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Analysis of feedback loop dynamics in turbulence spreading

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Introduction

- Here we introduce the effect of ZF/GAM feedback system to the turbulent spreading problem.
  - Turbulent spreading
    - Edge(unstable)-core(stable) coupling phenomena[Lin, Hahm]
      - One of the typical meso-scale phenomena
    - Insufficient analysis in terms of zonal flows
  - What is SPREADER?
    - Turbulence mode coupling[Garbet '94 NF]
      - Simulation [Lin and Hahm] and theory [Gurcan]
    - GAM propagation['06 K. Itoh PPCF],['08 Miki PoP],[L. Chen, submitted to EPL]
      - Polarization effect, Kinetic effect, effect of a coupling to turbulence
      - Eigen mode of ZF
        - Zero-frequency(0F) + High-frequency(HF)(=GAM)
      - 0FZF does not propagate, while GAM can propagate.
      - **Main issue**: **Can the GAM enhance turbulent spreading?**

Gyrokinetic PIC simulation(GTC)

- delta-f method global particle-in-cell gyrokinetic simulations(GTC) are used in this research
  - The variation of thermal velocity v_{Ti} by temperature profile is provided in the new code.
    - ➔Capable to reproduce the GAM propagation
- Basic parameters used as cyclone-base ones are employed.
  - a/R=0.358, a/ρ_i=125
  - $\kappa_{Ti}(=R/L_T)=6.9$
  - Electrostatic, collisionless

Time evolution of zonal flows and turbulence intensity

$$q(r) = q_0 + 1.092 * q + 1.092 * q^2$$

Propagation of GAM

Eigen-mode structure of the GAM spectrum is observed.

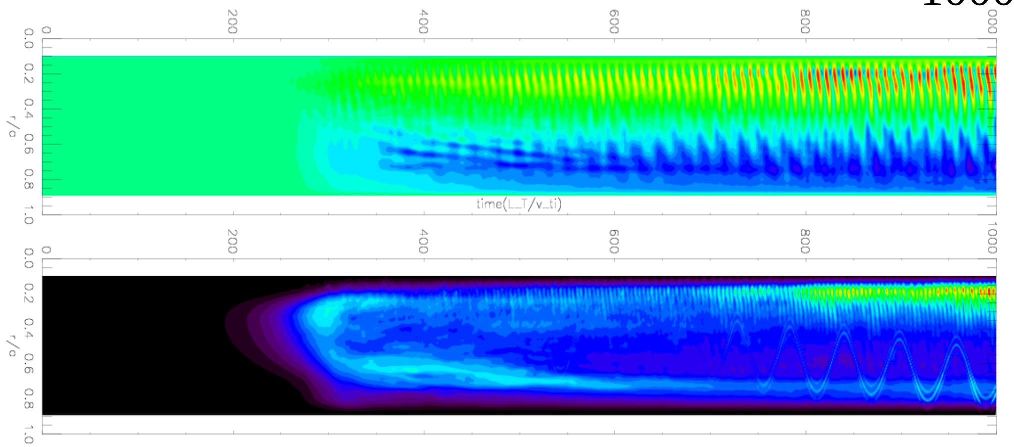
(a) q_0=0.581 (R/L_T=6.9)

Time (L_T/c_s) 1000

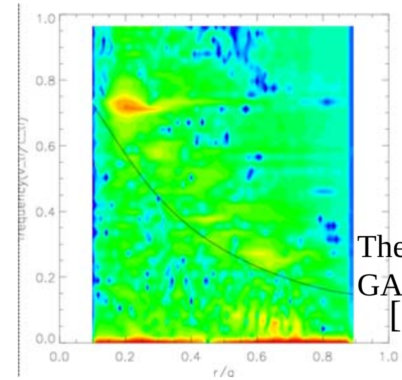
r/a

$\phi_{0/0}$

$|\tilde{\phi}|^2$



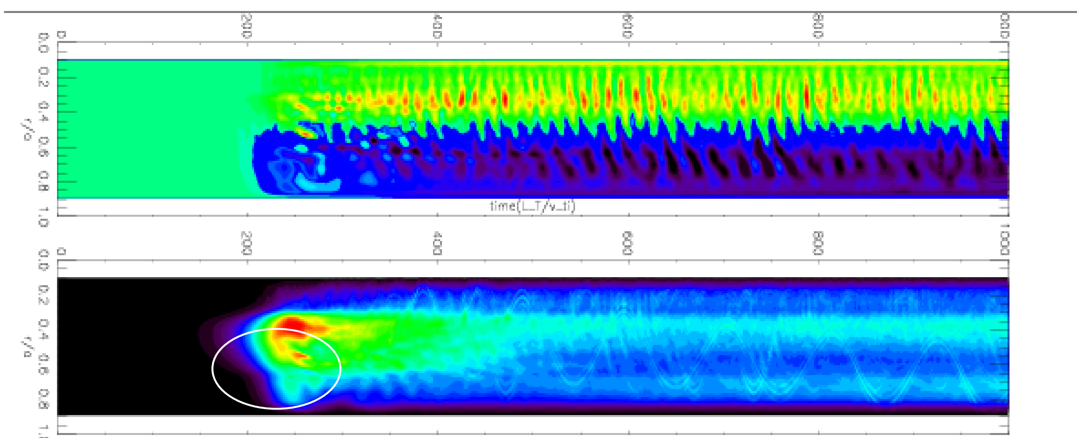
Spectrum of $\phi_{0/0}$

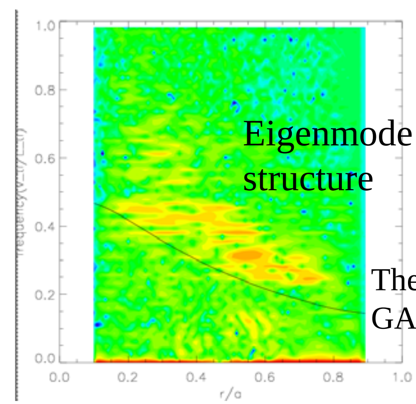


(b) q_0=1.581 (R/L_T=6.9)

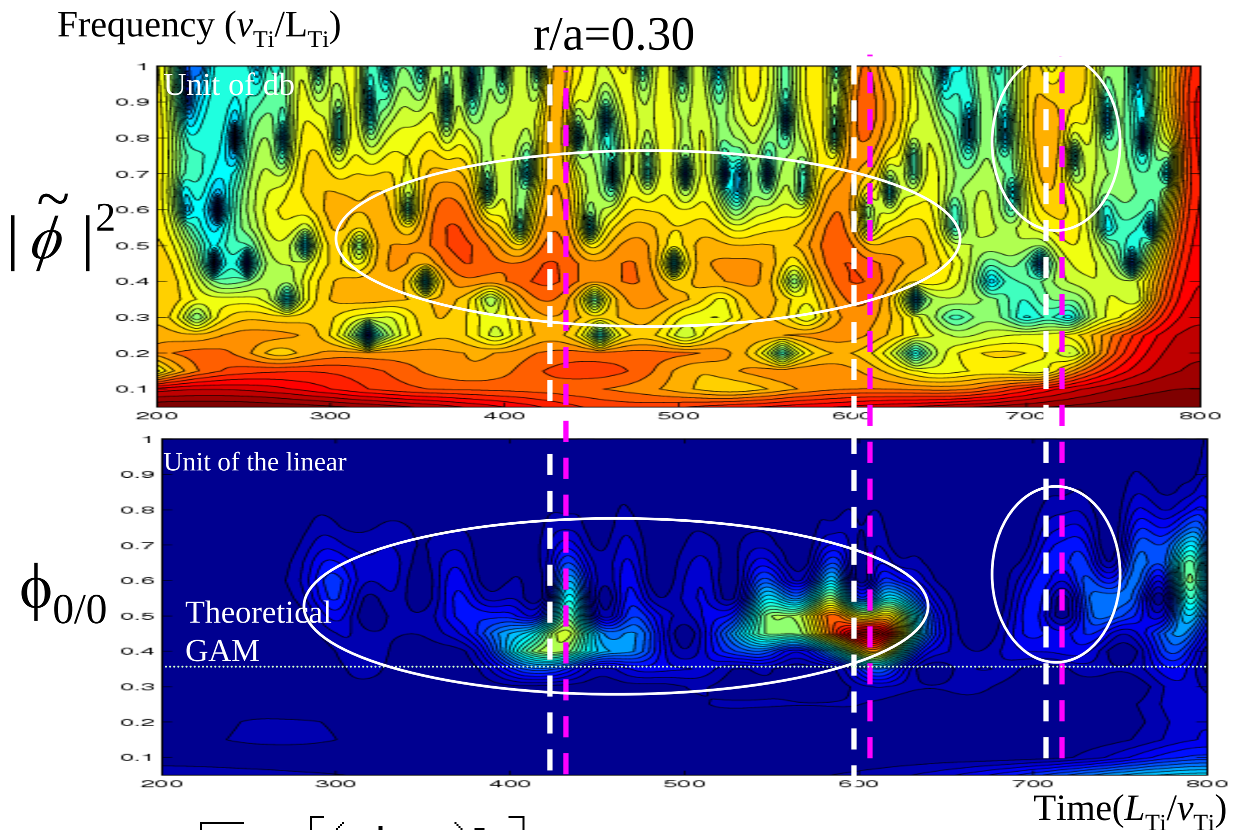
$\phi_{0/0}$

$|\tilde{\phi}|^2$





Wavelet analysis of turb. and ZFs



$$W_n(s) = \sum_{n'=0}^{N-1} x_{n'} \sqrt{\frac{\delta t}{s}} \Psi_0^* \left[\frac{(n'-n)\delta t}{s} \right]$$

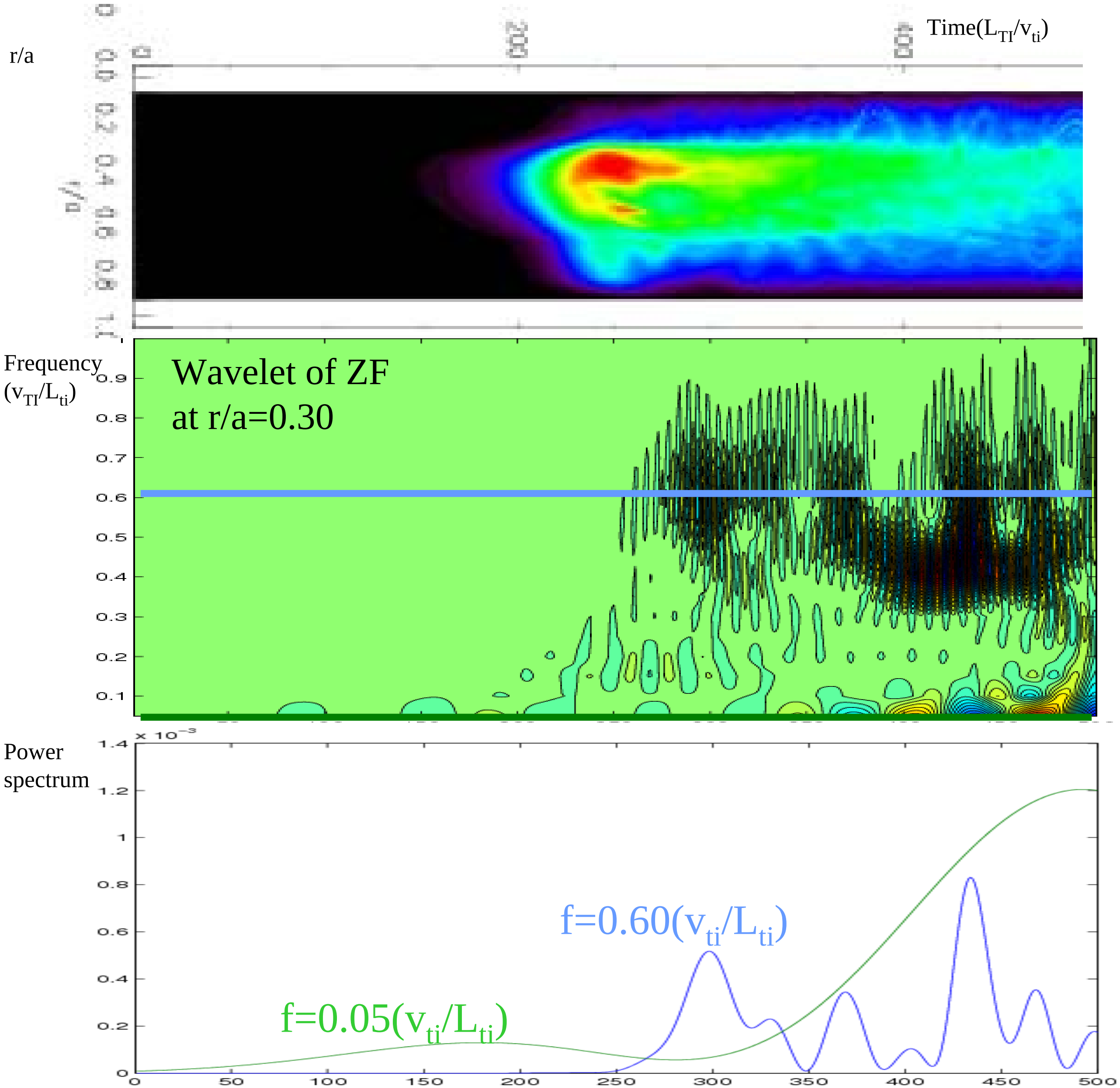
$W_n(s)$: resultant Wavelet, Ψ_0: Mother Wavelet Func.(Morlet)

s: scale, n: # of data, dt: time interval, x_n: the *n*th data

- Causality relation[Fujisawa '07 J. Phys. Soc. Jpn.] (excitation of the turbulence is proceeding to the excitation of the GAM) is found.

- Modulation of GAM frequency by turbulence is observed.

Threshold of excitation of the GAM



- Zero(low)-frequency zonal flow grows slowly in the weak turbulence.
- On the other hand, high-frequency zonal flows gets increasing when turbulence energy exceeds some level.
  - Threshold of the excitation of GAM.

Estimation of eigenmodes of zonal flows

- Based on the GAM system model[Miki '08 PoP]
  - Three eigen-modes

Γ $\gamma+i\omega$

→one real(zero frequency) + one couple of c.c. (GAM)

Zonal flows

$$\frac{\partial U}{\partial t} = R_1 U - \beta G,$$

Anisotropic pressure perturbation

$$\frac{\partial G}{\partial t} = R_2 G + \beta' U + \beta_2 V - \gamma_{\mathrm{LD}} G,$$

Anisotropic parallel flow perturbation

$$\frac{\partial V}{\partial t} = R_3 V - \beta_2' G,$$

$$\beta=(2a/R), \beta'=(a/R)T_{eq}(\tau+\Gamma),$$

$$\beta_2=(a/qR)T_{eq}(\tau+\Gamma), \beta_2'=(a/qR)$$

$$\omega_{GAM}=\sqrt{\beta\beta'},$$

$$\omega_{sound}=\sqrt{\beta_2\beta_2'}$$

$$R_{\mathrm{i}}(i=1,2,3)=\alpha_i N_{\boldsymbol{k}}$$

The exact solution are written in [Miki '08 PoP], but too lengthy!!!

Assuming the situation with weak turbulence N~O(ε) and slow variation of the turbulence dN/dt~γ_L~O(ε), we get more useful formula.

Growth rate of 0FZF and HFZF in the weak turbulence, N~O(ε)

- Neglect the combination of nonlinear contribution, ex. $R_1 R_2$
- the approximate formula of growth rates of ZFs including the effect of turbulence.
  - related to Pfirsch-Schluter factor

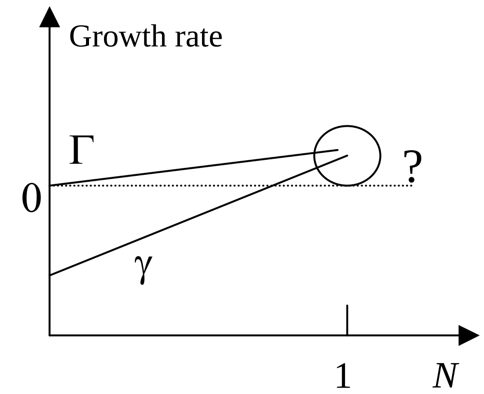
High-frequency Zonal flows
$$\gamma = -\frac{\gamma_{LD}}{2} + \left\{ \left(\frac{1-\epsilon_{PS}}{2}\right)\alpha_1 + \frac{1}{2}\alpha_2 + \left(\frac{\epsilon_{PS}}{2}\right)\alpha_3 \right\} N_{\mathbf{k}}$$

Zero-frequency zonal flows
$$\Gamma = \{\epsilon_{PS}\alpha_1 + (1-\epsilon_{PS})\alpha_3\} N_{\mathbf{k}},$$
where $\varepsilon_{PS}=(1+2q^2)^{-1}$

- The HFZF has originally damping mode due to the Landau damping,
  - and tends to be **more sensitive** to turbulence than 0FZF.
  - In the circumstance of the weak turbulence, 0FZF has weak a growing mode, but HFZF has a damping one.
  - However, when N is order unity, γ is over Γ in a certain value of N.
    - **Change of dominant mode -> appearance of the GAM**
- The sensitivity depends on α_1, α_2, α_3, and q-value.

A criterion of GAM dominancy

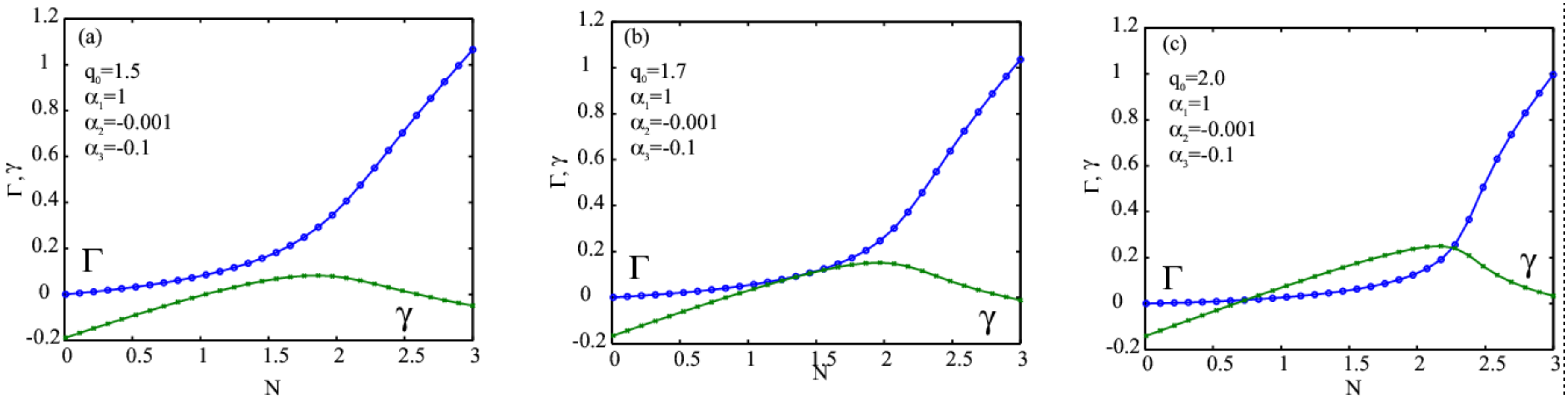
- Comparing the gradient of γ and Γ, we get the following criterion that high-frequency zonal flows can be dominant to zero-frequency zonal flows.



$$(1-3\epsilon_{\rm PS})\alpha_1+\alpha_2+(-2+3\epsilon_{\rm PS})\alpha_3>0$$

- This formula tells:
  1. NL cpl. coef. α_2 always affects on HFZF excitation and reduction of 0FZF.
  2. The effects of α_1 and α_3 depend on q-value:
     1. **For q>1, positive α_1 affects on HFZF more than on 0FZF**
     2. For q>0.5, negative α_3 affects on HFZF more than on 0FZF

Dominancy of ZFs in the strong turbulence regime, N~O(1)



- In strong turbulence regime, the combination terms (ex. R_1R_2) become dominant,
  - corresponding to the case that the nonlinear couplings are much stronger than the terms associated with the GAMs.
  - The actual critical value of q in terms of dominancy of the GAM affects the nonlinear effects. (In this case above, q~1.7 is identified as the critical.)
- Another problem is whether N value can reach the critical value or not.
  - Possible maximum value of N is the smaller one of which is determined by the nonlinear effect by turbulence or of which is determined by the saturation by zonal flows (and/or GAMs).
- To analyze large N region , more complicate treatments are needed.
  - Including the predator-prey model, etc.
  - α_1, α_2, α_3 should include the effect of propagation.

Conclusion

- GAM propagation could be another candidate for turbulent spreading. It is interesting to survey the effect of GAM on the turbulent spreading.
- By using the gyrokinetic particle-in-cell simulation code(GTC), time evolution of zonal flows and turbulence are investigated.
- Introducing wavelet analysis, causality of turbulence and the high-frequency zonal flows are identified as well as the modulation of GAM by turbulence(turbulence by the GAM?).
- The property of the GAM having threshold for turbulence level is found both in the simulations and the analysis based on the fluid model.
  - More detail should be done in future work.