5th IAEA Technical Meeting on Theory of Plasma Instabilities

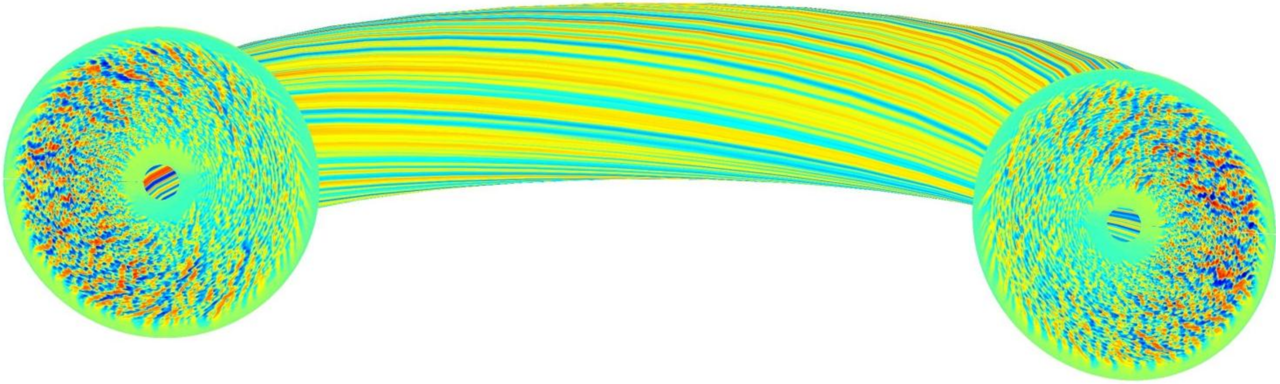
Austin, Texas, 2011

Convective motion in collisionless trapped electron mode turbulence

Presented by Wenjun Deng

Yong Xiao, Zhihong Lin and GPS/GSEP/CPES Team
University of California, Irvine

This work is supported by SciDAC Centers for GPS, GSEP & CPES



Introduction

- Electron heat transport is important for burning plasma
- Collisionless trapped electron mode (CTEM) is a prominent candidate for electron anomalous transport in tokamak core plasma
- Gyrokinetic simulation (GTC) has emerged as a major tool to study the nonlinear physics of CTEM turbulence

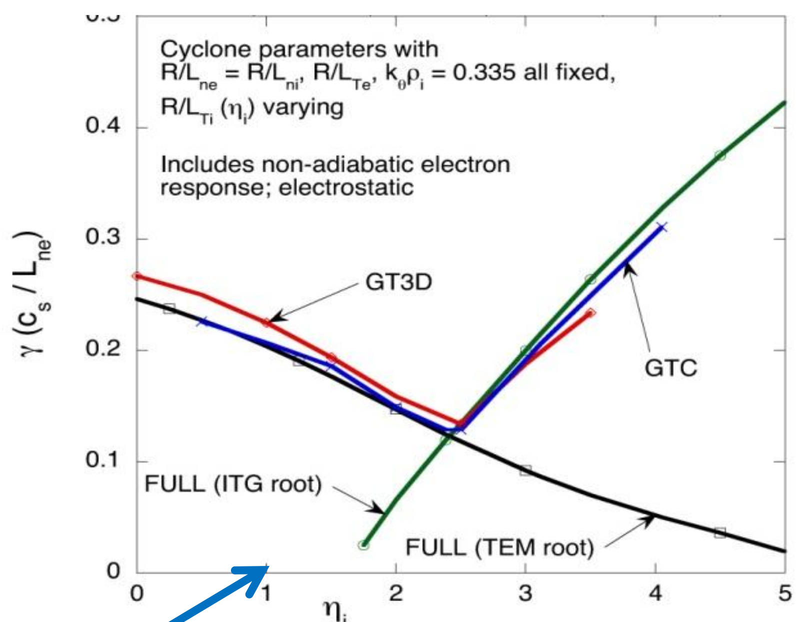
Linear benchmark

Simulation parameters

R_0/L_{Te}=6.9, R_0/L_{Ti}=2.2

R_0/L_n=2.2, T_e/T_i=1

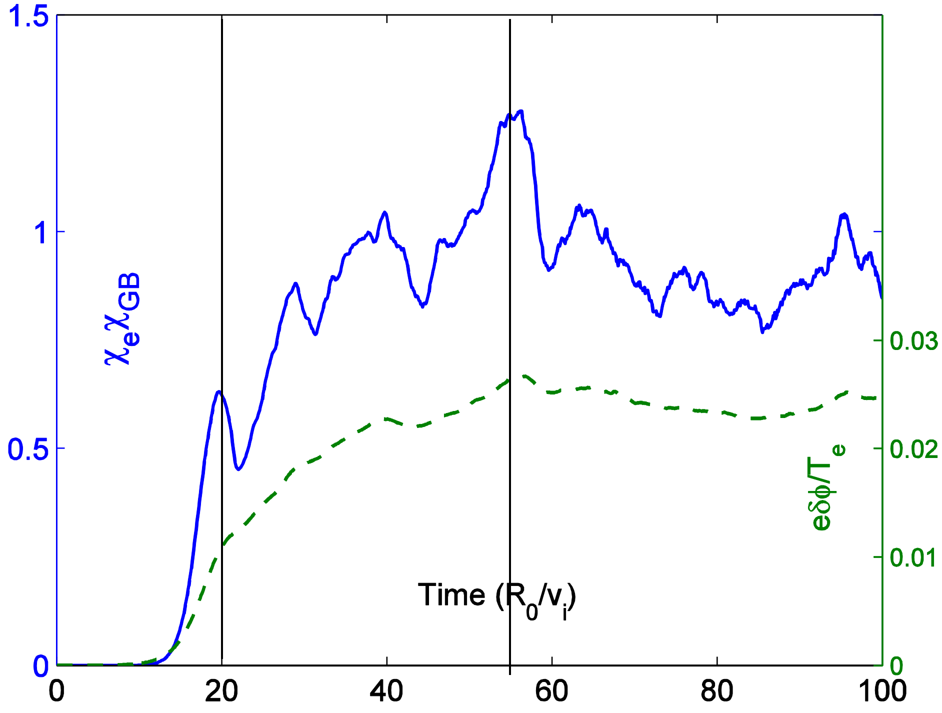
m_i/m_e=1837, q=1.4, s=0.78



Simulation point

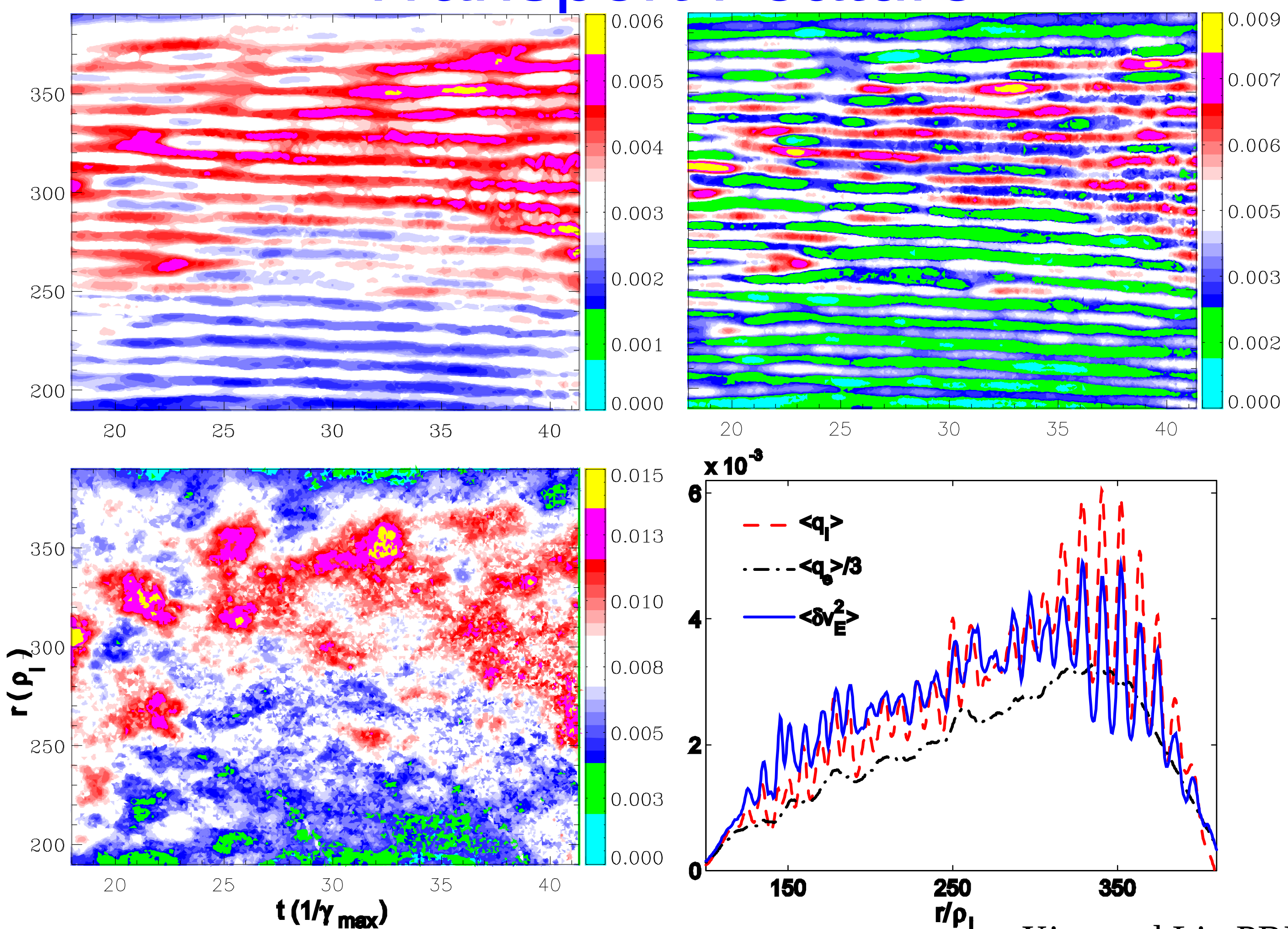
Rewoldt/Lin/Idomura
CPC 2007

Nonlinear CTEM Simulation



Linear Transient Nonlinear/saturation

Transport Feature

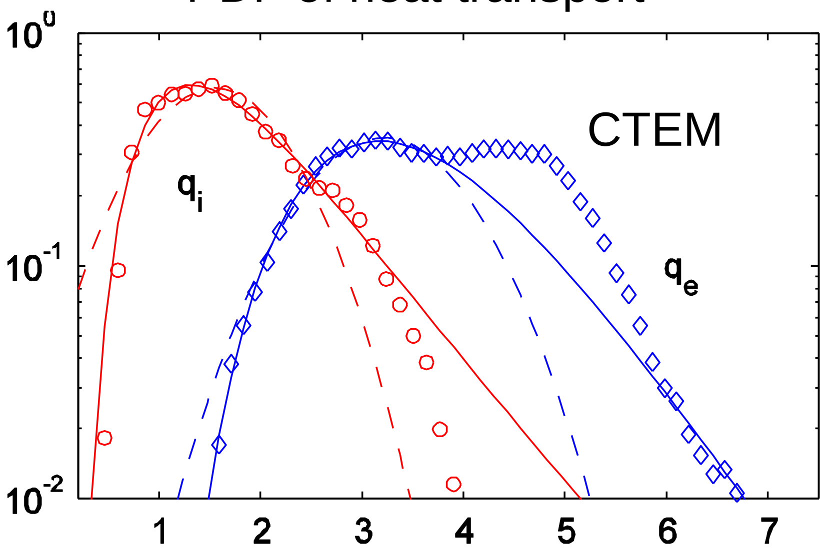


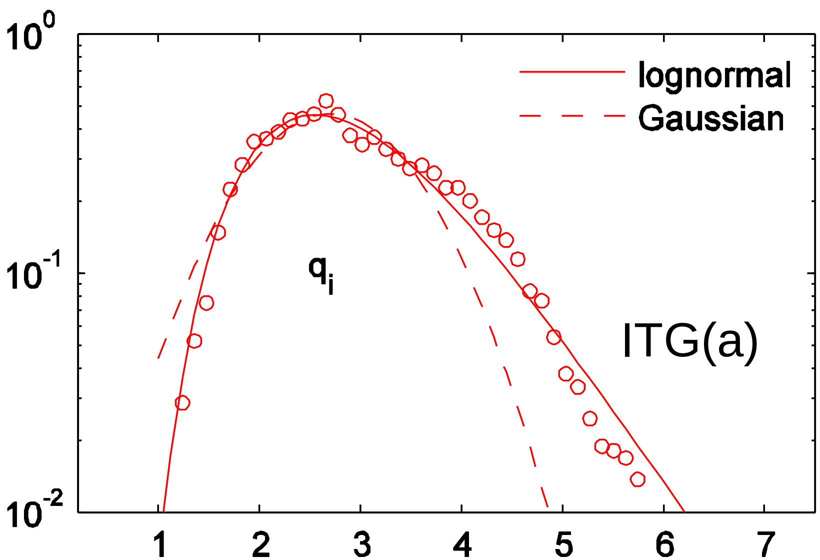
Xiao and Lin PRL 2009

- q_i: diffusive, proportional to local EXB intensity
- q_e: track global profile of intensity; but contain a nondiffusive component on mesoscale
- Nondiffusiveness is due to existence of meso-scalse eddies and weak detuning of the toroidal precessional resonance

More Evidence on Nondiffusive e transport

PDF of heat transport





Lin PoP 2004

- The folding of two Gaussian gives a lognormal distribution

Basu,PoP2003

- Ion heat transport in both ITG/CTEM is a diffusive process. The flux-surface averaged ion heat flux shows a log-normal distribution

- Electron heat transport in CTEM can not be described by the log-normal distribution model. The high density of PDF in the large transport range shows the non-diffusiveness of the electron transport.

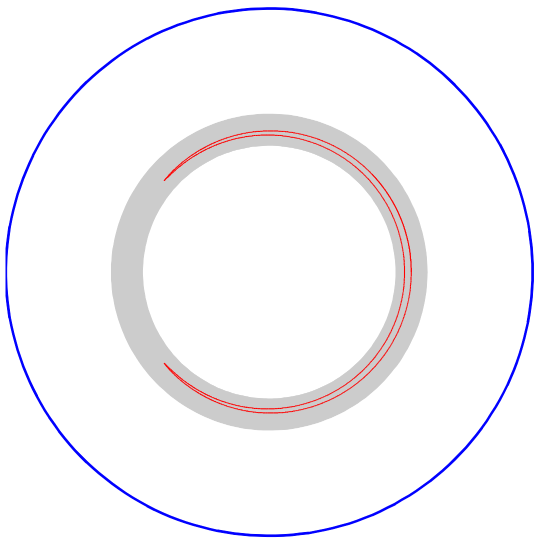
Xiao et al PoP 2010

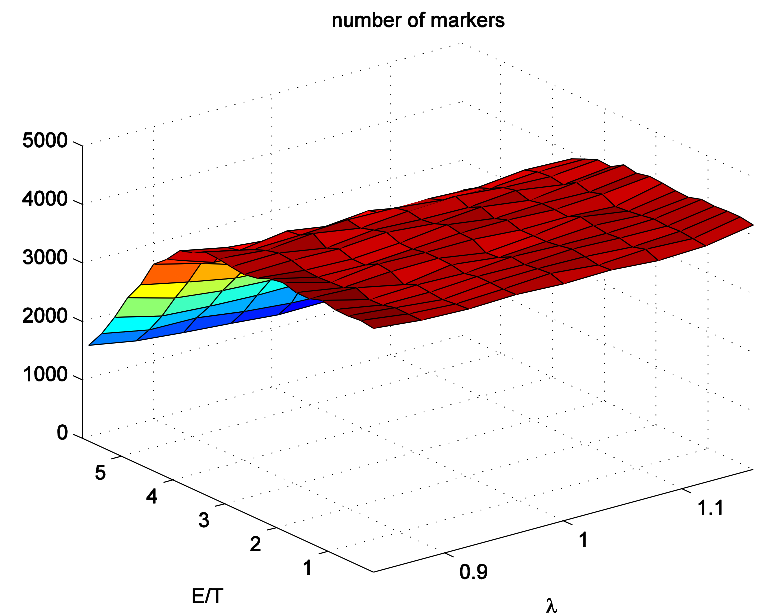
Need a Kinetic Picture

- The above investigations based on fluid picture provide important insights on the CTEM turbulent transport.
  - Trapped electrons move with turbulent eddies like fluids due to lack of parallel, toroidal and radial decorrelation.
  - Electron's moving within one eddy on mesoscale gives rise to non-diffusive (convective) motion; while moving across different eddies gives rise to diffusive motion.
  - Non-diffusive component can be separated from the diffusive component by statistic analysis
- A kinetic picture is still desirable
  - Provide a complementary perspective
  - More quantitative
  - More predictive
  - More fundamental
  - More definitive
- Lagrangian analysis is first choice to identify the non-diffusive component

Lagrangian Analysis of Electron Orbits

- Selected 1M electron markers out of total 2B trapped particles





Kinetic Energy:

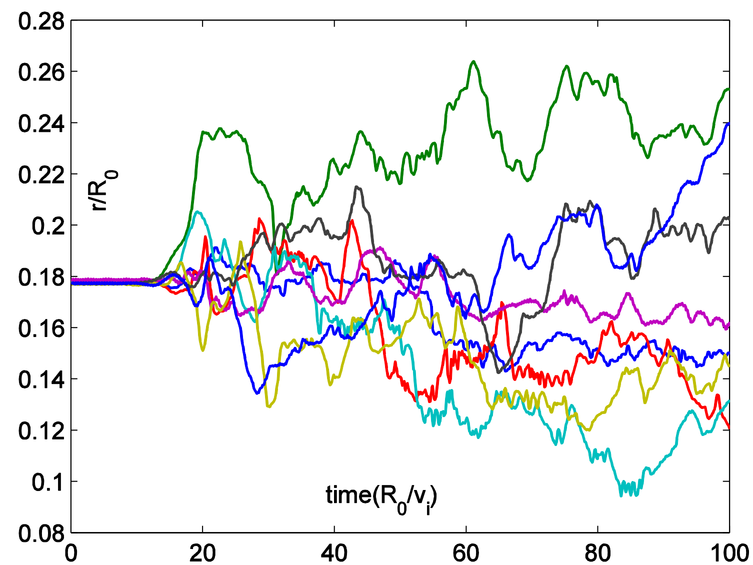
$E = m_e v^2/2$

Pitch Angle:

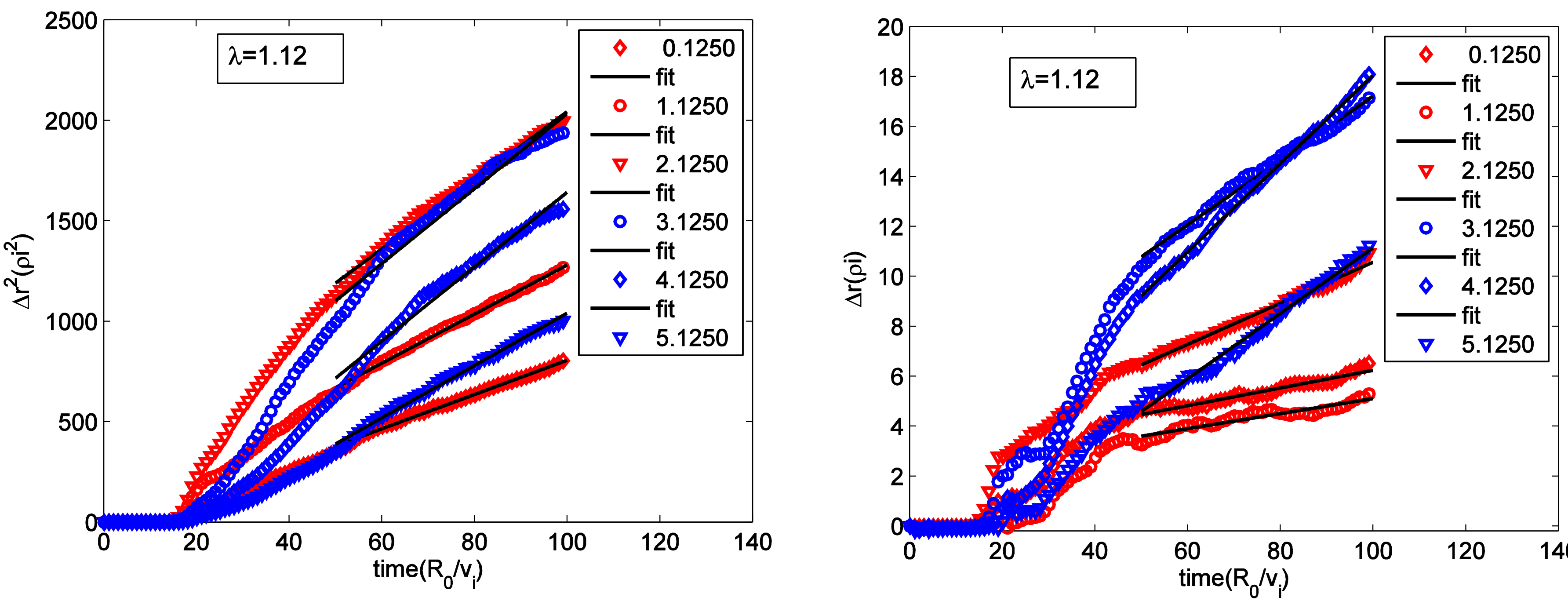
$\lambda = \mu B_0/E$

$$\Delta r(t) = \frac{\sum_{i=1}^{N} \delta r_i(t)}{N} \equiv \langle \delta r_i(t) \rangle \quad \rightarrow \quad v_r = \Delta r/\Delta t$$

$$\Delta r^2(t) = \frac{\sum_{i=1}^{N} \left(\delta r_i(t) - \langle \delta r_i(t) \rangle\right)^2}{N} \quad \rightarrow \quad D = \Delta r^2/2\Delta t$$



Diffusion and Convection



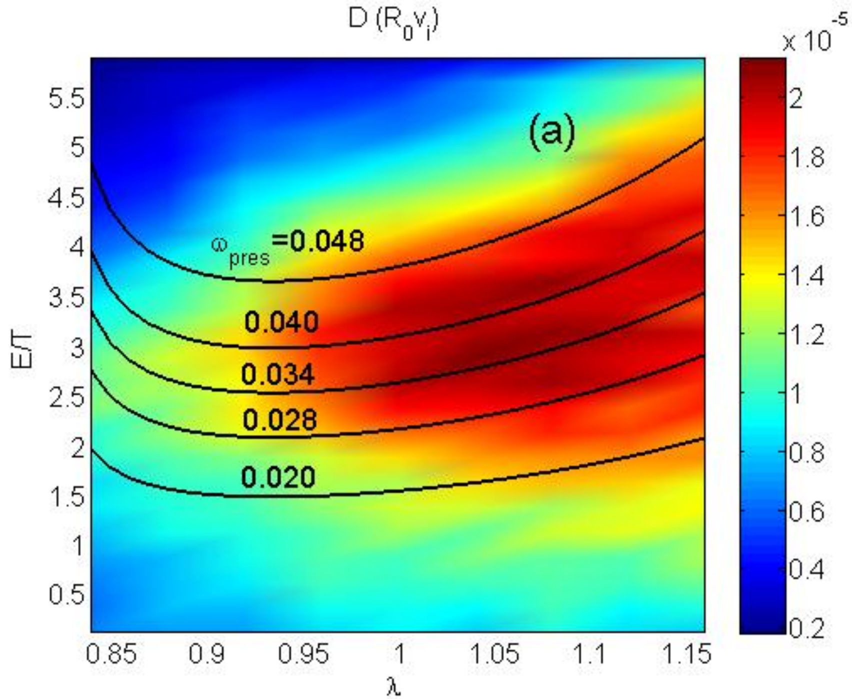
- Both diffusion and convection are observed in CTEM turbulence
- Both diffusion and convection first increase with energy. After reaching a maximum value, they both decrease with energy.

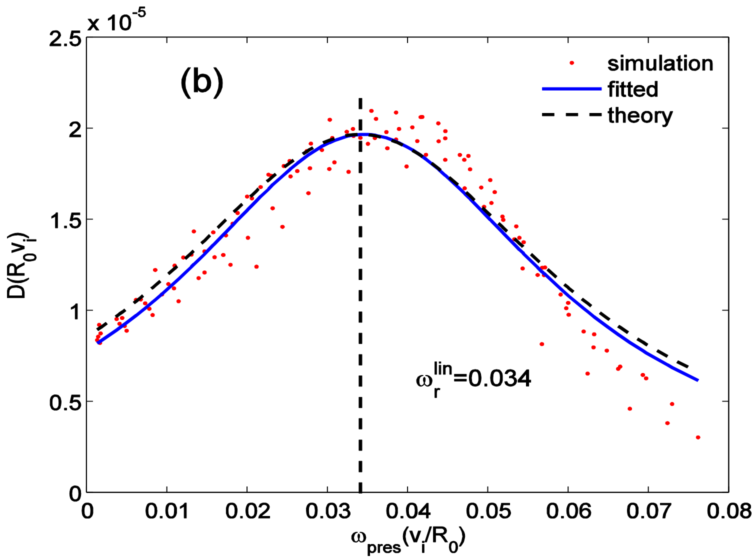
$$q = \alpha D \nabla T + \beta V_p T$$

Chen JGR 1999

- Linear fit of slope gives diffusion and convection coefficients

Diffusion in CTEM



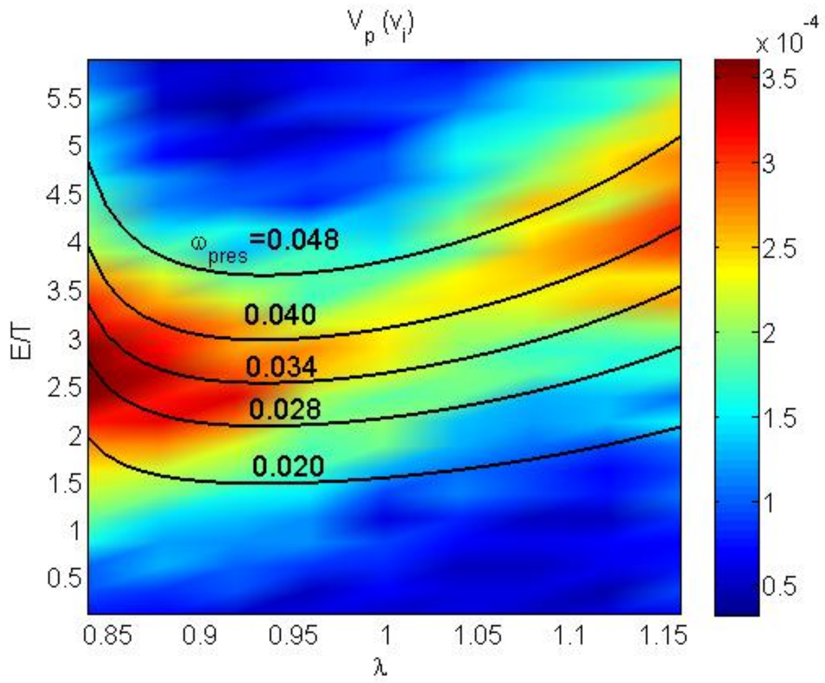


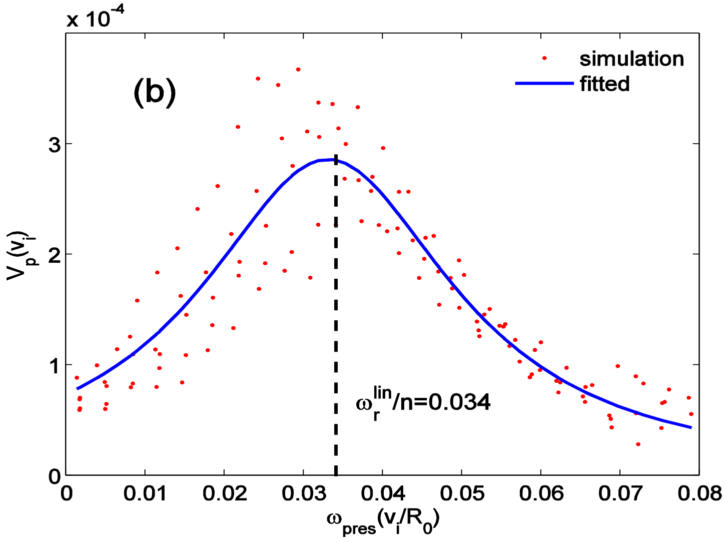
- For each pitch angle, there is an energy that maximizes the diffusion. This energy is found to be the one that gives rise to the toroidal precessional resonance.
- For each energy , the diffusion is larger for deeply trapped electrons than for the barely trapped electrons.
- Lorentzian distribution based on the resonance broadening

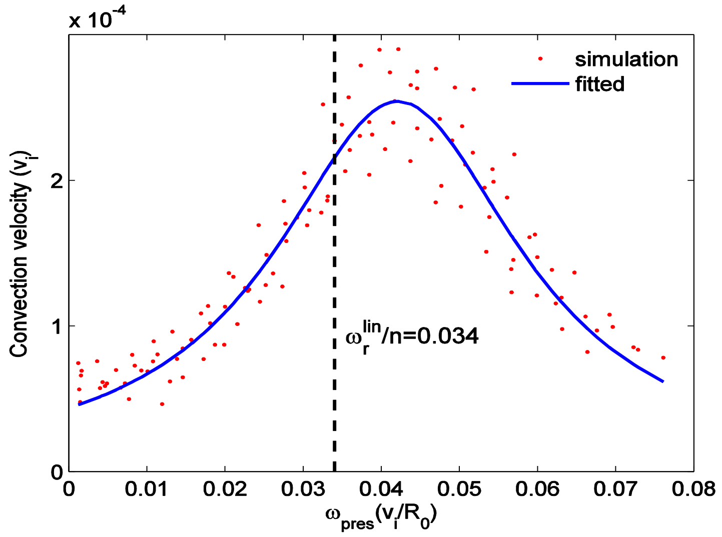
$$D(\omega_{pres}) = \frac{D_0 \gamma_0^{\ 2}}{(\omega_{pres} - \omega_0)^2 + \Delta\omega^2}, \text{ where we find } \Delta\omega = \frac{\gamma}{n}, \omega_0 = \frac{\omega_r}{n}$$

is found to well match the 1D diffusivity data: role of precessional resonance

Convection in CTEM







- Trapped electrons have an outward convection
- The barely trapped electrons have a larger convective effect than deeply trapped ones
- Lorentzian model is applicable for barely trapped, plausible for deeply trapped

Physics of Outward Convection

- In CTEM, trapped electrons lose energy to excite plasma waves
- The first invariant (magnetic moment) is conserved

$$\delta E = \mu \delta B \text{ at banana tip, } \delta E < 0 \rightarrow \delta B < 0 \rightarrow \delta x > 0$$

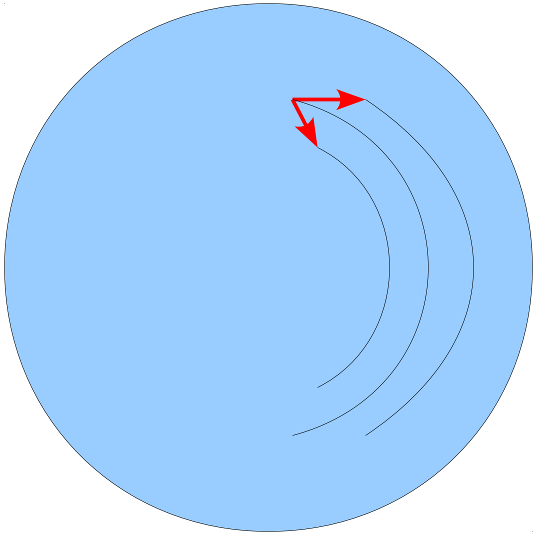
- The conservation of parallel(sencod) invariant $J_{\|} = \oint dlmv_{\|}$ leads to an outward convection

$$J_{\|} = 4R_0 q(r)\bar{v}_{\|}\theta_b \rightarrow q(r)\theta_b \approx \text{constant}$$

  – For $s > 0$, if $\mathrm{r}\uparrow$, then $\theta_{\mathrm{b}}\downarrow$; if $\mathrm{r}\downarrow$, then $\theta_{\mathrm{b}}\uparrow$

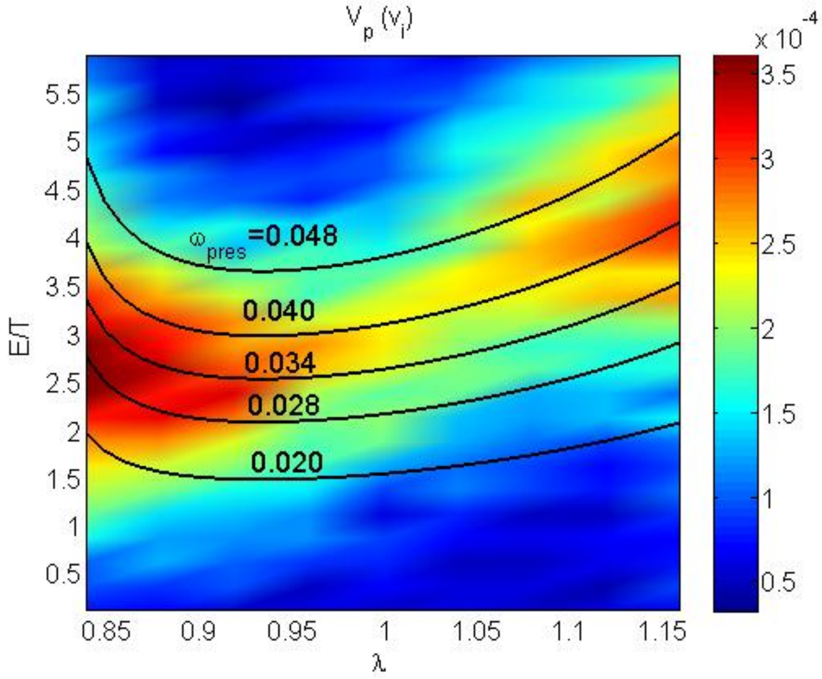
    $\delta x > 0 \rightarrow \delta r > 0$

  – For $\mathrm{s} < 0$, CTEM linearly stable

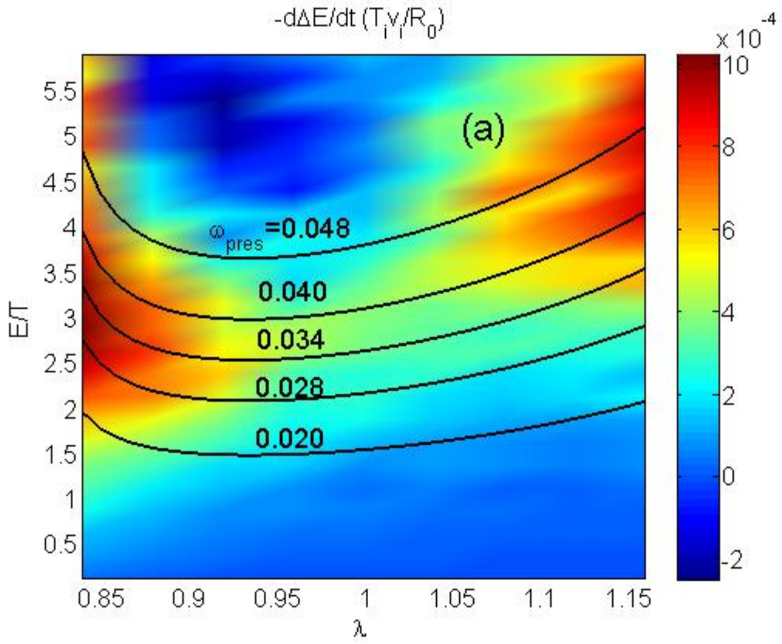


- Truly global feature: flux tube simulation would introduce artificial inward convection for large bounce angles

Energy Exchange in CTEM



Convection



Kinetic Energy exchange

- The phase space of energy exchange shows similar structure as that of the convection velocity, confirming that the kinetic energy loss of trapped electrons leads to outward convective motion.

Theoretical Analysis

- The second adiabatic invariant

$$J_\parallel \equiv m_e \oint dl v_\parallel = J_\parallel(\lambda, E, r)$$

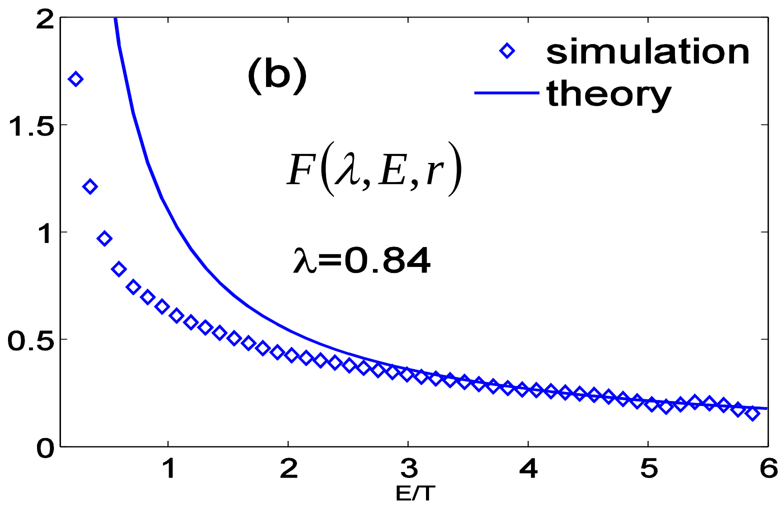
- Conservation of $J_{||}$

$$J_\parallel = J_\parallel(\mu, E, r)$$

$$\Delta J_\parallel = \Delta\lambda \frac{\partial J_\parallel}{\partial \lambda} + \Delta E \frac{\partial J_\parallel}{\partial E} + \Delta r \frac{\partial J_\parallel}{\partial r} = 0$$

gives $$V_p = \frac{d\Delta r}{dt} = -R_0 F(\lambda, E, r) \frac{d}{dt}\left(\frac{\Delta E}{T_i}\right)$$

with convection coefficient $$F(\lambda, E, r) = \frac{T_i}{2R_0 E} \frac{J_\parallel}{\partial J_\parallel / \partial r}\left(1 - \frac{2\lambda}{J_\parallel}\frac{\partial J_\parallel}{\partial \lambda}\right)$$



Summary

- Lagrangian analysis of electron orbits in CTEM turbulence shows that the turbulent transport contains both diffusive and convective motions.
- The phase space diagrams are made for both diffusion and convection of trapped electrons in the CTEM turbulence
- The diffusion of trapped electrons can be fit by a Lorentzian model, possibly described by a resonance-broadening theory.
- The outward convection of electrons is caused by the ***conservation of parallel invariant*** and ***loss of kinetic energy***, which is very robust no matter whether the underlying kinetic process is quasilinear or not.
- Important implications for other low frequency turbulent transport, such as energetic particle transport in fishbone instability and alpha particle tunneling

Work submitted to Physics of Plasmas (Letter)