Nonlinear wave-particle and wave-wave interactions in the outer radiation belt: physical mechanisms and observational effects

Oleksiy Agapitov[1], James Drake[4], Anton Artemyev[2], Ivan Vasko[1], Didier Mourenas[3], Forrest S. Mozer[1]

[1] *Space Science Laboratory, University of California, Berkeley, Berkeley, CA*

[2] *University of California, Los Angeles, Los Angeles, CA*

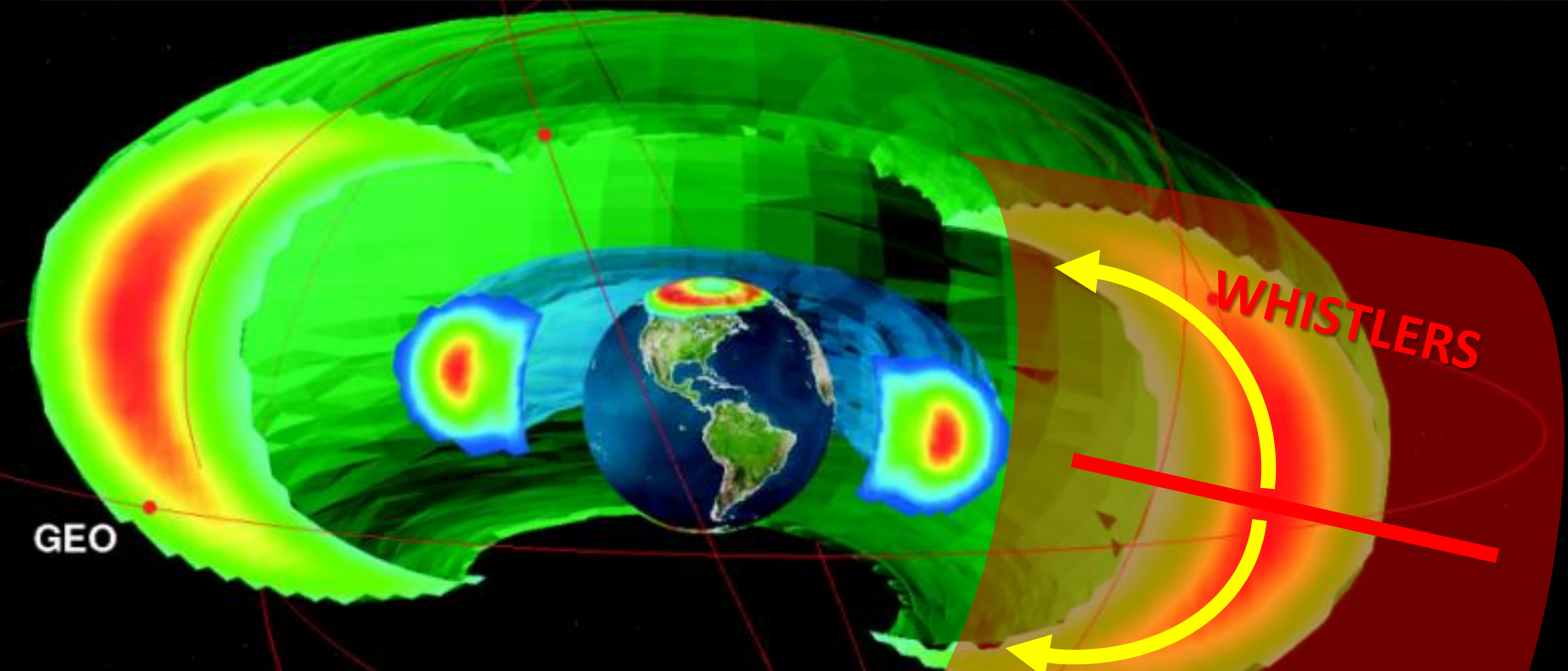
[3] *CEA, DAM, DIF, Arpajon, FRANCE*

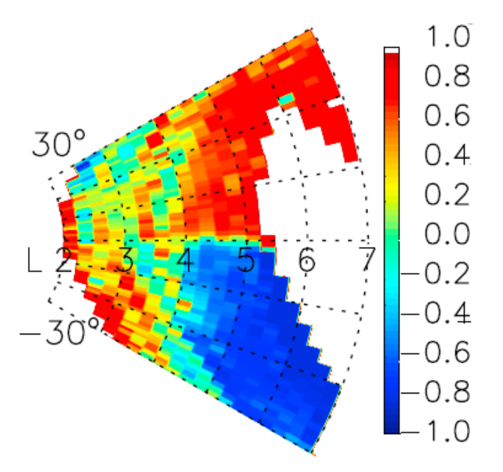
[4] *University of Maryland, MD*

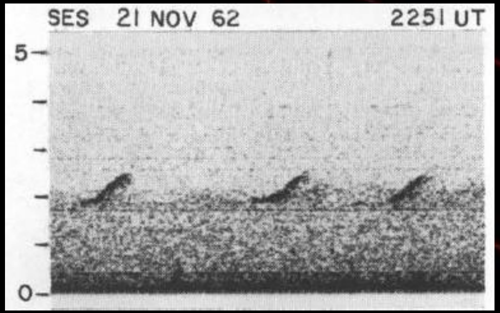
Agapitov, O., Drake, J. F., Vasko, I., et al. (2018). Nonlinear electrostatic steepening of whistler waves: the guiding factors and dynamics in inhomogeneous systems, *Geophysical Research Letters*. https://doi.org/10.1002/2017GL076957

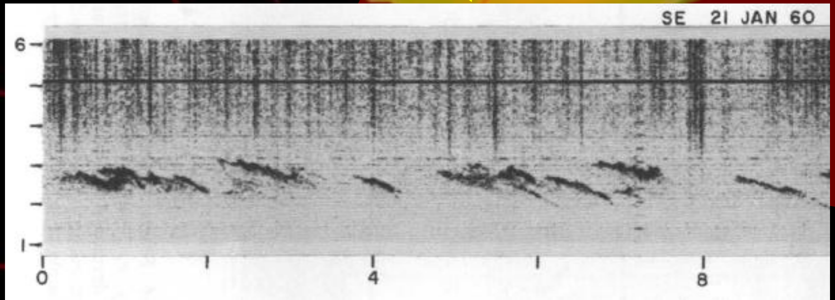
Radiation belts

The **key processes** for RB formation and dynamics are the same as in many astrophysical objects: **radial diffusion and local angular particles acceleration/scattering**









Quasi-|| Chorus Oblique Chorus

NL GENERATION

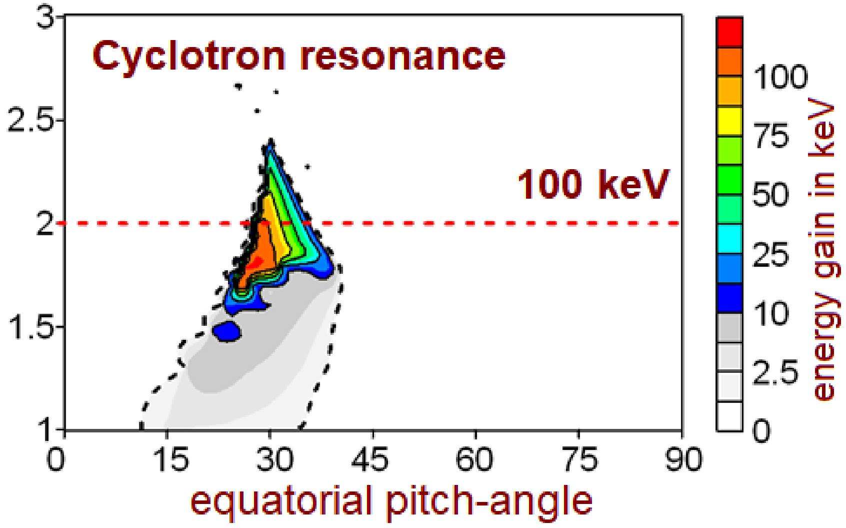
temperature anisotropy of 10-50 keV electrons

1-5 keV electrons streams

NL INTERACTION EFFECTS

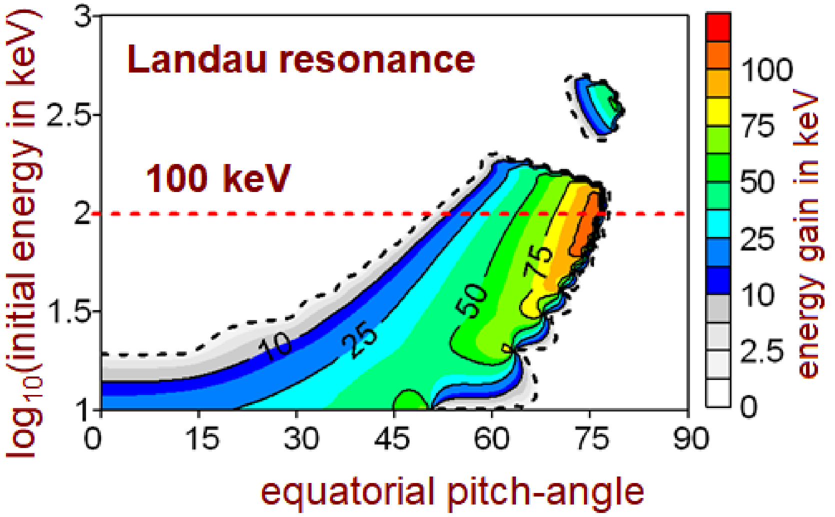
~100 keV electrons at Lat ~ 20-30° with

$\Delta E_{\perp}$~100 keV



~1-10 keV electrons at the equator

$\Delta E_{||}$~5-50 E_0 keV



DETECTABLE EFFECTS OF NL WAVE-PARTICLE INTERACTIONS

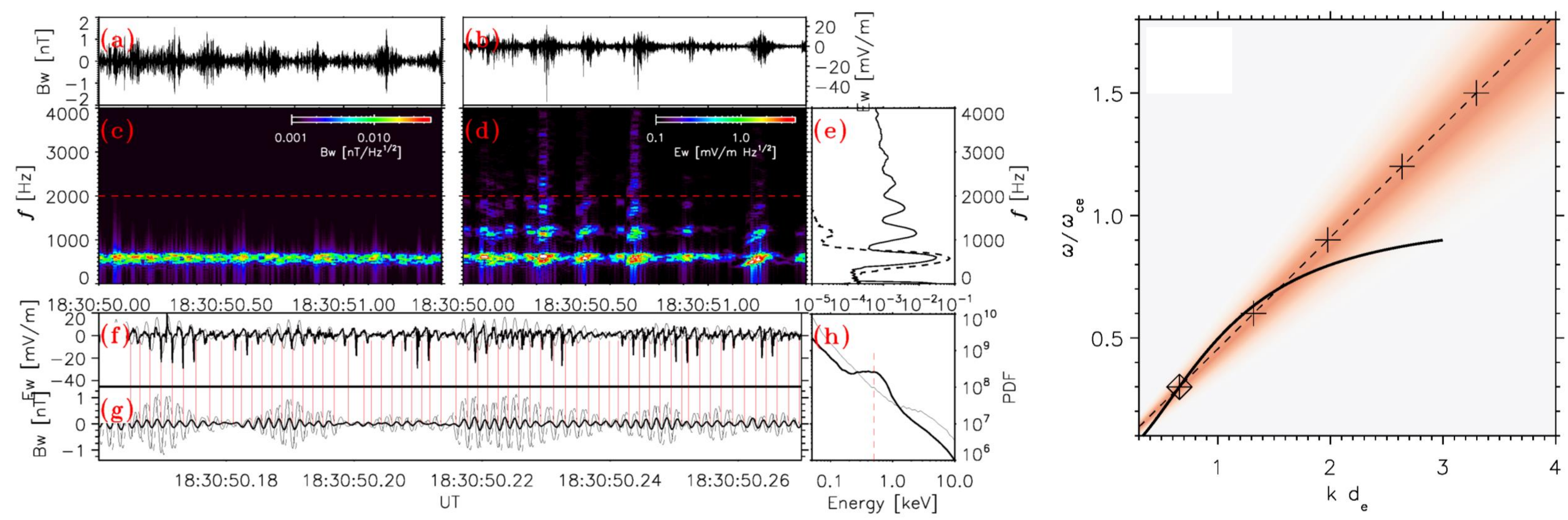
- Transverse acceleration
- Microbursts

Oliven & Gurnett, 1968; Rosenberg, 1981
Kersten et al., 11; Tsurutani et al., 13
Crew et al., 16
Breneman et al., 17; Mozer et al., 17
Shumko et al., 18 (under review)

- Parallel acceleration of 1-10 keV to 10-50 keV
- Suppressing the anisotropy of 10-50 keV in a statistical pattern and blocking generation of parallel chorus
- **Modification of $E_{||}$ waveform**

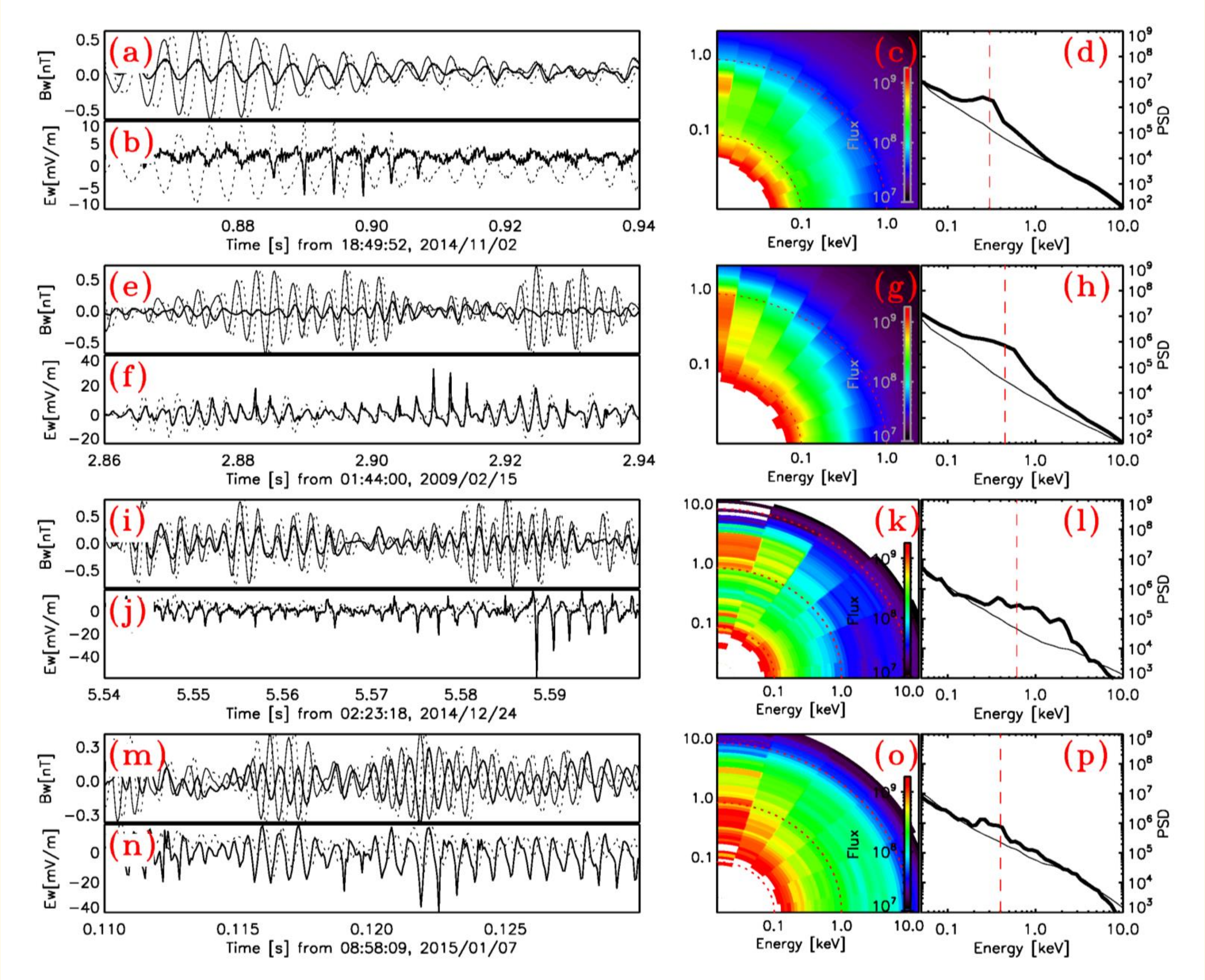
Kellogg et al., 10,12; Mozer et al., 14,15; Drake et al., 15; Agapitov et al. 18

Effects of Electron Acoustic Mode for Chorus



Magnetic and electric field waveforms (a,b) captured aboard Van Allen Probe A on April 24, 2013 and their dynamic spectra (c,d). Panel (e) presents the summary spectra of magnetic (the dashed curve) and electric (parallel component) field wave perturbation. The zoom of the wave perturbations are shown in panels (f) and (g) for the magnetic and electric field respectively. (h) - electron distributions along (the solid curve) the magnetic field and perpendicular (the thin curve) are presented.

Effects of Electron Acoustic Mode for Chorus



Magnetic (a) and electric (b) field perturbations. The electron distribution function is shown in panel (c), and its parallel and transverse slices are presented in panel (d) with the solid and thin black curves respectively.

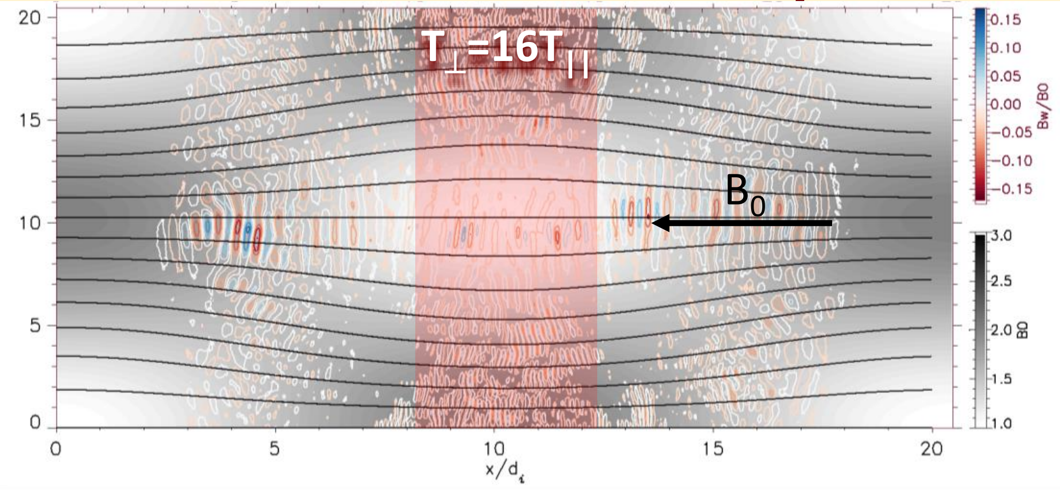
Parameters of the system for PIC numerical model

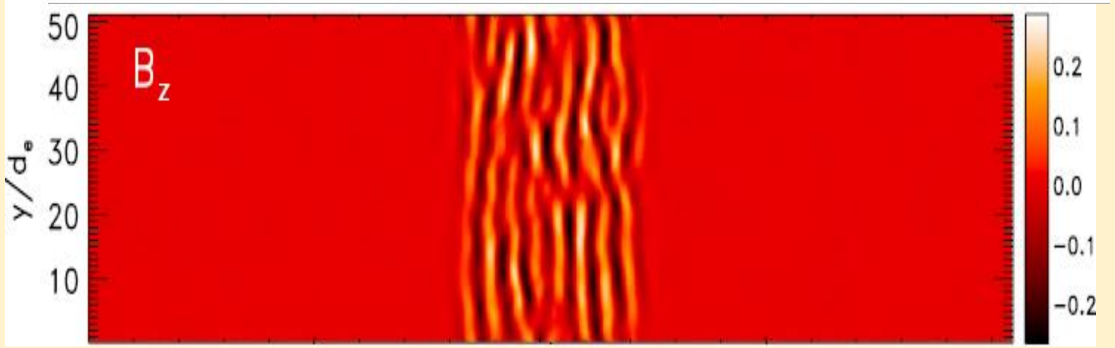
The results are presented in normalized units based on the electrons since they dominate the dynamics:

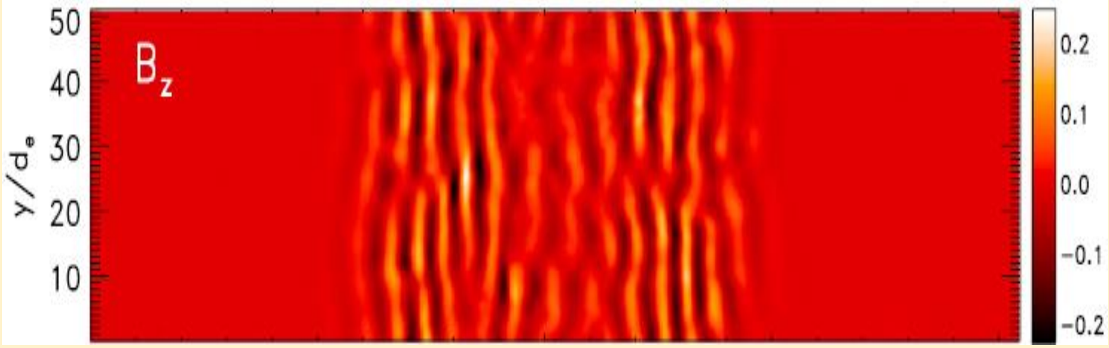
- the magnetic field to B_0,
- time to the inverse electron cyclotron time ω_{ce}^{-1}
- lengths to the electron skin depth d_e,
- velocities to the electron Alfven speed

$c_{Ae} = B_0/(4\pi m_e n_0)^{1/2}$

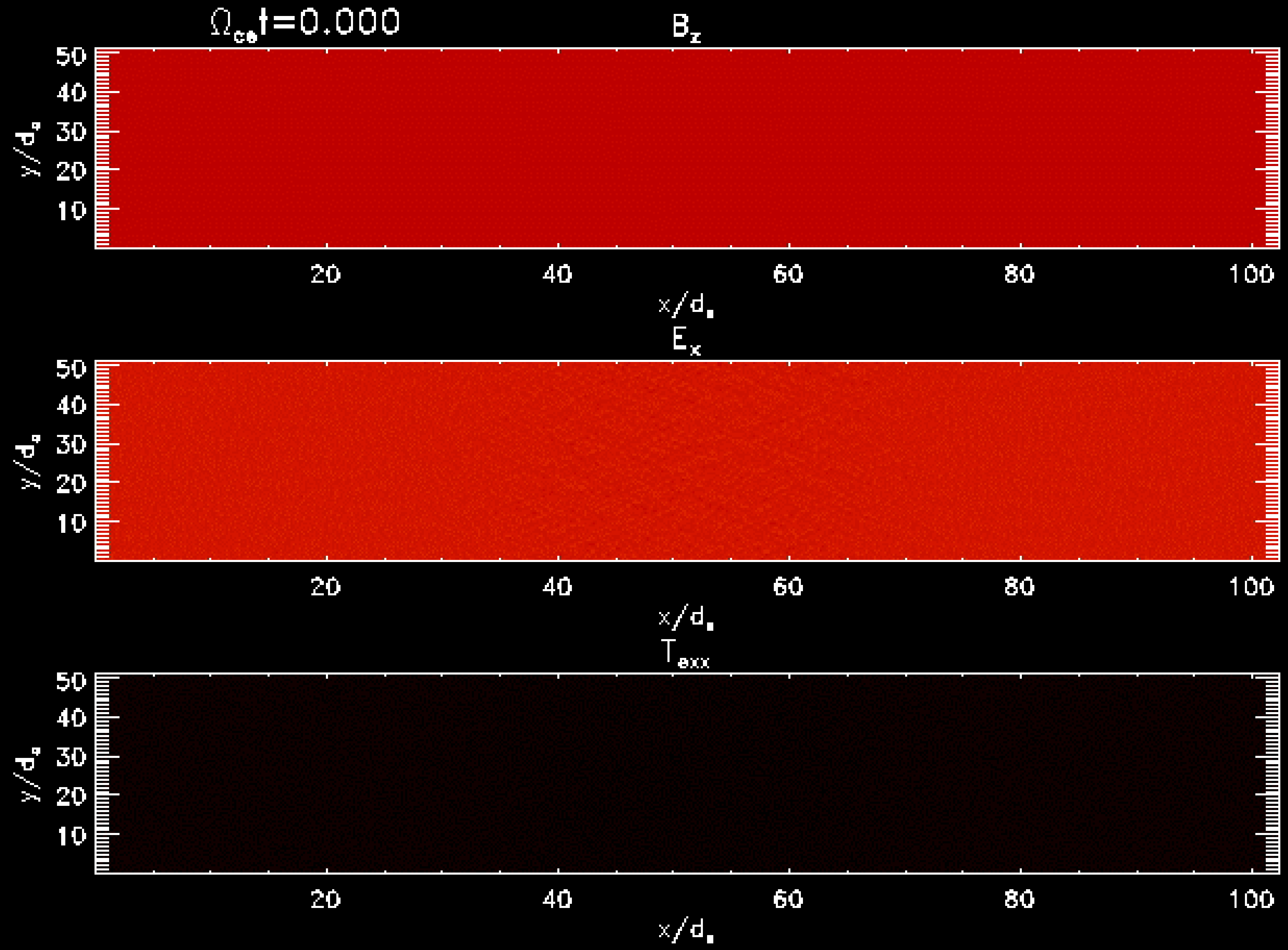
- temperatures to $m_e c_{Ae}^2$.
- grid scale of $0.05 d_e$.





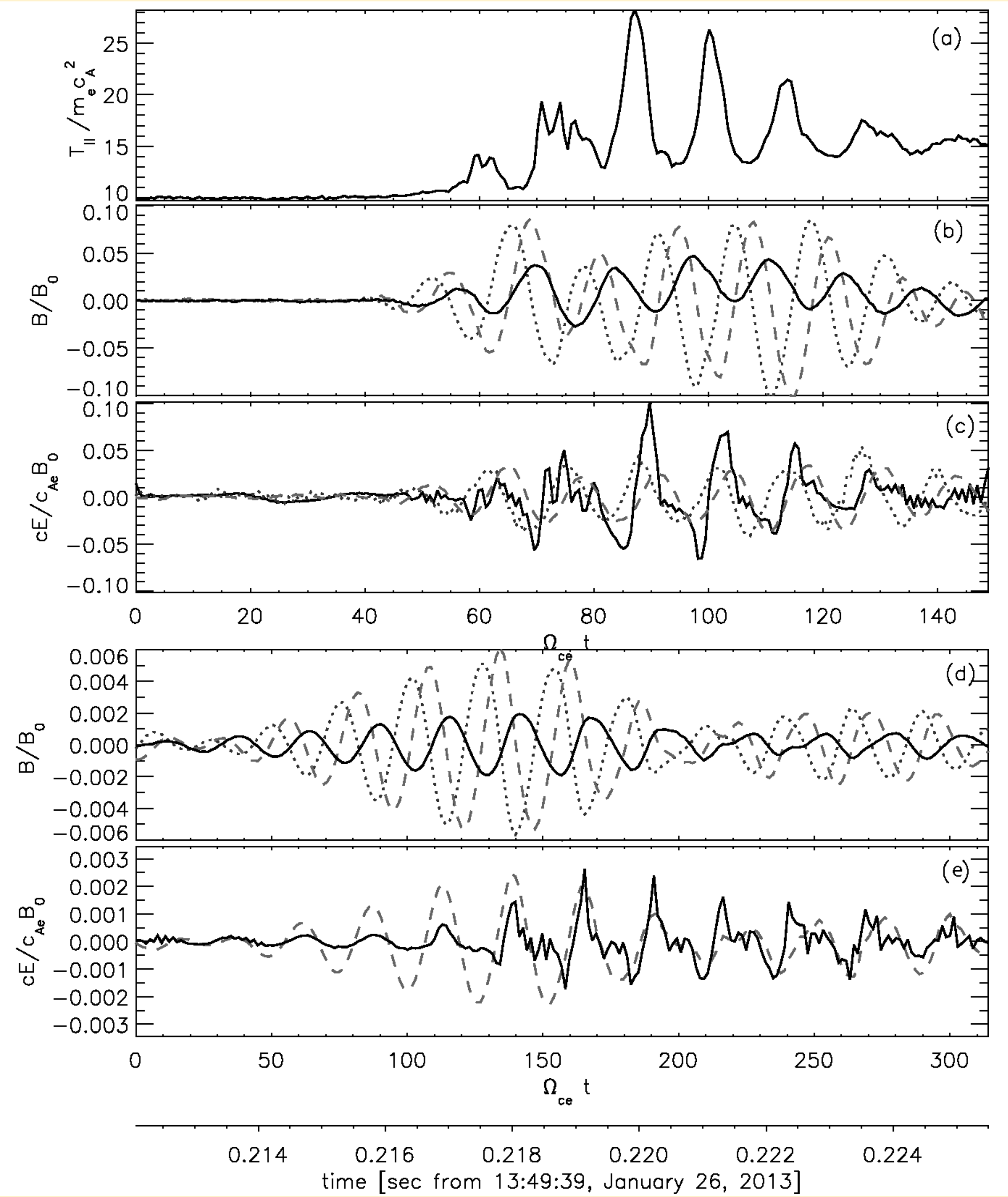


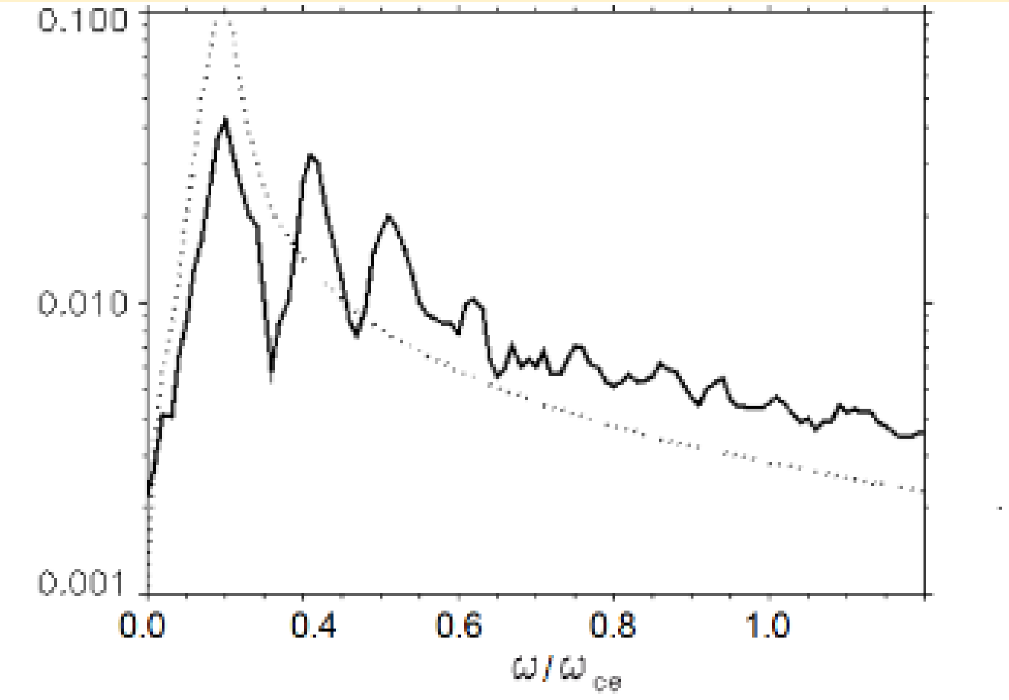
- Other parameters of the simulations are a mass-ratio $m_i/m_e = 200$, which is sufficient to separate the dynamics of the two species, and speed of light $c = 5c_{Ae}$, which yields a ratio of the electron plasma frequency ω_{pe} to ω_{ce} of five.
- The initial electron parallel temperature $T_{exx} = 0.025$ is uniform while the perpendicular temperature $T_{eyy} = T_{ezz}$ is from 0.1 to 0.4 in the center of the domain, $|x-L_x|/L_x < 1/12$



$\Omega_{ce}t=0.000$
B_z
E_x
T_{exx}
y/d
x/d
10
20
30
40
50
60
80
100

Effects of Electron Acoustic Mode: PIC calculation

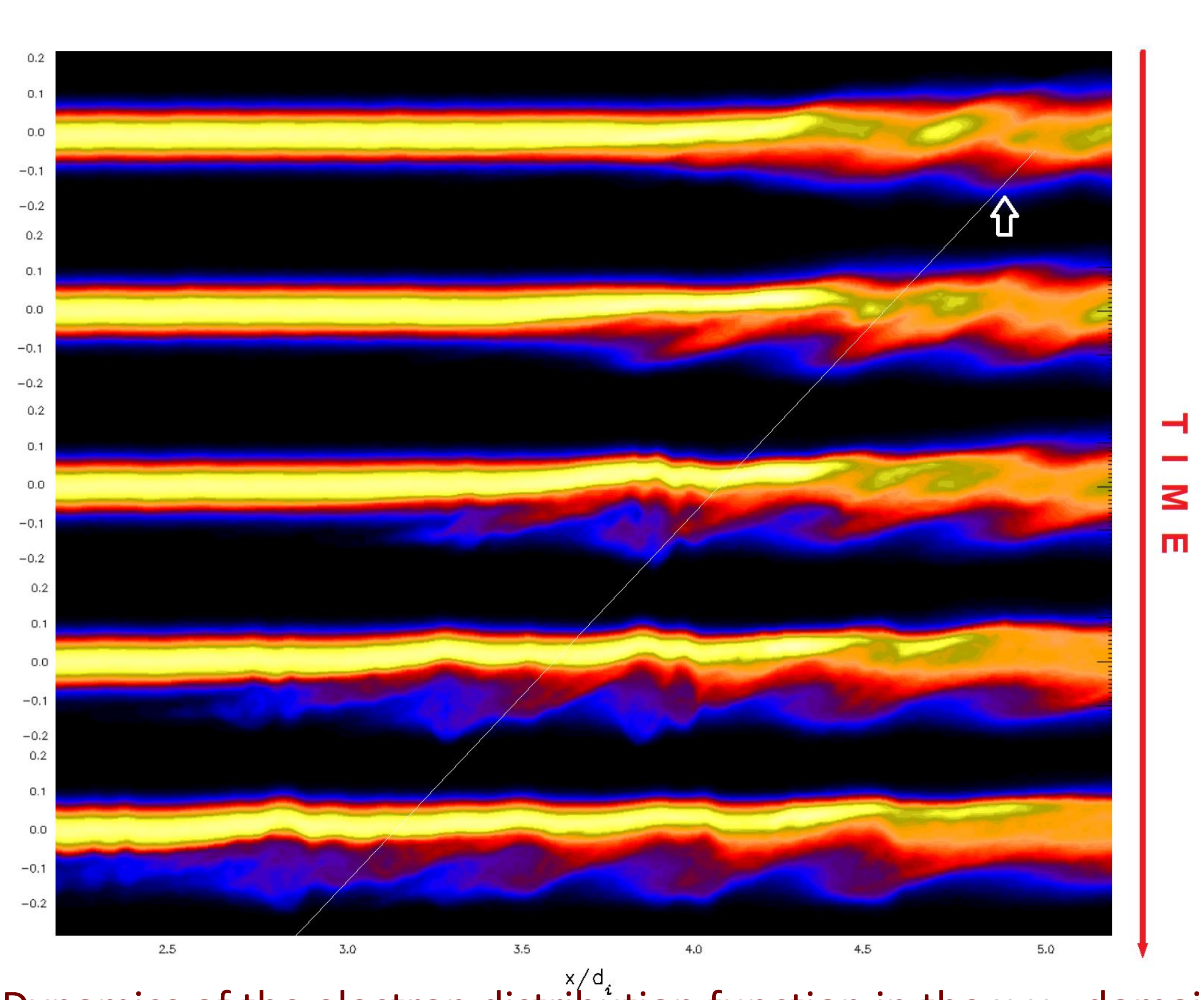


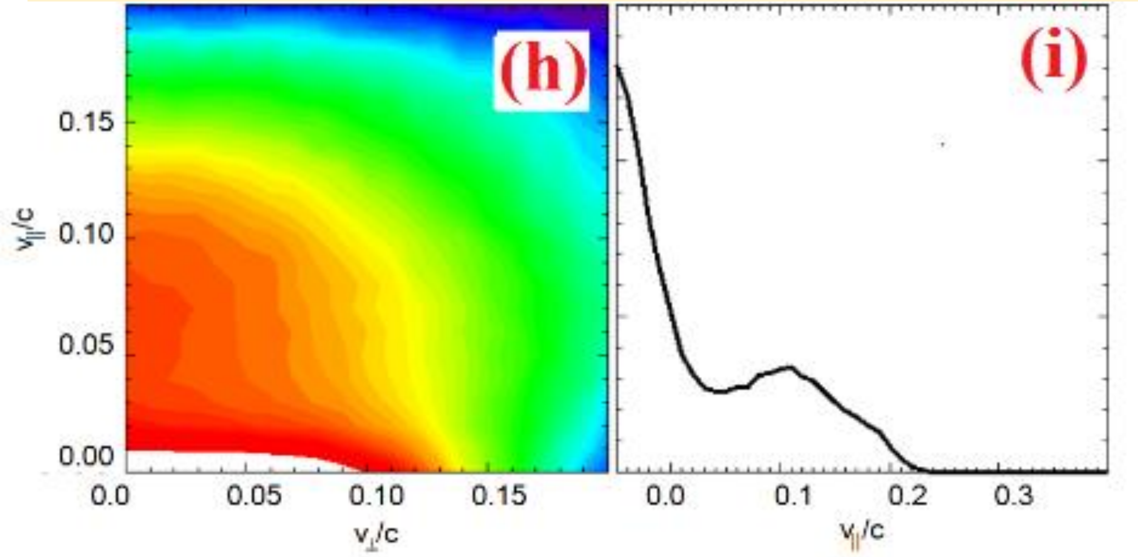


The power spectrum of the parallel electric field perturbation is presented in panel (k) with the solid black curve. Magnetic field spectrum is shown by the dashed curve.

<= Magnetic and electric field waveforms from the PIC simulation. The summary spectra of magnetic (the dashed curve) and electric (parallel component) field wave perturbation.

Effects of Electron Acoustic Mode: PIC calculation

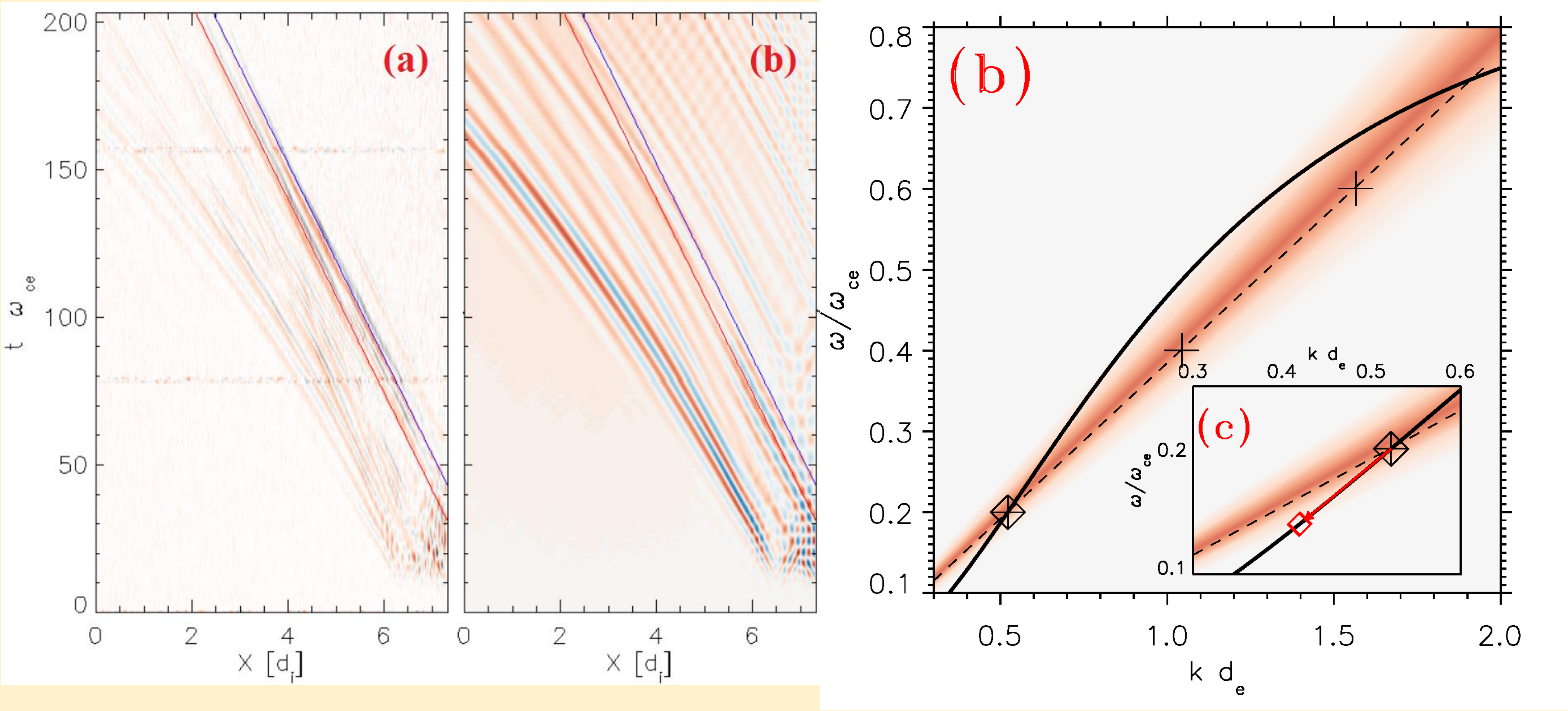




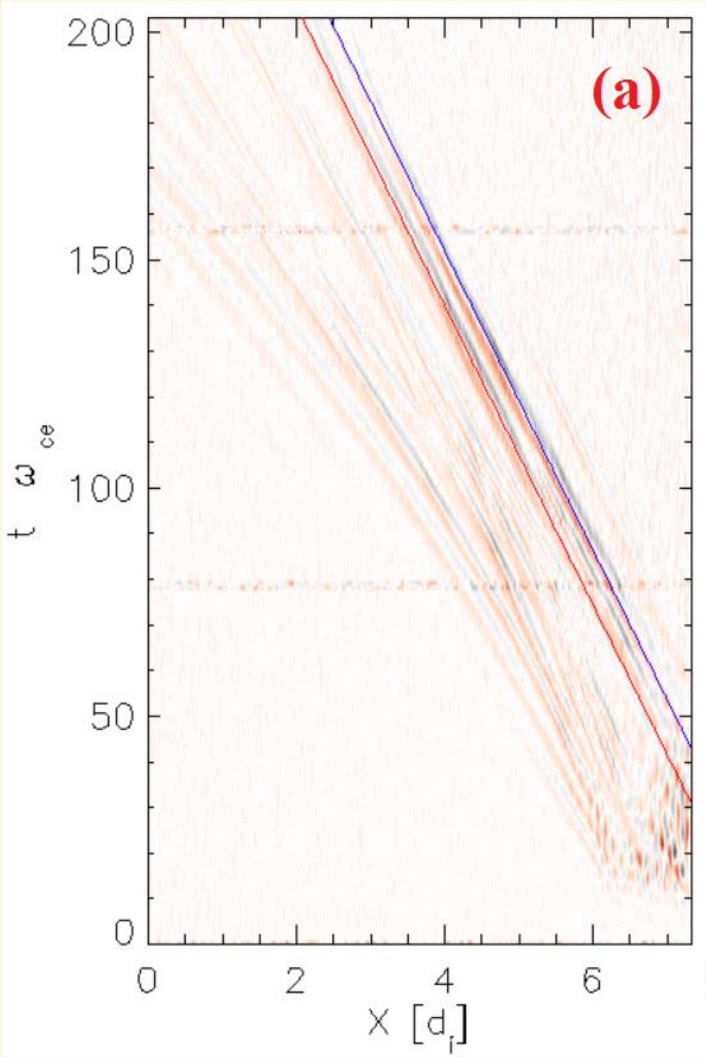
The electron distribution function in the parallel and transverse velocity domain captured at point #1 and the corresponding field-aligned electron distribution function (for $v_{\perp} = 0$)

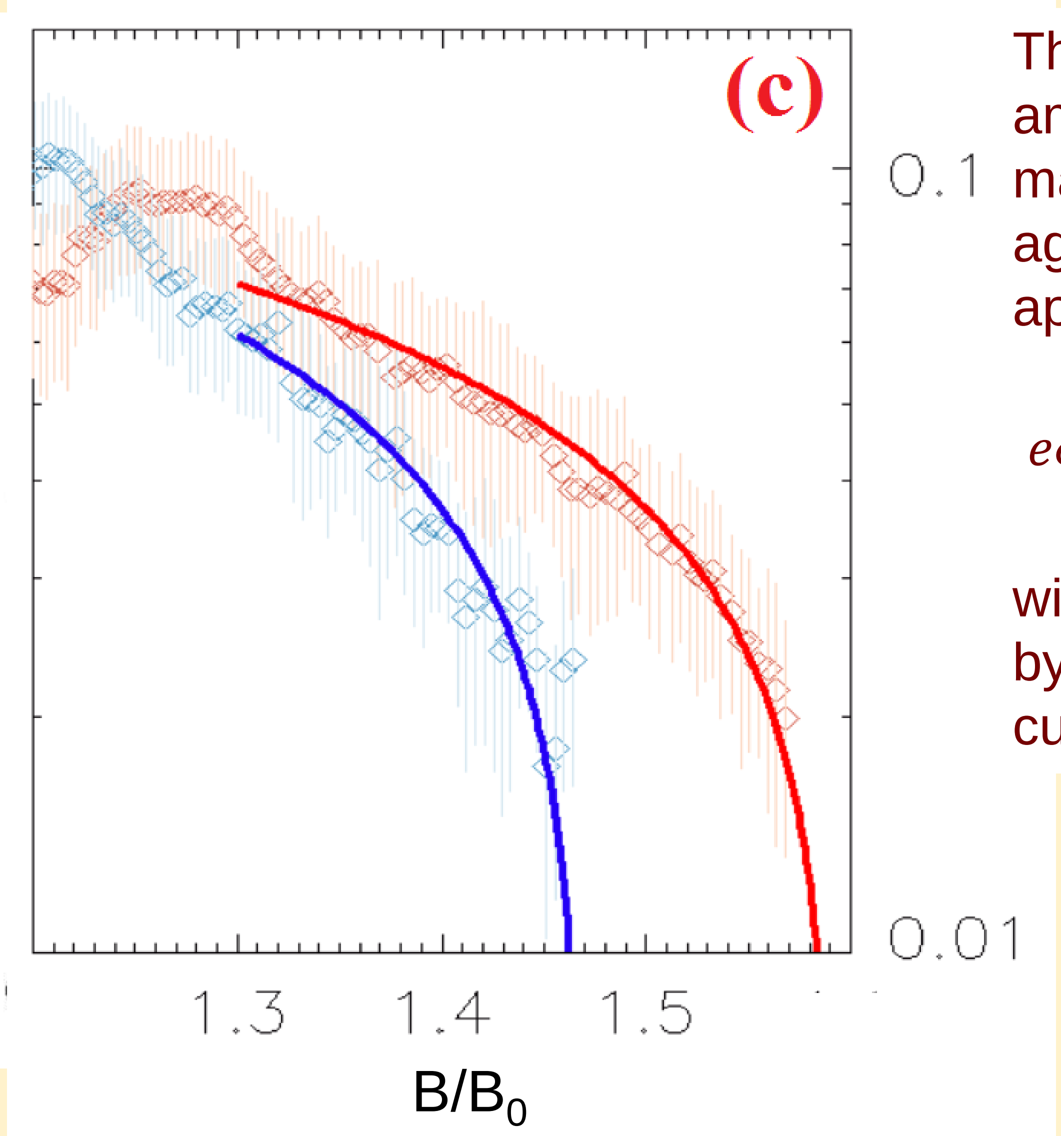
Dynamics of the electron distribution function in the x-$v_{||}$ domain. Whistler parallel electric field modulates the resonance beam, which leads to generation of the electron acoustic mode with following steepening, overturning and mixing the hot beam.

Effects of Electron Acoustic Mode: PIC calculation



Effects of Electron Acoustic Mode: PIC calculation





The rapid decay of the burst amplitude with grows of magnetic field is in a good agreement with the approximate dependence

$$e\varphi + T_{tr0}\frac{B}{B_0} \sim const$$

with $T_{tr} = T_{tr0}B/B_0$ shown by the red and blue solid curves respectively

Conclusions

we report the first direct observation of the electrostatic electron acoustic wave generation triggered by the electromagnetic whistler mode in the presence of the resonance electron beam:

- The process which has been thought of as the nonlinear electrostatic steepening of whistler waves is, instead, the coupling of the whistler with the electron acoustic mode.
- This plasma wave mode conversion is thought to be important for the energy transport to smaller scales and for plasma heating in space and laboratory plasma systems.
- The mechanism has been confirmed by a self-consistent numerical simulation that fully reproduces all steps of the process.