Linear Gyrokinetic Stability Analysis of ST40 Hot Ion Plasmas

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1. PPPL 2. Tokamak Energy

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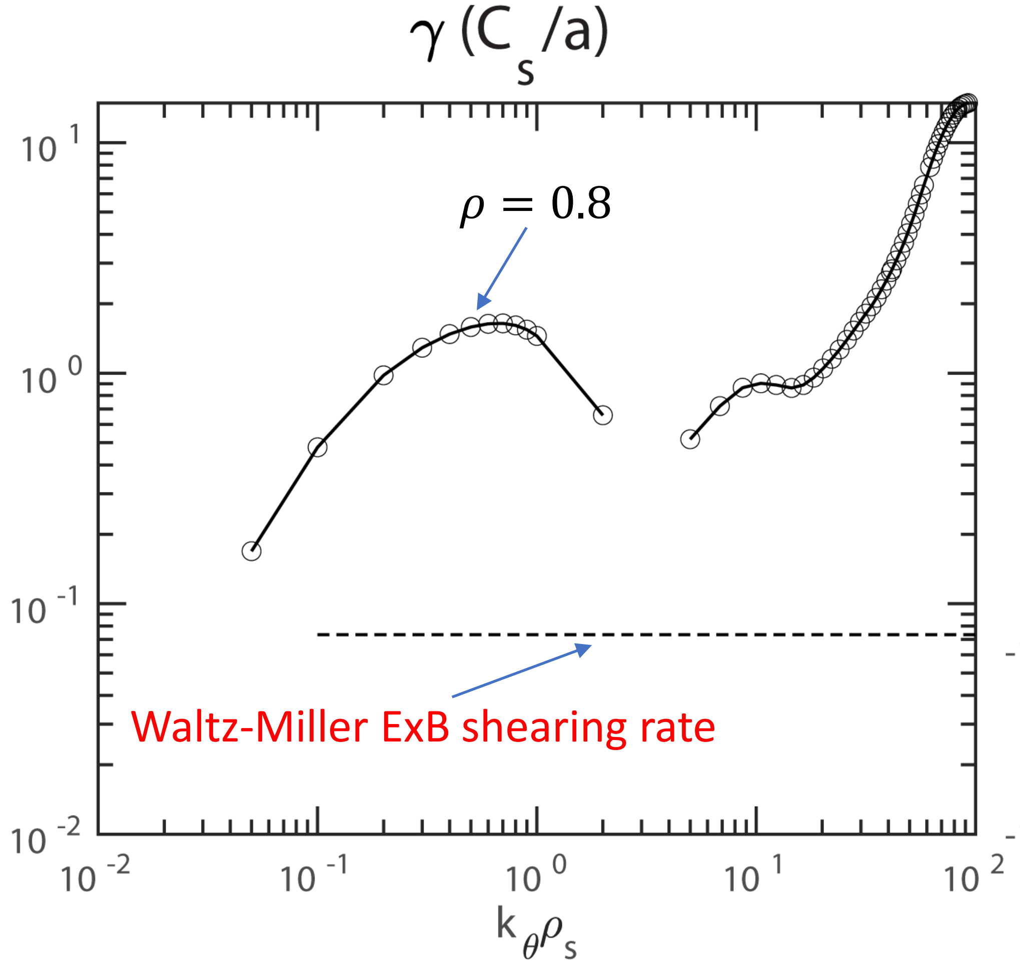
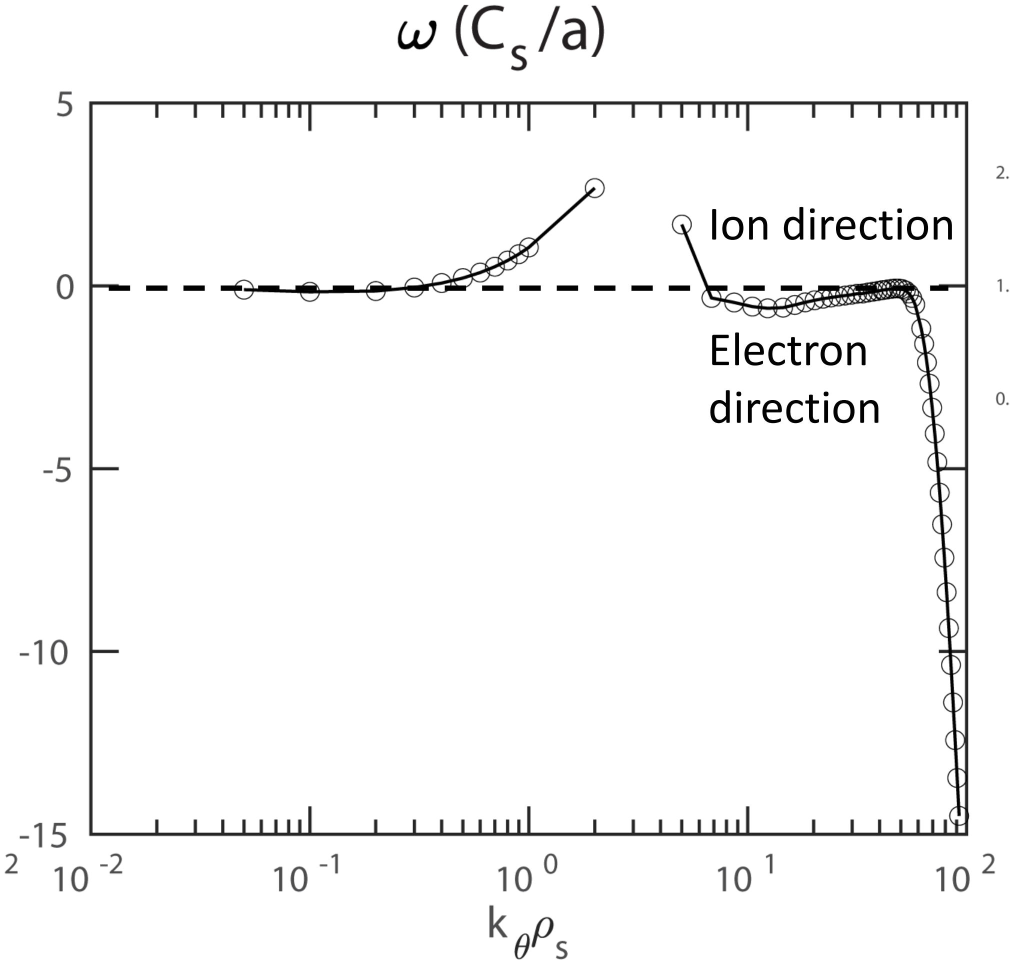
Highlights

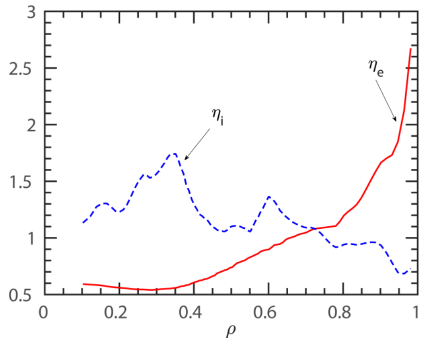
- Linear gyrokinetic stability analysis with the GS2 code has been carried out for a ST40 hot ion plasma
- Linear growth rates of both ion- and electron-scale ($k_\theta \rho_s \gtrsim 0.2$) modes decrease from the edge toward the core of the plasma ($\rho = 0.3$-0.8)
- Complete suppression of electron-scale modes ($k_\theta \rho_s \gtrsim 5$) is found at $\rho = 0.3$
- Ubiquitous mode (UM), ETG and an unidentified electron-scale instability are found at $\rho \geq 0.6$, with KMB/KSA and ITG/TEM at $\rho = 0.3$, through parametric scans, i.e., temperature gradients, aspect ratio, plasma beta

Significant Stabilization of Micro-instabilities towards the Plasma Core of a ST40 Hot-ion Shot 9831

- Linear growth rates of both ion- and electron-scale ($k_\theta \rho_s \gtrsim 0.2$) modes decrease from the edge towards the core of the plasma
- Complete suppression of electron-scale modes ($k_\theta \rho_s \gtrsim 5$) at $\rho = 0.3$; No-monotonic for $k_\theta \rho_s < 0.2$







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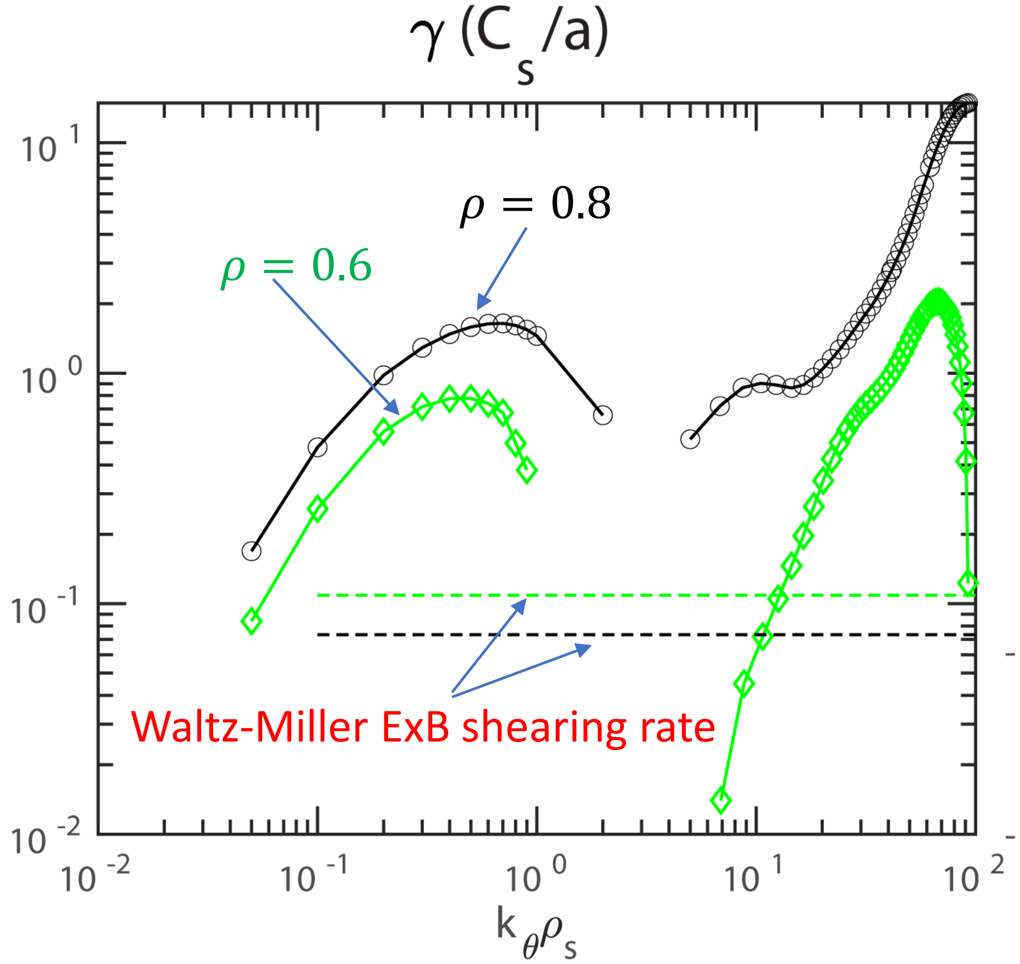

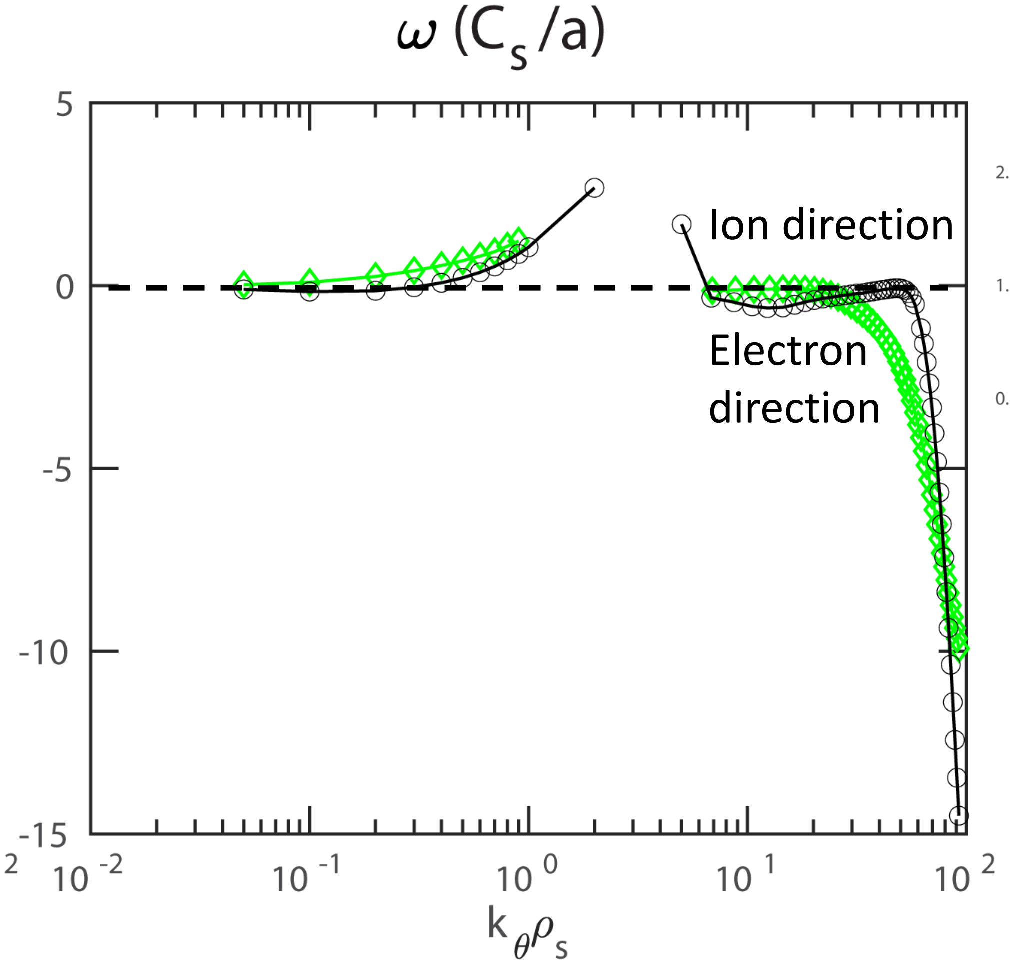

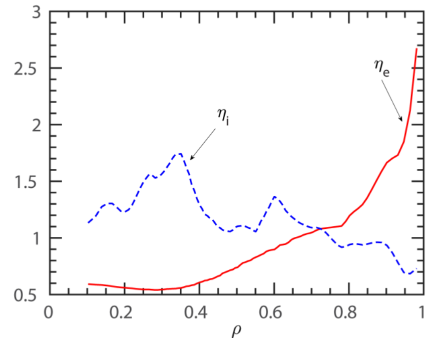

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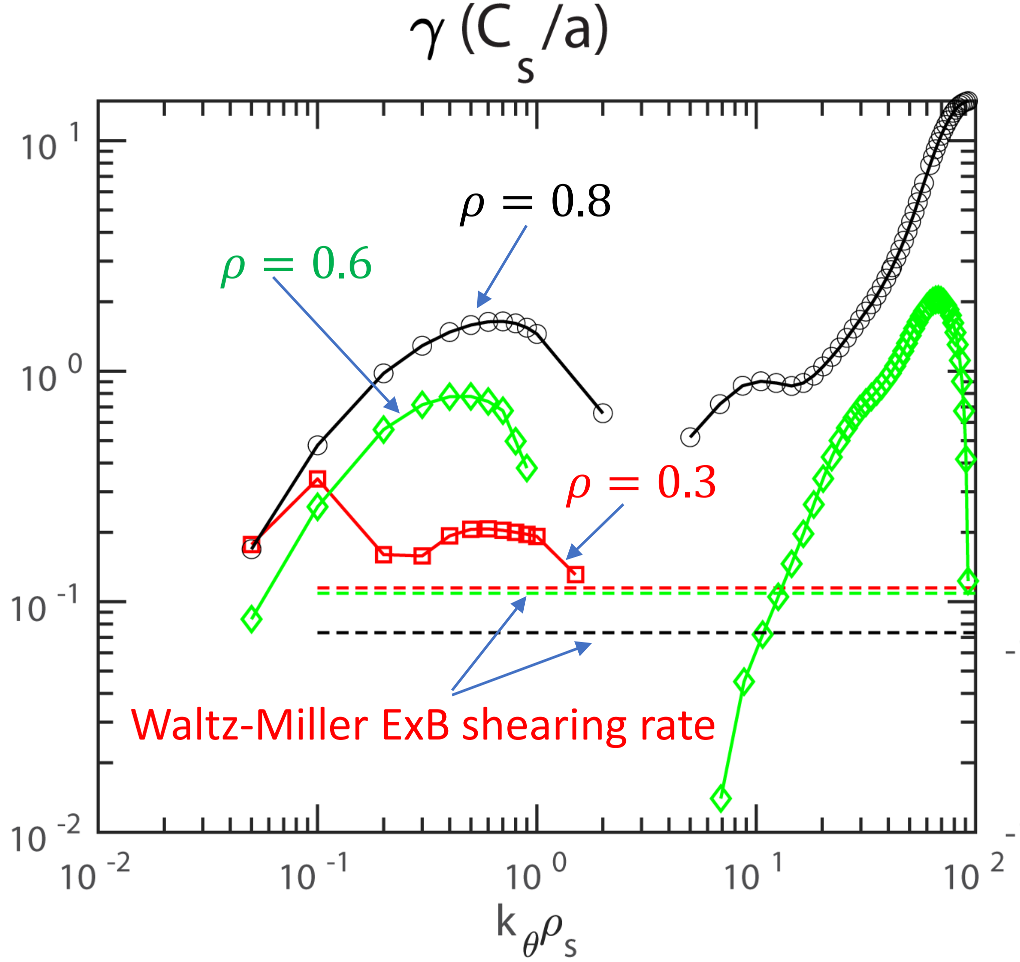
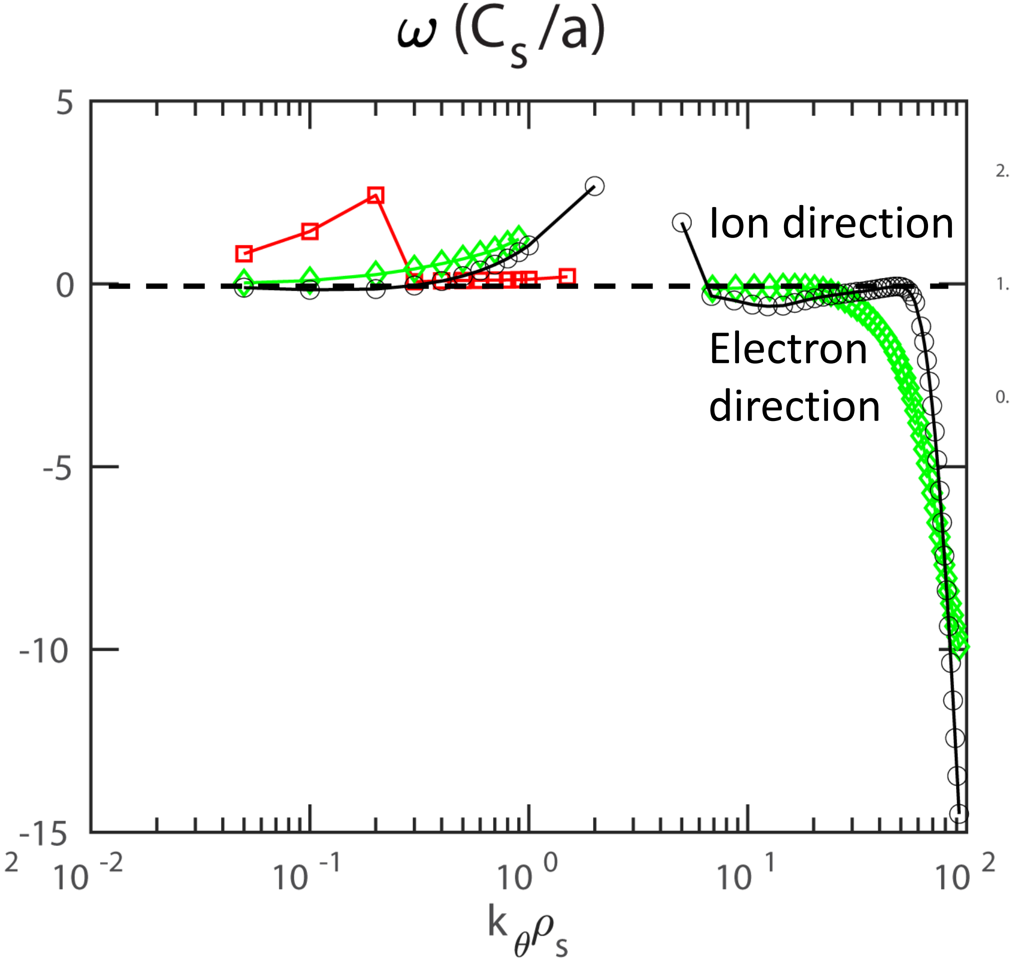
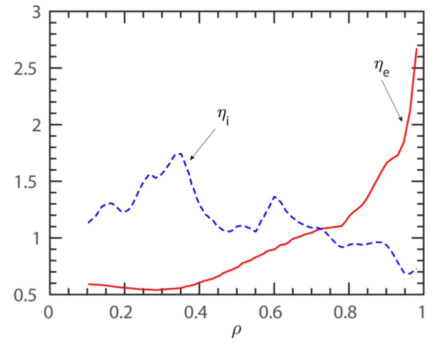
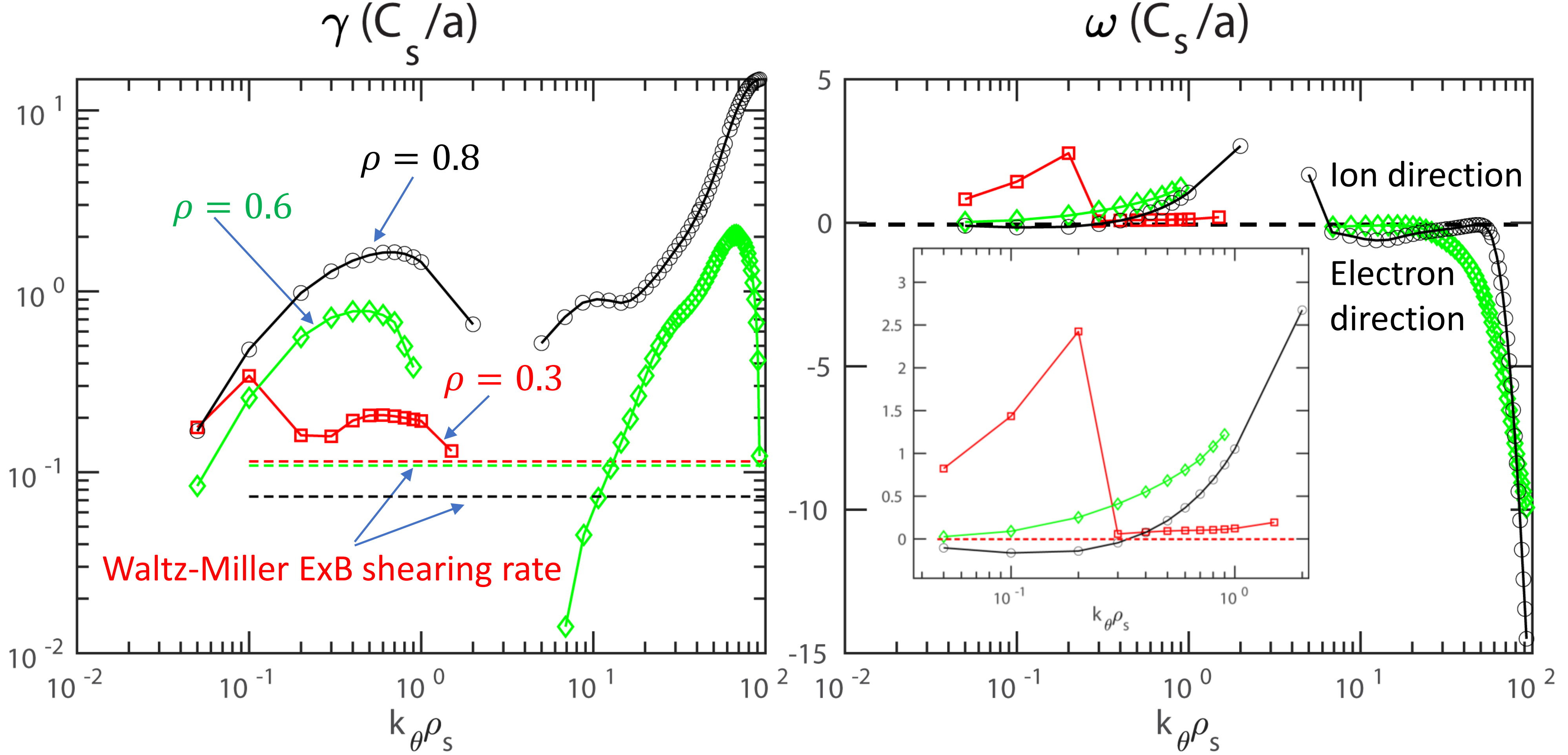






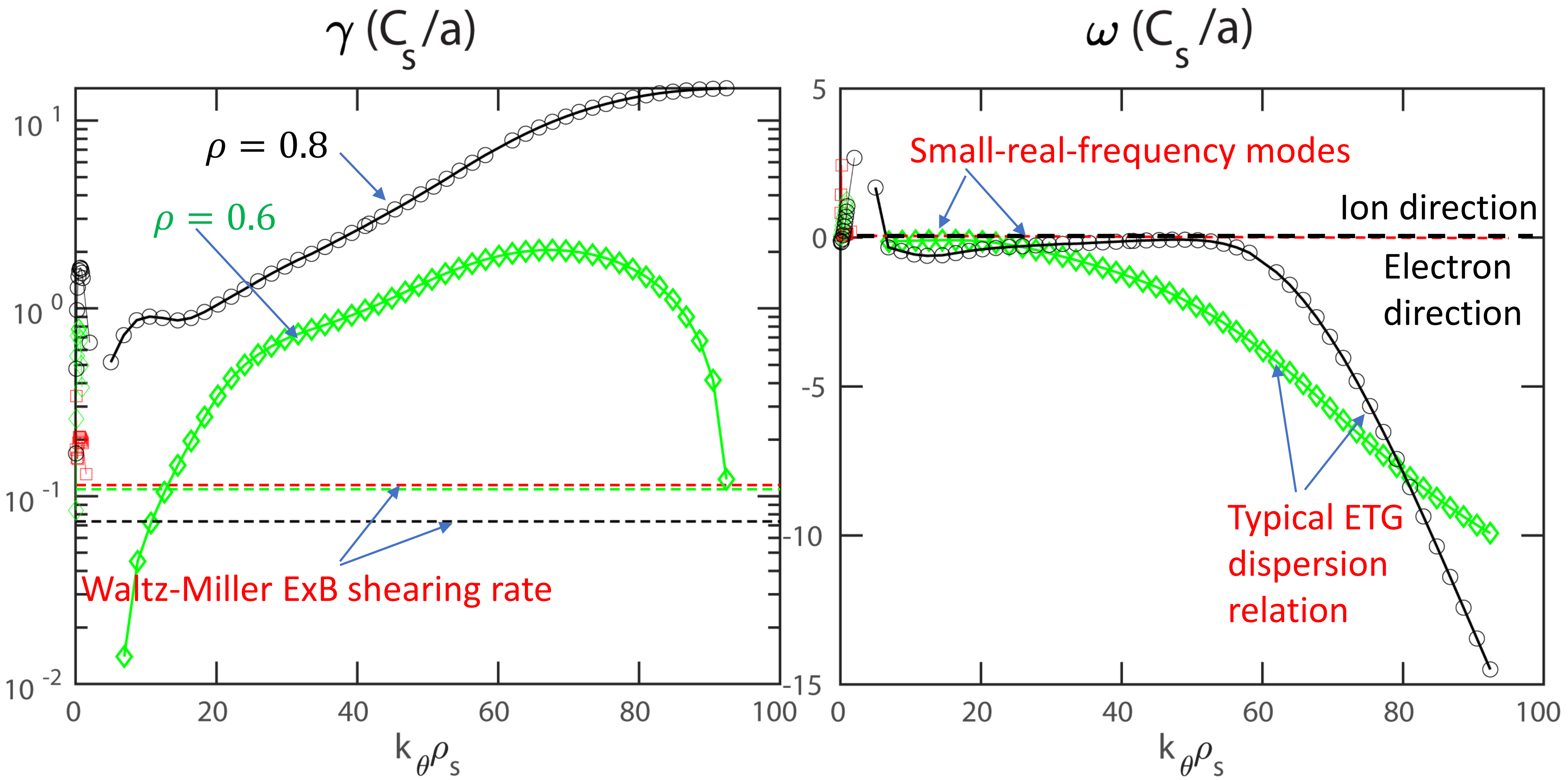
Propagation Directions Differ for Ion- and Electron-scale Modes

- Ion-scale modes are mainly in the ion direction and electron scale modes are mainly in the electron direction
  - At ρ=0.8, there is a change in propagation direction at $k_\theta \rho_s \approx 0.34$
- What are these ion-scale modes?



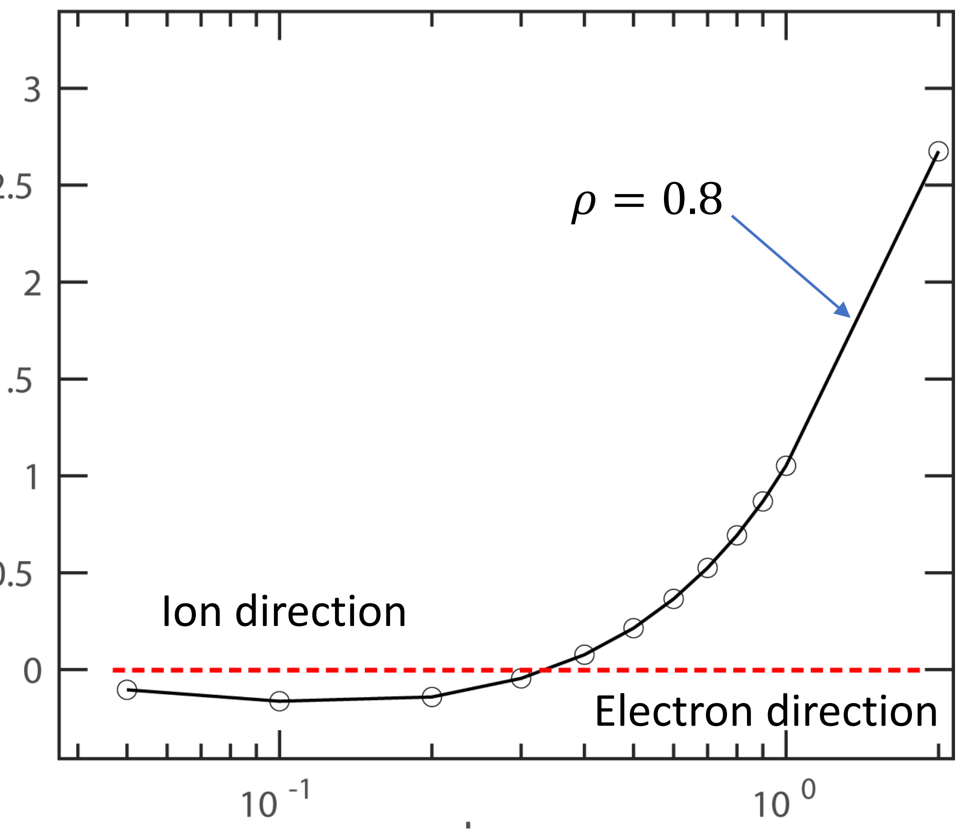
Small Real Frequency is Seen for a Range of Electron-scale modes

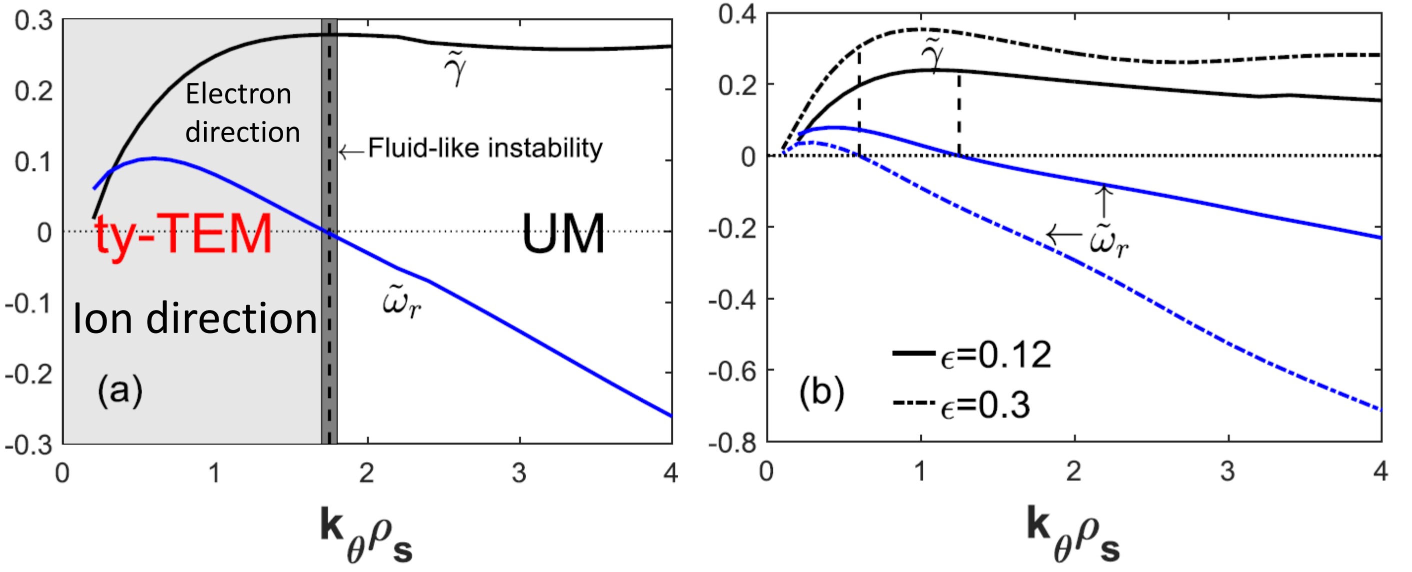
- These small-real-frequency k ranges extend from $k_\theta \rho_s \approx 5$ to 60 at $\rho = 0.8$ and from $k_\theta \rho_s \approx 5$ to 30 at $\rho = 0.6$
- Typical ETG dispersion is only seen at higher wavenumbers, ~ρ_e
- What are these small-real-frequency electron-scale modes?



A Real Frequency Reversal in the Ion-scale k Range is found at ρ=0.8

- Propagation direction changes from the electron direction to the ion direction from lower k to higher k at about $k_\theta \rho_s \approx 0.34$
- A smooth transition (rather than a jump) in real frequency indicates the same branch of solution of the dispersion relation
- Ubiquitous mode (UM) (Coppi, 1974 and 1977; Shen, 2019) seems consistent with these observations
  - UM is due to nonadiabatic responses of both trapped electrons and passing ions

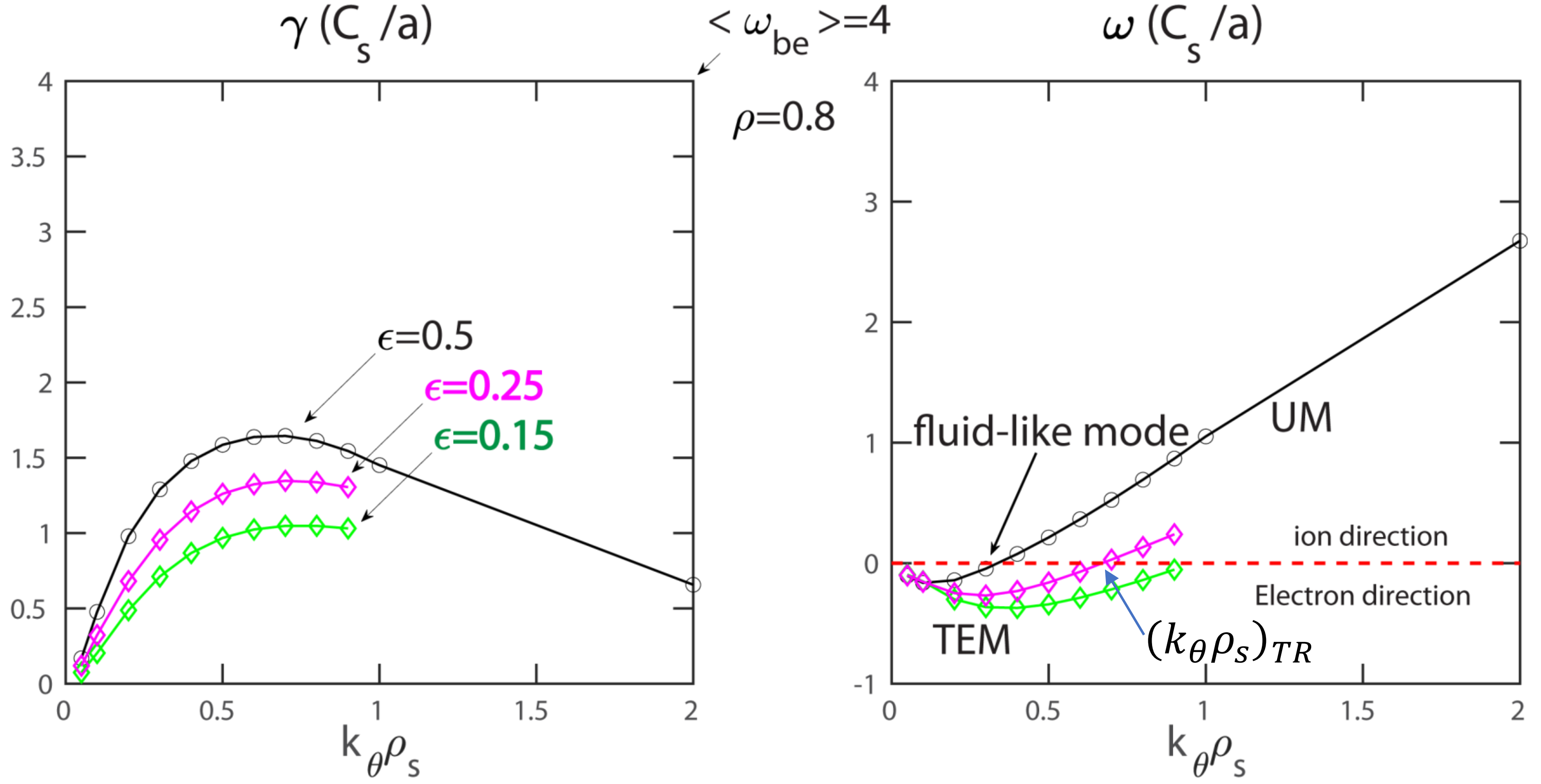


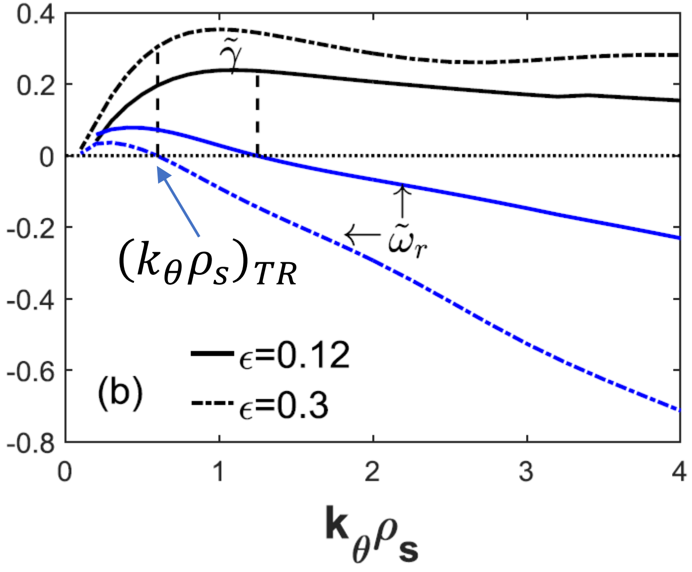


Shen et al., NF 2019

Inverse Aspect Ratio Scans at $\rho = 0.8$ Show a Consistent Trend with UM

- The propagation direction changes from the electron direction to the ion direction with an increase in wavenumber
- The smooth transition (rather than a jump) indicates the same branch of solution of the dispersion relation
- Ubiquitous mode (Coppi, 1974 and 1977; Shen, 2019) is consistent with these observations
- The transition wavenumber between TEM and UM, $(k_\theta \rho_s)_{TR}$, denotes relative dominance of TEM and UM, i.e., smaller $(k_\theta \rho_s)_{TR}$ meaning more dominant UM in the k spectrum.

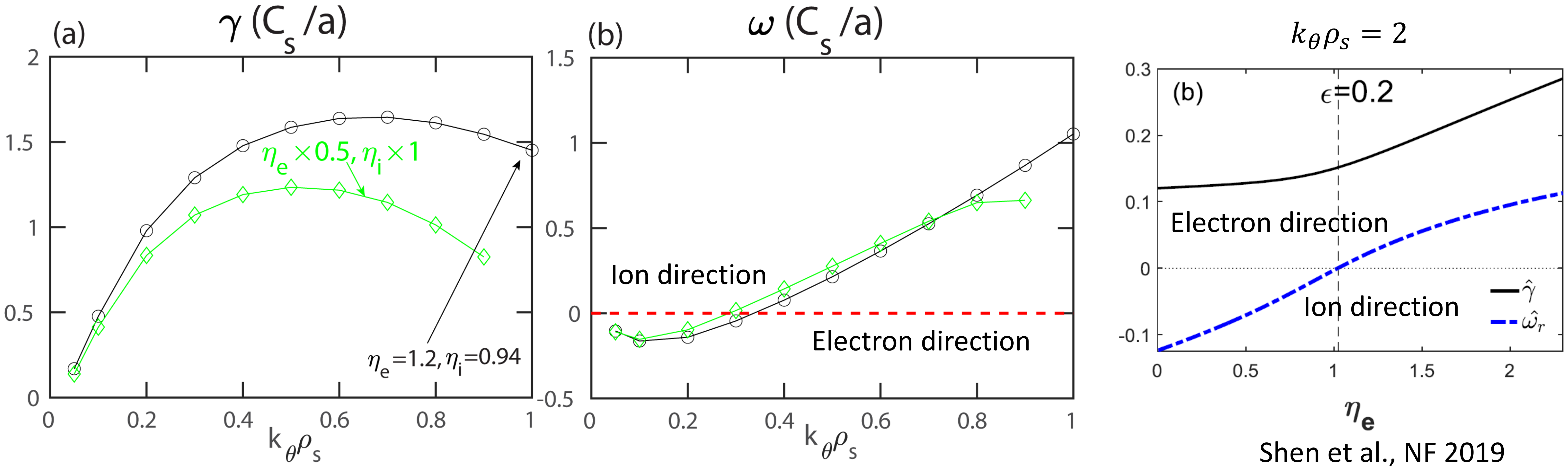




Shen et al., NF 2019

Ion and Electron Temperature gradient Scans at $\rho = 0.8$ Show a Consistent Trend with UM

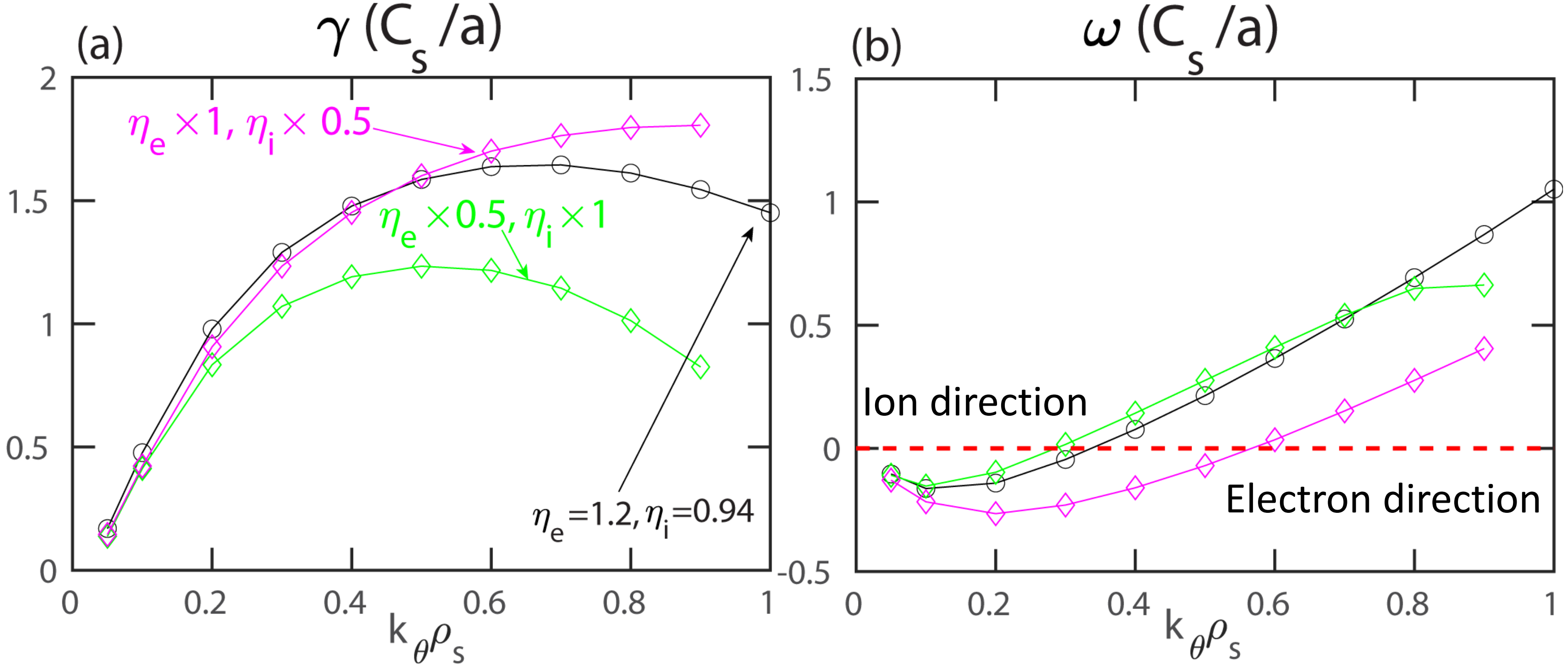
- Reducing η_e by 50% alone leading to reduced γ and more positive ω (more to the ion direction), except at $k_\theta \rho_s > 0.8$
  - η_e changed through T_e gradient
  - Smaller $(k_\theta \rho_s)_{TR}$ with reduced η_e, which makes UM more dominant in the k space

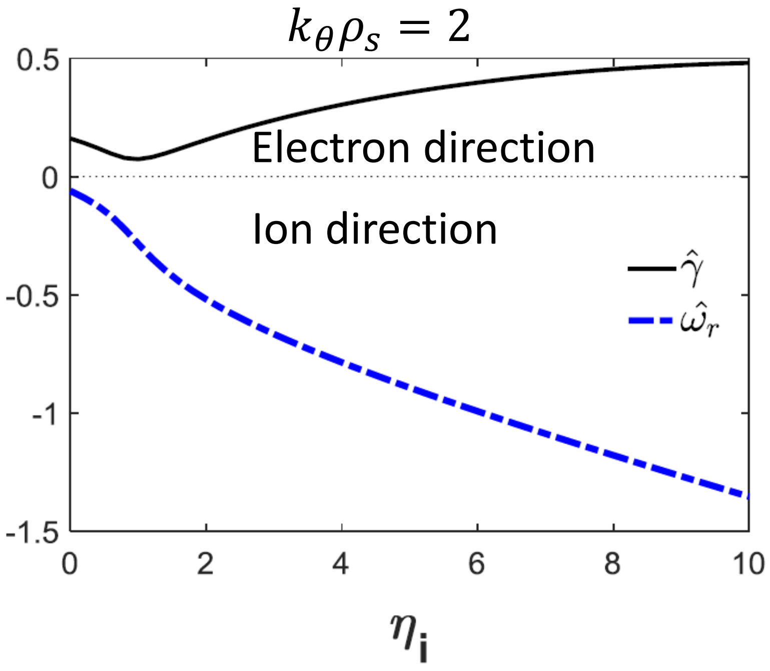


Shen et al., NF 2019

Ion and Electron Temperature gradient Scans at $\rho = 0.8$ Show a Consistent Trend with UM

- Reducing η_i by 50% alone leading to increased γ at $k_\theta \rho_s > 0.4$ and more negative ω overall (more to the electron direction)
  - Larger $(k_\theta \rho_s)_{TR}$ with reduced η_i, which makes UM less dominant in the k space

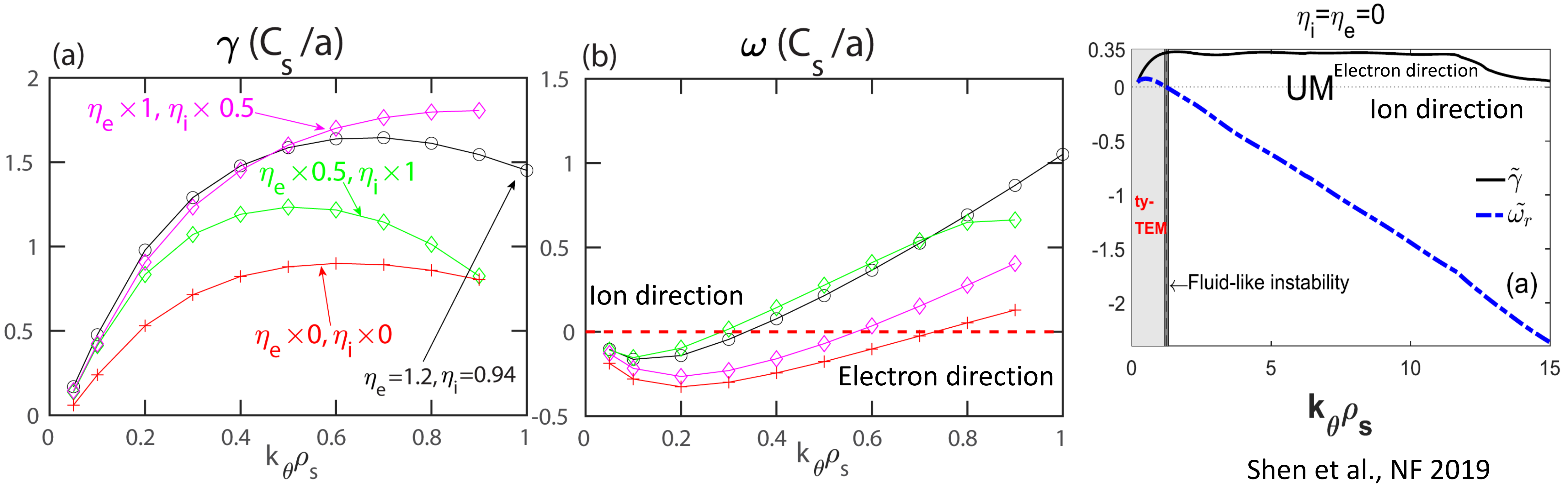




Shen et al., NF 2019

Ion and Electron Temperature gradient Scans at $\rho = 0.8$ Show a Consistent Trend with UM

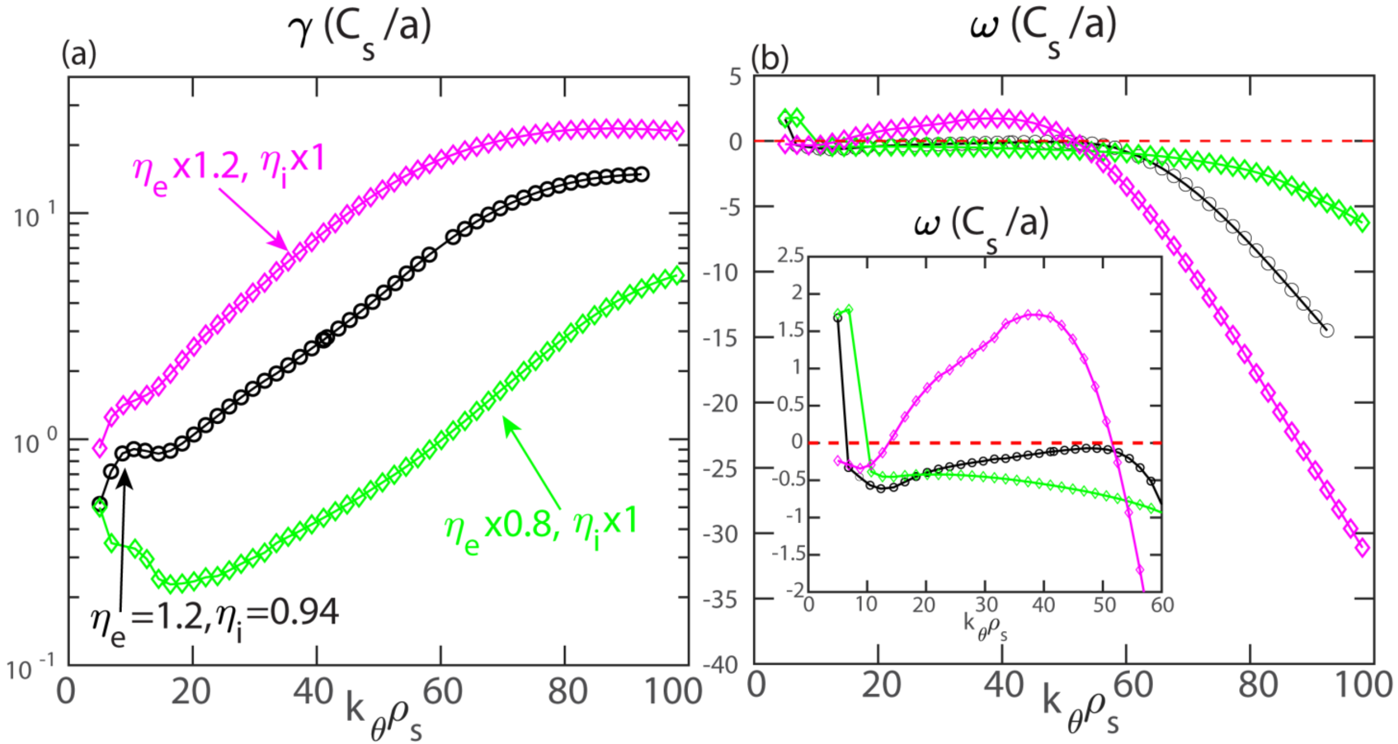
- Density gradient alone can drive UM as predicted by numerical simulations.
  - Larger $(k_\theta \rho_s)_{TR}$ with zero η_e and η_i , which makes UM less dominant in the k space



Shen et al., NF 2019

Electron-scale Modes at $\rho = 0.8$ are very Sensitive to η_e

- γ of electron-scale modes at $k_\theta \rho_s > 7$ is very sensitive to η_e (through a/L_{T_e}) and the response is uniform across a wide range
  - Up to a factor of 3 increase in γ at $k_\theta \rho_s \approx 44$ with a 20% increase in η_e
  - More than 80% decrease in γ in the $k_\theta \rho_s$ range of 23 to 78 with a 20% reduction in η_e
- ω of electron-scale modes at $k_\theta \rho_s > 7$ has very different response to η_e in the intermediate k range (between ρ_i^{-1} and ρ_e^{-1}) and in the high k range (ρ_e scale and beyond)
  - Intermediate k range modes having ω flipped to significantly positive values with a 20% increase in η_e, while high-k modes having more negative ω, consistent with the typical electrostatic ETG mode



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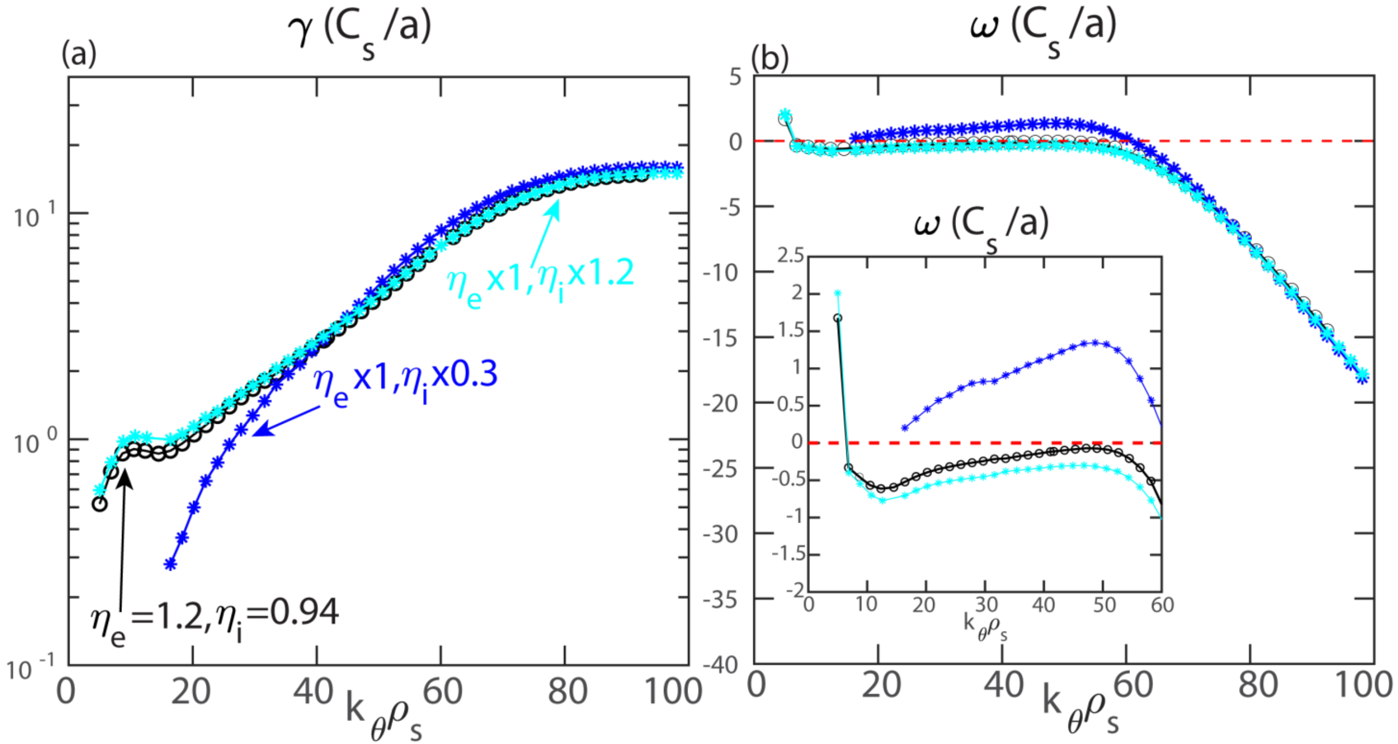
- The dependence on η_i is much weaker
  - γ or ω only significantly affected at $k_\theta \rho_s < 40$ with a 70% reduction in η_i
  - γ or ω not significantly affected with η_i increased by 20%
- T_e gradient is the main free energy driving the unstable modes in the electron scale



Two Instabilities May Exist in Electron-scale at $\rho = 0.8$

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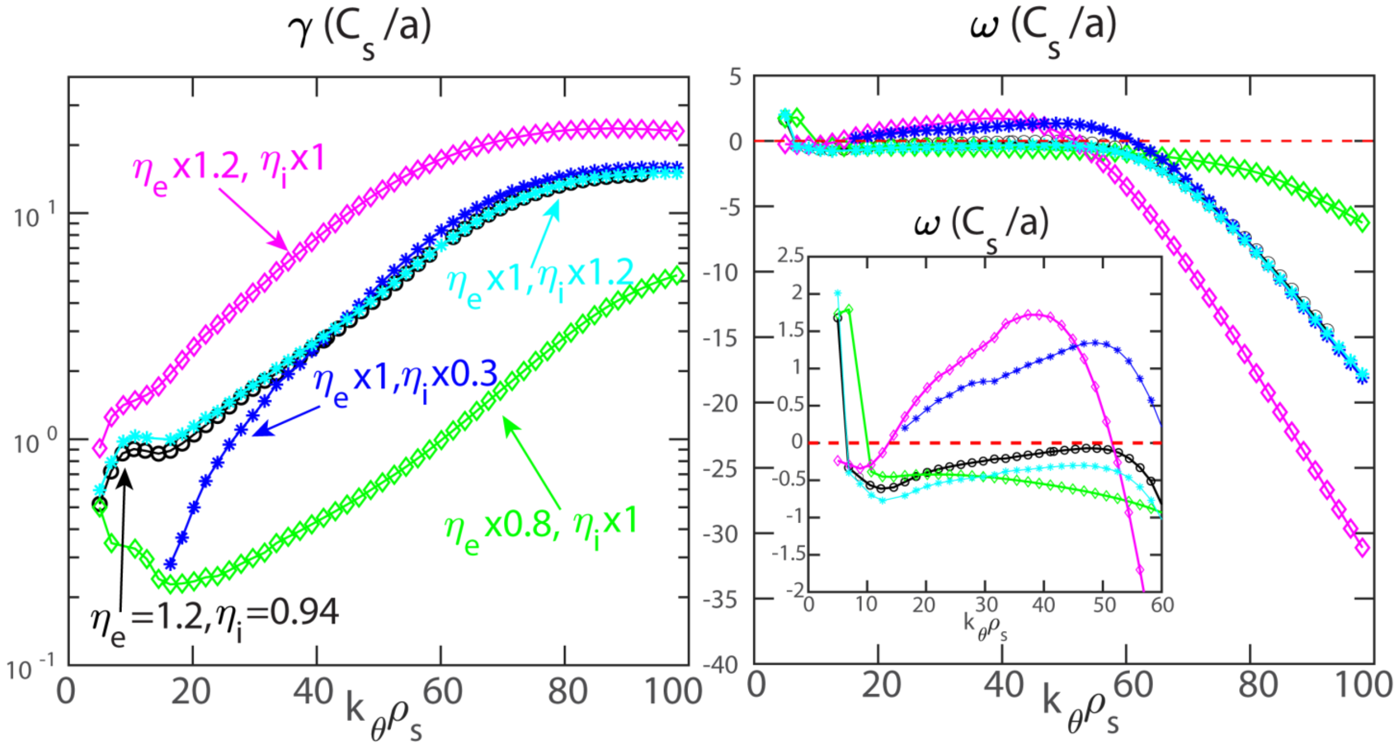
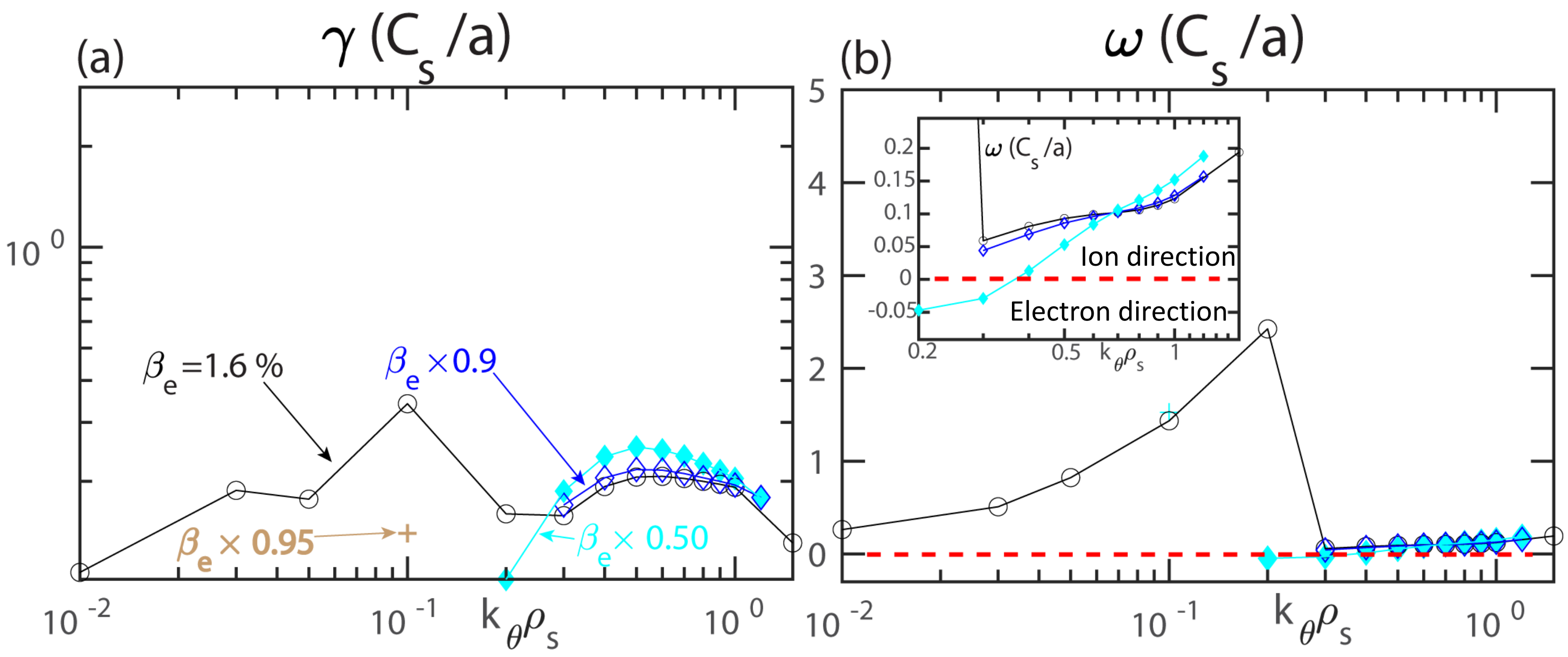
  - γ or ω not significantly affected with η_i increased by 20%
- T_e gradient is the main free energy driving the unstable modes in the electron scale
- ω is a continuous function of $k_\theta \rho_s$ at $k_\theta \rho_s$ >7, indicating the same branch of solution of the dispersion relation in the electron scale.
- The Intermediate range small-ω ETG-drive instability has quite a different parametric dependence than the typical ETG mode and should be categorized as a different instability.



β_e Scans Support the Existence of KBM/KSA and ITG/TEM at $\rho = 0.3$

- Different beta dependence found in the lower k range ($k_\theta \rho_s \leq 0.2$) and in the lower k range ($0.3 \leq k_\theta\ \rho_s \leq 1.2$)
  - With β_e reduced by 5%, only $k_\theta \rho_s = 0.1$ in the lower k range remaining unstable with much reduced γ; complete stabilization of the lower-k modes with β_e reduced by 10%
  - Reduced β_e leads to higher γ for the higher-k modes
  - Consistent with KBM/KSA in the lower k range and ITG/TEM in the higher-k range



- β_e is scanned with T_i/T_e fixed, and total β is also scanned.
- β_e scans were carried out with β' fixed.

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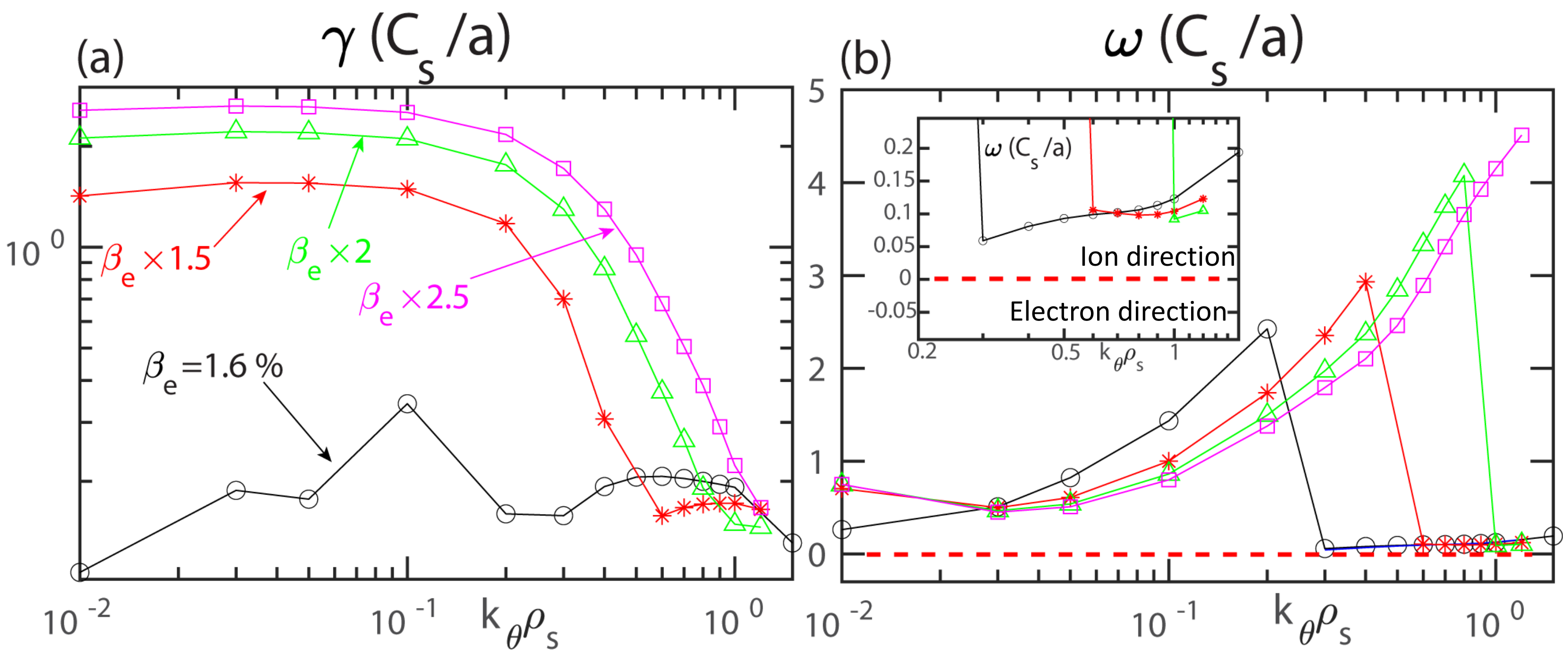
  - Increased β_e leading to much increased γ for the lower-k modes; The lower-k branch of solution pushed to higher wavenumbers
  - Increased β_e leading to lower γ for the higher-k modes
  - Consistent with KBM/KSA in the lower k range and ITG/TEM in the higher-k range



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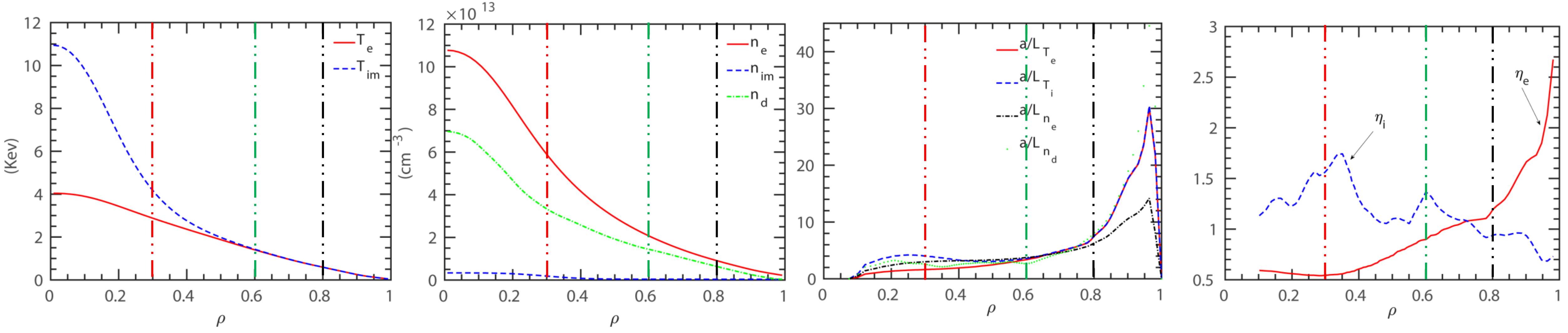
Summary and Conclusions

- Linear gyrokinetic stability analysis with the GS2 code has been carried out for ST40 hot ion plasmas.
- Linear growth rates of both ion- and electron-scale ($k_\theta \rho_s \gtrsim 0.2$) modes decrease from the edge toward the core of the plasma ($\rho =$ 0.3-0.8).
- Complete suppression of electron-scale modes ($k_\theta \rho_s \gtrsim 5$) is found at $\rho = 0.3$.
- Ubiquitous mode (UM), ETG and an unidentified low-real-frequency electron-scale instability are found at $\rho \geq 0.6$, with KMB/KSA and ITG/TEM at $\rho = 0.3$, through parametric scans

Linear Stability is Studied at Multiple Radii in a ST40 Hot-ion Shot 9831

- B_T~1.8 T, I_p~500 kA and not highly shaped with $\kappa \sim 1.3$ and $\delta \sim 0.2$
- Impurity temperature, T_{im}, ~ 11 keV in the core, and ion temperature, T_i, is 1-1.5 keV lower than T_{im} in the center, clearly in the hot-ion regime
  - $T_{im} = \mathrm{T_i}$ well satisfied in the outer half of the plasma, and ion temperature gradient independent of T_{im} or $\mathrm{T_i}$
- $\eta_e = \frac{L_{n_e}}{L_{T_e}}$ decreases from ~1 to ~0.5 from ρ=0.8 to 0.3, showing stabilization of ETG mode towards plasm core.
- $\eta_i = \frac{L_{n_d}}{L_{T_i}}$ increases from ~1 to ~1.5 from ρ=0.8 to 0.3, indicating ion mode becomes more important towards plasma core.
- The analysis was carried out at ρ=0.3, 0.6, 0.8 (ρ is the square root of normalized toroidal flux)



Temperature Gradient Scans Show the Existence of Two Instabilities in the Ion Scale at $\rho = 0.3$

- Enhanced growth rates in the lower k range ($k_\theta \rho_s < 0.3$) with increased $\eta_e$or η_i and complete stabilization with zero temperature gradient
  - Indicating a pressure dependence; Modes in ion direction; Characteristics of KBM/KSA
- Higher γ from increased η_e; Lower γ (higher ω) from increased η_i (forming a γ peak in lower k) ; density gradient-driven TEM with zero temperature gradient
  - Consistent with a ITG/TEM hybrid and $k_\theta \rho_s \geq 0.3$ modes belonging the same branch of solution