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Simulations on the Nonlinear Mode Coupling in Multiple-scale Drift-type Turbulence with Coherent Flow Structures

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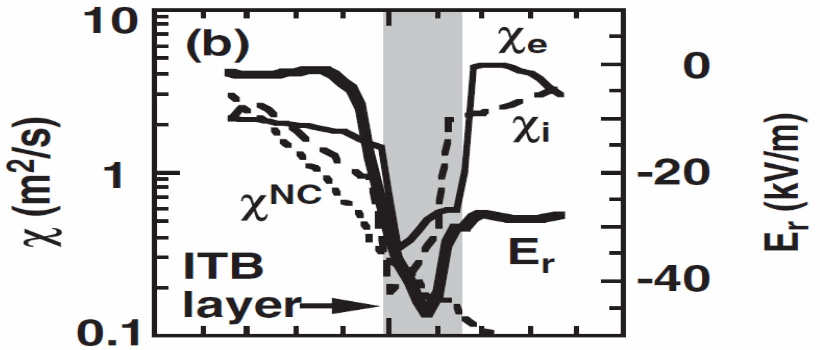
Motivation & Main Results

» Multi-scale turbulence and secondary/tertiary coherent flow structures coexist in plasmas (MHD; ITG; TEM; ETG;….. Mean/zonal flows; streamers; KH, GKH modes; ……)

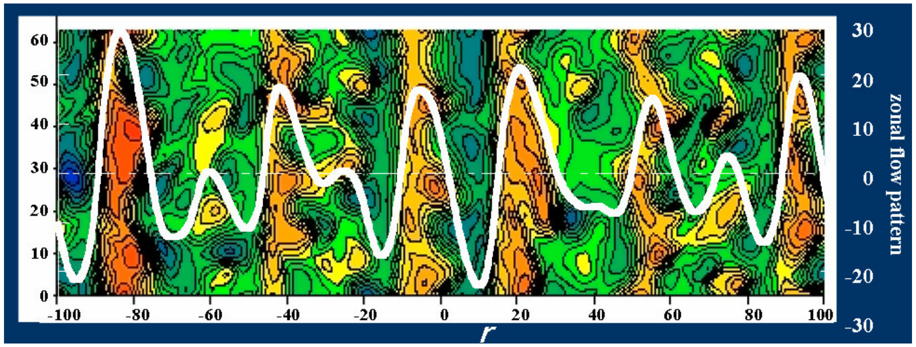
» Flow characteristics and interaction mechanisms

Smooth mean flow with zero frequency: shearing decorrelation



Shirai H. et al NF1999

Wave-type flow with low/zero frequency: nonlinear mode coupling ?



Li/Kishimoto PoP 2004

» Motivation:

Secondary and/or tertiary structures as a wave-type flow interact with turbulence through a primary mechanism: nonlinear mode coupling

» Main results

- Back-action of zonal flows/long wavelength modes on turbulence deforms the power-law spectrum into an exponential-law scaling.
- Secondary streamer-like long wavelength modes can saturate ETG turbulence, suggesting the possibility of a low ETG fluctuation level and electron transport.

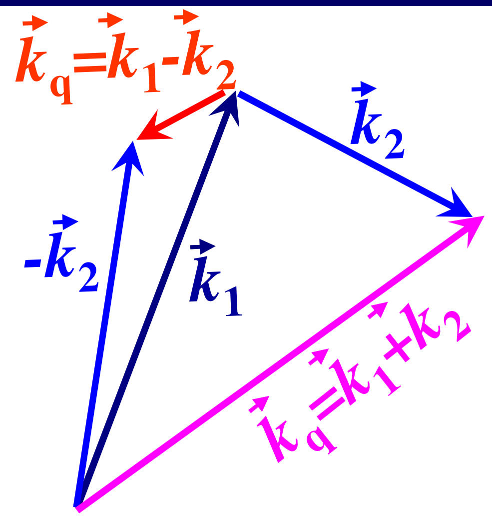
Spectral characteristics of turbulence due to back-action of flow structures

Schematic picture of nonlinear mode coupling

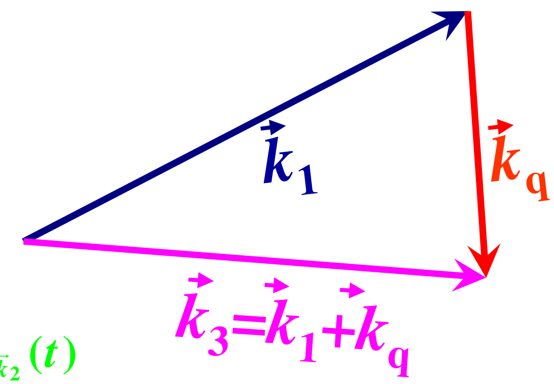
» Ubiquitous nonlinear process: basic four-wave & three-wave interaction

Modulation instability for flow generation

Nonlinear mode coupling for back-action ?



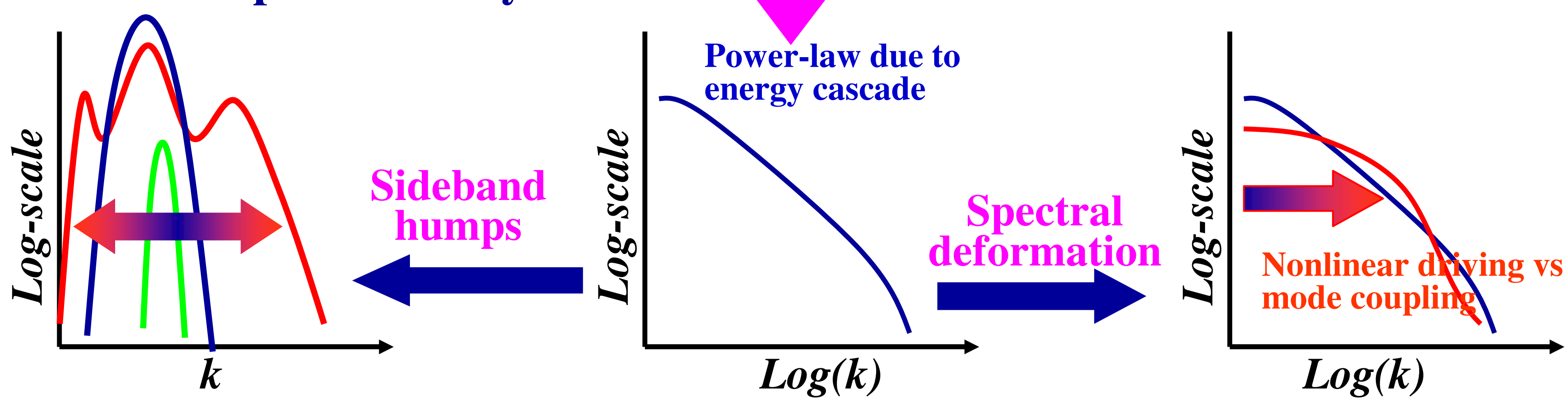
Wavenumber mismatch
Frequency mismatch



Nonlinear interaction=

$$\sum_{\vec{k}=\vec{k}_1+\vec{k}_2} \frac{1}{1+k^2}\left(\vec{k}_1\times\vec{k}_2\right)\cdot\vec{e}_z\left[k_2^2-k_1^2\right]\phi_{\vec{k}_1}(t)\phi_{\vec{k}_2}(t)$$

» What happens in turbulence with generation and back-action of strong flow structures? → spectral analysis



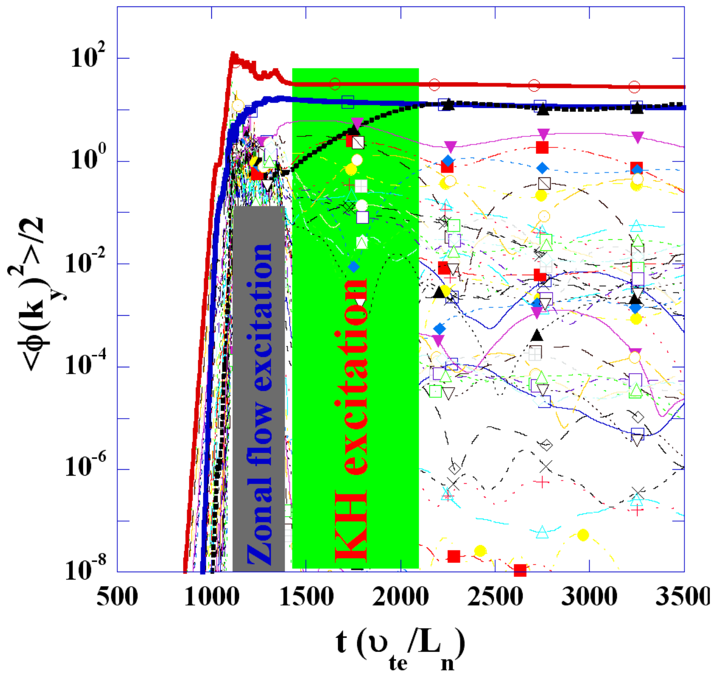
Simulations in 2D forced HM model vs GTC

» Forced HM turbulence modeling based on 2D ETG (Free energy system)

$$(1-\nabla_\perp^2)\frac{\partial\Phi}{\partial t}=\frac{\partial\Phi}{\partial y}+[\Phi,\nabla_\perp^2\Phi]+\gamma_{drive}^{ETG}(\vec{k})\Phi+\gamma_{damp}^{ETG}(\vec{k})\Phi$$

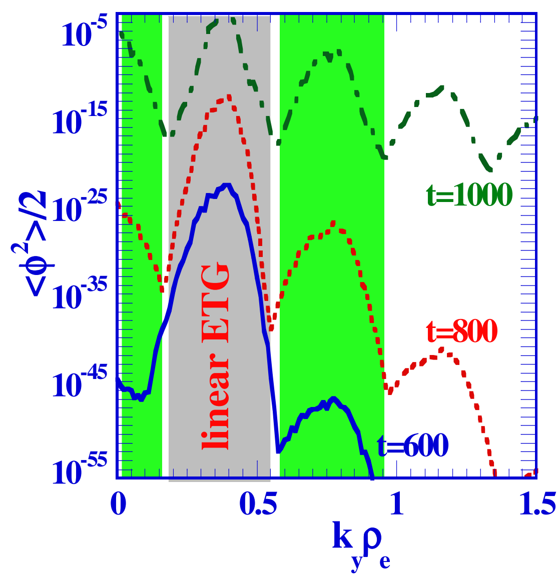
» Parameters:

$\hat{s}=0.1,\eta_e=5.5,D=1.5,\Delta k_y=0.0125$



4 evolution phases: (1)Linear ETG; (2)Zonal flow enhancement; (3)KH excitation; (4)quasi-steady state

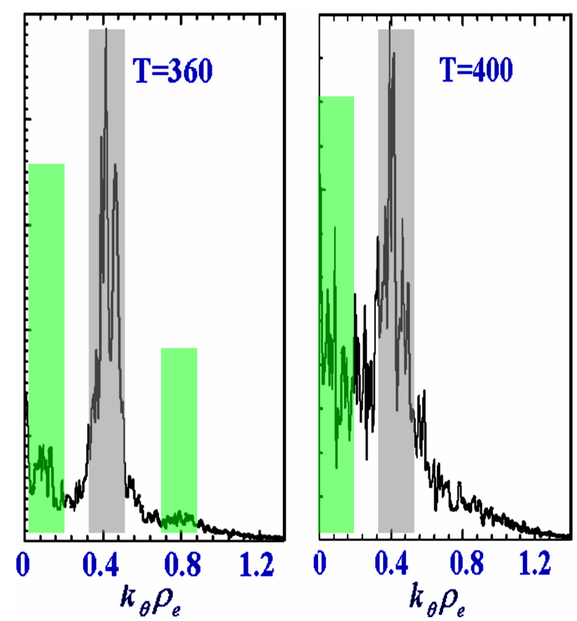
Before ETG saturation, GKH excitation



Mode coupling → beat wave

$k_{y1}\pm k_{y2}=k_{yq}$

$\hat{s}\approx 0.1, L_T=2.2, L_n=6.9,$
$a/R=0.345, a/\rho_i=240$



Gyrokinetic ETG by performing GTC code

Identifying mode coupling due to zonal flows

» k_x spectral relation between ETG fluctuations and zonal flows due to nonlinear mode coupling

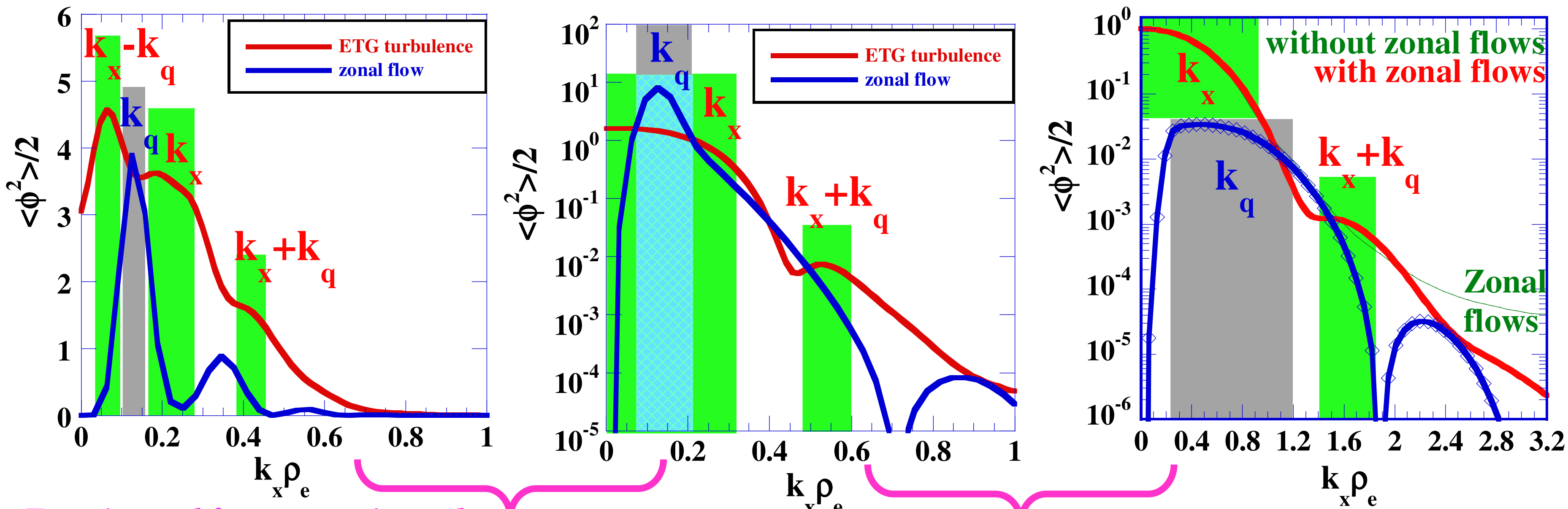
Zonal flow generation by ETG turbulence

Back-action of zonal flow on ETG turbulence

$\hat{s} = 0.1$ t=1200

$\hat{s} = 0.1$ t=1500

$\hat{s} = 0.8$ Quasi-steady state



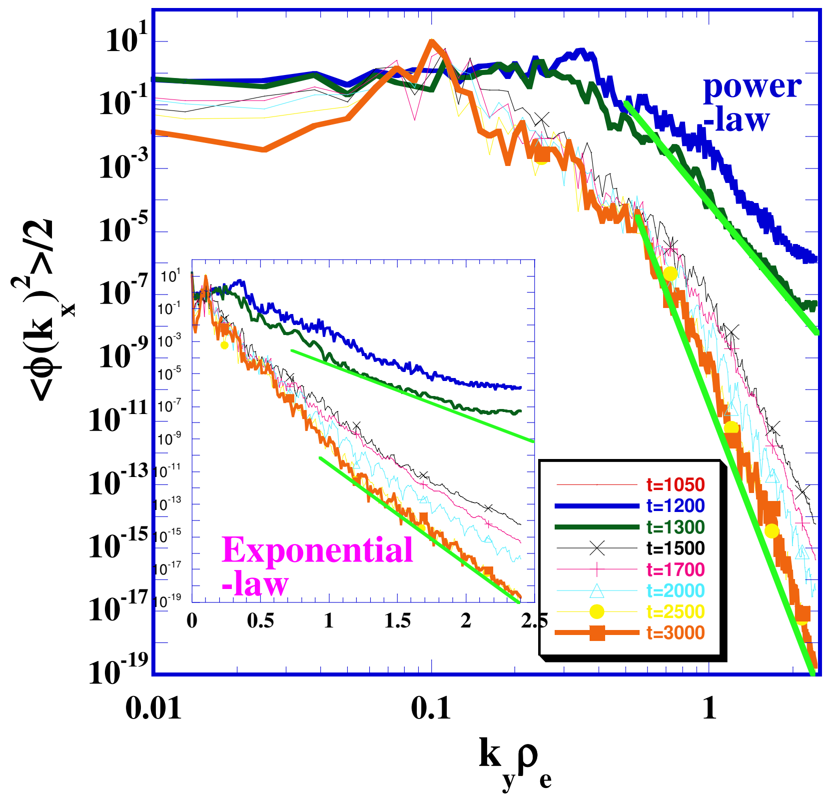
Experimental frequency mismatch
Sen et al. PoP 2006

4-wave coupling for zonal flow generation (modulation instability) also acts back on turbulence to produce high k_x fluctuation which is damped.

Larger k_q and wider zonal flow spectrum can make larger k_x spectral hump. Interaction becomes nonlocal.

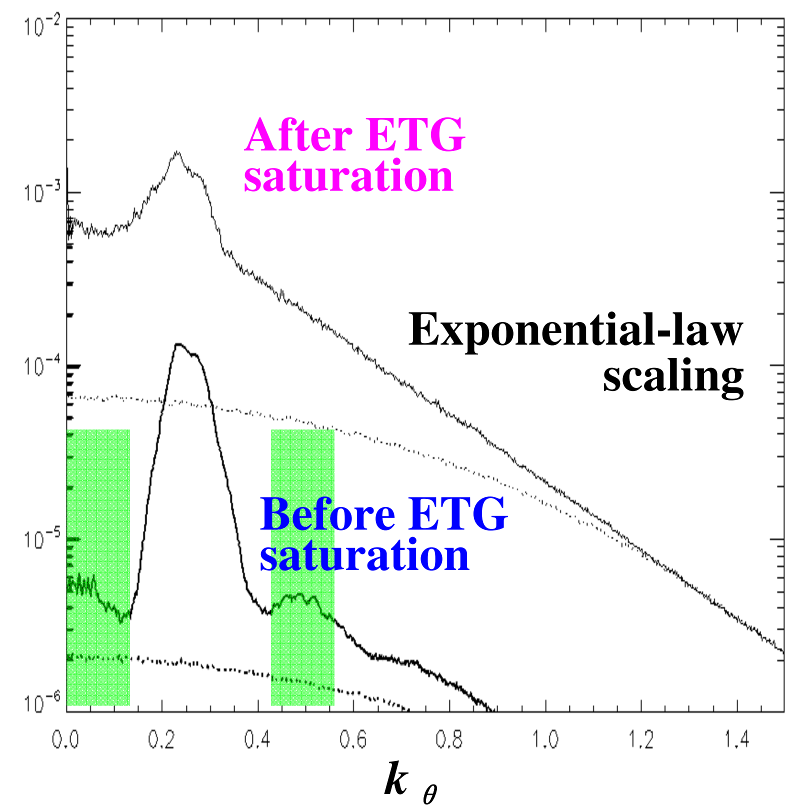
Spectral transition due to KH/GKH mode

2D forced HM modeling ETG simulation



Nonlinear mode coupling between KH mode with $k_y \approx 0.1$ interacts with ETG ($k_y \approx 0.4$) deform power-law spectrum (t<1500) into exponential scaling(t>1500)

Gyrokinetic ETG simulation by performing GTC code



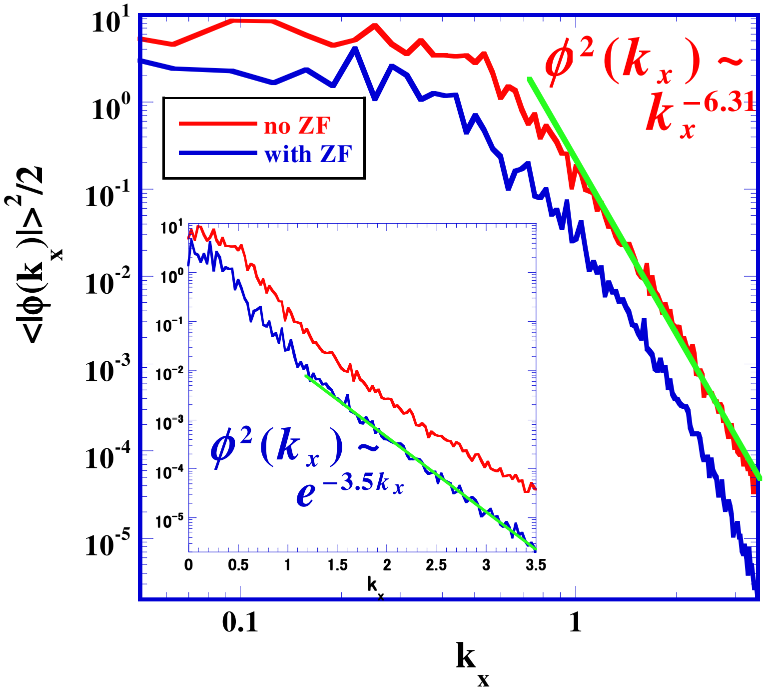
Similar to fluid simulation, long wavelength GKH is excited before ETG simulation; Exponential-law spectrum is also observed after ETG saturation.

Spectral characteristics in 3D slab ETG / ITG

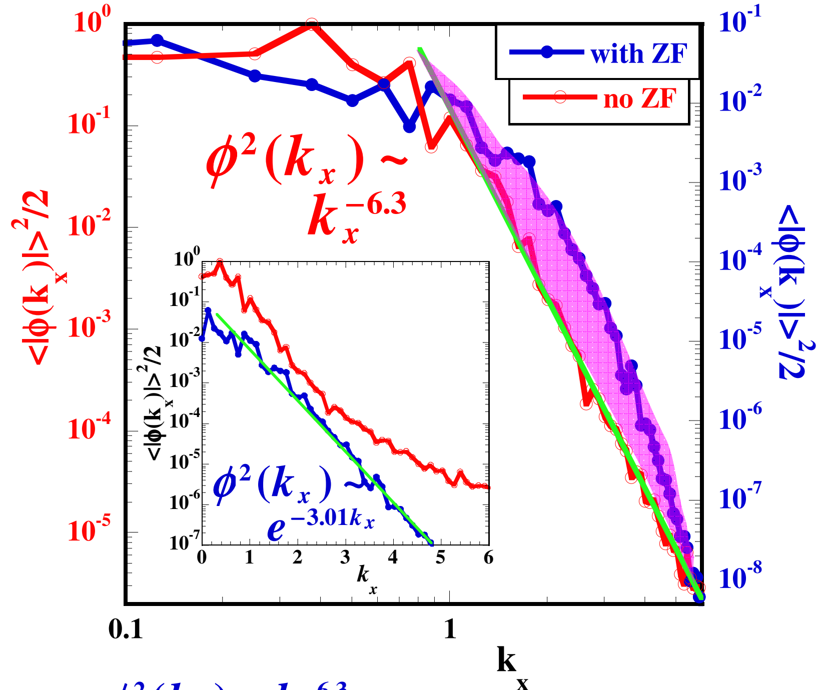
» Simulations with and no zonal flows for comparison

(3-field gyrofluid models: Li/Kishimoto PoP2003, 2004)

3D ETG with enhanced zonal flow
$\hat{s} = 0.1, \eta_e = 6, D = 0.5, \Delta k_y = 0.1$



3D ITG with robust zonal flow
$\hat{s} = 0.2, \eta_i = 2.5, D = 0.1,, \Delta k_y = 0.1$



» Without zonal flows: k_x or k_y power-law spectrum $\phi^2(k_x) \sim k_x^{-6.3}$
same as theoretical estimate α =6.29 [*Ottinger & Carati, PRE(1993)*]

» With zonal flows: exponential-law $\phi^2(k_x) \sim e^{-3.0k_x}$, almost no change for k_y spectrum.

Experimental exponential-law density spectra in Tore Supra, Hennequin, et al. TTF06

Back-action of zonal flows through nonlinear mode coupling may provide a drive force to deform power-law scaling into an exponential-law dependence

Role of streamer-like long wavelength structures in ETG saturation

Electron transport vs large-scale flow in ETG

» Several ETG simulations show streamer structures, but transport is different.

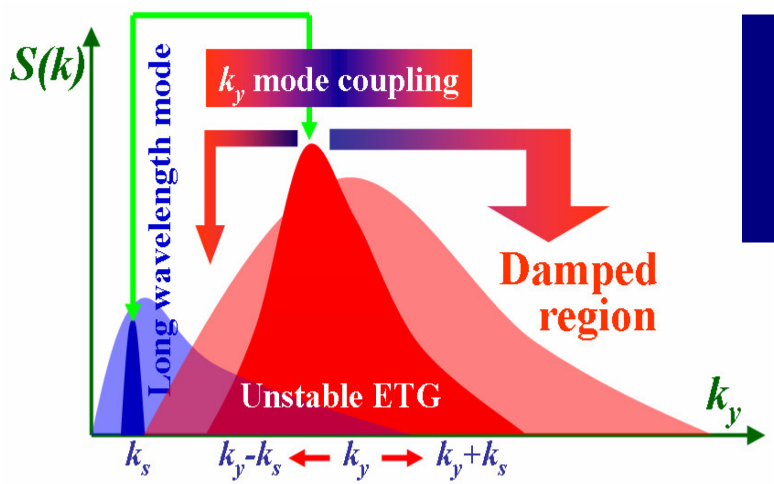
» Streamer structure is expected to enhance electron transport. However, what is its probable role in ETG saturation?

» Assuming wave-type streamer-like long-wavelength mode imposed in ETG (ignoring k_x)

$$\phi_s = \phi_{s0}(t)\cos(k_s y) \qquad k_s << 1$$

» Coupled equs. due to streamer-like long-wavelength mode

$$\begin{cases} \partial_t (1-\nabla_\perp^2)\phi^{k_y} = (1+K\nabla_\perp^2)\partial_y \phi^{k_y} - \frac{i}{2}k_s\phi_s\partial_x\nabla_\perp^2(\phi^{k_y+k_s}-\phi^{k_y-k_s}) + \nabla_{/\!/} v_{/\!/}^{k_y} - \mu_\perp \nabla_\perp^4 \phi^{k_y} \\ \partial_t v_{/\!/}^{k_y} = \nabla_{/\!/}(\phi^{k_y} - p_e^{k_y}) + \frac{i}{2}k_s\phi_s\partial_x(v_{/\!/}^{k_y+k_s} - v_{/\!/}^{k_y-k_s}) + \eta_\perp \nabla_\perp^2 v_{/\!/}^{k_y} \\ \partial_t p_e^{k_y} = -K\partial_y\phi^{k_y} - \frac{5}{3}\nabla_{/\!/} v_{/\!/}^{k_y} + \frac{i}{2}k_s\phi_s\partial_x(p_e^{k_y+k_s} - p_e^{k_y-k_s}) + \sqrt{\frac{32}{9\pi}}|k_{/\!/}|(p_e^{k_y}+\phi^{k_y}) + \chi_\perp\nabla_\perp^2 p_e^{k_y} \end{cases}$$



Streamer-like long-wavelength structure + ETG

↓

k_y-mode coupling

↓

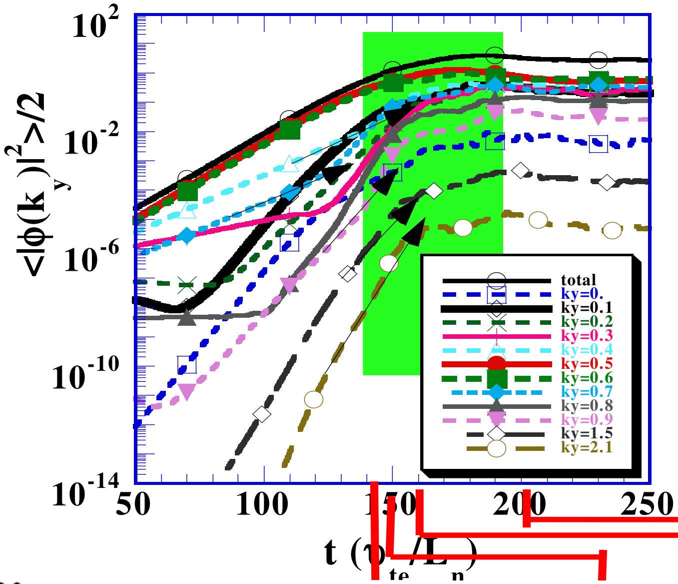
Stabilization!

k_y-mode coupling in slab corresponds to toroidal mode coupling in tokamak since slab is the local expansion near given q_0 surface.

Z. Lin / L. Chen et al. IAEA 2004, PoP2005, PPCF 2005

3D ETG simulation vs long-wavelength mode

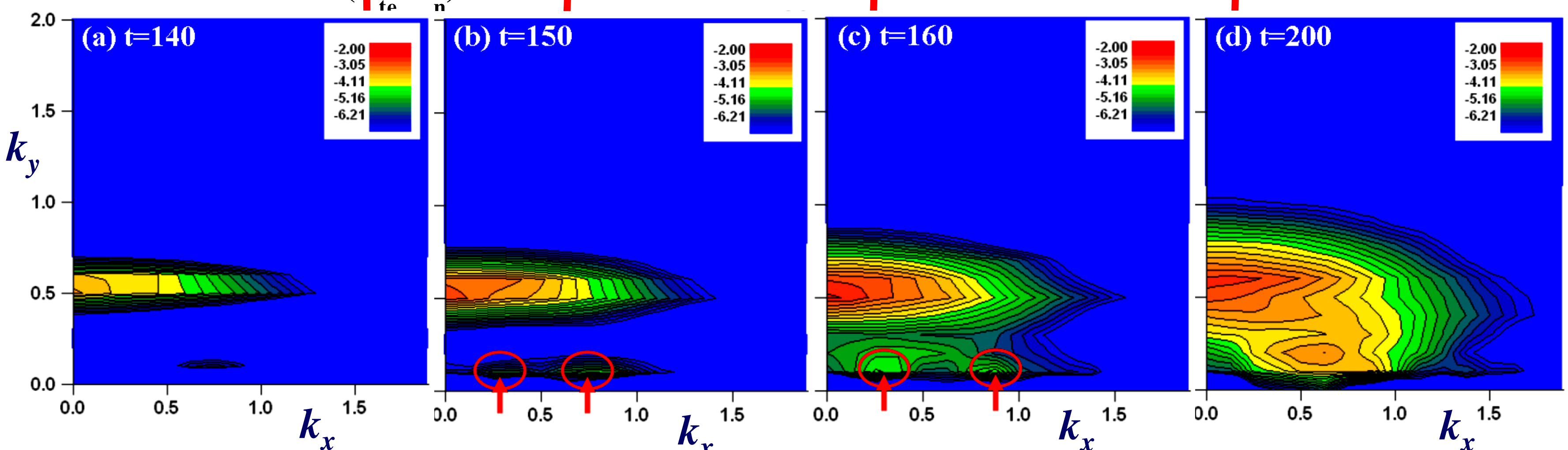
$\eta_e = 6, \hat{s} = 1.4, \mu_\perp = \eta_\perp = \chi_\perp = 0.5; \quad L_x = 50\rho_e, L_y = 20\pi\rho_e, L_z = 2\pi L_n$



- Unstable ETG k_y= 0.5 ~0.6
- produces a beat (weak instability) k_y=0.1
- ETG spectrum widened, ETG saturated

- Two radial peaks with $k_x \approx 0.8$ and 0.35 for k_y=0.1 mode

» Spectral evolution of ETG turbulence



Secondary long wavelength mode is excited

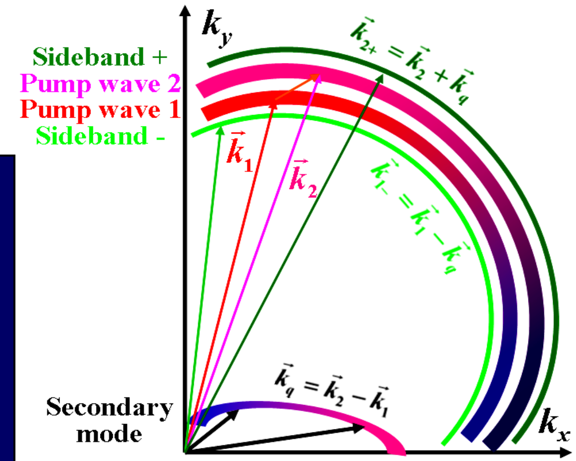
Interaction with ETG

ETG saturation

Excitation of long wavelength mode in ETG

» **Hasegawa-Mima turbulence model**

$$(1-\nabla_\perp^2)\frac{\partial}{\partial t}\phi = \frac{\partial}{\partial y}\phi + [\phi, \nabla_\perp^2\phi]$$



5-wave modulation: 2 pumps, 2 sidebands and flow seed

$$\phi_{p1,2} = \phi_{1,2} e^{i\vec{k}_{1,2}\cdot\vec{x} - i\omega_{1,2}t} + c.c. \quad \phi_q = \tilde{\phi}_q e^{i\vec{k}_q\cdot\vec{x} - i\omega_q t} + c.c.$$

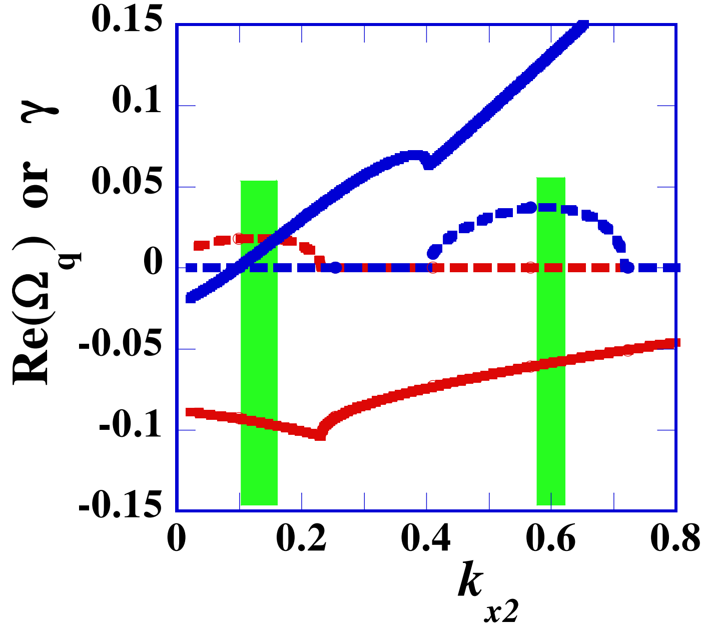
$$\phi_{2+,1-} = \tilde{\phi}_{2+,1-} e^{i\vec{k}_{2+,1-}\cdot\vec{x} - i\omega_{2+,1-}t} + c.c.$$

» **Dispersion relation of modulation instability**

$$F(\Omega_q; \tilde{\phi}_1; \tilde{\phi}_2; \vec{k}_1; \vec{k}_2) = 0$$

- **Low amplitude threshold for modulation instability**
- **Weak instability with peaks at k_x=0.8 and 0.35**
- **Wave number matches**

$|\phi_1| = |\phi_2| = 1.$; $k_{y1}=0.5$, $k_{y2}=0.6$, $k_{x1}= -0.2$



$k_{x1} = \pm 0.2$
$k_{x2} \approx \pm 0.15$
$k_{x2} \approx \pm 0.6$

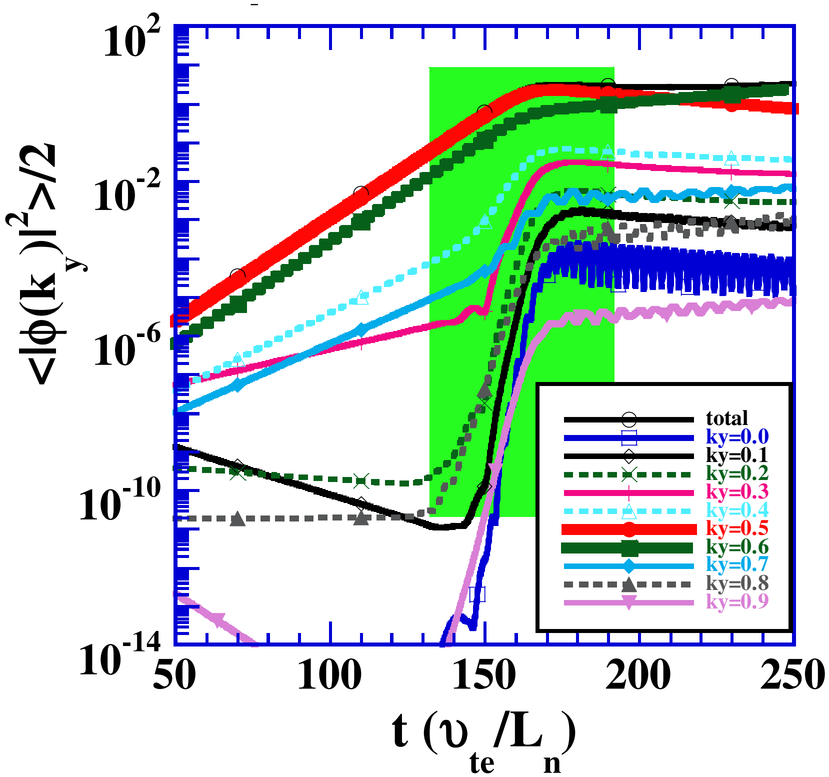
$k_{xq} = k_{x2} - k_{x1}$

$k_{xq} \approx 0.35 \quad 0.8$

ETG saturation due to streamer-like mode

» Streamer-like mode as a beat wave in pure linear ETG fluctuations

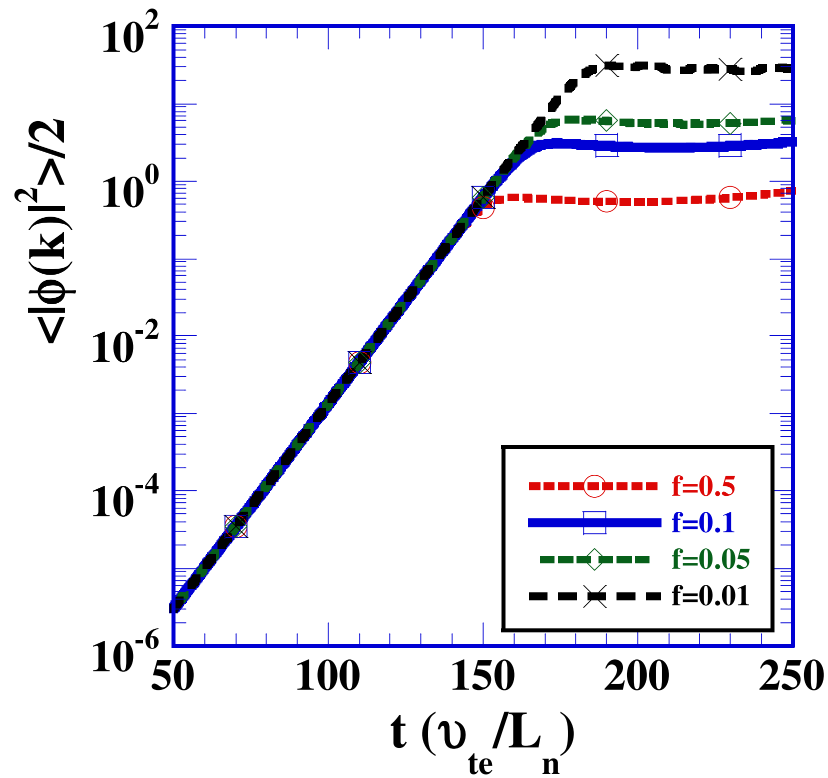
$$\phi_s = 0.1 | \phi(t)_{k_y=0.5} \phi(t)_{k_y=0.6} | \cos(0.1y)$$



Time-dependent long wavelength streamer-like mode interact with ETG modes to produce k_y-mode coupling so that ETG is saturated at lower level.

» ETG saturation level vs intensity of streamer-like mode

$$\phi_s = f^* | \phi(t)_{k_y=0.5} \phi(t)_{k_y=0.6} | \cos(0.1y)$$



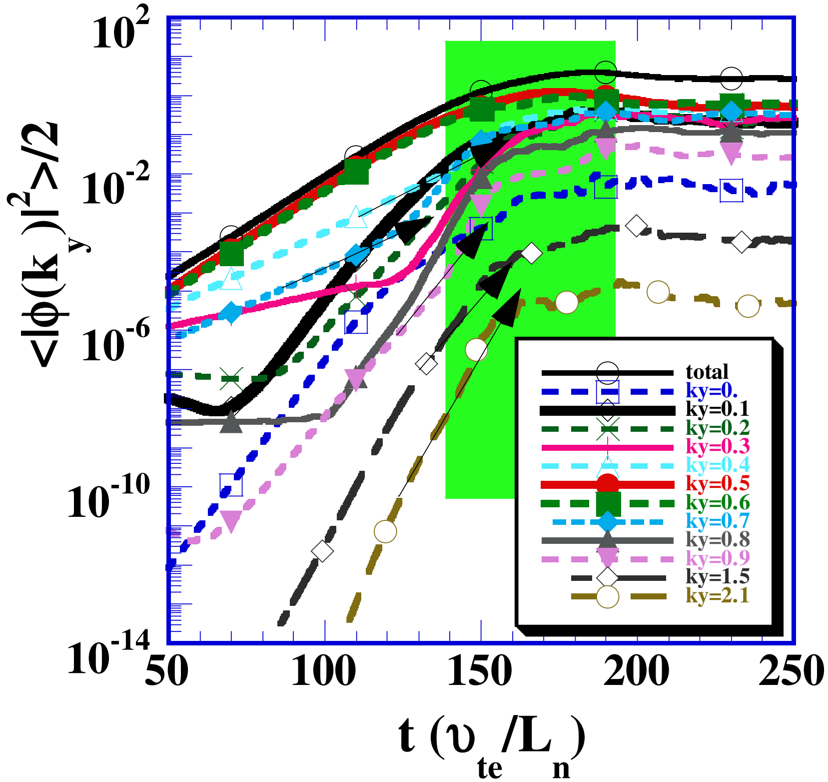
ETG saturation amplitude inversely proportional to intensity of streamer-like mode

Comparison of ETG saturation features

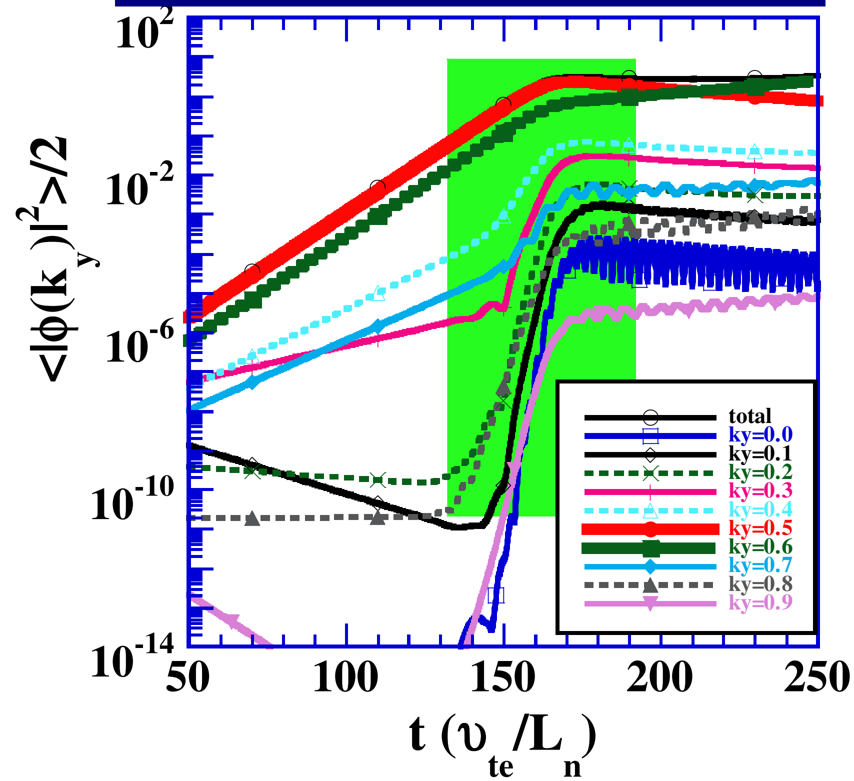
» **Same physical parameters and numerical settings:**

$\eta_e = 6, \hat{s} = 1.4, \mu_\perp = \eta_\perp = \chi_\perp = 0.5;\ L_x = 50\rho_e, L_y = 20\pi\rho_e, L_z = 2\pi L_n$

3D slab ETG turbulence



2D linear slab ETG modes + streamer-like beat wave



2D modeling simulation can well reproduce the main features of 3D ETG turbulence saturation (amplitude, time evolution ……)

Secondary long wavelength streamer-like flow saturate ETG turbulence through nonlinear mode coupling!

Summary and conclusion

Nonlinear mode coupling is testified and emphasized as a primary interaction mechanism in multiple-scale drift turbulence with coherent flows, which are characterized by wave-type structures. 2D modeling analysis and 3D gyrofluid slab ETG simulations well produce spectral features observed in gyrokinetic particle ETG simulation by using GTC code.

Main results:

» **Through nonlinear mode coupling , zonal flow or long wavelength KH (GKH) can deform the conventional power-law k_x or k_y spectra into an exponential-law scaling.**

» **Secondary long-wavelength streamer-like structure can saturate slab ETG turbulence at lower level through producing a k_y-mode coupling, suggesting the possibility of low electron transport in ETG turbulence.**

In addition, the effect of wave-type mean flows on the zonal flow generation in drift wave turbulence has also been investigated, the results will be presented in our poster: TH/2-3

Thank you !