# Understanding the Validity of the Near-Threshold Assumption for Nonlinear Kinetic Plasma Instabilities

*– Work proposal for either a 1st or 2nd year student or a thesis topic –*

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## Research Objective

To critically assess the foundations of nonlinear kinetic theory to determine the accuracy and limitations of the widely invoked near-marginal instability assumption. This investigation is particularly relevant in fusion-relevant regimes, where a fast ion distribution dynamically forms as a result of neutral beam injection. The work will involve deriving the conditions under which the marginality assumption holds and identifying bifurcation criteria within inverse nonlinear Landau damping where it fails to capture the essential nonlinear dynamics.

## Methodology

Mostly analytic theory work, with a component of simplified nonlinear Vlasov simulations. Applications to tokamak experiments can also be explored at a later stage, depending on the student's interest.

## Background and Motivation

In plasma physics, the near-marginal instability assumption simplifies the analysis of kinetic instabilities by focusing on behaviors close to the excitation threshold. This approach underpins models like the Berk–Breizman cubic equation, which describes the evolution of instability amplitudes when the underlying resonant distribution hovers near threshold. This assumption may not always be valid, especially when nonlinear effects become significant. For instance, the introduction of drag forces has been shown to influence the saturation amplitude and frequency of plasma modes, indicating that nonlinear behaviors can deviate from near-threshold predictions.

Understanding the limitations of the near-marginal assumption is crucial for accurately modeling plasma behaviors in fusion devices, where kinetic instabilities can impact confinement and overall performance. This research aims to provide critical insights into the nonlinear dynamics of plasma instabilities, challenging existing assumptions and thereby enhancing the fidelity of plasma modeling. While this research will be primarily theoretical, its outcomes can be relevant for the design and operation of fusion devices. Besides the theoretical derivation of criteria for the departure of the kinetic system from its weakly driven stage, the student will conduct simplified simulations across a range of parameters (e.g., target drive strength, collisionality, initial amplitudes) to test the theoretical predictions. This study will involve varying parameters, such as drive strength and collisionality.

While a code will be used in the work, the project is not primarily one of coding or simply running simulations. The student will help develop physical understanding of the consequences of a relatively simple, mathematically accessible, model. The supervisors look forward to working closely with a student to adapt the project as it develops. This project would be ideal for a student who is interested in getting their feet wet in theoretical physics research that is not exclusively computational in nature. Some programming experience would probably be helpful, but the most important traits that would enable a student to have a fulfilling experience working on this project would be curiosity and an eagerness to learn.

**Applications**

Fast ions are ubiquitous in fusion-grade plasmas. They result from auxiliary heating, such as ion cyclotron resonant heating and neutral beam injection, as well as the alpha particles that are products of the fusion reactions. Fast ions must be well confined to provide the sustainment of fusion reactions, however the energetically inverted distribution function is a source of free energy that excites instabilities of Alfvén waves. This project proposes the study of such fast-ion-driven instabilities in a simplified geometry. Beyond fusion plasmas, this research is also relevant to groove instabilities in galaxies.

**Research Questions**

- Under what plasma conditions does the near-marginal instability assumption accurately describe nonlinear kinetic instabilities while the resonant population distribution is being injected?
- How do nonlinear effects, such as frequency chirping and mode saturation, manifest when the system deviates from marginal stability?
- What are the implications of these deviations for plasma confinement and stability in fusion devices?

**Expected Outcomes**

- A comprehensive understanding of the conditions under which the near-marginal instability assumption holds or fails, as well as the derivation of a bifurcation criterion for its breakdown.
- Development of improved theoretical models that accurately capture nonlinear kinetic behaviors in plasmas across different scales of effective collisionality and phase mixing times.
- Recommendations for modeling practices in fusion research, potentially leading to better predictions of plasma stability and performance.