

Introduction

In situ measurements of the solar wind reveal that proton Velocity Distribution Functions (VDFs) display distinctly nonthermal kinetic features, including a faster, lower-density, magnetic field-aligned, proton beam alongside a dense core population. The beam is observed to have a drift velocity U_b relative to the core, comparable to the local Alfvén velocity v_A .

Proton beams may provide a sufficient source of free energy to excite plasma 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 Alfvén/ion cyclotron (A/IC), oblique Fast-Magnetosonic/Whistler (FM/W), and parallel FM/W instabilities. If the plasma exceeds the threshold of any of these instabilities, the instability grows. The resulting electromagnetic fluctuations interact with particles, causing a reduction in the free energy that drives the instability.

In this study, we investigate the thresholds of parallel and FM/W instabilities in the presence of an anisotropic proton beam. We derive analytic expressions for the parallel FM/W 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. By analyzing data from the Parker Solar Probe (PSP) spacecraft, we show how the linear FM/W instability can limit the drift velocity and temperature anisotropy of proton beams observed in solar wind.

Resonance Interaction of Beams and Waves

Considering $|\gamma_k| \ll |\omega_k|$, secondary protons with $v_{\parallel} = U_b + \sigma w_{\parallel b}$ can resonate with the right-circularly polarized FM/W wave with real frequency ω_{kr} , only if they fulfill the resonance condition below:

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

where σ is a constant of order unity.

Conditions for the FM/W wave, to be unstable:

- Only solutions of the dispersion relation at $k < k_{max}$ ($\omega_{kr} < \omega_{max}$) can have destabilizing influence on a proton beam at a given temperature anisotropy and drift:

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

- Only solutions of the dispersion relation satisfying $k > k'$ ($\omega_{kr} > \omega'$) can interact resonantly with a sufficiently large number of protons in the beam to excite an instability.

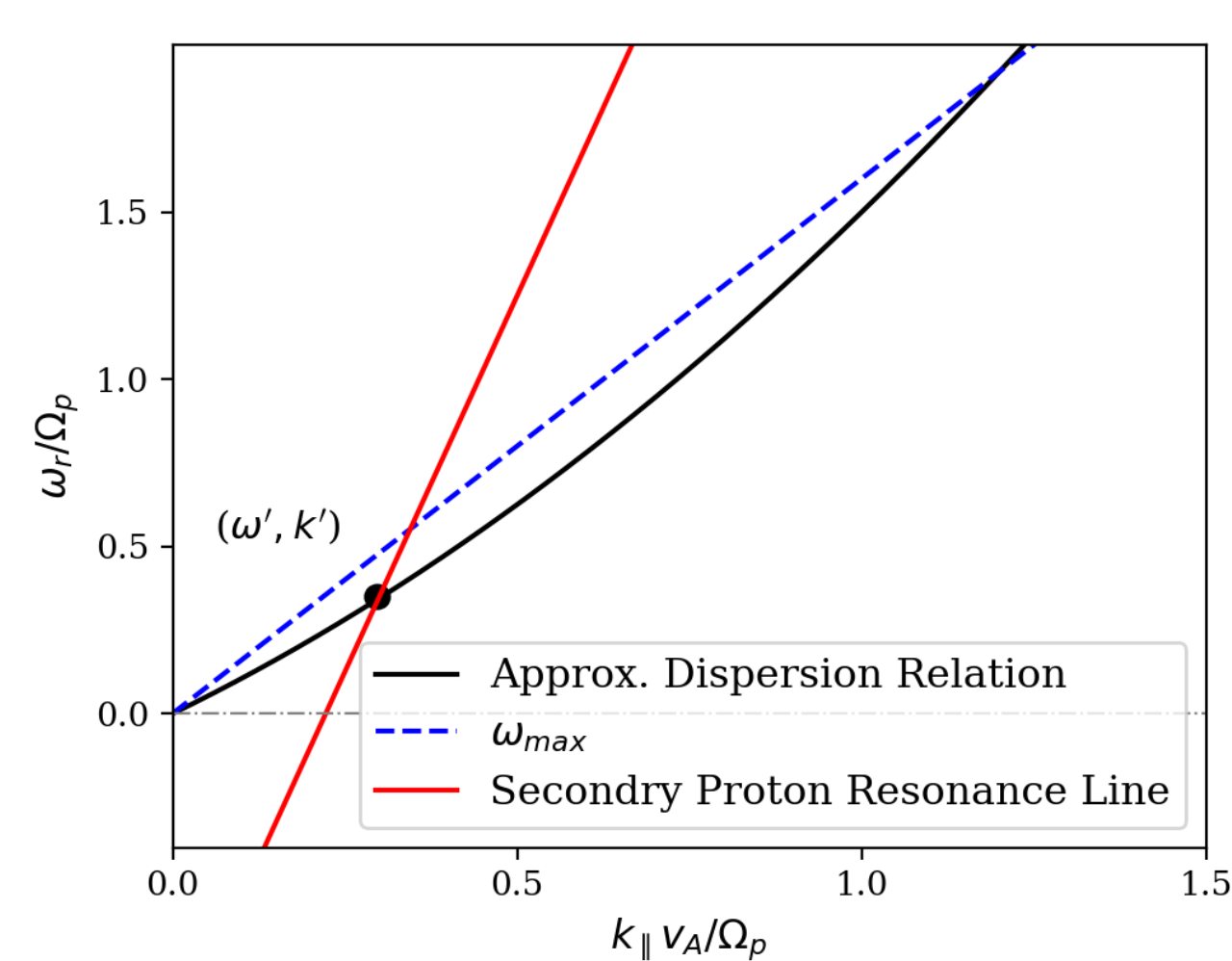


Figure 3: Resonance and instability conditions of the FM/W mode.

Constraints on Beam Parameters in the Solar Wind from PSP Observations

- In situ data during a 3-day long interval from PSP measurements in Encounter 9 (August 9-11, 2021) were analyzed.
- During the studied interval, $V_{sw} < 400$ km/s and the probe dipped to 16.1 R_s at the perihelion.
- Only a small fraction of data lies above the analytical thresholds.
- Majority of the data lie below the curve corresponding to parameter conditions leading to maximum FM/W growth rate $\gamma_m = 10^{-3} \Omega_p$.

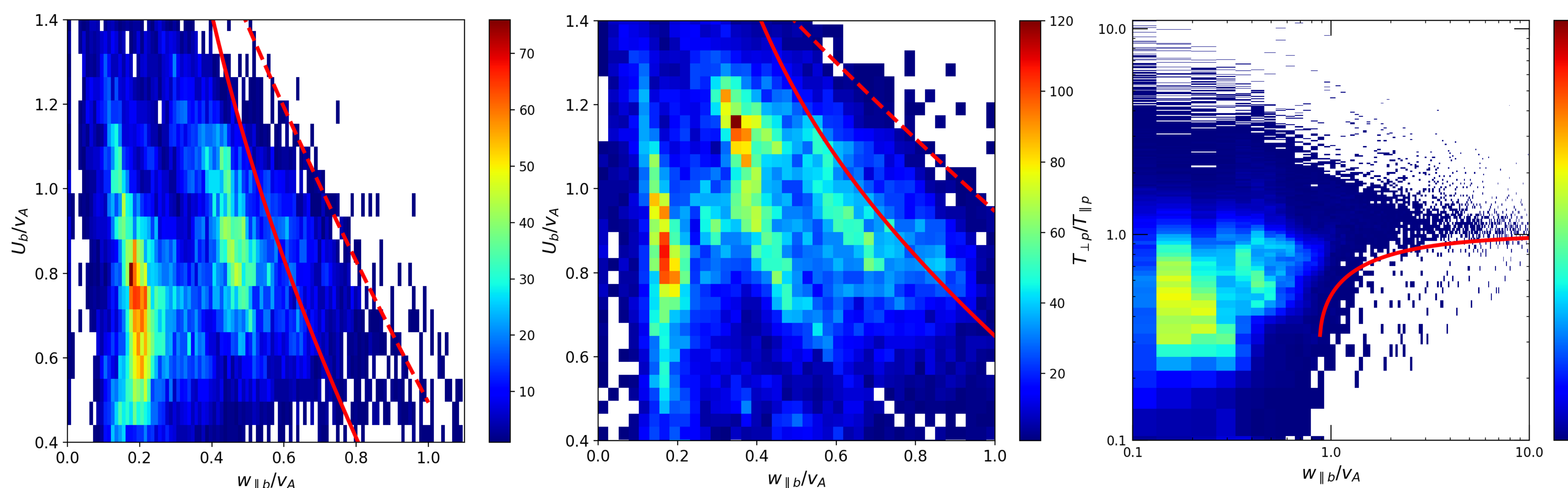


Figure 6: Distribution of data in the $U_b/v_A - w_{\parallel b}/v_A$ plane for a subset of data with (left) $0.4 < T_{\parallel b}/T_{\perp b} < 0.6$ and (middle) $0.6 < T_{\parallel b}/T_{\perp b} < 0.9$. The analytic FM/W instability thresholds corresponding to (left) $T_{\perp b}/T_{\parallel b} = 0.5$, and (middle) $T_{\perp b}/T_{\parallel b} = 0.75$ for maximum growth rates of $\gamma_m = 10^{-4} \Omega_p$ (solid line) and $\gamma_m = 10^{-3} \Omega_p$ (dashed line). (Right) Distribution of data in the $T_{\perp b}/T_{\parallel b} - w_{\parallel b}/v_A$ plane. The solid curve is the analytic threshold on the temperature anisotropy with $U_b/v_A = 0$. The color bars corresponds to the number of measurements in each bin.

Instability of the FM/W Mode

- The maximum growth rate γ_m of FM/W instability occurs at wavenumbers $k_{\parallel} v_A / \Omega_p$.
- FM/W instability growth rate increases monotonically as U_b rises.
- The growth rate of parallel FM/W mode decreases sharply with increasing $T_{\perp b} / T_{\parallel b}$.

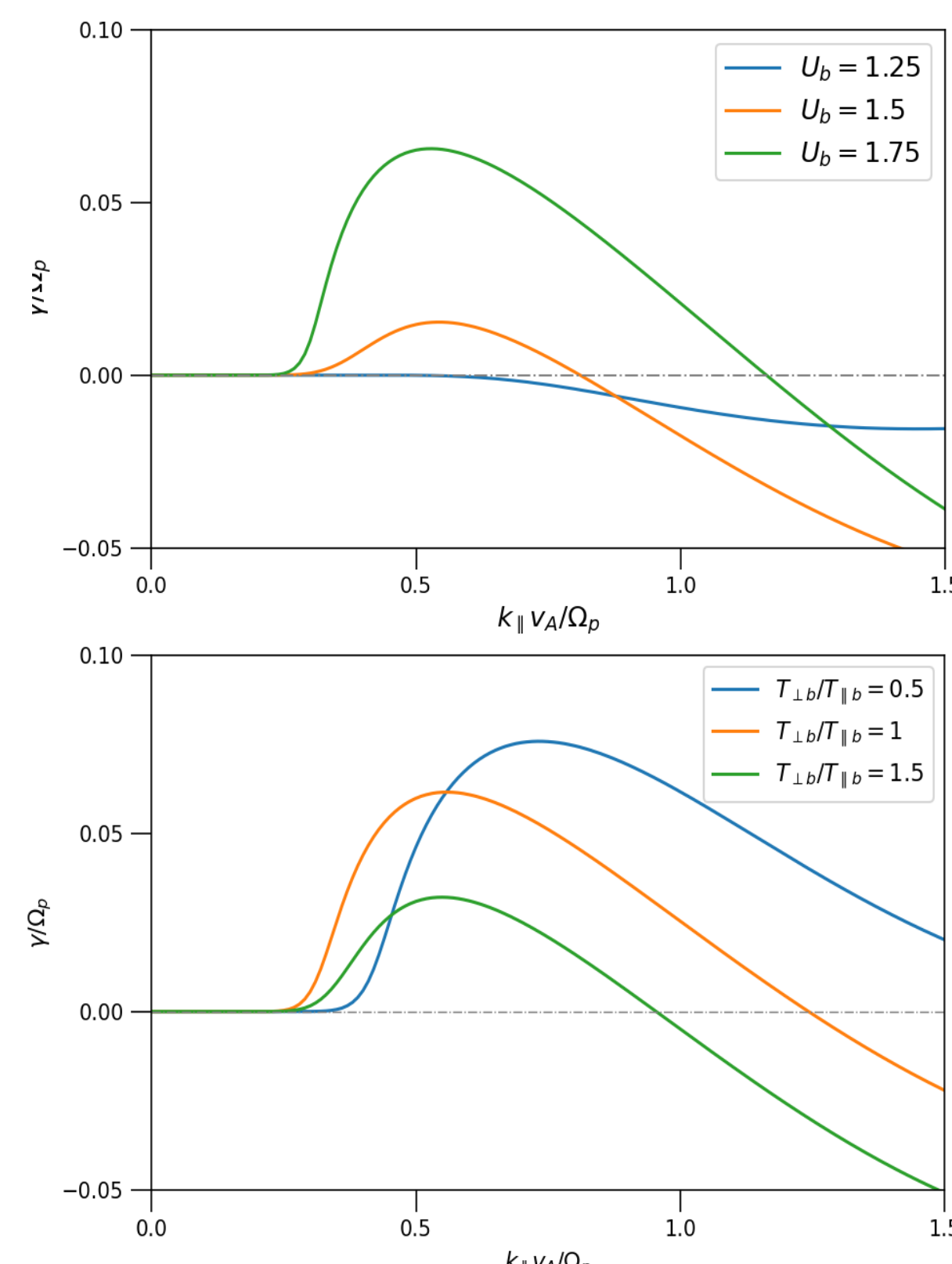


Figure 1: Growth rates of parallel FM/W for (top) different values of U_b at $T_{\perp b}/T_{\parallel b} = 1$ and (bottom) different values of $T_{\perp b}/T_{\parallel b}$, at $U_b = 1.6 v_A$.

- Using numerical solutions to the hot plasma dispersion relation, analytic thresholds are fit to contours of constant γ_m or FM/W waves in the $U_b/v_A - w_{\parallel b}/v_A$ and $T_{\perp b}/T_{\parallel b} - w_{\parallel b}/v_A$ planes.

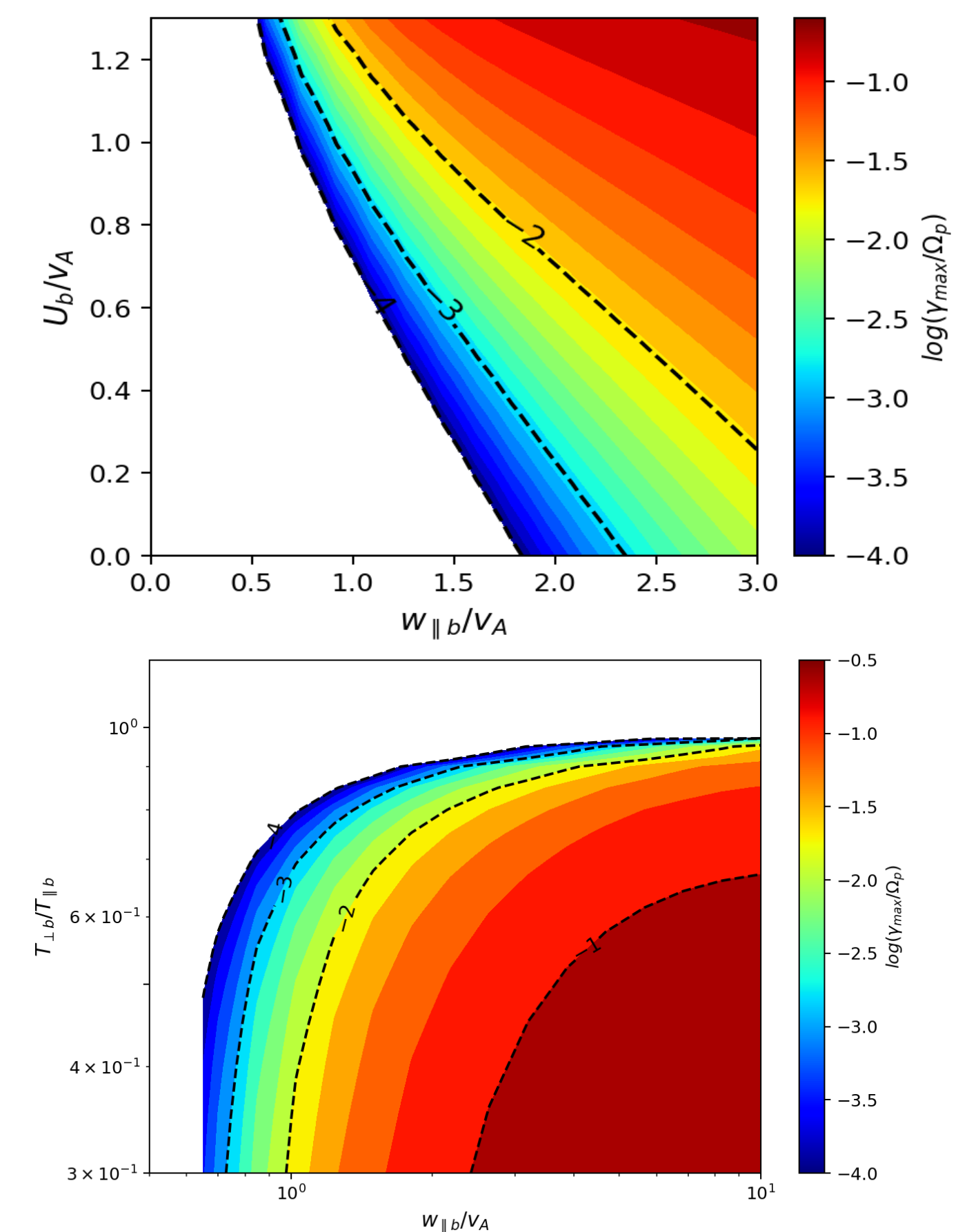


Figure 2: Distribution of the growth rate for the FM/W mode (top) in the $U_b/v_A - w_{\parallel b}/v_A$ plane for $T_{\perp b}/T_{\parallel b} = 0.75$ and (bottom) in the $T_{\perp b}/T_{\parallel b} - w_{\parallel b}/v_A$ plane for $U_b = 0.8 v_A$.

Analytic Instability Thresholds of the Parallel FM/W Instability

- The condition $k_{res} < k_{max}$ defines the lower threshold for U_b :

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

- The above condition can be rewritten to get an upper threshold for the temperature anisotropy at a given drift speed:

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

- The FM/W wave is unstable if U_b and/or $T_{\perp b}/T_{\parallel b}$ are large enough that the resonant interactions with the proton beam are destabilizing within the wavenumber interval $[k_{res}, k_{max}]$.

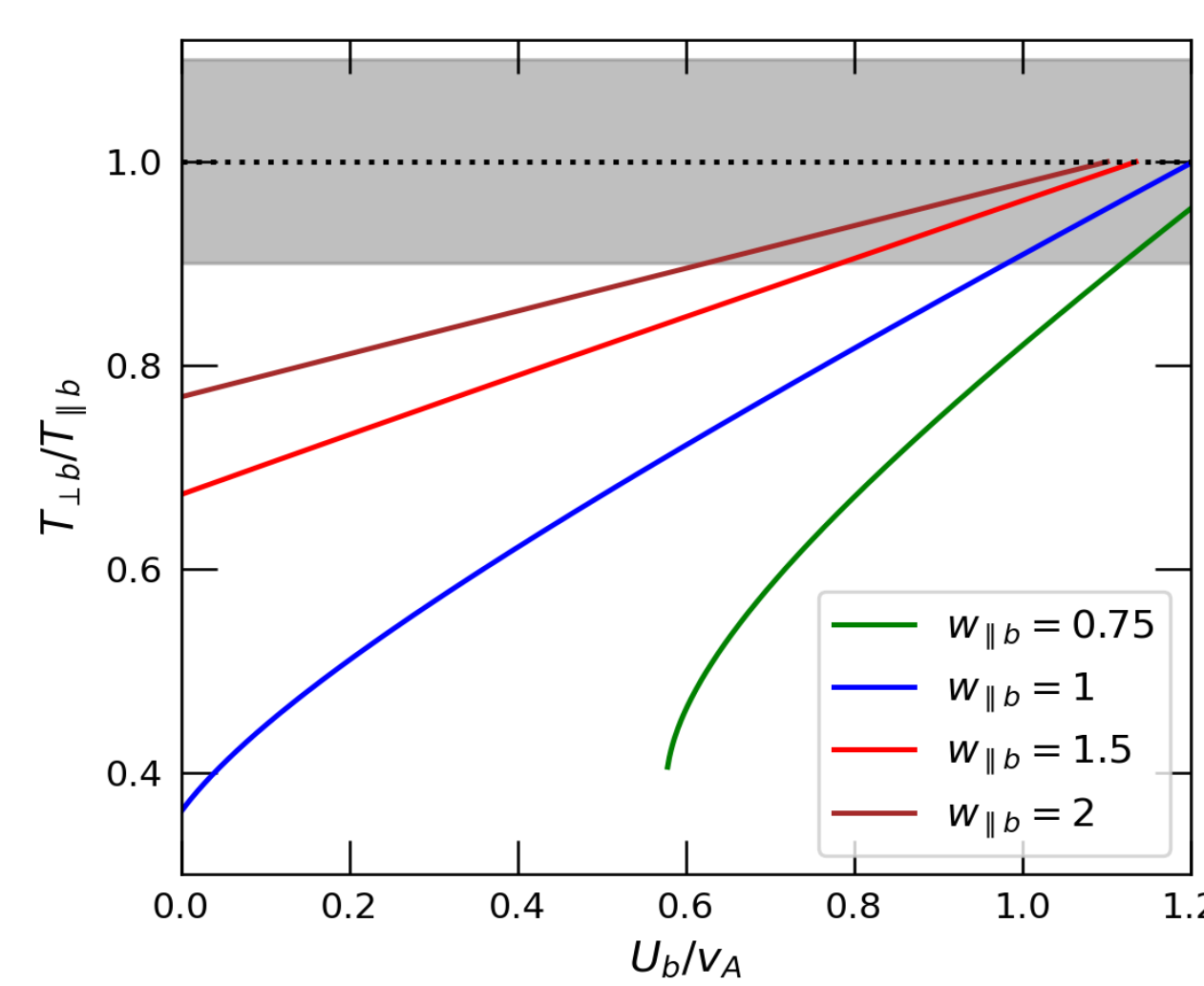


Figure 4: Instability thresholds in the $T_{\perp b}/T_{\parallel b} - U_b/v_A$ plane for different values of $w_{\parallel b}$.

- The proton thermal speed must be sufficiently small such that proton damping can be neglected within some part of the wavenumber interval $[k_{res}, k_{max}]$.

- Our analytic thresholds match well with numerical solutions to the full-hot plasma dispersion relation with $\sigma = 2.45$.
- The quantity σ defines the range of particle velocities in units of the thermal speed that can effectively resonate with the wave.

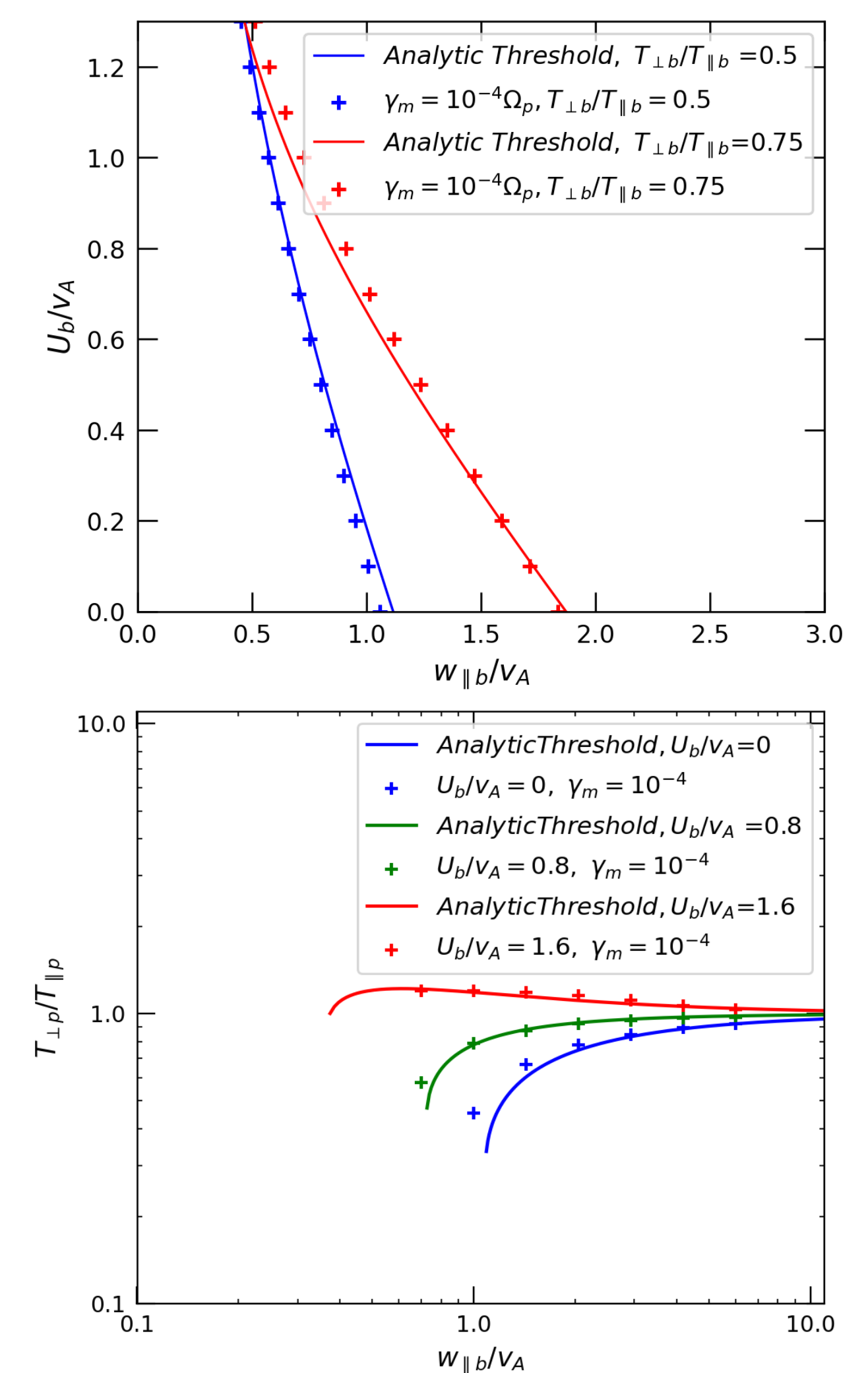


Figure 5: Comparison of the analytic instability thresholds and the numerical solutions to the full hot-plasma dispersion relation.

Summary and Future Work

Summary:

- A FM/W wave is unstable if and only if $U_b + \sigma w_{\parallel b}$ is sufficiently large that a proton beam can resonate with the FM/W wave.
- Choosing $\sigma = 2.45$ causes our analytic thresholds to correspond to parameter combinations where $\gamma_m \approx 10^{-4} \Omega_p$.
- The presence of an anisotropic proton beam with $T_{\perp b}/T_{\parallel b} < 1$ can lead to a reduction of the instability threshold velocity.
- The majority of observed data lies within the stable region of the parallel FM/W mode.

Future Work:

- Comparing these analytical thresholds with larger datasets from PSP and observations of other spacecrafts
- Examine the extent to which the parallel FM/W instability limits the differential flow and temperature anisotropy of proton beams in the solar wind at different heliocentric distances.

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