PIC Simulations of Sunward and Anti-sunward Whistler Waves in the Solar Wind

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Heat flux in the solar wind

$$\boldsymbol{q}_e \sim \int (\boldsymbol{v} - \langle \boldsymbol{v} \rangle)(\boldsymbol{v} - \langle \boldsymbol{v} \rangle)^2 f(\boldsymbol{v})\, d^3\boldsymbol{v}$$

$$\langle \boldsymbol{v} \rangle = \int \boldsymbol{v} f(\boldsymbol{v})\, d^3 v$$

Spitzer-Härm law

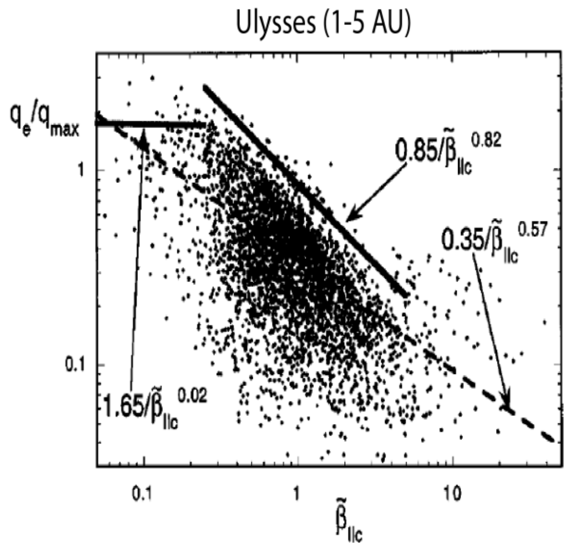
$$\boldsymbol{q}_e = -\kappa \nabla T_e$$

there is an upper bound on the electron heat flux that depends on the electron beta

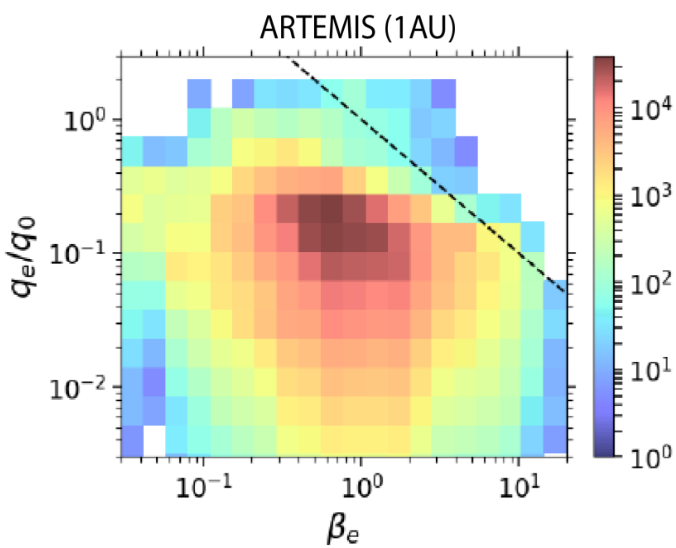
$$q_e/q_0 \lesssim A\, \beta_e^{-\alpha}$$

$$\beta_e = 8\pi n_e T_e / B_0^2$$

$$q_0 = 1.5\, n_e T_e (2T_e/m_e)^{1/2}$$



Gary+ Phys. Plasmas 1999



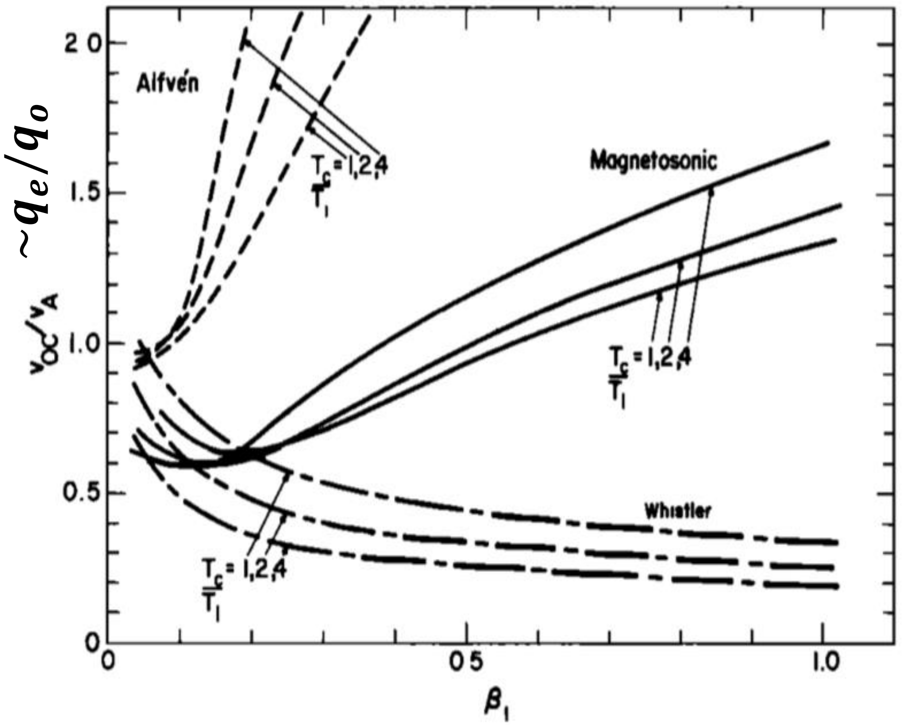
Tong+ ApJ 2019

The collisional Spitzer-Härm law is not applicable in the solar wind and solar corona [e.g., *Hollweg* 1974; *Scudder,* 1992]

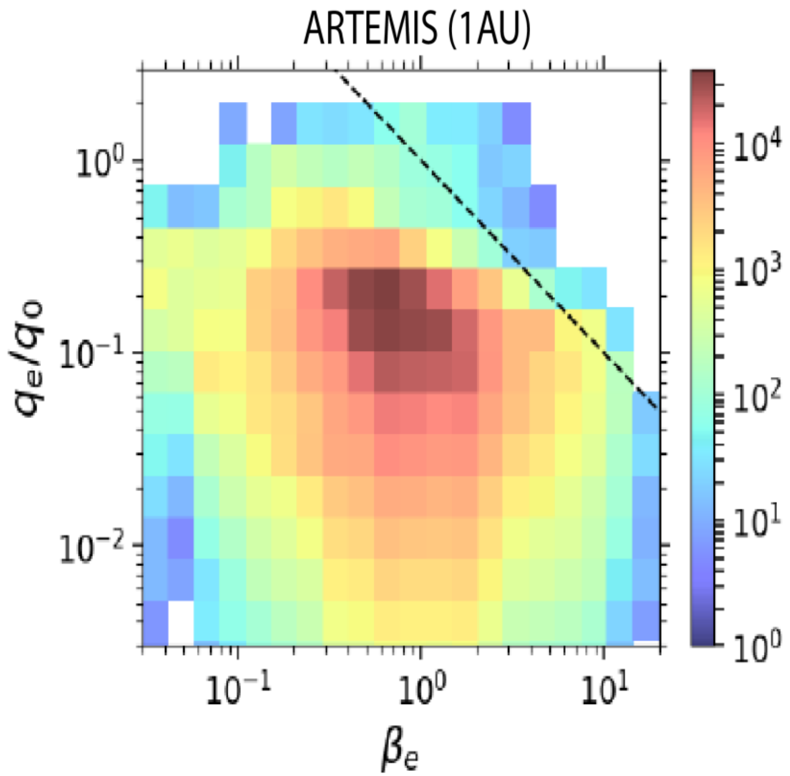
The heat flux suppression below the collisional values was demonstrated by direct in-situ measurements in the solar wind (*Feldman+ JGR* 1975; *Scime+ JGR*, 1994; *Gary+ Phys. Plasmas* 1999; *Tong+ ApJ* 2019)

One of the possible mechanisms of the heat flux regulation in the solar wind is the wave-particle interaction. It was hypothesized that <u>whistler waves driven by the whistler heat flux instability might be responsible for the heat flux regulation</u> (*Gary+ Phys. Plasmas*, 1999; *ApJ* 2000)

Heat flux regulation in the solar wind



Gary+ JGR 1975

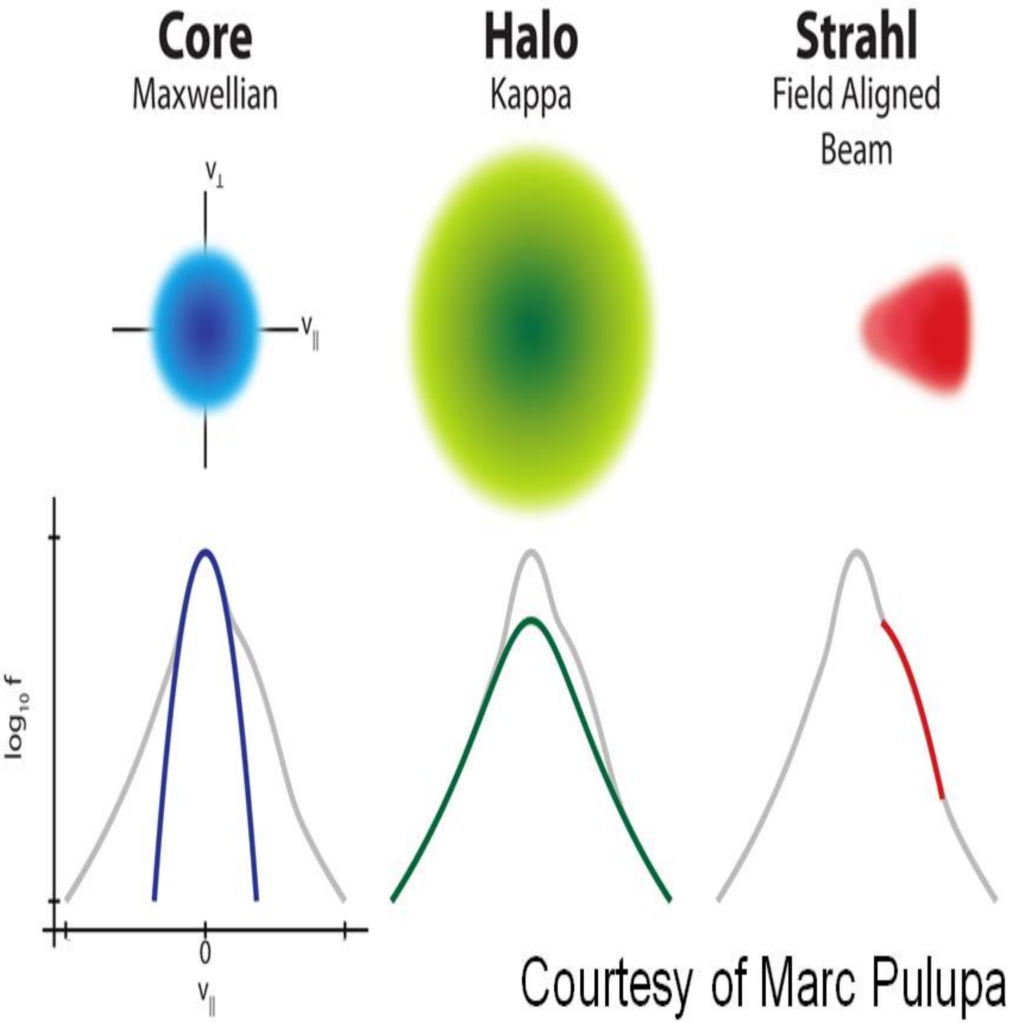


Tong+ APJ 2019

<u>the major argument behind Gary+ hypothesis:</u>
beta dependence of the observed upper bound on the electron heat flux is similar to the linear marginal stability threshold of the WHFI

Whistler waves: R-mode with frequencies
$\omega_{ci} \ll \omega < \omega_{ce}$

Solar wind electrons



Courtesy of Marc Pulupa

- three electron populations drift along magnetic field lines
- halo and strahl electrons carry the major part of the electron heat flux that is generally directed anti-sunward
- core electrons drift sunward to keep zero current

Whistler instabilities

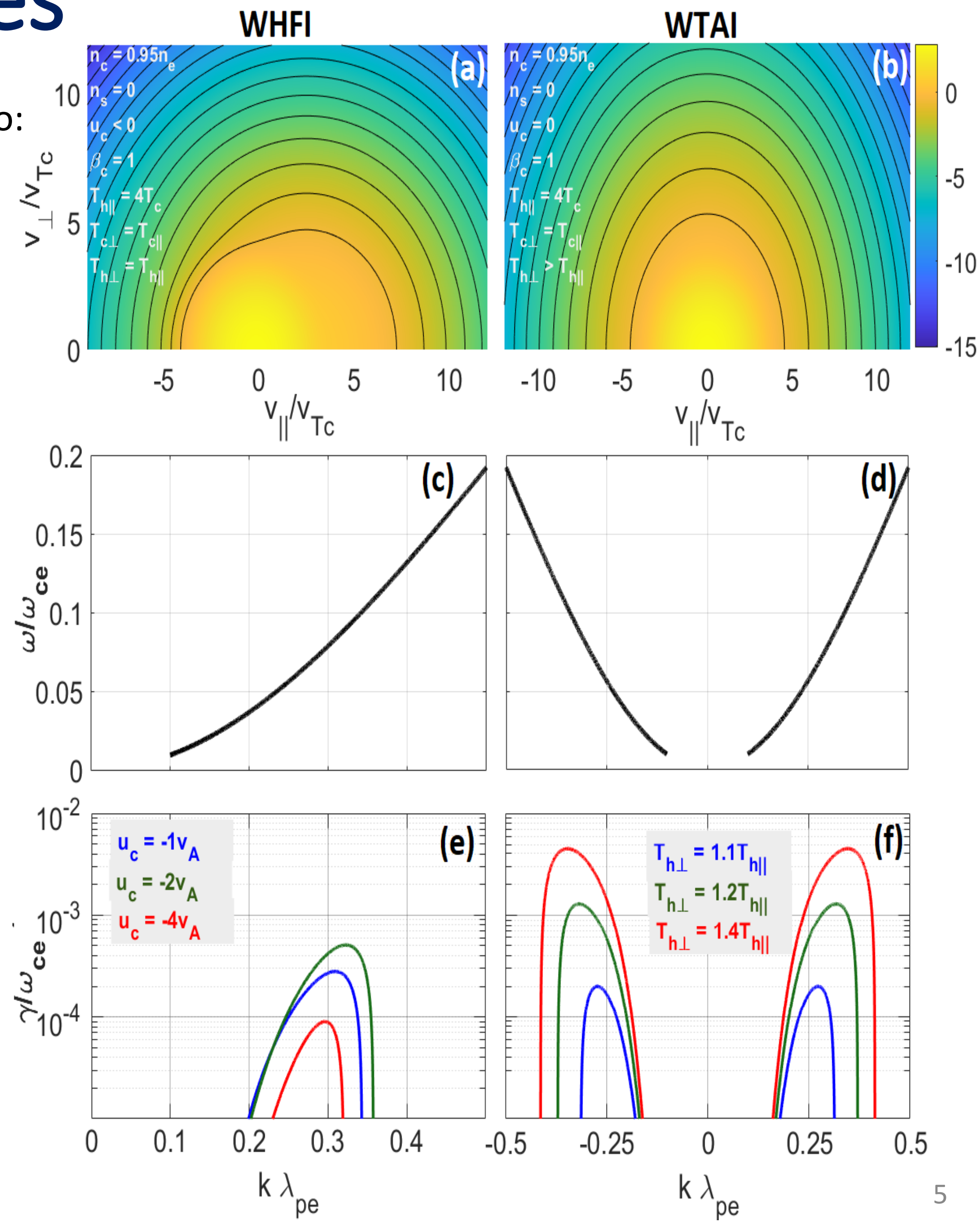
electrons = Maxwellian Core + Maxwellian Halo:

$$F_e = \frac{n_c}{(2\pi v_c^2)^{3/2}} \exp\left(-\frac{(\vec{v}-\vec{u}_c)^2}{2v_c^2}\right) + \frac{n_h}{(2\pi v_h^2)^{3/2} A_h} \exp\left(-\frac{(v_\parallel - u_h)^2}{2v_h^2} - \frac{v_\perp^2}{2v_h^2 A_h}\right)$$

$$A_h = \frac{T_{h\perp}}{T_{h\parallel}}; \qquad v_{c,h} = \sqrt{\frac{T_{c,h\parallel}}{m_e}}$$

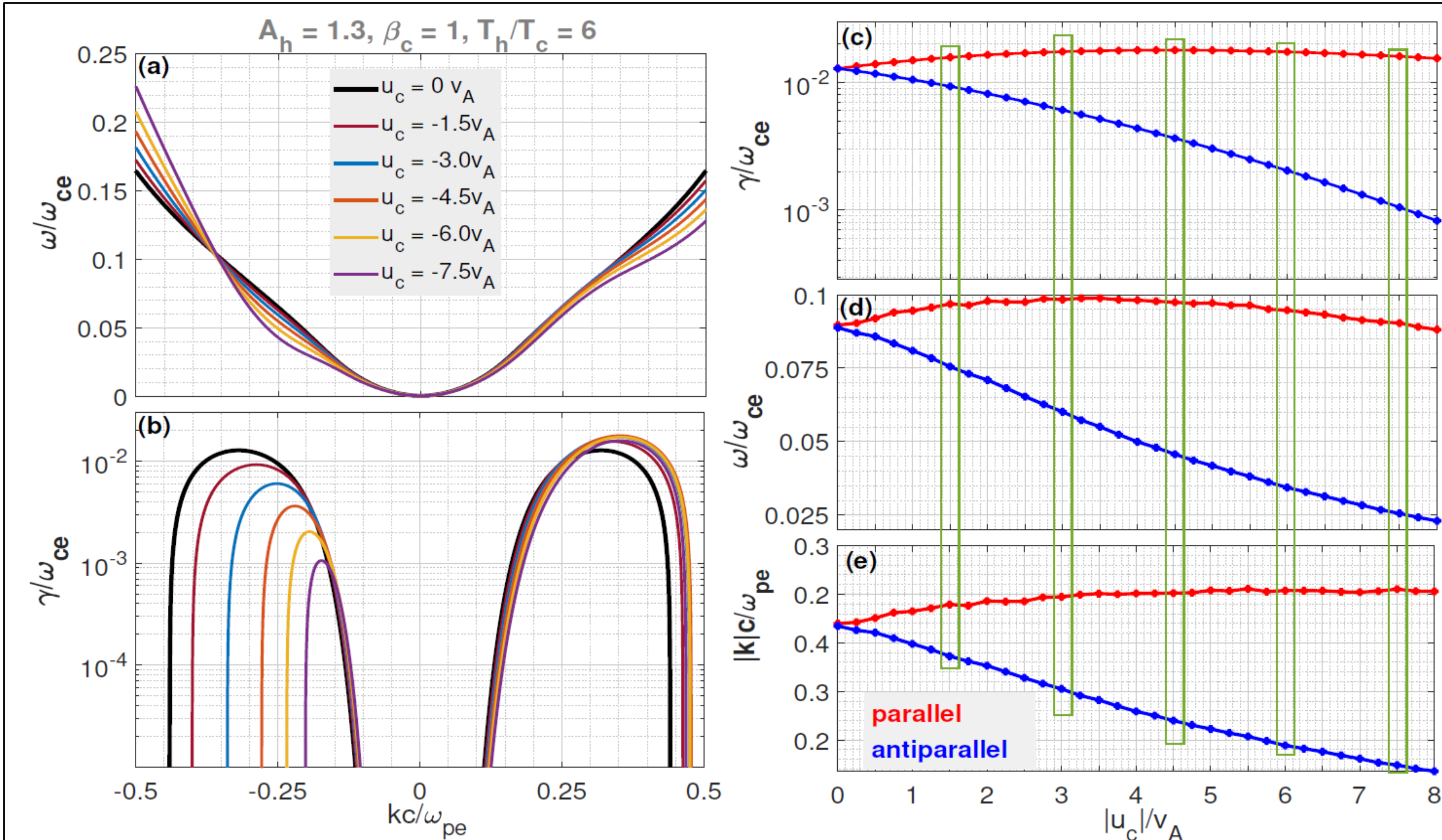
WHFI: Whistler Heat Flux Instability
Generates only parallel whistler waves
Does not reduce the heat flux
(Kuzichev et al. ApJ 2019)

WTAI: Whistler Temperature Anisotropy Instability
Generates both parallel and anti-parallel whistler waves



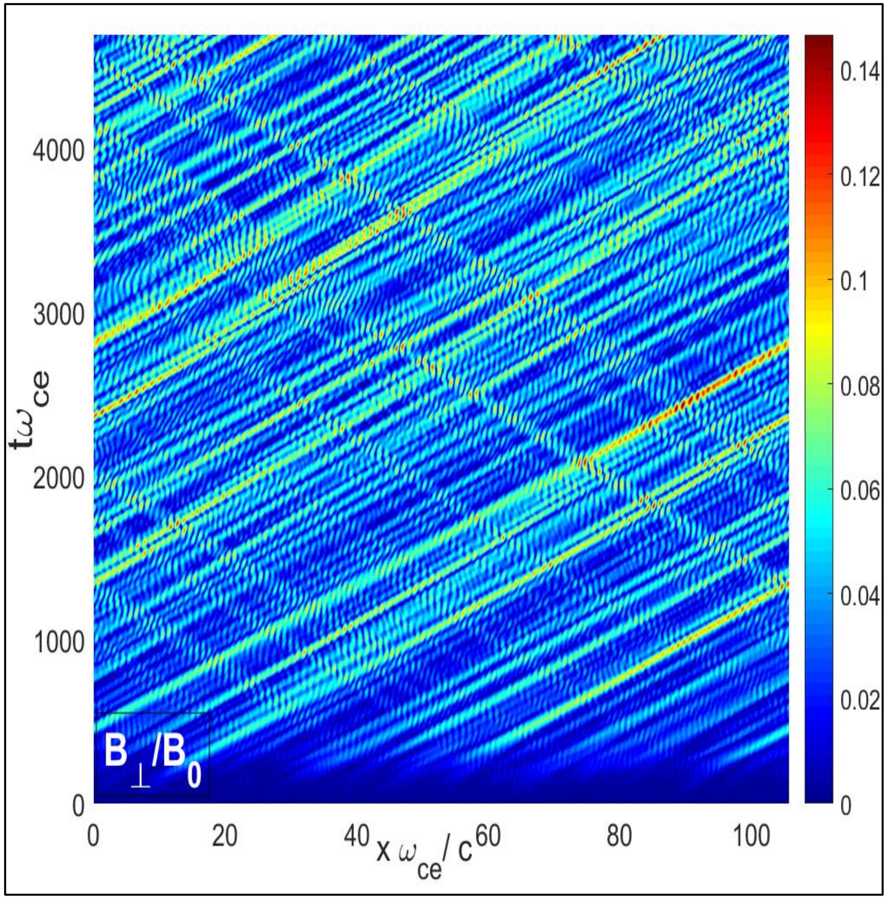
Effects of anisotropy on WHFI: linear theory

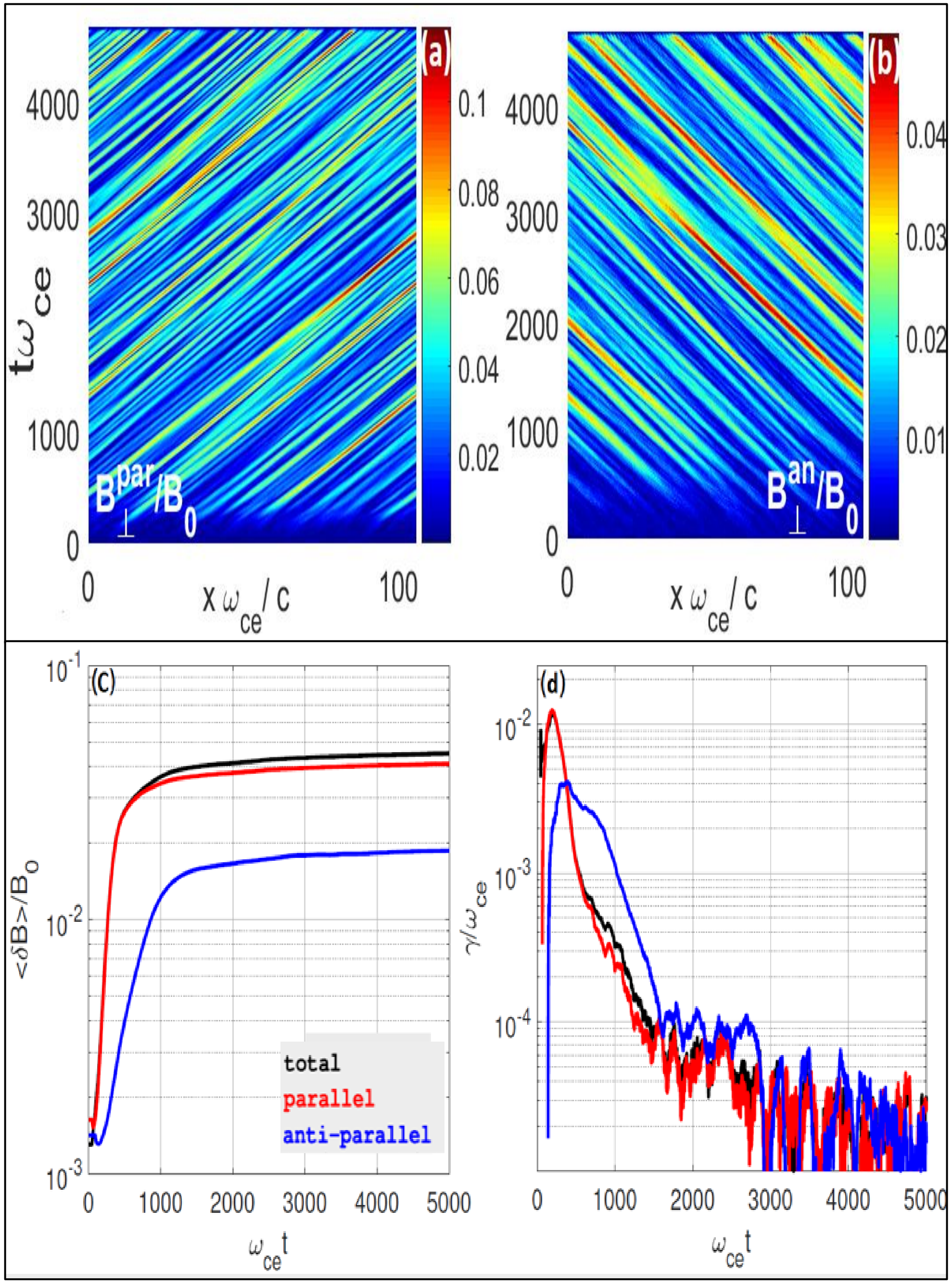
$$F_e = \frac{n_c}{(2\pi v_c^2)^{3/2}} \exp\left(-\frac{(\vec{v}-\vec{u}_c)^2}{2v_c^2}\right) + \frac{n_h}{(2\pi v_h^2)^{3/2} A_h} \exp\left(-\frac{(v_\parallel - u_h)^2}{2v_h^2} - \frac{v_\perp^2}{2v_h^2 A_h}\right) \qquad A_h = \frac{T_{h\perp}}{T_{h\parallel}};\ v_{c,h} = \sqrt{\frac{T_{c,h\parallel}}{m_e}}$$



PIC simulations

$$\beta_c = 1,\ n_c = 0.85, u_c = -3v_A$$
$$A_h = 1.3, v_h^2/v_c^2 = 6$$





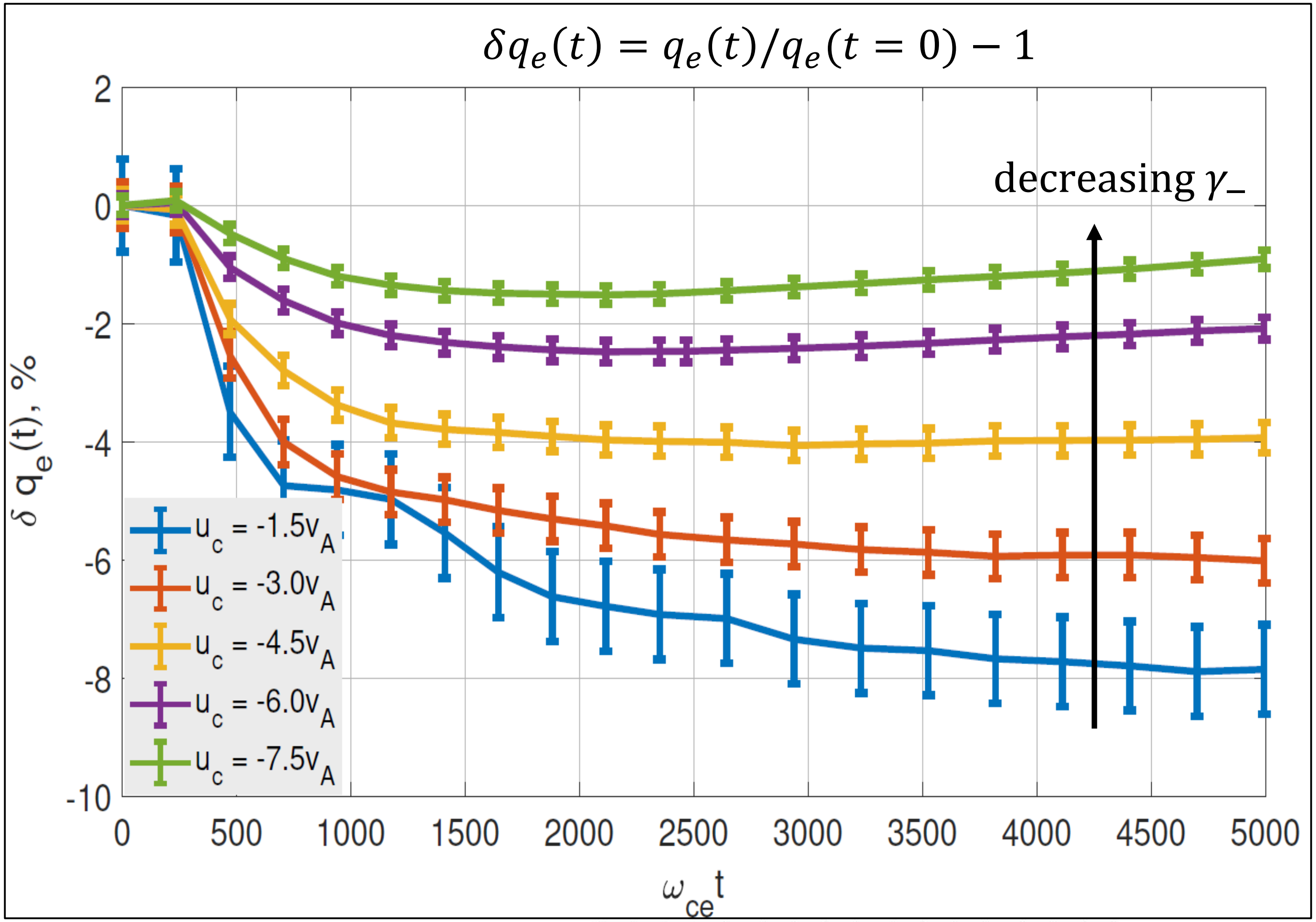
$$< \delta B(t) > = \sqrt{< B_\perp^2(t,x) >_x}$$

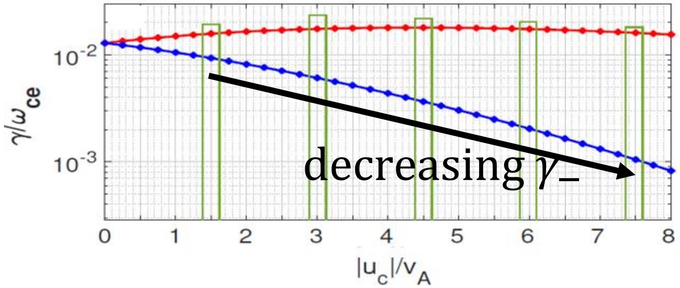
Heat flux variation for $A_h = 1.3, \beta_c = 1$

- Heat flux decreases by up to 10%

- Heat flux variation is correlated with the linear growth rate for the anti-parallel whistler waves.

- Growth rates (and, consequently, saturated amplitudes) of the parallel whistlers are almost the same for all of the simulations.





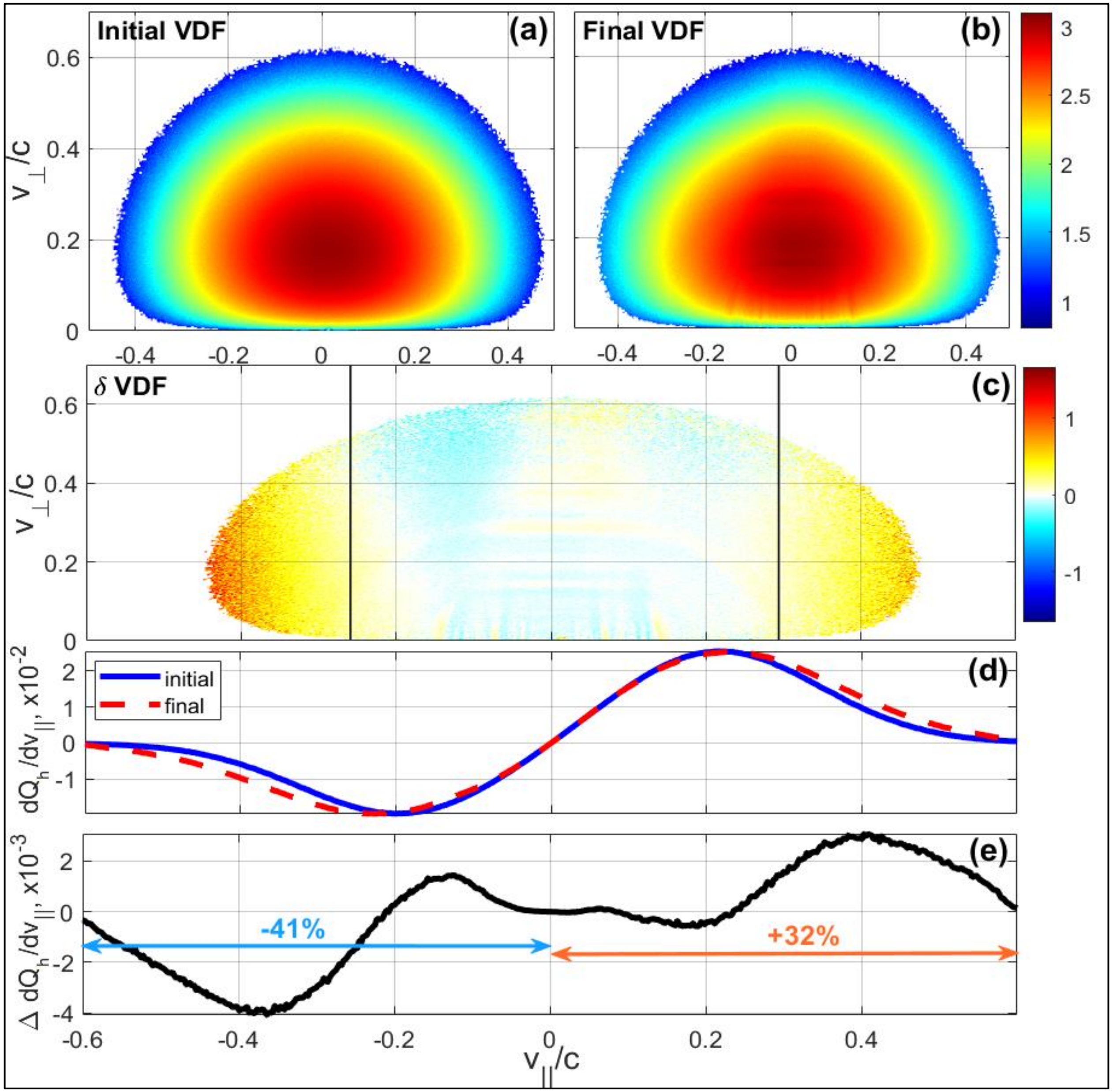
What changes the heat flux?

- Variation of the phase space density (for hot electrons) demonstrate that the instability saturation is consistent with the QL theory predictions: formation of a plateau around the resonant velocities (black vertical lines)

- Parallel heat flux density shows

$$\frac{dQ_h}{dv_\parallel} = \frac{m_e}{2} \int v_\parallel \boldsymbol{v}^2 f_h(\boldsymbol{v})\, d^2 v_\perp$$

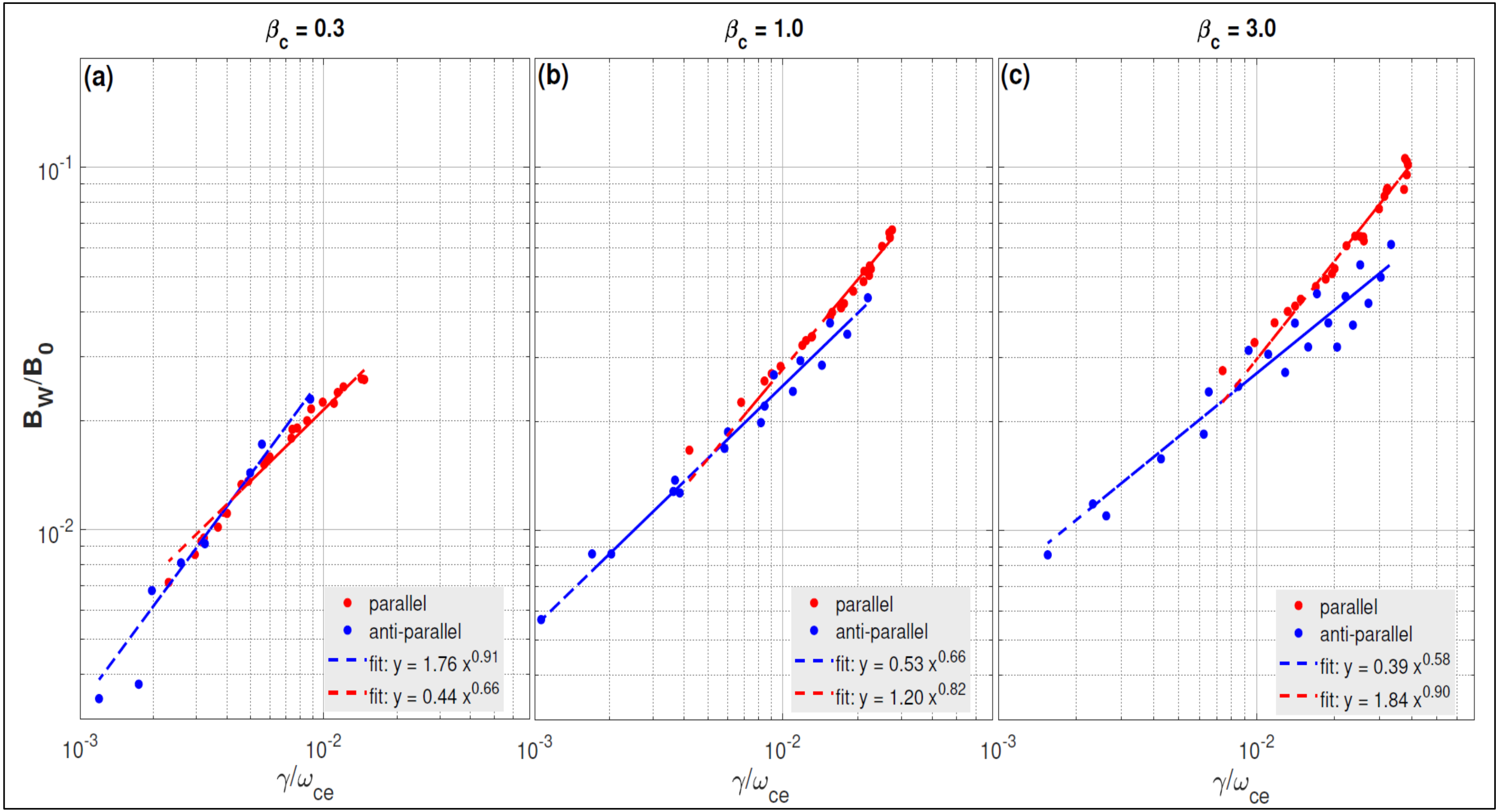
that the anti-parallel waves increase the heat flux, while the parallel waves decrease it, with overall effect being a heat flux reduction.



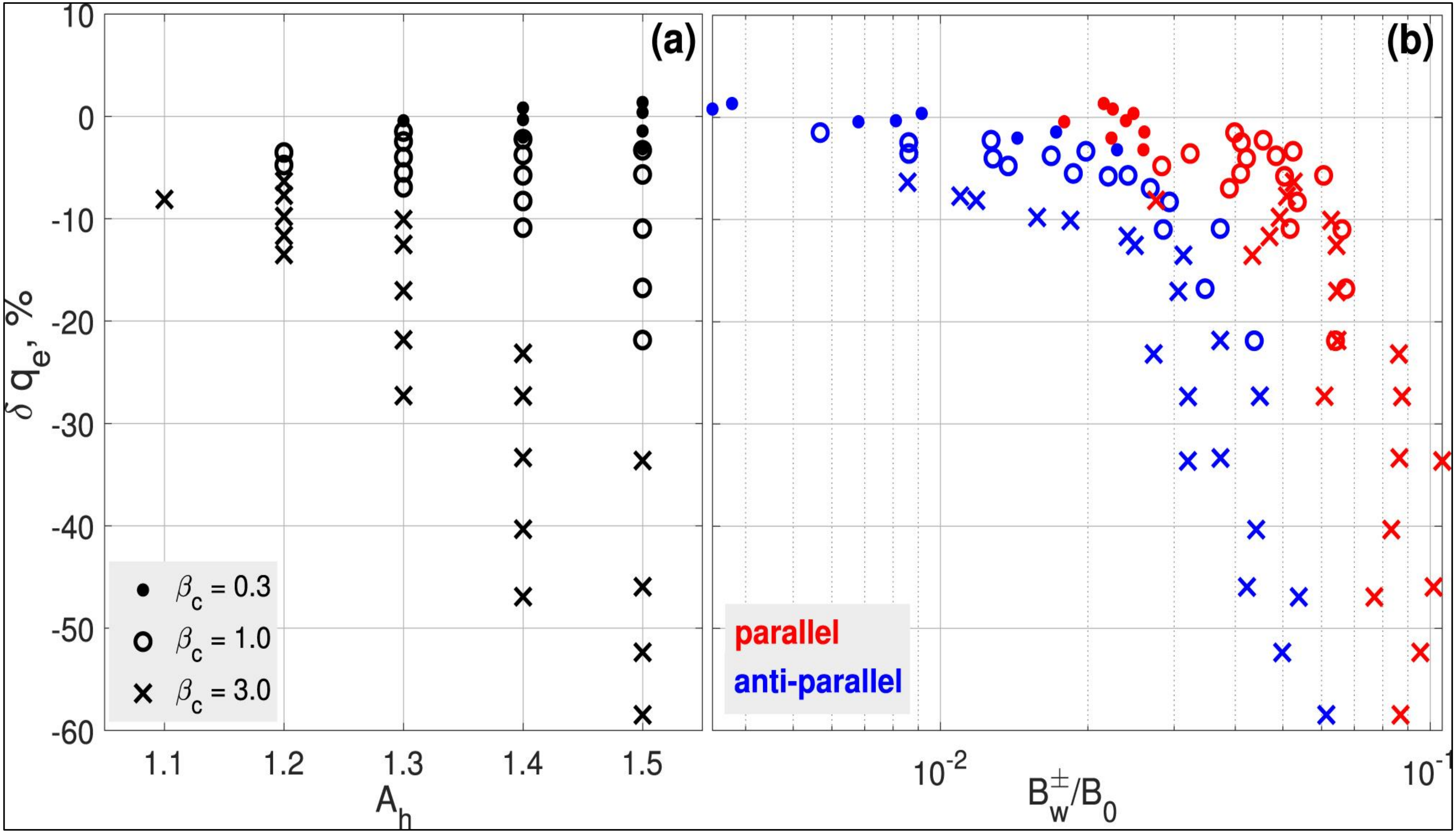
Full set of simulations: scalings

$$B_w^{\pm}/B_0 = C_{\pm}(\gamma_{\pm}/\omega_{ce})^{\nu_{\pm}} \qquad v_{\pm} \in (0.6, 0.9)$$

run sets	β_c	$-u_c/v_A$	A_h
I	0.3	1.5:1.5:7.5	1.1:0.1:1.5
II	1	1.5:1.5:7.5	1.1:0.1:1.5
III	3	1.5:1.5:7.5	1.1:0.1:1.5



Full set of simulations: heat flux variation



Full set of simulations: wave frequencies

$$\omega = \frac{\int PSD(\omega')\omega' d\omega'}{\int PSD(\omega')d\omega'} \qquad \Delta\omega^2 = \frac{\int PSD(\omega')(\omega'-\omega)^2 d\omega'}{\int PSD(\omega')d\omega'}$$

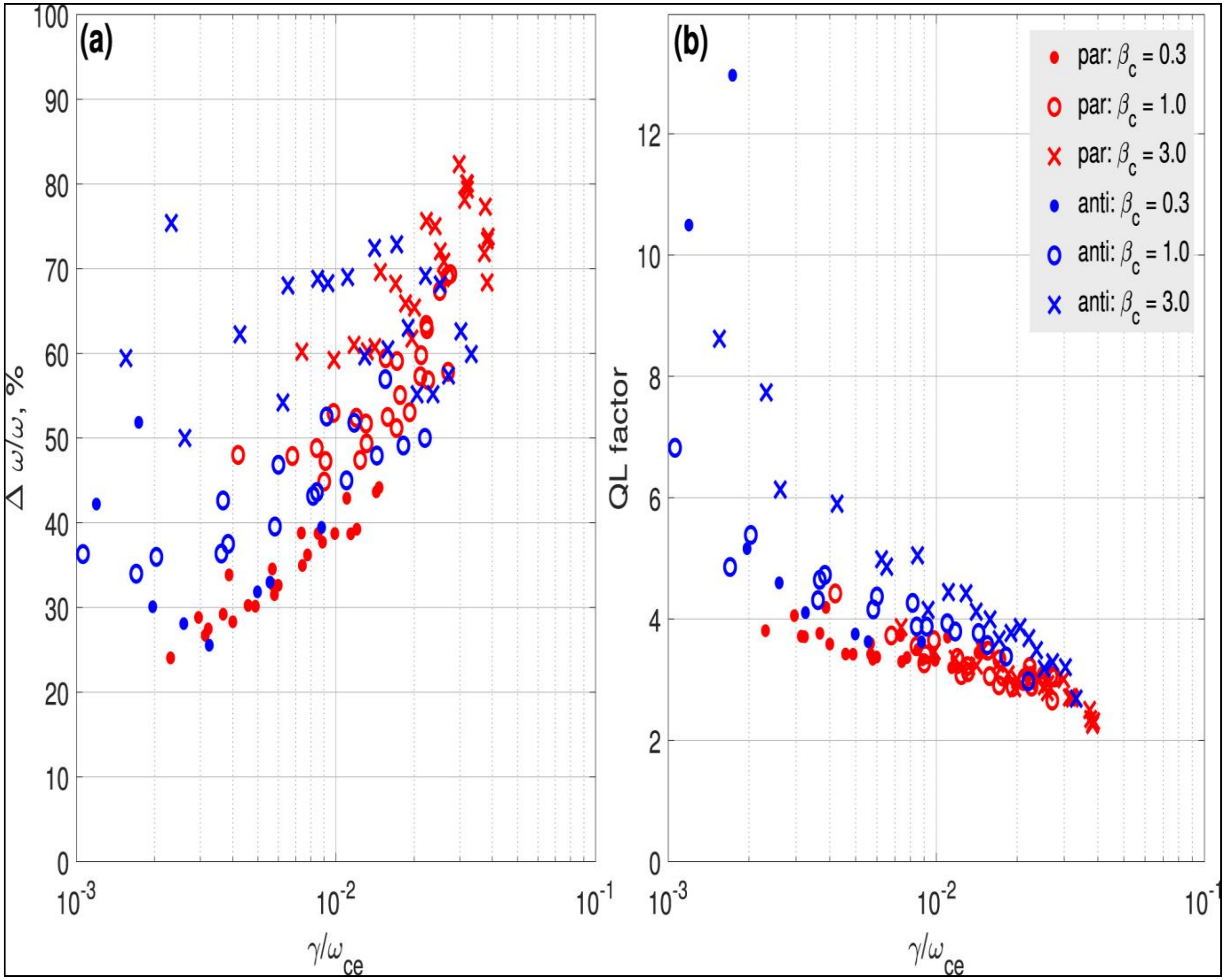
Wave frequencies and spectral widths were identified via Fourier analysis.

Gaussian fitting of the signal's spectrum provided similar results in the most cases.

Quasi-linear theory applicability:

$$\frac{\Delta\omega}{\omega} \gg \left(\frac{B_w}{B_0}\right)^{1/2} \left(\frac{\beta\,\omega}{\omega_{ce}-\omega}\right)^{1/4}$$

Karpman, SSRv, 1974; Tong et al., ApJ, 2019



Summary

- We modeled generation of whistler waves driven by the combined heat flux and anisotropy instability that likely operates in the solar wind.
- We found a positive correlation between linear increment and saturated wave amplitude and investigated the corresponding relation for different plasma parameters. It has been shown that a simple relation $B_w = C\gamma_{lin}^{\nu}$ exists, with $\nu \in (0.6, 0.9)$
- Our calculations suggest that whistler waves generated by the combined heat flux + anisotropy instability can contribute to the heat flux regulation.
- Spectral analysis of the generated whistler waves demonstrate that the quasi-linear theory should be applicable, as the frequency spectrum is sufficiently wide.

1. I Kuzichev, I Vasko, A Artemyev, SD Bale, F Mozzer (2023), Particle-In-Cell Simulations of Sunward and Anti-sunward Whistler Waves in the Solar Wind, The Astrophysical Journal, 959 65 DOI 10.3847/1538-4357/acfd28

2. Vasko, I. Y., I. V. Kuzichev, A. V. Artemyev, S. D. Bale, J. W. Bonnell, and F. S. Mozer (2020), On quasi-parallel whistler waves in the solar wind, Physics of Plasmas 27, 082902; https://doi.org/10.1063/5.0003401

3. Kuzichev I.V., I. Yu. Vasko, A.R. Soto-Chavez, Y. Tong, A. V. Artemyev, S.D. Bale, and A. Spitkovsky, (2019), Nonlinear Evolution of the Whistler Heat Flux Instability, ApJ 882 81, doi: 10.3847/1538-4357/ab3290

Thank you!