UCSD

Intrinsic Axial Flows in CSDX and Dynamical Symmetry Breaking in ITG Turbulence

-- Negative Viscosity Effects and Flow Saturation

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Outline

- Introduction:
  - Why intrinsic rotation + weak shear?
  - Intrinsic flow at zero shear: CSDX experiments; ion features
  - Theory: Dynamical Symmetry Breaking in Collisional Drift Wave turbulence
- Symmetry Breaking in ITG turbulence at zero magnetic shear?
  - PSF-ITG system
  - Symmetry breaking in 3 instability regimes
  - Summary: $\nabla V_{\|}$ effects on ITG turbulence
- Lesson for tokamaks: interaction with symmetry breaking based on magnetic shear
  - Rotation profiles

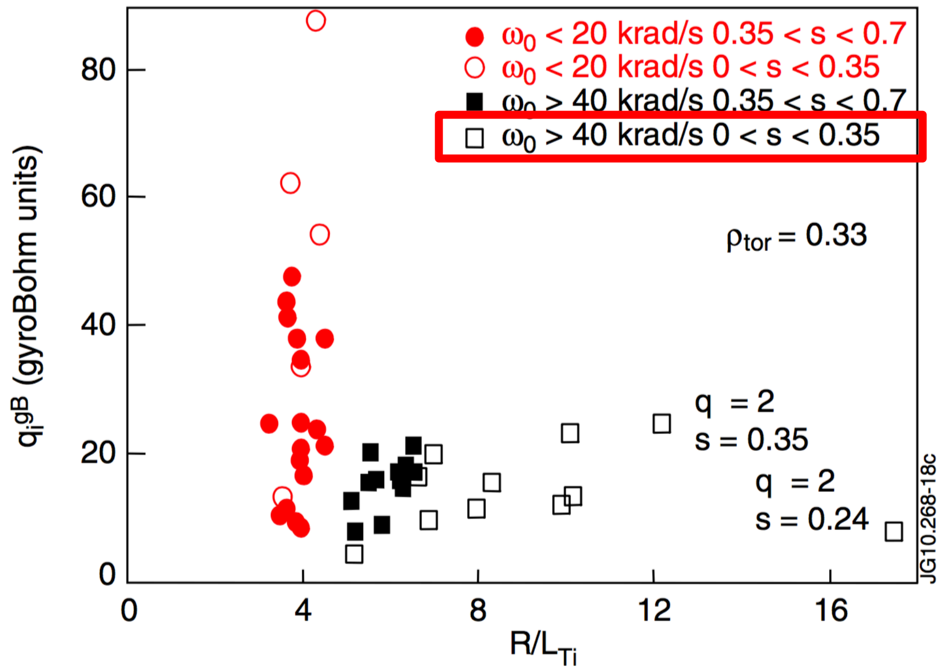
Intrinsic Rotation in Weak Shear

- JET: Weak shear **AND** Rotation → Enhanced confinement
- But external torque limited in ITER
- Need understand: ***Intrinsic rotation in weak shear regimes***

- Important for:
  - Total effective torque

    $$\tau = \tau_{ext} + \tau_{intr}$$

  - Contribution to $V'_{E\times B}$

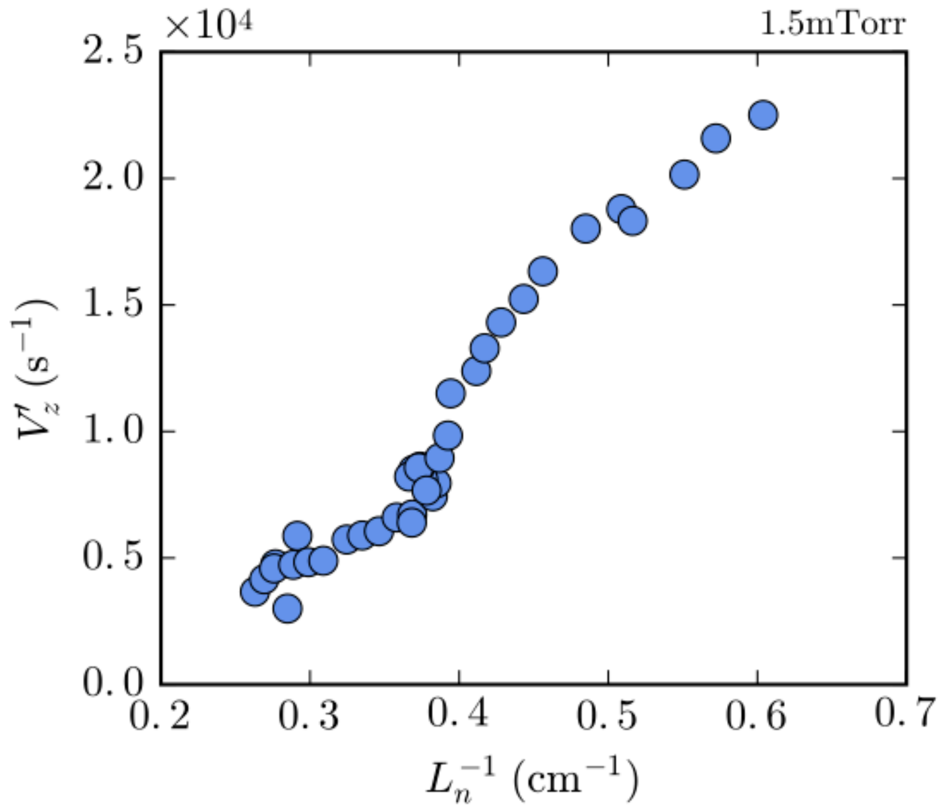


[P. Mantica, PRL, 2011;
Rice, PRL, 2013]

FIG. 4 (color online). q_i^{GB} vs R/L_{T_i} at $\rho_{tor} = 0.33$ for similar plasmas with different rotation and s values.

Intrinsic $\nabla\langle v_z\rangle$ in Drift Wave Turbulence

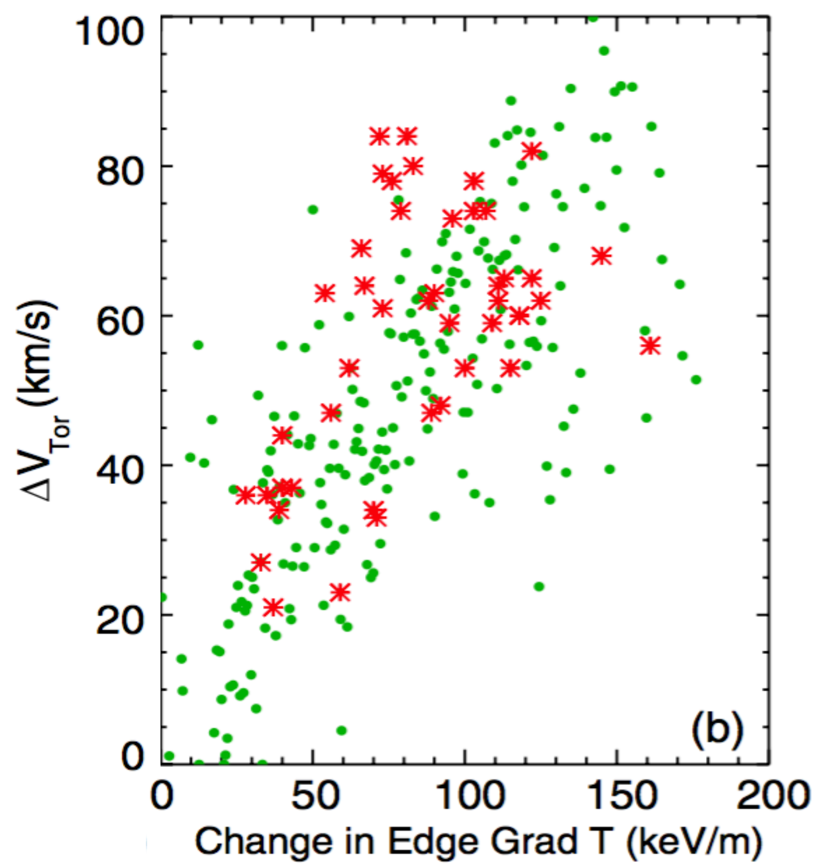
- Axial flow in CSDX:
- ∇n_0 is free energy source
- $\langle v_z\rangle' \sim \frac{1}{n_0}\nabla n_0$



(Zero magnetic shear)

- Compare:
- Intrinsic $\nabla\langle v_z\rangle$ in C-Mod pedestal:
- $\Delta\langle v_\phi\rangle \sim \nabla T$

[Rice, PRL, 2011]



(Standard shear)

Theory of Intrinsic Rotation at Zero Shear

- Intrinsic flow accelerated by residual stress ($\tau_{intr} = -\nabla \cdot \Pi^{Res}$)

$$\langle \tilde{v}_r \tilde{v}_\parallel \rangle = -\chi_\phi \frac{d\langle v_\parallel \rangle}{dr} + V_P \langle v_\parallel \rangle + \Pi_{r\parallel}^{Res}$$

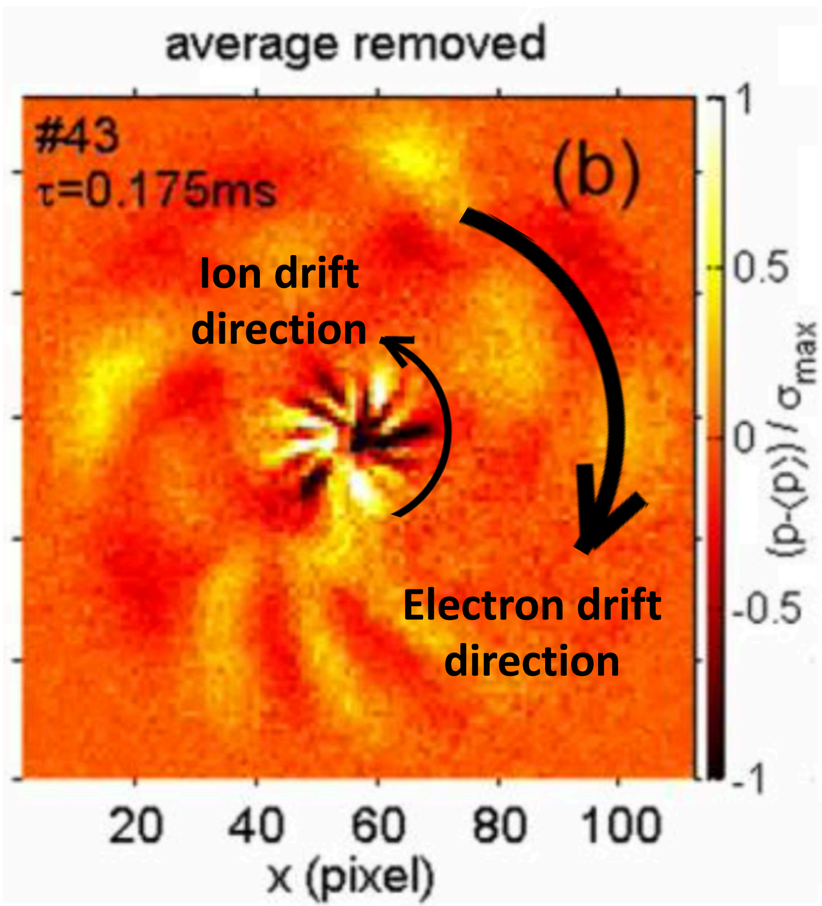
- Residual stress driven by turbulence, i.e. $\Pi_{r\parallel}^{Res} \sim \nabla P, \nabla T, \nabla n_0$
- $\Pi_{r\parallel}^{Res} \sim \langle k_\theta k_\parallel \rangle$ etc. requires symmetry breaking in $k_\theta k_\parallel$ space, at ZERO shear
- → Dynamical symmetry breaking
- Negative viscosity increment induced by Π^{Res}
  - $\delta\Pi^{Res} = \left|\chi_\phi^{Res}\right| \delta\langle v_z \rangle'$ → Total viscosity: $\chi_\phi^{tot} = \chi_\phi - \left|\chi_\phi^{Res}\right|$
  - $\chi_\phi^{tot} < 0$ → Modulational growth of $\delta\langle v_z \rangle'$
- Broader lesson for tokamaks
  - Synergy of $\langle v_\phi \rangle'$ self-amplification and Π^{Res}
  - $\langle v_\phi \rangle'$ driven by τ_{NBI}, $\Pi^{Res}(\nabla n_0, \nabla T)$, and enhanced by $-\left|\chi_\phi^{Res}\right|$
  - $\langle v_\phi \rangle' \sim \frac{\tau_{NBI} + \Pi^{Res}(\nabla n_0, \nabla T)}{\chi_\phi - \left|\chi_\phi^{Res}\right|}$

Compare Symmetry Breaking Mechanisms

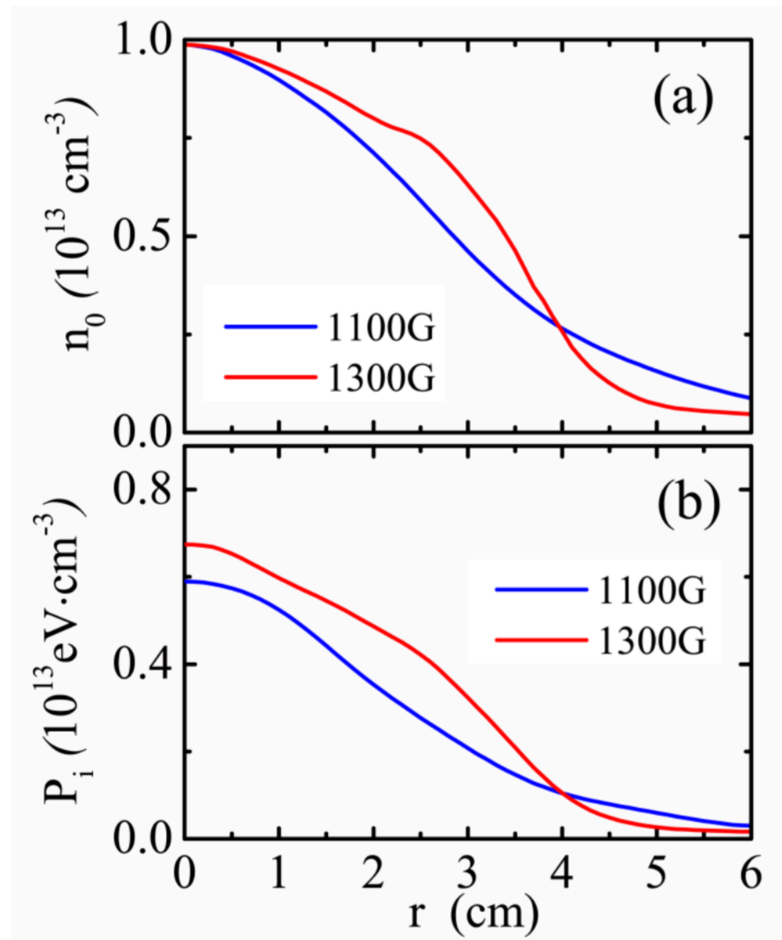
	Standard Symmetry Breaking	Dynamical Symmetry Breaking
Free energy	$\nabla T_i, \nabla T_e, \nabla n_0, \dots$	∇n_0, ∇T_e--electron drift waves
Symmetry breaker	$E_r', I(x)', \dots$ All tied to magnetic field configuration	Test toroidal flow shear, $\delta\langle v_\phi\rangle'$; No requirement for shear of $\boldsymbol{B}$ structure.
Effect on flow	Intrinsic torque, $-\partial_r \Pi_{r\parallel}^{Res}$	Negative viscosity, $-\lvert\chi_\phi^{Res}\rvert$ driven by ∇n_0
Flow profile	$\langle v_\parallel\rangle' = \dfrac{\Pi_{r\parallel}^{Res}}{\chi_\phi}$	$\langle v_\phi\rangle' = \dfrac{\text{Flow drive (e.g. } \Pi_{r\phi}^{Res}, \Delta P_i)}{\chi_\phi(\nabla n_0, \nabla\langle v_\phi\rangle) - \lvert\chi_\phi^{Res}\rvert}$
Feedback loop	Heat flux → ∇T_i + geometry (magnetic shear) → $\Pi_{r\parallel}^{Res}$ → $\langle v_\parallel\rangle'$ Open loop	Test flow shear $\delta\langle v_\phi\rangle'$ → Spectral imbalance → Residual stress $\Pi_{r\phi}^{Res} \to \lvert\chi_\phi^{Res}\rvert$ → Intrinsic flow, feedback on $\delta\langle v_\phi\rangle'$ → Test flow shear $\delta\langle v_\phi\rangle'$ Self-amplification Driven by ∇n_0

Ion Features in CSDX

- Mode Coexistence



- T_i profile steepening



Questions

- What happens to ITG turbulence?
  - How does $\nabla V_{\parallel}$ affect the ITG turbulence?
  - Does ITG turbulence have dynamical symmetry breaking?
- How does $\nabla V_{\parallel}$ induced symmetry breaking interact with symmetry breaking by magnetic shear?

PSF-ITG System

- Fluid model with ion dissipation

$$\frac{d}{dt}(1-\nabla_\perp^2)\phi + \mathbf{v}_E \cdot \cancel{\frac{\nabla n_0}{n_0}} + \nabla_\parallel \tilde{v}_\parallel = 0,$$

$$\frac{d\tilde{v}_\parallel}{dt} + \mathbf{v}_E \cdot \boxed{\nabla V_\parallel} = -\nabla_\parallel \phi - \nabla_\parallel \tilde{p}_i,$$

$$\frac{d\tilde{p}_i}{dt} + \frac{1}{\tau}\mathbf{v}_E \cdot \boxed{\frac{\nabla P_0}{P_0}} + \frac{\Gamma}{\tau}\nabla_\parallel \tilde{v}_\parallel + \nabla_\parallel Q_\parallel = 0.$$

- 2 free energy sources: $\nabla V_\parallel$ and ∇T_i
- Magnetic shear = 0
  → No correlation between parallel and perpendicular directions
  → Simplified geometry (cylindrical)
- Landau damping closure: $Q_{\parallel,k} = -\chi_\parallel n_0 i k_\parallel \tilde{T}_{i,k}$

(Hammett and Perkins, PRL, 1995) $\chi_\parallel = 2\sqrt{2} v_{Thi}/(\sqrt{\pi}|k_\parallel|)$

- Dispersion relation:

$$A\Omega^3 - (C_0 - V')\Omega - D = 0$$

$$A \equiv 1 + k_\perp^2 \rho_s^2, \qquad \Omega \equiv \frac{\omega}{|k_\parallel c_s|},$$

$$C_0 \equiv 1 + \frac{1 + k_\perp^2 \rho_s^2}{\tau}\Gamma, \quad V' \equiv \frac{k_\theta k_\parallel \rho_s c_s}{k_\parallel^2 c_s^2}\frac{\partial V_\parallel}{\partial r},$$

$$D \equiv \frac{\omega_T}{\tau |k_\parallel c_s|}. \qquad \tau \equiv \frac{T_e}{T_i}$$

- Landau damping effect ignored because

$$\frac{|k_\parallel|\chi_\parallel}{c_s} \sim \frac{v_{Thi}}{c_s} = \frac{1}{\sqrt{\tau}} < 1 \text{ in CSDX}$$

- Criterion for instability: $\Delta \equiv \left(\frac{D}{2A}\right)^2 - \left(\frac{C_0 - V'}{3A}\right)^3 > 0$

$\nabla V_\parallel$ and ∇T_i are coupled nonlinearly

Can be decoupled by limiting relative scale length $L_T/L_V \equiv \partial_r \ln T_{i0}/\partial_r \ln V_\parallel$

E.g. consider two extreme cases:

- ITG Instability: $A\Omega^3 - D \approx 0,\ \omega \sim e^{i2\pi/3}(\omega_T k_\parallel^2 c_s^2/\tau A)^{1/3}$
- PSFI (parallel shear flow instability):

$$A\Omega^3 + (V' - C_0)\Omega \approx 0, \quad \omega \sim e^{i\pi/2}\sqrt{V' - C_0/A}$$

Instability Regimes

- Goal: decouple $\nabla V_\parallel$ and ∇T_i
  - Residual stress → χ_ϕ^{Res}
  - $\chi_\phi^{tot} = \chi_\phi^{ITG} + \chi_\phi^{PSFI} + \chi_\phi^{Res}$

  ⇒Flow profile $V_\parallel' \sim \Pi_{r\parallel}^{Res} / \chi_\phi^{tot}$

- Regimes in $\nabla V_\parallel$-∇T_i space:

  (1) Marginally unstable regime: $\Delta \gtrsim 0$

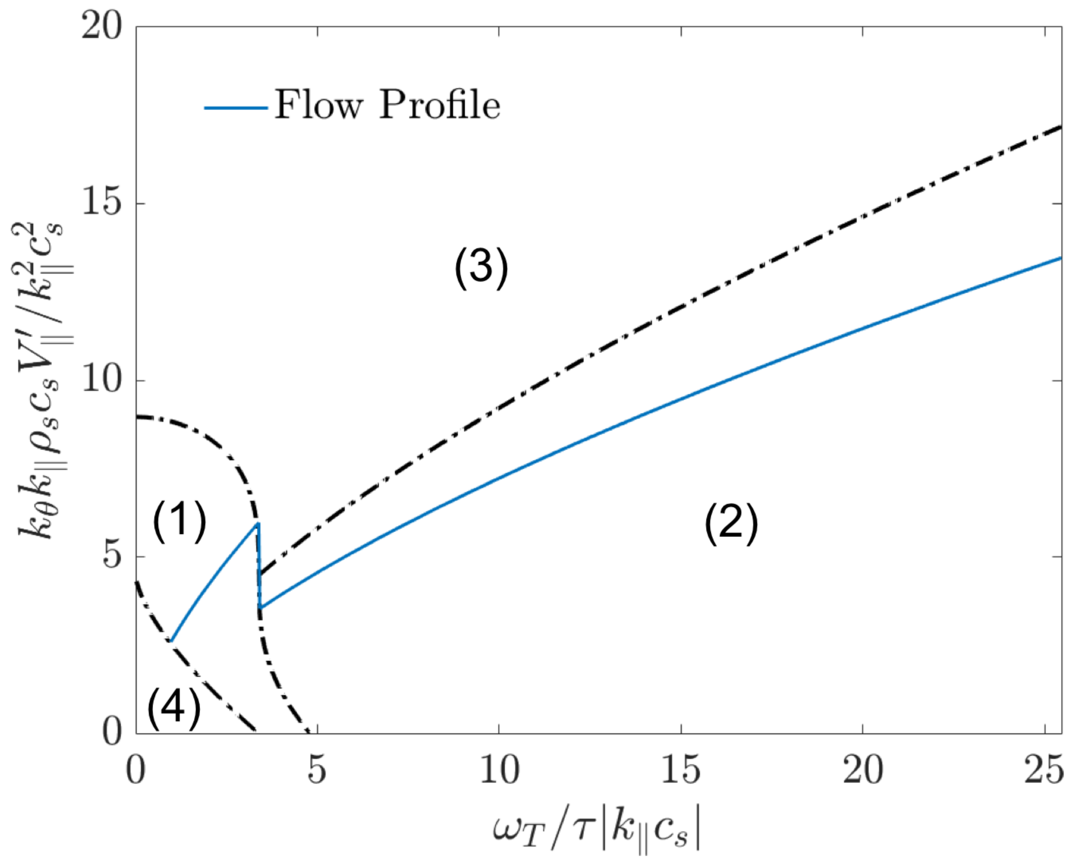
  (2) ITG dominant regime

  $$\frac{(|k_\parallel| L_T)^{2/3}}{|k_\parallel| L_V} < \frac{3}{2^{2/3}} \frac{c_s}{V_\parallel} \frac{\mathrm{A}^{1/3}}{(k_\theta \rho_s)^{1/3} \tau^{1/3}}$$

  (3) PSFI dominant regime

  $$\frac{(|k_\parallel| L_T)^{2/3}}{|k_\parallel| L_V} > \frac{3}{2^{2/3}} \frac{c_s}{V_\parallel} \frac{\mathrm{A}^{1/3}}{(k_\theta \rho_s)^{1/3} \tau^{1/3}}$$

  (4) Stable regime: $\Delta < 0$



Flow profile in different instability regimes. The regimes are identified according to the magnitude of relative scale length $\frac{(|k_\parallel| L_T)^{2/3}}{|k_\parallel| L_V}$ and magnitude of Δ.

Residual Stress Direction Determined by Mode Phase

- Mode phase θ_k:
  - Defined as $\omega = \omega_k + i\gamma_k \equiv |\omega| e^{i\theta_k}$ $\rightarrow \theta_k^{ITG} = \frac{2\pi}{3}, \theta_k^{PSFI} = \frac{\pi}{2}$

- Residual stress:

$$\Pi_{r\|}^{Res} \approx \Re \sum_k \boxed{\frac{i}{\omega^2}} \frac{\omega_T}{\tau} k_\theta k_\| \rho_s c_s |\phi_k|^2$$

Deterimined by mode phase θ_k: $\Re \frac{i}{\omega^2} \sim \cos\left(\frac{\pi}{2} - 2\theta_k\right)$

- Residual stress due to $\delta V_\|'$:

$\delta V_\|' \rightarrow \delta\omega \equiv |\delta\omega| e^{i\delta\theta_k}$, $\delta\theta_k$: perturbed mode phase

$$\delta\Pi_{r,\|}^{Res} \sim -2 \sum_k \cos\left(\frac{\pi}{2} + \delta\theta_k - 3\theta_k\right) \frac{|\delta\omega|}{|\omega|^3} \frac{\omega_T}{\tau} k_\theta k_\| |\phi_k|^2$$

$$|\delta\omega| \sim k_\theta k_\| \delta V_\|'$$

given by $\delta V_\|'$ induced spectral imbalance

$\delta\Pi_{r\|}^{Res} = -\chi_\phi^{Res} \delta V_\|'$, with

$$\chi_\phi^{Res} \sim \cos\left(\frac{\pi}{2} + \delta\theta_k - 3\theta_k\right)$$

$\nabla V_{\parallel}$ Effects on ITG Turbulence

$\nabla V_{\parallel}$

PSFI Turbulence

Flow Saturation

Spectral imbalance
$\rightarrow \langle k_{\theta} k_{\parallel} \rangle V_{\parallel}' > 0$

Mode phase $\delta\theta_k$
$\rightarrow$Cross phase $\delta\Theta_k$

Direction

$\delta\Pi_{r\parallel}^{Res} \sim -\chi_{\phi}^{Res} \nabla V_{\parallel}$

Guideline: Physics of the 3 Regimes

- Marginal regime:
  - Dual perspective: PSFI enhanced by ∇T_{i0}; ITG enhanced by $\nabla V_\parallel$
  - Coexistence of PSFI and ITG turbulence
- ITG regime:
  - Negative viscosity increment induced by $\delta V_\parallel' \rightarrow \chi_\phi^{Res} < 0$
  - Total viscosity positive $\chi_\phi^{tot} = \chi_\phi - |\chi_\phi^{Res}| > 0$
  - Flow profile enhanced by χ_ϕ^{Res}: $V_\parallel' \sim \Pi_{r\parallel}^{Res} / (\chi_\phi - |\chi_\phi^{Res}|)$
- PSFI regime:
  - Flow saturated by PSFI, profile gradient stay at the threshold: $V_\parallel' \sim V_{\parallel,crit}'$

	Marginally Unstable	ITG Dominant	PSFI Dominant
Primary Turbulence Drive	∇T_{i0} and $\nabla V_\parallel$	∇T_{i0}	$\nabla V_\parallel$
Mode Phase θ_k	$\lesssim \pi$	$2\pi/3$	$\gtrsim \pi/2$
$\nabla V_\parallel$ Effect on Mode Phase $\delta\theta_k$	$\pi/2$	$\pi/3$	NA
$\nabla V_\parallel$ Induced Symmetry Breaking	$k_\theta k_\parallel V_\parallel' > 0$	$k_\theta k_\parallel V_\parallel' > 0$	$k_\theta k_\parallel V_\parallel' > 0$

Marginal Regime: Flow Profile and Symmetry Breaking

- Weakly unstable ITG turbulence: $\gamma_k \sim \sqrt{\omega_T^2 - \omega_{T,crit}^2}$
- $\omega_{T,crit}^2$ nonlinear in $\nabla V_\parallel$ ⟺ $\omega_{T,\mathrm{crit}}^2(V_\parallel') = \dfrac{4\tau^2 k_\parallel^2 c_s^2 (C_0 - V')^3}{27A}$

→ $\Pi_{r\parallel}^{Res}$ and χ_ϕ are nonlinear in $\nabla V_\parallel$, but $V_\parallel' \sim$ their ratio independent on $\nabla V_\parallel$

$$\Pi_{r\parallel}^{Res} \cong -\frac{2\sqrt{3}}{3}\sum_k \frac{(2A)^{2/3}}{\tau^{1/3}|k_\parallel c_s|^{4/3}} \frac{\sqrt{\omega_T^2 - \omega_{T,\mathrm{crit}}^2}}{\omega_T^{2/3}} k_\theta k_\parallel \rho_s c_s |\phi_k|^2,$$

$$\chi_\phi \cong \frac{\sqrt{3}}{3}\sum_k \frac{(2A\tau)^{1/3}}{|k_\parallel c_s|^{2/3}} \frac{\sqrt{\omega_T^2 - \omega_{T,\mathrm{crit}}^2}}{\omega_T^{4/3}} k_\theta^2 \rho_s^2 |\phi_k|^2$$

$$\boxed{|V_\parallel'| = \frac{|\Pi_{r\parallel}^{Res}(\nabla V_\parallel, \nabla T_{i0})|}{\chi_\phi(\nabla V_\parallel, \nabla T_{i0})} \sim 2^{4/3} A^{1/3} \left(\frac{\omega_T}{\tau |k_\parallel c_s|}\right)^{2/3} \frac{|k_\parallel| c_s}{k_\theta \rho_s}}$$

- Symmetry breaking by $\nabla V_\parallel$: $V' = k_\theta k_\parallel V_\parallel' > 0$ lowers $\omega_{T,crit}^2$

ITG more unstable for $k_\theta k_\parallel V_\parallel' > 0$

Spectral imbalance, setting $\langle k_\theta k_\parallel \rangle V_\parallel' > 0$

$\delta\Pi_{r\parallel}^{Res} = -\chi_\phi^{Res} \nabla V_\parallel$

due to spectral imbalance

- Mode phase $\theta_k = \pi - \epsilon$, because $\gamma_k \ll \omega_k$
- $\nabla V_\parallel$ induced mode phase $\delta\theta_k = \frac{\pi}{2}$

  → $\cos\left(\frac{\pi}{2} + \delta\theta_k - 3\theta_k\right) > 0$

$$\chi_\phi^{Res} \cong \frac{4^{4/3}}{3^{5/2}} \sum_k \frac{C_0^2}{A^{1/3}} \frac{\tau^{5/3}}{\omega_T^{2/3}} \frac{k_\theta^2 \rho_s^2 |k_\parallel c_s|^{2/3}}{\sqrt{\omega_T^2 - \omega_{T,\mathrm{crit}}^2(0)}} |\phi_k|^2 > 0$$

PSFI and ITG Coexists in Marginal Regime

- ITG turbulence with $\nabla V_{\parallel}$ in this regime is equivalent to weakly unstable PSFI turbulence
- $\gamma_k \sim \sqrt{\omega_T^2 - \omega_{T,crit}^2} \Leftrightarrow \gamma_k \sim \sqrt{V' - V'_{crit}}$, with $V'_{crit} = C_0 - \left(\frac{27A\omega_T^2}{4\tau^2 k_{\parallel}^2 c_s^2}\right)^{1/3}$
- $\rightarrow$ ∇T_{i0} lowers the PSFI threshold

- Dual perspective:
  ITG turbulence enhanced by $\nabla V_{\parallel} \Leftrightarrow$ PSFI turbulence enhanced by ∇T_{i0}
- Both PSFI and ITG turbulences exist in marginal regime
- ∇T_{i0} and $\nabla V_{\parallel}$ effects are coupled nonlinearly

ITG Regime

- Dominated by ∇T_{i0}, with $\nabla V_{\parallel}$ as perturbation

- Growth rate and frequency:

$$\gamma_k \cong \frac{\sqrt{3}}{2}\frac{\omega_T^{1/3}|k_{\parallel}c_s|^{2/3}}{(\tau A)^{1/3}}\left[1-\left(\frac{\omega_{T,\mathrm{crit}}}{2\omega_T}\right)^{2/3}\right]$$

$$\omega_k \cong -\frac{1}{2}\frac{\omega_T^{1/3}|k_{\parallel}c_s|^{2/3}}{(\tau A)^{1/3}}\left[1+\left(\frac{\omega_{T,\mathrm{crit}}}{2\omega_T}\right)^{2/3}\right]$$

$\omega_T^2 \gg \omega_{T,crit}^2$

$$\omega \cong e^{i2\pi/3}\frac{\omega_T^{1/3}|k_{\parallel}c_s|^{2/3}}{(\tau A)^{1/3}}$$

$$\delta\omega = e^{i\pi/3}\left(\frac{\tau}{\omega_T}\right)^{1/3}\frac{k_\theta k_{\parallel}\rho_s c_s \delta V_{\parallel}'}{3A^{2/3}|k_{\parallel}c_s|^{2/3}}$$

With $\theta_k = \frac{2\pi}{3}$, $\delta\theta_k = \frac{2\pi}{3}$

- Symmetry breaking by $\nabla V_{\parallel}$
  → Spectral imbalance in $k_\theta k_{\parallel}$ space
  → $\langle k_\theta k_{\parallel}\rangle V_{\parallel}' > 0$

$$\chi_\phi^{Res} \sim \cos\left(\frac{\pi}{2}+\delta\theta_k-3\theta_k\right) < 0$$

$$\chi_\phi^{Res} = -\frac{\sqrt{3}}{6}\sum_k \frac{(\tau A)^{1/3}}{\omega_T^{1/3}|k_{\parallel}c_s|^{2/3}}k_\theta^2\rho_s^2|\phi_k|^2$$

Negative viscosity induced by residual stress due to perturbed mode phase set by $\nabla V_{\parallel}$

Symmetry Breaking by $\nabla V_{\parallel}$ Compared to Drift Wave

- In ITG turbulence, the $\nabla V_{\parallel}$ induced spectral imbalance:
  - Negative viscosity increment: $\chi_{\phi}^{Res} < 0$
  - Total viscosity positive: $\chi_{\phi}^{tot} = \chi_{\phi}^{ITG} - \left|\chi_{\phi}^{Res}\right| = \frac{2}{3}\chi_{\phi}^{ITG} > 0$
  - Evolution of a test flow shear set by

    $\partial_t \delta V_{\parallel}' = \chi_{\phi}^{tot} \partial_r^2 \delta V_{\parallel}' \rightarrow \gamma_q = -\chi_{\phi}^{tot} q_r^2 < 0$

    $\rightarrow \delta V_{\parallel}'$ cannot reinforce itself!

	ITG turbulence	Drift Wave turbulence
Direction of correlator	$\langle k_\theta k_\parallel \rangle V_\parallel' > 0$	$\langle k_\theta k_\parallel \rangle V_\parallel' > 0$
Viscosity increment	$\chi_{\phi}^{Res} < 0$	$\chi_{\phi}^{Res} < 0$
Total viscosity	$\chi_{\phi}^{tot} > 0$	χ_{ϕ}^{tot} can be negative
Modulational instability	No	Can exist

Flow Profile in ITG Regime

- $\nabla V_{\parallel}$ decoupled from ∇T_{i0}

$$\Pi_{r\parallel}^{Res}(\nabla V_{\parallel}, \nabla T_{i0}) \approx \Pi_{r\parallel}^{Res}(\nabla T_{i0}) + |\chi_{\phi}^{Res}(\nabla T_{i0})| \nabla V_{\parallel}$$

Need geometrical symmetry breaking

$\nabla V_{\parallel}$ induced symmetry breaking not self-sustained

$V_{\parallel}'$ enhanced by $-|\chi_{\phi}^{Res}|$:

$$|V_{\parallel}'| = \frac{|\Pi_{r\parallel}^{Res}(\nabla T_{i0})|}{\chi_{\phi}(\nabla T_{i0}) - |\chi_{\phi}^{Res}(\nabla T_{i0})|} \sim \frac{3}{2} A^{1/3} \left(\frac{\omega_T}{\tau |k_{\parallel} c_s|} \right)^{2/3} \frac{|k_{\parallel}| c_s}{k_{\theta} \rho_s}$$

- $|V_{\parallel}'|$ below PSFI regime threshold

$$|V_{\parallel,regime}'| \sim \frac{3}{2^{2/3}} A^{1/3} \left(\frac{\omega_T}{\tau |k_{\parallel} c_s|} \right)^{2/3} \frac{|k_{\parallel}| c_s}{k_{\theta} \rho_s}$$

PSFI Regime

- Dominated by $\nabla V_{\parallel}$, with ∇T_{i0} as a correction
- Regime threshold is different from PSFI threshold
  - Regime threshold: $\nabla V_{\parallel}$ and ∇T_{i0} are well above threhold, and $\nabla V_{\parallel}$ is larger than ∇T_{i0}
  - PSFI threshold: $\nabla V_{\parallel}$ is large enough to trigger instability, in presence of ∇T_{i0}
  - Consider $\left|V'_{\parallel,crit}\right| \ll \left|V'_{\parallel}\right| \lesssim \left|V'_{\parallel,regime}\right|$
- γ_k nonlinear in $\nabla V_{\parallel}$, $\omega_k \lesssim 0$ due to ∇T_{i0} correction:

$$\gamma_k \cong \frac{|k_{\parallel} c_s|}{\sqrt{A}} \sqrt{V' - C_0}, \quad \omega_k \cong -\frac{\omega_T}{2\tau(V' - C_0)}.$$

  - $\rightarrow$ $\Pi_{r\parallel}^{Res}$ and χ_{ϕ} are nonlinear in $\nabla V_{\parallel}$

$$\Pi_{r\parallel}^{Res} \cong -\sum_k \frac{\omega_T^2}{\tau^2} \frac{A^{3/2}}{|k_{\parallel} c_s|^3 (V' - C_0)^{5/2}} k_\theta k_{\parallel} \rho_s c_s |\phi_k|^2, \quad \chi_\phi = \sum_k \frac{\sqrt{A}}{|k_{\parallel} c_s| \sqrt{V' - C_0}} k_\theta^2 \rho_s^2 |\phi_k|^2.$$

  - $\rightarrow$ $\nabla V_{\parallel}$ saturated since $\left|\Pi_{r\parallel}^{Res}\right|$ drops as $\nabla V_{\parallel}$ increases

Flow Profile in PSFI Dominant Regime

- $|V_\parallel'|$ driven by ITG turbulence always below $|V_{\parallel,regime}'|$
  → Additional flow drive can lead to PSFI regime $|V_\parallel'| \gtrsim |V_{\parallel,regime}'|$
  → Result: $|V_\parallel'|$ saturated by strong PSFI turbulence → $|V_\parallel'| \lesssim |V_{\parallel,regime}'|$

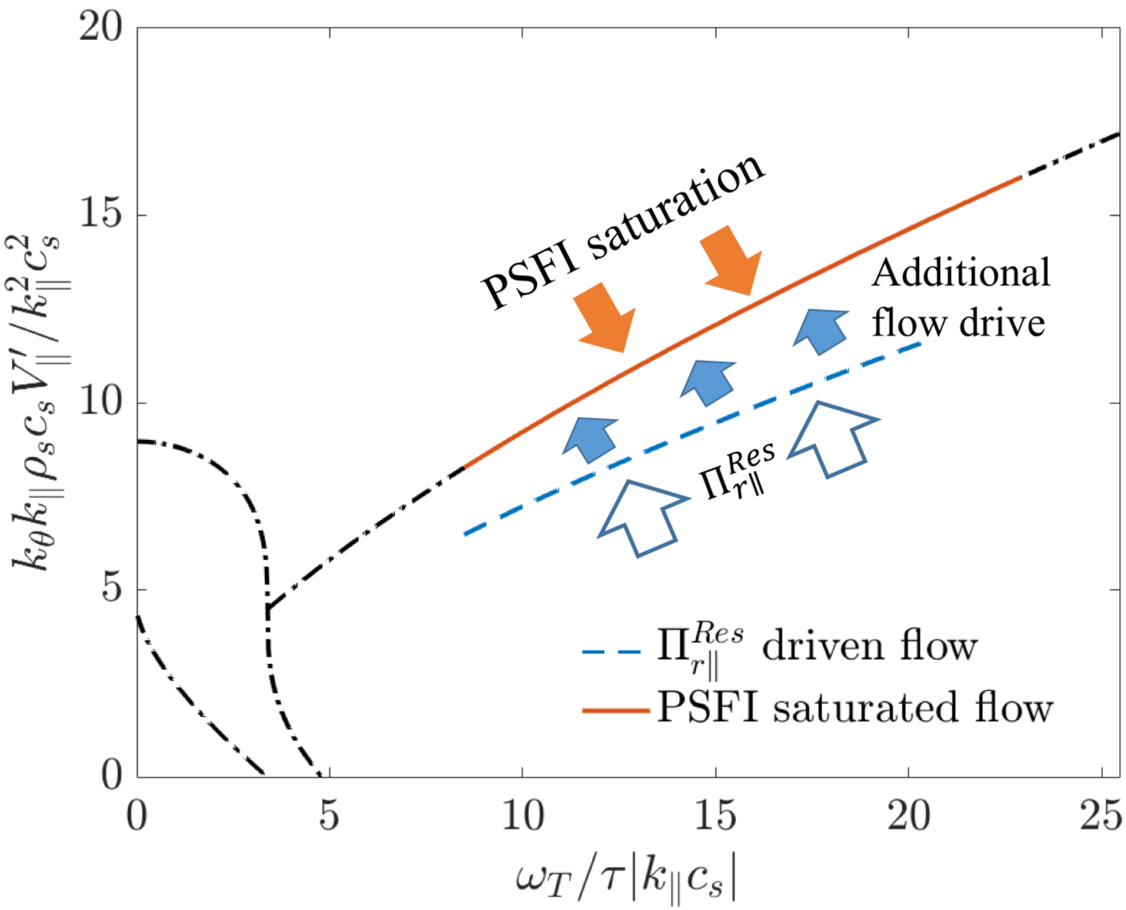
- $\Pi_{r\parallel}^{Res}$ and χ_ϕ nonlinear in $\nabla V_\parallel$

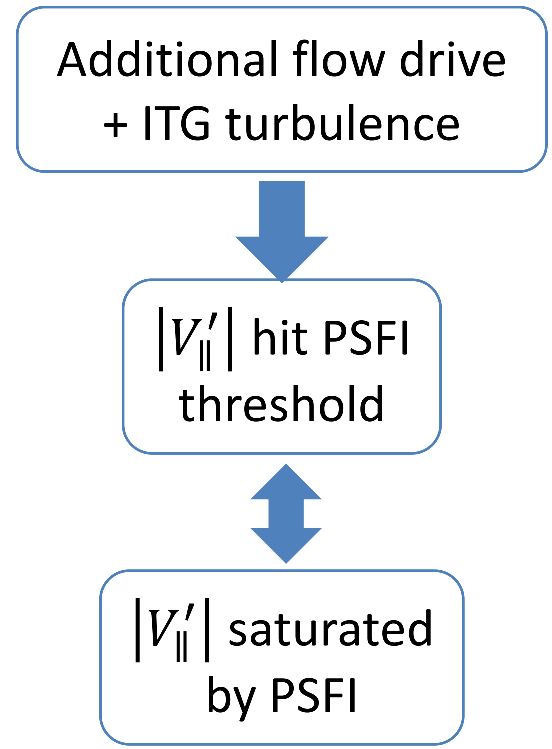
$$|V_\parallel'| = \frac{|\Pi_{r\parallel}^{Res}(\nabla T_{i0}, \nabla V_\parallel)|}{\chi_\phi(\nabla T_{i0}, \nabla V_\parallel)} \sim \frac{A}{(V_\parallel')^2}\left(\frac{\omega_T}{\tau|k_\parallel c_s|}\right)^2 \left(\frac{|k_\parallel|c_s}{k_\theta\rho_s}\right)^3$$

$$\Rightarrow |V_\parallel'| \sim A^{1/3}\left(\frac{\omega_T}{\tau|k_\parallel c_s|}\right)^{2/3} \frac{|k_\parallel|c_s}{k_\theta\rho_s} < |V_{\parallel,regime}'|$$

- $|V_\parallel'|$ stays at PSFI threshold due to balance between flow drive and PSFI saturation

$|V_\parallel'|$ profile saturated by PSFI





Summary

- $\nabla V_{\parallel}$ plays 3 roles in ITG turbulence
  - Drive PSFI → saturate $V_{\parallel}'$ profile
  - Symmetry breaking → spectral imbalance, $\langle k_\theta k_\parallel \rangle V_{\parallel}' > 0$
  - Modify mode phase → $\chi_\phi^{Res} \sim \cos\left(\frac{\pi}{2} + \delta\theta_k - 3\theta_k\right)$
- Interaction between symmetry breaking set by $\nabla V_{\parallel}$ and by magnetic shear depends on instability regimes
  - In marginal regime:
    → $\Pi_{r\parallel}^{Res}$ primarily set by geometrical symmetry breaking mechanisms
    → Ratio $\Pi_{r\parallel}^{Res}/\chi_\phi$ independent from $\nabla V_{\parallel}$
    - Coexistence of PSFI and ITG turbulence
  - In ITG regime:
    → $\Pi_{r\parallel}^{Res}$ primarily set by geometrical symmetry breaking mechanisms
    → $-\left|\chi_\phi^{Res}\right|$ enhances $V_{\parallel}'$ profile
  - In PSFI regime:
    → $V_{\parallel}'$ saturated by PSFI → $V_{\parallel}'$ stays at the PSFI threshold