Gyrokinetic Simulation of Turbulence Driven Momentum Transport

W. Wang

T.S. Hahm, W.W. Lee, W.M. Tang, A. Jin

S. Ethier, G. Rewoldt, P.H. Diamond

Princeton University, Plasma Physics Laboratory

University of California, San Diego

GPS-TT Project Meeting, PRCPS-DPP, 2008

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Understanding the momentum transport is one of highlighted issues of current fusion research

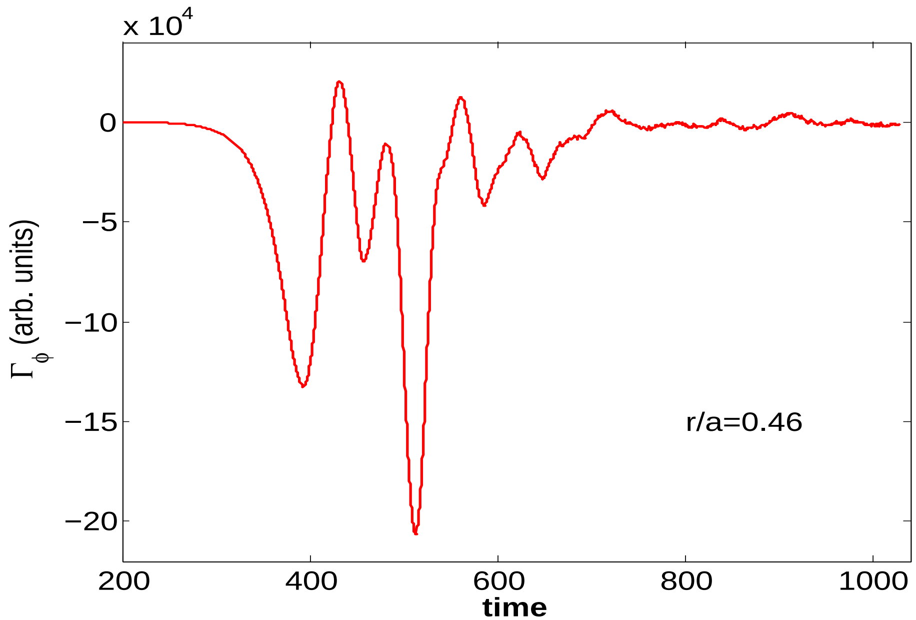
Toroidal momentum transport exhibits very complex phenomenology

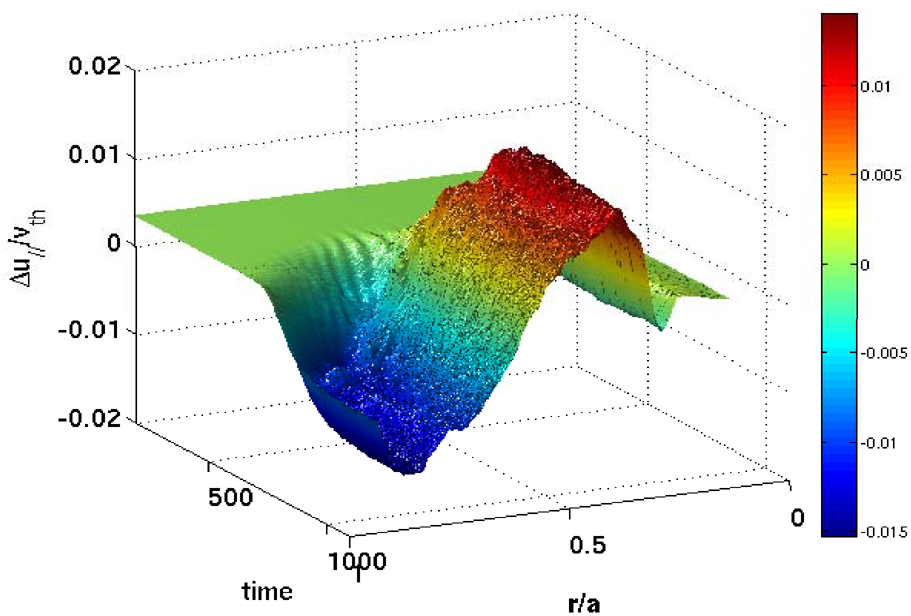
- Diffusive momentum transport alone will lead to relaxation of rotation profile and release of associated free energy.
- Toroidal momentum transport is always highly anomalous regardless ion energy transport is anomalous or neoclaasical
- Finding of intrinsic or spontaneous rotation (Rice et al. '04) critical for ITER
- Development of intrinsic rotation requires mechanisms to generate a flow and rearrange its profile radially
- A generic structure of toroidal momentum flux (Diamond et al. '08)

$$\Gamma_\phi \propto -\chi_\phi \frac{\partial U_\phi}{\partial r} + V_p U_\phi + \Pi_{r,\phi}^{\mathrm{resid}}$$

Searching for nondiffusion elements and understanding underlying mechanisms have been the focus of recent intensive theoretical and experimental effort

II. Large inward toroidal angular momentum flux found in post-saturation phase – rigid rotation with $\omega_\phi \neq 0$





- Large, non-diffusive, inward toroidal momentum flux driven by ITG turbulence in post-saturation phase
- Core plasma spins up with $\Delta u_{\|}$ few % of local v_{th} (no momentum source at edge)
- Global momentum conservation approximately maintained
- In long term steady state Γ_ϕ decays to small (or zero) level

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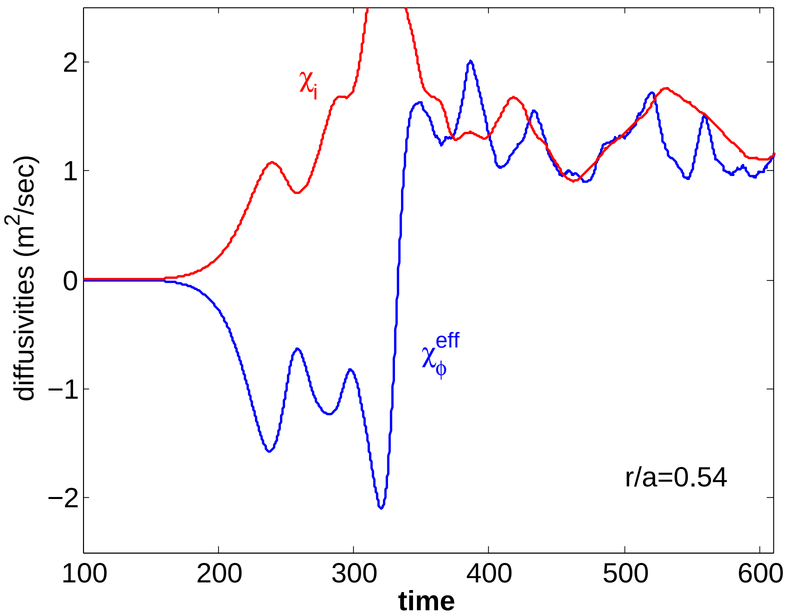
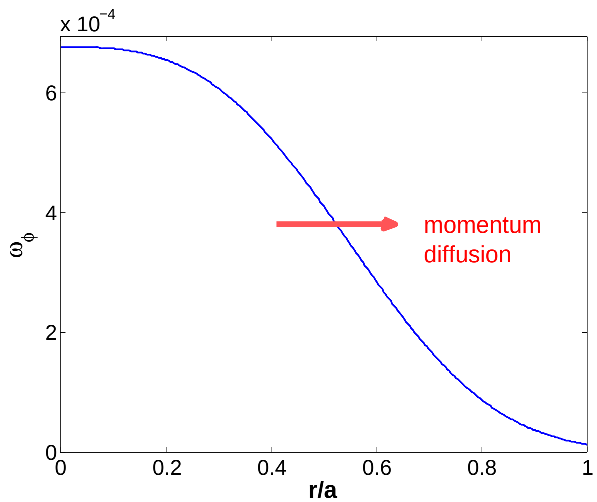
Non-diffusion momentum flux is driven in the same direction as rotation gradient





- initial $u_{\|} \sim 0.1 v_{th}$

- Γ_ϕ in post-saturation phase in direction opposite to momentum diffusion (i.e., same direction as rotation gradient)

- Net Γ_ϕ reverses to diffusive direction in long-time steady state

- Strong coupling between momentum and energy transport with $\chi_\phi^{\text{eff}}/\chi_i \sim 1$, in broad agreement with tokamak experiments[Scott et al.'90] and early ITG theory [Mattor-Diamond, '88]

What is the inward momentum flux: pinch? off-diagonal (residual stress)? or ... ?

- Radial flux of toroidal angular momentum:

$$\Gamma_\phi \propto -\chi_\phi \frac{\partial U_\phi}{\partial r} + V_p U_\phi + \Pi^{\text{resid}}_{r,\phi}$$

- Nondiffusive flux needs a mechanism for symmetry breaking $\Rightarrow \langle k_\| \rangle \neq 0$

  equilibrium $\mathbf{E} \times \mathbf{B}$ velocity shear $\rightarrow \Pi^{\text{resid}}_{r,\phi}$ (Gurcan et el. '07, ...)

  $\mathbf{b} \cdot \nabla \mathbf{b} \leftrightarrow$ ballooning mode structure $\rightarrow V_p$ (Hahm et al. '07)

  . . .

- Experimental identification is highly interesting but not easy

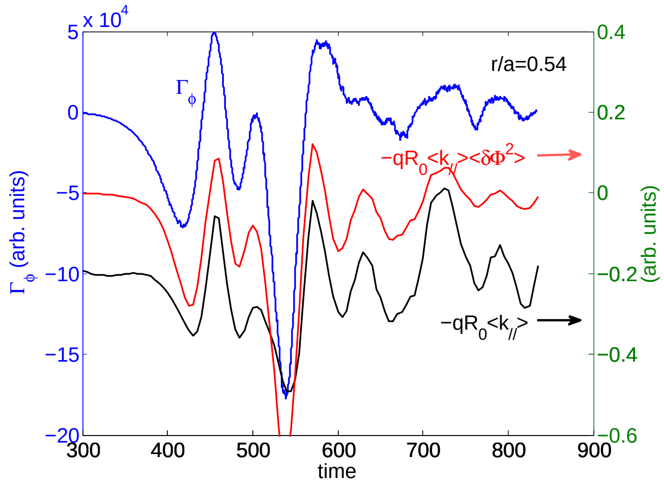
- Off-diagonal flux robustly observed in various simulation experiments:

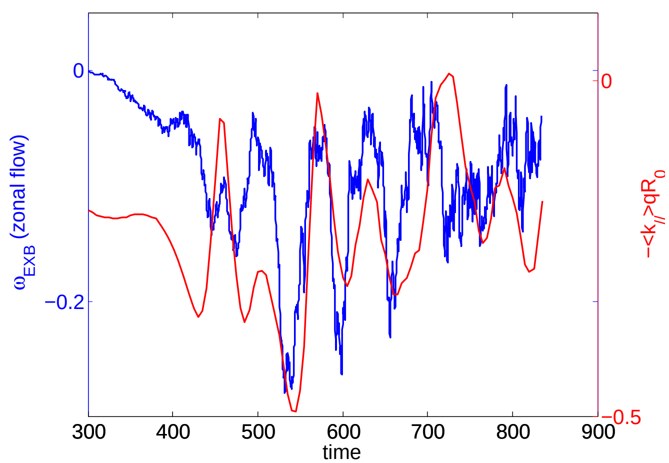
  different machines size and plasma parameters

  with or w/o equilibrium $\mathbf{E} \times \mathbf{B}$, toroidal rotation, rotation gradient

- $\Longrightarrow$ Suggest the existence of new dynamics

Underlying physics for off-diagonal momentum transport is found to be residual stress generation due to ZF shear

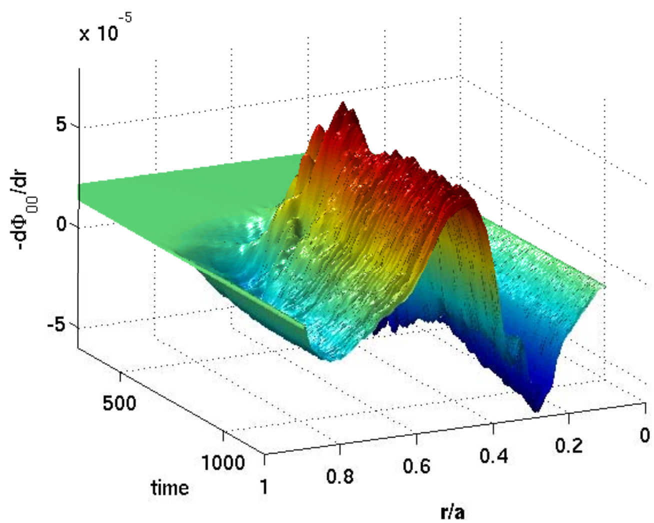




$\omega_\phi = 0$ case

$\Rightarrow$ no χ_ϕ and V_p

$$\langle k_\parallel \rangle \equiv \frac{\sum (nq - m)\delta\Phi_{mn}^2}{qR_0 \sum \delta\Phi_{mn}^2}$$



- Self-generated zonal flow is quasi-stationary in global ITG simulations

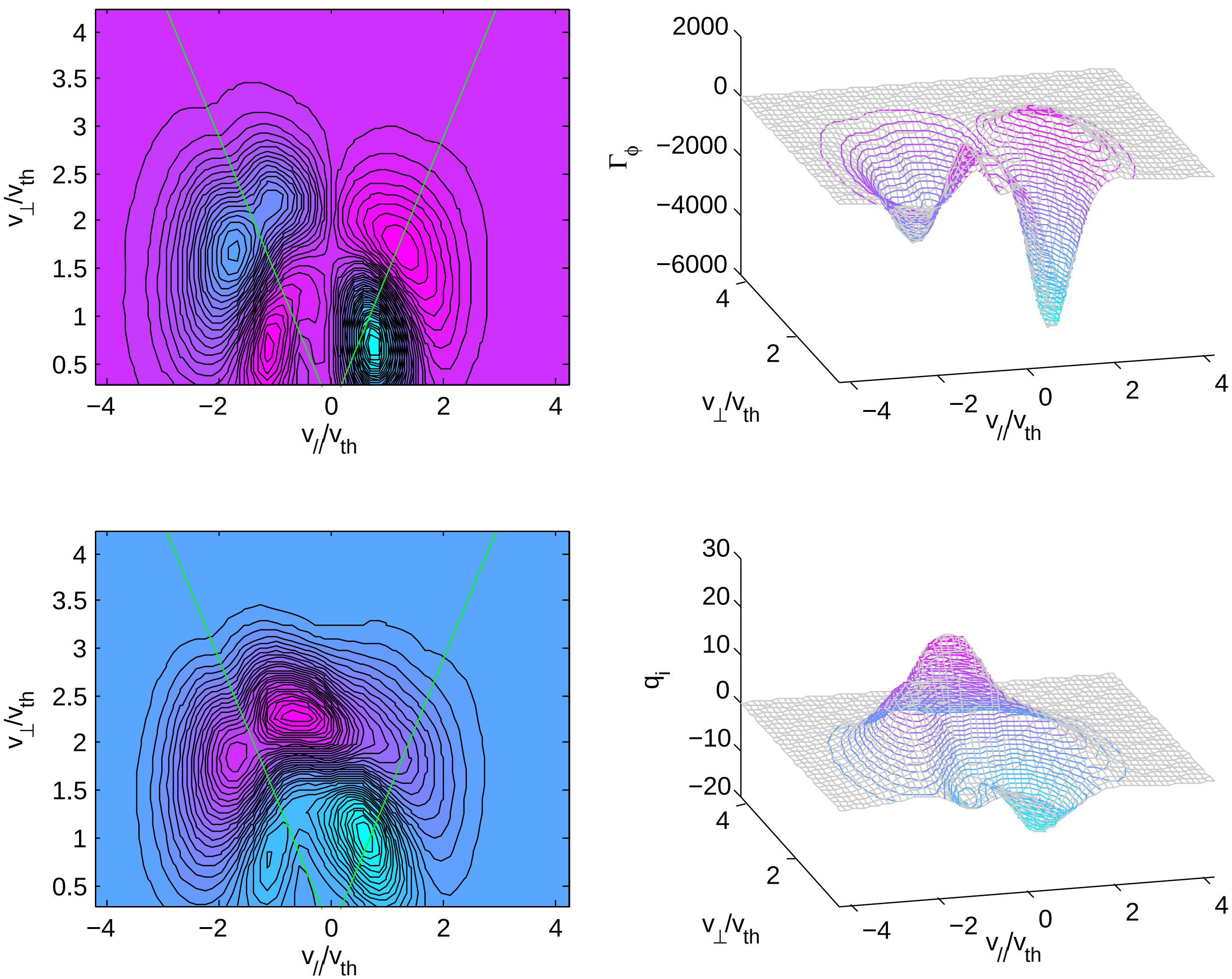
  $\rightarrow$ showing existence of toroidal zonal flow

- Slow varying large scale ZF structure experimentally identified recently in DW turbulence (Tynan et al. IAEA'08)

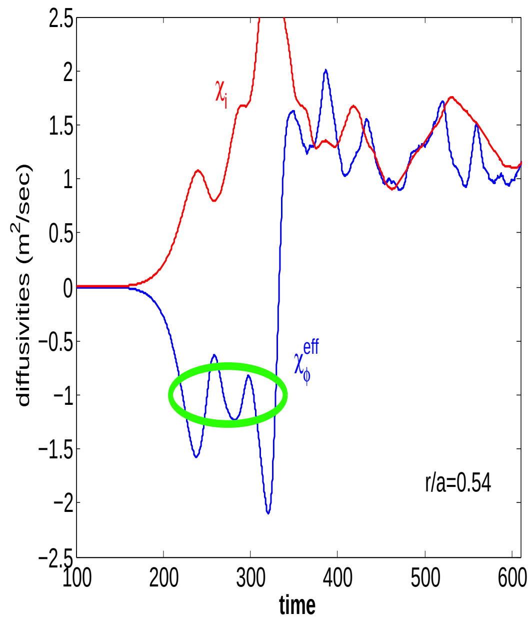
- Nonlinear residual stress generation is found due to $k_\parallel$ symmetry breaking induced by self-generated quasi-stationary ZF shear

- A universal mechanism to drive $\Pi_{r,\phi}^{\text{resid}} \sim \nabla T_i$ via dependence on $\delta\Phi^2$

Which and how particles contribute to momentum and energy transport: resonance and non-resonance



- at $r/a = 0.54$, $\theta = 0$ (mid-plane)



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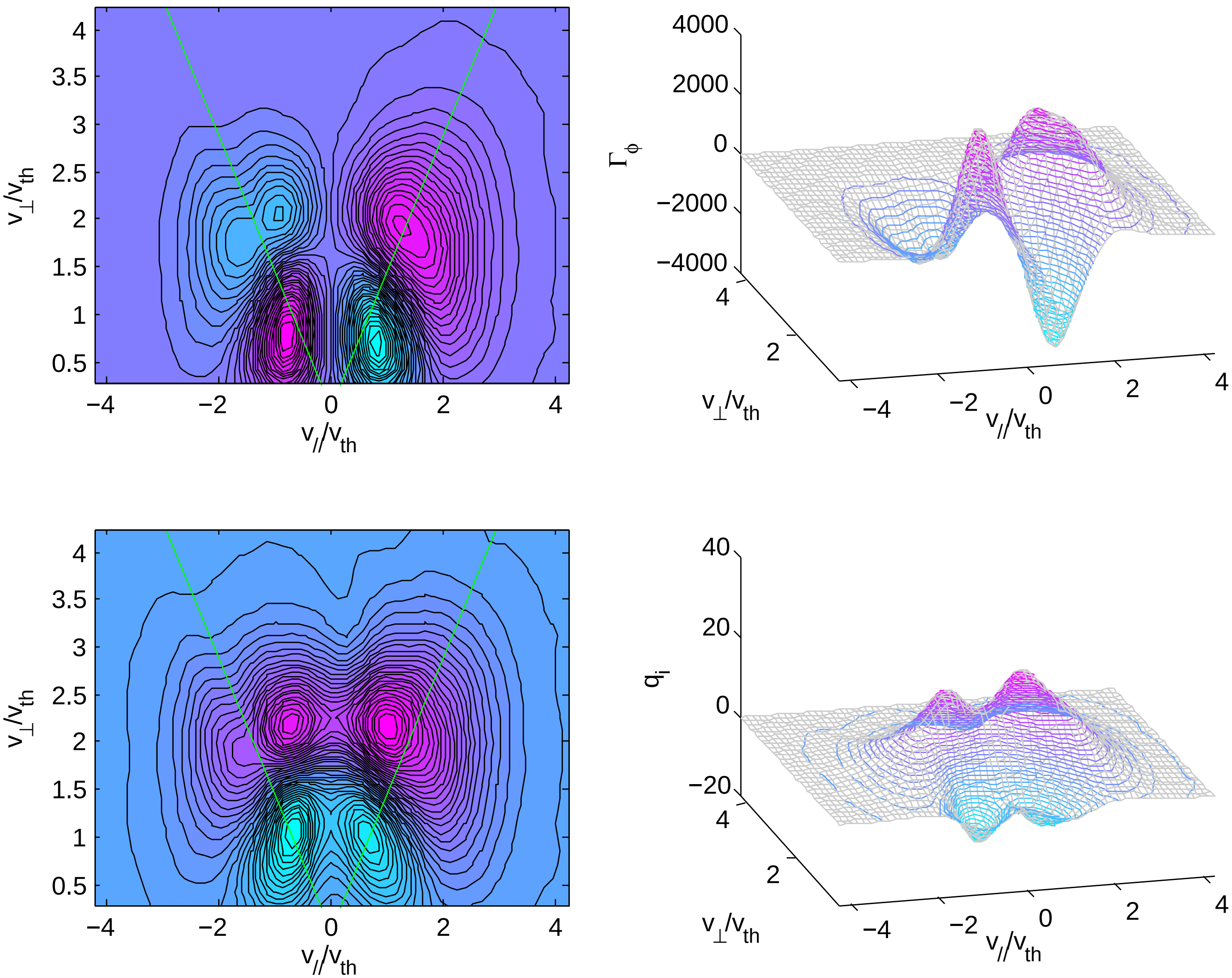
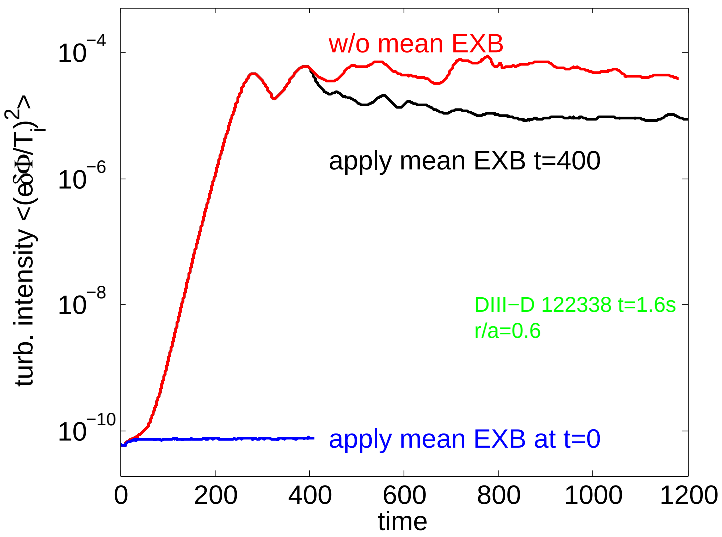
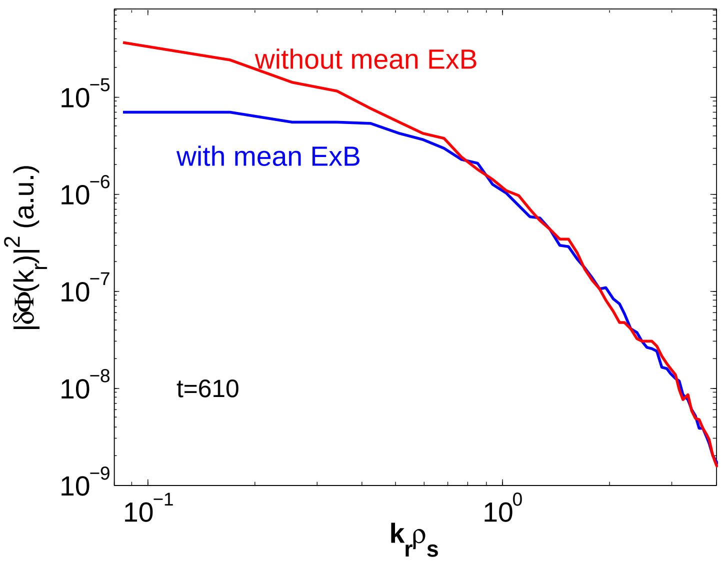


Resonance condition: $\omega - \omega_{di}(v_{\|}^2) - \omega_{\nabla B}(\mu) - k_{\|} v_{\|} = 0$

VI. Residual fluctuations are found to exist in the presence of strong mean $\mathbf{E} \times \mathbf{B}$ flow shear





- Strong toroidal rotation and $\mathbf{E} \times \mathbf{B}$ flow are driven by neutral beam injection $\Rightarrow$ stabilize ITG linearly
- However, $\mathbf{E} \times \mathbf{B}$ shear induced dissipation is fluctuation-mode-dependent:

  more efficient on lower k_r linear eigenmodes

  less efficient on higher k_r maturated fluctuations
- Finite residual fluctuations with higher k_r can survive strong mean $\mathbf{E} \times \mathbf{B}$ flow shear induced damping

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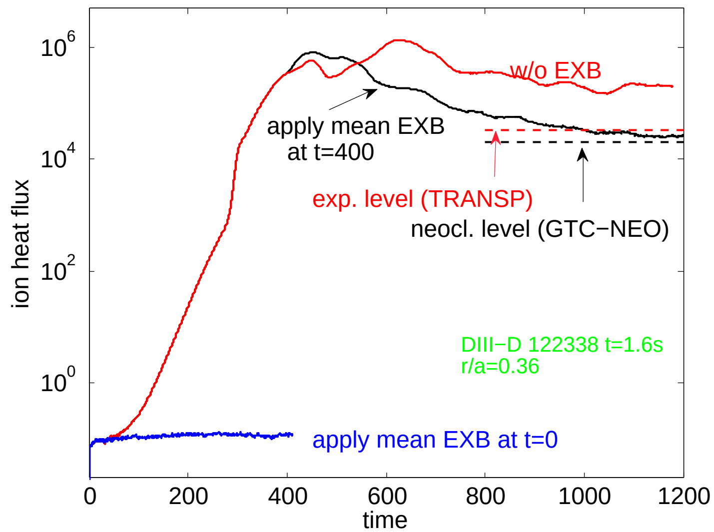
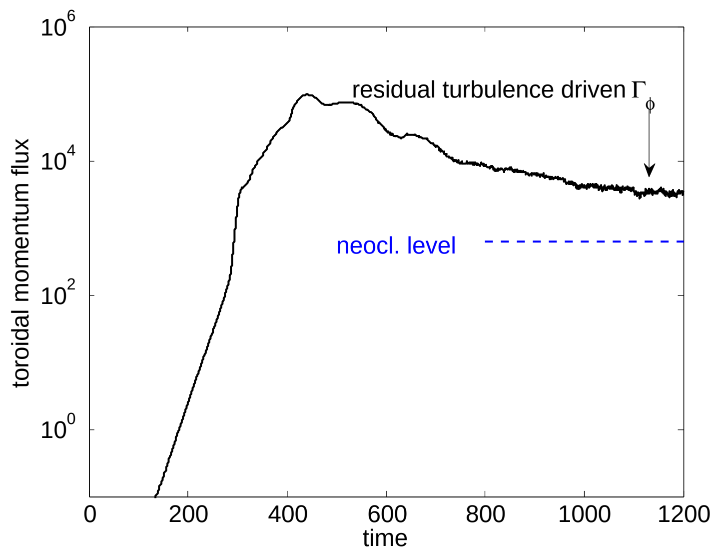
Residual turbulence may drive experimentally relevant toroidal momentum and energy transport





Residual turbulence may account for puzzling co-existence of neoclassical-level ion heat and anomalous momentum transport

- Distinct relationship between momentum and energy transport:

  for low-k fluctuations, $\chi_\phi^{\text{eff}} \sim \chi_i$

  neoclassically $\chi_\phi^{\text{eff}} \sim (0.01 - 0.1)\chi_i$

- Residual fluctuations may drive finite transport:

  $\chi_i \lesssim \chi_i^{\text{nc}}$ (insignificant ion heat flux)

  $\chi_\phi^{\text{eff}} \sim \chi_i \sim 50\chi_\phi^{\text{nc}}$ (highly anomalous)