US-Japan JIFT workshop on Integrated Modeling
September 21-24, Princeton Plasma Physics laboratory, US.

Dynamics of Large Scale Structure in ETG/ITG turbulence based on fluid simulation

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In collaboration with
JAERI NEXT (Numerical Experiment of Tokamak) turbulence research
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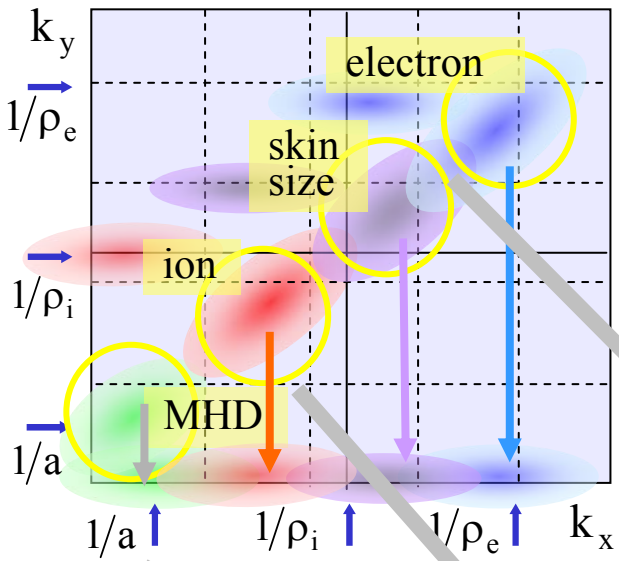
Acknowledge
M. Yagi (Kyushu-u) and H. Sugama (NIFS)

Contents

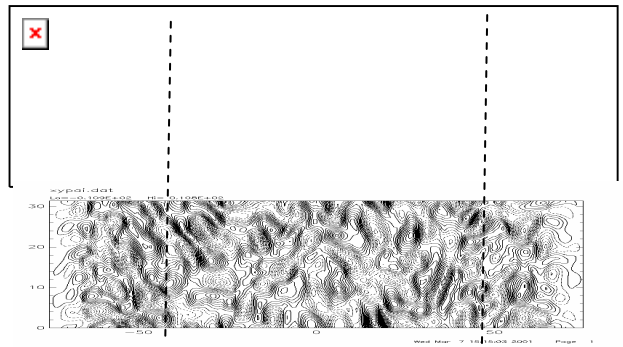
- **Background and motivation**
  - Hierarchical interaction among different scale fluctuation and control of the fluctuation
- **Fluctuation dynamics of micro-scale ETG turbulence**
  - Enhanced ETG-driven zonal flow dynamics based gyro-fluid model
  - Statistical properties of fluctuation such as fractal dimension and PDF
- **Fluctuation dynamics of meso-scale ITG turbulence**
  - Nonlinear Global gyro-Landau fluid simulation
  - Toroidal and electromagnetic effect on zonal flow
- **Summary**

Fluctuation dominated by large scale convective cells

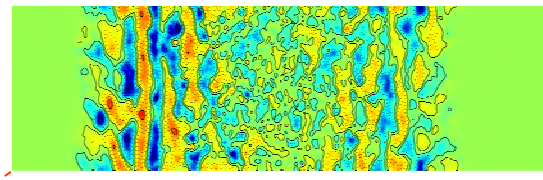


Turbulent speading

[*courtesy of J-Li*]



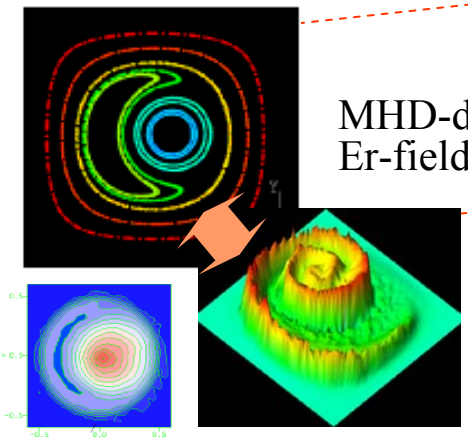
Reversed magnetic shear



[GK-slab, *Idomura, PoP, '00*]

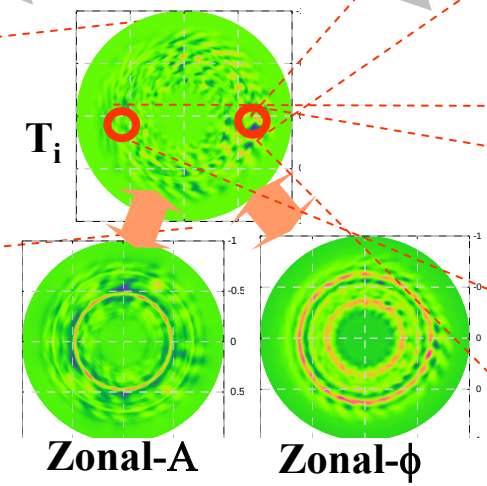
Normal magnetic shear

Internal kink event

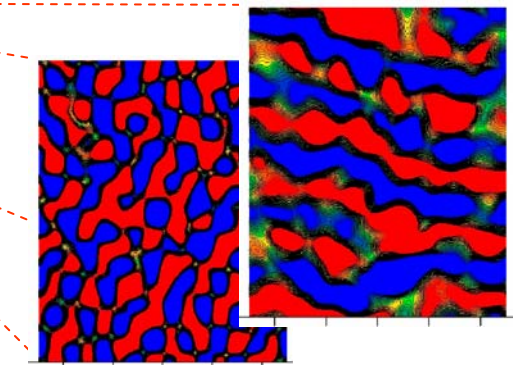


MHD-driven Er-field

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



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



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

Toward the control of fluctuation and transport

- **Key parameter to change the partition**

  "Fluctuation"
  = Turbulent part + Laminar-like flow part

$$\eta_{zF} \equiv \frac{E^{(ZF)}}{E^{(tot)}} = \frac{E^{(ZF)}}{E^{(turb)} + E^{(ZF)}}$$

- **Key parameter to control the fluctuation and the structure**

  Need to identify the "energy transfer channel" in wide frequency and wave number space.

cf . Possibility for driving strong flow using nonlinear energy source without using external source ?

Hierarchy of transport simulation

1. **Application level:** [*TRANSP (PPPL), TASK, TOPICS, JETRO (JET)*]

   Predictable transport simulation with parameterized transport coefficient

2. **Intermediate level:**

   2.1 Extended transport approach with fluctuation-flow equation

   [*Newman, et al., Yagi et al., Fukuyama, et al.]*

   2.1 Classical transport linked with coefficients from local GK/GF simulation

   Linkage with fundamental level [*GS2 (PPPL), GLF23 (Waltz et al.,)*]

3. **Fundamental level :**

   3.1 Local/global gyro-fluid (GF) simulation, GF based transport-MHD approach with renormalized transport coefficients

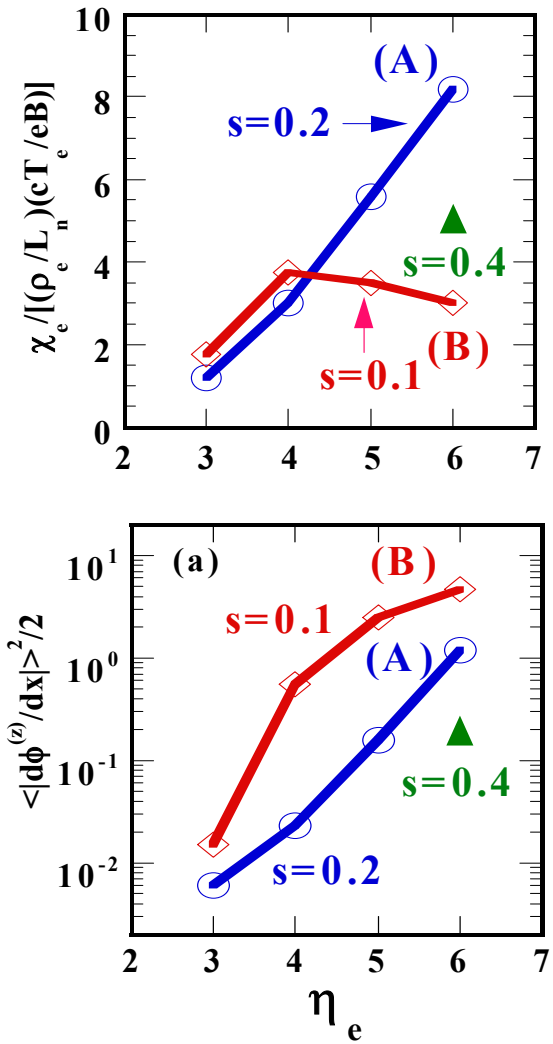
   [*Gabert et al., Lebeuf et al, Yagi, et al., Miyato et al. etc.*]

Treat the wide dynamical range with less accuracy, but keeping fundamental physical issues like non-local and transient process, EM effect etc.

   3.2 Local/global gyro-kinetic simulation

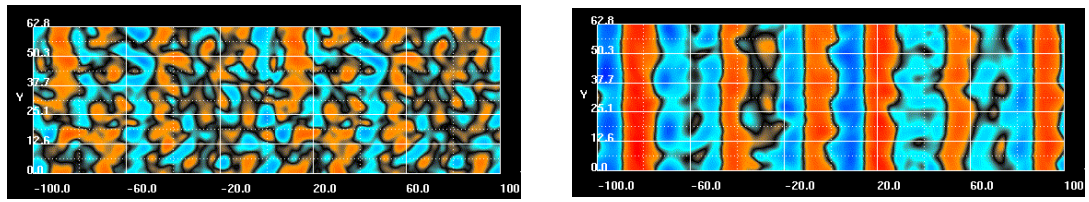
   [*Lin, et.al., Idomura, et al., Candy et al., Naitoh et al., Watanabe et al. etc.*]

ETG turbulence and zonal flows

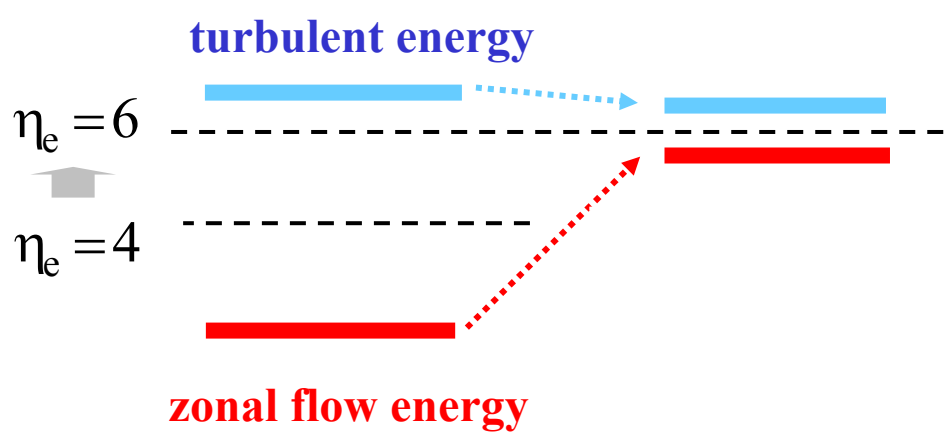


[*Kishimoto,Li, et al., IAEA '02*]

- Electrostatic slab 3D ETG turbulence
- Disappearance of anomaly in low magnetic shear regime

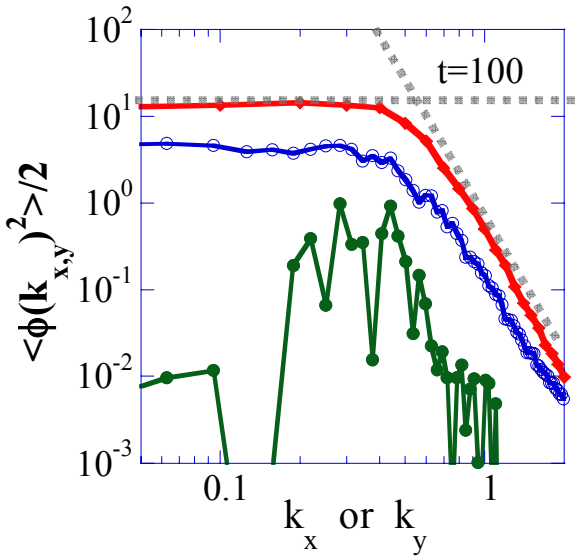


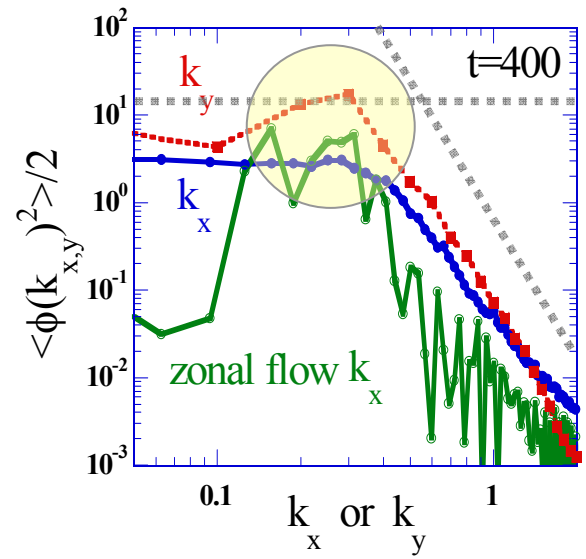
(A) $\hat{s} = 0.2$ → (B) $\hat{s} = 0.1$

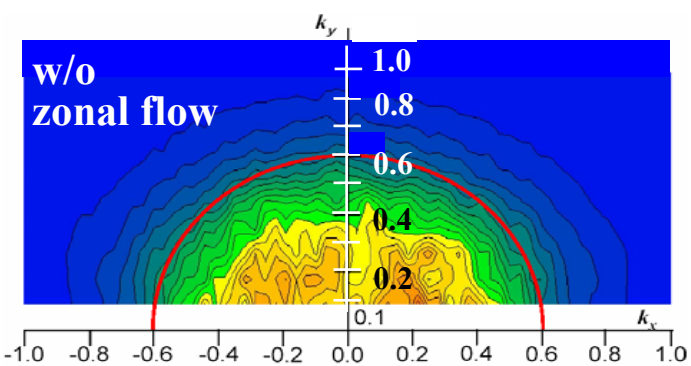


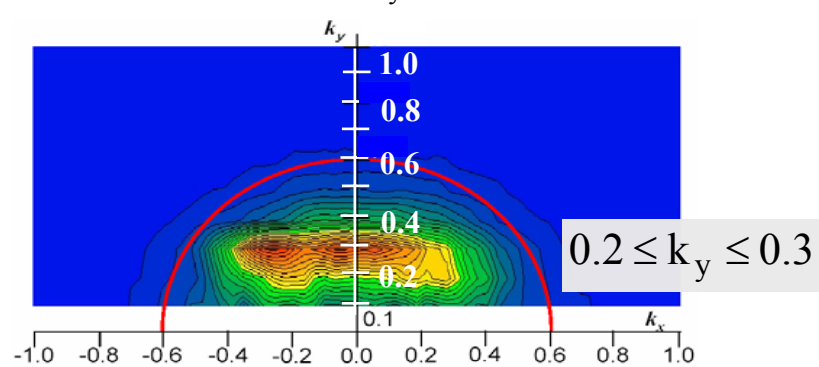
ETG turbulence and zonal flows

- Condensation of turbulent energy in flow dominated plasma









Isotropic spectra in short and long wavelength region

Isotropic spectra at short wavelength, but energy condensation to narrow k_y region.

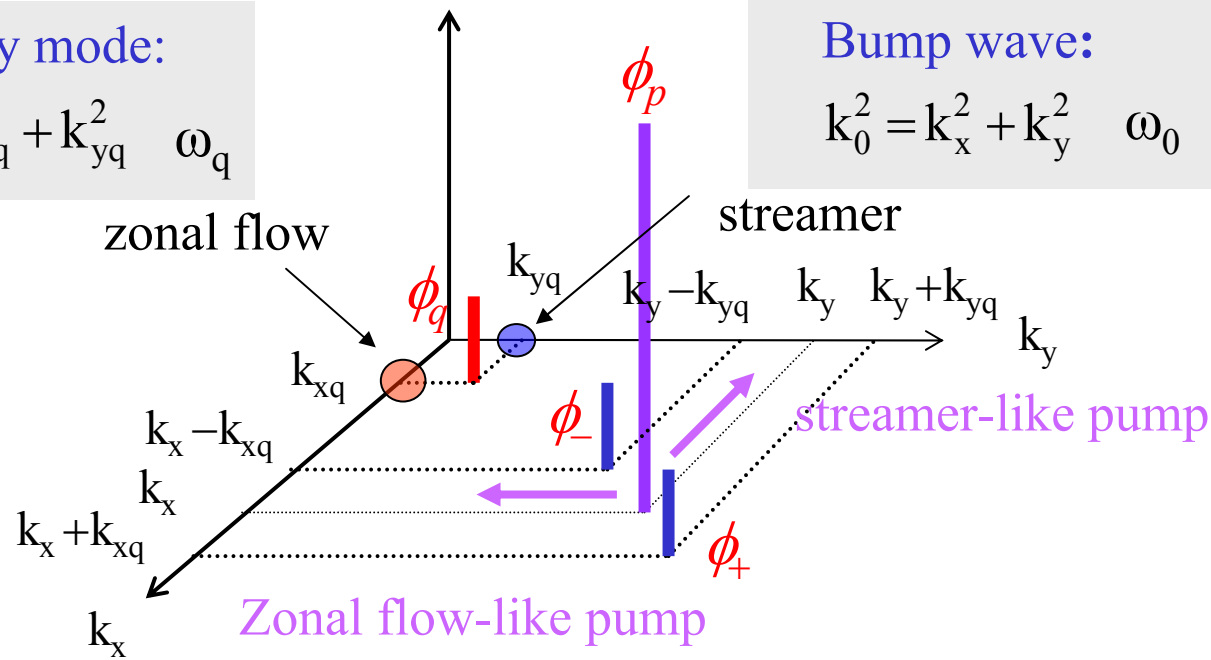
Modulational analysis for convective cell by ETG mode

Secondary mode:

$$k_q^2 = k_{xq}^2 + k_{yq}^2 \quad \omega_q$$

Bump wave:

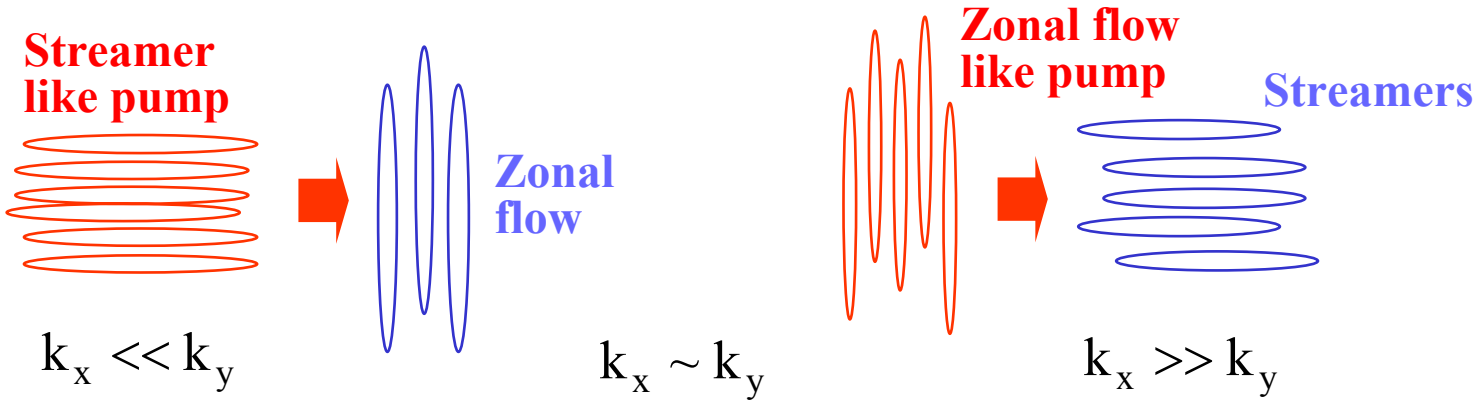
$$k_0^2 = k_x^2 + k_y^2 \quad \omega_0$$



$$\left(1-\nabla_\perp^2\right)\frac{\partial}{\partial t}\phi_k = \frac{\partial}{\partial y}\phi_k + \sum_{k=k'+k''}\left[\phi_{k'}, \nabla_\perp^2\phi_{k''}\right]$$

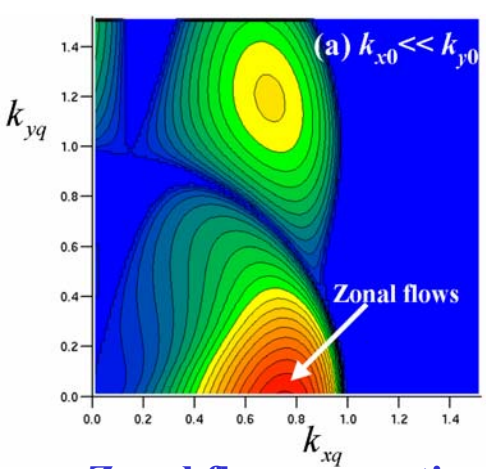
$$\omega_q\left(1+k_q^2\right)+k_{yq} = -\frac{2k_q^2(k_{xq}k_y - k_{yq}k_x)^2(k_0^2-k_q^2)\left\{\omega_q\left[1+k_0^2+k_q^2-4(k_{xq}k_x+k_{yq}k_y)^2/k_q^2\right]+k_{yq}\right\}}{\left[2\omega_0(k_{xq}k_x+k_{yq}k_y)+k_{yq}+\omega_q(1+k_0^2+k_q^2)\right]^2-\left[\omega_0 k_q^2+2\omega_q(k_{xq}k_x+k_{yq}k_y)\right]^2}\left|\varphi_0\right|^2$$

Structure of turbulence and convective cell



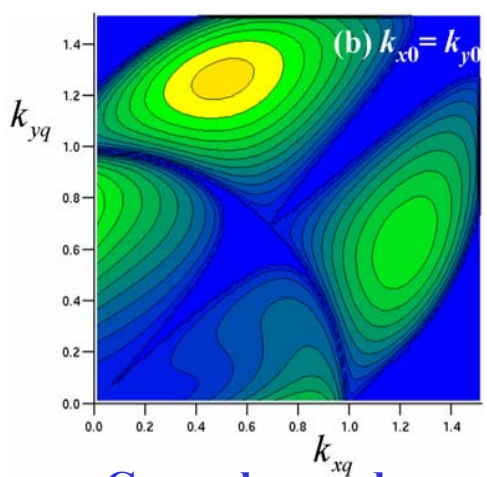
$$\Phi_0 = 4,\ k_0\left(= \sqrt{k_x^2 + k_y^2}\right) = 1$$

Streamer-like pump



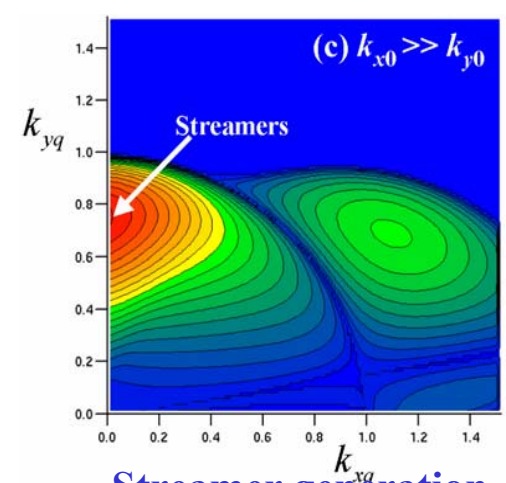
Zonal flow generation

Homogeneous pump



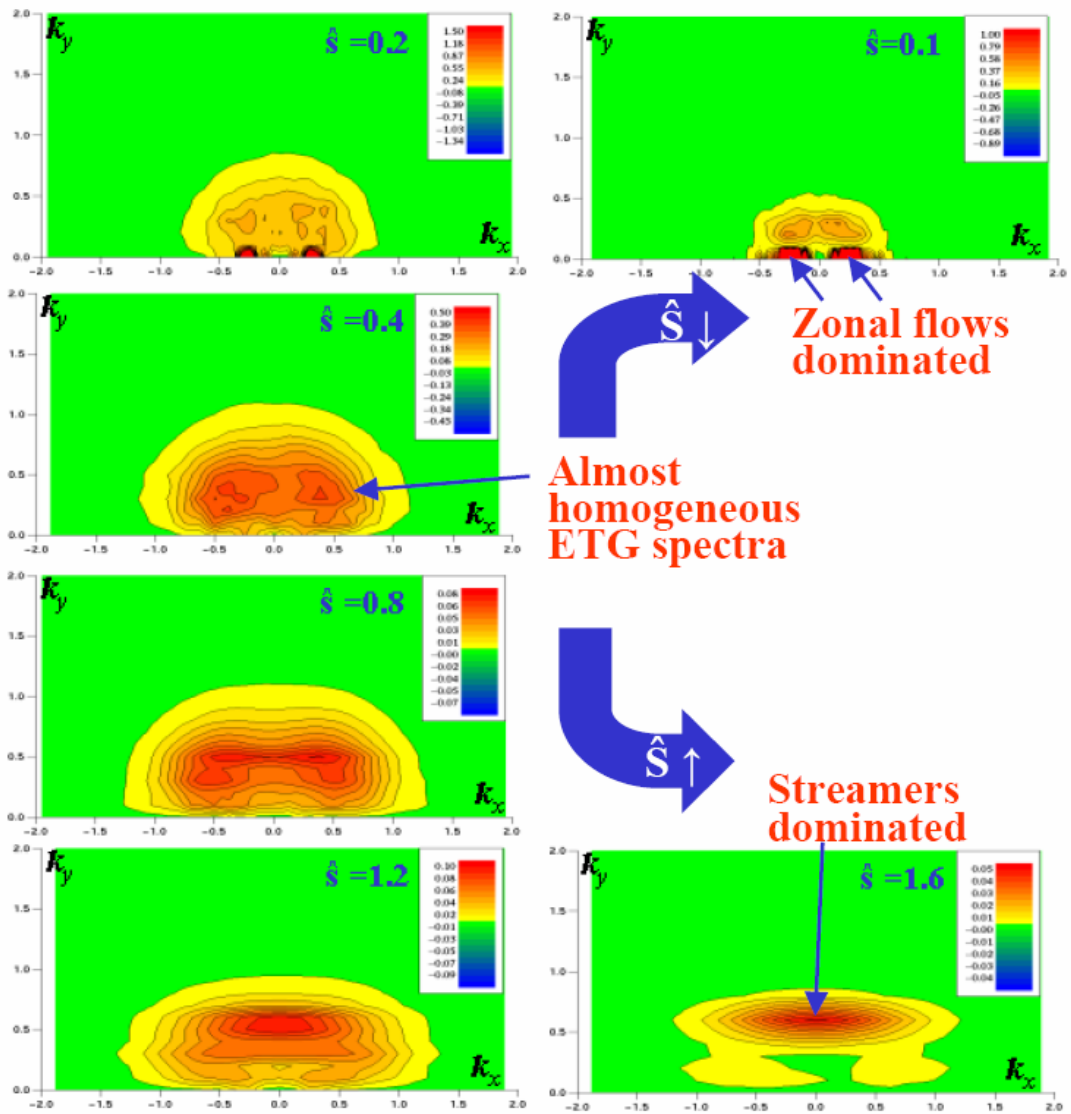
General secondary fluctuation (GKH)

Zonal flow-like pump

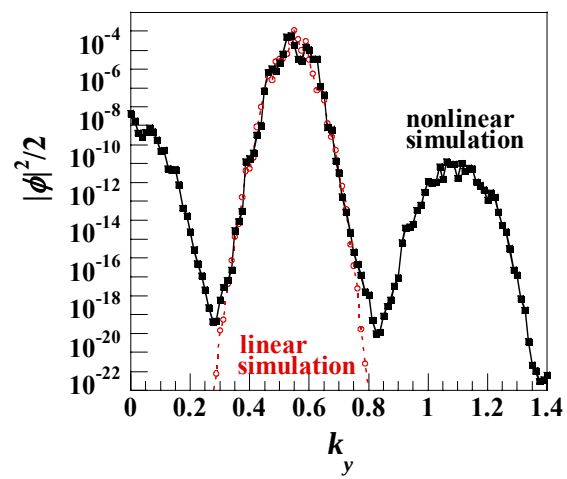


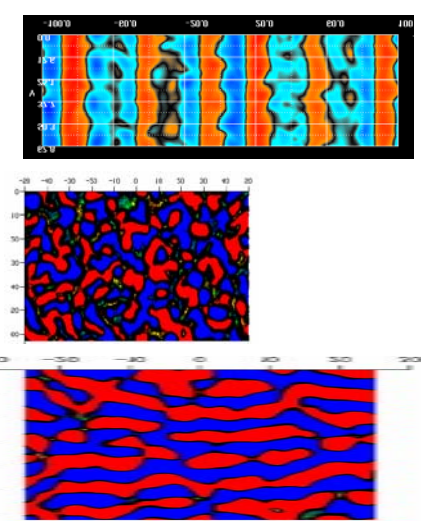
Streamer generation

Control of fluctuation via magnetic shear



Linear zonal flow instability has a spectrum





ŝ = 0.1

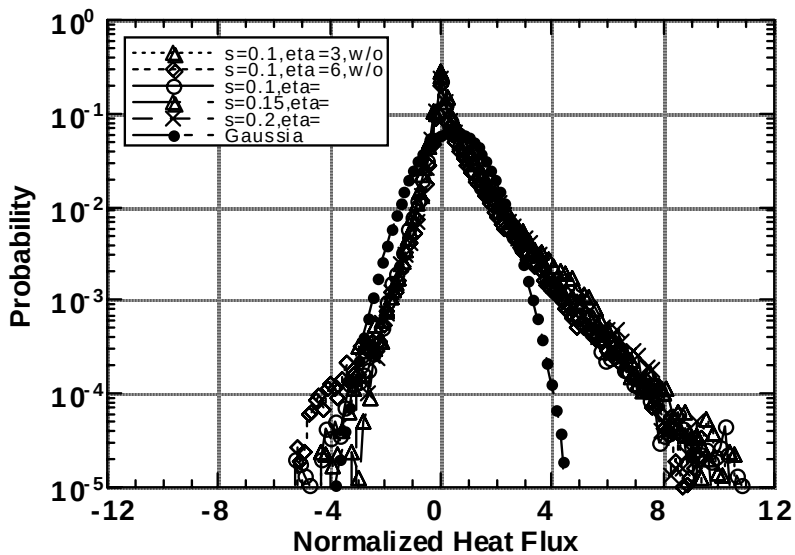
ŝ = 0.4

ŝ = 1.6

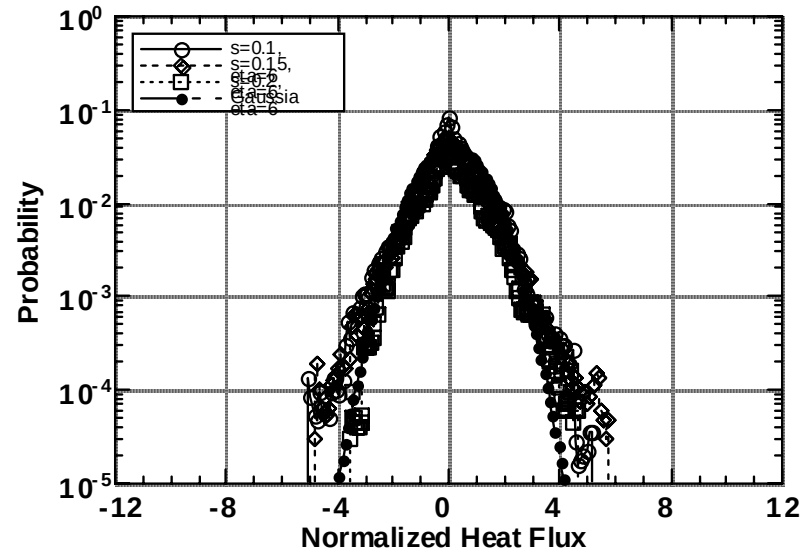
Heat Flux PDF from ETG driven GF simulation

- Similarity of PDF in ETG driven turbulent plasma
  [*Matsumoto et al, Toki-conf., '03*]
- ZF dominant plasma shows a Gaussian, but not diffusive process

turbulent plasma



ZF dominated plasma



$\hat{s} = 0.1 \quad \eta_e = 3$ w/o ZF

$\hat{s} = 0.1 \quad \eta_e = 6$ w/o ZF

$\hat{s} = 0.1 \quad \eta_e = 3$

$\hat{s} = 0.15 \quad \eta_e = 3$

$\hat{s} = 0.2 \quad \eta_e = 3$

$\hat{s} = 0.1 \quad \eta_e = 6$

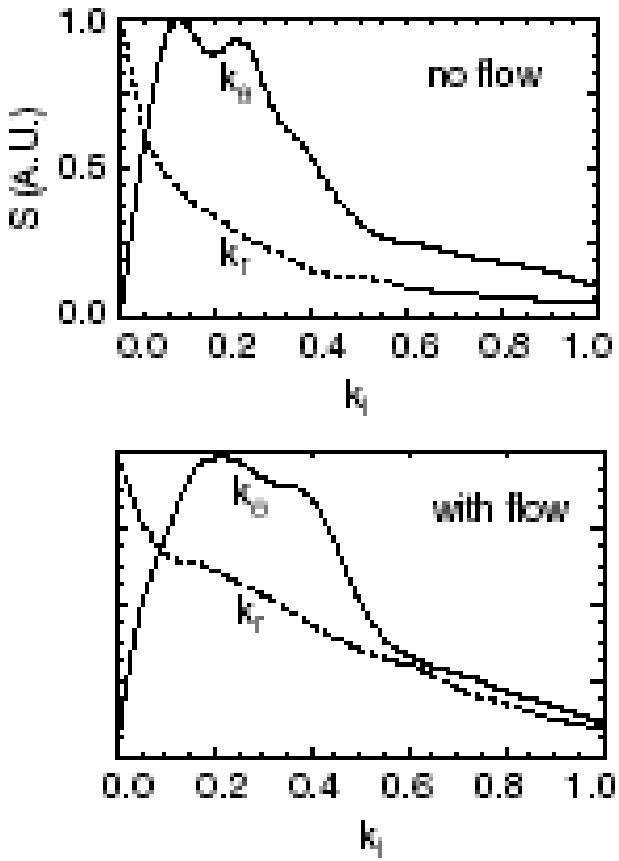
$\hat{s} = 0.15 \quad \eta_e = 6$

$\hat{s} = 0.2 \quad \eta_e = 6$

PDF from GTC Simulation

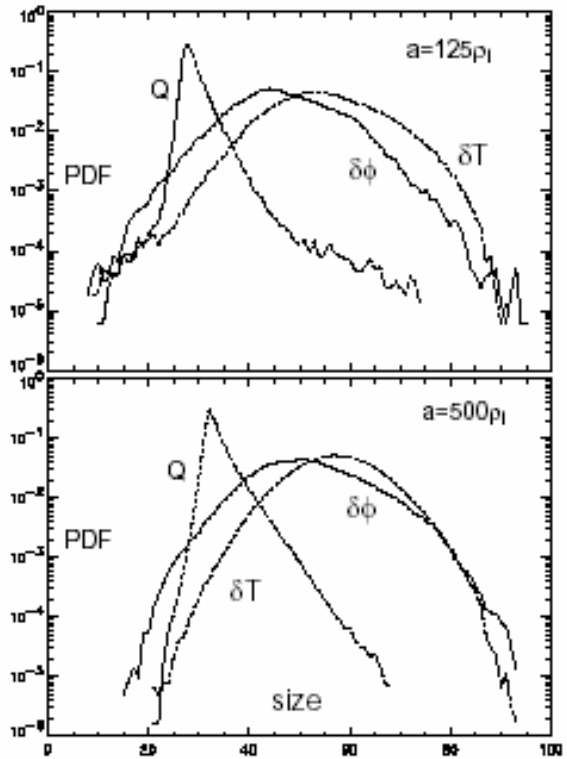
[*courtesy of Lin and Hahm*]

- Spectrum broadening due to Scattering to high-k



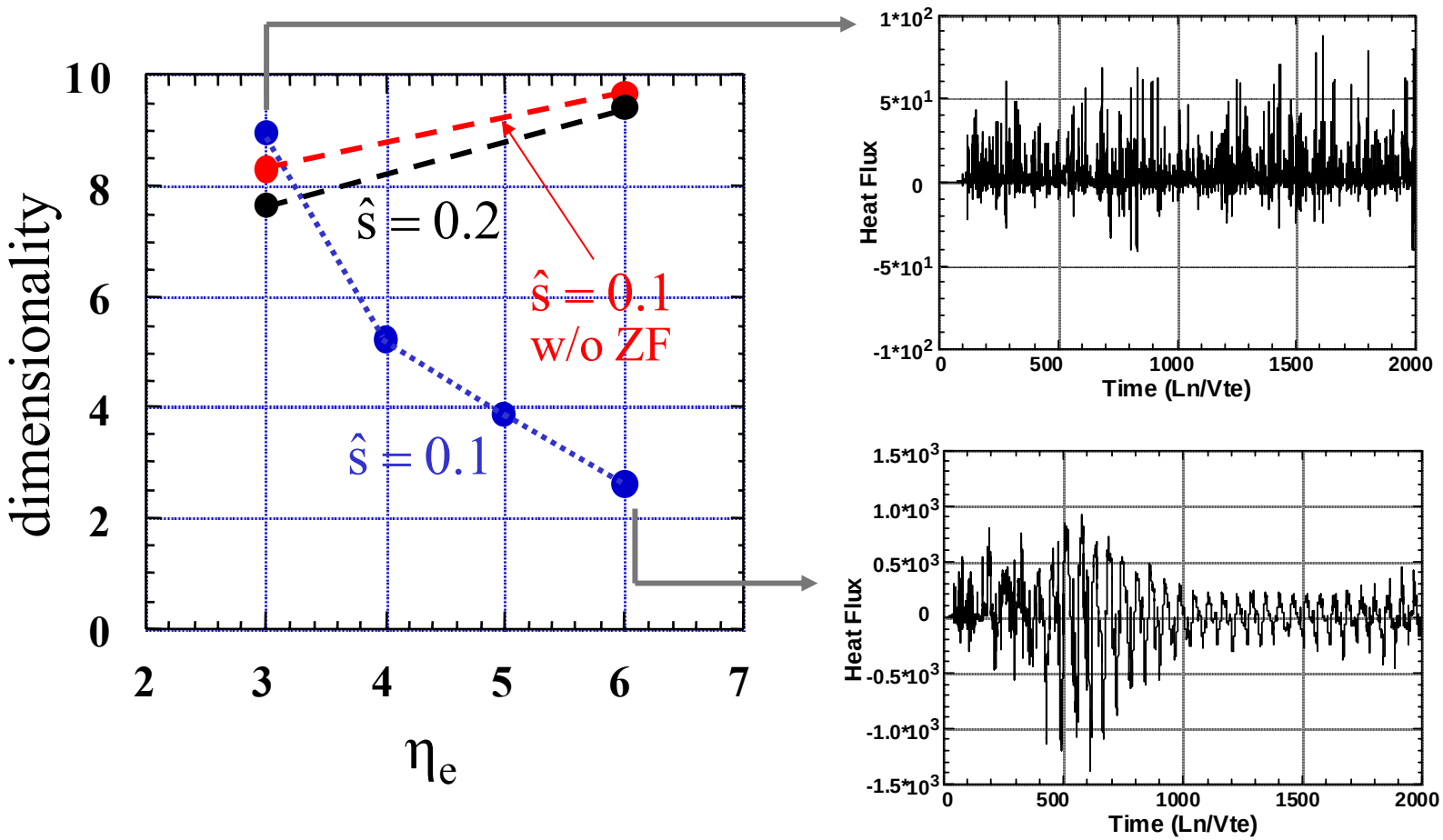
[*Hahm, et al. IAEA, '02*]

- Heat flux PDF is almost Gaussian process



Dimension of ETG driven turbulent plasma

- Lowering of dimensionality in plasma dominated by zonal flows [*Matsumoto et al, Toki-conf., '03*]

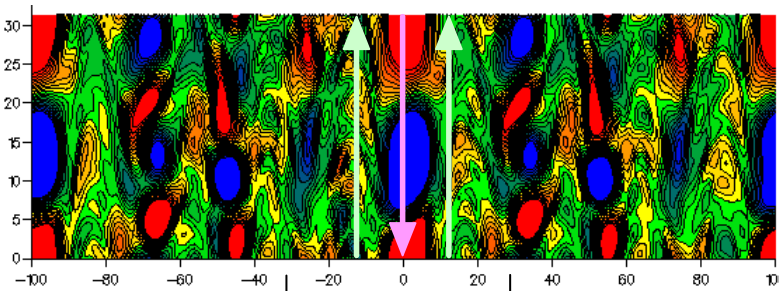


Dimension of ETG driven turbulent plasma

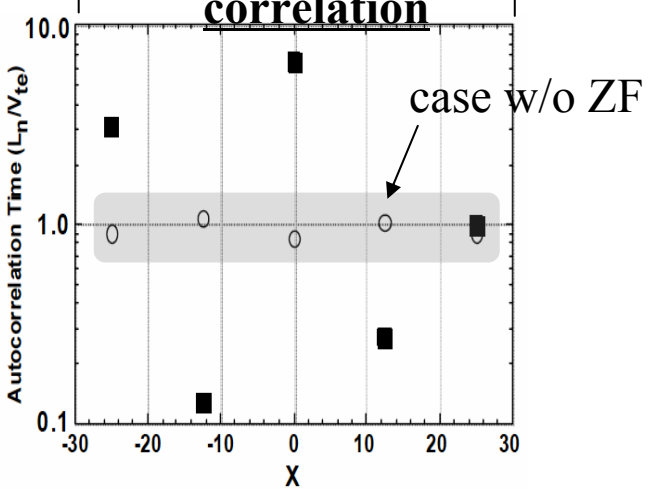
- Constraint of dimensionality in ZF dominant plasma

[*Matsumoto et al, to be submitted '04*]

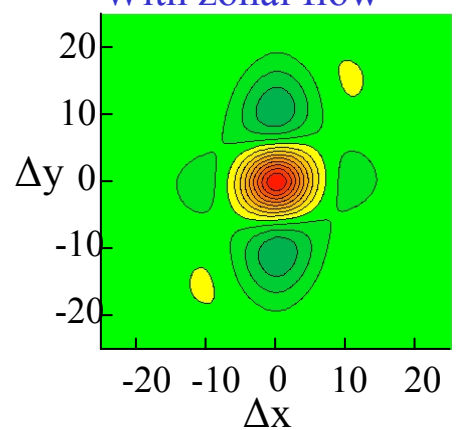
$\hat{s} = 0.1 \quad \eta_e = 6$



Time correlation



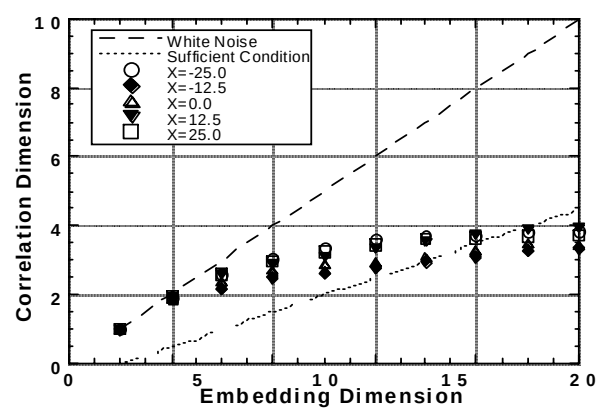
With zonal flow



Spatial correlation

$$\overline{C}_\phi(0,\Delta y) = \exp(-0.125|\Delta y|^{3/2}) \times \cos(0.262\Delta y)$$

Dimension in different spatial coordinates

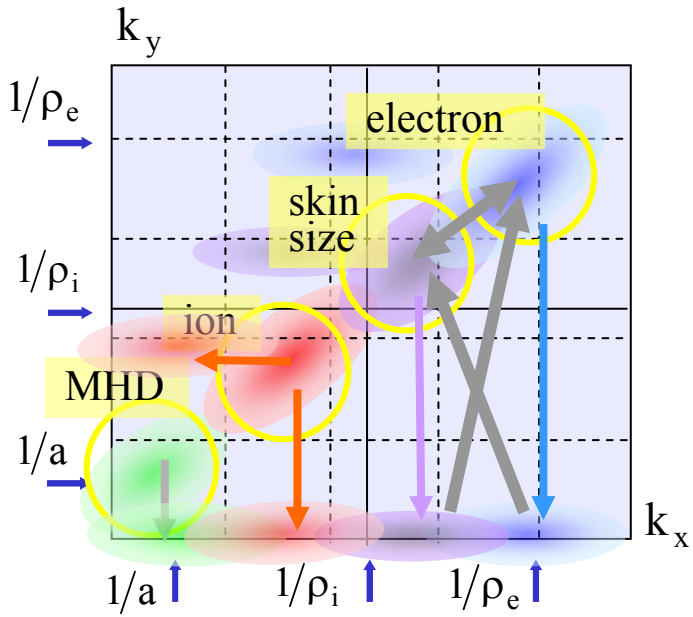


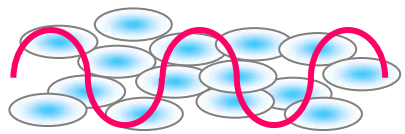
d=3-4

- Fluctuations is multi-scales, but correlate each other leading to a similar dimension.

Interaction among different scale fluctuation

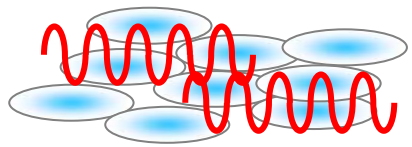
Energy transfer channel in wide frequency and wave number space





$\left(\Omega << \omega,\ q_x < k_x^{(\mathrm{turb})}\right)$

[*Hahm-Burrel, PoP, '02, Hahm, et al., PoP, '99*]



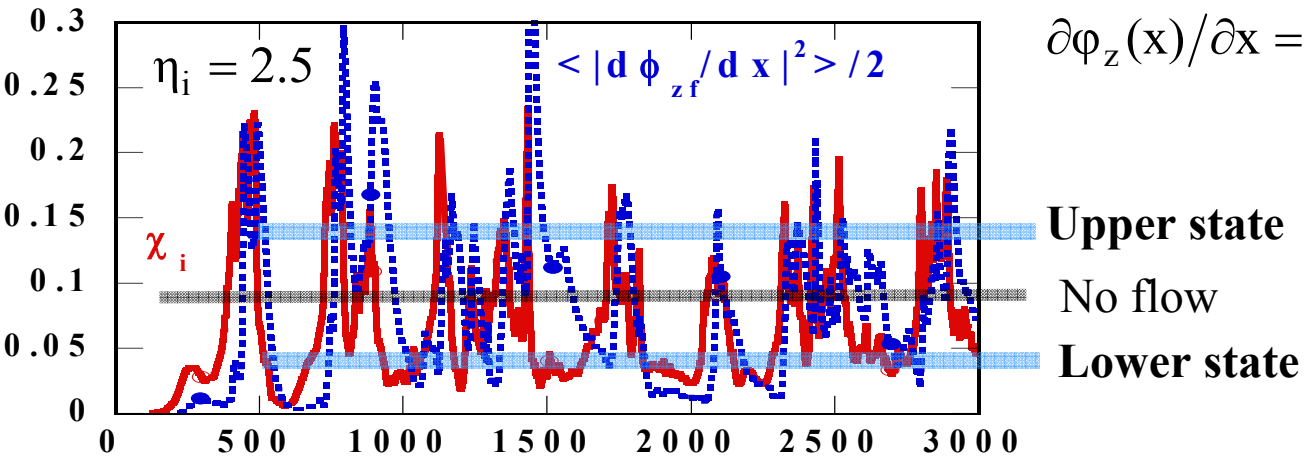
$\left(\Omega << \omega,\ q_x > k_x^{(\mathrm{turb})}\right)$

[*Li-Kishimoto, PRL, '02, Idomura, et al., NF, '02*]

- Overlapping of different linear free energy sources
- Indirect interaction through quasi-coherent zonal flows
  - From macro flow to micro turbulence and vice-versa
  - Action to direct turbulent vortices and to secondary instabilities
- Direct interaction between turbulent fluctuations
  - Eddy (turbulent) viscosity and noise trigger

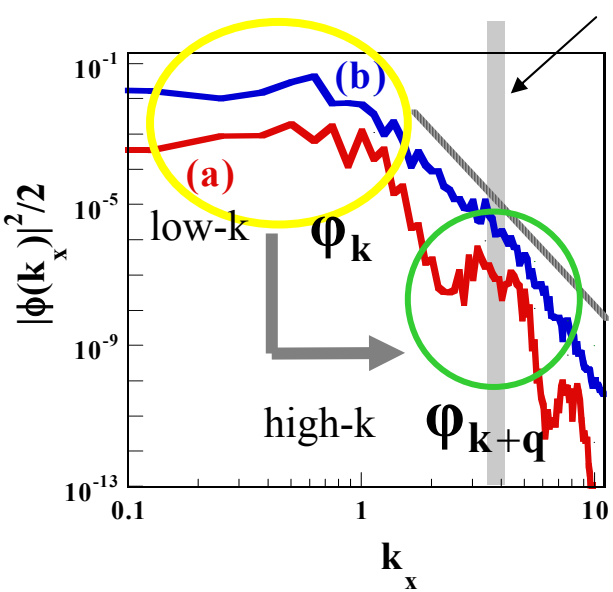
ITG transport modulation due to small scale flow

GF-ITG simulation with micro-scale ETG driven flows *[Li-Kishimoto, PRL '02]*



$$\partial\varphi_z(x)/\partial x = A_0\Gamma_0^{1/2}(q)\cos(qx)$$

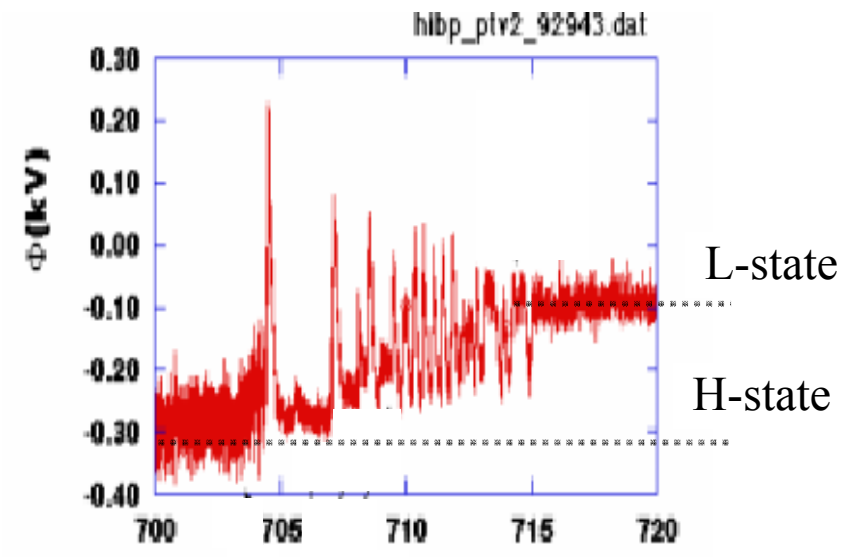
Probabilistic damping trigger

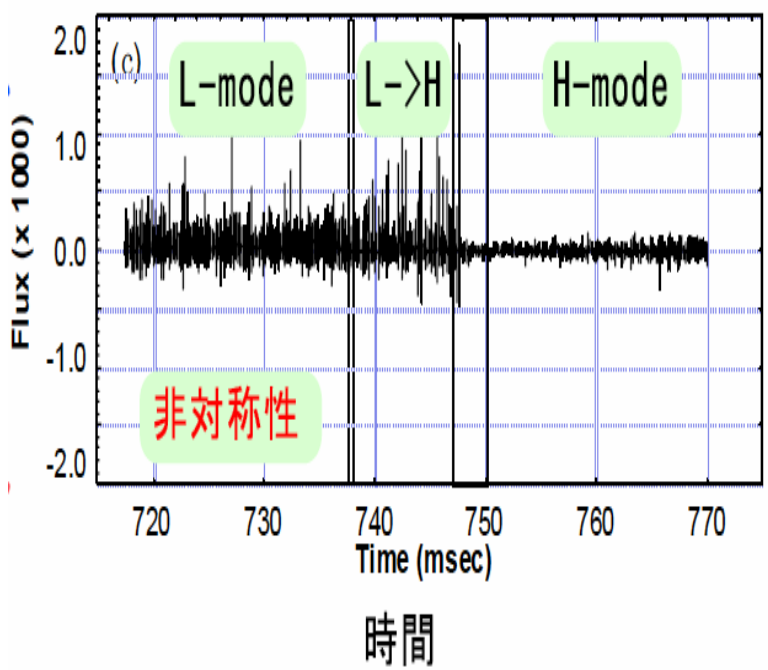


- Non-local mode coupling and associated energy transfer to high k_x damped region
- Complex interaction among ITG turbulence, ITG driven zonal flows, and micro-scale flows may contributes to the intermittency

ITG transport modulation due to small scale flow

[*courtesy of Miura, Ido and JFT-2M group*]

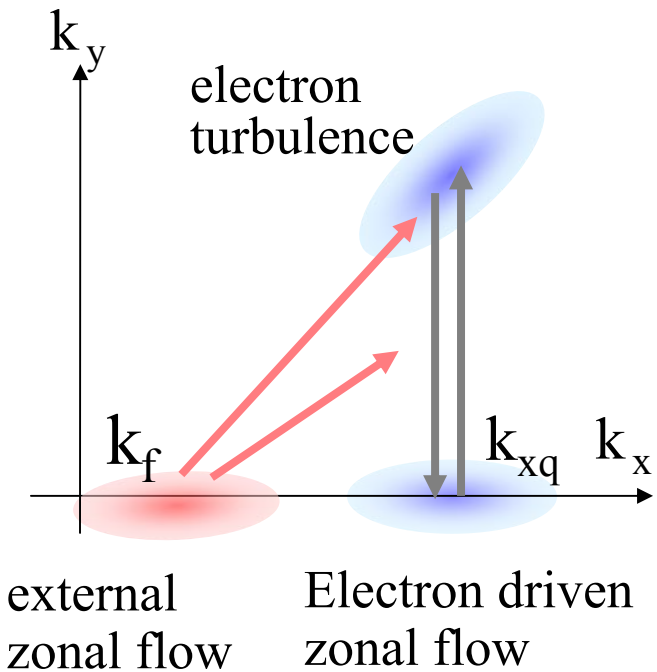




- The amplitude of bursting increases in transition phase, suggesting the increase of PDF tail

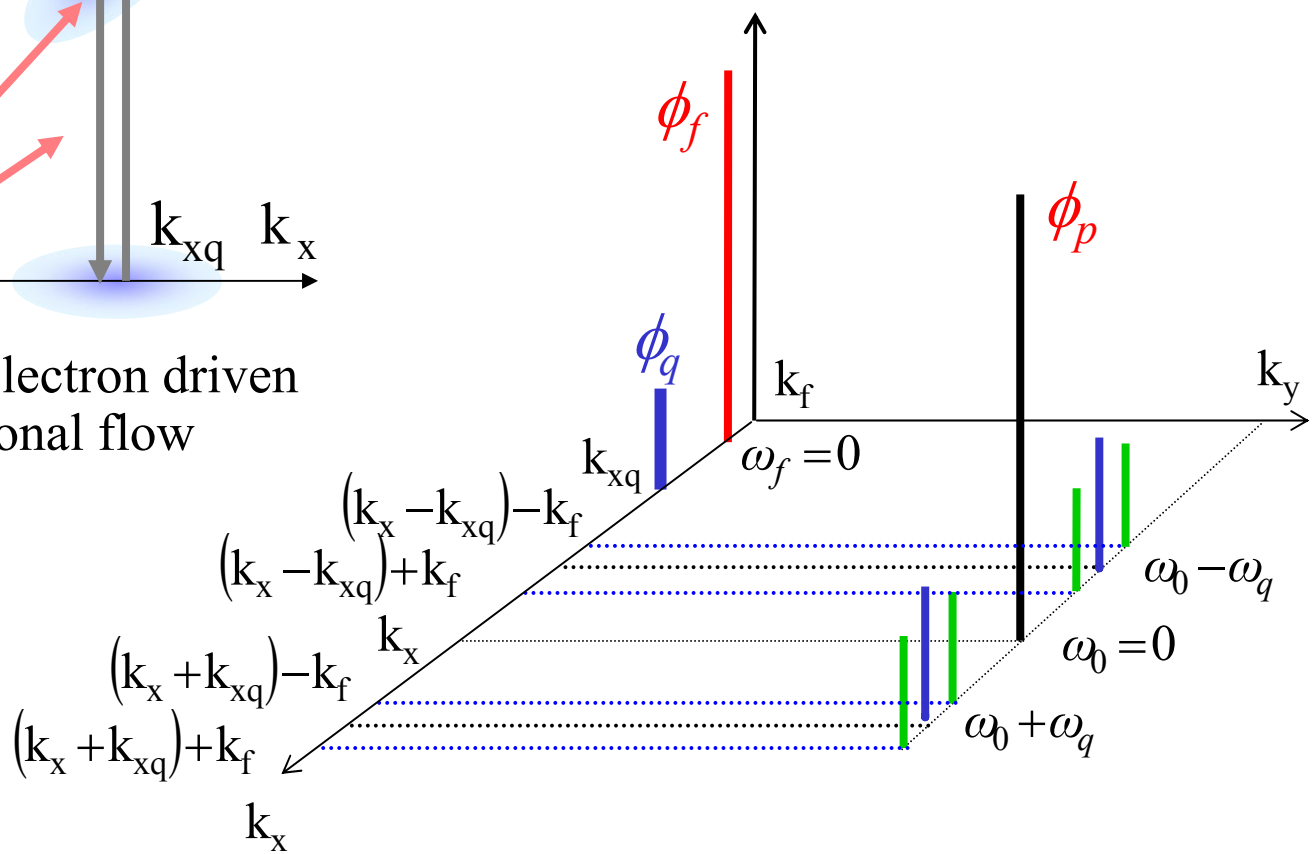
Modulational analysis including external flow

[by Uzawa, Kyoto-univ.]



Effect of external flow on turbulence

- Direct turbulent de-correlation
- Indirect modulational dynamics

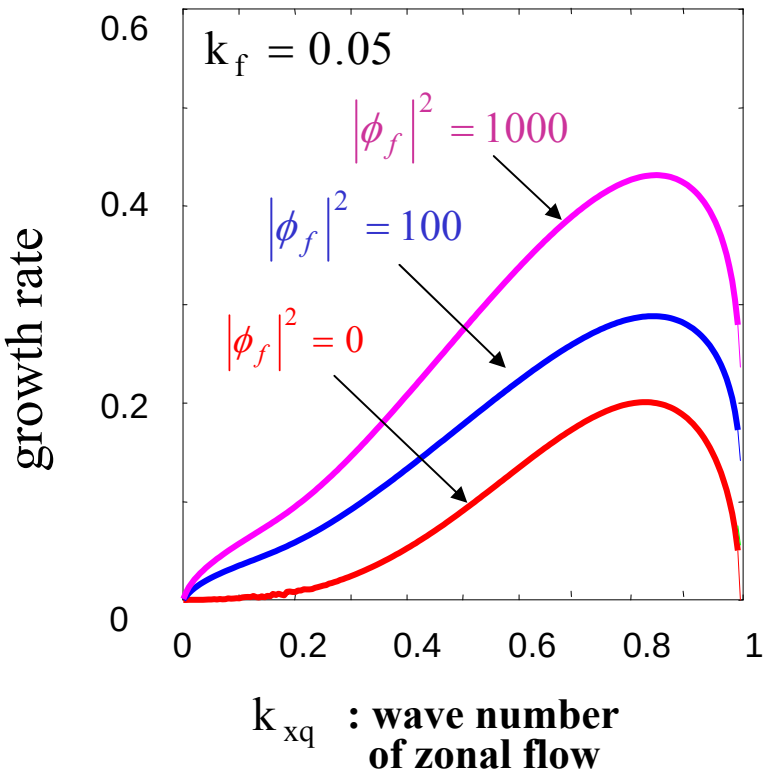


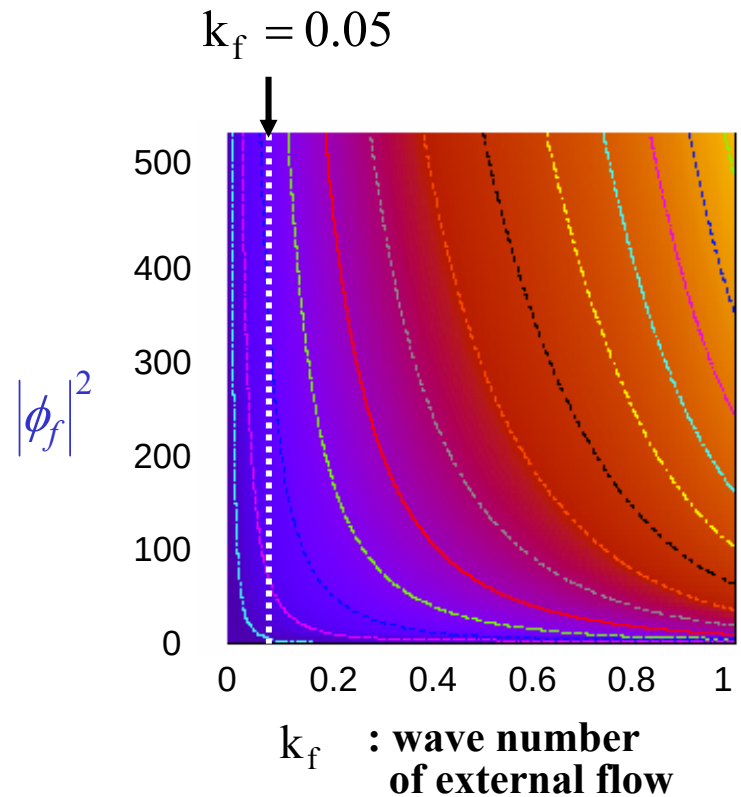
Modulational analysis including external flow (2)

[by Uzawa, Kyoto-univ.]

Homogeneous pump case

$(k_x = k_y = 0.71, \quad |\phi_0|^2 = 4.0)$

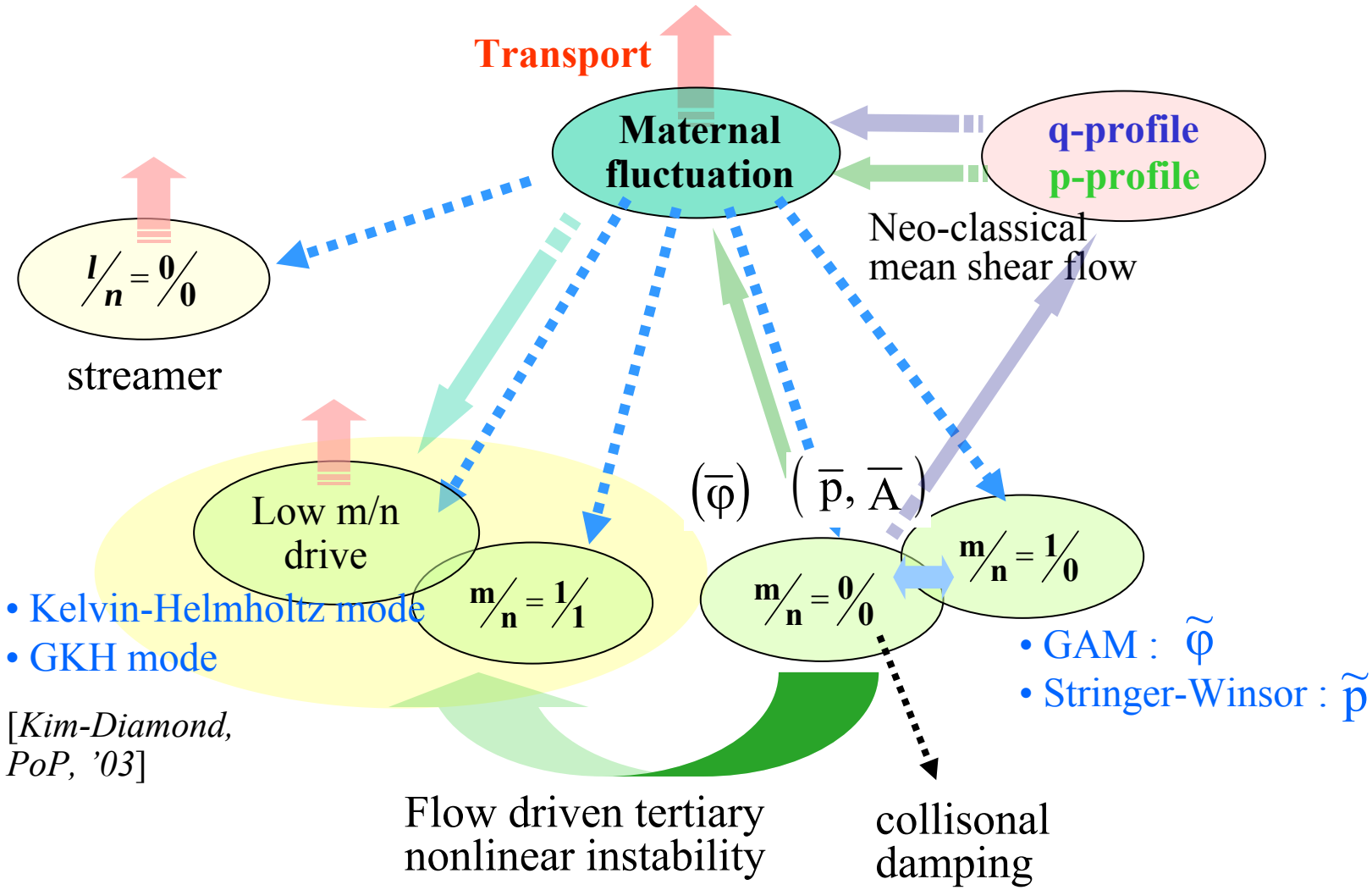




- External flow enhances the modulational instability, i.e. additive role

Nonlinear free energy source

Nonlinear turbulent-convective cell system with complex "activator" and "suppressor" roles



Zonal flow dynamics in toroidal geometry

Oscillation between zonal low, asymmetric pressure and parallel flow

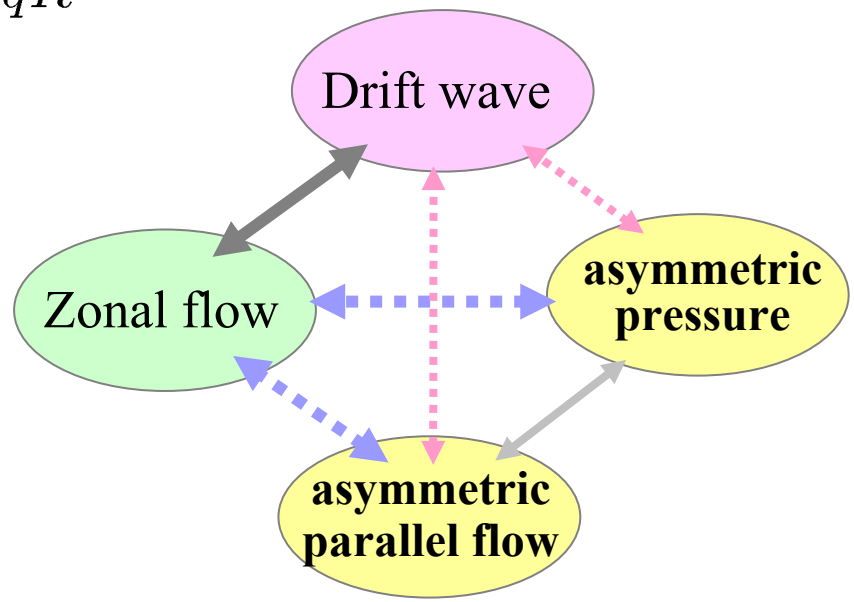
$$\frac{\partial \langle v_E \rangle}{\partial t} = -\frac{1}{r^2}\frac{\partial}{\partial r} r^2 \langle \tilde{v}_{Er} \tilde{v}_{E\theta} \rangle + \frac{\beta}{n_{eq}} \frac{1}{r^2}\frac{\partial}{\partial r} r^2 \langle \tilde{B}_r \tilde{B}_\theta \rangle - \frac{2}{n_{eq}} \frac{a}{R} \langle p \sin\theta \rangle$$

$$\frac{\partial}{\partial t} \langle p \sin\theta \rangle = -\langle [\tilde{\phi}, \tilde{p}] \sin\theta \rangle + (\Gamma + \tau) p_{eq} \frac{a}{qR} \langle v \cos\theta \rangle + (\Gamma + \tau) \frac{a}{R} p_{eq} \langle v_E \rangle$$

$$\frac{\partial}{\partial t} \langle v \cos\theta \rangle = -\langle [\tilde{\phi}, \tilde{v}] \cos\theta \rangle - \frac{1}{n_{eq}} \frac{a}{qR} \langle p \sin\theta \rangle$$

$$\hat{\omega}_{GAM} = \sqrt{2(\Gamma + \tau) T_{eq}} \frac{a}{R} \qquad (q \gg 1)$$

$$\hat{\omega}_{\text{sound}} = \sqrt{(\Gamma + \tau) T_{eq}} \frac{a}{qR} \qquad (q \ll 1)$$

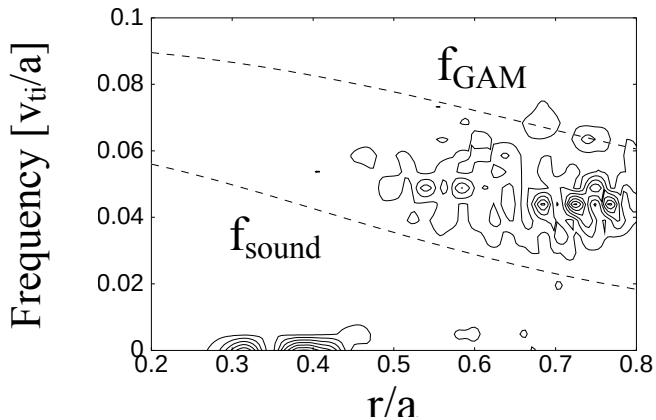


GAM term is a sink or a source for zonal flows ?

[Scott 2003, Hallatschek-Biskamp 2001]

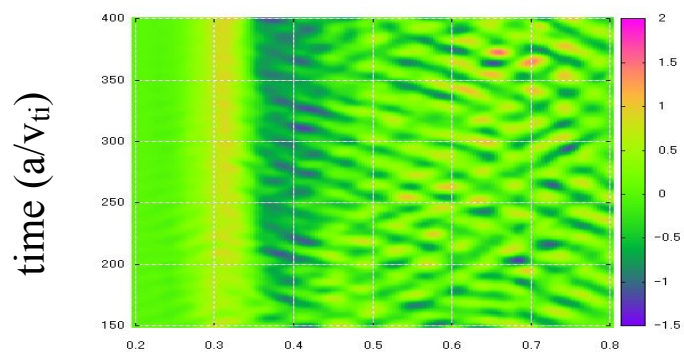
Zonal flow dynamics in toroidal geometry

5-field Landau-fluid EM global toridal simulation : H-P closure elecron LD

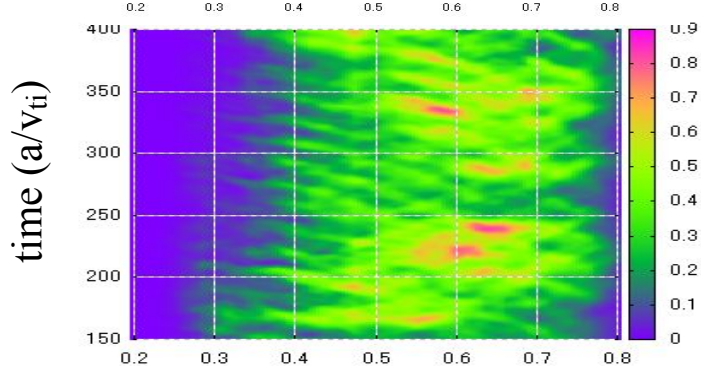


$S(\omega, r)$

[*Miyato, Kishimoto, Li, PoP, No.12, 2004*]

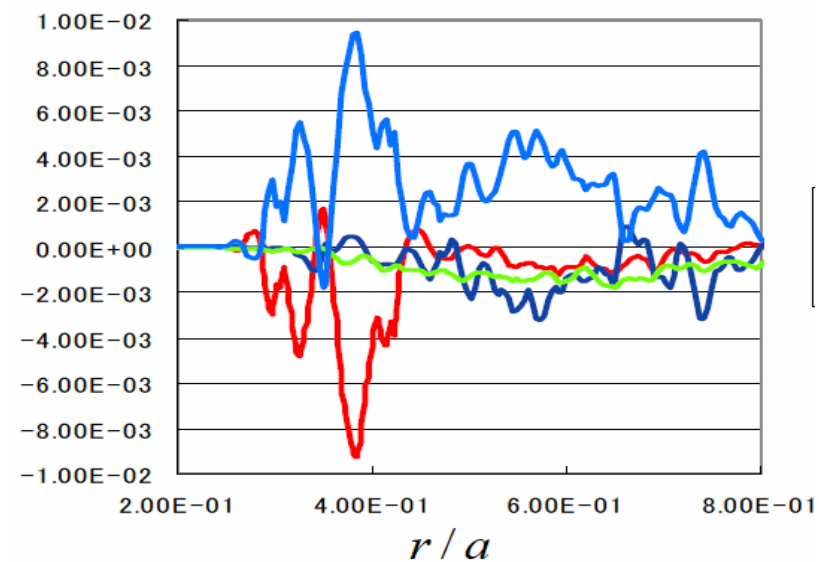


$\langle v_E \rangle$



$\langle Q \rangle$

Energy balance of $\langle p_i \sin\theta \rangle$



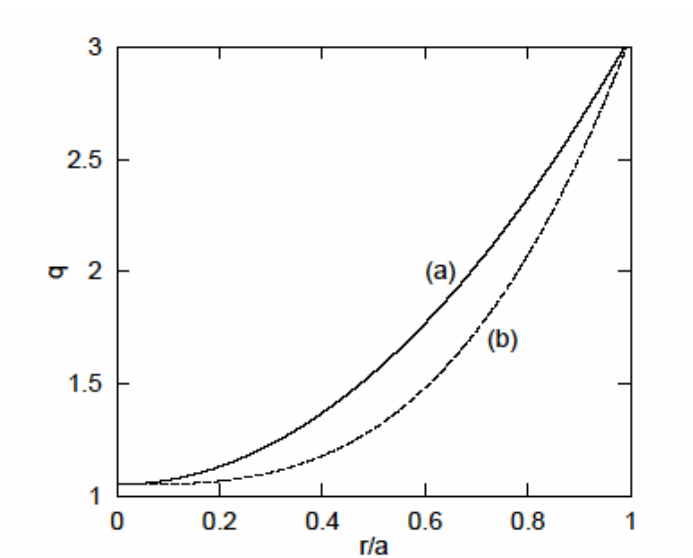
Parallel flow

Nonlinear turbulent sink

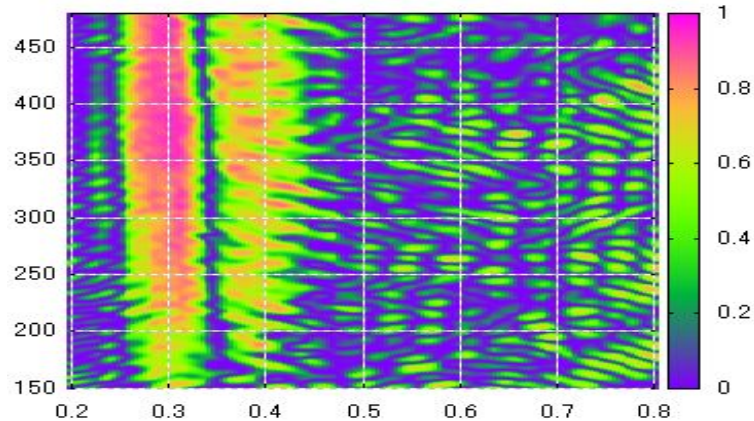
Landau damping

Zonal flow drive

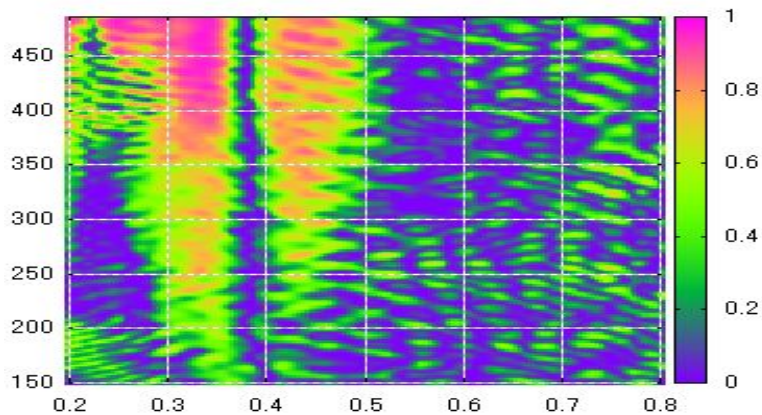
Control of zonal flow dynamics via q-profile



(a) $q=1.05+2(r/a)^2$



(b) $q=1.05+2(r/a)^3$



- Expansion of steady state ZF region by lowering q-value
- Increase of the ratio

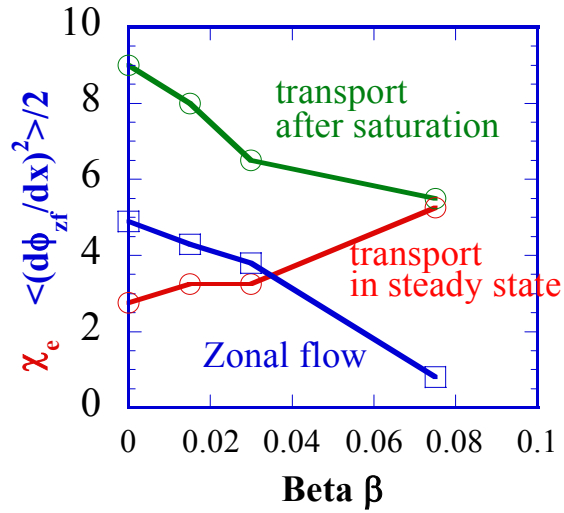
$$\eta_{zF} \equiv \frac{E^{(ZF)}}{E^{(tot)}} = \frac{E^{(ZF)}}{E^{(turb)} + E^{(ZF)}}$$

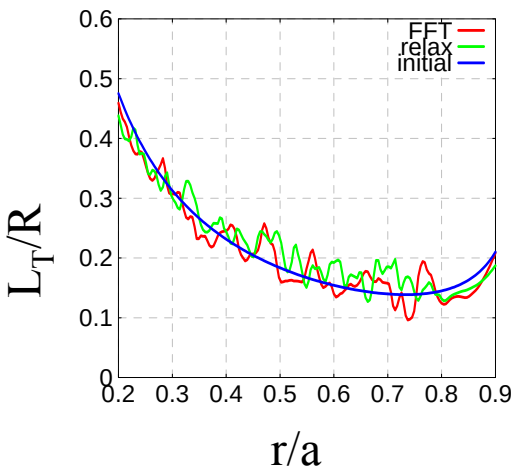
Other effects that affect on convective cell

1. **Rigorous electron response, specifically trapped electron mode**
   - Full gyro-kinetic treatment

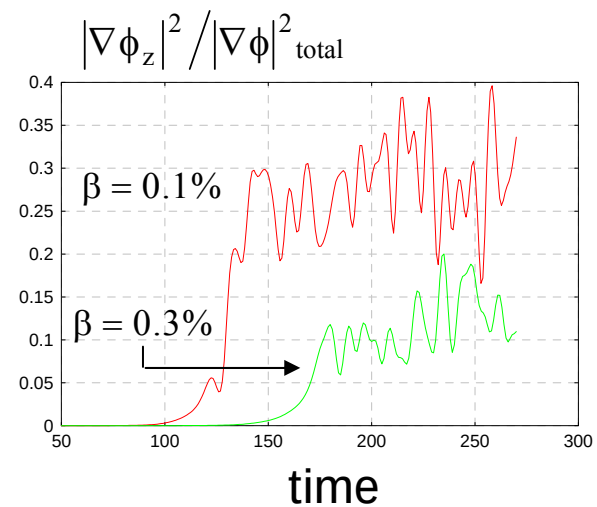
2. **Electromagnetic effect**
   - Cancellation between Reynolds stress and Maxwell stress
   - Zonal field that modified equilibrium q-profile

3. **Zonal pressure and realistic external source and sink.**



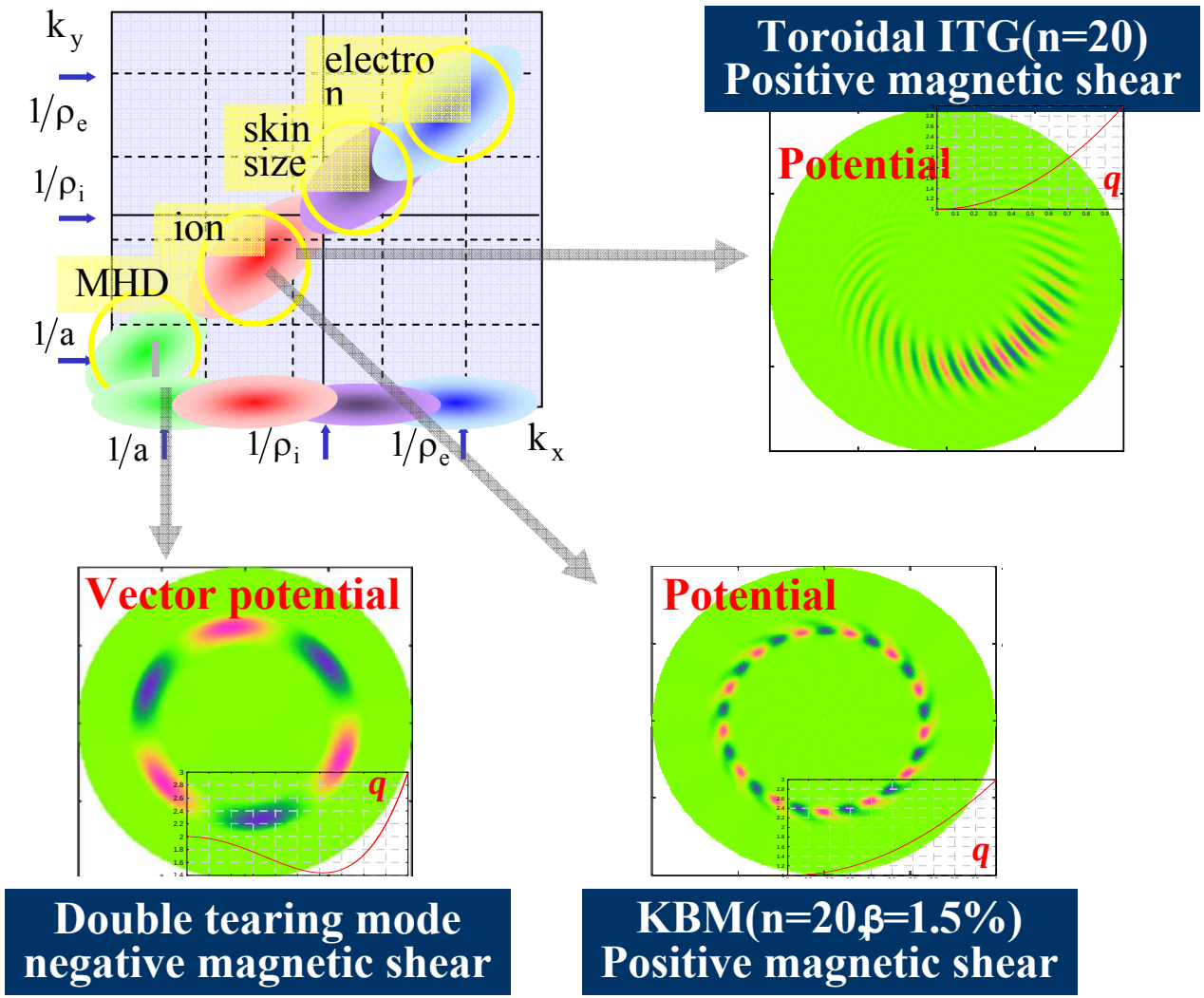


Large scale component is fixed, but micro-scale corrugations are hardly sustained.



From MHD to EM-ITG turbulence simulation

Simulation of wide dynamical range with less accuracy, but keeping fundamental physical issues based on fluid model



Coupling between ion and electron system

Nonlinear term in ion response:

$$\aleph\, n_i^k = [\varphi^p, n_i^q]$$
$$= [\varphi^{pi}, n_i^{qi}] + [\varphi^{pi}, n_i^{qe}] + [\varphi^{pe}, n_i^{qi}] + [\varphi^{pe}, n_i^{qe}]$$

(Ai) — **Ion scale self-interaction and contribution to electron scale**

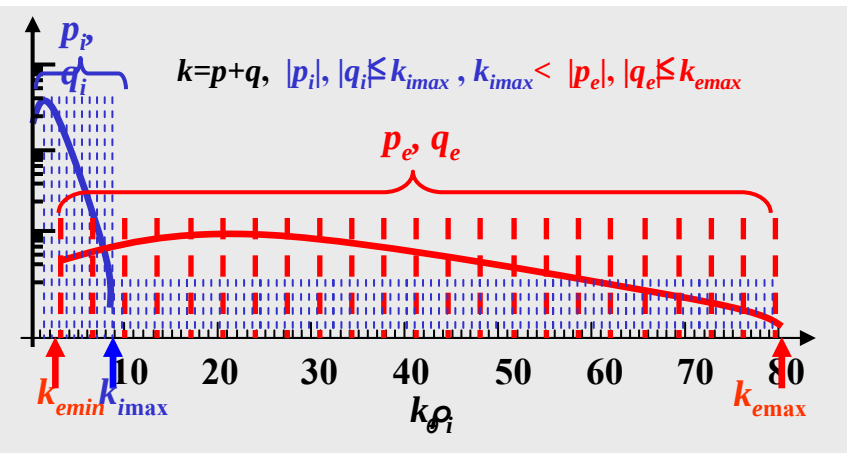
(Bi) — **Ion-electron scale interaction**

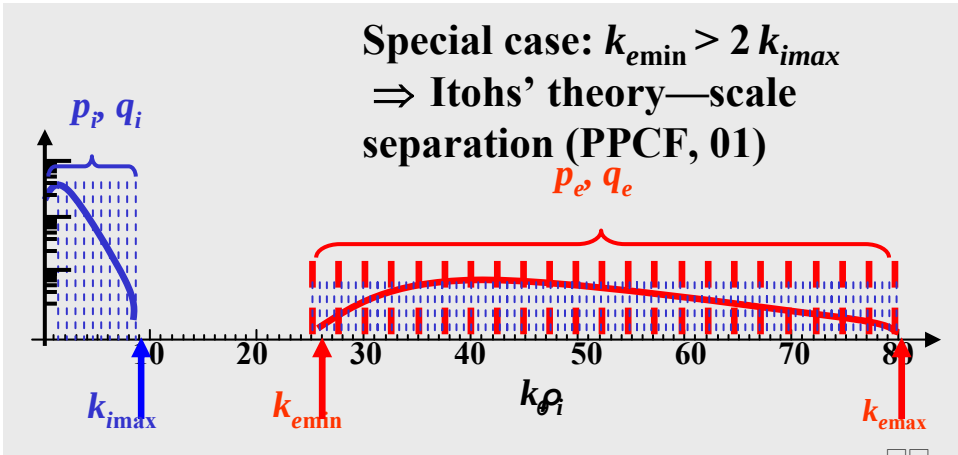
(Ci)

(Di) — **Electron scale self-interaction and contribution to ion scale**

ITG

$$Ai = [\varphi^{pi}, n_i^{qi}] = \boxed{[\varphi^{pi}, n_i^{qi}]_{k \le k_{imax}}} + \sum_{qi=0}^{k_{imax}} [\varphi^{k-qi}, n_i^{qi}]_{k > k_{imax},\, k-qi \le k_{imax}}$$





Summary

- Key parameters to change the ratio of zonal flow energy to that of total fluctuations are investigated based of fluid simulation. Magnetic structure, i.e. safety factor and shear, plays an important role.
- ETG and ITG driven turbulent plasmas dominated by zonal flows and related statistical characteristics are investigated. Quasi-coherent secondary KH-like mode sustains the heat flux and dimensionality lowering is observed.
- GAM's plays an important role for the global structure of zonal flows. Energy back transfer from zonal flow and the maternal turbulence is observed, but the channel direction sensitively depends on beta-value.
- Indirect interaction between ITG turbulence and ETG driven micro-scale flow is investigated. Complex interplay leads to an intermittent transport dynamics in the case of weak ITG drive.