# Particle acceleration by circularly and elliptically polarised dispersive Alfven waves (DAWs) in a transversely inhomogeneous, 2.5D and 3D plasma in the inertial and kinetic regimes


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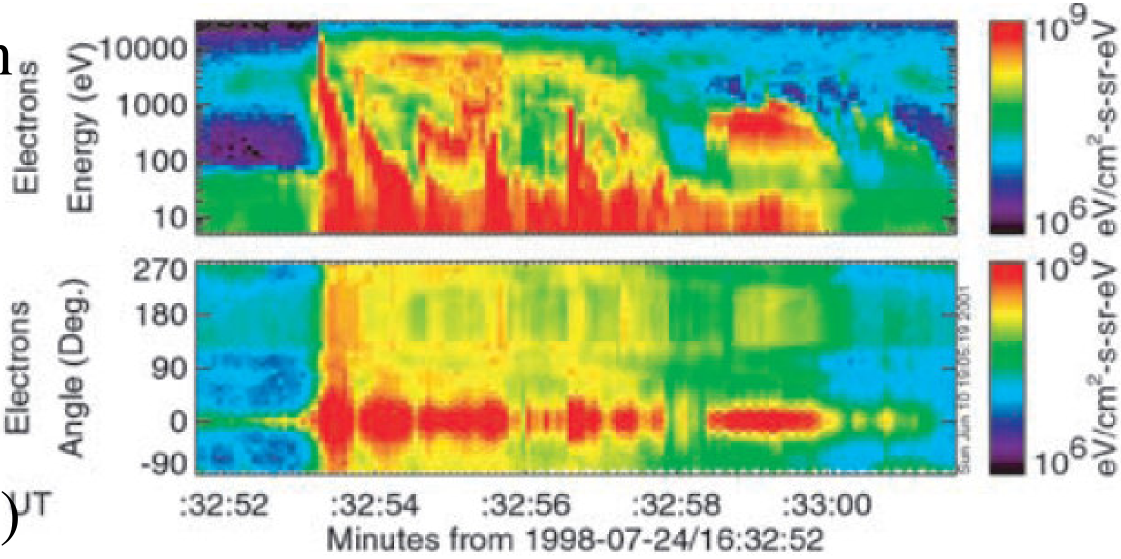
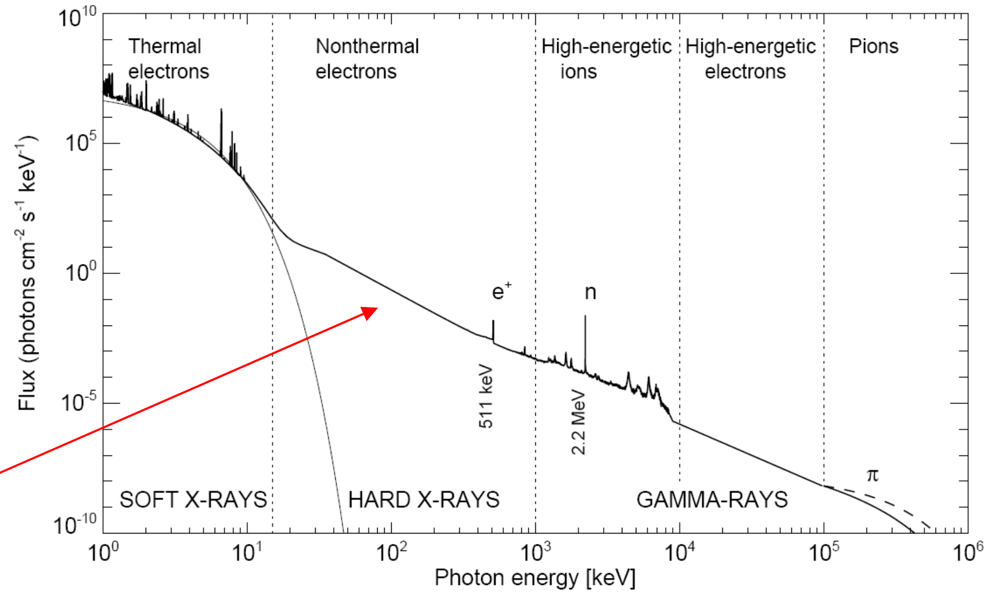
**This poster will be also given as a Splinter Session, SPM1.29, Talk on 25 April, 11:30-11:45, Room SM8, Red Level**

1) FAST satellite, has shown accelerated auroral $e$'s exhibit distributions that are narrow in pitch angle and broad in energy, consistent with acceleration in a time-varying $E_{\|}$ (DAWs) [e.g., Chaston et al., 2002, JGR, 107, A11, 1413 ]




2) In solar corona, upto 50% of the energy released during solar flares is converted into the energy of accelerated particles [Emslie, et al JGR. 109, A10104, (2004)].




Super-thermal electrons in the solar corona, Aschwanden book, page 608

It is clear why one needs to study particle acceleration by DAWs in the Earth Auroral Zone, but why do we need to invoke DAWs for particle acceleration in flares in the solar corona?

The answer is in so called "number problem" --

too high total number ($10^{34}$–$10^{37}$ per second) of accelerated *e*'s are required to produce the observed hard x-ray emission compared to that available in the corona, if the particle acceleration takes place at the *loop apex*.

This would mean that, if the solar flare particle acceleration volume is in the range of 1–10 $Mm^3$ with the number density of $n=10^{16}$ $m^{-3}$, to match the observational $10^{34}$–$10^{37}$ accelerated electrons per second, full 100% of electrons need to be accelerated!

(no mechanism is known that operates with the 100% efficiency)





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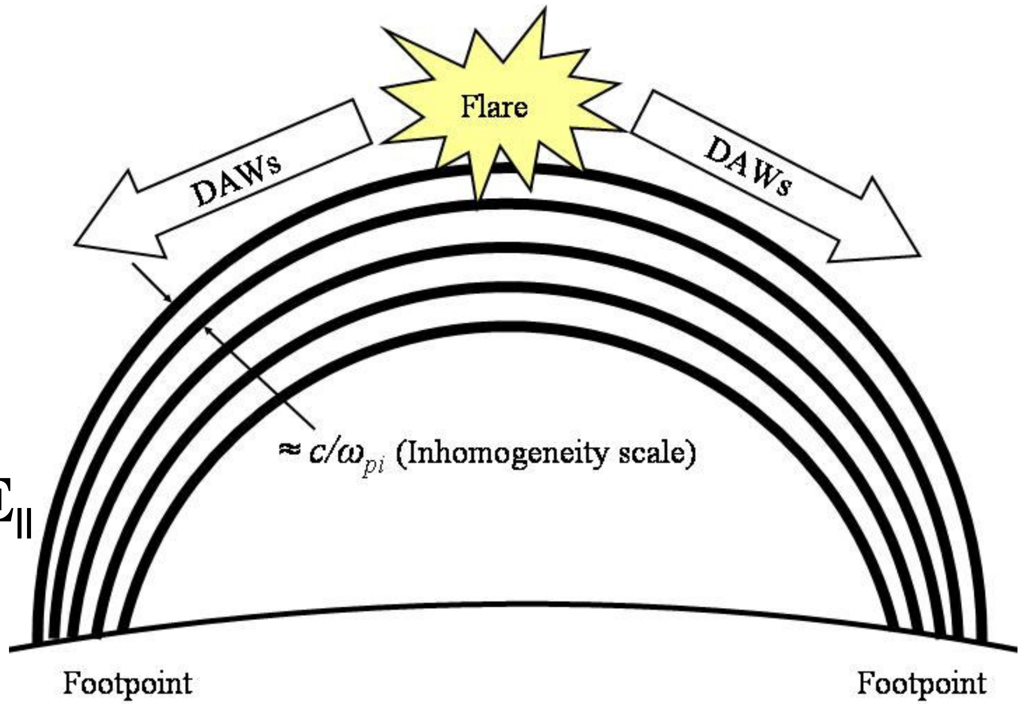
## Kinetic (PIC) simulations of DAWs

Tsiklauri D., et al., A&A, 435, 1105, (2005) ← mechanism proposed
Tsiklauri D., New J. Phys. 9, 262 (2007)
Tsiklauri D., T. Haruki, Phys. of Plasmas, 15, 112902 (2008)
Tsiklauri D., Phys. Plasmas 18, 092903 (2011) ← discussed here
Tsiklauri D. Phys. Plasmas (2012) in preparation ← discussed here

- 2.5D and 3D fully relativistic, electromagnetic, PIC code used **also** two-fluid code developed.
- **New mechanism for electron acceleration via generation of $E_{||}$ found.**



# 2.5D model 200x10000 grid (upto 72h on 512 processor cores)

We use EPOCH (Extendible Open PIC Collaboration) a fully electromagnetic, relativistic, 2.5D particle-in-cell code.

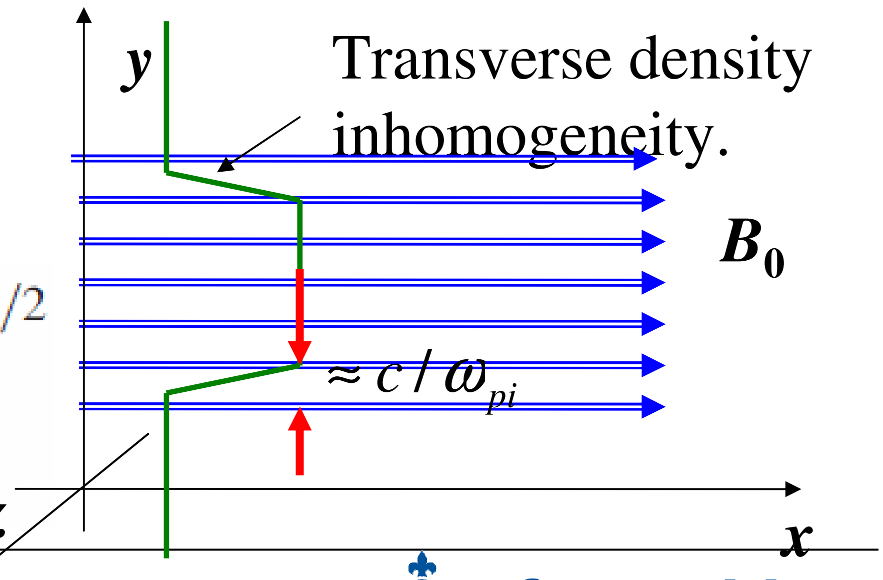
- Equilibrium is such that the total pressure is constant. $B_0 = const \parallel$ to $x$;
- density $\rho = \rho(y)$; $T = T(y)$. Such set up mimics solar coronal loop.
- Transverse inhomogeneity scale is $\approx 30\lambda_D \approx 0.75 c/\omega_{pi}$ for $m_i/m_e$=16.
- Initial conditions are: DAW driven at $x$=1 with $\omega_d = 0.3\omega_{ci}$

$$n_i(y) = n_e(y) = 1 + 3\exp\left[-\left(\frac{y - 100\lambda_D}{50\lambda_D}\right)^6\right] \equiv f(y). \quad (1)$$

$$T_i(y)/T_0 = T_e(y)/T_0 = f(y)^{-1}, \quad (2)$$

The dispersion relation:

$$k = \frac{\omega}{c}\left(1 + \frac{\omega_{pe}^2 + \omega_{pi}^2}{(\omega_{ce} \pm \omega)(\omega_{ci} \mp \omega)}\right)^{1/2}$$



The case of left-polarised DAW:

$$E_y(1,y,t+\Delta t) = E_y(1,y,t) - A_y \sin(\omega_d t)(1-\exp[-(t/t_0)^2]),$$
$$E_z(1,y,t+\Delta t) = E_z(1,y,t) - A_z \cos(\omega_d t)(1-\exp[-(t/t_0)^2]),$$

Left-polarised DAW = Ion-Cyclotron

The case of right-polarised DAW:

$$E_y(1,y,t+\Delta t) = E_y(1,y,t) + A_y \sin(\omega_d t)(1-\exp[-(t/t_0)^2]),$$
$$E_z(1,y,t+\Delta t) = E_z(1,y,t) - A_z \cos(\omega_d t)(1-\exp[-(t/t_0)^2]),$$

Right-polarised DAW = Whistler

TABLE I. Numerical simulation parameters.

| Regime | Inertial | Kinetic |
|---|---|---|
| $m_i/m_e$ | 16 | 73.44 |
| $\omega_{ce}/\omega_{pe}$ | 1.000 | 1.000 |
| $\beta$ | 0.020 | 0.020 |
| $c/\omega_{pe}$ [m] | 0.053 | 0.053 |
| $\lambda_D = r_{L,e}$ [m] | 0.005 | 0.005 |
| $v_{th,e}/c$ | 0.101 | 0.101 |
| $v_{th,i}/c$ | 0.025 | 0.012 |
| $V_A/c = \omega_{ci}/\omega_{pi}$ | 0.25 | 0.117 |
| $V_{A,ph}/c$ | 0.243 | 0.116 |
| $V_L/c$ | 0.201 | 0.097 |
| $V_R/c$ | 0.264 | 0.131 |
| $t_{end} = 75\omega_{ci}^{-1} [\times 10^{-7}$ s] | 2.127 | 9.763 |
| $n_y$ | 200 | 200 |
| $n_x$ | 5000 | 10712 |



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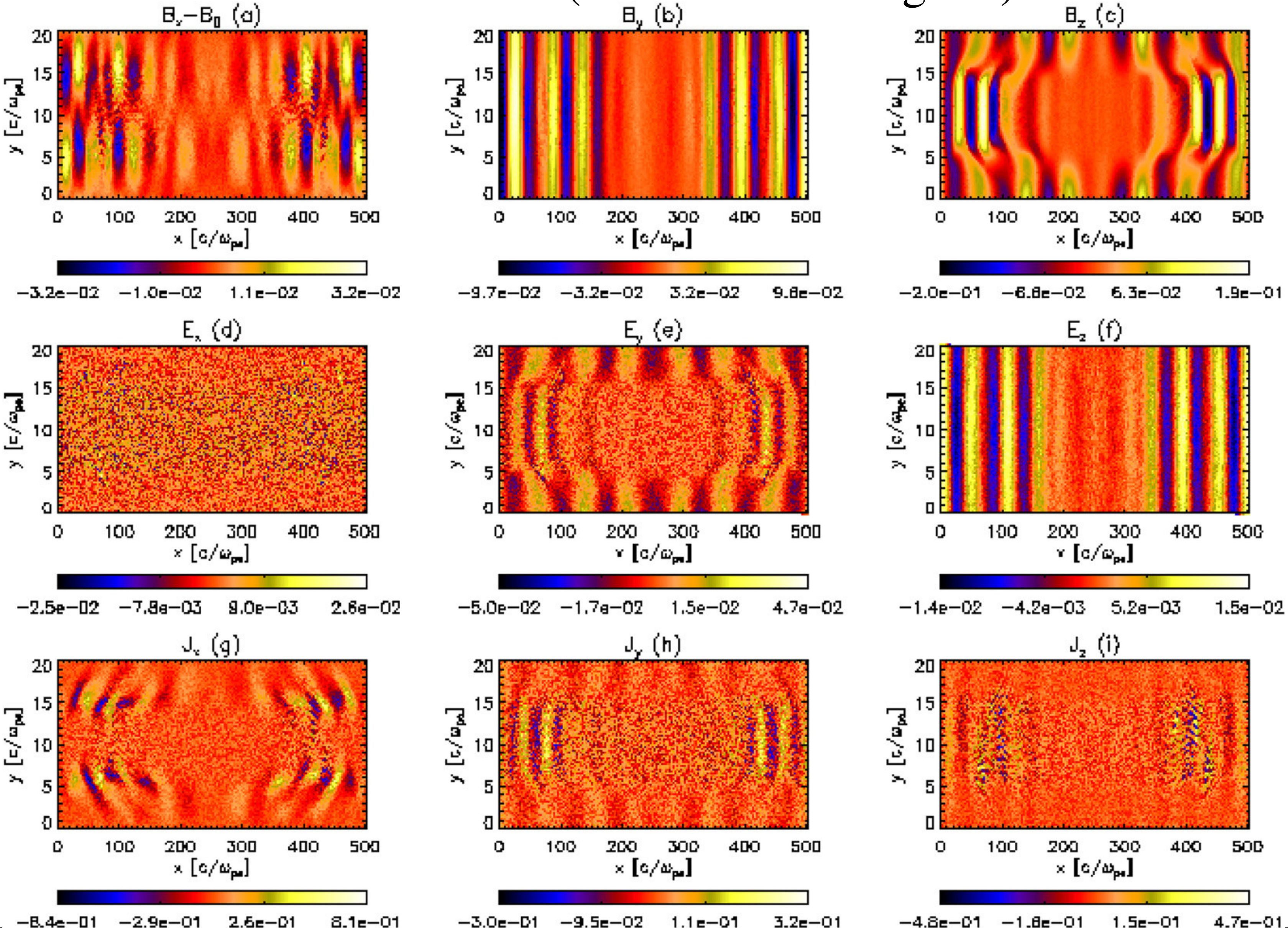
TABLE II. Numerical simulation run identification and physical parameters. I stands for inertial and K for kinetic. Reg. stands for regime.

| Run ID | Polarisation | $m_i/m_e$ | Reg. | $A_y/A_z$ | $t_{end}[\omega_{ci}^{-1}]$ | Figs. |
|---|---|---|---|---|---|---|
| L16 | L–circular | 16 | I | 1 | 75 | 1, 2, 3 |
| R16 | R–circular | 16 | I | 1 | 75 | 4 |
| EL16 | L–elliptical | 16 | I | 6 | 75 | 5 |
| ER16 | R–elliptical | 16 | I | 6 | 75 | 6 |
| $EL16_1$ | L–elliptical | 16 | I | 1/6 | 75 | 7 |
| $ER16_1$ | R–elliptical | 16 | I | 1/6 | 75 | 8 |
| L73 | L–circular | 73.44 | K | 1 | 75 | 9 |
| R73 | R–circular | 73.44 | K | 1 | 75 | 10, 11, 12 |
| EL73 | L–elliptical | 73.44 | K | 6 | 75 | 13 |
| ER73 | R–elliptical | 73.44 | K | 6 | 75 | 14 |
| $EL73_1$ | L–elliptical | 73.44 | K | 1/6 | 75 | 15 |
| $ER73_1$ | R–elliptical | 73.44 | K | 1/6 | 75 | 16 |
| L16Long | L–circular | 16 | I | 1 | 300 | 17, 18 |

# Numerical results for run L16 (Inertial DAW regime).

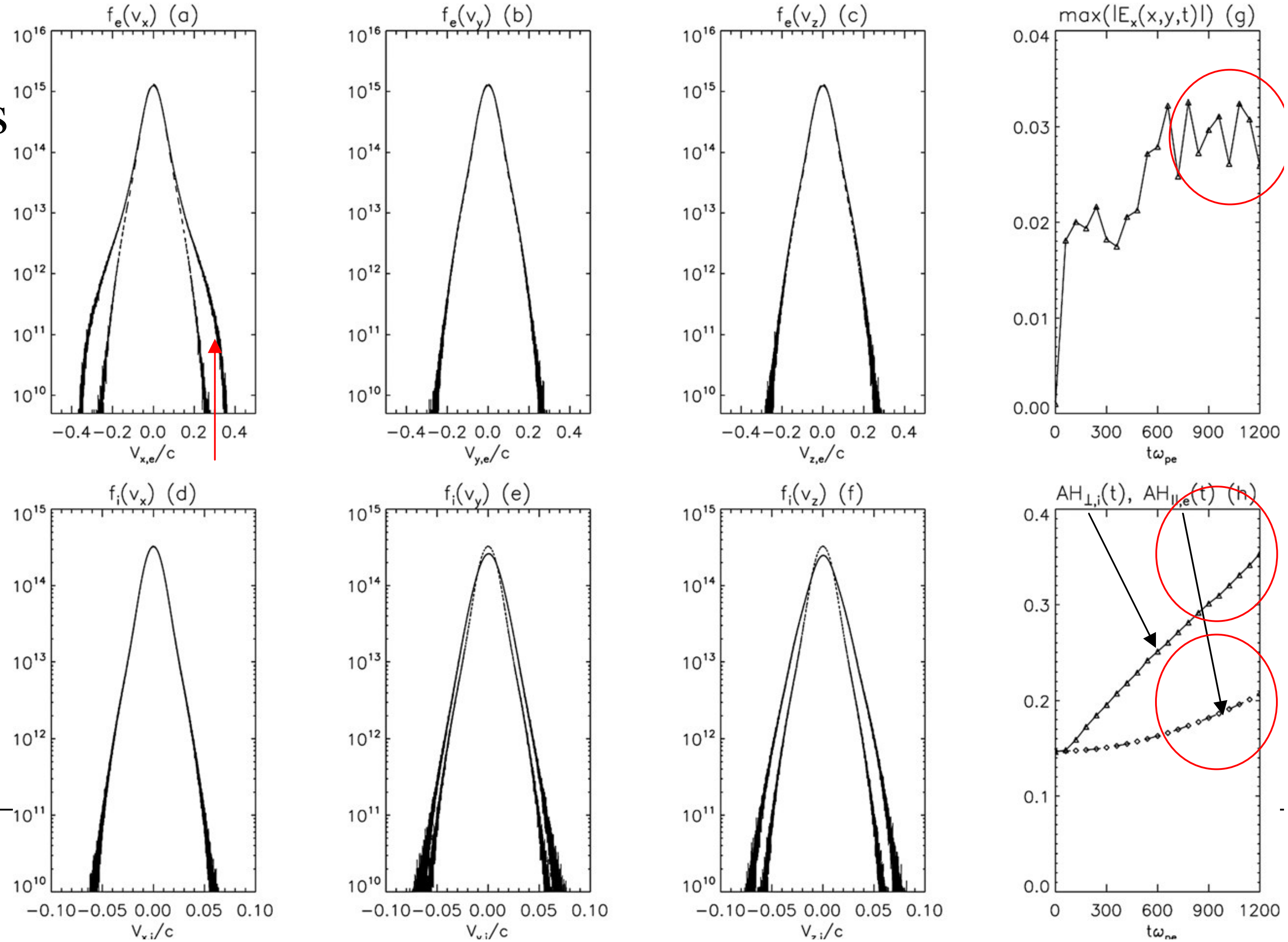


We quantify the particle acceleration and plasma heating by defining the following indexes:

$$AH_{\parallel,e}(t) = \frac{\int_{|v_x|>\langle v_{th,e}\rangle}^{\infty} f_e(v_x,t)dv_x/(2L_{IH,y}\times L_{x,max})}{\int_{-\infty}^{\infty} f_e(v_x,0)dv_x/(L_{y,max}\times L_{x,max})}, \quad (8)$$

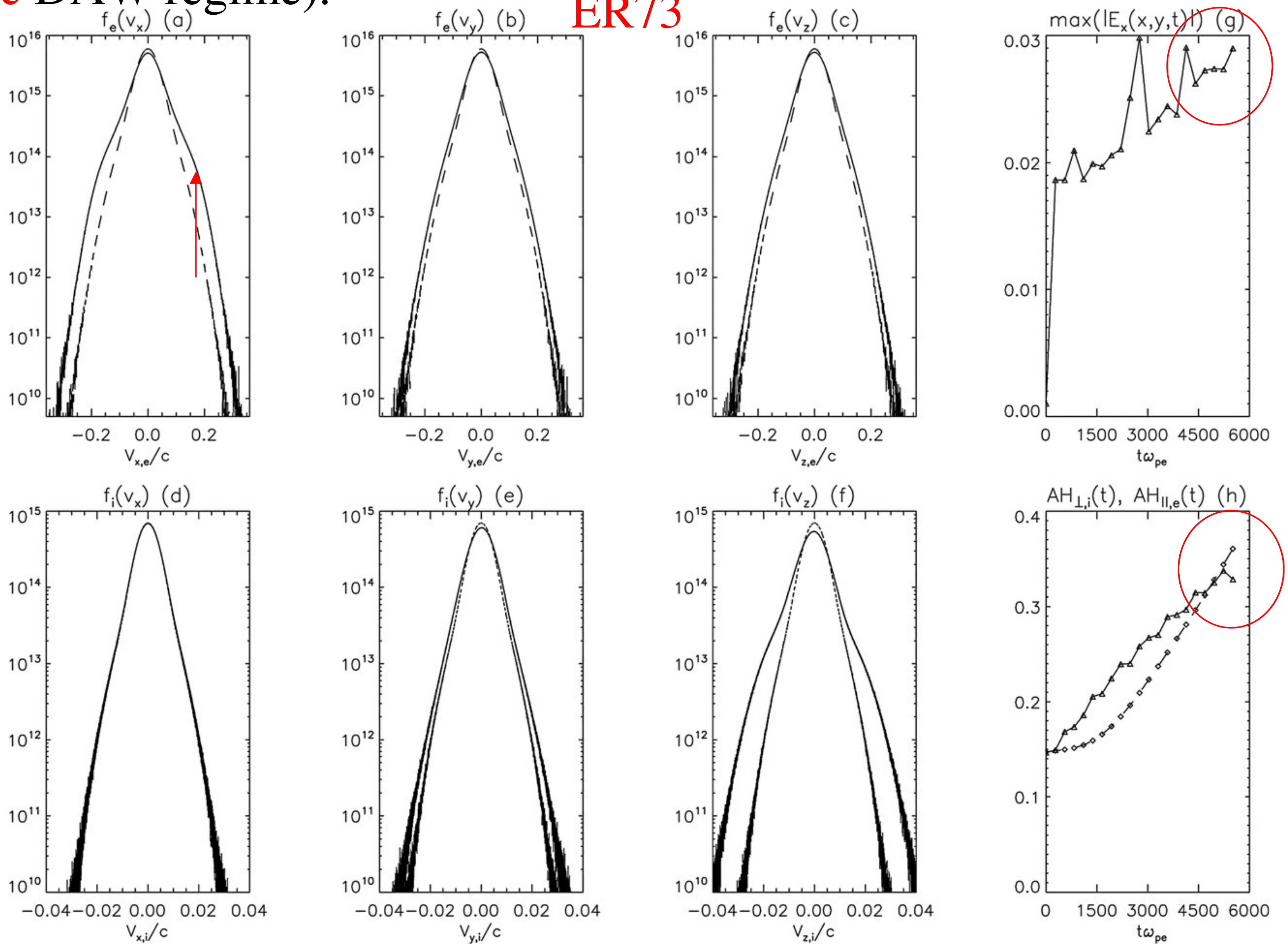
$$AH_{\perp,i}(t) = \frac{\int_{|v_\perp|>\langle v_{th,i}\rangle}^{\infty} f_i(v_\perp,t)dv_\perp/(2L_{IH,y}\times L_{x,max})}{\int_{-\infty}^{\infty} f_i(v_\perp,0)dv_\perp/(L_{y,max}\times L_{x,max})}. \quad (9)$$

Numerical results for run L16 (Inertial DAW regime).



(Kinetic DAW regime).

ER73







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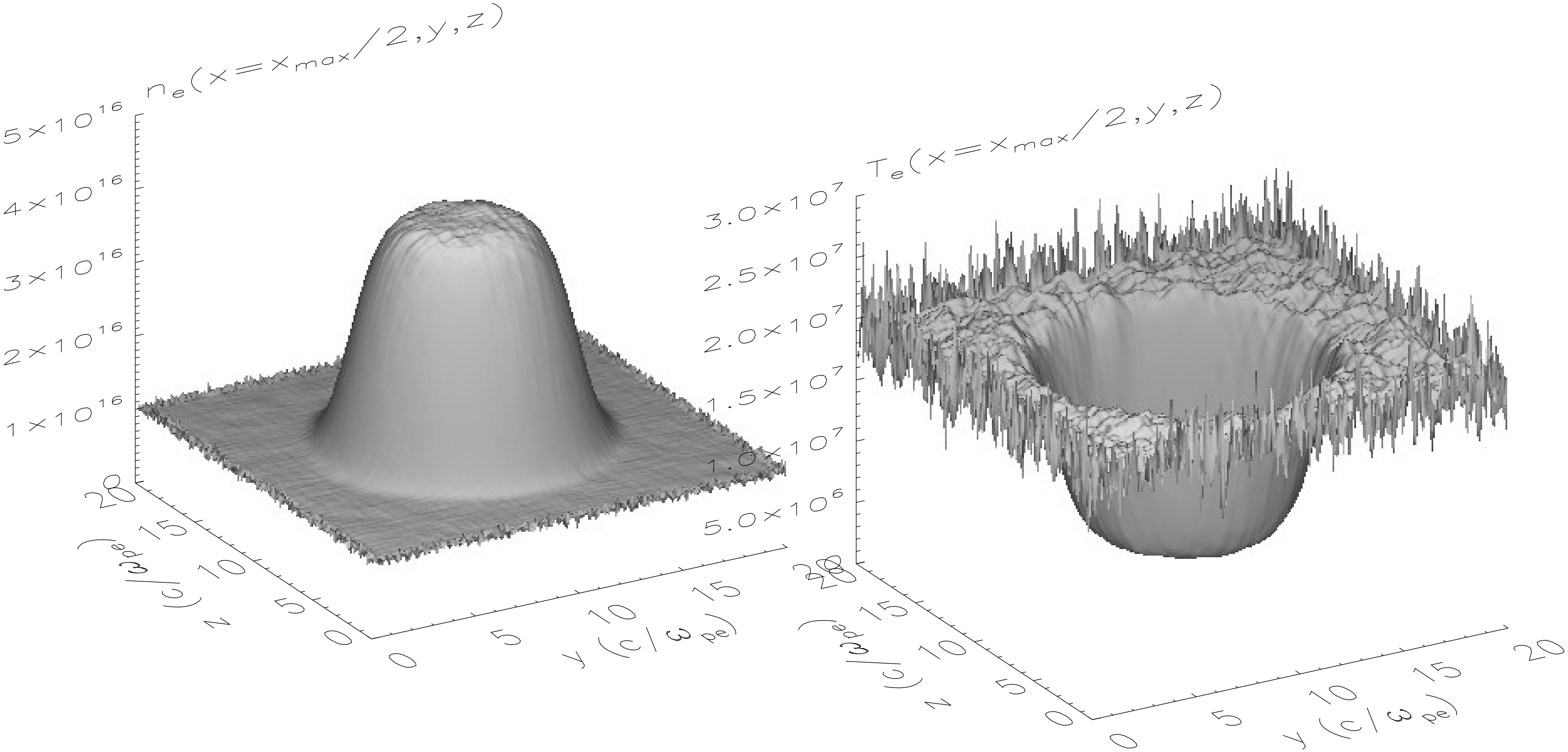
# Fully 3D model 200x200x5000 grid (10 days on 720 processor cores)




3D equilibrium is in the pressure balance $T(y,z) \sim 1/n(y,z)$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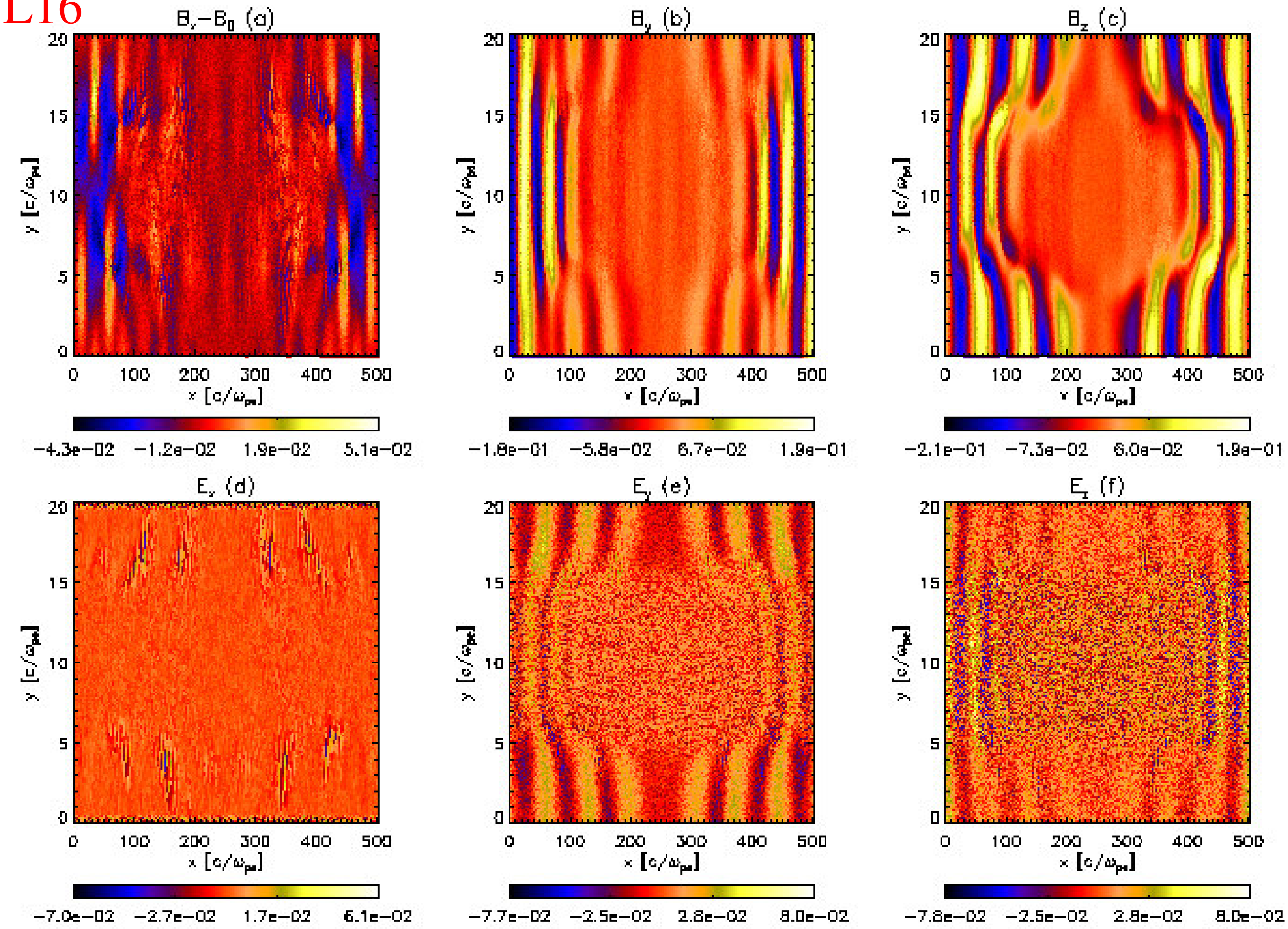
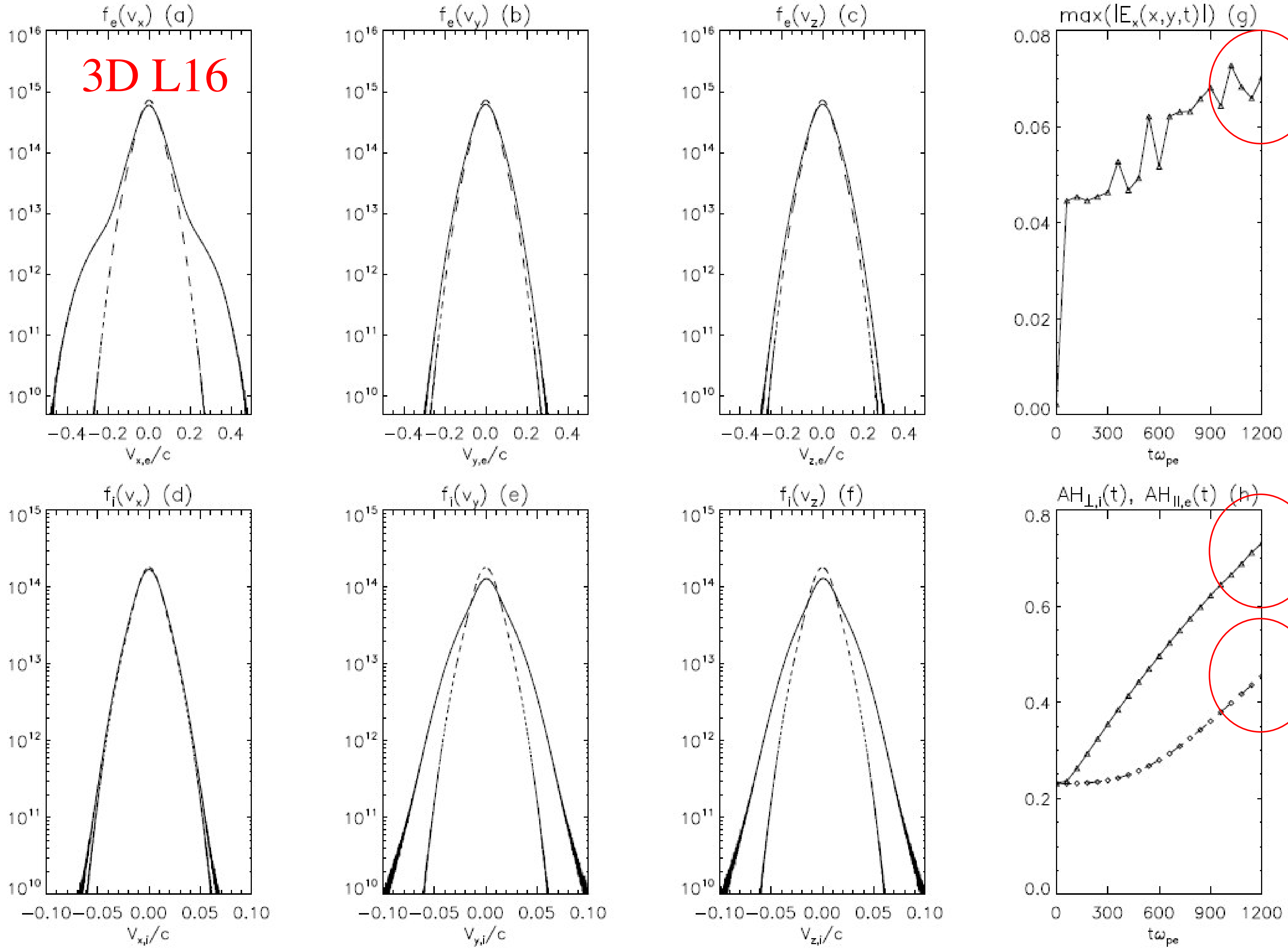
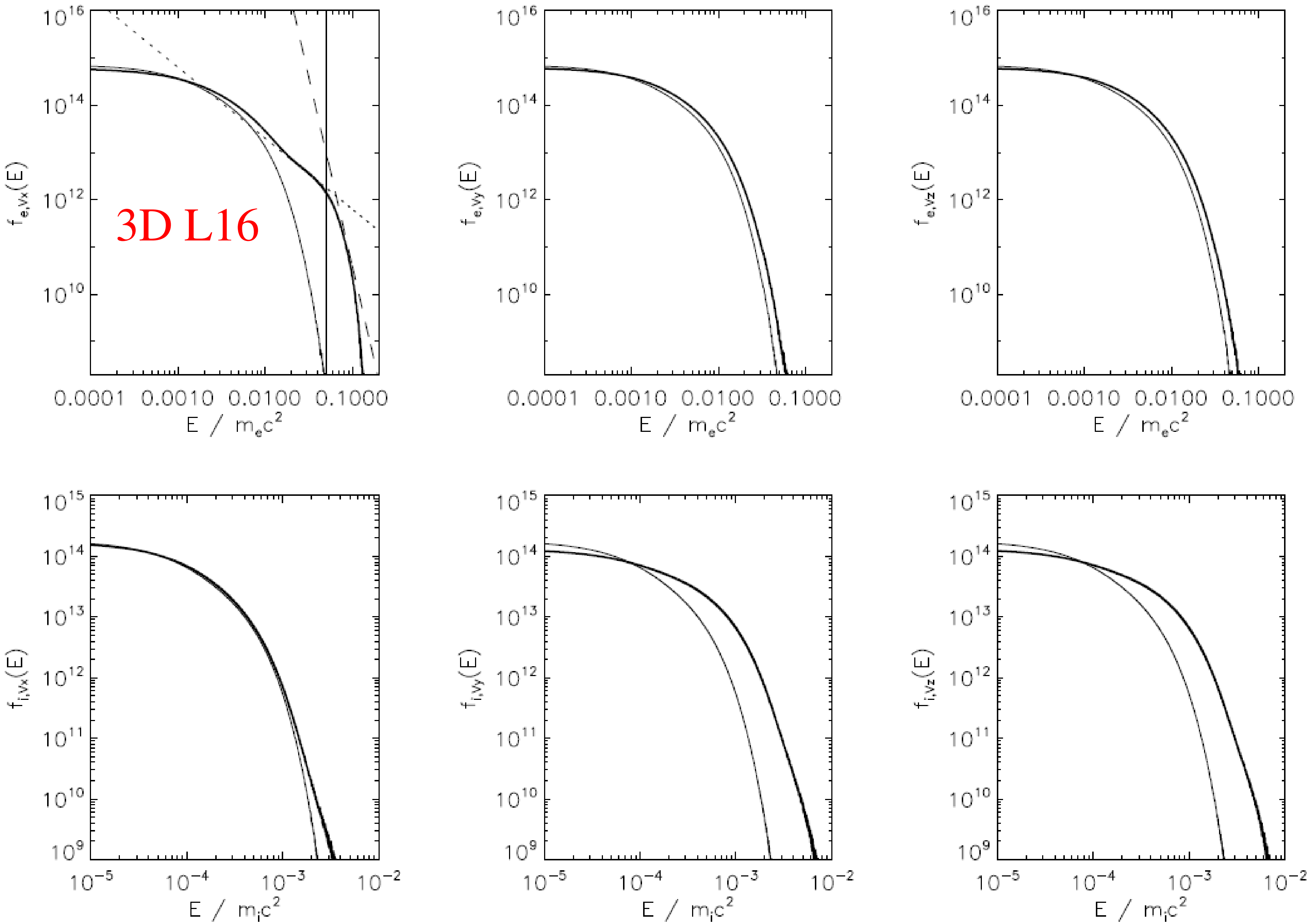
# 3D L16



$B_x - B_0$ (a)
$B_y$ (b)
$B_z$ (c)
$E_x$ (d)
$E_y$ (e)
$E_z$ (f)
x [c/ω_pe]
y [c/ω_pe]
−4.3e−02 −1.2e−02 1.9e−02 5.1e−02
−1.8e−01 −5.8e−02 6.7e−02 1.9e−01
−2.1e−01 −7.3e−02 6.0e−02 1.9e−01
−7.0e−02 −2.7e−02 1.7e−02 6.1e−02
−7.7e−02 −2.5e−02 2.8e−02 8.0e−02
−7.8e−02 −2.5e−02 2.8e−02 8.0e−02



3D L16
$f_e(v_x)$ (a)
$f_e(v_y)$ (b)
$f_e(v_z)$ (c)
$\max(|E_x(x,y,t)|)$ (g)
$f_i(v_x)$ (d)
$f_i(v_y)$ (e)
$f_i(v_z)$ (f)
$AH_{\perp,i}(t)$, $AH_{\parallel,e}(t)$ (h)
$V_{x,e}/c$
$V_{y,e}/c$
$V_{z,e}/c$
$t\omega_{pe}$
$V_{x,i}/c$
$V_{y,i}/c$
$V_{z,i}/c$



3D L16
$f_{e,Vx}(E)$
$f_{e,Vy}(E)$
$f_{e,Vz}(E)$
$E\ /\ m_ec^2$
$f_{i,Vx}(E)$
$f_{i,Vy}(E)$
$f_{i,Vz}(E)$
$E\ /\ m_ic^2$

# Conclusions

(i) The fraction of accelerated electrons (along the magnetic field), in the density gradient regions is 20%-35% in 2.5D and 45% in 3D. 75% ions get heated in 3D (in the transverse to **B**-field direction)!

(ii) While keeping the power of injected DAWs the same in all considered numerical simulation runs, in the case of right circular, left and right elliptical polarisation DAWs with $E_y/E_z$=6 produce more pronounced parallel electron beams.

(iii) The parallel electric field for solar flaring plasma parameters exceeds Dreicer electric field by eight orders of magnitude.

(iv) Electron beam velocity has the phase velocity of the DAW. This can be understood by  Landau damping of DAWs. The mechanism can readily provide electrons with few tens of keV.

(v) In 2.5D case, as we increased the mass ratio from $m_i/m_e$=16 to 73.44 the fraction of accelerated electrons has increased from 20% to 30-35% (depending on DAW polarisation).

This is because the velocity of the beam has shifted to lower velocity. Since there are always more electrons with a smaller velocity than higher velocity in the Maxwellian distribution, for the mass ratio $m_i/m_e$=1836 the fraction of accelerated electrons would be even higher than 35%.

cf. Tsiklauri D., Phys. Plasmas 18, 092903 (2011)
Tsiklauri D., Phys. Plasmas (2012) in preparation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