Joint ICTP-IAEA College on Advanced Plasma Physics
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Interaction between different scales

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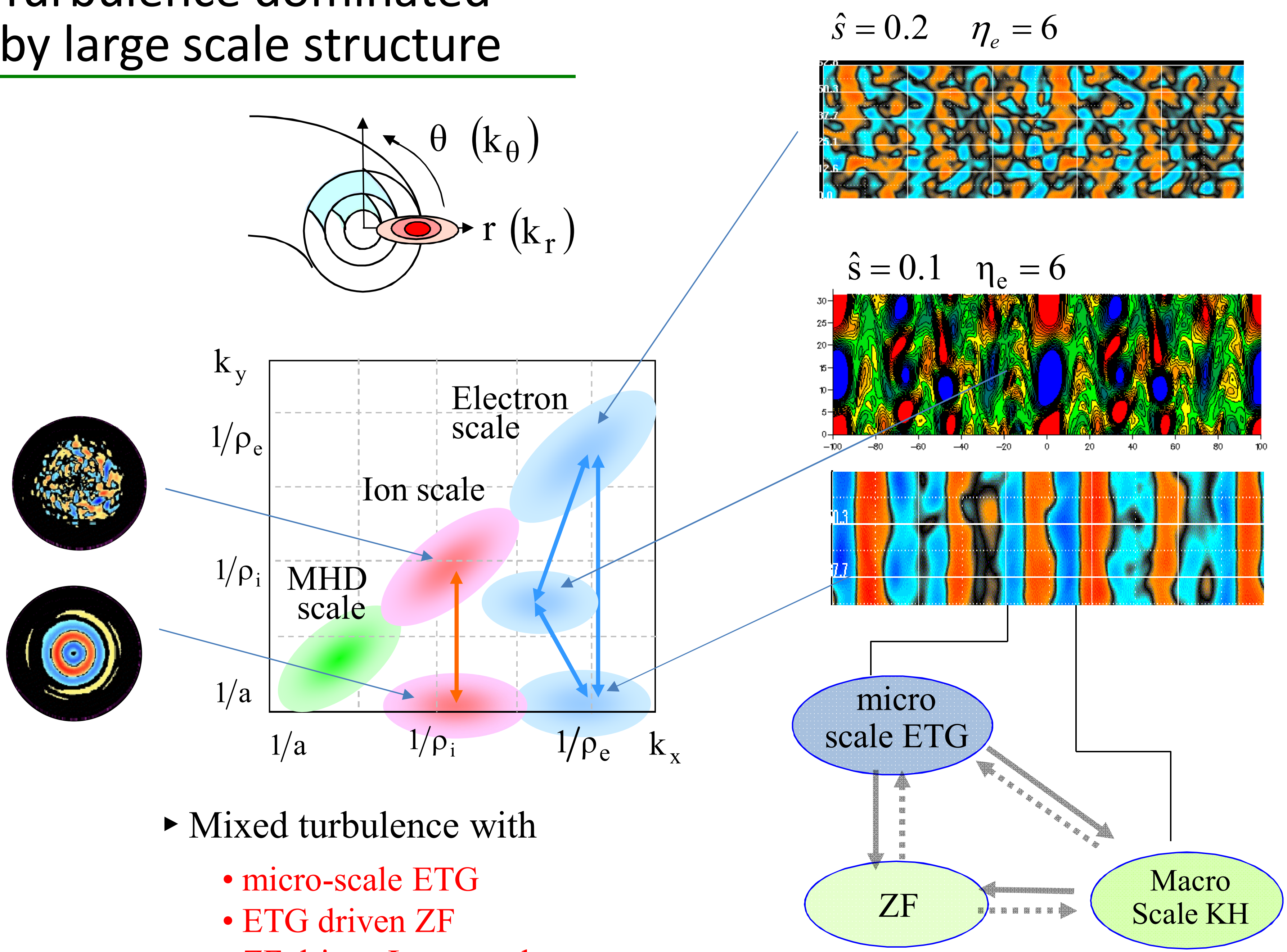
- August 19 : Structure/dynamics of fluctuations in fusion plasmas
- August 20 : Nonlinear instability and plasma dynamics
- August 21 : Interaction between different scales

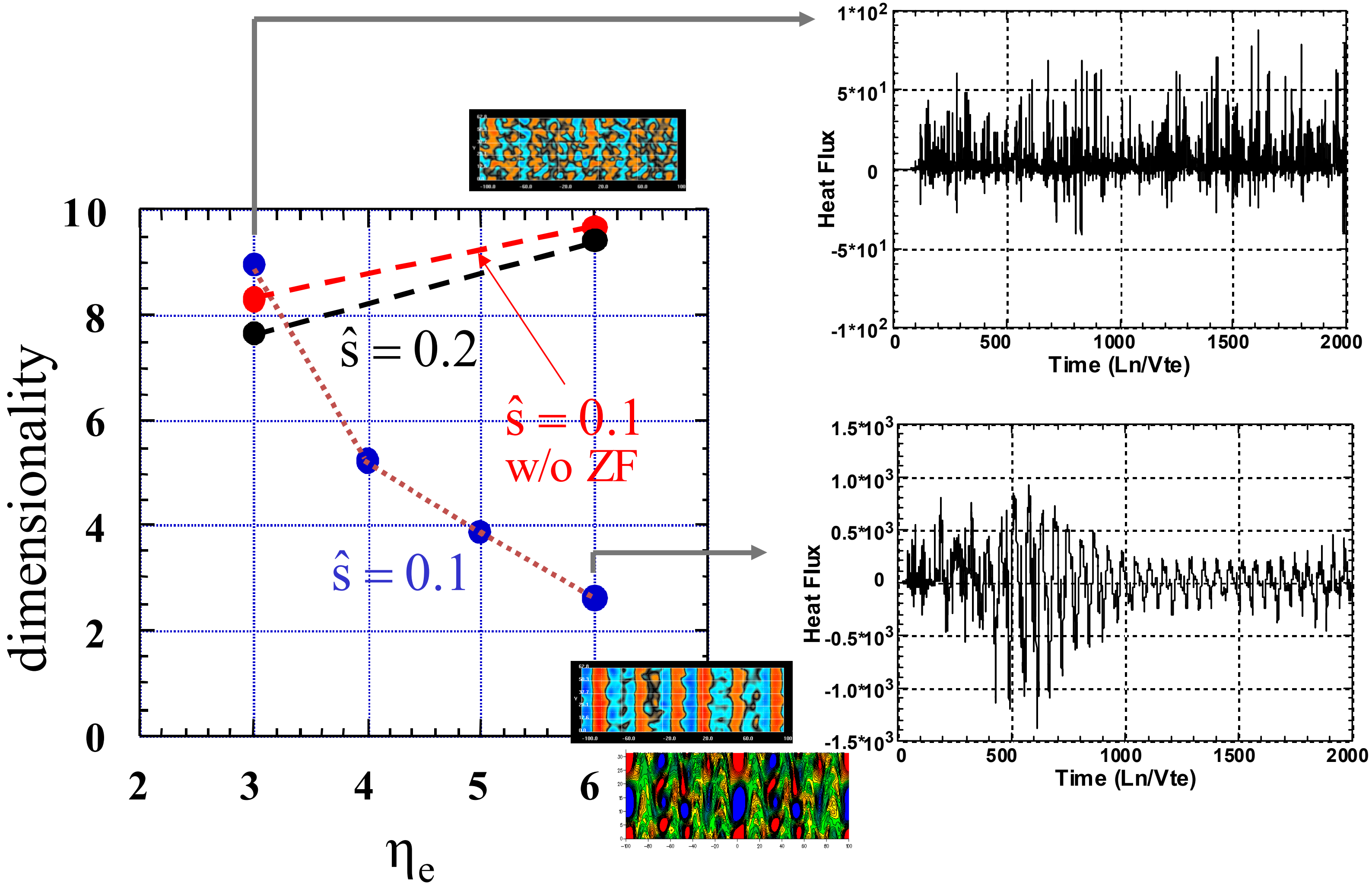
Turbulence dominated by large scale structure



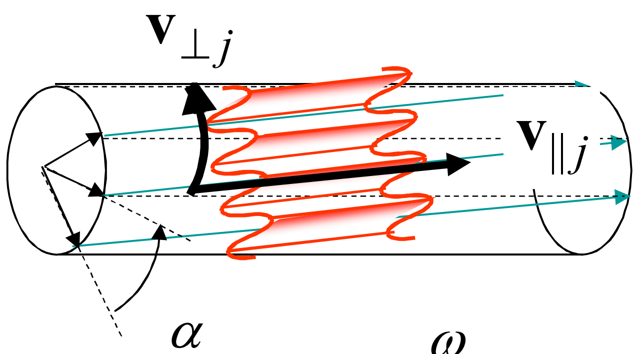
- Mixed turbulence with
  - micro-scale ETG
  - ETG driven ZF
  - ZF driven Large scale structure

Dimension of ETG driven turbulent plasma

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



Charney-Hasegawa-Mima equation



$$\varepsilon = \frac{\omega}{\omega_{cj}} << 1$$

$$\boldsymbol{v}_E = -\frac{\nabla_\perp \varphi \times \boldsymbol{B}_0}{B_0^{\ 2}} \qquad \mathbf{v}_d = -\frac{T_e \mathbf{B}_0 \times \nabla n_0}{e n_0 B_0^{\ 2}}$$

$$\boldsymbol{v}_p = \frac{1}{\omega_{ce} B_0} \frac{d\boldsymbol{E}}{dt} = \frac{1}{\omega_{ce} B_0} \left[\frac{\partial}{\partial t} + (\boldsymbol{v} \cdot \nabla) \right] \boldsymbol{E}$$

$$\frac{\partial n_i}{\partial t} - \nabla \cdot \left[n_i \left(\mathbf{v}_E + \mathbf{v}_p \right) \right] = 0 \qquad \tilde{n}_e = n_0(x) \frac{e\tilde{\phi}}{T_e}$$

neutrality condition

$$\tilde{n}_i = \tilde{n}_e$$

$$(1 - \nabla^2) \frac{\partial}{\partial t} \phi + \upsilon_d \frac{\partial}{\partial y} \phi - \underbrace{\left(\nabla \phi \times \boldsymbol{b} \cdot \nabla \right) \left(\nabla^2 \phi \right)} = 0$$

$$[\phi, \nabla^2 \phi] = \frac{\partial \phi}{\partial x} \frac{\partial \nabla^2 \phi}{\partial y} - \frac{\partial \phi}{\partial y} \frac{\partial \nabla^2 \phi}{\partial x}$$

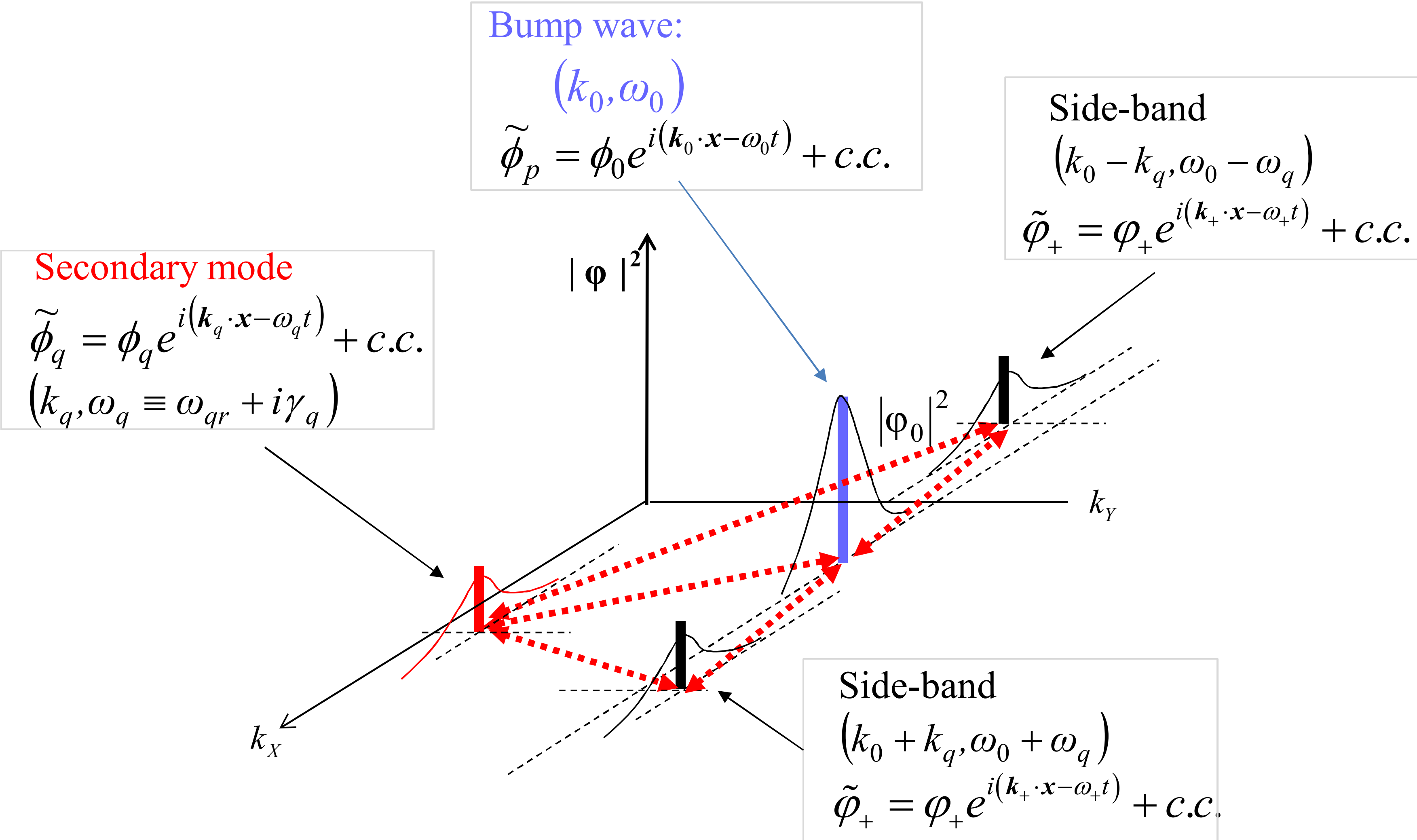
$$(1 - \nabla^2) \frac{\partial}{\partial t} \phi + \upsilon_d \frac{\partial}{\partial y} \phi - [\phi, \nabla^2 \phi] = 0$$

nonlinear term and origin of mode coupling

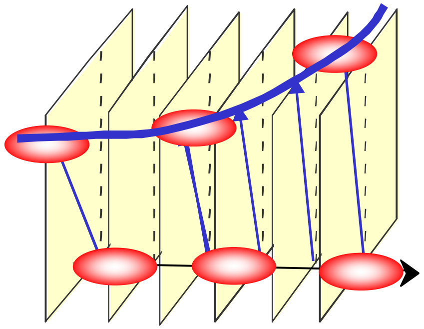
Modulational feedback loop and instability

Chen, et al, PoP 7, 3129, '00, Li and Kishimoto, PoP, 9, '02

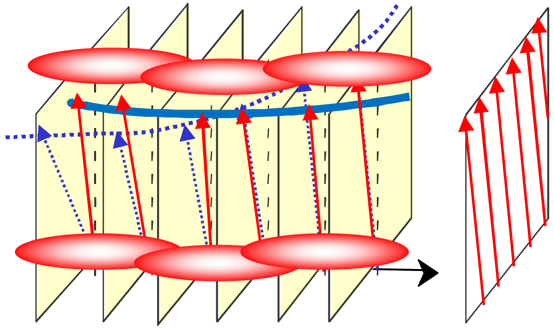
$$\left(1-\nabla_\perp^2\right)\frac{\partial}{\partial t}\varphi_k = \frac{\partial}{\partial y}\varphi_k + \sum_{k=k'+k''}\left[\varphi_{k'},\nabla_\perp^2\varphi_{k''}\right]$$



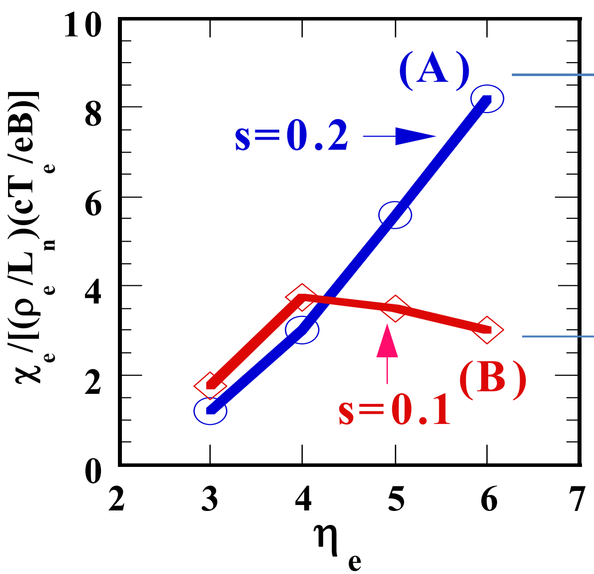
Conditional flow generation in high pressure region



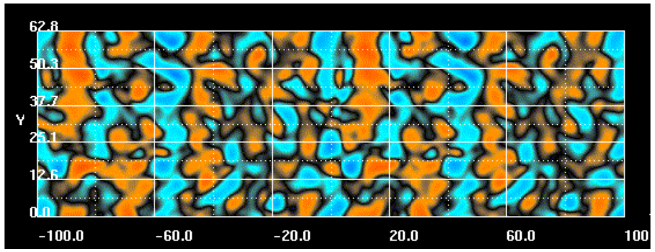
normal magnetic shear
(linearly more stable)



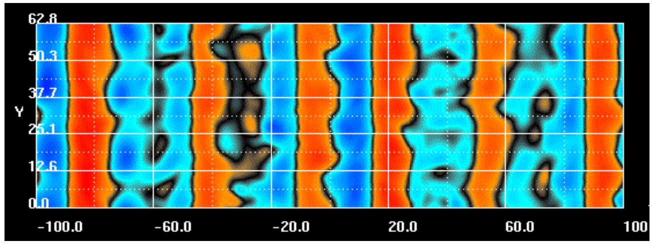
weak magnetic shear
(linearly unstable)



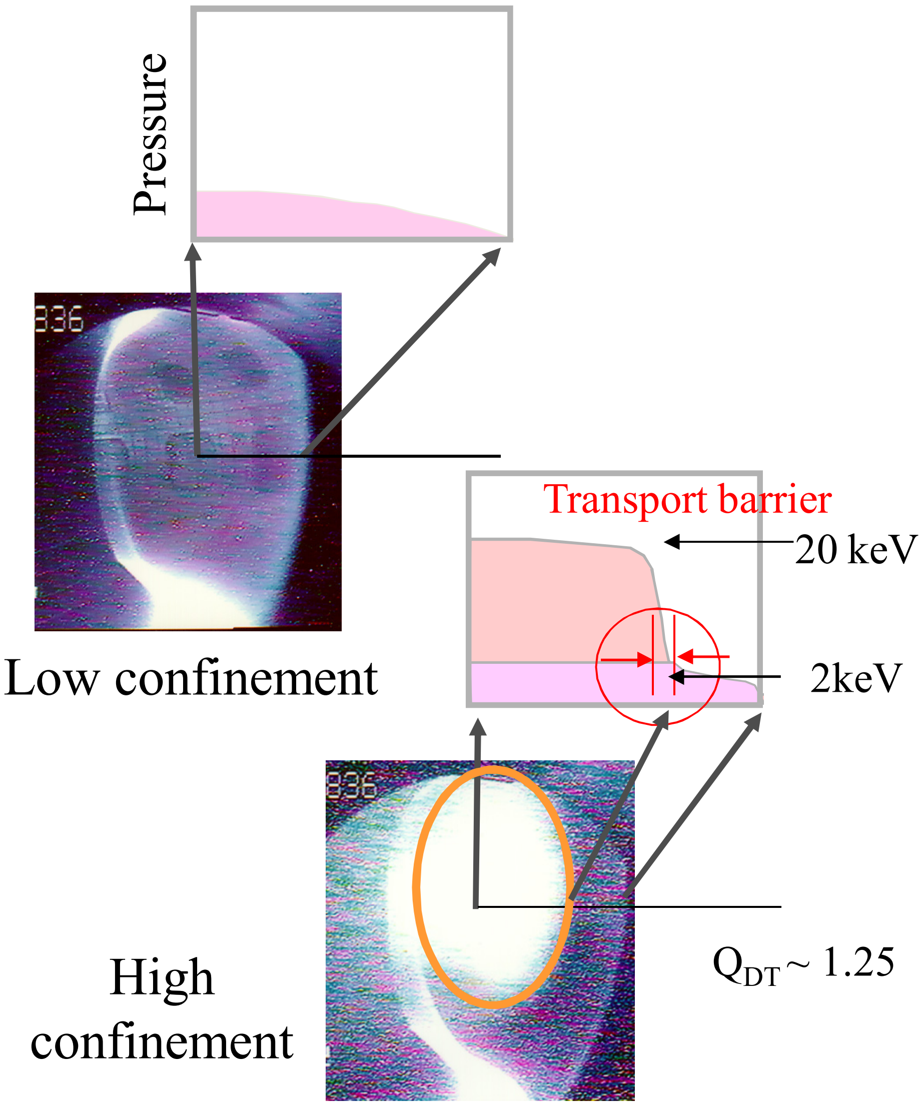
(A) S=0.2

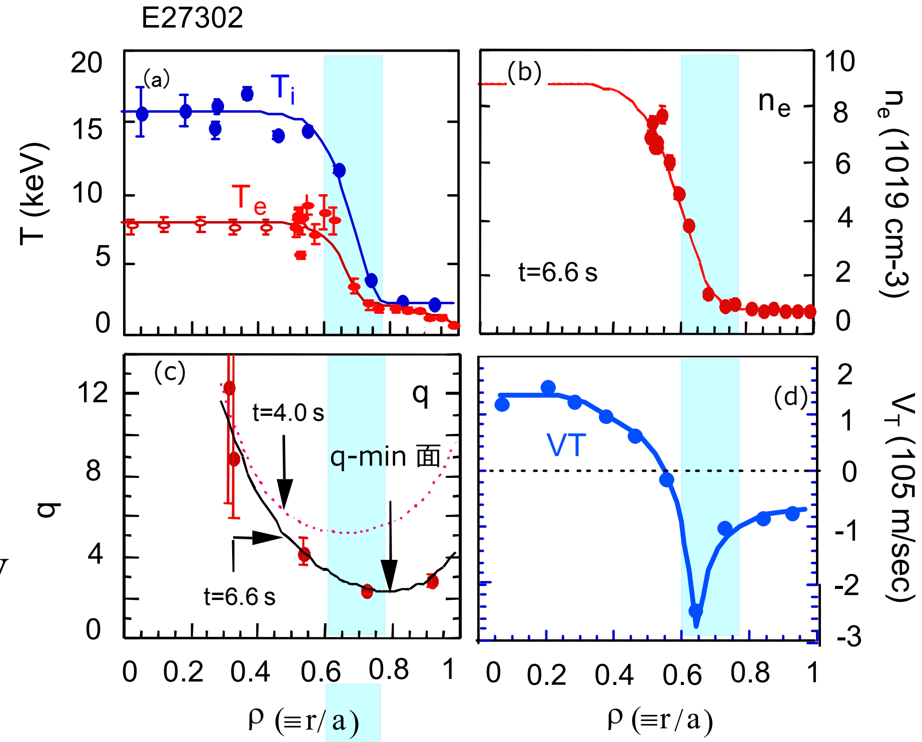


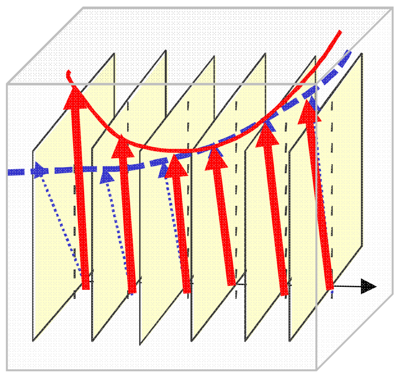
(B) S=0.1 : weak magnetic shear



High performance plasma (internal transport barrier : ITB) achieved by having a structure





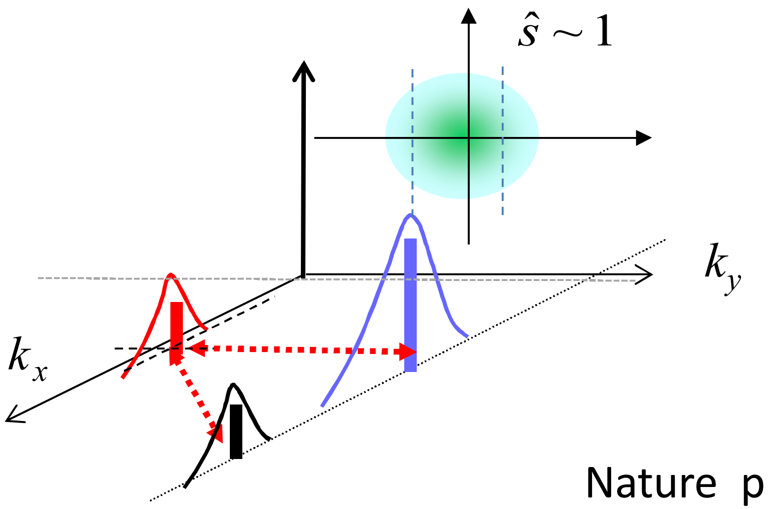


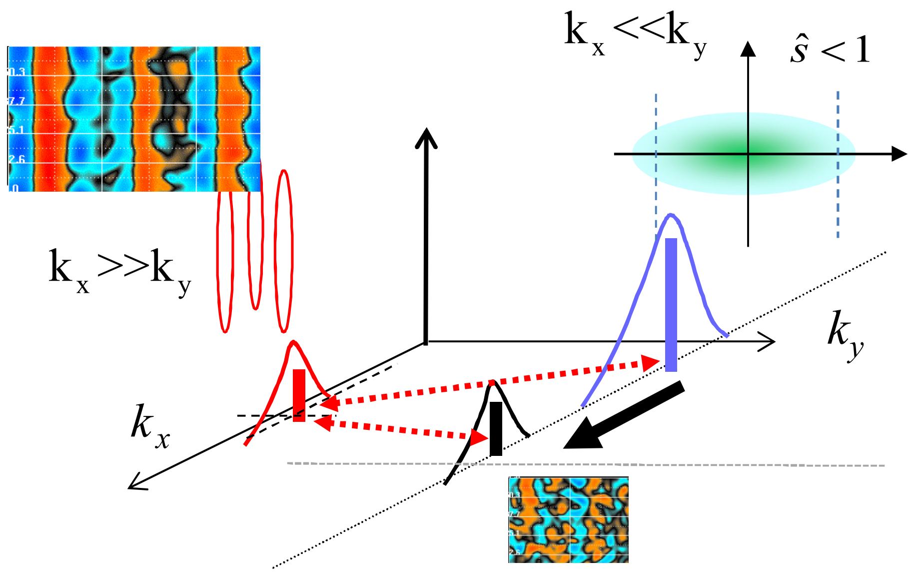
$$q(r) = \frac{2\pi}{\alpha} = \frac{r}{R}\left(\frac{B_T}{B_P}\right)$$

$$\hat{s} = \frac{r}{q}\frac{\partial q}{\partial r}$$

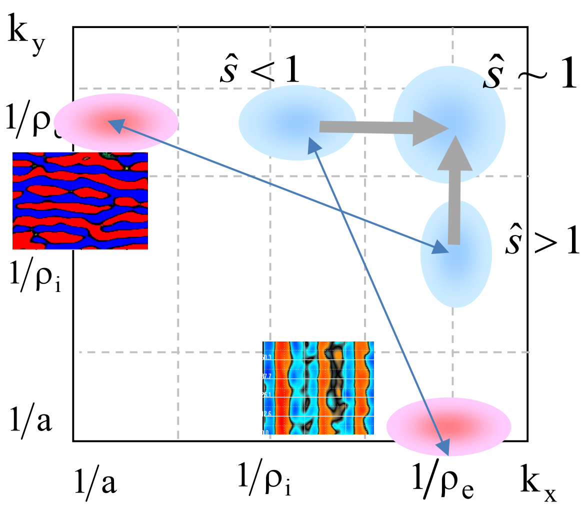
Control of secondary instability via maternal turbulence

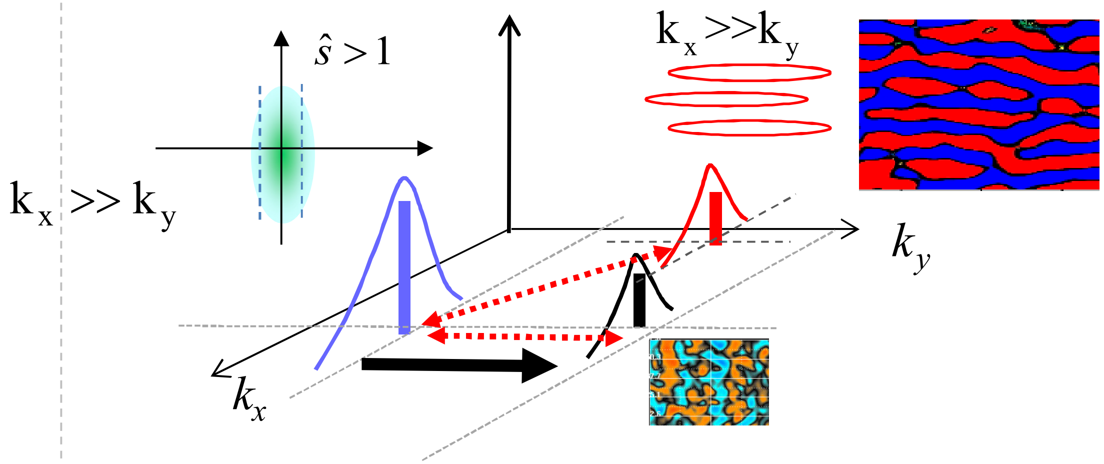
Li and Kishimoto, PoP 12, 062308 (2005)





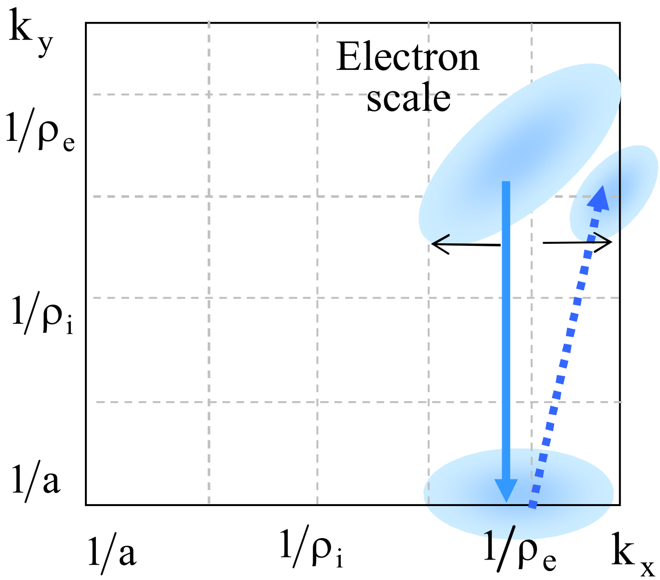
Nature prefers
"Homogenous turbulence"



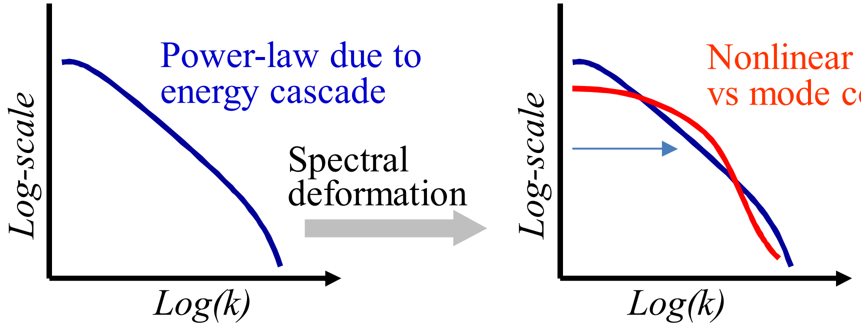


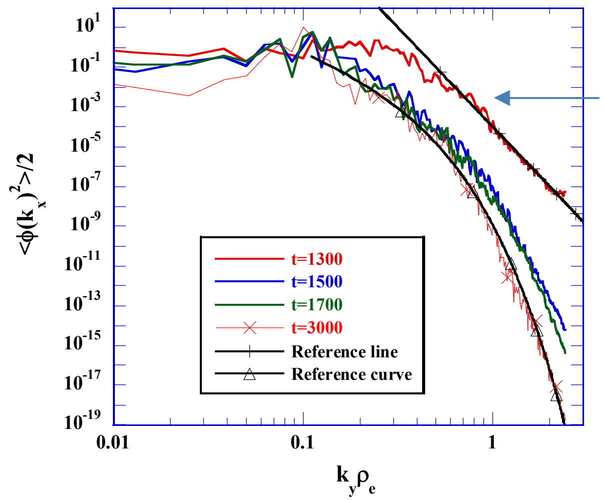
Turbulent spectrum in the presence of zonal flows

Scattering of turbulence
by zonal flows



Transfer of turbulent energy to stable dissipation region

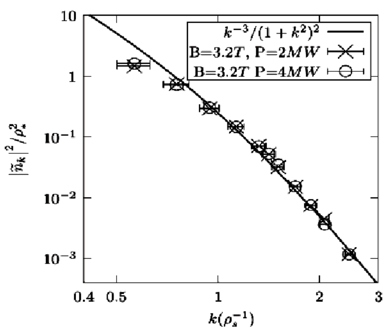




Early state before ZF and KH growing (t=1300)

Final state with KH (t=3000)

Theoretical spectral scaling
(shell model to HW turbulence)



$$<|\tilde{n}_k|^2> \sim <|\tilde{\phi}_k|^2> \sim \frac{k^{-3}}{(1+k^2)^2} e^{-\lambda k}$$

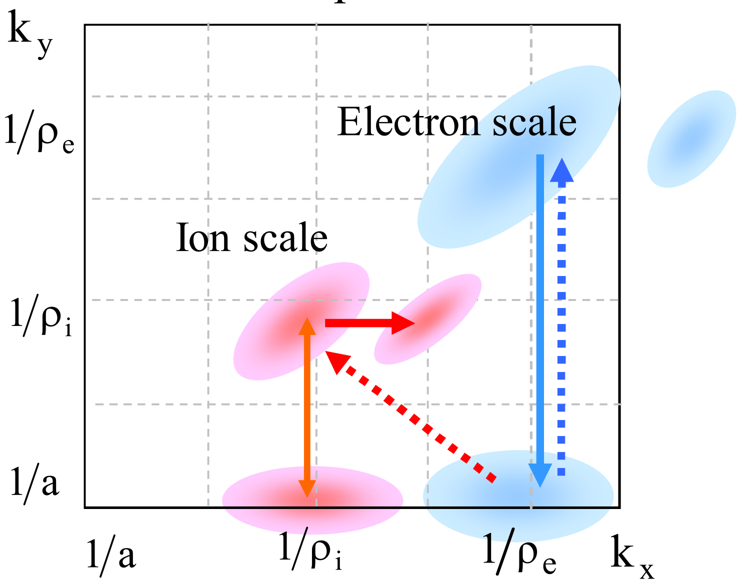
Gurcan, et al, PRL(2009)

$$<\phi^2(k_x)> \sim \frac{0.002 k_x^{-3}}{(1+k_x^2)^2} e^{-13.0 k_x}$$

Coupled Kolmogorov-exponential law

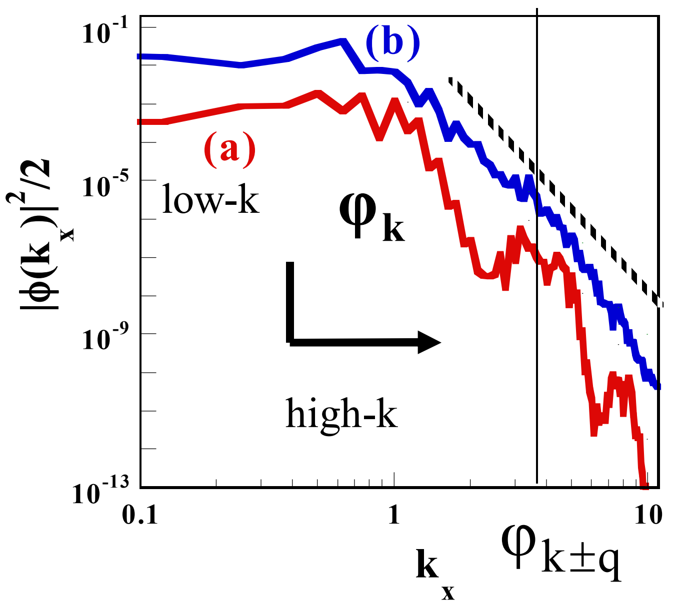
Effect of ETG-driven ZF on ITG turbulence

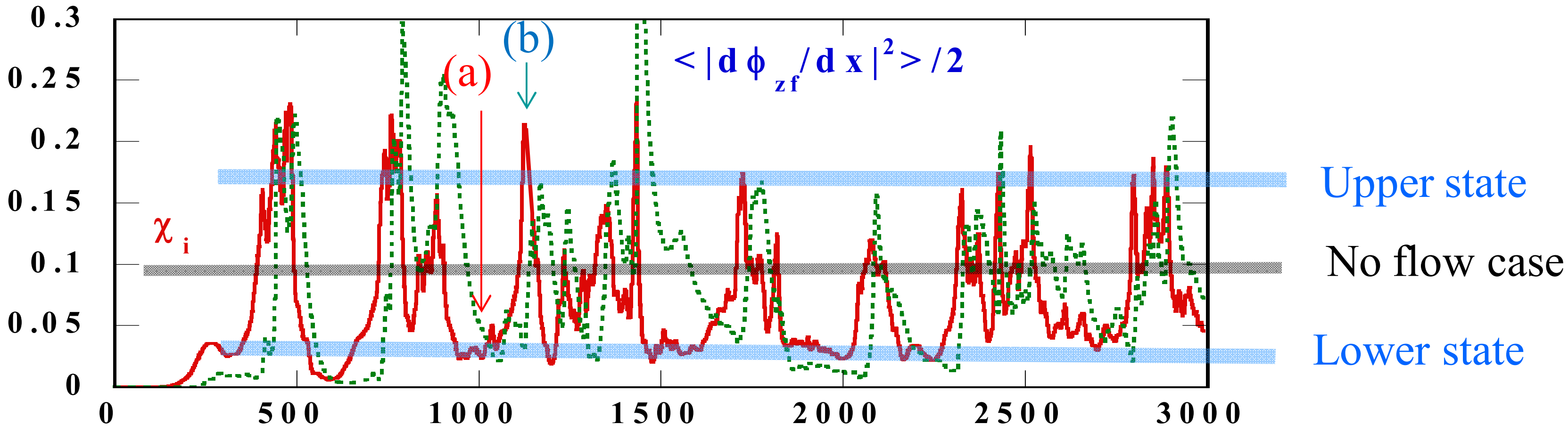
Effective dissipation due to ETG driven ZF



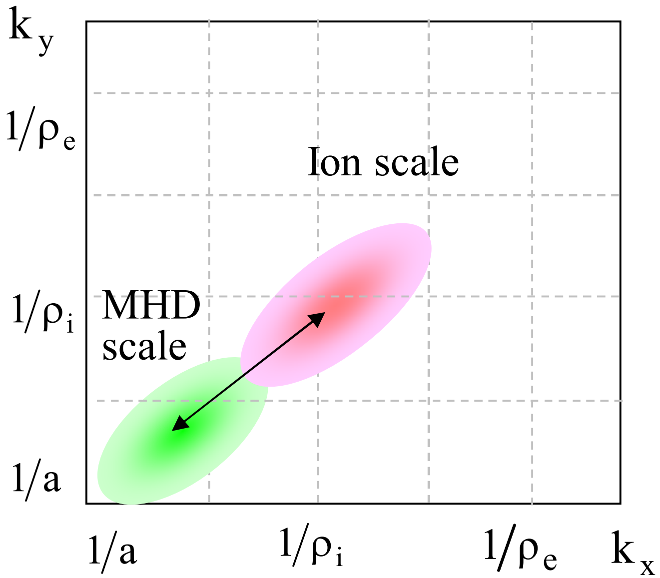
- Scattering of ITG energy to high-K
- Reducing ITG zonal flows

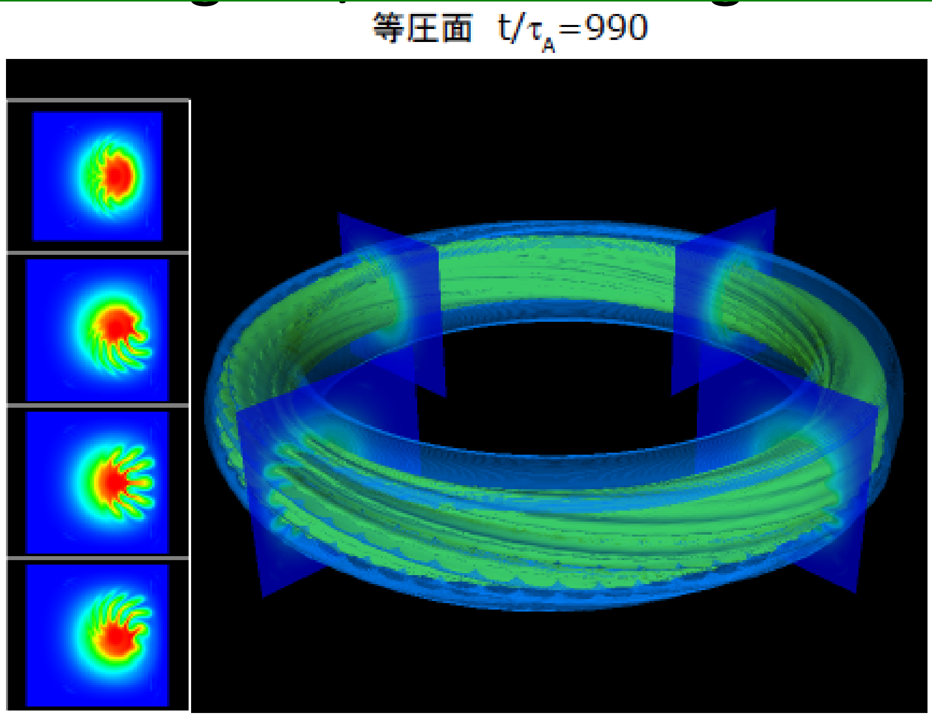
$\varphi_q = A_0 \Gamma_0^{1/2}(q)\cos(qx)$

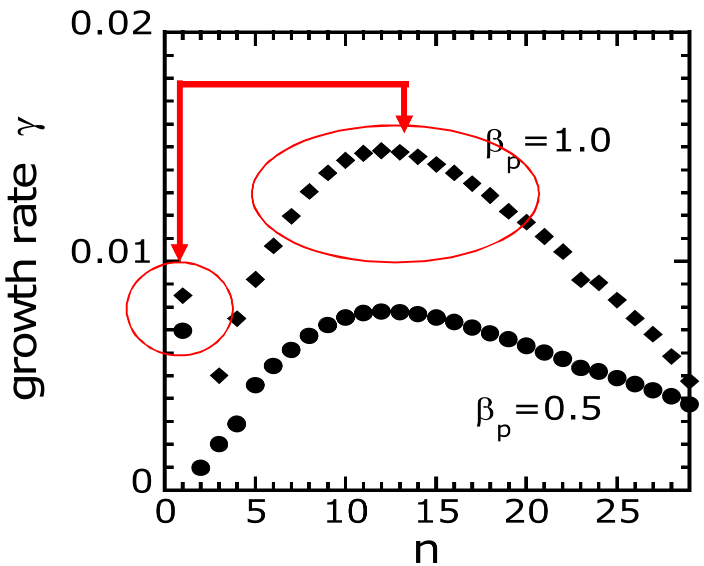




Coupling between 1/1 kind and high m/n ballooning mode







Structural deformation of ballooning modes, leading dissipation

$$\cdots\frac{m-2}{n-1},\frac{m-1}{n-1},\frac{m}{n-1},\frac{m+1}{n-1},\frac{m+2}{n-1}\cdots$$

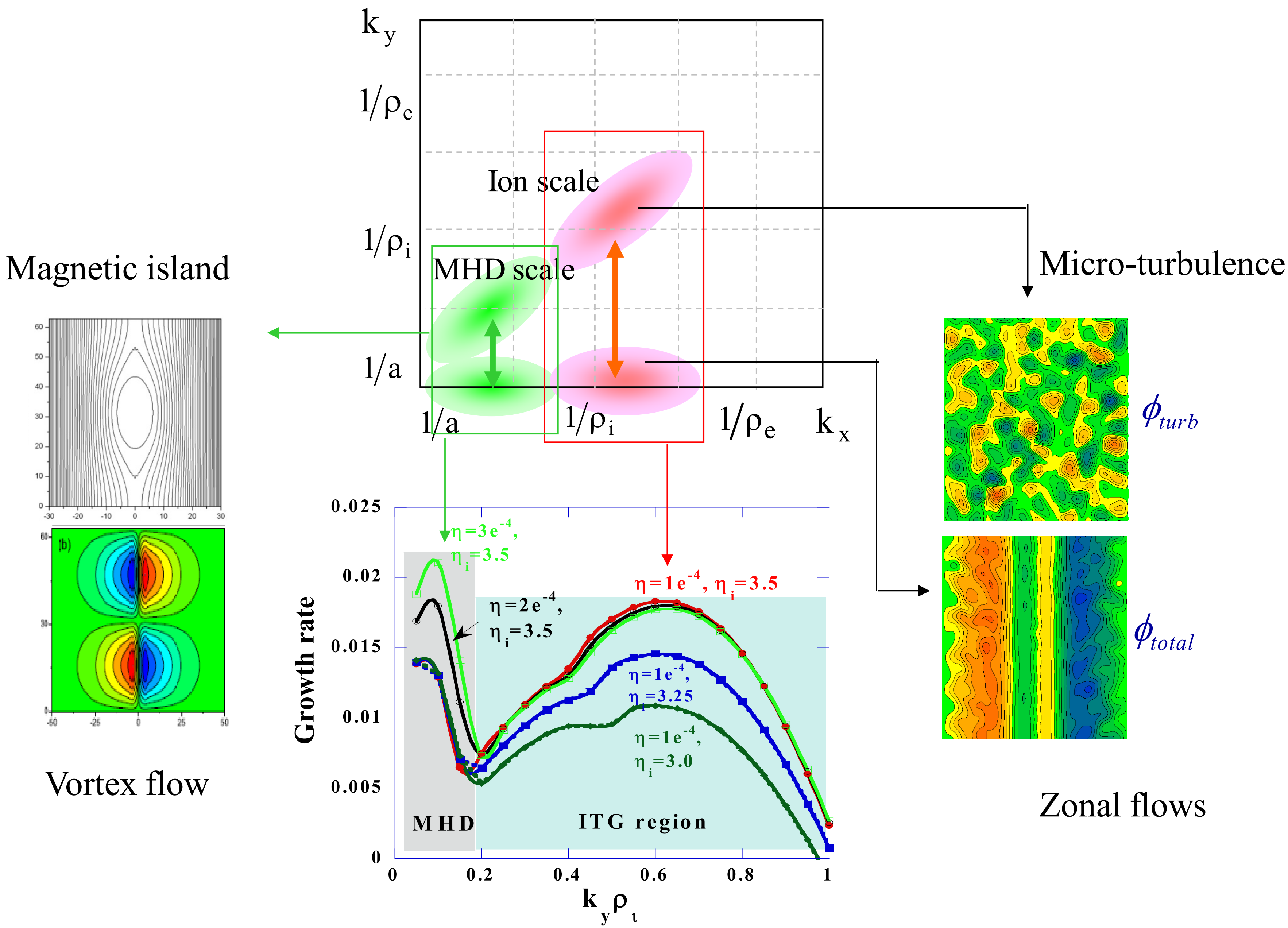
$$\cdots\frac{m-2}{n},\frac{m-1}{n},\frac{m}{n},\frac{m+1}{n},\frac{m+2}{n}\cdots$$

$$\cdots\frac{m-2}{n+1},\frac{m-1}{n+1},\frac{m}{n+1},\frac{m+1}{n+1},\frac{m+2}{n+1}\cdots$$

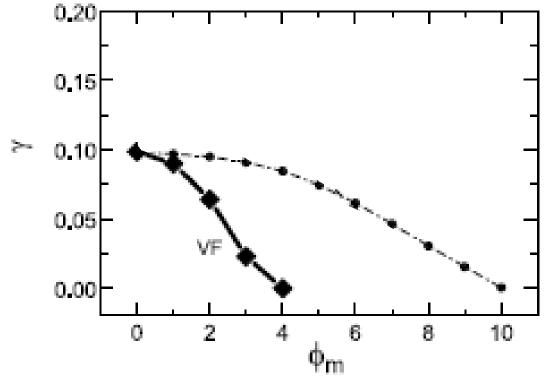
helical ballooning mode

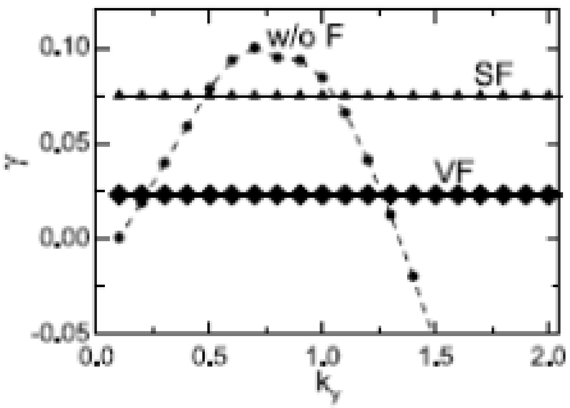
Y. Kagei and Y. Kishimoto:
Full set non-linear MHD simulation 2006, JPS

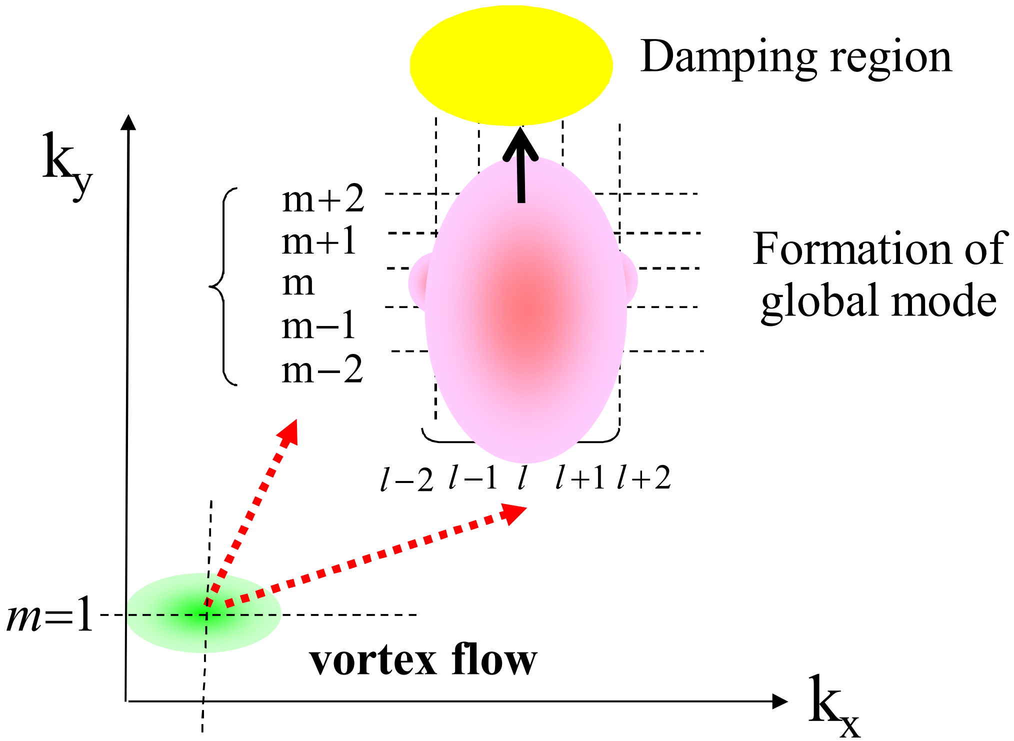
Physics ingredients in mixed MHD and turbulence model



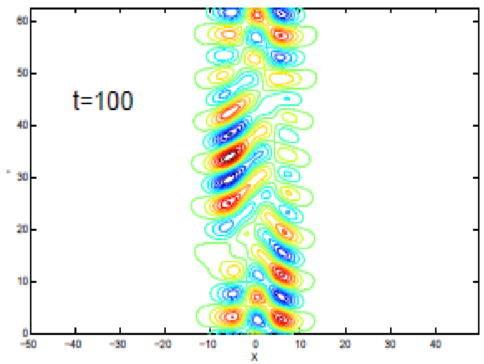
Coupling between vortex flow and microinstability



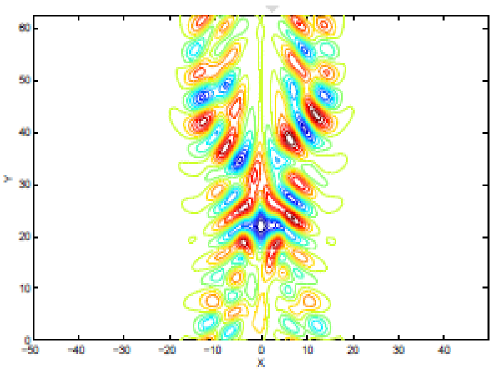




w/o vortex flow



with vortex flow



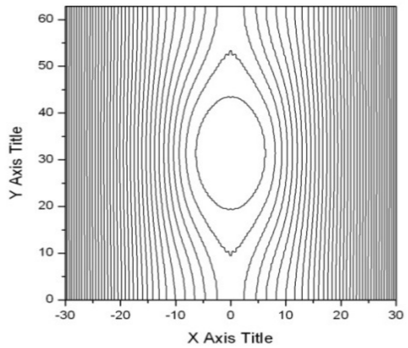
$$\Lambda(f_k) \equiv \frac{1}{2}\frac{\partial}{\partial x}\phi_{TX}\left(ik_{y+}f_{ky+} + ik_{y-}f_{ky-}\right)$$

$$+\frac{1}{2}ik_T\phi_{TX}\frac{\partial}{\partial x}\left(f_{ky+} - k_{y-}\right)$$

$$k_{y\pm} = k_y \pm k_T$$

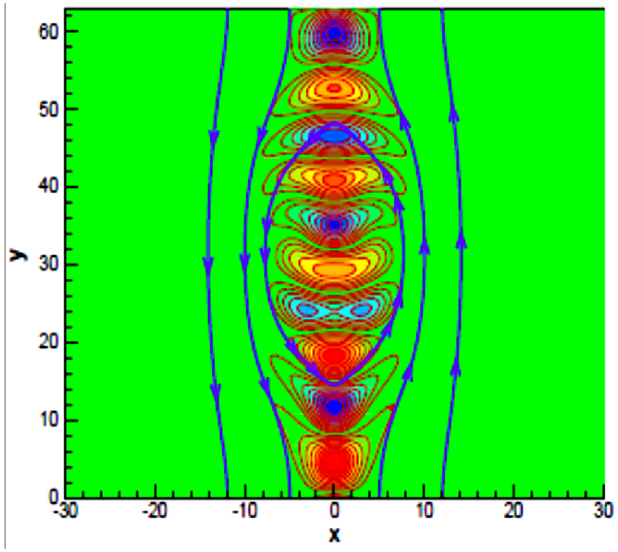
Magnetic island-induced ITG (MITG) mode

Wang et al. PoP 16, 060703 (2009)

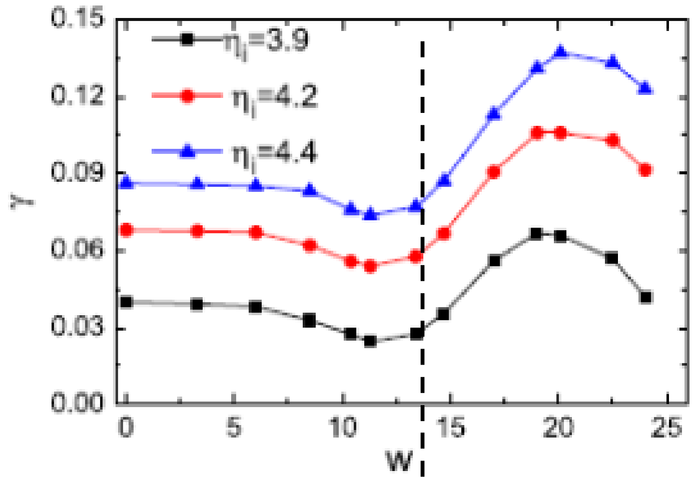


$$\psi = \hat{s}x^2/2 + \tilde{\psi}\cos(k_T y)$$

$$w = 4\sqrt{\tilde{\psi}(0)/\hat{s}}$$

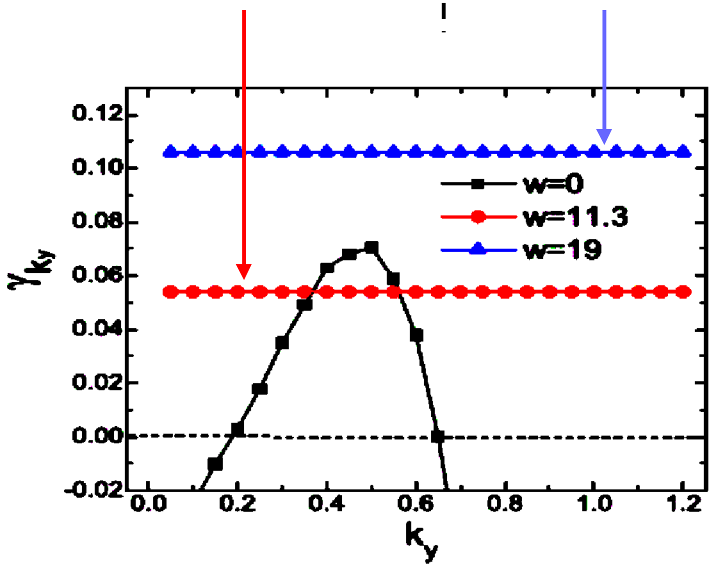


MITG (Magnetic island inuced ITG mode)



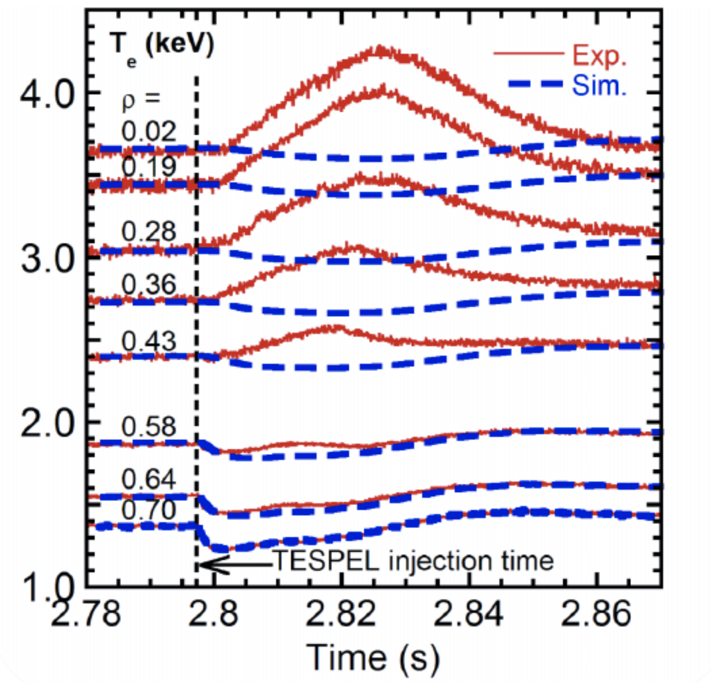
Stabilization due to poloidal mode coupling

Destabilization due to MITG mode

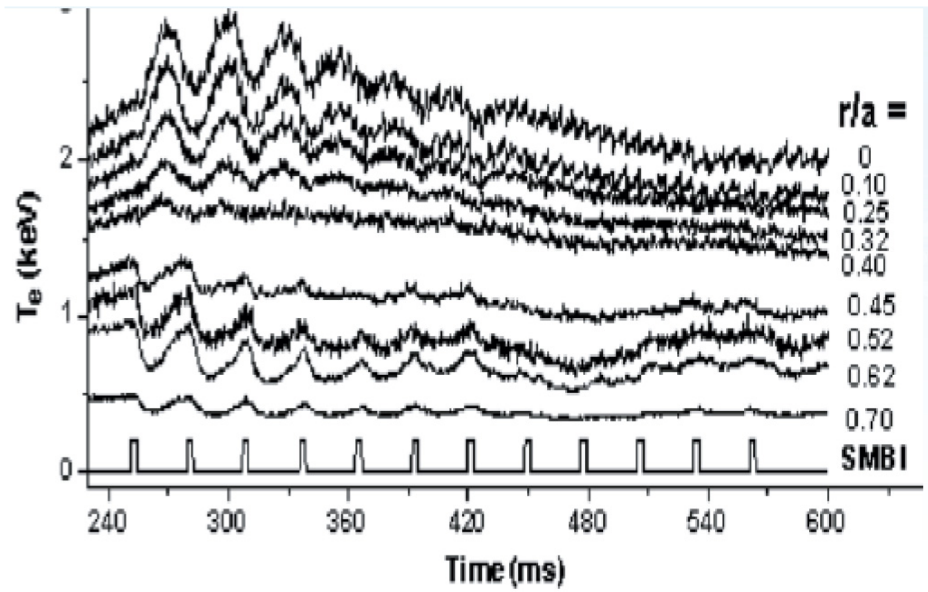


Non-local response of plasmas from edge to core

Cold pulse propagation from edge to center, which is changed to heat pulse leading to the increase of central Te



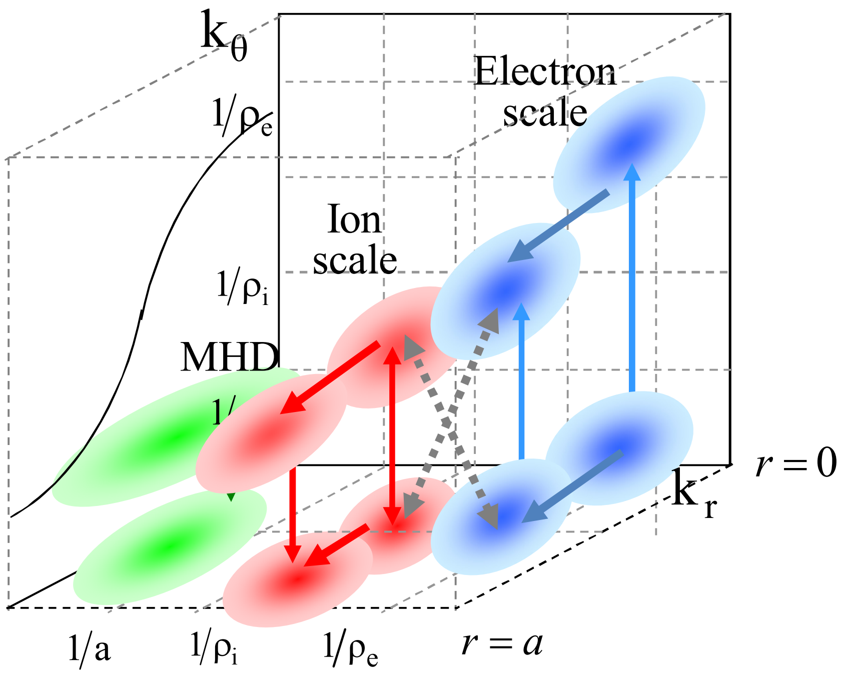
Propagation of perturbed Te due to TESPEL in LHD
N. Tamura, *et.al.*,
Phys. Plasmas 12, 110705 (2005)



Spatial propagation of perturbed Te due to SMBI
S. H. Juan, *et.al.*, Plasmas Phys. Controlled Fusion 52, 045003 (2010)

How multi-scale interaction couples in space

Coupling between Fourier space and real space



- Spatial dynamics of fluctuation and transport

✓ Diffusive/non-diffusive transport
✓ Trigger/onset of fluctuation and intermittency/burst
✓ Transition/ bifurcation dynamics, explosive/sudden event
……..

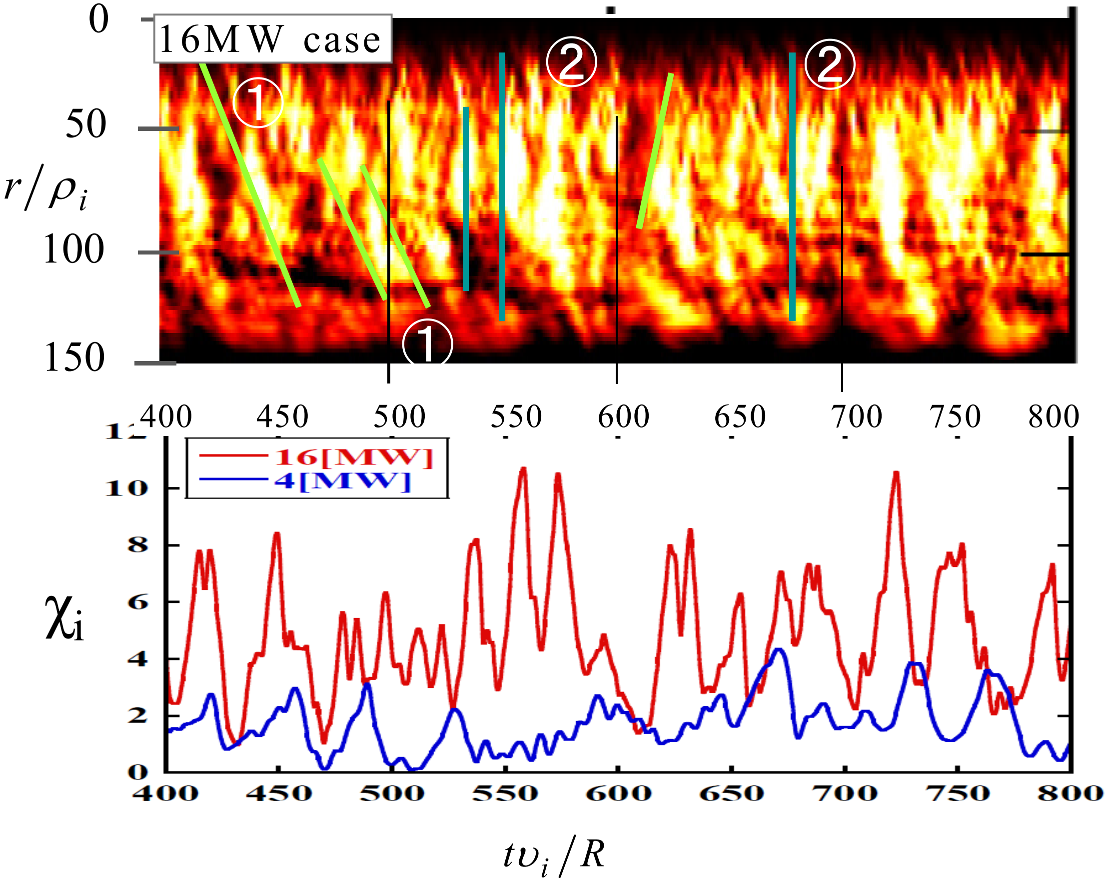
- Turbulence-profile interaction

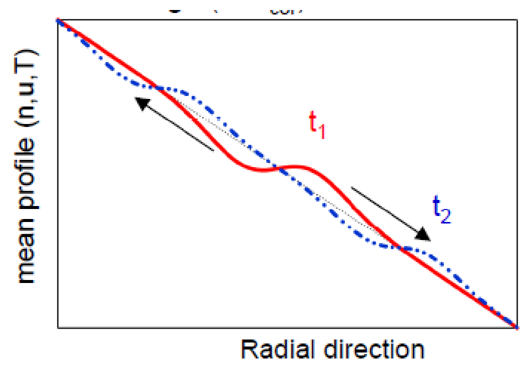
ITG turbulence and profile formation

① Diffusive (Gaussian) transport

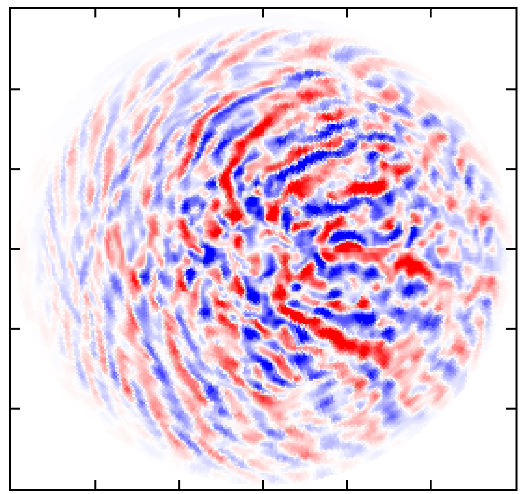
② Fast avalanche (ballistic) transport (~ v_d) coupled with stationary ExB staircase

③ Global intermittent transport (meso to macro scale) due to the formation of radially extended toroidal structures





Diamond-Hahm PoP (1995)

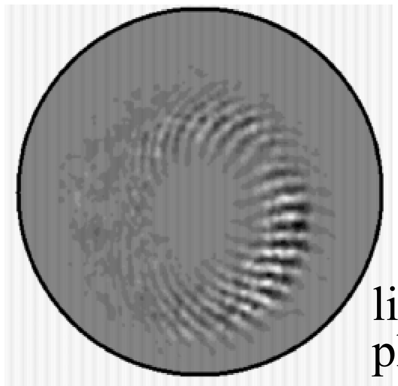


Turbulent spreading and diffusion

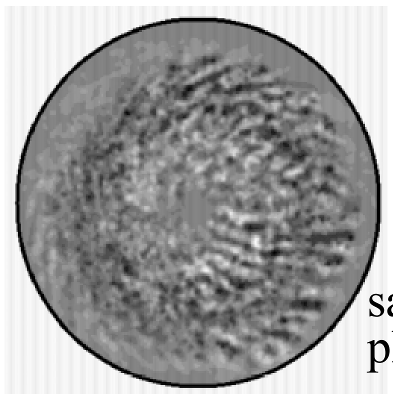
Some evidence from numerical simulation

Garbet, et al., NF, '94, Sydora, et al., PPCF, '96, Parker et al., PoP, '96, Lin, et al., IAEA, '02, also PRL, '02

ITG GK simulation



linear phase



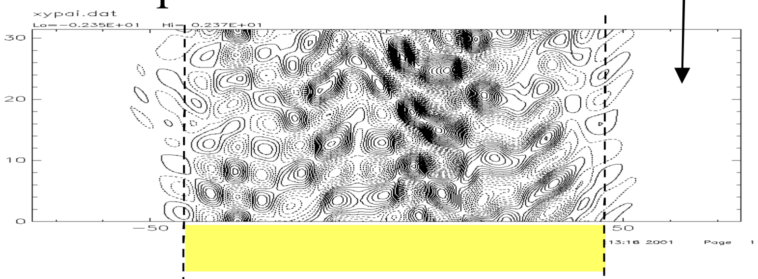
saturation phase

[*Sydora, et al., PPCF, '96*]

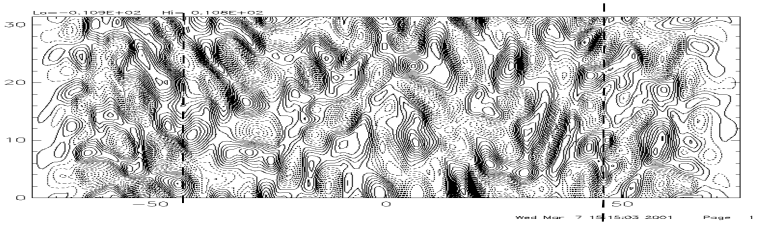
ETG GF simulation

no rational surface (no damping)

linear phase



steady state phase

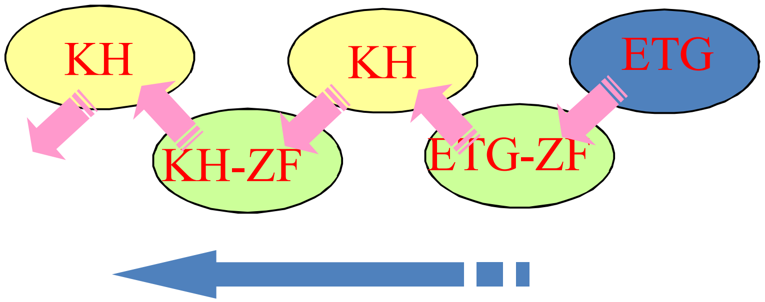


[*courtesy of J-Li*]

Spatial convection of instability

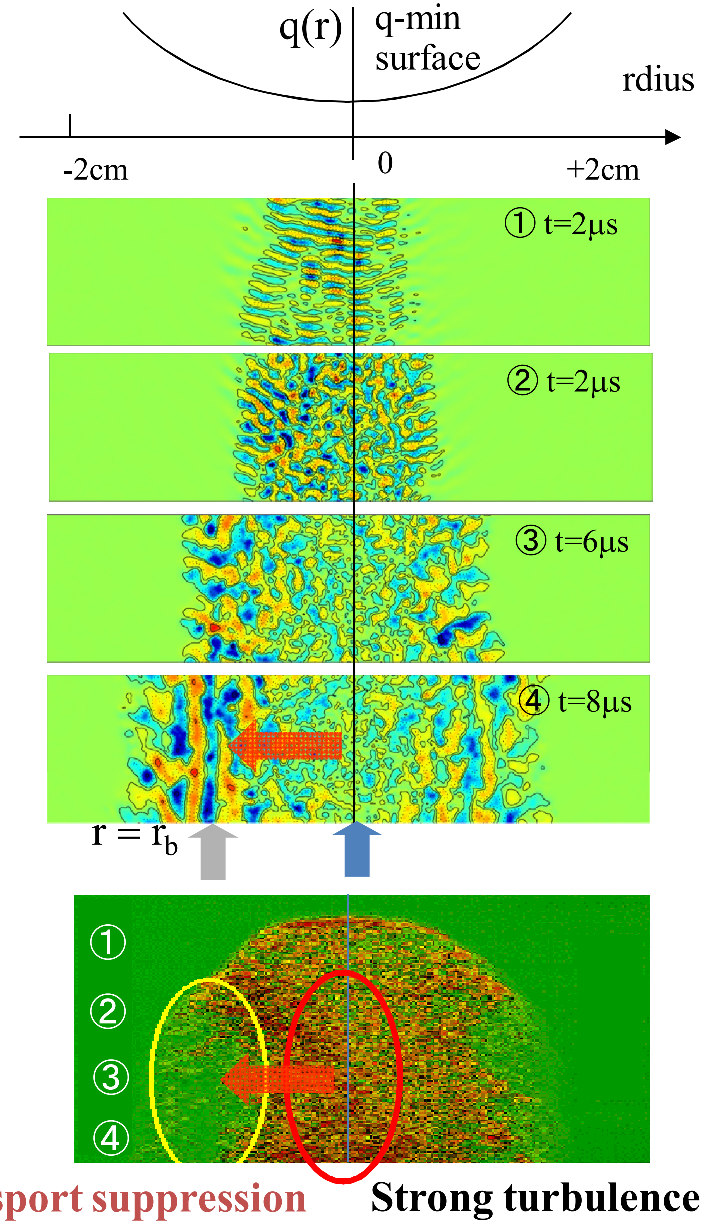
- Increase of linear instability source for reversed shear plasma

- Turbulent energy is "nonlinearly" converted to flow component through "spatial dimension".



Origin of "structure" is anomalous transport!!

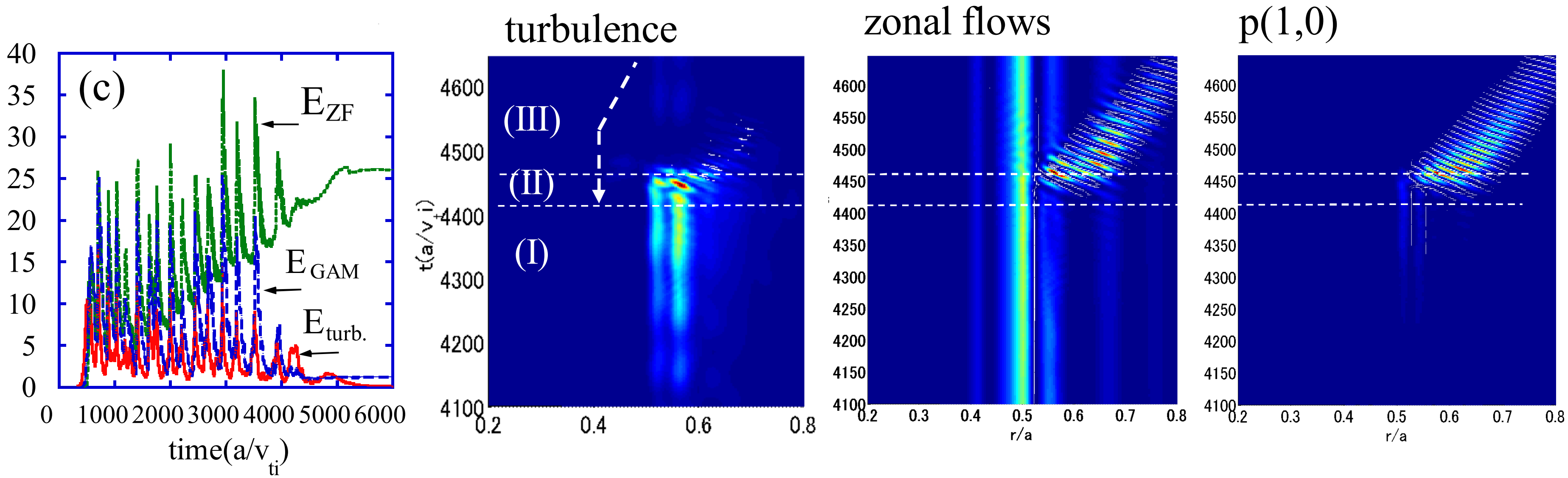
[*Idomura, et al., PoP, '00*]

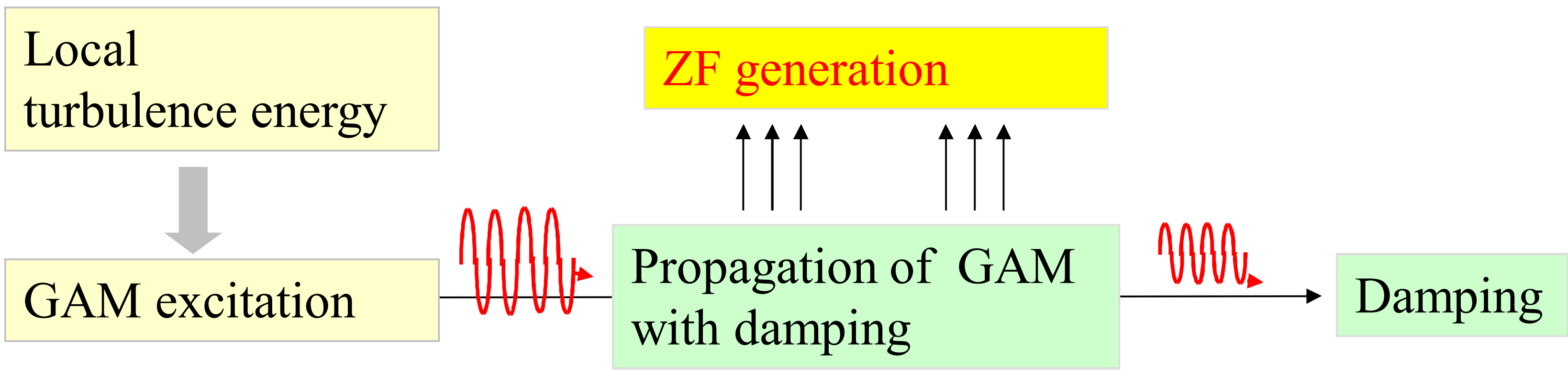


Non-local transport of turbulent energy

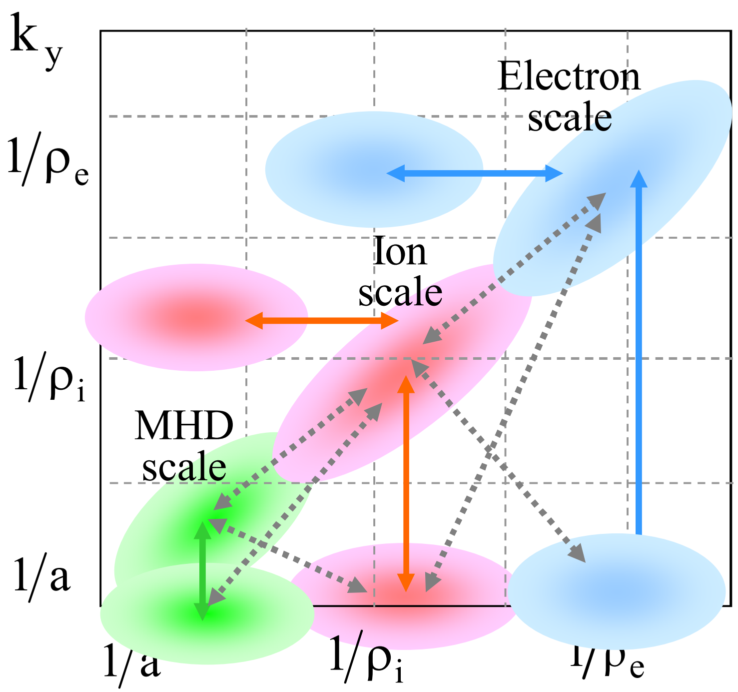
Non-local energy transfer through GAM

Intermittent transport associated
with the geodesic acoustic mode near critical gradient regime
Miki, Kishimoto et. al., PRL 99, 145003, (2007)





Interaction among different scale fluctuation



Zonal modes, streamers,
Larger scale structure

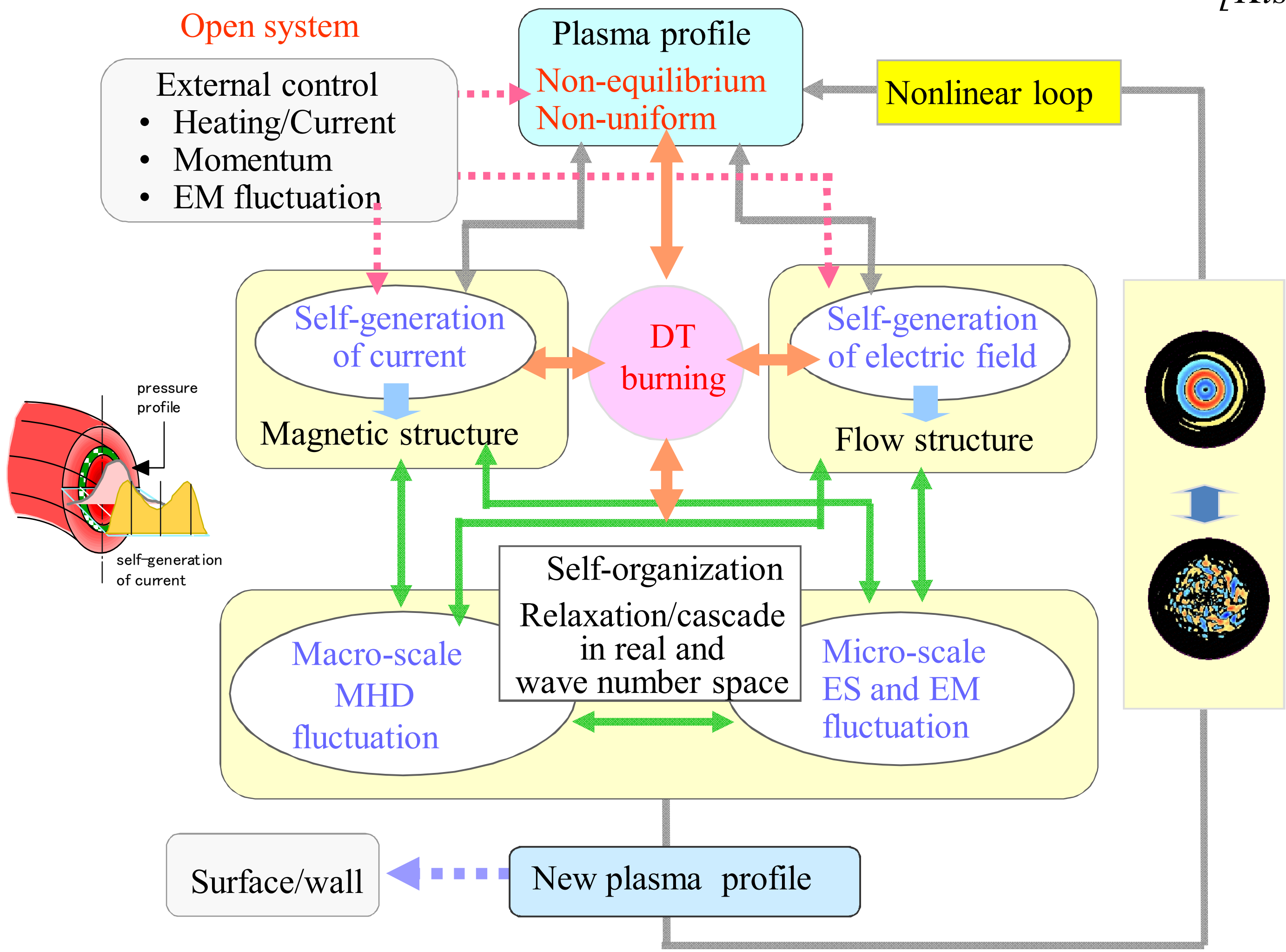
1. Linear free energy source

2. Non-linear free energy source
   - Generation of secondary fluctuations with different spatio-temporal
   - Mixed state with turbulence, zonal modes and large scale fluctuations (back-reaction)

3. Interaction/interference among different scale fluctuations
   - Direct and in-direct interaction with different scale fluctuations
   - Physical mechanism of the interaction and energy transfer channel

Complex nonlinear loop system of structural plasma

[Kishimoto, Simulation, 02]



- Neoclassical dynamics
- Fluctuation and self-organization dynamics
- Global linkage as nonlinear loop

Identification of the degree of freedom of hierarchical complex system and exploring the "control methodology"