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# Electron acceleration during 3D relaxation of electron beam-return current plasma system in magnetic field

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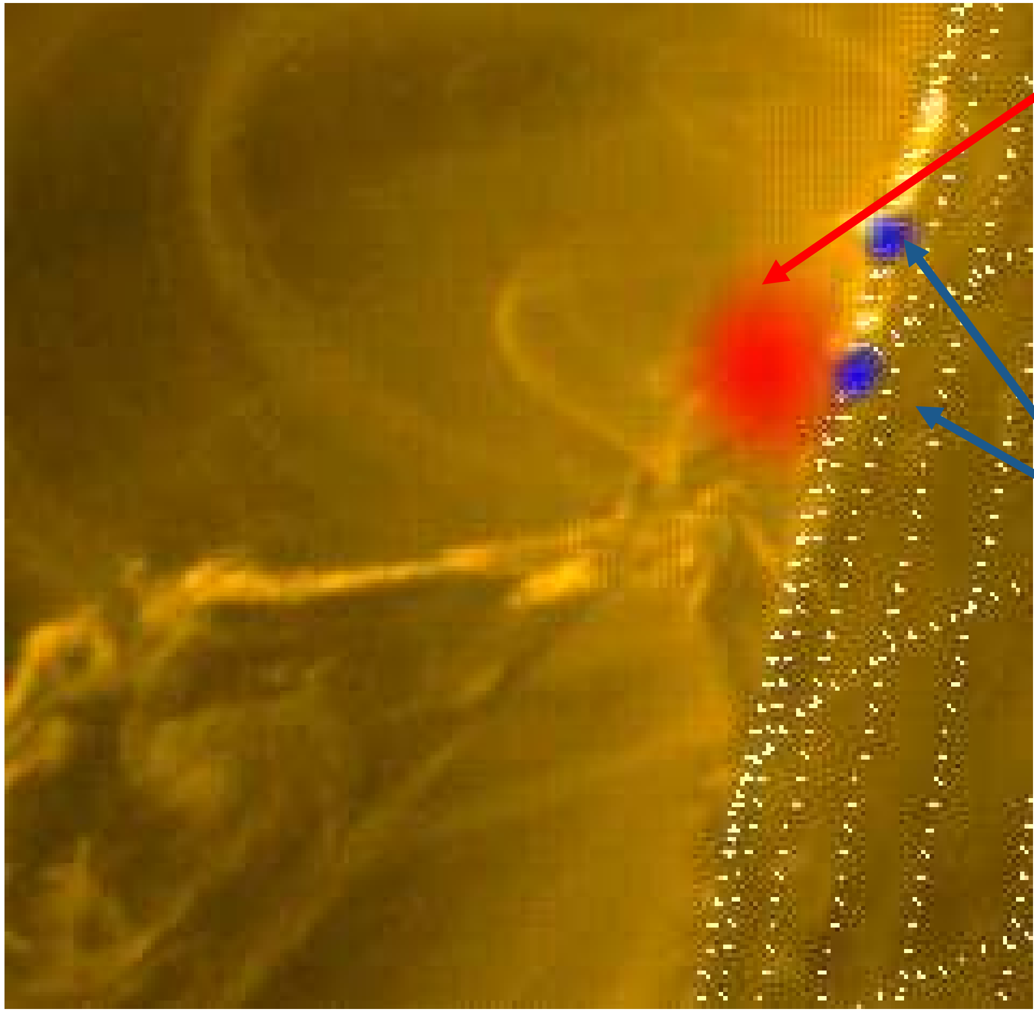
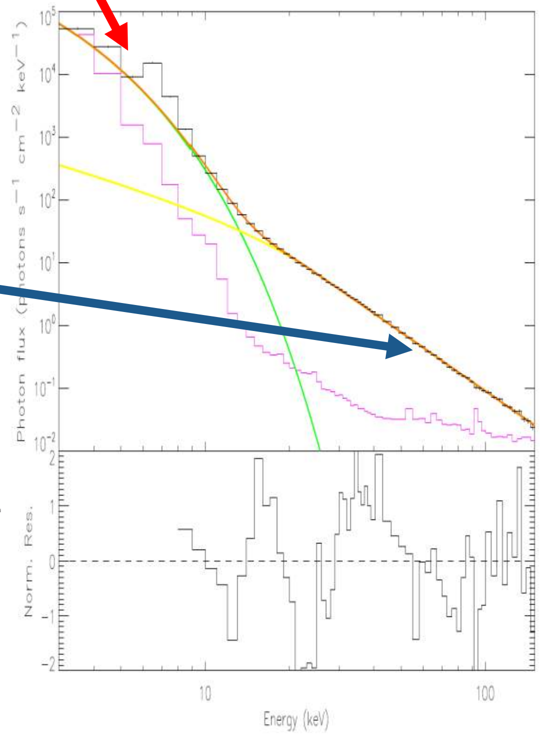
# Standard fare geometry

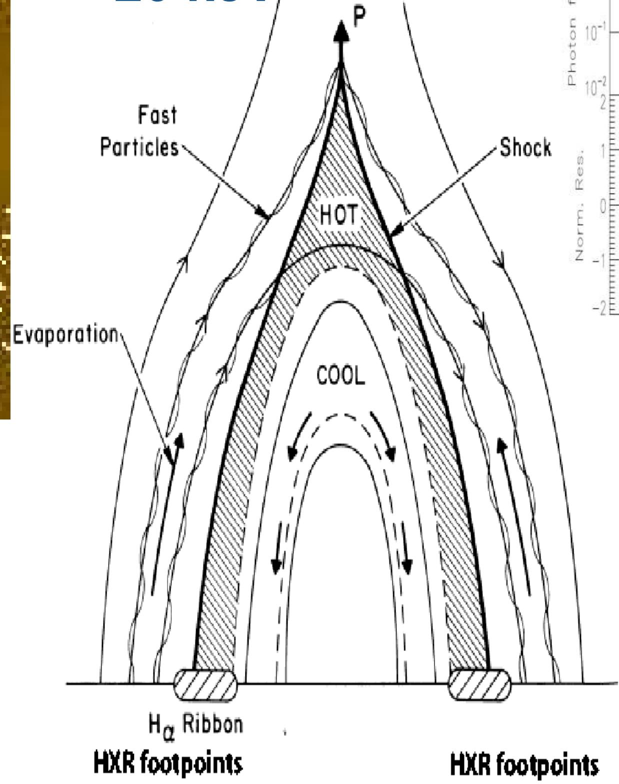


Battaglia and Kontar, 2011

Soft X-ray emission up to ~10 - 20 keV

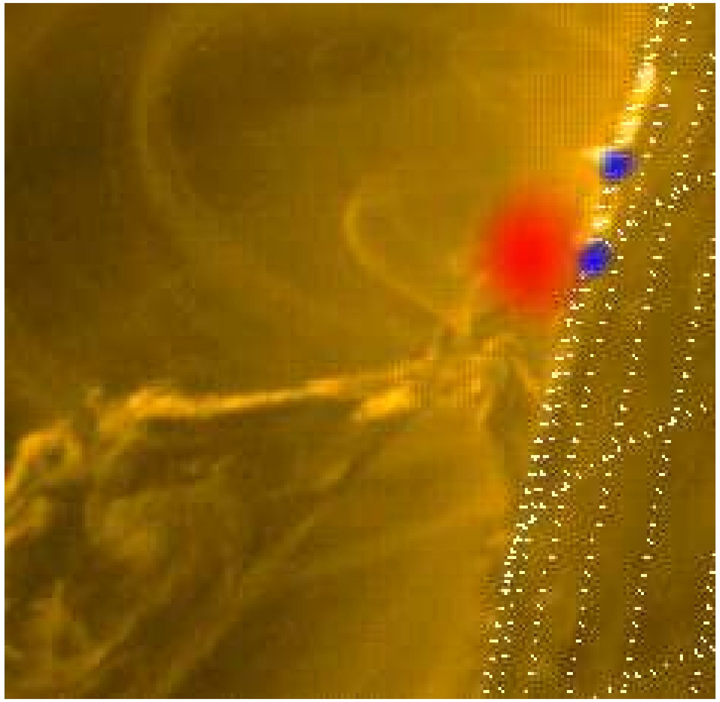
**Hard X-ray sources above ~20 keV**




‘Standard’ flare model picture in 2D (Shibata, 1996)

# Langmuir waves and HXR spectra



The number of accelerated electrons is determined using collisional thick-target approximation.

**Flaring region T ~ $4\times10^7$ K => 3 keV per particle**

**Flare volume $10^{27}$ cm$^3$ => $(10^4$ km$)^3$**

**Plasma density $10^{10}$ cm$^{-3}$**

**Number of energetic electrons $10^{36}$ per second**

=> Large efficiency of electron acceleration

## What is the role of Langmuir waves on electron transport and observed Hard X-ray flux spectrum?

# Langmuir waves and HXR spectra

**What is the role of Langmuir waves in X-ray spectra on collisional scales?**

Previous work: Emslie&Smith. 1984; Petrosian et al, 1987; McClemets 1987; Hannah et al, 2009…..

Langmuir waves are dominant for transport when the electrons are accelerated in bunches (time dependent acceleration)
=> Various effects (e.g. Hannah et al 2009)

Almost do not influence HXR spectrum for a continuous/constant injection of electrons.

**The role of non-uniform plasma?**

**Kontar, Ratcliffe & Bian, 2011 considered three cases:**

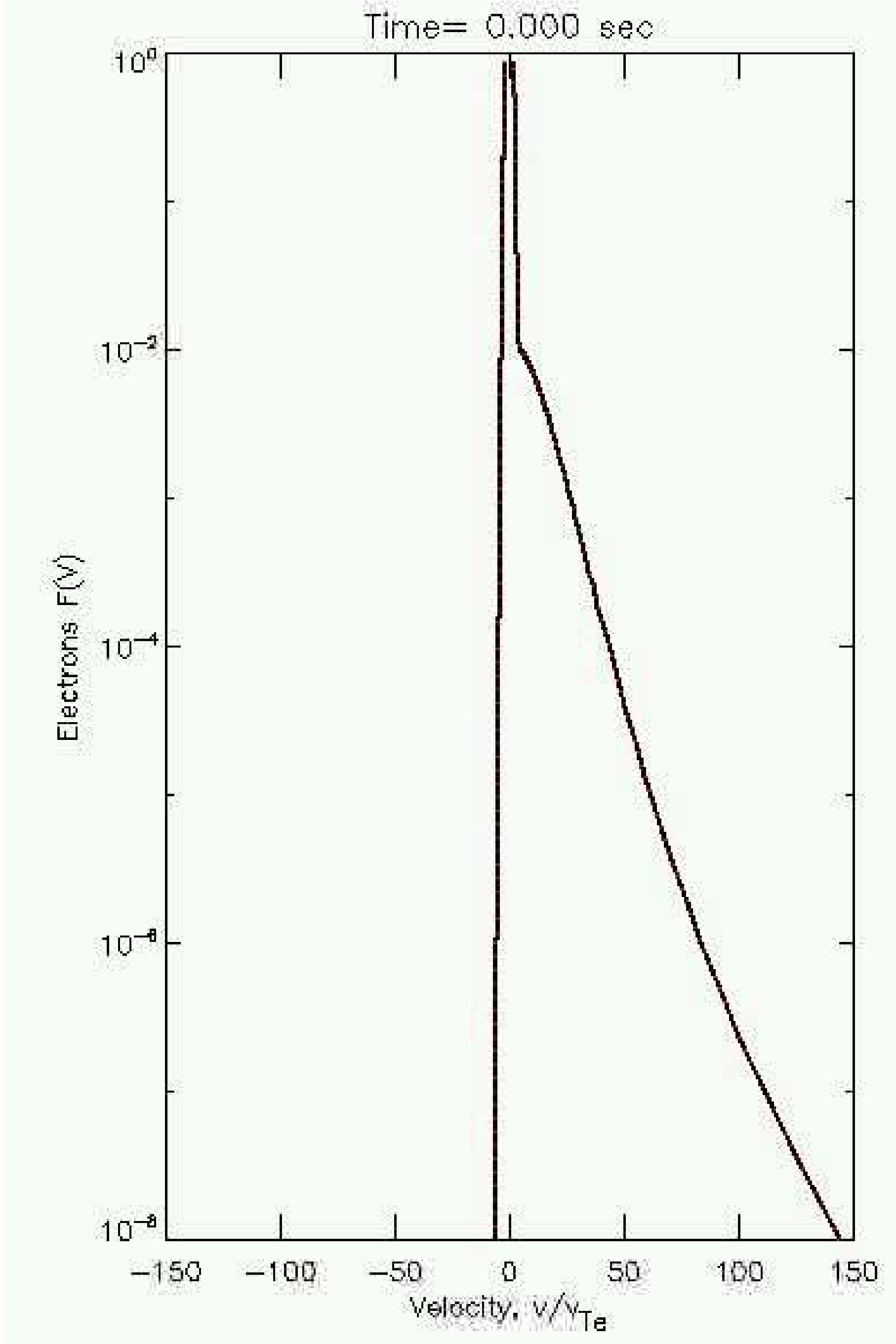
a) **Constant density gradient**
b) **Long wavelength random density fluctuations**
c) **Three-wave coupling/scattering**

# Collisional relaxation of a beam

Consider the temporal evolution of energetic electrons from a power-law distribution:

$$\frac{df}{dt} = \gamma_{ei}\frac{\partial}{\partial v}\left(\frac{f}{v^2} + \frac{v_{Te}^2}{v^3}\frac{\partial f}{\partial v}\right)$$

Then the electron distribution function integrated over the whole time is an equivalent to '*mean electron flux*'



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# Inhomogeneous plasma

Consider the temporal evolution of energetic electrons from a power-law distribution including Langmuir waves, and *density inhomogeneity*:

$$\frac{df}{dt} = \frac{4\pi^2 e^2}{m^2}\frac{\partial}{\partial v}\frac{W}{v}\frac{\partial f}{\partial v} + \gamma_{ei}\frac{\partial}{\partial v}\left(\frac{f}{v^2} + \frac{v_{Te}^2}{v^3}\frac{\partial f}{\partial v}\right)$$

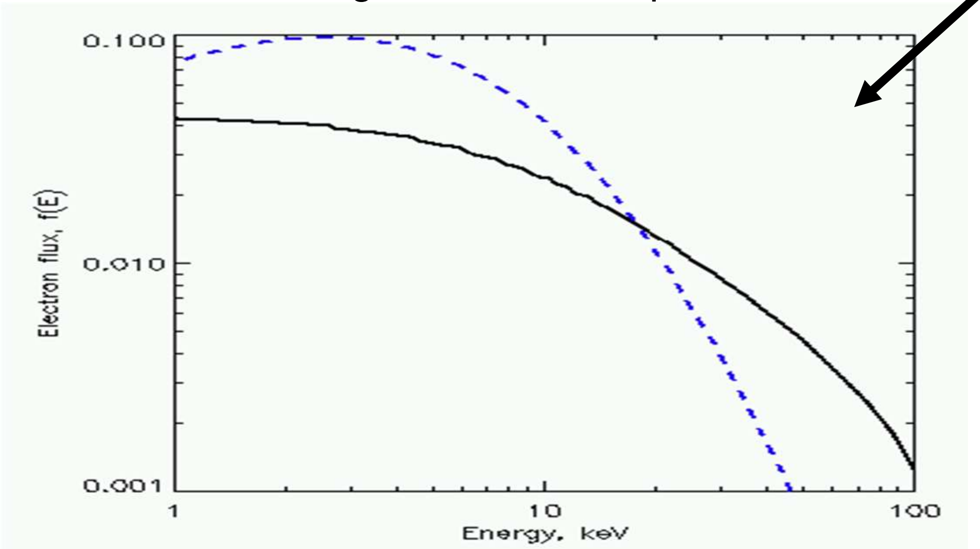
$$\frac{\partial W}{\partial t} - \frac{\partial \omega_{pe}}{\partial r}\frac{\partial W}{\partial k} = \frac{\pi \omega_{pe}}{n} v^2 W \frac{\partial f}{\partial v} - \gamma_c W + e^2 \omega_{pe} v f \log \frac{v}{v_{Te}}$$

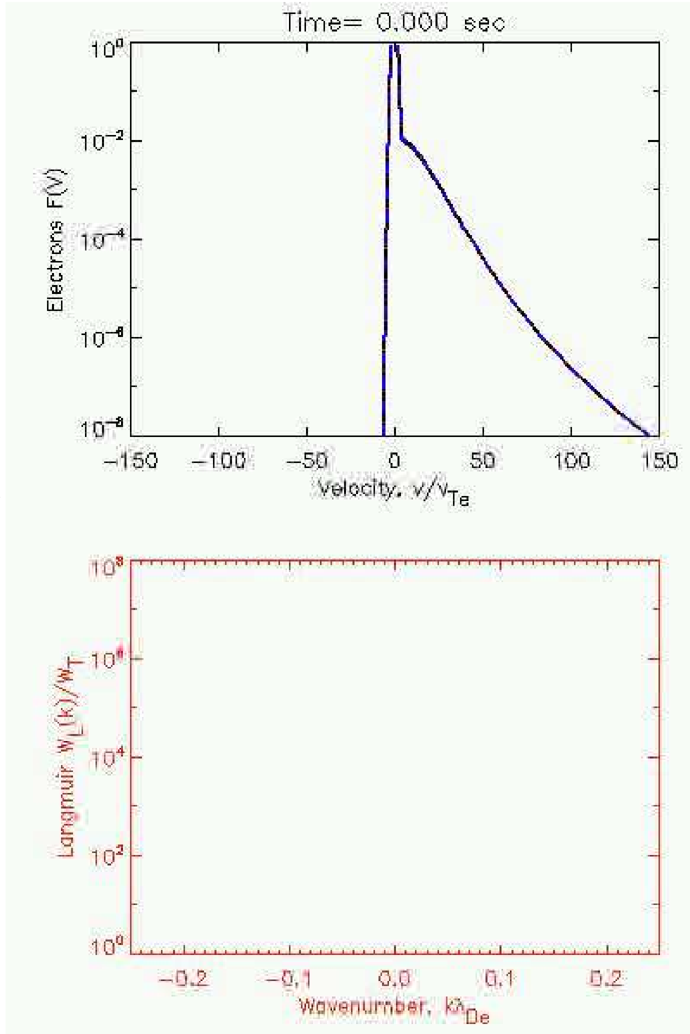
Collisions

Beam-plasma interaction

Density gradient (growing plasma density)

Time integrated electron spectrum



# Ion-sound turbulence

Consider the temporal evolution of energetic electrons from a power-law distribution including Langmuir waves, *density fluctuations* due to ion-sound waves:

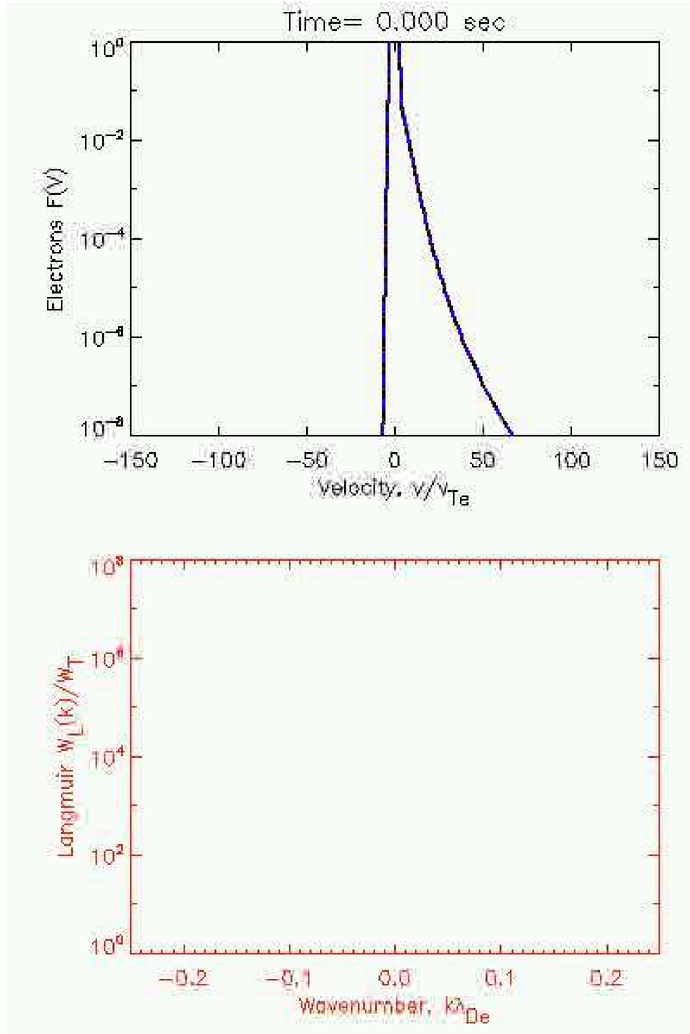
3-wave resonant scattering

$$\frac{df}{dt} = \frac{4\pi^2 e^2}{m^2}\frac{\partial}{\partial v}\frac{W}{v}\frac{\partial f}{\partial v} + \gamma_{ei}\frac{\partial}{\partial v}\left(\frac{f}{v^2} + \frac{v_{Te}^2}{v^3}\frac{\partial f}{\partial v}\right)$$

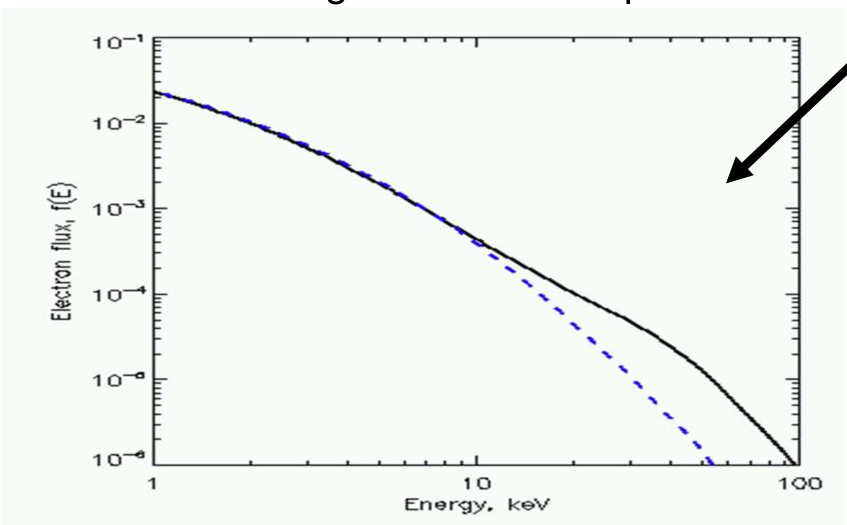
$$\frac{\partial W}{\partial t} = \frac{\pi\omega_{pe}}{n}v^2 W\frac{\partial f}{\partial v} - \gamma_c W + Sf(v) + St(W,W).$$

Collisions

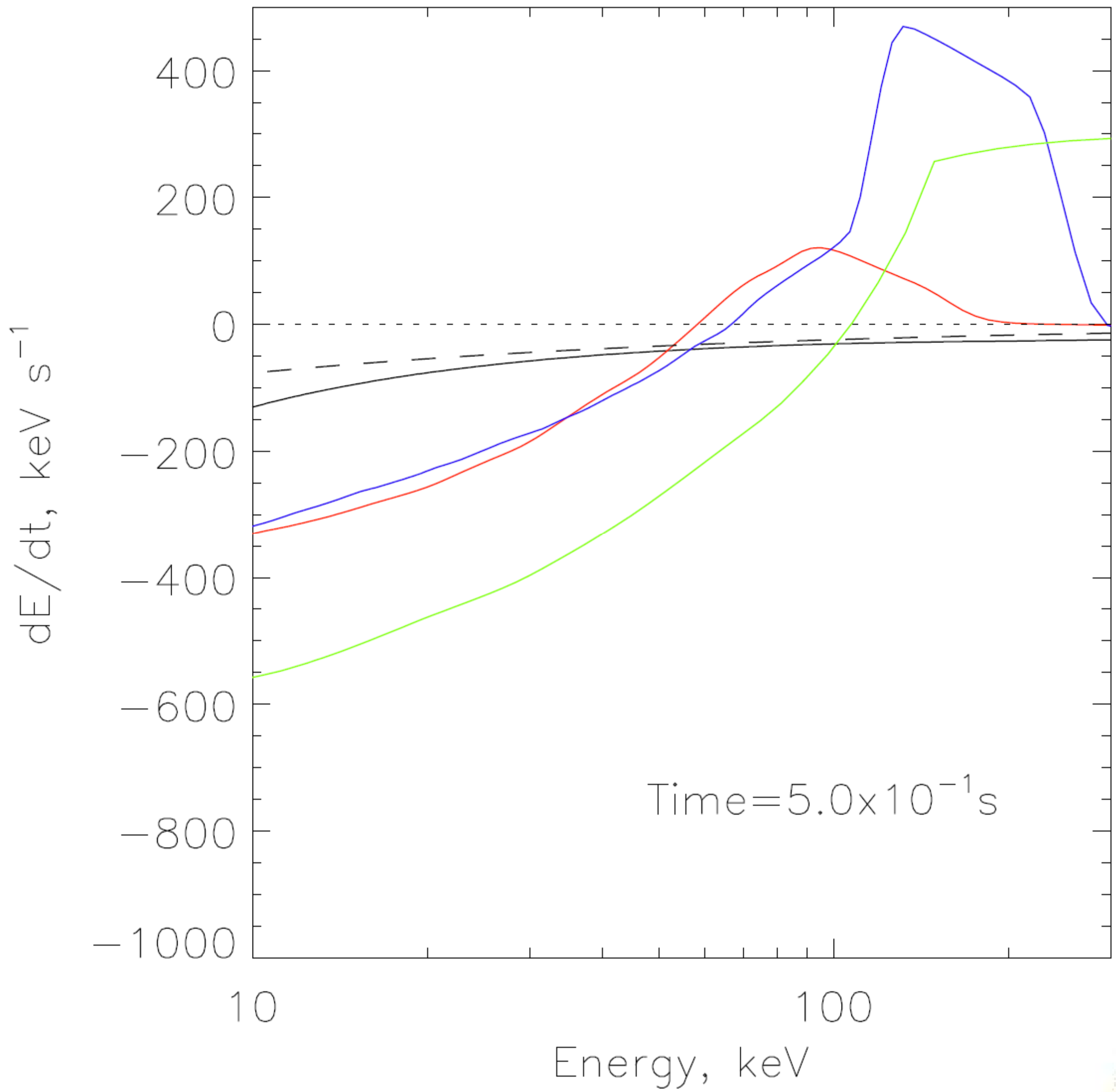
Beam-plasma interaction




Time integrated electron spectrum



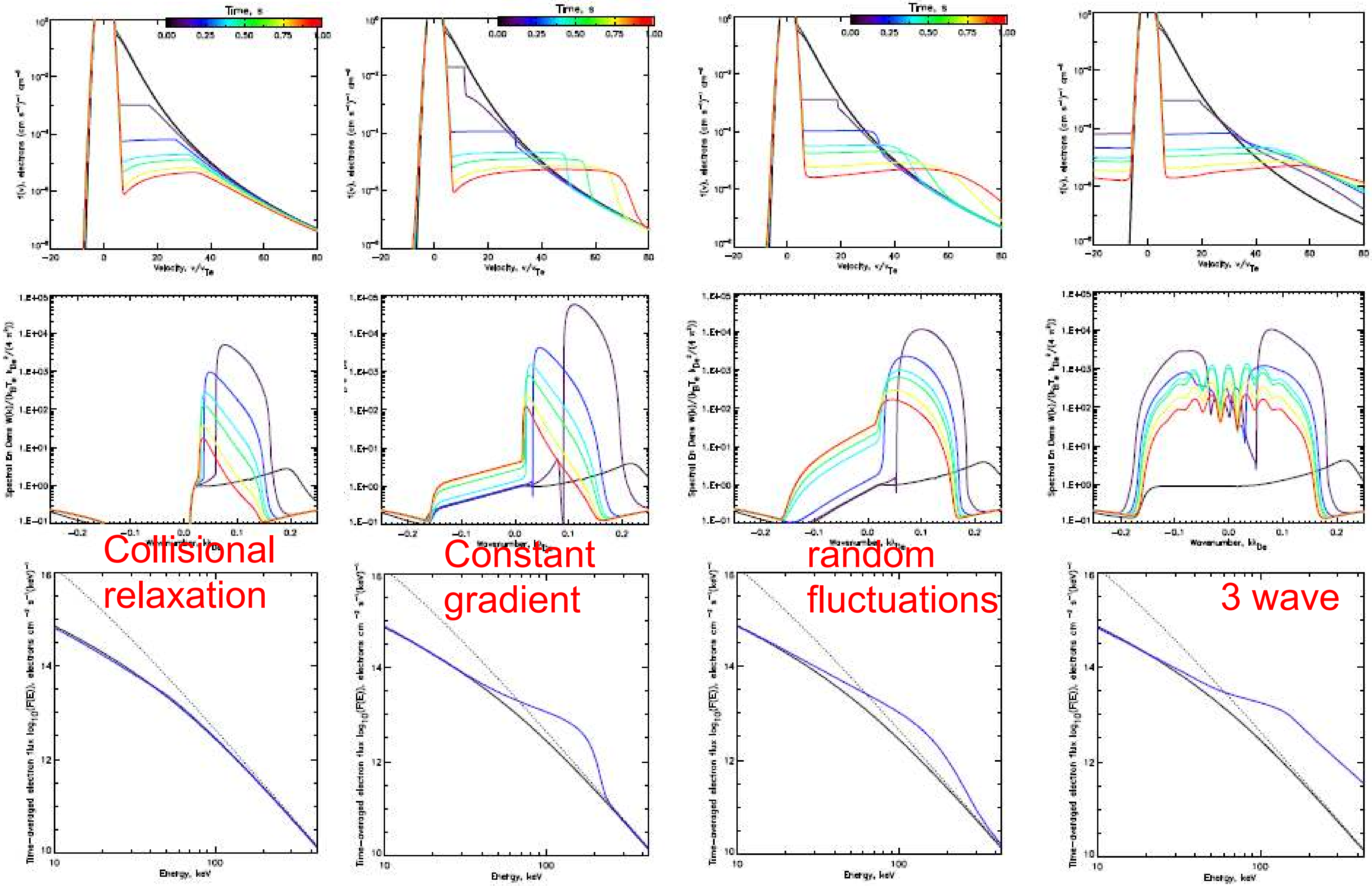
# Effective energy loss rate



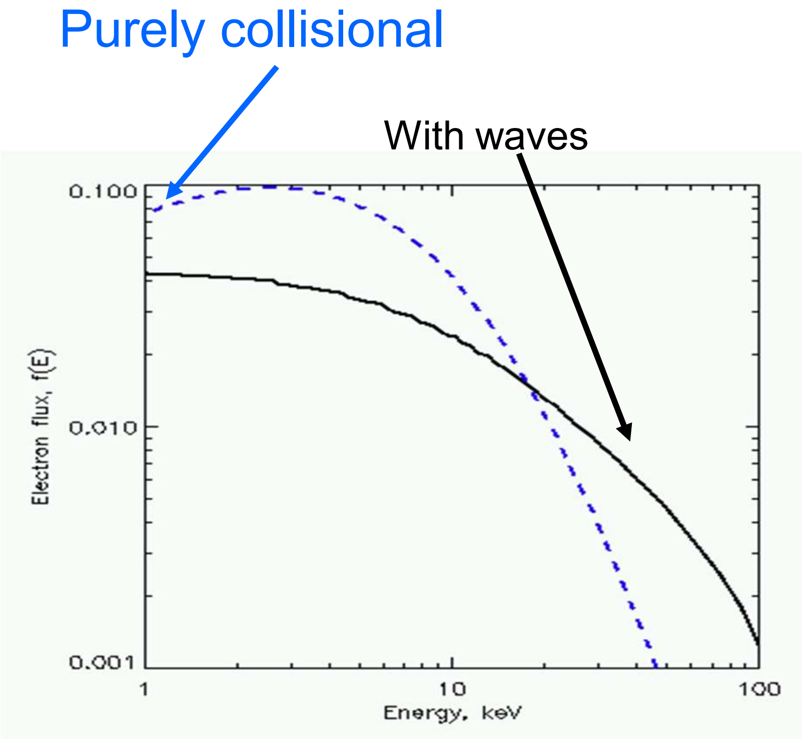

The effective energy loss rate of an electron

$$\frac{\partial f(E,t)}{\partial t} + \frac{\partial}{\partial E}\left(\langle\frac{dE}{dt}\rangle_{eff} f(E,t)\right) = 0$$

# Conclusions I



# Conclusions II




**When density gradient or resonant scattering is taken into account the energy of Langmuir waves is effectively transferred to larger phase velocities (larger electron velocities)**

**The time integrated spectrum (*mean flux spectrum*) in deka-kev range is enhanced by a factor of 5-30.**

**Interpretation of such mean electron spectrum using collisional thick target model will lead to over-estimation of the number of energetic electrons.**

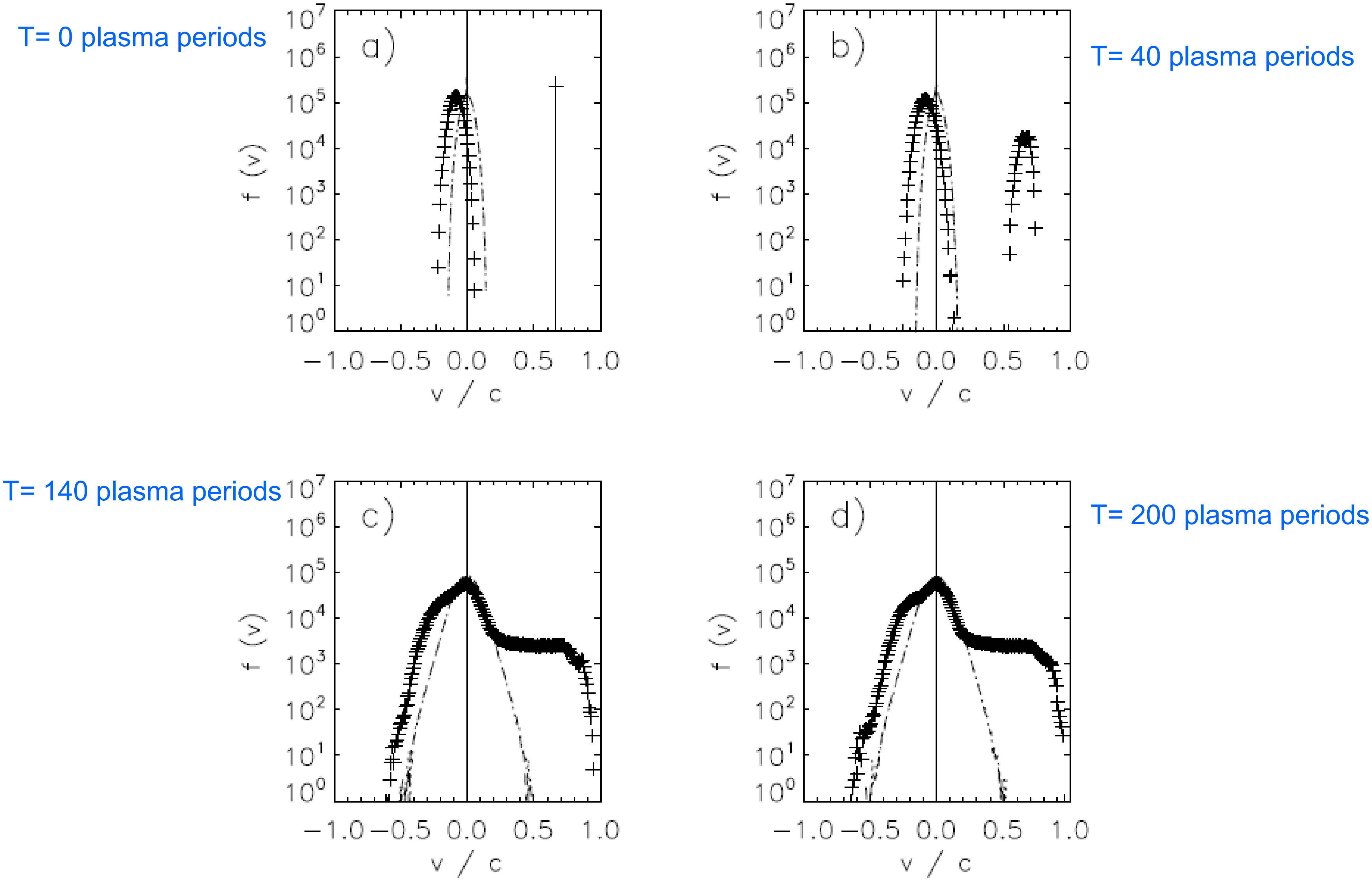
# PIC 3D relaxation of the beam

Motivation:
What is the role of the guiding magnetic field as well as 3D aspects of beam-plasma interaction ?

| Model | $m_i/m_e$ | $n_b/n_e$ | $v_b/c$ | $\omega_{ce}/\omega_{pe}$ |
|---|---|---|---|---|
| A | 16 | 1/8 | 0.666 | 0.0 |
| B | 16 | 1/8 | 0.666 | 0.1 |
| C | 16 | 1/8 | 0.666 | 0.5 |
| D | 16 | 1/8 | 0.666 | 0.7 |
| E | 16 | 1/8 | 0.666 | 1.0 |
| F | 16 | 1/8 | 0.666 | 1.3 |
| G | 16 | 1/40 | 0.666 | 0.0 |
| H | 16 | 1/40 | 0.666 | 1.0 |

Karlicky & Kontar, 2012 submitted

# Relaxation of the beam




Karlicky & Kontar, 2012 submitted

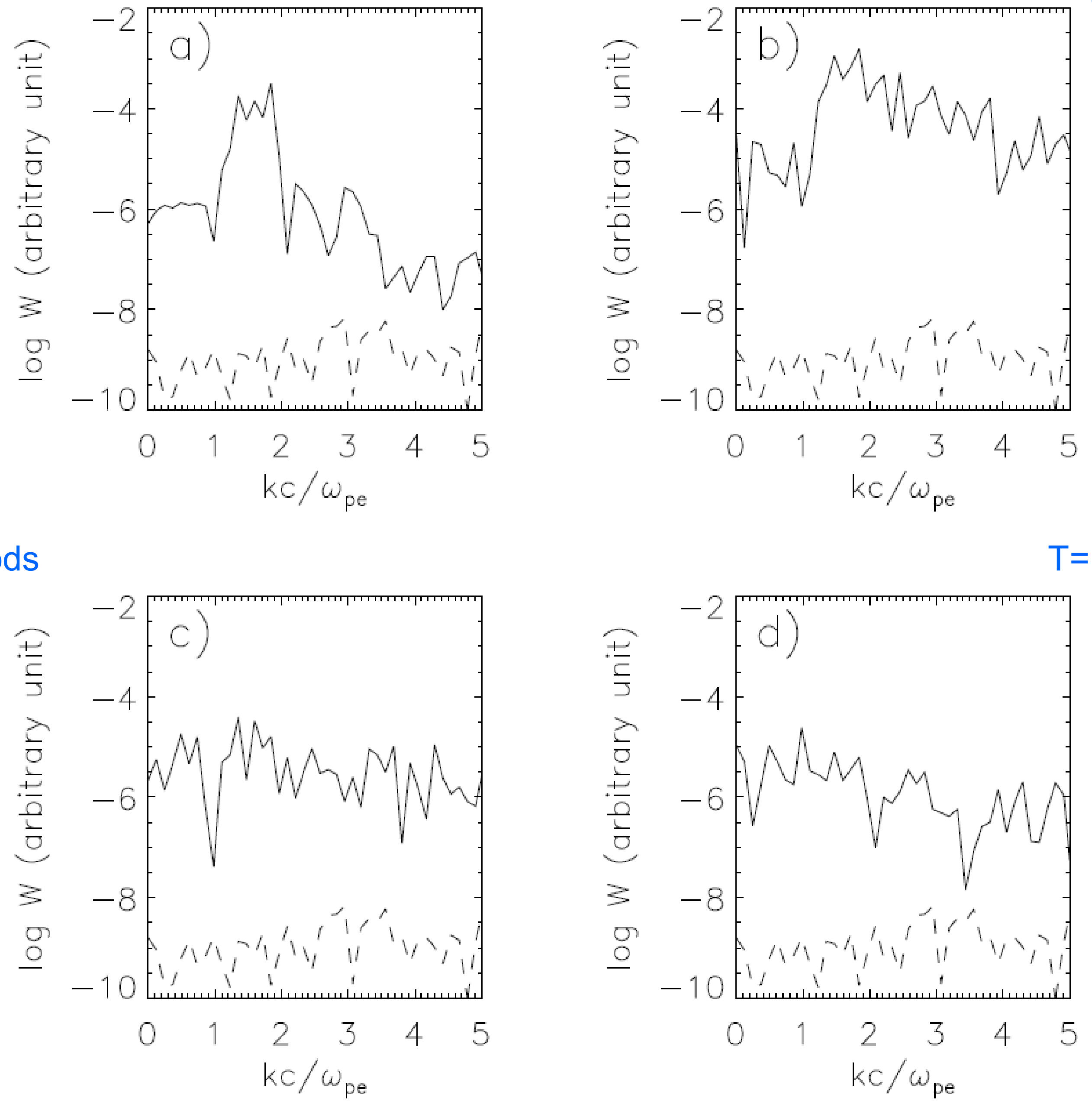
# Langmuir wave evolution

T= 0 plasma periods

T= 40 plasma periods

T= 140 plasma periods

T= 200 plasma periods

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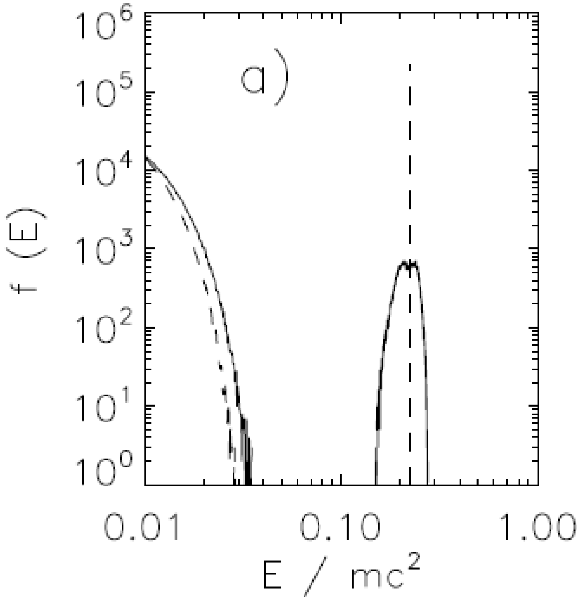
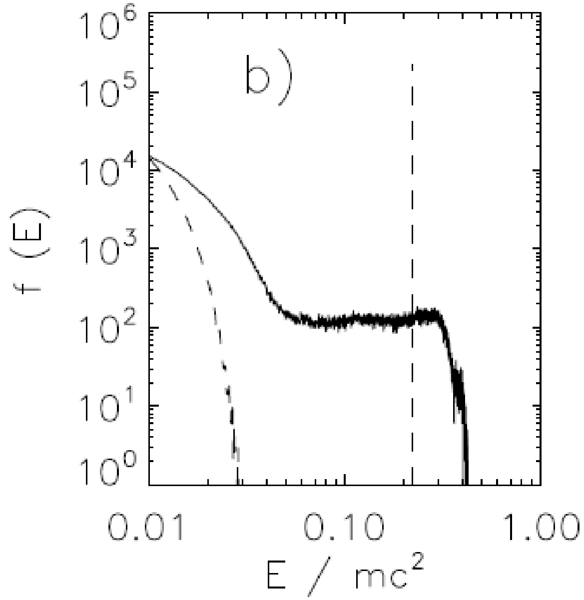
# Energy spectrum

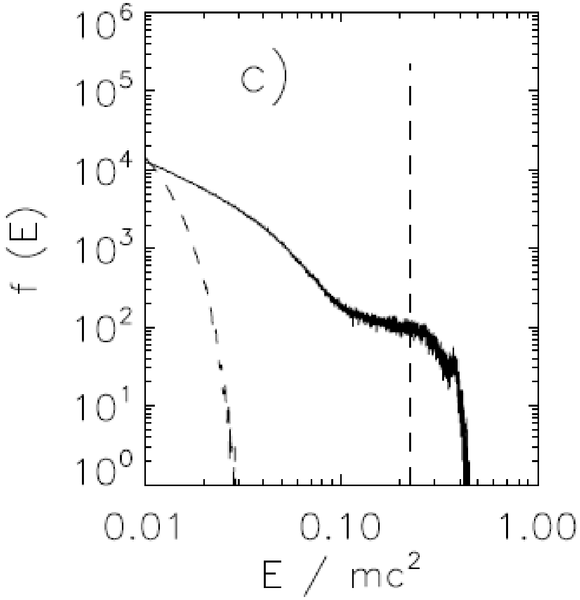
T= 0 plasma periods



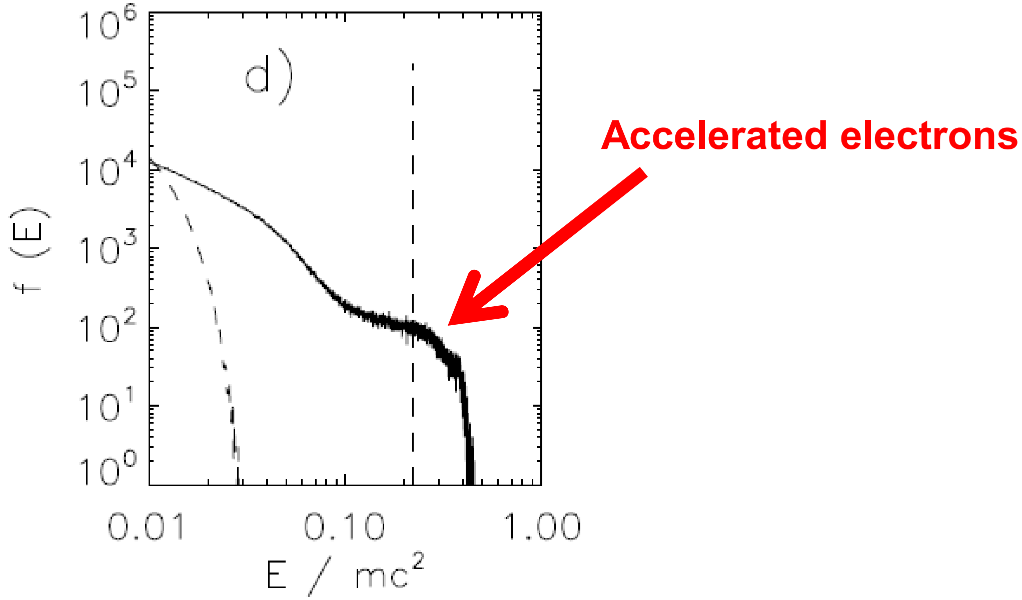

T= 40 plasma periods




T= 140 plasma periods




T= 200 plasma periods

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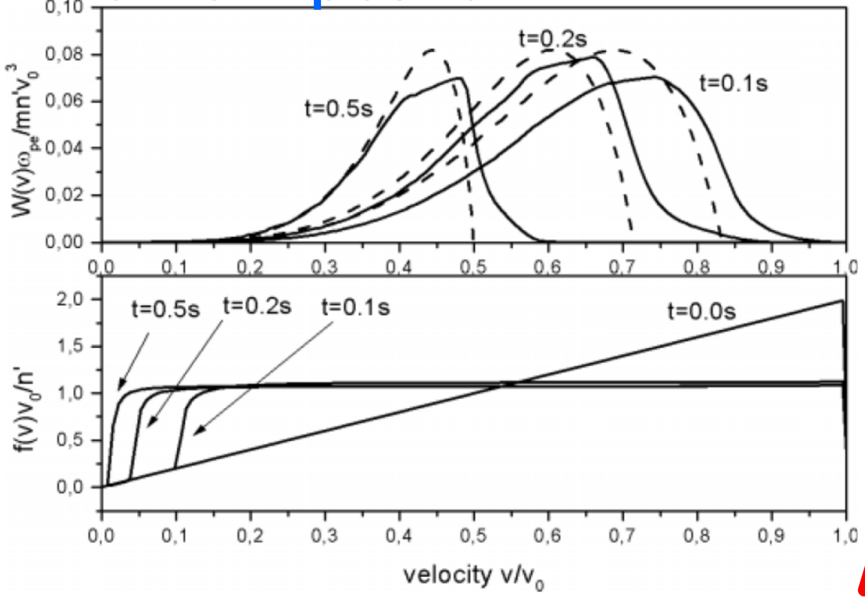
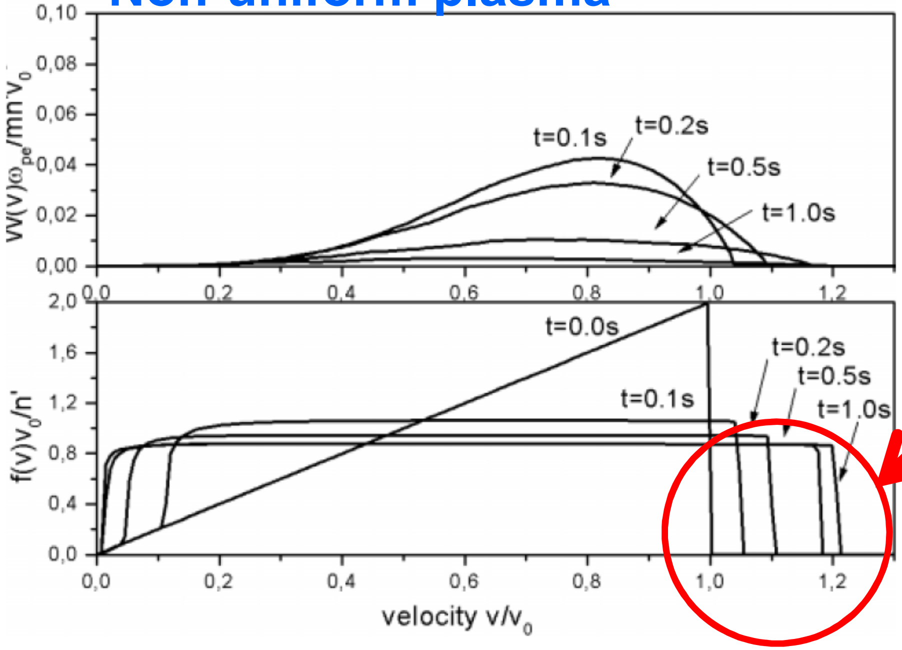
# QL estimates - positive gradient

## uniform plasma




## Non-uniform plasma




$$\frac{\partial f}{\partial t} = \frac{4\pi^2 e^2}{m^2}\frac{\partial}{\partial \mathrm{v}}\left(\frac{W_k}{\mathrm{v}}\frac{\partial f}{\partial \mathrm{v}}\right)$$

$$\frac{\partial W_k}{\partial t} - \frac{\partial \omega_{pe}(x)}{\partial x}\frac{\partial W_k}{\partial k} = \frac{\pi\omega_{pe}^3}{nk^2} W_k \frac{\partial f}{\partial \mathrm{v}}$$

## Initially:

$$g_0(v) = \begin{cases} \dfrac{2n'v}{v_0^2}, & v < v_0, \\ 0, & v > v_0. \end{cases}$$

## Final state:

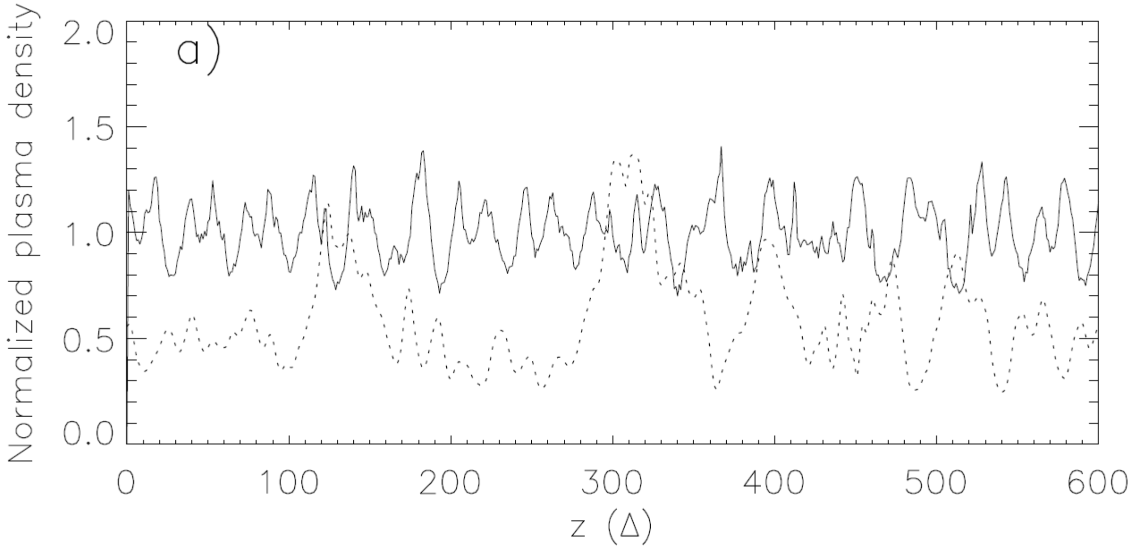
$$f(\mathrm{v}, t \to \infty) = \frac{n_b}{v_{max}}, \quad v < v_{max}, \quad v_{max} = \sqrt{3/2}\, v_b.$$

## Fraction of accelerated electrons:

$$n(\mathrm{v} > \mathrm{v}_b, t \to \infty) = \frac{\sqrt{3/2} - 1}{\sqrt{3/2}} n_b \simeq 0.18 n_b,$$

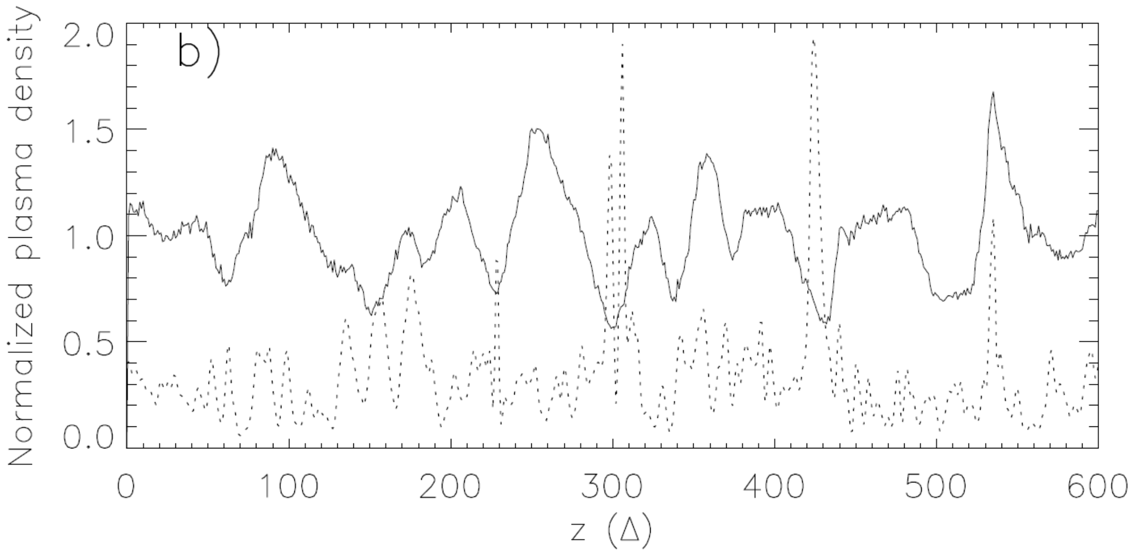
$$U(\mathrm{v} > \mathrm{v}_b, t \to \infty) = \frac{\sqrt{3/2}^3 - 1}{3\sqrt{3/2}} \frac{n_b v_b^2}{2} \simeq 0.22 \frac{n_b v_b^2}{2},$$

# Energy spectrum




Plasma density

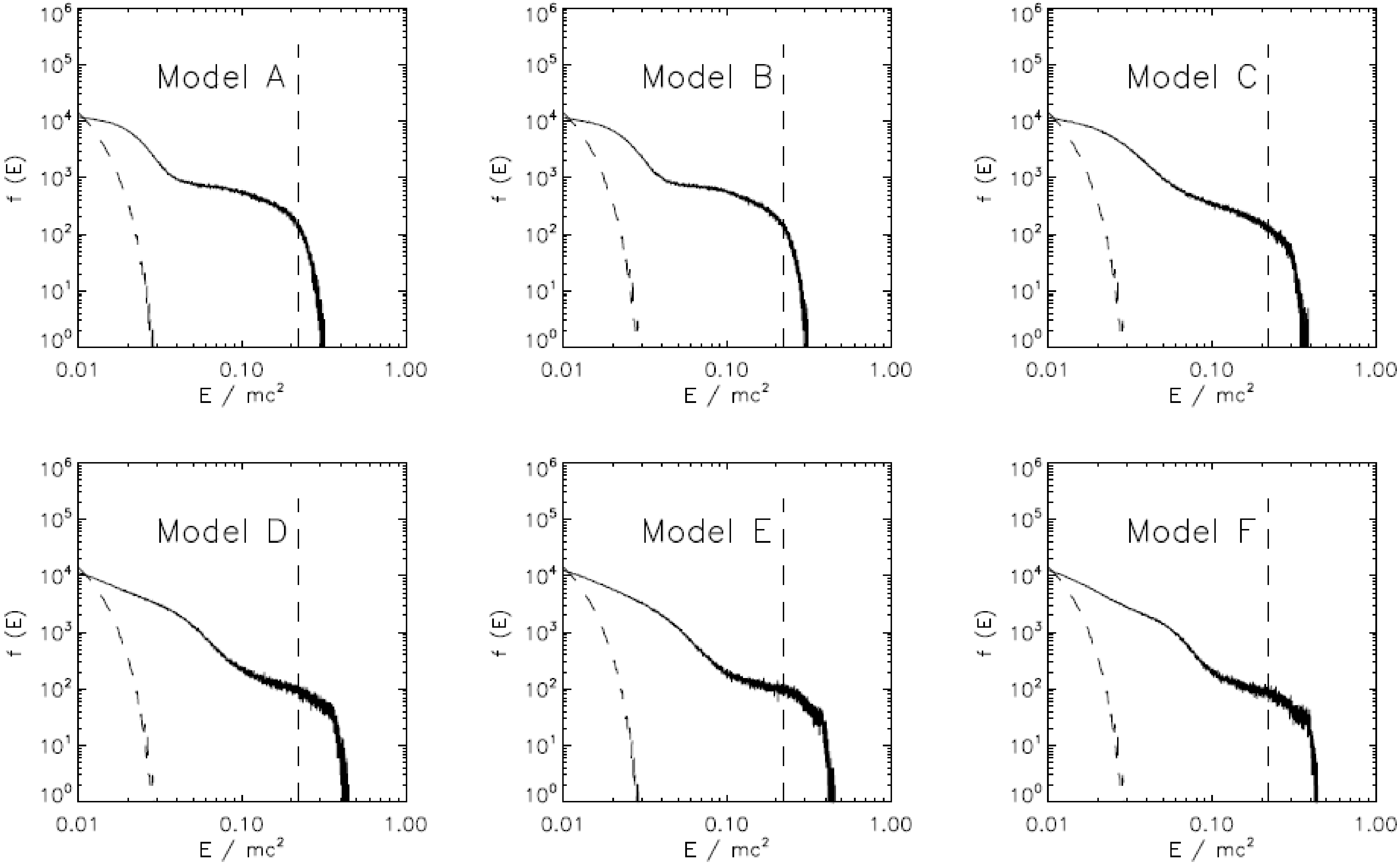
Langmuir wave energy density




Plasma density

Langmuir wave energy density

# Energy spectrum



# Conclusions III

| Model | $m_i/m_e$ | $n_b/n_e$ | $v_b/c$ | $\omega_{ce}/\omega_{pe}$ | FR (%) |
|---|---|---|---|---|---|
| A | 16 | 1/8 | 0.666 | 0.0 | 10 |
| B | 16 | 1/8 | 0.666 | 0.1 | 10 |
| C | 16 | 1/8 | 0.666 | 0.5 | 22 |
| D | 16 | 1/8 | 0.666 | 0.7 | 28 |
| E | 16 | 1/8 | 0.666 | 1.0 | 29 |
| F | 16 | 1/8 | 0.666 | 1.3 | 27 |
| G | 16 | 1/40 | 0.666 | 0.0 | 12 |
| H | 16 | 1/40 | 0.666 | 1.0 | 28 |

**3D PIC simulations suggest the acceleration of electrons during the relaxation phase with FR fraction 10-30 %**

**Increase of magnetic field "helps" by increasing the fraction.**