On ion heating by the decay of large amplitude Alfvén waves

Horia Comişel[1,2], Yasuhiro Nariyuki[3], Yasuhito Narita[4,5], and Uwe Motschmann[1,6]

[1]Institute for Space Sciences, Bucharest, Romania, [2] Institut für Theoretische Physik, Technische Universität Braunschweig, Germany,
[3]University of Toyama, Toyama, Japan, [4]Space Research Institute, Graz, Austria, [5] Institut für Geophysik und extraterrestriche Physik,
Technische Universität Braunschweig, Germany, [6] Deutches Zentrum für Luft- und Raumfahrt, Institut für Planetenforschung, Berlin, Germany

Technische Universität Braunschweig

INSTITUTUL DE ŞTIINŢE SPAŢIALE Filială INFLPR

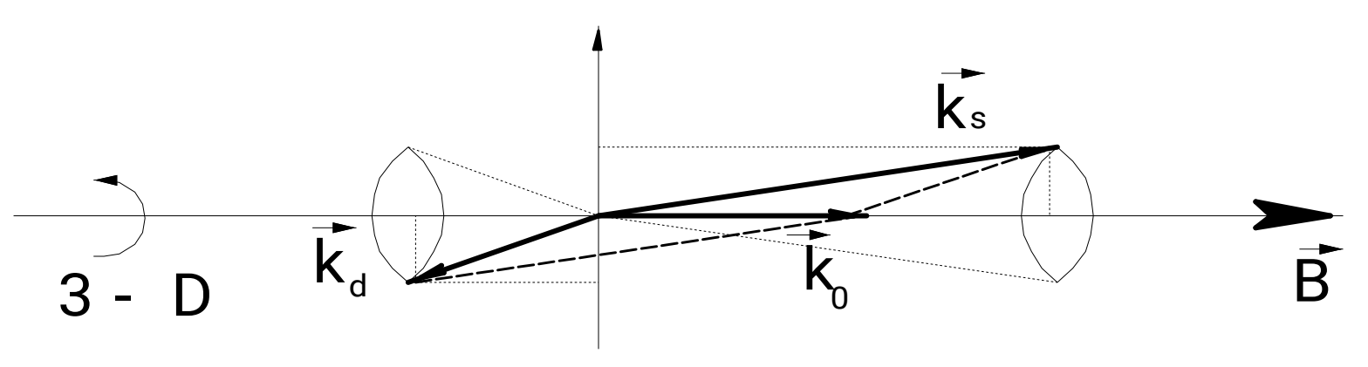
Abstract

By means of hybrid simulations, we present a study on ion heating by the field-aligned decay of a monochromatic left-hand polarized Alfvén wave. The comparison made among different spatial dimensions proves that the three-dimensional simulation exhibits more efficient heating. Plasma is heated parallel to the mean magnetic field by the damping of the ion acoustic waves while being heated perpendicular by the cyclotron resonance and damping of protons by the Alfvén daughter waves. The parametric decay and the pitch angle scattering mechanism are both involved in broadening the entire proton velocity distribution in directions peprendicular to the mean magnetic field. The left-hand circularly polarized Alfvén pump wave with forward propagation does perpendiculary broaden one side of the particle velocity distribution while the backward propagating Alfvén daughter wave enlarges the other side, respectively.

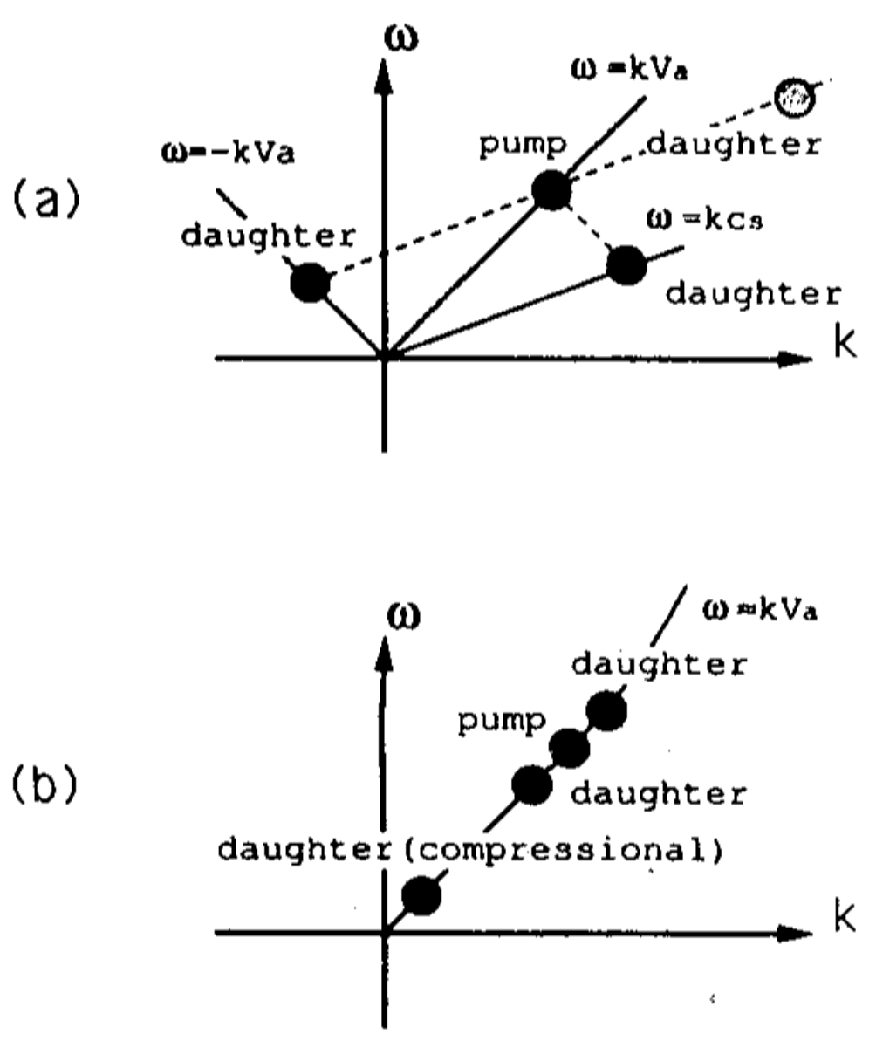
As an application in the solar wind context, the antisunward part of the core component of the proton velocity distributions is controlled by the sunward-propagating waves driven by the parametric decay.

Starting point and motivation

- Field aligned and oblique parametric instabilities well studies from multi-dimensional MHD, and 1-D, 2-D PIC simulations.
- 3-D hybrid simulations are missing.
- The oblique geometry of the daughter waves for the field aligned instability is less known in great details (former 2-D MHD studies by Ghosh&Goldstein 1994).



Sketch of the wave vector couping of the field aligned pump wave (**k**$_0$) and the two daughter waves (**k**$_d$ and **k**$_s$) in the 3D setup.



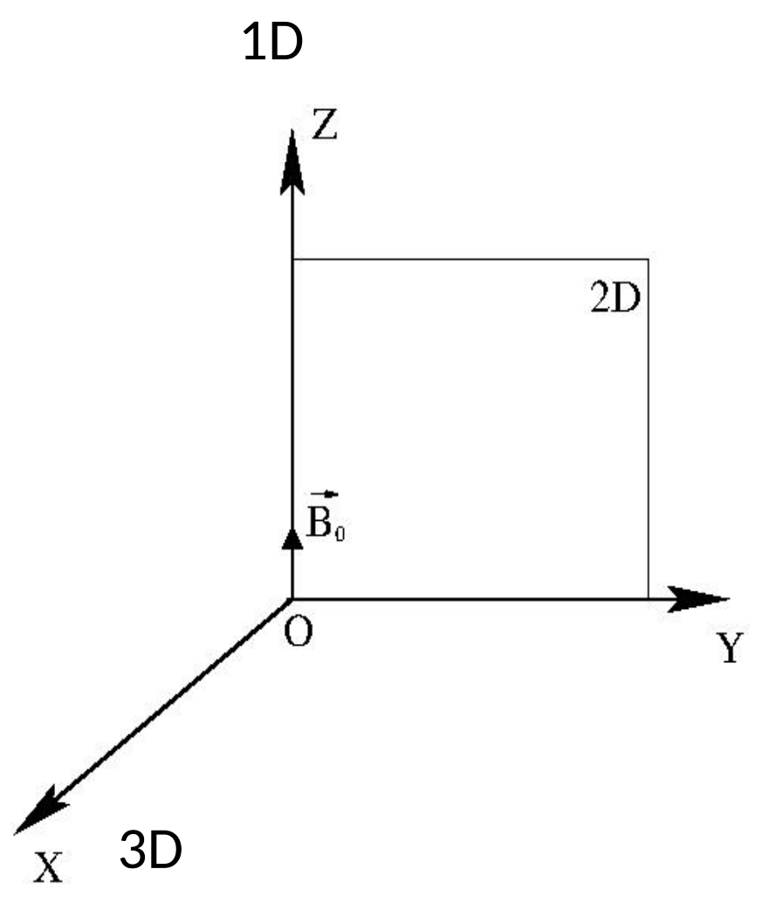
Schematic representation of the wave resonance conditions for: (a) decay instability and (b) modulational instability (Hoshino and Goldstein 1989).

Parametric decay of LH Alfvén wave

Numerical Setup

- A.I.K.E.F hybrid code (Müller et al., 2011).
- Three different setups: 1D, 2D, and 3D.
- Simulation box: 288x288x288 d_i & 288x288x288 grid points (3D)
- N=1000 particles/cell

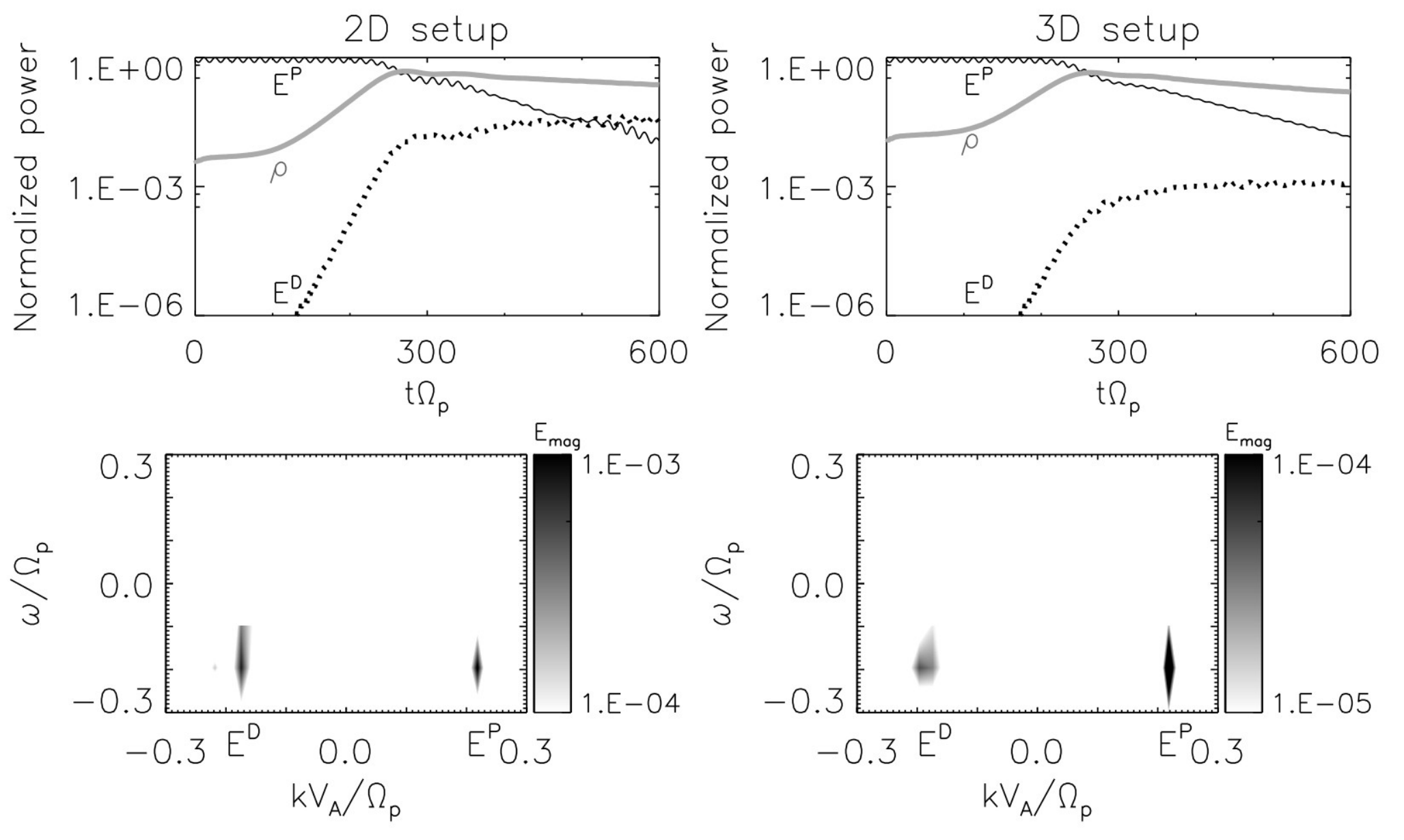
- Pump wave: $k_{0||}V_A/\Omega_p=0.21$, $\omega_0/\Omega_p=0.19$
- Amplitude of the pump wave: $\delta B/B_0=0.20$
- Polarization: circularly left (LH)
- Plasma beta: $\beta_i= \beta_e=0.01$



Results

Time evolution of the normalized magnetic field energy of the Alfvén pump wave (E^P) and the counter propagating Alfvén daugter wave (E^D). Overplotted by gray are given the rms density fluctuations.

Power spectrum in the wavenumber frequency domaian of the magnetic field derermined at time $t\Omega_p$=500.

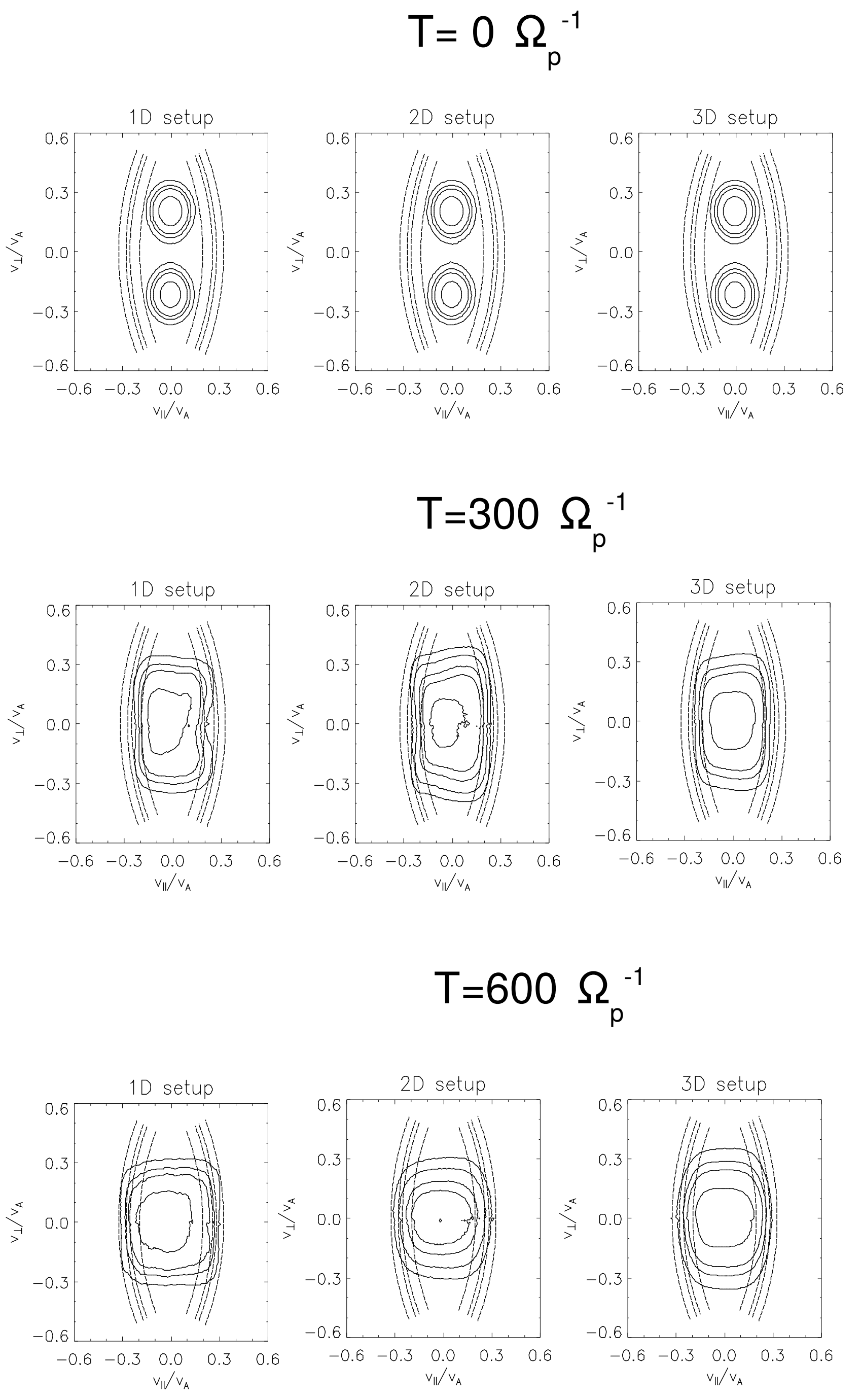


References

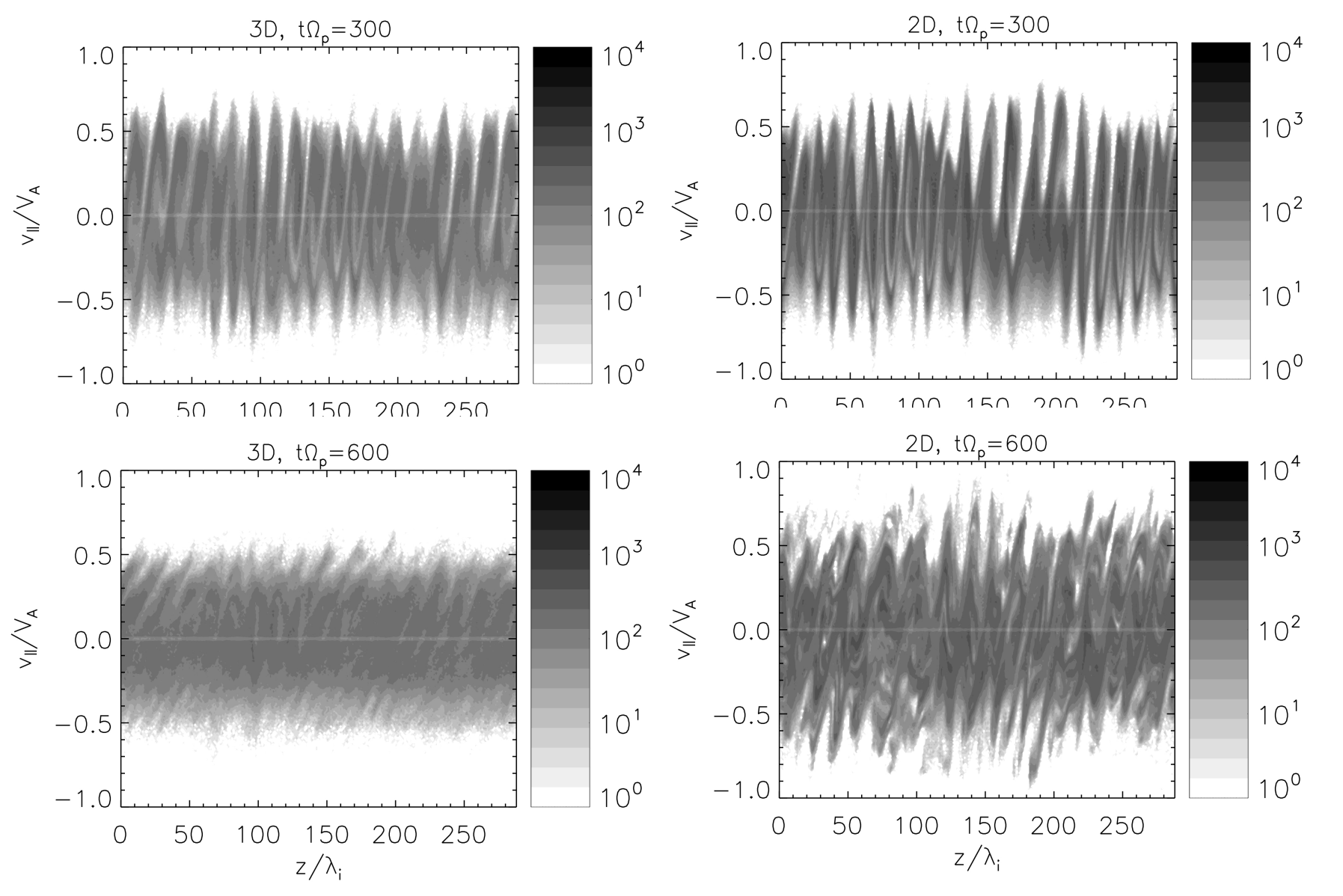
Araneda, J.A., Marsch, E., and Vinas, A. F., J. Geophys. Res. 112, A04104, 2007.
Ghosh, S. and Goldstein, M. L., J. Geophys. Res. 99, 1994.
Hoshino, M. and Goldstein, M. L., Phys. Fluids B 1, 1989.
Marsch, E. and Tu, C.-Y., J. Geophys. Res. 106, 8357, 2001.
Müller, J., Simon, S., Motschamnn, U., Schuelle, J., Glassmeier, K.-H., and Pringle, G. J., Comp. Phys. Comm. 182, 2011.
Narita, Y., Glassmeier, K.-H., Fraenz, M., Nariyuki, Y., and Hada, T., Nonlin. Processes Geophys. 14, 2007.
Nariyuki, Y., Hada, T., and Tsubouchi, K., Astrophys. J. 793, 2014.
Terasawa, T., Hoshino, M., Sakai, J.-I., and Hada, T., J. Geophys. Res. 91, 1986.
Verscharen, D., Marsch, E., Motschmann, U., and Müller, J., Phys. Rev. E. 86, 2012.

Ion heating by the parametric decay

Proton distribution functions



Velocity phase space



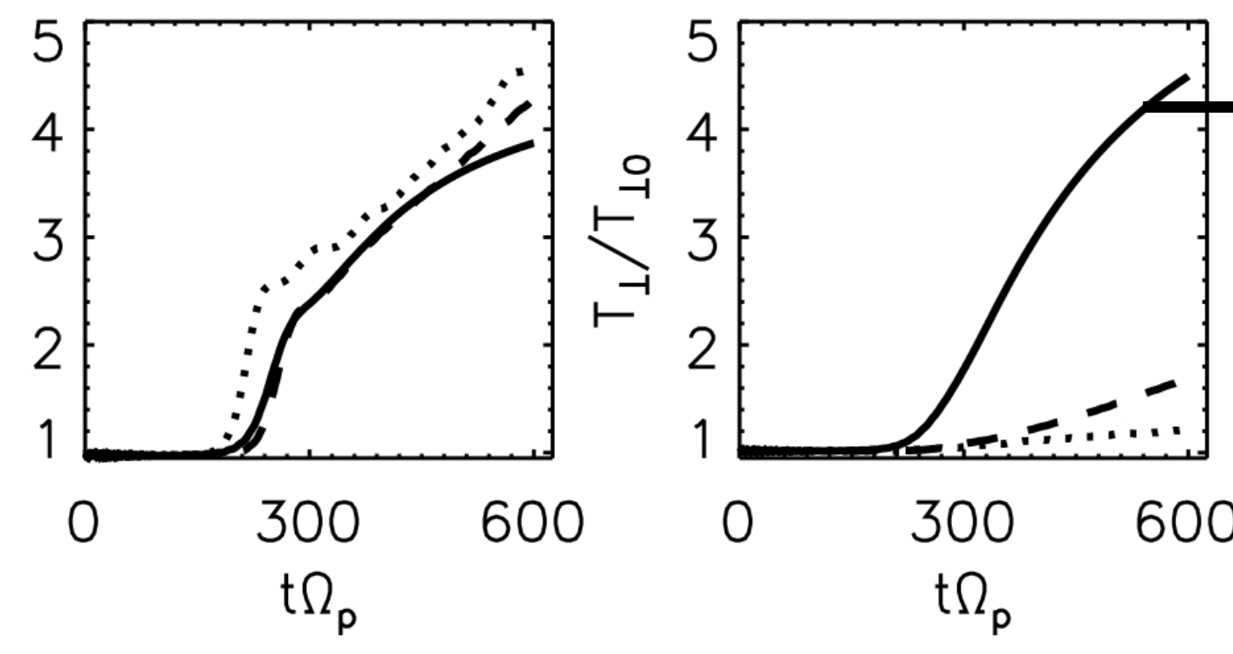
Proton phase space z-$v_{||}$ at time $t\Omega_p$=300 close to the linear saturation of the decay instability. Proton phase space z-$v_{||}$ at the final time $t\Omega_p$=600 of the simulation.

$$v=\sqrt{(v_{||}-V_{ph})^2+v_\perp^2}$$

Proton distribution functions represented as contours levels (solid line) determined in the plane ($v_\perp$,$v_{||}$) at different times. The dashed lines describe the locus ($v_\perp$,$v_{||}$) of the particle velocities where their energy is conserved in the wave frame. V_{ph} is the phase speed of the Alfvén wave.

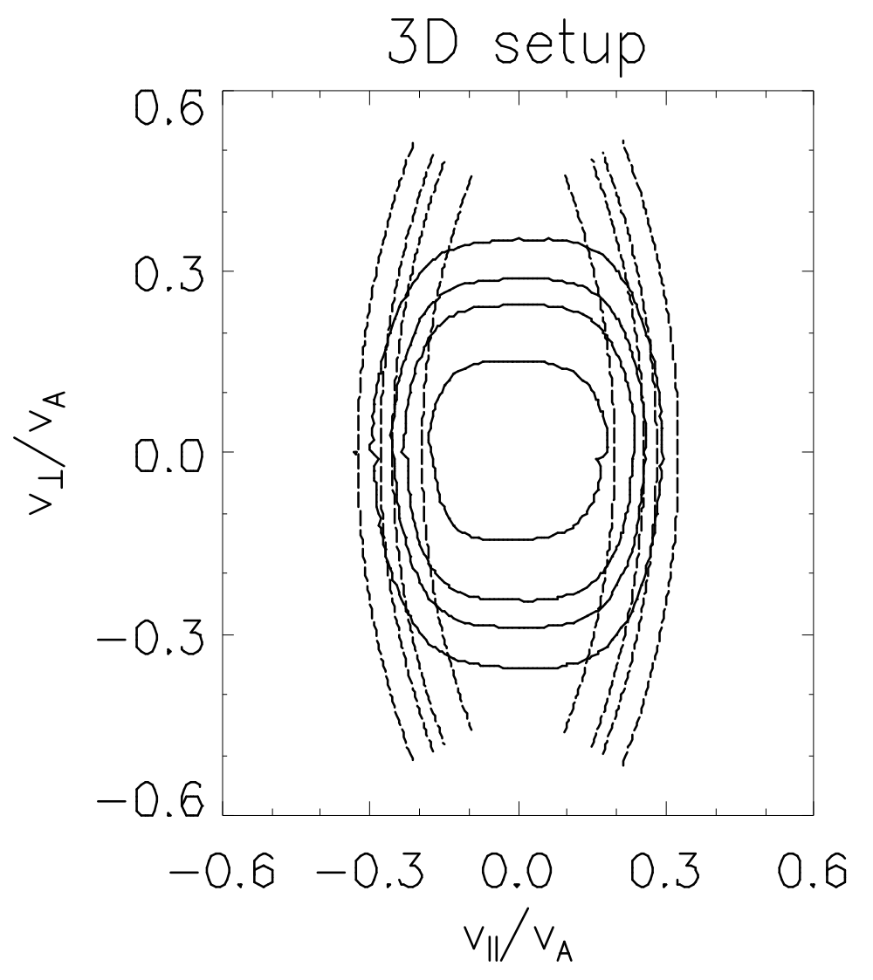
Comparison with spacecraft observation

Parallel and perpendicular ion temperatures



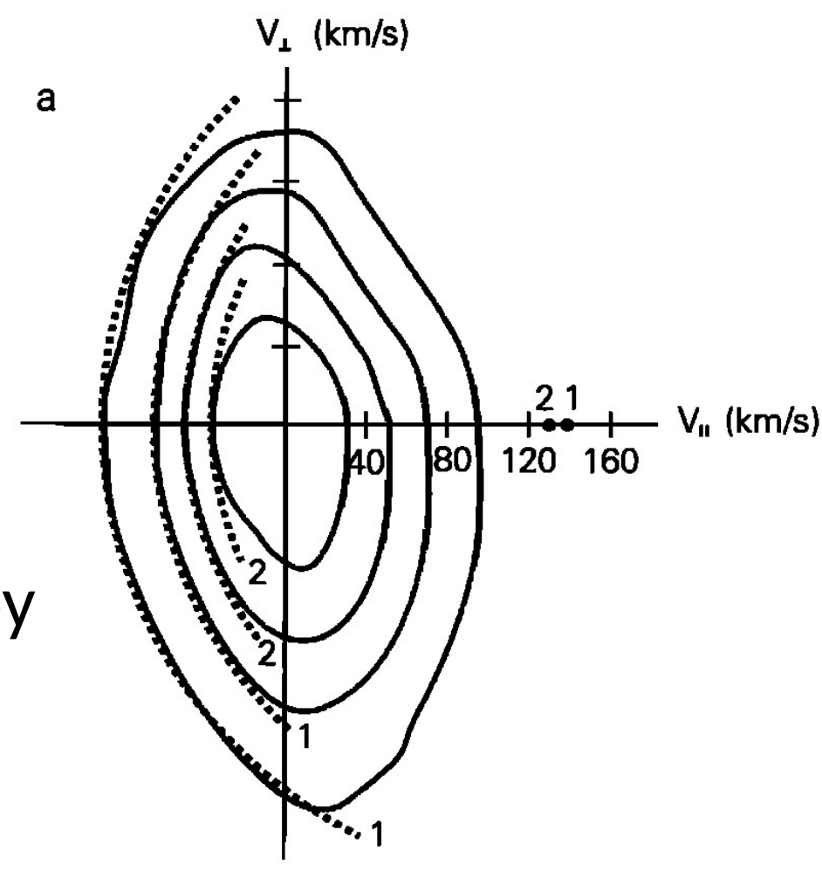
Perpendicular heating predominant in the 3D system due to the cyclotron resonance and pitch angle scattering mechanism. Here, the solid, dashed, and dotted lines correspond to the 3D, 2D, and 1D setups, respectively.

Pitch angle scattering of solar wind protons



Simulation versus observation:

Measured proton velocity distributions obtained by Helios 2 with the theoretical cyclotron-resonance plateaus as predicted by quasy-linear theory (Marsch and Tu, 2001).



Conclusions

We studied by 3D hybrid simulations the proton acceleration and heating driven by the parametric decay of a large amplitude Alfvén wave.

By comparing the wave modes and the proton velocity distribution functions for the 1D, 2D, and 3D systems, we conclude that plasma is heated more efficient in the 3D setup.

Parallel heating is provided by the damping of the ion sound waves.

Perpendicular heating is mostly given by the perpendicular scattering of protons by the field aligned and oblique propagating Alfvén daughter waves.

The pitch-angle scattering is the mechanism to describe the perpendicular broadening observed in the particle velocity distribution functions.

Parametric decay, besides its implication in the reduction of the cross-helicity in the solar wind and in the local production of turbulence, could also play a key role in pitch angle scattering of the solar wind protons and finally in the perpendicular temperature anisotropy observed in the inner heliosphere.