Parametric decay of Alfvén waves in oblique propagation: 1-D and 2-D hybrid simulations

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Abstract

The kinetic evolution of the parametric instability of a monochromatic Alfvén wave in oblique propagation with respect the ambient magnetic field is investigated, performing one-dimensional (1-D) and two-dimensional (2-D) hybrid simulations.
We study the plasma response to the instability and we focus on the ion evolution under the effects of the parametric wave-wave coupling.
We find that the parallel component of the mother wave is subject to a parametric decay which excites an ion-acoustic wave along the magnetic field and a backward propagating daughter Alfvén wave as in the usual instability for purely parallel waves.
The acoustic wave generation supports the acceleration and formation of a velocity beam in the ion distribution, due to the non-linear trapping of resonant protons.
Moreover, the instability leads to the generation of broad band oblique spectra of coupled Alfvénic and compressive modes with variable perpendicular wavevector; as a consequence the magnetic field after the saturation is characterized by a strong transverse modulation.

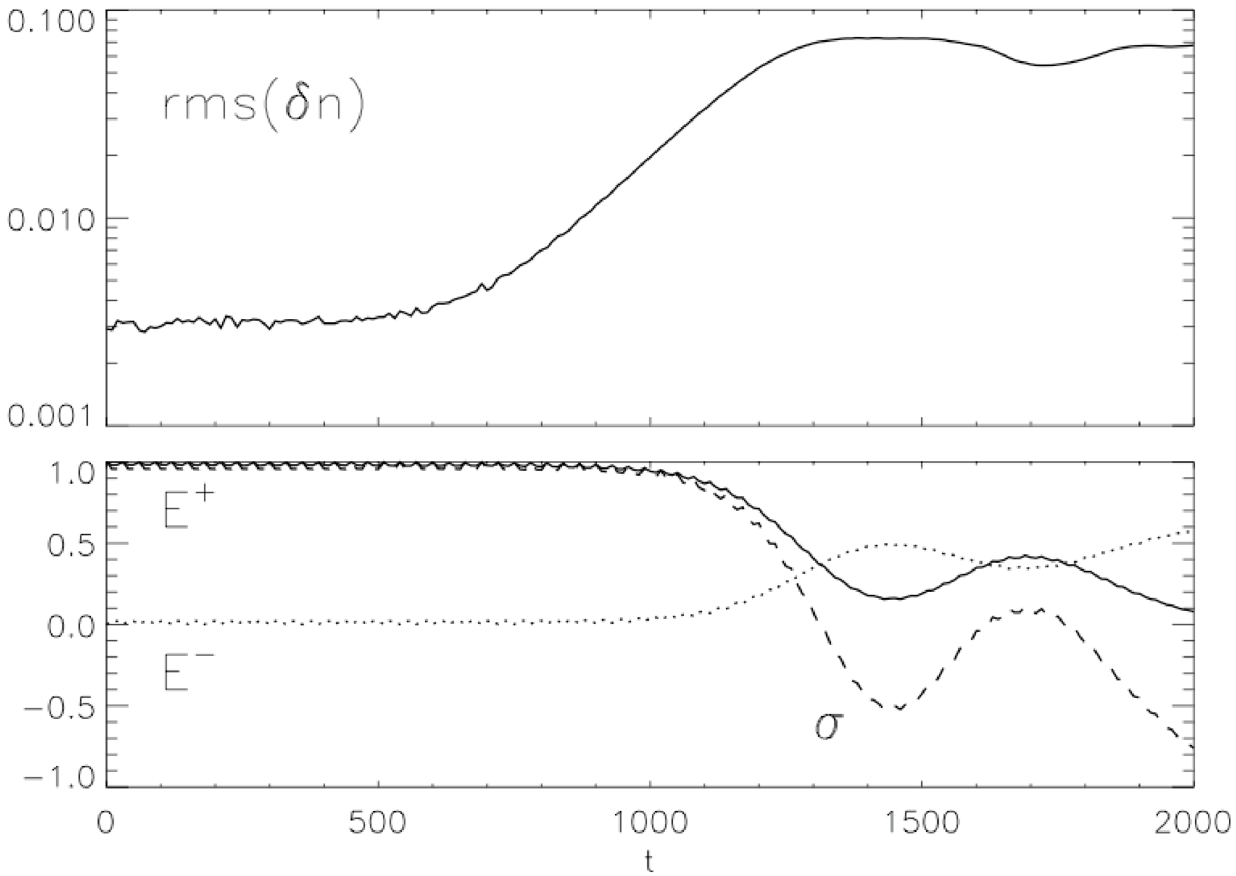
Parametric instability of Alfvén waves

parallel propagation case

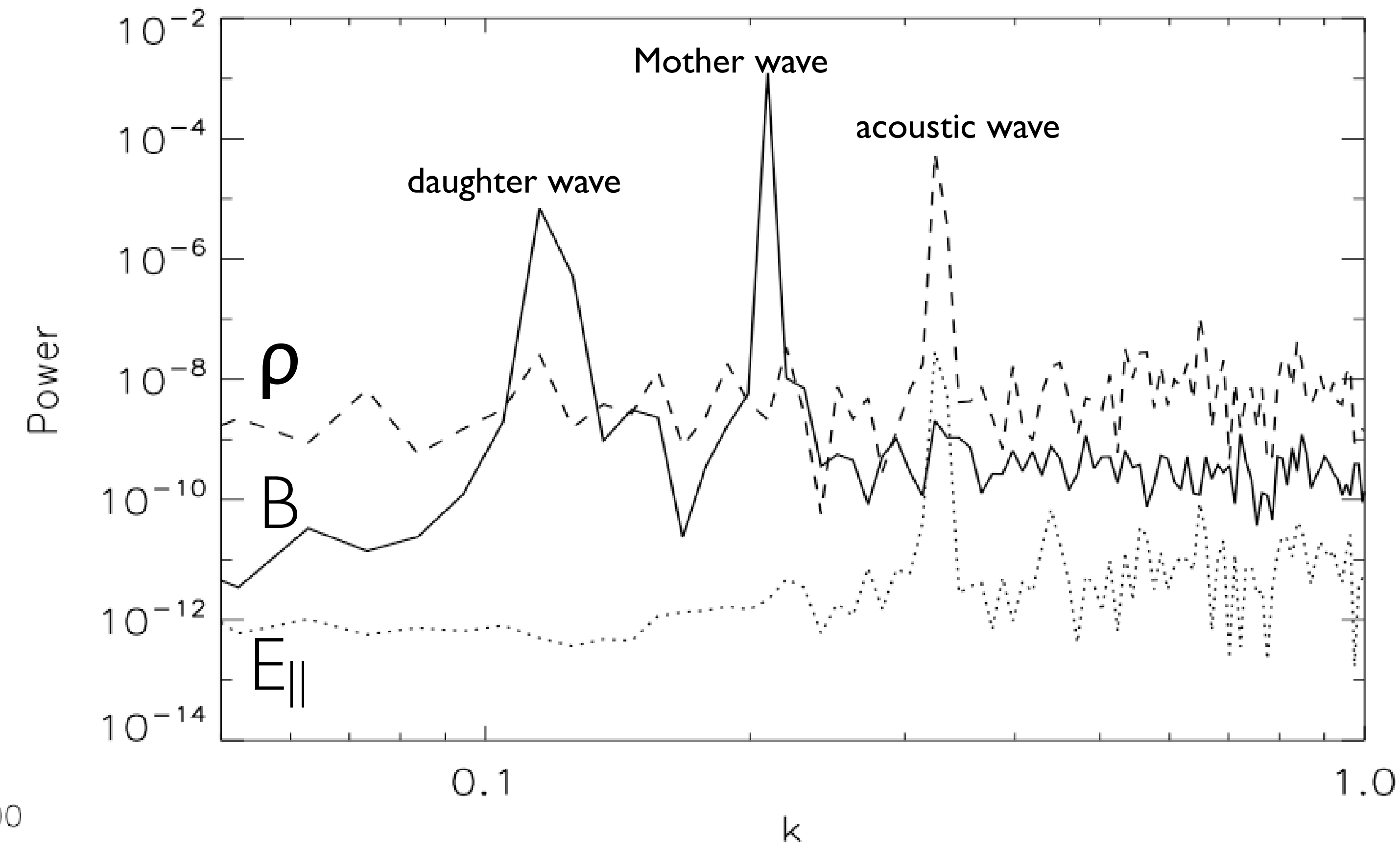
(large literature: theory and simulations in MHD, Hall-MHD, and kinetic regime)

Hybrid simulations: fluid electrons and kinetic ions

Parametric decay



three-wave coupling



E^+ forward

E^- backward

σ cross helicity

Coupling of the mother wave with density fluctuations: generation of an ion-acoustic mode and a backward propagating daughter Alfvén wave

$$\mathbf{k}_0^- = \mathbf{k}_0 - \mathbf{k}_s$$

Evolution of ion distribution function

The non-linear evolution of the parametric instability of Alfvén waves including kinetic effects influences the ion dynamics with the formation of a velocity beam parallel to the magnetic field:

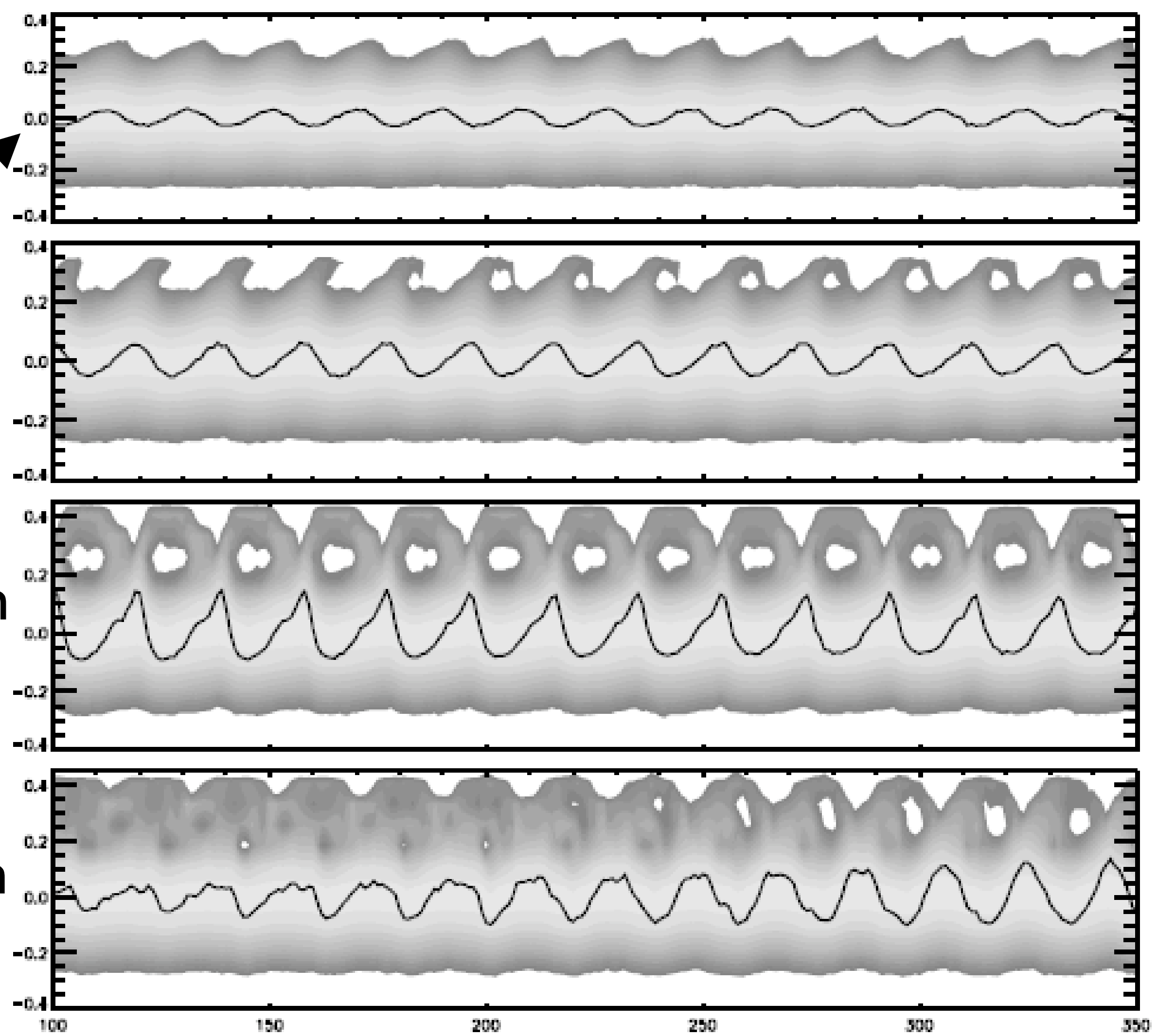
Modulational instability (*Araneda et al. 2008, 2009),* decay instability *(Matteini et al. 2010*), dispersive wave packets evolution (*Velli et al, in prep.*), and also Alfvénic cascade including the generation of ion-acoustic waves (*Valentini et al. 2008*).

Proton phase space x-vx

Linear phase

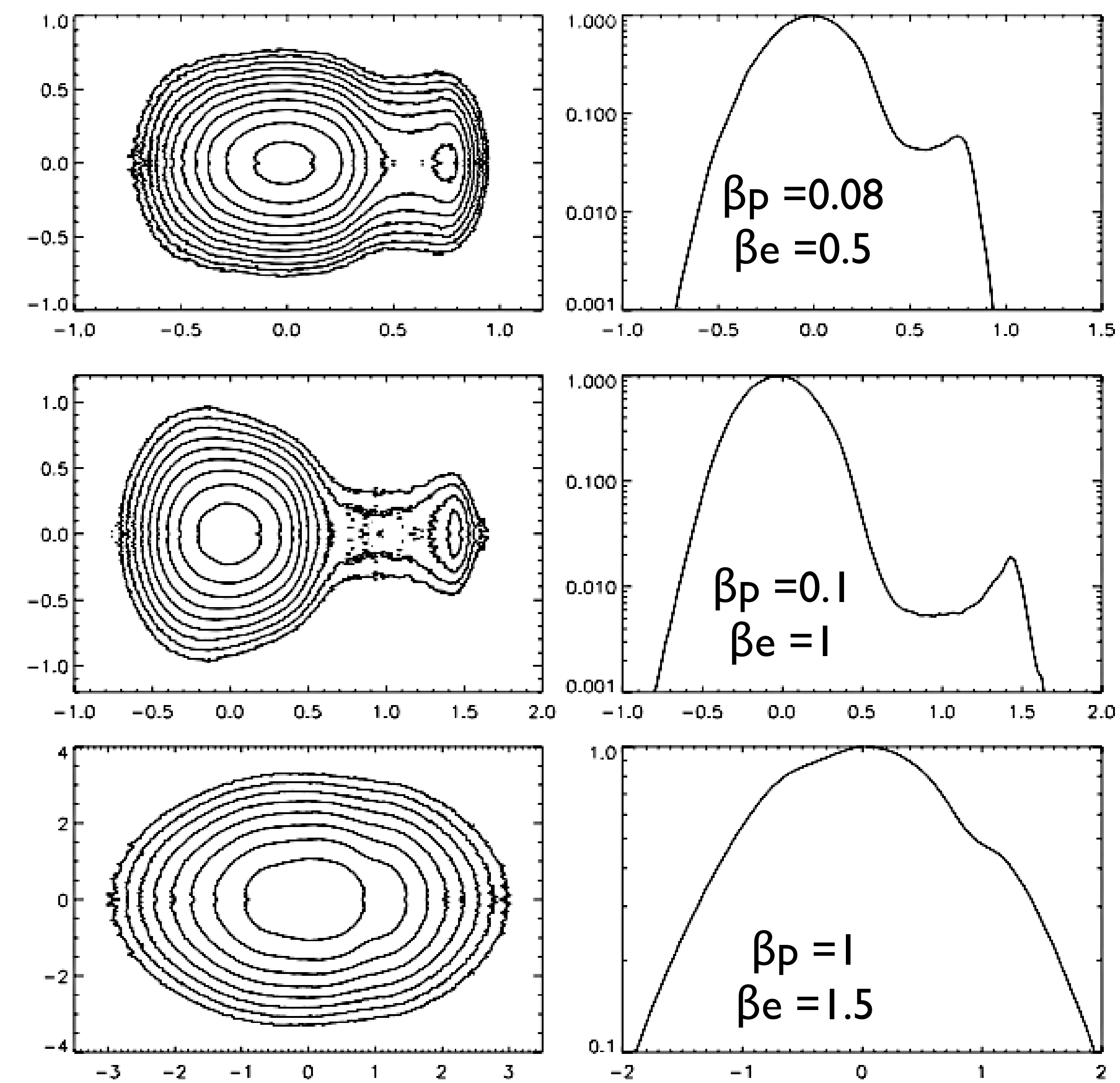
Saturation

Post-saturation



Parametric decay of a monochromatic Alfvén wave (*Matteini et al. 2010, JGR*)

Beam properties with different betas



Parametric decay of oblique Alfvén waves
(1-D results)

Linearly polarized mother wave Bz, propagating along x and with angle θ with respect B lying in the x-y plane

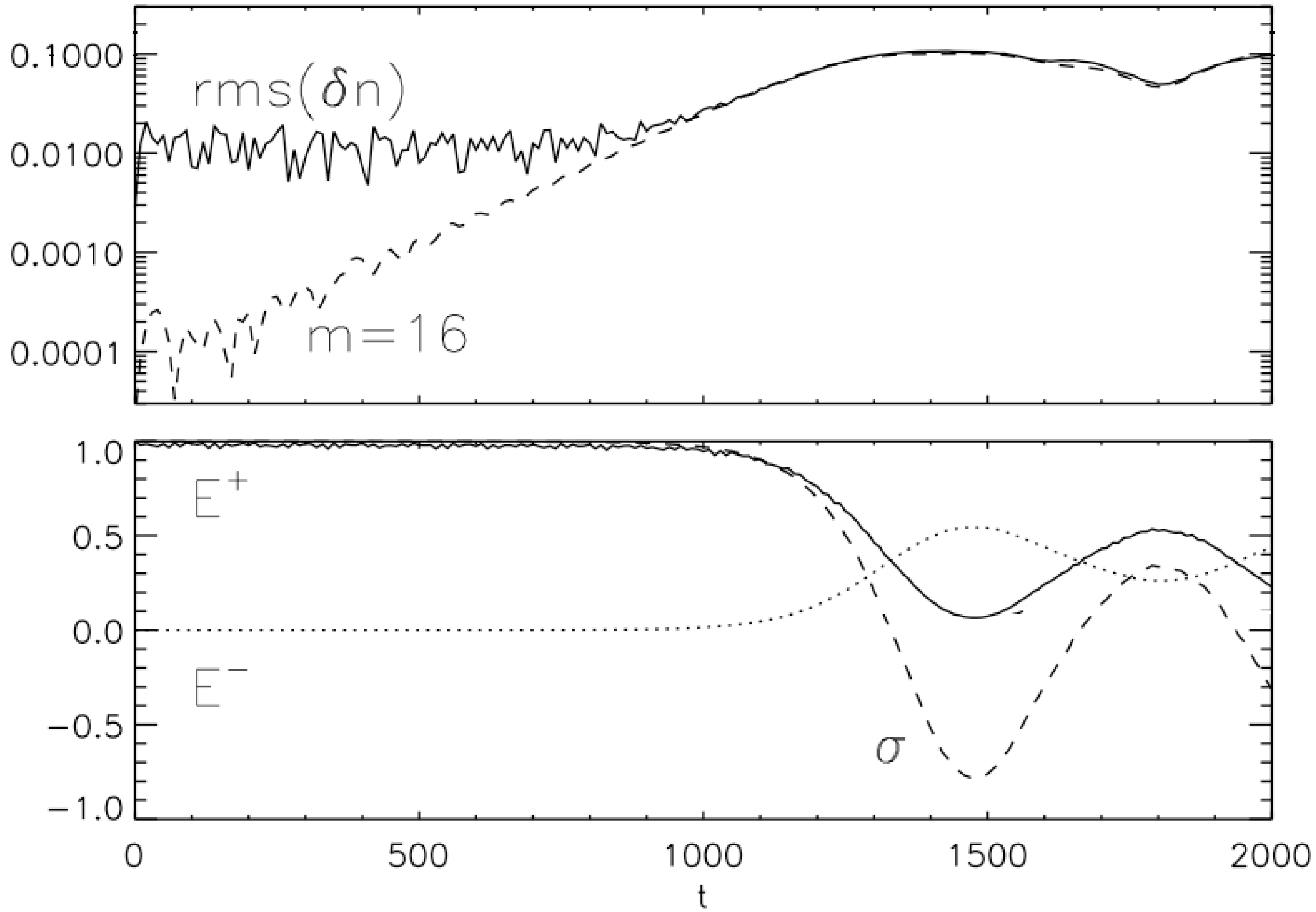


Table 1. Growth rate of parametric decay at various angles. For each angle we report the measured growth rate γ and the corresponding $\gamma_{||} = \gamma/\cos(\theta)$

Run	θ_{kB}	k_0	k_s	k_-	γ	$\gamma_{||}$
A	30	0.21	0.33	0.12	0.007	0.008
B	45	0.21	0.33	0.12	0.006	0.008
C	60	0.21	0.33	0.12	0.004	0.008

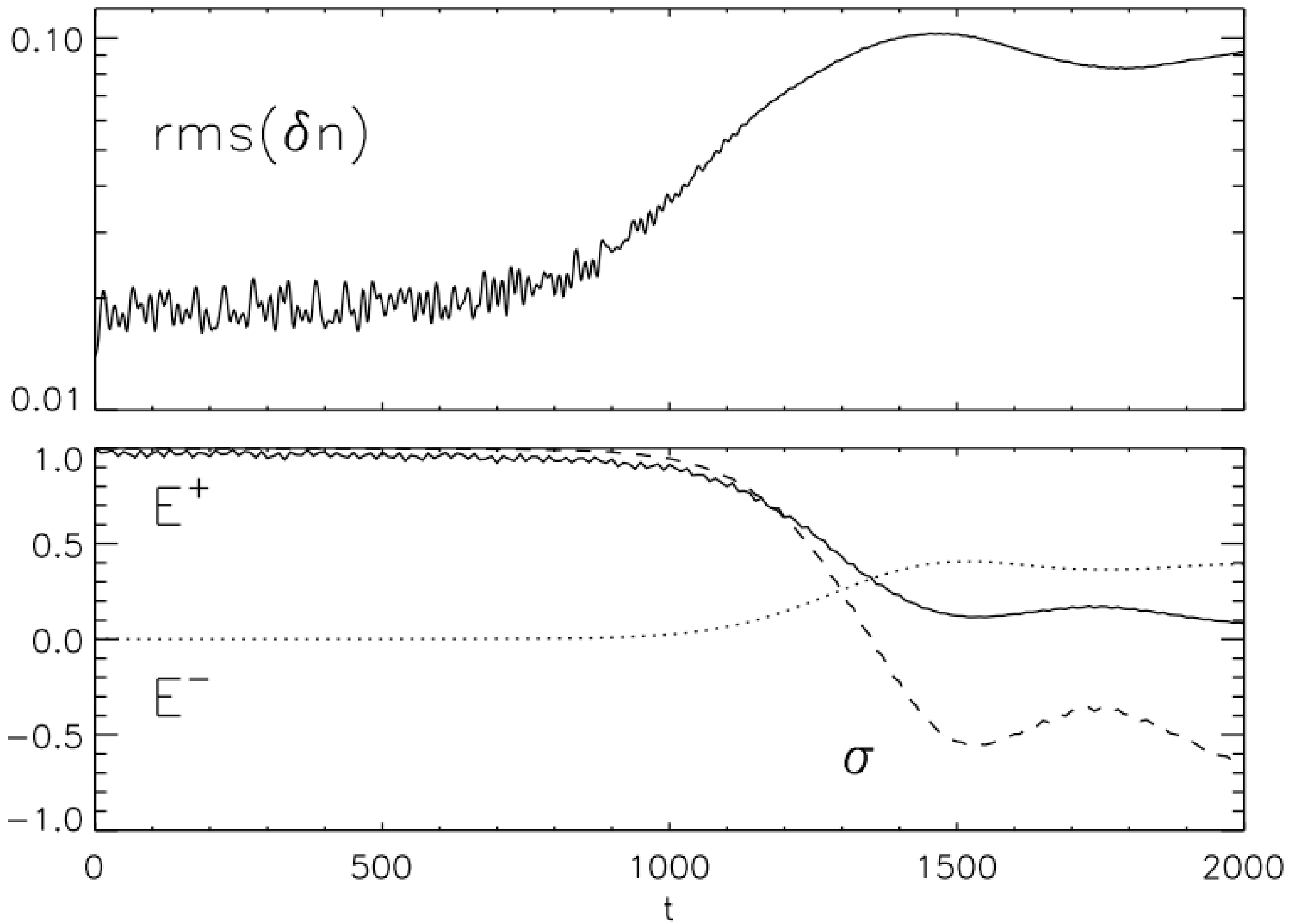
The instability growth rate scales with cos(θ)

(in agreement with results of Del Zanna 2001 in MHD)

Parametric decay in 2-D and vdf evolution

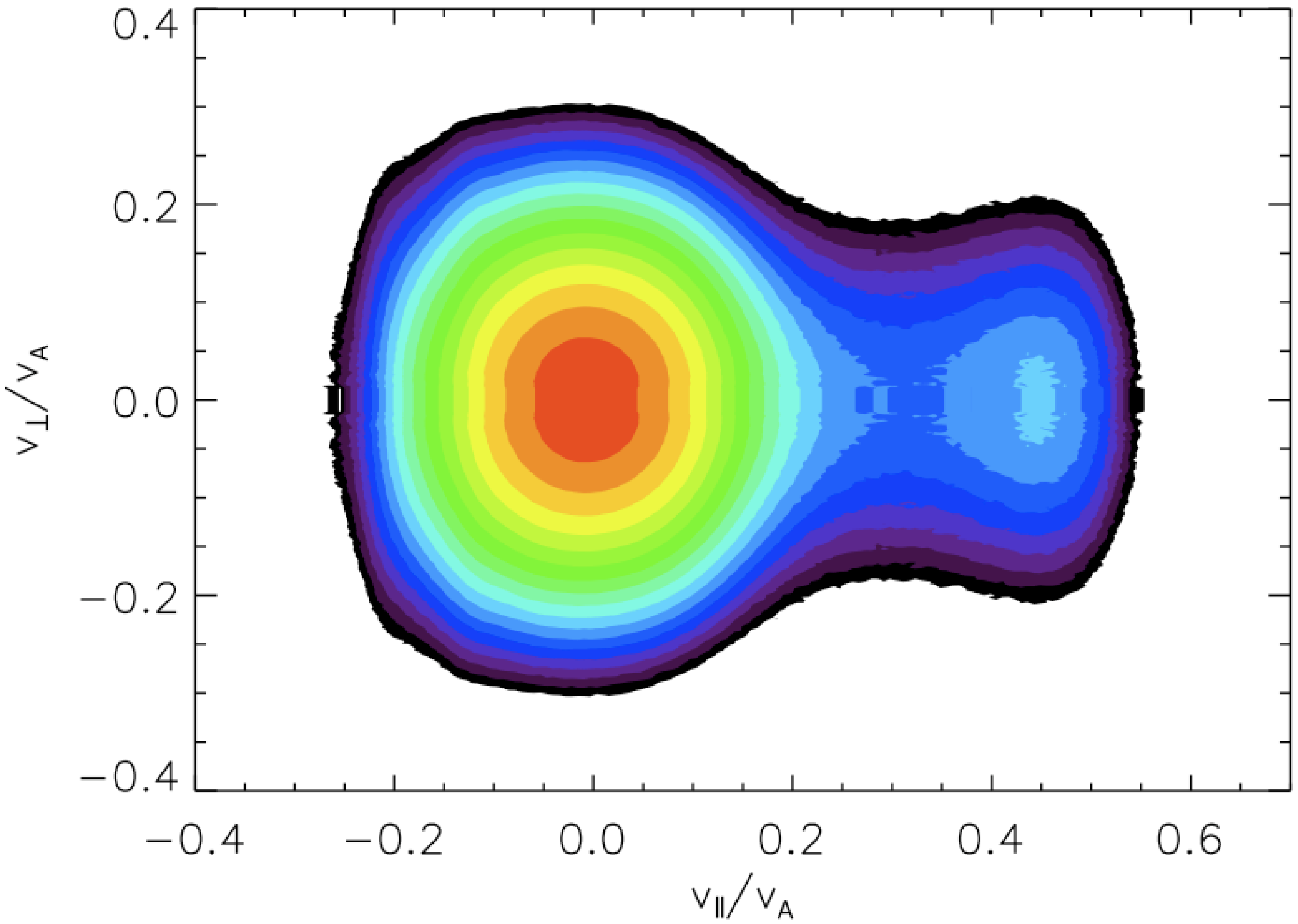
Possibility to describe the coupling along and across B

Wave-wave interaction



Decay confirms the 1-D results

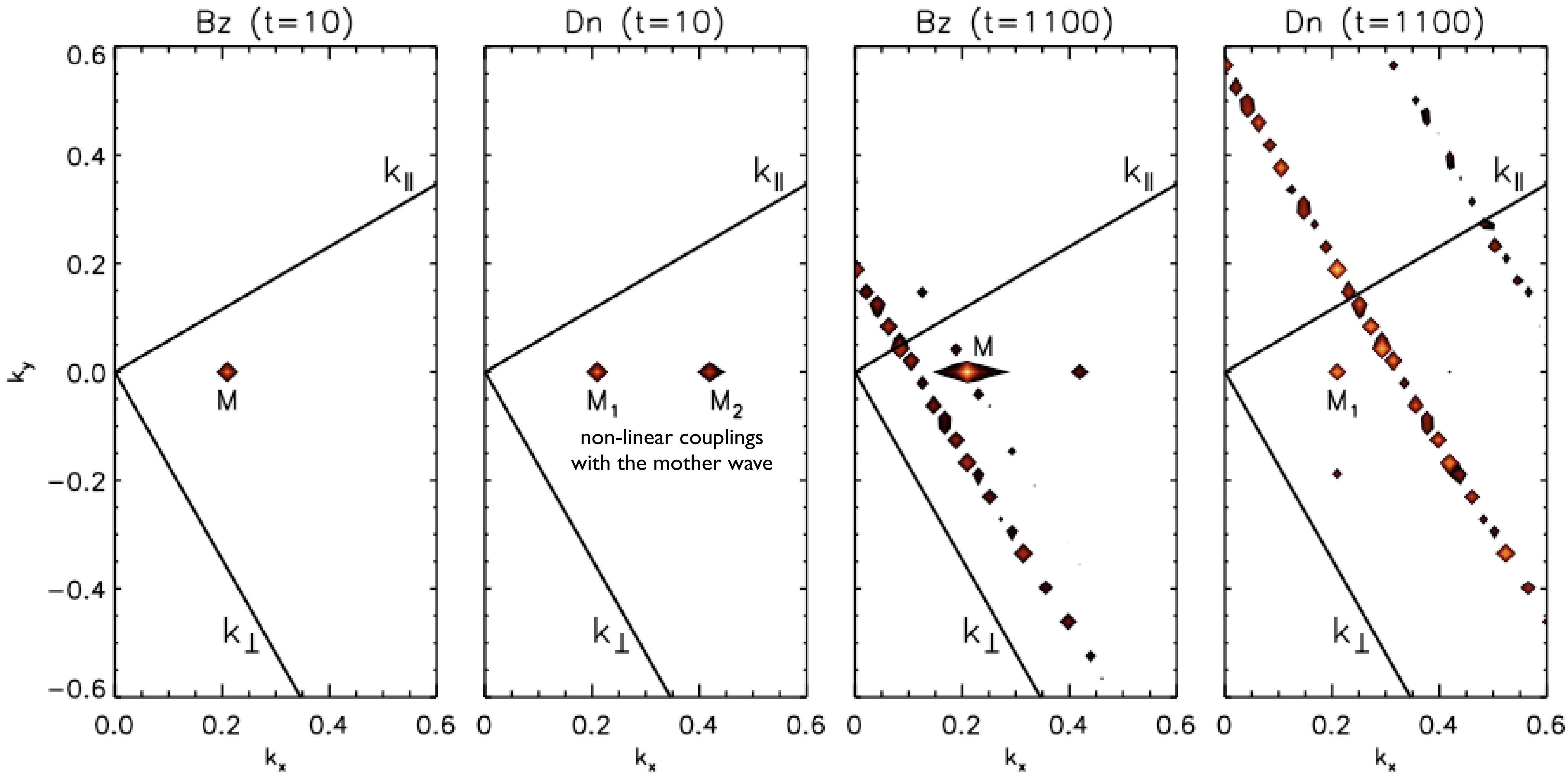
Wave-particle interaction



Generation of a velocity beam parallel to the magnetic field

2-D Fourier analysis of fields

Initial conditions | Linear phase of the instability



$$\mathbf{k}_0^- = \mathbf{k}_0 - \mathbf{k}_s$$

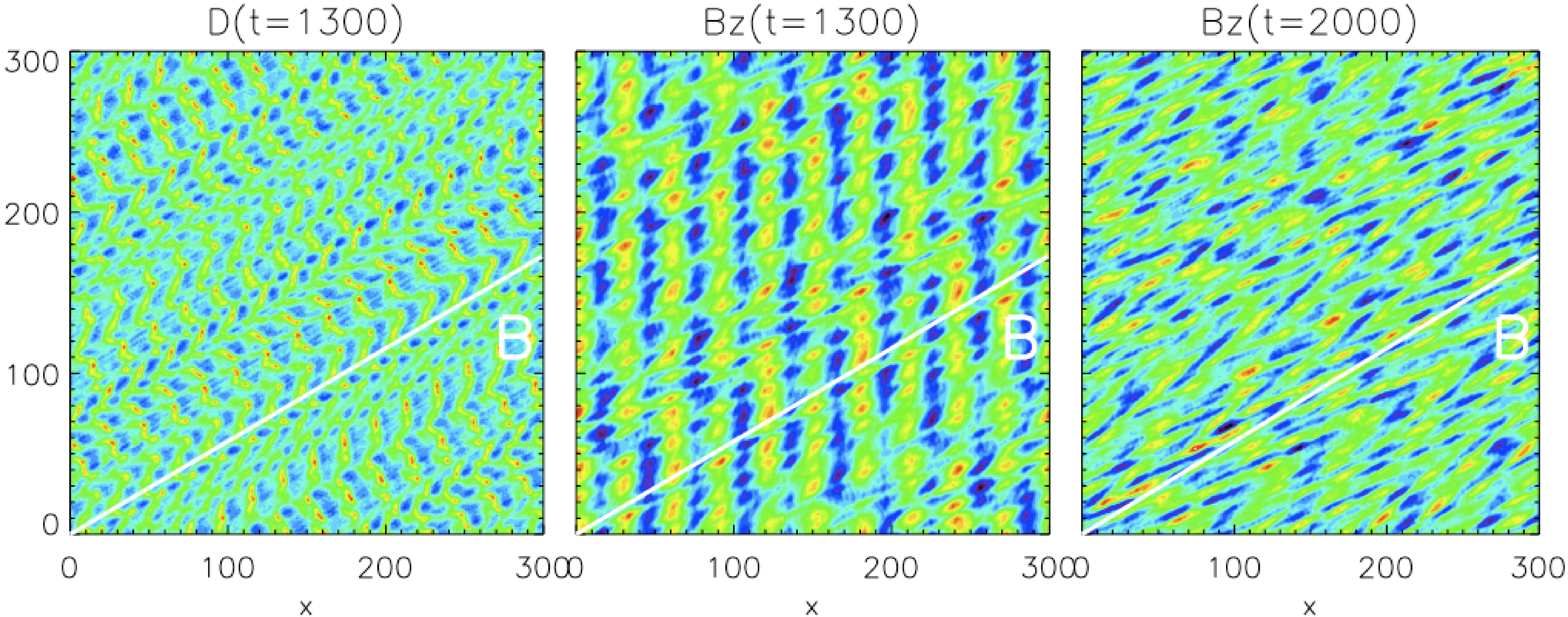
$$\mathbf{k_0} = \mathbf{k_{0\|}} + \mathbf{k_{0\perp}}$$

Decay still driven by a coupling parallel to B, but also generation of large spectra of oblique modes with variable $k_\perp$ and fixed $k_{\|}$ to conserve the initial mother wave energy and momentum

2-D evolution of fields: density and magnetic field

Linear phase

Saturation



Growth of ion-acoustic wave || B

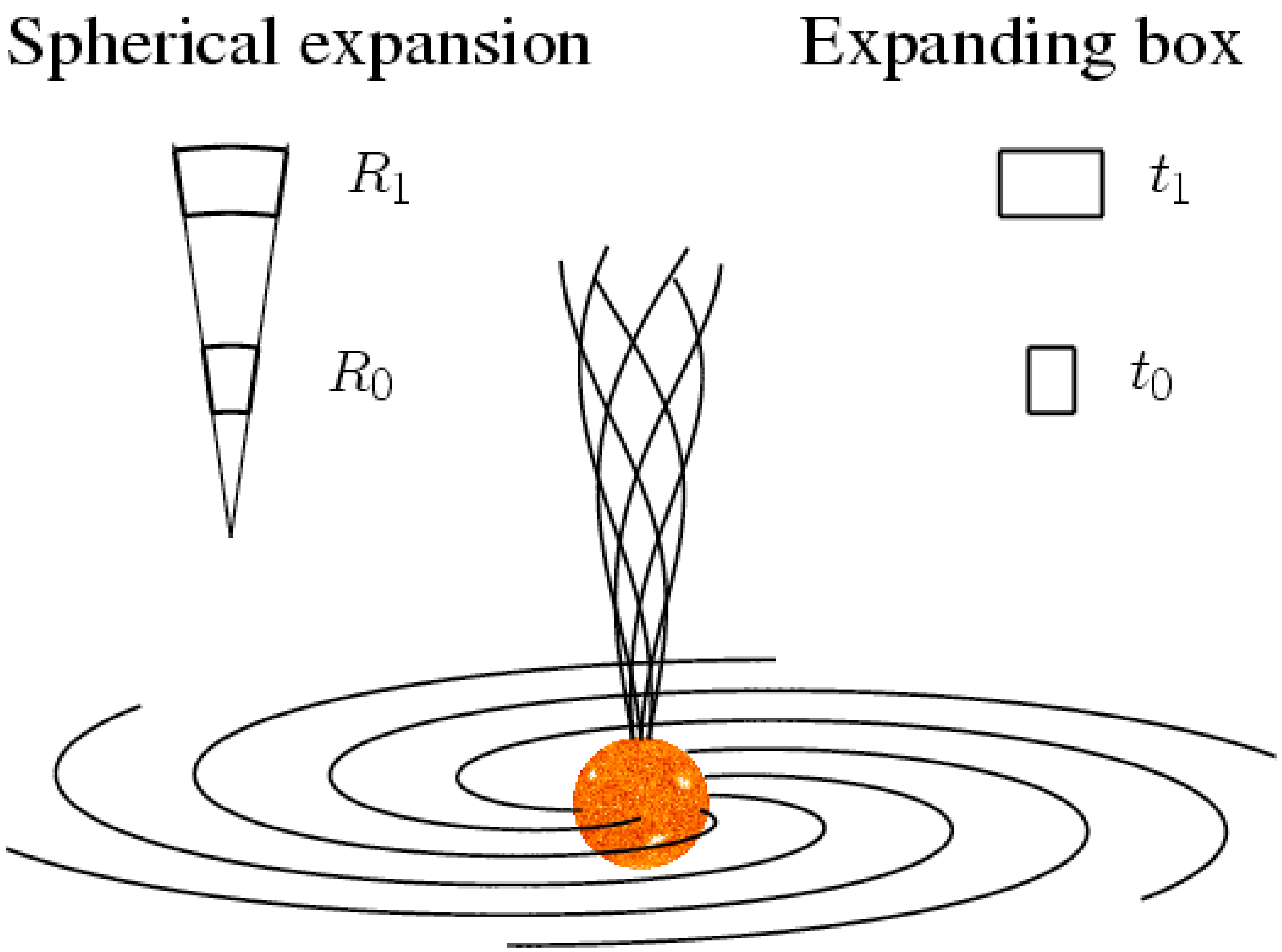
Decay of the mother Alfvén wave propagating along x

Magnetic field after saturation is characterized by a strong transverse modulation

The Hybrid Expanding Box code (HEB)

To study non-linear wave-particle interactions during the solar wind expansion, we perform numerical simulation using a hybrid code implemented with an expanding box model (Liewer et al. 2001, Hellinger et al. 2003).

Hybrid model: electrons are described as an isotropic massless fluid and protons (ions) as particles (Matthews 1994).
The expanding box model assumes a radial linearly driven evolution with a constant expansion velocity; the transverse dimensions of the box (which co-moves with the wind) increase with distance (Grappin et al. 1993).

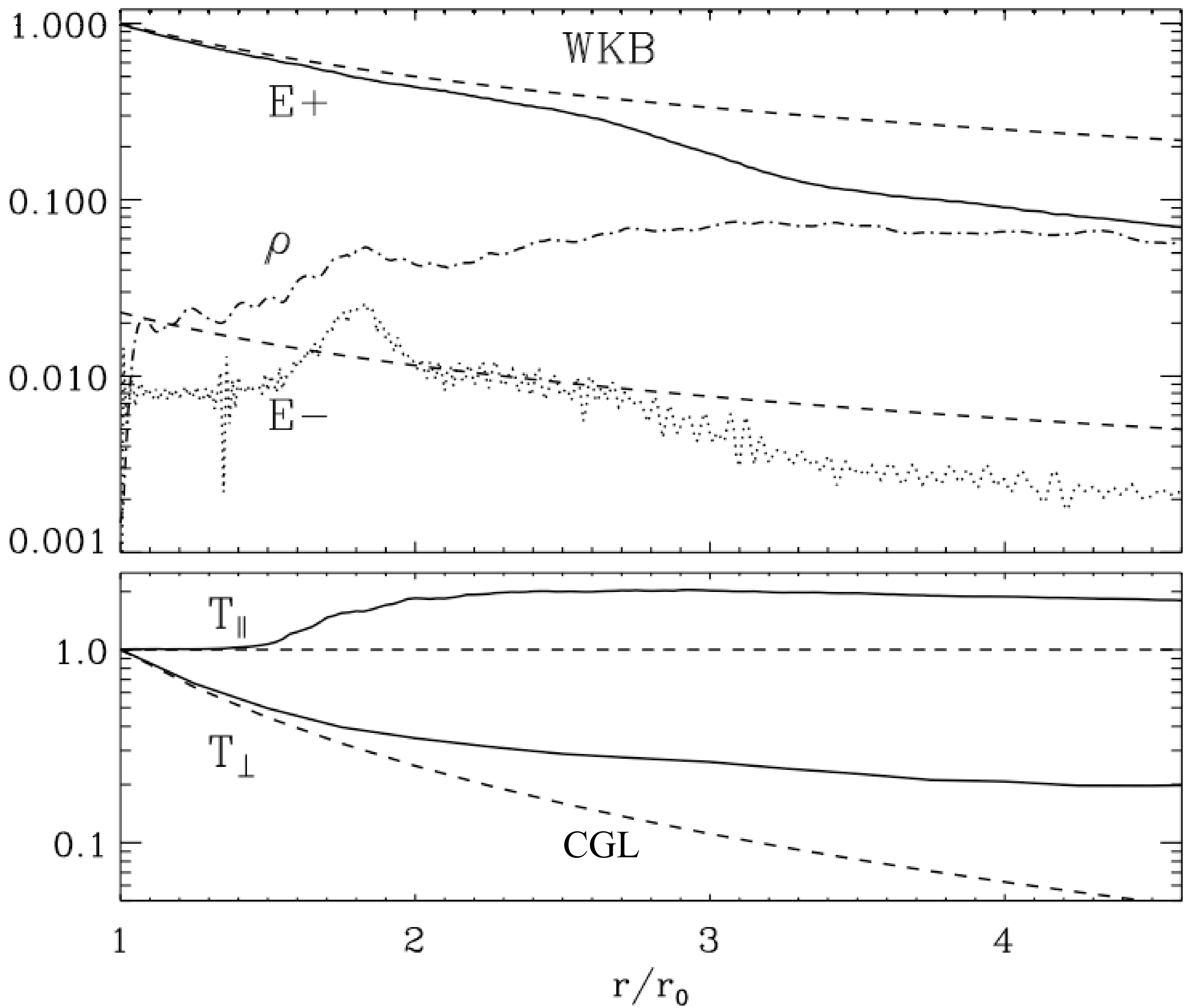


Adiabatic evolution for ions (CGL) and waves (WKB)

Self-consistent competition between the cooling driven by the expansion and the heating provided by wave-particle interactions and wave-wave instabilities

Parametric instability in the expanding solar wind

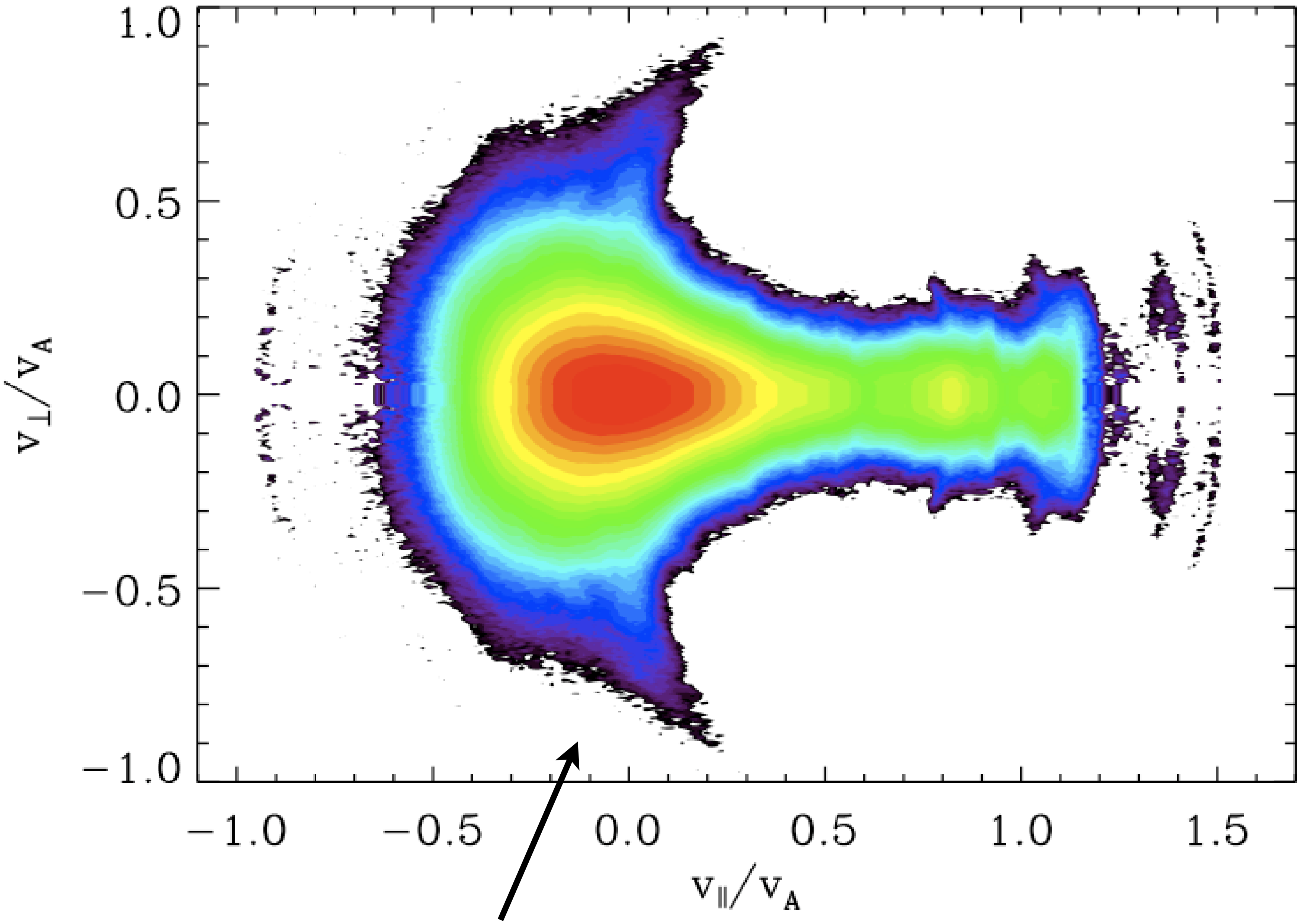
Evolution with distance of an initial spectrum of left-handed Alfvén waves



Wave energy decays faster than WKB prediction: dissipation by wave-wave and wave-particle interactions

Deviation from double adiabatic cooling; local heating

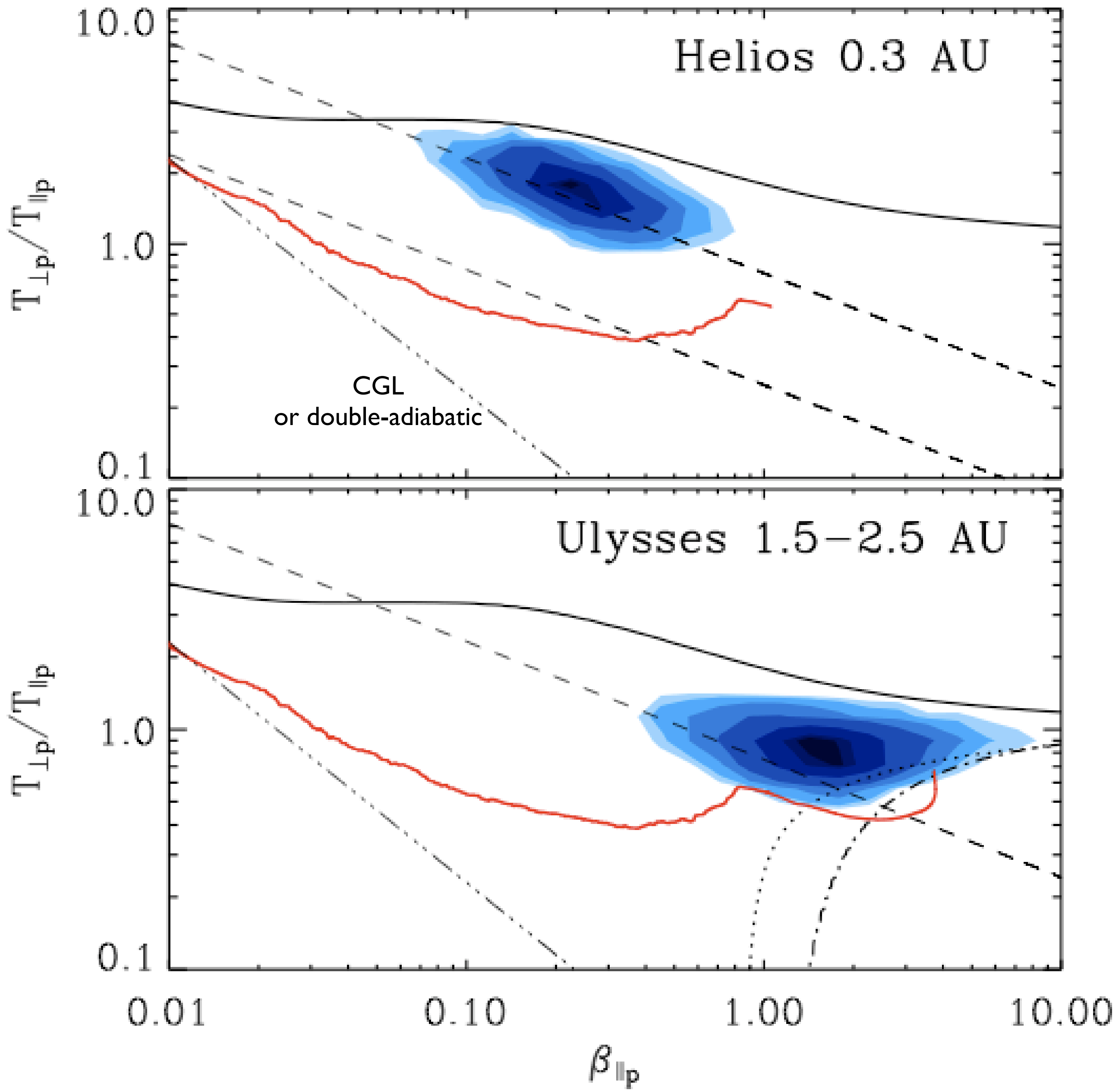
Shaping the proton vdf through wave-particle interactions



Velocity beam acceleration by parametric instability

Ion-cyclotron perpendicular heating

Evolution of proton temperature anisotropy in the expanding solar wind: simulations vs. observations



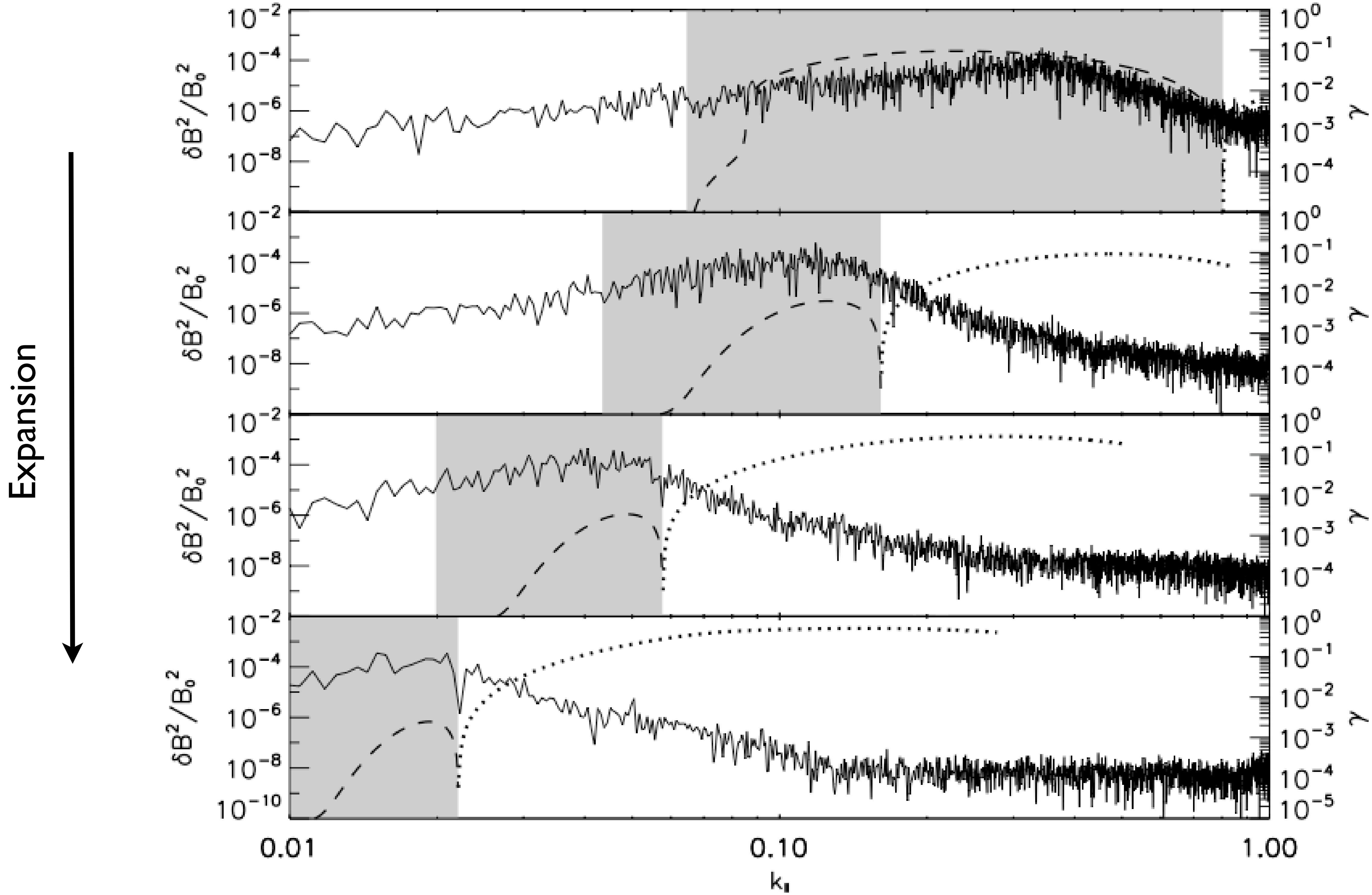
Wave-particle interactions regulate the evolution of the temperature anisotropy

Perpendicular heating by ion-cyclotron resonance and ion-beam instabilities

Role of temperature anisotropy driven instabilities

Fire Hose instabilities counteract the adiabatic cooling of the expansion

Evolution of magnetic fluctuations close to Parallel Fire Hose marginal stability



Solar wind observations? Bale et al. 2009, Wicks et al. 2010

Also other instabilities contribute to the local generation of wave power: Oblique Fire Hose (Hellinger&Travnicek 2008), Mirror, Ion-cyclotron, and Ion-beam instabilities

Conclusions

- Parametric decay of oblique Alfvén waves in kinetic regime: similar evolution as in parallel propagation, smaller growth rate
- Acceleration of resonant proton by parallel ion-acoustic waves driven by the decay; generation of velocity beams along B
- In 2-D excitation of a large spectrum of oblique modes and strong transverse modulation of the magnetic field
- Parametric instabilities play a role in shaping proton distribution functions in the solar wind expansion