帯状流及び大規模構造に支配された乱流の特性

Characteristics of Turbulence Dominated by Zonal Flows and Large Scale Structures

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第１０回若手科学者によるプラズマ研究会、
2007年3月15日、原子力機構那珂核融合研究所

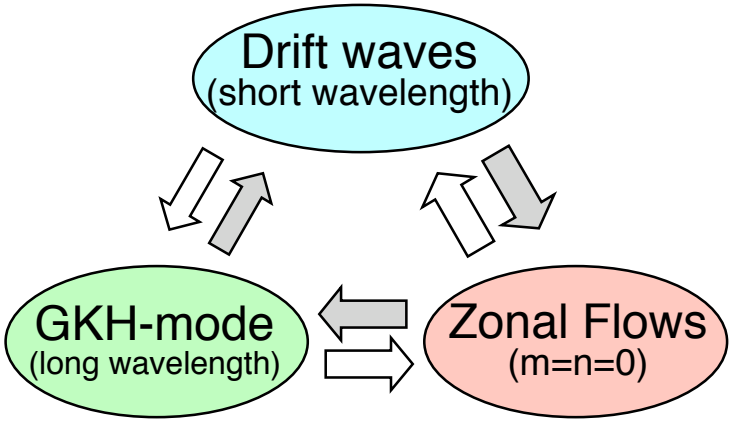
Outline

- Background and Motivation
  - Simulation model and parameters
- Structure of ETG turbulence dominated by Z.F.
  - Statistical mechanism of heat flux reduction
  - Interaction with GKH mode
- Statistical characteristics of fluctuations
  - Correlation dimension and PDF
  - ITG fluctuations
- Summary

Background and Motivation

Plasmas autonomously construct turbulent structures such as zonal flows, which play an important role for regulating the turbulent transport.

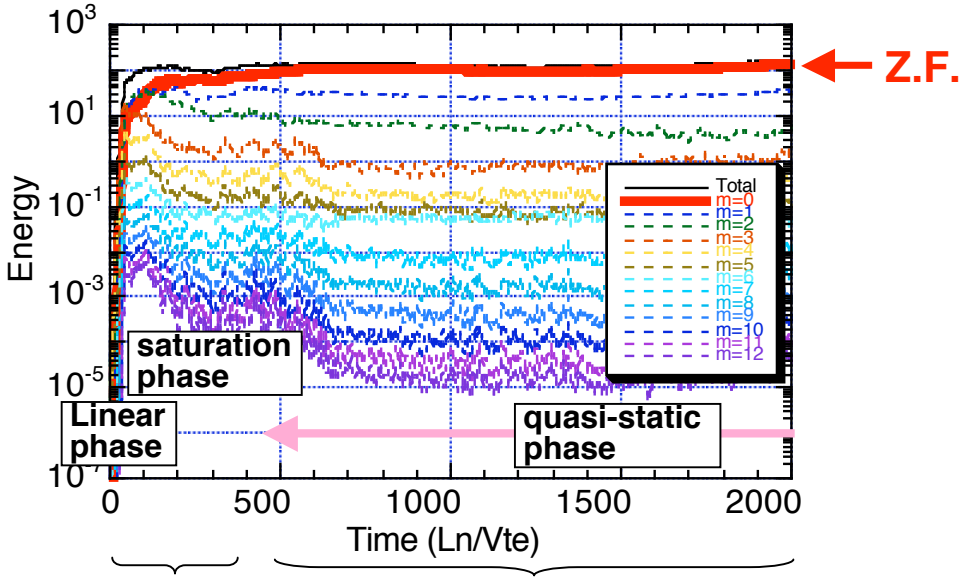
Mode interactions in turbulence



[ex. P.H.Diamond, PPCF, '05]

Nonlinear interactions are not well understood.

Energy history in ZF-dominated plasma



First principle simulations
[ex. N. Miyato, IAEA, '06]

❶ Transport ?
Turbulent structure ?
Mode interactions ?

❷ Statistical characteristics of fluctuations ?
Intermittency, Complexity, Unpredictability

Parameter dependence of heat conductivity

❶ Transport ? Turbulent structure ? Mode interactions ?

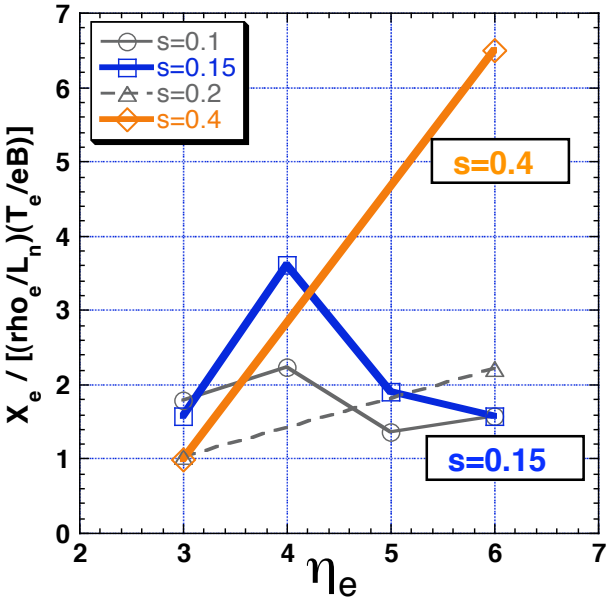
Temperature gradient

$$\eta_e = \frac{d \ln T_e}{d \ln n}$$

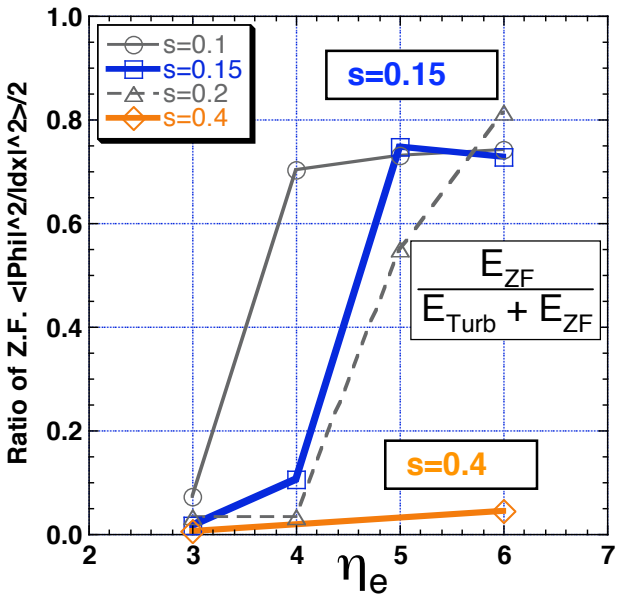
Magnetic shear

$$s = \frac{B_y}{B_0} \frac{d \ln B_y}{d \ln n}$$

Heat conductivity

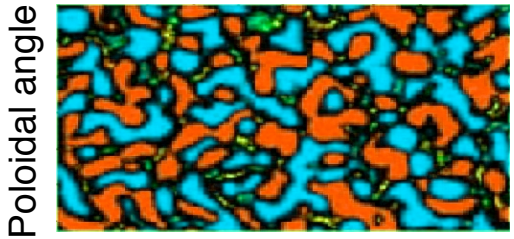


Z.F. Energy ratio

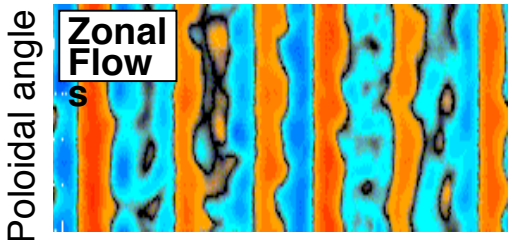


Electrostatic potential contours (for low magnetic shear)

isotropic turbulence



non-isotropic coherent structure



Low ⟵ η_e ⟶ High

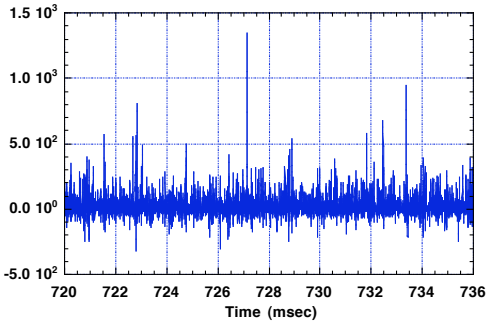
Long-time Behaviors of Fluctuations

❷ Statistical characteristics of fluctuations ?
Intermittency, Complexity, Unpredictability

Experimental Plasmas

[HIBP Measurement by Ido, et al.]

Particle Flux in JFT-2M



First Principle Simulation (GK, Vlasov)

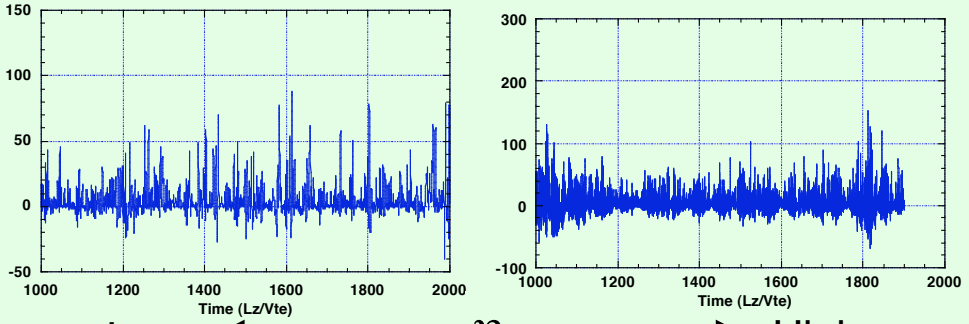
More precise results will be obtained, however huge computational resource is necessary.

Interrelation

Fluid Simulations (GF, GLF)

Long-time fluctuations are obtained at realizable computational resource.

Heat Flux in ETG Simulations



Low ← η_e → High

Transport Simulation

Transport are evaluated for averaged fluctuations.

Simulation model and parameters

The dynamics of electrostatic ETG turbulence in the sheared slab configuration of the magnetic field can be generally described by following normalized system of nonlinear gyrofluid equations.

- **Nonlinear gyrofluid equations** [ex. J.Li, et al., POP, '02]

$$\left(1-\hat{\nabla}_\perp^2\right)\frac{\partial\hat{\phi}}{\partial\hat{t}} = \left[1+\left(1+\eta_e\hat{\nabla}_\perp^2\right)\frac{\partial\hat{\phi}}{\partial\hat{y}}\right] + \left[\hat{\phi},\hat{\nabla}_\perp^2\hat{\phi}\right] + \hat{\nabla}_\parallel\hat{v}_\parallel - \mu_\perp\hat{\nabla}_\perp^4\hat{\phi}$$

$$\frac{\partial\hat{v}_\parallel}{\partial\hat{t}} = \hat{\nabla}_\parallel\hat{\phi} - \hat{\nabla}_\parallel\hat{p} + \left[\hat{\phi},\hat{v}_\parallel\right] + \eta_\perp\hat{\nabla}_\perp^2\hat{v}_\parallel$$

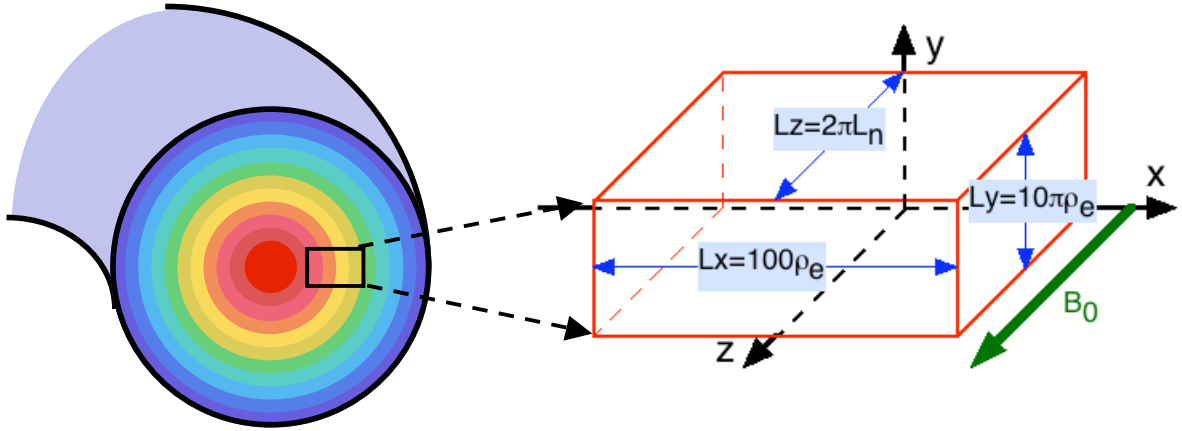
$$\frac{\partial\hat{p}}{\partial\hat{t}} = -\left(1+\eta_e\right)\frac{\partial\hat{\phi}}{\partial\hat{y}} - \left[\hat{\phi},\hat{p}\right] + \Gamma\hat{\nabla}_\parallel\hat{v}_\parallel - \left(\Gamma-1\right)\sqrt{\frac{8}{\pi}}\hat{k}_\parallel\left(\hat{p}+\hat{\phi}\right) + \chi_\perp\hat{\nabla}_\perp^2\hat{p}$$

- **Normalization**

$$\left(\hat{x},\hat{y},\hat{z},\hat{t}\right) \leftarrow \left(\frac{x}{\rho_e},\frac{y}{\rho_e},\frac{z}{L_n},\frac{t}{L_n/v_{te}}\right)$$

$$\left(\hat{\phi},\hat{v}_\parallel,\hat{p}\right) \leftarrow \frac{L_n}{\rho_e}\left(\frac{e\tilde{\phi}}{T_e},\frac{v_\parallel}{v_{te}},\frac{\tilde{p}_e}{p_0}\right)$$

- **Configuration**

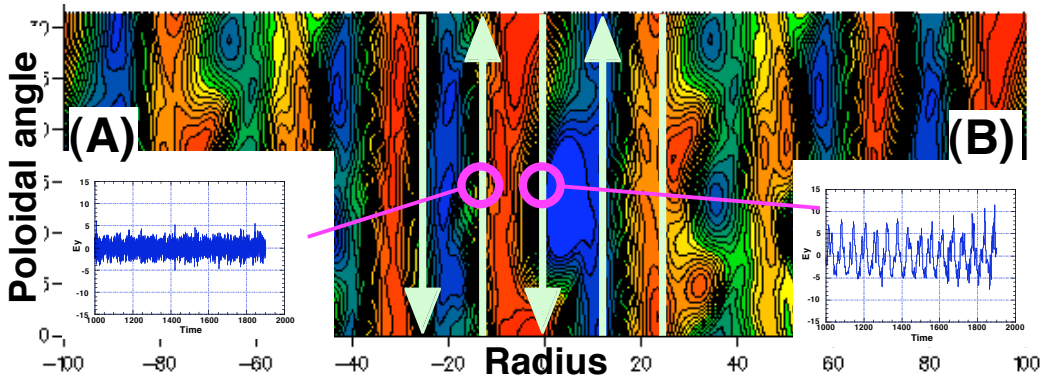


- **Parameter regime**

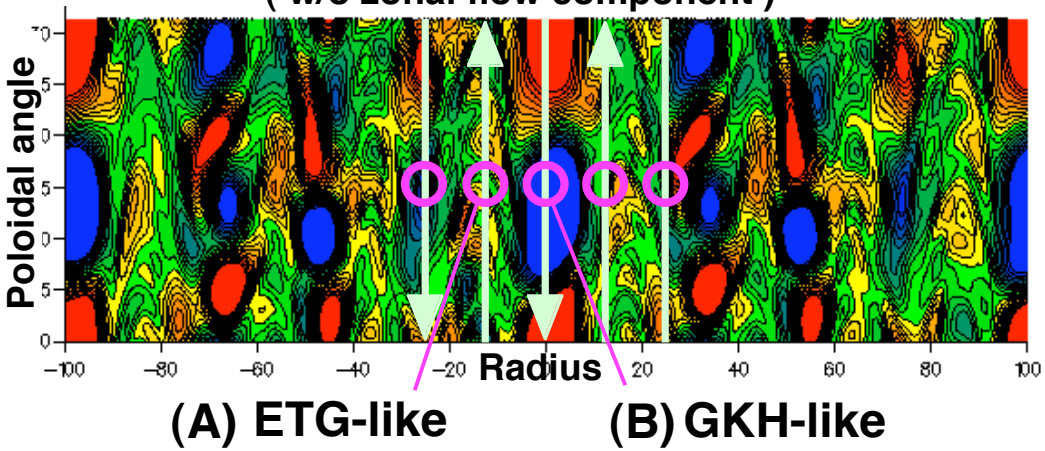
Temperature gradient :
$\eta_e = 3 - 6$
Magnetic shear :
$s = 0.1 - 0.4$
Zonal flow :
on / off

Structure of ETG turbulence dominated by ZF

❶ Electrostatic Potential ($s = 0.1$, $\eta_e = 6$)



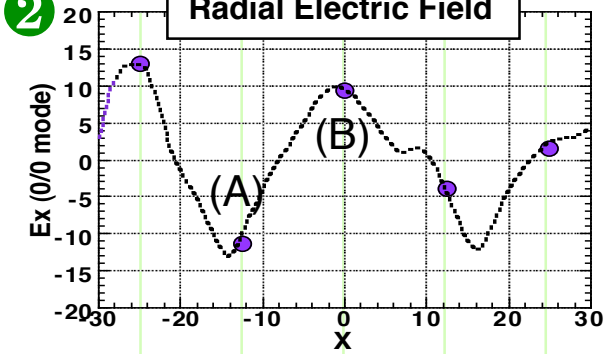
(w/o zonal flow component)



(A) ETG-like (B) GKH-like

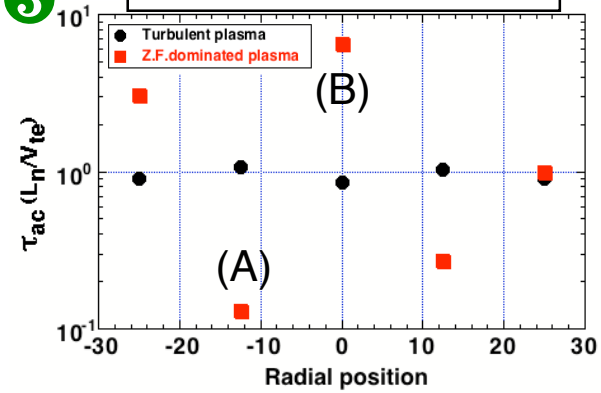
❺ Behind static zonal flows, there are fluctuations with radial dependent scales of time and space.

❷ Radial Electric Field



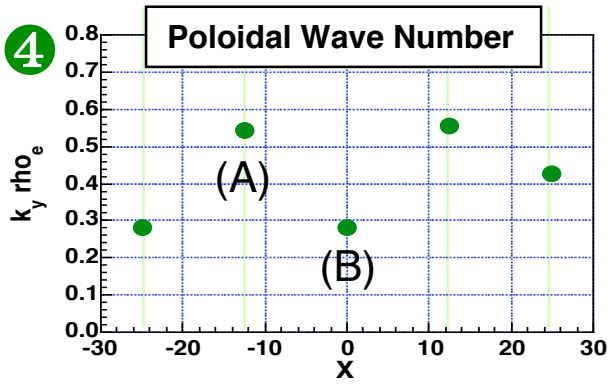
Flow pattern is almost static.

❸ Autocorrelation Time



Characteristic time is varied by Doppler shift.

❹ Poloidal Wave Number

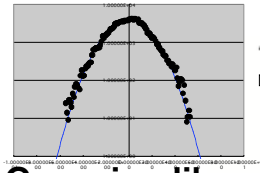


$$\frac{\int |\phi(k_y)|^2 k_y dk_y}{\int |\phi(k_y)|^2 dk_y}$$

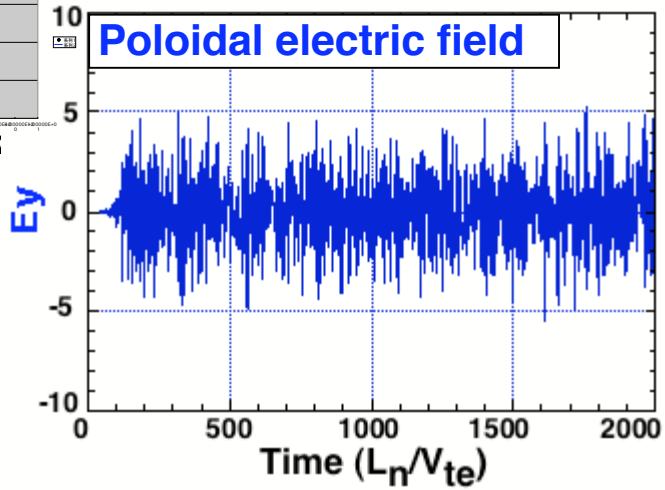
Characteristic wave number is also varied.

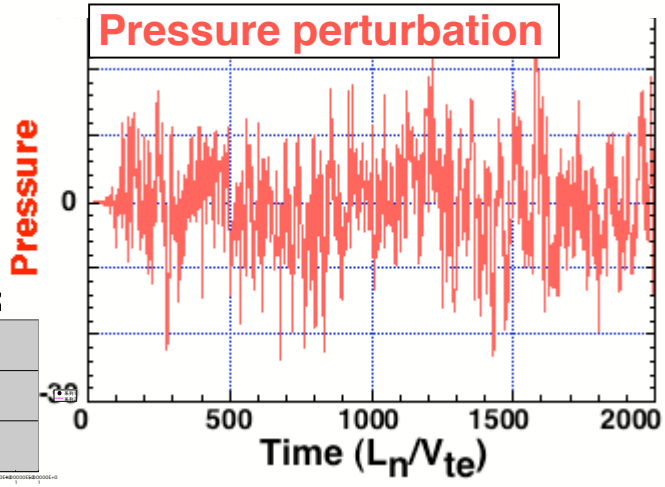
Probability density function of heat flux

Time series data (s=0.1, η_e=3)

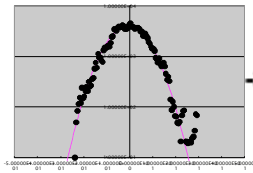


Gaussian-lik

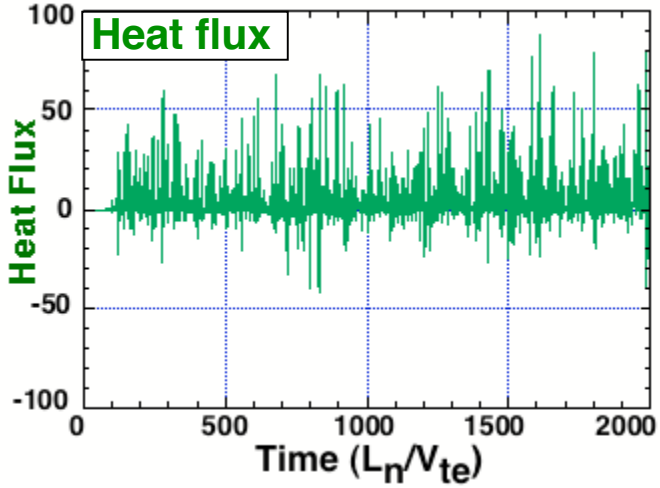




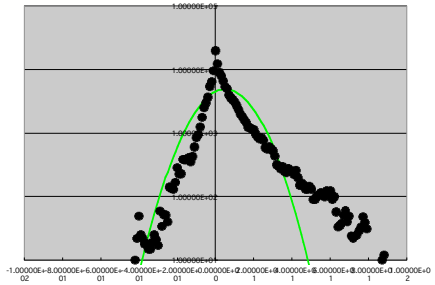
Gaussian-lik



As a result of coupling two Gaussian-like perturbations, prominent intermittency is obtained.



As a index of such intermittency, tail component appears in PDF.



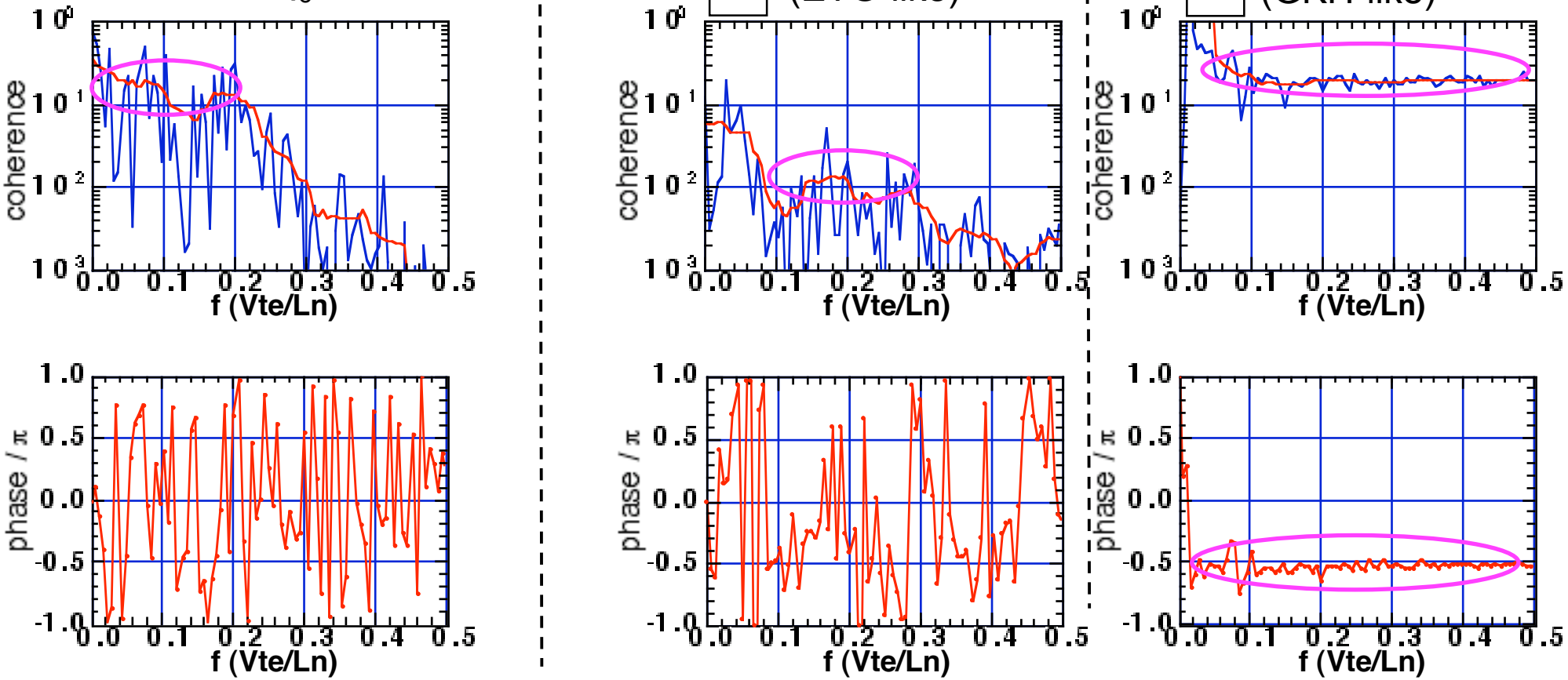
Cross correlation between Ey and P determines heat flux intermittency.

Elemental processes of heat flux reduction

Coherence and phase difference of *Ey* and *P*

Isotropic ETG turbulence
(s = 0.1 , η_e = 3)

Zonal flow-dominated ETG turbulence
(s = 0.1 , η_e = 6)

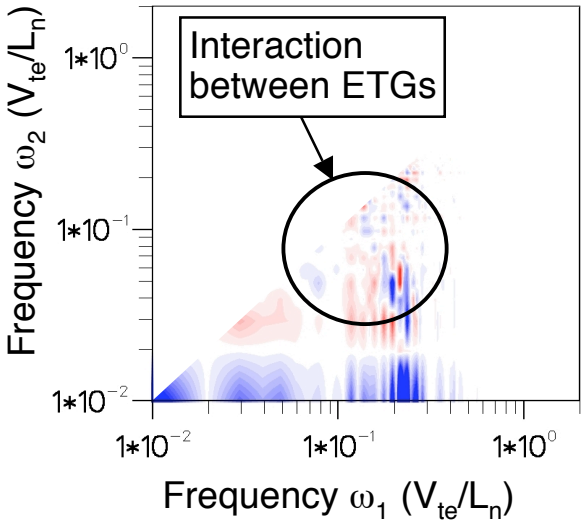


[A] Microscopic ETG-like turbulence → Decreasing of coherence
[B] GKH-like turbulence → Synchronization of phase

Mode interactions in ZF-dominated plasma

Bi-spectrum Analysis of Ey ($\omega_1 \pm \omega_2 = \pm\omega_3$)

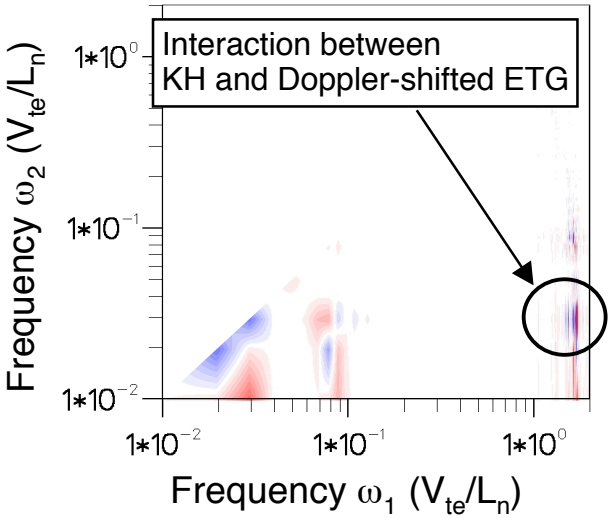
Isotropic ETG turbulence
(s = 0.1 , η_e = 3)



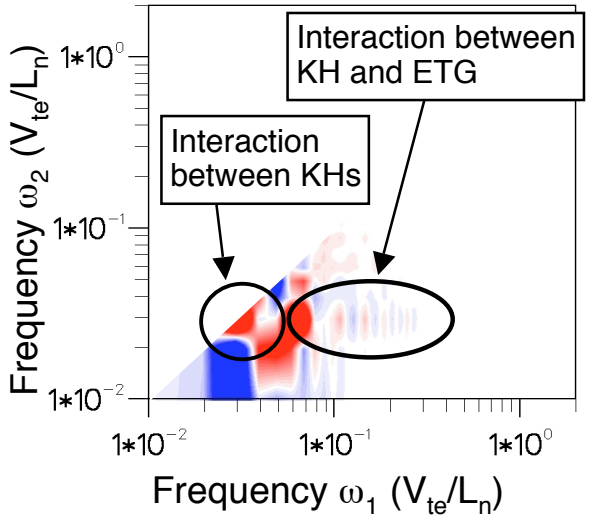
Drift waves
(short wavelength)
$\mathbf{k}_1 \Leftrightarrow \mathbf{k}_2$

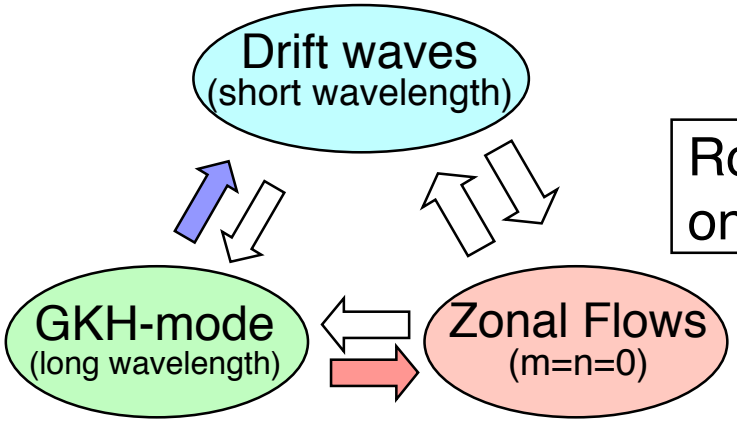
Zonal flow-dominated ETG turbulence
(s = 0.1 , η_e = 6)

A (ETG-like)



B (GKH-like)





Role of GKH depends on radial position.

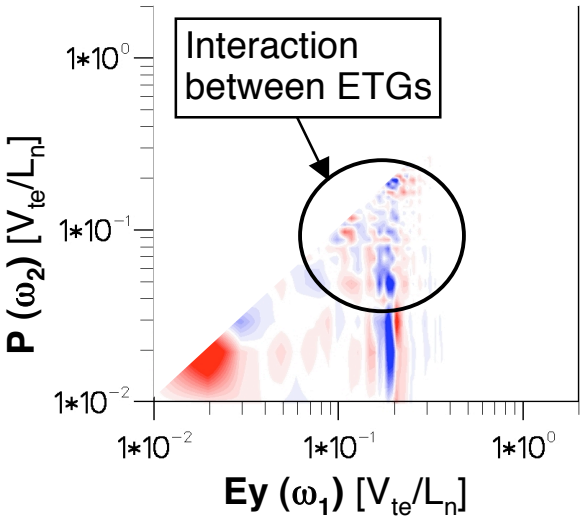
Mode interactions in ZF-dominated plasma (cont.)

Cross-Bi-spectrum Analysis of Ey(ω_1), P(ω_2), and Q(ω_3)

($\omega_1 \pm \omega_2 = \pm\omega_3$)

Isotropic ETG turbulence

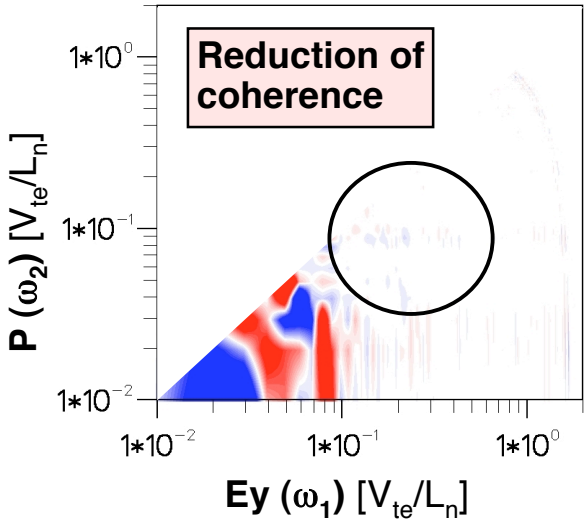
(s = 0.1 , η_e = 3)



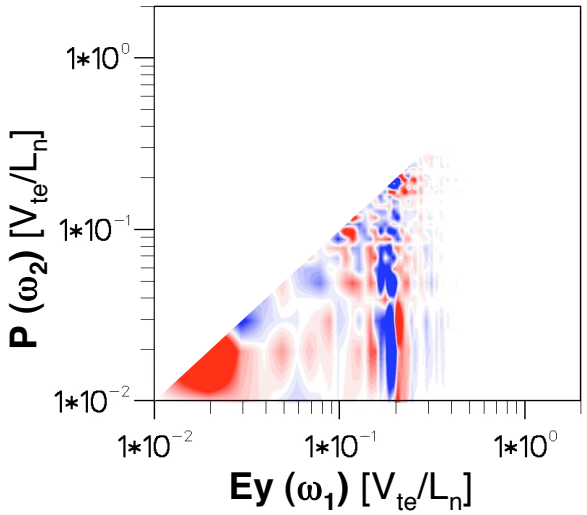
Zonal flow-dominated ETG turbulence

(s = 0.1 , η_e = 6)

A (ETG-like)

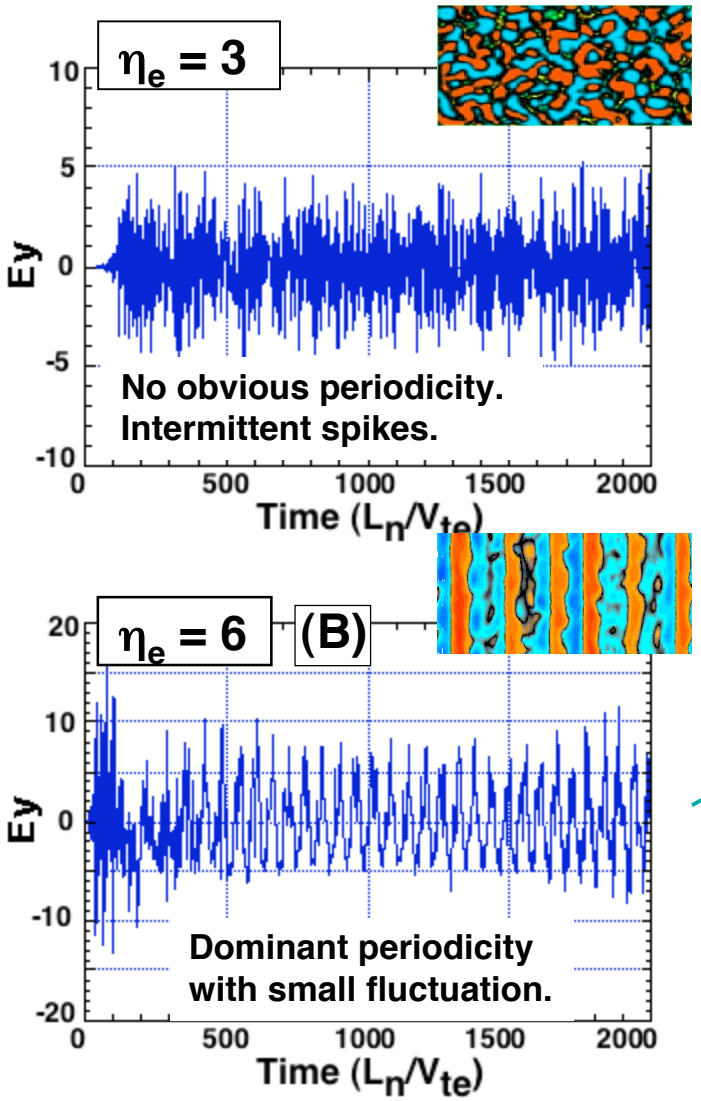


B (GKH-like)

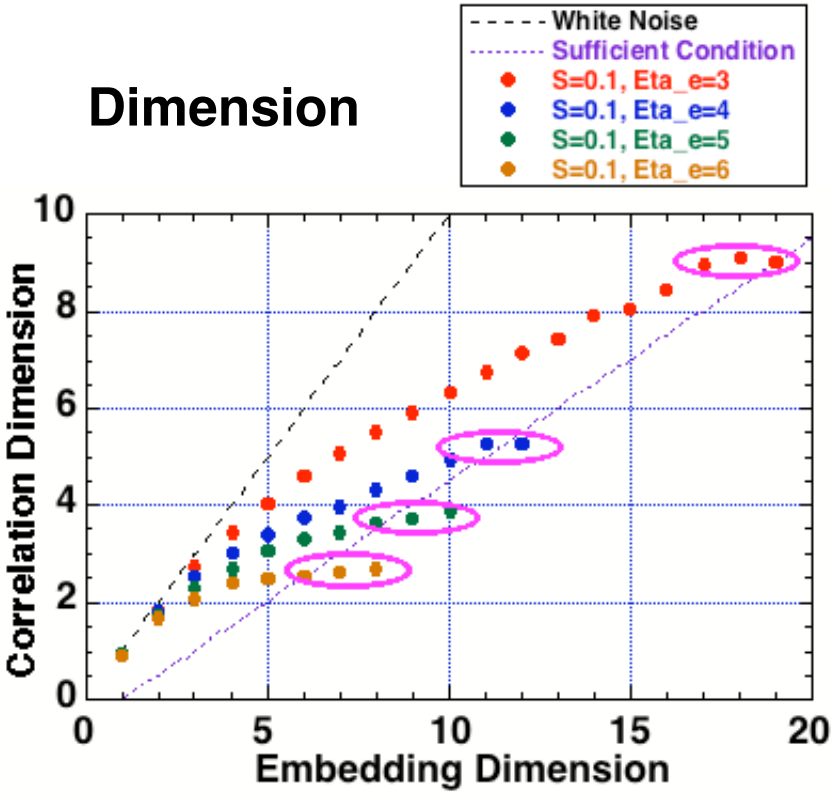


Correlation dimension

Time series data (s=0.1)



Dimension

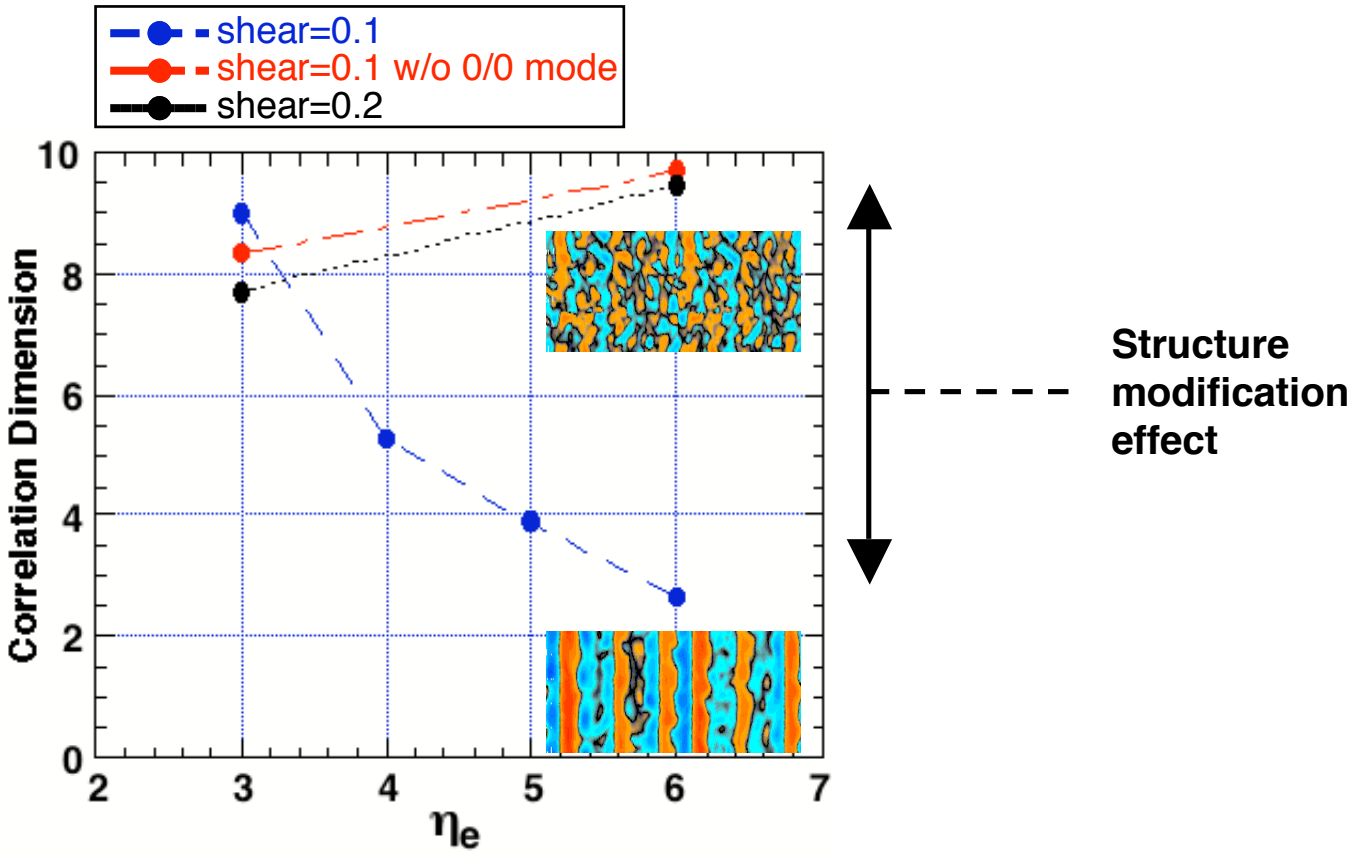


High dimensionality is observed in turbulent plasma.

Significant reduction of dimension is observed in ZF dominated plasma.

Correlation dimension via η_e

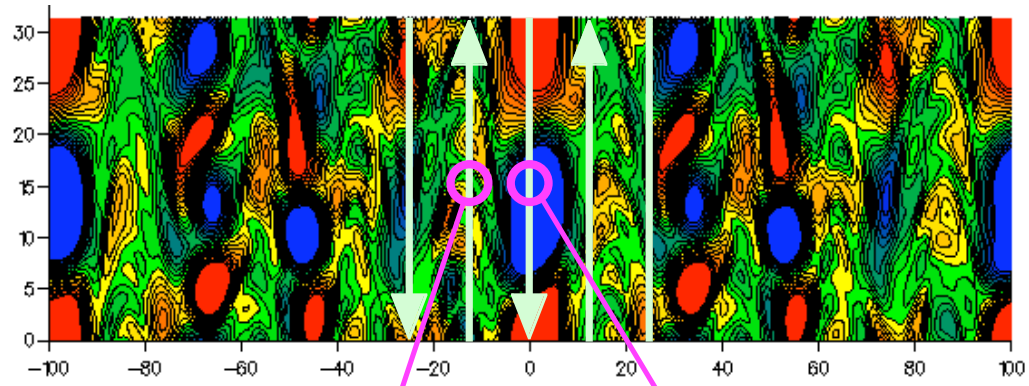
Change of turbulent structure significantly reduces dimensionality.



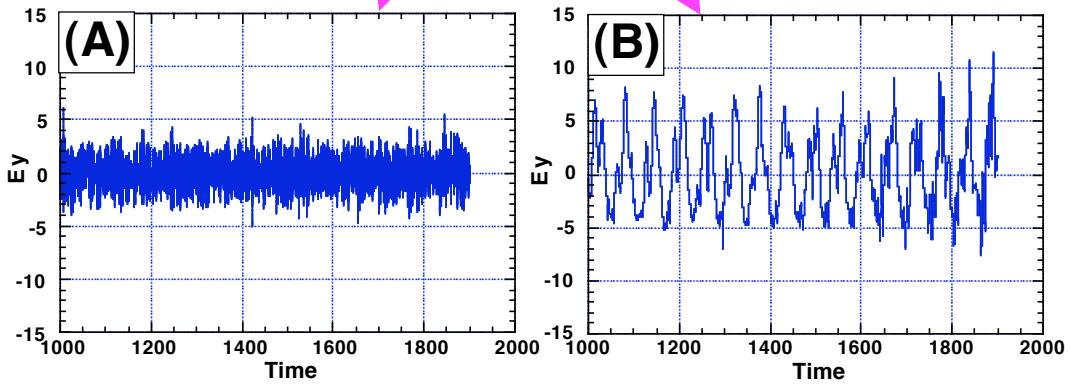
Change of correlation dimension corresponds with the change of structure.

Radial dependency of dimension

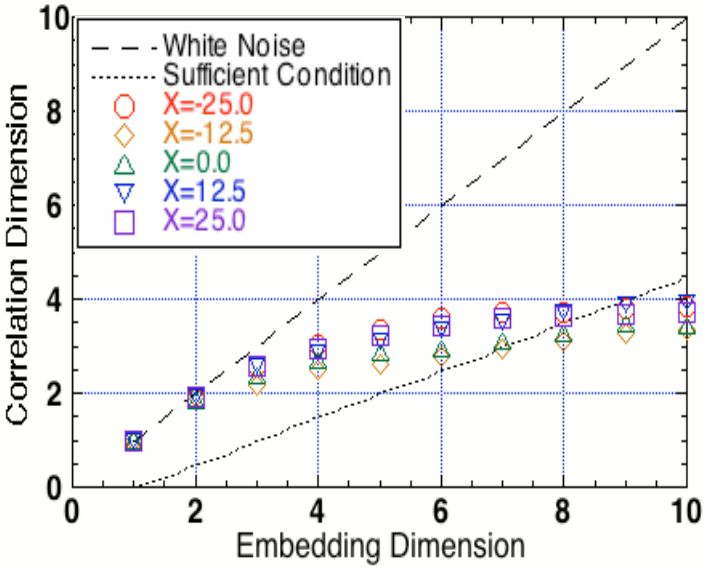
Electrostatic Potential ($s = 0.1$, $\eta_e = 6$)
(w/o zonal flow component)



Poloidal Electric Field



Dimension



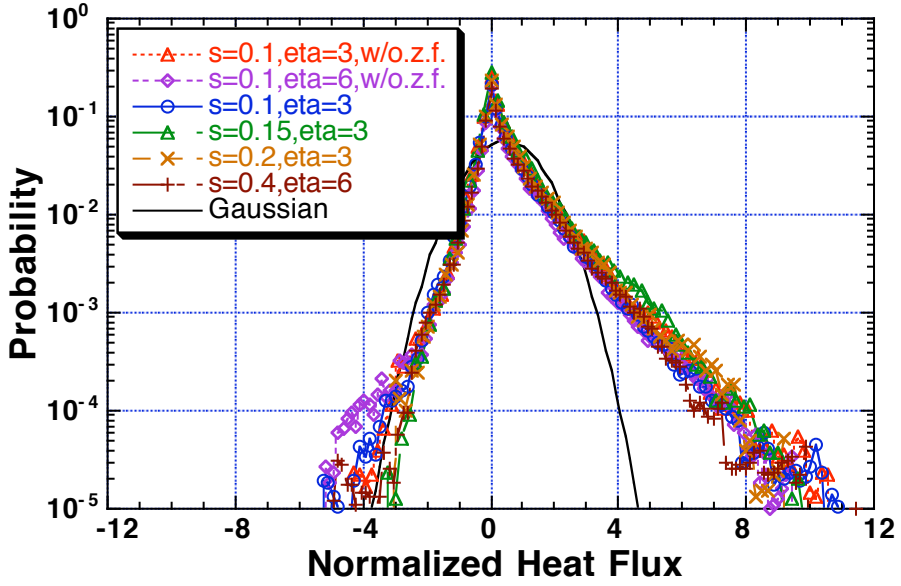
Two regions with different temporal and spatial scales exhibit almost similar correlation dimension.

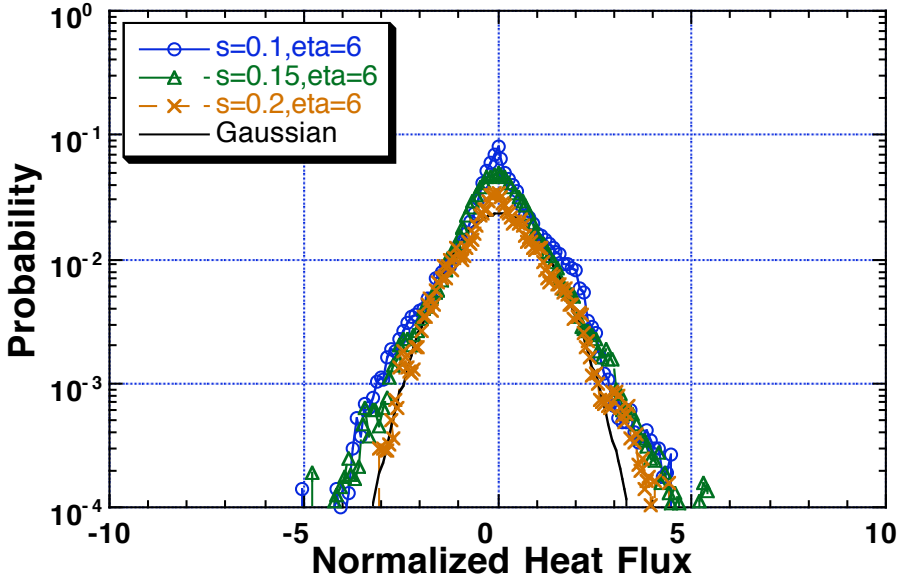
Similitude of PDF in Turbulence

Turbulent plasma

$\eta_e = 3 - 6$
$s = 0.1 - 0.4$

Z.F. dominated plasma



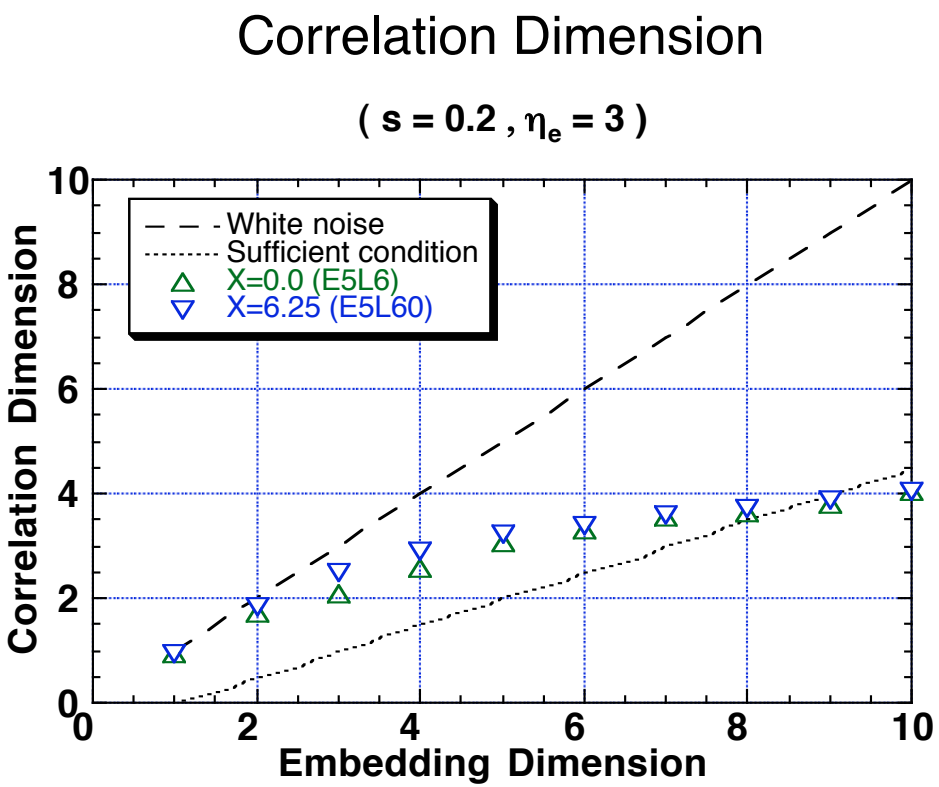


Similitude of heat flux PDF in ETG driven turbulent plasma

Symmetry of PDF is recovered in Z.F. dominated plasma.

ETG turbulence has a specific intermittency insensitive to magnetic shear and temperature gradient, as long as zonal flow level is low.

Z.F.dominated plasma driven by ITG



- Correlation dimension saturates around 3.5-4.0, similar to zonal flow dominated ITG plasma.
- Constraint of dimensionality is also observed in ITG plasma.

Summary

- It is found that the spatiotemporal characteristic scale of fluctuations behind zonal flows significantly varies, depending on the direction of flow.
- By the cross correlation analysis, it is found that the heat flux reduction in ZF-dominated plasma results from two mechanisms : the coherence reduction and the phase synchronization between Ey and p.
- By the bi-spectrum analysis of turbulent fluctuations, the mode interactions in quasi-static turbulence are clarified.

- High dimensionality (8 - 10) and prominent exponential PDF tails are observed in ETG turbulent plasma, which manifest an intermittent transport dynamics with large heat flux.
- The PDF tails are found to have a prominent similarity insensitive to the plasma parameters such as temperature gradient and magnetic shear unless zonal flows are excited. ⟹ Prediction of frequency and size of intermittent bursts.
- In plasmas dominated by zonal flows and tertiary waves, a significant reduction of dimensionality (3 - 4) is observed accompanied by disappearance of the exponential tails of PDF. ⟹ Evaluation of zonal flows dominancy.