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Nonlinear Interaction and Turbulent Transport in Mixed Scale MHD and ITG Fluctuations

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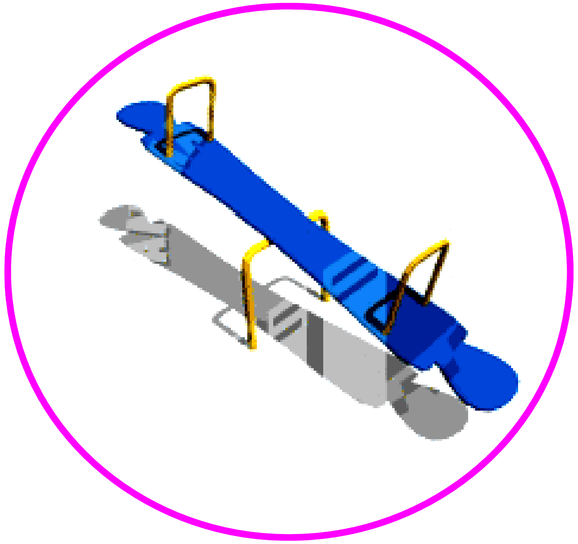
Outline

- Back ground and motivation

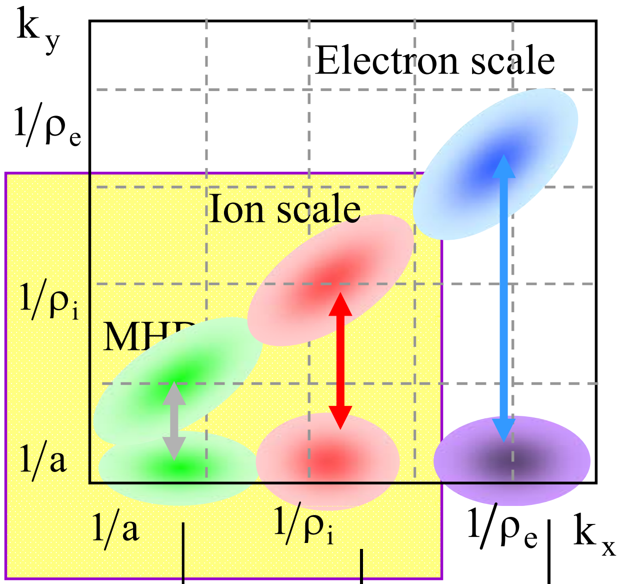
- Mixed-scale MHD-turbulence interaction

  - Modeling and equations
  - Nonlinear Interaction between ITG and MHD
  - Magnetic island dynamics : island seesaw
  - zonal flow dynamics : finite frequency
  - Turbulent transport

- Summary

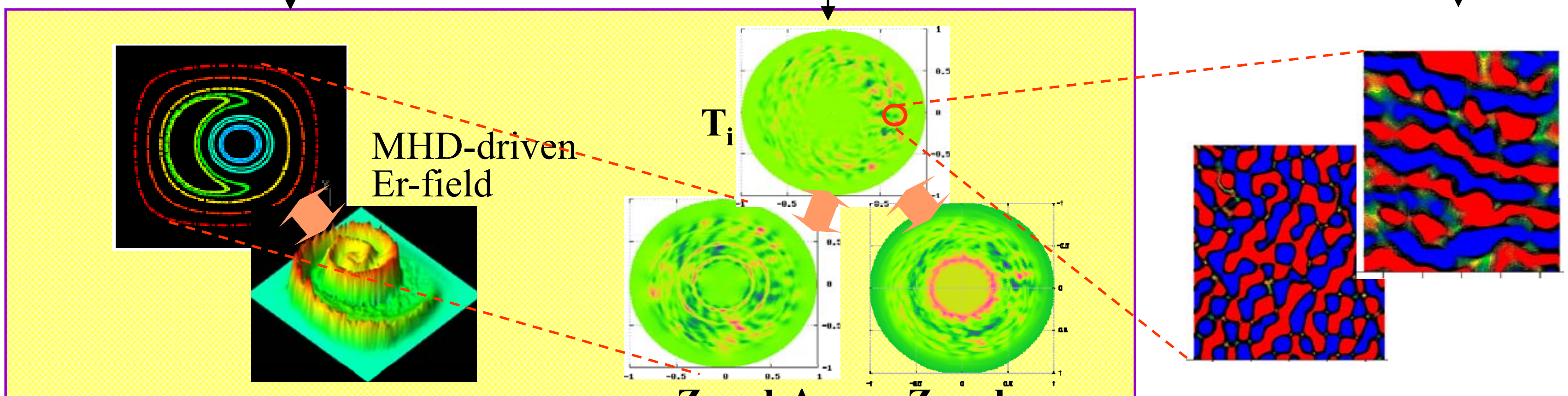


Multiple fluctuations in fusion



- ► Many linear & nonlinear driving force covering $\Delta k \sim 10^5$, $\Delta\omega \sim 10^8$ with overlapping of multi-scale fluctuations
- ► Understanding prominent transport events taking into account these nature

(trigger dynamics of TB, non-diffusive transport, sudden events ….)



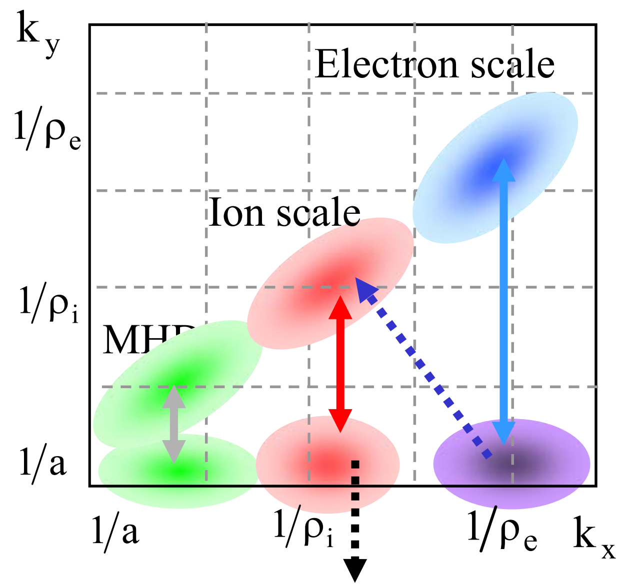
[*Matsumoto, Naitoh, PoP, '03*]

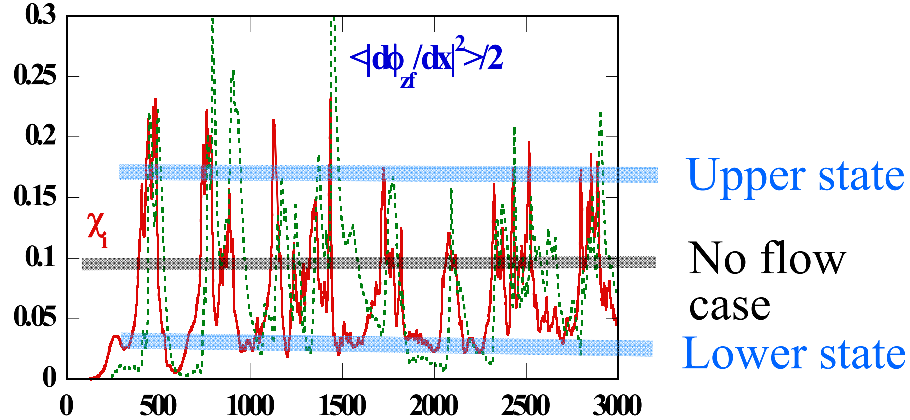
[*Miyato-Kishimoto, PoP, '04*]

[Local toroidal GF, *Li-Kishimoto,EPS, '04*]

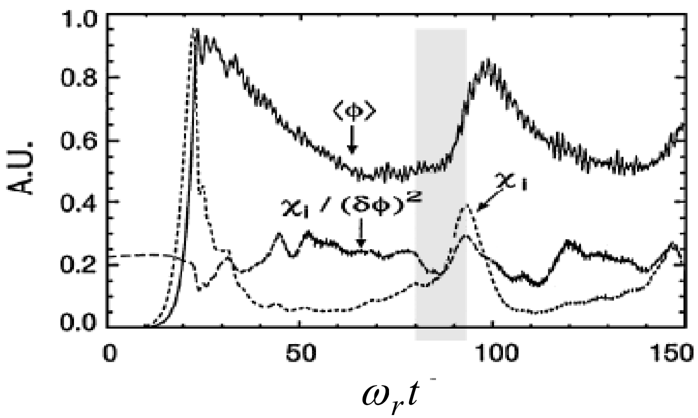
Ex. Effect of ETG driven zonal flow on ITG turbulent

Different scale fluctuation works as a dynamical dissipation through nonlinear mode coupling, causing intermittency near critical gradient region

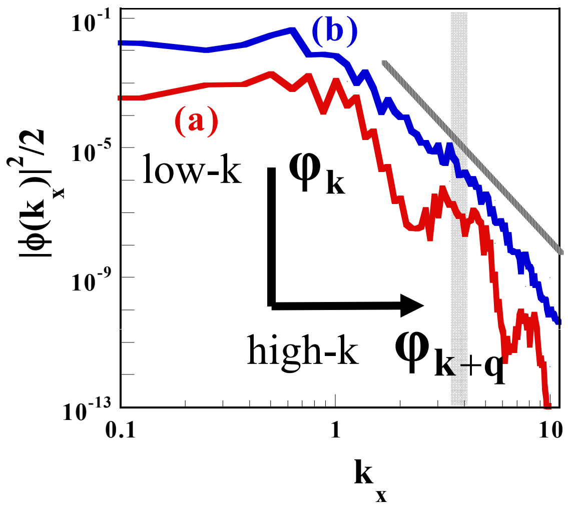




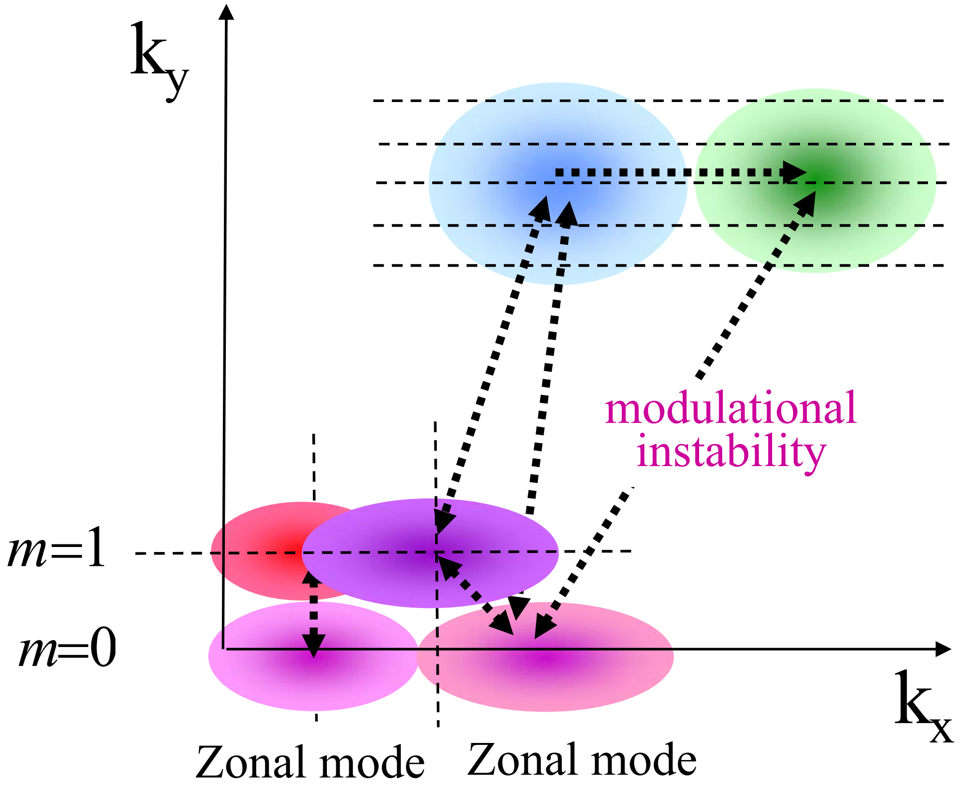
[Li-Kishimoto, PRL, ’02]

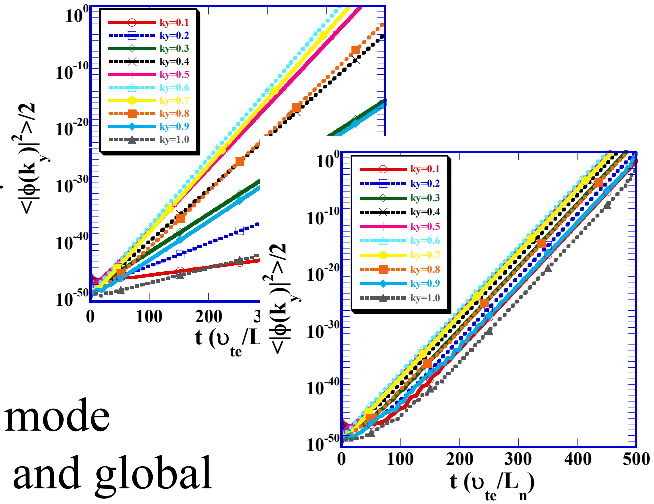


Collisional ZF damping causing intermittency
[Lin et al., PRL, ’99, Markov et al., PoP, ’01]

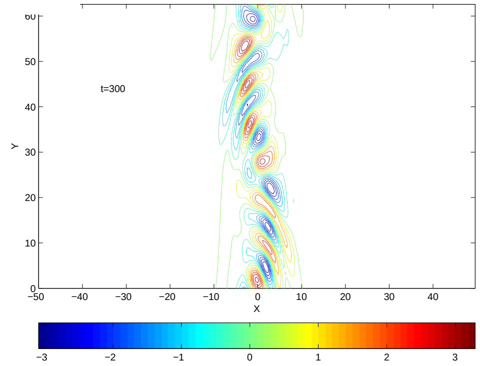


Mode coupling among different scale fluctuations



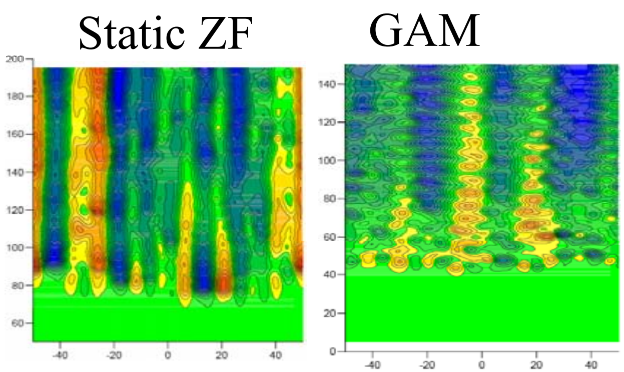


Poloidal mode coupling and global eigen-mode



Effcet of ω* on MHD mode

- Eigen-mode frequency
- Zonal mode
  (Zonal flow, field , pressure)



Gyrofluid modeling equations

Modeling equation – 5-field EM gyrofluid ITG with MHD in slab
(Miyato et al. PoP 04 for toroidal version)

$$\left\{\begin{aligned}
&\frac{\partial}{\partial t}\nabla_\perp^2\phi = -[\phi,\nabla_\perp^2\phi] + (1+\eta_i)\frac{\partial}{\partial y}\nabla_\perp^2\phi + \nabla_{//} j_{//} + D_U\nabla_\perp^4\phi \\
&\frac{\partial}{\partial t} n = -[n,\phi] + \frac{\partial\phi}{\partial y} - \nabla_{//}\upsilon_{//i} + \nabla_{//} j_{//} + D_n\nabla_\perp^2 n \\
&\beta\frac{\partial}{\partial t}A_{//} = -\nabla_{//}\phi + \tau\nabla_{//} n + \beta\tau\frac{\partial A_{//}}{\partial y} - \eta j_{//} + \sqrt{\frac{\pi}{2}\tau\frac{m_e}{m_i}}\left|\nabla_{//}\right|(\upsilon_{//i} - j_{//}) \\
&\frac{\partial}{\partial t}\upsilon_{//i} = -[\phi,\upsilon_{//i}] - (1+\tau)\nabla_{//} n - \nabla_{//} T_i + \beta(1+\tau+\eta_i)\frac{\partial A_{//}}{\partial y} - \eta j_{//} + D_\upsilon\nabla_\perp^2\upsilon_{//i} \\
&\frac{\partial}{\partial t}T_i = -[\phi,T_i] - \eta_i\frac{\partial\phi}{\partial y} - (\gamma-1)\nabla_{//}\upsilon_{//i} - (\gamma-1)\sqrt{\frac{8}{\pi}}\left|\nabla_{//}\right| T_i + D_\upsilon\nabla_\perp^2 T_i
\end{aligned}\right.$$

with $j_{//} = -\nabla_\perp^2 A_{//}$ $\quad A_{//} = -\psi$

Mean parameters:

- η_i Ion temperature gradient for ITG fluctuations
- η Resistivity for MHD (kink-tearing) modes

✔ Here the spatio-temporal scales and all corresponding quantities are normalized by ion-scale, similar to those in ITG turbulence.

Physics ingredients in mixed model

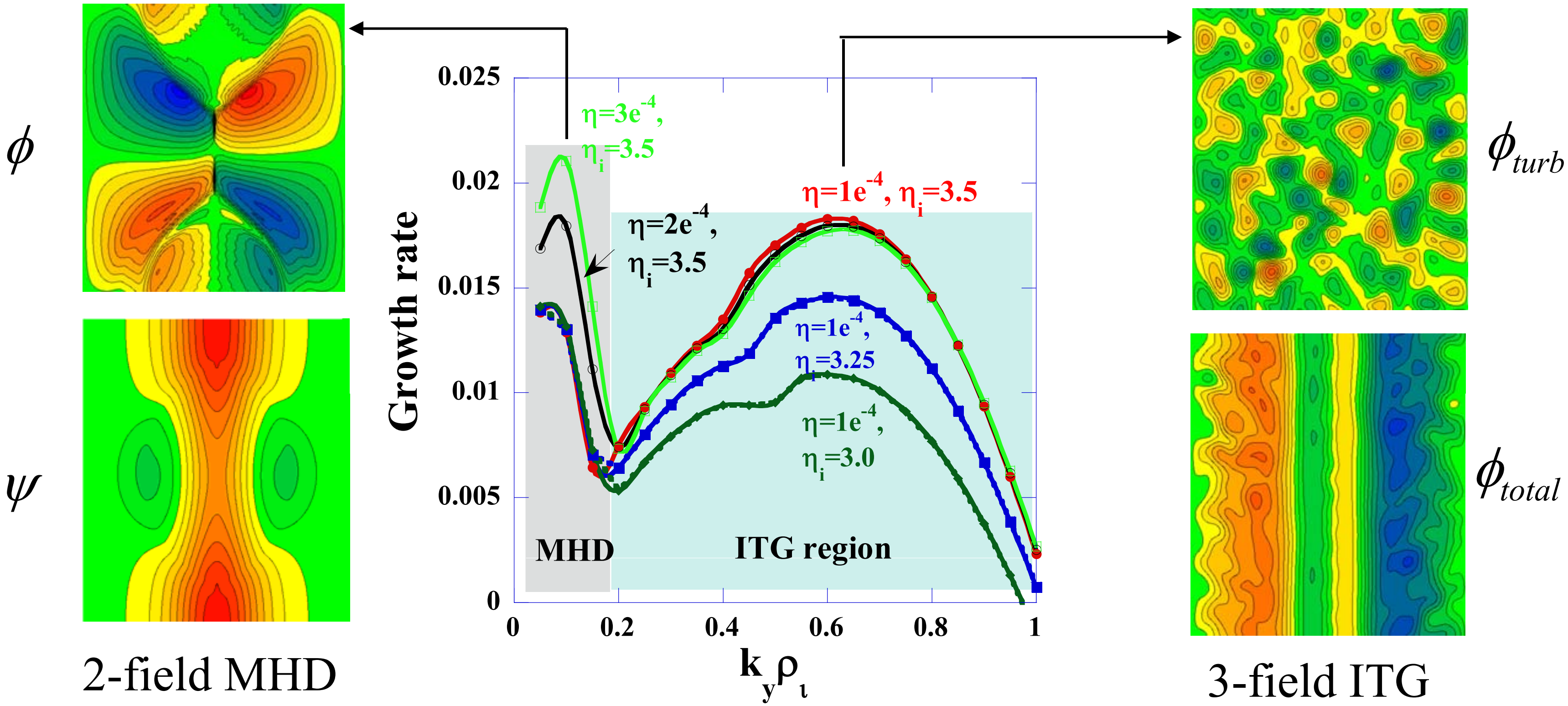
- Initial equilibrium and parallel wave number

$$B_y = \frac{L_x}{\pi}\hat{s}B_0 \frac{\sinh(\pi x/L_x)}{\cosh^3(\pi x/L_x)} \qquad k_{//} = k_z - k_y \frac{L_x}{\pi}\hat{s}\frac{\sinh(\pi x/L_x)}{\cosh^3(\pi x/L_x)}$$

- Linear stability and independent nonlinear calculation

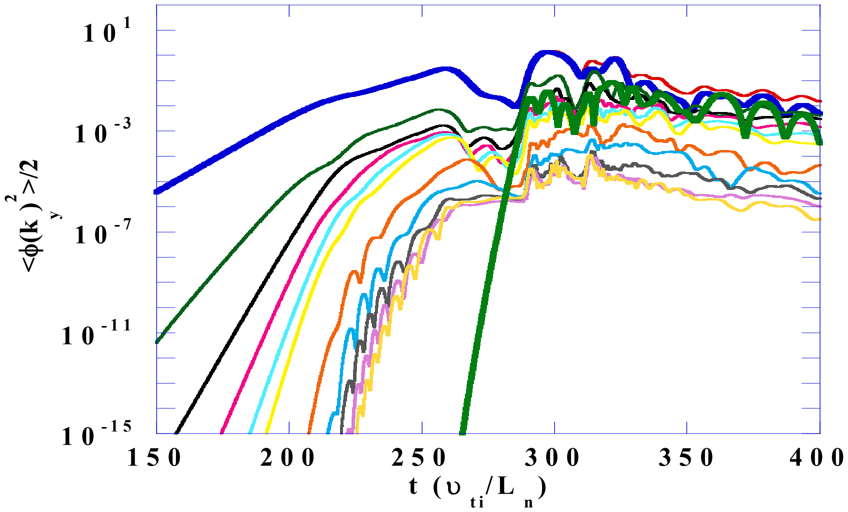
Resistive tearing mode

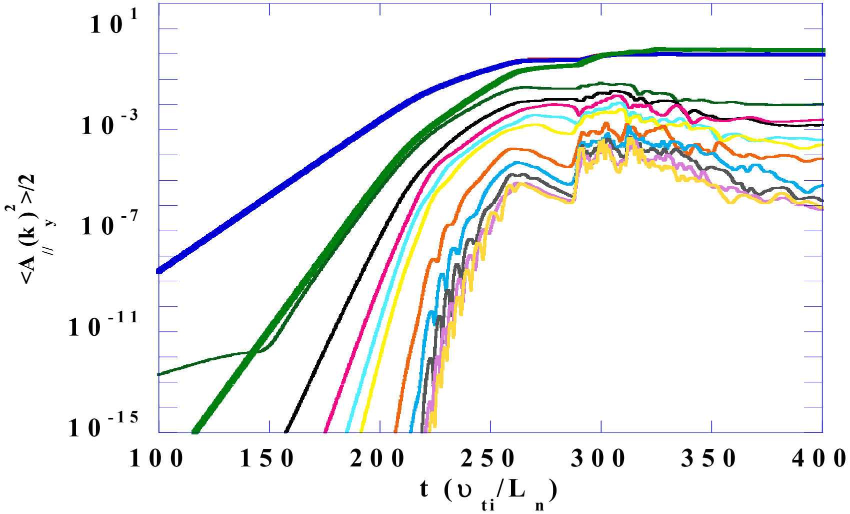
ITG (with ZF) turbulence

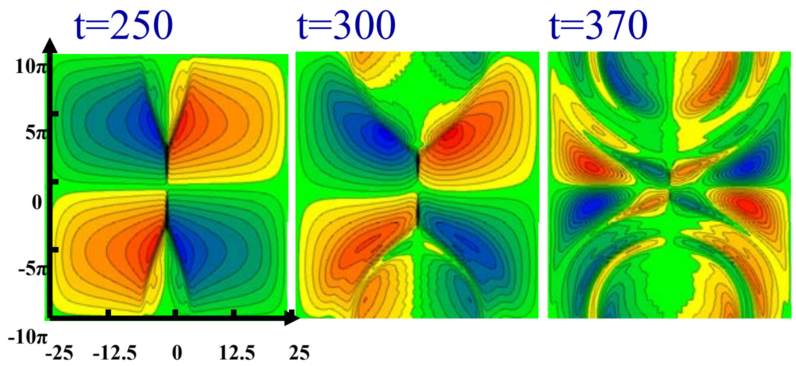


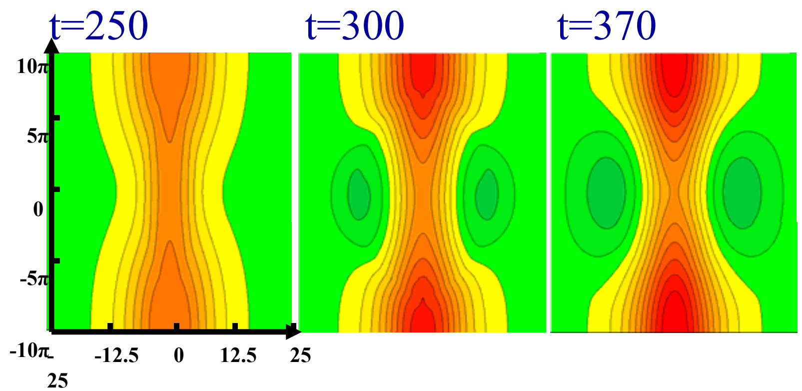
Reduced resistive MHD simulation

$\eta = 5\times10^{-4}; \beta = 0.01; \hat{s} = 0.2; L_x = 50; L_y = 20\pi$





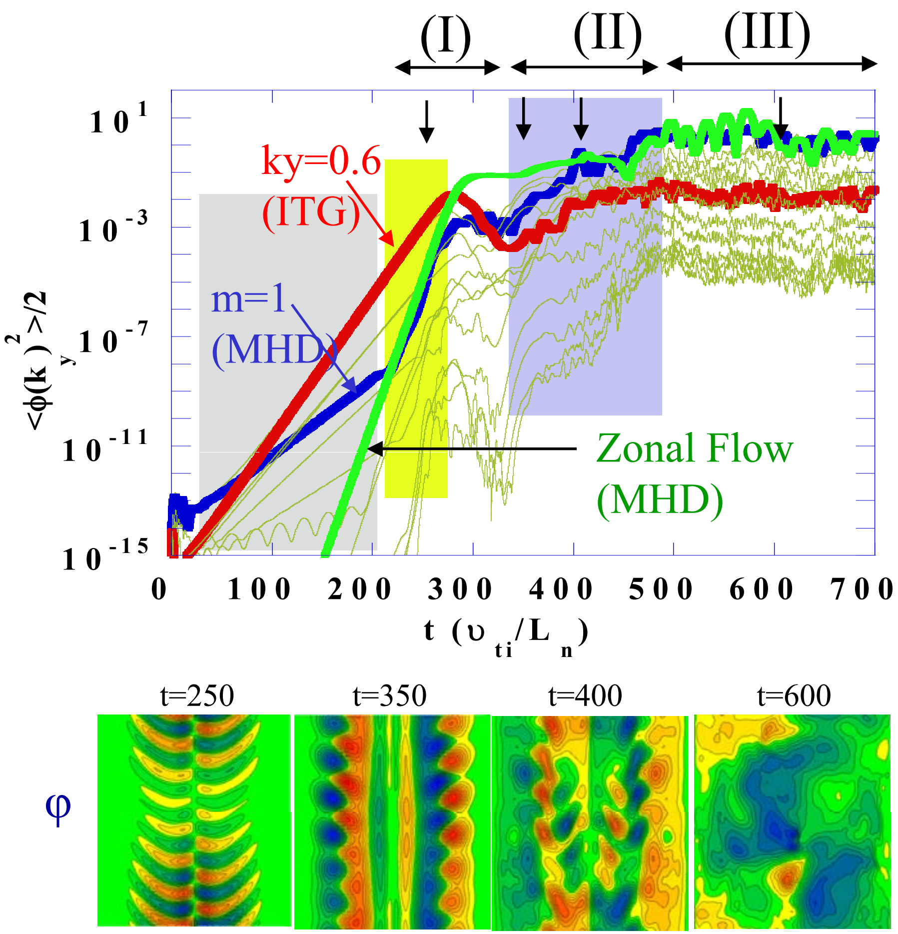


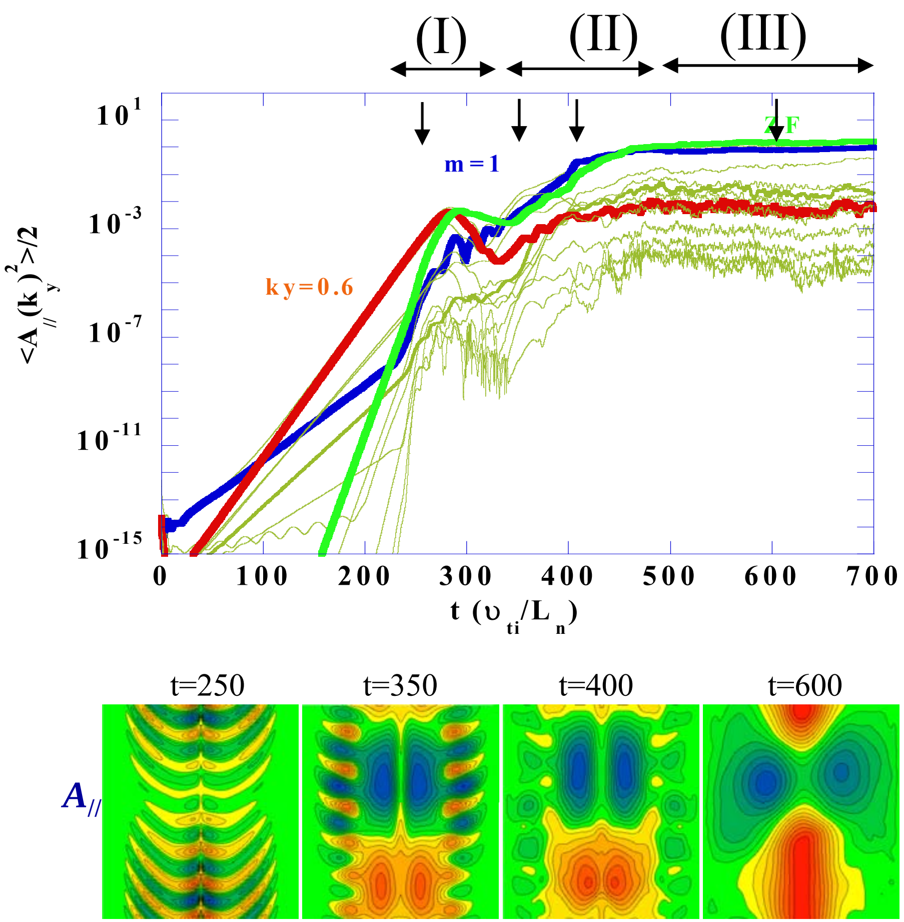


Zonal flow can be generated after magnetic reconnection in some cases, maybe due to state bifurcation [*D Grasso et al PPCF 2006*]. BUT the zonal flow has ALMOST no effect on reconnection.

Evolution of multi-scale turbulence

Case of Strong ITG drive $\eta_i = 3 \quad \eta = 2\times10^{-4} \quad \beta = 0.01, \quad \hat{s} = 0.2$





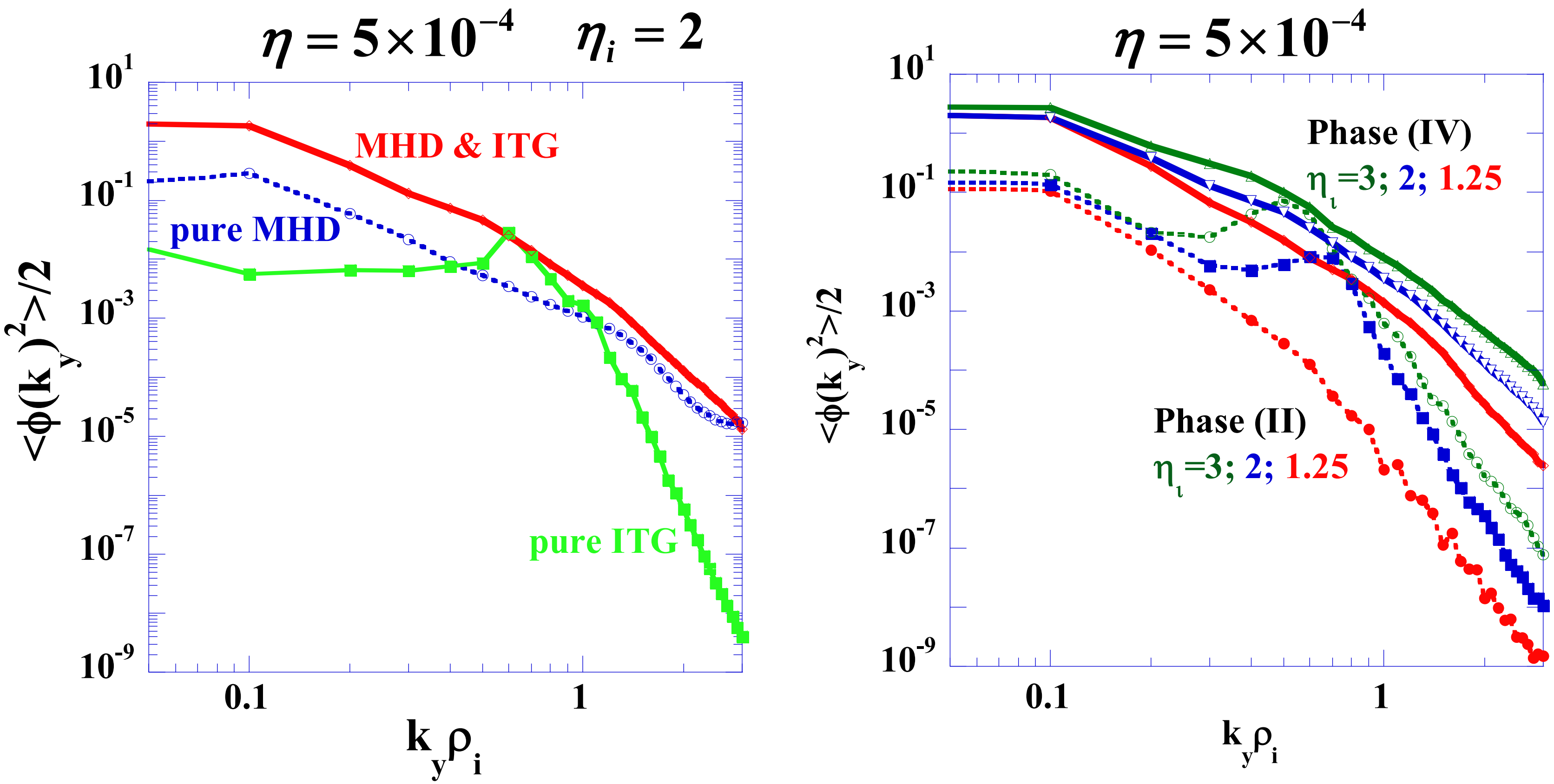
(I) Nonlinear acceleration and saturation of MHD mode due to ITG

(II) Secondary acceleration due to nonlinear interaction

(III) Quasi-steady state dominated by MHD with robust zonal flow

Spectra of multi-scale turbulence

- Spectral dependence on resistivity and ITG

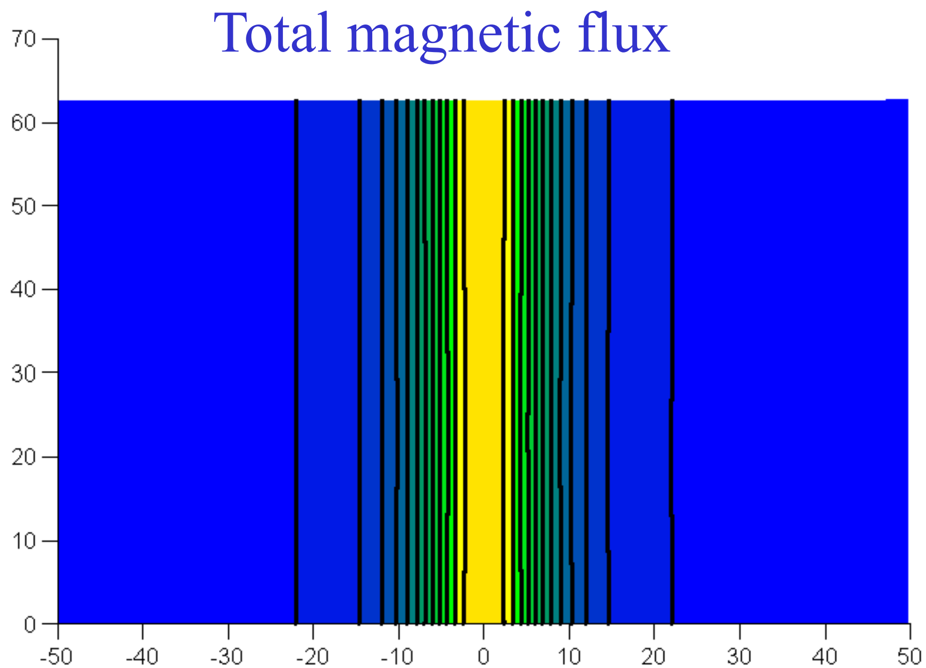


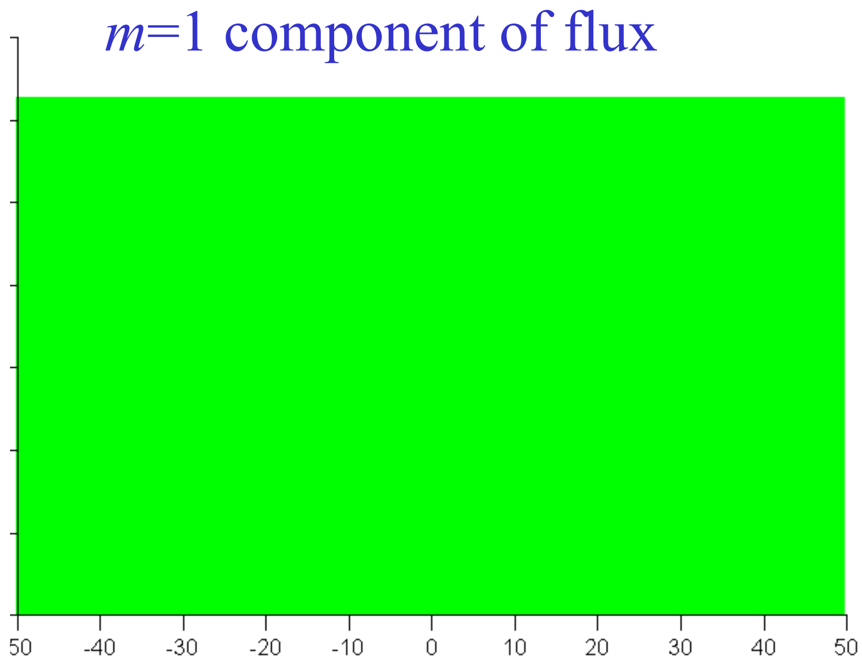
✔ Spectrum of multi-scale MHD & ITG turbulence is characterized by MHD turbulence, the fluctuation level is determined by ITG;

✔ ITG drives kinetic free energy, which is nonlinearly pumped to electromagnetic fluctuation, then results in island dynamics.

Magnetic island dynamics (animations)

$\eta = 5\times10^{-4}\quad \eta_i = 1.;\quad \beta = 0.01;\quad \hat{s} = 0.2;\quad L_x = 100; L_y = 20\pi$

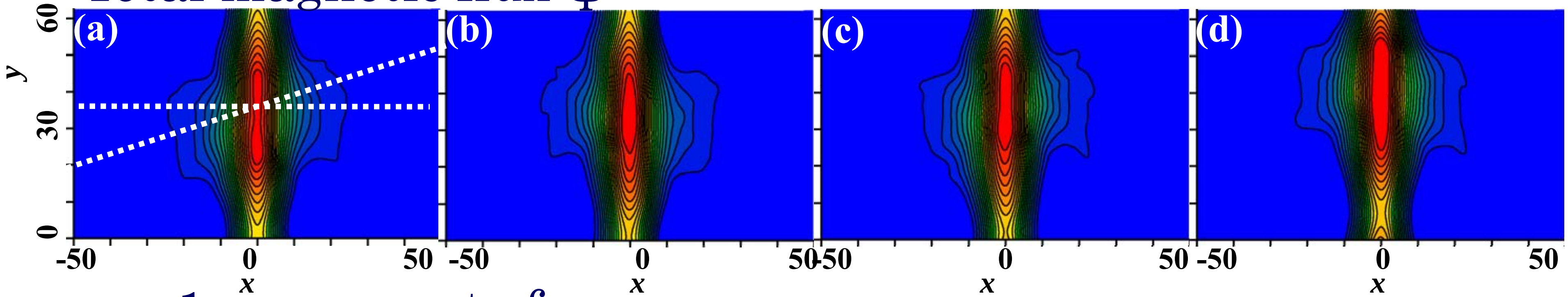




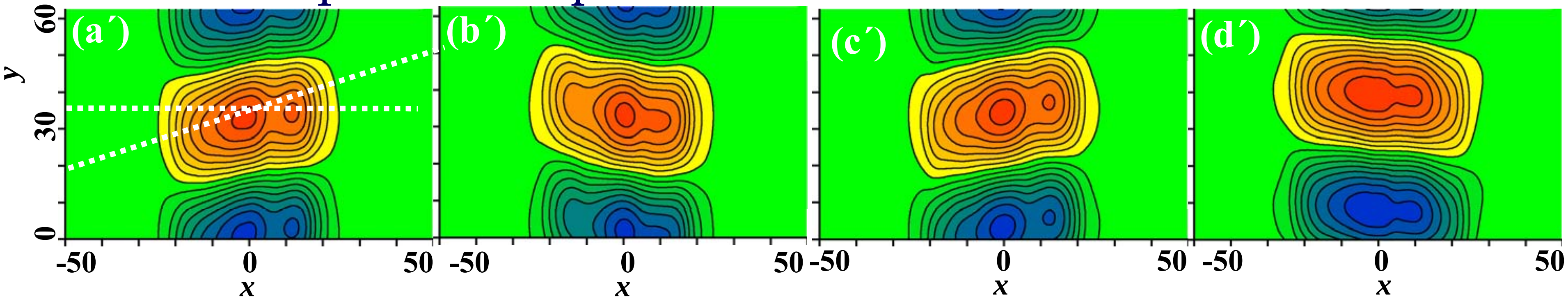
- ✔ A magnetic island seesaw occurs when ITG becomes unstable linearly or nonlinearly
- ✔ ITG stability threshold down-shifted nonlinearly from $\eta_i \approx 1.25$ to $\eta_i \approx 0.65$ due to zonal field.

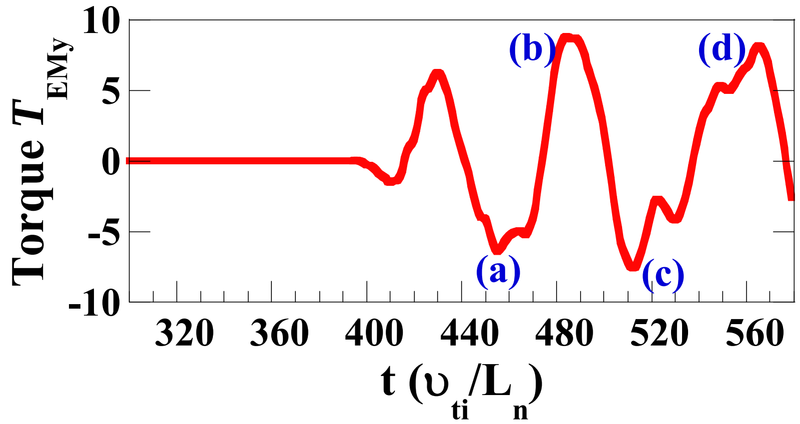
Magnetic island seesaw vs EM torque

Total magnetic flux ψ



m=1 component of ψ



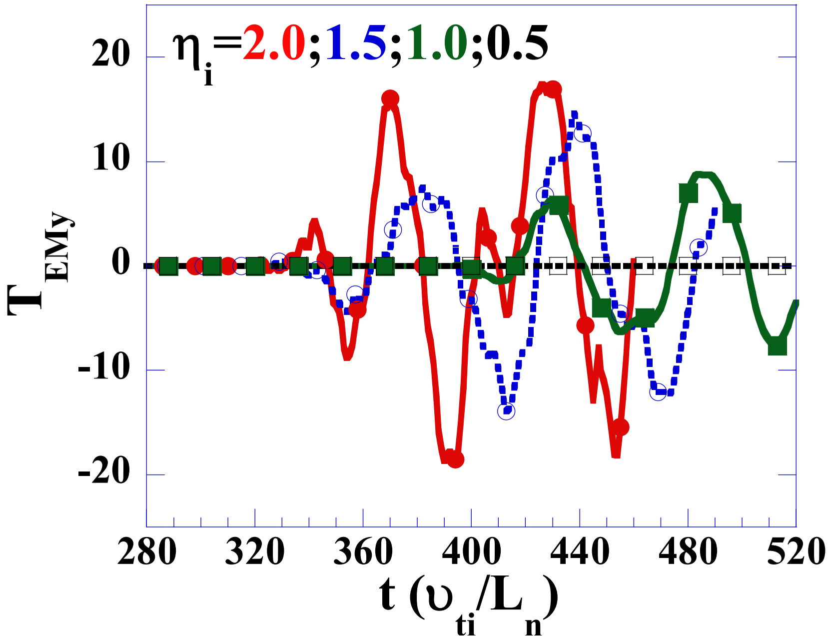


✔ Island seesaw is due to a net oscillating EM torque (same phase)

$$T_{EMy}\hat{e}_z = \iint_{xy} x\hat{e}_x \times (\vec{j}\times\vec{B})_y \, dxdy$$

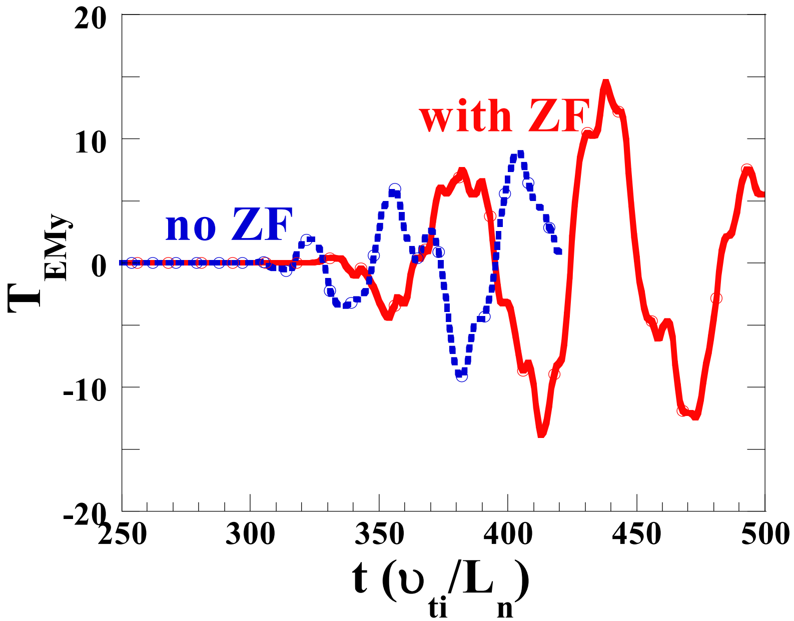
EM torque vs micro-instability

- EM torque increases with ITG instability



✔ Stronger EM torque for larger ITG, and torque is driven earlier

- EM torque is not due to zonal flow, BUT enhanced by ZF



✔ Zonal flow stabilizes micro-turbulence BUT enhances EM torque.

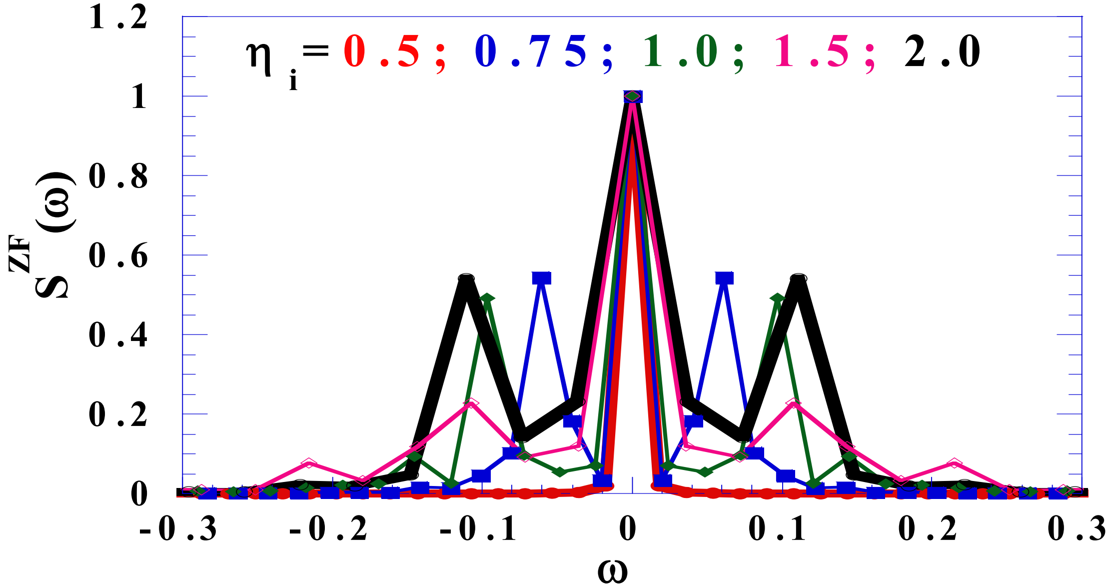
Zonal flow dynamics

- Zonal flow is created through Reynolds & Maxwell stresses

$$\partial_t \nabla_\perp^2 \phi_{ZF} = -[\phi, \nabla_\perp^2 \phi]_{(0,0)} + [A_{//}, \nabla_\perp^2 A_{//}]_{(0,0)} + D_U \nabla_\perp^4 \phi_{ZF}$$

- Zonal flow causally gains a frequency vs nonlinear coupling

Zonal flow spectrum

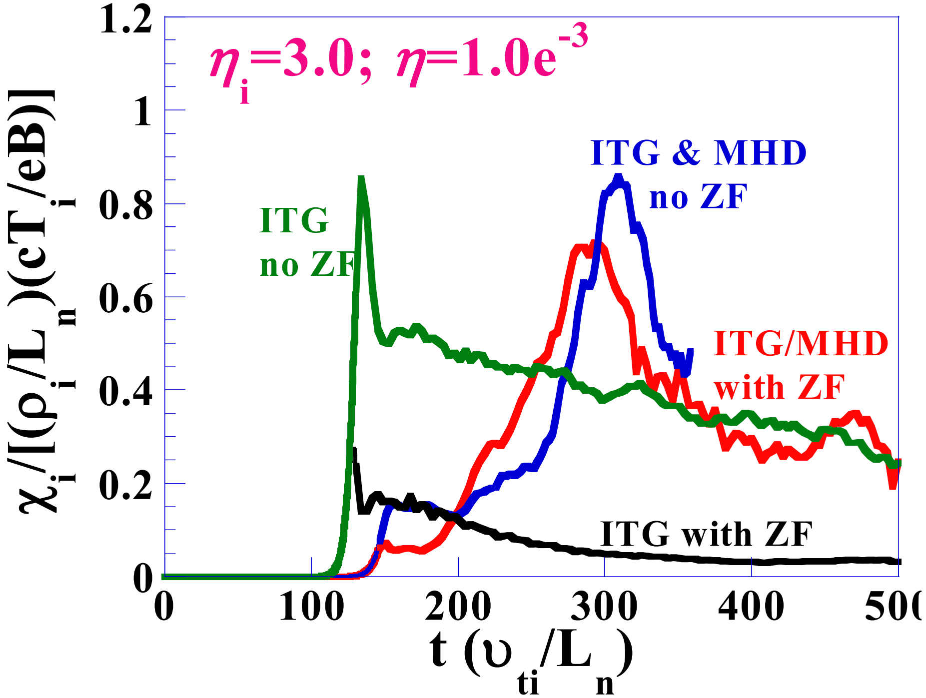


✔ Zonal flow has same frequency as EM torque;
✔ No EM torque and no oscillating zonal flow for stable ITG;
✔ Frequency is around diamagnetic drift frequency of m=1 mode;

Effect on the turbulent heat transport

- Oscillating zonal flow fails to suppress turbulent heat transport

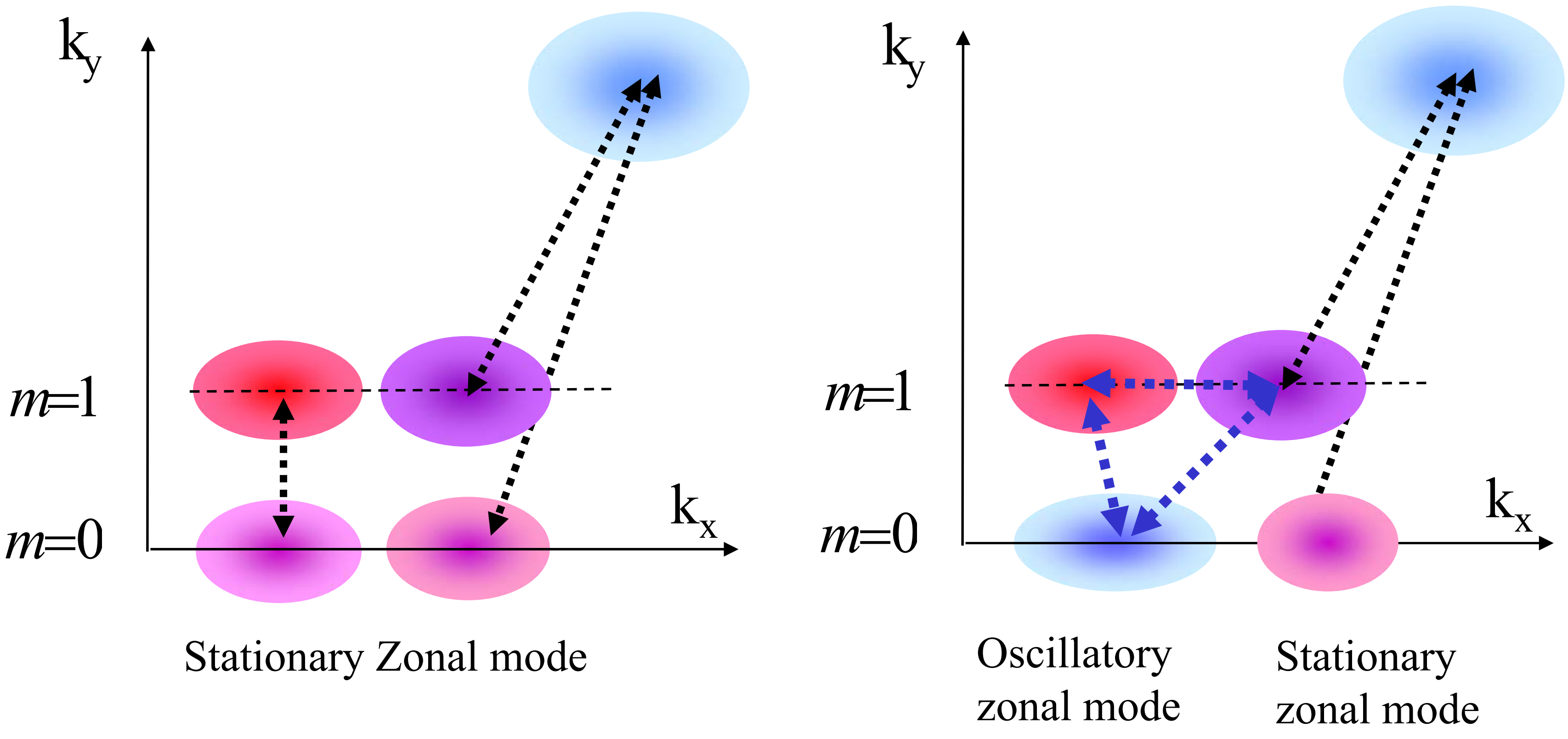
Comparison
with pure ITG or MHD



✔ Zonal flows suppress transport due to finite frequency (like GAM).
✔ Turbulent transport is mainly due to ITG micro-turbulence.

Mode coupling among different scale fluctuations

Mode coupling between different parity modes (m=1 MHD mode and ITG driven nonlinear m=1 mode) through zonal mode ("flow" and "field") and associated transition in the zonal mode dynamics from stationary to oscillatory



Summary

The evolution of mixed-scale resistive MHD and ITG driven micro-turbulence is simulated based on a 5-field gyro-fluid simulation

- We observed energy transfer between micro-scale ITG and MHD mode via mode coupling through zonal mode (flow and field) and subsequent transition dynamics of zonal mode from stationary to oscillatory.

- Specifically, a magnetic island seesaw due to a net oscillatory EM torque, sustained by micro-instability through multi-scale interaction and associated oscillatory zonal flow which reduces the suppression role of turbulent transport.