Cold electron impact on parallel-propagating whistler chorus waves

Opal Issan [1, 2] Gian Luca Delzanno [2] Vadim Roytershteyn [3] Salomon Janhunen [2]

[1]Department of Mechanical and Aerospace Engineering, University of California San Diego

[2]T-5 Applied Mathematics and Plasma Physics Group, Los Alamos National Laboratory

[3]Space Science Institute

Background and motivation

- Cold electrons = below 100eV ⇒ "hidden population" due to spacecraft charging.
- Recently, Roytershteyn et al. [1, 2] identified secondary instabilities that involve direct energy exchange between the cold plasma and parallel propagating chorus waves, suggesting that cold plasma heating could significantly damp parallel propagating whistler waves.
- We aim to quantify this energy exchange via quasilinear theory.
- We also speculate that the electrostatic drift-driven instabilities between cold electrons and ions may contribute to the discrepancy between simulated and observed energies of parallel-propagating whistler waves.

How do cold electrons impact the whistler anisotropy instability?

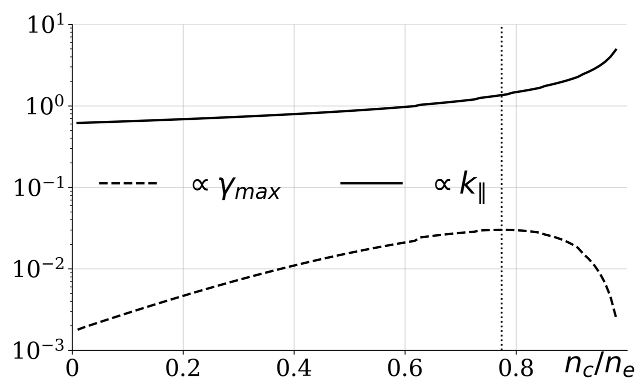
- What causes the instability? hot electron anisotropy (source of "free energy")

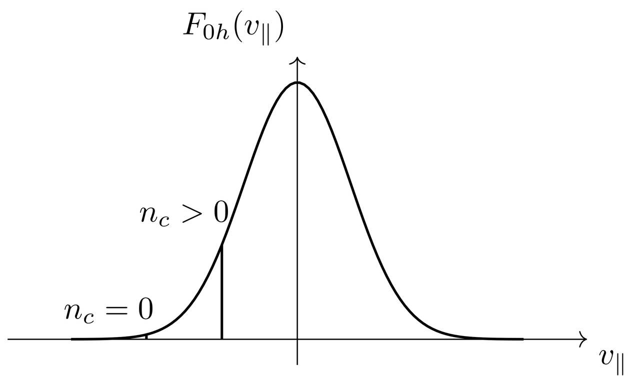
$$A_h := \frac{T_{\perp h}}{T_{\parallel h}} - 1 > 0$$

- Resonance for parallel propagating whistler waves

$$v_\parallel^{\text{res}} = \frac{\omega - |\Omega_{ce}|}{k_\parallel}$$

- As $\frac{n_c}{n_e}\uparrow$ then $k_\parallel \uparrow$, and $v_\parallel^{\text{res}}\downarrow$, allowing a larger portion of the hot electron distribution to resonate with the wave leading to $\gamma_{\max}\uparrow$ [3].
- As $\frac{n_c}{n_e}\uparrow$ then $\beta_{\parallel h}^{\text{critical}}\downarrow \Rightarrow$ parallel-propagating whistler.





Beyond linear theory ⇒ quasilinear theory (QLT)

- Parallel propagating whistler instability QLT [4]:

$$\partial_t F_{0h}(\vec{v},t) = \nabla_{\vec{v}} \cdot \left[\mathcal{D}(\vec{v}, k_\parallel, t, \vec{B}_W)\cdot \nabla_{\vec{v}} F_{0h}(\vec{v},t)\right] \quad (1)$$

$$\partial_t |\vec{B}_W(k_\parallel,t)|^2 = 2\gamma(k_\parallel,t)|\vec{B}_W(k_\parallel,t)|^2 \quad (2)$$

+ dispersion relation depending on $\frac{n_c}{n_e}, \ldots$

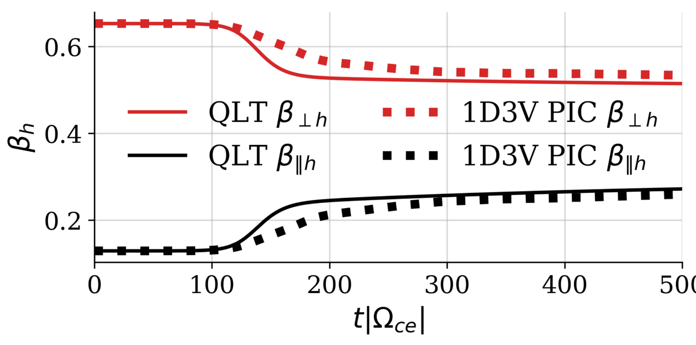
- We assume $F_{0h}(\vec{v},t)$ is bi-Maxwellian for all times:

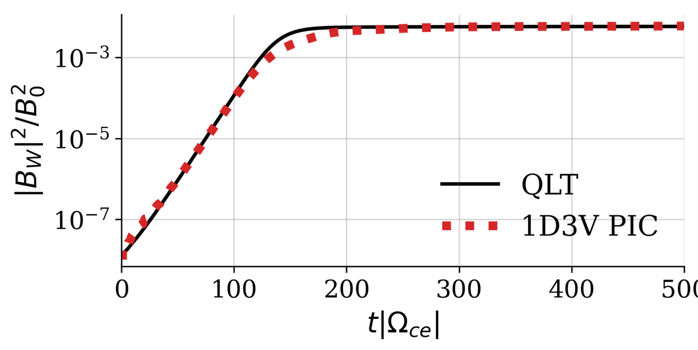
$$F_{0h} \propto \exp\left(-\frac{m_e}{2}\left[\frac{v_\parallel^2}{T_{\parallel h}(t)} + \frac{v_\perp^2}{T_{\perp h}(t)}\right]\right) \quad (3)$$

and take moments of Eq. (1)

$$\frac{\mathrm{d}T_{\perp h}}{\mathrm{d}t} = \mathcal{F}_{\perp h}\left(k_\parallel, \omega, A_h, \vec{B}_W\right) \quad (4)$$

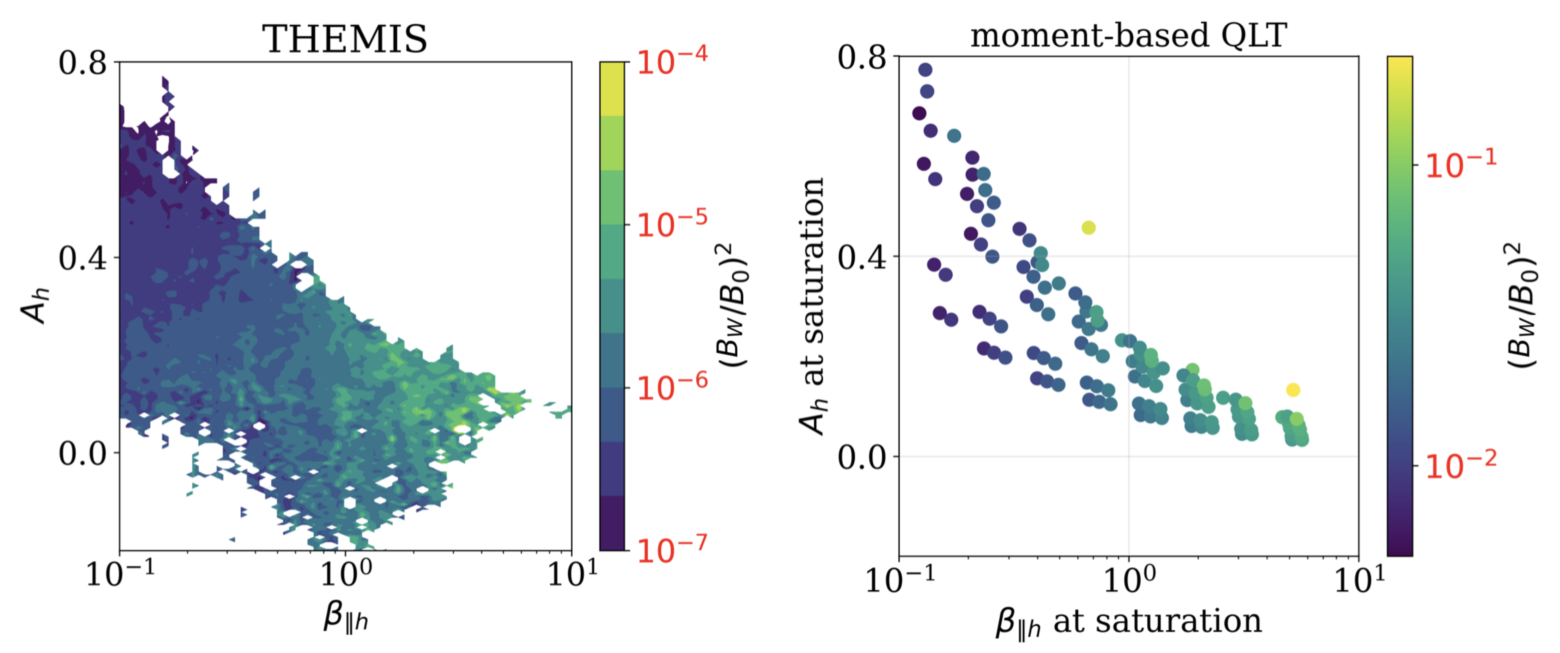
$$\frac{\mathrm{d}T_{\parallel h}}{\mathrm{d}t} = \mathcal{F}_{\parallel h}\left(k_\parallel, \omega, A_h, \vec{B}_W\right) \quad (5)$$





Parametric setup: $\frac{n_c}{n_e}=0.8$ $\frac{\omega_{pe}}{|\Omega_{ce}|}=4$ $T_{\parallel h}(t=0)=2\text{keV}$ $A_h(t=0)=4$ $A_{c/i}(t=0)=0$ $T_{c/i}(t=0)=10\text{eV}$

THEMIS vs. QLT whistler wave magnetic energies



Why do the normalized wave energies differ by a few orders of magnitude?

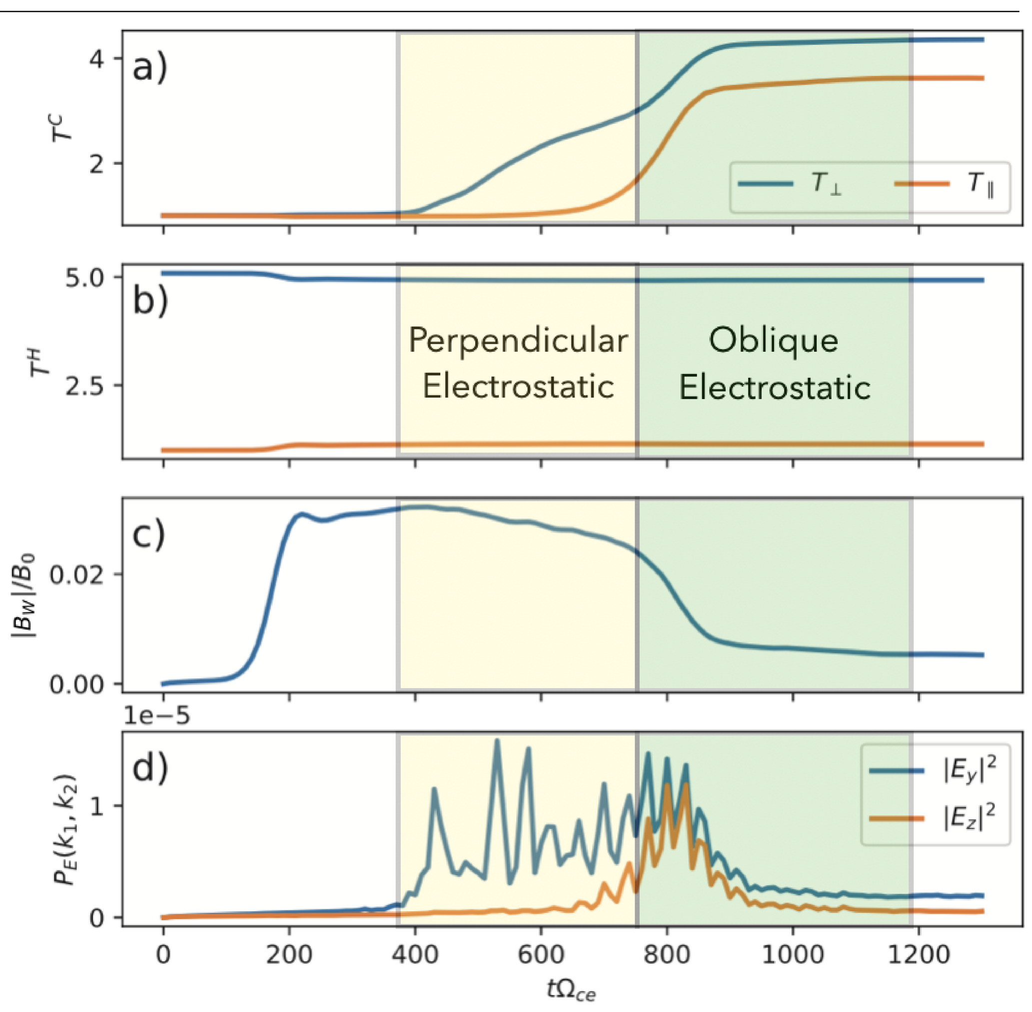
Secondary instabilities as a source of whistler wave damping

- Whistler waves excite electrostatic waves through drift-type secondary instabilities ⇒ heating the cold populations and damping the primary whistler waves.
- Primary whistler as the driver

$$E_{W\perp}(t) := |E_W(t)|\exp(i\omega_0 t)$$
$$B_{W\perp}(t) := i|B_W(t)|\exp(i\omega_0 t)$$
$$\vec{B}_0 := B_0\hat{z}$$

$$V_{\perp s}(t) = \frac{-iq_s}{m_s}\frac{|E_W(t)|}{\omega_0 + \Omega_{cs}}\exp(i\omega_0 t)$$

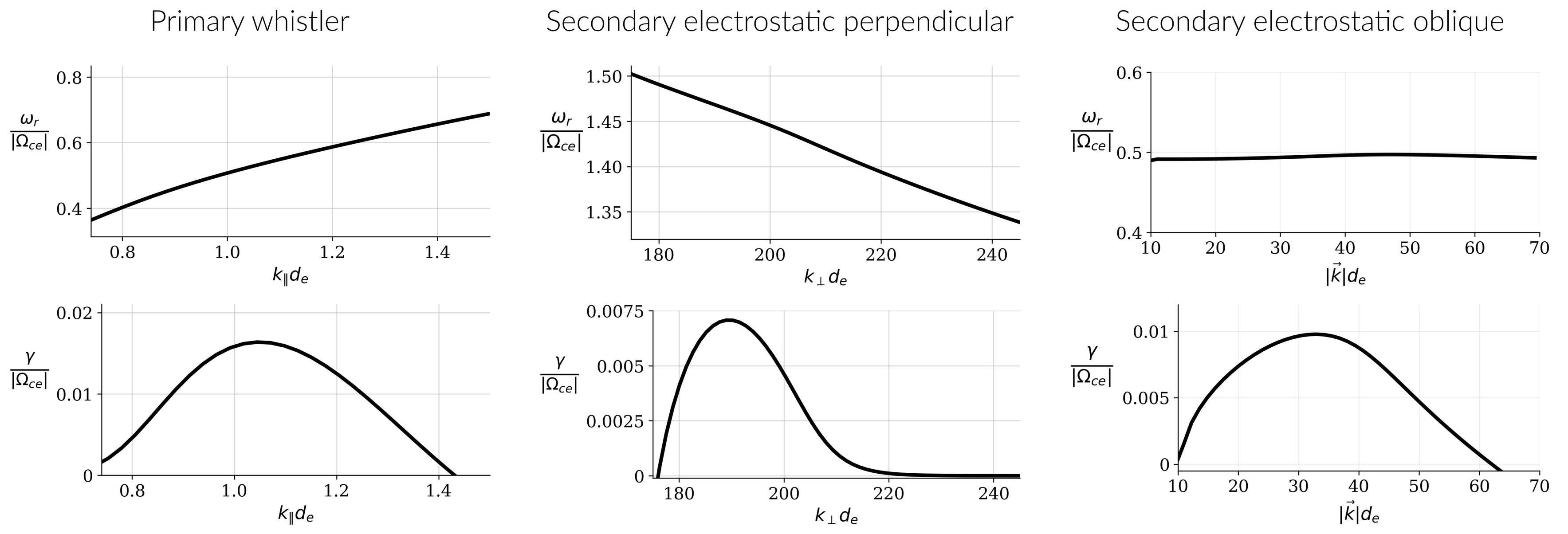
$|V_{\perp i}| \ll |V_{\perp c}| \sim \sqrt{T_c/m_e}$ and $|V_{\perp h}| \ll \sqrt{T_h/m_e}$



Credit: Figure 8 in [1] 3D3V PIC $\sim 10^6$ CPU hours.

Understanding the secondary instabilities via linear theory

Parametric setup: $\frac{n_c}{n_e}=0.8$ $\frac{|V_{\perp c}(t=0)|}{d_e|\Omega_{ce}|}=0.005$ $\frac{\omega_{pe}}{|\Omega_{ce}|}=4$ $\frac{\omega_0}{|\Omega_{ce}|}=0.5$ $k_{\parallel 0}d_e=1$ $A_{c/i}(t=0)=0$ $T_{c/i}(t=0)=1\text{eV}$



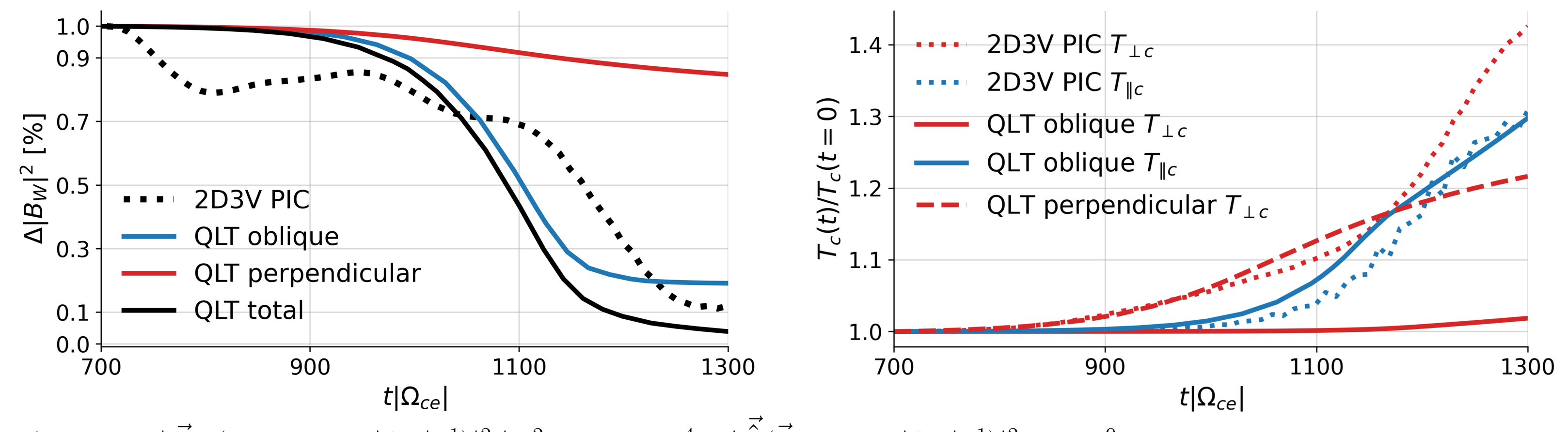
Understanding the secondary instabilities via QLT

- Electrostatic QLT equations in magnetized plasma [4]:

$$\partial_t F_{0c}(\vec{v},t) = \frac{1}{v_\perp}\partial_{v_\perp}\left[v_\perp\left[\mathcal{D}_{\perp\perp}\partial_{v_\perp}F_{0c} + \mathcal{D}_{\perp\parallel}\partial_{v_\parallel}F_{0c}\right]\right] + \partial_{v_\parallel}\left[\mathcal{D}_{\parallel\perp}\partial_{v_\perp}F_{0c} + \mathcal{D}_{\parallel\parallel}\partial_{v_\parallel}F_{0c}\right] \quad (6)$$

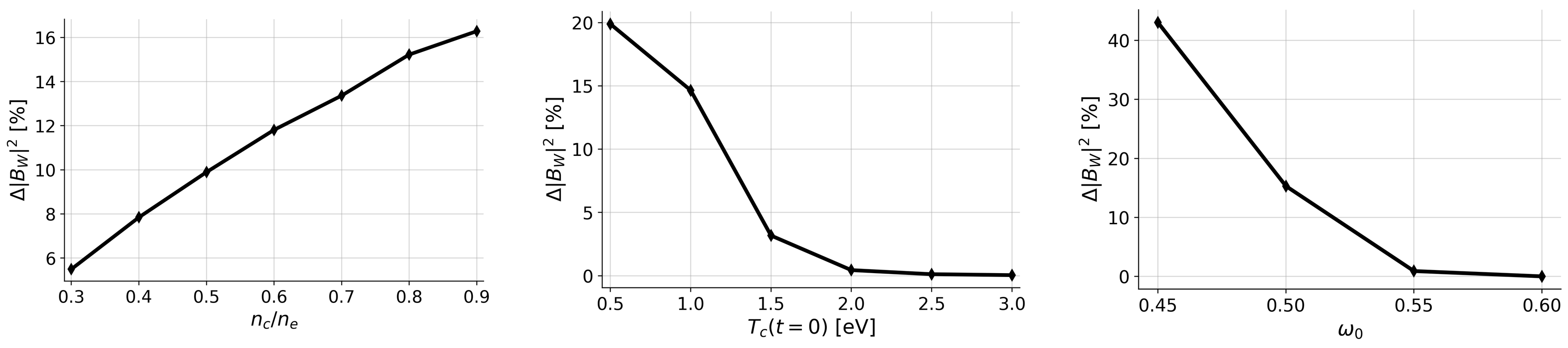
$$\begin{bmatrix}\mathcal{D}_{\perp\perp}\\ \mathcal{D}_{\perp\parallel}\\ \mathcal{D}_{\parallel\parallel}\end{bmatrix} := \frac{ie^2}{m_e^2}\sum_{n=-\infty}^{\infty}\int \mathrm{d}\vec{k}\frac{|\vec{E}(\vec{k},t)|^2}{|\vec{k}|^2}\frac{J_n^2(k_\perp v_\perp/\Omega_{ce})}{\omega - k_\parallel v_\parallel - n\Omega_{ce}}\begin{bmatrix}\frac{n^2\Omega_{ce}^2}{v_\perp^2}\\ \frac{n\Omega_{ce}k_\parallel}{v_\perp}\\ k_\parallel^2\end{bmatrix} \quad (7)$$

- We assume $F_{0c}(\vec{v},t)$ is bi-Maxwellian, see Eq. (3), and take moments of Eq. (6).
- We derive the whistler damping rate by conservation of energy.

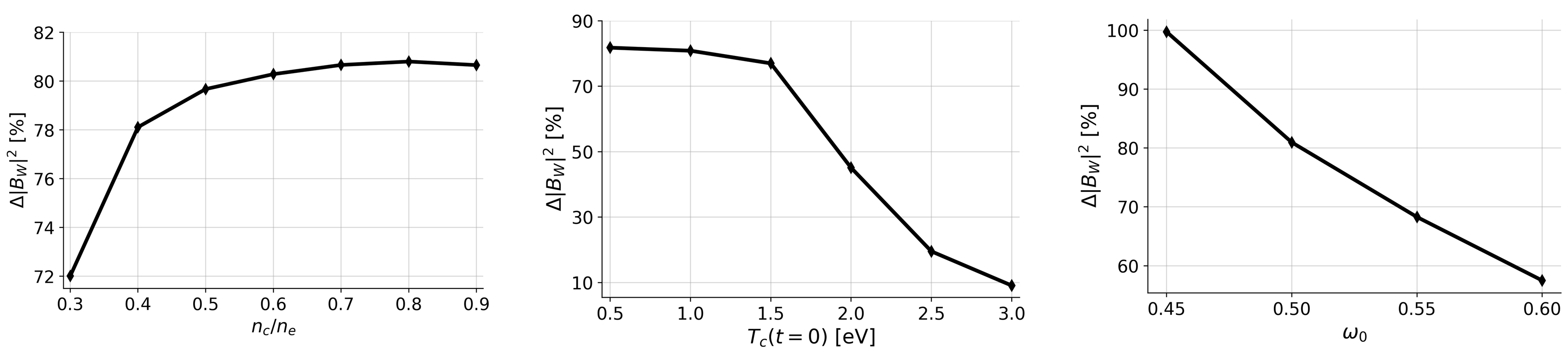


Parametric setup: $|\vec{B}_W(k_{\parallel 0}, t=700|\Omega_{ce}|^{-1})|^2/B_0^2 = 4\times 10^{-4}$ $|\vec{E}(\vec{k}, t=700|\Omega_{ce}|^{-1})|^2 = 10^{-9}$

Parametric dependence of secondary perpendicular waves as a damping source



Parametric dependence of secondary oblique waves as a damping source



Conclusions and future work

- Parallel propagating whistler waves are damped due to secondary drift-driven instabilities between cold electrons and ions.
- Both secondary instabilities weaken significantly as $T_c(t=0)\uparrow$. Changes in $\frac{n_c}{n_e}\in[0.6, 0.9]$ do not significantly impact the energy exchange.
- Open questions and future directions:
  1. How do observations of the secondary electrostatic waves compare to QLT?
  2. Are EMIC waves and cold ions susceptible to the same secondary instabilities?

Link to preprint

Acknowledgment

This research was partially supported by the Los Alamos National Laboratory Center for Space and Earth Science Student Fellowship. We thank Myeong Joon Kim for providing the THEMIS whistler data.

References

[1] V. Roytershteyn and G. L. Delzanno. *Nonlinear coupling of whistler waves to oblique electrostatic turbulence enabled by cold plasma*. Physics of Plasmas, 28(4):042903, 04 2021.

[2] V. Roytershteyn, G. L. Delzanno, and J. Holmes. *Oblique instability of quasi-parallel whistler waves in the presence of cold and warm electron populations*. Frontiers in Astronomy and Space Sciences, 11, 2024.

[3] S. Cuperman and R. W. Landau. *On the enhancement of the whistler mode instability in the magnetosphere by cold plasma injection*. Journal of Geophysical Research, 79(1):128–134, 1974.

[4] C. F. Kennel and F. Engelmann. *Velocity Space Diffusion from Weak Plasma Turbulence in a Magnetic Field*. The Physics of Fluids, 9(12):2377–2388, 12 1966.