Parallel Fast-Magnetosonic/Whistler Instability Driven by Temperature Anisotropic Proton Beam in Solar Wind

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Introduction

Wave-particle instabilities are driven by deviations of Velocity Distribution Functions (VDF) from Maxwellian equilibrium. *In situ* measurements have shown that proton VDFs in the solar wind exhibit non-Maxwellian features including the existence of a magnetic field-aligned proton beam alongside the ambient proton population. The secondary proton population is observed to have a drift velocity U_b with respect to the core comparable to the local Alfven velocity v_A.

Proton-beams may provide a sufficient source of free energy to excite electromagnetic instabilities. Linear Vlasov theory shows that in a plasma containing a proton core (c), proton beam (b) and electrons (e), the proton beam can induce three types of instabilities: oblique Alfven/ion cyclotron (A/IC), oblique Fast-Magnetosonic/Whistler (FM/W), and parallel FM/W instabilities. The growth of these instabilities lead to the conversion of energy from the proton beam to plasma waves, causing a reduction in the proton beam drift velocity. This sets an upper bound on the drift velocity of proton beams in the solar wind.

In this study, we investigate the parallel FM/W instability in the presence of an anisotropic proton beam. We derive analytic expressions for this instability's thresholds, which show the effects of the proton beam temperature anisotropy and parallel proton beta on the real frequency and growth rate of the proton beam instability. We compare the analytical threshold expressions with numerical solutions to the full hot-plasma dispersion relation.

Instability of the FM/W Mode

The model consisting of Vlasov and Maxwell's equations to a collisionless plasma with a background magnetic field of the form $\boldsymbol{B}_0 = (0, 0, B_0)$, yields the wave equation in Fourier space

$$\frac{\boldsymbol{kc}}{\omega} \times \left(\frac{\boldsymbol{kc}}{w} \times \boldsymbol{E}_k\right) + \varepsilon \boldsymbol{E}_k = 0$$

where ε is the dielectric tensor and E is the wave electric field. The plasma eigen modes correspond to solutions of the equation.

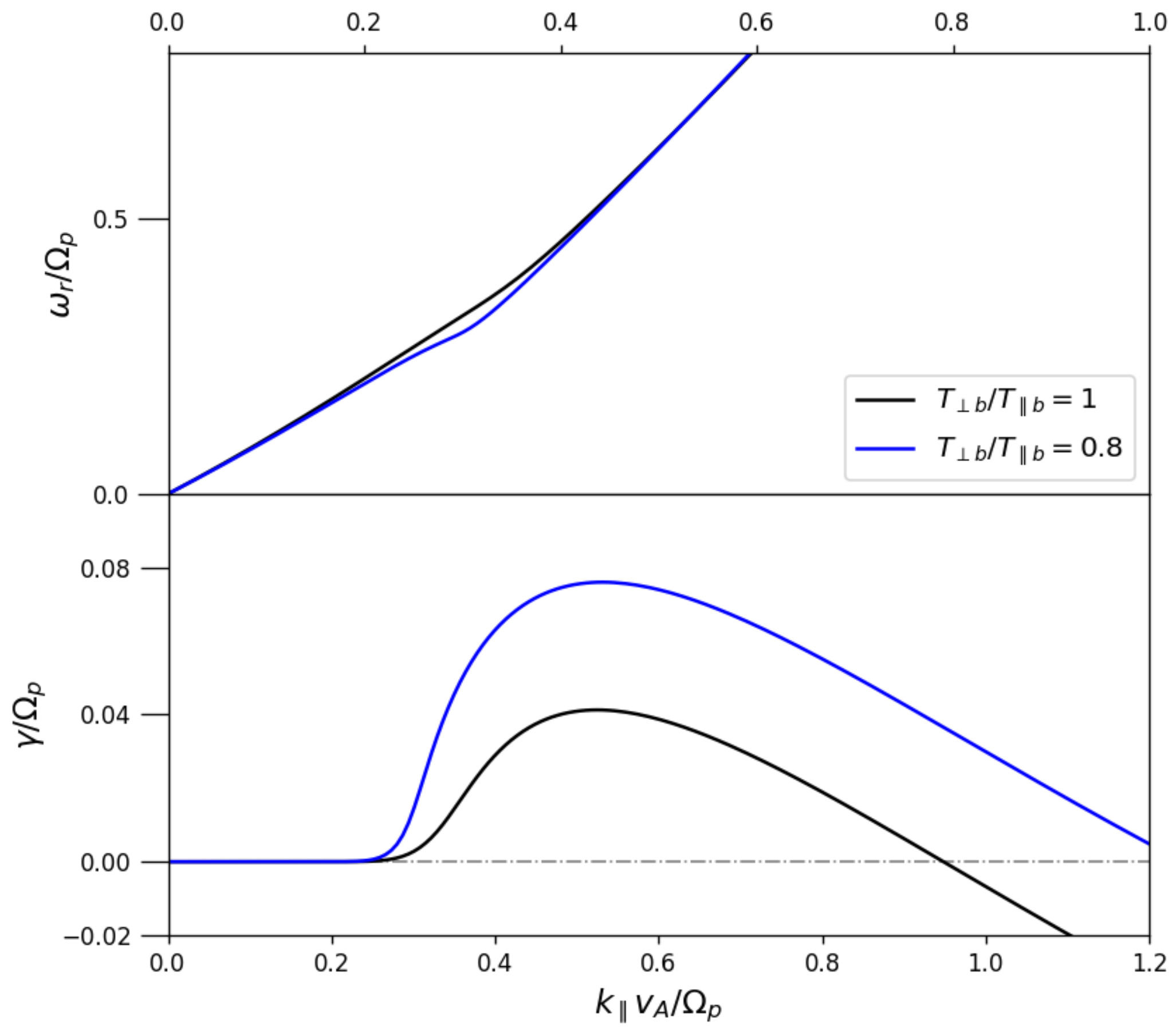

Figure 1: Real frequency and growth rate of FM/W mode as a function of normalized wavenumber for $U_b = 1.6 v_A$, $T_{\perp b} / T_{\parallel b} = 0.8$ (blue) and 1 (black), $w_{\parallel b} = \sqrt{1.2}\, v_A$, and $\sigma = 2.45$.

Analytic Instability Thresholds

- For $|\gamma| \ll |\omega_{kr}|$, only waves particles fulfilling the resonance condition participate in resonant wave–particle interactions:

$$\omega_{kr} = k_\parallel v_\parallel + n\Omega_p$$

- For the right-circularly polarized FM/W waves propagating parallelly, proton damping occurs at the $n = -1$ resonance.
- Instability occurs if secondary protons with $v_\parallel = U_b + \sigma w_{\parallel b}$ resonate with the wave, where σ is a constant of order unity.
- The resonant line of secondary protons is

$$\omega_{kr} = k_\parallel (U_b + \sigma w_{\parallel b}) - \Omega_p$$

- The point (k', ω') is the intersection of the secondary proton resonance line in the $\omega_{kr} - k_\parallel$ plane with the solution to the dispersion relation for FM/W wave.
- Only solutions of the dispersion relation at $k_\parallel > k'$ and $\omega_{kr} > \omega'$ can interact resonantly with a sufficiently large number of protons in the beam to excite an instability.

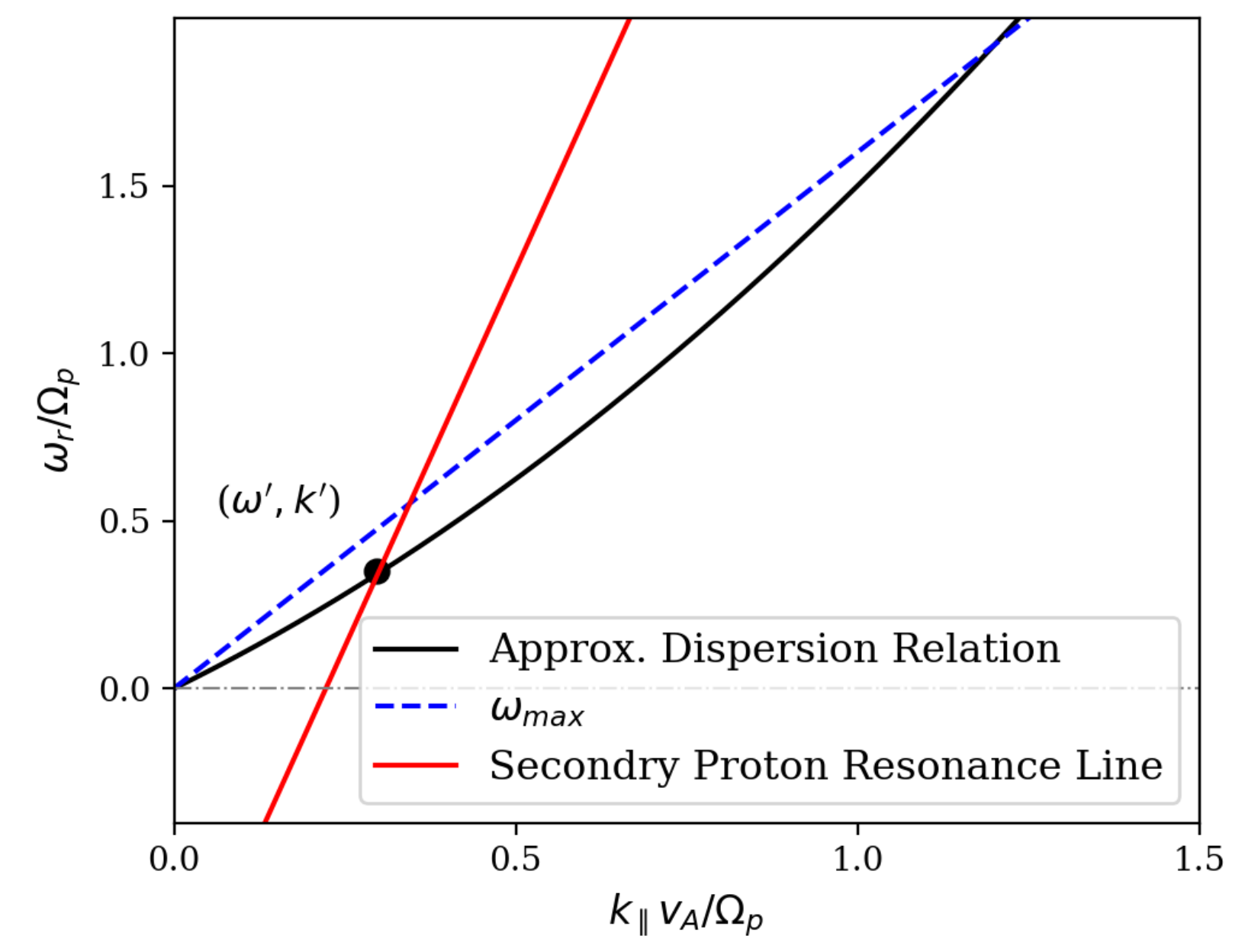

Figure 2: FM/W mode resonance and instability conditions.

Conditions for the FM/W wave to be unstable:

- There is a range of wavenumbers $k > k'$ with $\omega_{kr} < \omega_{max}^{FM/W}$ at which secondary protons have a destabilizing influence on the wave at a given temperature anisotropy, drift, and wavenumber:

$$\omega_{max}^{FM/W} = \Omega_b \left(\frac{T_{\parallel b}}{T_{\perp b}} - 1\right) + k_\parallel U_b$$

leading to an upper limit for the drift velocity of proton beams:

$$\frac{U_b}{v_a} > 1 + \left(\frac{T_{\parallel b}}{2 T_{\perp b} \sigma w_{\parallel b}}\right) + \sigma w_{\parallel b} \left(\frac{T_{\perp b}}{T_{\parallel b}} - 1\right)$$

which determines a lower threshold for the temperature anisotropy at a given drift speed:

$$\frac{T_{\perp b}}{T_{\parallel b}} < \frac{U_b + \sigma w_{\parallel b} - v_A + \sqrt{(U_b + \sigma w_{\parallel b} - v_A)^2 - 2 v_A^2}}{\sigma w_{\parallel b}}$$

- The proton thermal speed must be sufficiently small such that proton damping can be neglected:

$$\sigma w_{\parallel p} < \frac{(3U_b + 3\sigma w_{\parallel b} - v_A) + \sqrt{(U_b + \sigma w_{\parallel b} - v_A)^2 - 2 v_A^2}}{2}$$

- If thermal protons can resonate with the FM/W wave, then proton damping dominates over any possible destabilizing influence from the resonant protons in proton beam.

Instability Criteria

- Parallel propagating FM/W waves are stable/unstable as a function of five parameters: $w_{\parallel b} / v_A$, U_b / v_A, $T_{\perp b} / T_{\parallel b}$, $T_{\parallel b} / T_p$, and n_b / n_p.
- The proton core and electrons are assumed to have Maxwellian distribution functions.
- Plasma parameters used in Figure 3 are: $n_b / n_p = 0.25$, $T_b = T_p = T_e$, $\sigma = 2.45$.

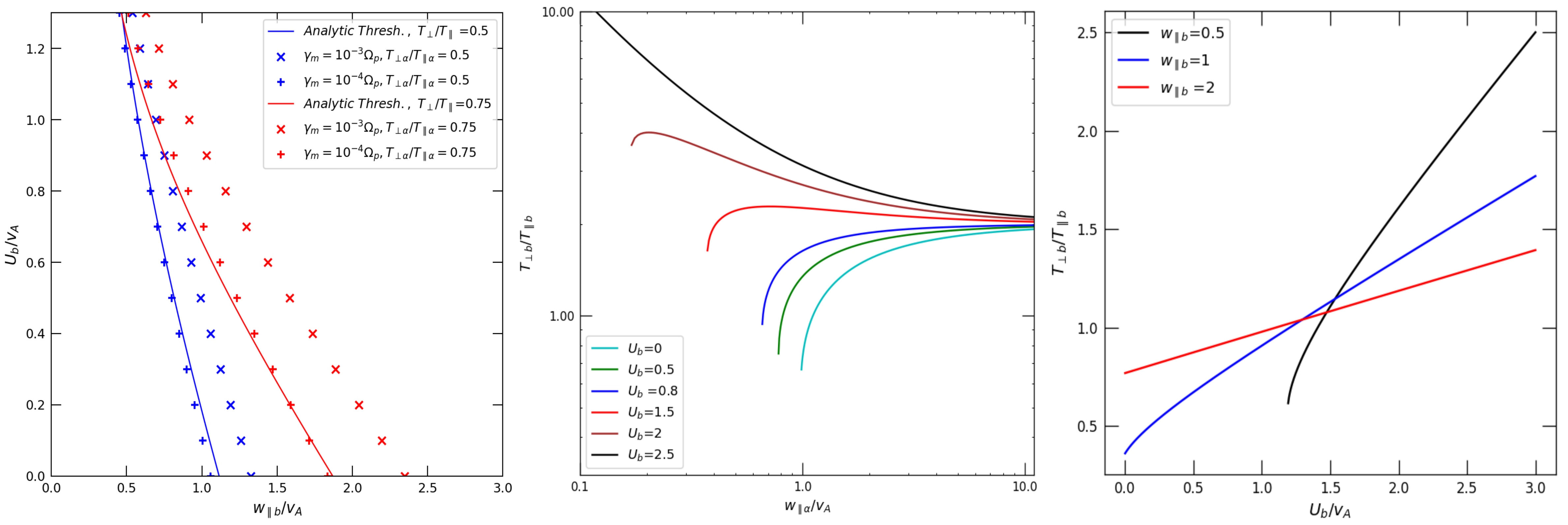

Figure 3: (left) The comparison of the analytic instability criterion and numerical solutions to the hot-plasma dispersion relation in the U_b / v_A and $w_{\parallel b} / v_A$ plane, (middle) Upper thresholds of instability in the $T_{\perp b} / T_{\parallel b}$ and $w_{\parallel b} / v_A$ plane, (right) Instability thresholds for different values of U_b / v_A in the $T_{\perp b} / T_{\parallel b}$ and $w_{\parallel b} / v_A$ plane.

Contours of Constant γ_m

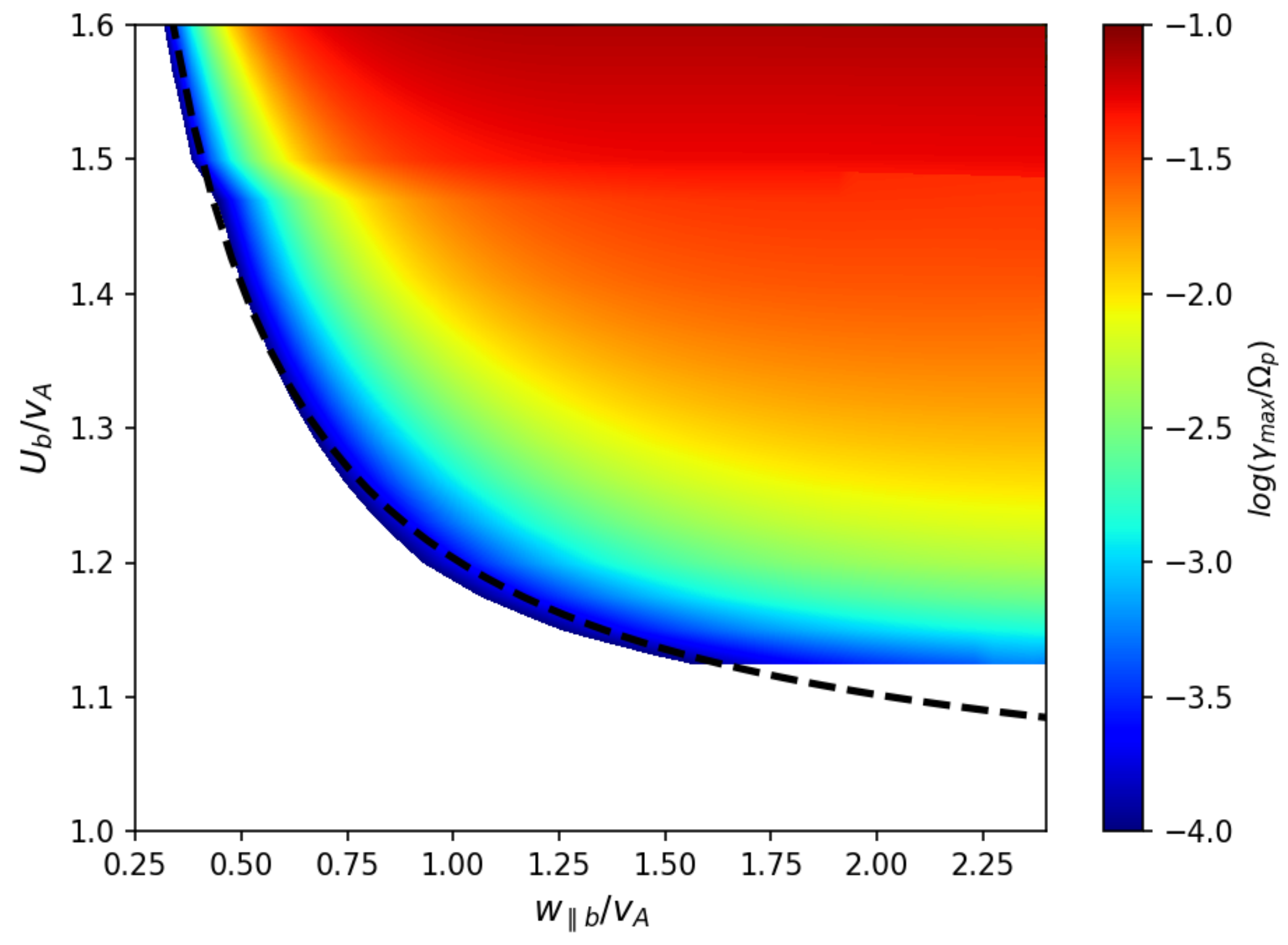

Figure 7: Contour plot of maximum growth rate as a function of $w_{\parallel b}$ and U_b. The black dashed line is the lower analytic threshold. The plasma parameters used are the same as in Figure 4.

- The quantity σ is the maximum number of thermal speeds that $v_\parallel$ can deviate from the center of the distribution before the number of resonant particles becomes too few to significantly amplify or dampen a wave mode.
- σ determined by comparing analytic thresholds to numerical solutions of the hot-plasma dispersion relation for $T_{\perp b} / T_{\parallel b} = 1$
- The choice of $\sigma = 2.45$ corresponds to parameter combinations for the maximum growth rate $\gamma_m \simeq 10^{-4} \Omega_p$.

Summary and Future Work

The FM/W wave is unstable if and only if :

- $U_b + \sigma w_{\parallel b}$ being sufficiently large such that thermal secondary protons can resonate with the FM/W wave.
- U_b and/or $T_{\parallel b} / T_{\perp b}$ being large enough that there is an interval of wavenumbers within which resonant interactions with secondary protons are destabilizing.
- $w_{\parallel p}$ being less than a certain threshold so resonant protons are unable to damp the FM/W waves within at least part of the wavenumber interval

Future Work:

- Compare analytic thresholds with spacecraft observations of solar wind proton beams
- Generalize our study to oblique wave modes

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