A fluid model for ion-scale dynamics of a collisionless plasma

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SHOCK.
SOLAR AND HELIOSPHERIC COLLISIONLESS KINETICS

Modeling collisionless space plasmas

A fluid model for ion scales

Should **include low-frequency kinetic effects**.

FLR-Landau fluid model: constructed by performing a suitable ***closure of the moment hierarchy*** derived from the Vlasov equation, ***within the gyrokinetic scaling****.*

Alternative approaches include ***gyrofluids*** , obtained by closing the moment hierarchy derived from the gyrokinetic equations.

The **FLR-Landau fluid model** can be viewed as an **extension of the anisotropic Hall-MHD which retains** ***linear Landau damping*** and ***finite Larmor radius (FLR) corrections***,
in a way that accurately **reproduces the low-frequency linear kinetic theory at the ion scales**.

T. Passot & P.L. Sulem, Phys. Plasmas ***14****, 082502, (2007);*
T. Passot, P.L. Sulem & P. Hunana, Phys. Plasmas ***19****, 082113 (2012).*

Extension of the Landau fluid for purely MHD scales *(Snyder, Hammett, Dorland, Phys. Plasmas* ***4****, 3974, 1997).*

Outline

- Brief description of the FLR-Landau fluid model
- Validation at the linear level
- 3D turbulence simulations:
  - Alfvenic regime
  - Mirror unstable regime (in the presence of temperature anisotropy)

The FLR-Landau fluid model

When **neglecting inertia and FLR contributions of the electrons,**

15 scalar dynamical eqs. (derived from Vlasov-Maxwell equations) for

- plasma density
- ion velocity (3)
- magnetic field (Faraday equation) (3)
- (gyrotropic) ∥ and ⊥ ion and electron pressures (2x2)

NO APPROXIMATION

- (gyrotropic) ∥ and ⊥ ion and electron heat fluxes (2x2) *(non-gyrotropic terms are retained only if contributing to the linear theory).*

Additional unknown quantities:

- gyrotropic ion & electron 4th rank cumulants
- non-gyrotropic contributions to ion-pressure,
  ion & electron heat fluxes
  4th rank cumulants

Specific closures are thus needed.

Closure procedure:

Unknown quantities are determined by

- ***evaluating the various fields from the linear kinetic theory within the gyrokinetic scaling near the corresponding biMaxwellian distribution functions,***
- ***combining them in a way which minimizes the occurrence of the plasma dispersion function.***
- ***The latter is otherwise replaced by suitable Padé approximants, in a way leading to local-in-time relations.***
- ***In order** to account for the evolution of the plasma parameters, **equilibrium quantities are replaced by instantaneous space averages.***

REMARKS:

- **Landau damping of ions and electrons** arises through the highest-rank retained moments (here the 4^{th} order cumulants), where *its signature is the presence of a **Hilbert transform**.*
- Electron Landau damping is often an essential ingredient (which may question the assumption of isothermal electrons in hybrid models).
- Although non-gyrotropic electron pressure is subdominant at the ion scales, non-gyrotropic electron flux and 4^{th} order moment do contribute.

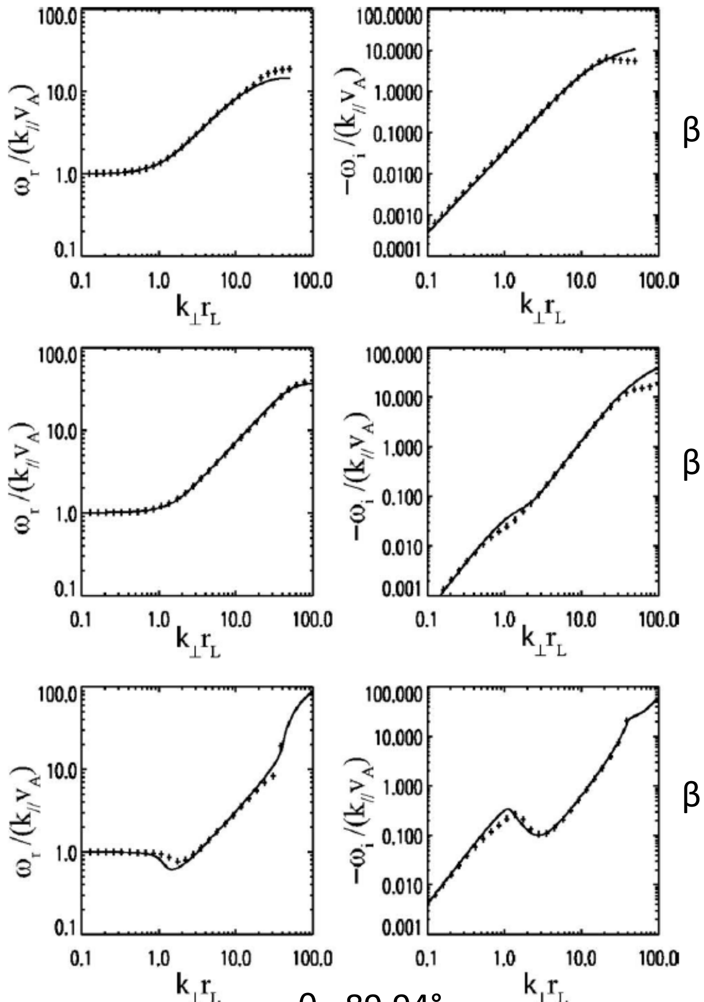
Validation of the FLR-Landau fluid model

Dispersion and damping of kinetic Alfvén waves

solid line: full kinetic theory (WHAMP program)
doted line: linearized FLR-Landau fluid model (Maple code)

Isotropic and equal ion and electron temperatures

real part | imaginary part



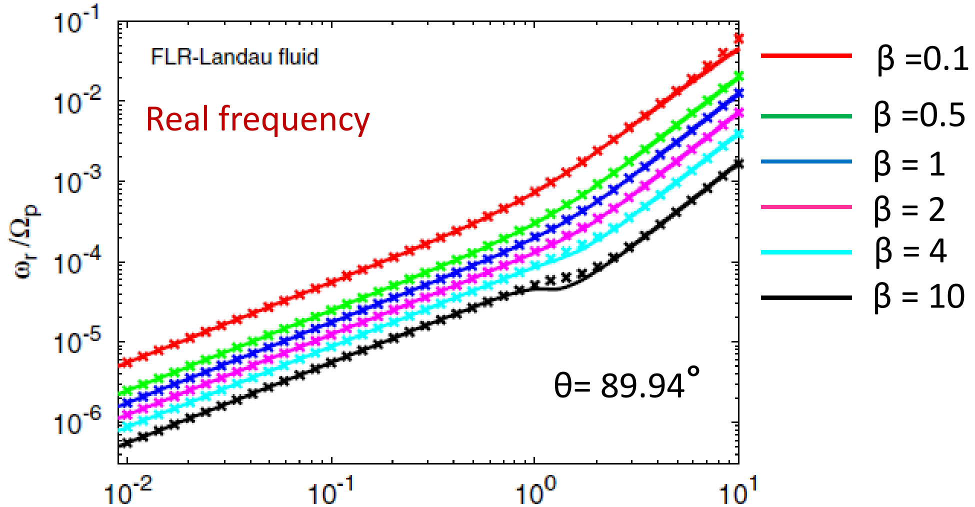
β = 0.1

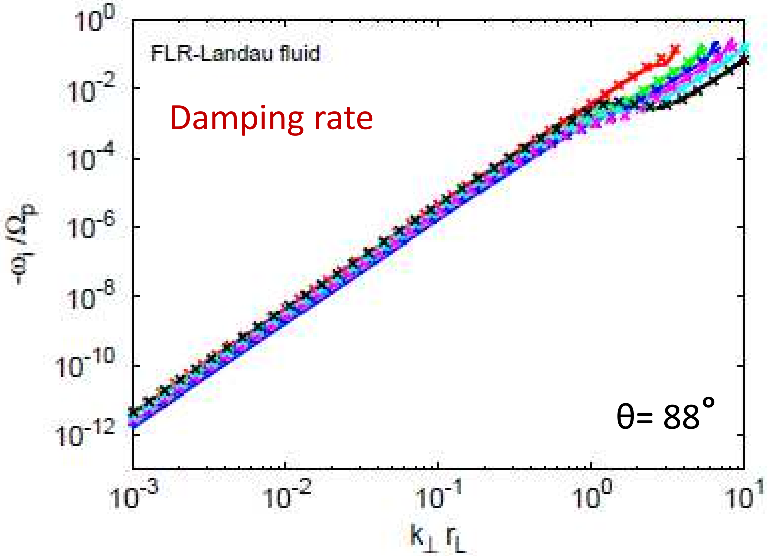
β = 1

β = 10

θ= 89.94°

$T_{\parallel e}/T_{\parallel p}$ =0.01 ; $T_{\perp p}/T_{\parallel p}$ = 1 ; $T_{\perp e}/T_{\parallel e}$ = 1

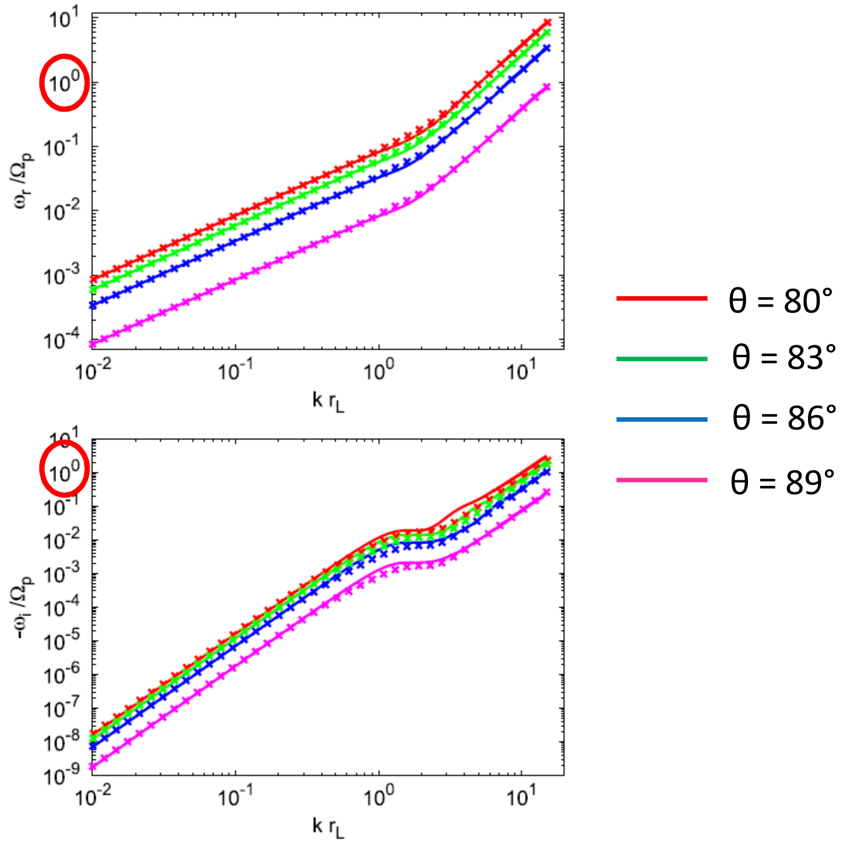




Kinetic Alfvén waves (continued)

Isotropic ion and electron temperatures

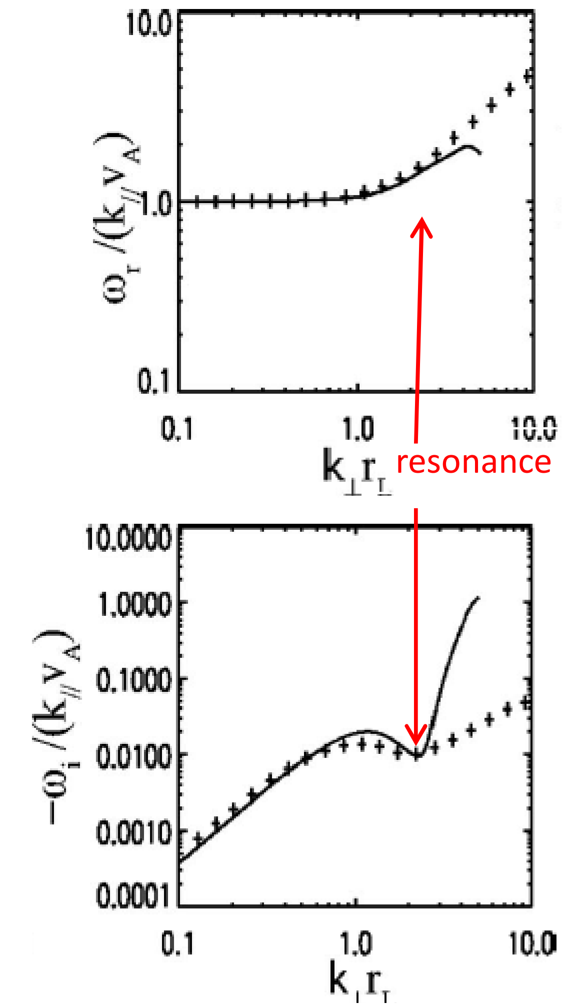
solid line: full kinetic theory (WHAMP program)
crosses : linearized FLR-Landau fluid model (Maple code)



β = 4.2

In the absence of resonances (large β and large θ), the model remains accurate for $\omega > \Omega_p$

Fast magnetosonic waves



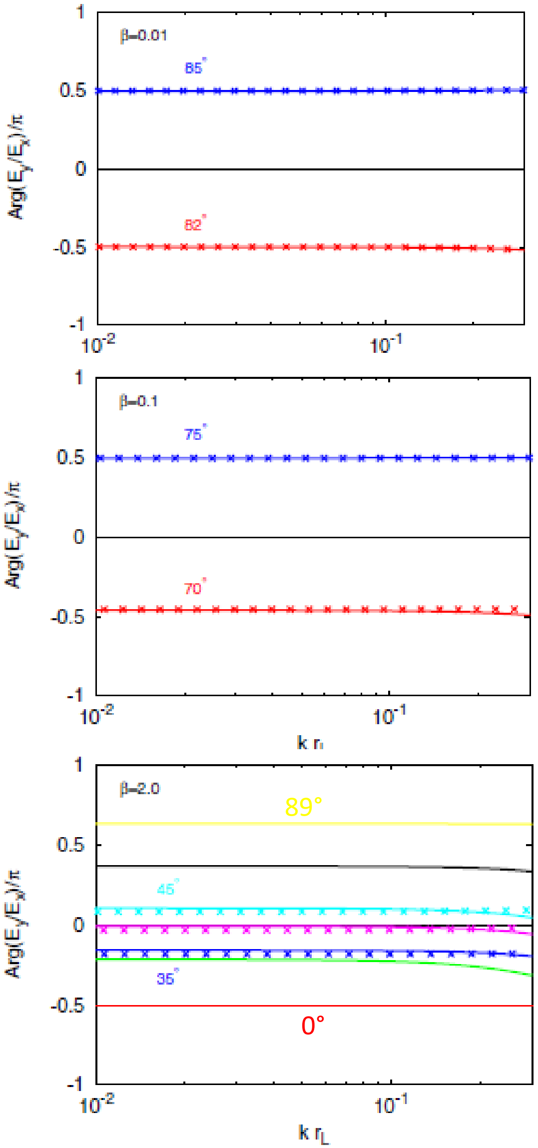
β = 1

θ= 89.9°

$T_e/T_i = 10^{-2}$

FLR-Landau fluid captures fast magnetosonic waves up to the ion cyclotron resonance

FLR –Landau fluid accurately captures
Alfvén wave polarization, and in particular its change of sign at a critical propagation angle that depends on β.



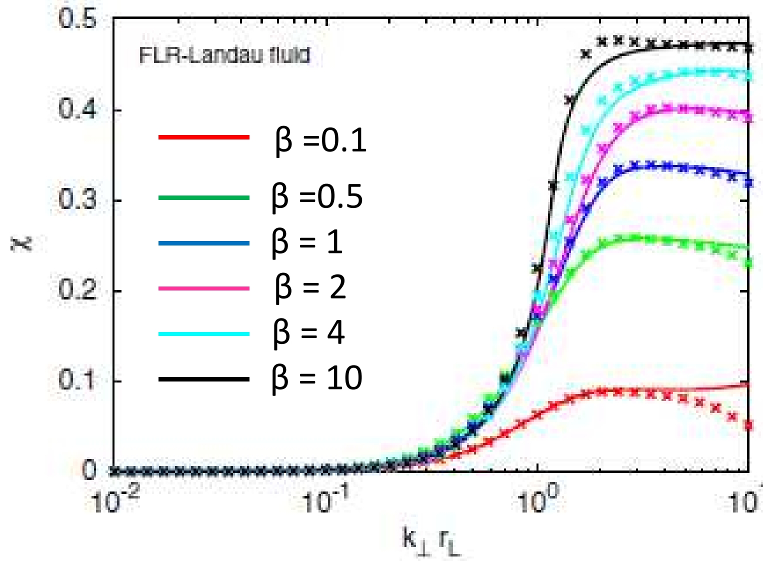
Positive polarization:
(right hand polarized wave)

Negative polarization
(left hand polarized wave)

Magnetic compressibility of KAWs

$$\chi(k_\perp r_L) = |B_z(k_\perp r_L)|^2 / |B(k_\perp r_L)|^2$$

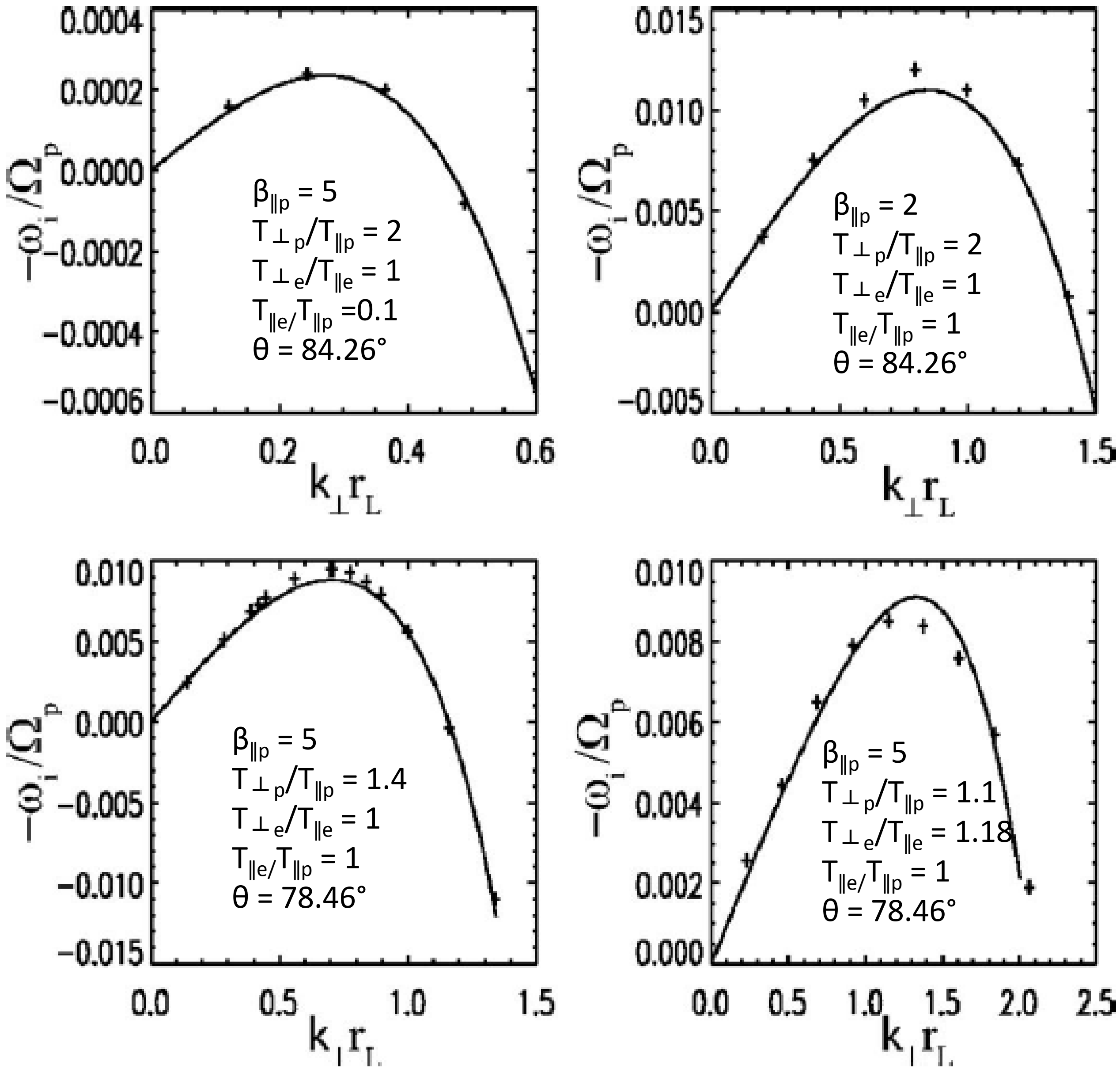
θ = 89.99° *(in order to accurately capture large $k_\perp$)*



Landau damping and also FLR corrections are needed for an accurate magnetic compressibility, ***even at large scales****.*

Mirror instability (in the presence of temperature anisotropy)

Growth rate



NONLINEAR REGIMES

Alfvenic turbulence

Generation of a kinetic Alfvén wave (KAW) turbulence:
system driven by a random forcing

$$F_i(t, \mathbf{x}) = \sum_{1<n<N} F^0_{i,n} \cos(\omega_{KAW}(\boldsymbol{k}_n)t - \boldsymbol{k}_n \cdot \boldsymbol{x} + \phi_{i,n})$$

KAW frequency for a wavevector ***k***
Propagation angle : 80º

KAWs are generated by resonance

Driving is turned on (resp. off) when the sum of kinetic and magnetic energies is below (resp. above) a certain threshold corresponding to typical magnetic field fluctuations of the order of 20% of the ambient field magnitude.

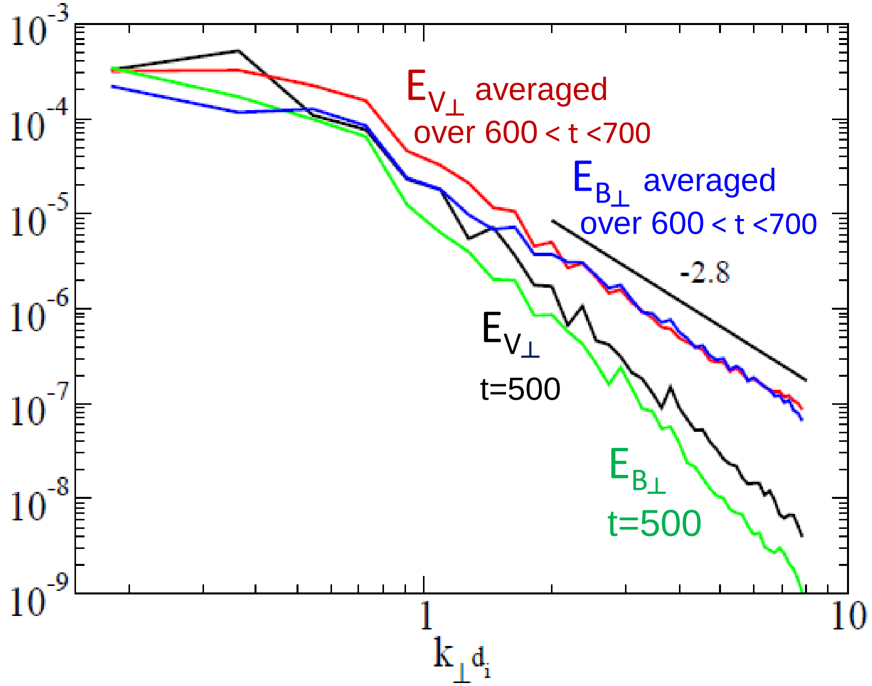
Initially, equal isotropic ion and electron temperatures with β= 1.

FLR-Landau fluid model is numerically integrated using a Fourier spectral method in a 3D periodic domain with a physical extension 5.7 times larger in the parallel than in the perpendicular ones in order to focus on the quasi-transverse dynamics.

No artificial dissipation.

Resolution of 128^3 points before aliasing is removed.

After t= 600 $1/\Omega_p$, a quasi-statistically stationary regime establishes.
KAW cascade is quasi-transverse at large scales (see below)
Perpendicular spectrum at k_z=0 : $k_\perp^{-2.8}$ for $v_\perp$ and $B_\perp$, between $k_\perp d_i$ = 2 and end of numerical zone.

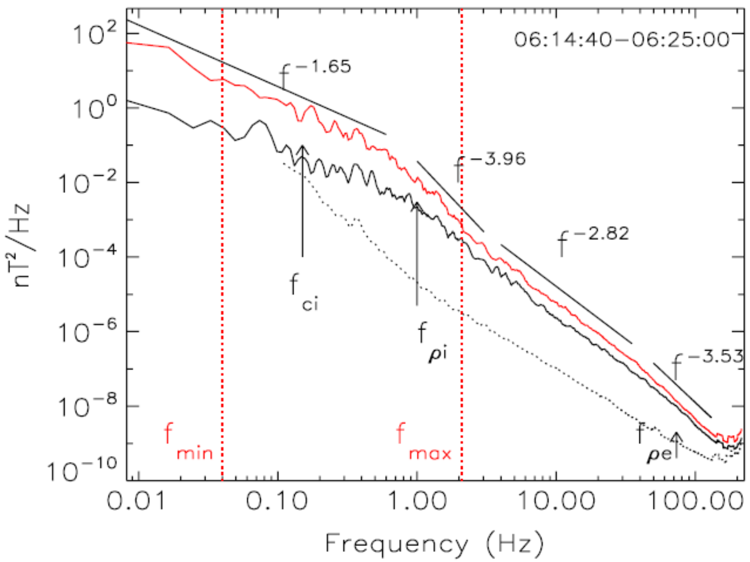


No exponentially-decaying dissipative zone in the simulation: In the transverse plane, dissipation is mediated by nonlinear couplings which drain energy to oblique modes where it can be Landau damped.

Power-law spectra but NOT an inertial range: Landau damping affects most of the scales.

CONSISTENT WITH

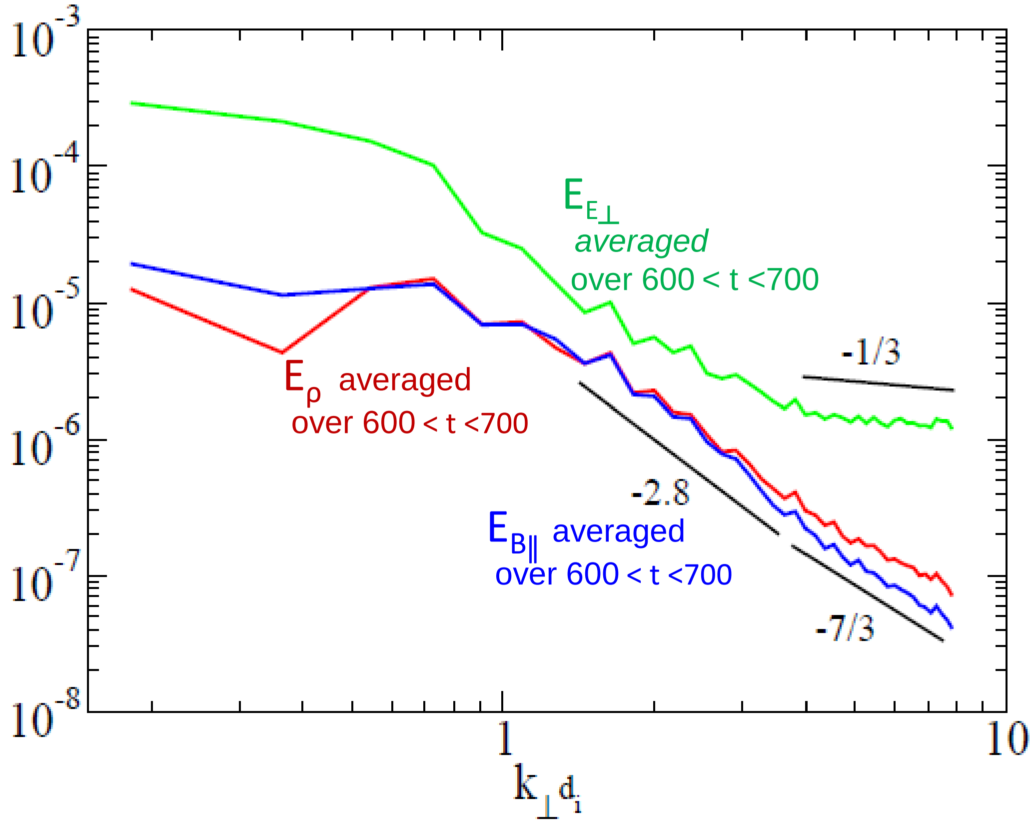
Solar Wind observations: "dissipation range" **(exponent between -2.5 and -2.8)** separated from the usual Kolmogorov range by a transition region where the slope can be much steeper.

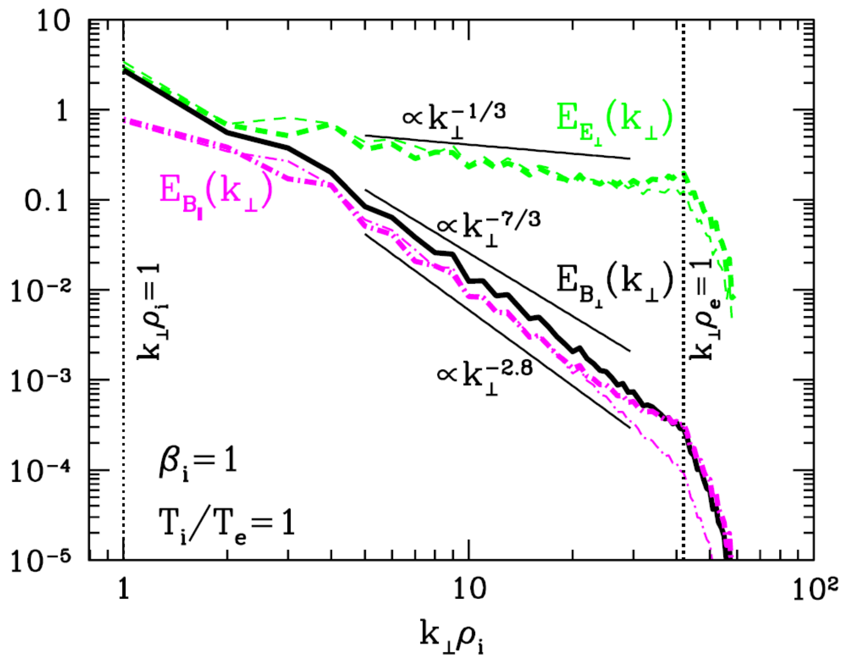


*Sahraoui et al. PRL, **105**, 131101 (2010)*

See also
*Alexandrova et al., Ann. Geophys. **26**, 3585, 2008;*
*Sahraoui et al., PRL, **102**, 231102 (2009);*
*Planet. Space. Sci. **59**, 585 (2011)*

Perpendicular electric field ($E_\perp$) spectrum: $k_\perp^{-1/3}$, for $k_\perp r_L > 4$,
associated with a $k_\perp^{-7/3}$ $B_\parallel$ spectrum.
Similar shallow range on the density spectrum.
Link with **sharp** grad$_\perp$ B_z , possibly associated with magnetosonic waves.

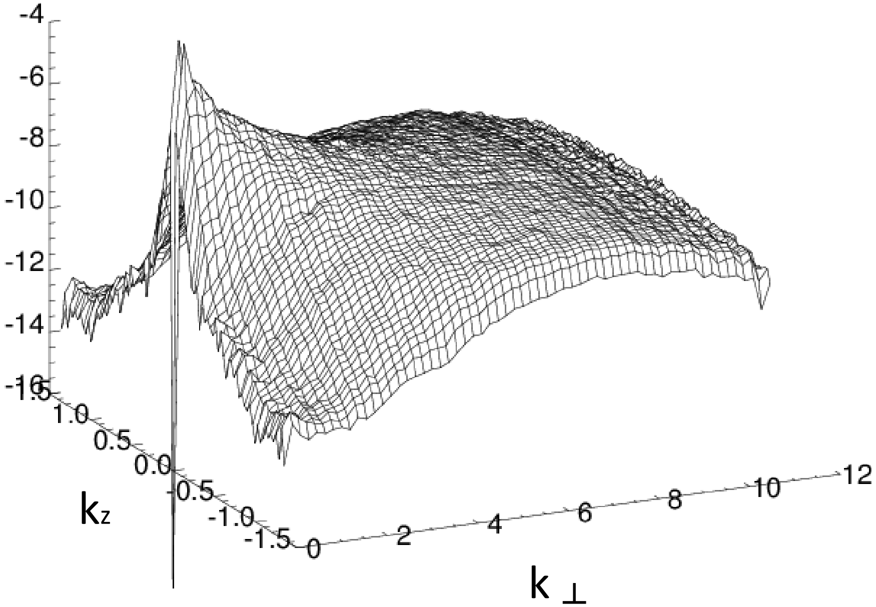


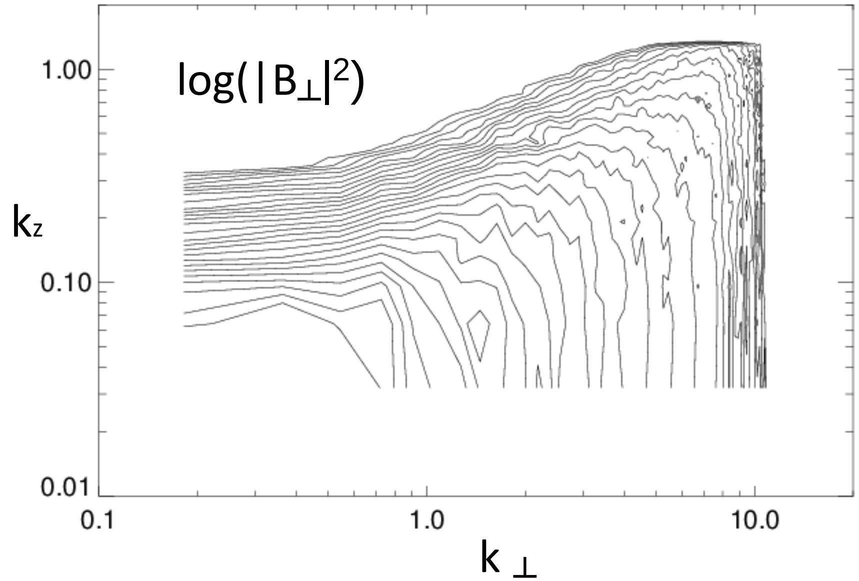


Consistent with **gyrokinetic simulation**
*(Howes et al. PRL **107**, 035004, 2011)*

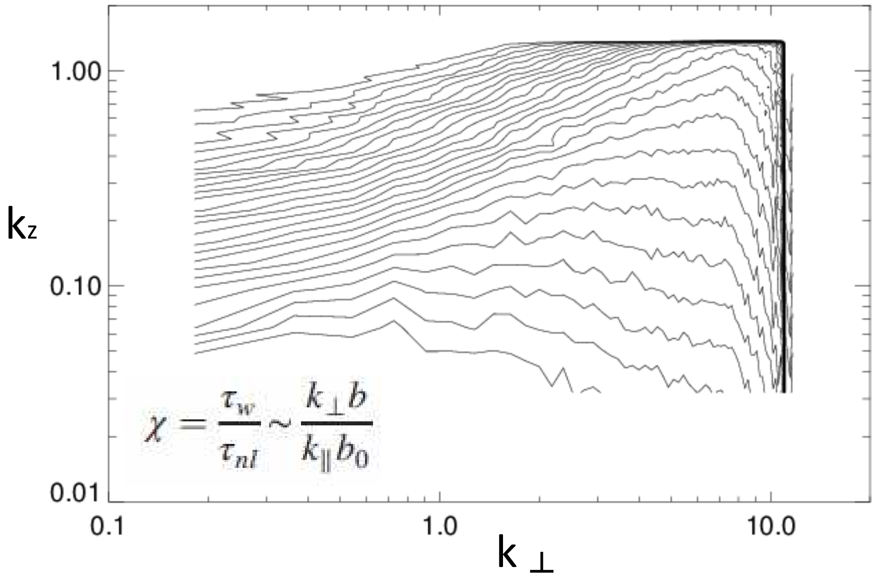
$\beta_i = 1 \quad T_i/T_e = 1$

2D spectrum of $|B_\perp|^2$

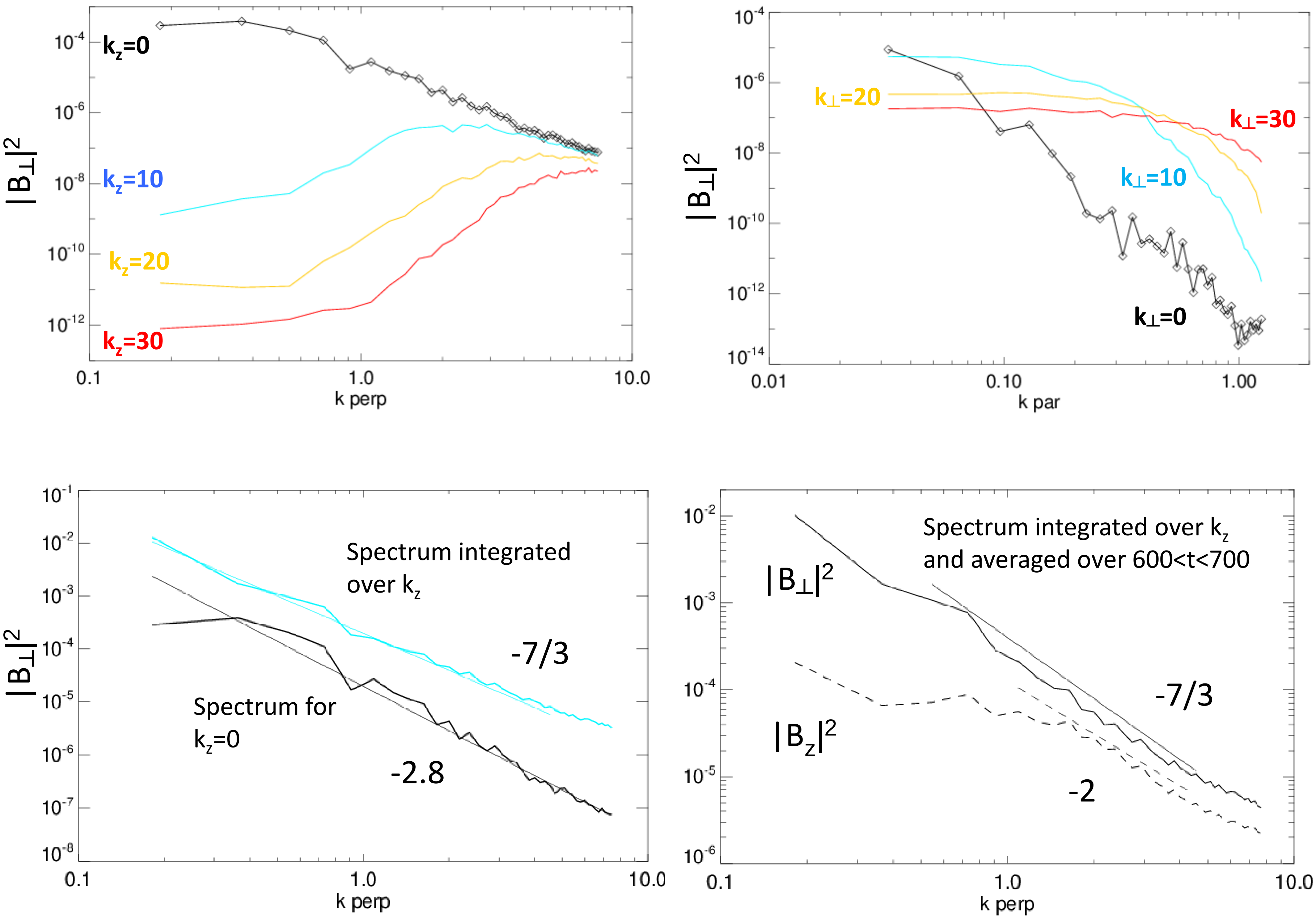




Scale anisotropy decreases with scale below the ion scale.

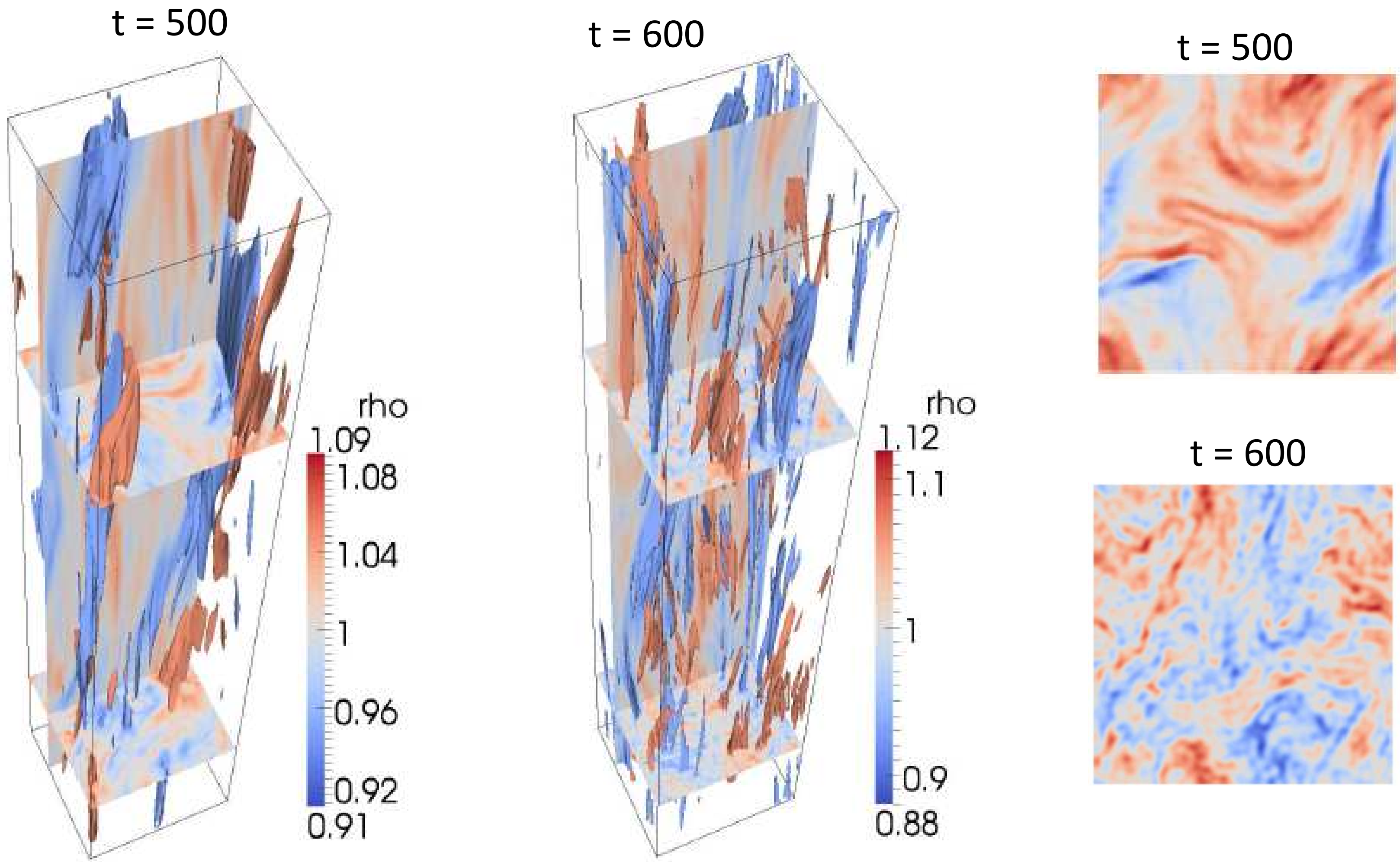


$$\chi = \frac{\tau_w}{\tau_{nl}} \sim \frac{k_\perp b}{k_\parallel b_0}$$



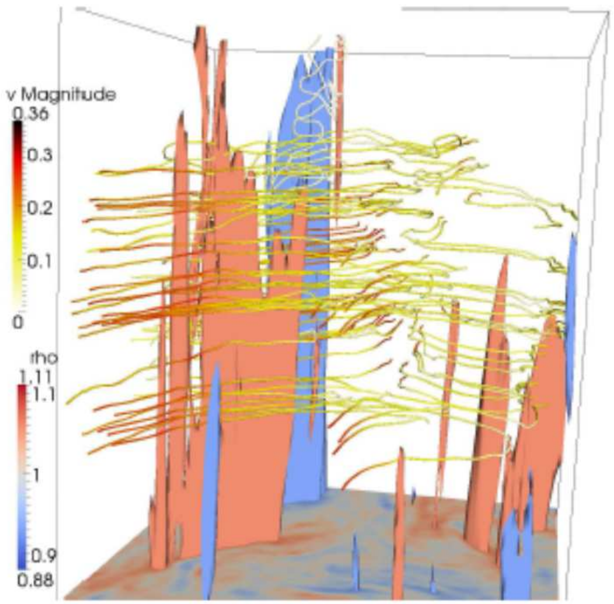
k_z=0
k_z=10
k_z=20
k_z=30
$|B_\perp|^2$
k perp
$k_\perp$=20
$k_\perp$=30
$k_\perp$=10
$k_\perp$=0
k par
Spectrum integrated over k_z
Spectrum for k_z=0
-7/3
-2.8
Spectrum integrated over k_z and averaged over 600<t<700
$|B_z|^2$
-2

Transition in the exponent of the transverse spectra associated with a **change in the topology of the density structures from sheets** (at early times) **to parallel filaments** (in the statistically stationary regime):
breakup (rather than rolling up) **of the sheets with a later pile up of the structures**.

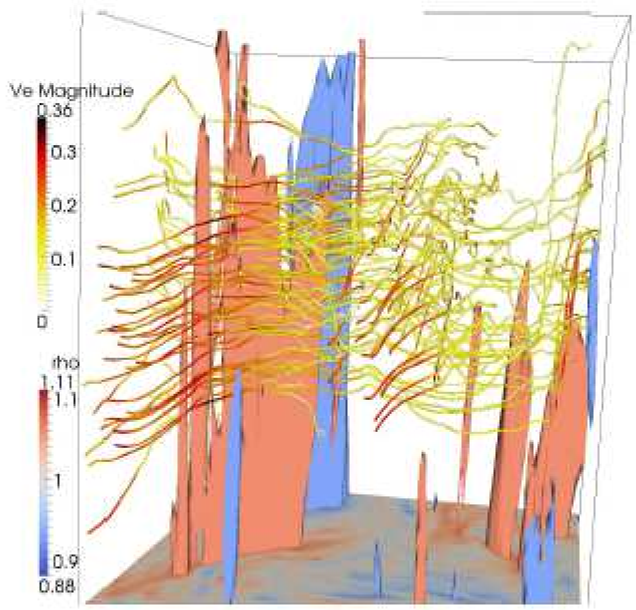


Plasma density

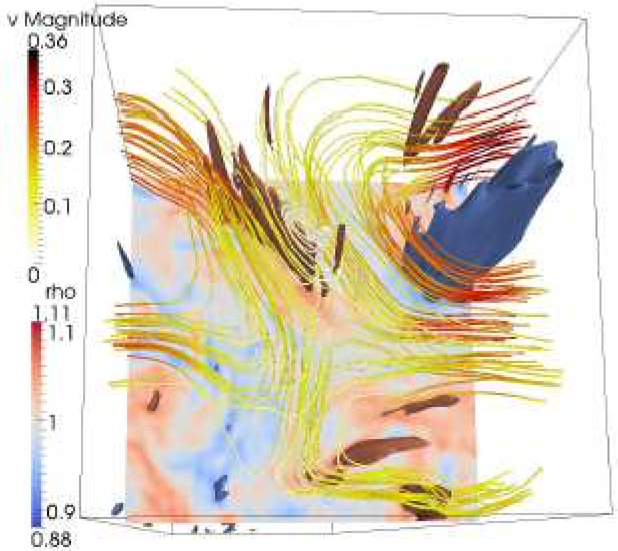
t=550



Ion velocity field: Quasi-2D

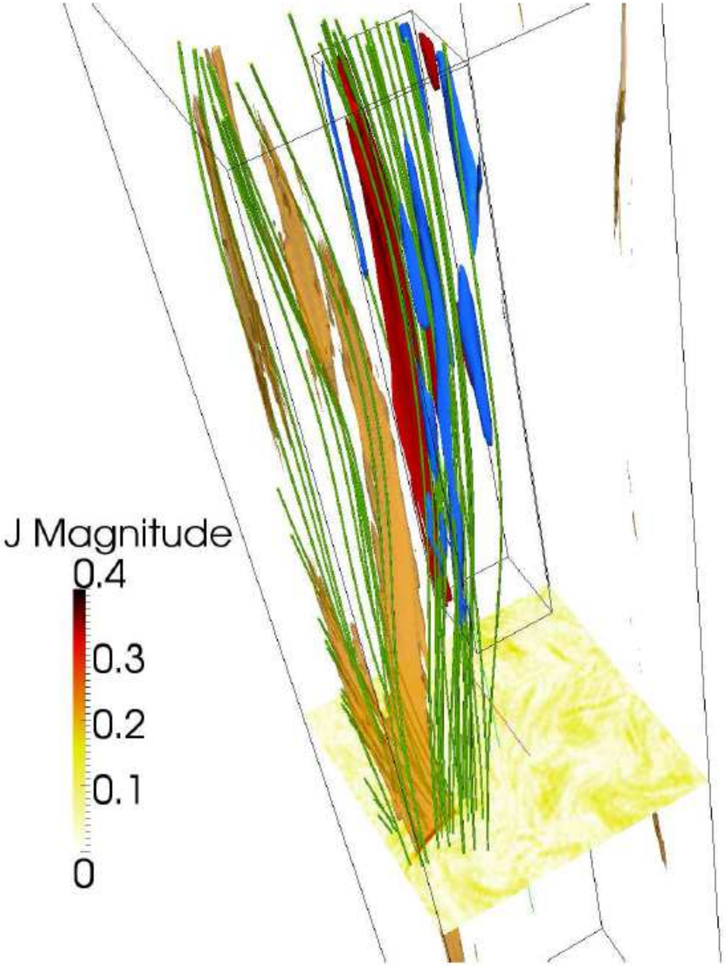


Electron velocity field: 3D with at some places, large component along the ambient field.



View from above of the ion velocity:
Vortical motions around density minima
and stretching of large-density regions between corotating vortices.

Current density also undergoes a transition towards filamentary structures



Isosurfaces at t = 500

- of the current at 50% of its maximum value, (still sheet shaped)
- of the density (in a sub-domain) at $\rho/\rho_0 = 0.98$ and 1.023 (elongated filamentary structures).

Superimposed magnetic field lines show that **the structures tend to align with the magnetic field.**

Transition from sheets to filaments remains an open problem

Structures of the electric current density:

- Usual MHD leads to **current sheets**
- **Current filaments** obtained in incompressible Hall-MHD *(Miura & Araki , J. Phys. Conf. Series **318**, 072032, 2011)* and in Electron MHD *(Meyrand & Galtier, Phys. Rev. Lett. **111**, 264501, 2013).* **Due to Hall term.**

Magnetic spectra: various predictions in the literature:

$\mathbf{k}_\perp^{-7/3}$: for KAWs *(Schekochihin et al., Astrophys. J. Suppl. Series **182**, 310, 2009)*
whistlers *(Biskamp et al., Phys. Plasmas **6**, 751, 1999)*
Hall-MHD *(Galtier, Phys. Rev. E **77**, 015302, 2008)*
on the basis of phenomenological arguments.

$\mathbf{k}_\perp^{-8/3}$: in simulations of a simple fluid model for KAWs, where density structures are observed to be sheets *(Boldyrev et al., Astrophys. J. **777**, 41, 2013) .*

Filaments or sheets in a KAW model: could depend on the ratio of diffusive to resistive dampings *(Smith & Terry, Astrophys. J. **730** , 133, 2011).*

In the present FLR-LF simulations , no resistive damping : density filaments.
Further developments: influence of resistivity due to collisional effects.

Mirror unstable regime

FLR-Landau fluid can also address regimes with **temperature anisotropy.**

Parameters: $\beta_{\|p} = 2,\ T_{\perp p}/T_{\|p} = 2,\ T_{\perp e}/T_{\|e} = 1,\ T_{\|e}/T_{\|p} = 1$

Initial conditions: small random noise on a uniform density,
no velocity,
uniform magnetic field and gyrotropic pressures,
zero heat fluxes.

After a phase of linear growth, the mirror instability saturates leading to **coherent structures**.

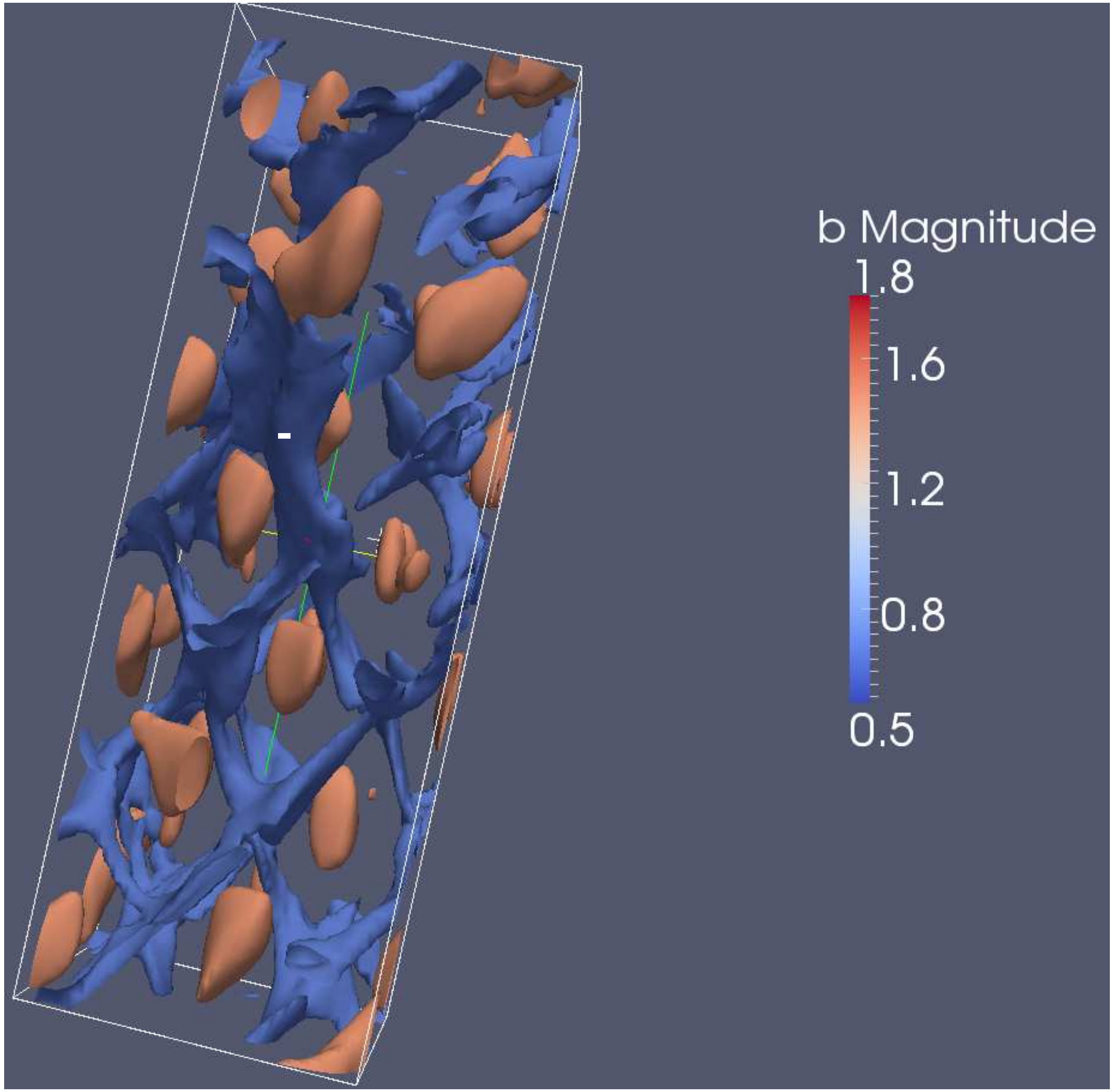
Saturation of the mirror instability

Magnetic structures:
cigar-shaped maxima
saddle-shaped minima

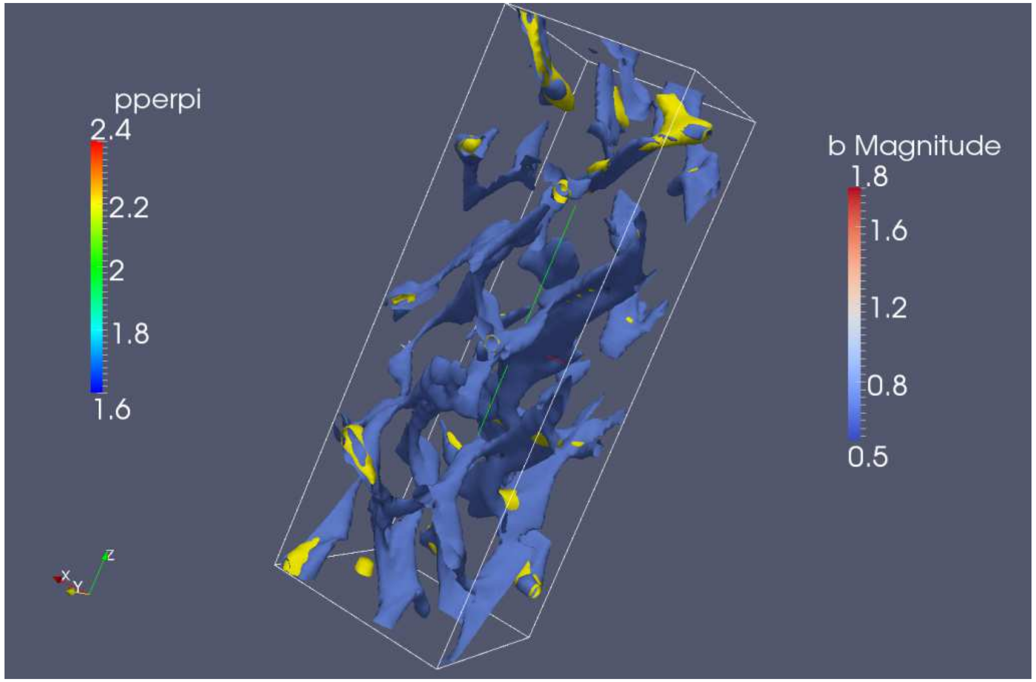
Stronger maxima at larger β.

Dominance of magnetic holes or peaks, correlated with distance to threshold.

$\beta=5$
$T_{\perp,i}/ T_{\parallel,i}=2$
$T_{\perp,e}/ T_{\parallel,e}=1$
$T_{\parallel,e} / T_{\parallel,i}=1$

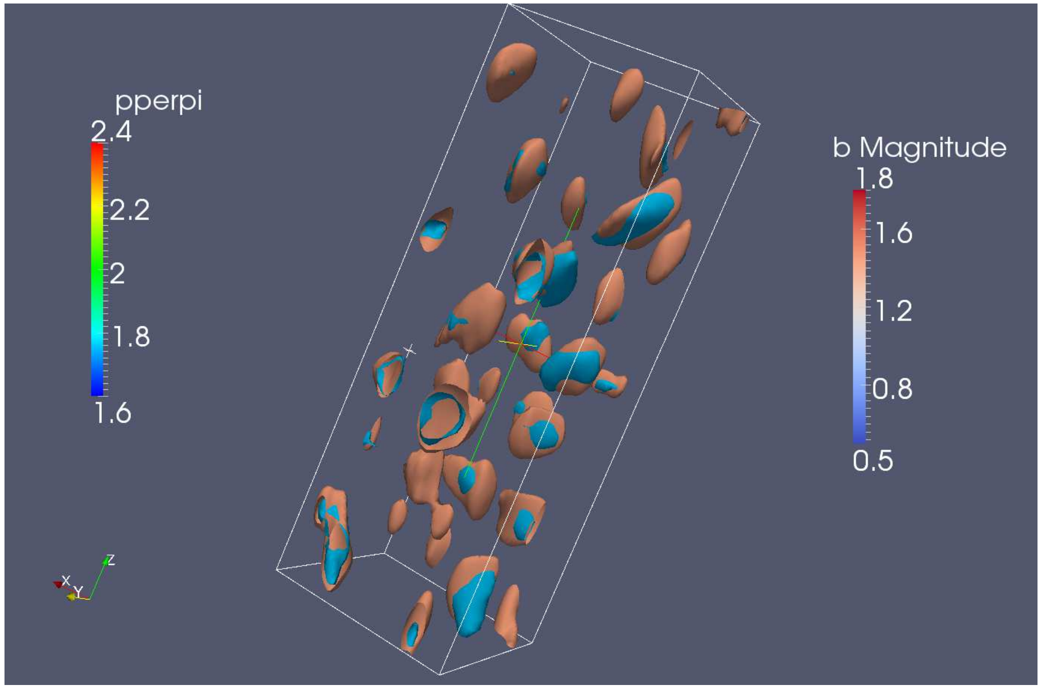


Anti-correlation between magnetic field magnitude and perpendicular pressure
(as predicted by linear theory).



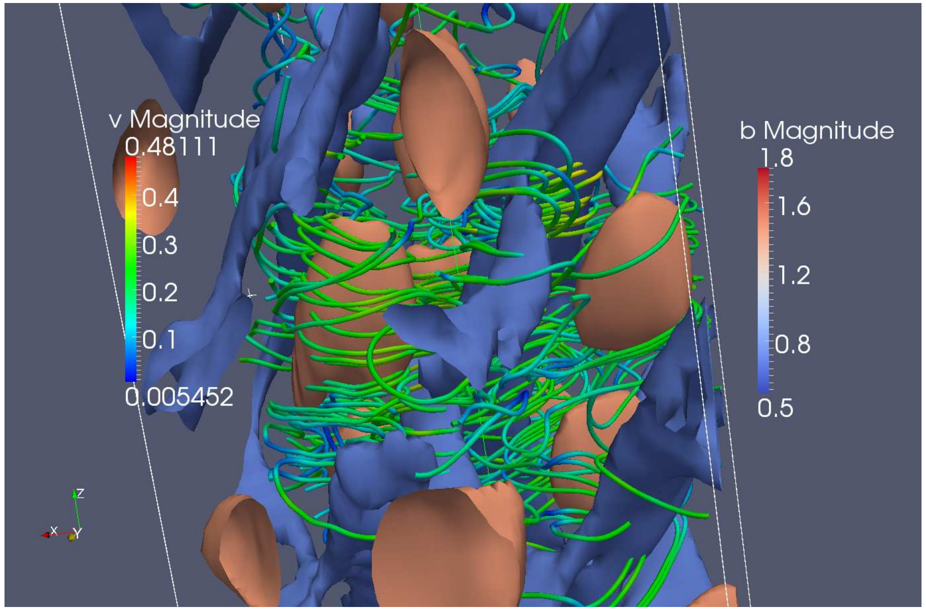
Large perpendicular pressure
in regions where magnetic amplitude
is small.

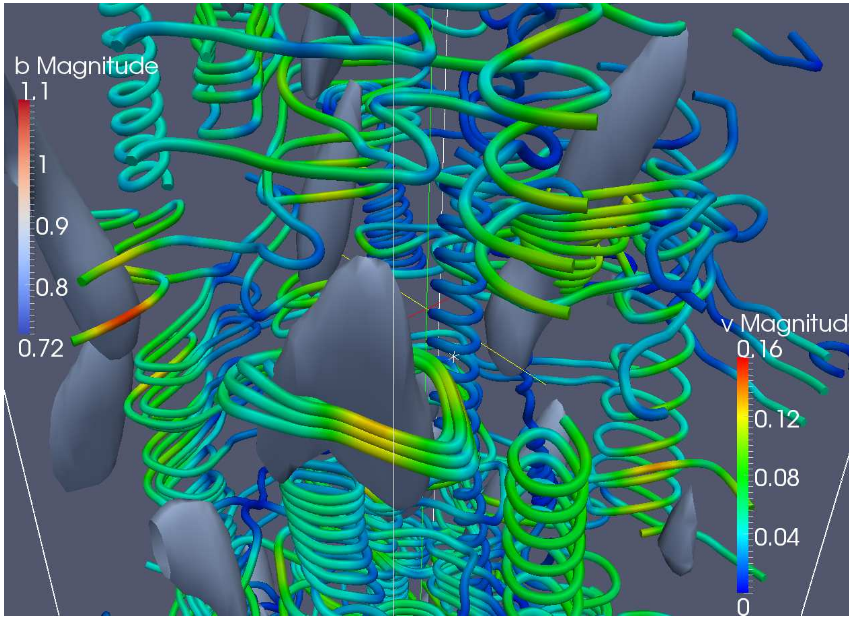
β=5
$T_{\perp,i}/\,T_{\|,i}=2$
$T_{\perp,e}/\,T_{\|,e}=1$
$T_{\|,e}\,/\,T_{\|,i}=1$



Low perpendicular pressure
in regions where magnetic amplitude
is large.

Significant ion velocity around structures in planes perpendicular to the ambient field.





$\beta_{\parallel i}$ =2
$T_{\perp,i}/ T_{\parallel,i}$=2
$T_{\perp,e}/ T_{\parallel,e}$=1
$T_{\parallel,e} / T_{\parallel,i}$=1

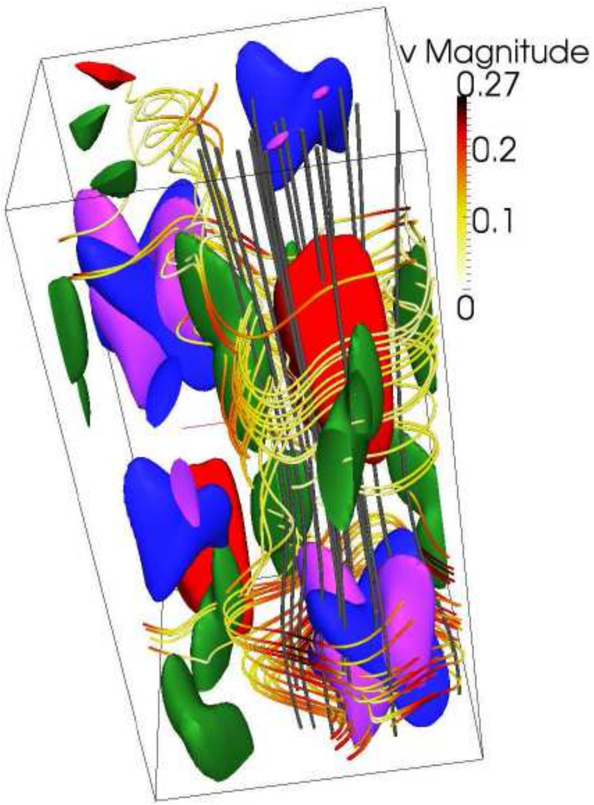
Quasi 2D ion velocity fields surrounding magnetic structures.

$\beta_{\parallel i}$ =0.8
$T_{\perp,i}/ T_{\parallel,i}$=2
$T_{\perp,e}/ T_{\parallel,e}$=1
$T_{\parallel,e} / T_{\parallel,i}$=1

Contrast with asymptotic ordering in weakly nonlinear regime near instability threshold which involves quasi-static dynamics.

In any realistic situation, the deviation to threshold can hardly be so small as to ensure quasi-static evolution.

Towards mirror turbulence



Early time: t = 390

Cigar-shaped magnetic maxima
Saddle-shaped magnetic minima .

Some anticorrelation between **magnetic field magnitude and density** (although in a less obvious way than with perpendicular pressure).

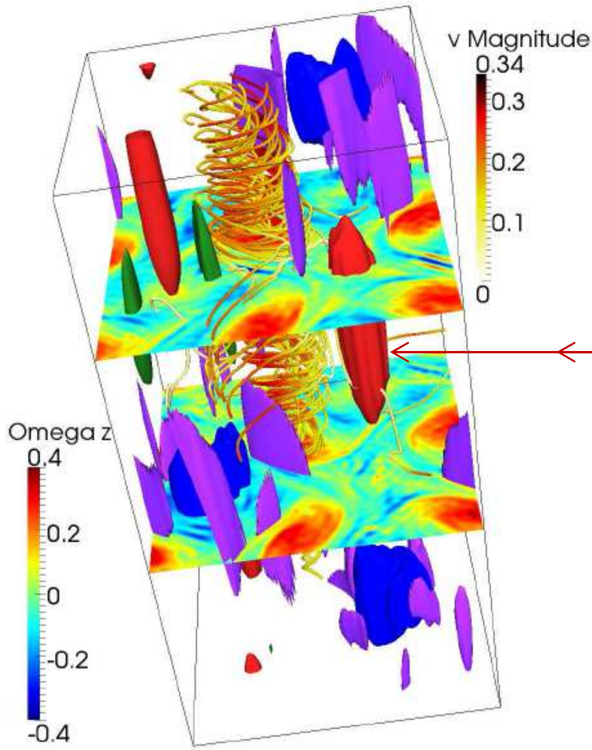
Quasi 2D ion velocity fields surrounding the magnetic structures (max velocity ~ 0.2 v_A).

$\beta_{\|p} = 2$

$T_{\perp p}/T_{\|p} = 2$

$T_{\perp e}/T_{\|e} = 1$

$T_{\|e}/T_{\|p} = 1$



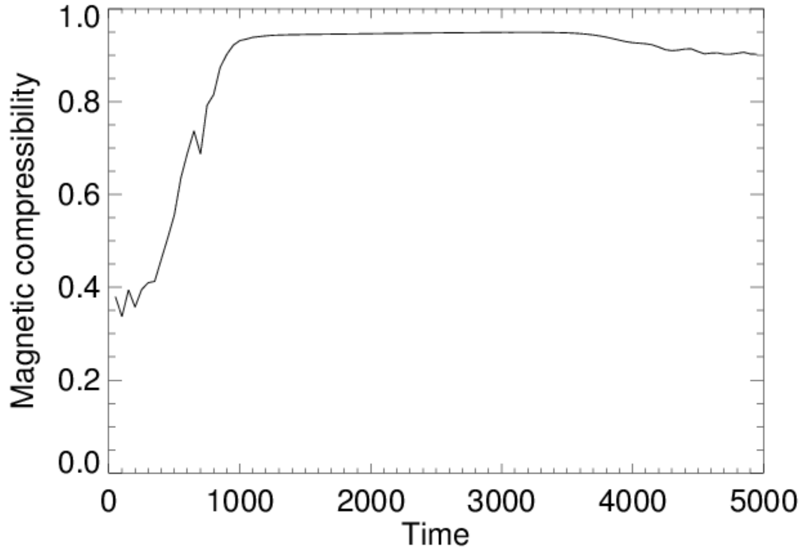
Later time: t =425

Density maxima : thin sheets located in the strain field of two counter-rotating vortices.

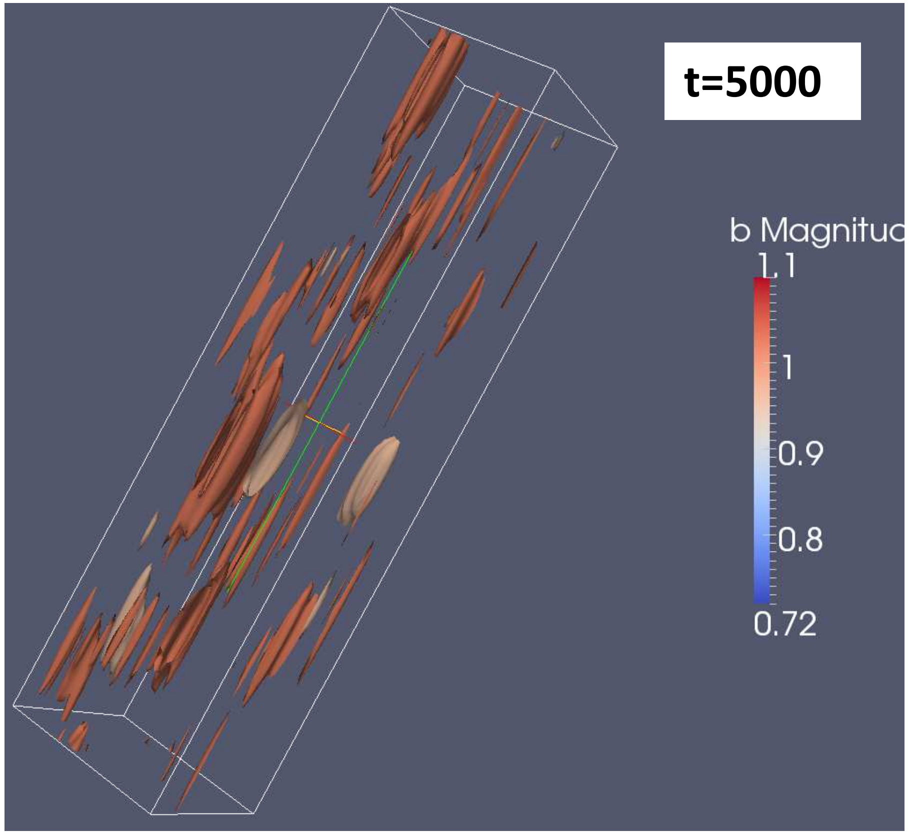
Ion velocity has developed parallel component (**stream lines** spiraling along a vortex).

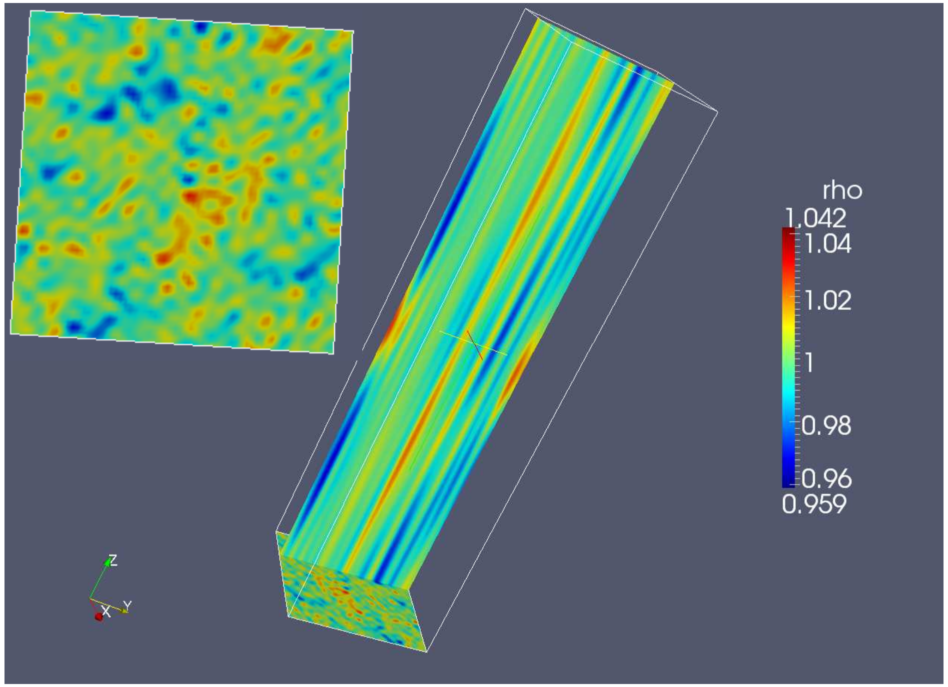
Isosurfaces of large magnetic intensiy have developed ripples which ultimately leads to the **formation of magnetic filaments,** along the (now straighter) magnetic field lines.

Large magnetic compressibility throughout the simulation while kinetic compressiblity rapidly drops to very small values.

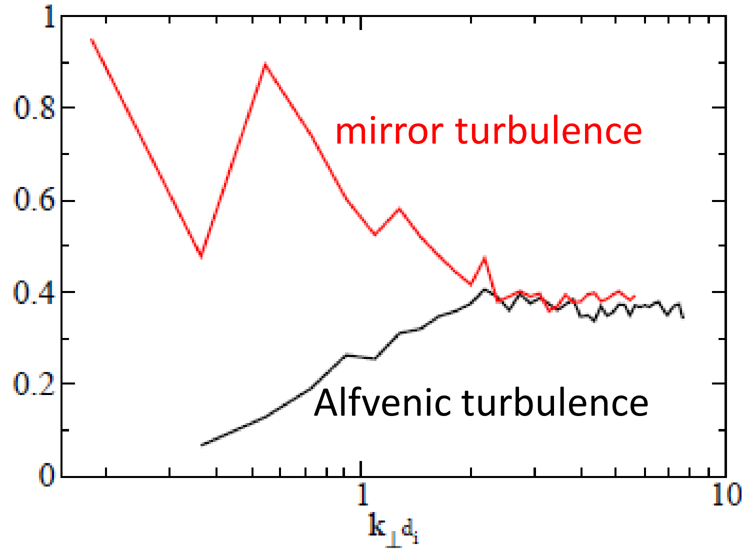


Quasi-2D turbulence for $\boldsymbol{\beta_{\parallel i}}$ **=0.8**





The magnetic fluctuations are mostly parallel, as can also be seen from the **magnetic compressibility spectrum** (averaged over 402.5 < t < 450).



Magnetic compressibility spectrum

$$\chi(k_\perp r_L) = |B_z(k_\perp r_L)|^2/|B(k_\perp r_L)|^2$$

"Mirror turbulence" significantly different from the one resulting from Alfvenic driving. Should be identifiable in observations where temperature anisotropy exceeds the mirror instability threshold (e.g. behing a shock wave).

Is this turbulence which develops in the simulations related to that observed in the terrestrial magnetosheath? *(Sahraoui et al., Astrophys. J.* ***748****, 100, 2012)* .

Conclusions

When the distribution functions *are close enough to biMaxwellian*,
fluid models give a realistic description **of low-frequency phenomena, provided they retain**

- the dynamical equations for the gyrotropic pressures and heat fluxes,
- A linearly accurate description of the FLR corrections at the ionic scales to all the retained moments, and a closure that includes Landau damping for both ions and electrons.

FLR-Landau fluid model

- accurately reproduces linear properties of low-frequency waves and micro-instabilities,
- retains all the non-linear hydrodynamic couplings,
- provides realistic dissipation.

3D nonlinear simulations (do not require artificial dissipation).

- **Alfvenic turbulence:**
  - Spectra consistent with Solar wind observations
  - Transition from early-time density and current sheets to quasi-stationary filaments.
- **Mirror unstable plasma:**
  - Topology of magnetic structures resulting from mirror instability is explored.
  - A **new type of turbulence** generated after the saturation of the mirror instability is observed.

FLR-Landau fluid model provides a promising tool for simulations of the close sub-ionic range of collisionless plasmas, where important dynamical effects were revealed by satellite observations of the Solar Wind and of the Terrestrial magnetosheath.