From Alfvén waves to kinetic Alfvén waves in an inhomogeneous equilibrium structure.

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Motivations

Observations have shown that solar wind turbulence is highly anisotropic with the cascade in the direction perpendicular to the local magnetic field being dominant at kinetic scales.

Kinetic Alfvén waves are quasi perpendicular fluctuations that have been invoked as one of the ingredients that can explain such an anisotropy.

At large (MHD) scale solar wind spectra show turbulence activity along with the propagation of Alfvénic oscillations.

Since solar wind is an highly inhomogeneous medium an Alfvén packet propagating in it can be distorted and converted to other mode.

In which cases can such interaction bring to the formation of kinetic Alfvén waves?

We study this problem using a simplified numerical model.

Summary

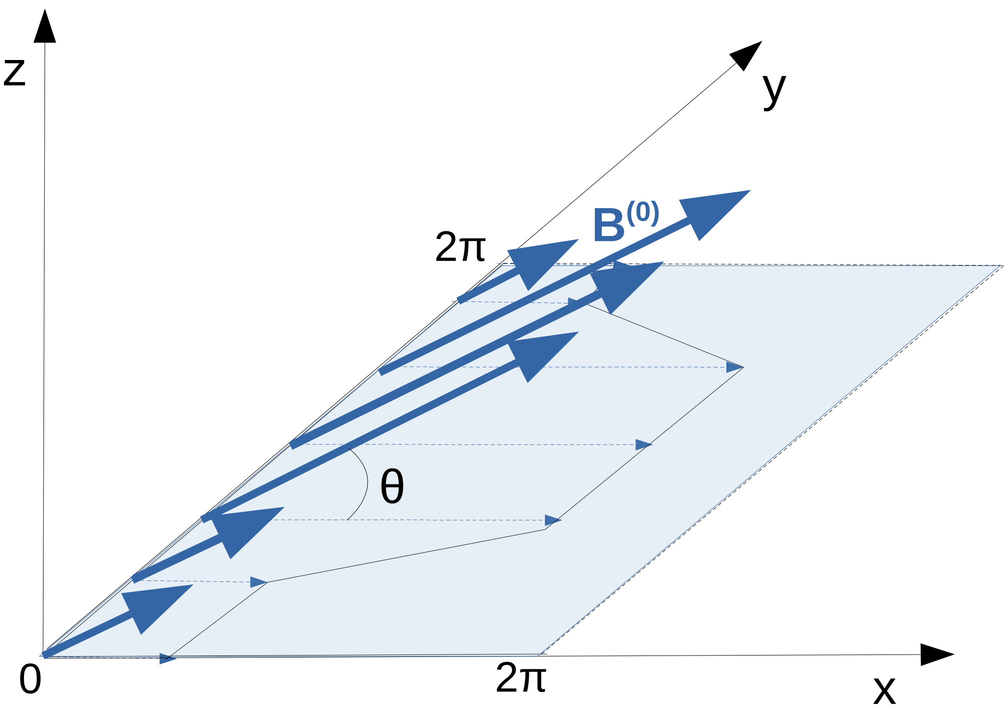
Initial conditions: equilibrium structure and perturbation

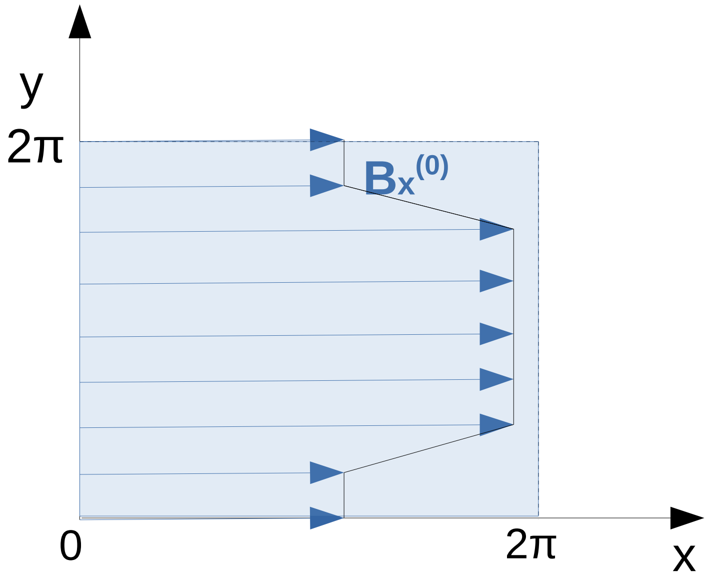
Hall MHD linear model

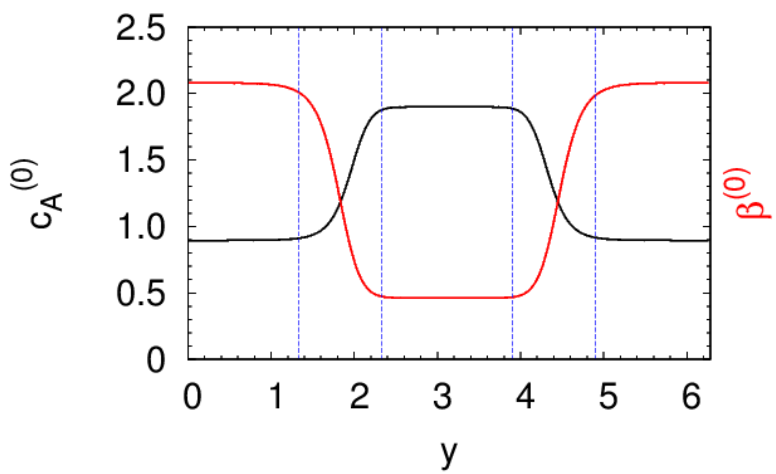
Hybrid Vlasov Maxwell non-linear model

Conclusions

PRESSURE BALANCE EQUILIBRIUM STRUCTURE







$\beta^{(0)}(y) = (c_s{}^{(0)}/c_A{}^{(0)})^2$ Plasma beta

$c_A{}^{(0)} = B^{(0)}(y)/\sqrt{\rho^{(0)}(y)}$ Alfvén velocity

Density and pressure:

$$\rho^{(0)}(y)T^{(0)} + \frac{{B^{(0)}}^2(y)}{2} = P_T^{(0)}$$

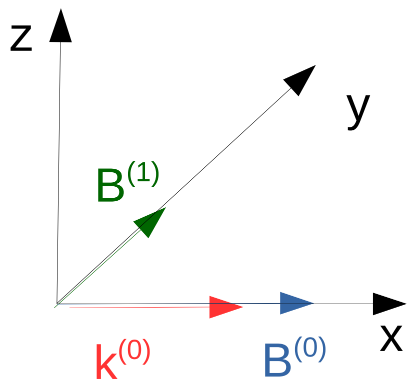
Temperature:

$$T = T^{(0)}$$

ALFVÉNIC INITIAL PERTURBATION: DIFFERENT CASES CONSIDERED

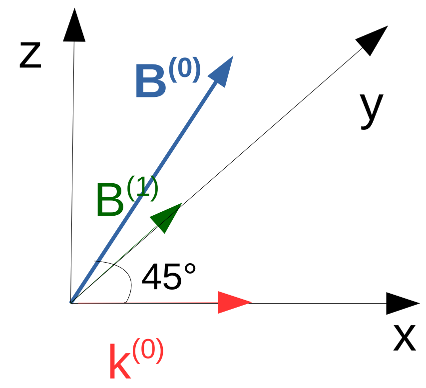
$$\mathbf{B}^{(1)}(x,y,t=0) = a\cos(x)\mathbf{e}_y, \quad \mathbf{v}^{(1)}(x,y,t=0) = -a[\rho^{(0)}(y)]^{-1/2}\cos(x)\mathbf{e}_y$$

CASE 1

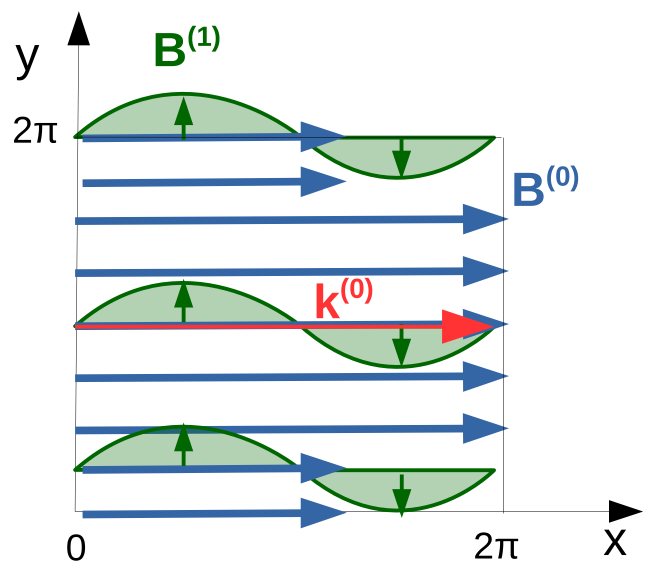


In plane equilibrium magnetic field

CASE 2



Out of plane equilibrium magnetic field



HMHD MODEL

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{\tilde{\beta}}{2\rho}\nabla(\rho T) + \frac{1}{\rho}\left[(\nabla \times \mathbf{B}) \times \mathbf{B}\right]$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left[\mathbf{v} \times \mathbf{B} - \frac{\tilde{\epsilon}}{\rho}(\nabla \times \mathbf{B}) \times \mathbf{B}\right]$$

$$\frac{\partial T}{\partial t} + (\mathbf{v} \cdot \nabla)T + (\gamma - 1)T(\nabla \cdot \mathbf{v}) = 0$$

$$\tilde{\epsilon} = \tilde{d}_p/\tilde{L} = 0.125$$ Hall parameter

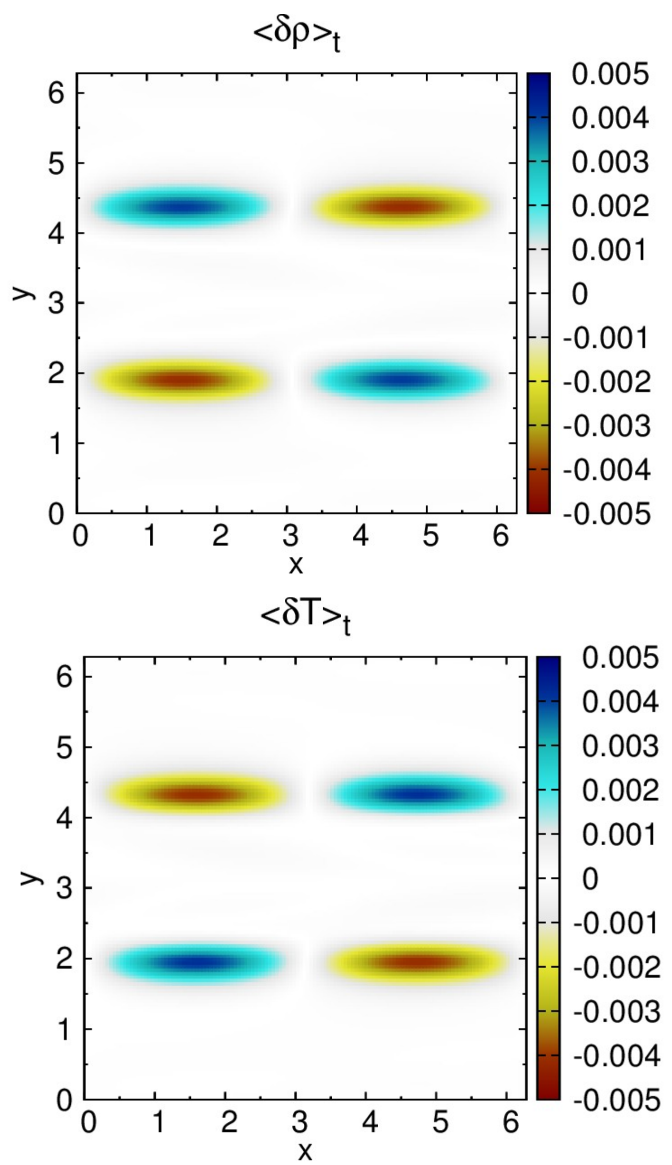
$$\tilde{d}_p = \tilde{c}_A/\tilde{\Omega}_{cp} = \tilde{c}_A m_p c/(q\tilde{B})$$ proton inertial length

In the HMHD model we perturb the equilibrium structure with a small amplitude perturbation (linear case):

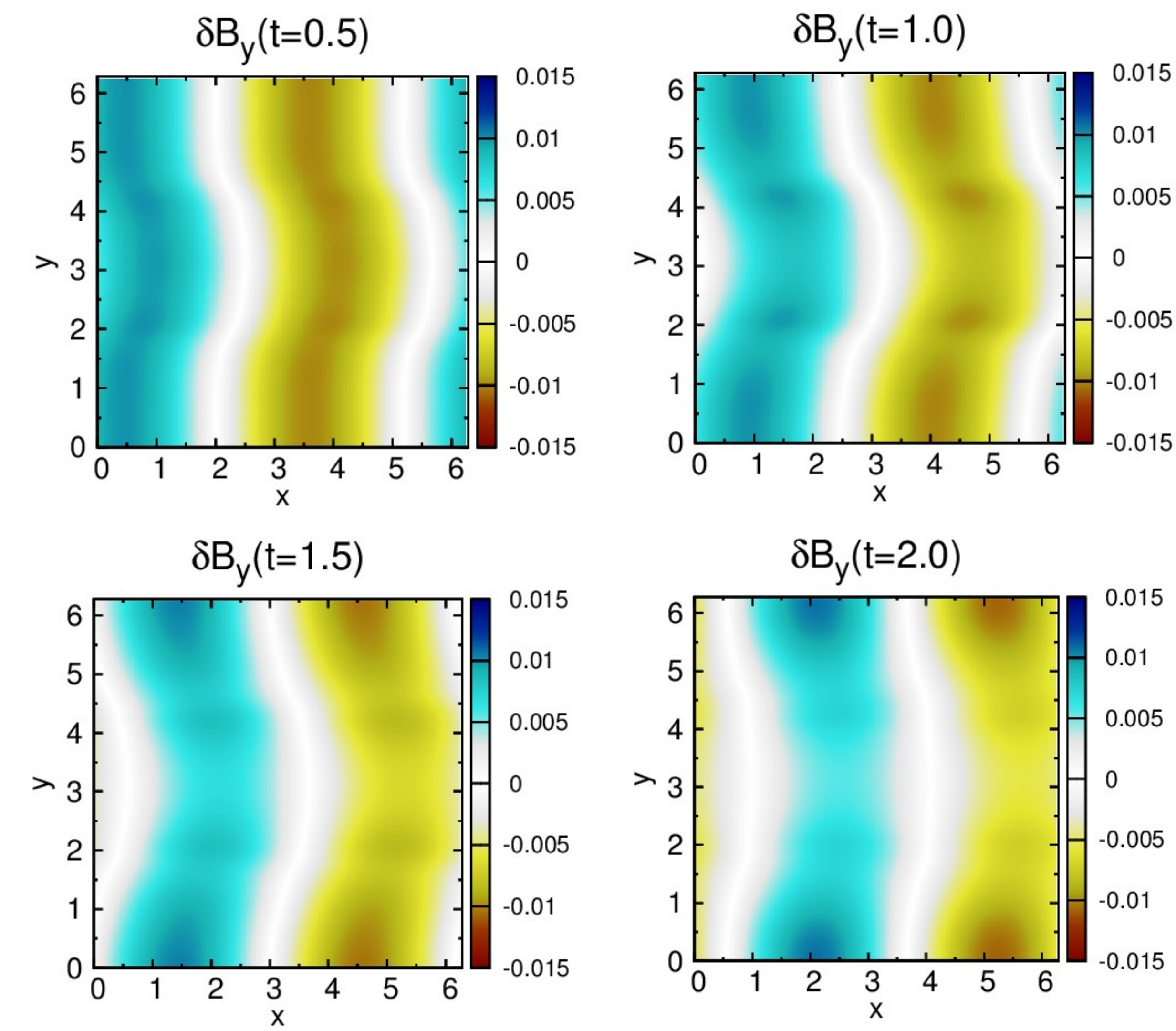
$$a = 0.01$$

NUMERICAL SIMULATIONS - CASE 1 LINEAR (HMHD)
Compressive effects

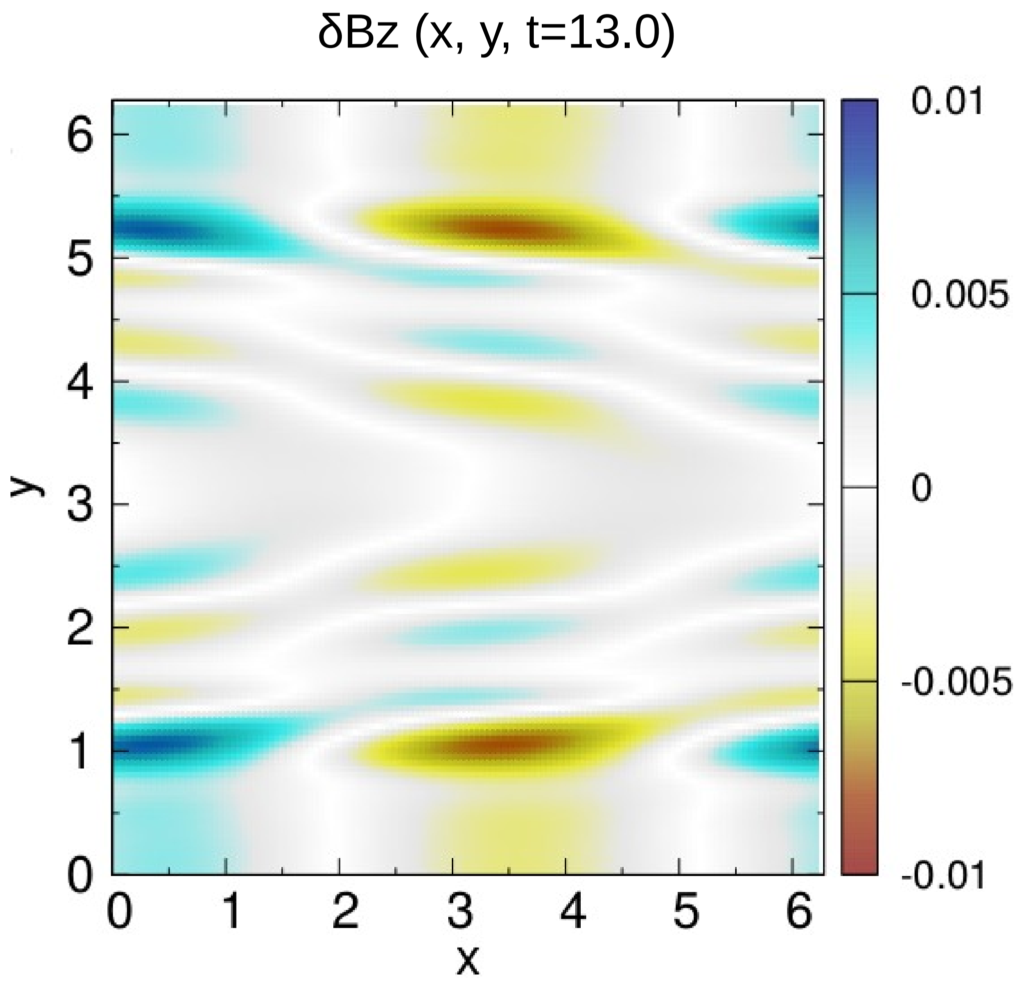
ENTROPY WAVES



FAST MODE

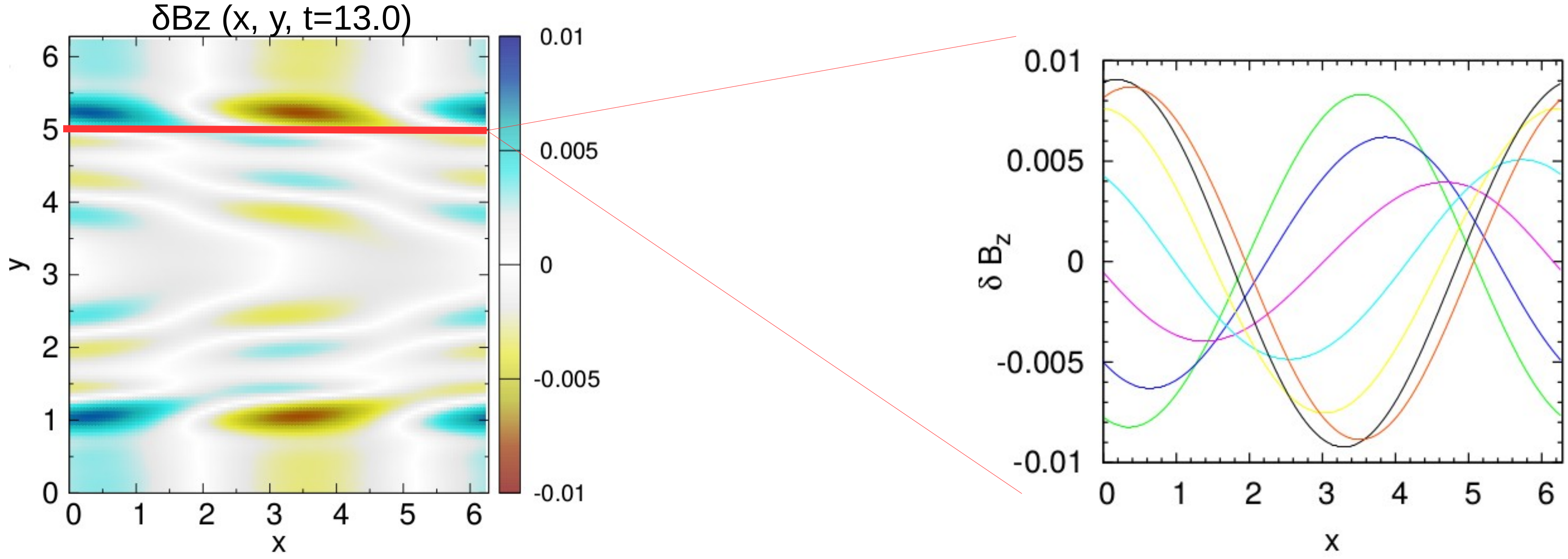


NUMERICAL SIMULATION - CASE 1 LINEAR (HMHD) OUT OF PLANE PERTURBATION

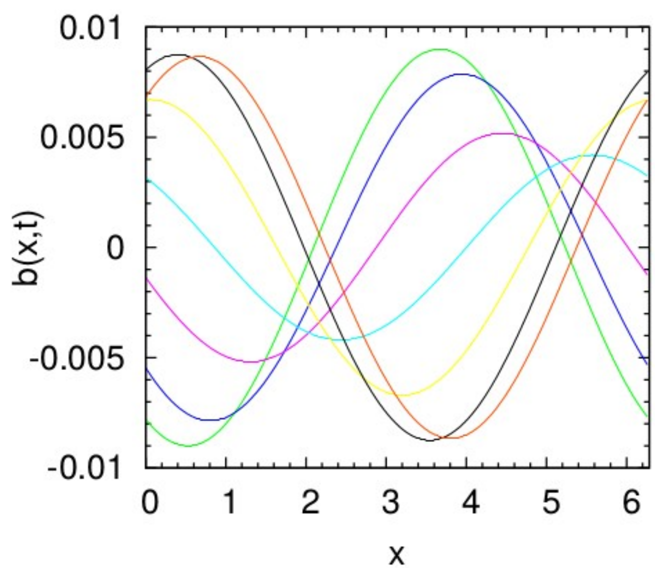


Case 1

NUMERICAL SIMULATION - CASE 1 LINEAR (HMHD) OUT OF PLANE PERTURBATION



$$b(x,t) = A_1 \sin\left[k_x x - \omega(t-t_0) + \phi_1\right] - A_2 \sin\left[k_x x + \omega(t-t_0) + \phi_2\right]$$



$A_1 = 6.5 \times 10^{-3},\ A_2 = 2.5 \times 10^{-3},\ \omega = 1.2,$

$\phi_1 = -(2/3)\pi,\ \phi_2 = \pi/3$ and $t_0 = 13.$

NUMERICAL SIMULATION - CASE 1 LINEAR (HMHD) OUT OF PLANE PERTURBATION: KAW

Extimated quantities:

$\omega \simeq 1.2$

$k_\perp \simeq 6.24$

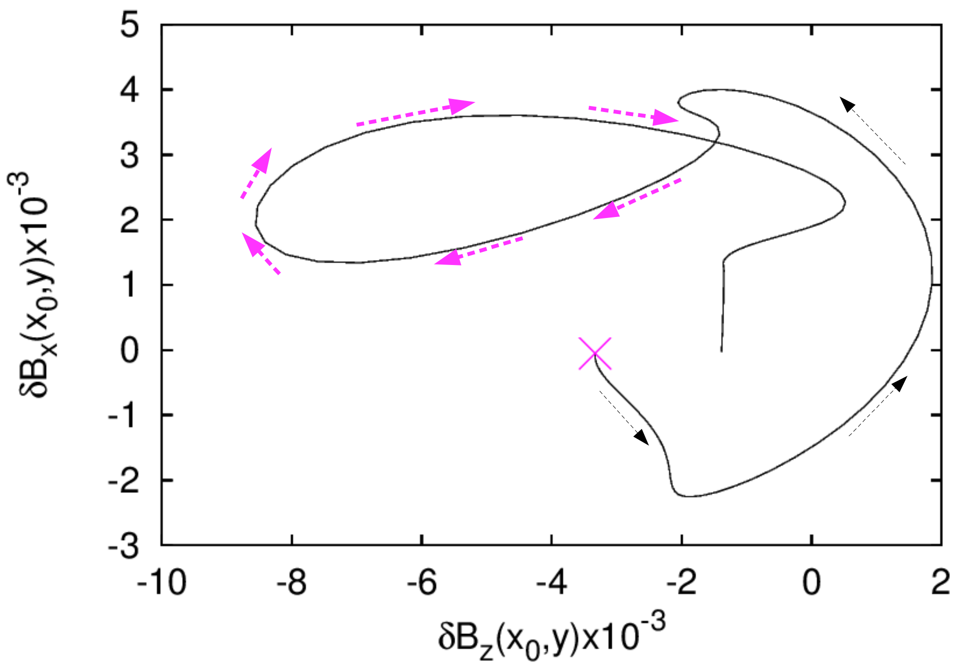
$\varphi = \arctan(k_\perp/k_\parallel) \simeq 81°$

$v_\parallel \simeq 1.2$

$v_\perp \simeq 0.053$

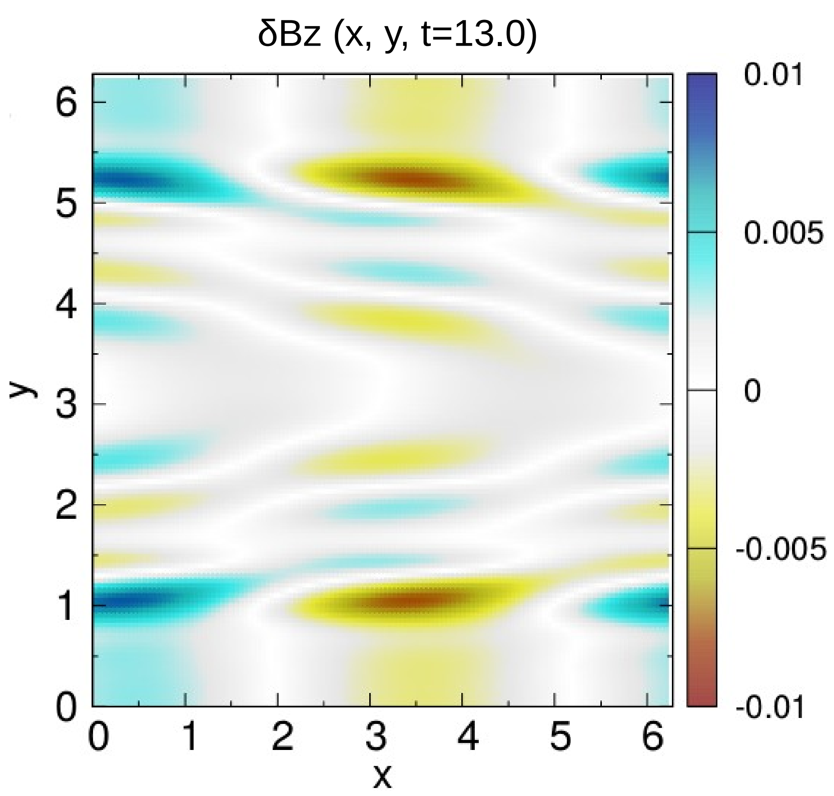
Values from linear theory

	ω	$v_{g\parallel}$	$v_{g\perp}$
KAW	1.30	1.31	0.066
FM	11.0	0.23	1.74
SM	0.062	0.62	−0.032

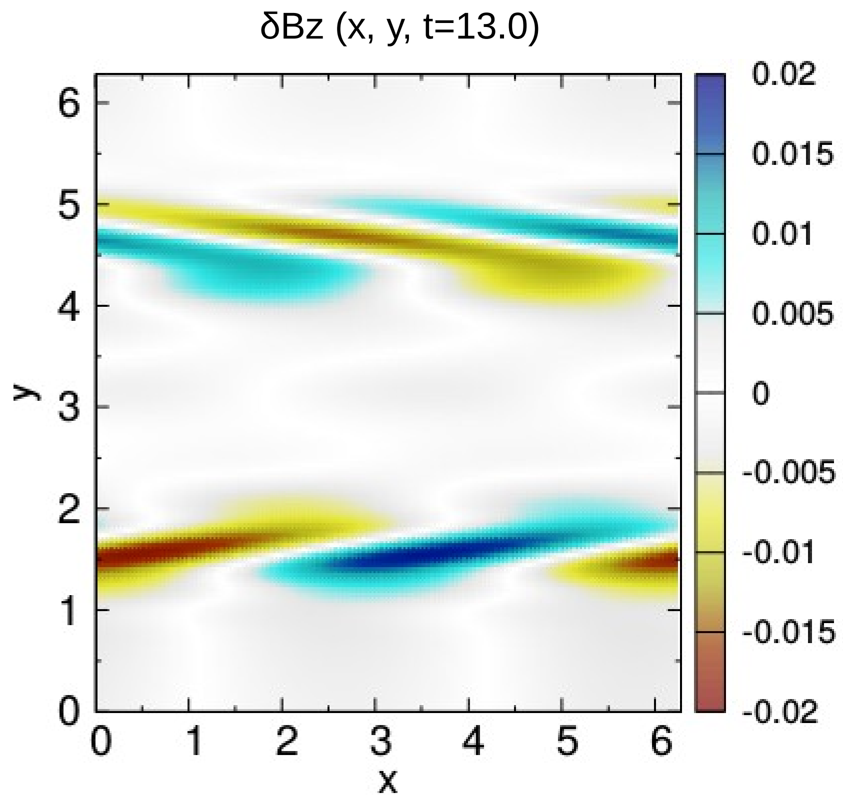


The magnetic field turns clockwise moving along y

NUMERICAL SIMULATION - CASE 1 and 2 LINEAR (HMHD) OUT OF PLANE PERTURBATION



Case 1



Case 2

HVM MODEL

$$\frac{\partial f}{\partial t} + \mathbf{u} \cdot \nabla f + \frac{1}{\tilde{\epsilon}} (\mathbf{E} + \mathbf{u} \times \mathbf{B}) \cdot \frac{\partial f}{\partial \mathbf{u}} = 0$$

$$\mathbf{E} = -\mathbf{v} \times \mathbf{B} + \frac{\tilde{\epsilon}}{n} \left(\mathbf{j} \times \mathbf{B} - \frac{\tilde{\beta}}{2} \nabla P_e \right)$$

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

$f = f(\mathbf{x}, \mathbf{u}, t)$ proton distribution function

$n = \int d^3u \, f$ proton density

$\mathbf{v} = n^{-1} \int d^3u f \, \mathbf{u}$ proton bulk velocity

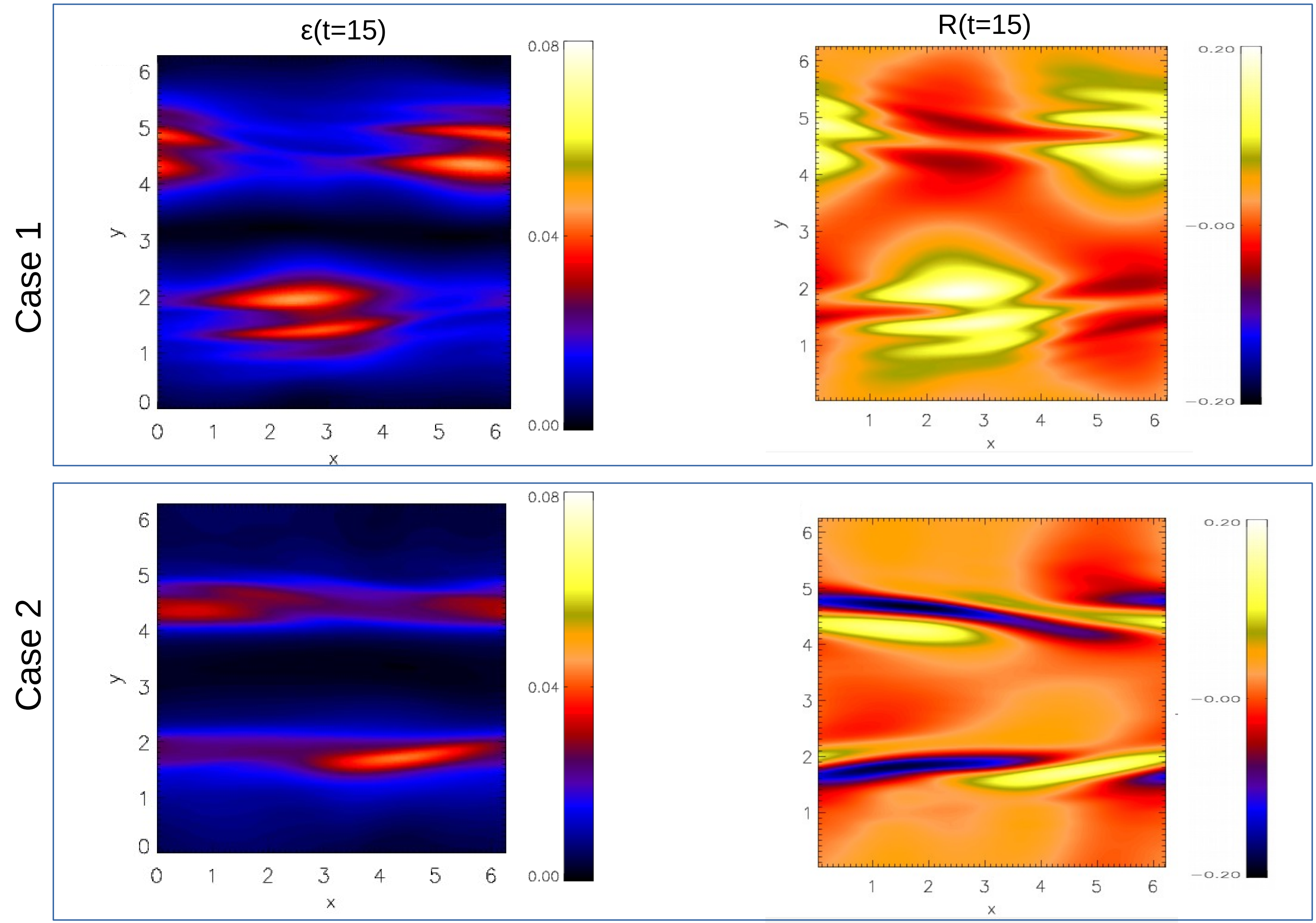
Electrons are treated as an isothermal fluid.
In the HVM model we perturb the equilibrium structure with a large amplitude perturbation (non linear case):

$$a = 0.25$$

NUMERICAL SIMULATION – KINETIC EFFECTS (I)

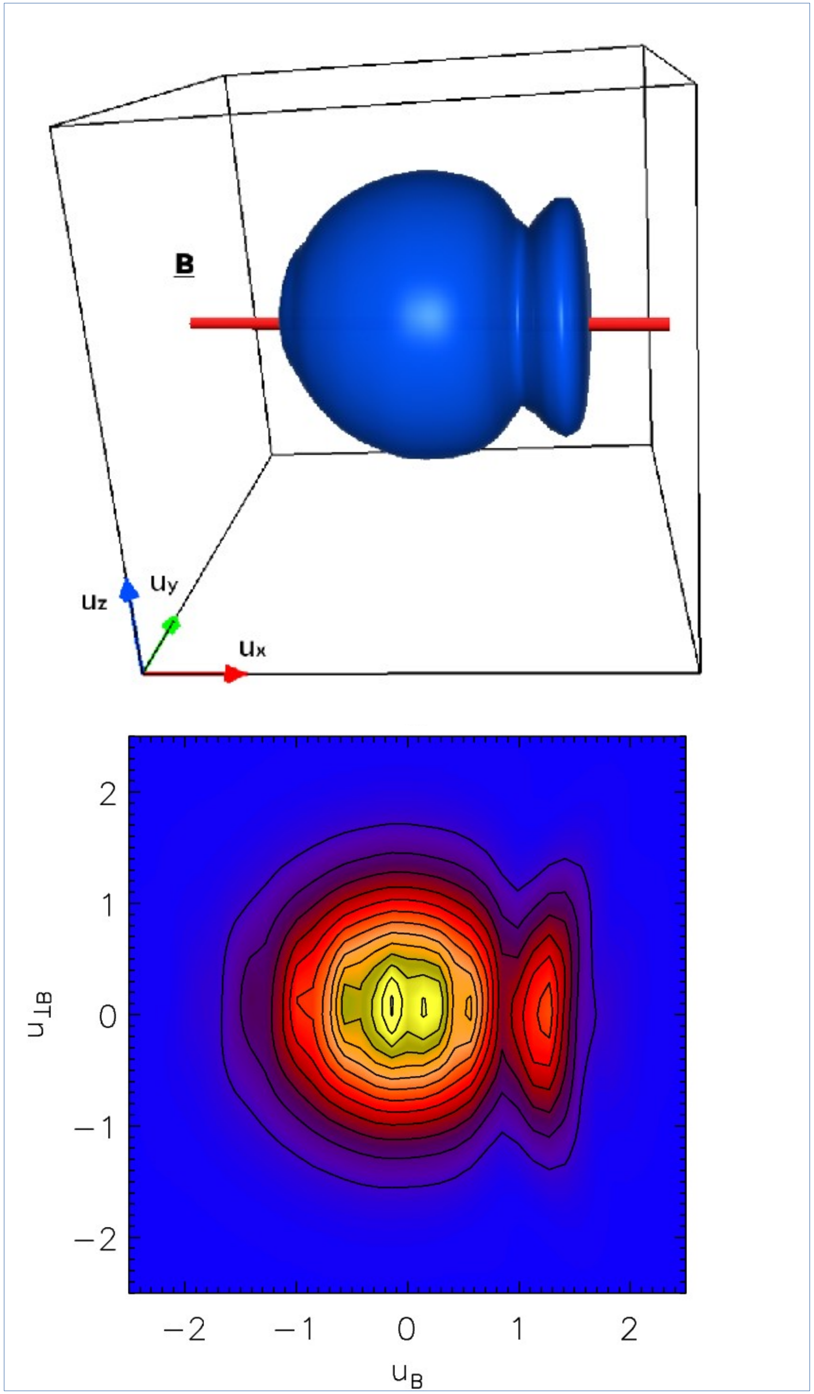
$$\varepsilon(x,y,t) = \frac{1}{n}\sqrt{\int \left[f(\mathbf{x},\mathbf{u},t) - f_M(\mathbf{x},\mathbf{u},t)\right]^2 d^3\mathbf{u}}$$

$$R(x,y) = 1 - \frac{T_\perp(x,y)}{T_\parallel(x,y)}$$

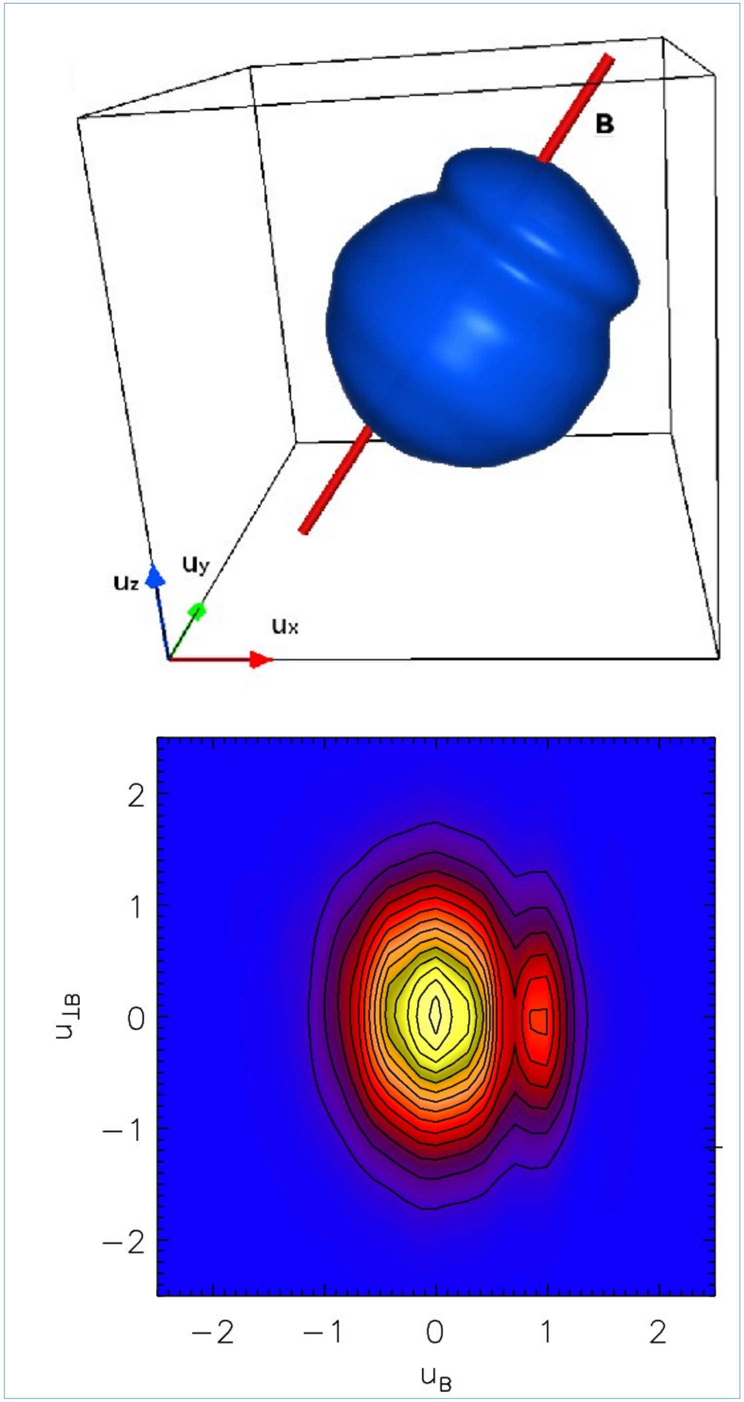


NUMERICAL SIMULATION – KINETIC EFFECTS (II)

Case 1

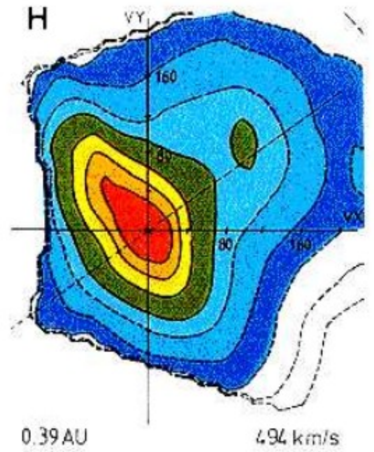


Case 2

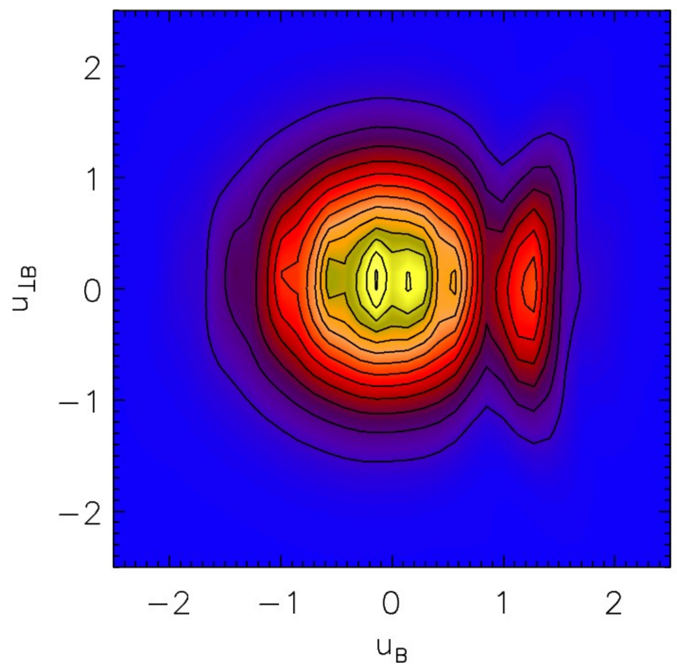


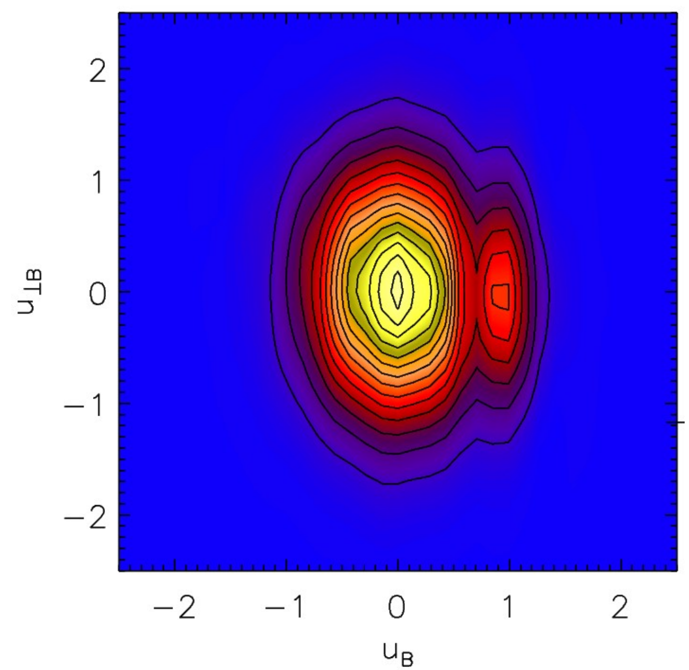
NUMERICAL SIMULATION – KINETIC EFFECTS (III)

Observation



Simulation





Vasconez C. L., Pucci F. et al., ApJ, 2015

Pucci et. al., submitted to JGR, 2015

Conclusions

When an initially parallel propagating Alfvén wave travels through a region where a perpendicular magnetic shear is present a Kinetic Alfvén waves forms in the shear region.

If the amplitude of the initial perturbation is not linear the KAW that is generated deforms the ion distribution function (deviation from Maxwellian and temperature anisotropy).

In particular a beam of accelerated ion forms moving in the direction of the background magnetic field at a velocity comparable to the KAW velocity of propagation.

Even if the model consider is very simplified it shows how through phase mixing and triadic interaction (coupling between the perturbation and equilibrium magnetic field wave vectors) energy can be transfer from the parallel to the perpendicular direction in the wave-vector space through mode conversion from Alfvén waves to Kinetic Alfvén waves.