Identification of new turbulence contributions to plasma transport in NSTX

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in collaboration with

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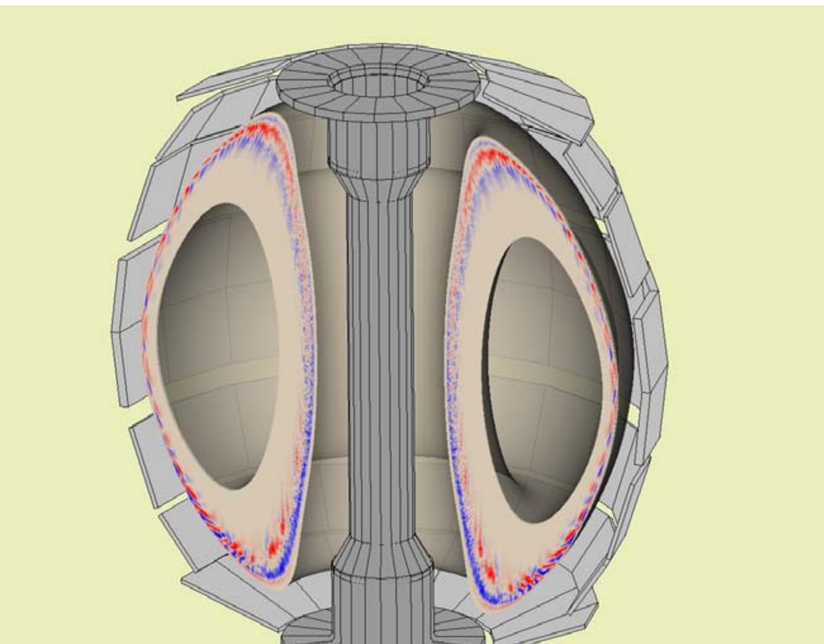

by E. Feibush

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Outline

- Introduction – physics features of NSTX and simulation model
- Distinct turbulence sources for NSTX transport newly identified
  - Shear flow driven drift wave Kelvin-Helmholtz instability in L-mode
  - Dissipative trapped electron mode (DTEM) in H-mode
- Collisonality dependence and confinement scaling
- Summary

Highly distinct features and key transport issues in STs

- Highly different plasma parameter regime associated with low toroidal field in NSTX/U
- ρ^* $(= \rho_i/a)$ in NSTX/U can be up to a factor of 10 greater making global effects particularly important for transport in NSTX/U
- Enhanced toroidicity and strong shaping strongly impact threshold and growth rate of microinstabilities, trapped particle fraction, and zonal flow damping
- NBI-driven very large toroidal rotation which creates a strong $\mathbf{E} \times \mathbf{B}$
- High-β which may make electromagnetic effects much more important in determining plasma transport
- Key issues: electron transport, confinement scaling, momentum transport, finite-β effects ...
- Global GK simulations are critical for STs, but highly challenging

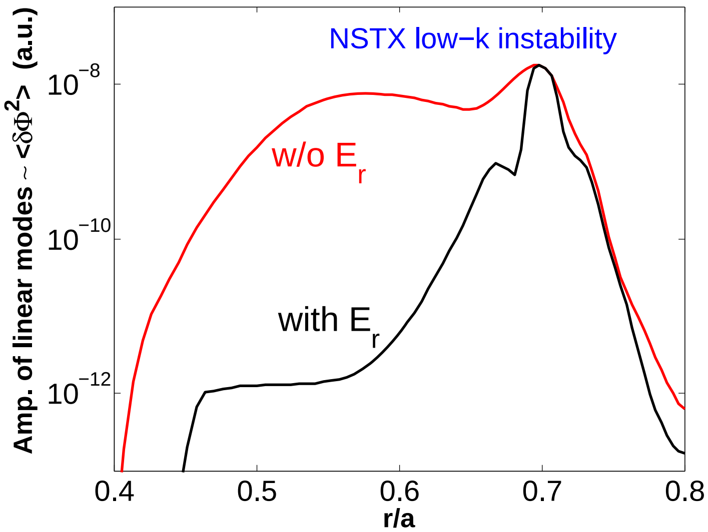
GTS - a global gyrokinetic code with robust capability for treating strong shaped ST plasmas

- δf PIC code solving modern GK equation in conservative form

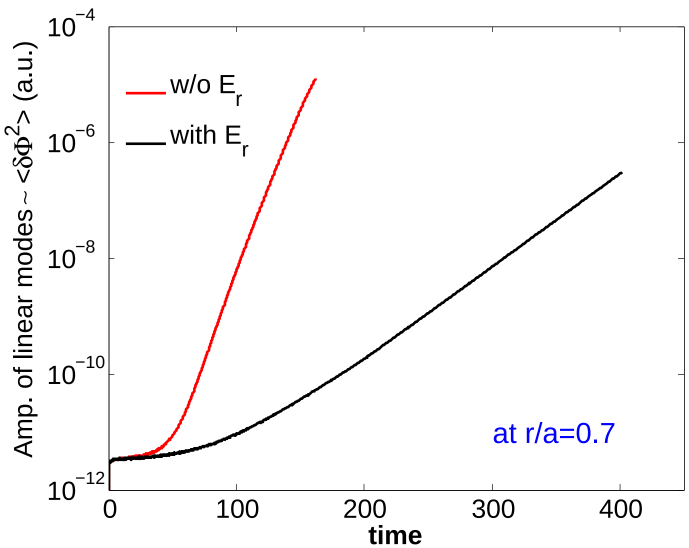
$$\frac{\partial f_a}{\partial t} + \frac{1}{B^*}\nabla_Z \cdot (\dot{\vec{Z}} B^* f_a) = \sum_b C[f_a, f_b]$$

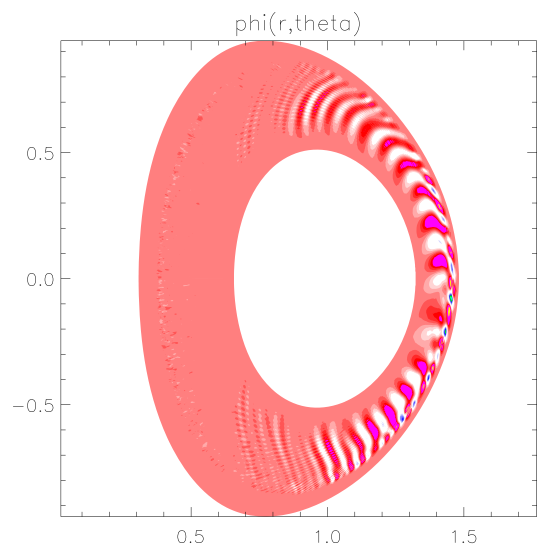
- New, improved weight scheme ensuring phase space imcompressibility
- Full geometry, global simulation (without local ballooning approximation)
  - real space field solvers with field-line-following mesh
  - retains all toroidal modes and full channels of nonlinear energy couplings
  - enable to treat modes with low-n, with finite $k_{\|}$ (e.g., shear flow mode)
- Fully kinetic electrons (both trapped and untrapped electron dynamics)
- Linearized Fokker-Plank operator with particle, momentum and energy conservation for i-i and e-e collisions; Lorentz operator for e-i collisions
- Include neoclassical physics self-consistently in turbulence simulations
  - significant impact on some important transport & confinement issues (bootstrap current, poloidal flow, GAMs and particle transport, etc.)

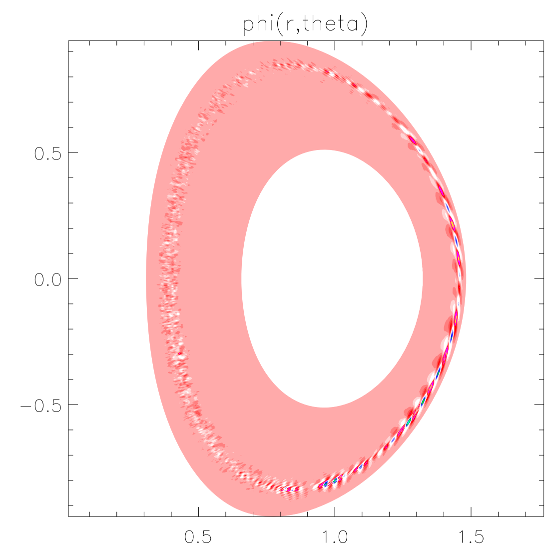
V_ϕ-induced $\vec{E}\times\vec{B}$ shear largely suppresses low-k instability



- $$E_r = \frac{1}{c}(B_\theta V_\phi - B_\phi V_\theta) + \frac{1}{ne}\frac{\partial p}{\partial r}$$
  – V_ϕ contribution dominated in NSTX
- Strong $\mathbf{E}\times\mathbf{B}$ suppression over wide radii

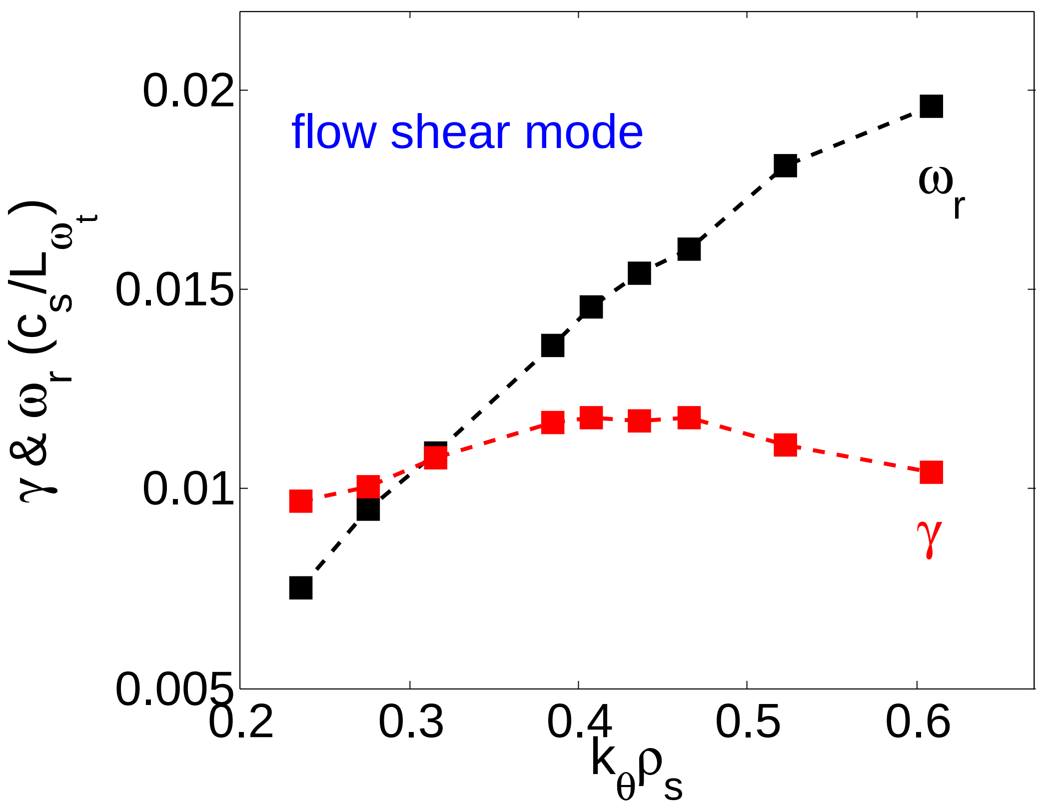


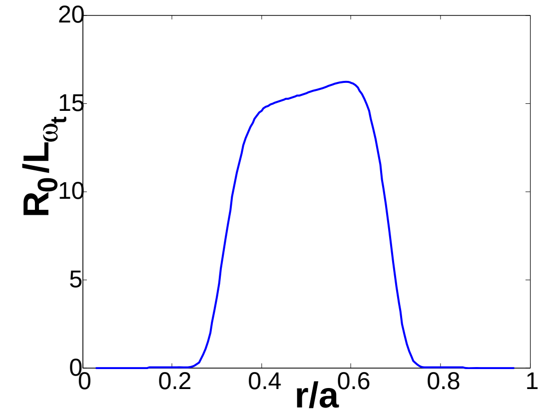


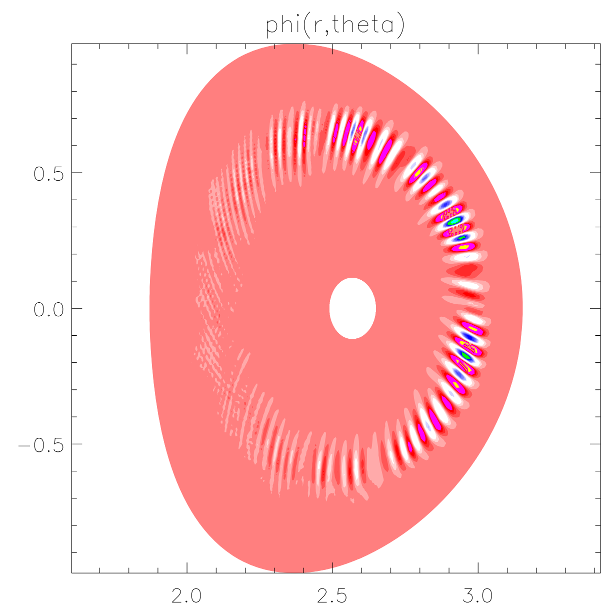


Strong shear flow may drive K-H instability in tokamak

- Global GK simulation with kinetic electrons
- DIII-D-size geometry
- $R_0/L_{T_i} = R_0/L_{T_e} = R_0/L_n = 1.2$ – ITG and TEM are stable

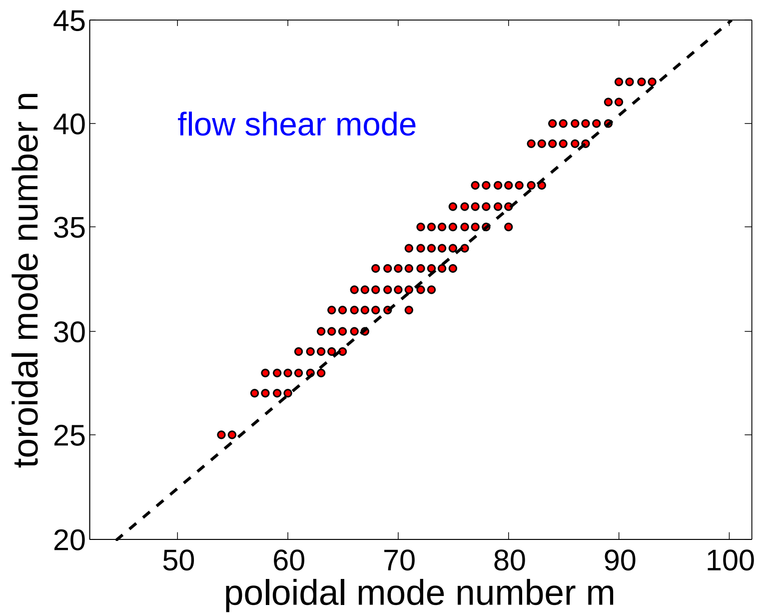




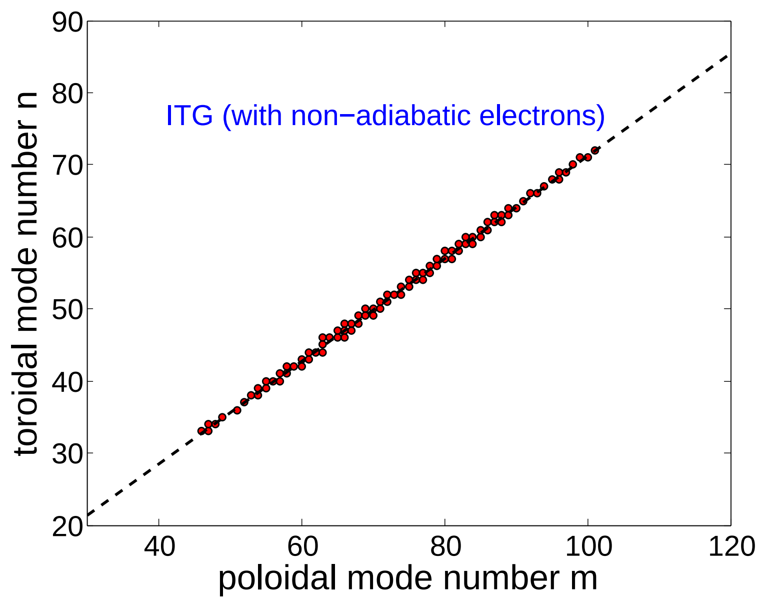


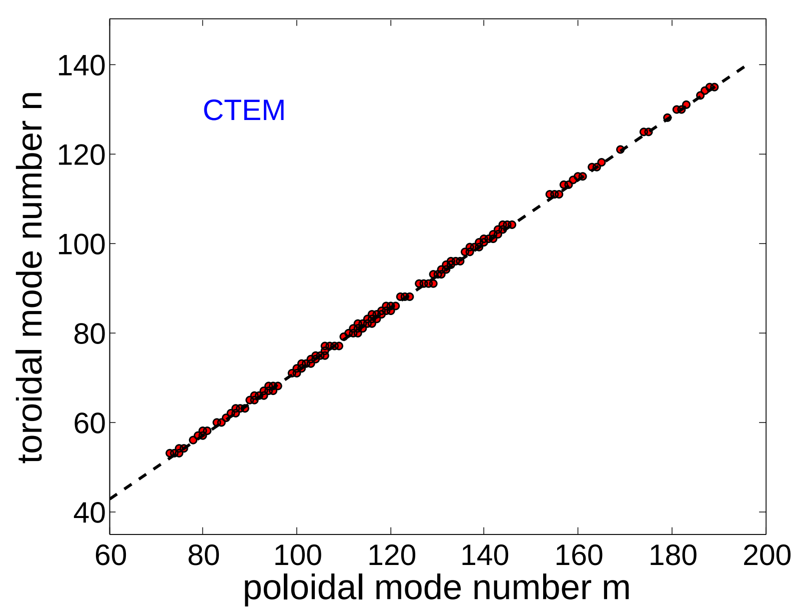
- Low-k mode (in same range of ITG mode)
- Almost constant growth rate

Distinct features of shear flow instability



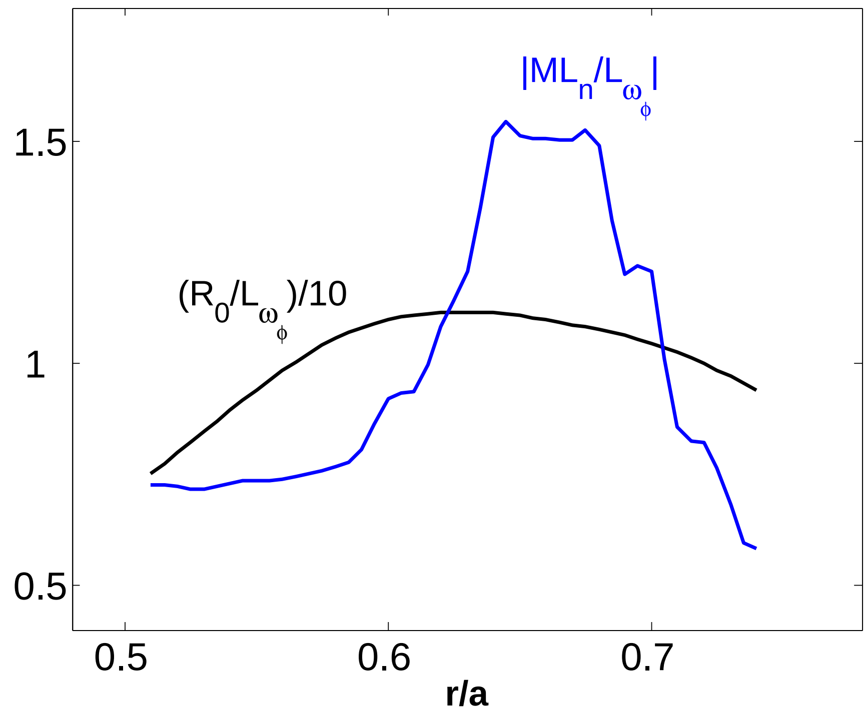
- significant finite $k_{\|}$
  $k_{\|} \sim \hat{b} \cdot \nabla\theta(m - nq)$
- stronger Landau damping
  $\rightarrow$ increase instability threshold
  $R_0/L_{\omega_t} > R_0/L_{T_i}$ (for ITG)
  $R_0/L_{\omega_t} > R_0/L_{T_{e,n}}$ (for TEM)
- asymmetry (impact on residual stress generation)





Strong shear flow in NSTX can destabilize K-H mode

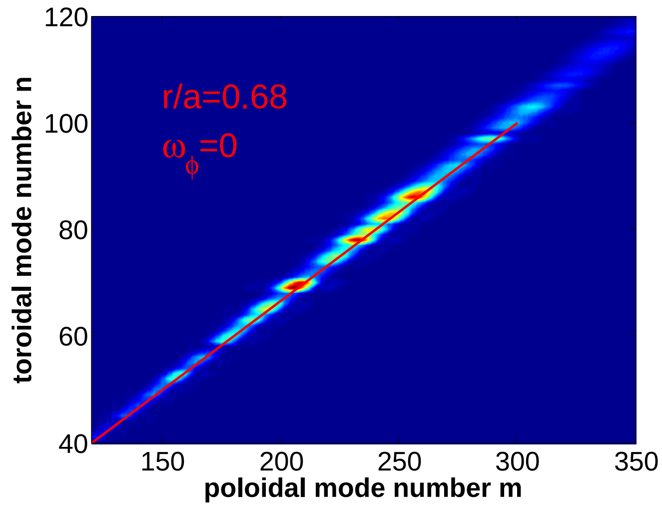
- NBI-heated L-mode with anomalous ion transport in outer core region
  – transport "shortfall"? (Ren et al., '13)

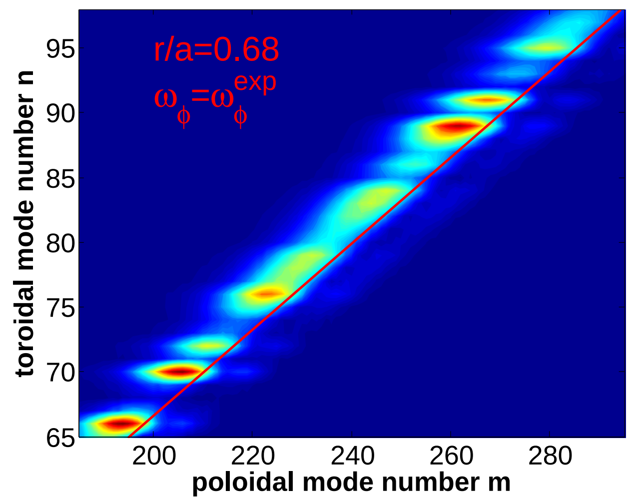


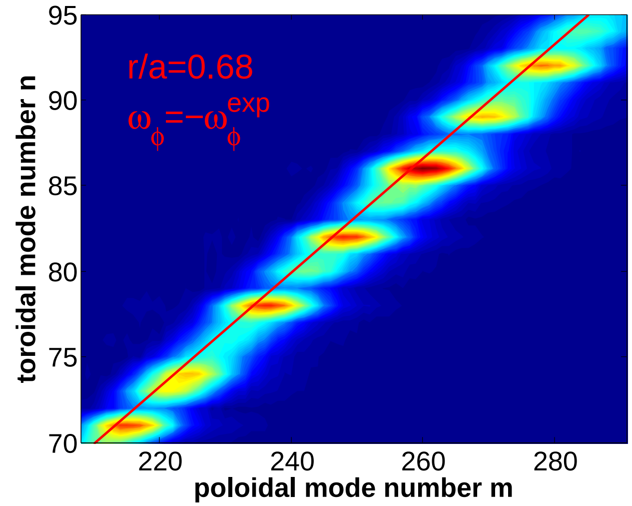
- Rough guideline for K-H threshold from linear theory (e.g., Catto et al., '73; Garbet et al., '99):

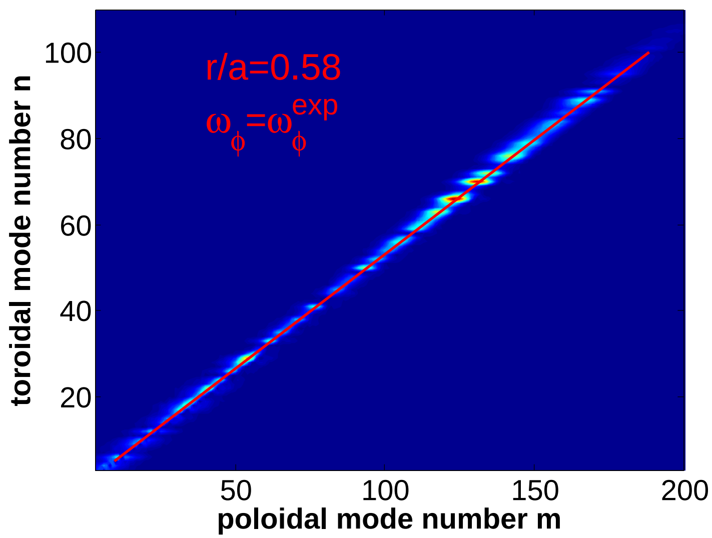
$$\left|\frac{ML_n}{L_{\omega_\phi}}\right| > 1$$

First identification of K-H mode in NSTX









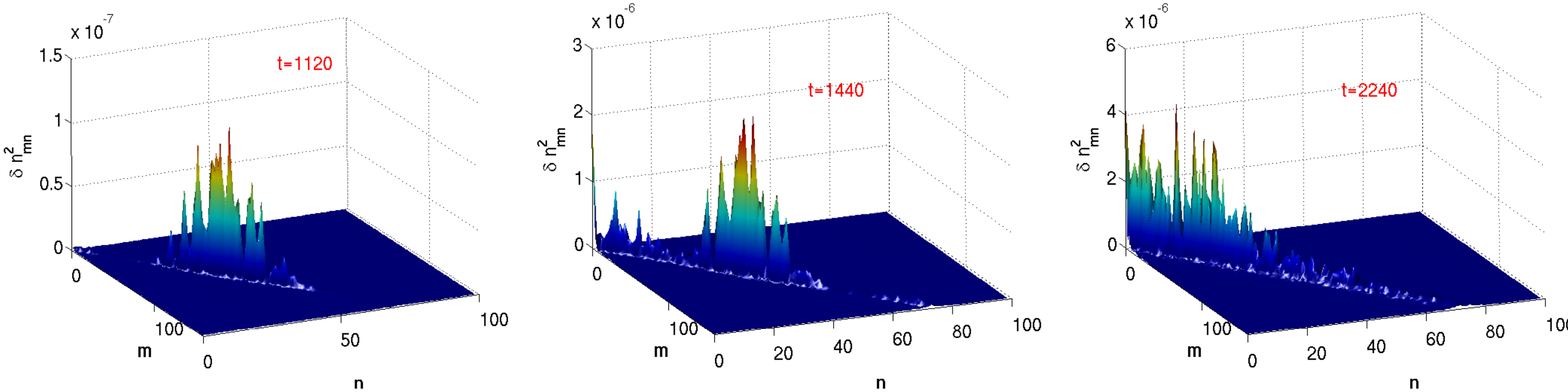
- Mostly unstable K-H mode has finite $k_\parallel$:

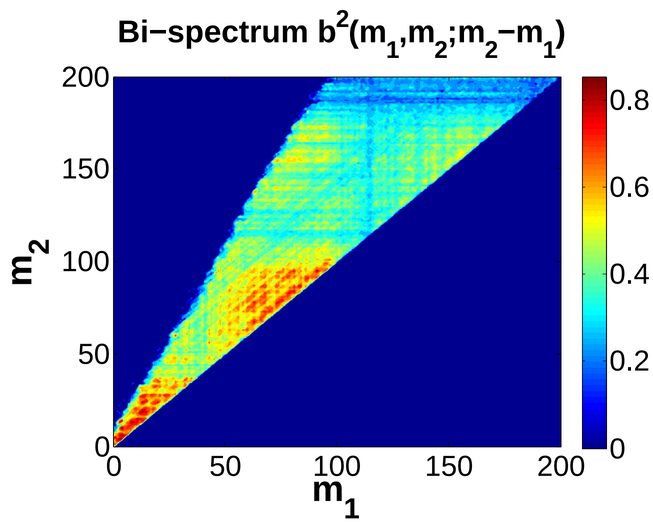
$$k_\parallel \sim \frac{k_\theta \rho_s}{2c_s} \frac{1}{n} \frac{d(nV_\parallel)}{dr} \sim \frac{d\omega_\phi}{dr}$$

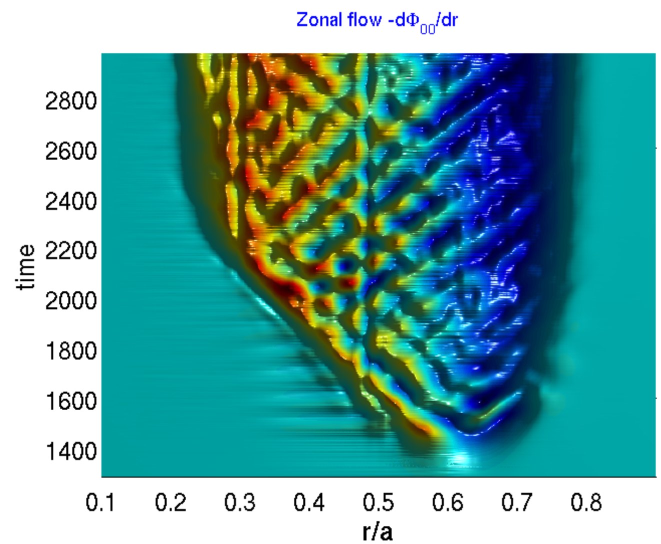
(e.g., Drake et al., '92; Garbet et al., '99)

- ITG unstable too

Nonlinear toroidal mode couplings play a key role to cause shear flow turbulence saturation





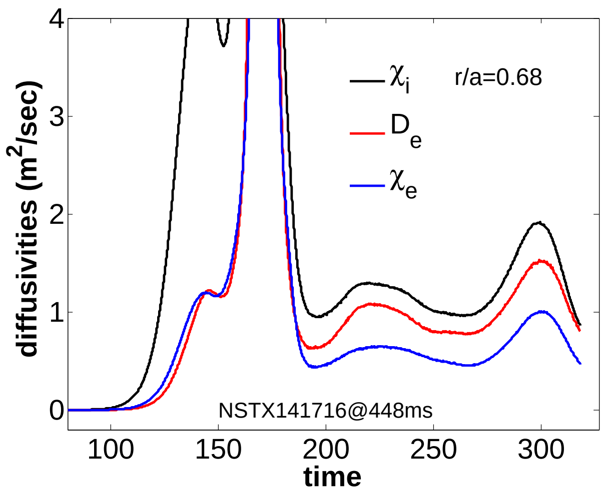


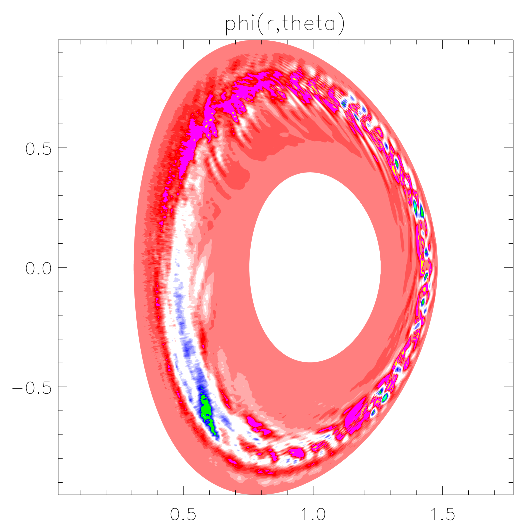
- NL energy transfer to longer wavelength modes via toroidal couplings
- Strong zonal flows and GAMs generation

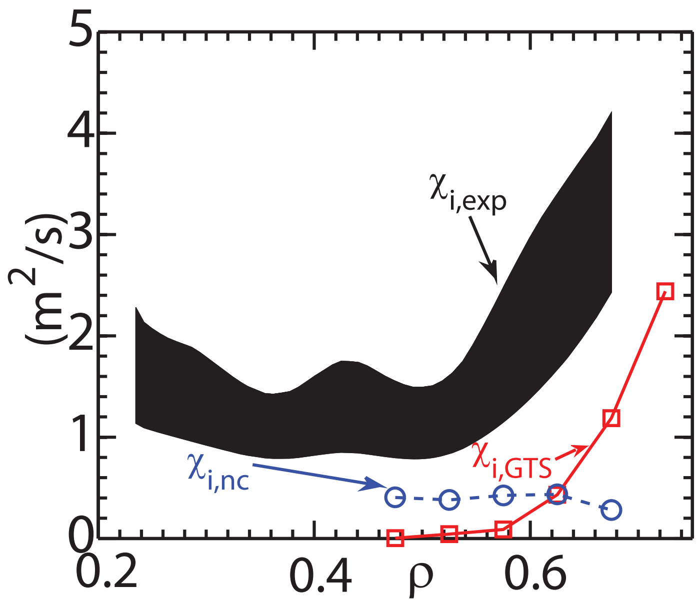
PPPL

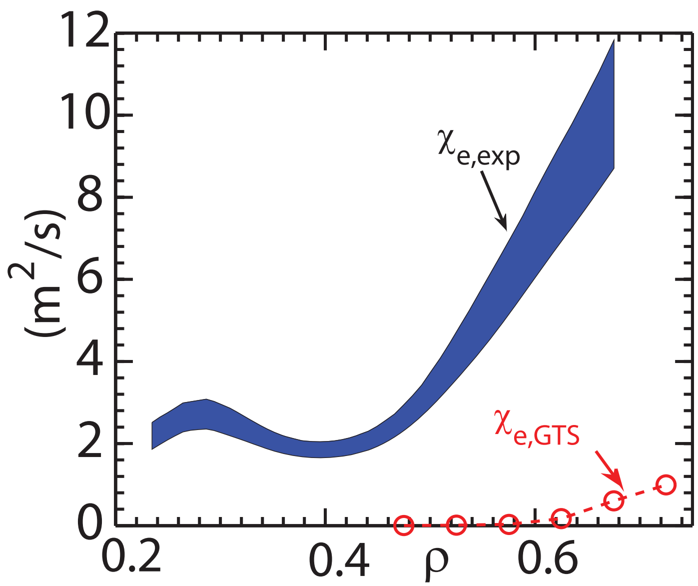
Remaining ITG/K-H fluctuations produce significant ion thermal transport relevant to NSTX L-mode

- Reproduce expt. χ_i profile fairly well
- No ion transport "shortfall" in outer core observed
- Weak contribution to highly anomalous electron thermal transport

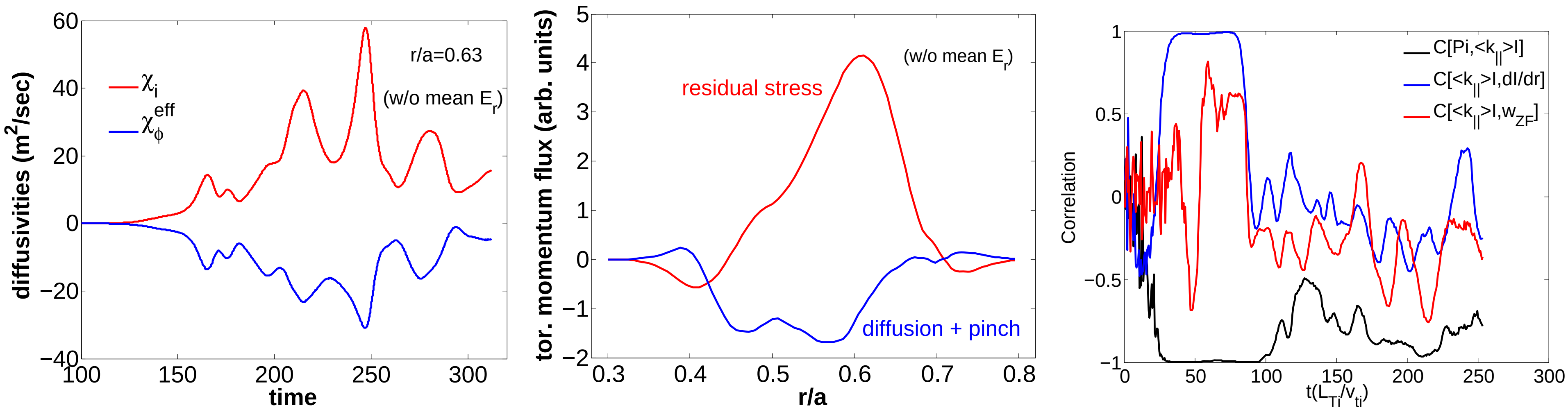








Low-k fluctuations may significantly impact toroidal momentum transport in L-modes

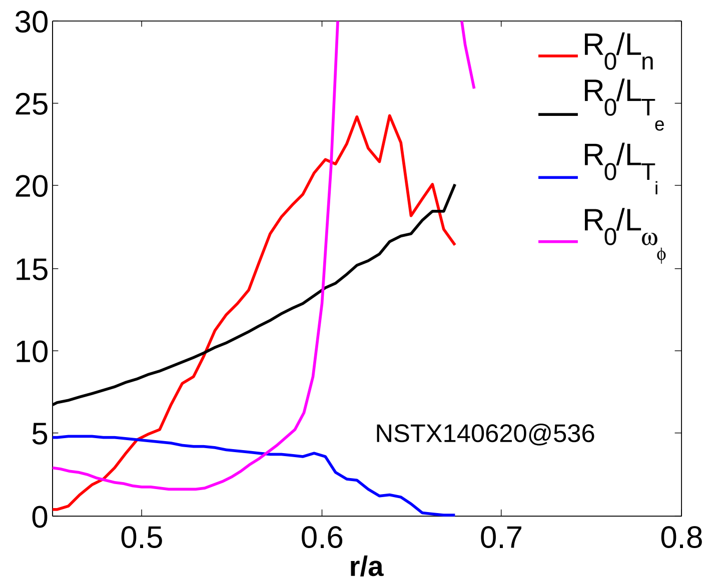


- Total momentum flux with $\chi_\phi^{\rm eff} \sim \chi_i$ but in direction opposite to diffusion
- Consists of a large anti-gradient residual stress

  (inward Π_ϕ also observed in GYRO for same case – Guttenfelder's TTF)
- ZF $\mathbf{E} \times \mathbf{B}$ shear dominates over turbulence intensity gradient for creating $k_{||}$ spectrum asymmetry needed for residual stress generation
- Equilibrium E_r effects on momentum transport need to be clarified

Both CTEM and DTEM could be important turbulence source in unique ST plasma regime

- Large trapped electron fraction
- Subtle, sensitive dependence on collisions
- DTEM plays little role in conventional tokamaks (Romanelli et al., PoP'07)

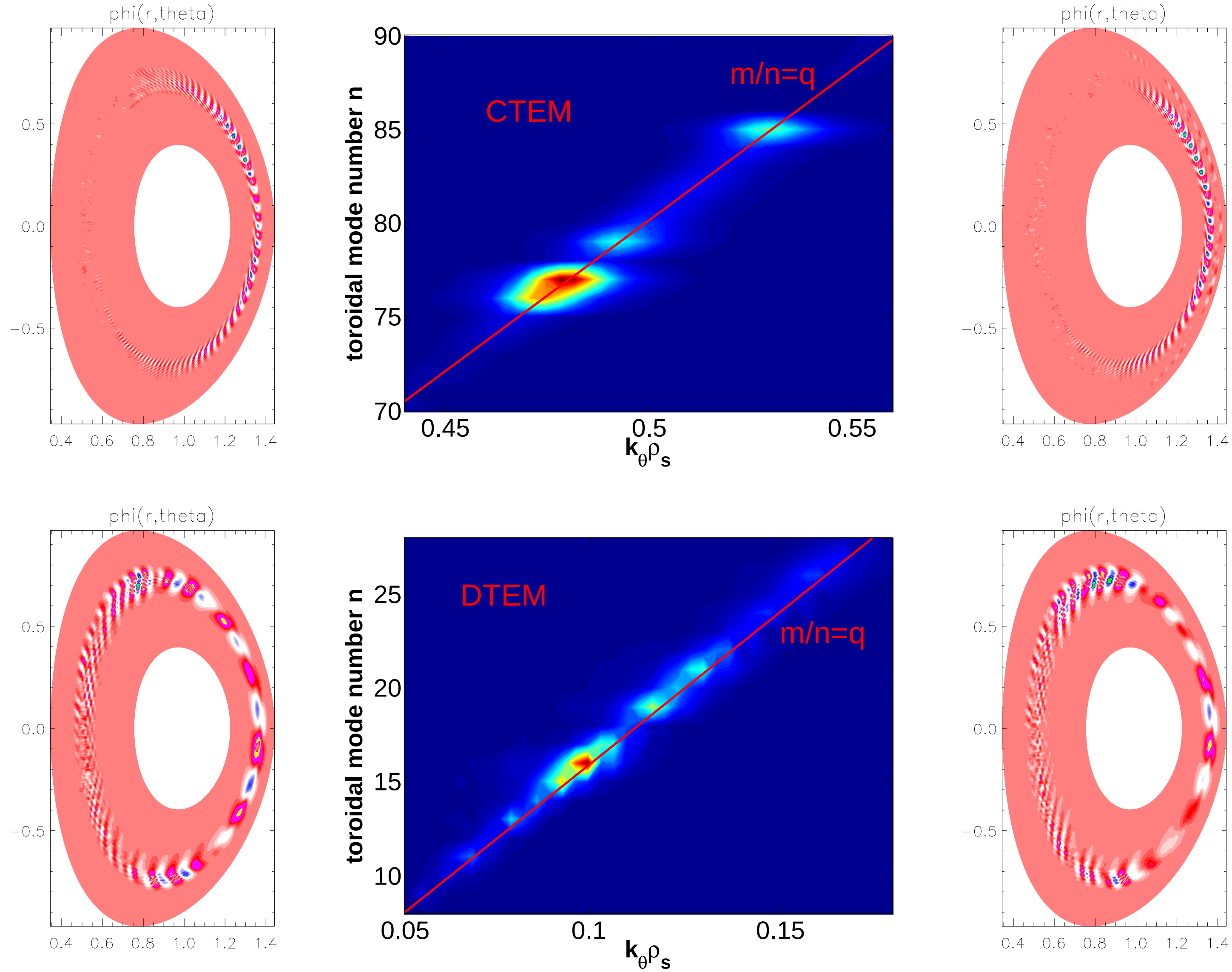


- NBI-heated H-mode with strong toroidal rotation (Ren et al., '11)
- Strong ∇n driver dominates in center core region
- Global GTS simulations cover $\rho = 0.3 - 0.8$ with focus on $\rho \lesssim 0.6$

Long wavelength DTEM identified in NSTX collisionality regime with steep electron gradient achieved there

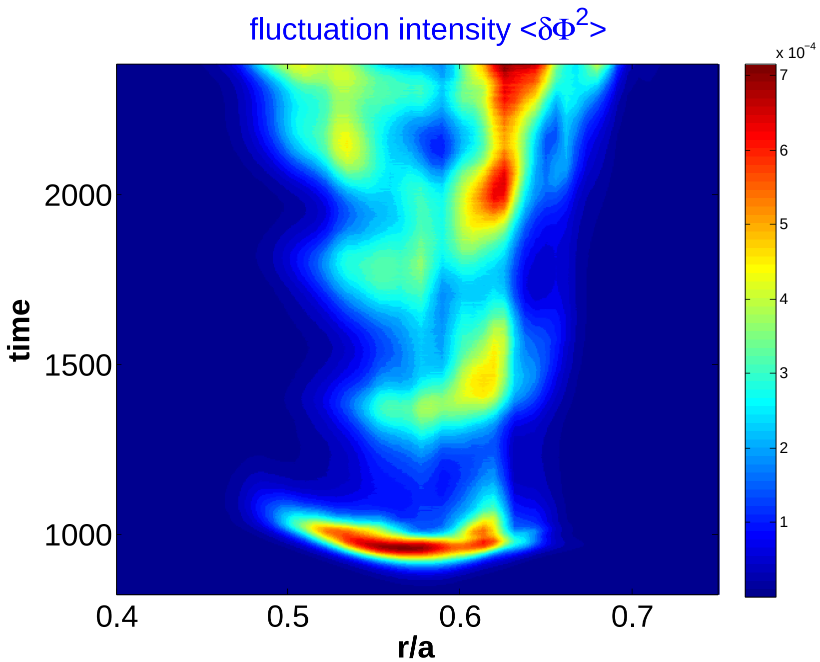
$\nu_i = 0,\ \nu_e = 0$ (top left); $\nu_i = 1,\ \nu_e = 0$ (top right)

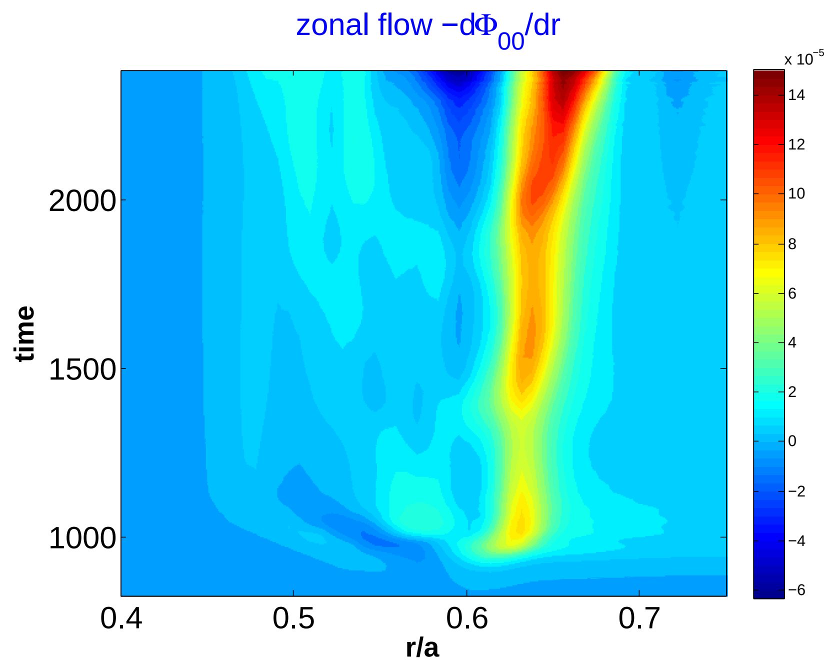
$\nu_i = 1,\ \nu_e = 1$ (bottom left); $\nu_i = 0,\ \nu_e = 1$ (bottom right)



- CTEM ($k_\theta \rho_s \sim 0.5$) $\rightarrow$ DTEM ($k_\theta \rho_s \sim 0.1$) induced by electron-collisions
- Both C/DTEM survive strong, experimental equilibrium $\mathbf{E} \times \mathbf{B}$ shear

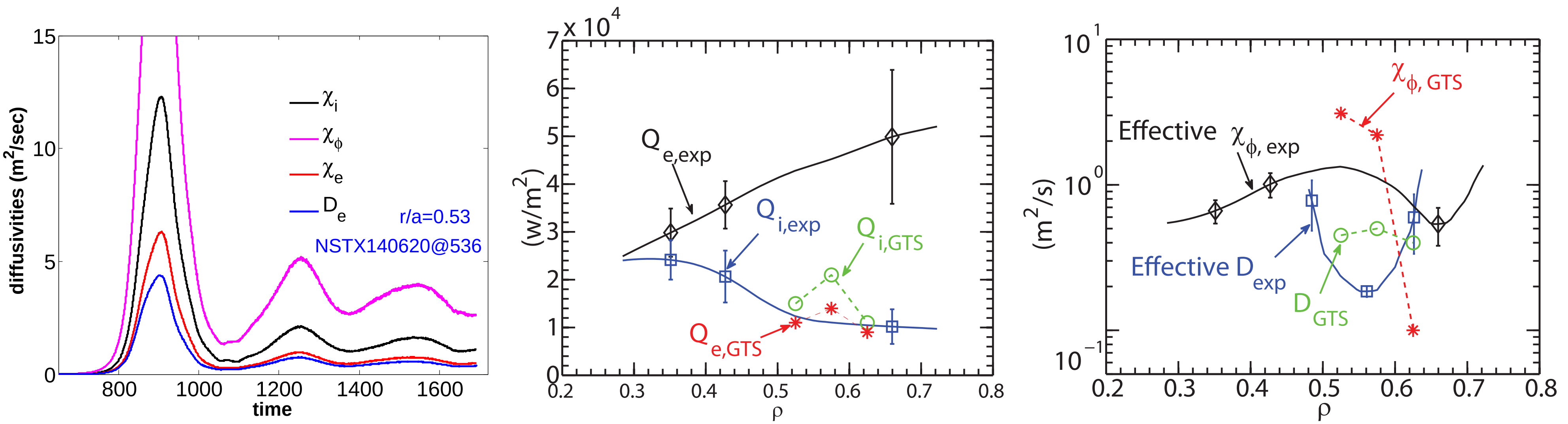
Nonlinear feature of DTEM – stationary zonal flow generation



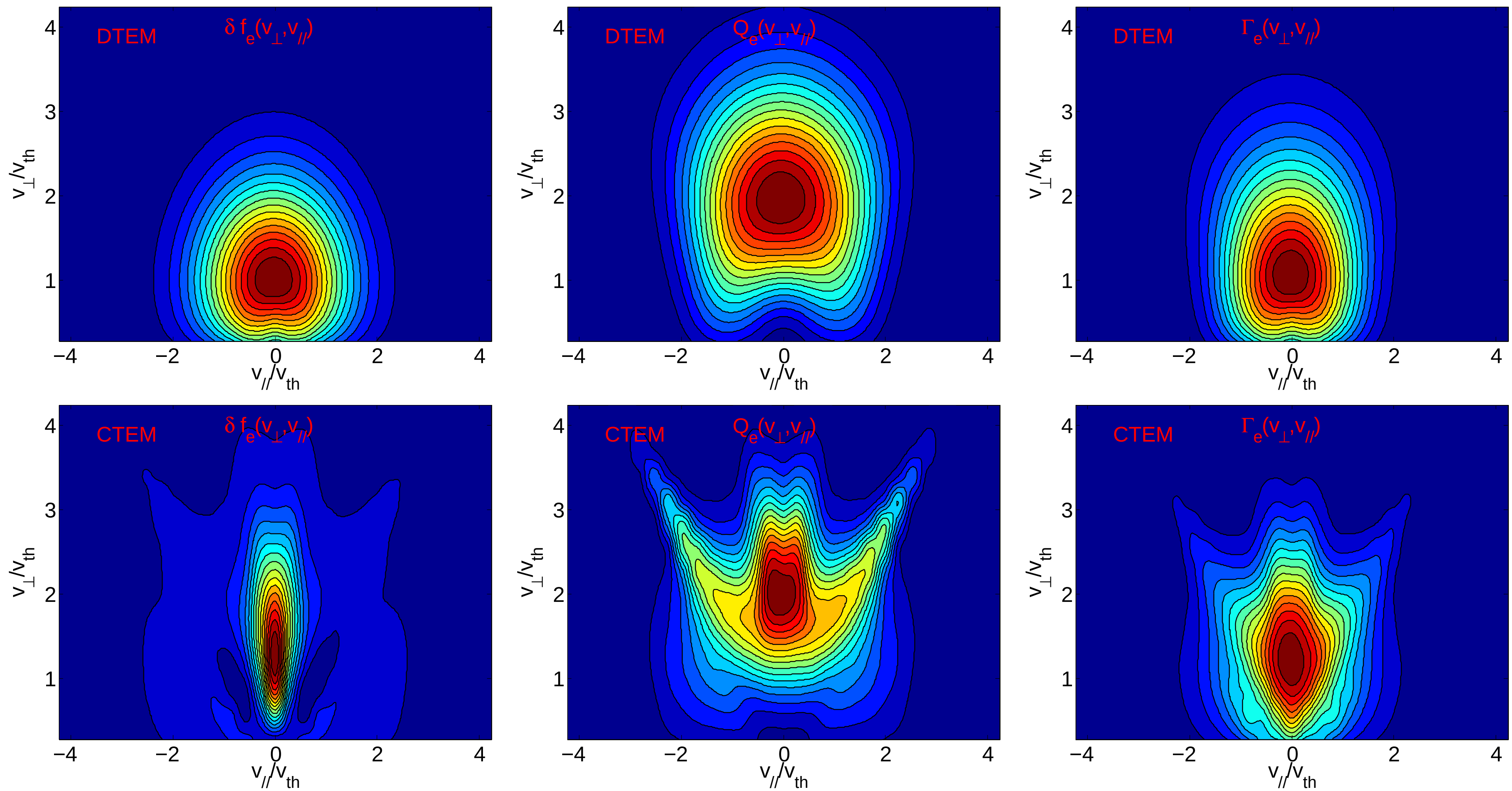


DTEM drives experimentally relevant transport in multiple channels but not for electron energy

- DTEM-induced particle, ion energy and toroidal momentum transport are at experimental level
- ∇n-driven DTEM seems not to produce enough transport to account for highly anomalous electron thermal transport in expts.



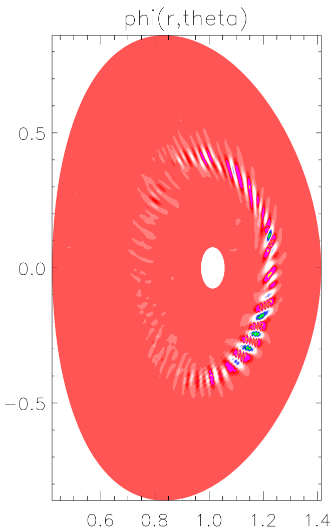
How DTEM differs from CTEM – phase space structures

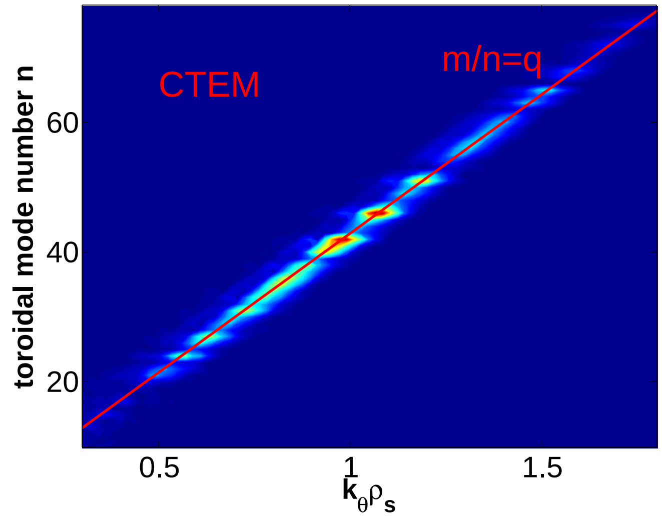


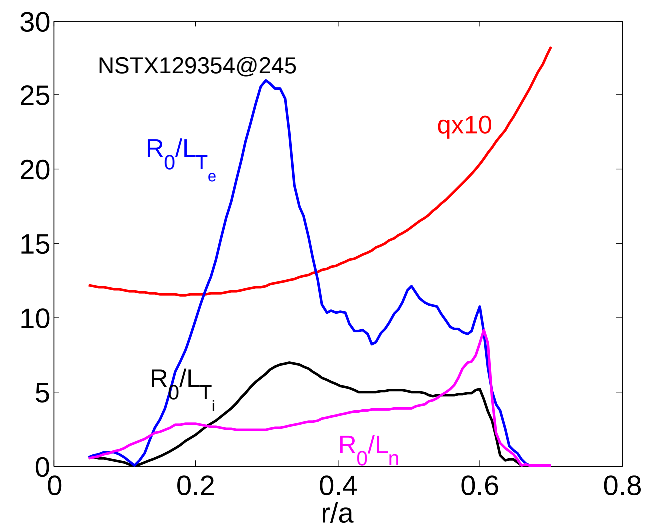
- (Deeply) trapped electrons are major player in both CTEM and DTEM
- Complex structures in CTEM due to collisionless processional magnetic resonance are eliminated by collisions in DTEM

∇T_e-driven DTEM may drive highly anomalous electron heat flux

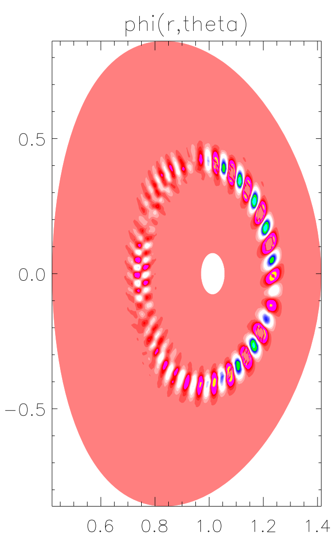
$\nu_i = 1,$
$\nu_e = 0$

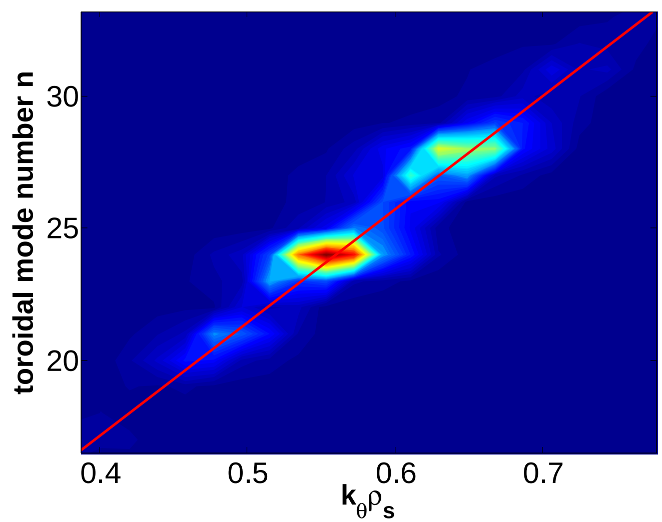






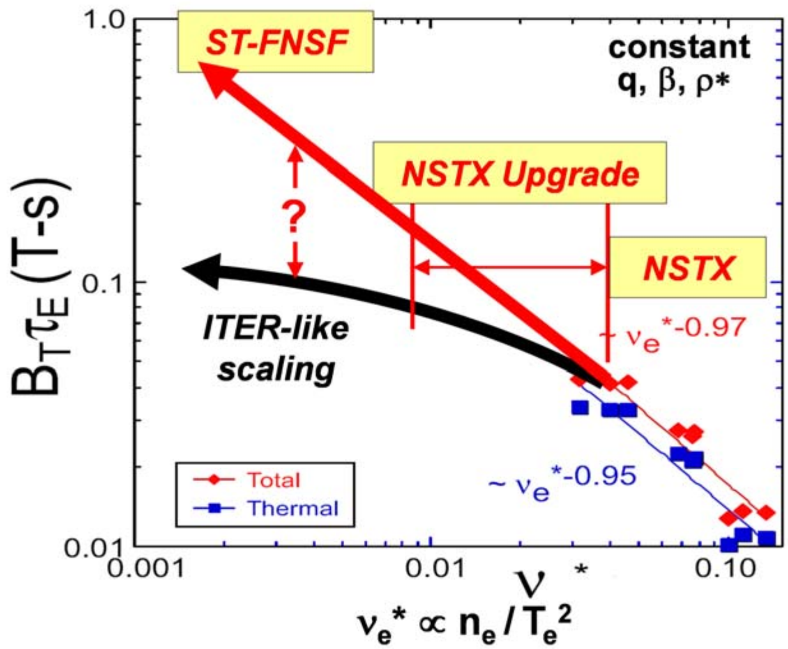
$\nu_i = 1,$
$\nu_e = 1$





What underlying physics controls confinement scalings in NSTX/U (and beyond)

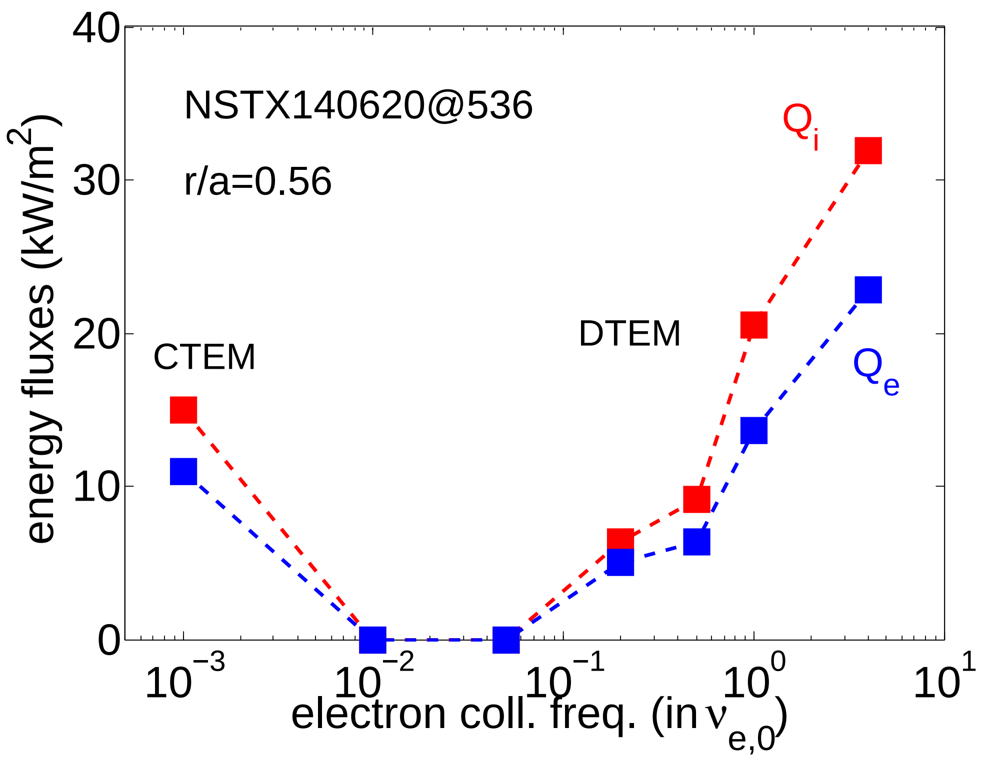
- Confinement time $\sim 1/\nu_{*,e}$ (electron transport dominated)



(Kaye et al, NF'07)

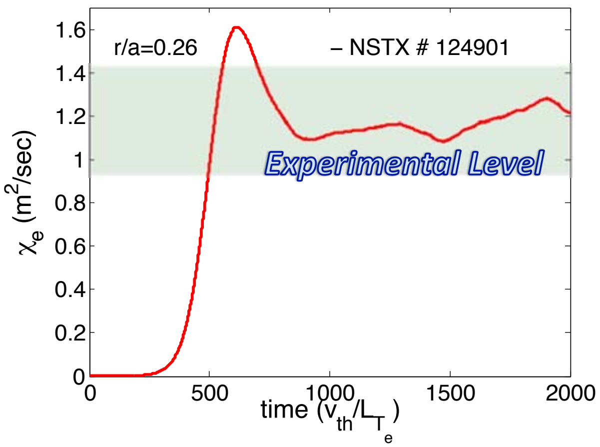
- Observed in NSTX H-mode plasmas
  - predict higher performance for future STs
  - to be further tested in NSTX-U lower $\nu_{*,e}$ regime
  - Underlying mechanism still unclear
- Microtearing may introduce $\sim 1/\nu_{*,e}$-scaling
  - but strong $\mathbf{E} \times \mathbf{B}$ shear may wipes out it (Guttenfelder et al., NF'13)

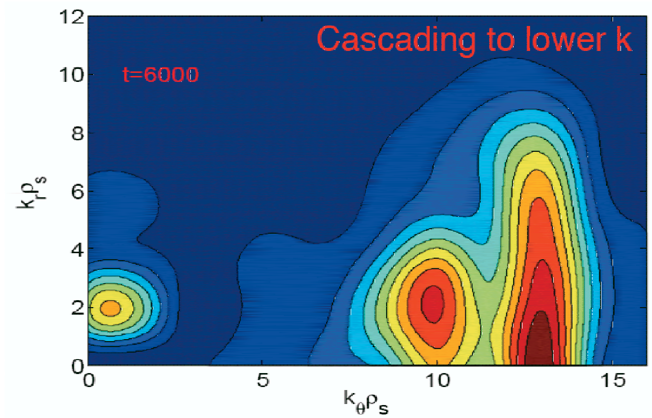
DTEM destabilized by ν_e in NSTX/U may contribute to $\sim 1/\nu_{*,e}$-scaling

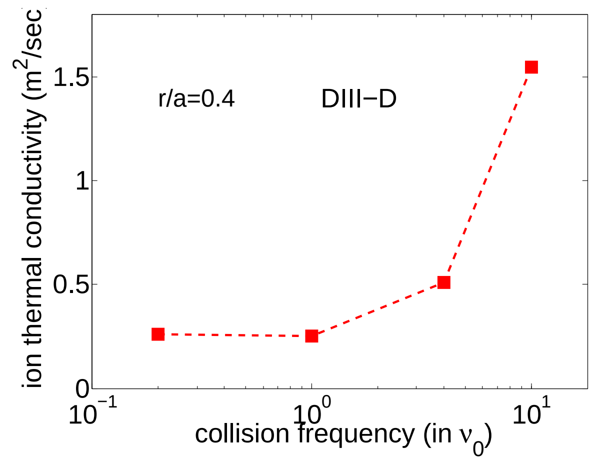


- Both C/DTEM found to survive strong equilibrium $\mathbf{E} \times \mathbf{B}$ shear of NSTX
- However, CTEM subjected to strong stabilization by collisions in NSTX
- Turbulence-free regime may exist – more relevant to NSTX-U, ST-FNSF?
- Experimental identification of DTEM in NSTX-U is needed
- $\tau_E \sim n^{9/8}$ for Ohmic discharges from theory (Simion & Diamond, '84)

How about electron scale turbulence?



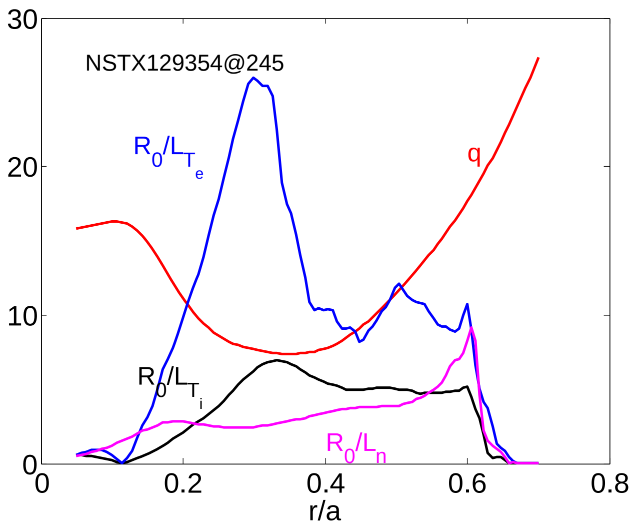




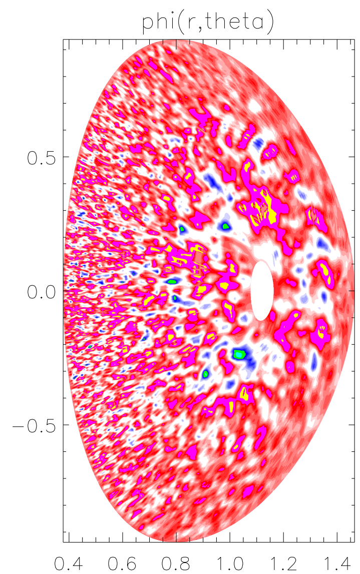
- ETG identified in NSTX experiments and simulations
  - Simulated fluctuation spectra are comparable to high-k measurements ($k_r^{-(2.5 \text{ to } 5.3)}$ from GTS vs $k_r^{-4.5}$ in expt.)
  - Significant ETG-induced contributions to anomalous χ_e
  - Strong energy coupling to electron version of GAM (very high-ω ZF) (Mazzucato et al., NF'09; Ethier et al., IAEA FEC'10)
- Strong $\nu_{*,e}$ dependence possible via collisional ZF(e-GAM) damping (direct dependence of ETG on $\nu_{*,e}$ is weak)
  - Strong $\nu_{*,i}$ dependence of ITG driven χ_i observed in ion-transport dominated H-modes (Greenwald et.al., '98; Petty & Luce)
  - Same behavior possible for ETG driven χ_e

More about effects of mean $\mathbf{E} \times \mathbf{B}$ shear, magnetic shear and collisionality on turbulence in NSTX regime

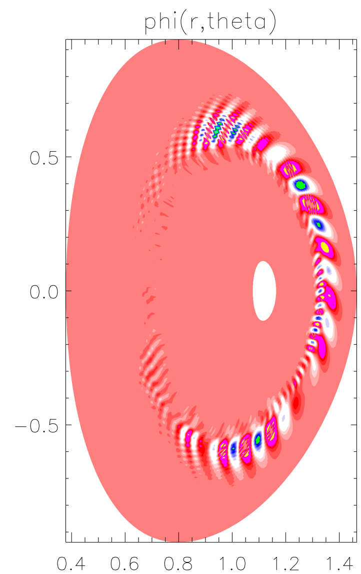
H-mode with e-ITB



$E_r = 1, \nu_e = 1$



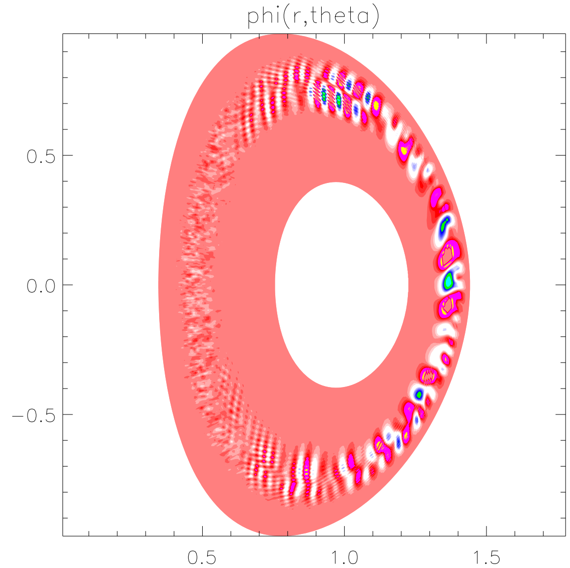
$E_r = 1, \nu_e = 0$

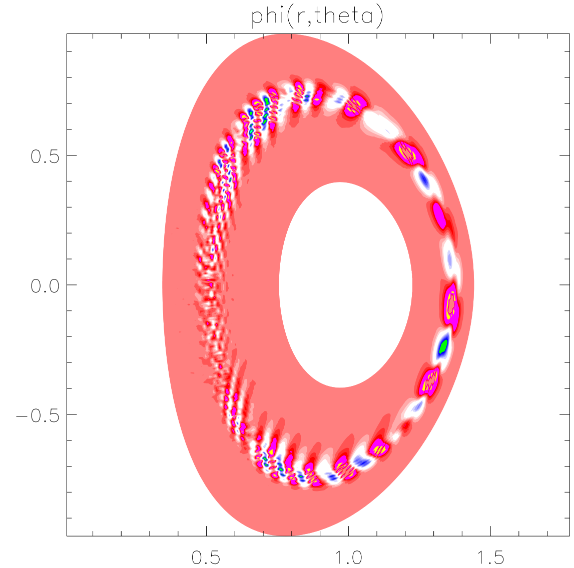


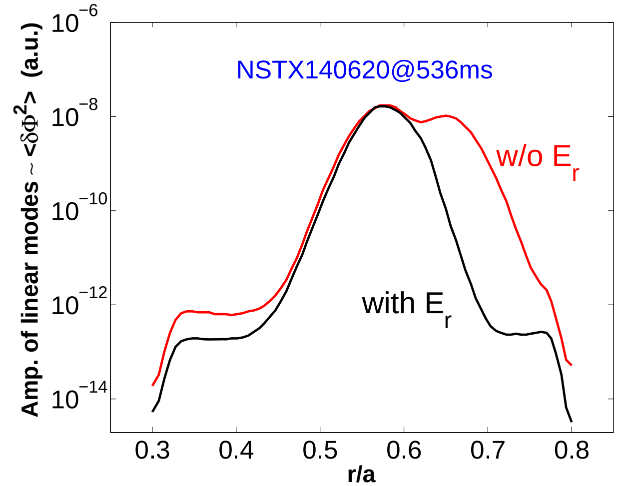
- No instabilities presents in e-ITB region even with $E_r = 0$, $\nu_e = 0$
  – negative shear is the key for e-ITB formation
- CTEM seems strongly stabilized by electron collisions in NSTX regime

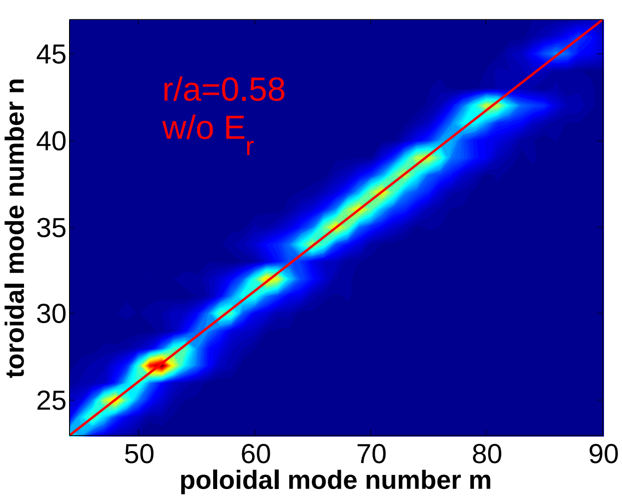
Mean $\mathrm{E} \times \mathrm{B}$ shear effect goes beyond a simple picture through mode growth rate vs $\gamma^{E\times B}$ comparison

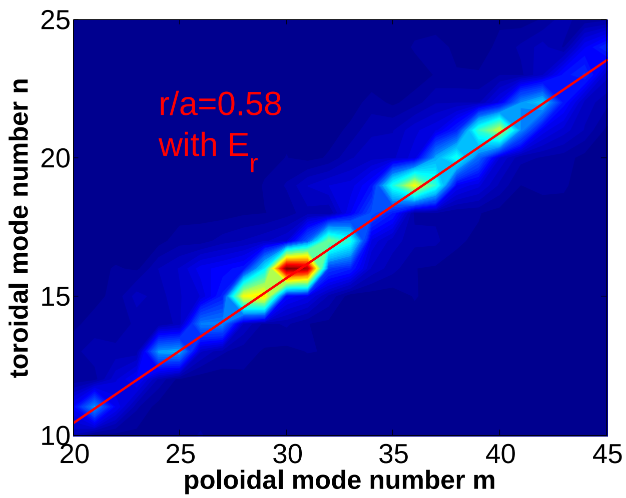
It changes unstable mode family member & structure











- Most unstable modes:
  - $n > 25$, w/o E_r
  - $n < 25$, with E_r
- shift modes away from resonance surface $\Rightarrow$
  - stronger Landau damping
  - $k_{\parallel}$ asymmetry

Summary

Two distinct turbulence sources are identified in unique NSTX ST regime

- For the first time, shear flow mode is found relevant to fusion experiments
- Shear flow mode along with ITG under the effect of strong $\mathbf{E} \times \mathbf{B}$ shear created by the flow itself can produce a significant ion (but not electron) thermal transport relevant to experimental level in the outer core region of L-mode (no "transport shortfall" observed)
- DTEM is identified in NSTX H-mode regime to produce experimentally relevant particle, ion (but not electron) energy and momentum transport
- DTEM-driven transport is shown to increases with ν_e in NSTX/U regimes, contributing to observed confinement $1/\nu_e$-scaling
- CTEM subjected to strong stabilization by collisions in NSTX/U regimes
- Existence of C/DTEM-free regime possibly relevant to NSTX-U and ST-FNSF is predicted $\rightarrow$ an access to electron transport barrier
- Low-k turb. may produce a large anti-gradient residual stress in L-mode

Experimental identification of KHM and DTEM is needed