Trapped Electron Effects on Transport Relationship in Tokamak Plasmas

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in collaboration with

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

Toroidal momentum transport exhibits very complex phenomenology

- Toroidal momentum transport is always highly anomalous regardless of whether ion energy transport is anomalous or neoclassical
- 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 nondiffusive elements and understanding underlying mechanisms have been the focus of recent intensive theoretical and experimental effort

Outline and Principle Results

I. Gyrokinetic simulation models of rotating plasmas

II. Gyrokinetic turbulence driven toroidal momentum transport

– via GTS simulations

- An inward non-diffusive momentum flux, driven by ITG turbulence, found to cause core plasma rotation spin up
- Discovery of residual stress due to $k_{\|}$ symmetry breaking induced by global quasi-stationary ZF shear
- Phase space structure of momentum and energy flux
- Impact of trapped electron dynamics

III. Residual fluctuations and effects in strong equilibrium $\mathbf{E} \times \mathbf{B}$ flow shear

- Residual fluctuations survive strong $\mathbf{E} \times \mathbf{B}$ shear induced dissipation
- $\Rightarrow$ Co-existence of anomalous momentum and NC-level ion heat flux

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I. Simulation models for rotating plasmas

- Gyrokinetic Tokamak Simulation (GTS) code: generalized gyrokinetic simulation model; PIC approach; global simulation
- Turbulence fluctuation is perturbation on top of neoclassical equilibrium
- GTC-NEO $\Longrightarrow$ Neoclassical equilibrium f_0, Φ_0 and transport

  Non-local physics associated with large ion orbits and steep gradients
- Lowest order equilibrium solution for rotating plasma (used in GTS):

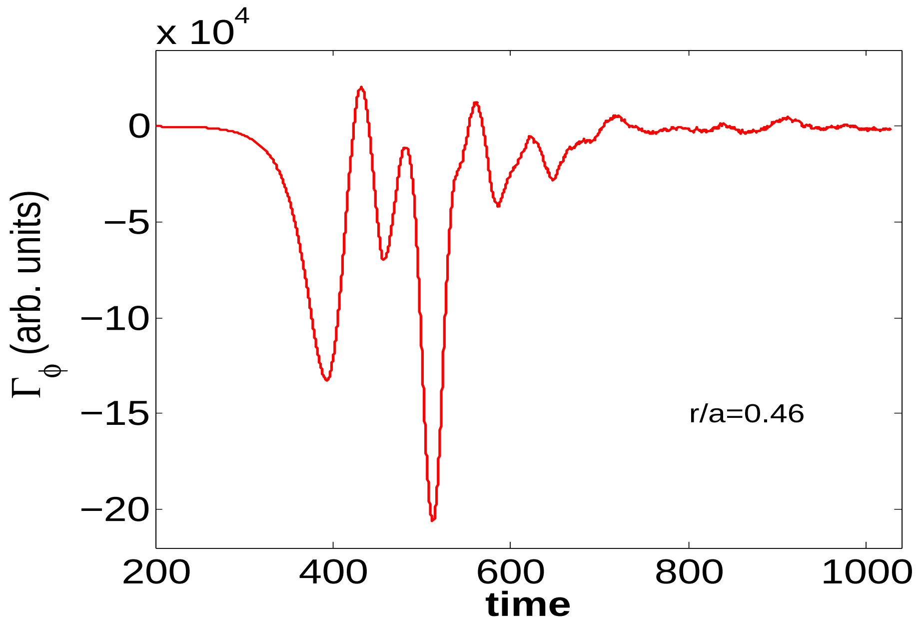
$$f_0 = f_{SM} = n(r,\theta)(\frac{m_i}{2\pi T_i})^{3/2} e^{-\frac{m_i}{T_i}[\frac{1}{2}(v_\parallel - U_i)^2 + \mu B]}$$

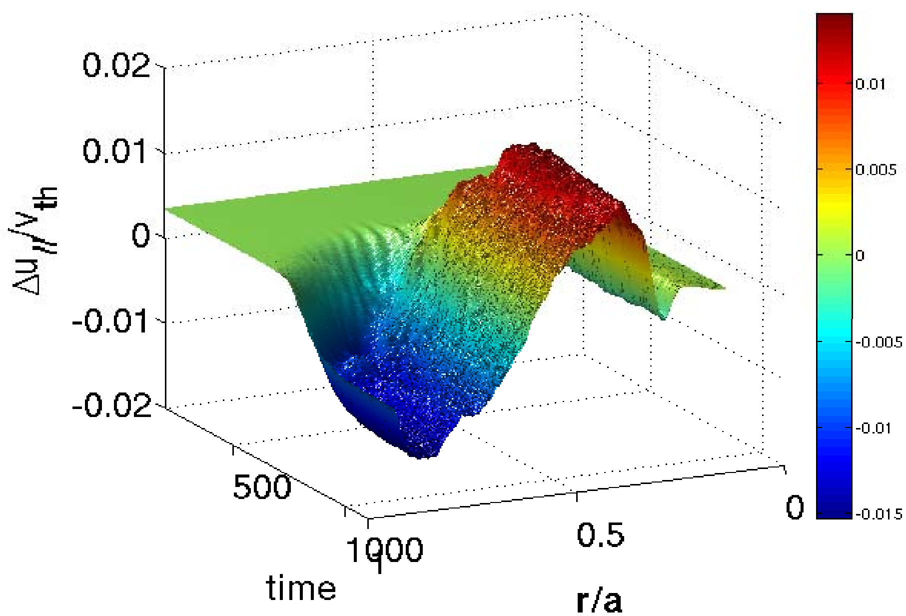
parallel flow: $U_i = I\omega_t/B$, density: $n(r,\theta) = N(r) e^{\frac{m_i U_i^2}{2T_i} - \frac{e\tilde{\Phi}_0}{T_i}}$

- $\{\langle n(r,\theta)\rangle, T(r), \Phi_0(r)$, and $\omega_t(r)\} \Longrightarrow$ turbulence & transport

  (energy, particle and momentum flux)
- Interfaced with MHD equilibrium codes (based on ESI interface by Zakharov and White) and experimental data base via TRANSP
- GTS turbulence simulation is interfaced with GTC-NEO simulation

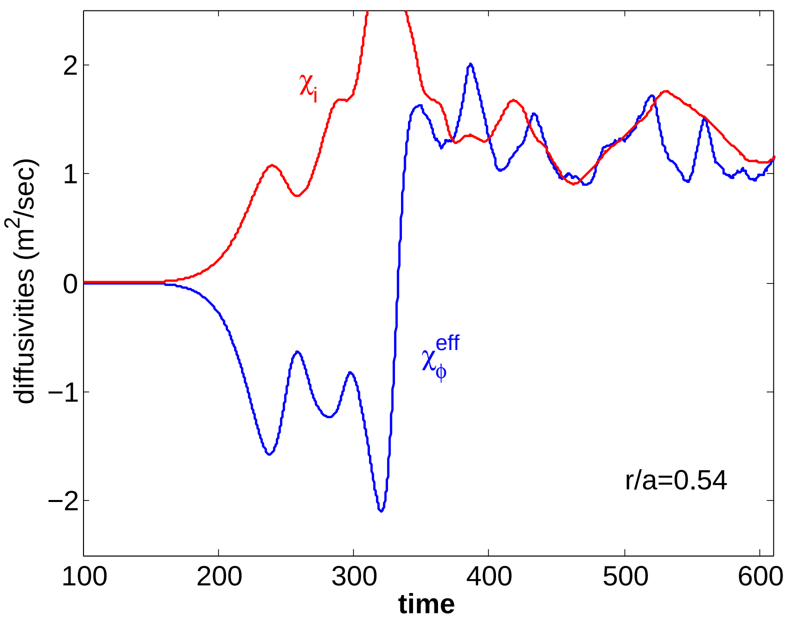
II. Large inward toroidal angular momentum flux found in post-saturation phase – rigid rotation with $\omega_\phi \neq 0$

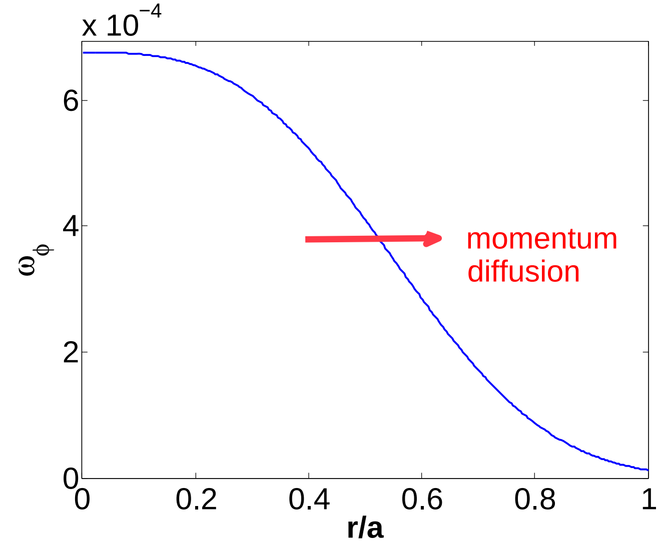




- Large, non-diffusive, inward toroidal momentum flux driven by ITG turbulence in post-saturation phase
- Core plasma spins up with $\Delta u_{||}$ few % of local v_{th} (no momentum source at edge)
- Global momentum conservation approximately maintained
- In long term steady state Γ_ϕ decays to small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

Inward Non-diffusive momentum flux is driven





- 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 $\chi_\phi^{eff}/\chi_i \sim 1$, 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:

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

- Nondiffusive flux needs a mechanism for $k_\parallel$-symmetry breaking

  mean $\mathbf{E} \times \mathbf{B}$ velocity shear $\Rightarrow \langle k_\parallel \rangle \neq 0 \rightarrow \Pi_{r,\phi}^{\text{resid}}$ (Gurcan et al. '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

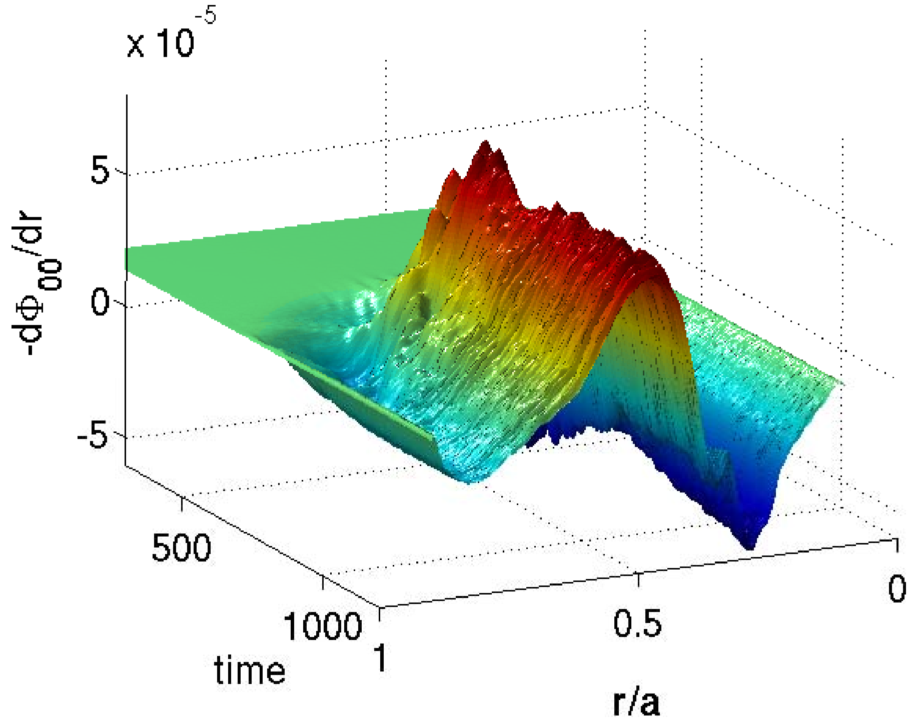
- Off-diagonal flux robustly observed in various simulation experiments:

  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 a novel mechanism

Global quasi-stationary zonal flow is observed



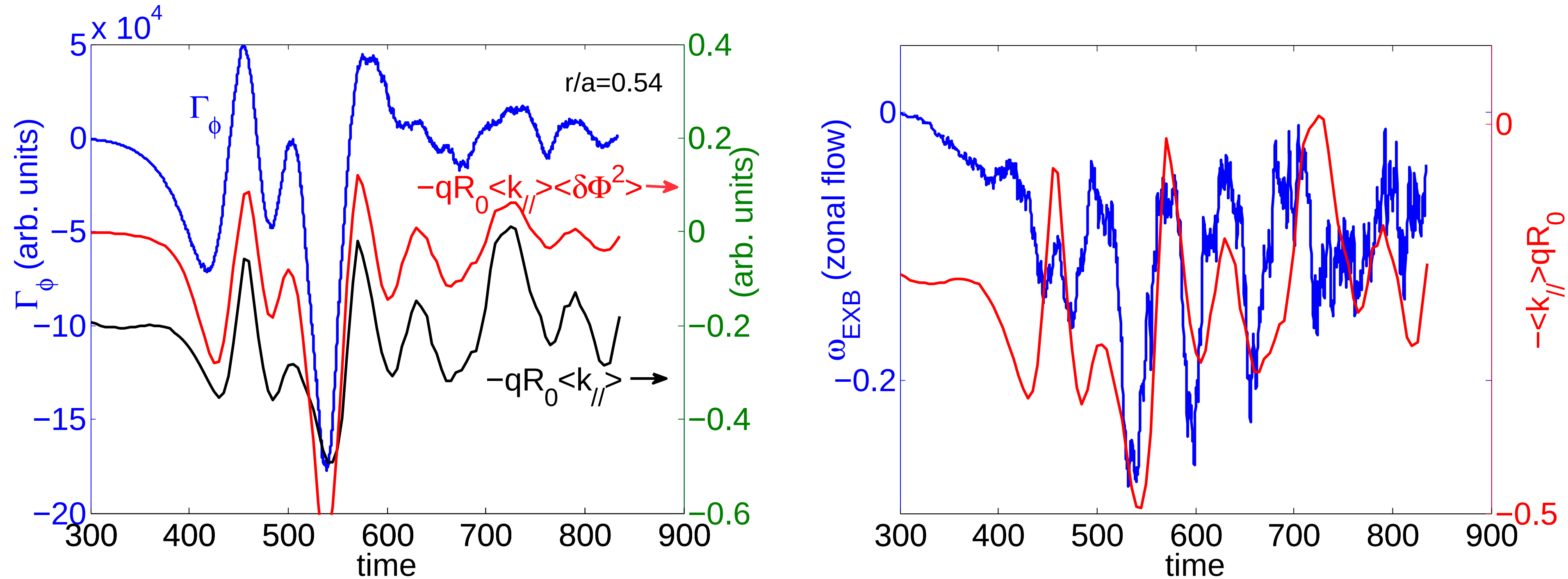
- Self-generated zonal flow is quasi-stationary in global ITG simulations

  $\rightarrow$ showing existence of toroidal zonal flow

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

- Effect on $k_{||}$ spectrum?

Residual stress is nonlinearly generated due to zonal flow shear



- $\omega_\phi = 0$ case $\Rightarrow$ neither momentum diffusion nor pinch is driven
- 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 $\Pi^{\text{resid}}_{r,\phi} \sim \nabla T_i$ via dependence on $\delta\Phi^2$

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

(Wang et al., PRL'09)

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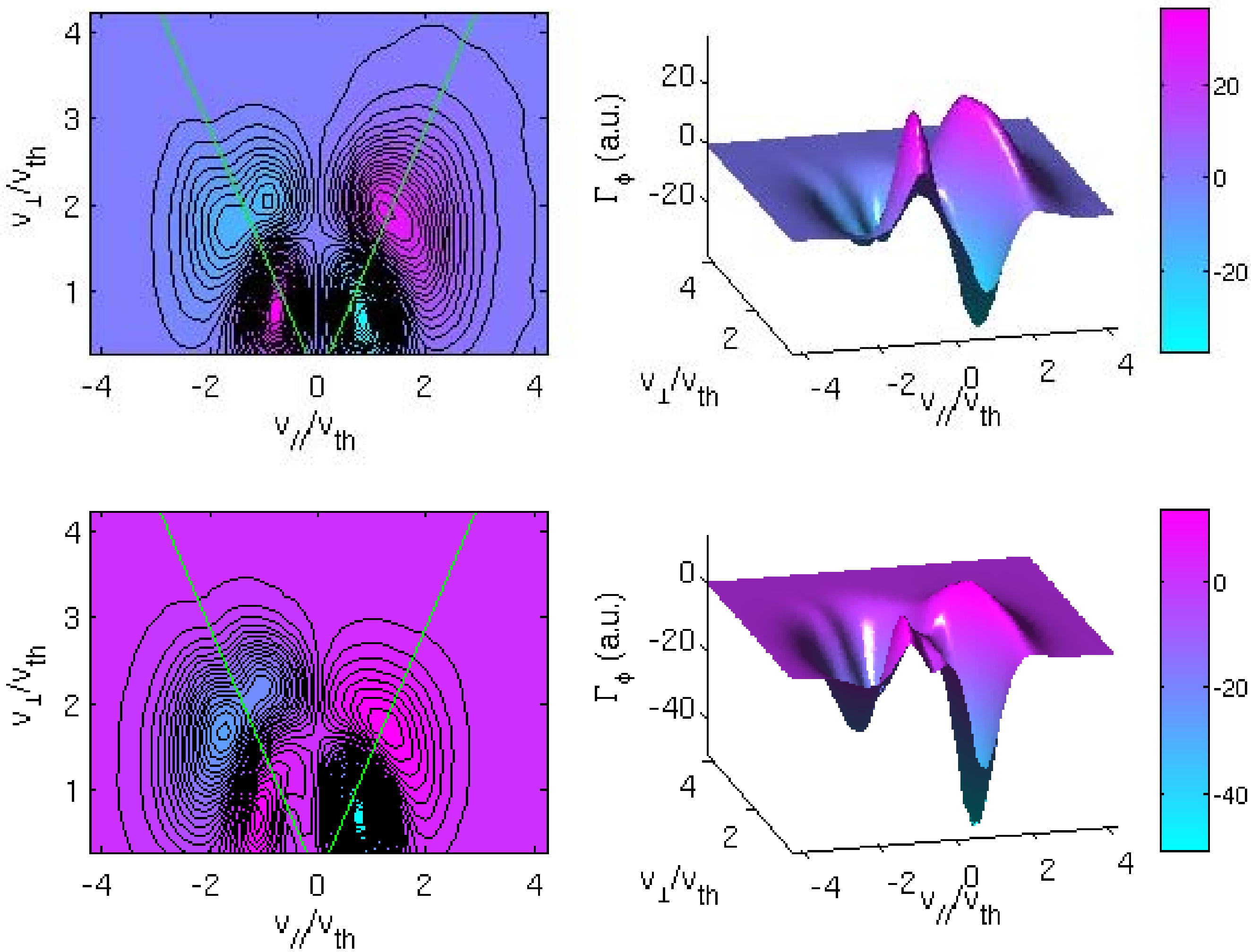
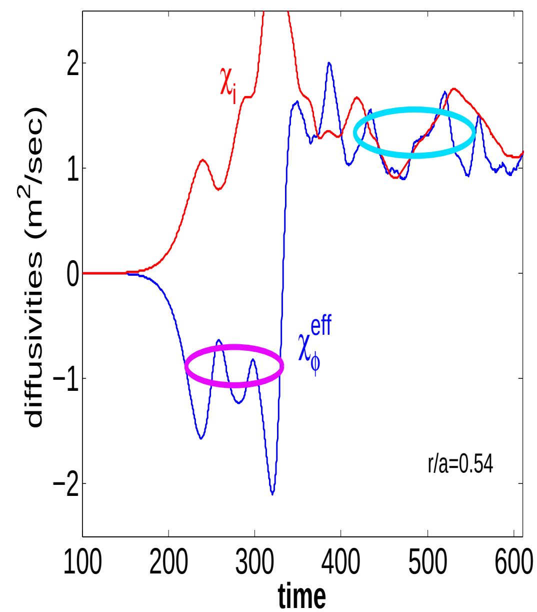
Which and how particles contribute to momentum transport: resonance and non-resonance



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



Interesting phase space structure is fairly persistent

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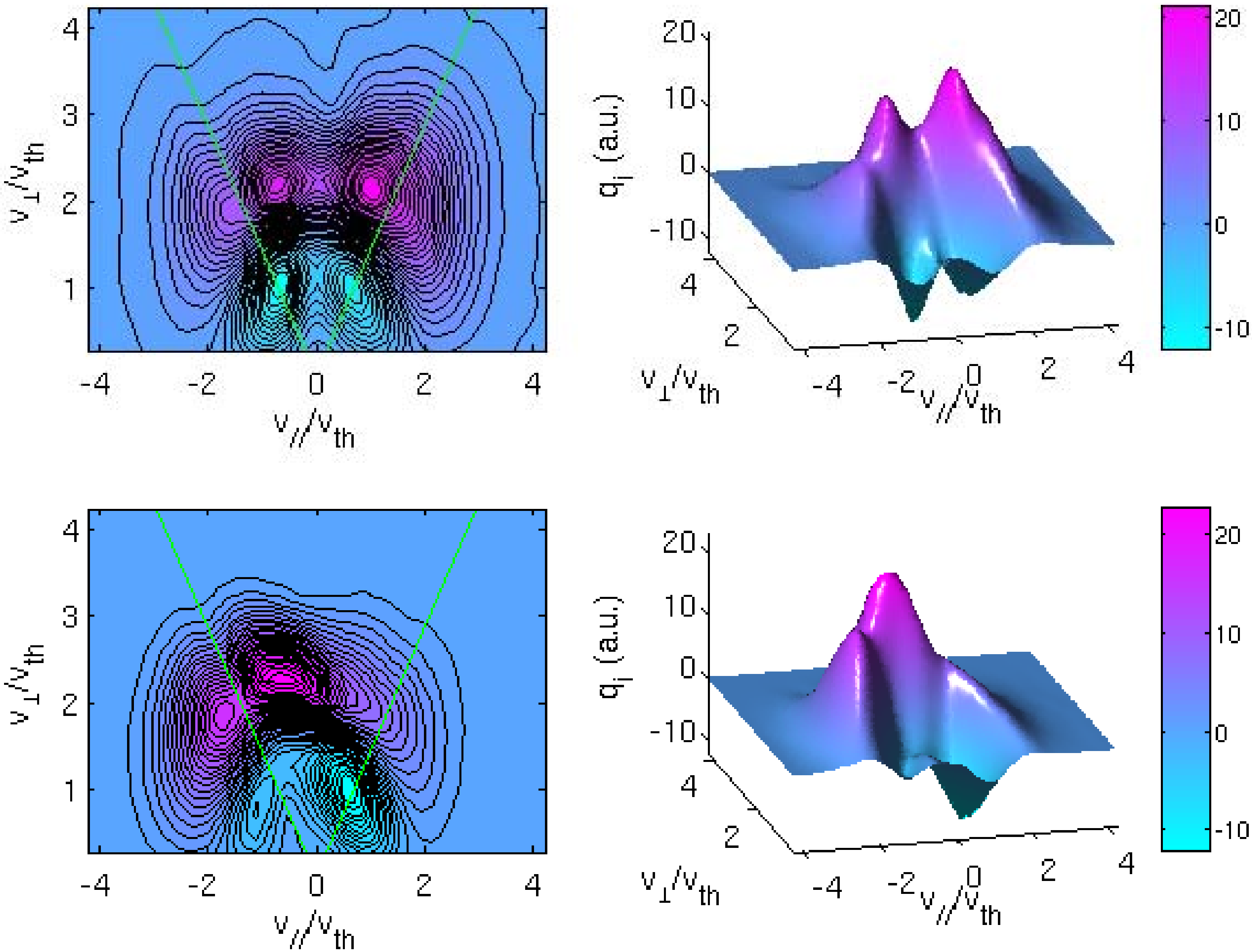
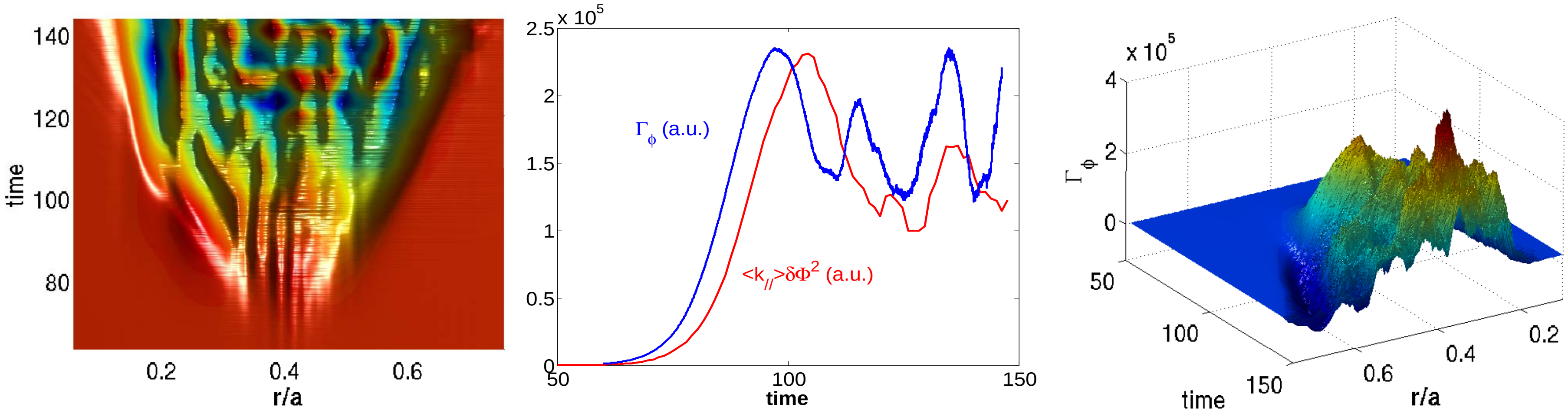
Which and how particles contribute to **energy** transport: resonance and non-resonance



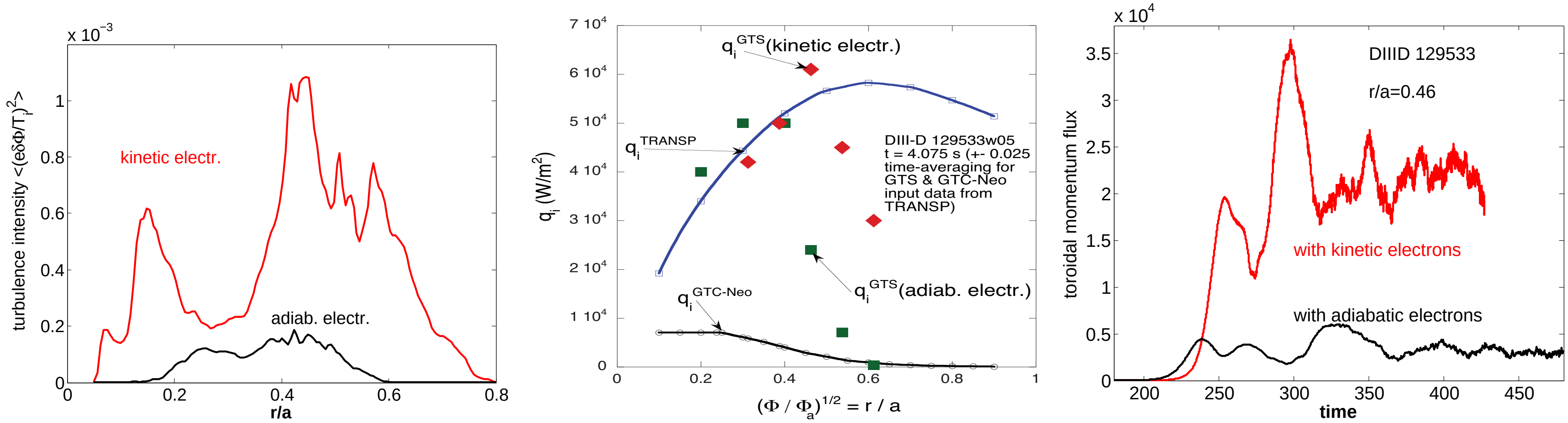
Resonance condition: $\omega - \omega_{di}(v_\parallel^2) - \omega_{\nabla B}(\mu) - k_\parallel v_\parallel = 0$

Effects of electron dynamics: ITG case with $\omega_\phi = 0$



- Finer radial scale introduced into ZF by electron dynamics (left fig.)
- Large outward momentum flux driven by residual stress at most minor radii (right fig.)
- Generation of residual stress is due to $k_{\|}$ symmetry breaking (middle fig.)
- Q: what determine sign of non-diffusive momentum flux – may to do with details of turbulence spectrum?

Trapped electron physics plays a critical role in producing right transport in experiments

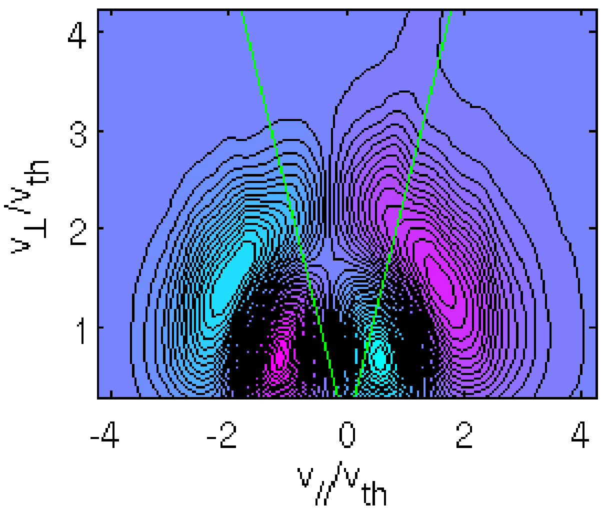


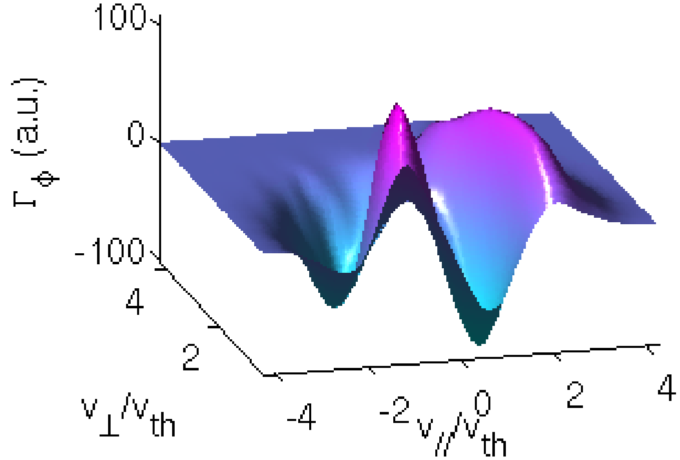
- Ion transport dominated DIII-D discharge with low toroidal rotation
- ITG turbulence fluctuations largely enhanced by trapped (non-adiabatic) electrons
- A critical role in accounting for experimental q_i in outer core region (where ITG is marginal or stable)
- Toroidal momentum flux is largely increased too
  (in a region with small, flat rotation profile, implying a residual stress or/and pinch)

But trapped electrons **do not** significantly change phase space structure of momentum flux of ITG turbulence

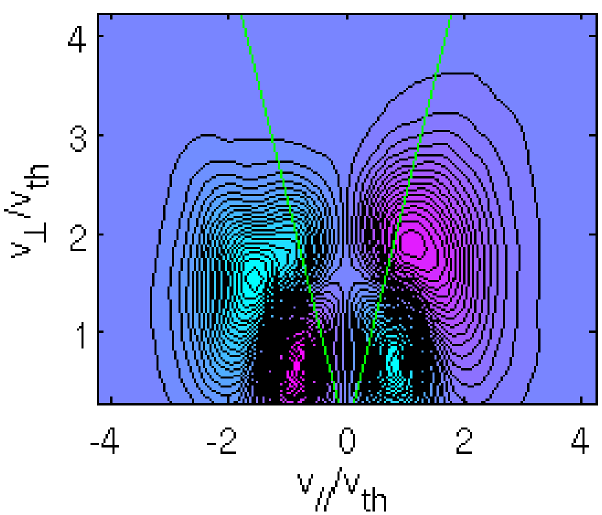
– ITG turbulence

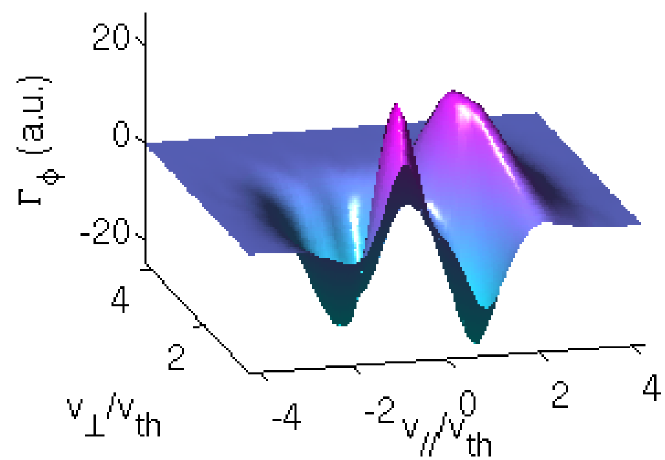
– at $\theta = 0$ (mid-plane)





with kinetic electrons

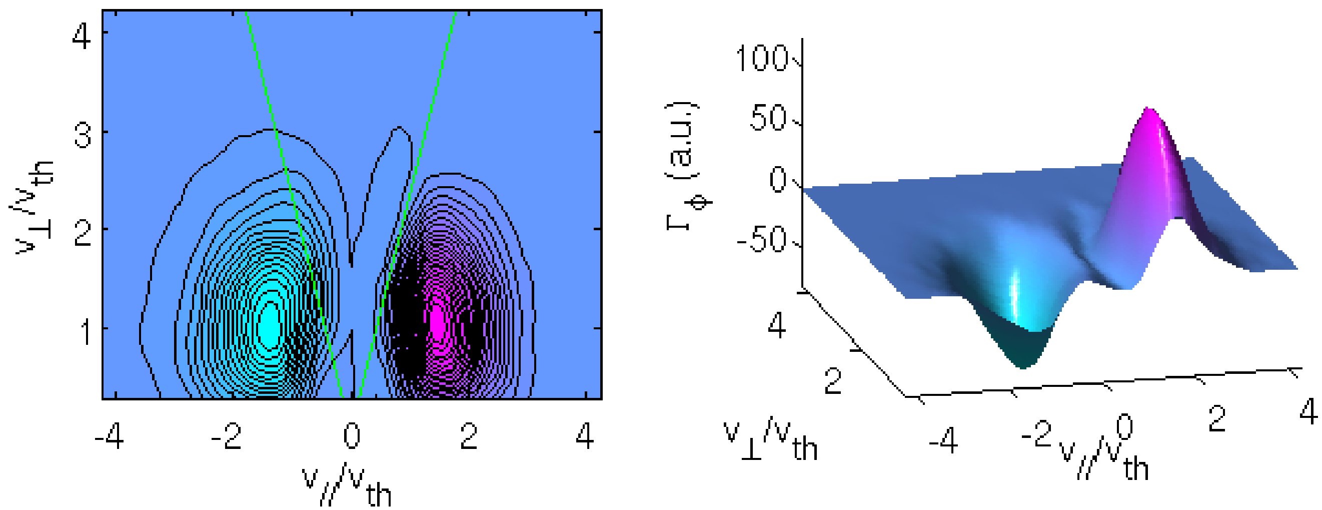




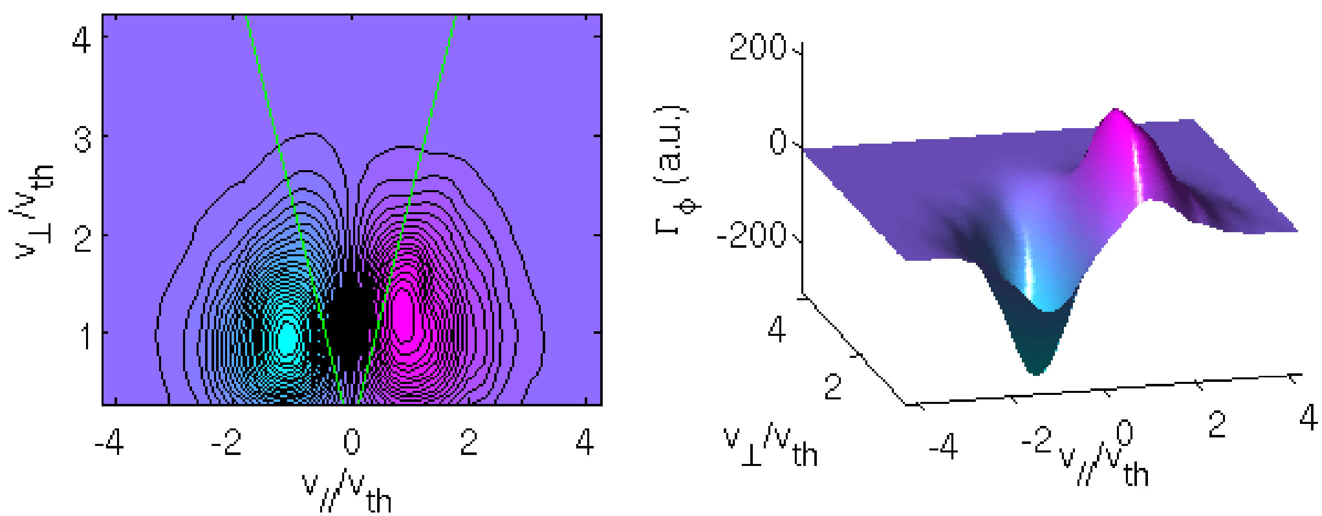
with adiab. electrons

Highly distinct phase space structures of momentum (and other) flux are shown for TEM turbulence

- CTEM turbulence
- at $\theta = 0$ (mid-plane)



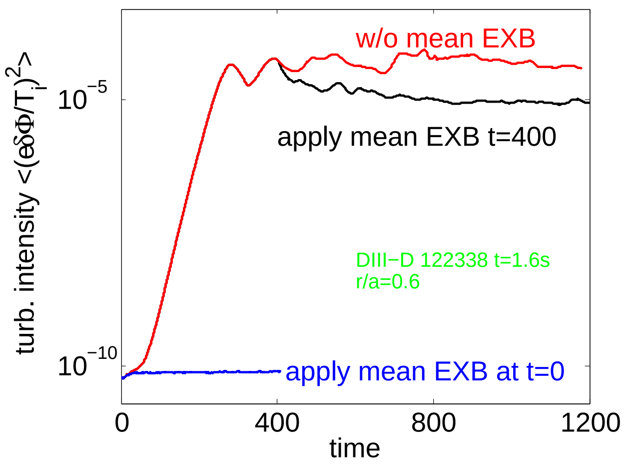
∇T_e-driven

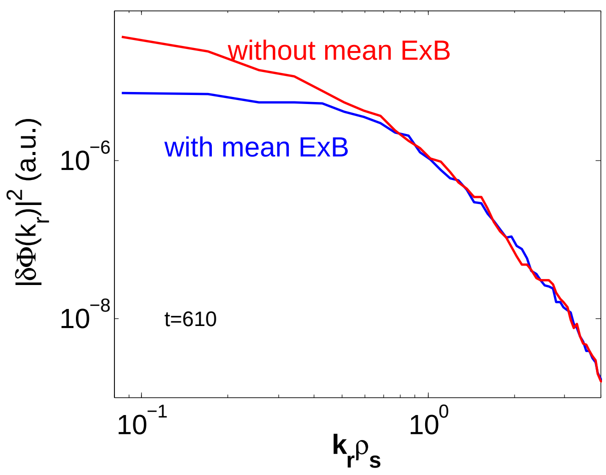


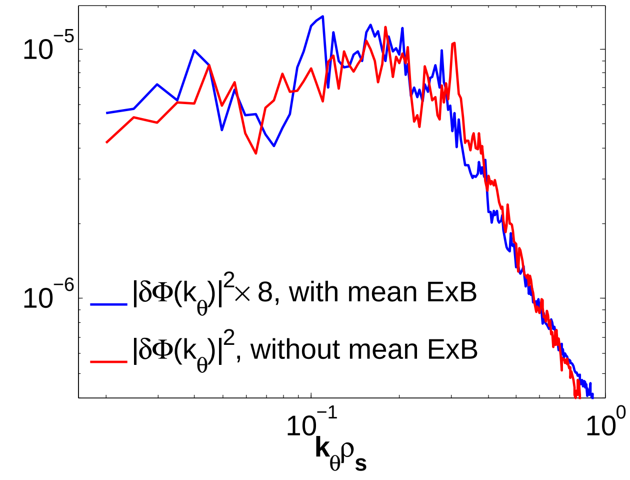
∇n-driven

Compared to ITG case, TEM turbulence driven momentum transport is made by ions from different regions, and in a different way!

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





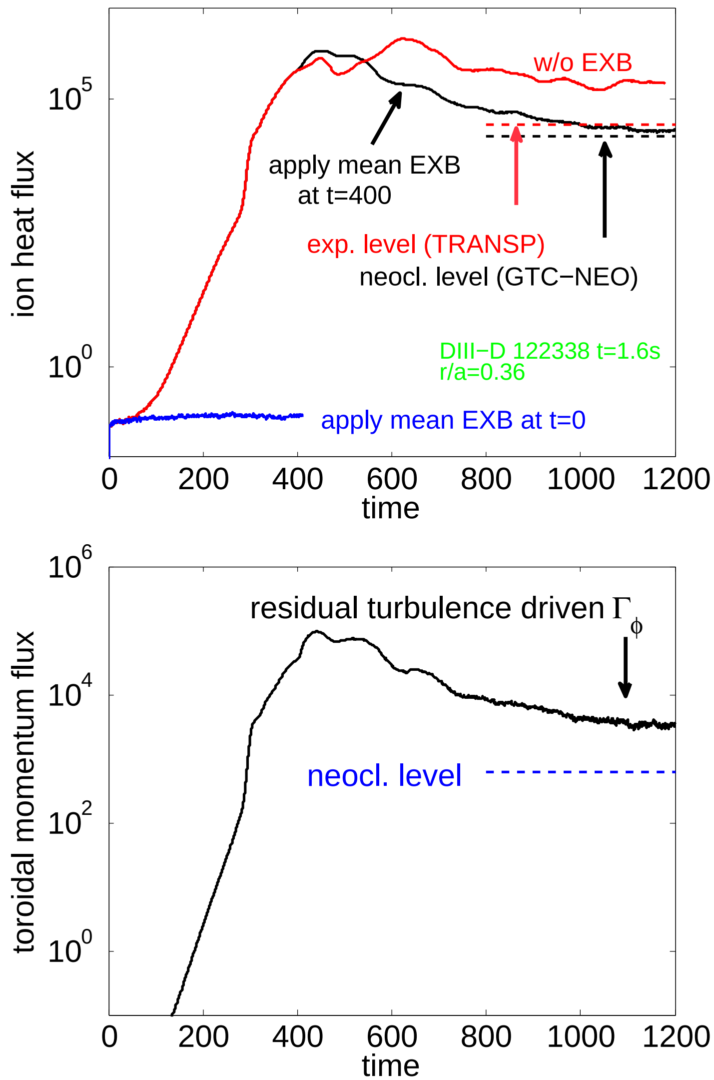


- Strong toroidal rotation and $\mathbf{E} \times \mathbf{B}$ flow are driven by neutral beam injection $\Rightarrow$ stabilize ITG linearly
- However, $\mathbf{E} \times \mathbf{B}$ shear induced dissipation is fluctuation-mode-dependent:

  more efficient on lower k_r linear eigenmodes

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

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, $\chi_\phi^{\rm eff} \sim \chi_i$

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

- Residual fluctuations may drive finite transport:

  $\chi_i^{\rm turb} \lesssim \chi_i^{\rm nc}$ (NC-level ion heat flux)

  $\chi_\phi^{\rm turb} \sim \chi_i^{\rm turb} \sim 40\chi_\phi^{\rm nc}$ (highly anomalous)

Summary – turbulence driven nondiffusive momentum transport

- A large inward flux of toroidal momentum is driven robustly in the post-saturation phase of ITG turbulence, leading to core rotation spin up with $\Delta u_{\|} \sim$ few % of v_{th} (in the case of no momentum source at the edge)

- The underlying dynamics is the nonlinear generation of residual stress due to the $k_{\|}$ symmetry breaking induced by global quasi-stationary zonal flow shear.

- Net momentum flux in the long-time steady state appears to be diffusion dominated with strong coupling with ion heat flux, $\chi_\phi^{\text{eff}} \sim \chi_i$.
(consistent with experiments and ITG theory)

- Momentum and energy flux show fairly persistent phase space structures (with a lot of interesting details $\cdots$)

- Trapped electron physics may change stories significantly ...

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Summary – Residual turbulence and its effect

- Residual fluctuations can survive in a strong mean **E**×**B** flow shear and drive experimentally relevant momentum and energy transport (the **E**×**B** shear induced dissipation is mode-dependent!)

  $\Longrightarrow$ one possible explanation to the puzzle of co-existence of neoclassical-level ion heat and anomalous momentum transport in experiments

- Ongoing simulation study: residual TEM turbulence and driven transport in NSTX (strong rotation and **E**×**B** shear, ITG is very minor player)

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