Turbulence Simulation in General Geometry

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in collaboration with

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Outline

- Turbulence spreading and global turbulence
  – the effects of zonal flows
  – turbulence spreading through a transport barrier — the effects of $\mathbf{E} \times \mathbf{B}$ shear flow
- Mutual interaction between turbulence and zonal flows in collisionless plasma
- Nonlinear energy transfer in ITG turbulence

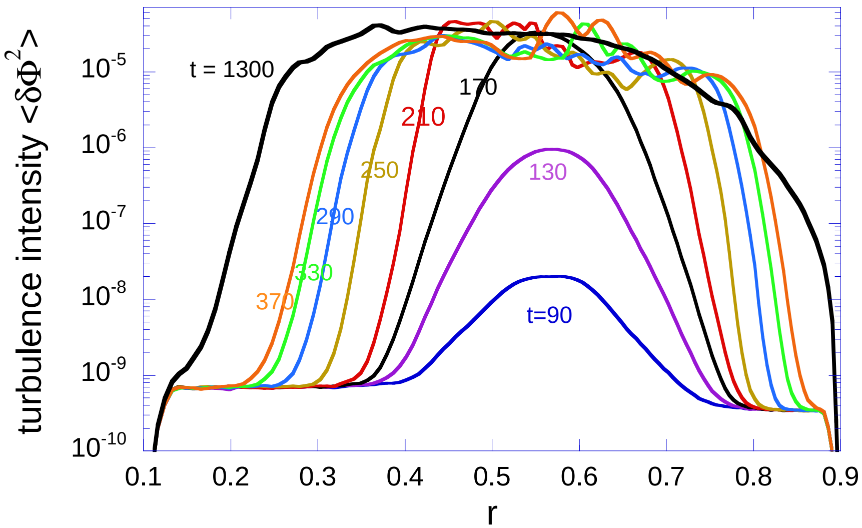
Nonlocal Physics of Turbulence Transport

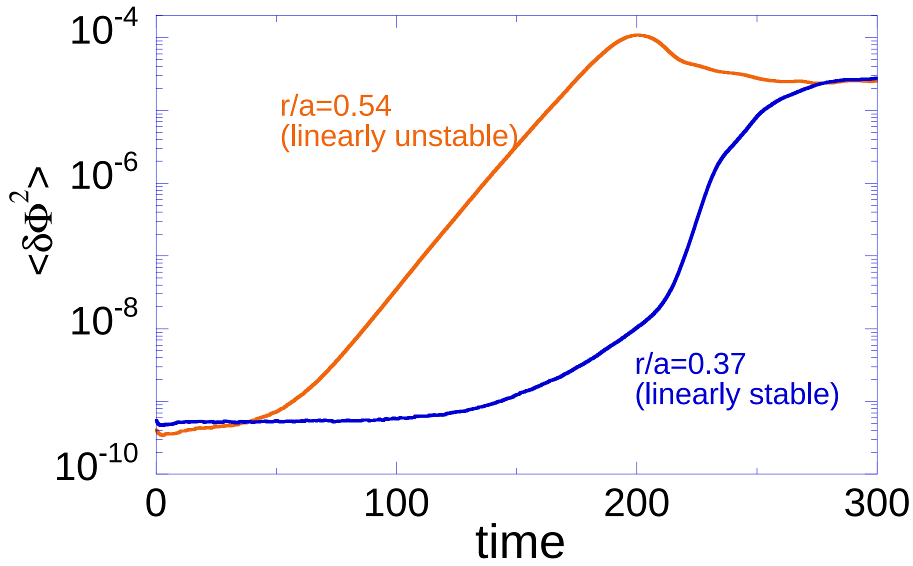
- Turbulence propagation (Garbet et al.) $\rightarrow$ transport nonlocality: transport scaling (Lin et al.); edge-core coupling(Hahm et al.); size scaling of drift-wave intensity (Chen, White & Zonca); turbulence tunneling through stable gaps (Gurcan & Diamond); transport scaling (Waltz et al.); $\cdots$

- To understand possible mechanisms of turbulence spreading
  – linear toroidal coupling;
  – nonlinearity in waves;
  – self-generated zonal flow effects

- Can turbulence penetrate a transport barrier with strong $E \times B$ shear?
  $\rightarrow$ insight into transport barrier physics

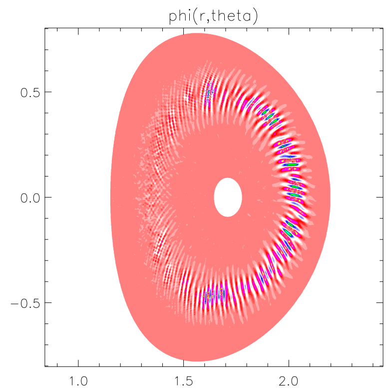
Global Turbulence and Transport Nonlocality due to Turbulence Propagation



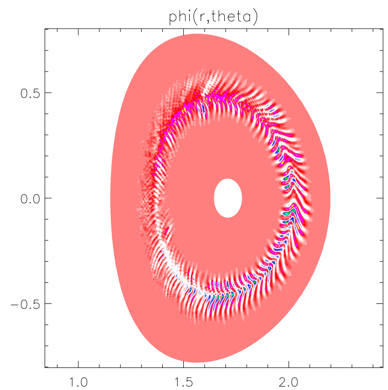


- Simulation of ITG turbulence using general geometry GTC
- Turbulence spreads both inward and outward into linearly stable zones
- Two-phase spreading: i) early small, linear spreading and ii) a more diffusion-like propagation takes over after the saturation of the linear instability, radially extending the fluctuations to linearly stable zones. Fluctuation intensity level is comparable to original unstable zone

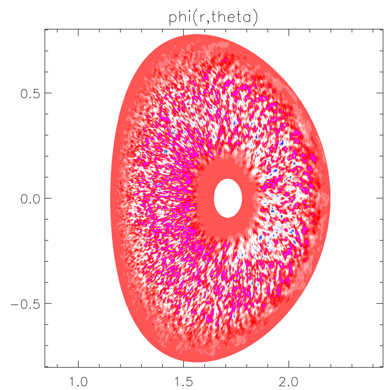
Global Turbulence Development



- $t = 150 L_T / c_s$: Elongated radial streamers linearly driven in $0.42 < r < 0.76$;

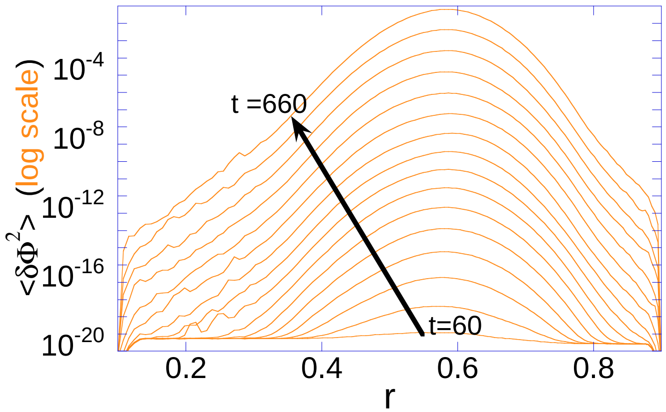


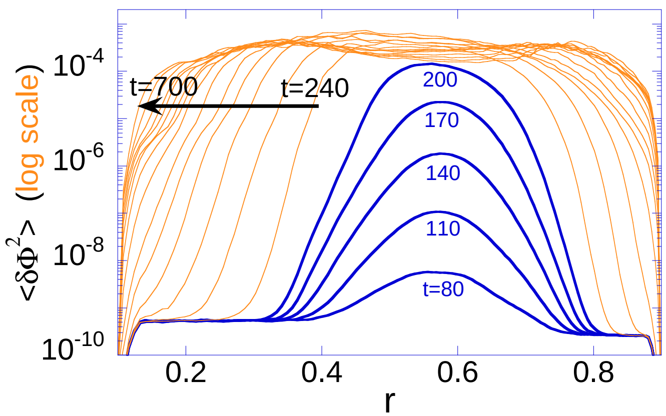
- $t = 190 L_T / c_s$: Turbulent eddies broken up by self-generated zonal flow during nonlinear saturation phase;

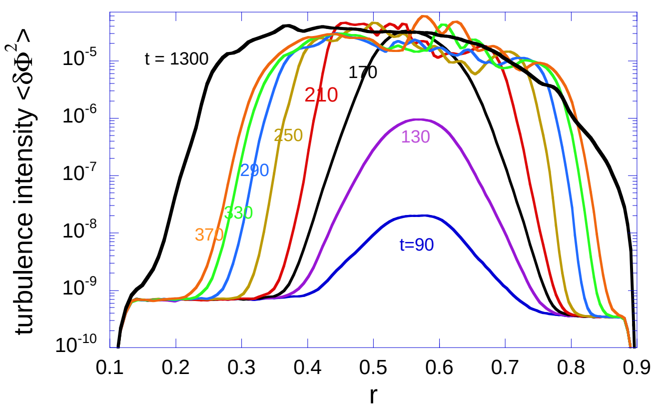


- $t = 1300 L_T / c_s$: Evolution into widely spread global turbulence

Turbulence Always Spreads, But with Different Nature





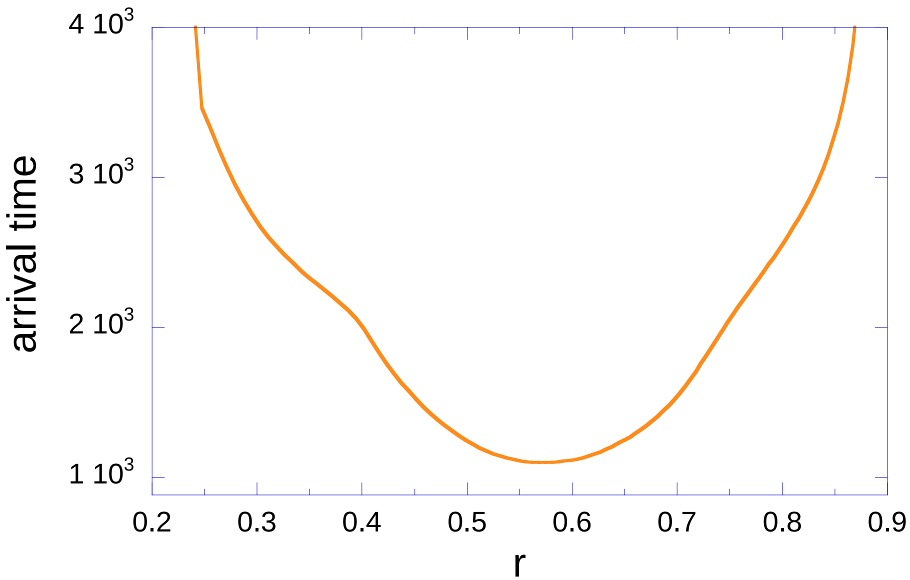


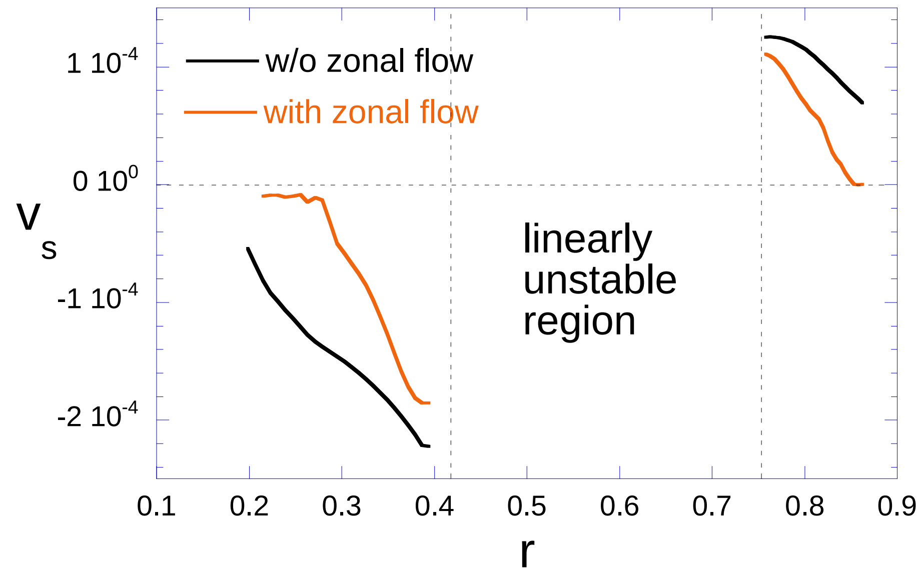
- LINEAR simulation with all modes: toroidal mode coupling induces convective propagation (Garbet et.al); uniform $v_s \sim 1.2(\rho_i/R_0)c_s$, independent of $< \delta\phi^2 >$

- NO ZONAL FLOWS: diffusive nature induced by nonlinear coupling (no longer convective); making spreading faster

- WITH ZONAL FLOWS:
  $\rightarrow$ lowers $< \delta\phi^2 >$ by a factor of 10
  $\rightarrow$ reduces turbulence spreading

Zonal Flow Effects on Turbulence Spreading





- The propagation velocity v_s of turbulence front is obtained by measuring the moving velocity of a given turbulence intensity
- v_s decreases as the flunctuation propagates away from the ITG source region, showing strong dependence on turbulence intensity (theory predicts $v_s \propto |\delta\phi|^2$, Gurcan et al. '05)
- The effects of zonal flows on turbulence spreading:
  $\rightarrow$ lowers $< \delta\phi^2 >$ (by a factor of 10)
  $\rightarrow$ slows down spreading & reduces the spreading extent

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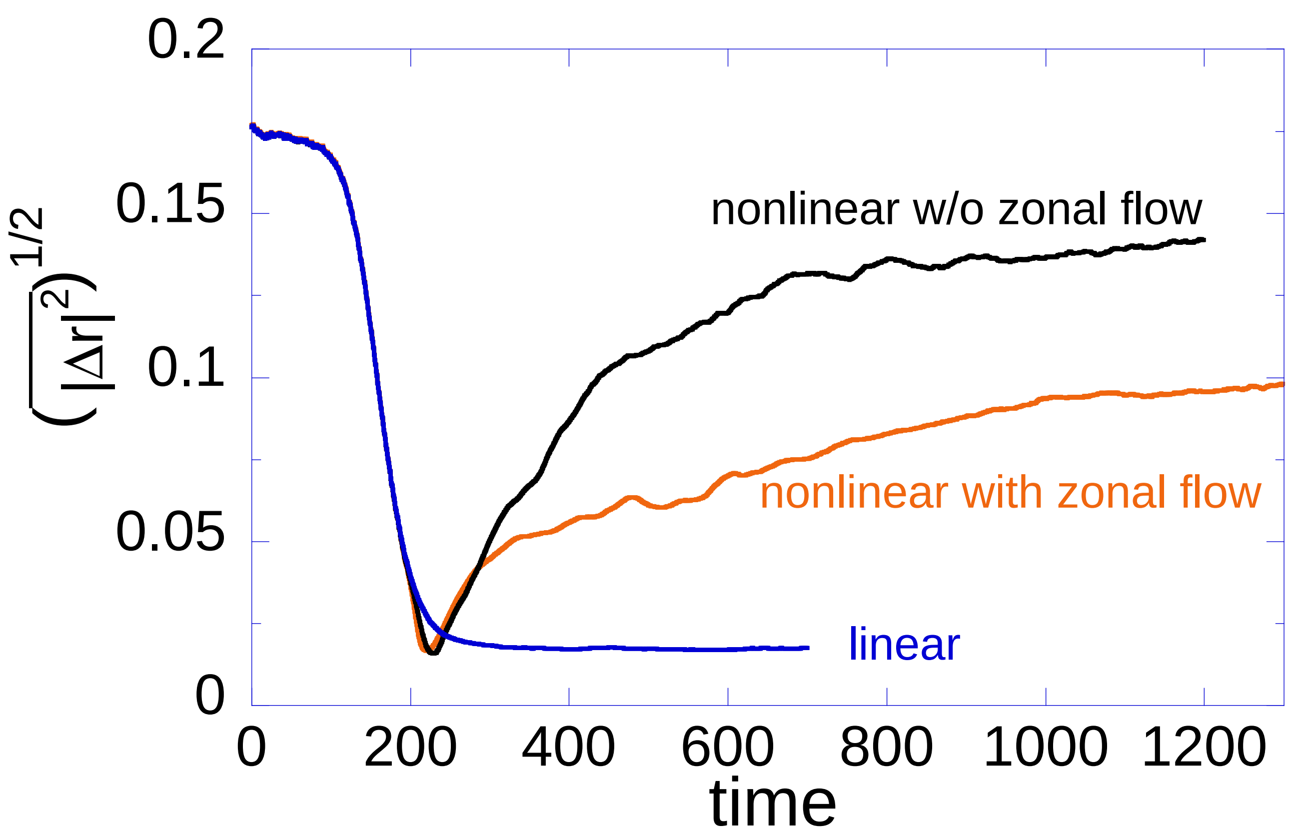
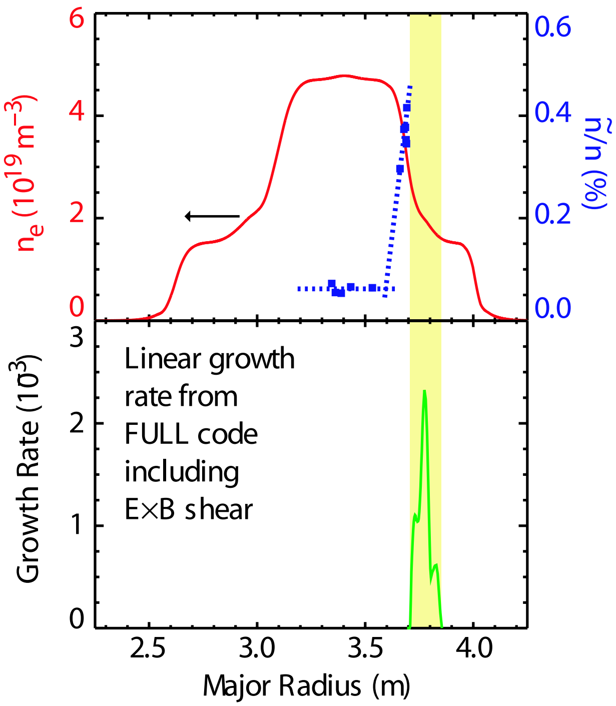
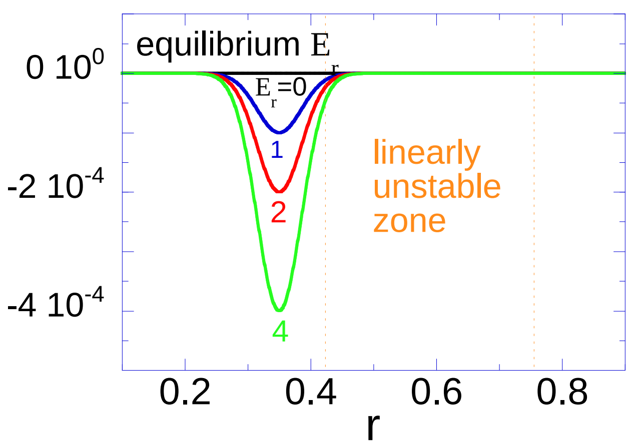
Turbulence Always Spreads, But with Different Nature

$$\overline{|\Delta r|^2} \equiv \frac{\int_{r_1}^{r_c} d^3x (r - r_c)^2 |\delta\phi|^2}{\int_{r_1}^{r_c} d^3x |\delta\phi|^2}, \qquad r_c = 0.42 \text{ (boundary of unstable region)}$$



Can $E \times B$ Shear Layer Prevent Turbulence Spreading?





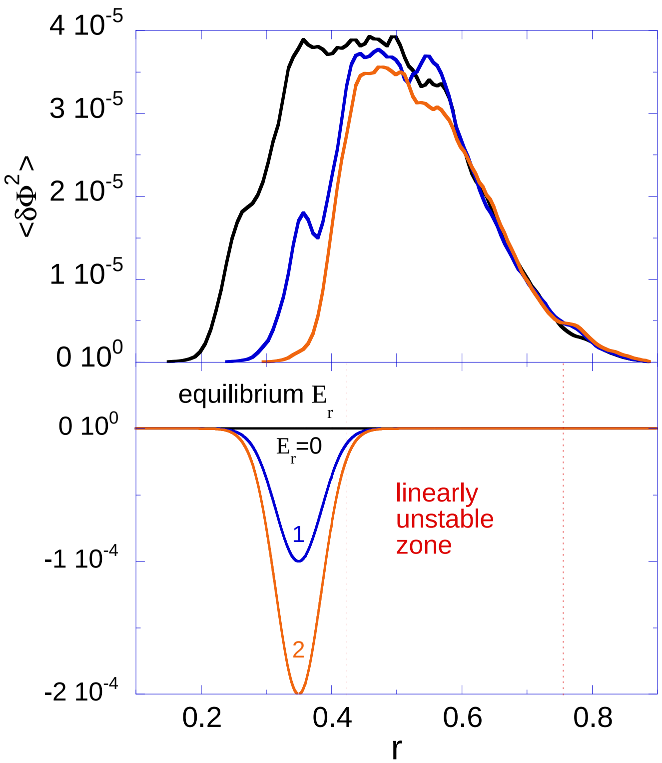
- Finite transport & density fluctuations seen in stable region inside ITB in JT60U (Nazikian et al.) – is it due to turbulence spreading?

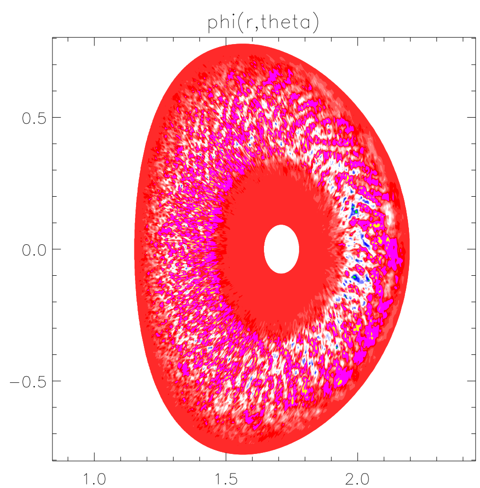
- An outstanding issue associated with transport barrier physics: in addition to quenching effect on local instability, can shear layer prevent turbulence from penetrating?

- We investigate this by introducing a model $E \times B$ shear layer to represent transport barrier:

$$E_r = -E_0 \exp[-(\frac{r-r_c}{\Delta r})^2] \quad \text{with } r_c = 0.35$$

$E \times B$ Shear Layer Blocks Turbulence Spreading





- $\omega^{max}_{E\times B} = 0$: turbulence widely spreads to fill up big area in both directions
- $\omega^{max}_{E\times B} = 0.13\frac{c_s}{a}$: inward spreading partially blocked
- $\omega^{max}_{E\times B} = 0.26\ c_s/a$: almost completely blocked
- Shear layer not only reduces turbulence spreading extension but also slows down the spreading
- Turbulence level not increased in source region as spreading blocked
- Outward spreading is not affected

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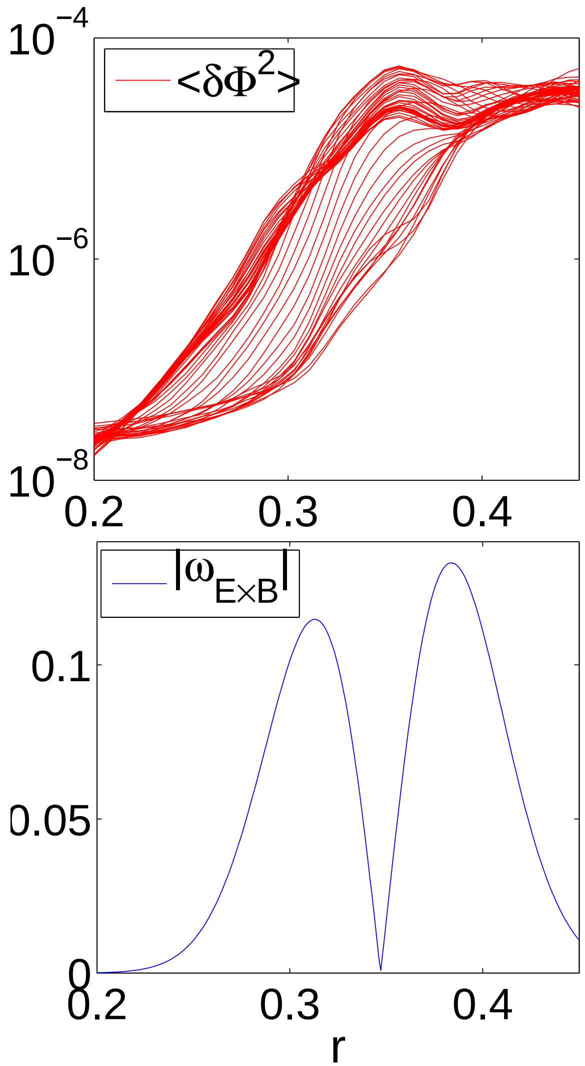
What Matters is $E \times B$ Shear, Not E_r

Spatial-temporal Evolution of Front Propagation



- $E \times B$ Shear blocking is essentially a local process while turbulence spreading is a global phenomenon

- Local shearing rate $|\omega_{E\times B}^{max}|$ is the key quantity

- Blocking is most effective at $|\omega_{E\times B}^{max}|$

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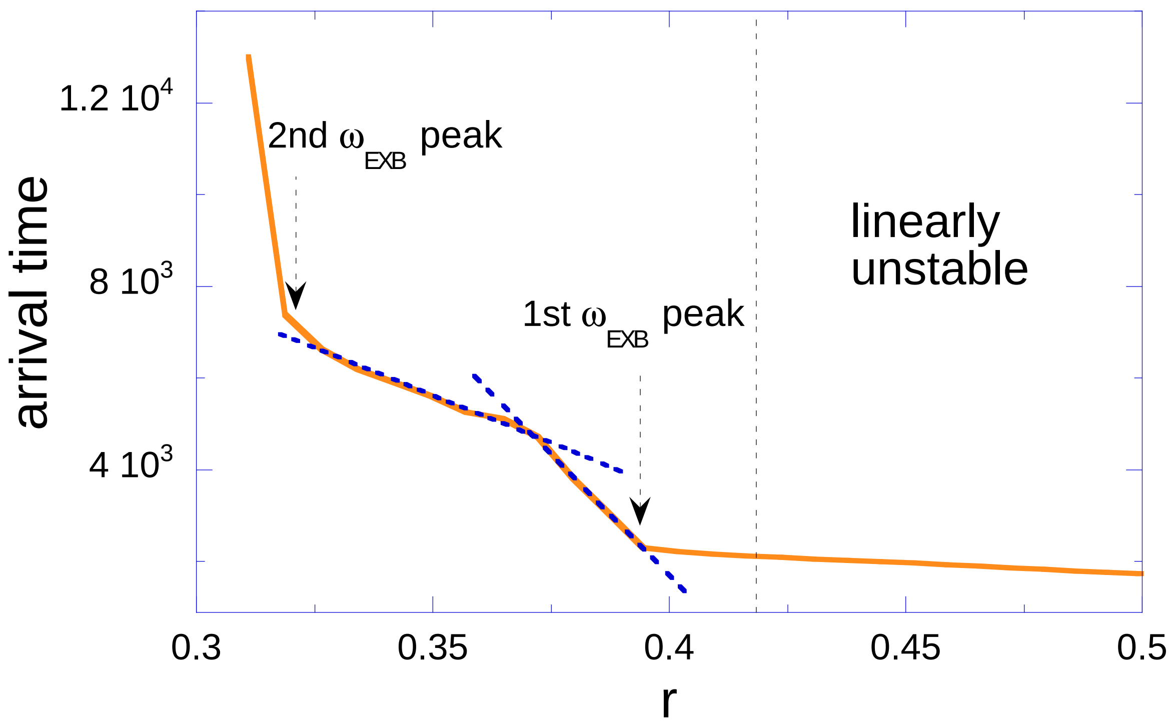
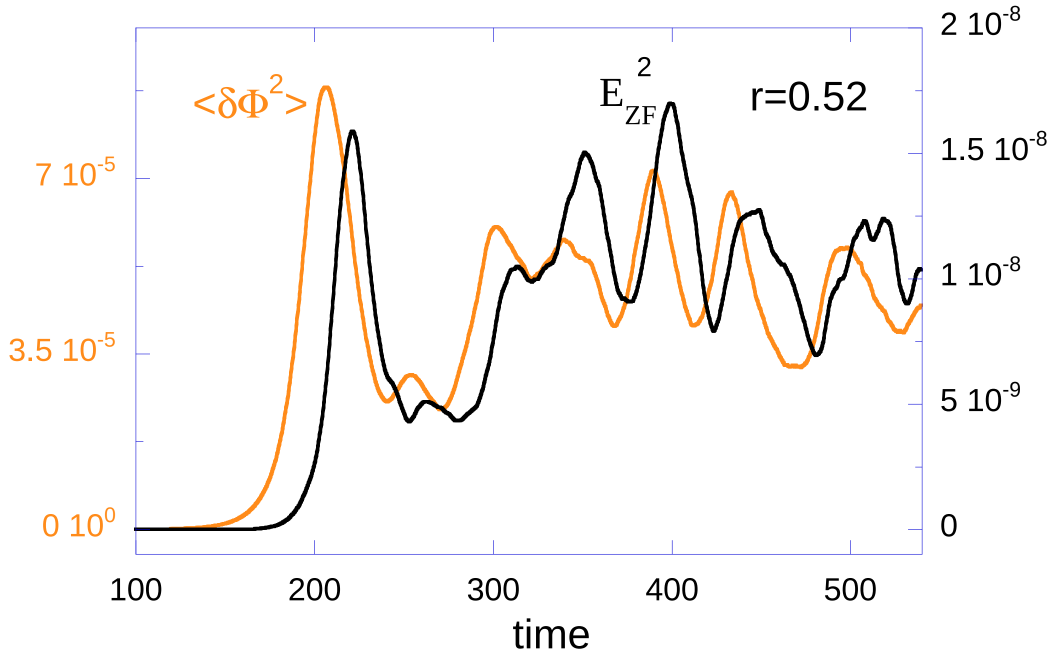
Local Shearing Rate $|\omega_{E\times B}^{max}|$ Is the Key Quantity



Mutual Self-regulation between Turbulence and Zonal Flows in Collisionless Plasma



- A "bursting" temporal behavior with a period much longer Geodesic Acoustic Oscillation period
- Different than the self-regulation associated with the collsional damping of zonal flows (Lin et al.)
- Existence of collisionless damping mechanism for zonal flows

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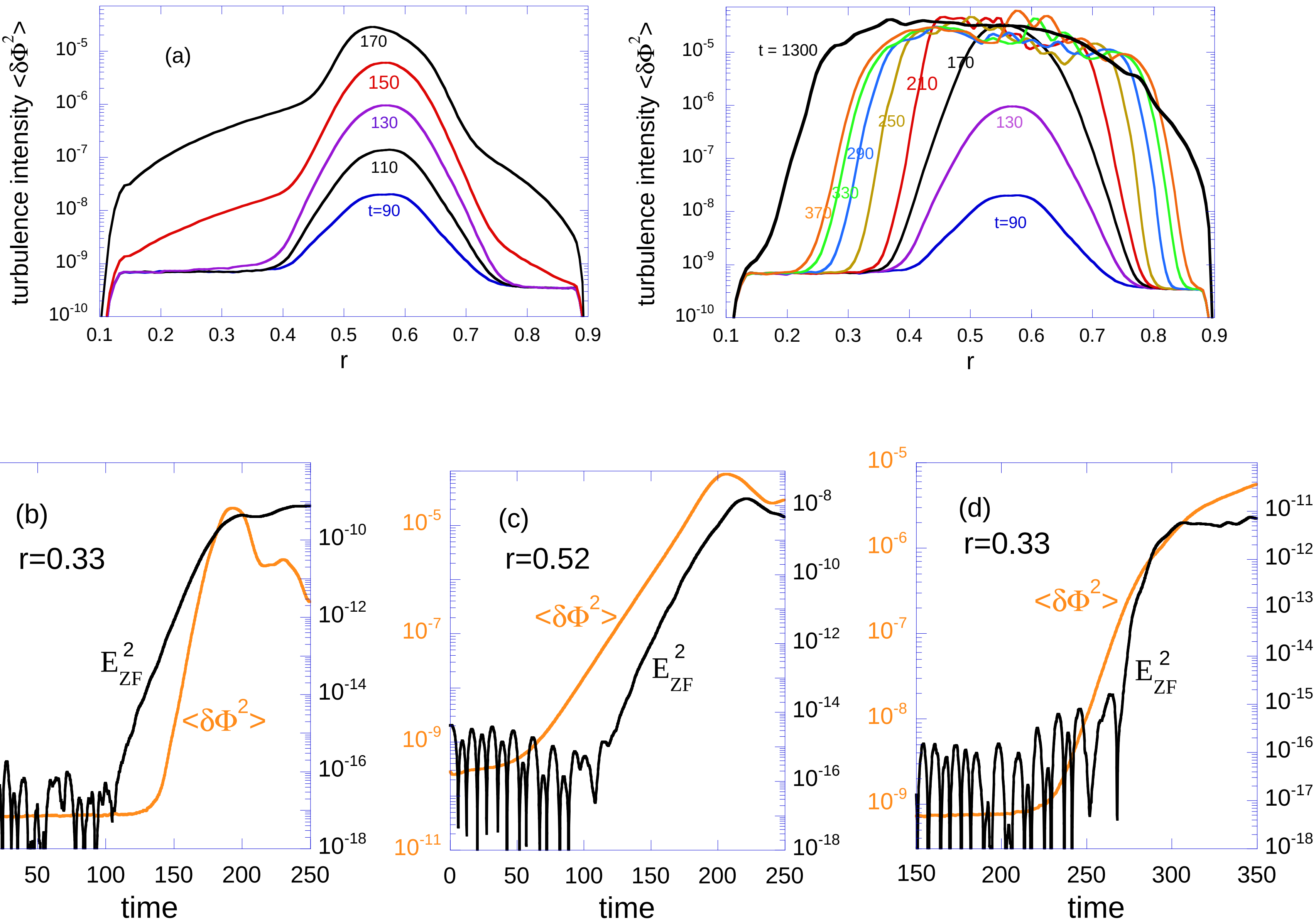
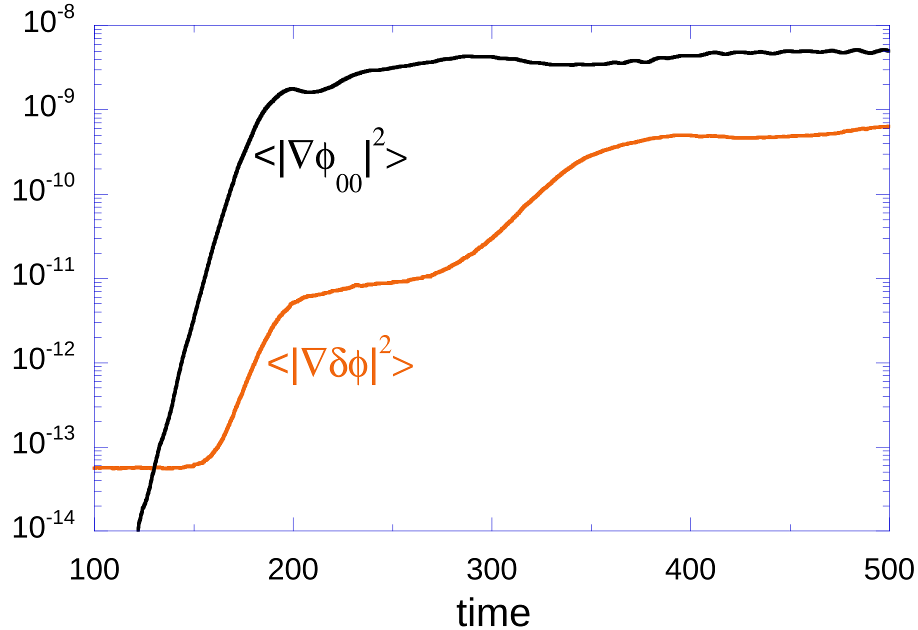
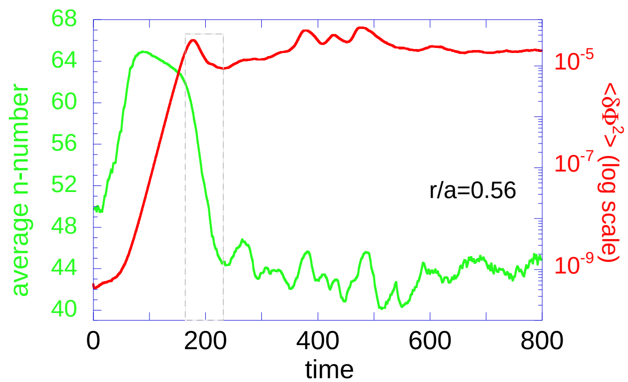
Zonal Flows Can Drive Turbulence, However ...

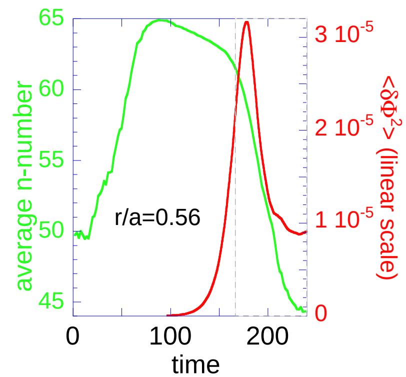


Energy Coupling from Zonal Flows to Turbulence Is Weak



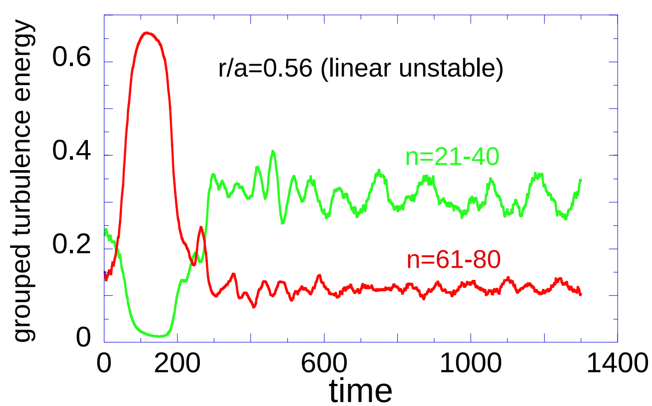
ITG Saturation Correlated with Energy Transfer to Longer Wavelength

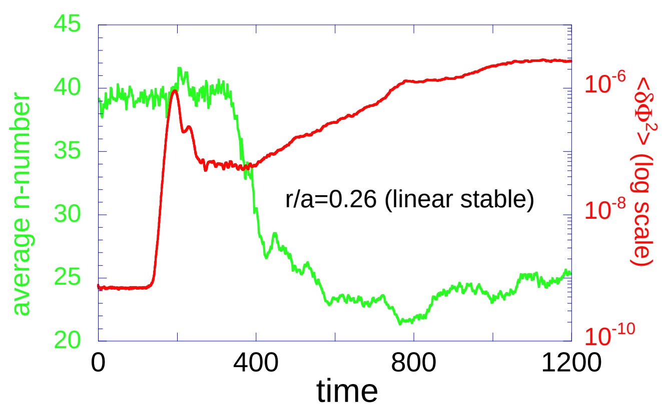




- Define average toroidal mode number (L. Chen):

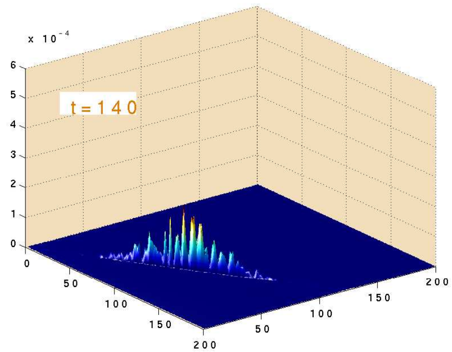
$$< n >= \frac{\sum_{m,n} n\delta\Phi^2_{mn}}{\sum_{m,n} \delta\Phi^2_{mn}}$$

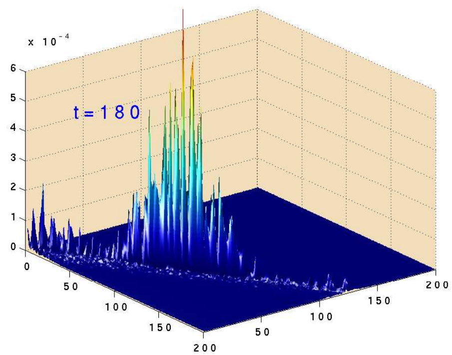


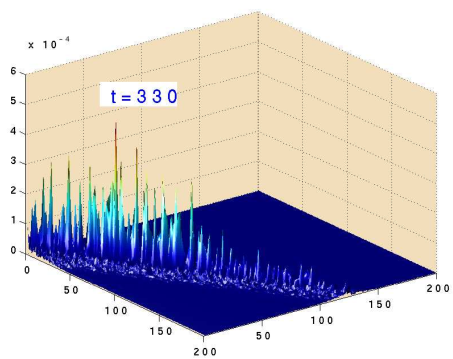


- $< n >$ down-shifts by 2/3 (the down-shift observed in many previous simulations)
- This is observed to occur during turbulence saturation process
- Turbulence energy is transfered from unstable modes (61-80) to stable modes (21-41)
- $< n >$ down-shifted for turbulence in stable zone.

Nonlinear Toroidal Coupling is the Dominant Channel for Energy Transfer to Lower-n Modes







- Energy transfer to lower-n modes along resonance surface $m/n \approx q$ ($k_{\|} \ll k_{\perp}$)

- Nonlinear coupling in toroidal geometry: $(n_1, m_1) + (n_2, m_2) \Rightarrow (n_2 \pm n_1, m_2 \pm m_1)$

- Nonlinear toroidal coupling is identified as dominant k-space activity for ITG saturation

- High-n modes ($k_\theta \rho_i \gtrsim 1$) heavily Landau damped

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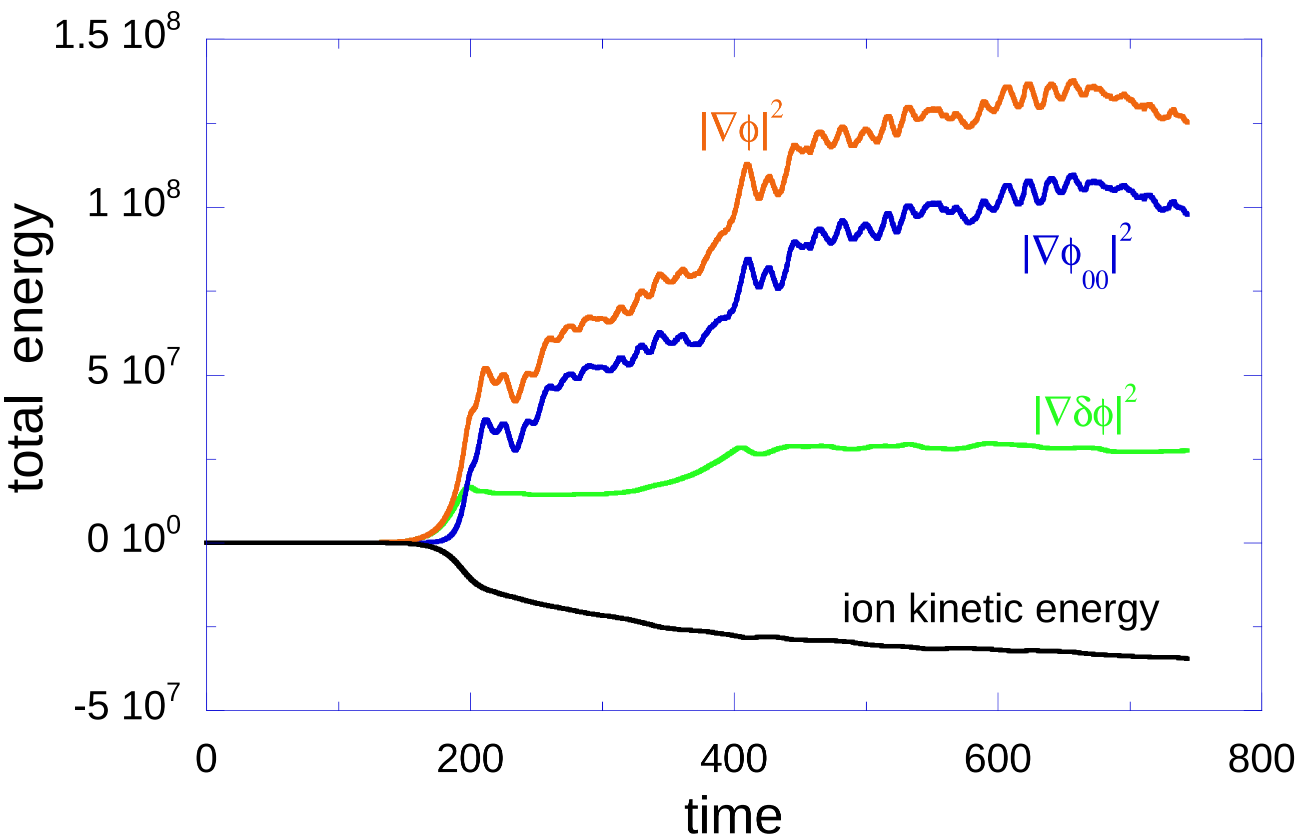
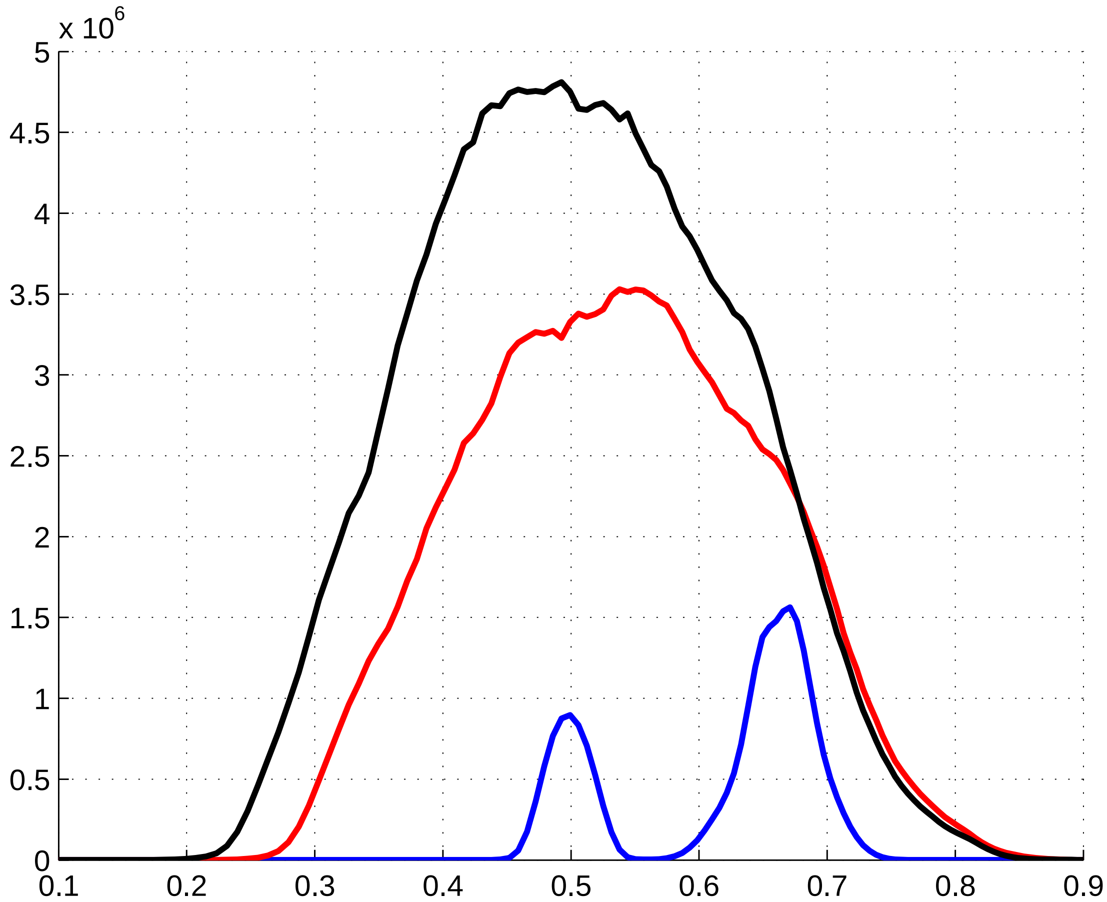
Nonlinear Energy Exchange



- Zonal flows contain energy remarkably higher than turbulence
- Zonal flows extract a large amount of energy from turbulence components during their generation process. This, in part, appears to be a natural picture of turbulent transport reduction by zonal flows.

Global Turbulence vs Local Analysis



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SUMMARY

- Zonal flow slows down the turbulence spreading by regulating turbulence to lower intensity level.
- The $E \times B$ shear layer associated with a transport barrier can significantly reduce, and sometimes even block turbulence spreading by reducing the spreading extend and speed
- The local shearing rate $|\omega_{E\times B}^{max}|$, not E_r, is the key to the control of turbulence spreading
- ITG saturation is strongly correlated with nonlinear energy transfer to longer-wavelengths (lower-n modes)
- Zonal flows extract a large amount of energy from turbulence components — a natural picture of turbulent transport reduction by zonal flows
- Zonal flows can drive turbulence. However, the associated energy coupling is too weak to provide sufficient zonal flow damping to be responsible for zonal flow saturation and the bursting behavior in the fluctuations observed in collisionless simulations.