한양대학교

Simultaneous destabilization of GAM and GAM-like modes in the presence of energetic particles with finite orbit width effects

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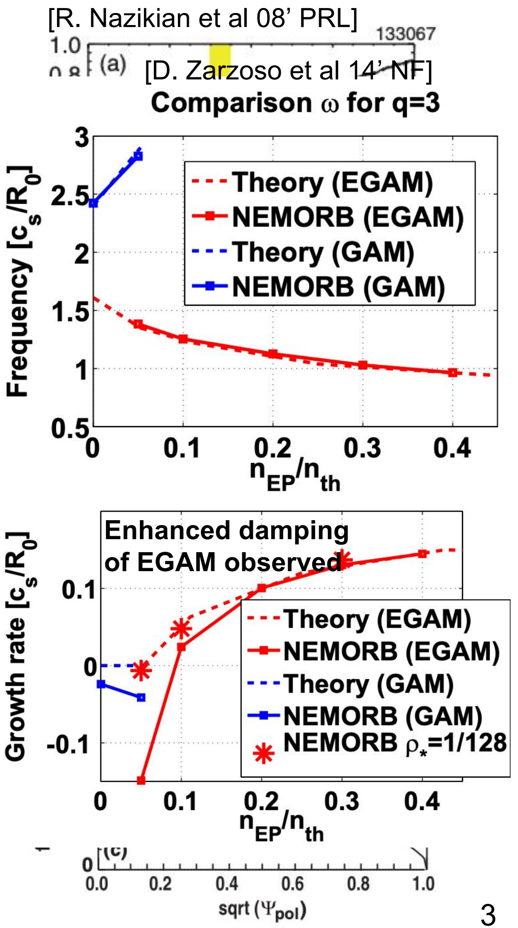
CONTENTS

Introduction

Energetic particle driven geodesic acoustic modes (EGAMs) and finite orbit width (FOW) effects

- **Energetic particles (EPs)** are a robust source of GAM-like modes.
- In the 2000s, DIII-D has reported **energetic particle driven GAM** (**EGAM**).
- EGAM is featured with mode bursting with **frequency chirping**.
- Each burst have **a few millisecond** duration and accompanied by **EP loss**.
- Fu first found that the EGAM is driven by **anisotropic distribution of EPs** using hybrid MHD-kinetic model.
- Later, Zarzoso* derived the **gyrokinetic EGAM dispersion relation**.
- **Mismatches** between theory and simulations were observed.
- In this study, the EGAM dispersion relation **considering FOW effects** has been derived.



* : [G.Y. Fu 08' PRL] * * : [D. Zarzoso et al 12' POP, D. Zarzoso et al 14' NF, J.-B. Girardo 14' POP]

Gyrokinetic EGAM dispersion relation with FOW effects

- **Gyrokinetic EGAM dispersion relation considering FOW effects** has been derived* !
- In the limit of zero-FOW $\delta(\equiv k_r \rho_{ti} q) \to 0$, the dispersion relation reduces to the results by Zarzoso.

EGAM by EPs [Zarzoso et al 12' POP] → $G(\omega)$

FOW effects on EGAM ($\delta \equiv k_r \rho_{ti} q$ means FOW) (new) → $\frac{\delta^2}{8} F(\omega)$

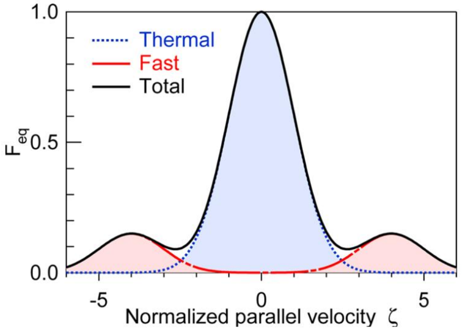
$$G(\omega) + \frac{\delta^2}{8} F(\omega) = 0$$

$$F(\omega) = \left[\left\{\left(A_{1th}^{\delta} + A_{1EP}^{\delta}\right) - \frac{\left(N_{1th}^{\delta} + N_{1EP}^{\delta}\right)^2}{2\left(D_{th}^{\delta} + D_{EP}^{\delta}\right)}\right\} - \frac{2N}{D}\left\{\left(A_{2th}^{\delta} + A_{2EP}^{\delta}\right) - \frac{\left(N_{1th}^{\delta} + N_{1EP}^{\delta}\right)\left(N_{2th}^{\delta} + N_{2EP}^{\delta}\right)}{2\left(D_{th}^{\delta} + D_{EP}^{\delta}\right)}\right\}\right]$$
$$- \frac{N}{D}\left[\left\{\left(A_{3th}^{\delta} + A_{3EP}^{\delta}\right) - \frac{\left(N_{1th}^{\delta} + N_{1EP}^{\delta}\right)\left(N_{2th}^{\delta} + N_{2EP}^{\delta}\right)}{\left(D_{th}^{\delta} + D_{EP}^{\delta}\right)}\right\} - \frac{2N}{D}\left\{\left(A_{4th}^{\delta} + A_{4EP}^{\delta}\right) - \frac{\left(N_{2th}^{\delta} + N_{2EP}^{\delta}\right)^2}{\left(D_{th}^{\delta} + D_{EP}^{\delta}\right)}\right\}\right]$$

There are total six parameters which control the GK dispersion relation.

$$\frac{n_f}{n_0},\ k_r \rho_{ti},\ u_{\parallel EP},\ q,\ \tau_e,\ \tau_{EP}$$

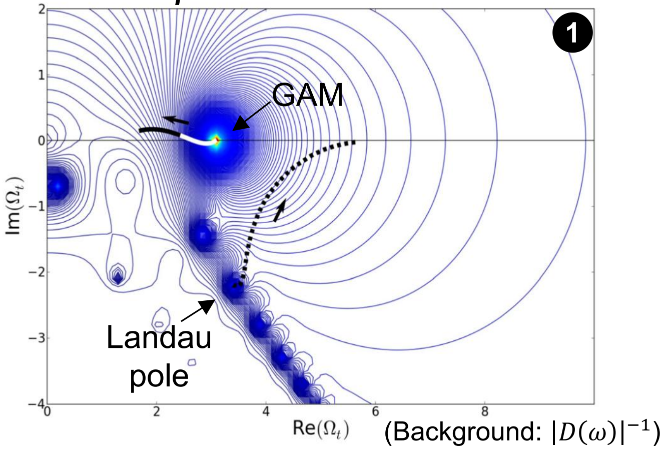
- $\frac{n_f}{n_0}$: Fast particle fraction
- $k_r \rho_{ti}$: Radial wavenumber (k_r) X Larmor radius of thermal ions
- $u_{\parallel EP}$: Location of the bump In energetic particle distribution
- τ_e: Temperature ratio of Electrons to thermal ions
- τ_{EP}: Temperature ratio of energetic ions to thermal ones



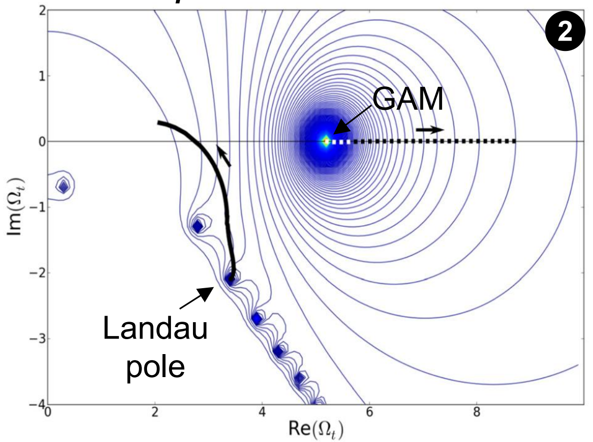
∗ : [Sugama & Watanabe 06' JPP]

Type of EGAM: (i) EGAM from GAM, (ii) Landau-EGAM

q = 1.6 EGAM-fG case

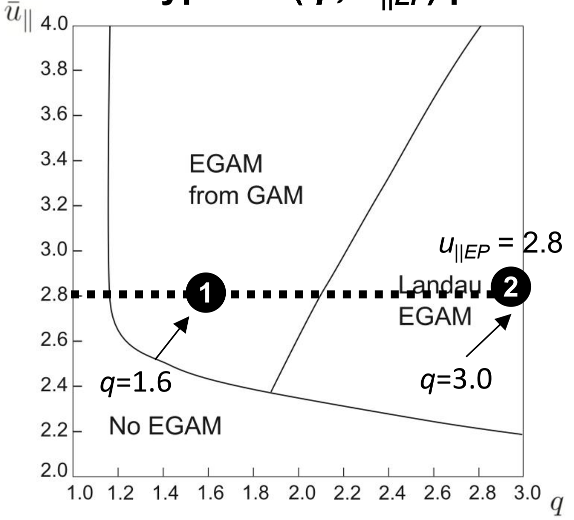


q = 3.0 Ld-EGAM case



[J.-B. Jirardo et al 14' POP]

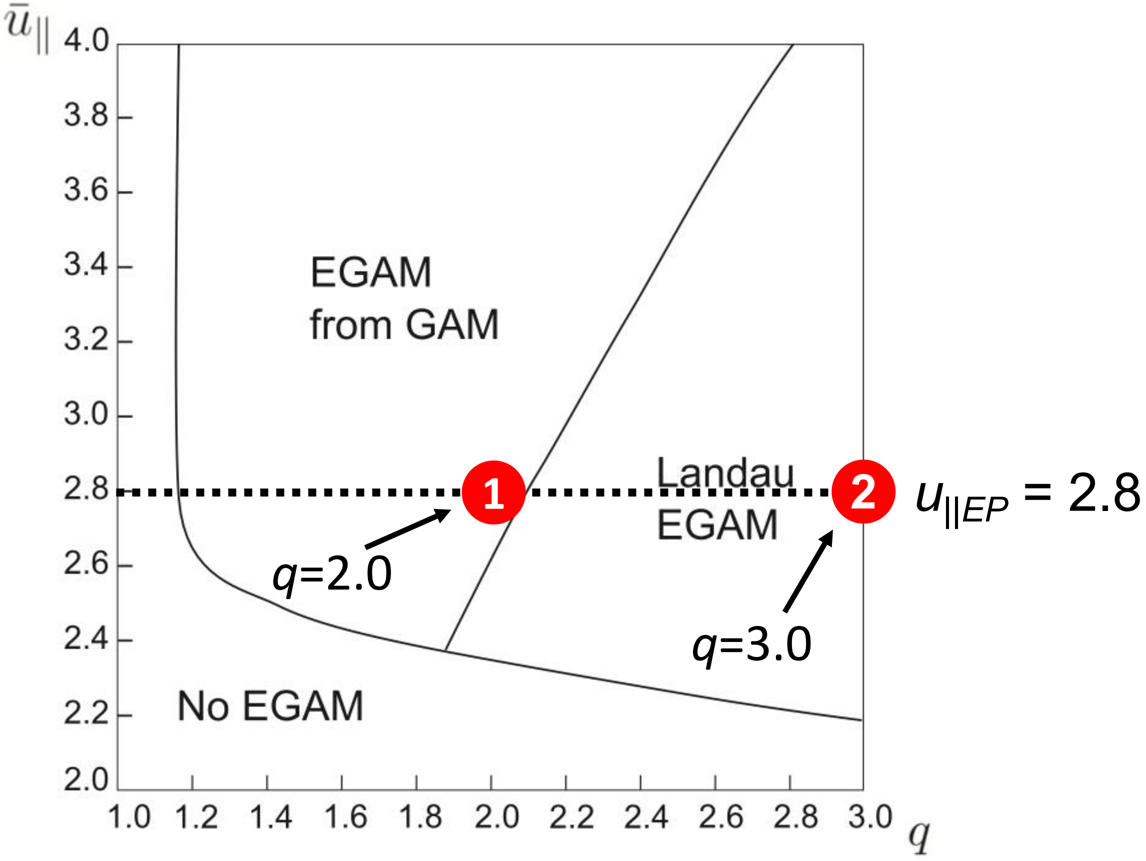
EGAM type on (q , $u_{||EP}$) plane



- **EGAM has two different types**:
  (i) for low $q \downarrow$ and high $u_{||EP} \uparrow$,
  the GAM becomes an EGAM: ***EGAM from GAM*** (**EGAM-fG**);
  (ii) for high $q \uparrow$ and low $u_{||EP} \downarrow$,
  a strongly damped Landau pole become an EGAM: ***Landau EGAM*** (**Ld-EGAM**).

FOW effects on EGAM: Comparison with GK simulations

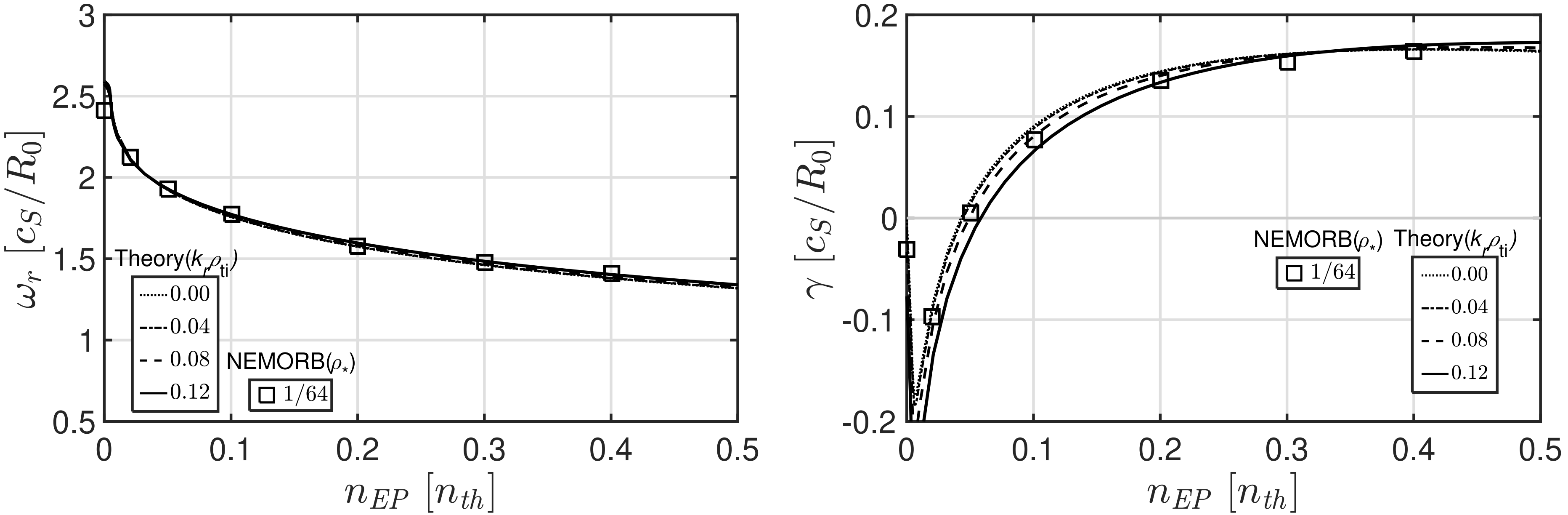
(NOTE: NEMORB data for 1 and 2 are taken with permission from [Zarzoso et al 14' NF])



∗ : NEMORB: electromagnetic version of ORB5 code (nonlinear GK, δf, PIC).

FOW effects on EGAM: Comparison with GK simulations

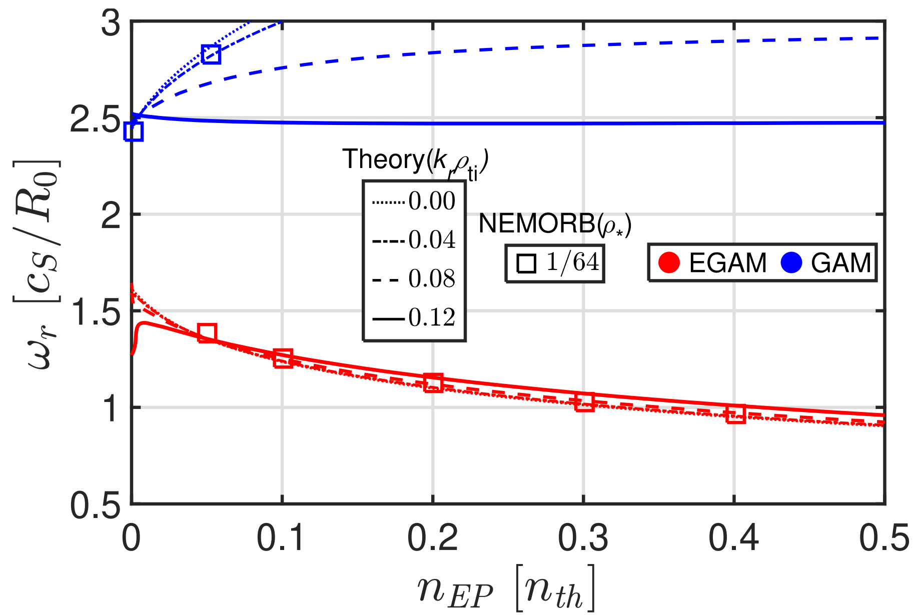
(2.0, 2.8) EGAM-fG case 1

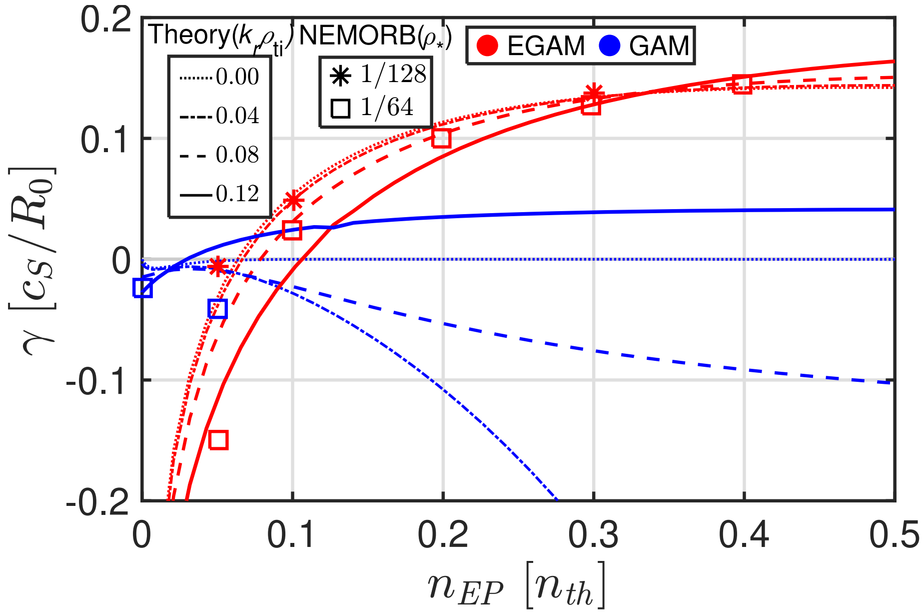


- The **FOW effects on EGAM** was observed to be very **weak**.
- Real **frequency** is almost **unchanged**.
- Only a **slightly enhanced damping of the EGAM** is observed with increasing $k_r\rho_{ti}$.

FOW effects on EGAM: Comparison with GK simulations

(3.0, 2.8) Ld-EGAM case ❷

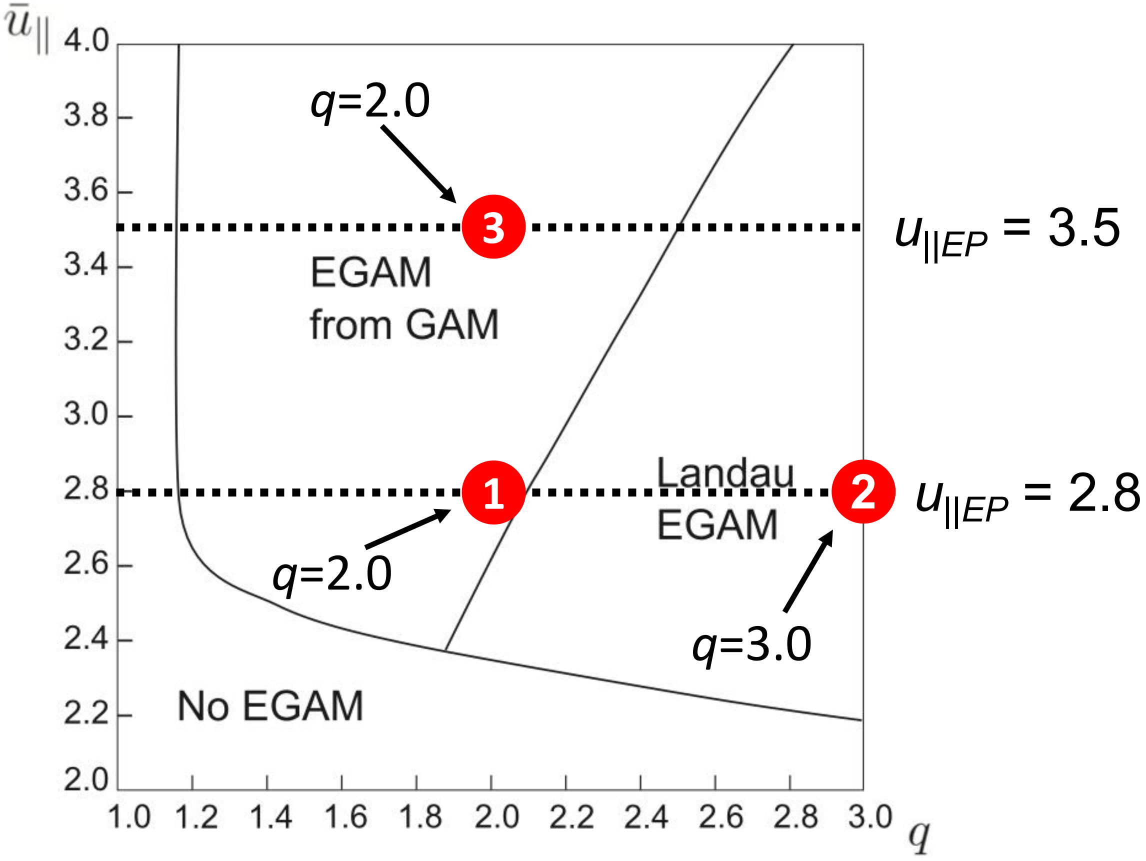




- **Enhanced damping of the EGAM** become more significant.
- The **GAM become highly stabilized** with increasing $k_r\rho_{ti}$.
- However, when $k_r\rho_{ti}$ exceeds a certain value, suddenly the **GAM also becomes unstable**.

FOW effects on EGAM: Comparison with GK simulations

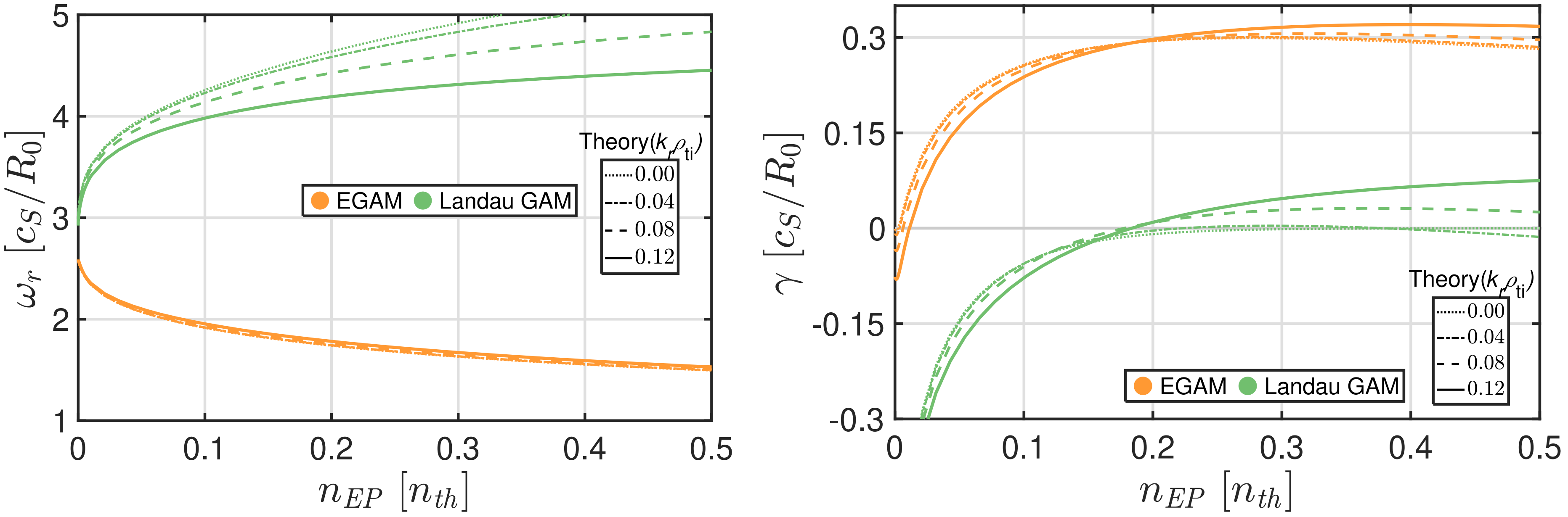
(NOTE: NEMORB data for 1 and 2 are taken with permission from [Zarzoso et al 14' NF])



∗ : NEMORB: electromagnetic version of ORB5 code (nonlinear GK, δf, PIC).

FOW effects on EGAM: Comparison with GK simulations

(2.0, 3.5) EGAM-fG case ❸

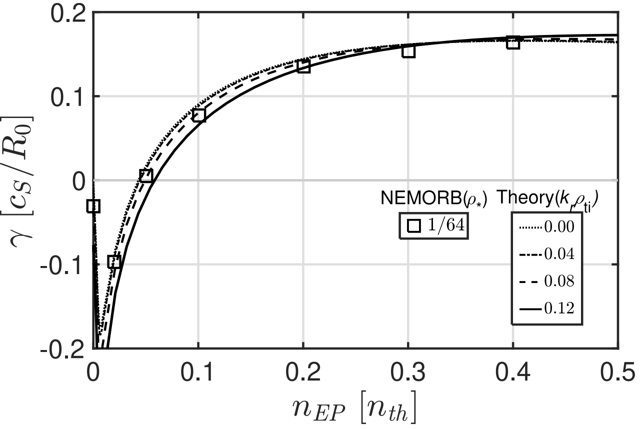


- The FOW does not affect the frequency, while it gives **a slightly enhanced damping to the EGAM**.
- Surprisingly, **a new unstable EGAM branch** can be also found in this new EGAM-fG case.
- The new EGAM branch **comes from a damped Landau pole** with a frequency close to the GAM.

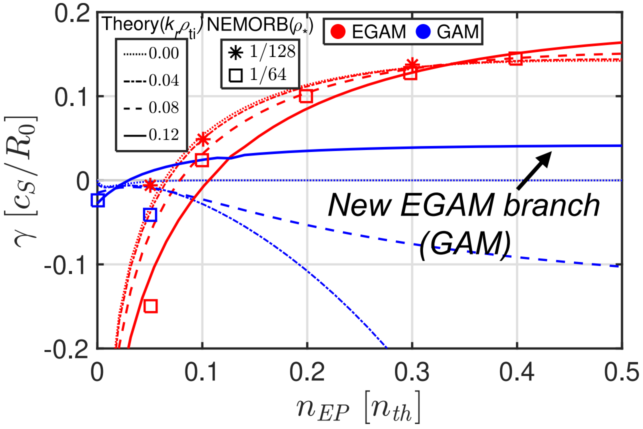
FOW effects on EGAM: Comparison with GK simulations

- A **good match** between gyrokinetic simulations and theoretical predictions is demonstrated.
- In both EGAM types, **FOW enhanced damping of EGAM** can be observed (more significant for Ld-EGAM).
- In both EGAM types, a **new unstable EGAM branch** is identified when the FOW become larger than a certain value.
- We have named this newly discovered unstable EGAM branch **δEGAM** (δ: FOW of passing thermal ions).

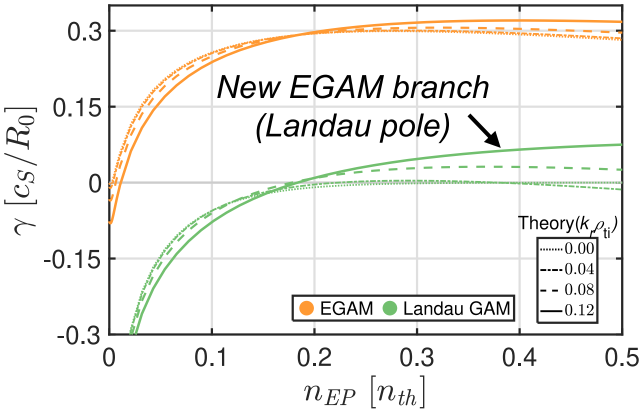
(2.0, 2.8) EGAM-fG case 1



(3.0, 2.8) Ld-EGAM case 2

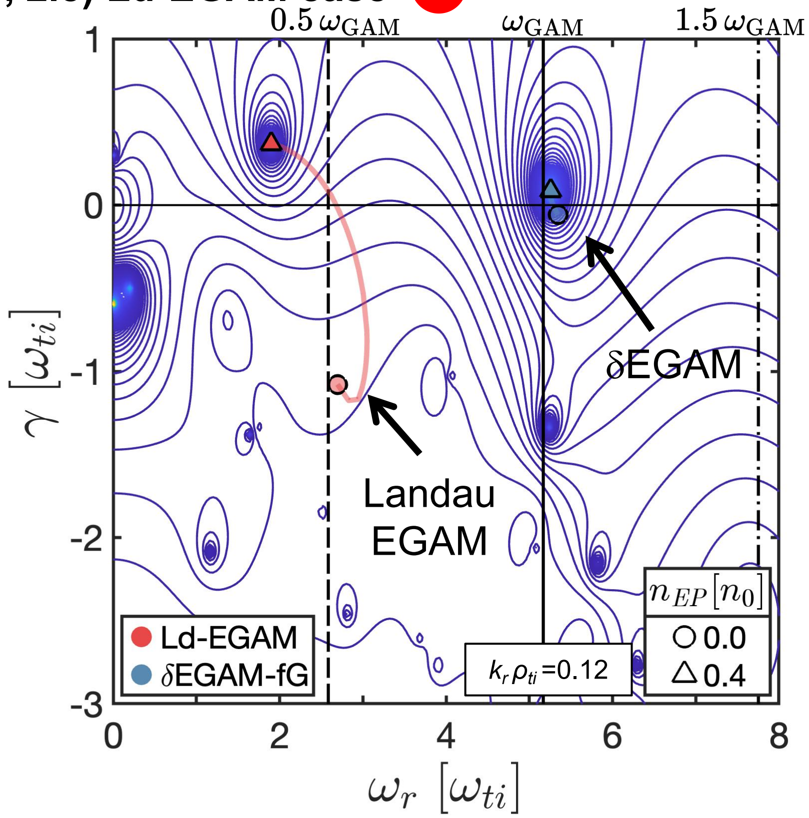


(2.0, 3.5) EGAM-fG case 3



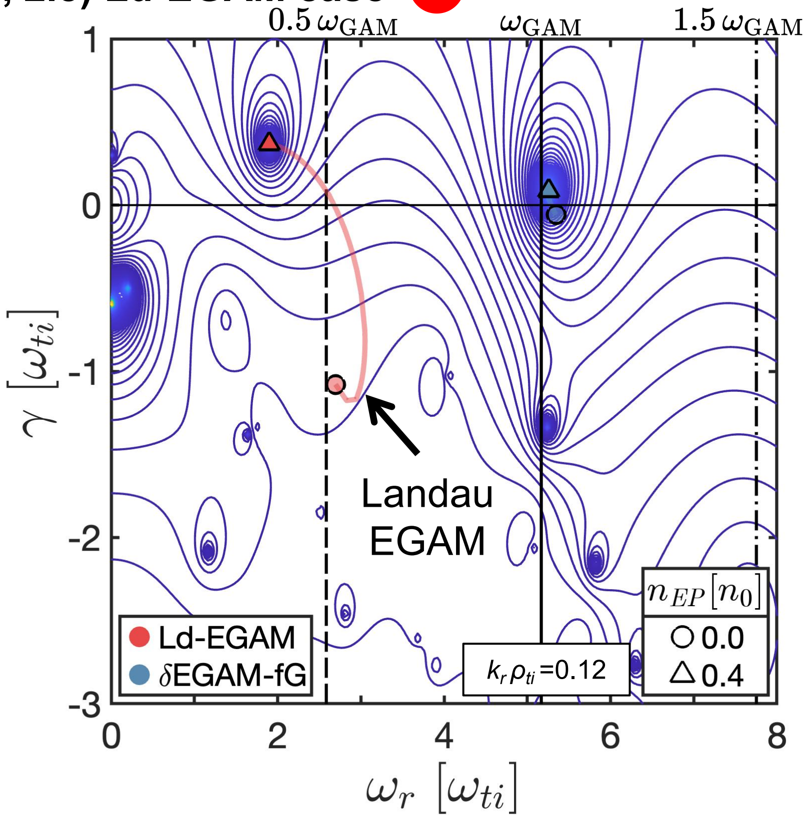
Root-locus plot of EGAM dispersion relation

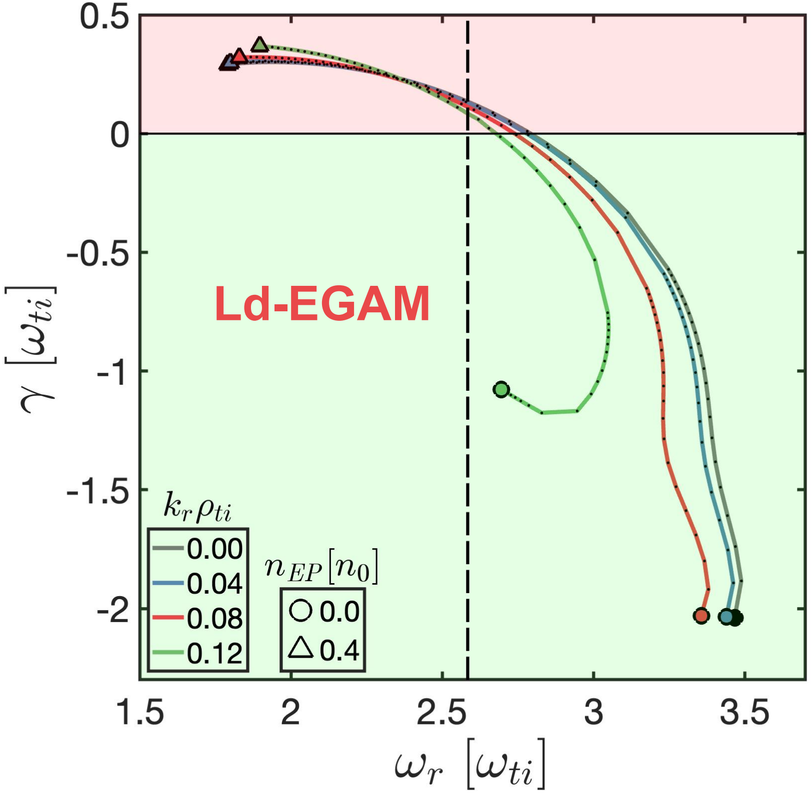
(3.0, 2.8) Ld-EGAM case 2



Root-locus plot of EGAM dispersion relation

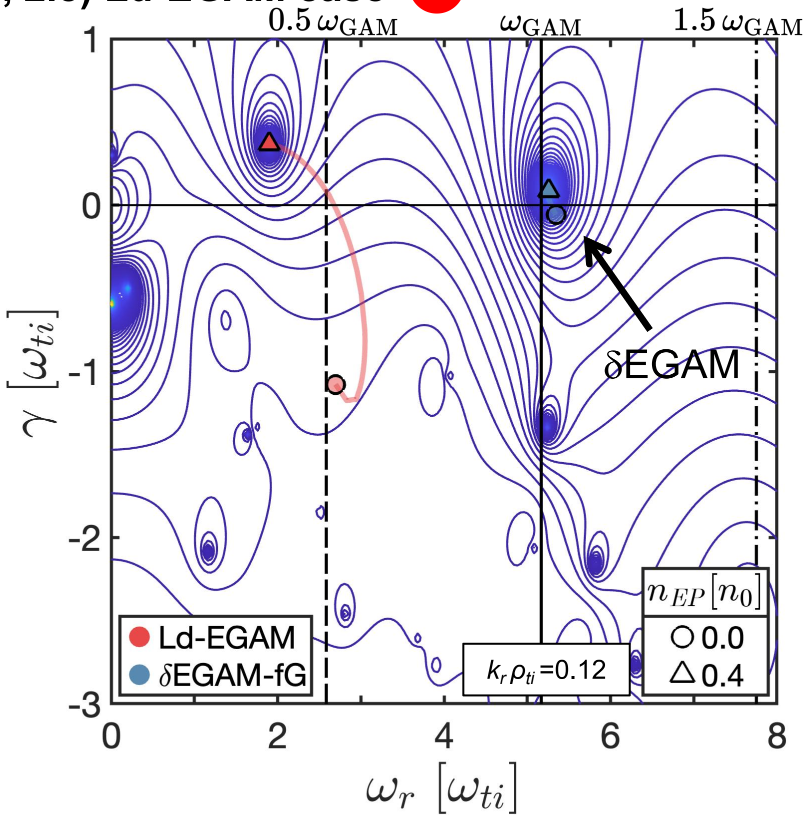
(3.0, 2.8) Ld-EGAM case 2

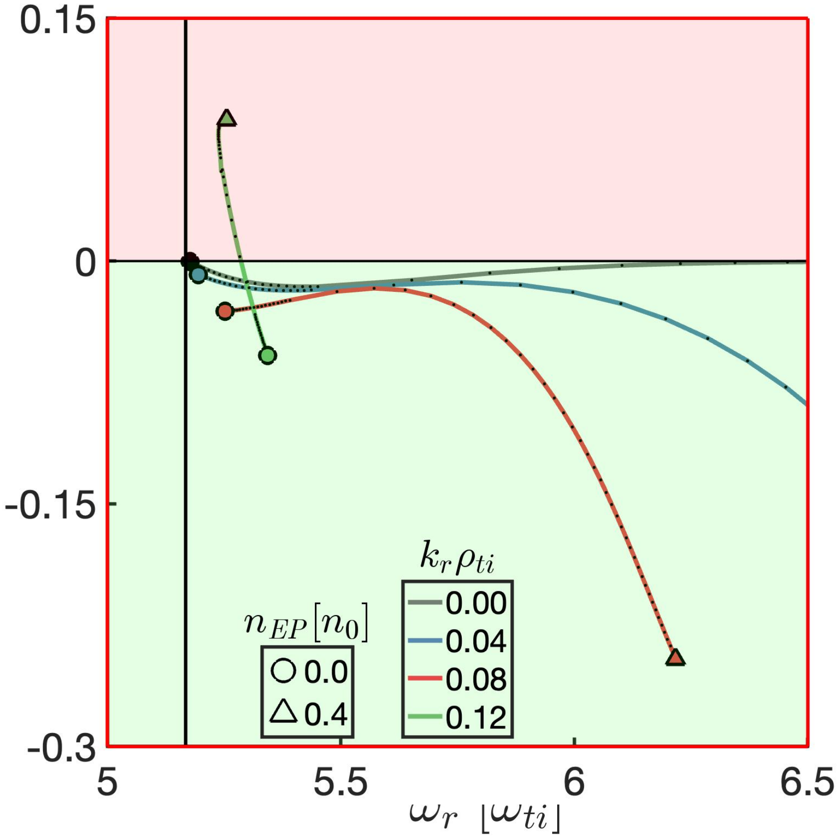




Root-locus plot of EGAM dispersion relation

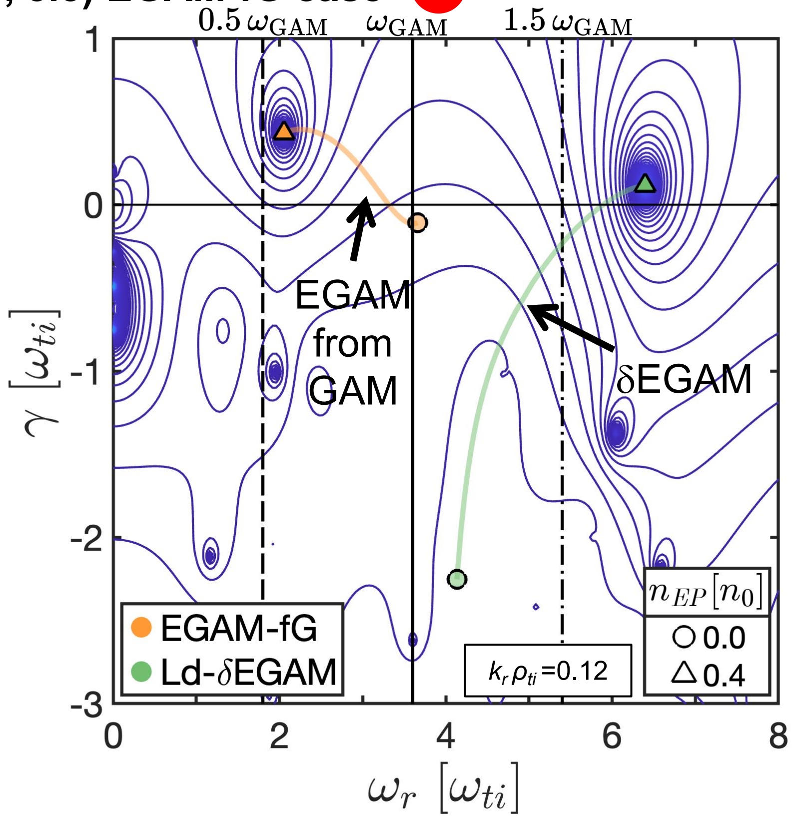
(3.0, 2.8) Ld-EGAM case 2





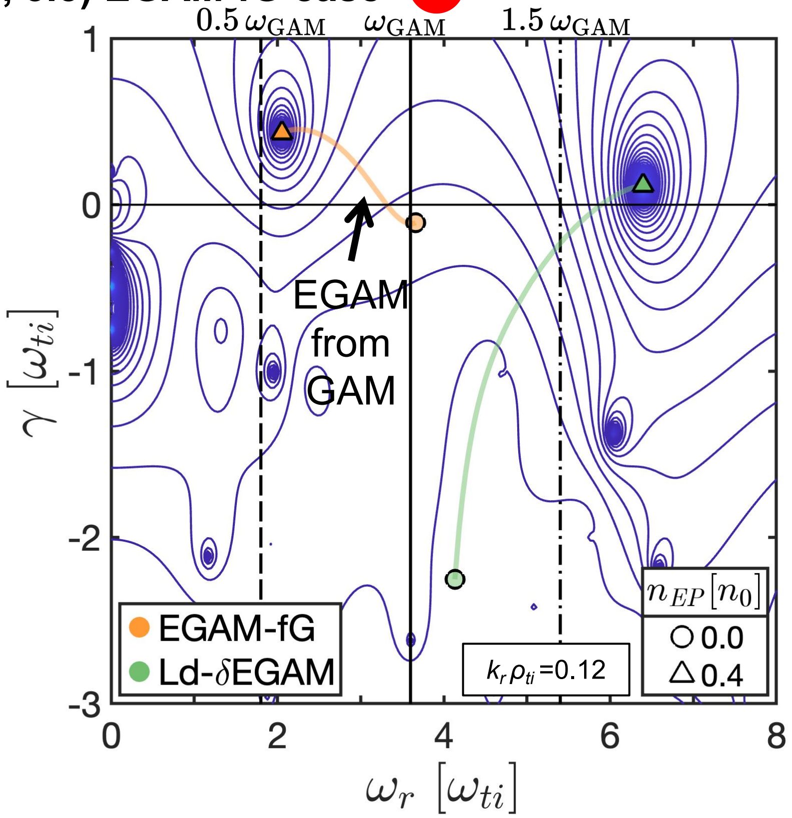
Root-locus plot of EGAM dispersion relation

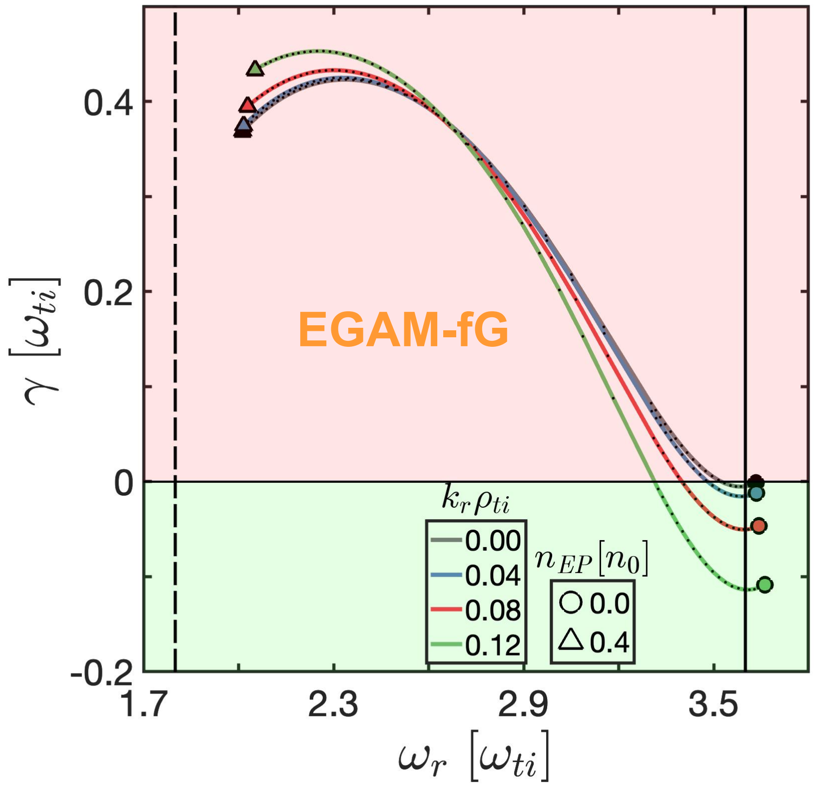
(2.0, 3.5) EGAM-fG case 3



Root-locus plot of EGAM dispersion relation

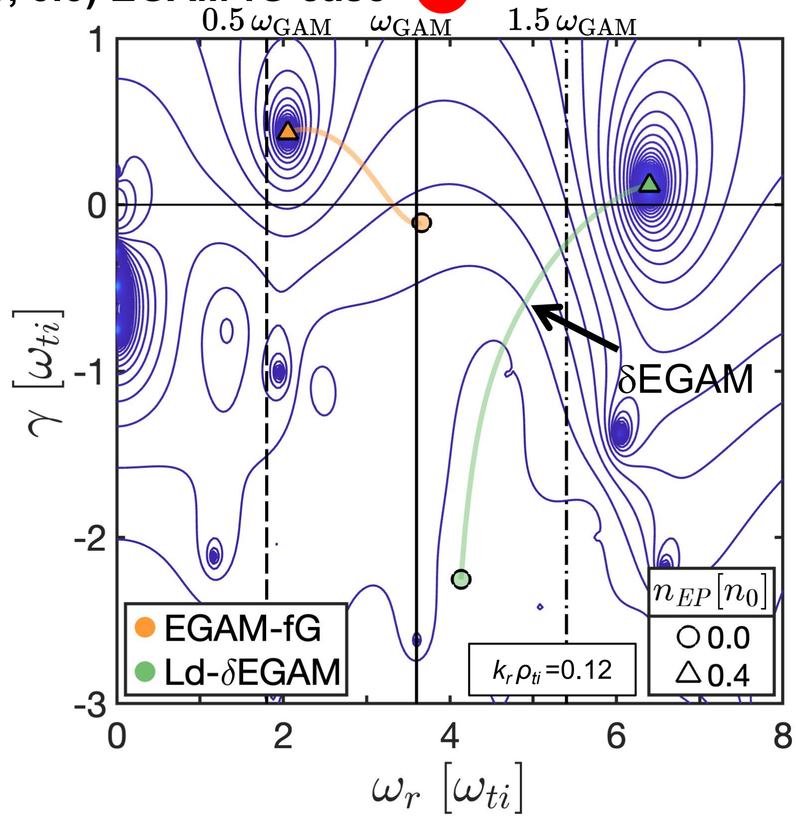
(2.0, 3.5) EGAM-fG case 3

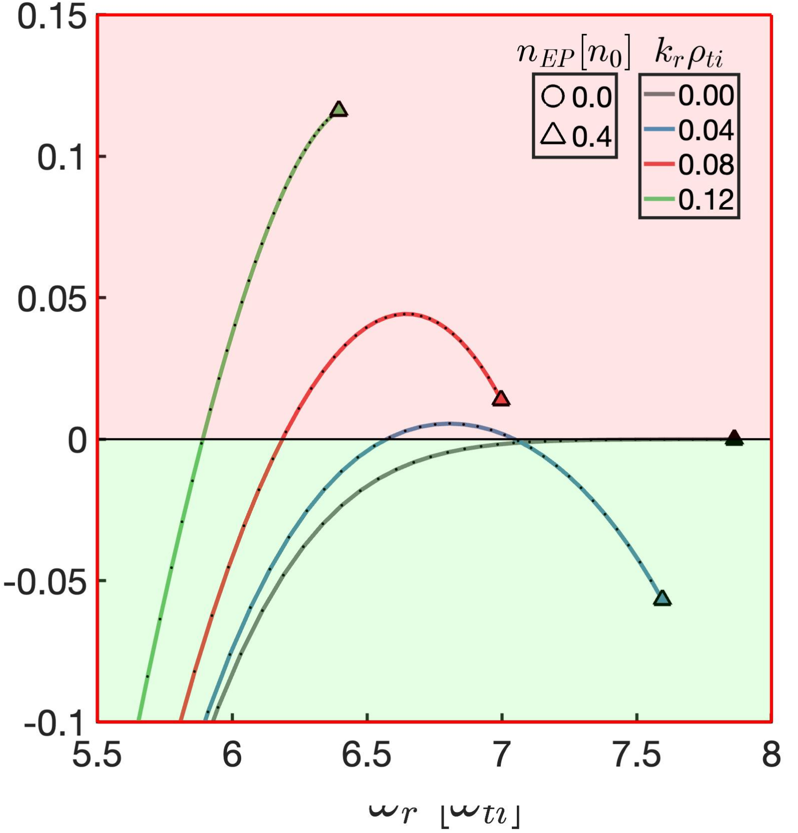




Root-locus plot of EGAM dispersion relation

(2.0, 3.5) EGAM-fG case 3

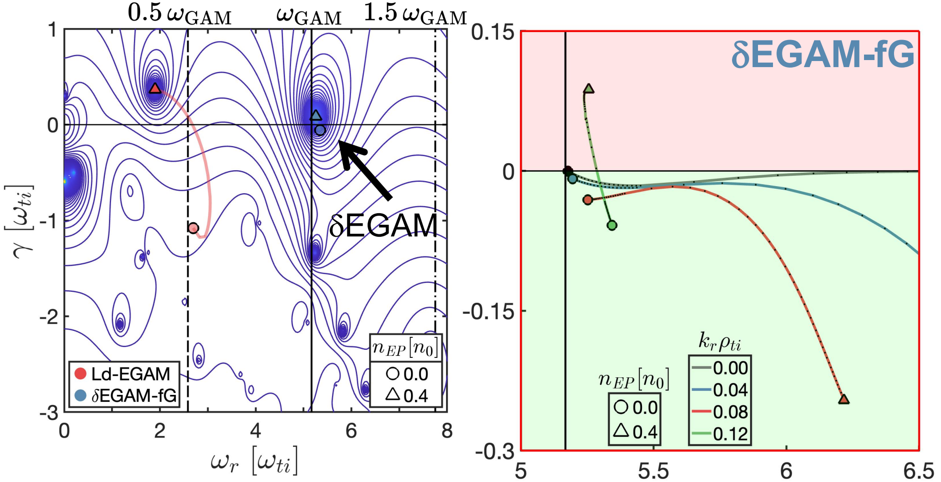




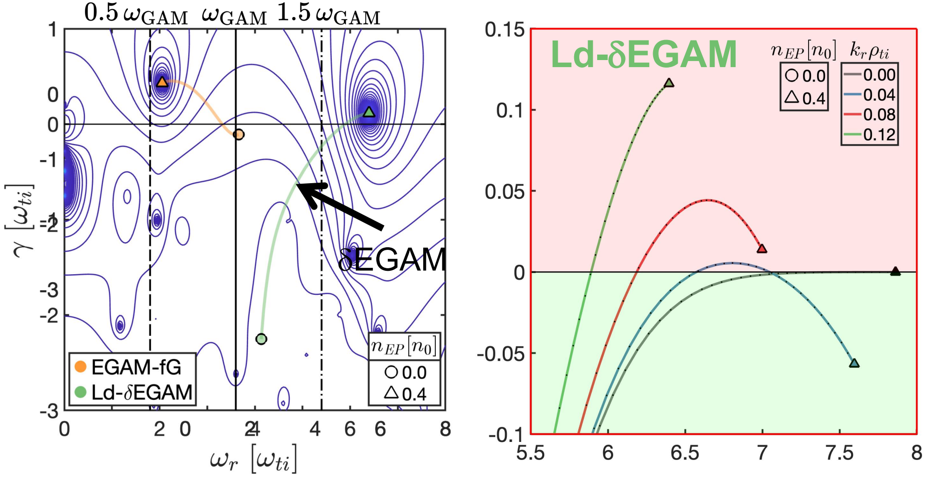
Simultaneous destabilization of EGAM and δEGAM

- Depending on the EGAM type, **δEGAM also have two different kinds:**
  (i) **Ld-EGAM case**, the GAM becomes a δEGAM: ***δEGAM from GAM*** (***δEGAM-fG***);
  (ii) **EGAM-fG case**, a Landau pole becomes a δEGAM: ***Landau-δEGAM*** (**Ld-*δEGAM***).
- δEGAM has a frequency similar to or higher than the GAM depending on the type:
  (i) **δEGAM-fG case**, $\boldsymbol{\omega_{\delta EGAM} \sim \omega_{GAM}}$; (ii) **Ld-δEGAM case**, $\mathbf{1.5}\boldsymbol{\omega_{GAM}} < \boldsymbol{\omega_{\delta EGAM}} < \mathbf{2.0}\boldsymbol{\omega_{GAM}}$.

Ld-EGAM + ***δEGAM-fG*** *case*

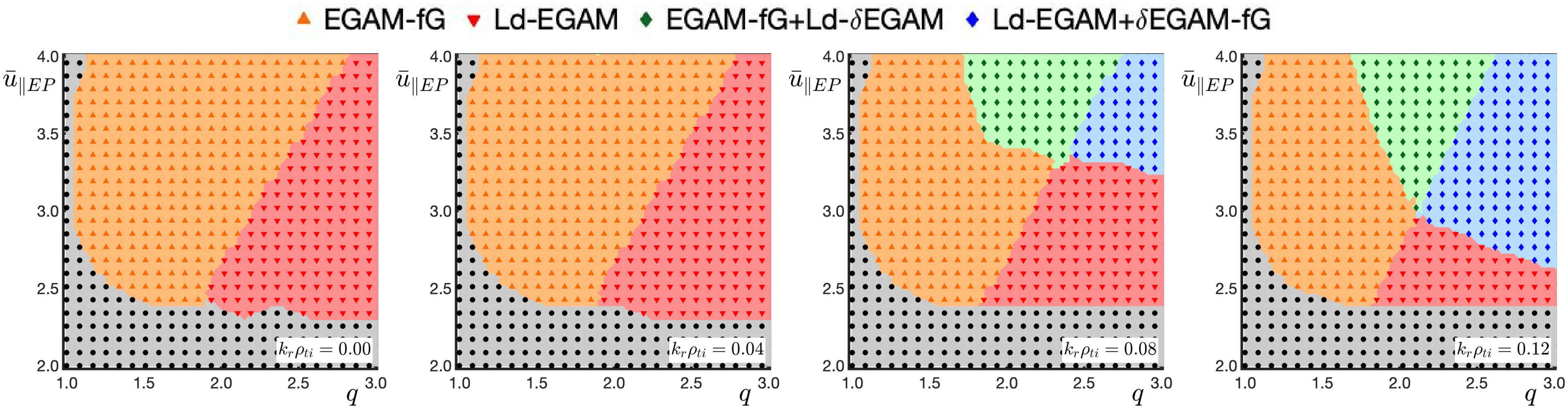


EGAM-fG + ***Ld-δEGAM*** *case*

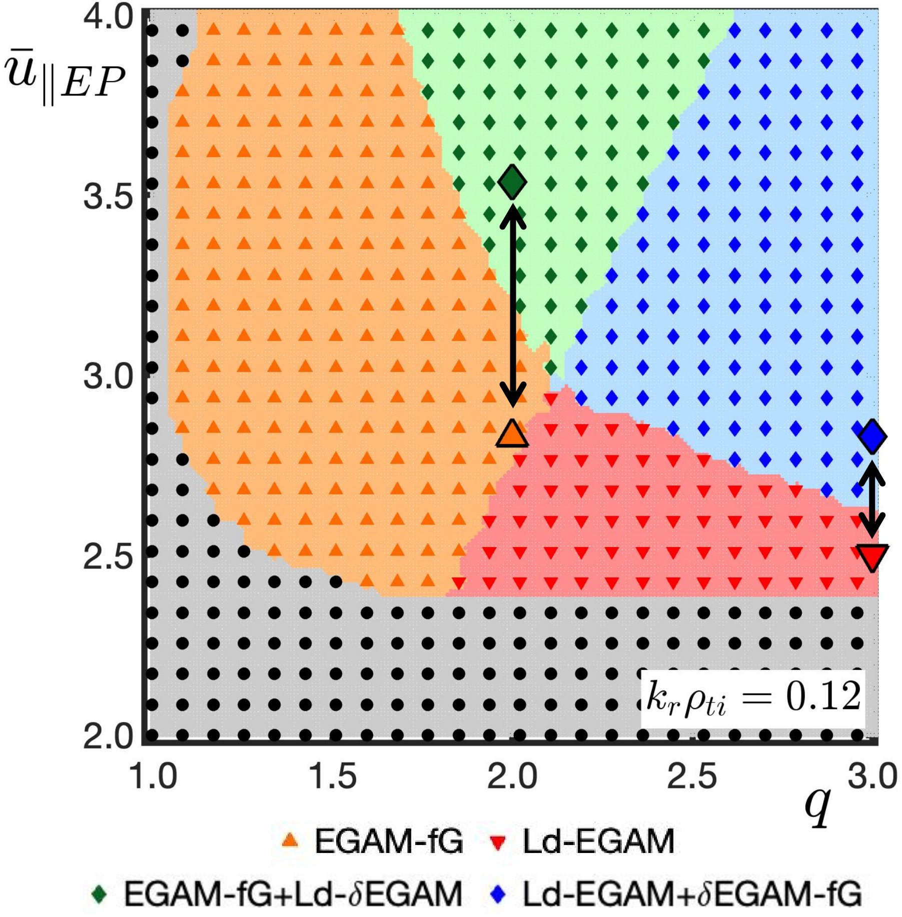


Type of EGAM/δEGAM on q-$u_{||EP}$ surface with different $k_r\rho_{ti}$

- The δEGAM begins to emerge when **$k_r \rho_{ti} \gtrsim$ 0.05 (threshold)**.
- With **higher $k_r \rho_{ti}$ ↑**, the space of **EGAM+δEGAM zone expands**.
- For a given type of EGAM, the δEGAM prone to be unstable with **higher q ↑ and $u_{||EP}$ ↑**.



How the FOW effects destabilizes the δEGAM?



We will show how the $F(\omega)$ destabilizes the δEGAM by comparing δEGAM

"***unstable***" case with higher $u_{\|EP}$

"***stable***" case with lower $u_{\|EP}$.

***q* = 3** **δEGAM-fG**	***q* = 2** **Ld-δEGAM**
with $u_{\|EP}$ ↑ (unstable) ↕ **with $u_{\|EP}$ ↓ (stable)**	**with $u_{\|EP}$ ↑ (unstable)** ↕ **with $u_{\|EP}$ ↓ (stable)**

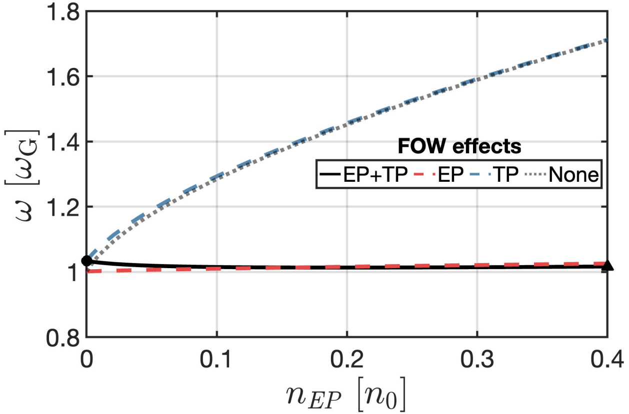
(NOTE: Results will be shown as below)

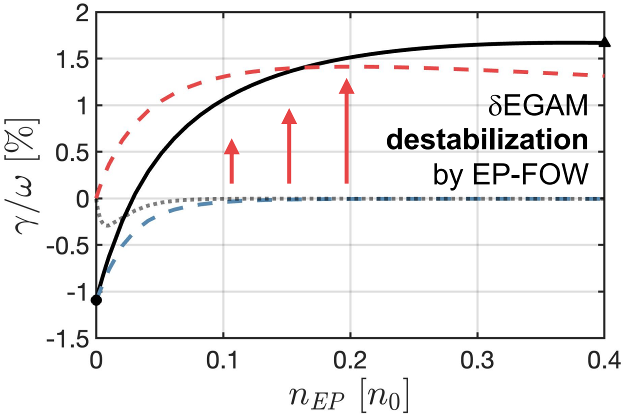
***F*(ω)**	***F*$_{EP}$(ω)**	***F*$_{th}$(ω)**	w/o ***F*(ω)**

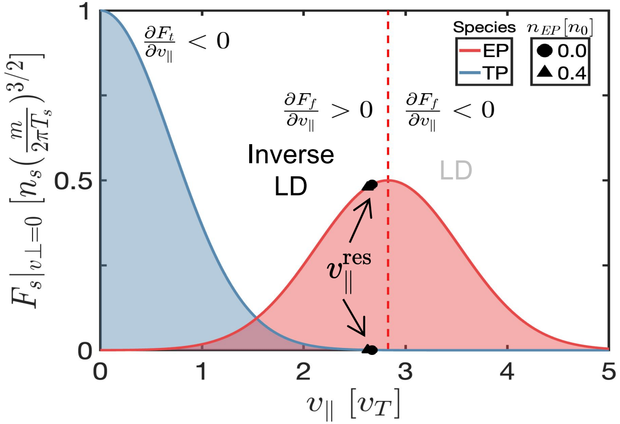
q=3 δEGAM-fG case

NOTE: $v_{\parallel}^{\mathrm{res}} = (qR_0\omega)/2$

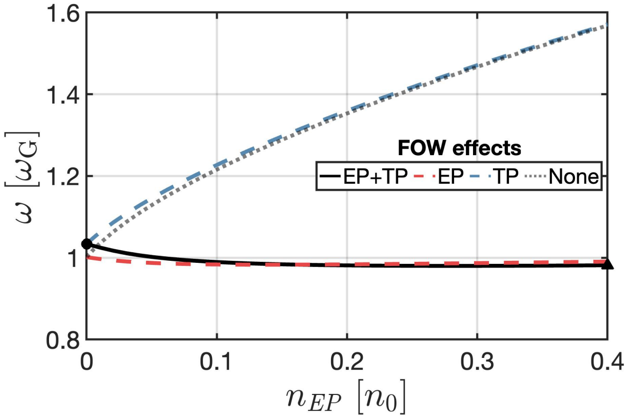
δEGAM-fG (unstable) with $u_{\parallel EP}$ ↑

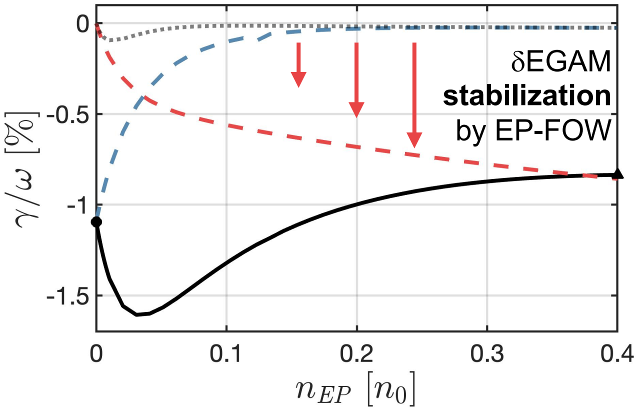


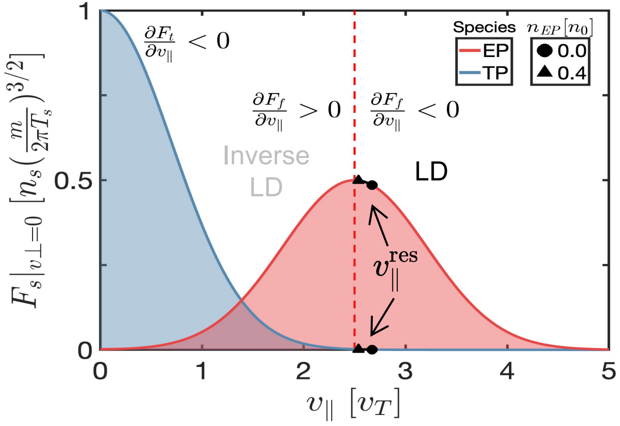




δEGAM-fG (stable) with $u_{\parallel EP}$ ↓





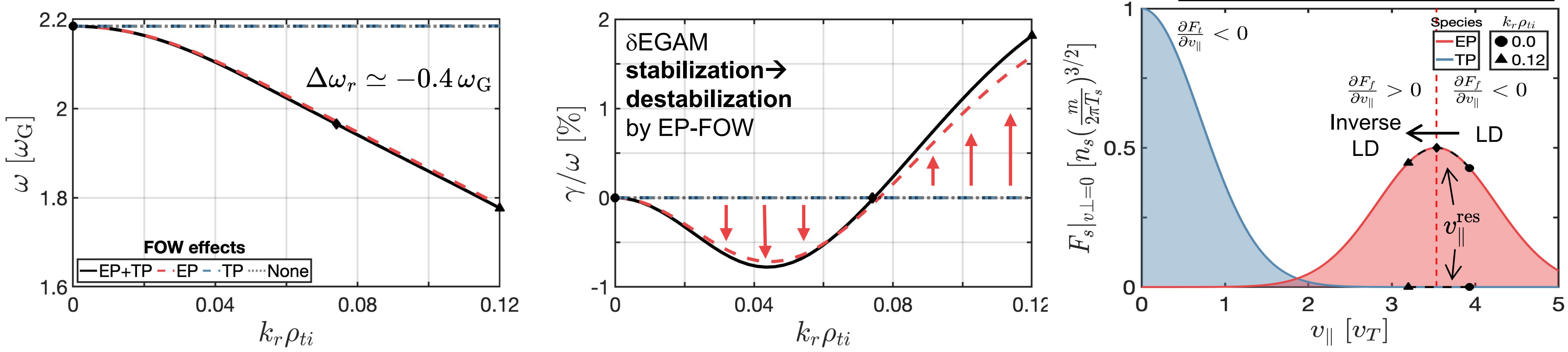


→**δEGAM-fG** is destabilized by ***inverse Landau damping*** arisen from ***EP-FOW*** effects

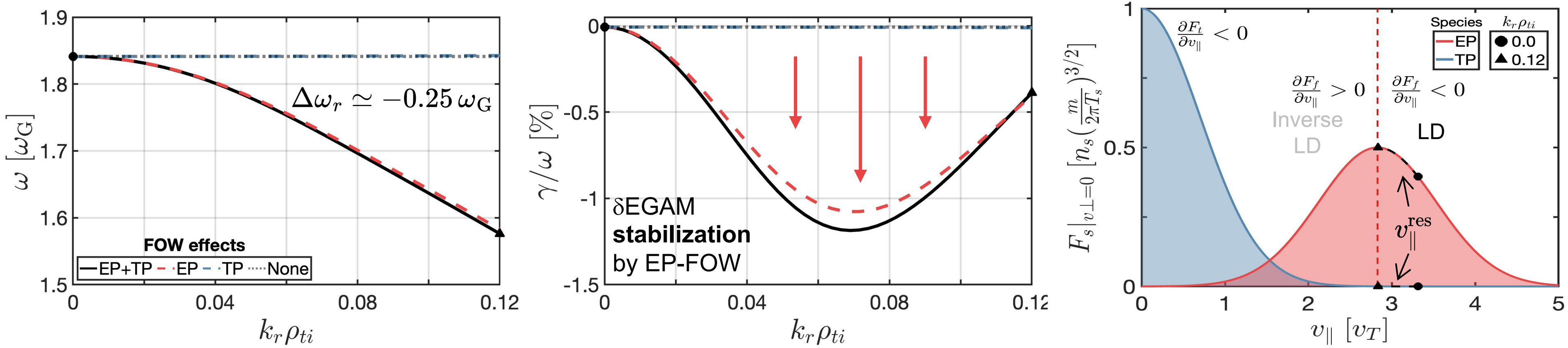
q=2 Ld-δEGAM case

NOTE: $v_{\parallel}^{\rm res} = (qR_0\omega)/2$

Ld-δEGAM (unstable) with $u_{||EP}\uparrow$



Ld-δEGAM (stable) with $u_{||EP}\downarrow$



→**Ld-δEGAM** is also destabilized by ***inverse Landau damping*** arisen from ***EP-FOW*** effects

Summary and conclusion

- Gyrokinetic EGAM dispersion relation considering FOW effects is newly derived.
- **FOW enhanced damping of EGAM** is predicted with the dispersion relation and shows a good match with NEMORB simulations.
- If **FOW is large** enough, another unstable EGAM branch appears, referred to as **δEGAM**.
- δEGAM have two different types:
  (i)δEGAM from GAM (**δEGAM-fG**), (ii)Landau δEGAM (**Ld-δEGAM**).
- Depending on the type, δEGAM has different thresholds and frequency range as follows:

	δEGAM from GAM	Landau δEGAM
Threshold	$n_{\delta\mathrm{EGAM}}^{EP,\ th} \ll n_{\mathrm{EGAM}}^{EP,\ th}$	$n_{\delta\mathrm{EGAM}}^{EP,\ th} \gg n_{\mathrm{EGAM}}^{EP,\ th}$
Frequency	$\omega_{\delta\mathrm{EGAM}} \sim \omega_{\mathrm{GAM}}$	$1.5\omega_{\mathrm{GAM}} < \omega_{\delta\mathrm{EGAM}} < 2.0\omega_{\mathrm{GAM}}$

- δEGAM is driven by **inverse Landau damping**, which arises from the **higher harmonic transit resonance** caused by FOW effects.