Global Gyrokinetic Simulations of Toroidal ETG Mode in Reversed Shear Tokamaks

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Outline

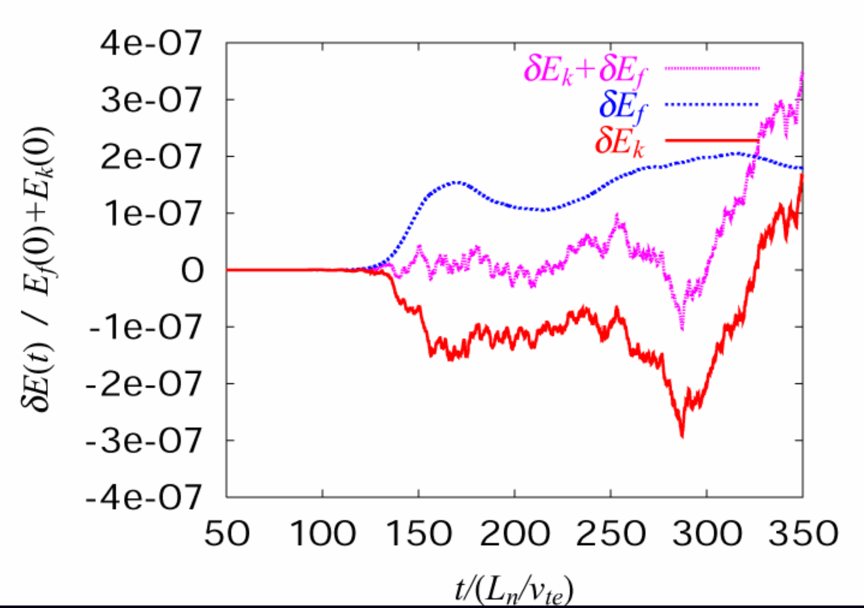
- **Introduction**
- **Linear analysis and mixing length estimate of ETG modes**
- **ETG turbulence simulations in PS and RS tokamaks**
- **Summary**

Introduction

- ETG turbulence is experimentally relevant candidate of χ_e in tokamak
  - High suppression threshold $\omega_{ExB} > \gamma$ than TEM (Stallard 1999)
  - Stiff T_e profile consistent with critical L_{te} of ETG (Hoang 2001)
- Results from several ETG simulations contradict with each other
  - In PS tokamaks, local flux tube toroidal GK simulations (Jenko 2002) show extremely high χ_e~$10\chi_{GB}$ due to streamers
  - High χ_e was not recovered in local slab GF simulations (Li 2004) and large ρ^* (ρ^{*-1}~100) global toroidal GF simulations (Labit 2003)
  - In RS tokamaks, global slab GK simulations (Idomura 2000) show χ_e suppression by ETG driven microscopic zonal flows
- To understand these qualitatively and quantitatively different results, ETG turbulence is studied using global toroidal GK simulations
  - Linear global analysis of toroidal ETG modes in PS/RS tokamaks
  - Correspondence between mixing length theory and ρ^*-scaling
  - Zonal flow and streamer formations in PS/RS-ETG turbulence

ETG turbulence simulation using GT3D

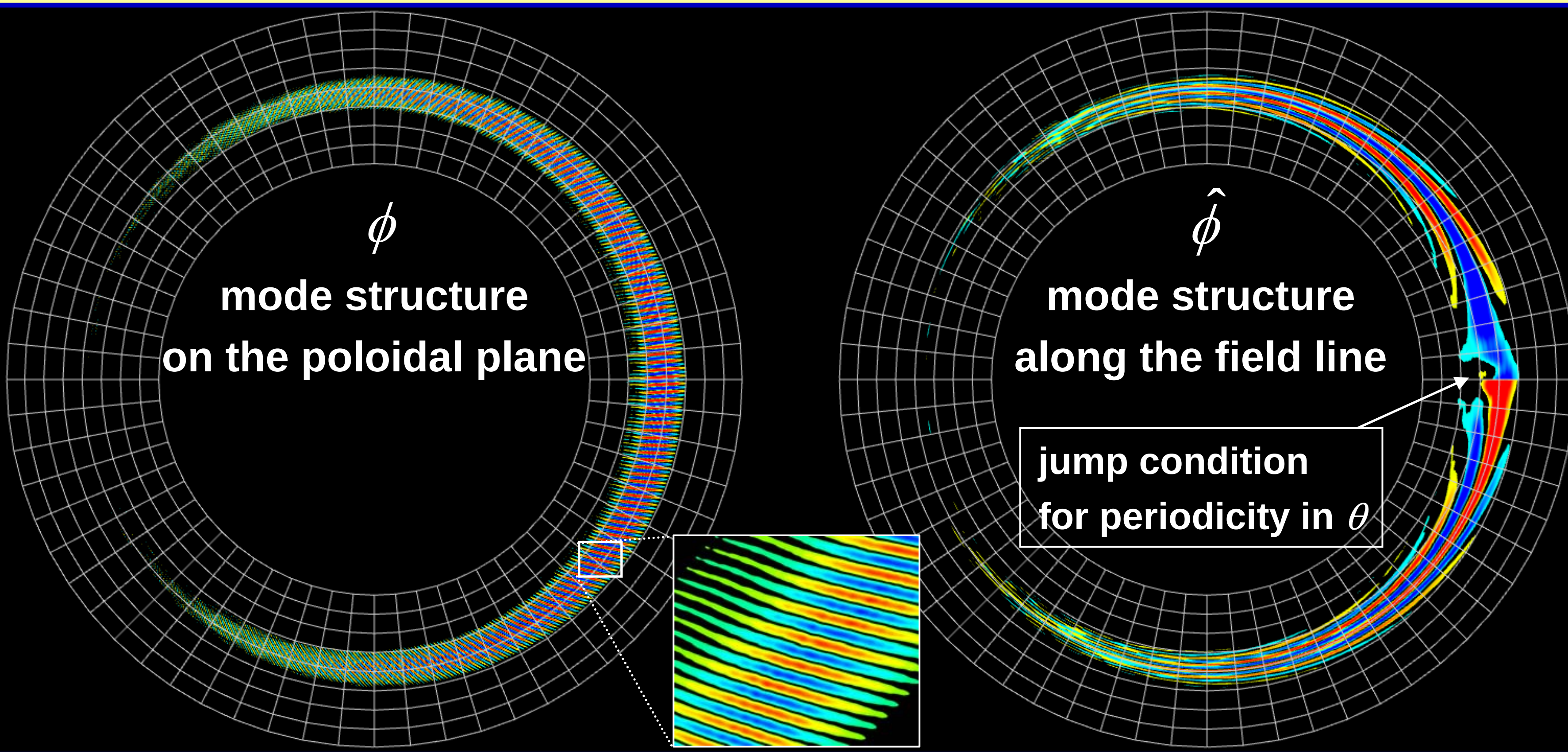
- GK toroidal PIC code based on finite element δf PIC method
- Gyrokinetic electrons with adiabatic ions ($k_\perp \rho_{ti} >> 1$)
- Annular torus geometry with fixed boundary condition $\phi = 0$
- $1/N$ wedge torus model $n = 0, N, 2N, 3N\ldots$
- Realistic small $\rho^* = \rho_{te}/a$ with quasi-ballooning representation
- Global profile effects (n_e, T_e, q, $1/r$)
  - Self-consistent T_e, n_e are relaxed by heat/particle transport
  - ω^*_{te}-shearing effect
  - Reversed $q(r)$ profile
- Optimized particle loading
  - energy/particle conservation



Validity of simulation is checked by conservation properties !

High-n solver with quasi-ballooning representation

$$\phi(r,\theta,\varphi)=\sum_n \hat{\phi}_n(r,\theta)e^{-in\varphi+in\hat{q}(r_s)\hat{\theta}},\quad \hat{\phi}_n(r,0)=\hat{\phi}_n(r,2\pi)e^{i2\pi n\hat{q}(r_s)},\quad r_s : \text{reference surface}$$



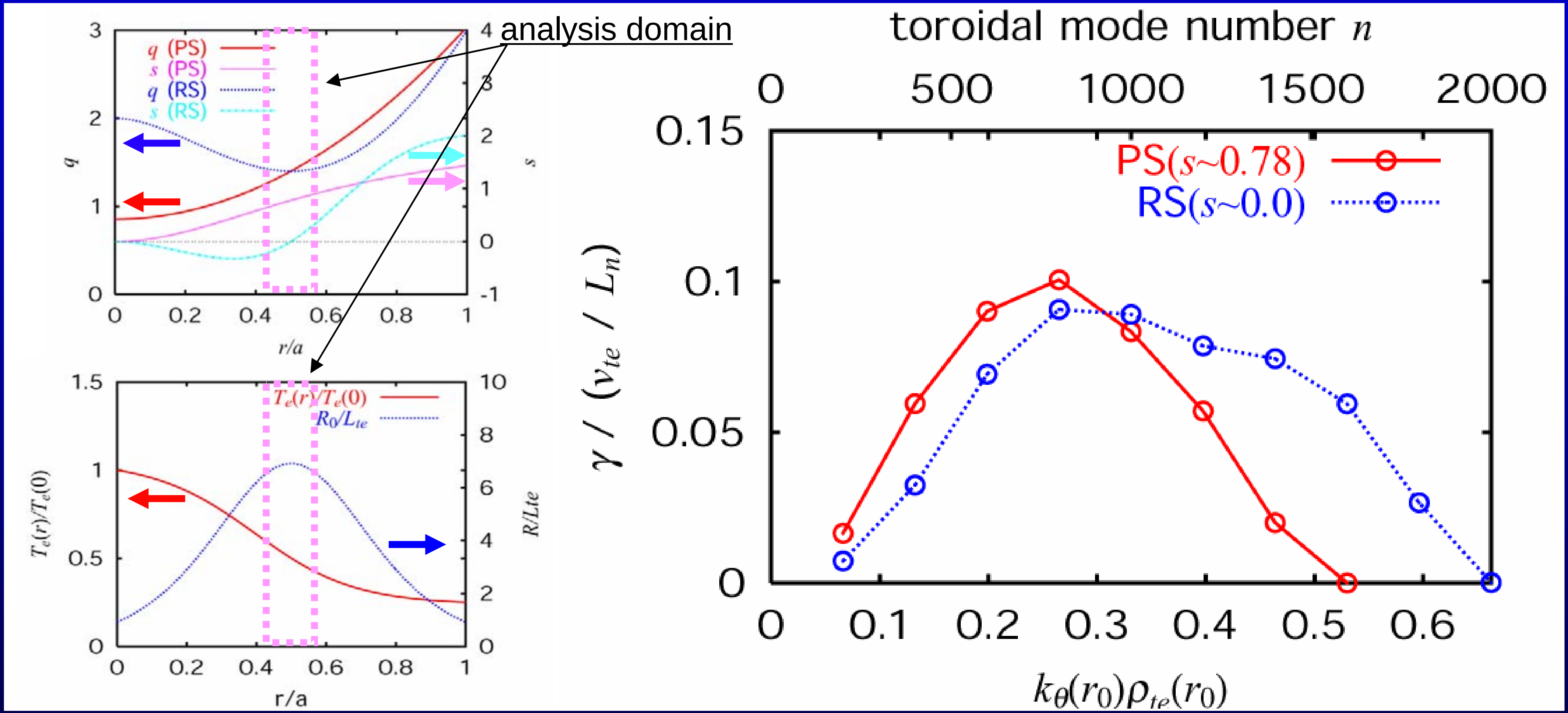
Realistic tokamak size a/ρ_{te}~10^4: $k_\theta\rho_{te}$~1 (q=1.4) $\longrightarrow$ m=5000

- ~10^4 poloidal grids are needed without QB representation
- ~10^2 poloidal grids are enough with QB representation

Linear analysis and mixing length estimate of ETG modes

Linear ETG growth rate spectrum

Cyclone like parameters (R_0/L_{te}=6.9, η_e=3.12, a~8600ρ_{te}~150ρ_{ti})



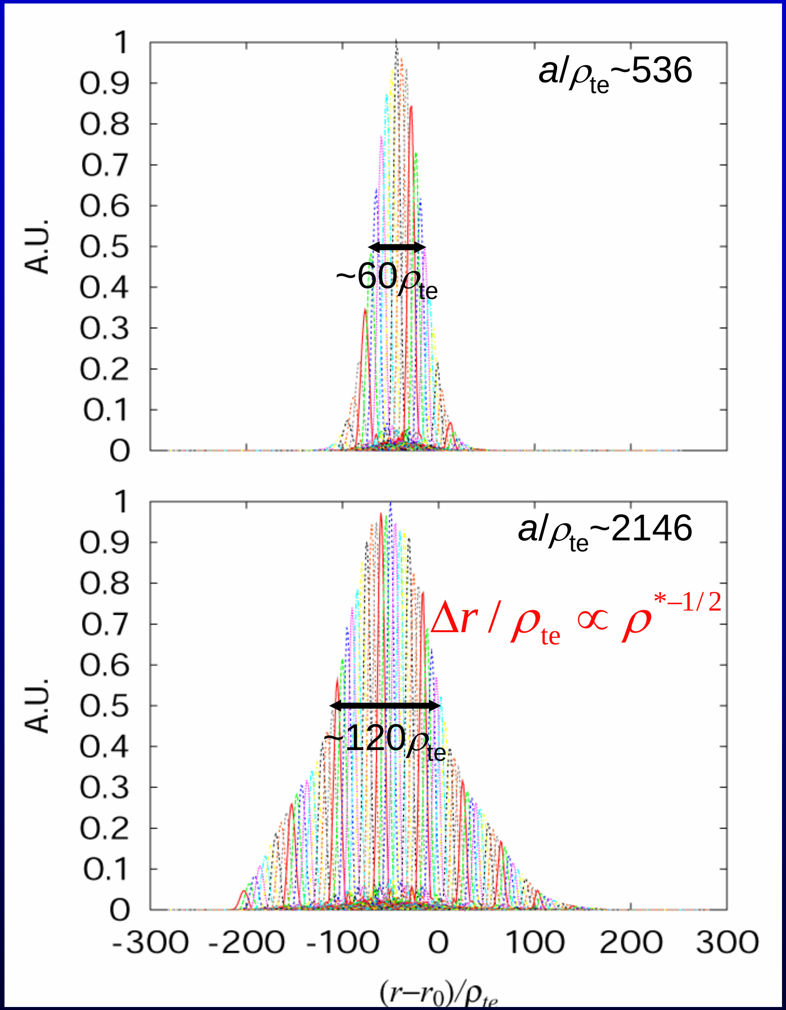
– Unstable region spreads over n~2000 (m~3000, $k_\theta\rho_{te}$~0.7)

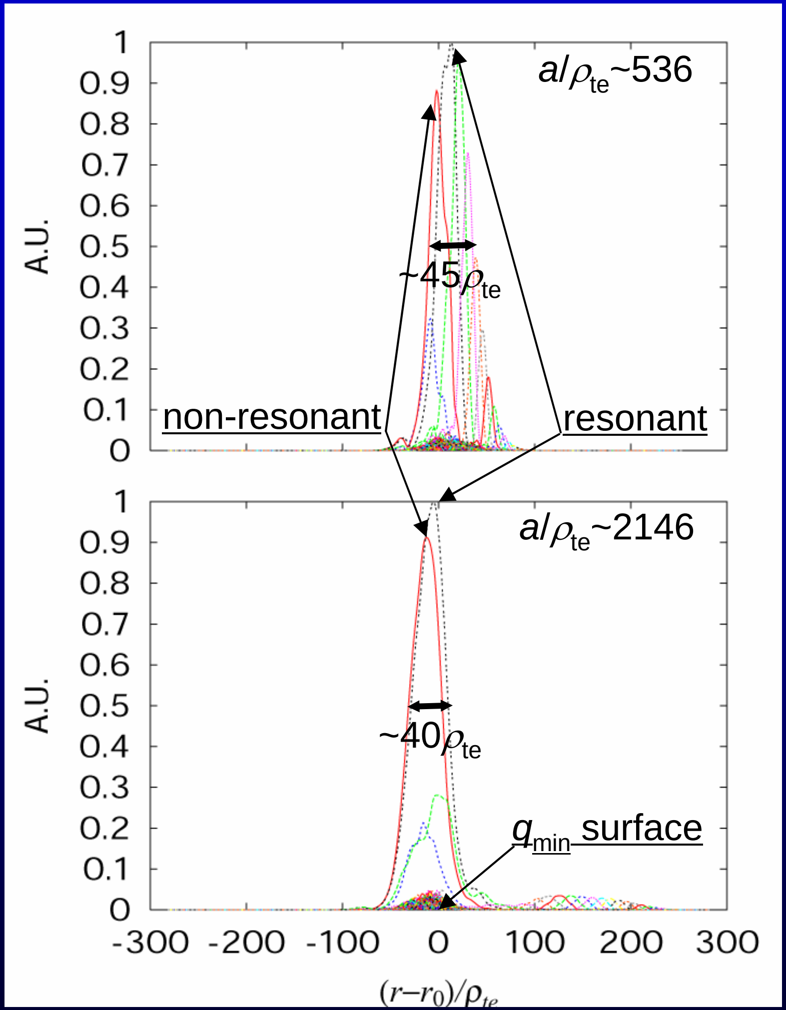
– RS-ETG mode is excited around q_{min} surface (Idomura 2000)

– Almost the same γ_{max} in PS and RS configurations

ρ^* scan of eigenfunctions in PS/RS tokamaks

- Positive shear configuration
- Reversed shear configuration





– Δr of PS-ETG mode is limited by ω^*-shearing effect (Kim 1994)

– Δr of RS-ETG mode is determined by q profile (Idomura 2000)

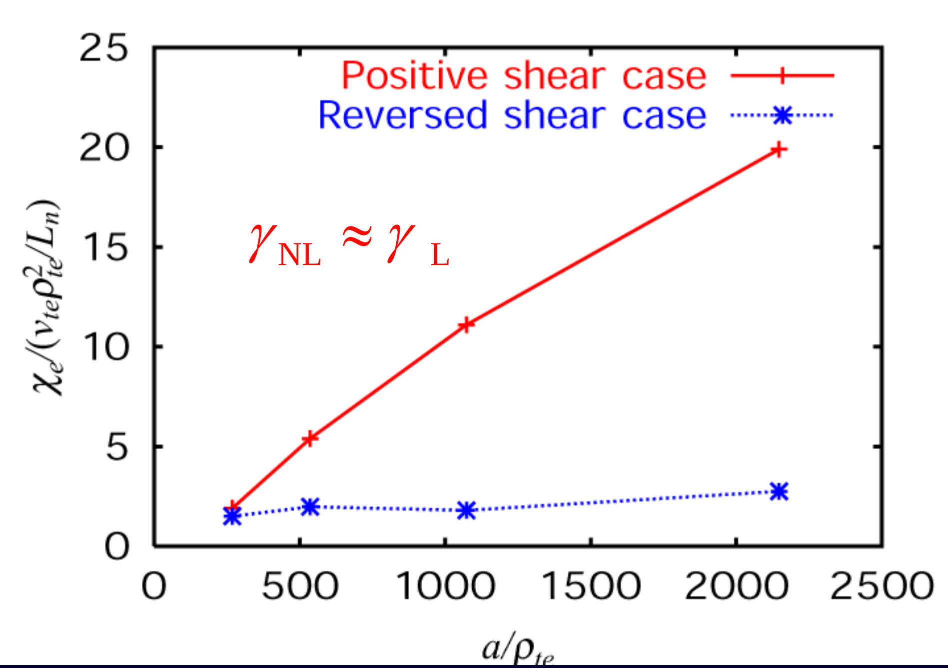
Mixing length theory and ρ^*-scaling

- Mixing length theory of ETG modes in PS/RS plasmas
  - PS-ETG mode $\Delta r / \rho_{te} \propto \rho^{*-1/2}$ $\longrightarrow$ $\chi_{ML} / \chi_{GB} \propto \gamma_n \rho^{*-1}$
  - RS-ETG mode $\Delta r / \rho_{te} \propto \left(L_{ns} / L_n\right)^{-1/2}$ $\longrightarrow$ $\chi_{ML} / \chi_{GB} \propto \gamma_n L_{ns} / L_n$

$$\gamma_n = \gamma L_n / v_{te} \qquad L_n = \left(d \ln n_e / dr\right)^{-1} \qquad L_{ns} = \left(2qR_0 / q'' r\right)^{1/2}$$

- ρ^* scan of the saturation amplitude in single-*n* simulations

Fixed local parameters
R_0/L_{te}=6.9, η_e=3.12
$k_\theta\rho_{te}$~0.3, a/R_0=0.358
γ_{NL}: eddy turn over time

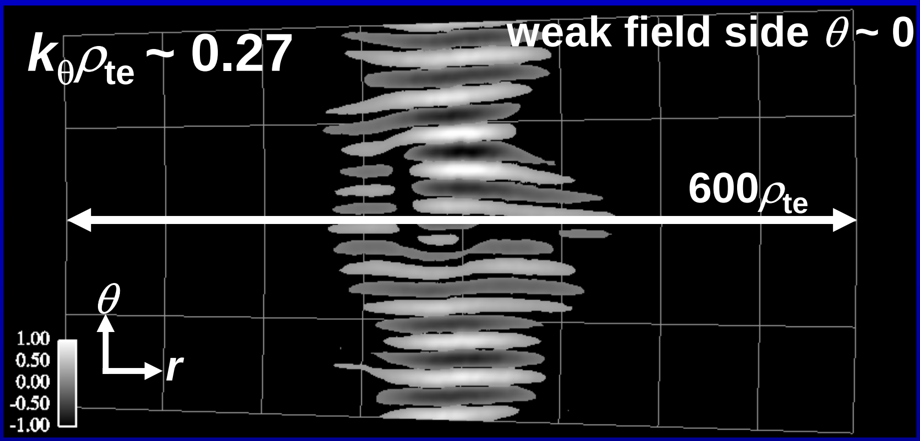


  - Small ρ^* PS-ETG modes give order of magnitude higher saturation level than RS-ETG and large ρ^* PS-ETG modes

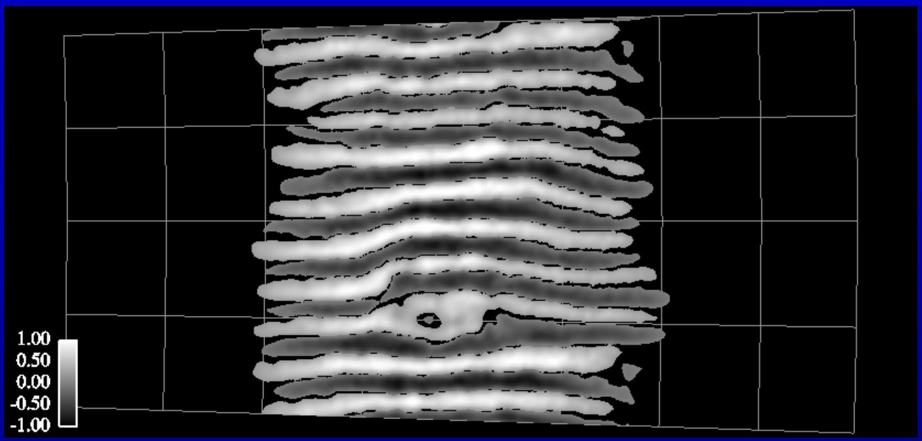
ETG turbulence simulations in PS and RS tokamaks (Cyclone like parameters with a/ρ_{te}~8600)

Streamer formation in PS-ETG turbulence

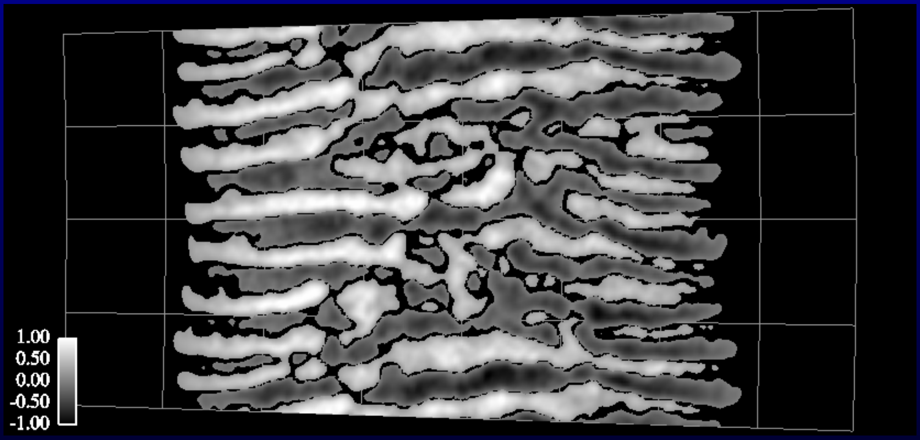
- Linear phase ($t\ v_{te}/L_n$ ~110)



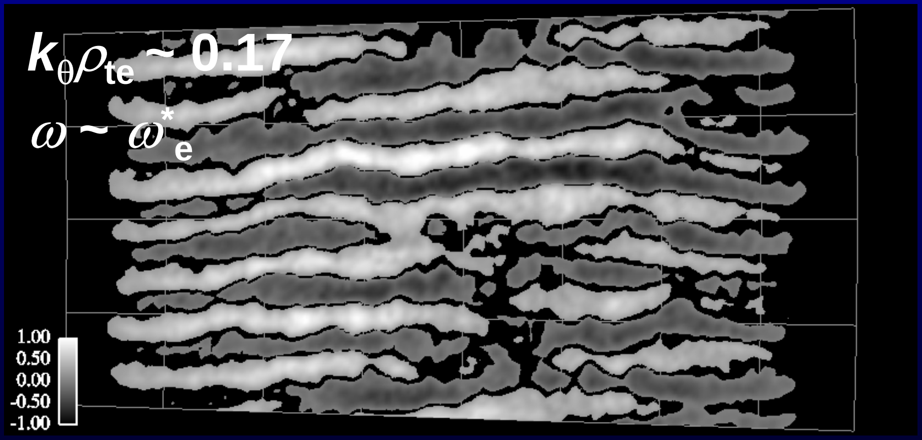
- Primary streamers ($t\ v_{te}/L_n$ ~175)



- Saturation phase ($t\ v_{te}/L_n$ ~208)



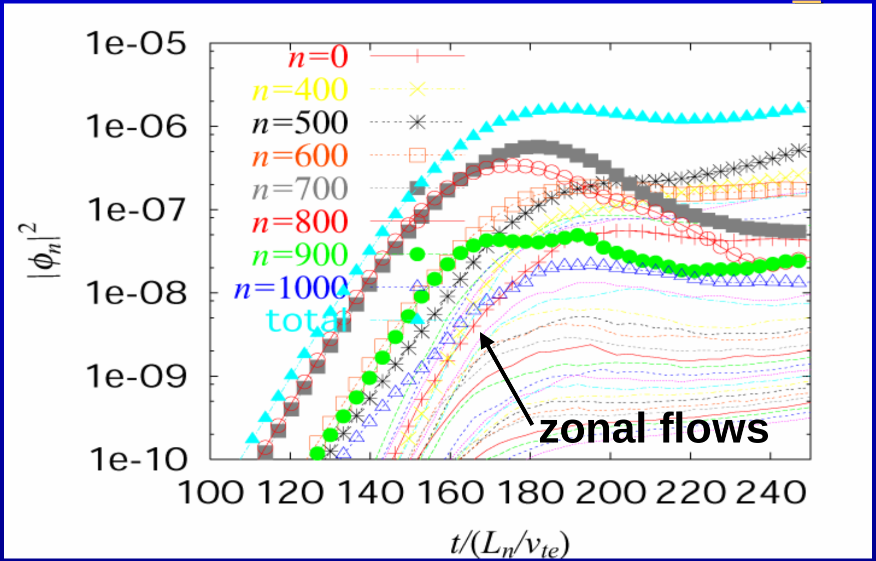
- Secondary streamers ($t\ v_{te}/L_n$ ~250)

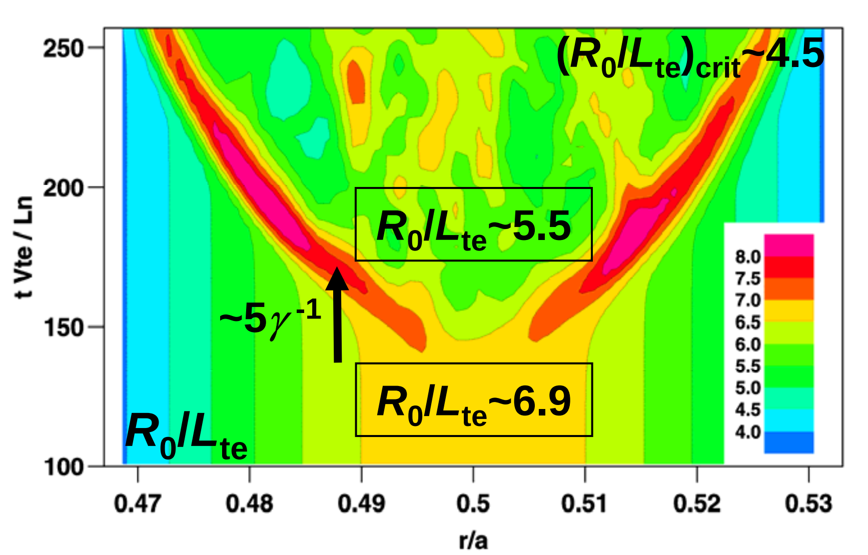


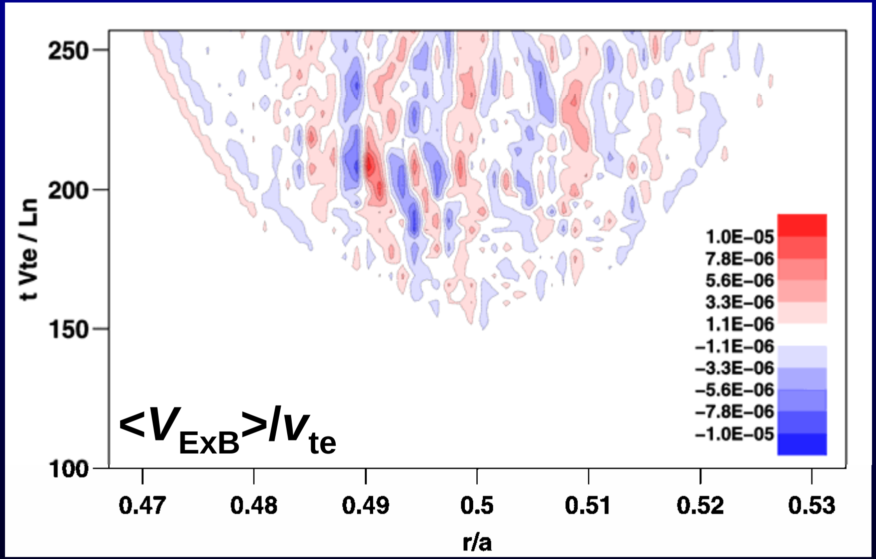
– PS-ETG turbulence is dominated by streamers

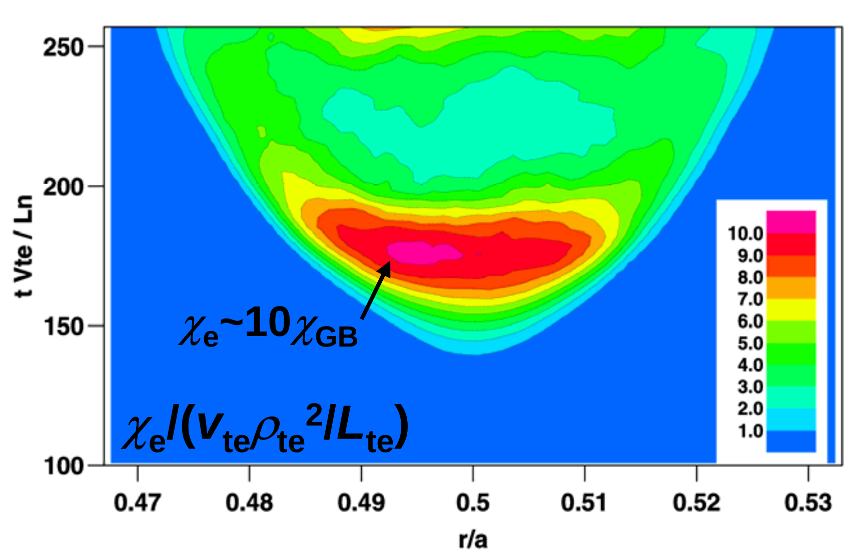
– Streamers are characterized by ballooning structure and ω~ω^*_e

Extremely high χ_e in PS-ETG turbulence





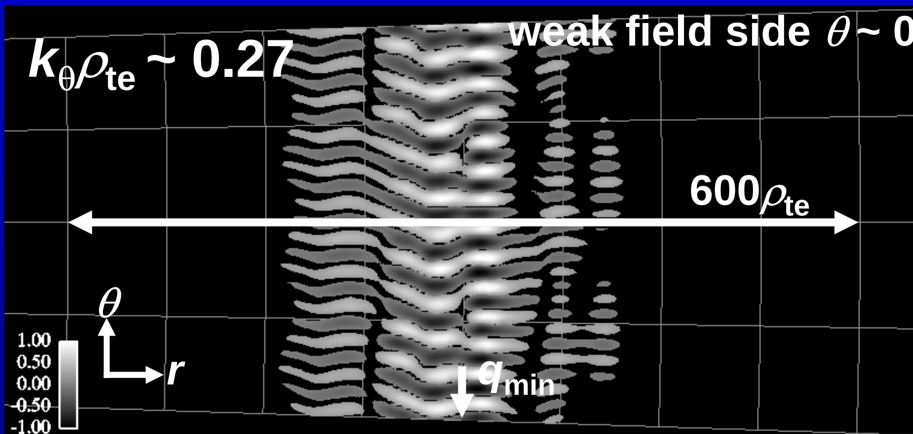




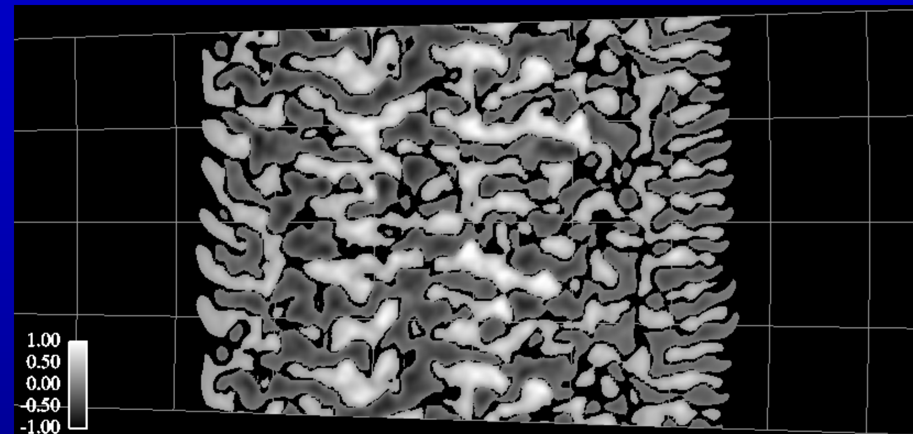
T_e profile is strongly relaxed in a turbulent time scale ~$5\gamma^{-1}$

Zonal flow formation in RS-ETG turbulence

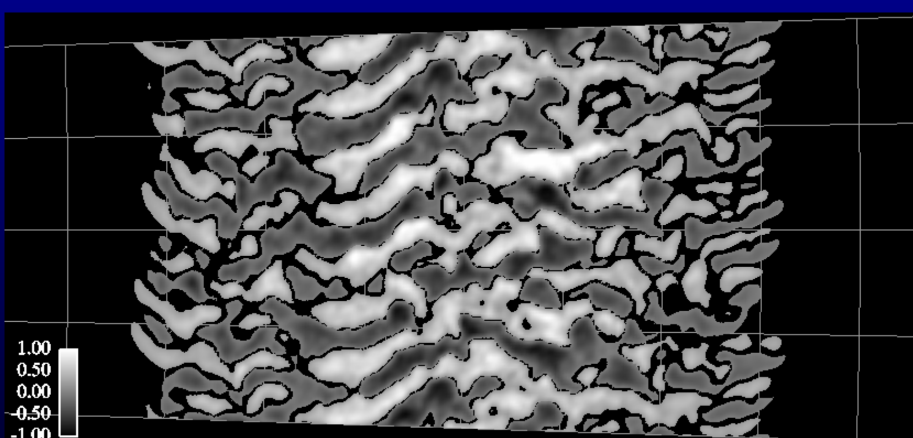
- Linear phase ($t\ v_{te}/L_n$ ~110)



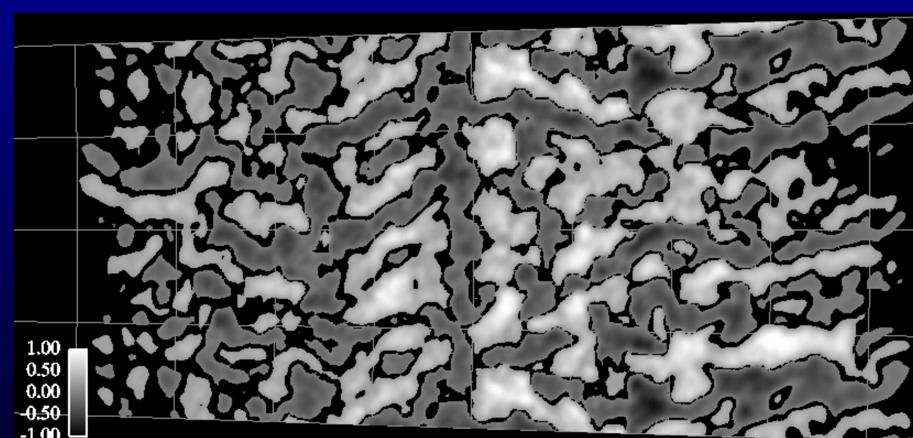
- Saturation phase ($t\ v_{te}/L_n$ ~207)



- Secondary mode ($t\ v_{te}/L_n$ ~255)

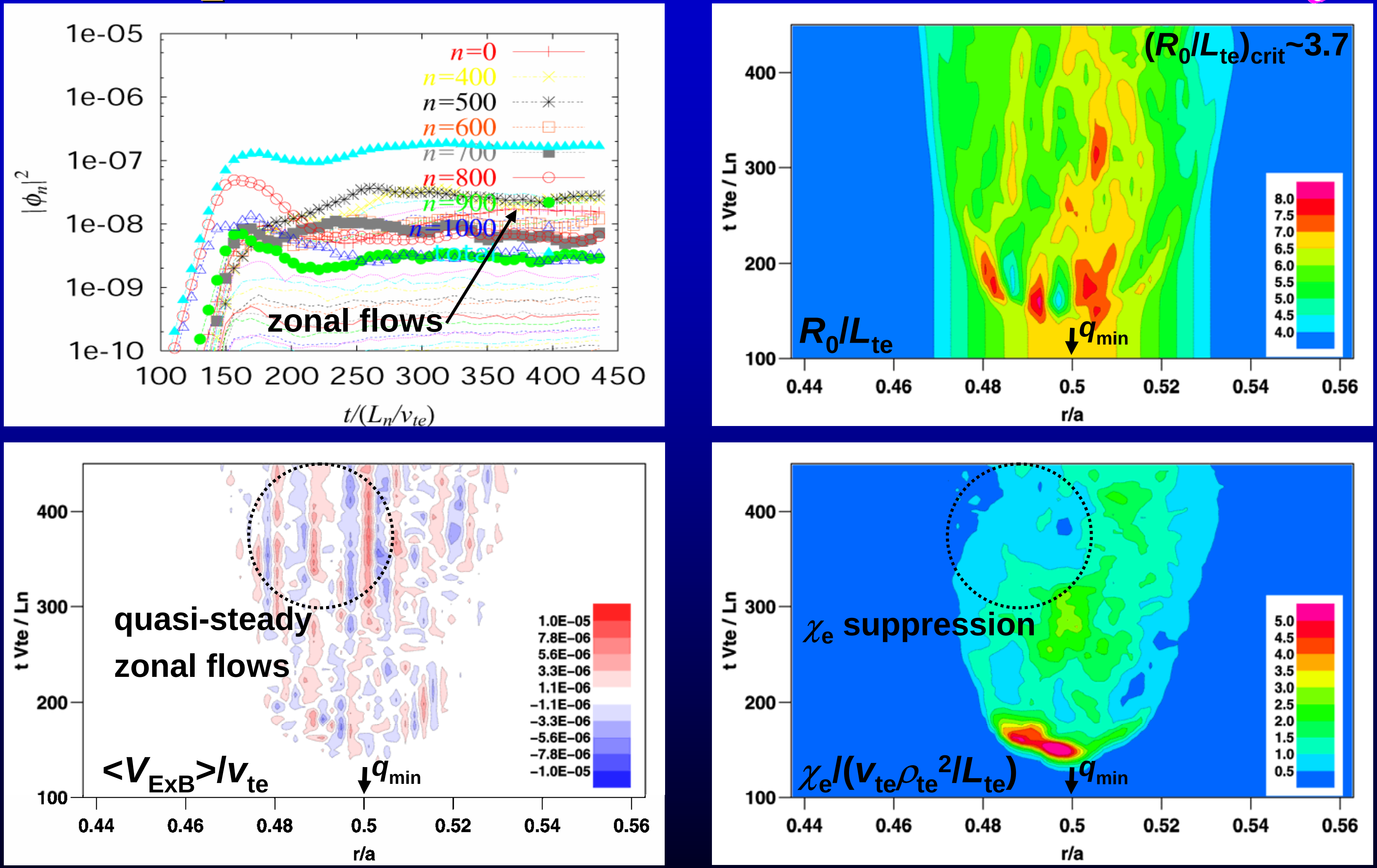


- Zonal flow formation ($t\ v_{te}/L_n$ ~380)



  - RS-ETG turbulence show different behavior across q_{min}
  - Zonal flows (streamers) appear in negative (positive) shear region

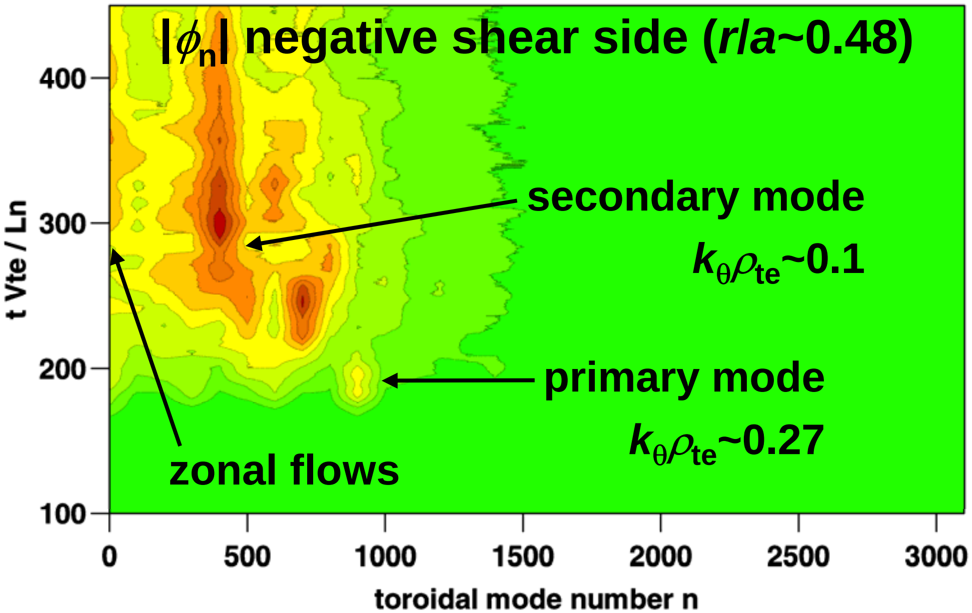
χ_e gap structure in RS-ETG turbulence

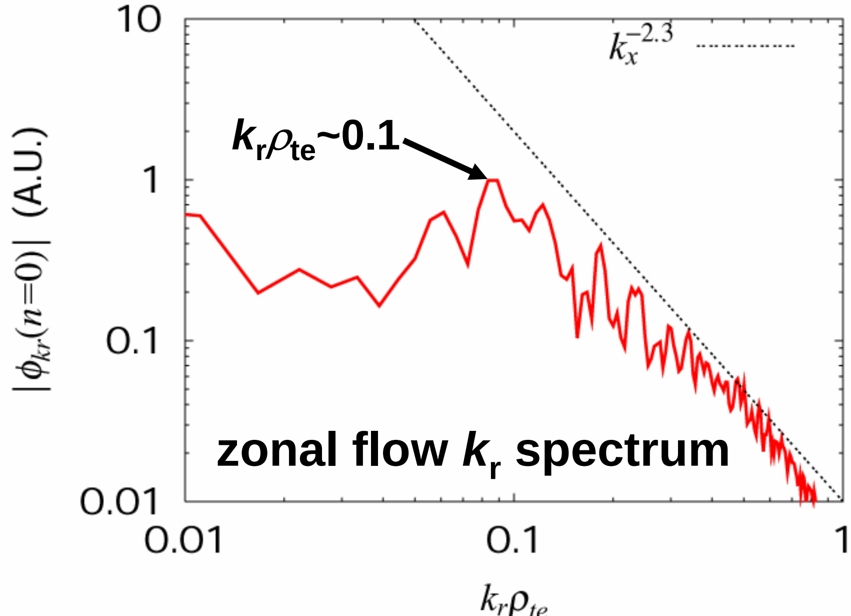


T_e gradient is sustained above its critical value in quasi-steady state

Properties of zonal flows in *k* spectrum

- *n*-spectrum in NS region
- k_r spectrum of zonal flows





- ZF generation similar to slab GK simulation (Idomura 2000)
  - Secondary mode is excited at $k_\theta\rho_{te}$~0.1
  - Quasi-steady ZF spectrum peaks at $k_r\rho_{te}$~0.1
- Weak collisionless ZF damping for $(k_r\rho_{te})^2 << 1$ (Kim2003)
- Microscopic ZF spectrum decay with $|\phi_{kr}| \propto k_r^{-2.3}$ (Jenko2002)

Summary

- ETG turbulence is studied using global toroidal GK simulations
- Initial saturation levels consistent with the mixing length theory
  - Ballooning PS-ETG modes show Bohm like ρ^*-scaling
  - Slab like RS-ETG modes show gyro-Bohm like ρ^*-scaling
  - Small ρ^* PS-ETG modes give order of magnitude higher saturation level than RS-ETG and large ρ^* PS-ETG modes
- PS/RS ETG turbulences show different structure formations
  - PS-ETG turbulence is dominated by streamers
    - T_e profile is quickly relaxed by large $\chi_e \sim 10\chi_{GB}$
  - RS-ETG turbulence is characterized by zonal flows (streamers) in negative (positive) shear region
    - T_e profile is sustained by χ_e gap structure
- These results suggest a stiffness of T_e profile in PS tokamaks, and a possibility of the T_e transport barrier in RS tokamaks