Role of Whistler Waves in Regulation of the Heat Flux in the Solar Wind

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Heat flux in the solar wind

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

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

Spitzer-Härm law

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

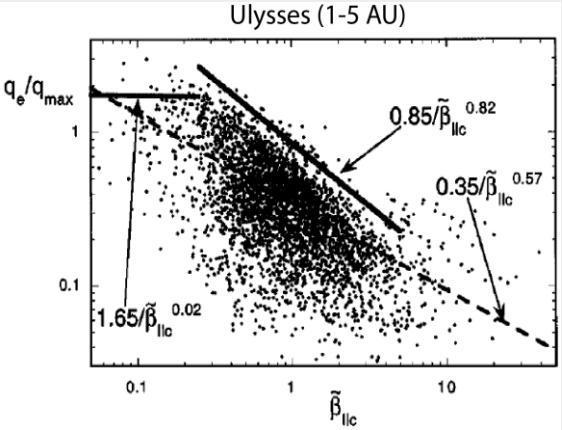
there is an upper bound on the electron heat flux that depends on the electron beta

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

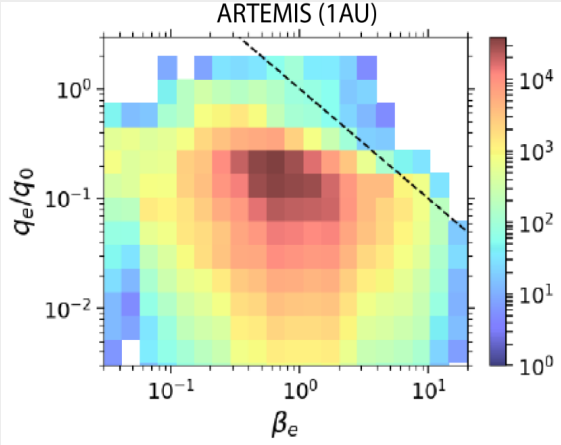
$$\beta_e = 8\pi n_e T_e / B_0^2$$

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

Gary+, Phys. Plasmas, 1999



Tong+, ApJ, 2019

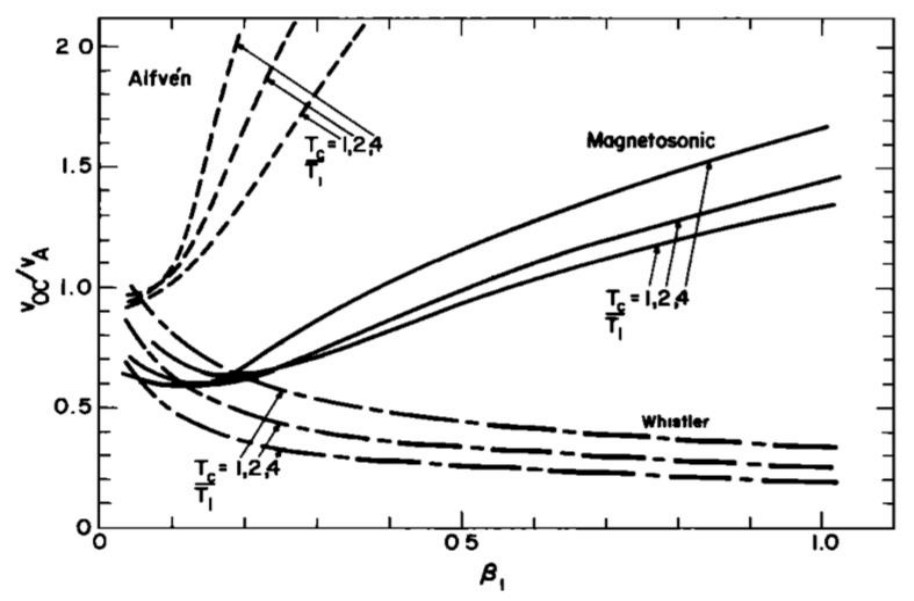


The collisional Spitzer-Härm law is not applicable in the solar wind and solar corona [e.g., *Hollweg*, 1974; *Scudder*, 1992]

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)

Whistler heat flux instability (WHFI)



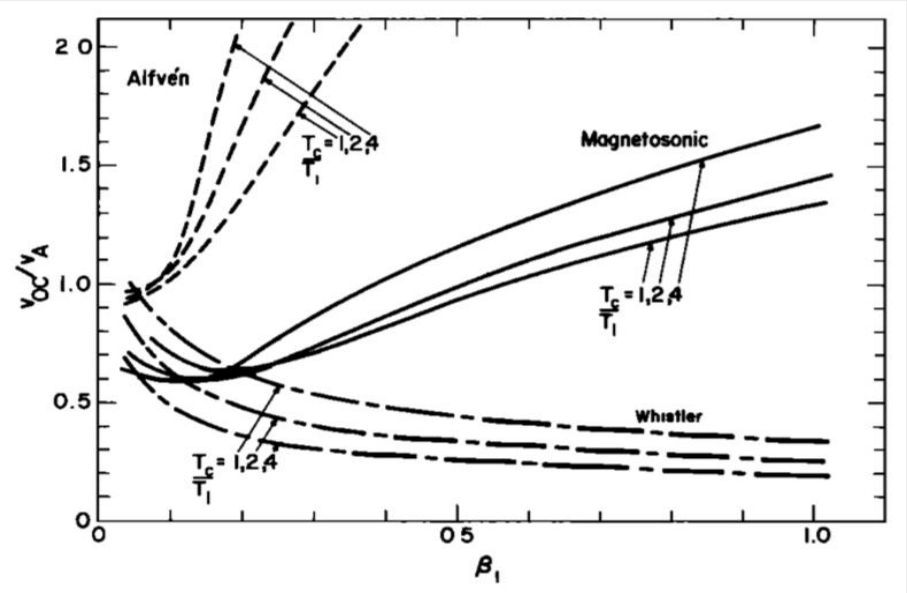
Gary+, *JGR*, 1975

- consider electron VDF with drifting <u>core + halo</u> populations
- the electron heat flux is proportional to drifts of core and halo populations
- heat flux is a free energy capable of driving several so-called heat flux instabilities
- whistler waves grow fastest for a wide range of parameters (whistler heat flux instability)

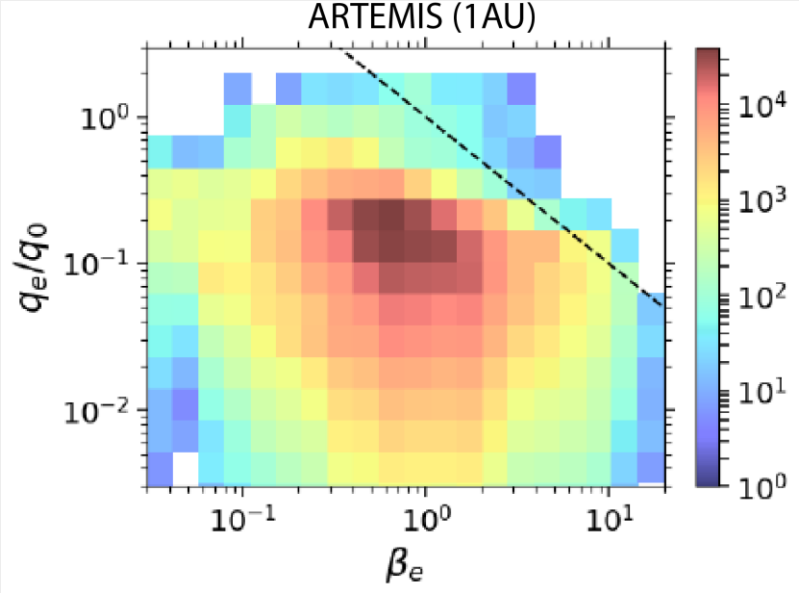
WHFI

- whistler are quasi-parallel propagating, $\mathbf{k} \,||\, \mathbf{q}_e$
- whistlers are driven by cyclotron resonant halo electrons
- whistlers produced by WHFI were suggested to regulate the heat flux in the collisionless solar wind

Heat flux regulation in the solar wind



Gary et al., JGR, 1975



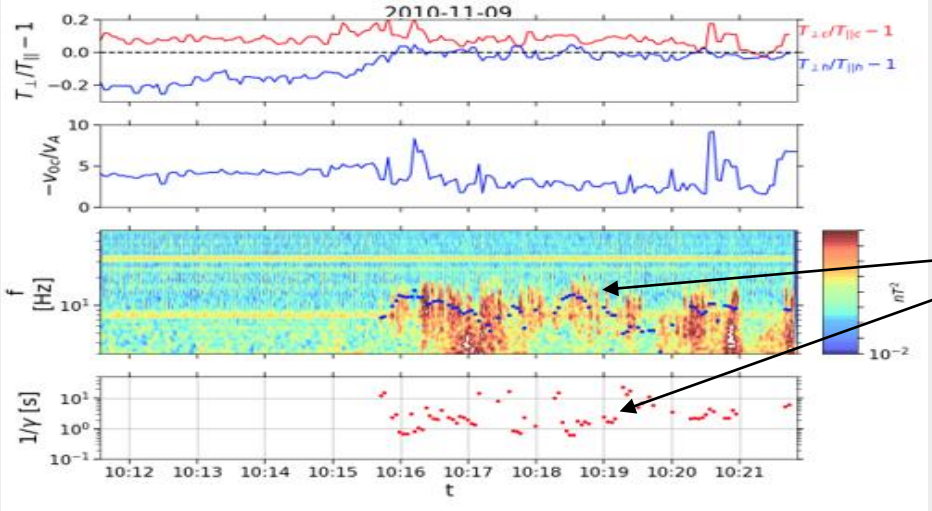
Tong+, APJ, 2019

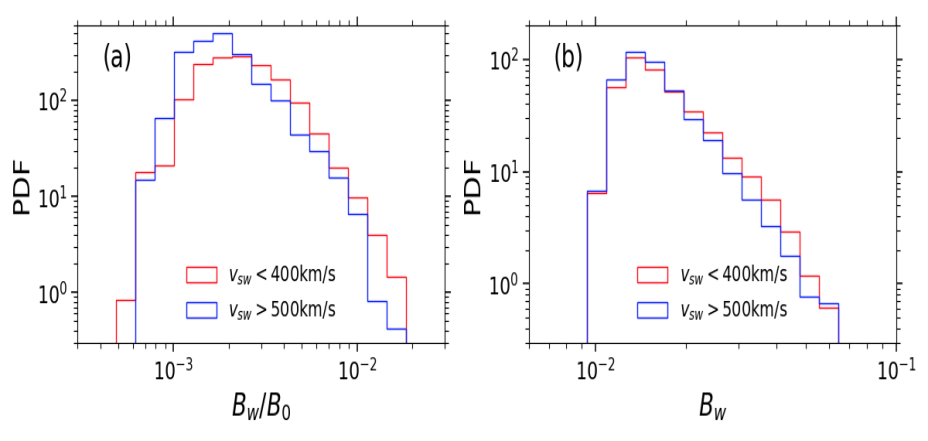
<u>the major argument behind Gary+ hypothesis:</u>
beta dependence of the observed upper bound on the electron heat flux is similar to the linear marginal stability threshold of the WHFI

Problems

- no direct evidence of whistler waves generated by WHFI in the solar wind and no detailed understanding of typical whistler wave parameters in the solar wind
  - Are whistler waves generated locally by the WHFI in the solar wind?
  - What are whistler wave amplitudes, obliqueness, frequency etc.?
- no PIC simulations that would demonstrate that whistler waves generated by the WHFI can regulate the electron heat flux in the solar wind

Observations of whistler waves at 1AU





Tong, Y., Vasko, I. Y., Artemyev, A., Bale, S. D., & Mozer, F. S. 2019, ApJ, doi: 10.3847/1538-4357/ab1f05

Tong, Y., Vasko, I. Y., Pulupa, M., et al. 2019, ApJL, 870, L6, doi: 10.3847/2041-8213/aaf734

frequencies and e-folding time of the most unstable whistler waves are consistent with linear stability analysis

All data

- ARTEMIS 2011-2013
- clean solar wind, 359 days, ~ 1300 hours
- 800,000 magnetic field spectra (8s res)
- restrict to $f_{lh} < f < f_{ce}$ and to [16, 300] Hz
- particle moments 3s or 96s cadence

intense whistler wave events

- significant power: $P_B > 3\ P_g$
- 17,000 spectra, ~ 30 hours
- 2% of all spectra
- || propagating whistler waves (>80%)

PIC simulations

electrons = Maxwellian Core + Maxwellian Halo:

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

Zero total current:

$$n_c\vec{u}_c + n_h\vec{u}_h = 0$$

Uniform background magnetic field

$$\vec{B}_0 = \{B_0, 0, 0\}, \quad \vec{u}_h || \vec{B}_0$$

PIC simulations parameters:

electrons = Maxwellian Core + Maxwellian Halo:

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

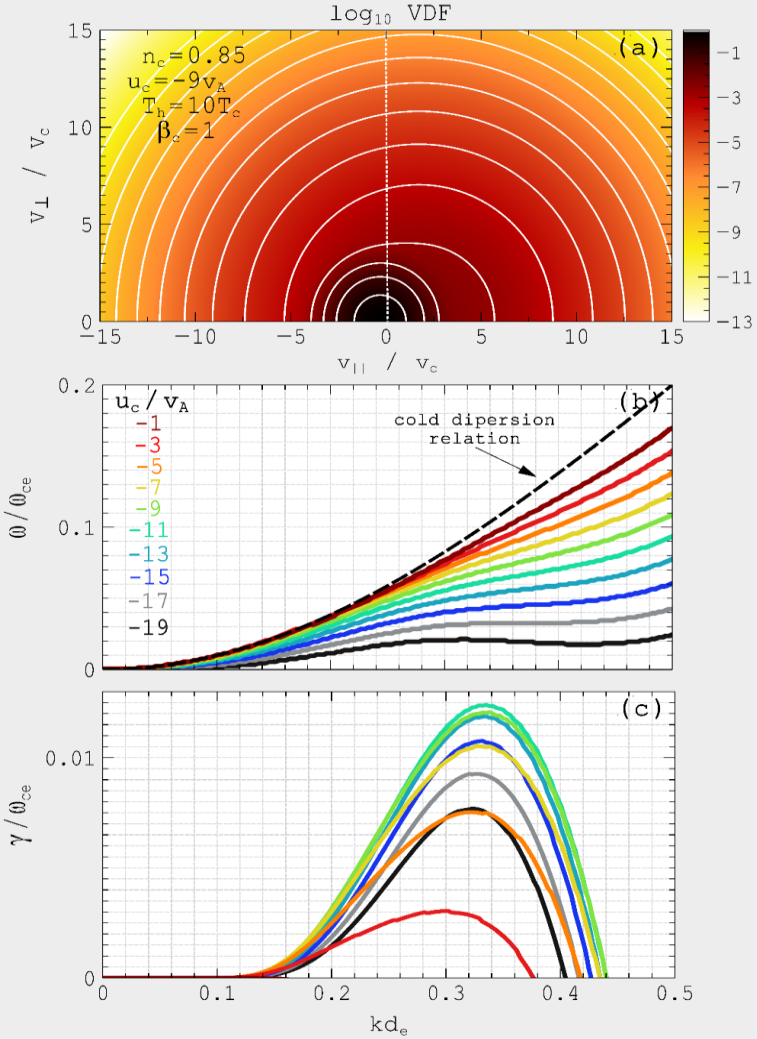
$$n_c = 0.85, n_h = 0.15$$

$$\beta_c = 1; 0.4; 2 \,\&\, 3$$

$$v_h^2/v_c^2 = 10$$

Electron plasma to cyclotron frequency ratio: $\omega_{pe}/\omega_{ce} \approx 10 - 20$
(varies within this range for various initial β_c)

Linear stability analysis of the WHFI



- core+halo electron VDF

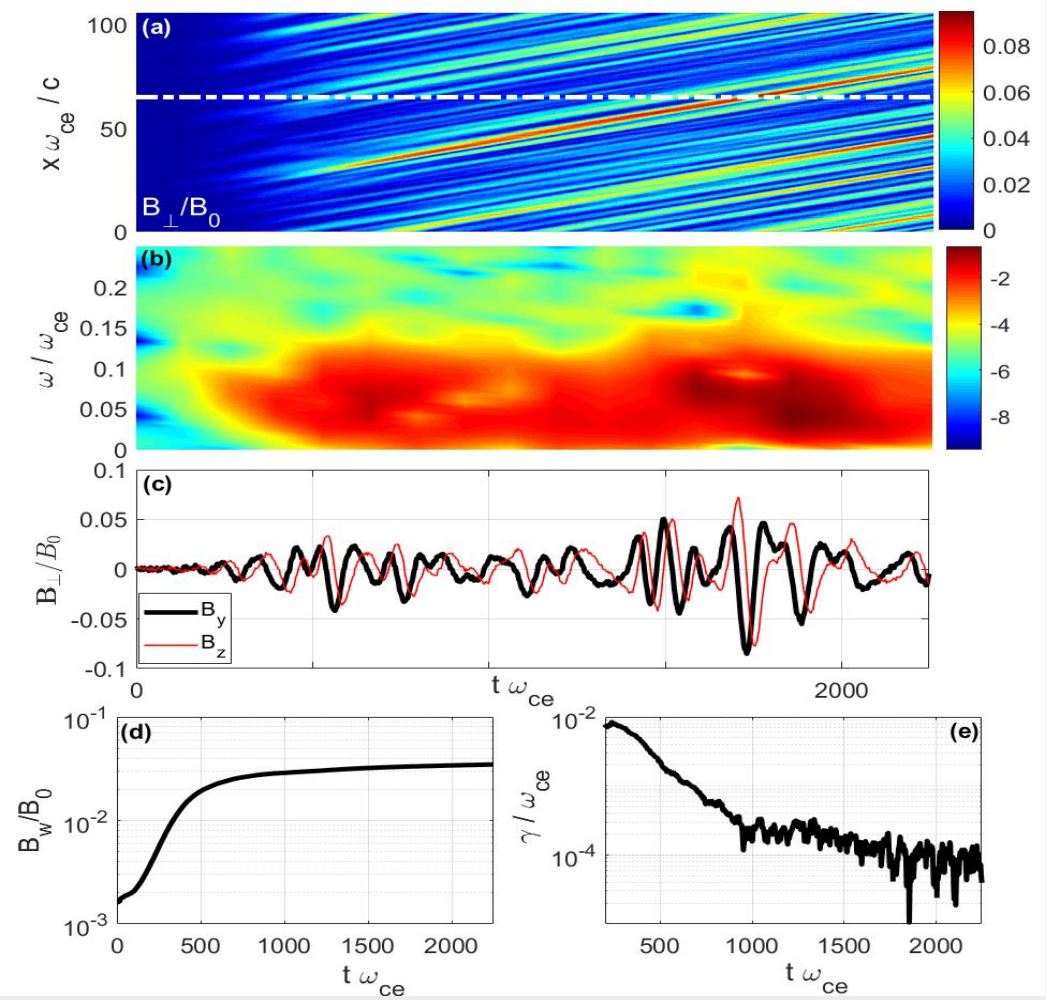
$$F_e = \frac{n_c}{(2\pi v_c^2)^{3/2}} \exp\left(-\frac{(\vec{v}-\vec{u}_c)^2}{2v_c^2}\right) + \frac{n_h}{(2\pi v_h^2)^{3/2}} \exp\left(-\frac{(\vec{v}-\vec{u}_h)^2}{2v_h^2}\right)$$

- Most unstable waves $\boldsymbol{\omega \leq 0.1\omega_{ce}}$; frequency decreases as the drift velocity $\boldsymbol{u_c}$ increases.

- typical wavelength $\sim 15\ c/\omega_{pe}$

- linear growth rates $\boldsymbol{\gamma_L \leq 0.015\omega_{ce}}$

$\beta_c = 1,\ u_c = -9\,v_A$



Results of the simulations

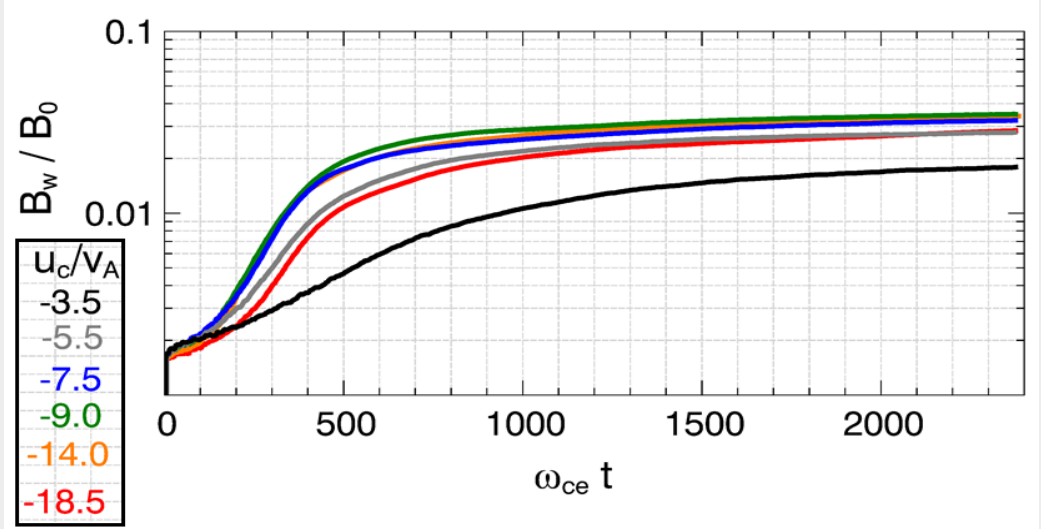
- TRISTAN-MP code (Spitkovsky, ApJ, 2008)
  1D code (only parallel whistler waves)
  $dx = 0.2\ c/\omega_{pe};\ dt = 0.09\ 1/\omega_{pe}$
  $N_{particles} \approx 5.2 \cdot 10^8$

- development of whistler wave **below 0.1 ω_{ce}** propagating **parallel to the electron heat flux**

- the frequencies and initial growth rate are consistent with the linear theory

- whistler waves saturate after a thousand of $1/\omega_{ce}$ at averaged (over the box) amplitudes $\boldsymbol{B_w/B_0 \sim 0.03}$ [consistent with spacecraft observations, Tong+, APJL, 2019]

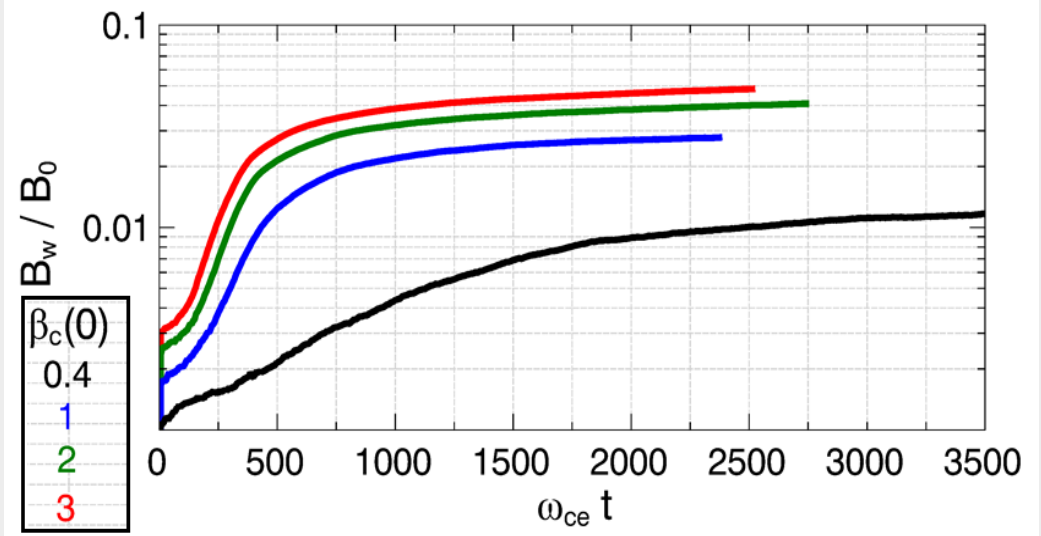
$$B_w(t) = \sqrt{< B_\perp^2(t,x) >_x}$$



1st set of simulations

- β_c=1 and various u_c/v_A or, equivalently, q_e/q_0
- whistler waves saturated at averaged amplitudes

$$B_w/B_0 \sim 0.02 - 0.04$$



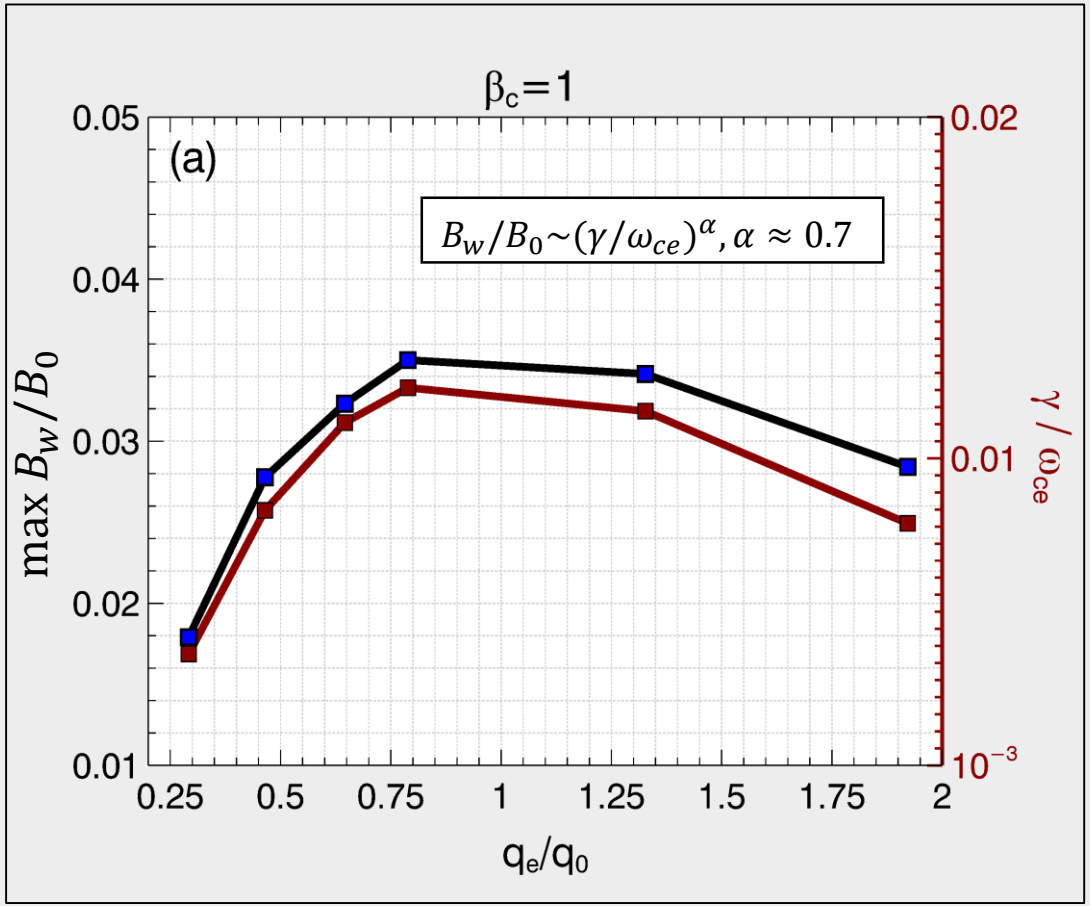
2nd set of simulations

- $q_e/q_0 = 0.45$, various β_c
- whistler waves saturated at averaged amplitudes

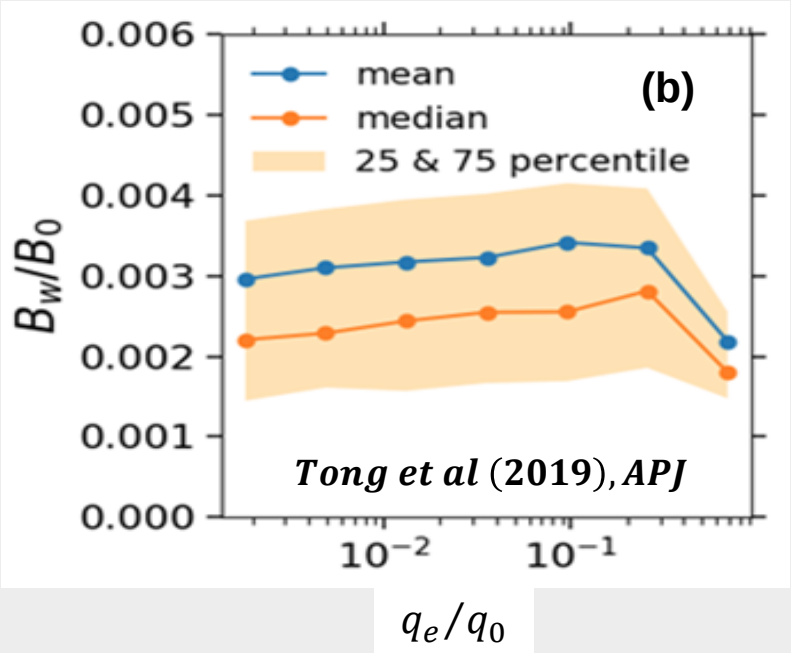
$$B_w/B_0 \sim 0.01 - 0.05$$

Saturated amplitude vs. initial heat flux

Simulations



Observations, solar wind

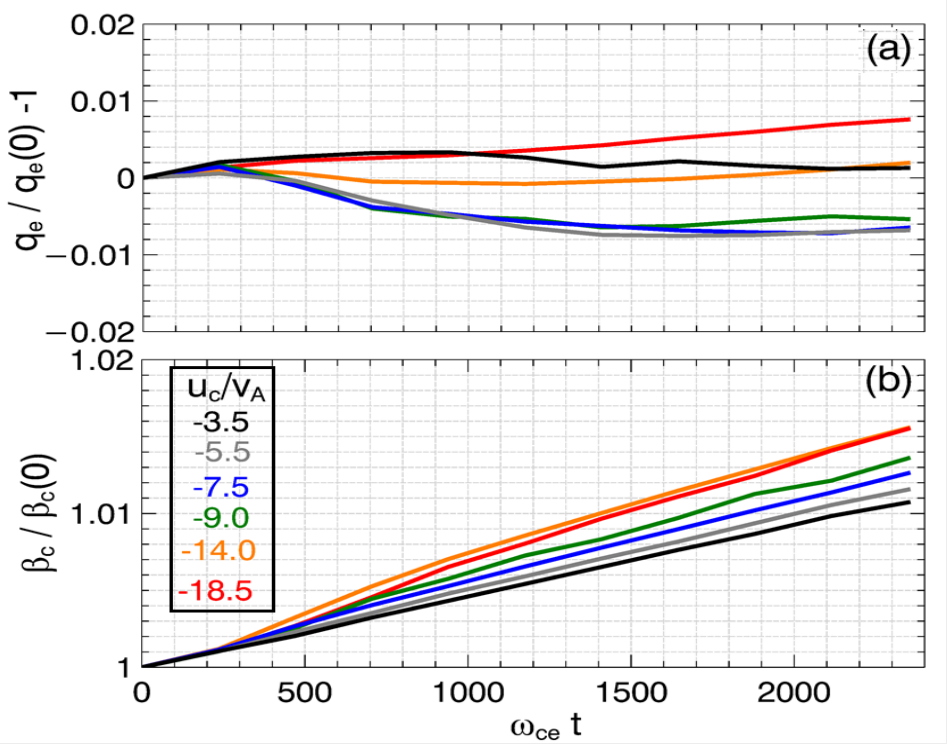


Does the heat flux change?

1st set of simulations

β_c=1 and various u_c/v_A or, equivalently, q_e/q_0

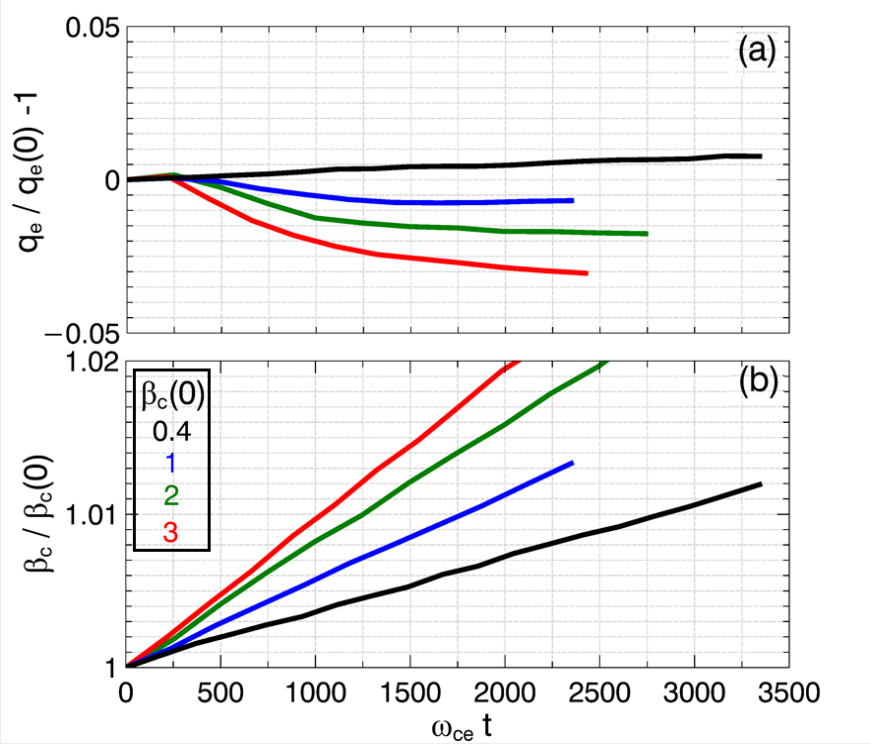
Heat flux variation is less than 1%



2st set of simulations

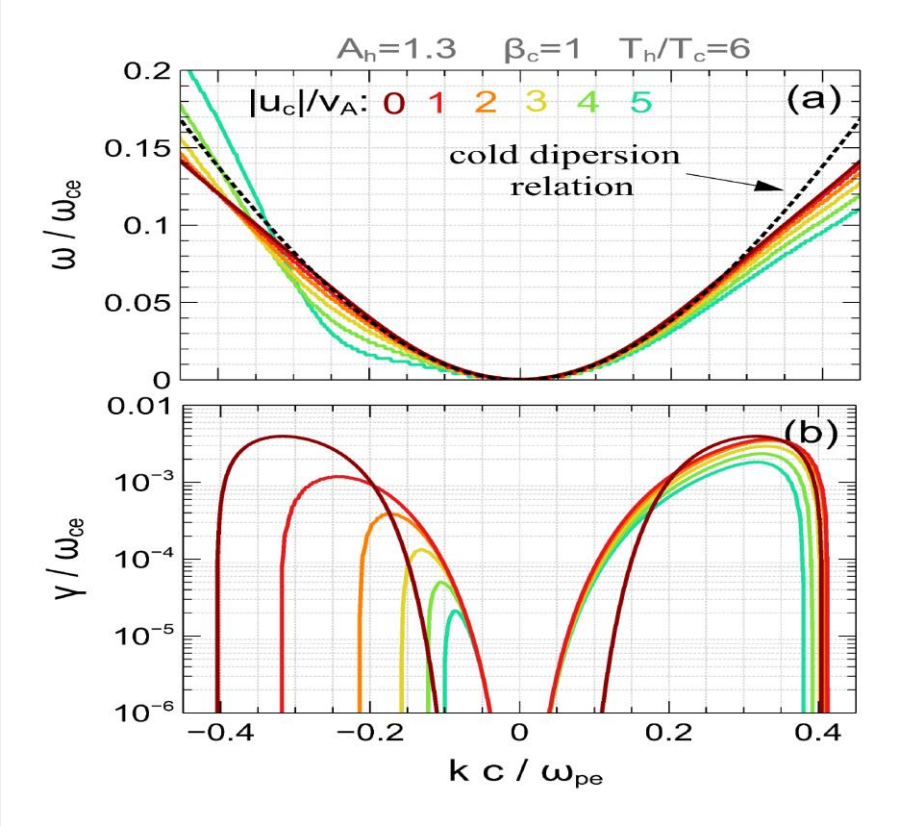
$q_e/q_0 = 0.45$, various β_c

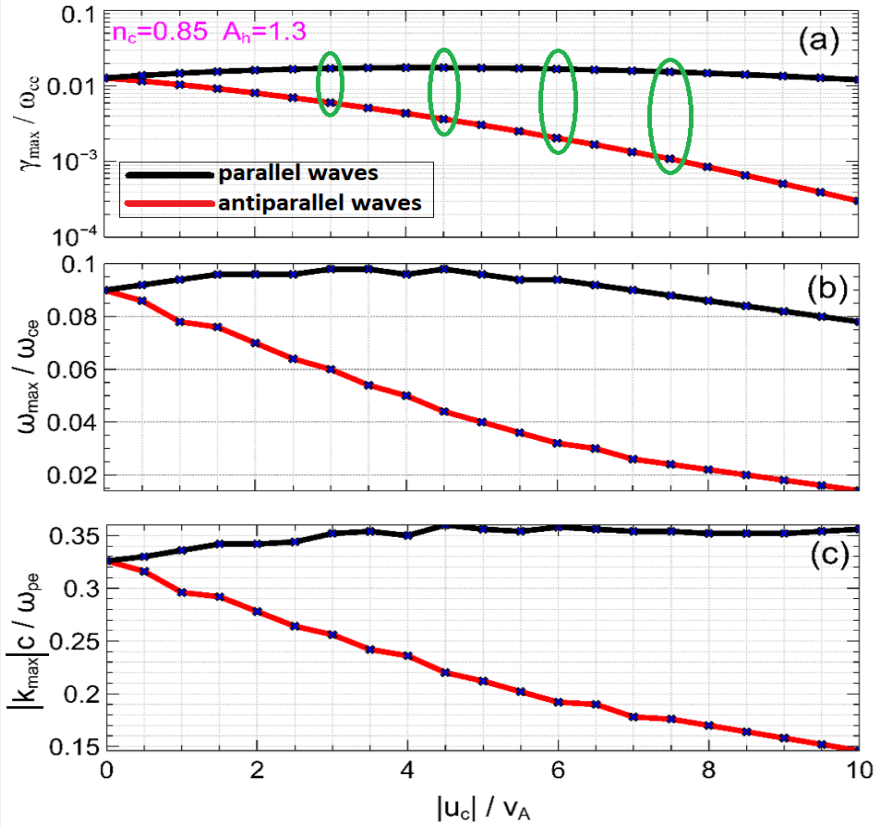
Heat flux variation is less than 3%



Effects of anisotropy on WHFI

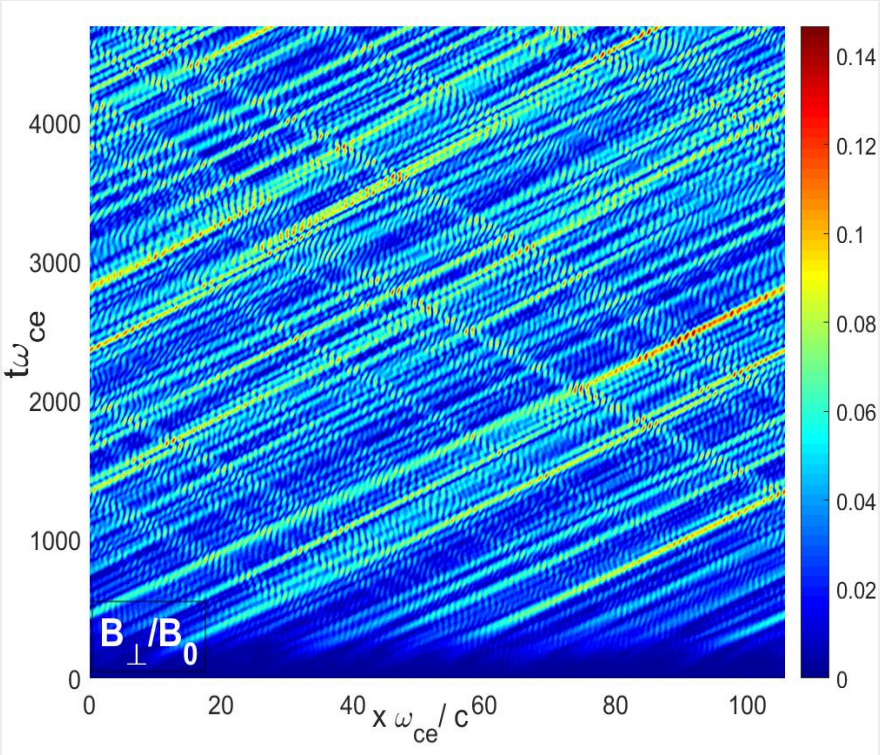
$$F_e = \frac{n_c}{(2\pi v_c^2)^{3/2}} \exp\left(-\frac{(\vec{v}-\vec{u}_c)^2}{2v_c^2}\right) + \frac{n_h}{(2\pi v_h^2)^{3/2} A} \exp\left(-\frac{(v_\parallel - u_h)^2}{2v_h^2} - \frac{v_\perp^2}{2v_h^2 A}\right)$$



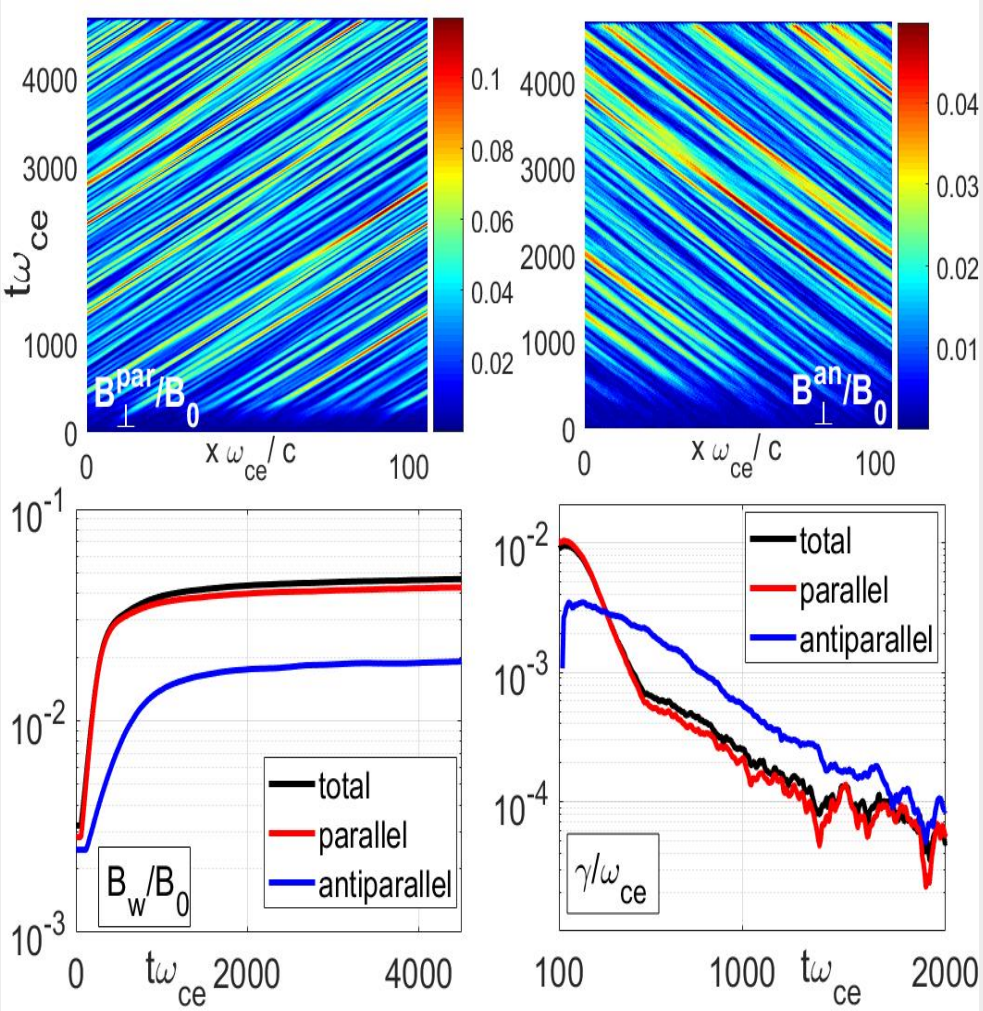


Results of the simulations

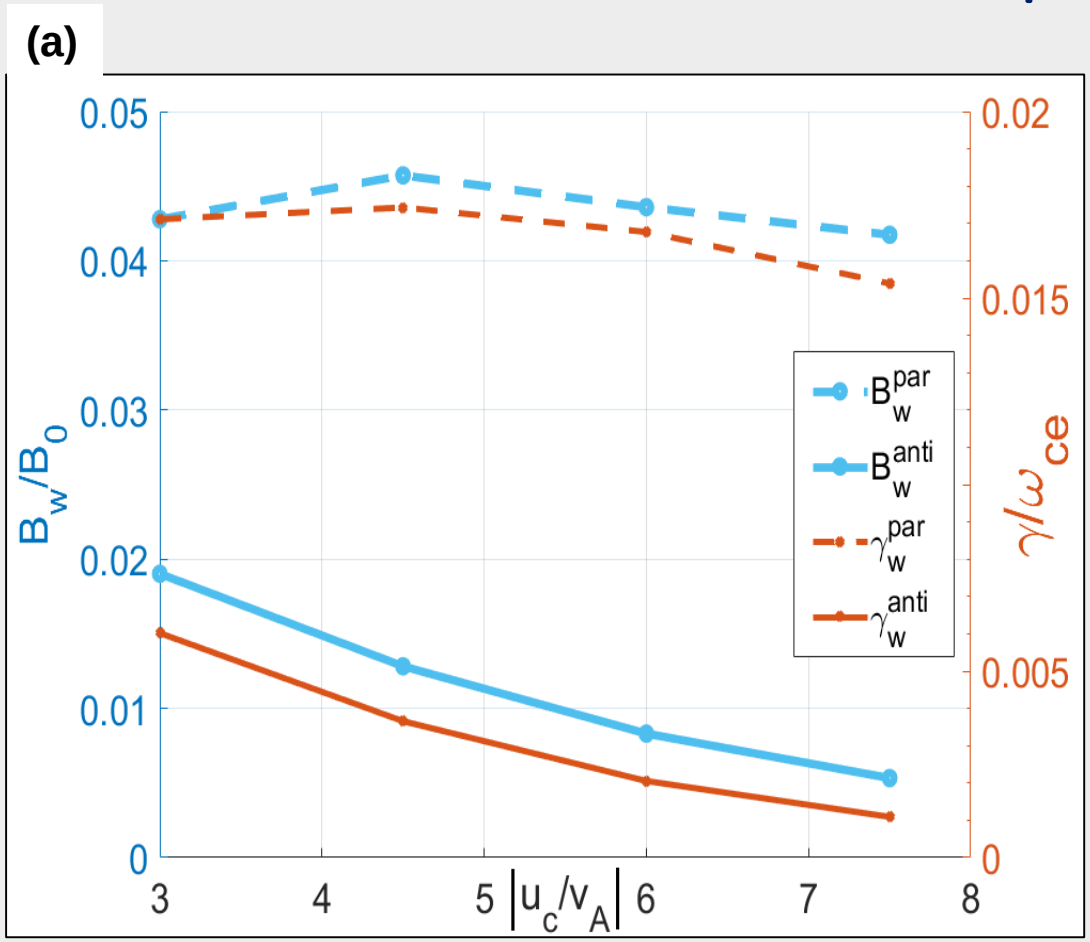
$\beta_c = 1,\ n_c = 0.85, u_c = -3v_A, A = 1.3, v_h^2/v_c^2 = 6$

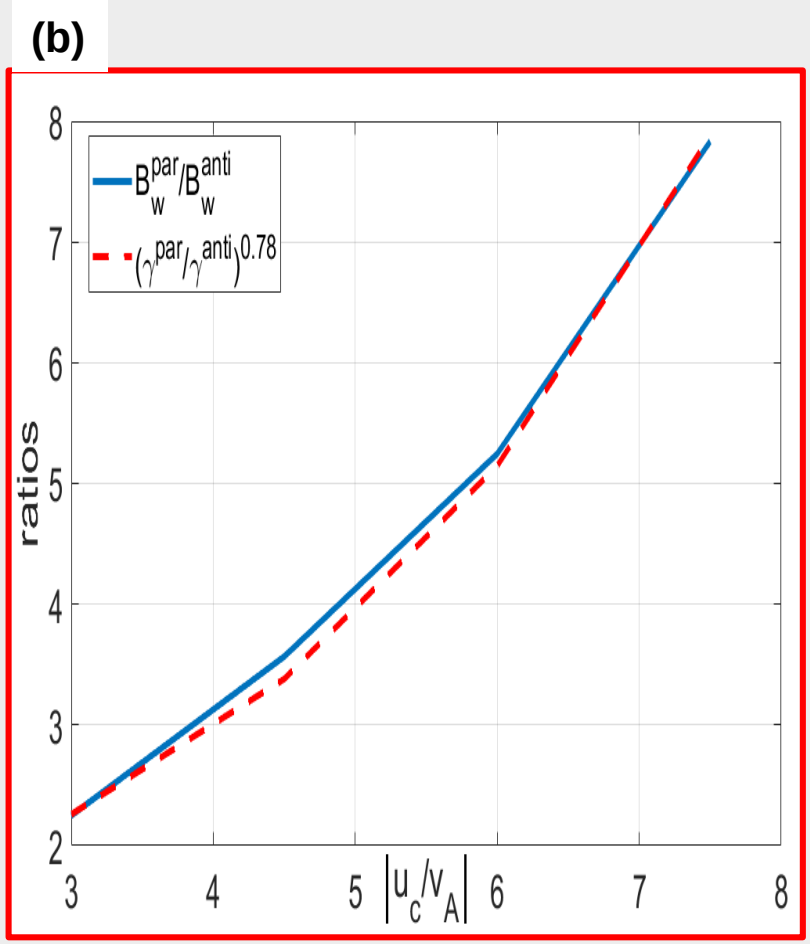


$$B_w(t) = \sqrt{< B_\perp^2(t,x) >_x}$$



Saturated amplitude

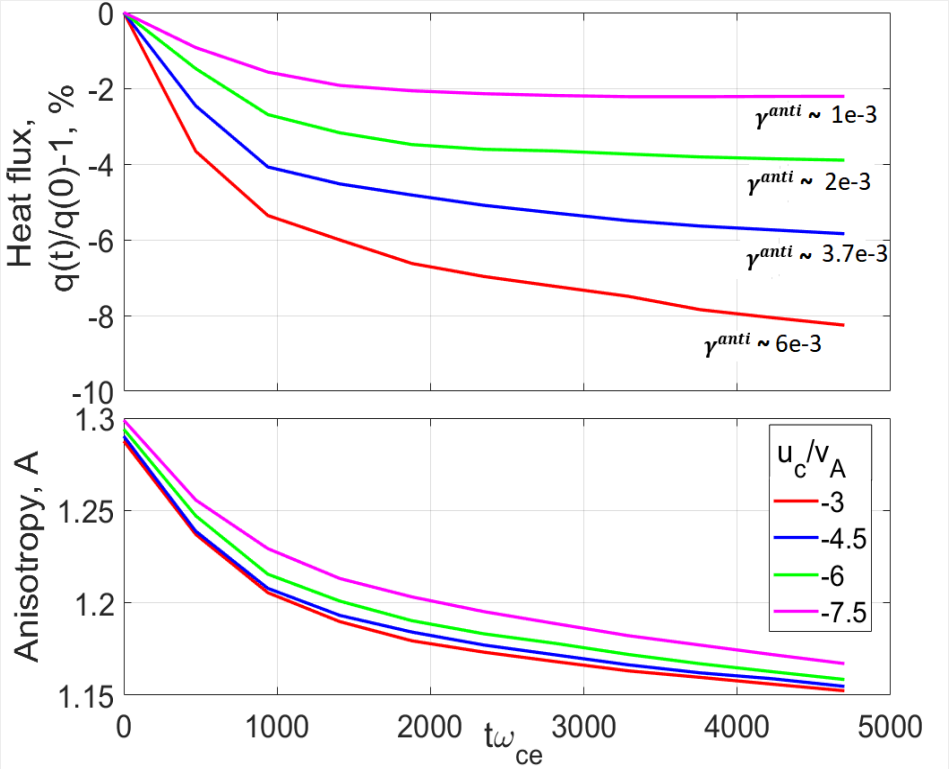




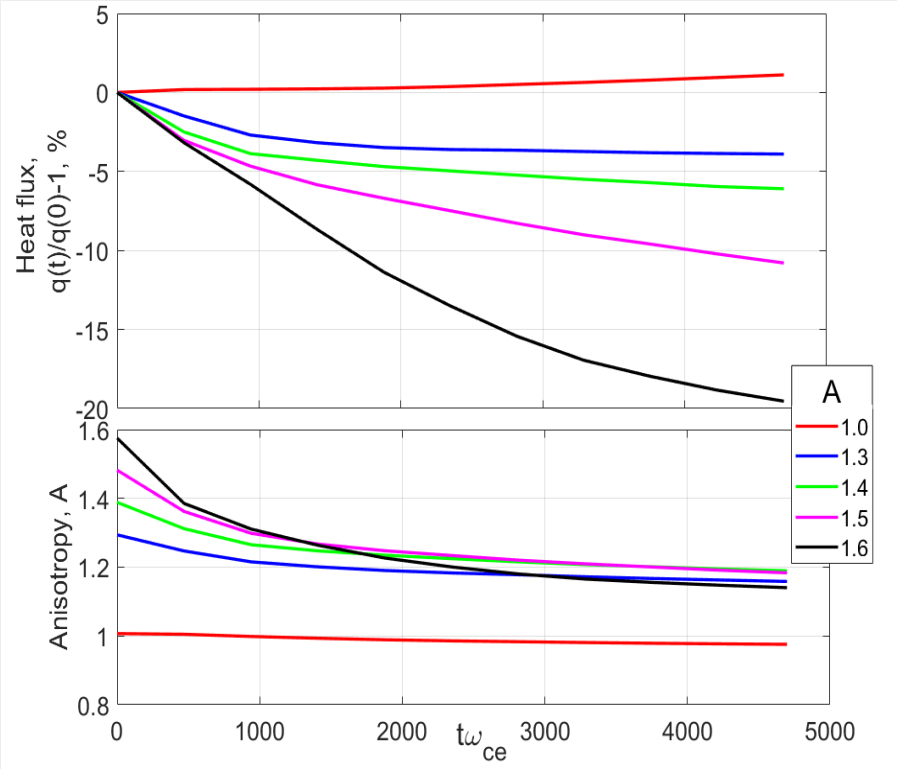
Does anisotropy help with the heat flux?

$A = 1.3$, various u_c/v_A or, equivalently, q_e/q_0

Heat flux variation decreases with $\boldsymbol{u_c}$ ($\boldsymbol{\gamma^{anti}}$ ↓)



$u_c/v_A = -6$ and different anisotropies ($\boldsymbol{\gamma^{anti}}$ increases with A)

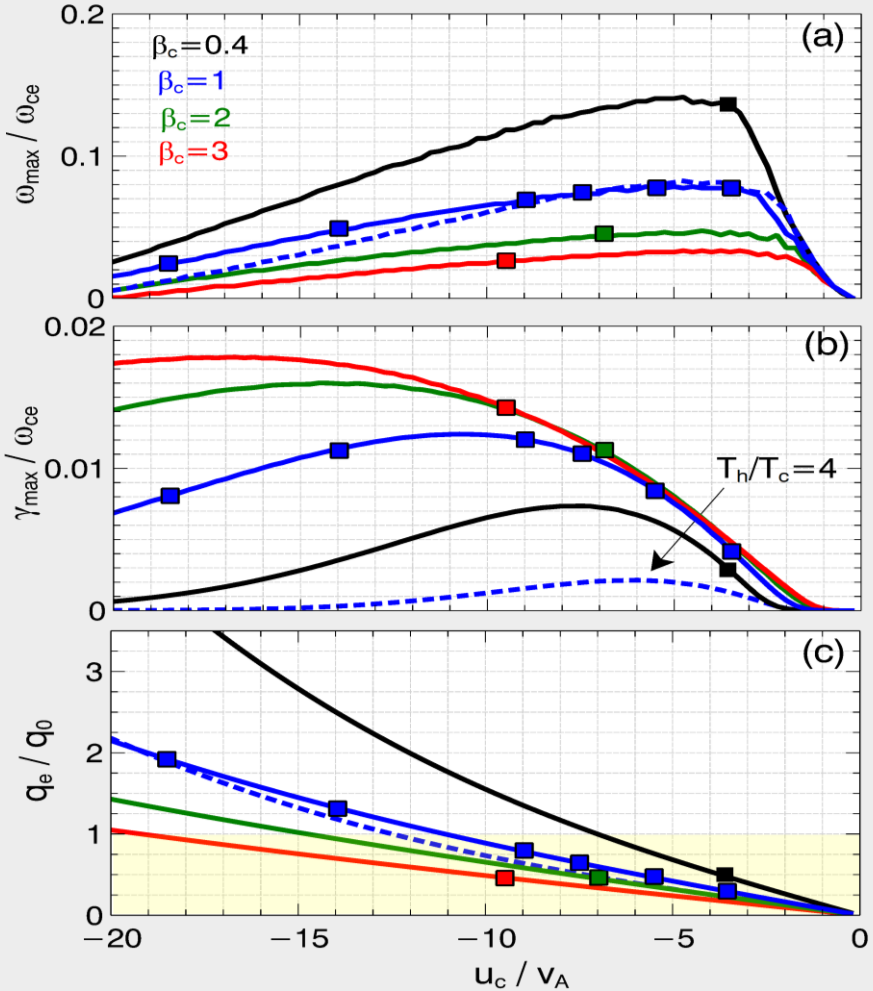


Summary

- We have successfully simulated the generation of whistler waves driven by the whistler heat flux instability combined with anisotropy instability.
- The amplitudes and frequencies of the generated waves are in agreement with the observations of whistler waves in the solar wind.
- For small heat flux, the wave amplitude is positively correlated with the heat flux. For larger heat flux, the correlation becomes negative. This is consistent with the observations.
- We have found a positive correlation between linear increment and saturated wave amplitude.
- Our calculations suggest that parallel whistler-mode waves cannot control the electron heat flux in the solar wind, but anti-parallel waves generated via combined heat flux + anisotropy instability can contribute to the heat flux regulation.

Thank you!

Fastest growing whistler wave at various $(\beta_c, u_c/v_A)$



- core+halo electron VDF
- core density 0.85 n_0, T_h/T_c=10 or 4
- halo ten times hotter than core in simulations (a bit higher than in reality)
- squares indicate initial conditions for simulations
- two sets of simulations:

1st: β_c=1 and various u_c/v_A or, equivalently, q_e/q_0

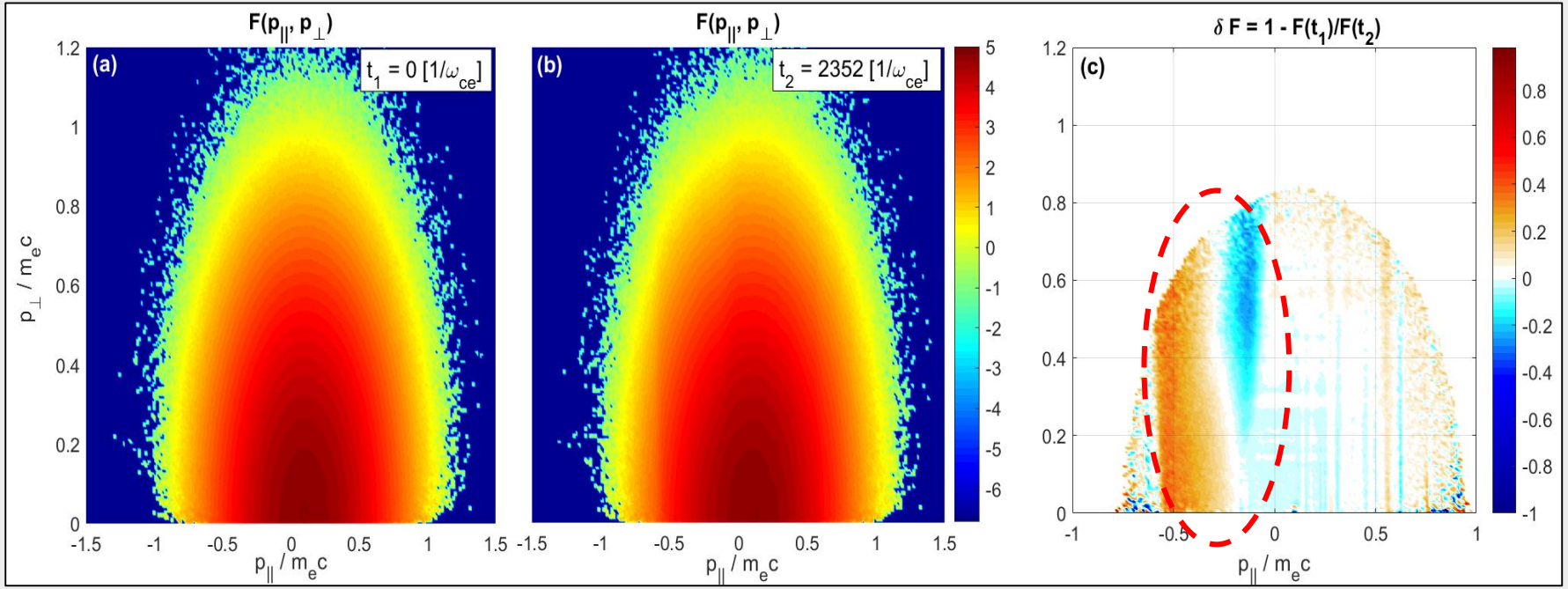
2nd: q_e/q_0~0.45 and various β_c

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

$$q_0 = \frac{3}{2} n_e T_e \sqrt{2T_e/m_e}$$

What leads to the instability saturation?

$$H = \frac{\vec{p}^2}{2m_e} + A_{eff}\sin(kx + \phi_g - \omega t) \rightarrow \frac{d}{dt}(kx + \phi_g - \omega t) = 0 \rightarrow v_R = \frac{\omega - \omega_c}{k}$$



- electrons in the first normal cyclotron resonance $v \approx v_R$ provide energy for the whistler wave growth

- the scattering of resonant electrons by the growing whistler waves leads to formation of the **plateau**, resulting in saturation of the wave growth