Suppression of the ETG instability by ion gyroradius scale turbulence

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Turbulent Dynamics of Tokamak Plasmas (TDoTP)

Outline

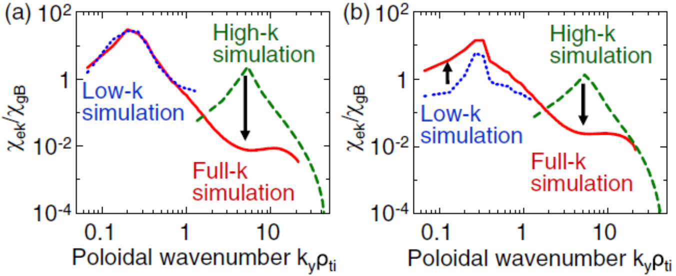
- Multiscale turbulence – instabilities drive transport at scales of
  - ion gyroradius $\rho_{\mathrm{th,i}}$ (ITG)
  - electron gyroradius $\rho_{\mathrm{th,e}}$ (ETG)
- Experimentally relevant transport is driven at both long ($\rho_{\mathrm{th,i}}$) and short ($\rho_{\mathrm{th,e}}$) wavelengths
- Recent work shows that cross-scale interactions can be significant in determining the transport level in multiscale turbulence

In this talk

- Brief introduction to theory of scale-separated multiscale turbulence Hardman et al. (2019)
  - A separated $\rho_{\mathrm{th,i}}$ scale – the "ion scale" (IS)
  - A separated $\rho_{\mathrm{th,e}}$ scale – the "electron scale" (ES)
  - $(m_{\mathrm{e}}/m_{\mathrm{i}})^{1/2} \to 0$
- Simulations show that IS turbulence can stabilise the ETG instability
- The suppression mechanism is novel: parallel-to-the-field-line shear in the $\rho_{\mathrm{th,i}}$ scale $\mathbf{E} \times \mathbf{B}$ drift stabilises $\rho_{\mathrm{th,e}}$ scale instabilities

Introduction: Multiscale turbulence

- simulation evidence where $Q_e \sim 10 Q_{e\text{gB}} \sim (?) Q_{i\text{gB}}$ e.g. Jenko and Dorland (2002)
- recent experimental evidence on NSTX Ren et al. (2017)
- Fig 2 from Maeyama et al. (2015):

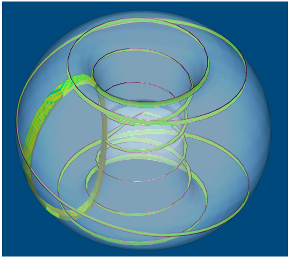


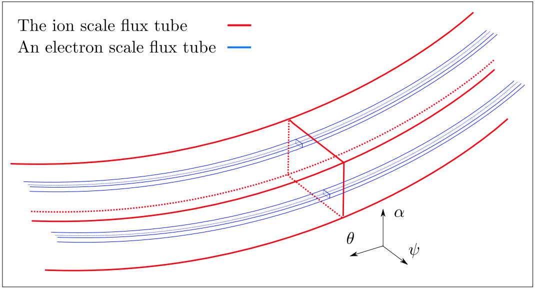
(a) $\beta = 0.04\%$ (b) $\beta = 2.0\%$

- Realistic $(m_e/m_i)^{1/2}$ multiscale simulations are extremely expensive. Examples in Maeyama et al. (2017); Howard et al. (2016); Bonanomi et al. (2018).

The asymptotic approach to studying multiscale turbulence

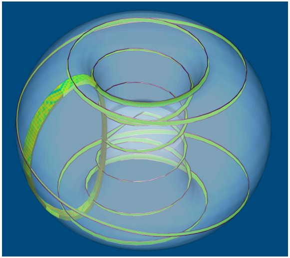
- Local δf gyrokinetics describes turbulence in a flux tube in the limit $\rho_* \to 0$
- Scale-separated, coupled IS-ES turbulence can be described with nested, flux tubes in the limit $(m_e/m_i)^{1/2} \to 0$
- Coupling is similar to that of coupling between turbulence and transport (cf. Barnes et al. (2010))

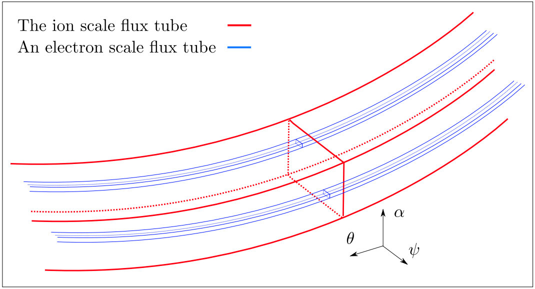




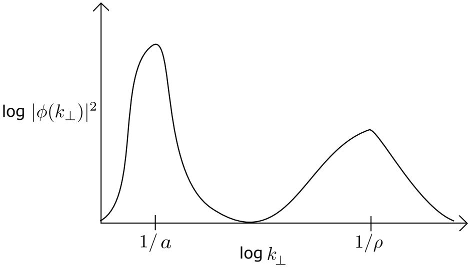
The asymptotic approach to studying multiscale turbulence

- Large-scale gradients and flows drive or suppress instabilities
- Small-scale fluctuations drive fluxes that relax the large-scale gradients





Separation between transport and local δf turbulence



- Scale separation: $\rho_* = \rho_{\mathrm{th}}/a \to 0 \Rightarrow \quad f = F + \delta f$
- Statistical periodicity: $\langle \delta f \rangle^{\mathrm{turb}} = 0$
- Gyro average: $\langle \cdot \rangle^{\vartheta}$
- Orderings:

$$\nabla F \sim \frac{F}{a}, \qquad \nabla_\perp \delta f \sim \frac{\delta f}{\rho_{\mathrm{th}}}, \quad \nabla_\parallel \delta f \sim \frac{\delta f}{a}$$

$$\frac{\partial F}{\partial t} \sim {\rho_*}^3 \Omega F, \qquad \frac{\partial \delta f}{\partial t} \sim \frac{v_{\mathrm{th}}}{a} \delta f \sim \rho_* \Omega \delta f$$

$$\delta f \sim \rho_* F$$

Separation between transport and local δf turbulence

The gyrokinetic equation for $h = \delta f + (Ze\phi/T)F_0$:

$$\frac{\partial h}{\partial t} + v_{\|}\mathbf{b}\cdot\nabla\theta\frac{\partial h}{\partial \theta} + (\mathbf{v}^M + \mathbf{v}^E)\cdot\nabla h + \mathbf{v}^E\cdot\nabla F_0 = \frac{ZeF_0}{T}\frac{\partial \varphi}{\partial t}, \tag{1}$$

where,

$$\varphi = \langle\phi\rangle^{\vartheta}_{,} \quad \mathbf{v}^E = \frac{c}{B}\mathbf{b}\times\nabla\varphi. \tag{2}$$

Closed by quasi-neutrality,

$$\sum_{\nu} Z_{\nu}\int d^3\mathbf{v}|_{\mathbf{r}} h_{\nu} = \sum_{\nu}\frac{Z_{\nu}^2 e n_{\nu}}{T_{\nu}}\phi(\mathbf{r}). \tag{3}$$

- Electrostatic approximation
- Zero equilibrium toroidal rotation

Separation between transport and local δf turbulence

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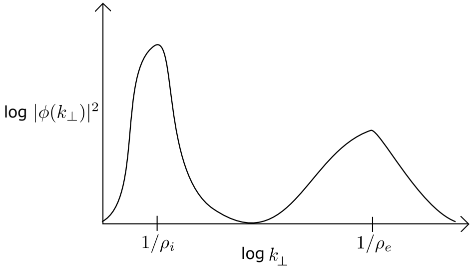
Transport equations have the form

$$\frac{3}{2}\frac{\partial p}{\partial t} + \frac{1}{\mathcal{V}'}\frac{\partial}{\partial\psi}\left(\mathcal{V}'Q\right) = S_+ + S_- \tag{4}$$

- Divergence of the flux Q relaxes $\partial p/\partial\psi$ – $Q = Q_{\mathrm{TB}} + Q_{\mathrm{NC}} + Q_{\mathrm{C}}$
- $Q_{\mathrm{TB}} \sim \left\langle\int d^3\mathbf{v}|_{\mathbf{r}}\, \varepsilon\, \mathbf{v}^E\delta f\right\rangle^{\mathrm{turb}}$

Separating IS and ES Turbulence



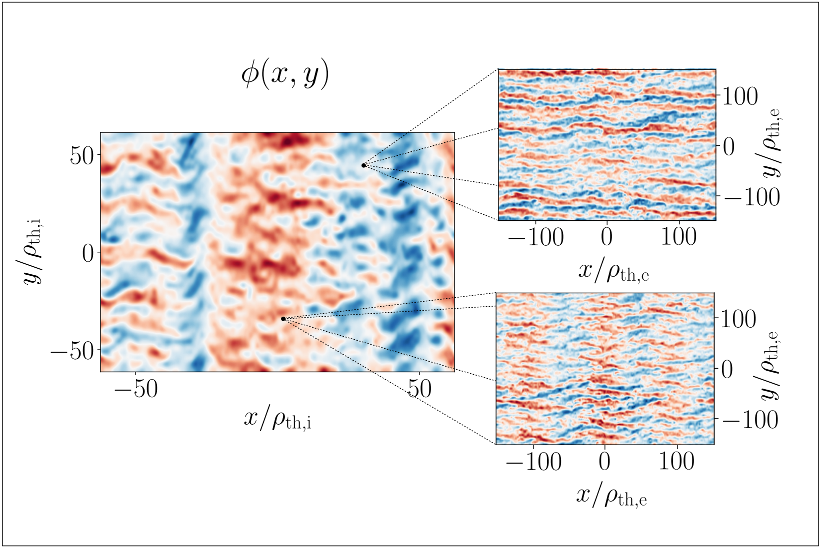
- Scale separation: $\rho_{\mathrm{th,e}}/\rho_{\mathrm{th,i}} \sim v_{\mathrm{th,i}}/v_{\mathrm{th,e}} \sim (m_{\mathrm{e}}/m_{\mathrm{i}})^{1/2} \to 0, \Rightarrow \delta f = \overline{\delta f} + \widetilde{\delta f}$
- ES statistical periodicity: $\left\langle \widetilde{\delta f} \right\rangle^{\mathrm{ES}} = 0$
- Orderings:

$$\nabla_\perp \overline{\delta f} \sim \frac{\overline{\delta f}}{\rho_{\mathrm{th,i}}}, \quad \nabla_\perp \widetilde{\delta f} \sim \frac{\widetilde{\delta f}}{\rho_{\mathrm{th,e}}}$$

$$\frac{\partial \overline{\delta f}}{\partial t} \sim \frac{v_{\mathrm{th,i}}}{a} \overline{\delta f}, \quad \frac{\partial \widetilde{\delta f}}{\partial t} \sim \frac{v_{\mathrm{th,e}}}{a} \widetilde{\delta f}.$$

$$\nabla_\parallel \overline{\delta f} \sim a^{-1} \overline{\delta f}, \quad \nabla_\parallel \widetilde{\delta f} \sim a^{-1} \widetilde{\delta f}.$$

Separating IS and ES Turbulence



Separating IS and ES Turbulence

The gyrokinetic equation for $h = \delta f + (Ze\phi/T)F_0$:

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where,

$$\varphi = \langle \phi \rangle^\vartheta, \quad \mathbf{v}^E = \frac{c}{B} \mathbf{b} \times \nabla \varphi. \tag{6}$$

Closed by quasi-neutrality,

$$\sum_\nu Z_\nu \int d^3\mathbf{v}|_\mathbf{r} h_\nu = \sum_\nu \frac{Z_\nu^2 e n_\nu}{T_\nu} \phi(\mathbf{r}). \tag{7}$$

- $h \to \overline{h} + \widetilde{h}$, $\phi \to \overline{\phi} + \widetilde{\phi}$
- $\nabla_\perp \to \nabla_\mathrm{s} + \nabla_\mathrm{f}$, $\nabla_\mathrm{f} \sim {\rho_\mathrm{th,e}}^{-1}$, $\nabla_\mathrm{s} \sim {\rho_\mathrm{th,i}}^{-1}$
- $\partial_t \to \partial_{t_\mathrm{s}} + \partial_{t_\mathrm{f}}$, $\partial_{t_\mathrm{f}} \sim v_\mathrm{th,e}/a$, $\partial_{t_\mathrm{s}} \sim v_\mathrm{th,i}/a$
- ES average $\langle \cdot \rangle^\mathrm{ES}$ extracts long wavelength – IS – equations
- Short wavelength – ES – equations are the residual
- Cross-scale interactions arise from $\mathbf{v}^E \cdot \nabla h$

Separating IS and ES Turbulence – The Coupled Equations

- IS equations.

$$\frac{\partial \overline{h}_i}{\partial t} + v_{\parallel} \mathbf{b} \cdot \nabla\theta \frac{\partial \overline{h}_i}{\partial \theta} + (\mathbf{v}_{\mathrm{i}}^{M} + \overline{\mathbf{v}}_i^{E}) \cdot \nabla \overline{h}_i + \overline{\mathbf{v}}_i^{E} \cdot \nabla F_{0i} = \frac{Z_i e F_{0i}}{T_i} \frac{\partial \overline{\varphi}_i}{\partial t}, \tag{8}$$

$$\frac{\partial \overline{h}_e}{\partial t} + \left\langle \mathbf{v}_{\mathrm{e}}^{M} \cdot \nabla\alpha \right\rangle^{\mathrm{o}} \frac{\partial \overline{h}_e}{\partial \alpha} + \left\langle \overline{\mathbf{v}}_e^{E} \cdot \left(\nabla \overline{h}_e + \nabla F_{0e} \right) \right\rangle^{\mathrm{o}} + \nabla \cdot \left\langle \left\langle \frac{c}{B} \widetilde{h}_e \widetilde{\mathbf{v}}_e^{E} \right\rangle^{\mathrm{ES}} \right\rangle^{\mathrm{o}} = -\frac{e F_{0e}}{T_e} \frac{\partial \left\langle \overline{\varphi}_e \right\rangle^{\mathrm{o}}}{\partial t}, \tag{9}$$

$$\int d^3\mathbf{v}|_{\mathbf{r}} (Z_i \overline{h}_i - \overline{h}_e) = \left(\frac{e Z_i^2 n_i}{T_i} + \frac{e n_e}{T_e} \right) \overline{\phi}, \tag{10}$$

- ES equations, with the new advection and drive terms

$$\frac{\partial \widetilde{h}_e}{\partial t} + v_{\parallel} \mathbf{b} \cdot \nabla\theta \frac{\partial \widetilde{h}_e}{\partial \theta} + (\mathbf{v}_{\mathrm{e}}^{M} + \widetilde{\mathbf{v}}_e^{E} + \overline{\mathbf{v}}_e^{E}) \cdot \nabla \widetilde{h}_e + \widetilde{\mathbf{v}}_e^{E} \cdot (\nabla \overline{h}_e + \nabla F_{0e}) = -\frac{e F_{0e}}{T_e} \frac{\partial \widetilde{\varphi}_e}{\partial t}. \tag{11}$$

$$-\int d^3\mathbf{v}|_{\mathbf{r}} \widetilde{h}_e = \left(\frac{e Z_i^2 n_i}{T_i} + \frac{e n_e}{T_e} \right) \widetilde{\phi}, \tag{12}$$

Separating IS and ES Turbulence – The Coupled Equations

- IS equations. Leading-order cross-scale terms are small by $\lesssim (m_e/m_i)^{1/2}$

$$\frac{\partial \overline{h}_i}{\partial t} + v_\parallel \mathbf{b}\cdot\nabla\theta \frac{\partial \overline{h}_i}{\partial \theta} + (\mathbf{v}_i^M + \overline{\mathbf{v}}_i^E)\cdot\nabla\overline{h}_i + \overline{\mathbf{v}}_i^E\cdot\nabla F_{0i} = \frac{Z_i e F_{0i}}{T_i}\frac{\partial\overline{\varphi}_i}{\partial t}, \qquad (8)$$

$$\frac{\partial \overline{h}_e}{\partial t} + \left\langle \mathbf{v}_e^M\cdot\nabla\alpha\right\rangle^{\circ}\frac{\partial \overline{h}_e}{\partial \alpha} + \left\langle \overline{\mathbf{v}}_e^E\cdot\left(\nabla\overline{h}_e + \nabla F_{0e}\right)\right\rangle^{\circ} + \nabla\cdot\left\langle\left\langle \frac{c}{B}\widetilde{h}_e\widetilde{\mathbf{v}}_e^E\right\rangle^{\mathrm{ES}}\right\rangle^{\circ} = -\frac{eF_{0e}}{T_e}\frac{\partial\left\langle\overline{\varphi}_e\right\rangle^{\circ}}{\partial t}, \qquad (9)$$

$$\int d^3\mathbf{v}|_{\mathbf{r}}(Z_i\overline{h}_i - \overline{h}_e) = \left(\frac{eZ_i^2 n_i}{T_i} + \frac{en_e}{T_e}\right)\overline{\phi}, \qquad (10)$$

- ES equations, with the new advection and drive terms

$$\frac{\partial \widetilde{h}_e}{\partial t} + v_\parallel \mathbf{b}\cdot\nabla\theta\frac{\partial\widetilde{h}_e}{\partial\theta} + (\mathbf{v}_e^M + \widetilde{\mathbf{v}}_e^E + \overline{\mathbf{v}}_e^E)\cdot\nabla\widetilde{h}_e + \widetilde{\mathbf{v}}_e^E\cdot(\nabla\overline{h}_e + \nabla F_{0e}) = -\frac{eF_{0e}}{T_e}\frac{\partial\widetilde{\varphi}_e}{\partial t}. \qquad (11)$$

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Separating IS and ES Turbulence – ES equations in terms of g_{e}

- Written in terms of $g_{\mathrm{e}} = \langle \delta f \rangle^{\vartheta}$ the ES gyrokinetic equation is

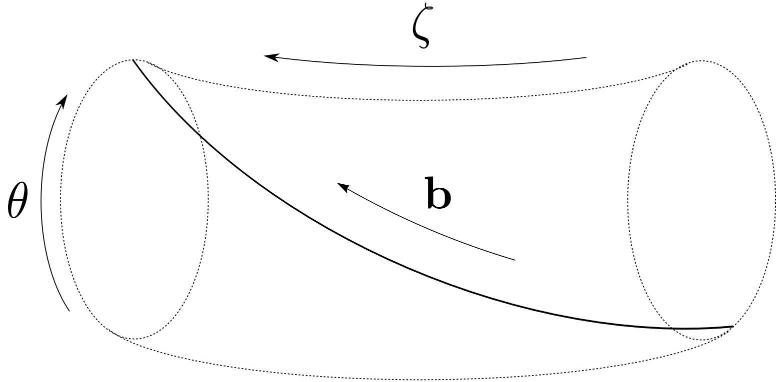
$$\left(\frac{\partial}{\partial t} + \overline{\mathbf{v}}_e^E \cdot \nabla\right)\widetilde{g}_{\mathrm{e}} + v_{\|}\mathbf{b}\cdot\nabla\theta\frac{\partial \widetilde{g}_{\mathrm{e}}}{\partial\theta} + (\mathbf{v}_{\mathrm{e}}^M + \widetilde{\mathbf{v}}_{\mathrm{e}}^E)\cdot\nabla\widetilde{g}_{\mathrm{e}}$$
$$+ \widetilde{\mathbf{v}}_{\mathrm{e}}^E \cdot (\nabla F_{0e} + \nabla\overline{g}_{\mathrm{e}}) = \frac{eF_{0e}}{T_{\mathrm{e}}}\left(v_{\|}\mathbf{b}\cdot\nabla\theta\frac{\partial\widetilde{\varphi}_{\mathrm{e}}}{\partial\theta} + \mathbf{v}_{\mathrm{e}}^M\cdot\nabla\widetilde{\varphi}_{\mathrm{e}}\right), \tag{13}$$

- with ES quasi-neutrality

$$\int d^3\mathbf{v}|_{\mathbf{r}}\left(\widetilde{g}_{\mathrm{e}}(\mathbf{R}) + \frac{eF_{0e}}{T_{\mathrm{e}}}\left(\widetilde{\phi}(\mathbf{r}) - \widetilde{\varphi}_{\mathrm{e}}(\mathbf{R})\right)\right) = -\frac{Z_{\mathrm{i}}e\widetilde{\phi}(\mathbf{r})}{T_{\mathrm{i}}}n_{0e}, \tag{14}$$

- $\widetilde{\mathbf{v}}_e^E \sim \overline{\mathbf{v}}_e^E$ and $(\mathbf{r}-\mathbf{r}_0)\cdot\nabla\overline{\mathbf{v}}_e^E \sim (\rho_{\mathrm{th,e}}/\rho_{\mathrm{th,i}})\overline{\mathbf{v}}_e^E \ll \overline{\mathbf{v}}_e^E$
- $\Rightarrow$ perpendicular-to-the-field shear small in the limit $(m_{\mathrm{e}}/m_{\mathrm{i}})^{1/2} \to 0$
- $\Rightarrow$ In each ES flux tube $\overline{\mathbf{v}}_e^E$ does not vary x or y – but does vary in poloidal angle θ
- The constant piece of $\overline{\mathbf{v}}_e^E$ may be removed by a toroidal rotation
- $\Rightarrow$ the θ variation in $\overline{\mathbf{v}}_e^E$ – parallel-to-the-field shear – is relevant

Physical picture for the effect of parallel-to-the-field shear in $\overline{\mathbf{v}}_e^E$



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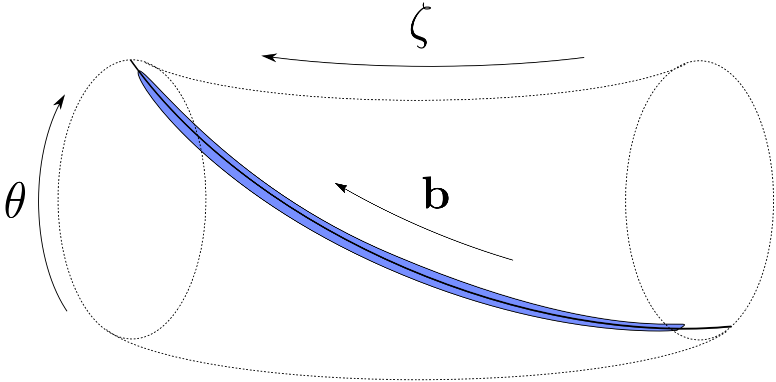

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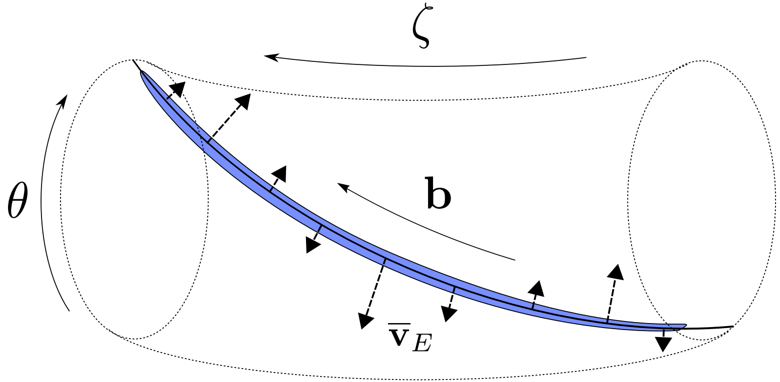

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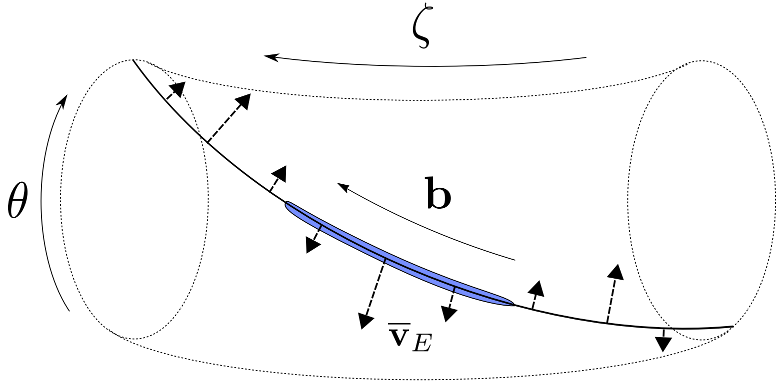
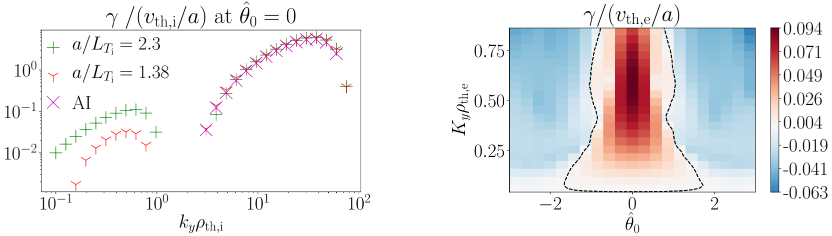


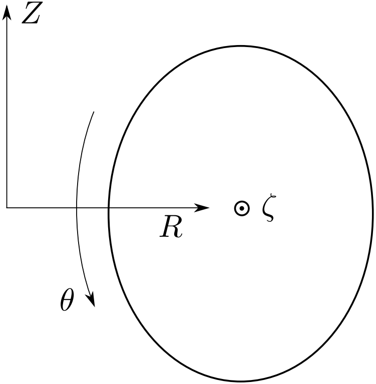
Outline: Effect of Cross-scale Interaction on the ETG Instability

- The coupled equations capture the $O(1)$ effects of IS turbulence on ES fluctuations
- We pick Cyclone Base Case like (CBC) parameters where there is a separation of scales:



- Collisions create a stable gap between the ITG and ETG modes in k_y
- We assume that this level collisional dissipation creates a gap in the nonlinear amplitude spectrum

Physical picture for the definition of $\hat{\theta}_0$



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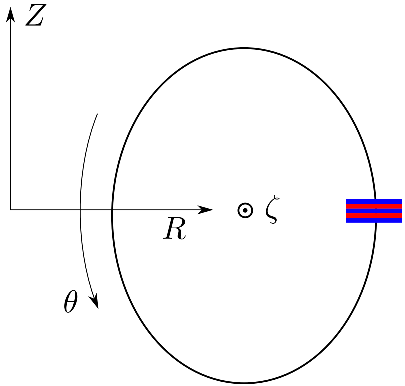

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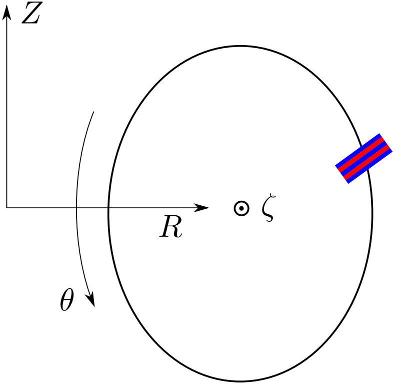

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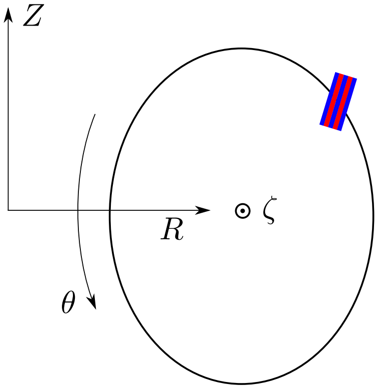

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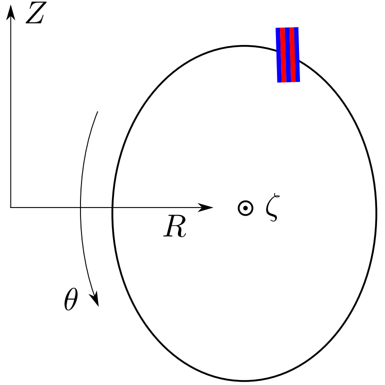

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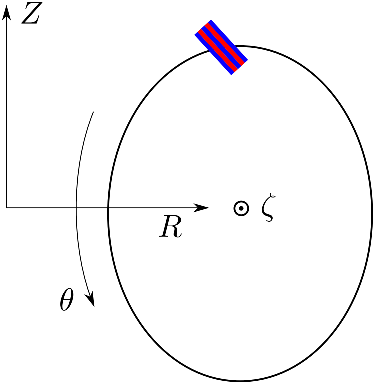

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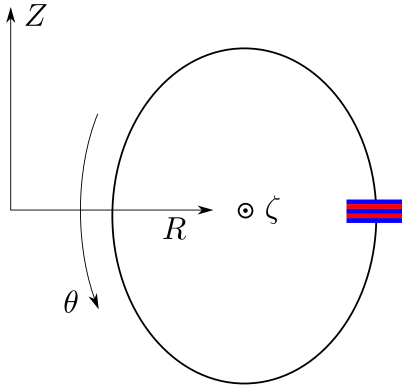
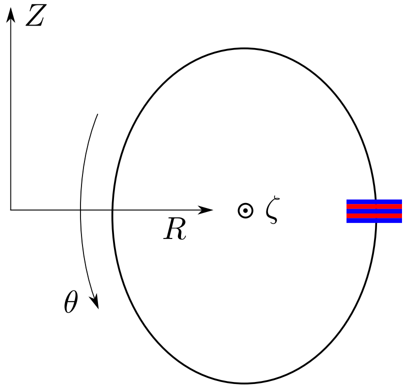


- Magnetic shear rotates the wave fronts of the mode w.r.t. the minor radial direction as the view of the mode rotates in ζ

Physical picture for the definition of $\hat{\theta}_0$



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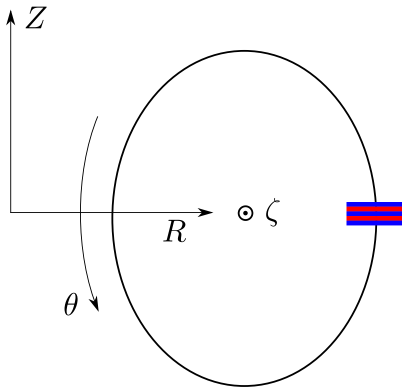
- There is only one θ where the radial wave number $k_r = 0$

Physical picture for the definition of $\hat{\theta}_0$



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- θ where $k_r = 0$ is $\hat{\theta}_0$

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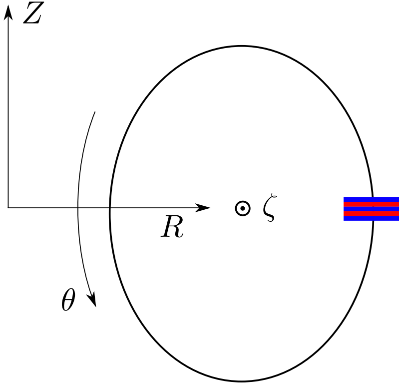

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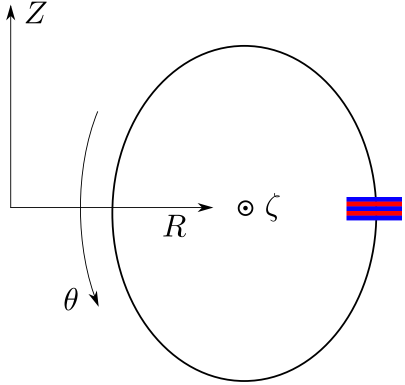
- $\hat{\theta}_0 = 0$ is the outboard midplane

Physical picture for the definition of $\hat{\theta}_0$



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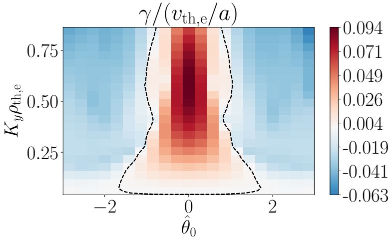

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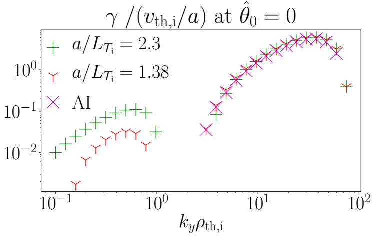
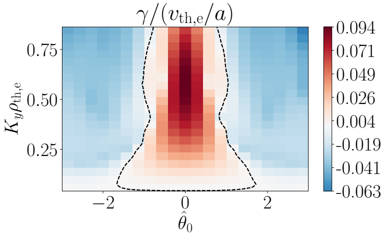
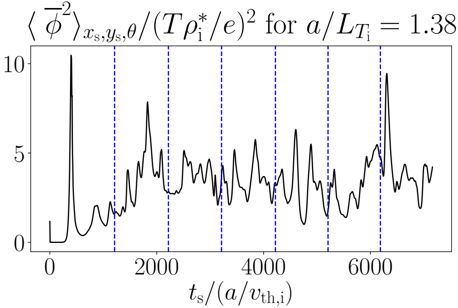
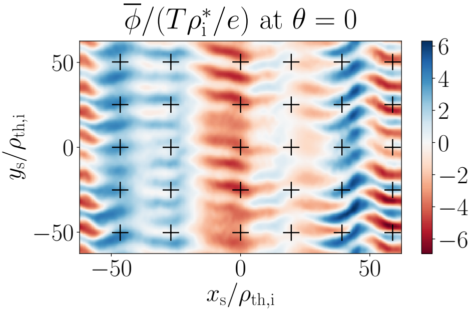




- We simulate the IS turbulence to obtain a sample of $\overline{\mathbf{v}}_e^E$ and $\nabla \overline{g}_e$
- Strongly driven ETG ($a/L_{T_\mathrm{e}} = 2.3$) is weakly suppressed by weakly driven ($a/L_{T_\mathrm{i}} = 1.38$) IS turbulence
- Strongly driven ETG ($a/L_{T_\mathrm{e}} = 2.3$) is stabilised by strongly driven ($a/L_{T_\mathrm{i}} = 2.3$) IS turbulence

Sampling IS Turbulence with $a/L_{T_\mathrm{i}} = 1.38$

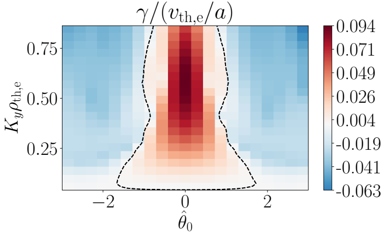




- Saturate IS turbulence
- Calculate $\nabla \overline{g}_e$
- Calculate $\overline{\mathbf{v}}_e^E$
- At 6 IS t_s times (blue dashes)
- At 6 radial (x_s) × 5 binormal (y_s) IS positions (crosses)

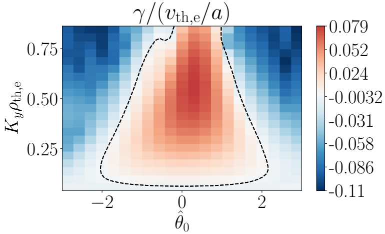
Simulations: Modification of ES linear physics: CBC $a/L_{T_i} = 1.38$

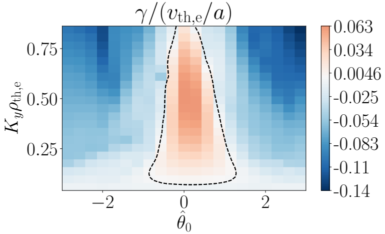
Top Right: No IS gradients.



Below: IS gradients from different IS (x_s, y_s) locations

Weak suppression



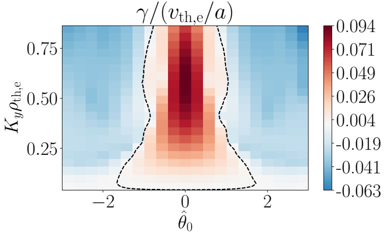


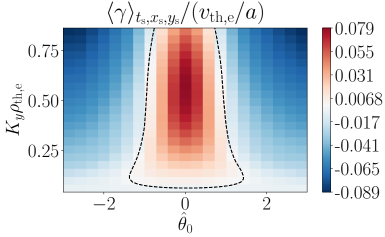
Simulations: Modification of ES linear physics: CBC $a/L_{T_i} = 1.38$

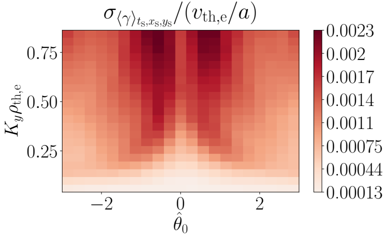
Top Right: No IS gradients.

Below: average ETG growth rate across all sampled IS (x_s, y_s) locations and t_s times

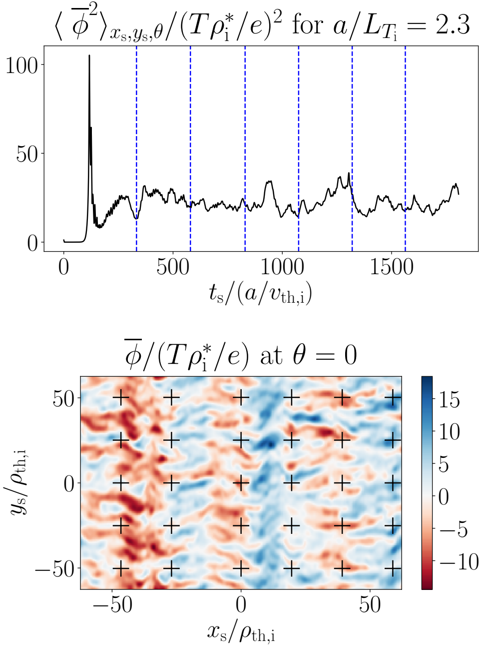
Weak suppression







Sampling IS Turbulence with $a/L_{T_i} = 2.3$



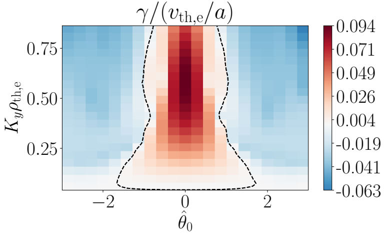
- Saturate IS turbulence
- Calculate $\nabla \overline{g}_e$
- Calculate $\overline{\mathbf{v}}_e^E$
- At 6 IS t_s times (blue dashes)
- At 6 radial (x_s) × 5 binormal (y_s) IS positions (crosses)

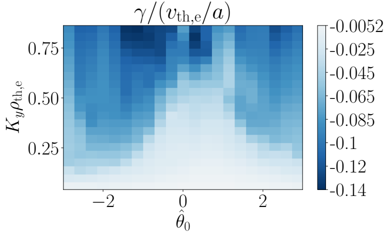
Simulations: modification of ES linear physics: CBC $a/L_{T_i} = 2.3$

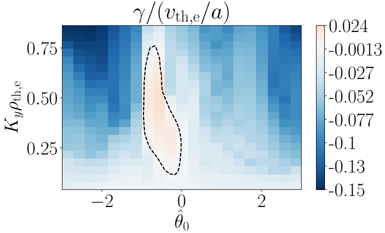
Top Right: No IS gradients.

Below: IS gradients from different IS (x_s, y_s) locations

Strong suppression!

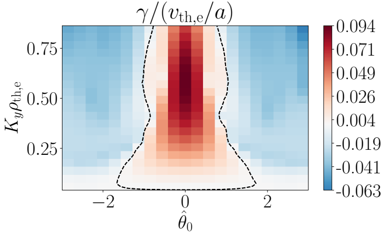






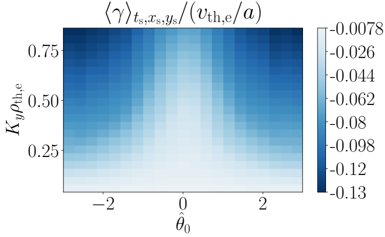
Simulations: Modification of ES linear physics: CBC $a/L_{T_i} = 2.3$

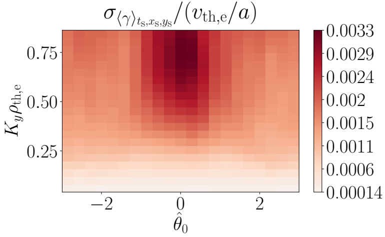
Top Right: No IS gradients.



Below: average ETG growth rate across all sampled IS (x_s, y_s) locations and t_s times

Strong suppression!





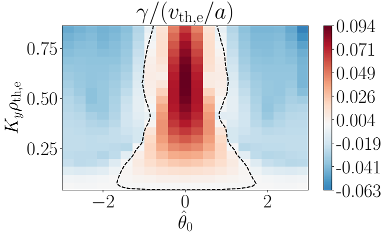
Simulations: Modification of ES linear physics: CBC $a/L_{T_i} = 2.3$

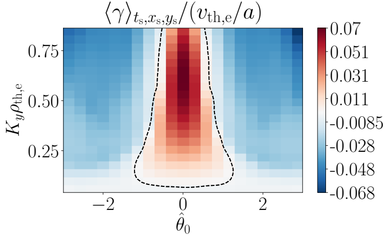
Top Right: No IS gradients.

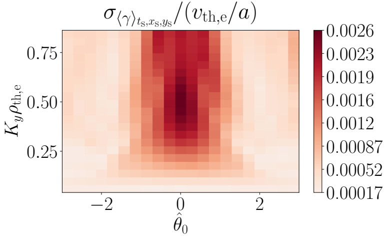
Below: average ETG growth rate across all sampled IS (x_s, y_s) locations and t_s times

INCLUDING ONLY $\nabla \overline{g}_e$ (with $\overline{\mathbf{v}}_e^E = 0$)

Weak suppression!







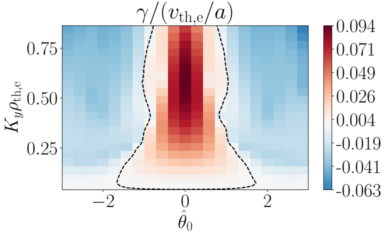
Simulations: Modification of ES linear physics: CBC $a/L_{T_i} = 2.3$

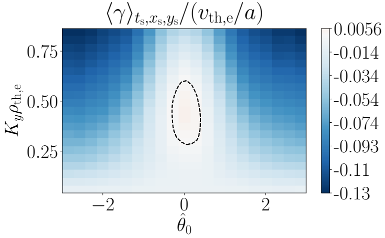
Top Right: No IS gradients.

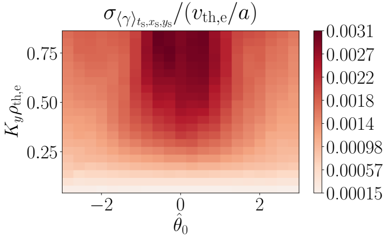
Below: average ETG growth rate across all sampled IS (x_s, y_s) locations and t_s times

INCLUDING ONLY $\overline{\mathbf{v}}_e^E$ (with $\nabla \overline{g}_e$=0)

Strong suppression!







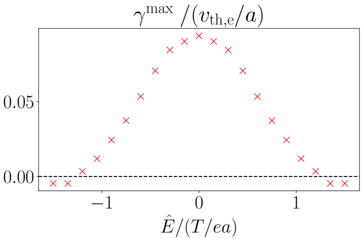
Simulations: A simple model of parallel-to-the-field shear in $\overline{\mathbf{v}}_e^E$

$$\overline{\mathbf{v}}_e^E \cdot \mathbf{k}_{\mathrm{f}} = \hat{\omega}_E \theta, \qquad (15)$$

- Simplest possible form for $\overline{\mathbf{v}}_e^E$ with local parallel-to-the-field shear (consistent with flux tube $\parallel$ b.c. Beer et al. (1995))
- (16) leads to $\overline{\mathbf{v}}_e^E \cdot \mathbf{k}_{\mathrm{f}}$ with linear variation e.g. (15) for $K_x = 0$ (and our parameters)
- Maximum ETG growth rate $\gamma^{\max}(\hat{E})$ shows suppression for all $\hat{E} \neq 0$
- $\Rightarrow$ Qualitative explanation of ETG behaviour in the presence of IS turbulence

$$\left.\frac{\partial \overline{\phi}}{\partial y_{\mathrm{s}}}\right|_{x_{\mathrm{s}}} = -\hat{E}, \quad \left.\frac{\partial \overline{\phi}}{\partial x_{\mathrm{s}}}\right|_{y_{\mathrm{s}}} = -\hat{s}\theta\hat{E}, \qquad (16)$$

$$\hat{\omega}_E = \frac{\hat{s}}{2}(K_y \rho_{\mathrm{th,e}}) \left(\frac{\hat{E}}{T/ea}\right)\left(\frac{v_{\mathrm{th,e}}}{a}\right). \qquad (17)$$



Simulations: A simple model of parallel-to-the-field shear in $\overline{\mathbf{v}}_e^E$

$$\overline{\mathbf{v}}_e^E \cdot \mathbf{k}_\mathrm{f} = \hat{\omega}_E \theta, \qquad (15)$$

- Expect suppression when

$$\hat{\omega}_E \approx \gamma^{\max}(\hat{E}=0) \simeq 0.1 v_{\mathrm{th,e}}/a$$

- Consider

$$\hat{E}/(T_\mathrm{e}/ea) = 0.5 \qquad \gamma^{\max} \approx \frac{\gamma^{\max}(\hat{E}=0)}{2}$$

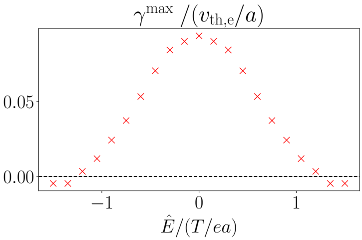
- $\hat{s}/2 = 0.4$, and typical $K_y \rho_{\mathrm{th,e}} \sim 0.5$

$$\Rightarrow \hat{\omega}_E \approx 0.1 \frac{v_{\mathrm{th,e}}}{a}$$

- $\Rightarrow$ Effect of $\overline{\mathbf{v}}_e^E$ matches expectation for the effect of a flow shear

$$\left.\frac{\partial \overline{\phi}}{\partial y_\mathrm{s}}\right|_{x_\mathrm{s}} = -\hat{E}, \quad \left.\frac{\partial \overline{\phi}}{\partial x_\mathrm{s}}\right|_{y_\mathrm{s}} = -\hat{s}\theta\hat{E}, \qquad (16)$$

$$\hat{\omega}_E = \frac{\hat{s}}{2}(K_y \rho_{\mathrm{th,e}}) \left(\frac{\hat{E}}{T/ea}\right) \left(\frac{v_{\mathrm{th,e}}}{a}\right). \qquad (17)$$



A criterion for when to expect ETG suppression

- We can expect parallel-to-the-field shear stabilisation of ETG when

$$\gamma_{\mathrm{ETG}} \lesssim \hat{\omega}_E \sim k_{\mathrm{ETG}} \frac{\Delta \overline{\mathbf{v}}^E}{\Delta \theta} \sim k_{\mathrm{ETG}} \overline{\mathbf{v}}^E$$

- A quasilinear estimate for $\overline{\mathbf{v}}^E$ gives

$$\overline{\mathbf{v}}^E \sim \frac{\gamma_{\mathrm{ITG}}}{k_{\mathrm{ITG}}}$$

- $\Rightarrow$ IS turbulence suppresses ES instabilities when

$$\frac{\gamma_{\mathrm{ETG}}}{k_{\mathrm{ETG}}} \lesssim \frac{\gamma_{\mathrm{ITG}}}{k_{\mathrm{ITG}}}$$

- Consistent with observations made in Creely et al. (2018a,b)

Conclusions

- We have derived coupled, scale-separated equations for IS and ES turbulence.
- The model is valid when $(m_\mathrm{e}/m_\mathrm{i})^{1/2} \to 0$; with space and time separation; no other small parameters
- This model describes the suppression of the ETG instability by ion gyroradius scale turbulence.
- The primary mechanism responsible for the suppression is parallel-to-the-field variation in the $\rho_{\mathrm{th,i}}$-scale $\mathbf{E} \times \mathbf{B}$ drift $\overline{\mathbf{v}}_e^E$.
- The level of suppression appears to be controlled by the relative sizes of the drives of instability with suppression when

$$\frac{\gamma_{\mathrm{ETG}}}{k_{\mathrm{ETG}}} \lesssim \frac{\gamma_{\mathrm{ITG}}}{k_{\mathrm{ITG}}}$$

Questions for Future Work

- When is the effect of $\nabla \overline{g}_e$ dominant? Near marginal stability?
- Can we retain the effect of ES turbulence on IS fluctuations by taking other parameters to be small? Distance to marginal stability?
- What is the perpendicular scale of an ETG streamer? Dorland et al. (2000); Jenko et al. (2000); Jenko and Dorland (2002); Guttenfelder and Candy (2011)
- Is it possible to enforce time scale separation if ETG turbulence saturates slowly? Colyer et al. (2017); Nakata et al. (2010)
- What is the effect of IS turbulence on nonlinear saturation of ETG turbulence?
- What changes in this picture with electromagnetic fluctuations?

Thank You for Listening!

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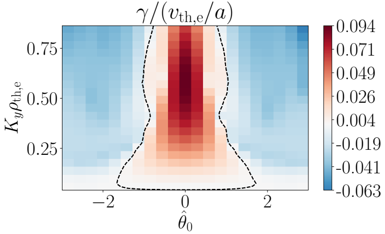
Simulations: A simple model of parallel-to-the-field shear in $\overline{\mathbf{v}}_e^E$

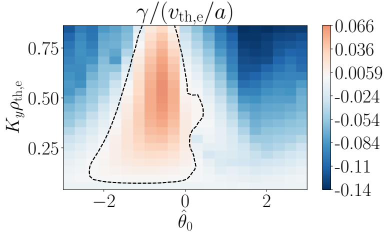
Top Right: No IS gradients.

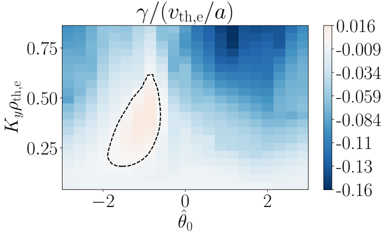
Below: ETG growth rate with model $\overline{\mathbf{v}}_e^E$; (left) $\hat{E} = 0.5T/ea$ (right) $\hat{E} = 1.0T/ea$

The peak $\gamma^{\max}$ reduces in size, and shifts in $\hat{\theta}_0$ and K_y with increasing shear.

Reminiscent of the effect of perpendicular-to-the-field flow shear



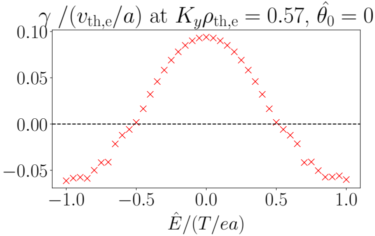


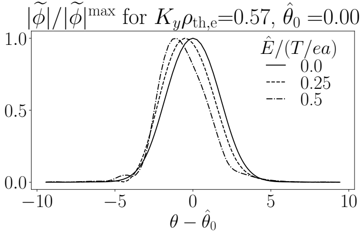


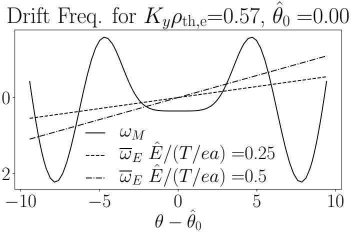
Simulations: A simple model of parallel-to-be-field shear in $\overline{\mathbf{v}}_e^E$

Top Right: ETG growth rate $\gamma(\hat{E})$ for $K_y\rho_{\rm th,e} = 0.57$, $\hat{\theta}_0 = 0.0$.

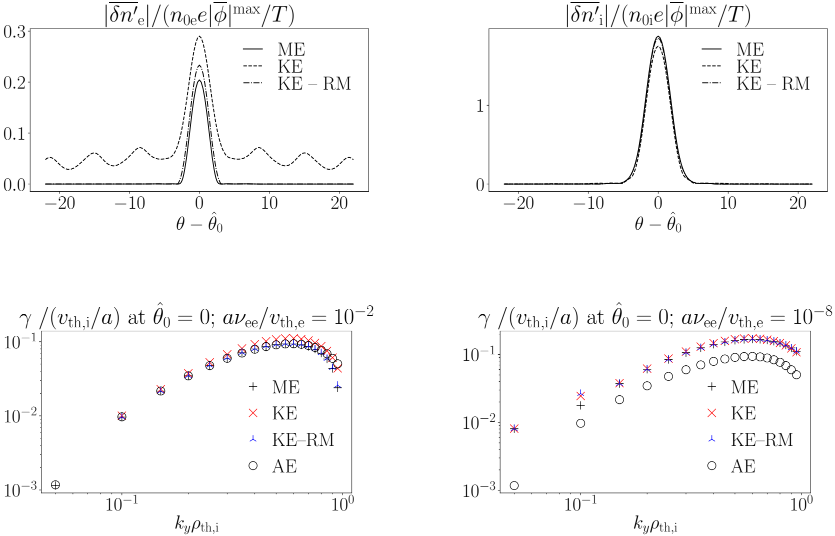
Below Left: corresponding eigenmodes
Below Right: corresponding drift coefficients
Strong suppression!



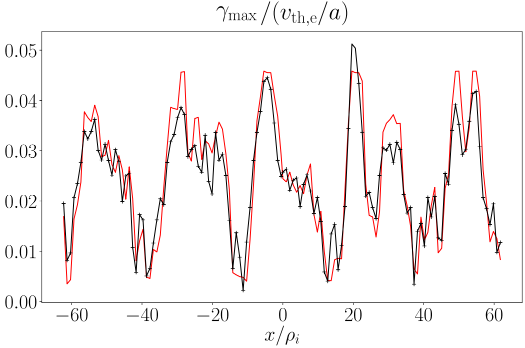




Electrons at IS



The effect of $\nabla\overline{g}_{\mathrm{e}}$ – Cross-scale interation near marginal stability



- ITG turbulence driven near marginal with $a/L_{T_{\mathrm{i}}} = a/L_{T_{\mathrm{e}}} = 1.38$
- ETG driven with $a/L_{T_{\mathrm{e}}} = 1.38$, $a/L_{n_{\mathrm{e}}} = 0.733$
- (Black) $\gamma^{\max}$ calculated with cross-scale terms $\nabla\overline{g}_{\mathrm{e}}$ and $\overline{\mathbf{v}}^E$
- (Red) $\gamma^{\max}$ calculated with only modifications to

$$\frac{a}{L_{n_{\mathrm{e}}}} \to \frac{a}{L_{n_{\mathrm{e}}}} - \frac{1}{n_{\mathrm{e}}}\frac{d\overline{n_{\mathrm{e}}}}{dx} \qquad \frac{a}{L_{T_{\mathrm{e}}}} \to \frac{a}{L_{T_{\mathrm{e}}}} - \frac{1}{T_{\mathrm{e}}}\frac{d\overline{T_{\mathrm{e}}}}{dx}$$