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Particle-In-Cell simulation of whistler heat flux instabilities: Scattering of the strahl electrons into the halo and heat flux regulation in the near-Sun solar wind

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MOTIVATIONS: OBSERVATIONS OF THE HALO FORMATION AND OF SOLAR WIND HEAT FLUX REGULATION BY INSTABILITIES.

Electron velocity distribution functions (VDFs) in the solar wind often consist of multiple components: an isotropic core, a suprathermal suprathermal halo, a suprathermal field-aligned strahl *(Marsh 2006)*.

The peculiar structure of the electron VDF carries an important amount of heat flux in the solar wind *(Feldman et al. 1975)*.

Recent observations by the Parker Solar Probe (PSP) mission have shown in the inner heliosphere: a low halo fractional density, a more pronounced strahl *(Halekas et al. 2020)*.

While the halo fractional density increases with the heliocentric distance, the strahl fractional density decreases *(Maksimovic et al. 2005)*.

These observations suggest that the formation of the halo population takes place from the pitch-angle scattering of the strahl.

Oblique whistler-mode waves, whose existence in the inner heliosphere has been recently confirmed by PSP observations*(Cattell et al. 2020)*, can explain the scattering of the strahl and the reduction of the solar wind heat flux.

METHOD: 2D FULLY KINETIC SIMULATION MODELING NEAR-SUN SOLAR WIND CONDITIONS.

2D fully kinetic Particle-In-Cell simulation of whistler heat flux instabilities performed with iPIC3D code *(Markidis et al. 2010)*.

A collisionless plasma with an initially uniform background magnetic field has been modeled: the plasma and magnetic field parameters correspond to those measured by Parker Solar Probe during its first perihelion.

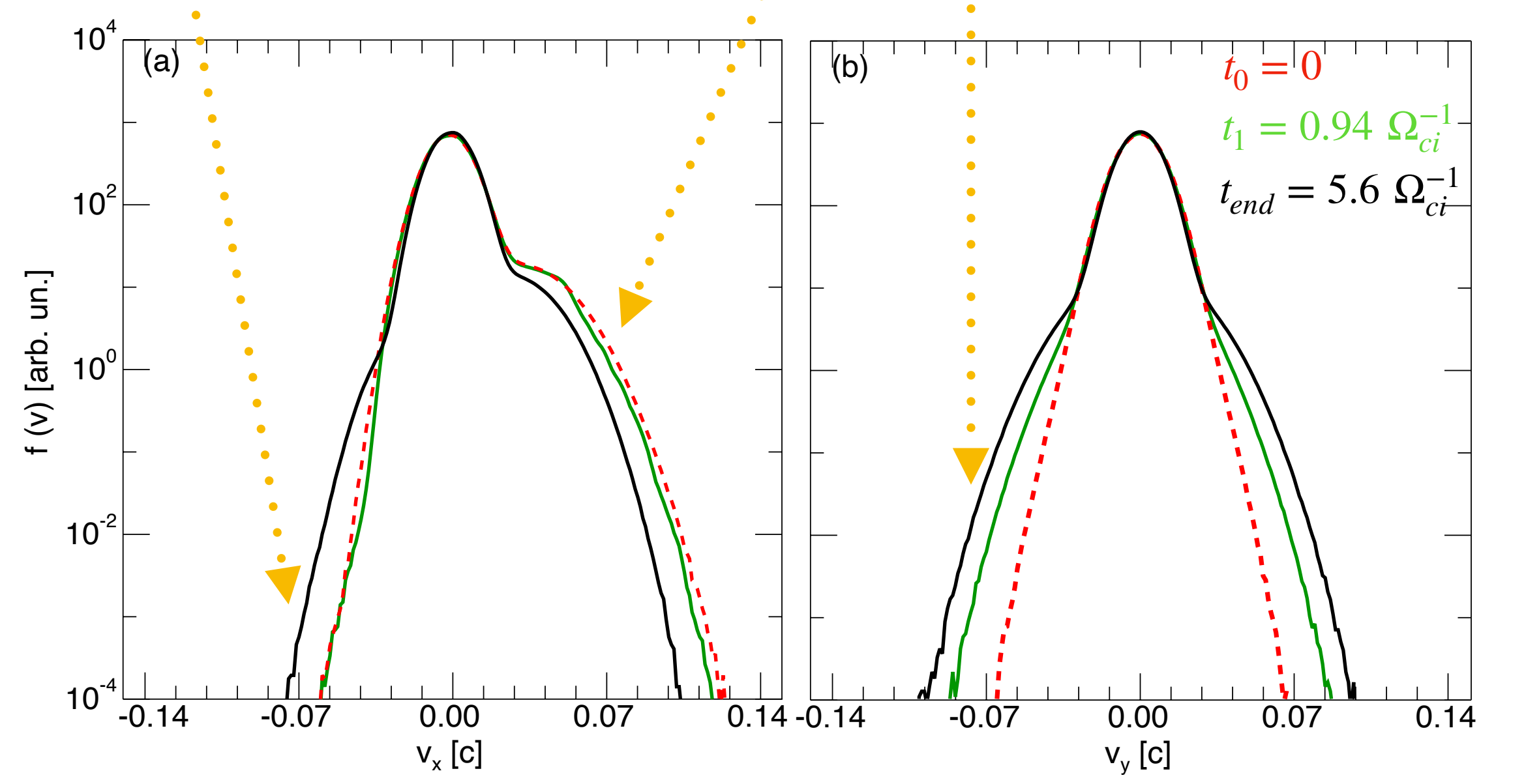
The initial electron VDF is composed of core and strahl populations.

The strahl is modeled as a drifting bi-Maxwellian distribution with a thermal spread in the direction parallel to the magnetic field.

RESULTS: STRAHL PITCH ANGLE SCATTERING AND FORMATION OF HALO ELECTRONS.

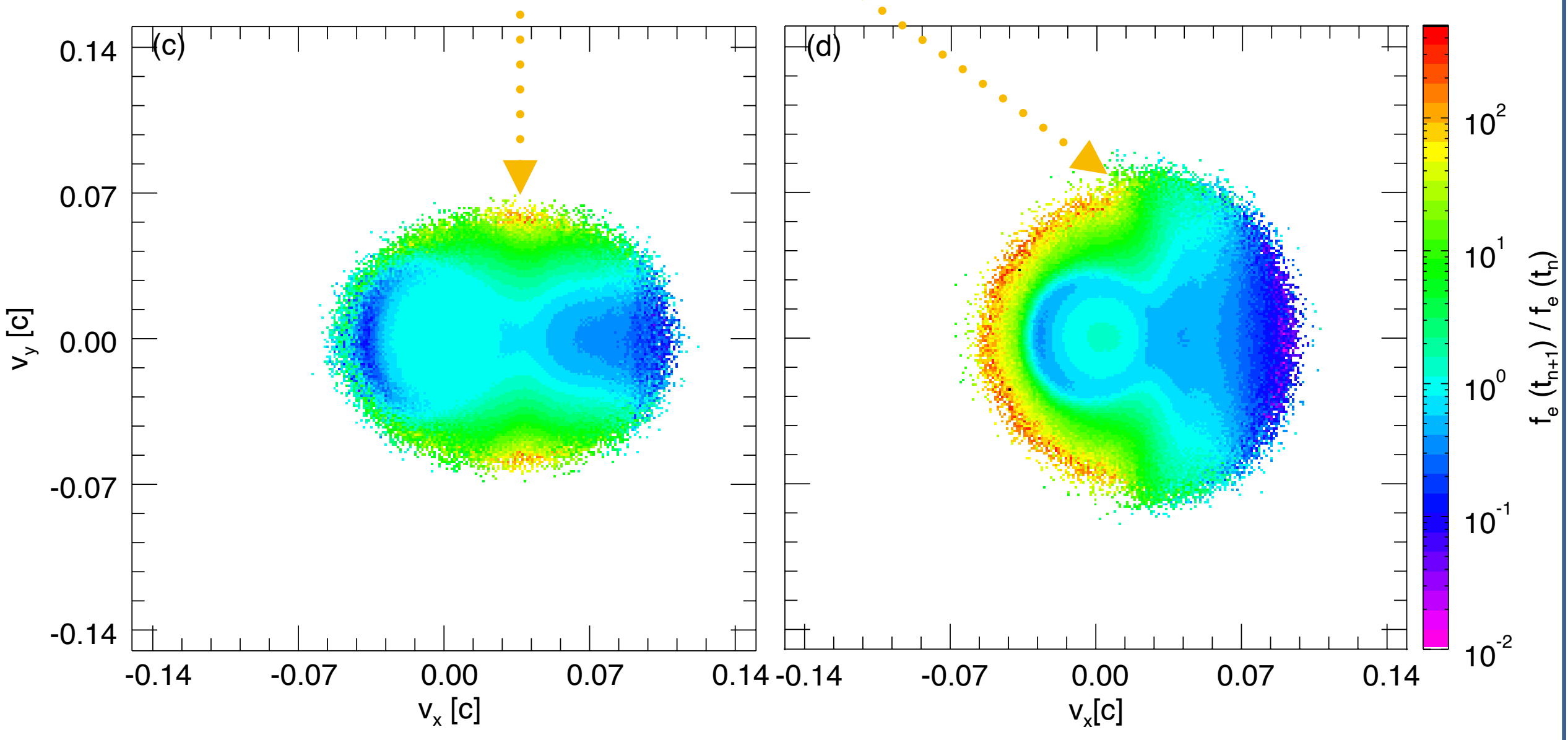
The strahl undergoes pitch-angle scattering by the excited whistler waves, which results in the reduction of the strahl drift velocity and in the simultaneous broadening of the strahl pitch angle distribution.

A further portion of suprathermal electrons undergoes secondary scattering processes, which lead to a consequent relaxation of the strahl drift velocity and to a more isotropic electron VDF.



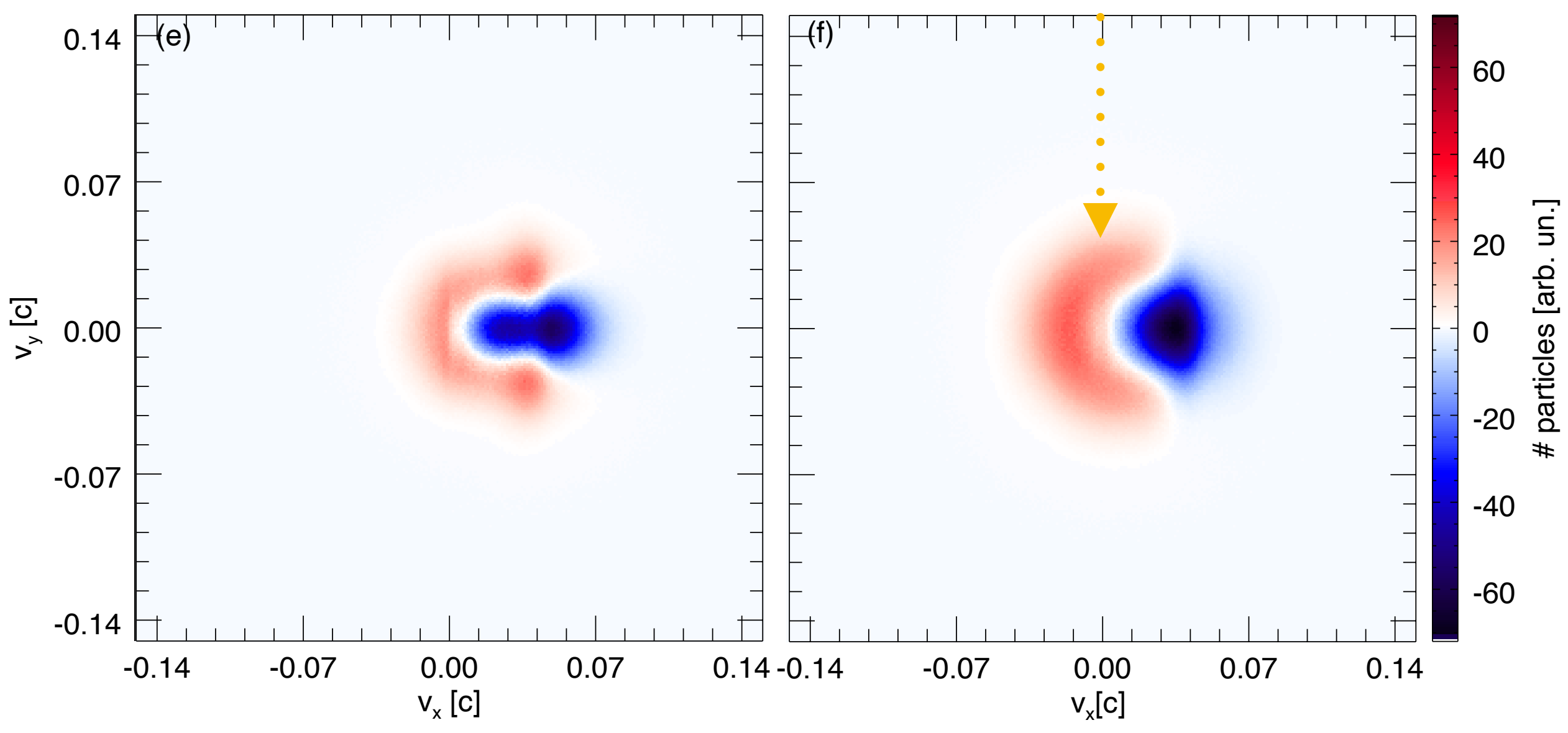
Cuts of the total electron VDFs at different times.

The scatter of the strahl electrons leads to the formation of a new population that can be seen as a halo, which, at higher energies, deviates from the Maxwellian distribution, and whose features are noticeable in the electron VDF from the onset of the oblique whistler heat flux instability (O-WHFI) to the final stages of the simulation.



Temporal variation of the total electron VDF: $f_e(t_2) / f_e(t_0)$ and $f_e(t_{end}) / f_e(t_2)$, with $t_2 = 0.94\ \Omega_{ci\text{-}1}$

Later on, scattering processes lead to the generation of a tail-like structure in the distribution function at $v_x < 0$ and hence of a more symmetric halo, in agreement with observations.

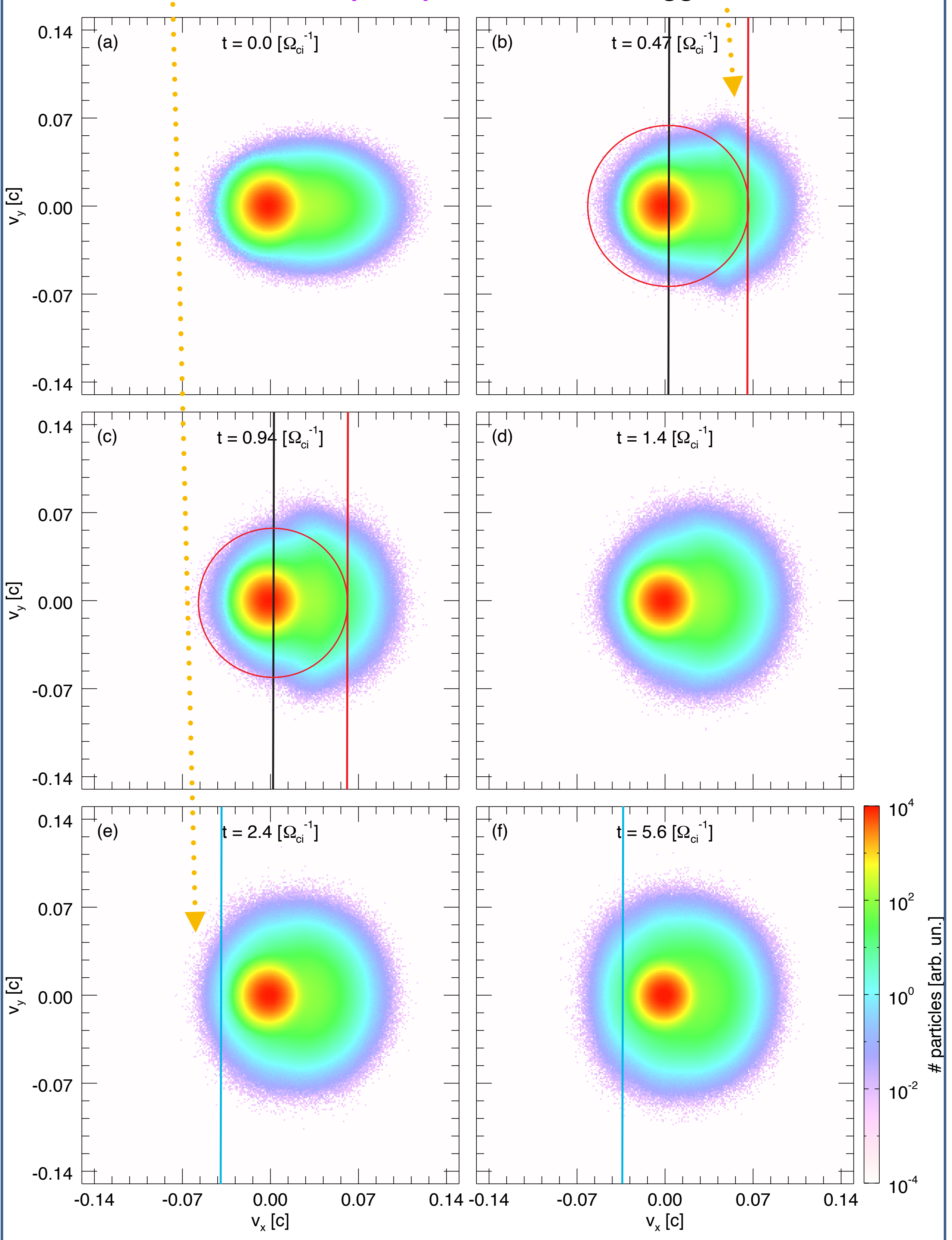


Variation of the strahl distribution function: $f_s(t_2) - f_s(t_0)$ and $f_s(t_{end}) - f_s(t_2)$.

RESULTS: CYCLOTRON AND LANDAU RESONANCES SHAPE THE ELECTRON VDF

The electron population, that fulfills the n=1 resonance condition with the oblique whistler waves, diffuses via pitch-angle scattering towards higher values of perpendicular velocities.

The generation of the tail in the distribution function can be traced back to the n= -1 cyclotron resonance that the electron VDF experiences later in time when there is a sufficient number of electrons with $v_x < 0$ and quasi-parallel WHFI is triggered.

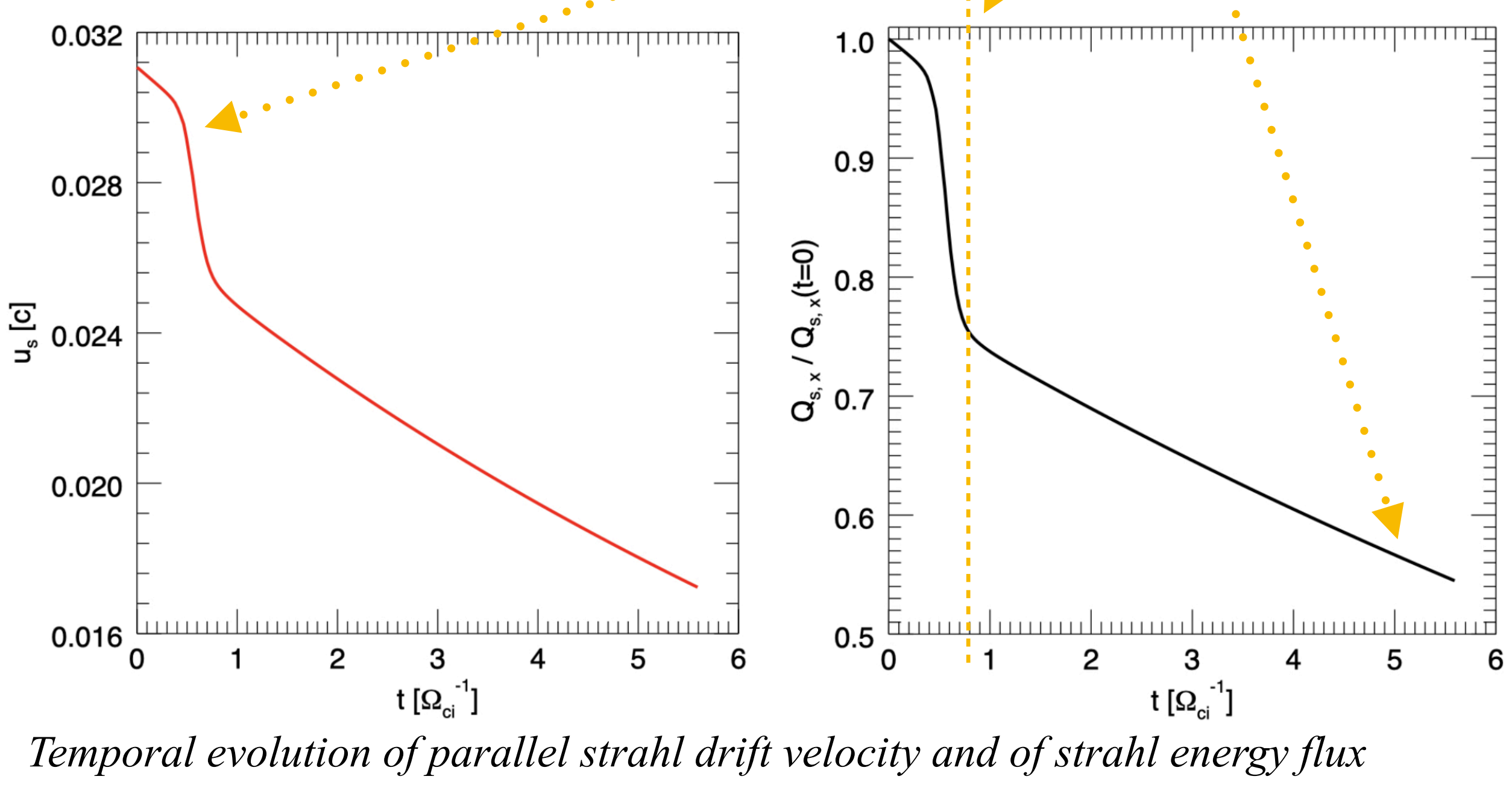


Electron VDF at different times. Black and red vertical lines indicate velocity values at which n=0 and n=1 resonances of oblique whistler waves are expected, while circles show electrons diffusion paths due to the n=1 resonance interaction. Cyan vertical lines in panels indicate velocity values at which n= -1 resonance is expected.

RESULTS: HEAT FLUX REDUCTION AS A CONSEQUENCE OF WHISTLER HEAT FLUX INSTABILITIES

The process is accompanied by a significant decrease of the heat flux carried by the strahl population: The decrease of the heat flux is around 46 % of the initial value.

The strongest heat flux rate decrease is simultaneous with the growth of the oblique wave modes and the consequent decrease of the strahl drift velocity that it produces, and it lasts until their saturation.

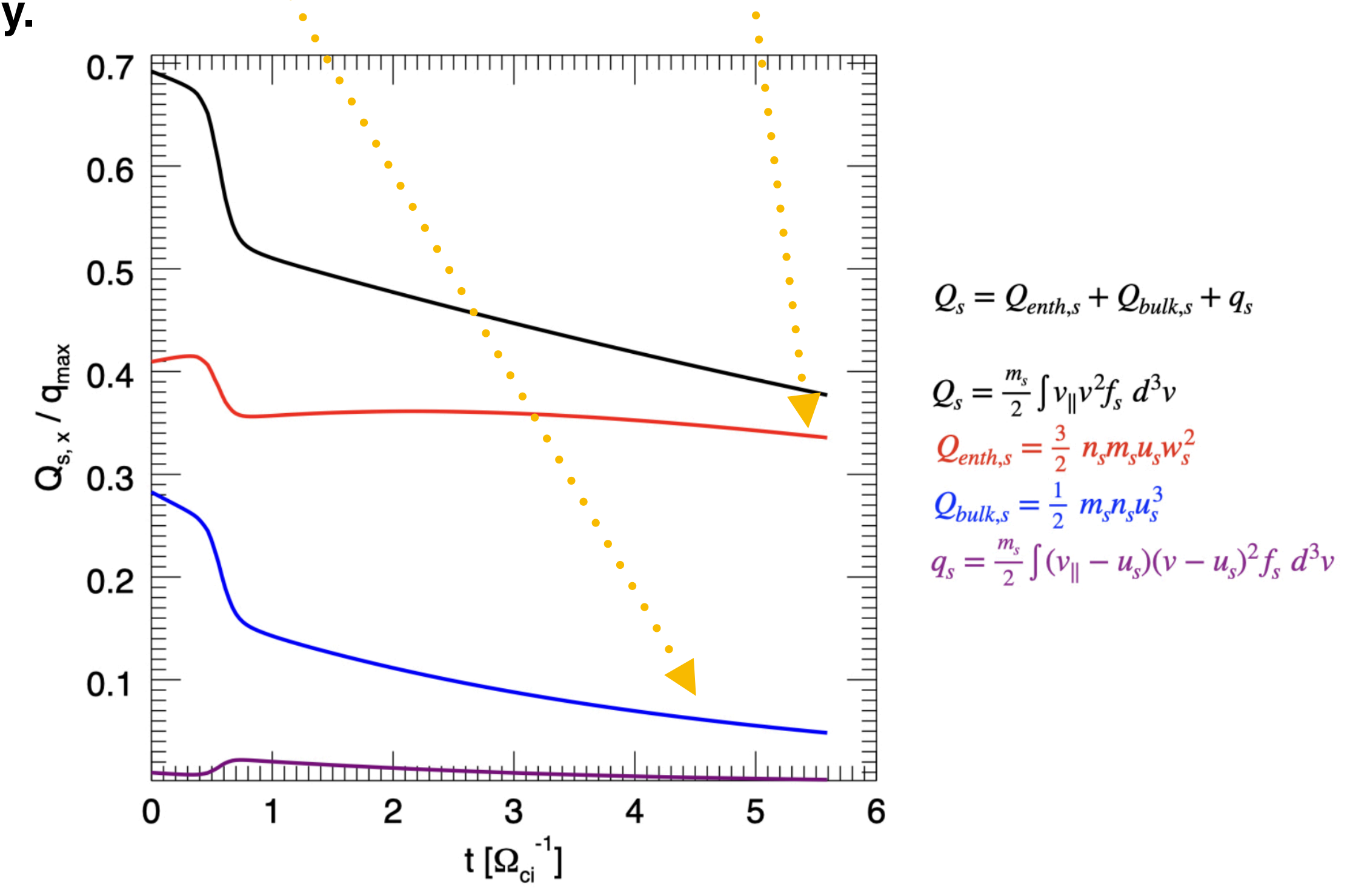


Temporal evolution of parallel strahl drift velocity and of strahl energy flux normalized to its initial value.

After the O-WHFI is already saturated, the plasma is still unstable to the quasi-parallel WHFI and then the heat flux is subject to a further decrease.

The heat flux is mostly carried by the convection of the strahl electron enthalpy.

However, the regulation of the global strahl energy flux along the background magnetic field is essentially produced by the relaxation of the strahl drift velocity rather than by the variation of the thermal velocity.



$$Q_s = Q_{enth,s} + Q_{bulk,s} + q_s$$

$$Q_s = \frac{m_s}{2} \int v_{\|} v^2 f_s \, d^3v$$

$$Q_{enth,s} = \frac{3}{2}\ n_s m_s u_s w_s^2$$

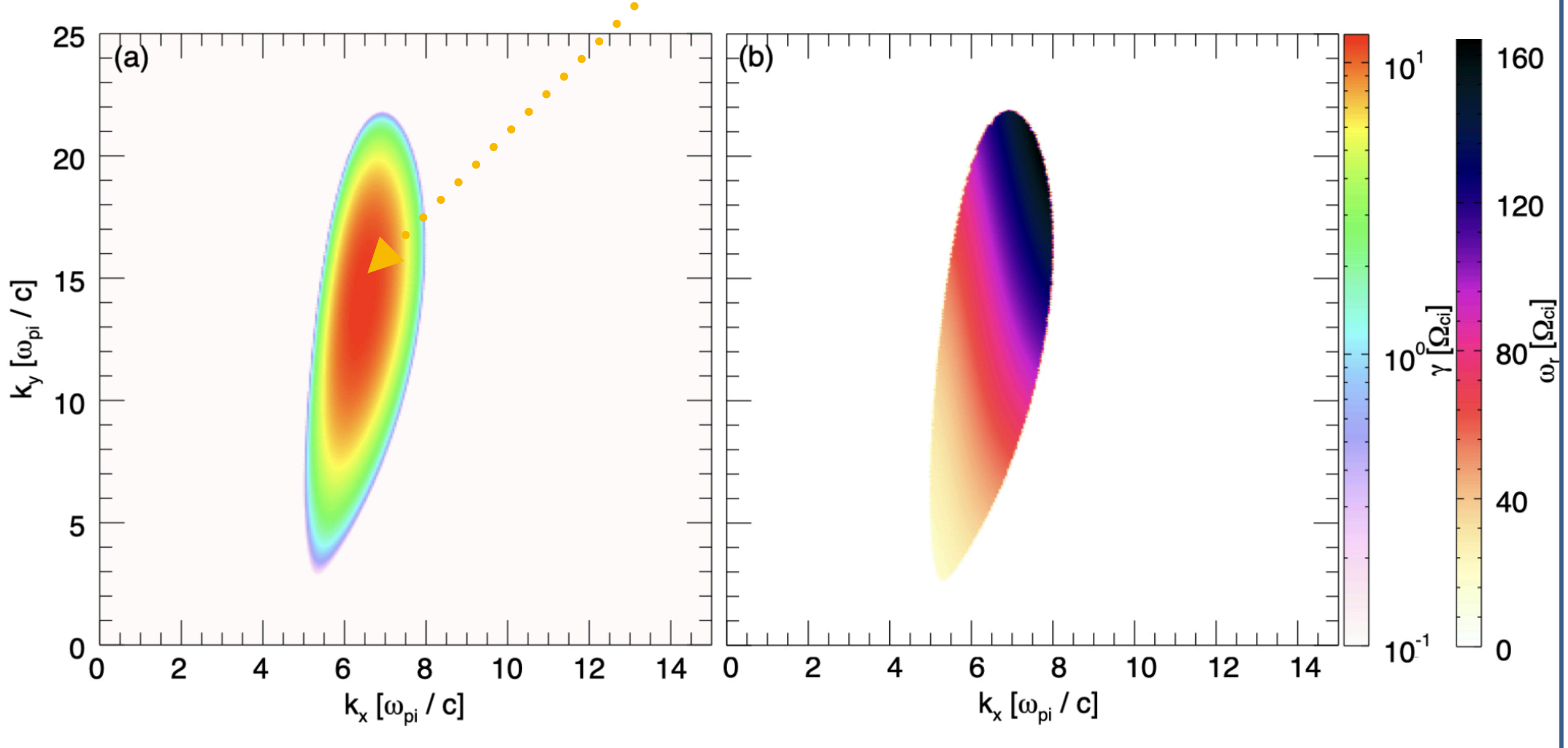
$$Q_{bulk,s} = \frac{1}{2}\ m_s n_s u_s^3$$

$$q_s = \frac{m_s}{2} \int (v_{\|} - u_s)(v - u_s)^2 f_s \, d^3v$$

Energy flux components carried by the electron strahl along the magnetic field direction.

RESULTS: ELECTRONS SCATTERED BY INTERACTIONS WITH WHISTLER-MODE WAVES.

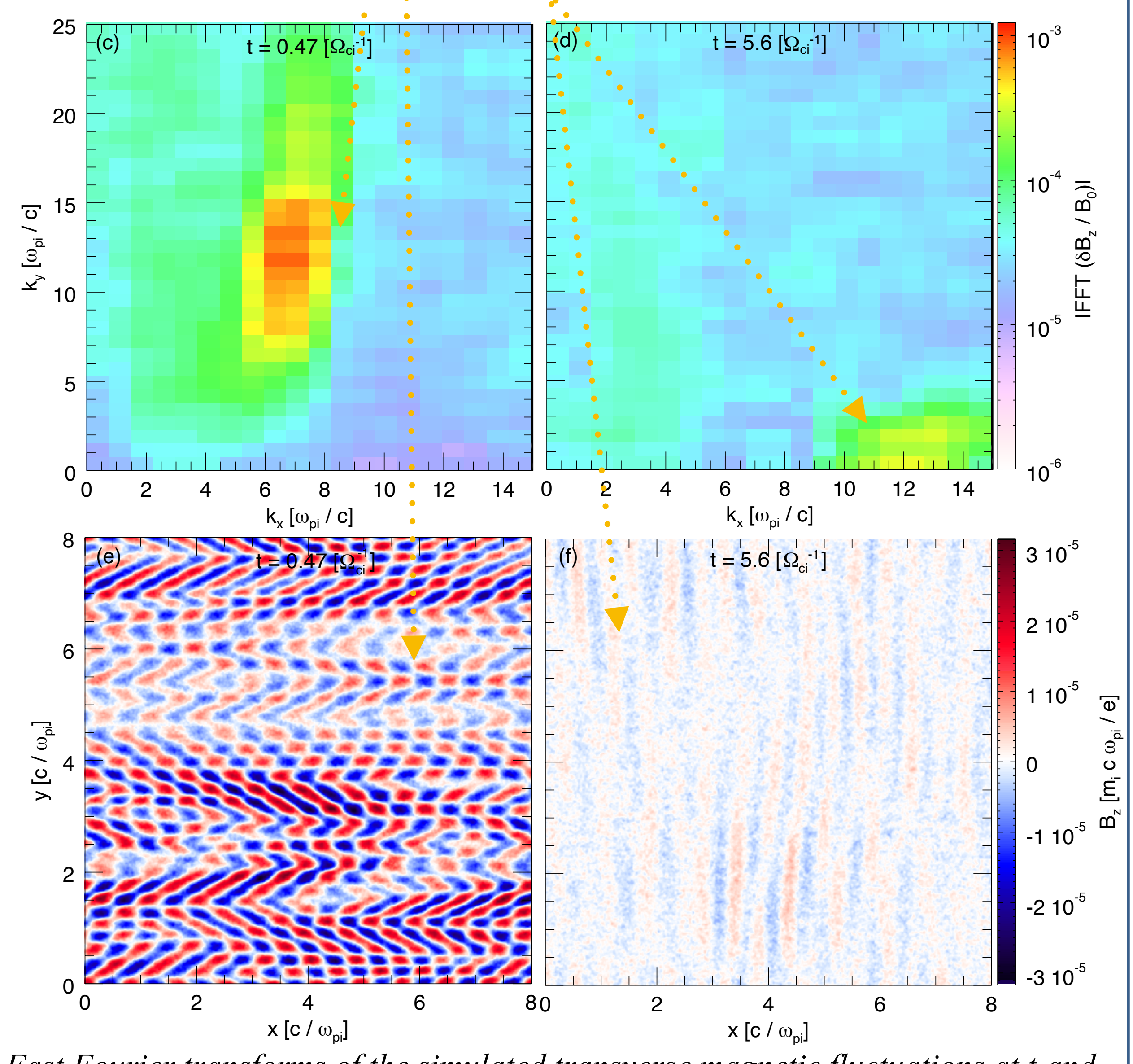
The strongest instability induced by the initialized core-strahl electron VDF is the Oblique Whistler Heat Flux Instability (O-WHFI), with the maximum growth rate at θ = 65°.



O-WHFI growth rates and wave frequencies obtained from the linear dispersion relation.

The simulation clearly exhibits evidence of the O-WHFI. Indeed, the FFT of the simulated $\delta B_z / B_0$ shows that the power is initially concentrated at highly oblique angles.

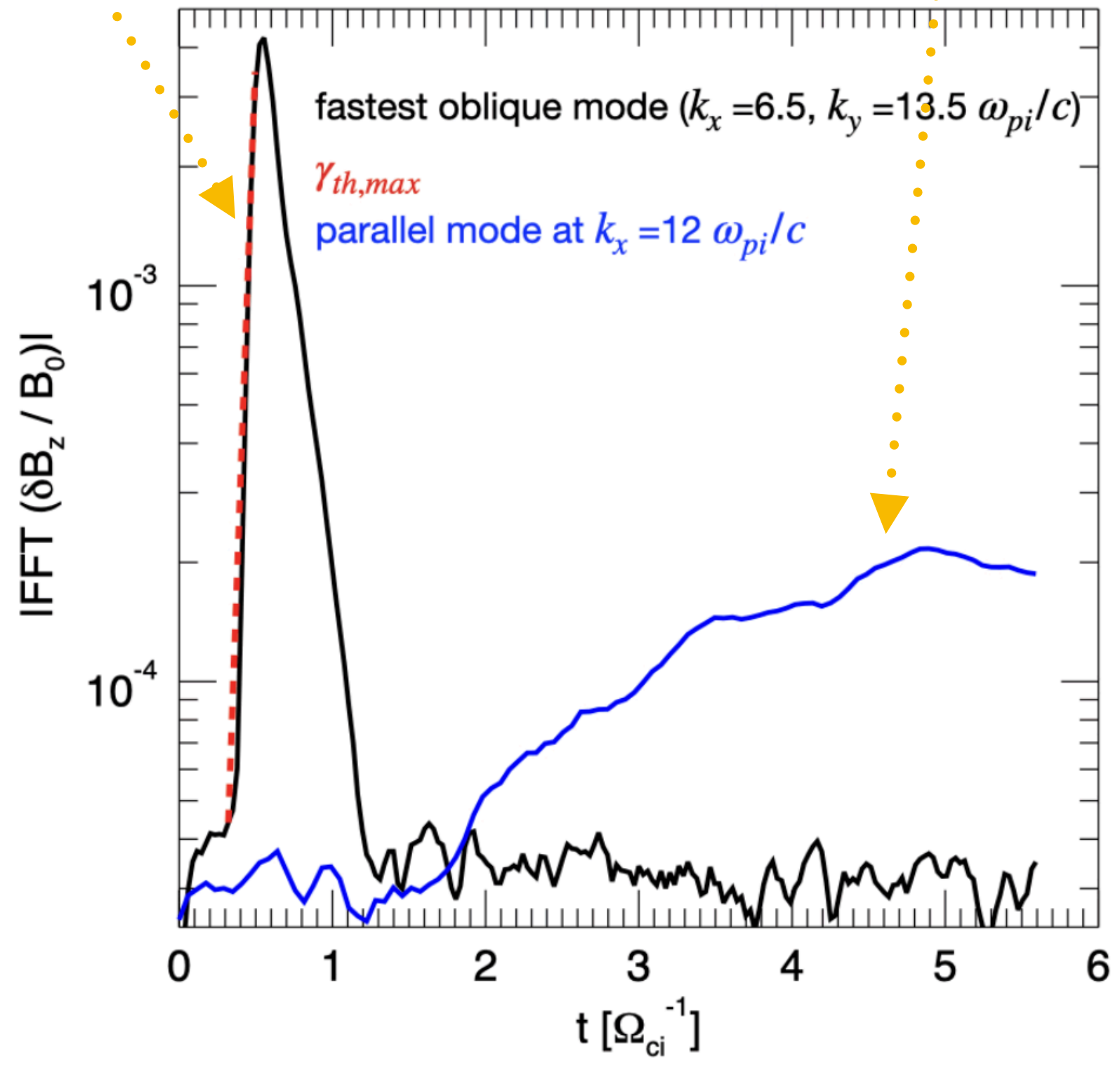
When the O-WHFI is already saturated, we observe weak modes which are mainly parallel or quasi-parallel to B_0.



Fast Fourier transforms of the simulated transverse magnetic fluctuations at t_1 and t_{end}. B_z component (color scale) in the x-y plane at two different time stages.

The scattering of the strahl electrons by the generated whistler waves provokes the saturation of the O-WHFI instability but, at this point, the newly generated halo provides the energy for the excitation of quasi-parallel whistler waves.

The theoretical growth rate of the fastest growing mode shows remarkable agreement with the numerical growth rate.



Temporal evolution of the simulated fastest-growing oblique mode, of the simulated parallel mode at $k_x = 12\ \omega_{pi} / c$, and comparison with the maximum theoretical growth rate.

SUMMARY AND CONCLUSIONS

2D fully kinetic simulation has been performed to investigate the role of the oblique and parallel branches of whistler heat flux instability in shaping the electron VDFs in the solar wind.

In a plasma consisting of a drifting core and strahl electrons, as recently observed by Parker Solar Probe in the near-Sun solar wind, whistler waves, propagating at oblique angles with respect to the background magnetic field, can be excited.

The oblique whistler waves drive a significant pitch-angle scattering of the strahl, which results in the formation of a suprathermal electron halo population.

The excited whistler-mode waves shift towards smaller angles of propagation as the bulk velocity of the strahl decreases.

The electron system experiences secondary effects due to the resonant interaction with parallel whistler waves, which lead to a further relaxation of the suprathermal electrons and hence to a more symmetric halo.

The process leads to a significant decrease of the heat flux carried by the strahl population.