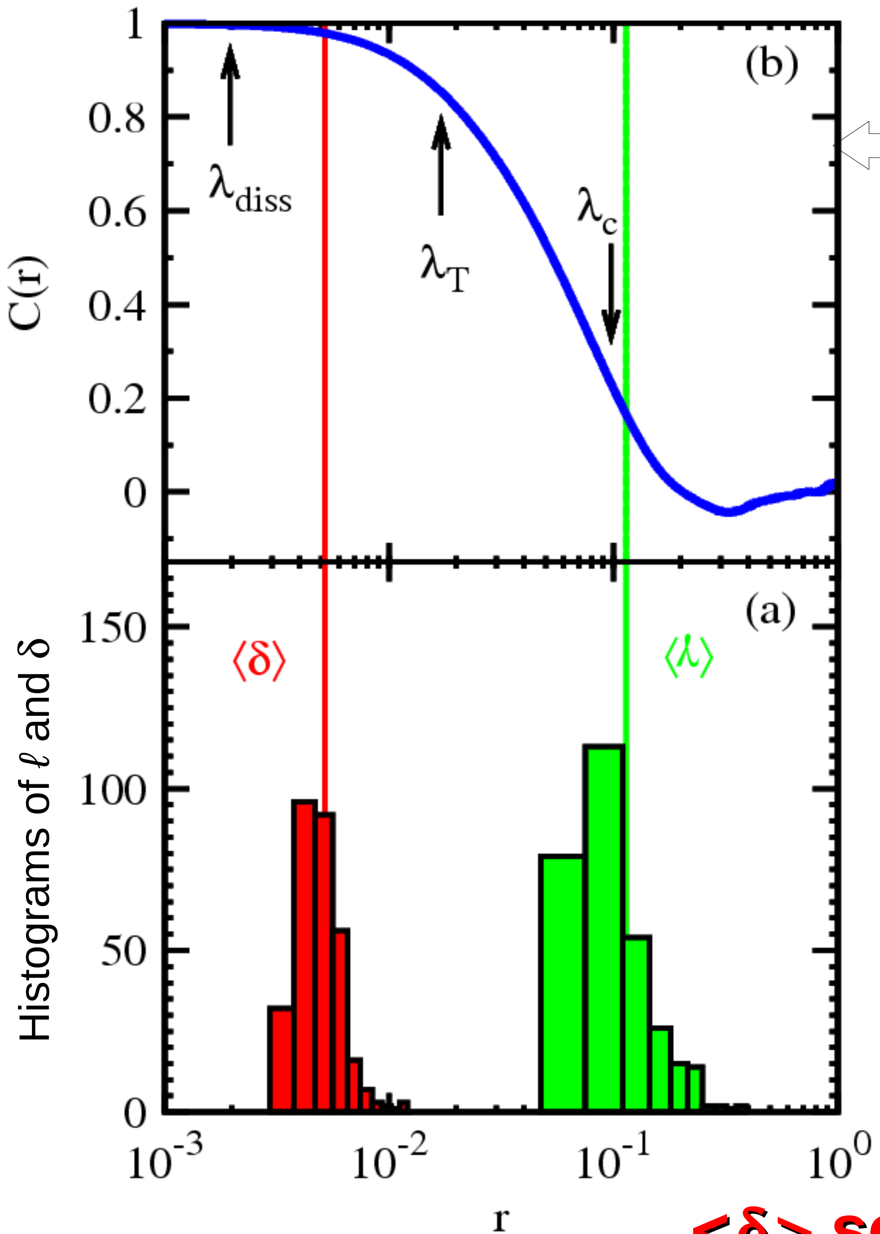
characteristic lengths



$$fit \to \delta$$

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

Link between Reconnection and Turbulence



$$C(\mathbf{r}) = \frac{\langle \mathbf{b}(\mathbf{x}+\mathbf{r}) \cdot \mathbf{b}(\mathbf{x}) \rangle}{\langle b^2 \rangle}$$

Characteristic lengths in turbulence and in reconnection:

$$\lambda_C = \int C(r)\, dr$$

$$\lambda_T = \sqrt{\frac{\langle b^2 \rangle}{\langle j^2 \rangle}}$$

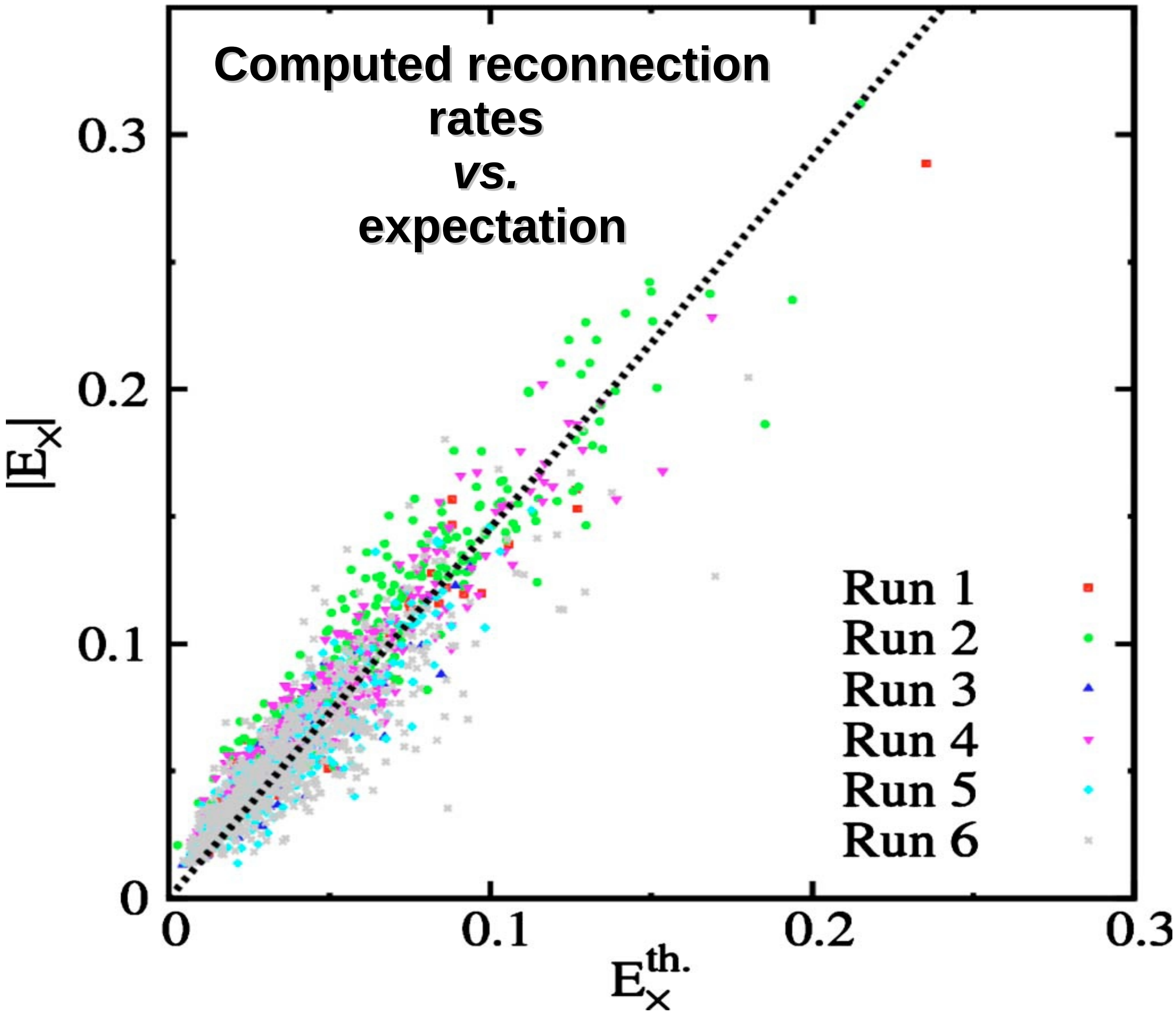
$$\lambda_{diss} = R_\mu^{-\frac{1}{2}} \langle j^2 \rangle^{-\frac{1}{4}}$$

⇔ ℓ, δ

<δ> scales with the dissipation length

<ℓ> is on the order of the correlation length

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.

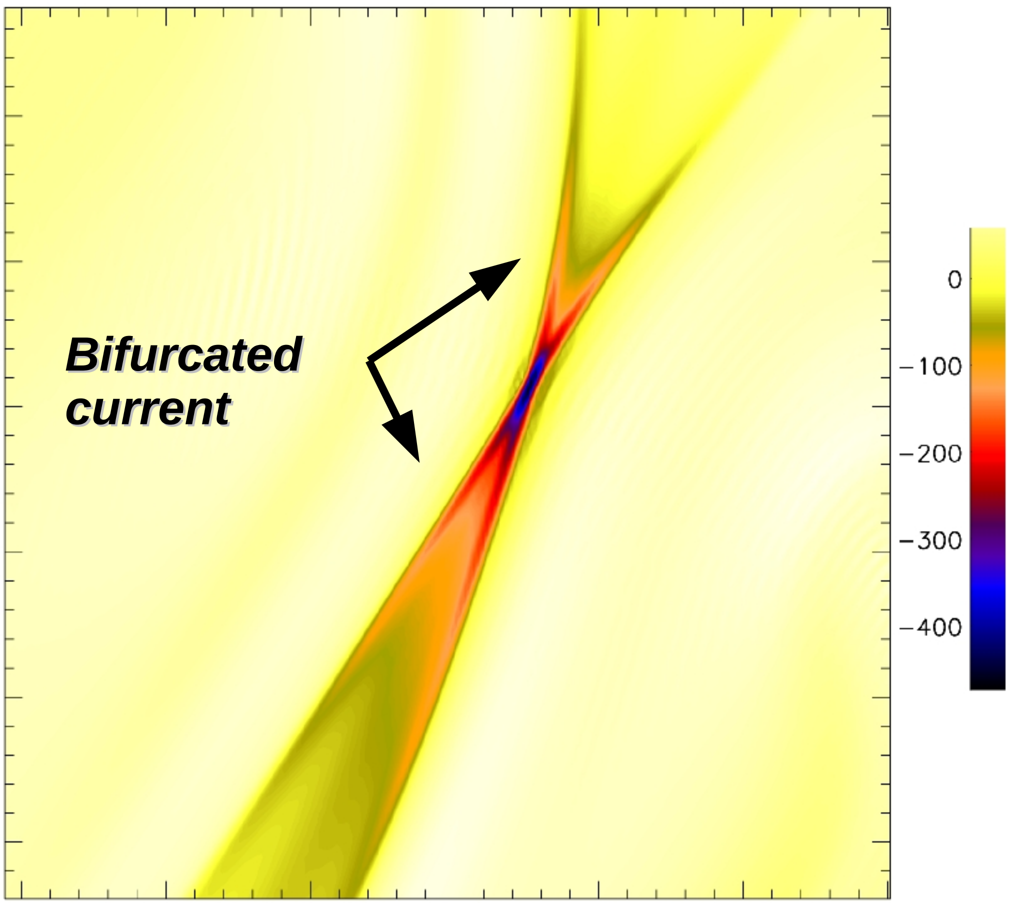
Servidio *et al.*, Phys Rev. Lett. (2009).

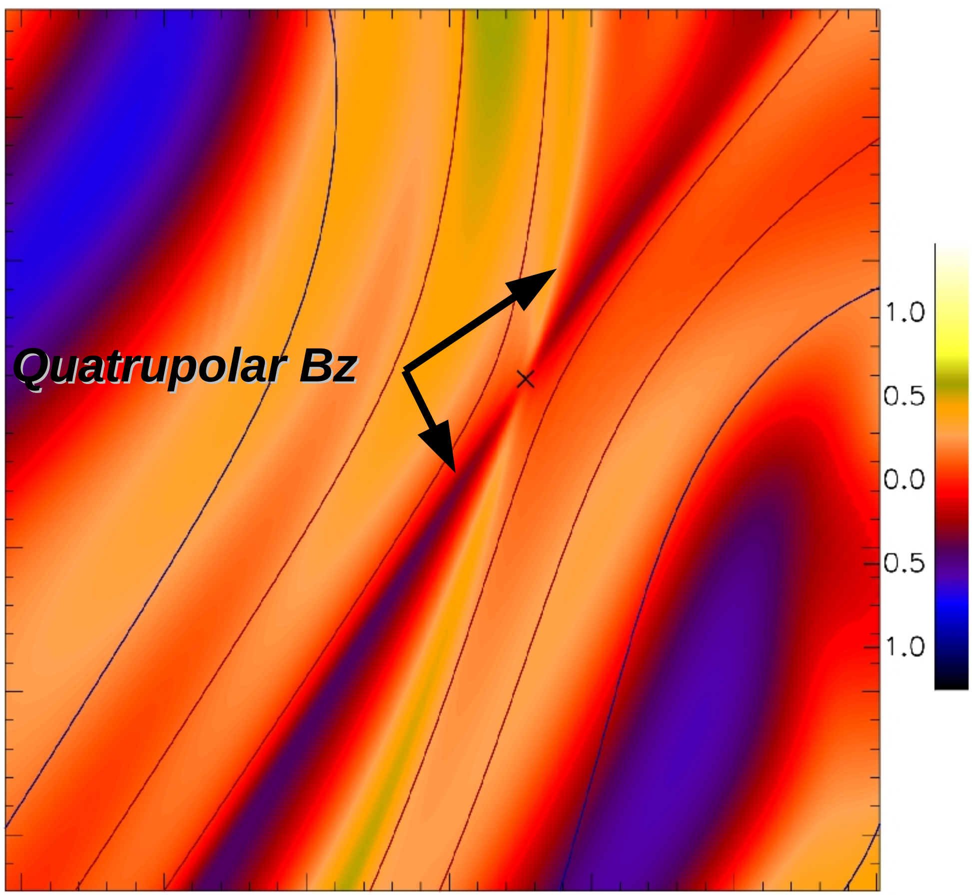
Hall Magnetohydrodynamics

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

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

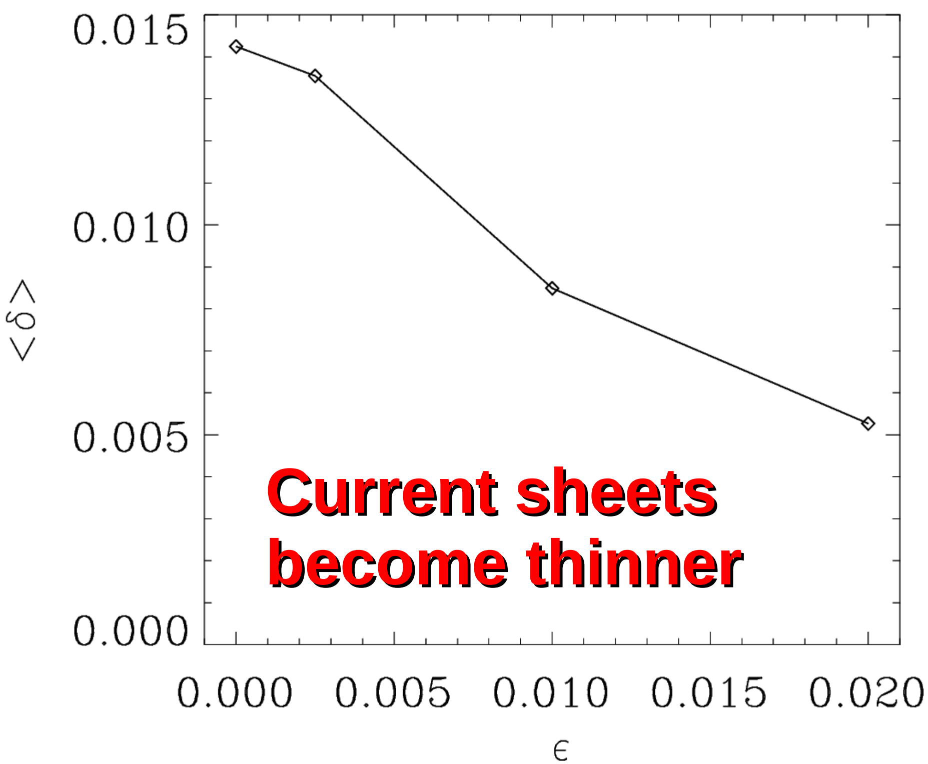
- ***pseudo-spectral***
- ***2.5D***
- ***8192^2***
- ***$R_\nu = R_\mu = 2000$***

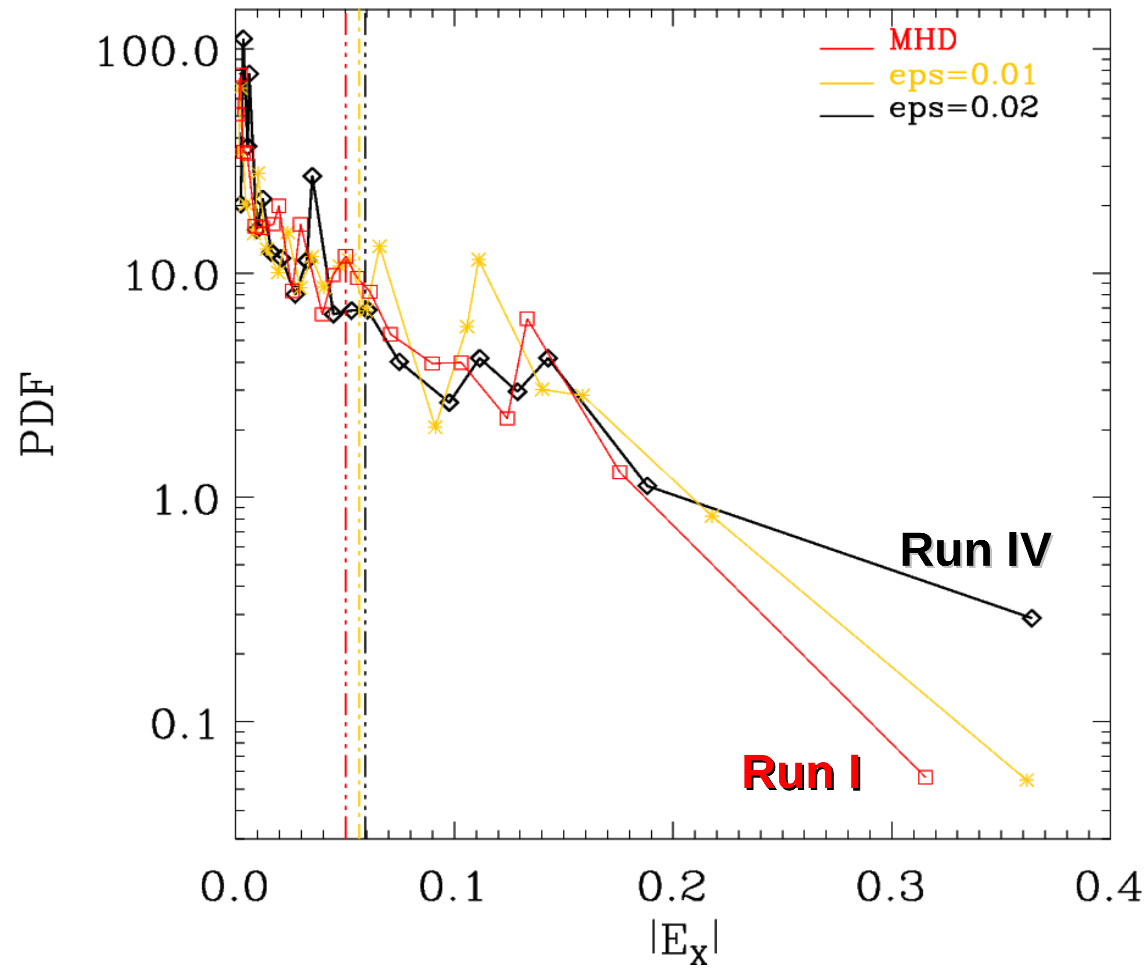




Reconnection in Hall MHD Turbulence

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



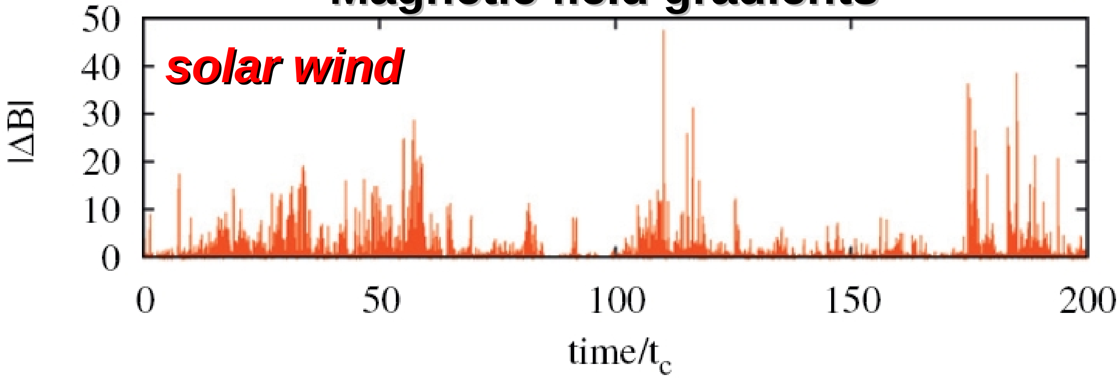


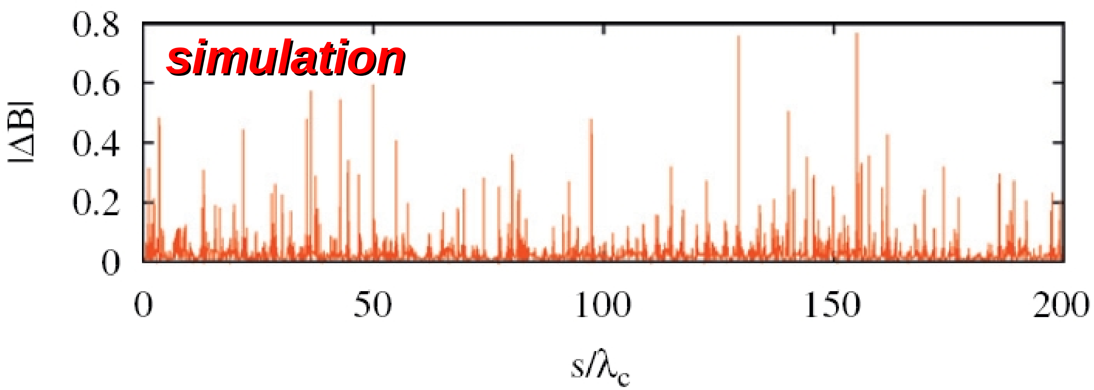
The Hall electric field increases the reconnection rate in turbulence

Donato et al., Phys. Plasmas

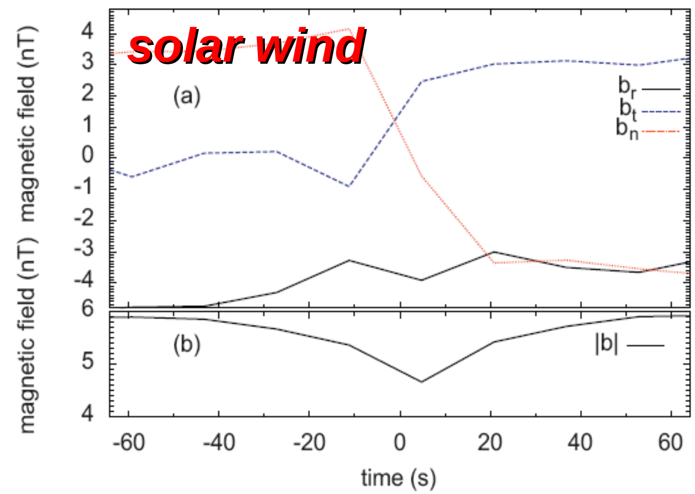
Solar Wind: Discontinuities & Reconnection

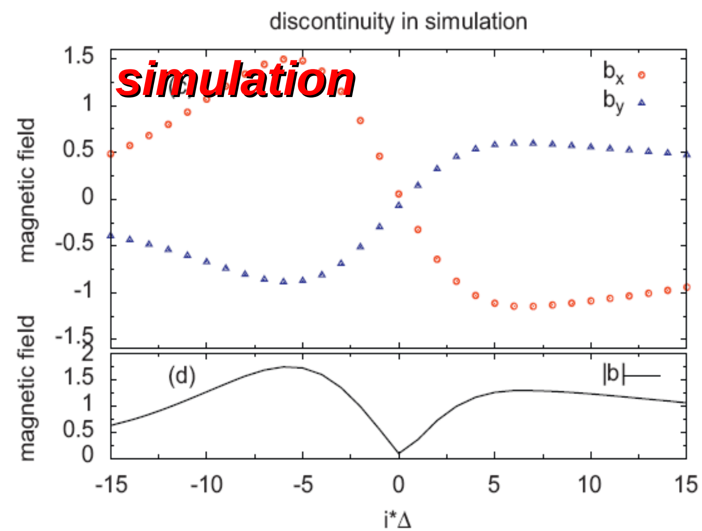
Magnetic field gradients





Magnetic discontinuity

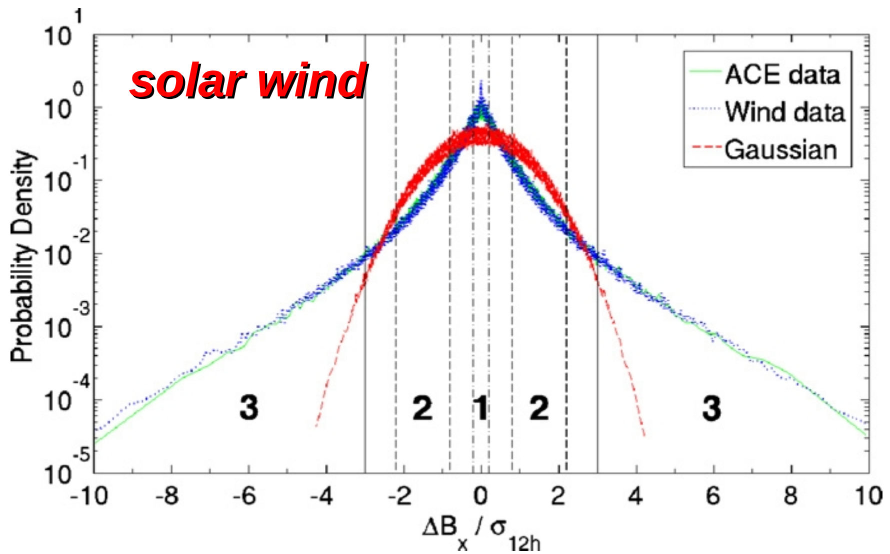


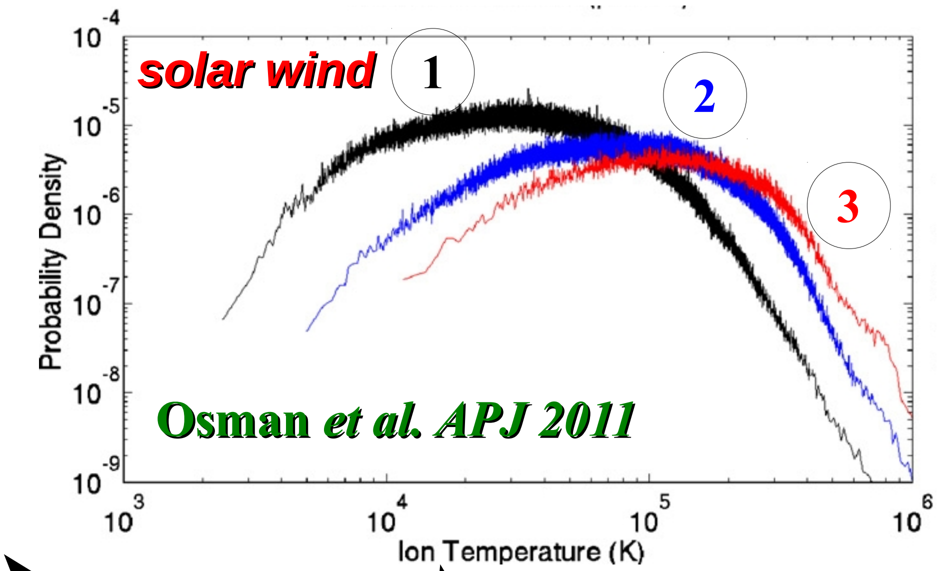


Magnetic discontinuities, commonly observed in the turbulent solar wind, may be local reconnection events

A. Greco, S. Servidio, Matthaeus..., Geophys. Rev. Lett. 2008; Atrophys J. 2009; Planet. Space Sci. 2010, Phys Rev. E 2009, Asptrophys J. Lett 2011, Journal Geophys. Res. 2011; Phys. Rev. Lett. 2014

…Discontinuities, Reconnection & Heating





Greco *et al.* GRL 2008, APJ 2009;
Sorriso-Valvo *et al.*, GRL 1999;
Bruno & Carbone, Liv. Rev. 2005;
Gosling & A. Szabo JGR 2008

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

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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]

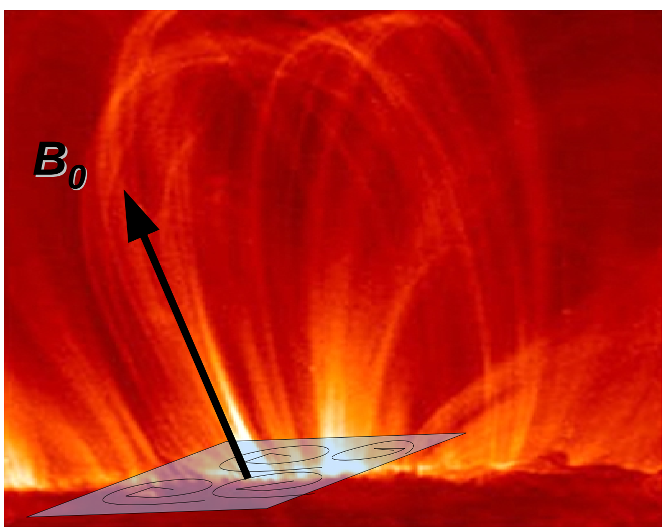
...and from fluid-like models of a plasma we explore now “Vlasov turbulence”

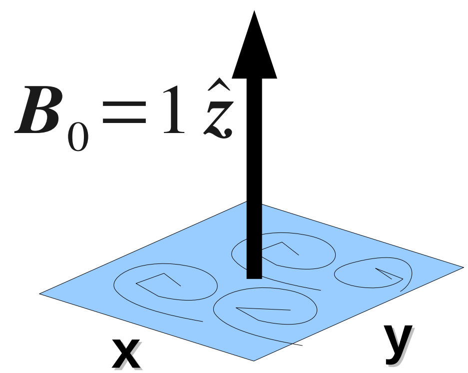
Hybrid Vlasov-Maxwell

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

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

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





NOISE–FREE!

Valentini *et al.*, J. Comp. Phys. 2007, PRL 2010, PRL 2011

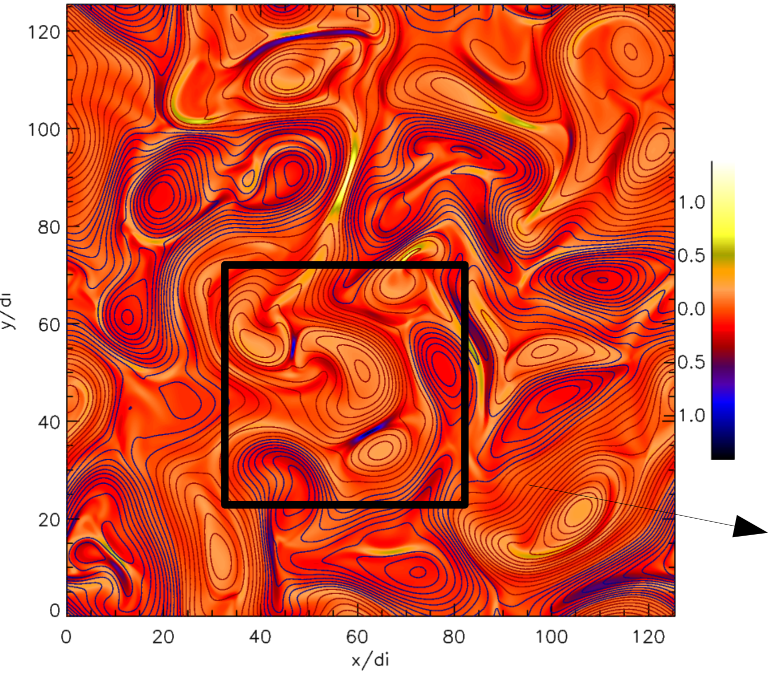
- ***Kinetic ions, fluid electrons***
- ***Eulerian model***
- ***2D in space + 3V in the velocity space***

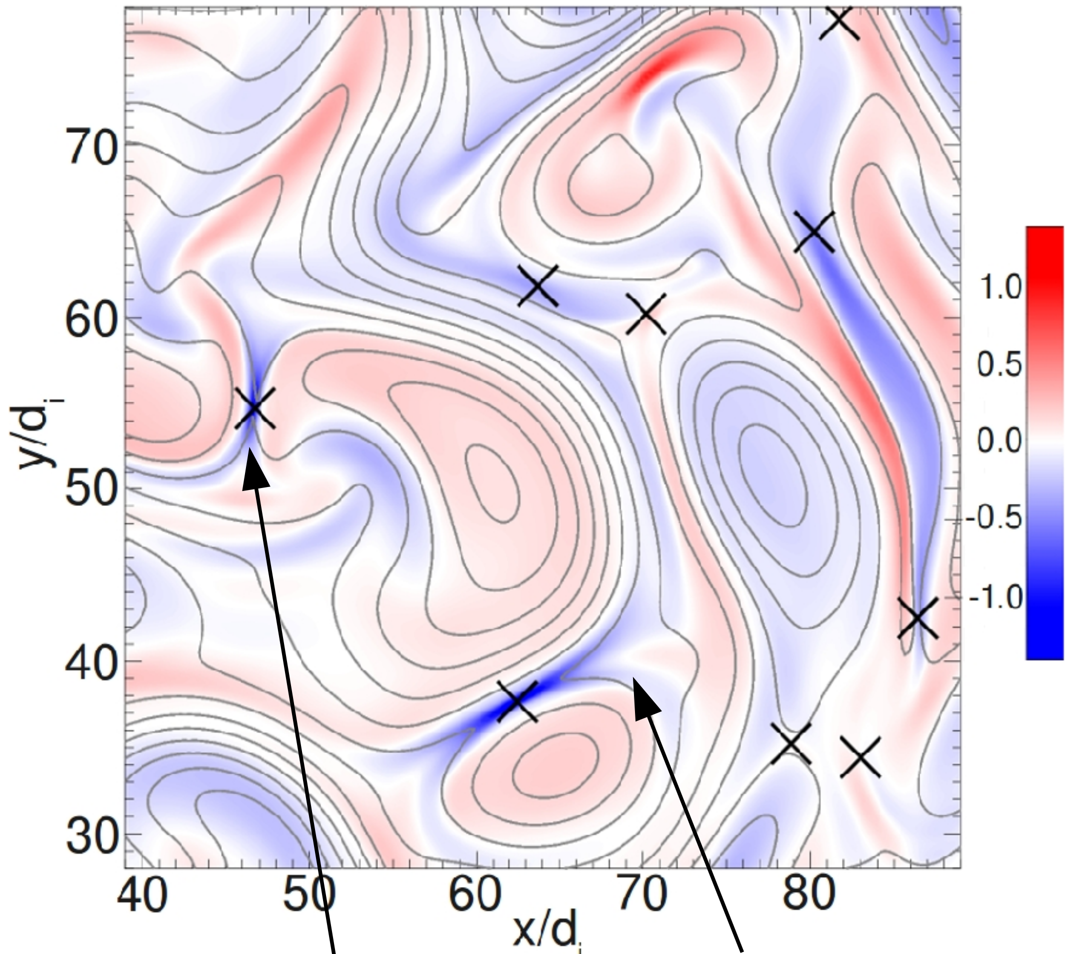
Some parameters ...

$$L_0 = 2\pi\alpha d_i,\ B_0 = 1\hat{e}_z,\ T_e/T_i = 1,$$
$$\eta = 1.7\times10^{-2},\ v_{max} = \pm 5 v_{ti},$$
$$N_X = N_Y = 512^2,\ N_v = 81^3 \rightarrow 3.5\times10^{10}\ \textit{points}$$

Local Reconnection Events

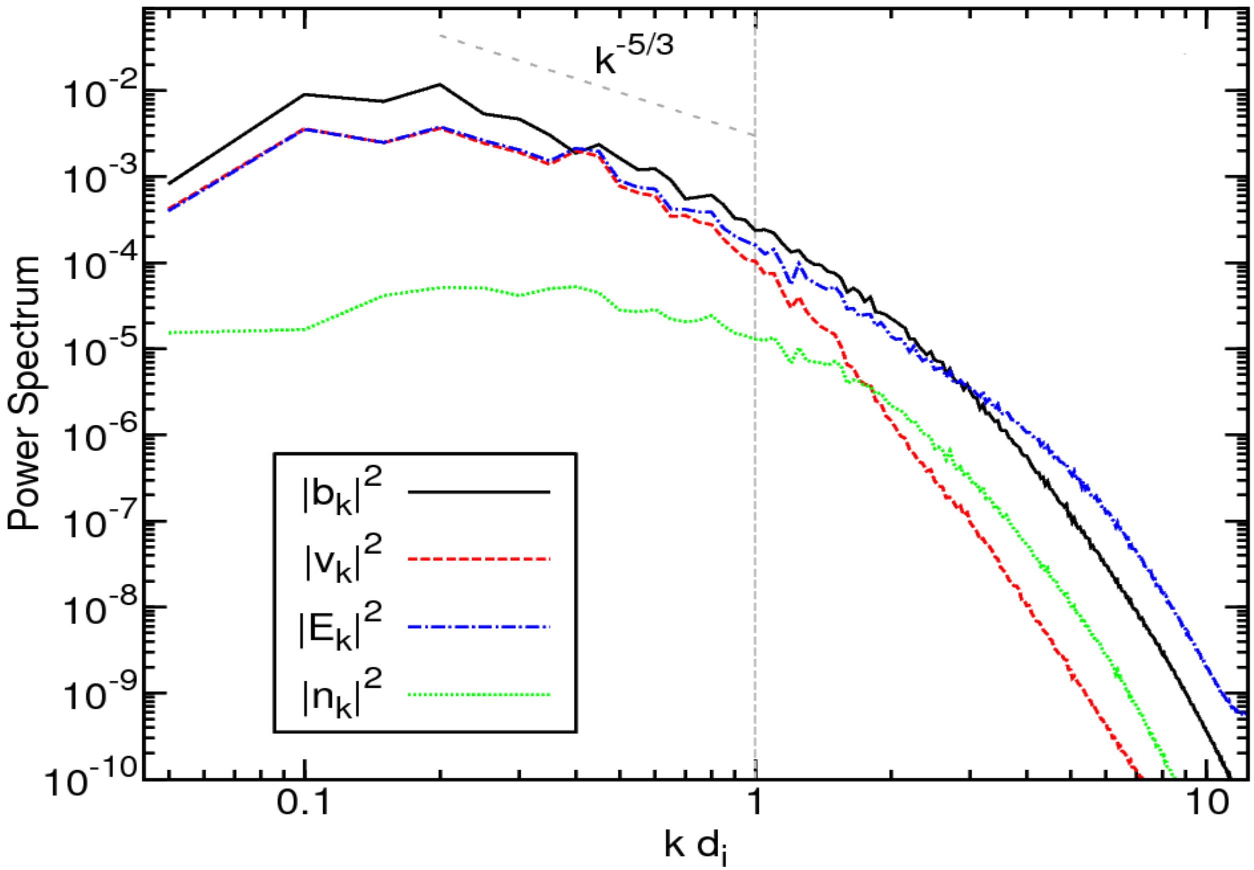
Current density j_z (colors) + magnetic potential

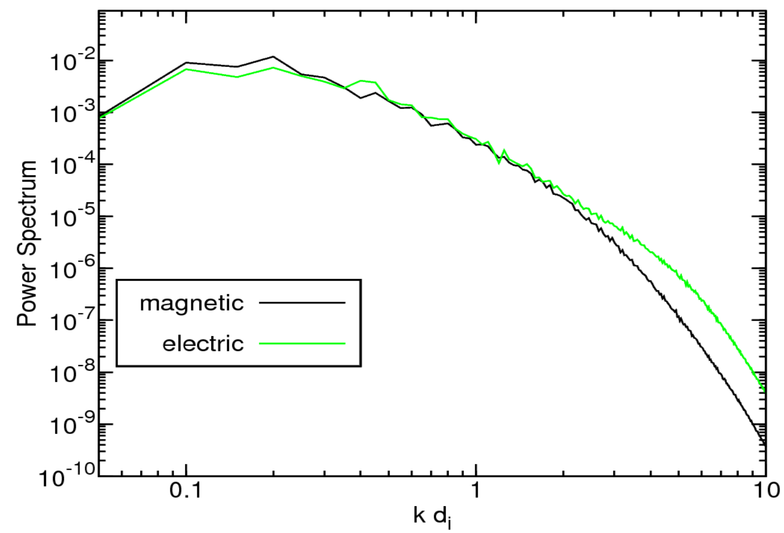


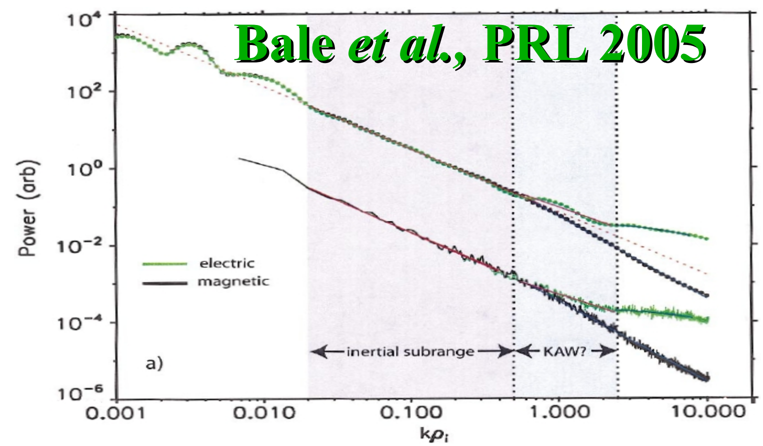


Servidio *et al.* PRL 2009
Drake *et al.* APJ 2010.

Power spectra







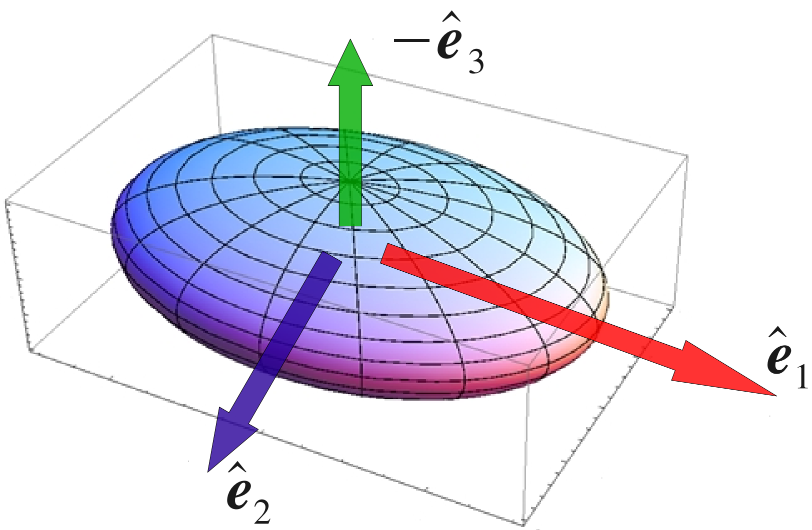
- **Large scale Alfvenic correlations**
- **Kolmogorov-like spectrum**
- **Low compressibility (density fluct. 8%)**
- **Intense electric activity at small scales**
- **Steepening of the magnetic spectrum at $kd_i \sim 1$**

...several features commonly observed in space plasmas!

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)

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

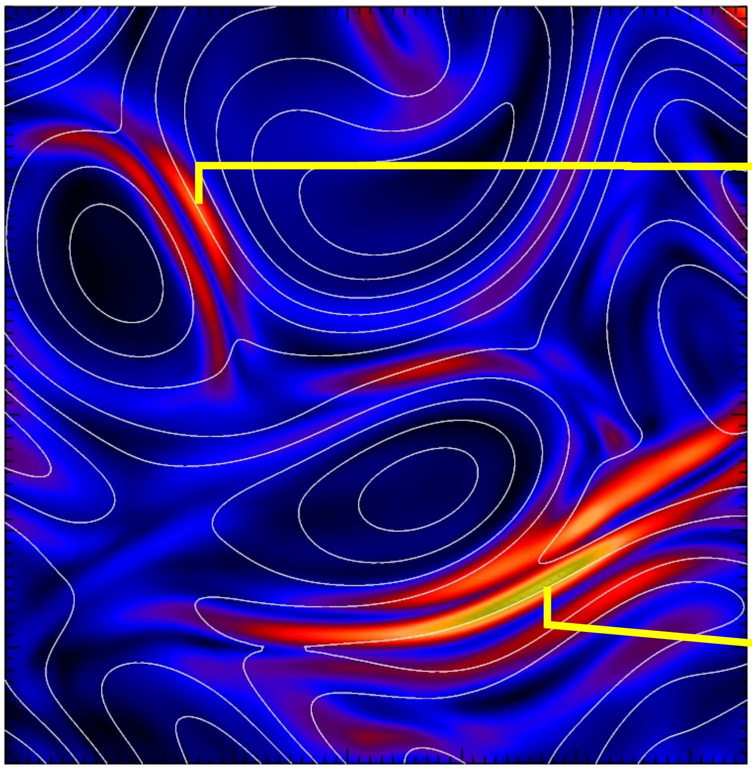
Eigenvalues (temperatures) $\lambda_1 > \lambda_2 > \lambda_3$

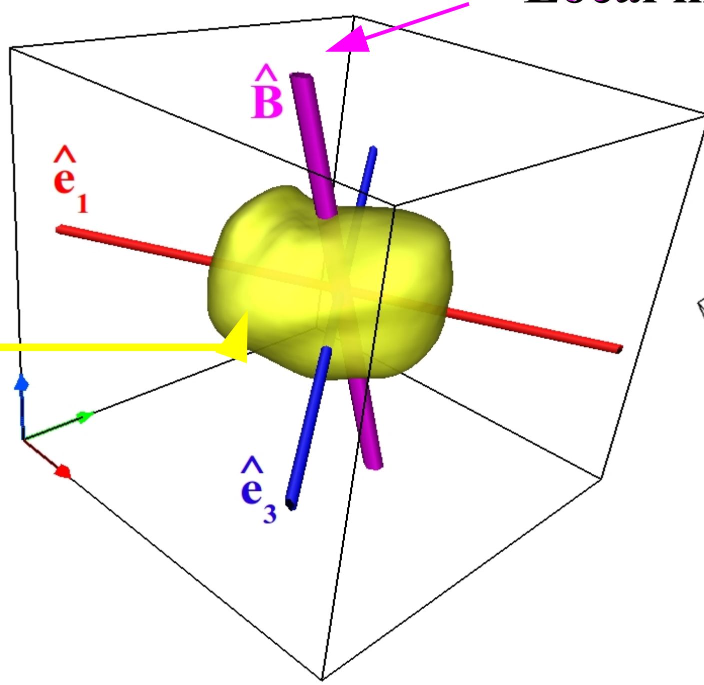
Eigenvectors $\hat{e}_1 \quad \hat{e}_2 \quad \hat{e}_3$

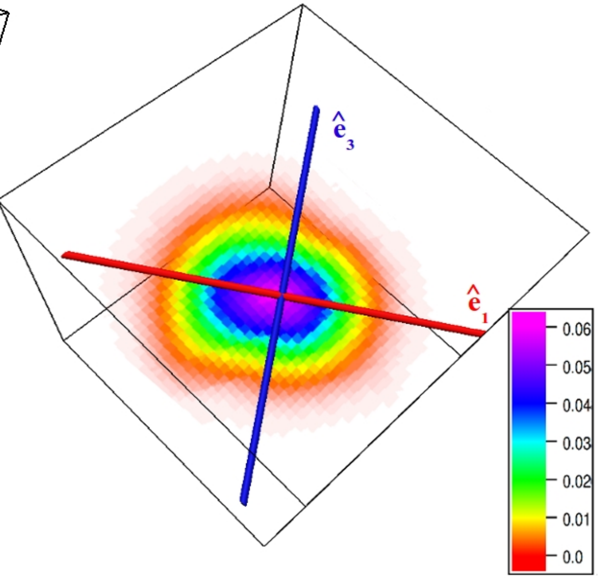
Note: for a Maxwellian $\lambda_1 = \lambda_2 = \lambda_3 = 1$

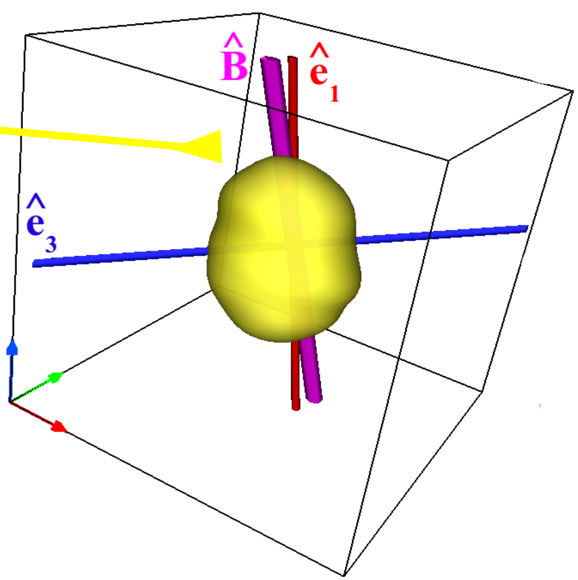
(Maximum) Temperature anisotropy ≡ λ_1 / λ_3

Distribution Functions in Turbulence





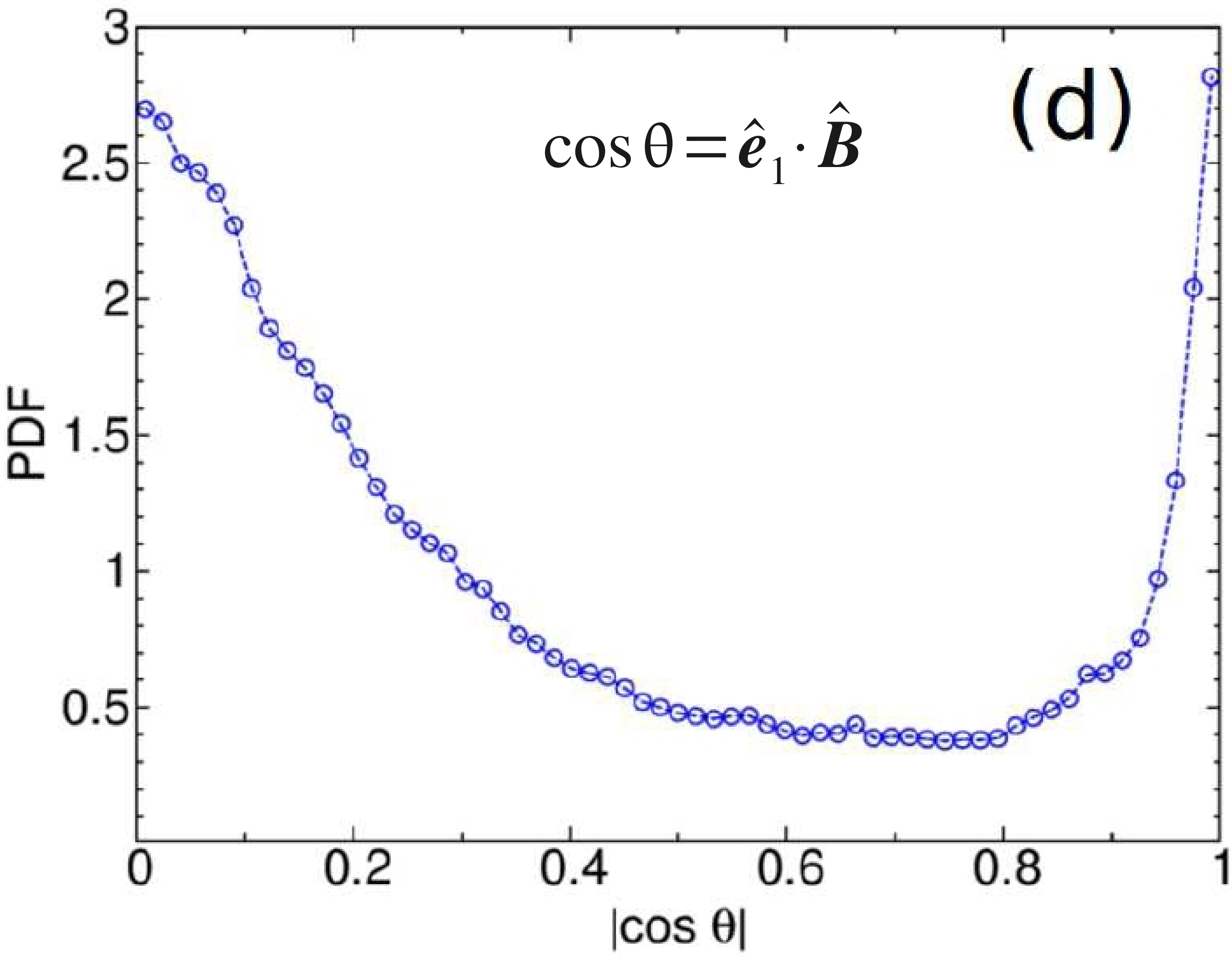




the DF is strongly affected by turbulence, resembling an elongated potato-like structure

Anisotropy can be either >1 or <1

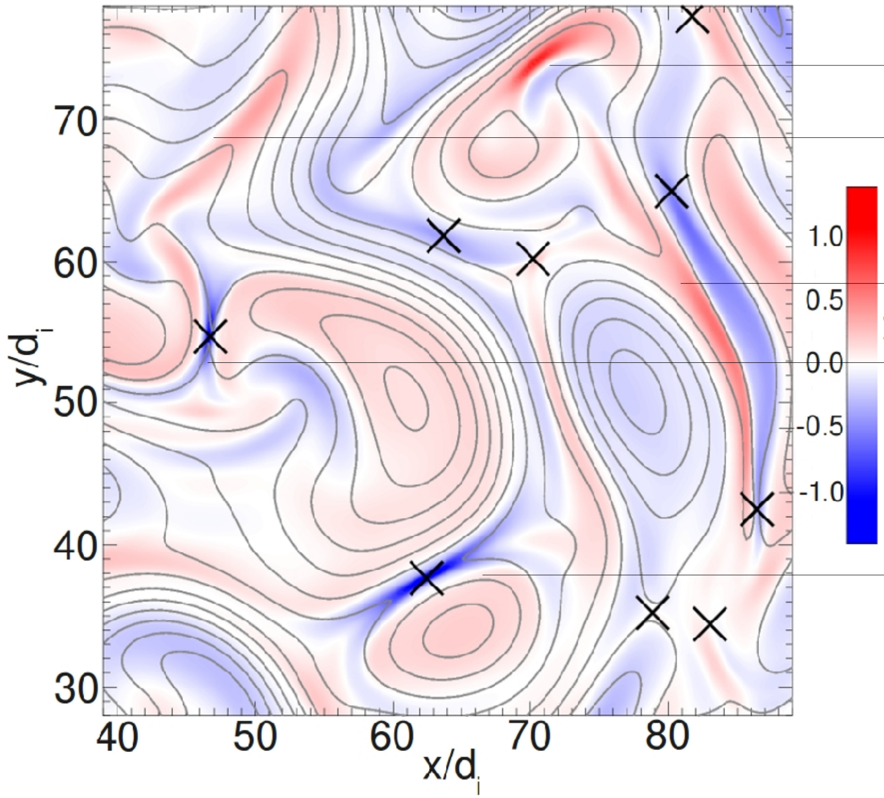
Temperature Anisotropy & the Magnetic Field

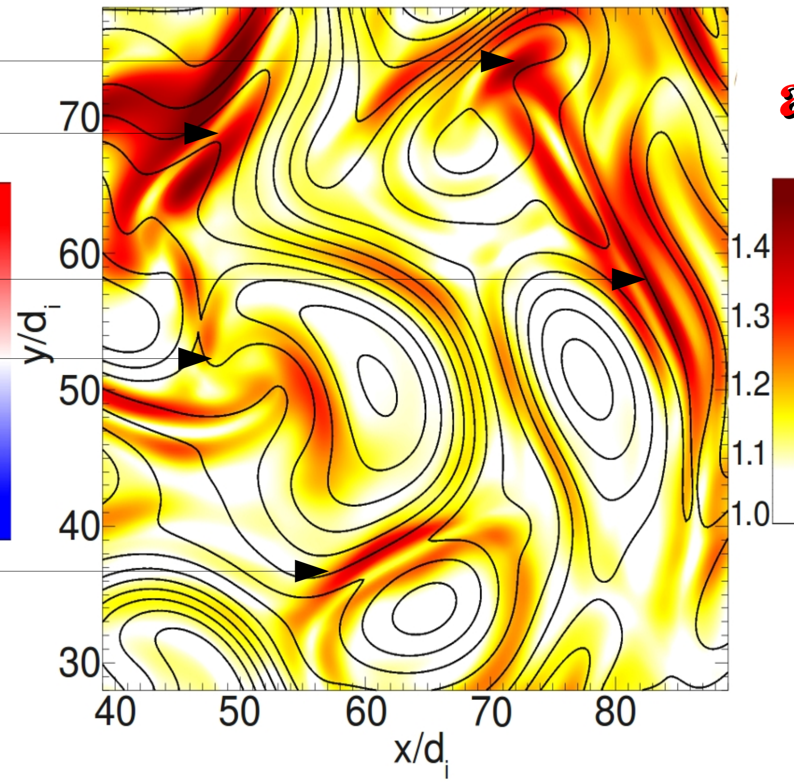


mainly e_1 can be both along or across B, but, because of turbulence, a broad distribution of angles is observed.

Note: If e_1 and B were spatially random and uncorrelated, PDF(|cos θ|) ~ const. (=1)

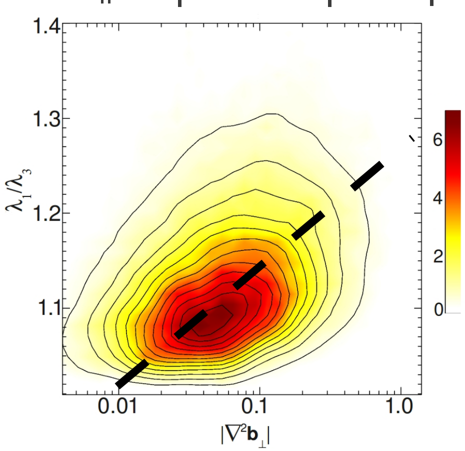
Where these "patches" are located?





anisotropy

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

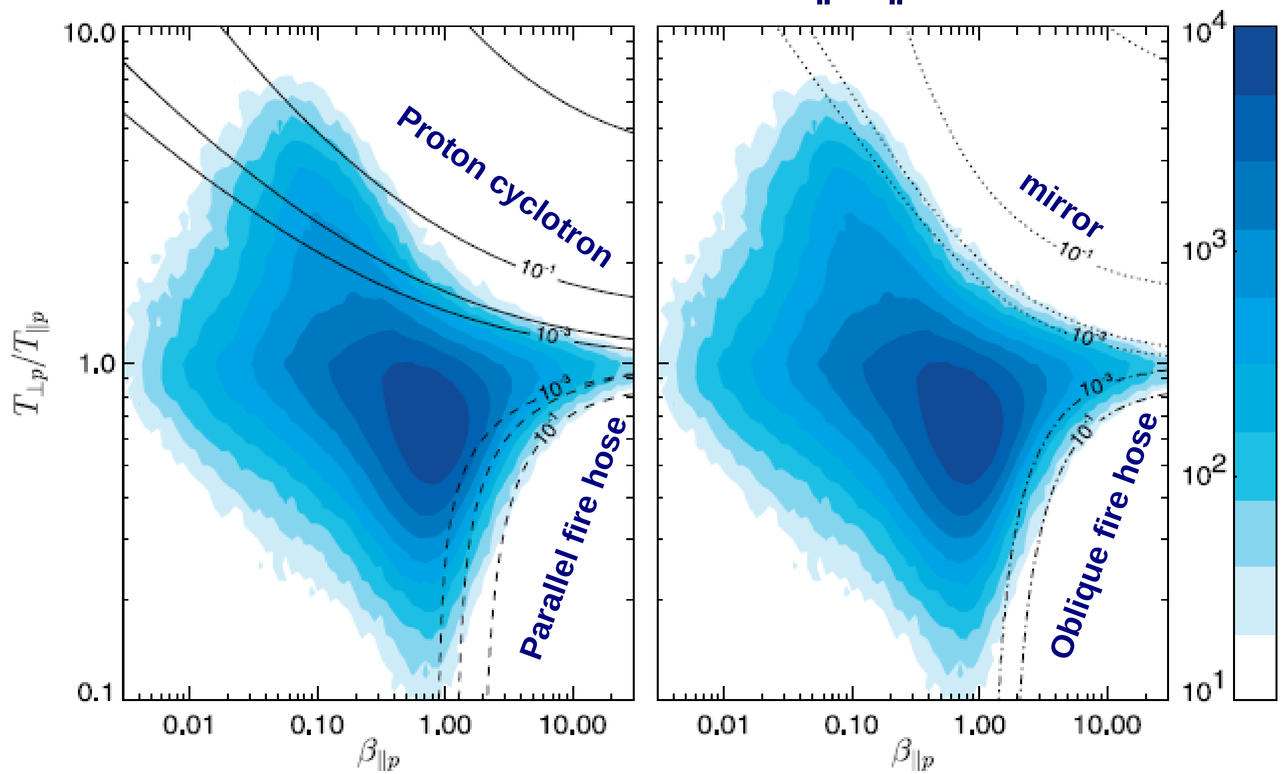


streams of kinetic effects (anisotropy, skewness and Kurtosis) are adjacent to reconnecting current sheets.
In a fluid model these would correspond to regions where collisional dissipation takes place. Here cyclotron and/or Landau resonances may be at work.

Servidio *et al*, PRL 2012

Applications: Solar Wind

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



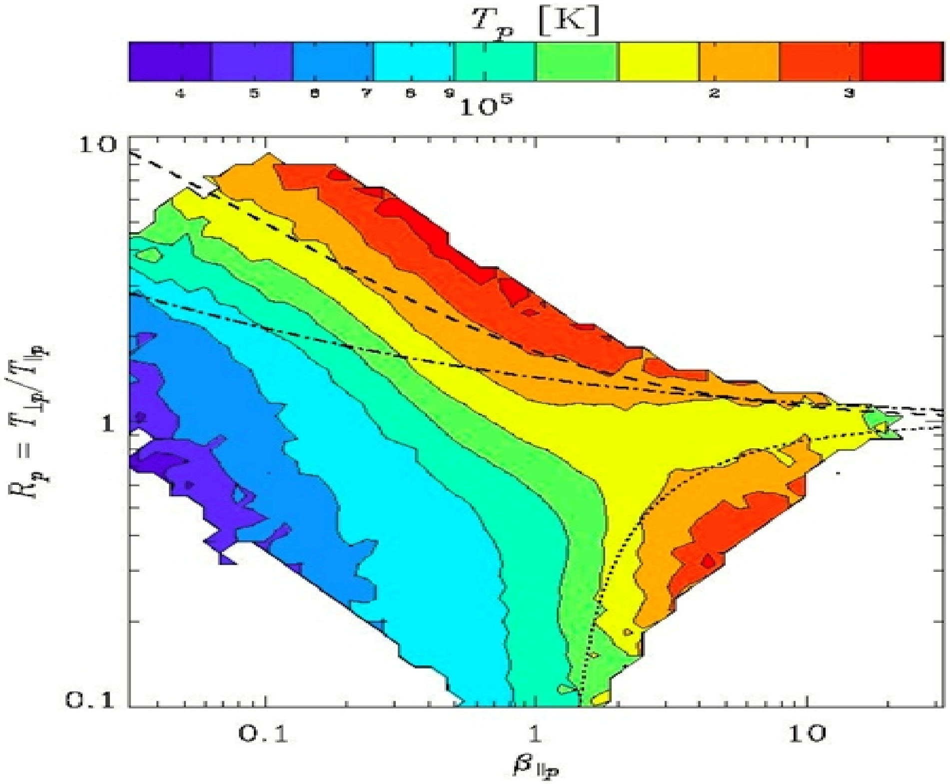
$T_{||}$ and $T_\perp$ ≡
parallel and perpendicular proton temperatures with respect to the ambient *B*

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

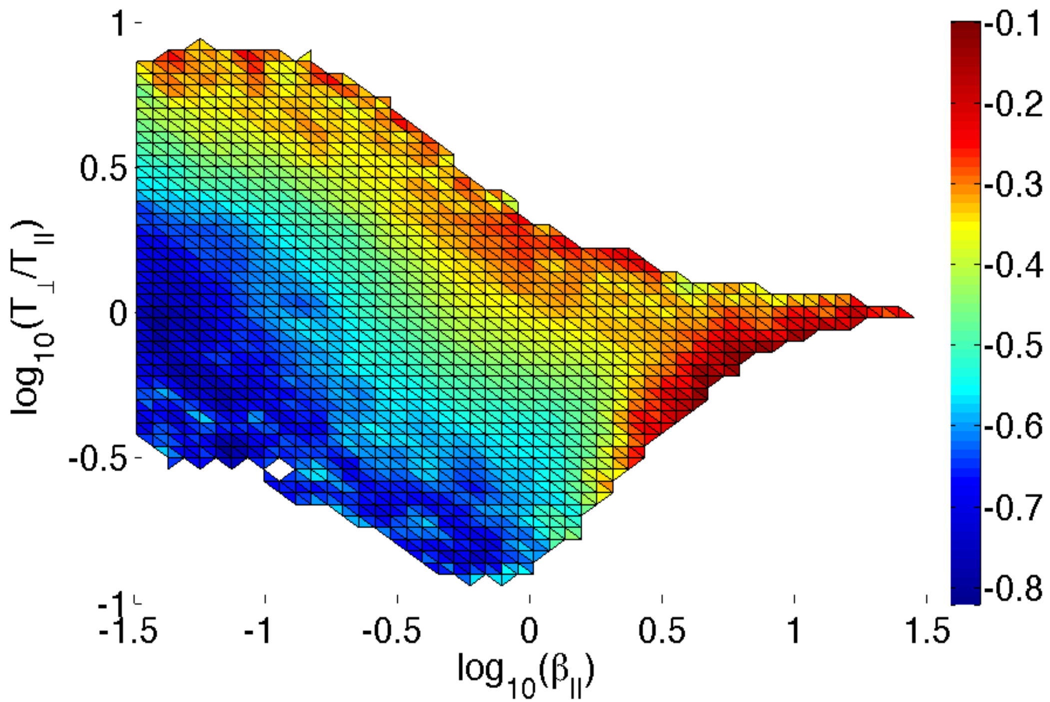
Kinetic instabilities influence the solar wind → **nonlinear kinetic processes may locally occur in turbulence!**

Non-homogeneous Effects ?

Temperature on ($\beta_{||}$, $T_\perp/T_{||}$)



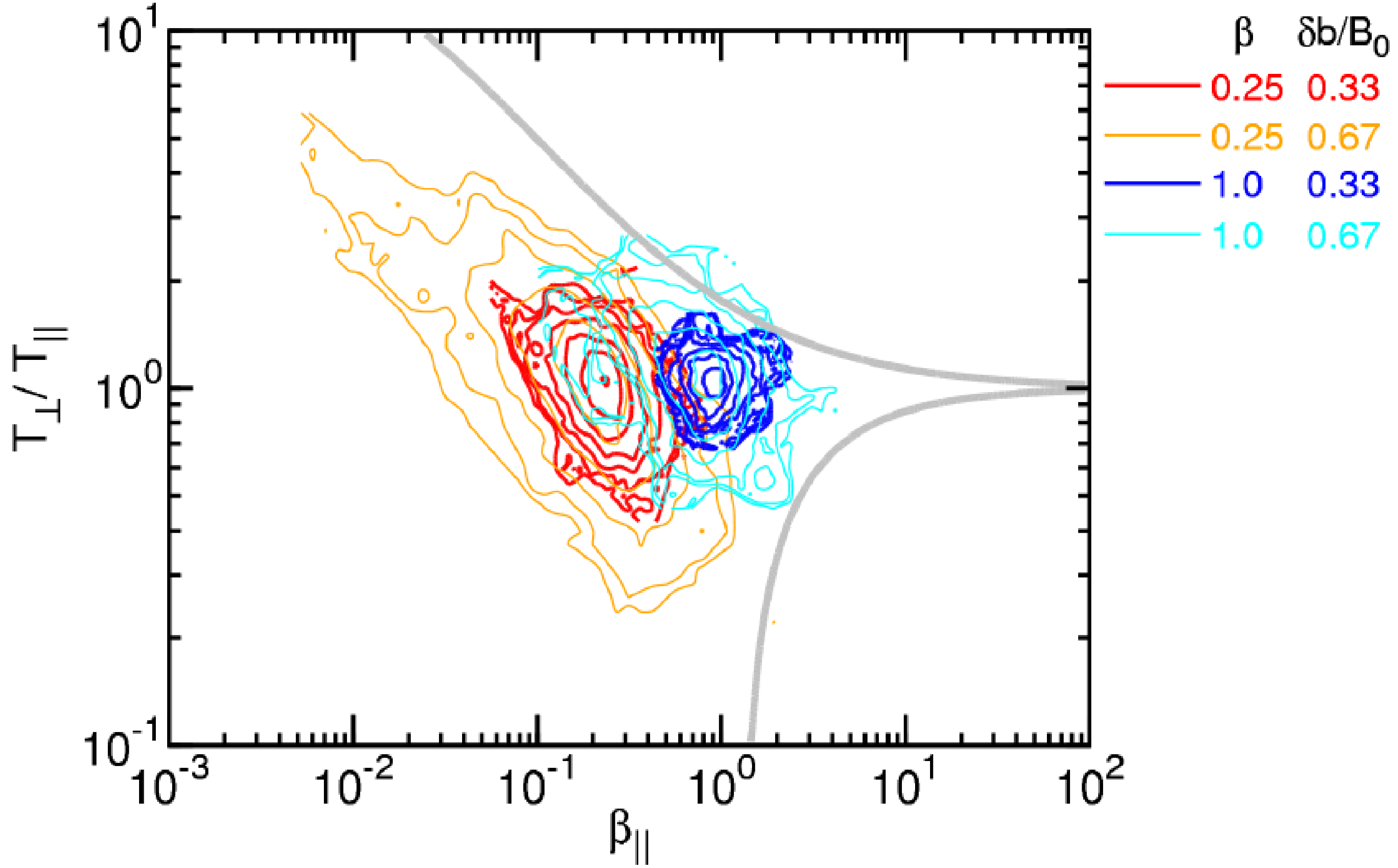
$$PVI = \frac{|\Delta B|}{\sqrt{\langle |\Delta B|^2 \rangle}}$$ **on ($\beta_{||}$, $T_\perp/T_{||}$)**



Osman et al., PRL 2012

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

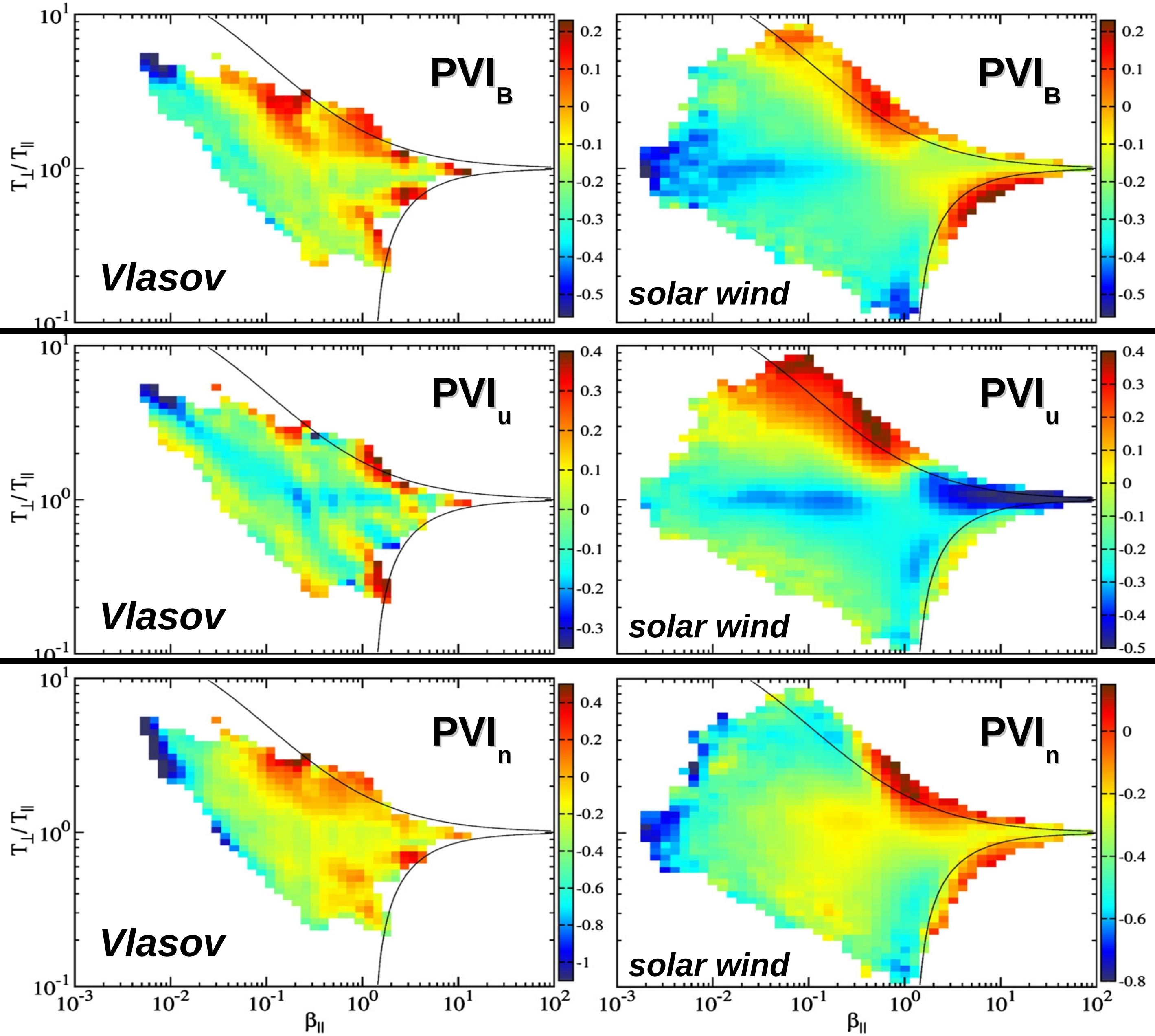
Vlasov Simulation(s)



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

Vlasov *vs.* Solar wind

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



Magnetic intermittent structures

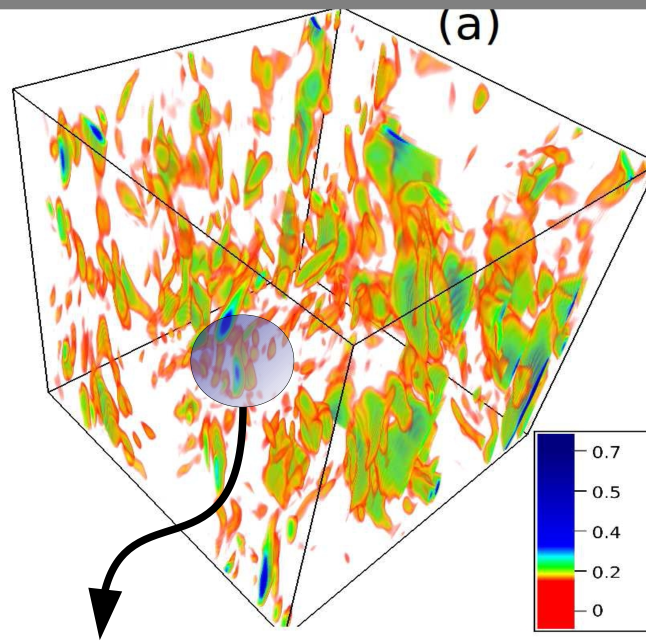
velocity intermittent structures

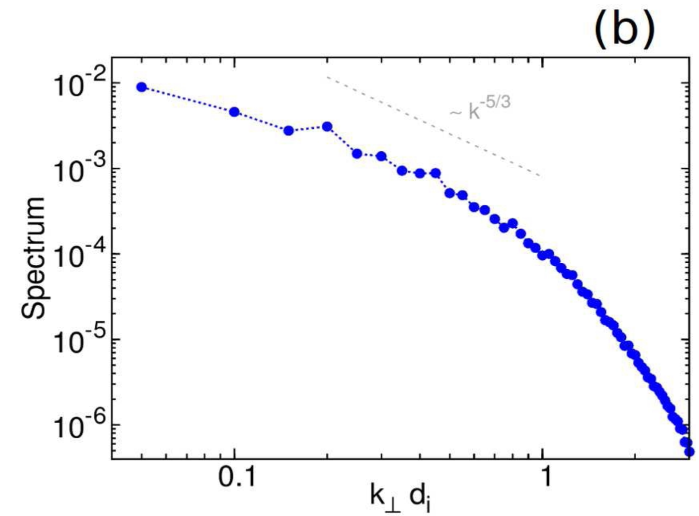
density intermittent structures

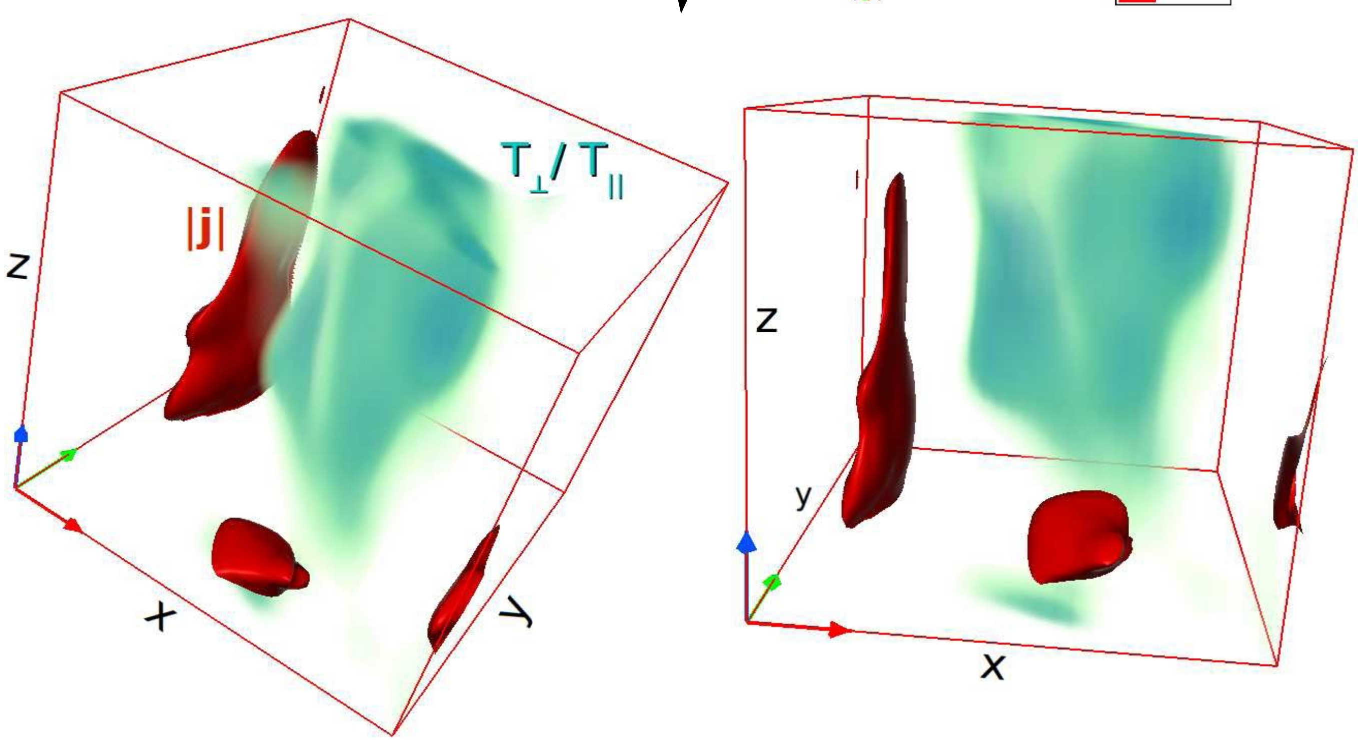
Servidio et al., APJL 2014

"6D" Vlasov

Intermittent, anisotropic Vlasov turbulence...



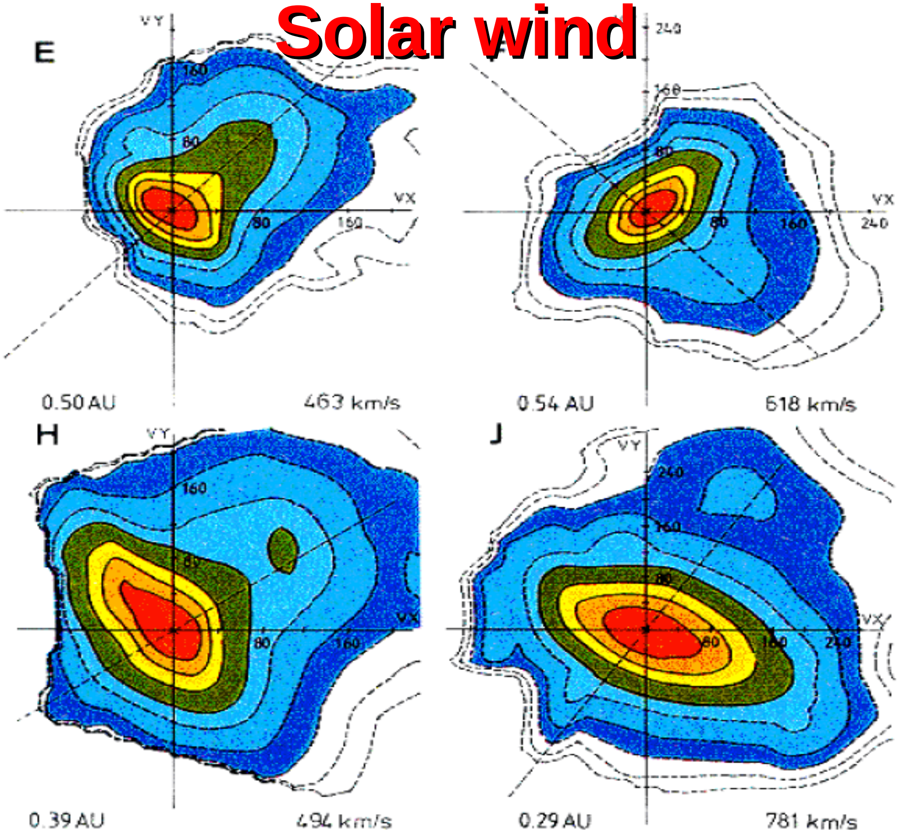




Patterns of temperature anisotropy are near current sheets

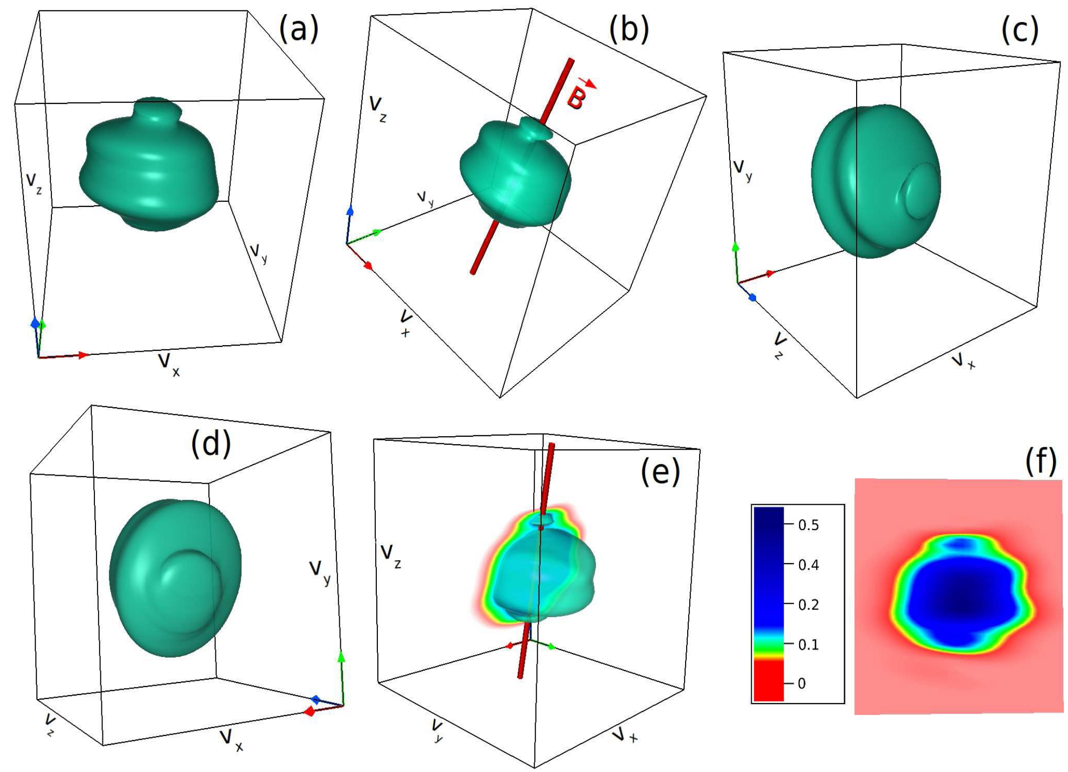
6D Vlasov: proton beams

Solar wind



beams, anisotropy, and strong non-gyrotropic modulations

Vlasov



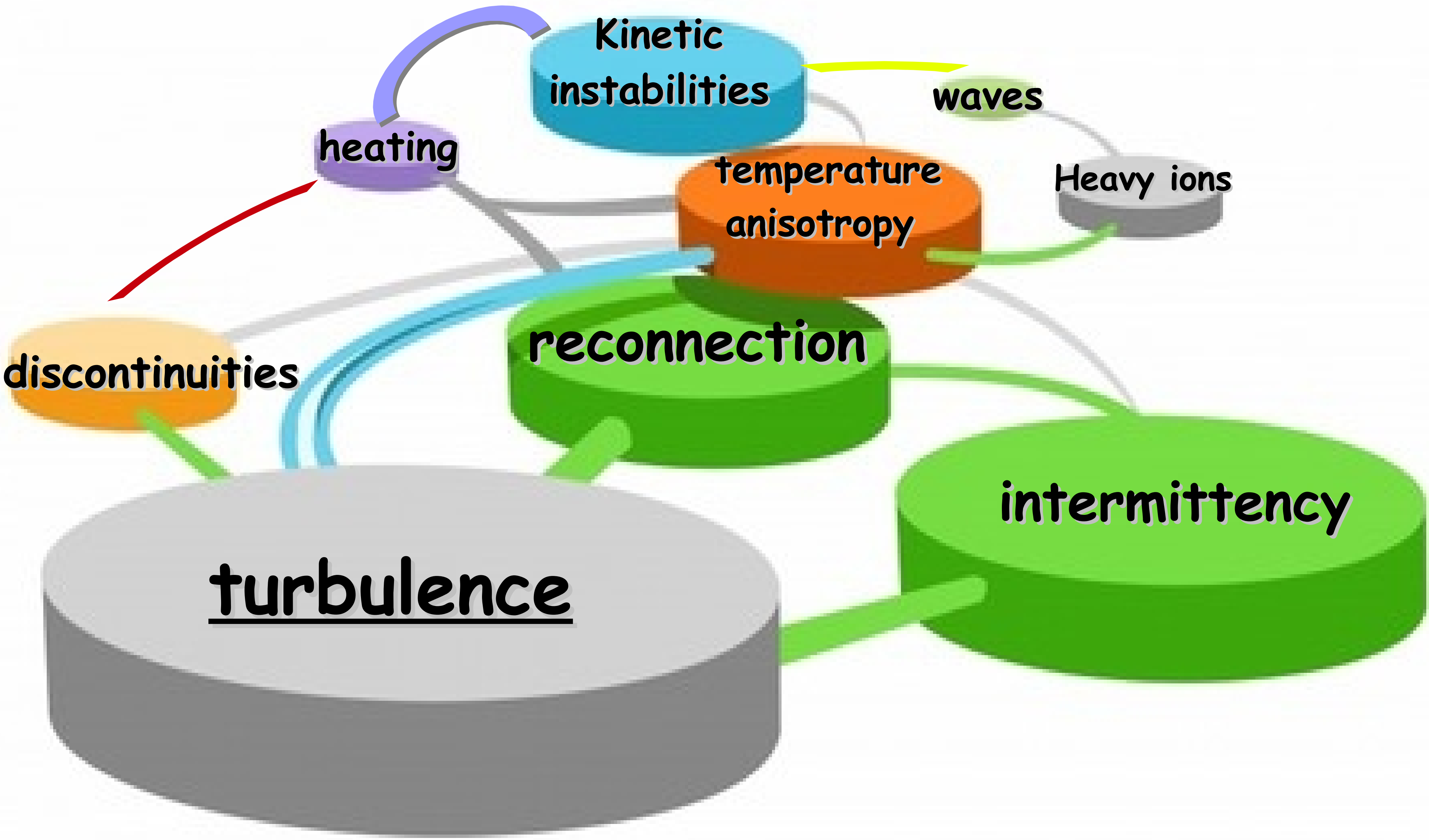
Landau resonances can be locally excited:

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

Conclusions

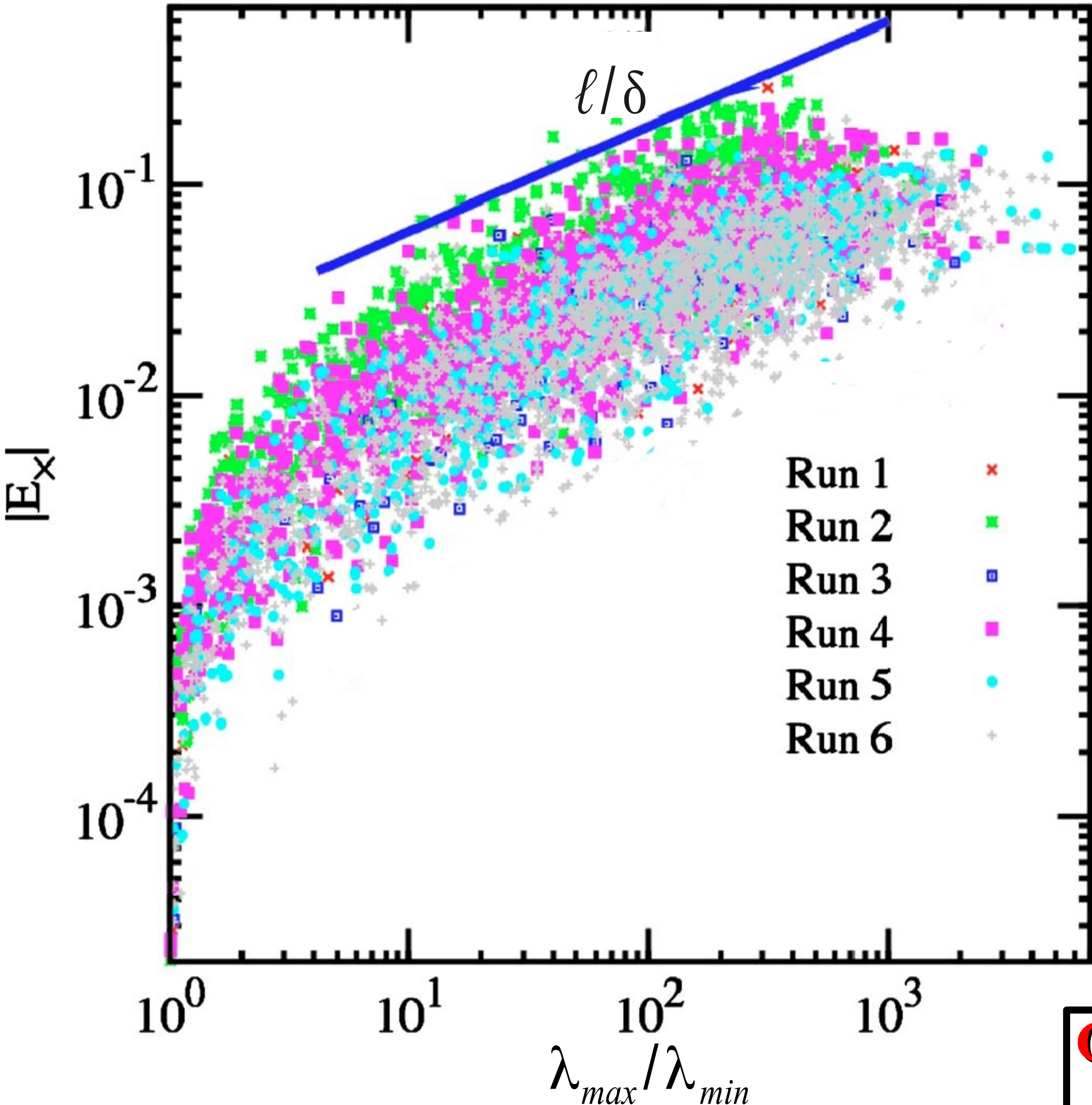
- MHD turbulence provides a broad range of reconnection rates
- Reconnection rates can be determined statistically in terms of measurable correlation, Taylor, and dissipation scales.
- Hall effect enhances the reconnection process in turbulence
- Hybrid-Vlasov simulations confirm the above results and moreover 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

A “simple” sketch



Extra slide

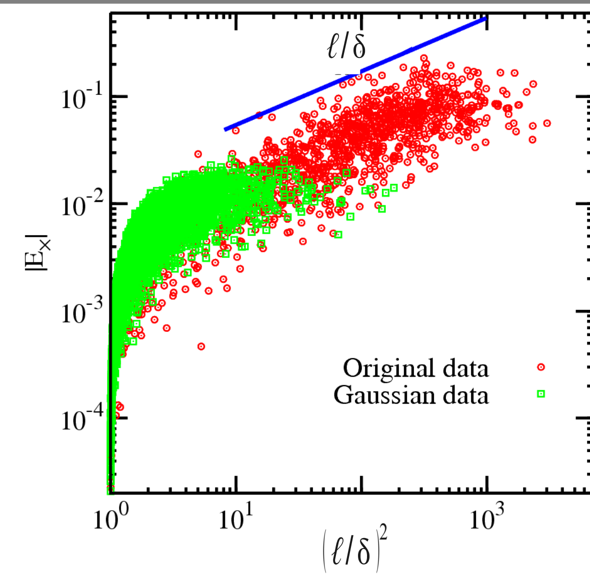
Dependency on the Geometry



Fastest reconnection rates depend on the geometry of the diffusion layer

$$E_X \sim \frac{\ell}{\delta}$$

$\ell \equiv elongation$
$\delta \equiv width$

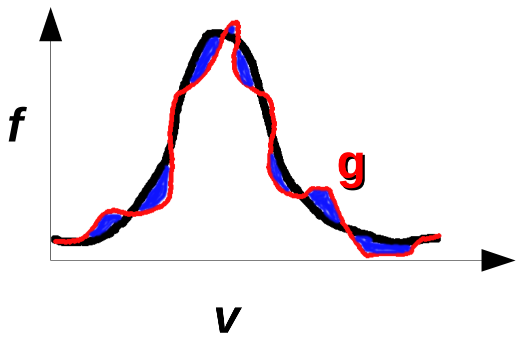


Gaussian fields have much slower reconnection rate: Turbulence enhances reconnection

Extra slide

Quantifying kinetic effects ...

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

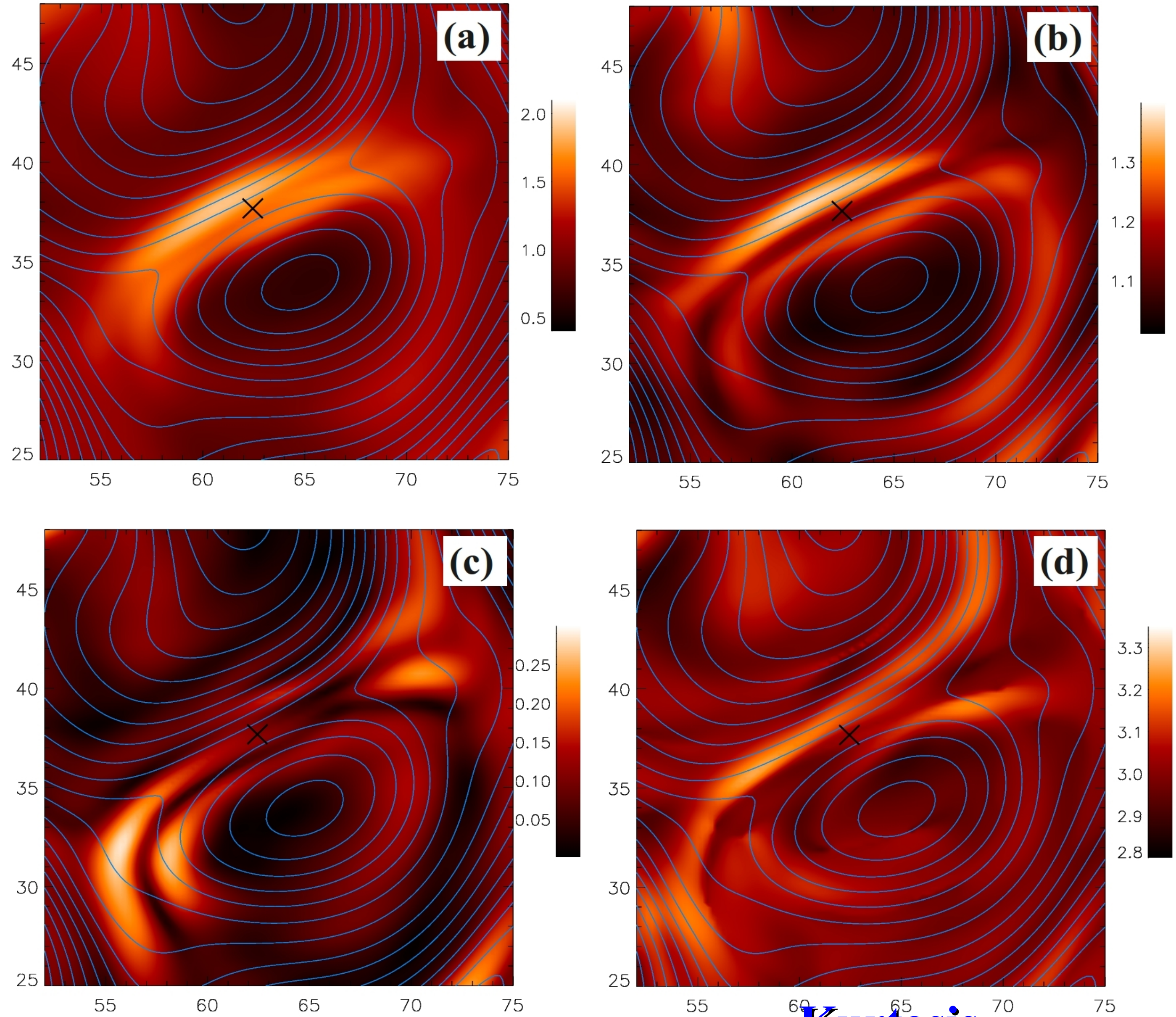


g is the Maxwellian associated to f (with same bulk velocity, density, and (isotropic) temperature.)

Anisotropy

Skewness

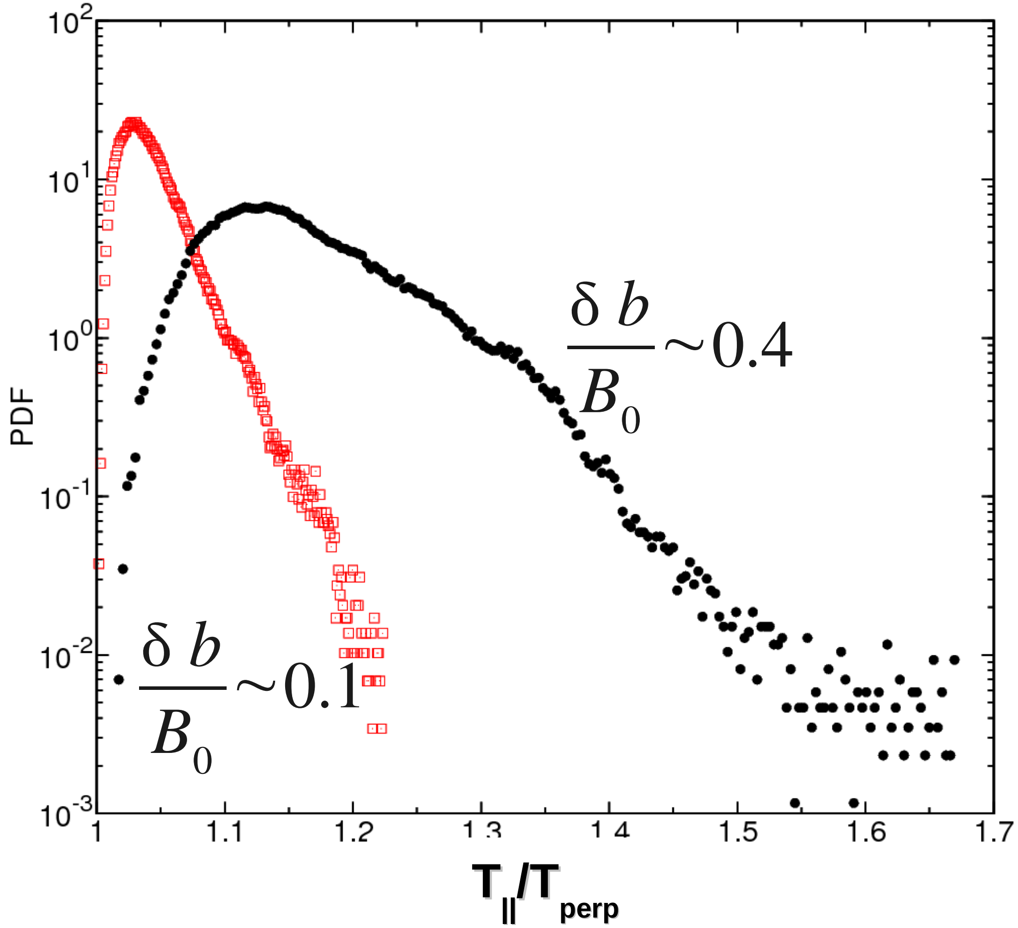
Kurtosis



A. Greco el al, PRE in press

Extra slide

Anisotropy & Reconnection



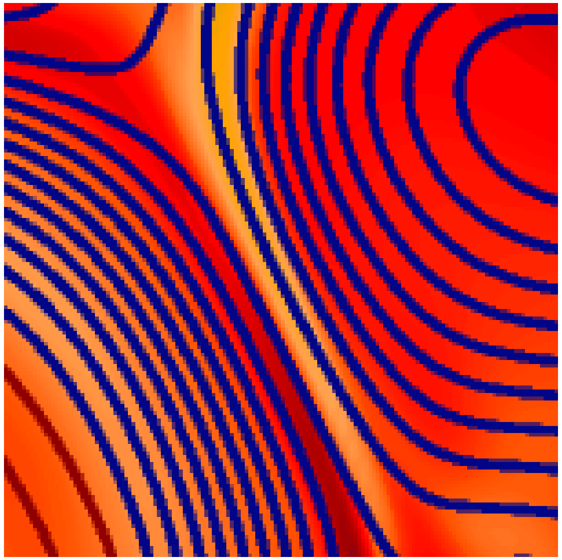
Turbulence enhances the level of local anisotropy nearby reconnection sites

Extra slide

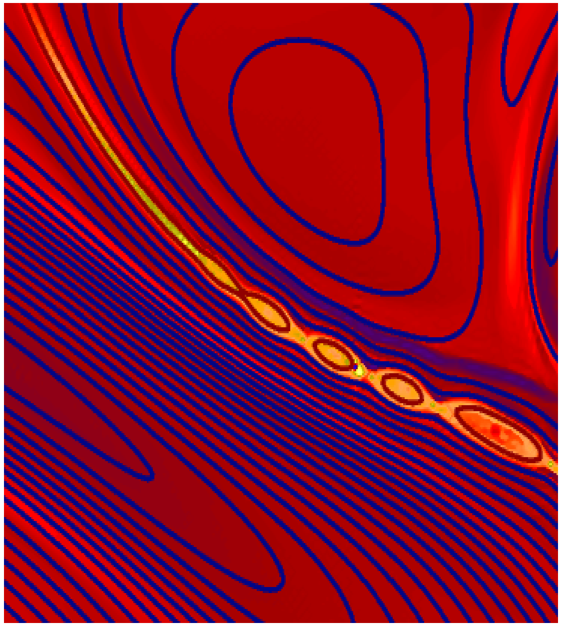
Note on the Numerics

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

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



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



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

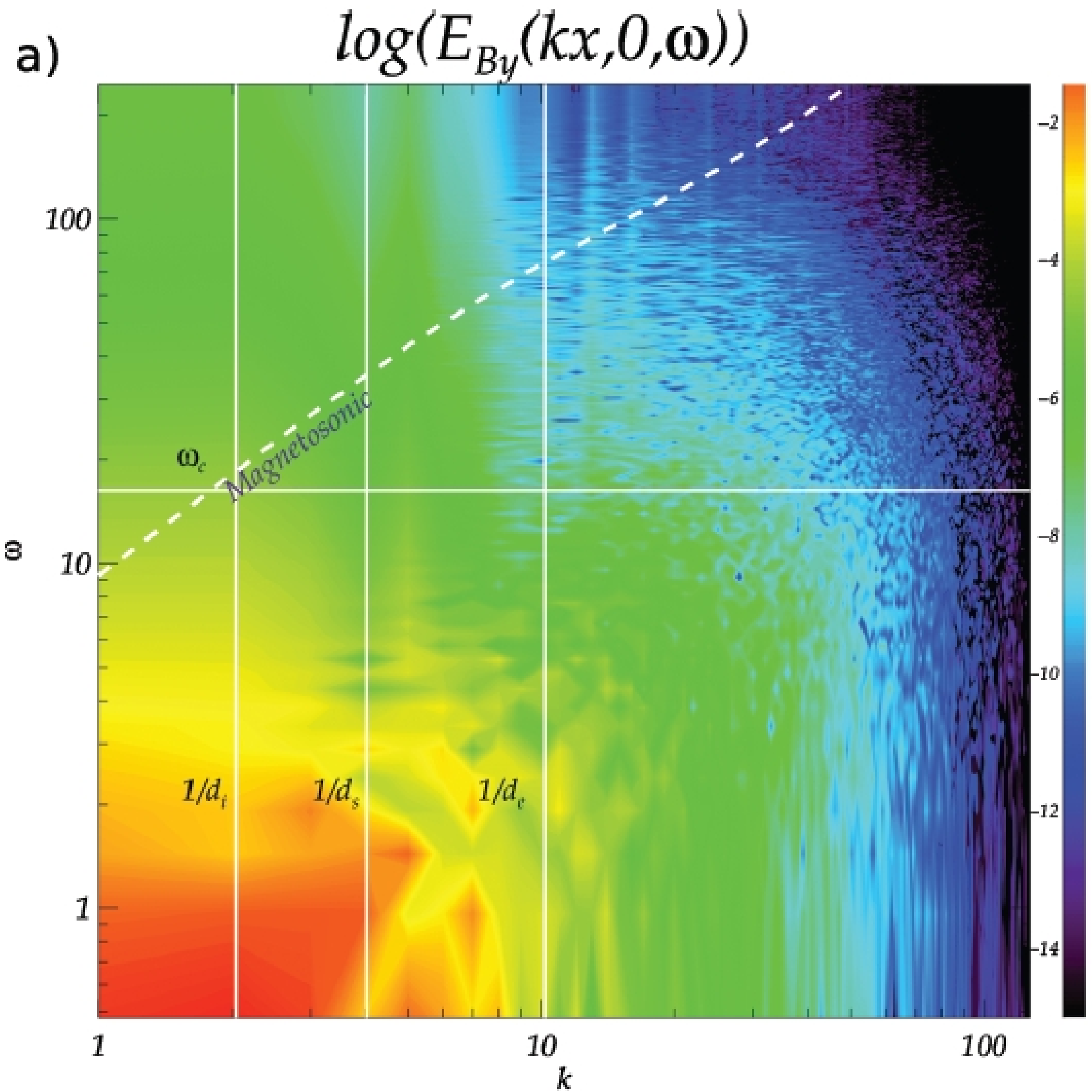
Reconnection events in turbulent regime are strongly affected by "Gaussianization" of small scales!!!

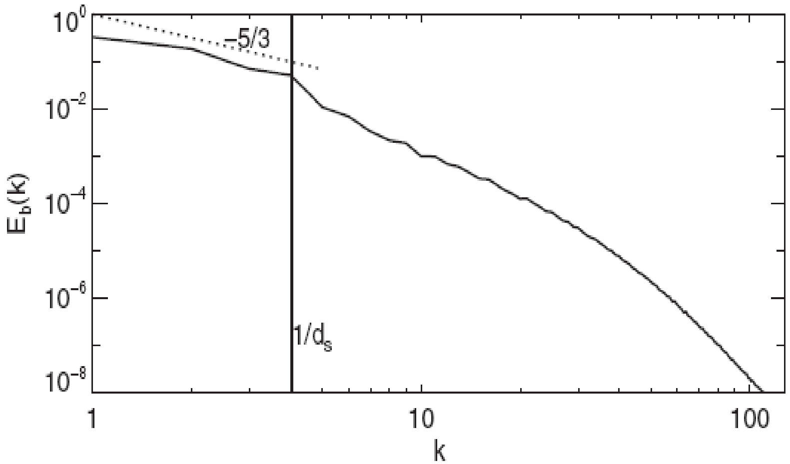
Wan *et al.*, Phys. Plasmas (2009,2010)

Extra slide

Waves in turbulence?...

Driven simulations of kinetic turbulence using Hybrid PIC code





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

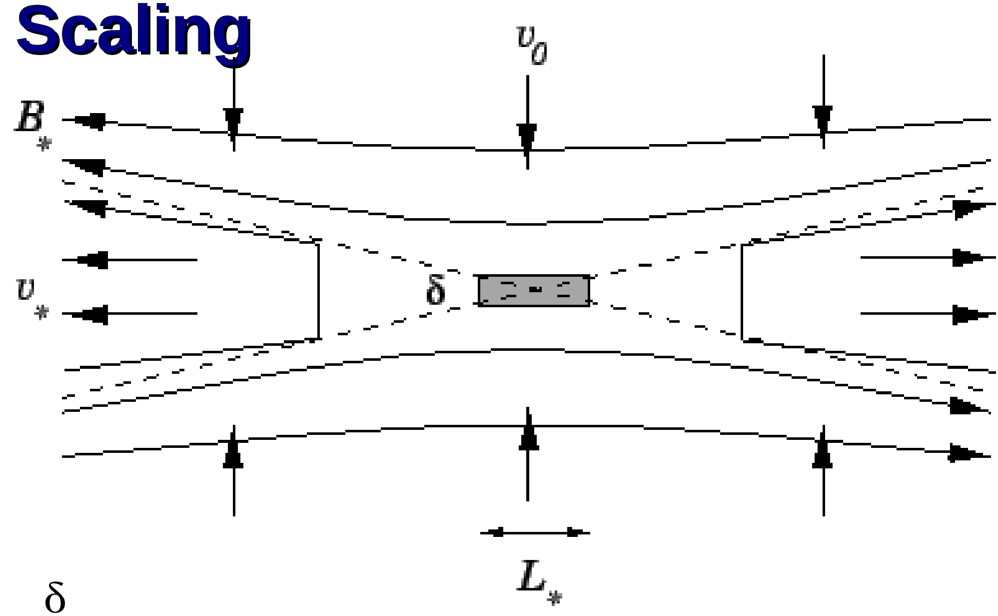
Parashar et al. Phys. Plasmas 2010, 2011

Extra slide

Theory of magnetic reconnection

Sweet-Parker Scaling

A steady-state is reached when field lines convect into the collisional layer at the same rate that they are annihilated



1) Continuity / mass conservation ➡ $v_{in} = \frac{\delta}{L} v_{out}$

2) The pressure available for squeezing the fluid out is magnetic ($B^2/8\pi$), so, from energy considerations, the outflow speed is: ➡ $v_{out} = \frac{B}{\sqrt{4\pi\rho}} = c_A$

3) Continuity of the electric field between x point and the upstream region ➡ $v_{in} = \frac{\eta c^2}{4\pi\delta}$

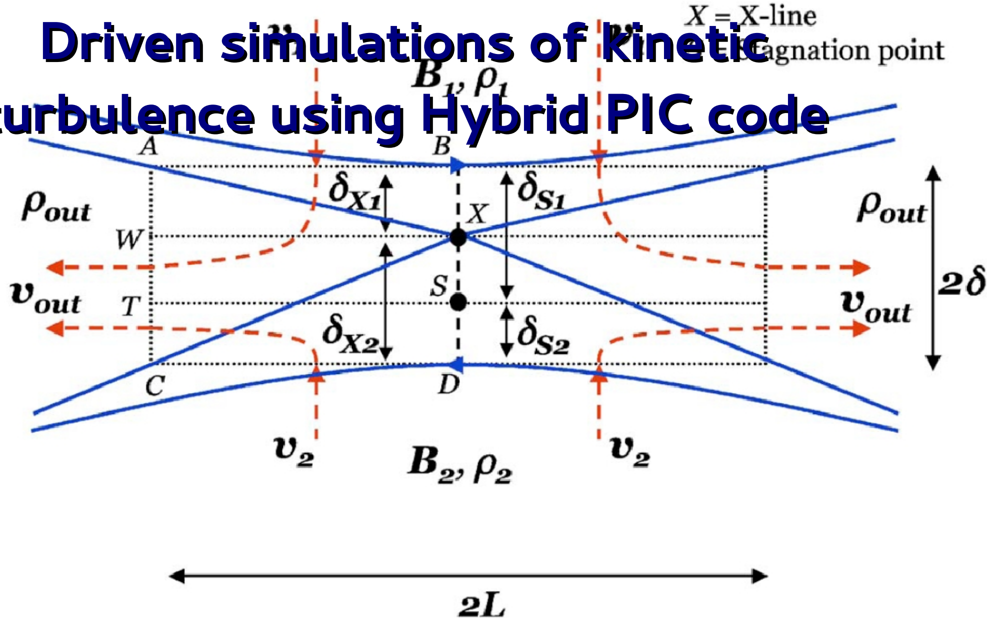
$$\frac{\delta}{L} \sim \frac{v_{in}}{v_{out}} \sim \frac{cE}{B c_A} \sim \sqrt{\frac{\eta c^2}{4\pi c_A L}} \sim S^{-1/2}$$

L is a free parameter which scales with the system size. Is approximately the size of the flux tube

Extra slide

Asymmetric Reconnection

Driven simulations of Kinetic turbulence using Hybrid PIC code



P. Cassak & M. Shay, Phys. Plasmas 2007

A Sweet-Parker-type scaling analysis for asymmetric, anti-parallel, reconnection has been recently proposed by Cassak & Shay (2007):

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

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

Extra slide

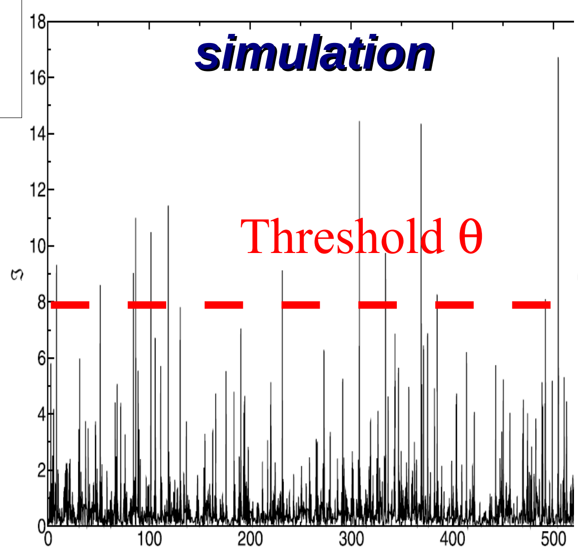
A method for identifying discontinuities

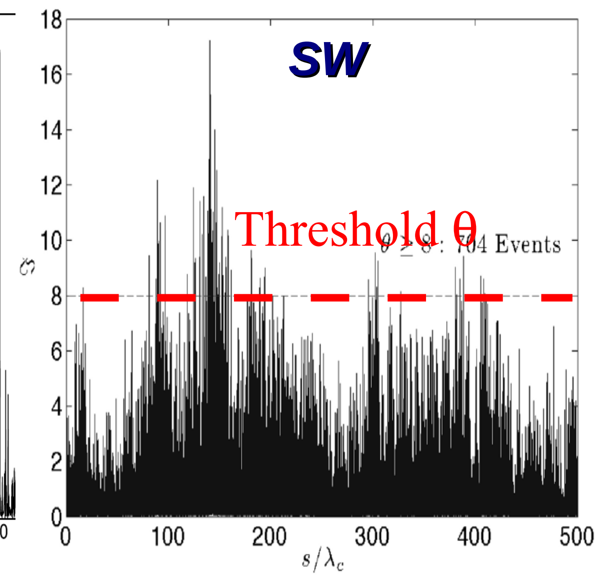
The Partial Variance of Increments (PVI)

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

$$\downarrow$$

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





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