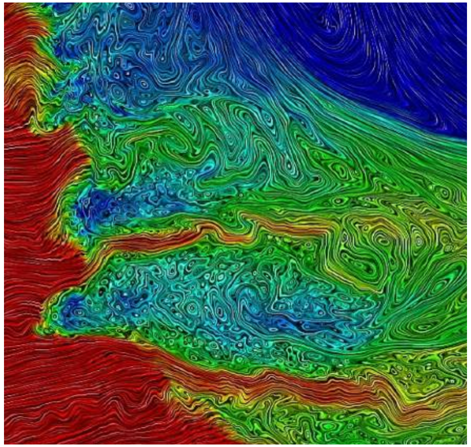
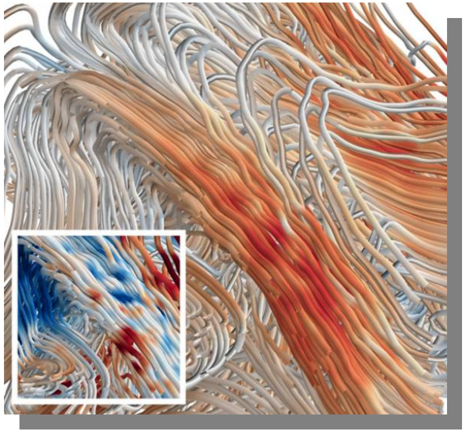
# Joint ICTP-IAEA College on Plasma Physics

## Vlasov simulatons of plasma turbulence: Part 2

Sergio Servidio
Dipartimento di Fisica
Università della Calabria
sergio.servidio@fis.unical.it
https://sergioservidio.wixsite.com/sergio





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DIPARTIMENTO DI FISICA

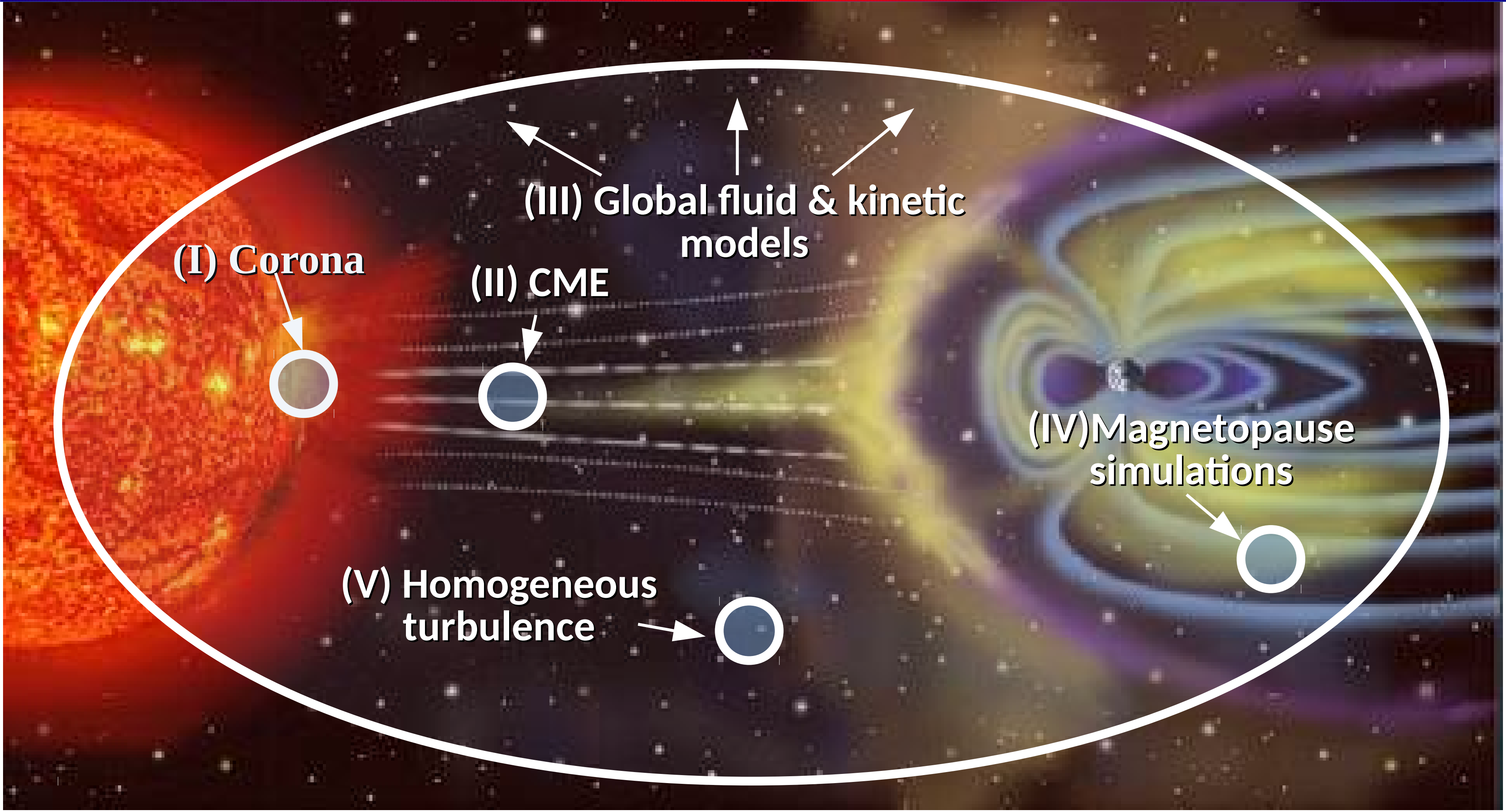
# Part II

Direct numerical simulations of plasma turbulence: Eulerian simulations

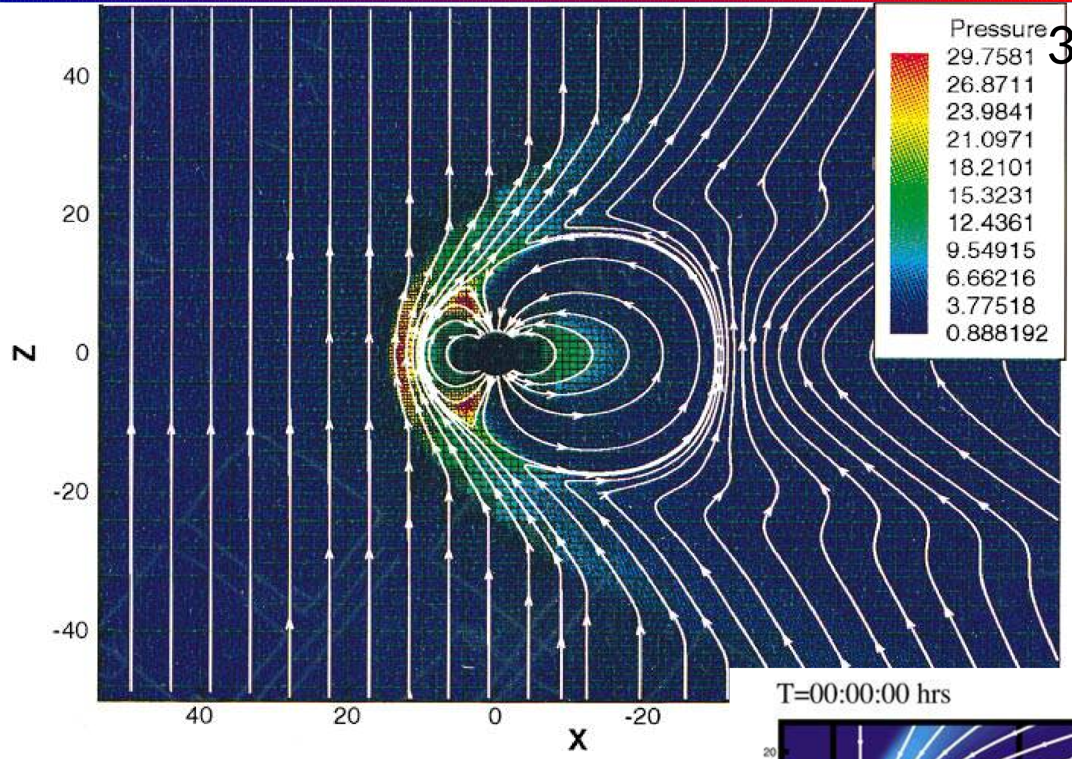
# Outline of Part II

- Global simulations of space plasmas
- From global to local simulations of the Vlasov equations: the hybrid Vlasov-Maxwell (HVM) code
- Direct numerical simulations of decaying plasma turbulence
- From 2D to 3D simulations

# Global & local simulations

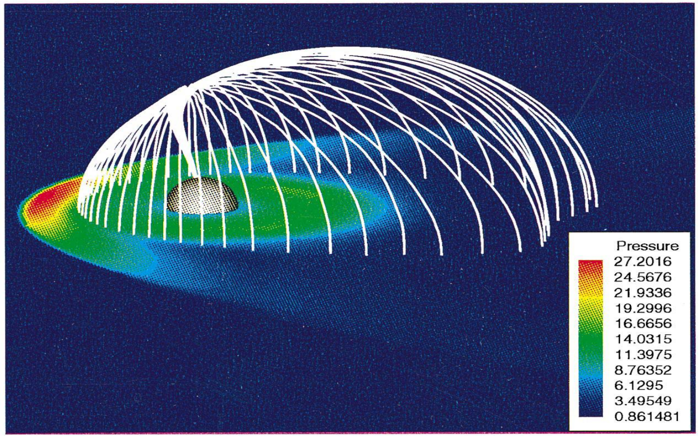


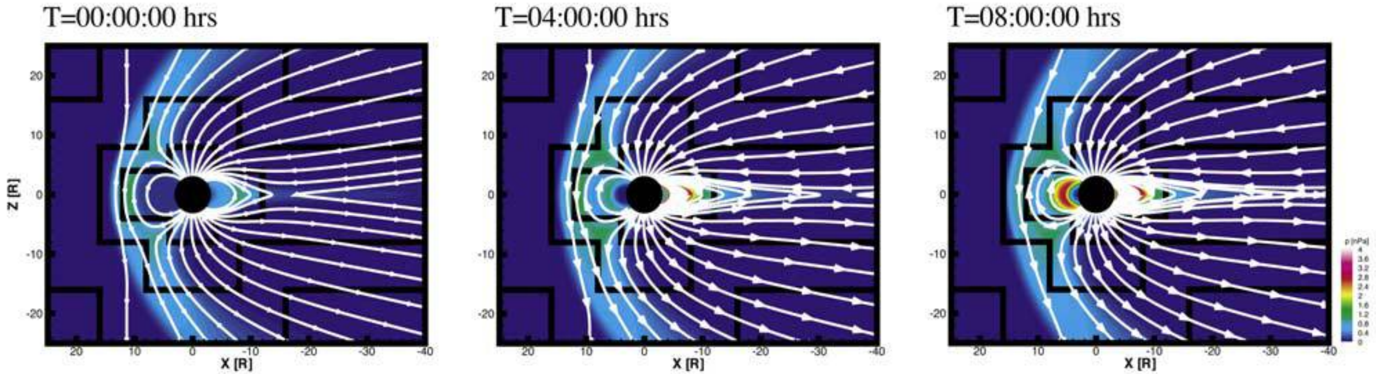
# A “classic”: MHD global simulations




Powel et al. 1998

3D compressible MHD simulation, based on a upwind finite volume method, of the solar wind – earth system



# Can we model large systems with self-consistent kinetic simulations?

# Hybrid-Eulerian simulations

Hybrid Vlasov-Maxwell

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + \frac{e}{m}\left[\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}\right] \cdot \nabla_v f = 0$$

$$\mathbf{E} = -\frac{\mathbf{u} \times \mathbf{B}}{c} + \frac{1}{nec}(\mathbf{j} \times \mathbf{B}) - \frac{1}{ne}\nabla P_e$$

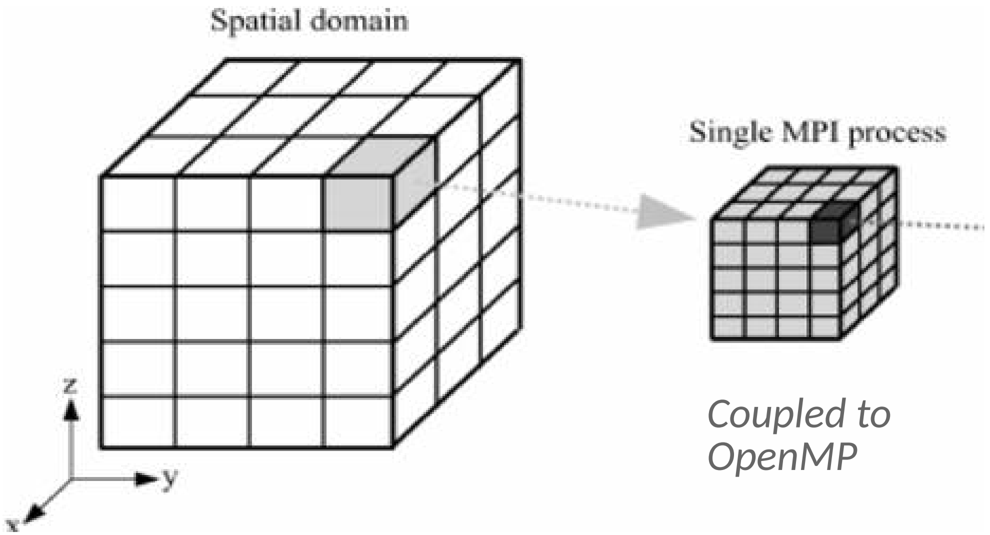
$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \frac{4\pi \mathbf{j}}{c}$$

$$n_e \simeq n_i \simeq n$$

$$P_e = P_e(n)$$

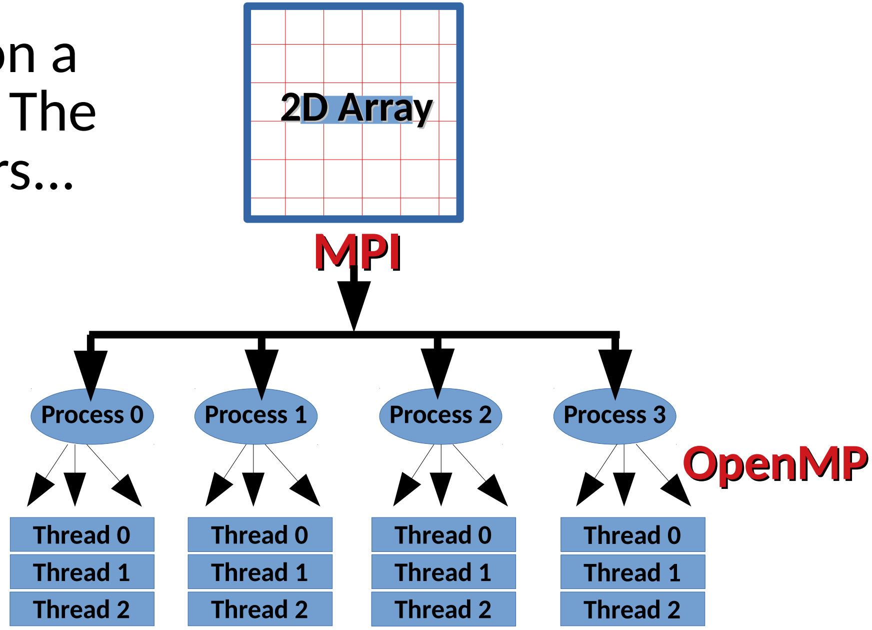
In full 3D-3V configuration or in high resolution 2D-3V configuration the distribution function is an array of 5-15 Tbytes. Massive parallelization is needed

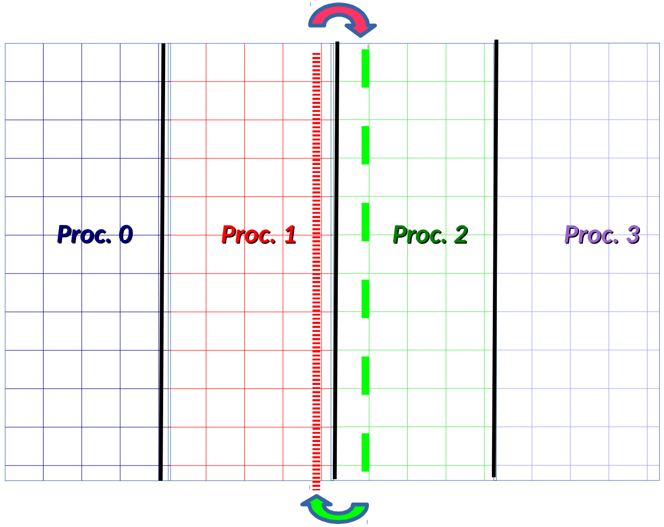



*Coupled to OpenMP*

# Parallel computing

Each processors works on a subspace of our domain. The problem is at the borders...



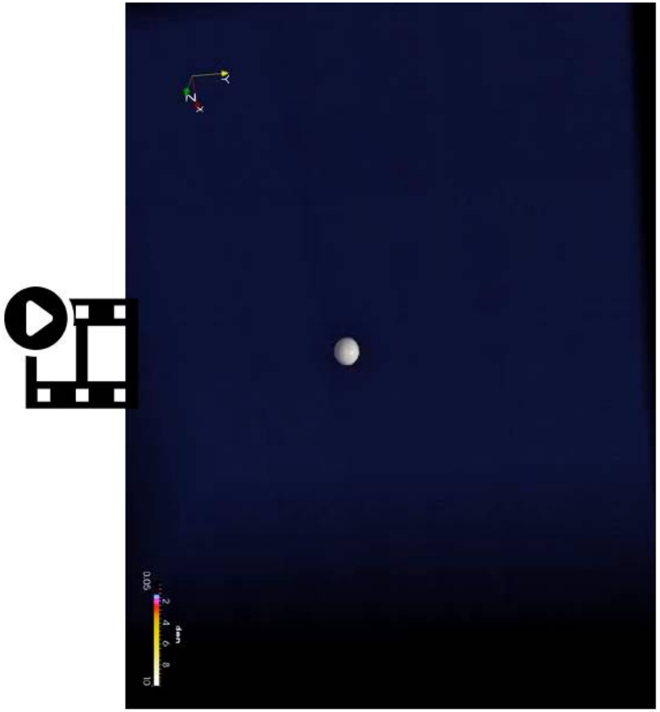

$$\left.\frac{\partial f}{\partial x}\right|_{x=x_i} = \frac{f(i+1,j,k)-f(i-1,j,k)}{2\Delta x}$$

Proc. 1 “sends” the column *f*(*i*-*1*,*j*,*k*) to Proc. 2, and Proc. 2 sends *f*(*i*+1, *j*, *k*) to Proc. 1. This can be done whit simple calls like “mpi_isend” and “mpi_ireceive”. In the mean time, each processor computes derivatives and products that are far from the domain boundaries, taking advantage of OpenMP directives

# New challenges

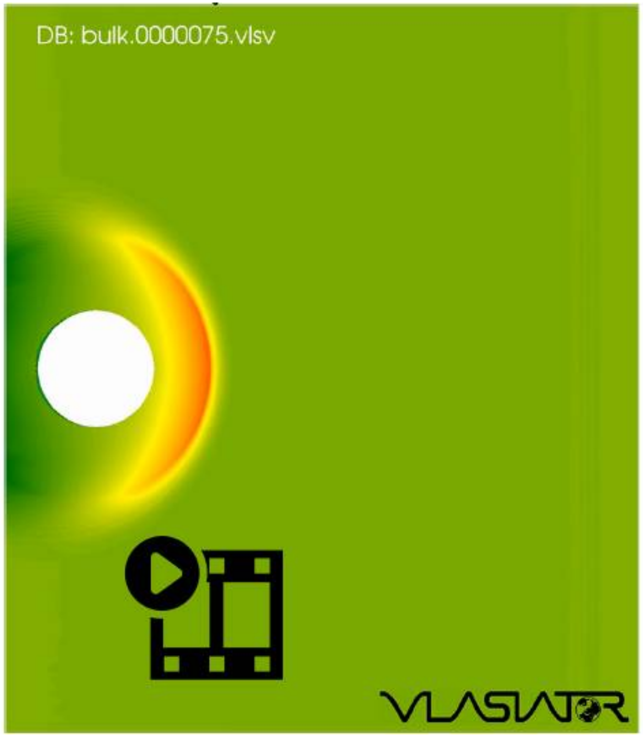
*Courtesy of V. Roythershteyn*

Kinetic simulations of the magnetosphere



# Global kinetic simulations

*Courtesy of M. Palmroth*



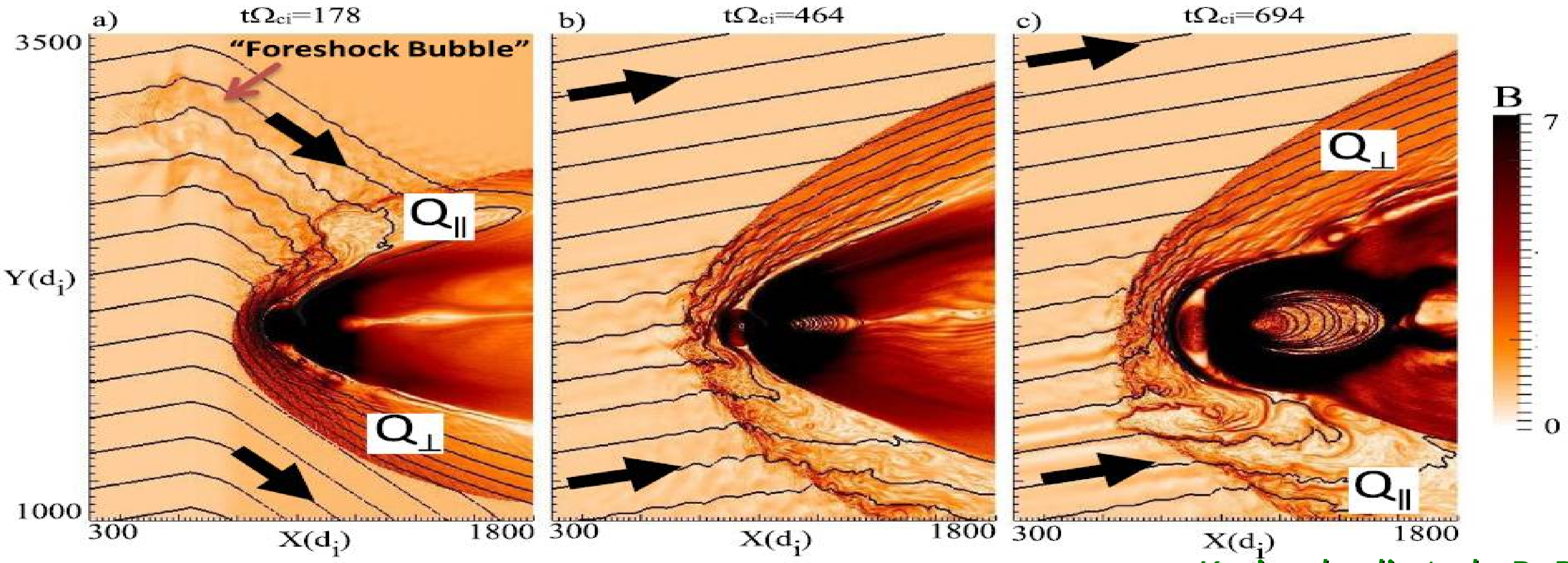

Global simulations with Vlasov models

# Global Vlasov simulations: kinetic effects

TABLE I. List of parameters for the global hybrid simulation runs shown in this paper. The number of particles per cell was 200. The spatial resolution was $0.5d_i$ except for runs 1, 5 ($1d_i$) and run 6 ($0.25d_i$).

| Run | $x_{max}$ | $y_{max}$ | $D_p$ | $IMFB_z$ | $M_A$ | $IMF_1$ | $IMF_2$ | $t_{flip}$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 2048 | 8192 | 100 | 0 | 8 | −45° | 10° | 90 |
| 2 | 2048 | 4096 | 100 | 0 | 8 | 10° | 10° | N/A |
| 3 | 2048 | 4096 | 100 | 0 | 8 | −45° | 10° | 90 |
| 4 | 8192 | 8192 | 300 | 0 | 10 | −45° | 10° | 150 |
| 5 | 2048 | 4096 | 100 | 0.6 | 8 | 10° | 10° | N/A |
| 6 | 512 | 512 | 50 | 0.6 | 8 | 10° | 10° | N/A |
| 7 | 4096 | 2048 | 150 | 0.6 | 10 | 10° | 10° | N/A |

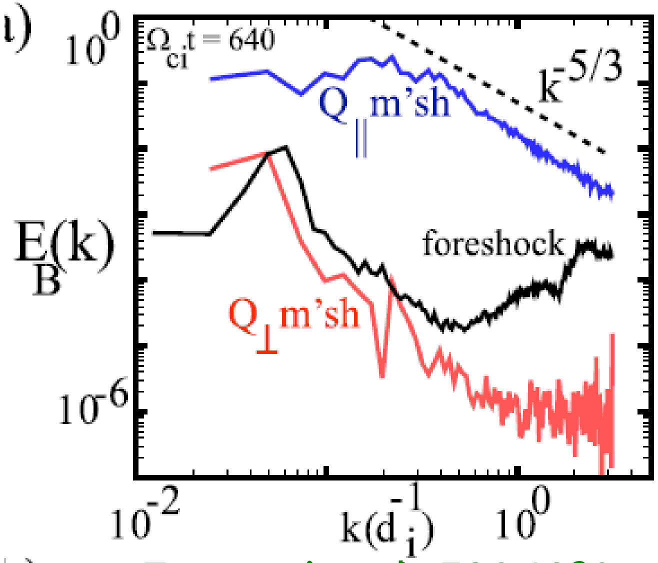
Time evolution of the magnetosphere where the IMF direction changes in time. The arrows indicate the direction of the magnetic field. A large foreshock bubble is evident



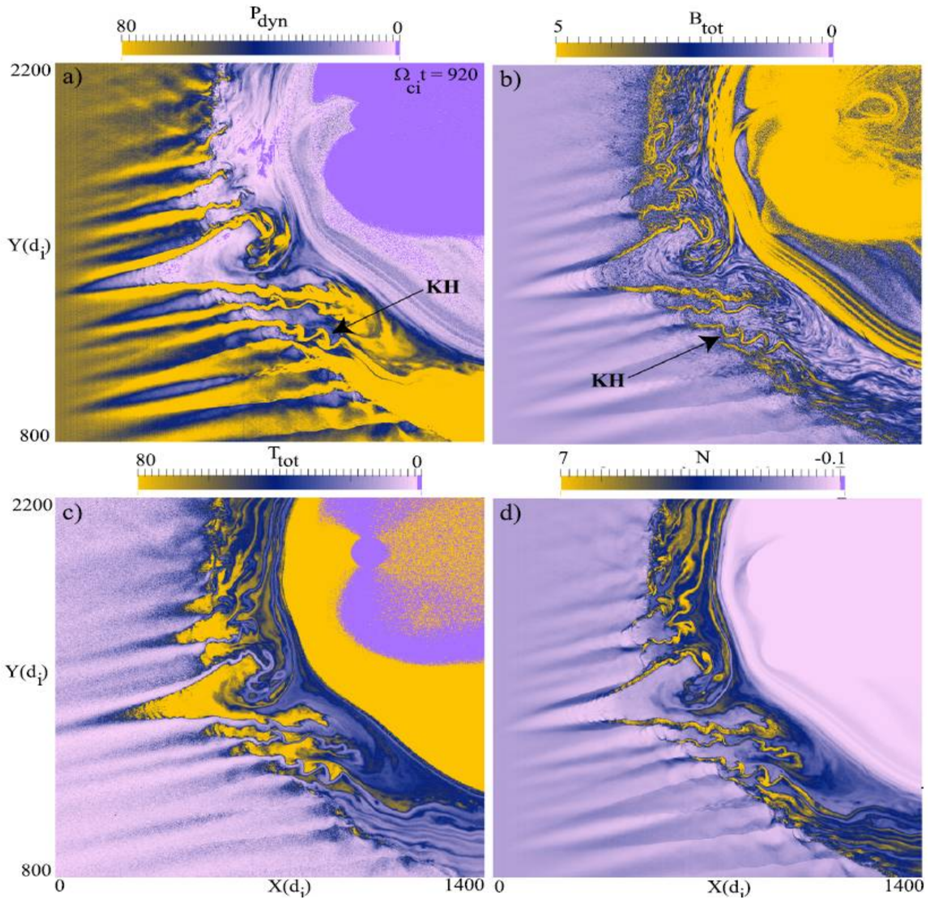

*Karimabadi et al., PoP, 2014*

# Kinetic turbulence at the shock

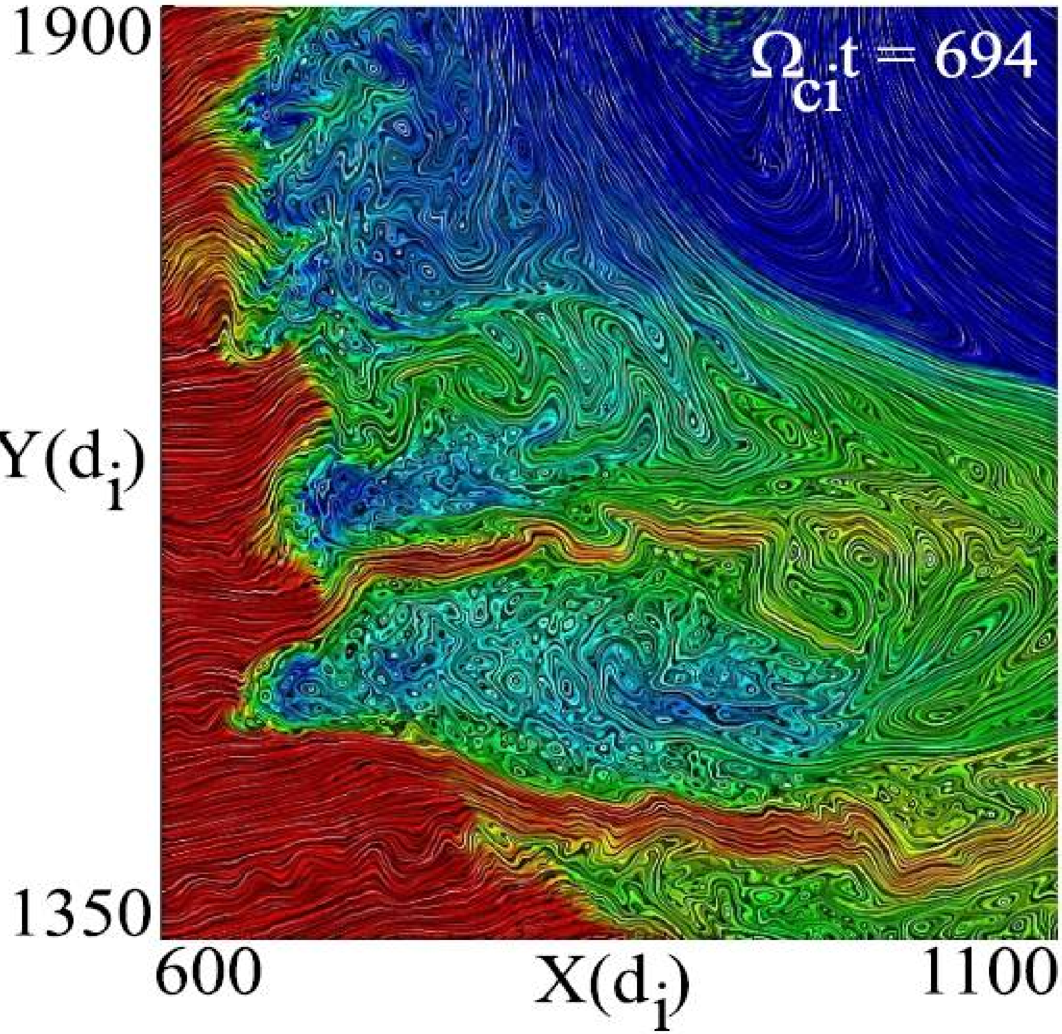
In the quasi-parallel $Q_{||}$ case, ions reflected from the shock reach to large distances upstream. The relative streaming between these ions and the incoming plasma excites instabilities which generate low frequency waves that can grow to large amplitudes, giving rise to magnetosonic/kinetic turbulence




*Tsurutani et al., EOS 1980*

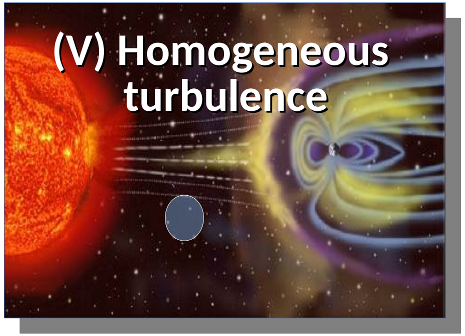


# Kinetic turbulence?



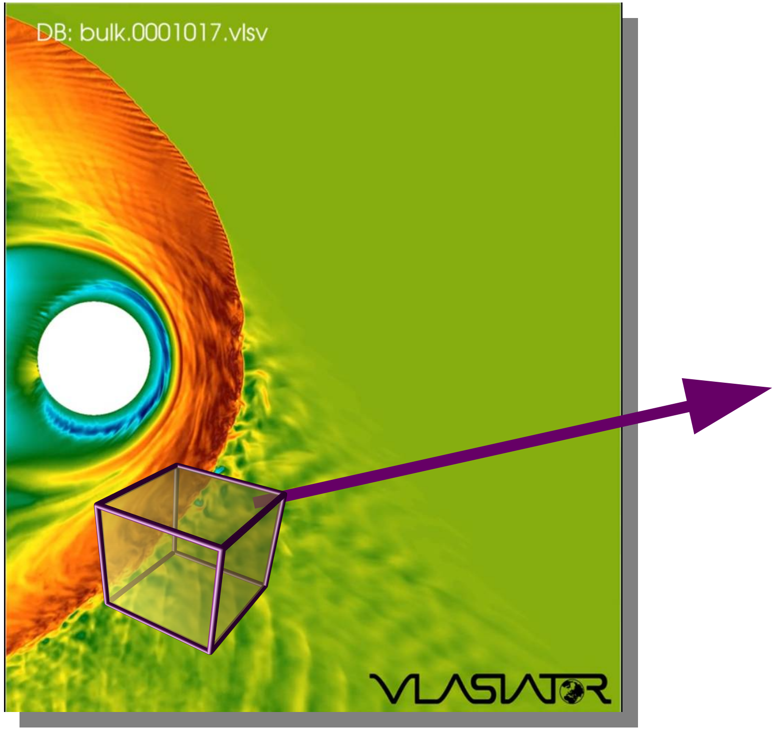

For all the systems we saw so far, high-resolution simulations suggest:

- Quasi-homogeneous turbulence
- Small scale structures
- Small scales reconnection events?

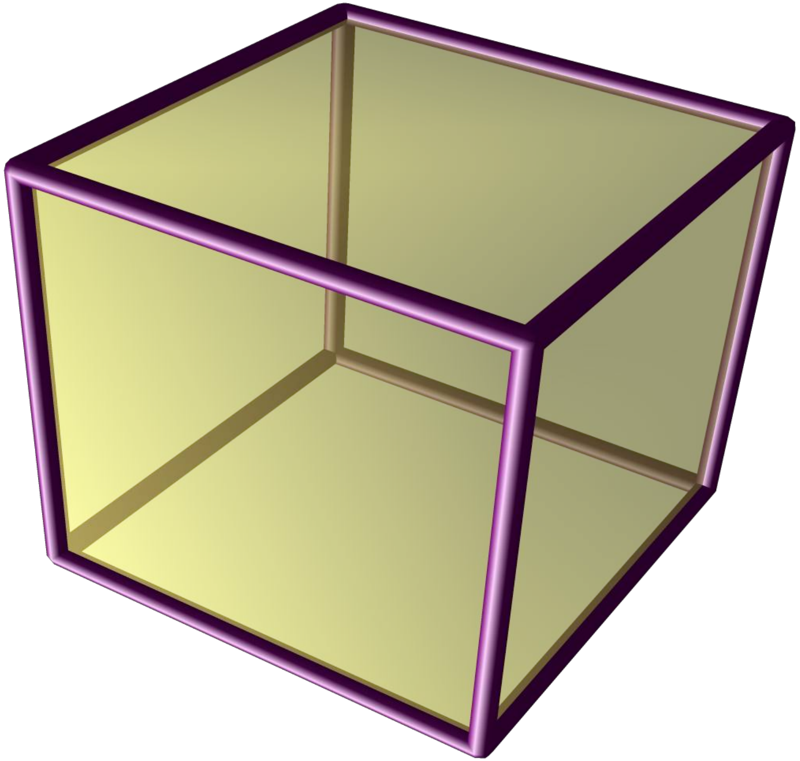


# From global to local

## Global simulations




## Local simulations



# Eulerian Hybrid Vlasov-Maxwell (HVM) solver

- Kinetic protons & alpha particles, while electrons are treated as a massless fluid
- *3rd* order splitting scheme

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + \left[\mathbf{E} + \mathbf{v} \times \mathbf{B}\right] \cdot \nabla_v f = 0$$

$$\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \frac{1}{n}\mathbf{j} \times \mathbf{B} - \frac{1}{n}\nabla P_e + \eta \mathbf{j}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mathbf{j}$$

$$n_e \simeq n_i \simeq n$$

$$P_e = nT_e$$

$$V_A = \frac{B}{(4\pi\rho_p)^{1/2}}; \qquad \Omega_p = \frac{eB}{m_p c}; \qquad d_p = \frac{V_A}{\Omega_p}$$

**NOISE-FREE!** but →

Phase space resolution needed for turbulence studies:

$N_x = N_y = N_z = 512$

$N_{vx} = N_{vy} = N_{vz} = 71$

To save $f$ → 1000 Tb !!

**Too expensive, from any point of view!**

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

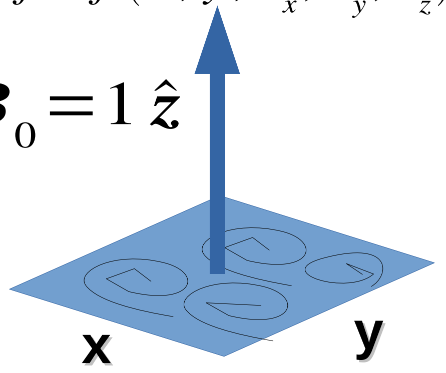
# HVM in a reduced geometry

**Reduced geometry 2D-3V:**

- 2D in space (fields have 3 components but depend only on 2 coordinates)
- 3V in the velocity space
- Turbulence is studied in a plane perpendicular to $B_0$, where its intensity is maximum (spectral anisotropy)

$$f \equiv f(x, y, v_x, v_y, v_z)$$

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




- Periodic boundary conditions in space
- $f(|v|) > v_{max} = 0$
- Parameters:

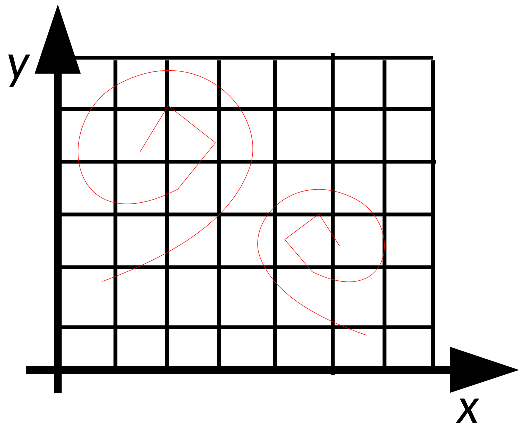
$$L_0 = 2\pi\alpha\, d_i,\ B_0 = 1\,\hat{e}_z,\ T_e/T_i = 1,$$

$$\eta = 1.7\times 10^{-2},\ v_{max} = \pm 5\, v_{ti},$$

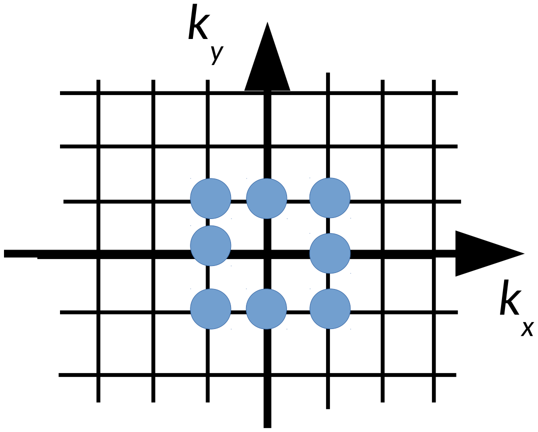
$$N_x = N_y = 512^2,\ N_v = 81^3 \rightarrow 3.5\times 10^{10}\ points$$

# A recipe to study turbulence: initial conditions

- Decay turbulence simulations
- $\delta b/B_0 \sim 1/3,\ 2/3$ (as in the solar wind)
- Plasma beta from $\beta \sim 0.2$ to 5
- Maxwellian distribution with uniform density and temperature
- $L_0 \sim 100\, d_i$ (large scale box)
- Incompressible initial conditions
- No correlation between velocity and magnetic field
- Large scale, uncorrelated (random) eddies, in order to mimic turbulent cascade in fluids: energy only in a box in $k$-space, for $|k|<|K_*|$, and with random Fourier phases $\phi_k$



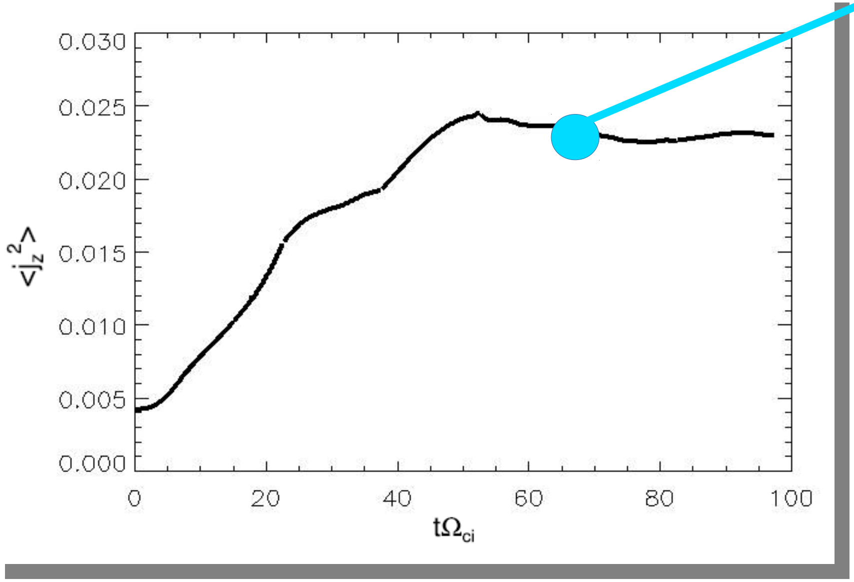

$$b_j(x,y) = \sum \left|\hat{b}_j(k_x,k_y)\right| e^{i(\boldsymbol{r}\cdot\boldsymbol{k}+\phi_k)}$$

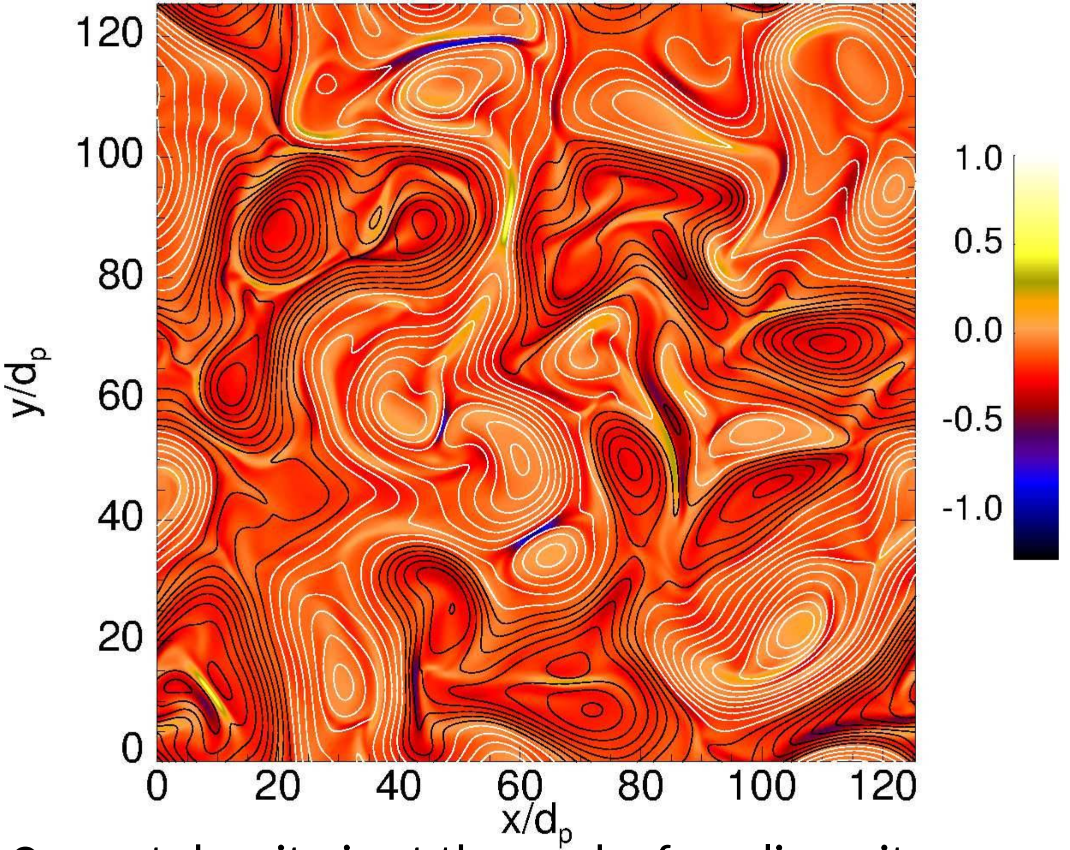


# Decaying turbulence

The cascade is fully developed when small scale activity reaches its maximum. This time can be quantified as the maximum of the mean square current density:

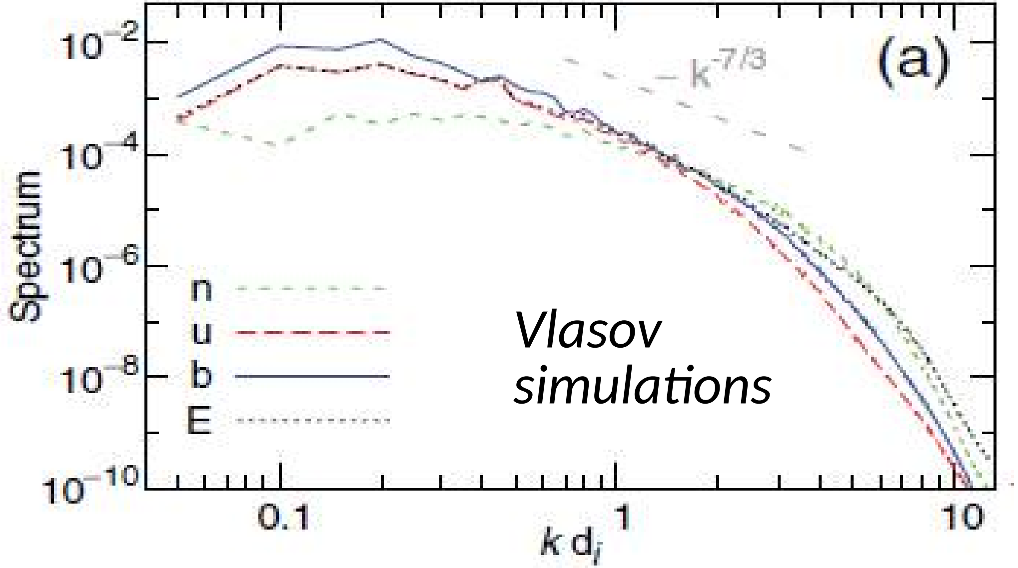
$$\langle j_z^2 \rangle = \frac{1}{L_0^2} \int [(\nabla \times \boldsymbol{B}) \cdot \hat{\boldsymbol{z}}]^2 \, d^2 x$$

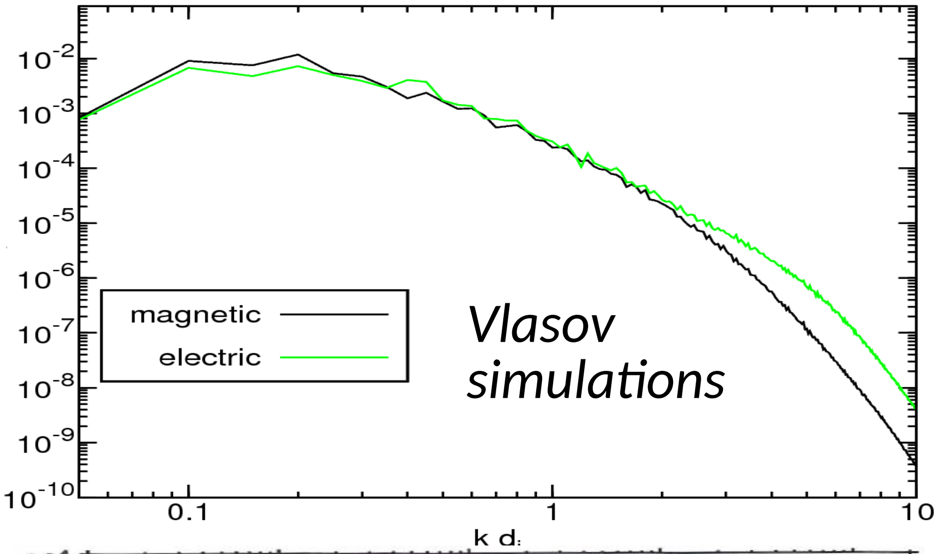



Current density $j_z$, at the peak of nonlinearity (shaded colors), together with the magnetic potential $a_z$, with black ($a_z$>0) and white ($a_z$<0) lines

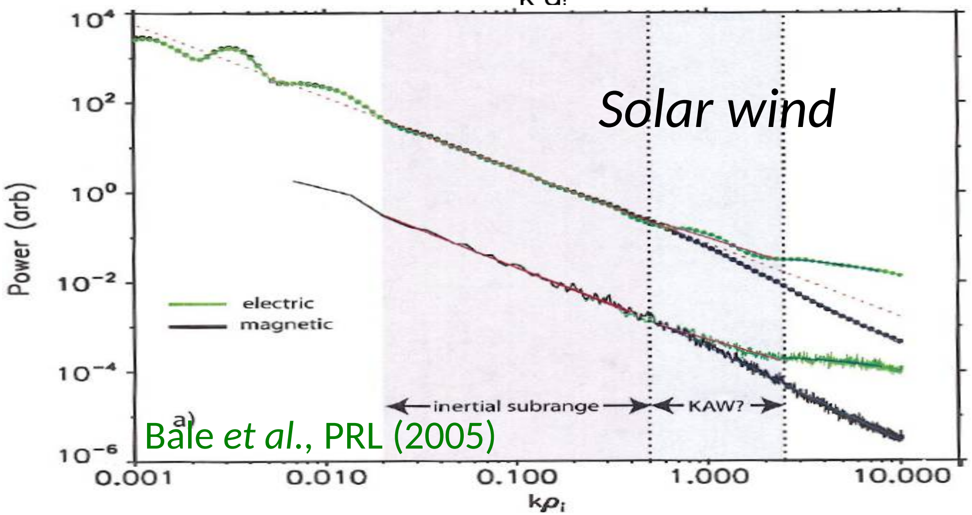
# Spectral features of turbulence



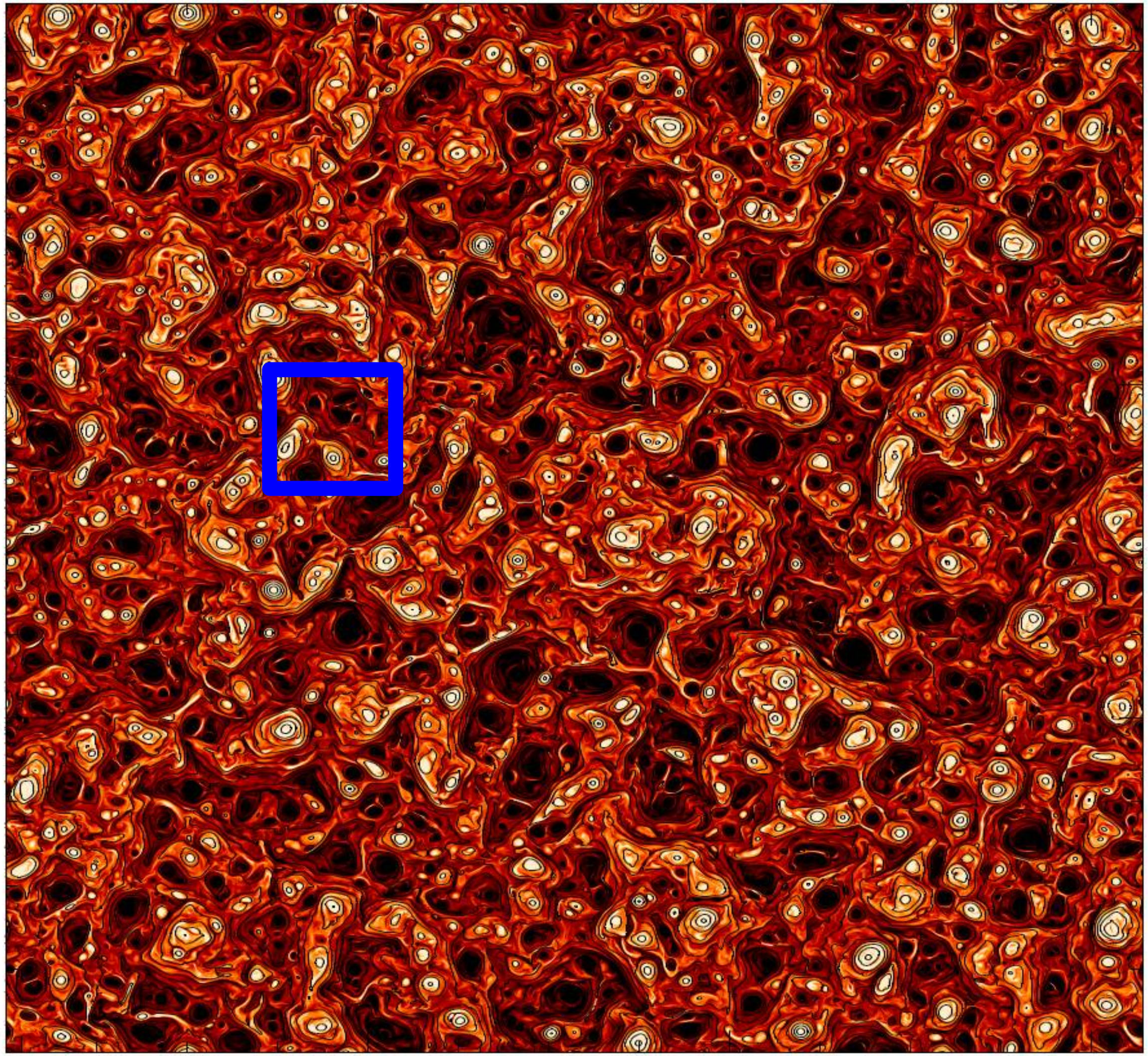



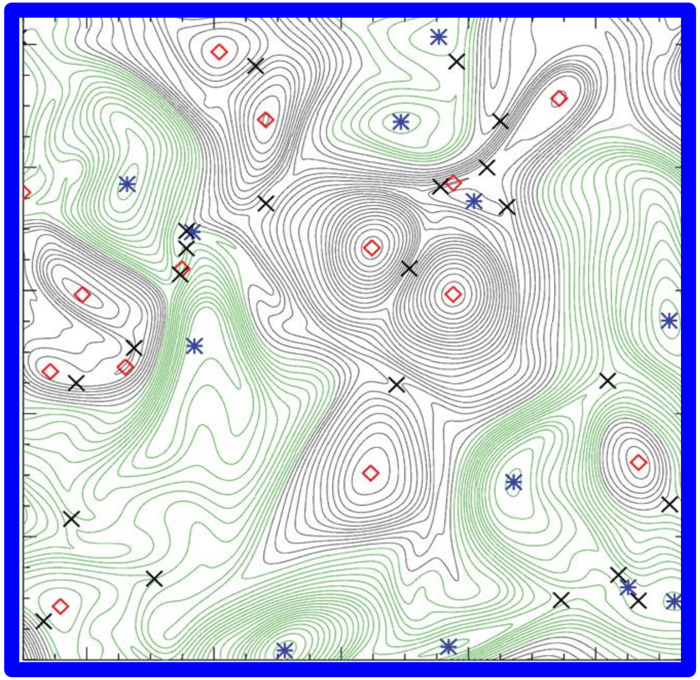

- Large scale Alfvenic correlations
- Intense electric activity at small scales
- Steepening of the magnetic spectrum at $kd_p \sim 1$

**Several features commonly observed in space plasmas!**



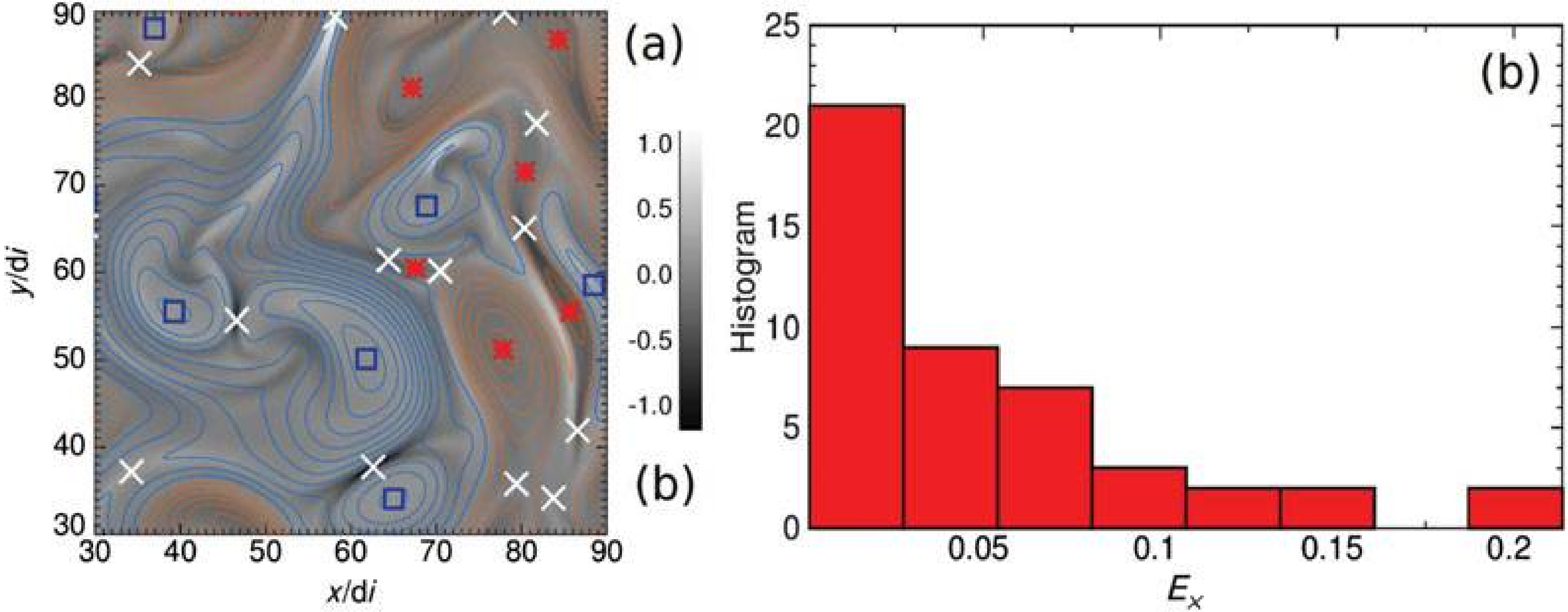
# Reconnection and turbulence: MHD





Micro-reconnecting events in 2D MHD, with many applications to the turbulent solar wind!

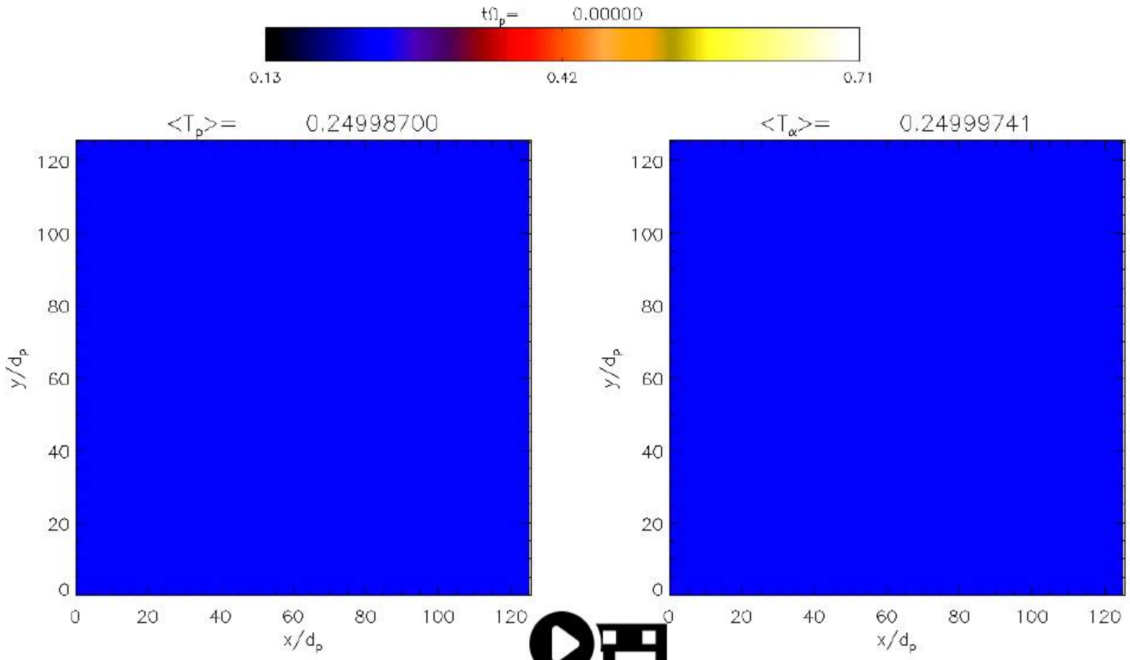
# Reconnection and turbulence: Vlasov




**As in 2D MHD, in Vlasov turbulence there is a network of reconnecting sites, with reconnection rated broadly distributed…**
**… but with Vlasov now we can study kinetic processes!**

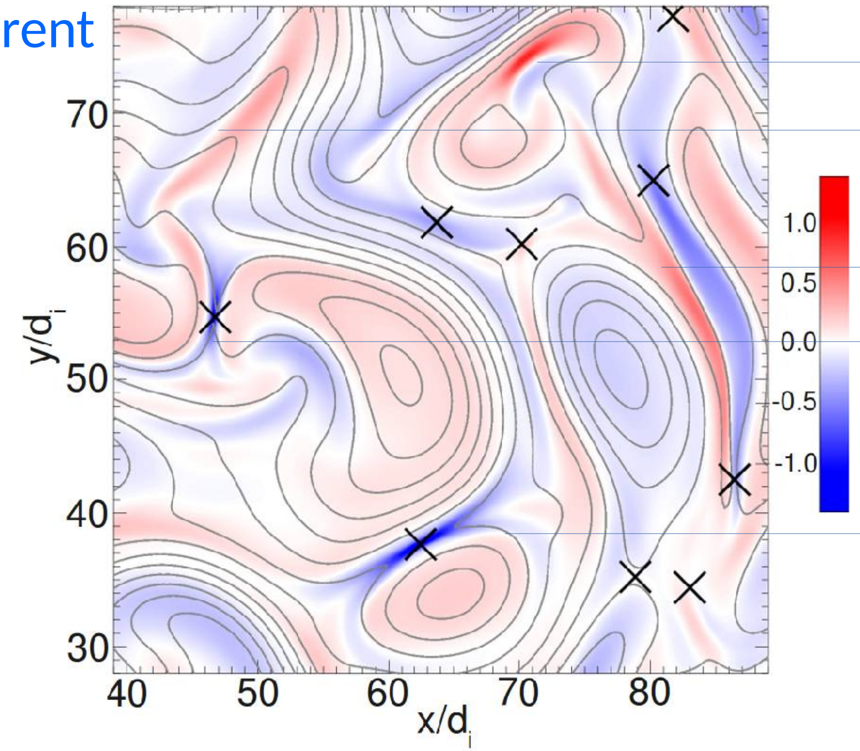
# Local heating of ions

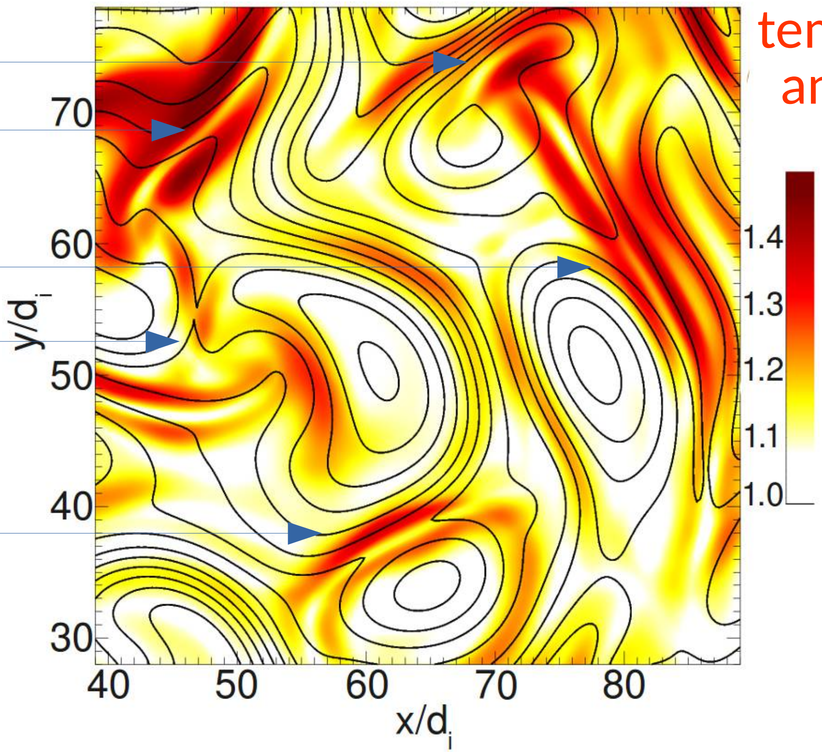
Heavy ions are preferentially heated with respect to protons



# Intermittent kinetic effects

current



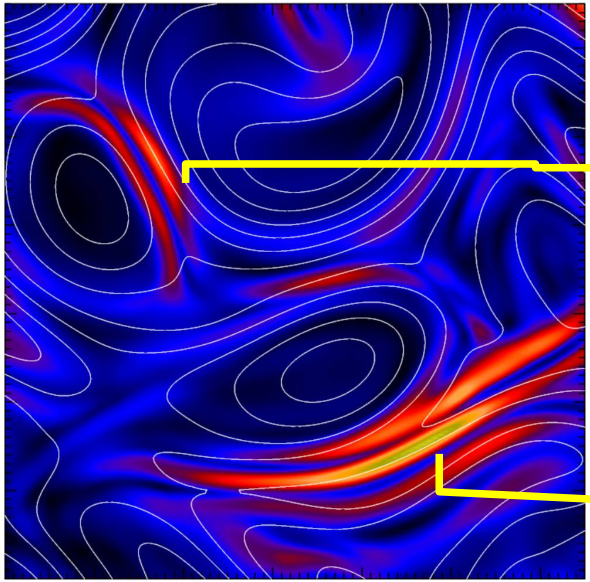




temperature anisotropy

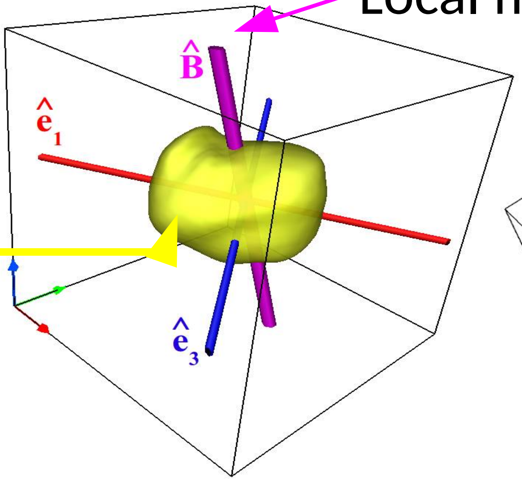
$$T_\perp / T_\parallel \propto \left|\nabla j_z\right| \left( \equiv \left|\nabla^2 \boldsymbol{b}_\perp\right| \right)$$

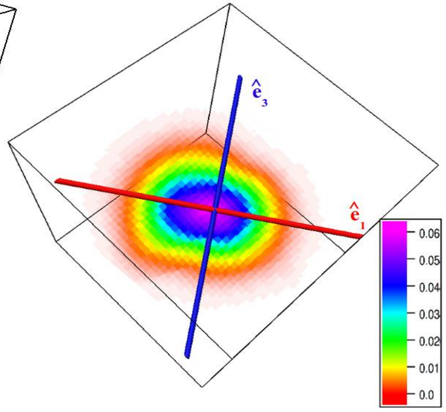
"Streams" of kinetic effects (anisotropy, skewness and kurtosis) are adjacent to reconnecting current sheets. In a fluid model these would correspond to regions where collisional dissipation takes place. Here cyclotron and/or Landau resonances may be at work

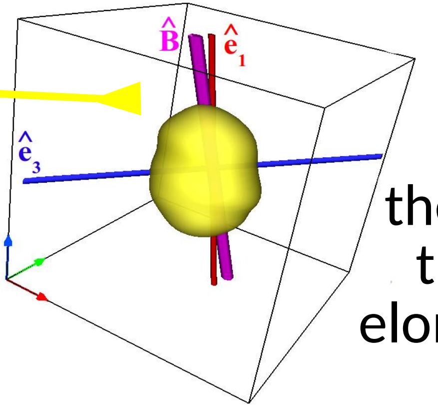
# Distribution functions in turbulence



Local magnetic field



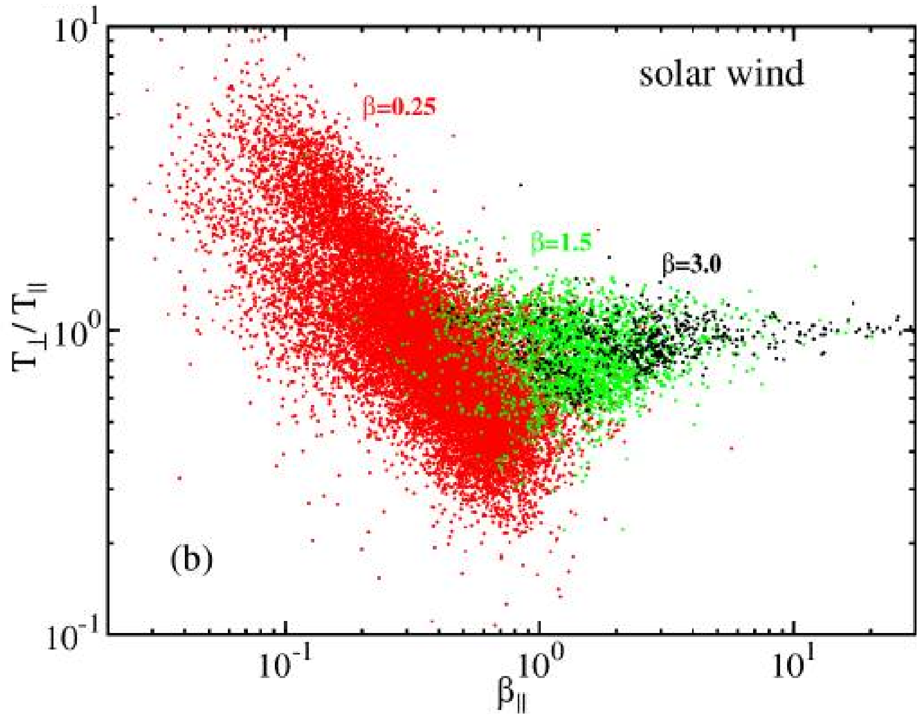

The distribution function (DF) is non-gyrotropic

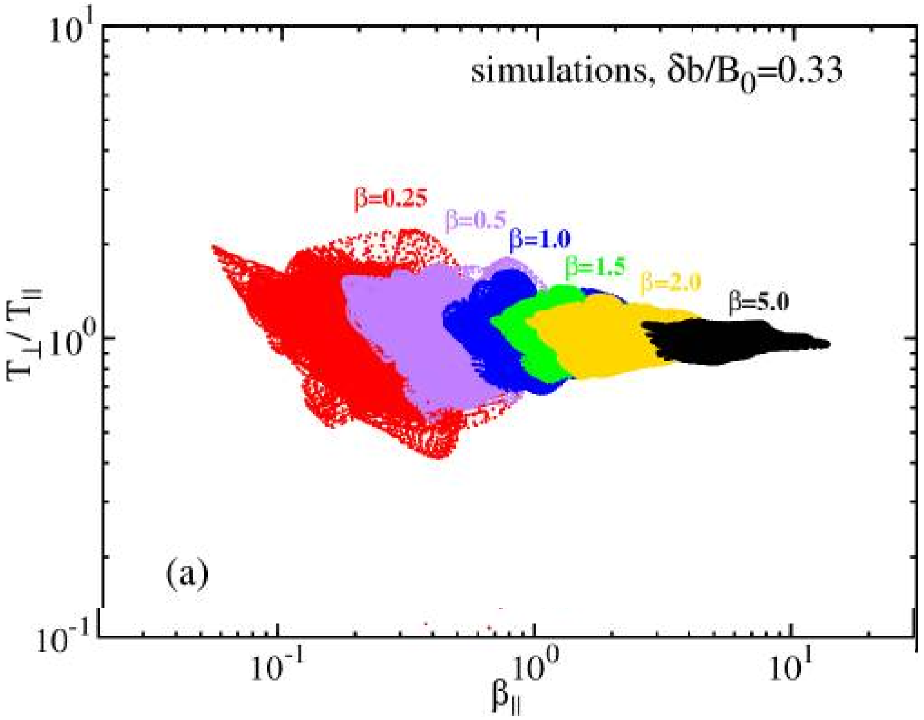
the DF is strongly affected by turbulence, resembling an elongated potato-like structure

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

# Anisotropy and parameters dependence

**Can we globally describe the solar wind?** → **Solar wind: high variability** → **Different Vlasov simulations, varying global parameters**



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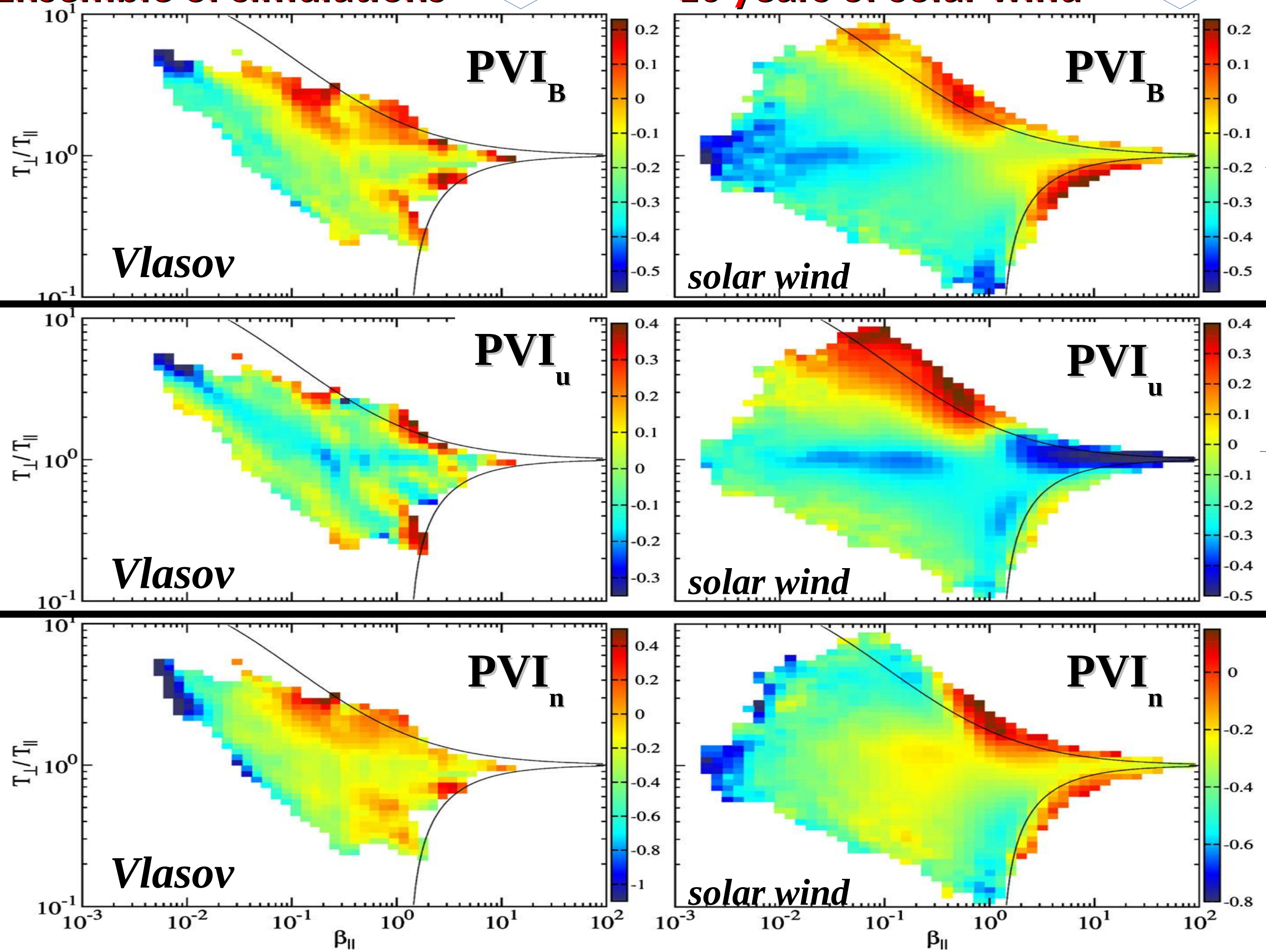
# Direct comparison with measurements

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




Magnetic intermittent structures (Reconnection?)

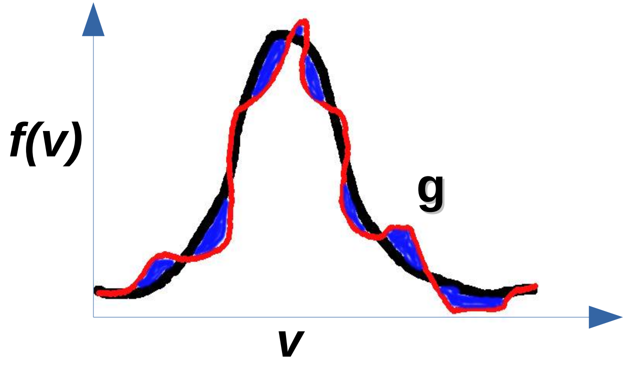
velocity intermittent structures

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

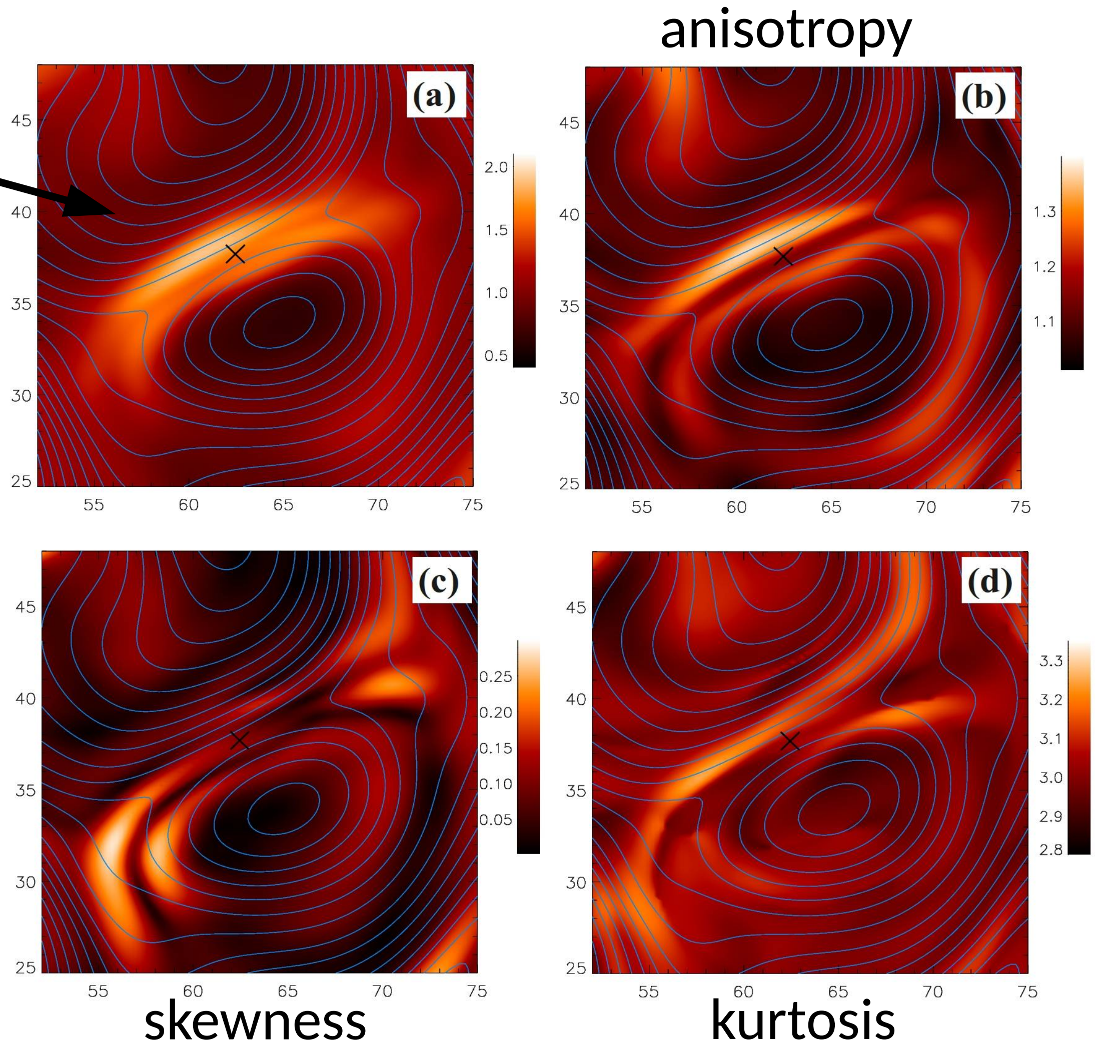
density intermittent structures

# High-order kinetic effects

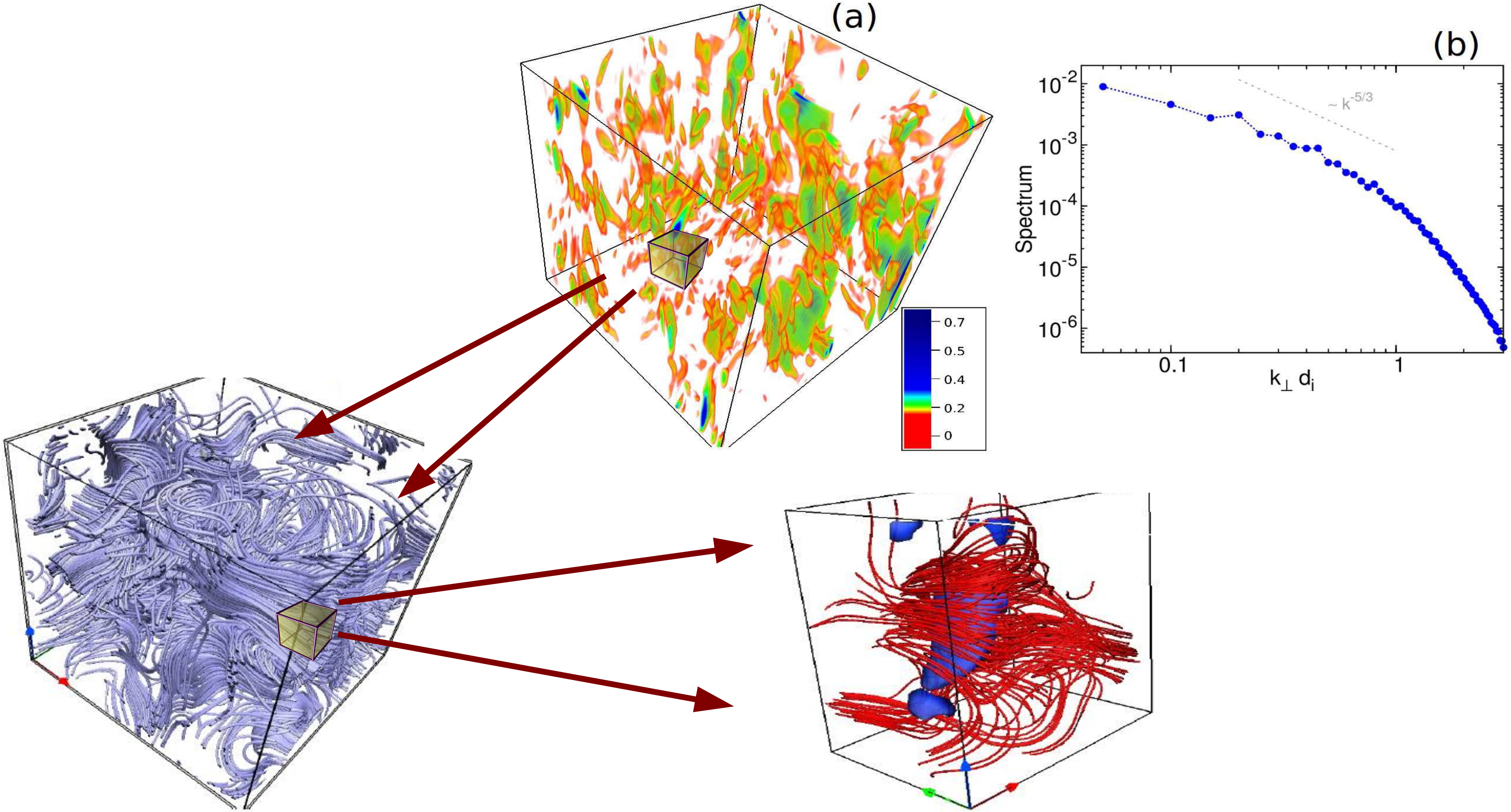
$$\epsilon(x)=\frac{1}{n}\sqrt{\int (f-g)^2 d^3 v}$$




**$g$ is the Maxwellian associated to $f$**

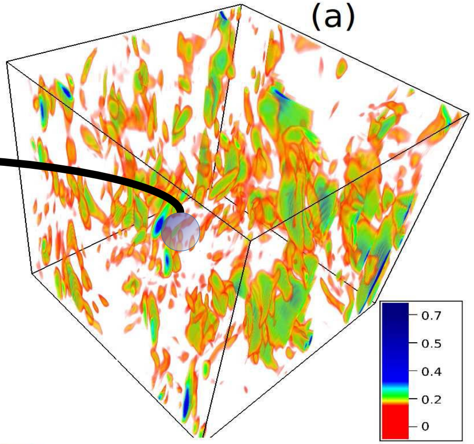


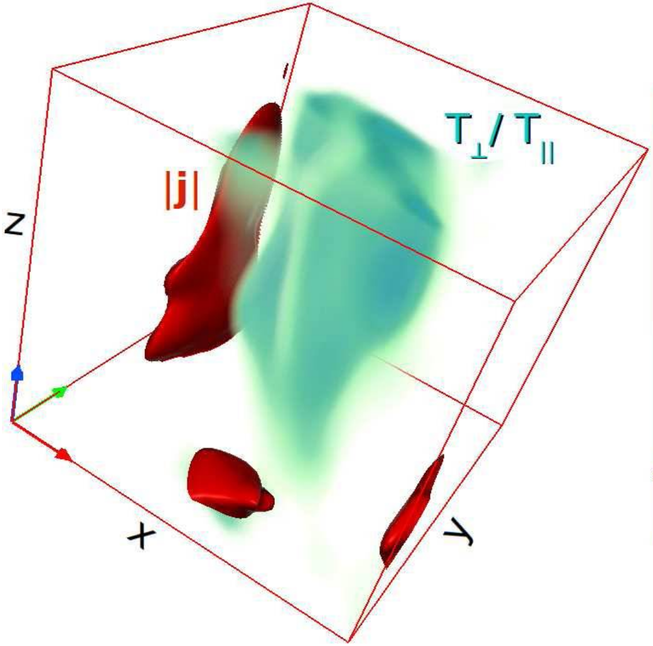
# 6D Vlasov turbulence

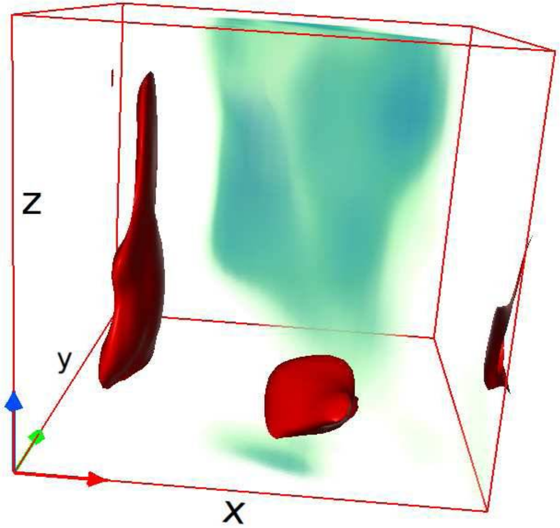


# 6D Vlasov turbulence

**Intermittent, anisotropic Vlasov turbulence…**

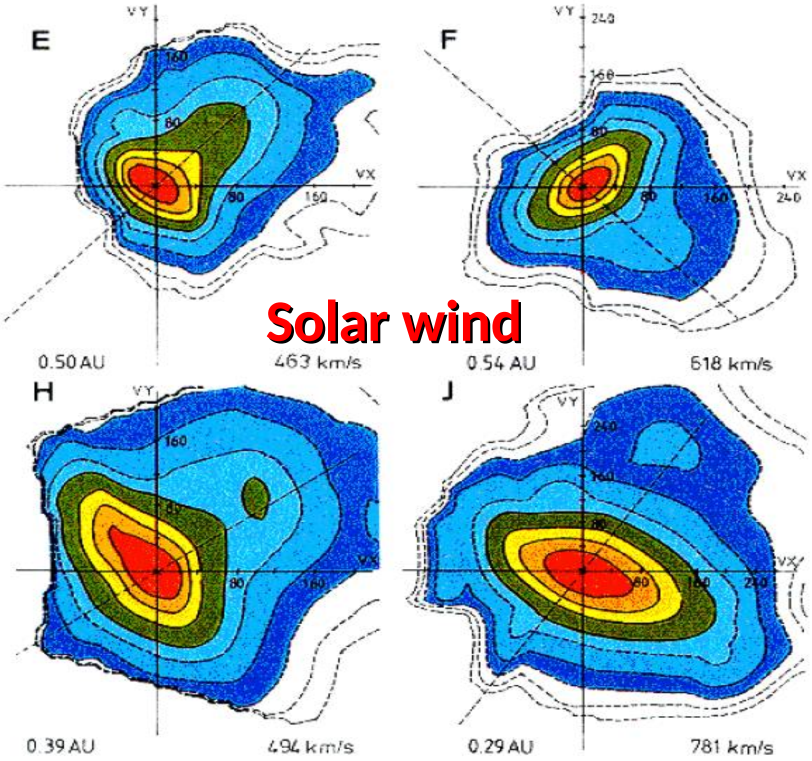



**Patterns of temperature anisotropy are near current sheets**

# 6D Vlasov Turbulence: more non-thermal effects




*Marsch, LRSP (2006)*

**Landau resonances can be locally excited**

**beams, anisotropy, and strong non-gyrotropic modulations**