ASDEX Upgrade

Max-Planck-Institut für Plasmaphysik

IPP

Beyond the standard DW-ZF paradigm: Nonlinear saturation in plasma turbulence

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Acknowledgements:

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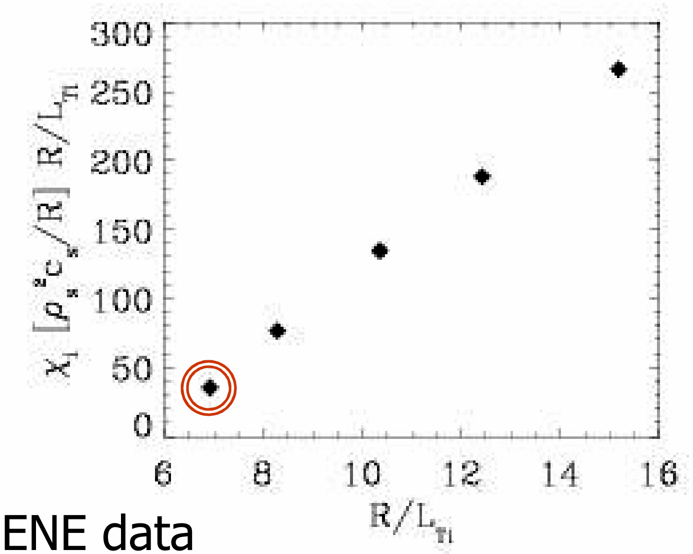
Adiabatic ITG turbulence in a simple tokamak

Reference case for core turbulence simulations:

- "Cyclone base case" – also serves as standard paradigm of turbulence
- idealized physical parameters; adiabatic electrons; s-α model equilibrium



GENE data

Key findings:

- saturation via zonal flows
- nonlinear upshift of threshold
- ion heat flux is offset-linear

How generic is the adiabatic ITG s-α scenario?

Overview

Turbulence in optimized stellarators:
The role of zonal flows

- Nonlinear saturation of TEM turbulence:
  Beyond the standard ZF scenario

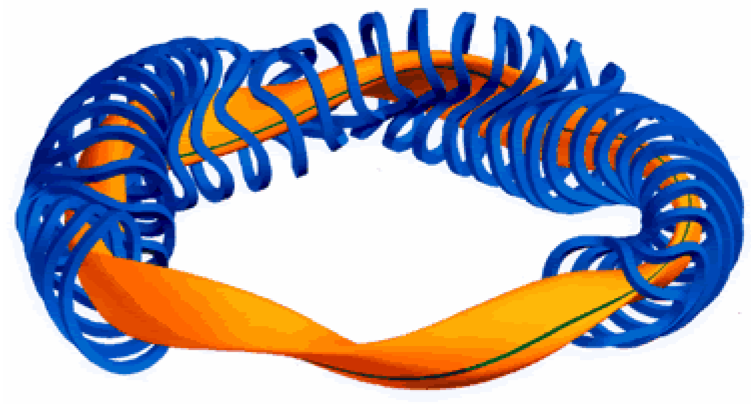
- Other alternatives to ZF saturation?

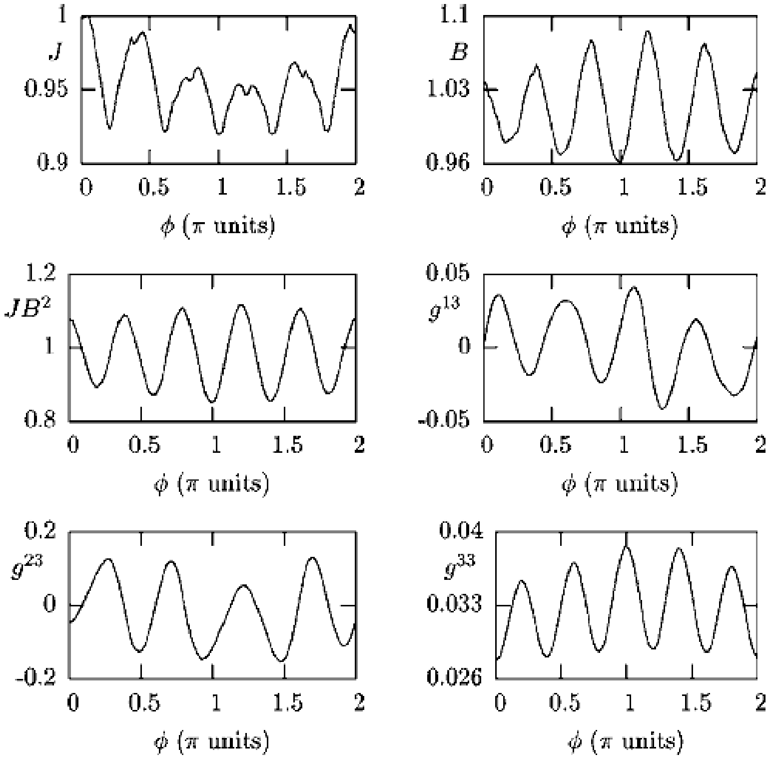
Numerical tool: GENE (see my talk on Tuesday)

Turbulence in optimized stellarators
(W7-X, NCSX)

GENE simulations for W7-X

- Wendelstein 7-X stellarator: optimized with respect to neoclassical transport

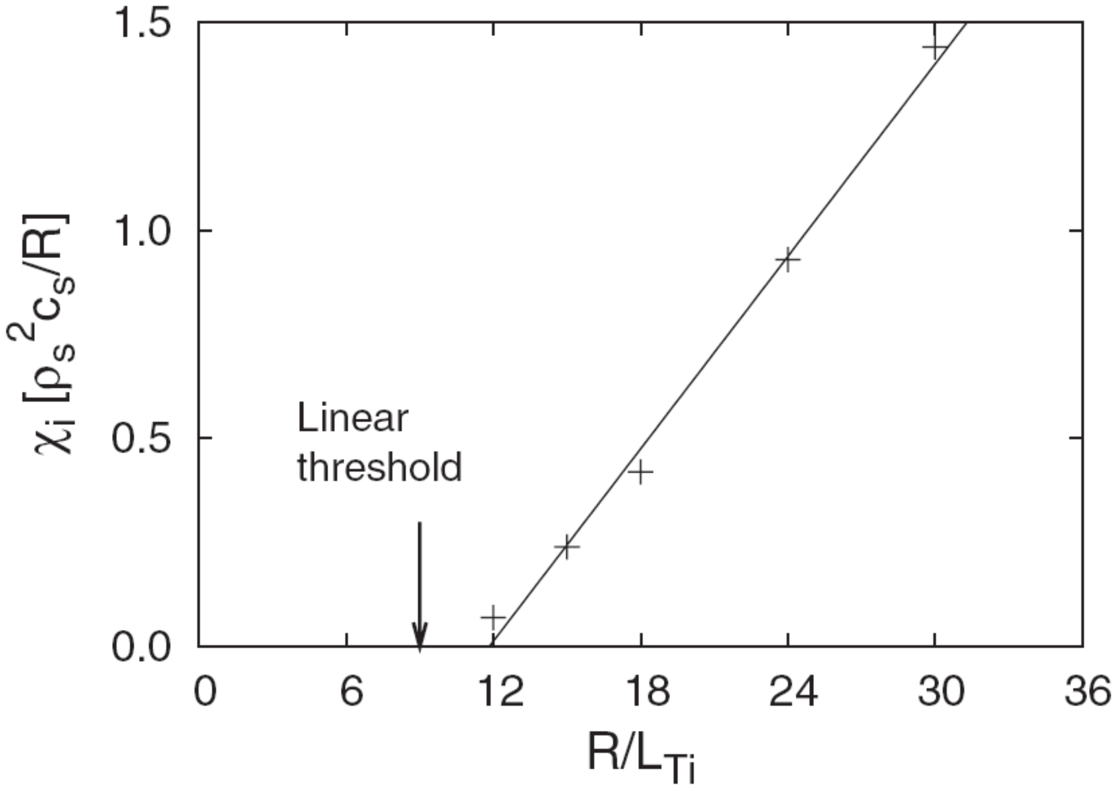




- Geometric coefficients are calculated by means of the TRACER code [Xanthopoulos & Jenko, PoP 2006]

Adiabatic ITG turbulence in W7-X

P. Xanthopoulos *et al.*, PRL **99**, 035002 (2007)



- zonal flows are important for saturation
- significant Dimits shift is observed
- however, diffusivity (not flux) is offset-linear

Different configuration and radial position: Similar behavior but much larger stiffness

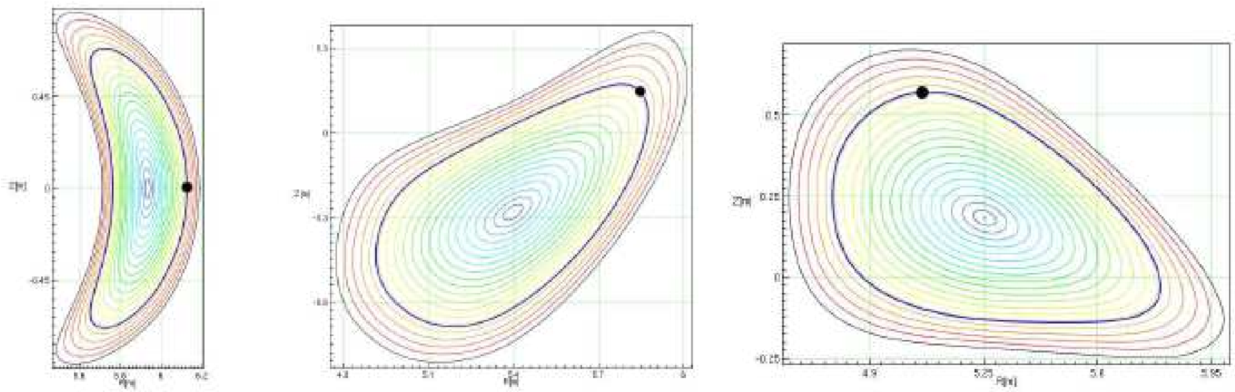


Figure 7.3.: Cross sections of the magnetic flux surfaces of the W7-X high mirror equilibrium for $z = 0,\ \pi/4$ and $\pi/2$. The blue line marks the flux surface under consideration, the black dot denotes the position of the flux tube.

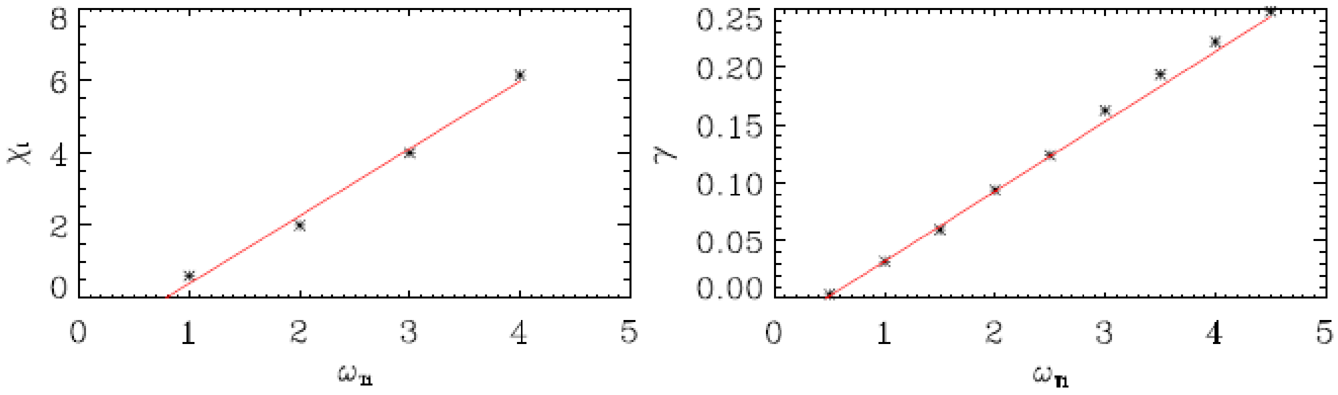


Figure 7.8.: Left: Ion heat diffusivity (in $\rho_s^2 c_s/a$) as a function of the ion temperature gradient. Right: Linear growth rate for the dominant $k_y = 0.6$ mode.

F. Merz, PhD Thesis (2008)

Same case, but with *kinetic* electrons

- again: diffusivity (not flux) is offset-linear
- however, no Dimits shift is observed
- zonal flows are found to be rather weak

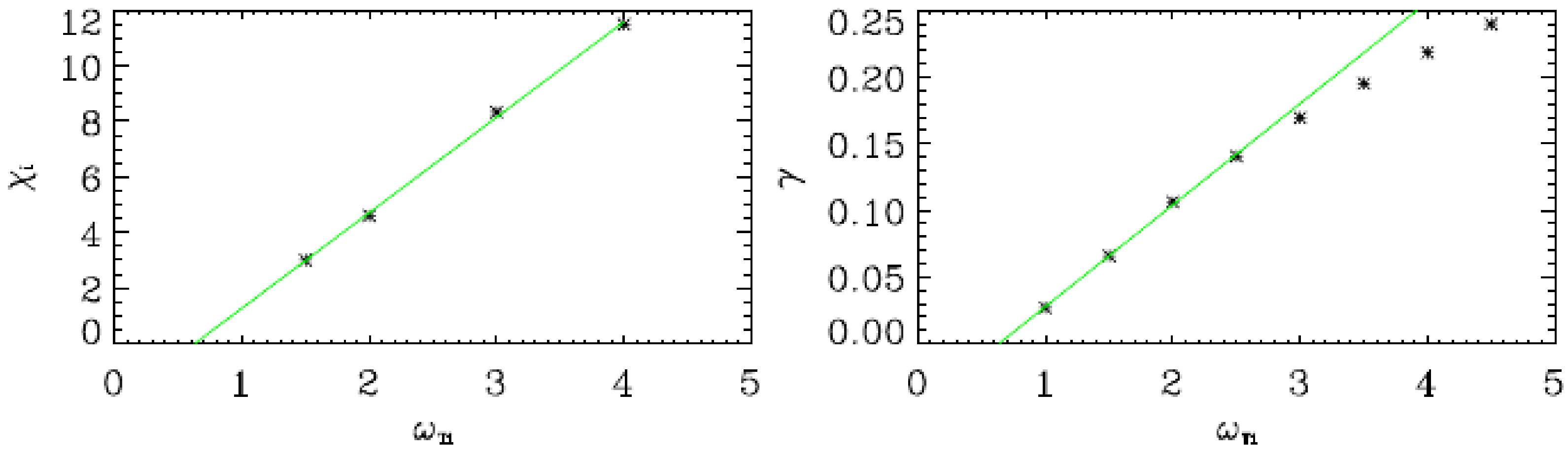


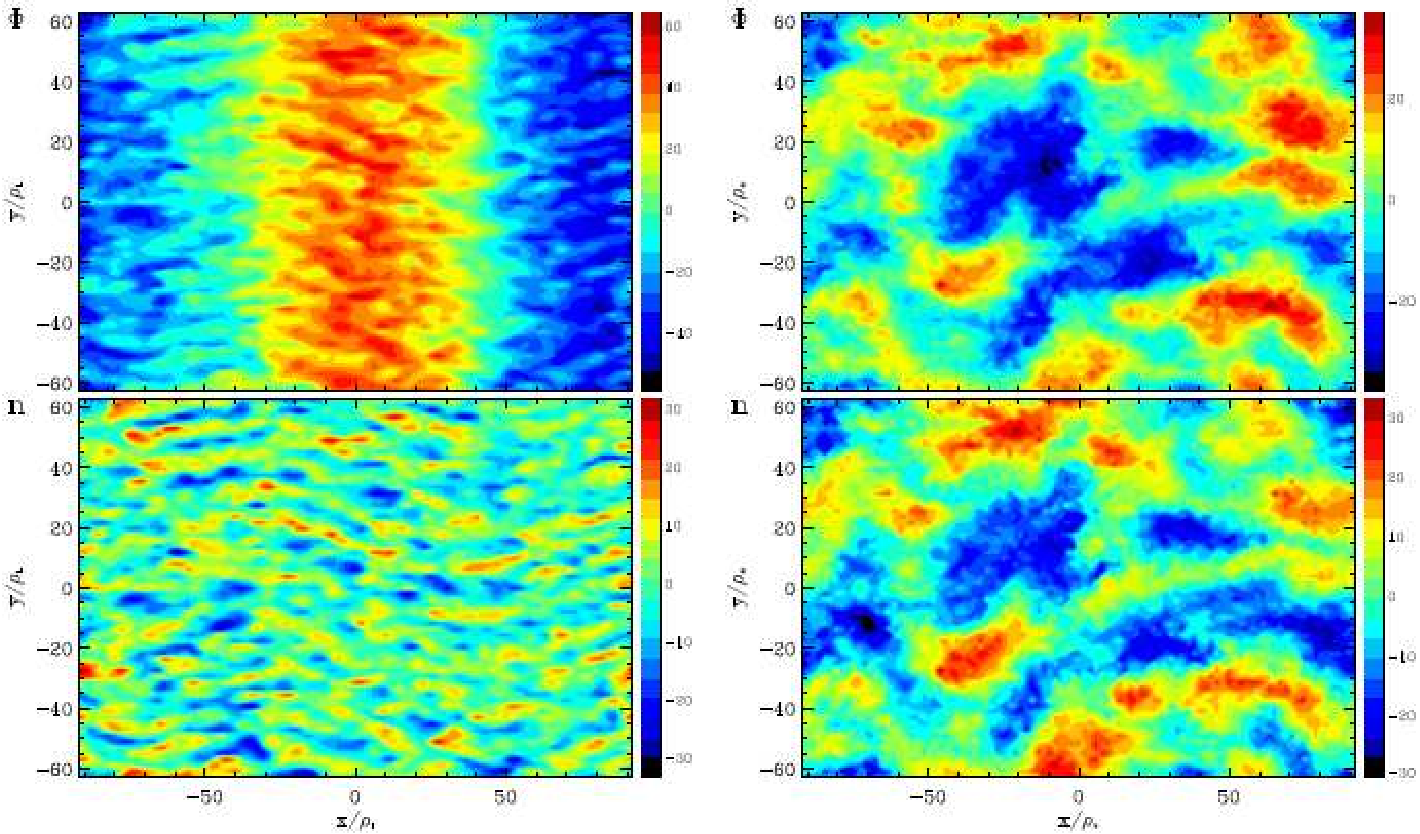
Figure 7.10.: Left: Ion heat diffusivity as a function of the ion temperature gradient. Right: Linear growth rate for the $k_y = 0.6$ mode.

F. Merz, PhD Thesis (2008)

Kinetic electrons: Weak zonal flows

Adiabatic electrons

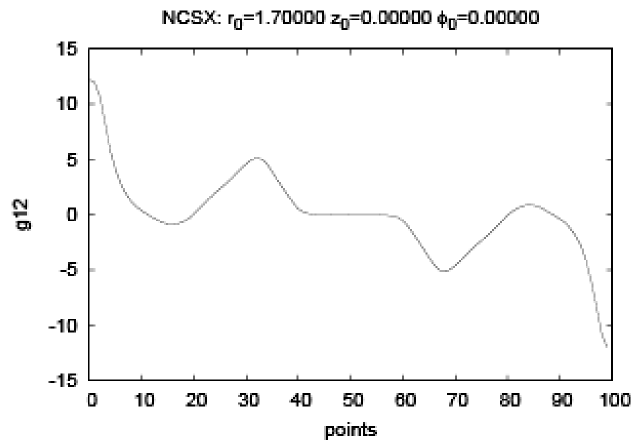
Kinetic electrons

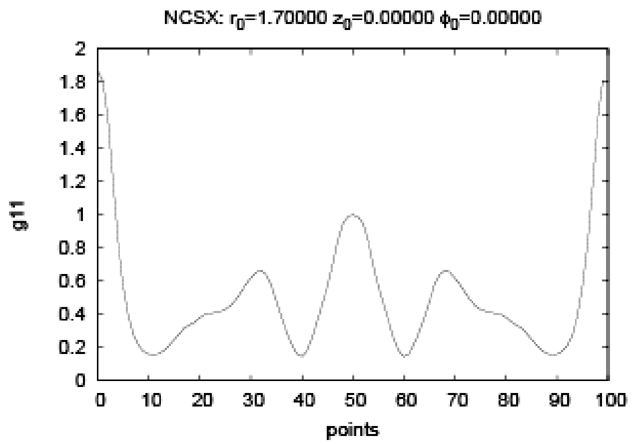


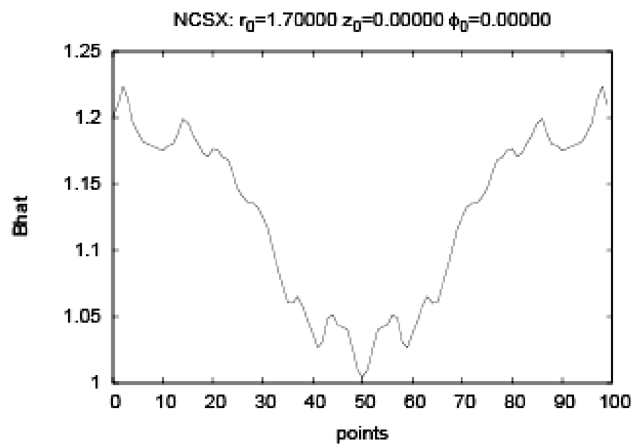
F. Merz, PhD Thesis (2008)

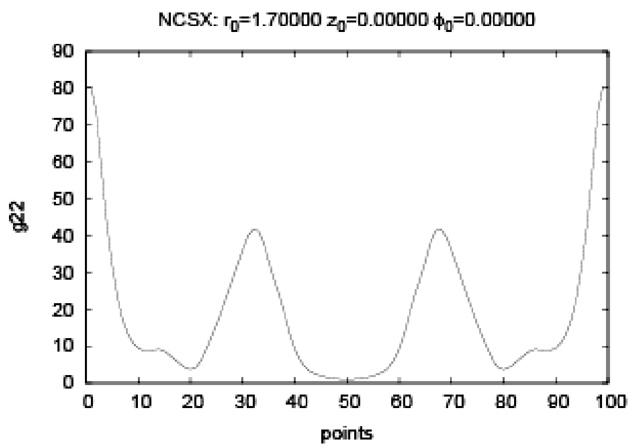
Figure 7.13.: Left: Contour of the electrostatic potential and perturbed density at $z = 0$ and for $a/L_{Ti} = 3$. Right: The corresponding plots for the simulation with gyrokinetic electrons.

Geometric coefficients for NCSX case



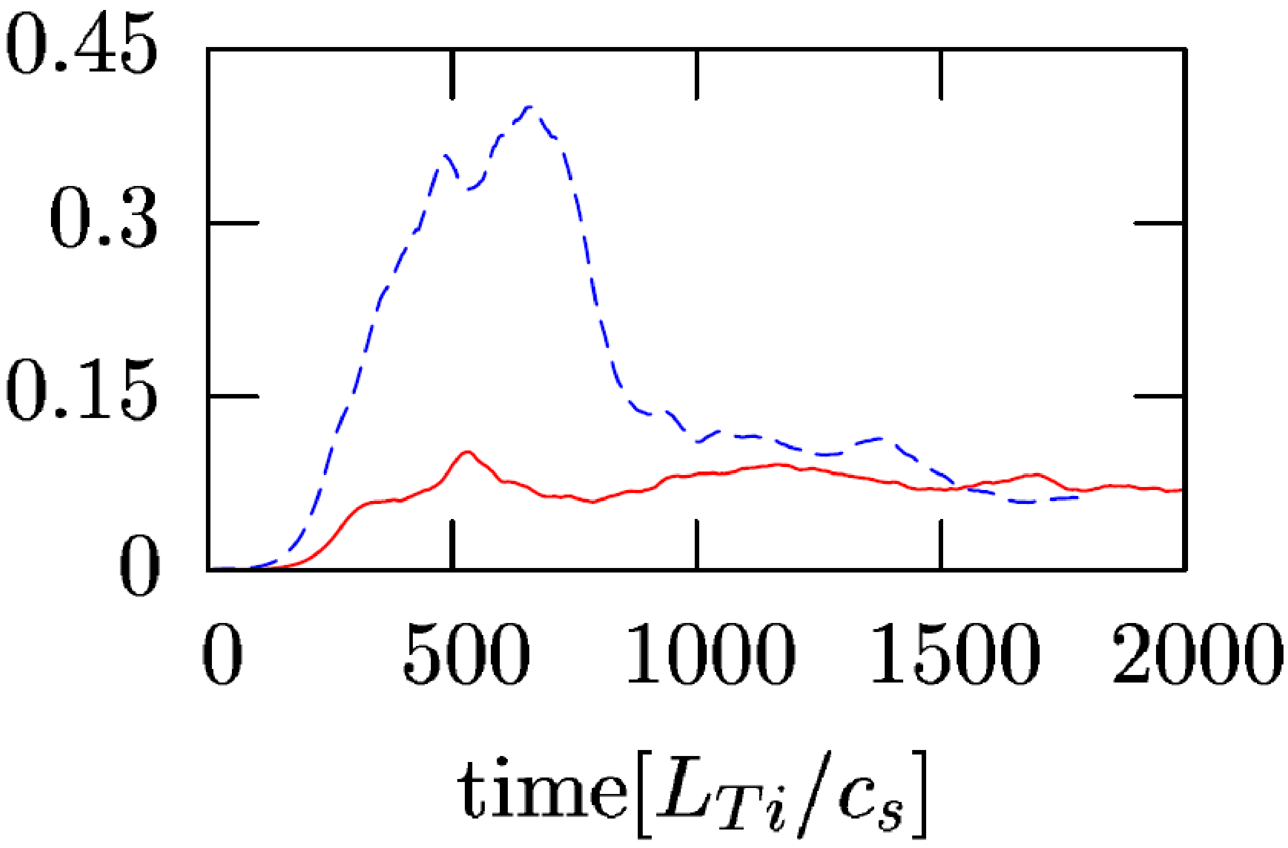






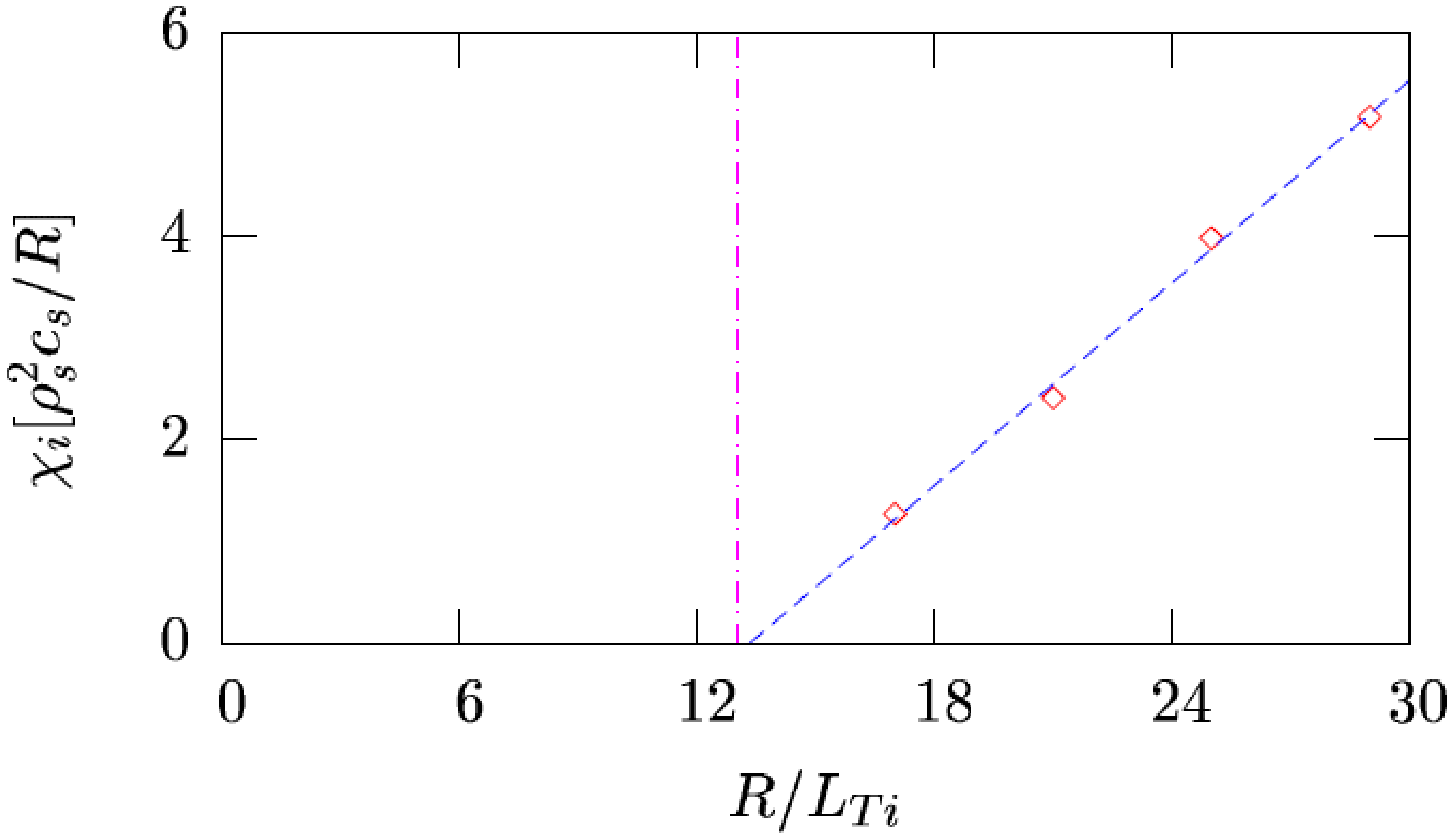
Zonal flows in adiabatic ITG turbulence

Simulation with suppressed zonal flows
yields the same (!) transport level



Flux-gradient relationship

- as before: offset-linear scaling for diffusivity
- no Dimits shift (but rather large threshold)



Conclusions (for part I)

- For *adiabatic* ITG turbulence in W7-X (two different configurations and radial positions), one observes strong zonal flow spin-up

- For *kinetic* ITG turbulence in W7-X as well as for NCSX, zonal flows are rather weak and there is no Dimits shift

- Calls for a better understanding of zonal flow physics in realistic geometries and with more complete physics

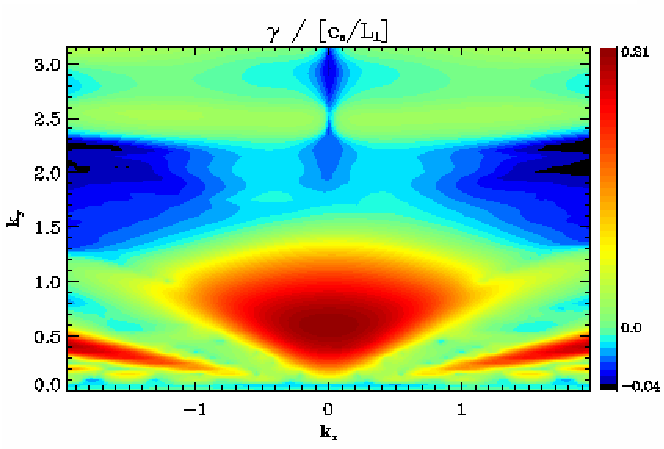
Nonlinear saturation of TEM turbulence (in tokamaks)

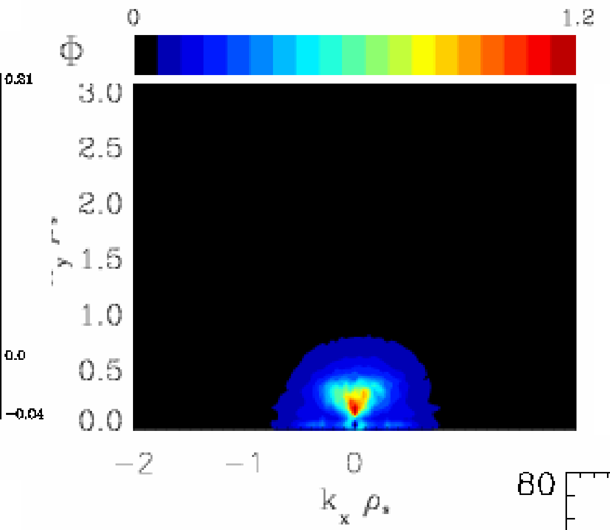
F. Merz and F. Jenko, PRL **100**, 035005 (2008)

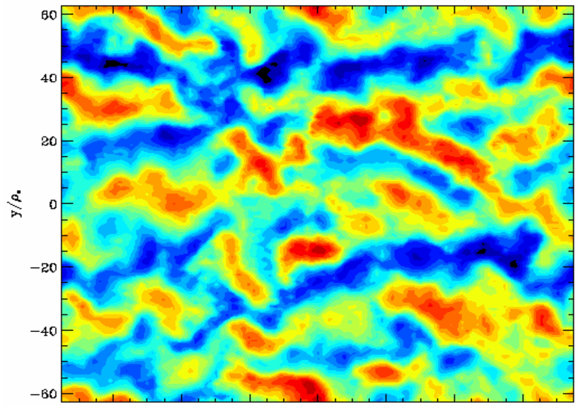
Characteristics of TEM turbulence

In the saturated phase, TEM turbulence often exhibits:

– radially elongated structures (“streamers”; remnants of linear modes), nonlinear spectrum reflects linear growth rate spectrum

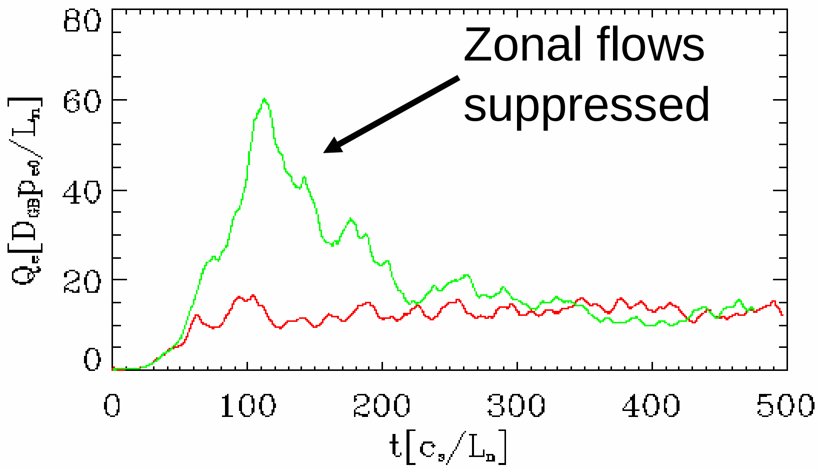




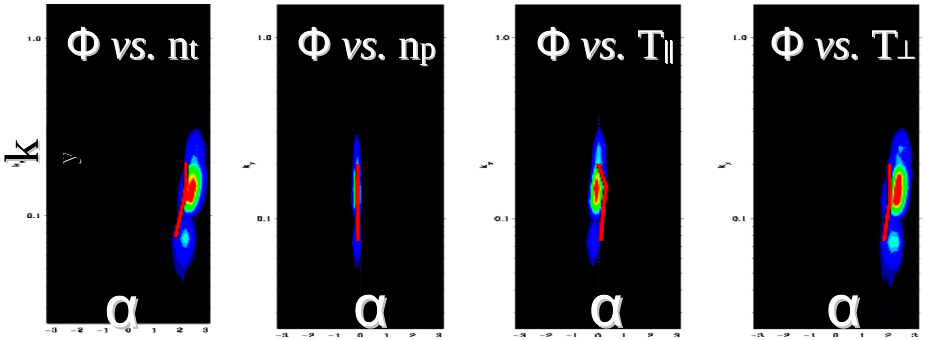


– no dependence of transport level on zonal flows

[Dannert & Jenko, PoP 2005]

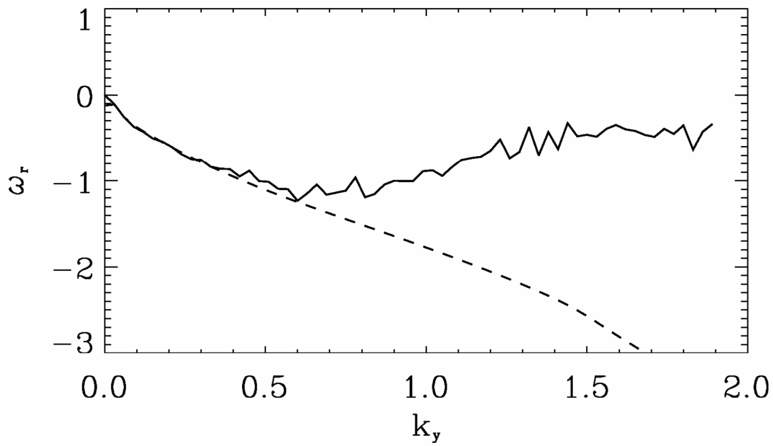


Characteristics of TEM turbulence (cont'd)



- no significant shift of cross phases w.r.t. linear ones

  [Dannert & Jenko, PoP 2005]



- nonlinear frequencies close to linear ones for low ky values

⇒ Description of the nonlinear system as linear modes in a turbulent bath?

Short-hand notation of gyrokinetics

- Gyrokinetic Vlasov-Maxwell system:

$$\frac{\partial g}{\partial t} = \mathcal{L} g + \mathcal{N}l[g]$$

where

– g: modified distribution function (state vector) depending on k_x, k_y, z, $v_{||}$, μ coordinates and species label

– $\mathcal{L}$: linear integro-differential operator

– $\mathcal{N}l[g]$: (quadratic) ExB nonlinearity

- Linear physics determined by eigenspectrum of $\mathcal{L}$ (eigenvalue solvers)

- Saturation provided by $\mathcal{N}l[g]$

- In the following, for simplicity, we use s-α geometry (with α=0); ETG modes are linearly stable

Quasilinear ansatz

- Assumption $\mathcal{N}l[g] \sim g$ leads to an effective linear equation

$$\frac{\partial g}{\partial t} = \mathcal{L}g + \mathcal{X}g$$

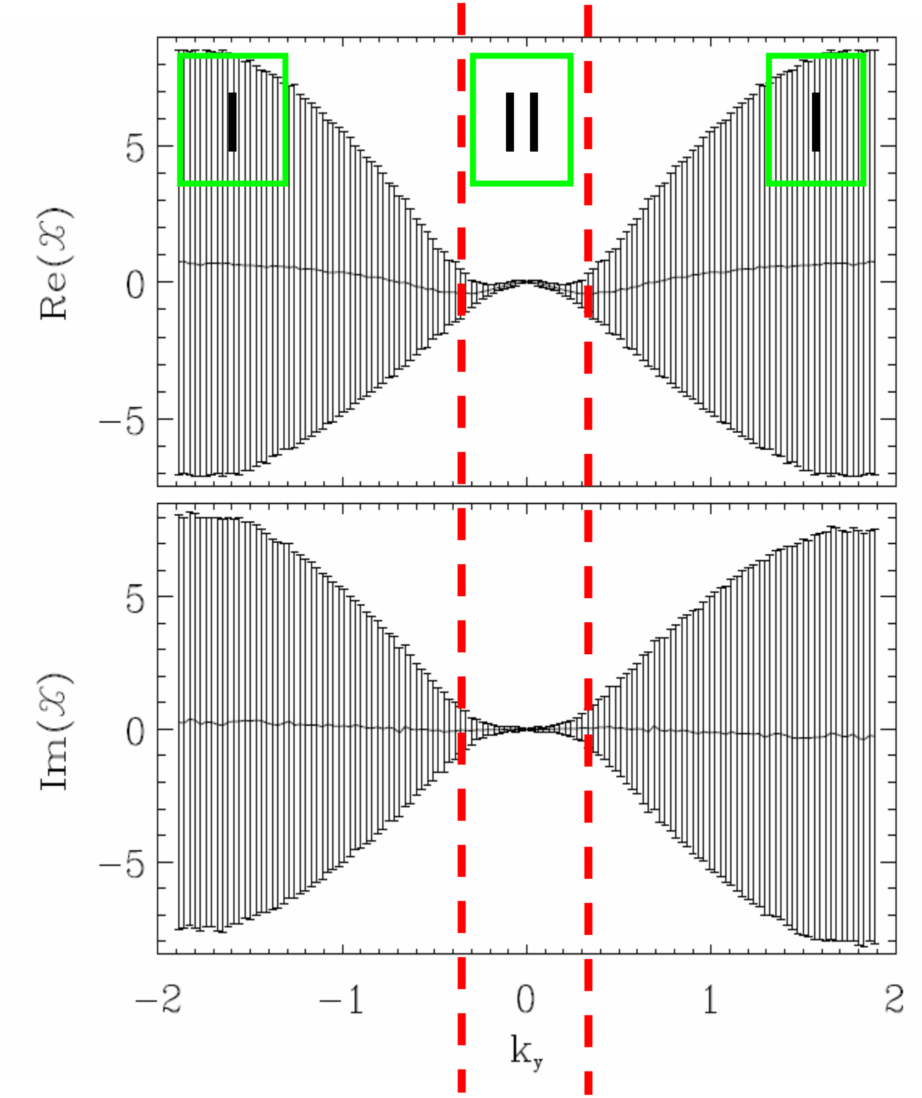
- $\mathcal{N}l[g]$ and g are fluctuating quantities; to get an estimate for the complex proportionality constant $X=X(k_x,k_y,z,spec)$, we minimize the model error $\langle|\mathcal{N}[g] - \mathcal{X}g|^2\rangle$

- The resulting expression $\mathcal{X} = \langle g^*\mathcal{N}[g]\rangle / \langle|g|^2\rangle$ is evaluated in numerical simulations of TEM turbulence

($\langle\rangle$: average over velocity space and time)

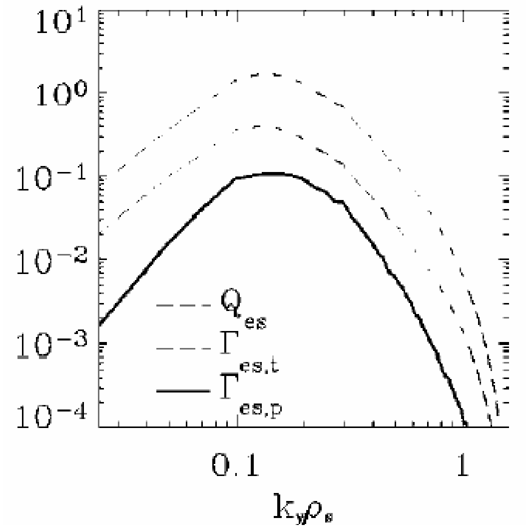
Structure of the nonlinearity

- Numerical result (k_x=0): two distinguishable regions
  - Region I, |ky|>1: dominated by fluctuations
  - Region II , |ky|<0.3: clear structure in X, the model error $\langle |\mathcal{N}[g] - \mathcal{X} g|^2 \rangle$ is small



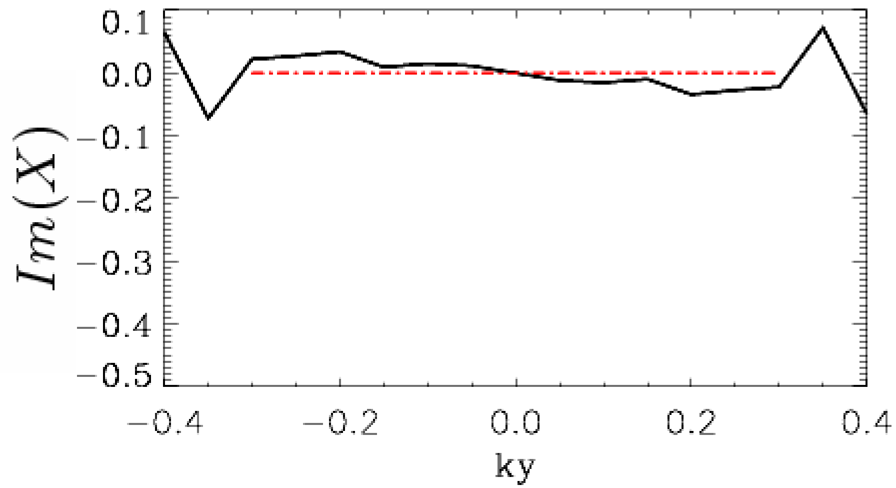
Region II: Transport relevant ky range

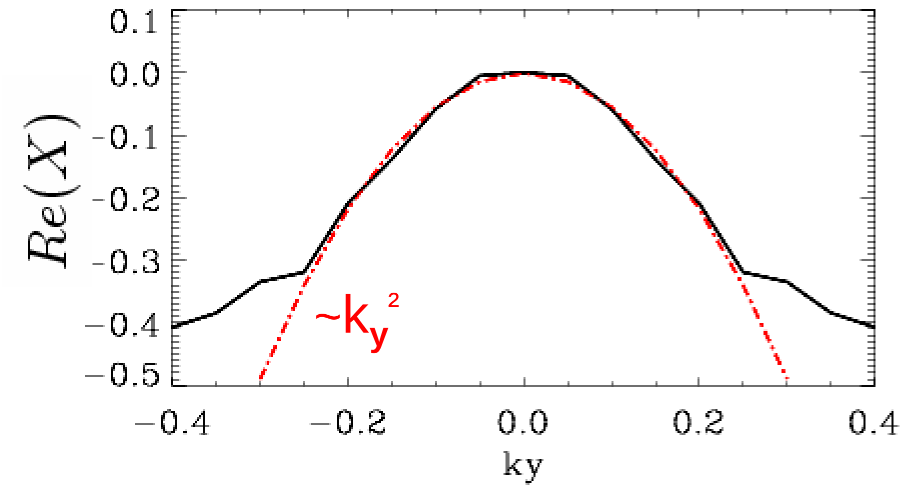
- The ky range where fluctuations are small coincides with the ky range relevant for transport



- Result: Im(X) is negligible, Re(X) is a parabola

$$\boxed{\mathcal{N}l[g] \simeq D(-k_\perp^2)g = D\nabla_\perp^2 g}$$

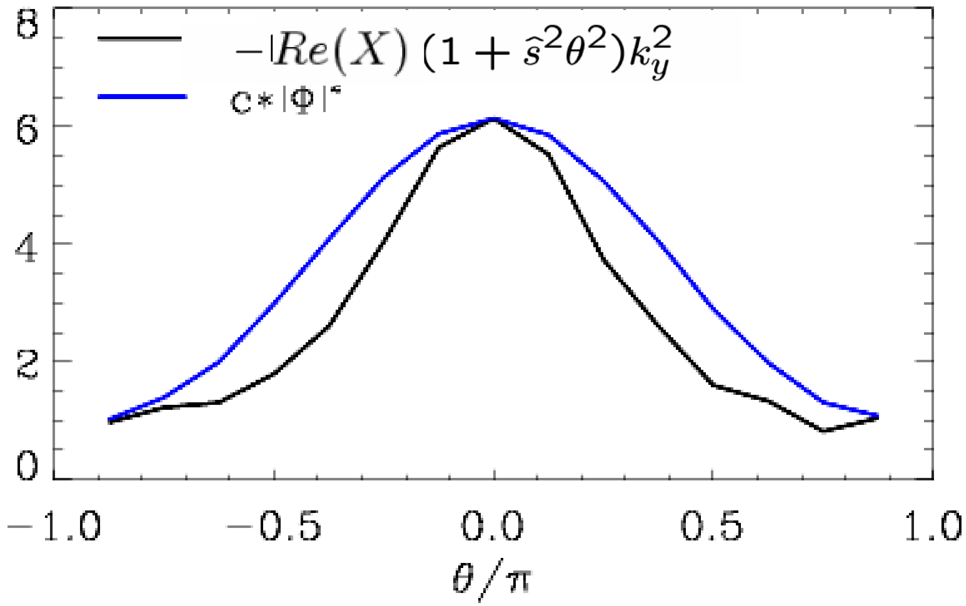




Cp. Resonance Broadening Theory (Dupree), MSR formalism (Krommes), Dressed Test Mode Approach (Itoh) in long wavelength, low frequency limit

Region II: Parallel structure of diffusivity

- Dependence on parallel coordinate: $\approx |\Phi|^2$



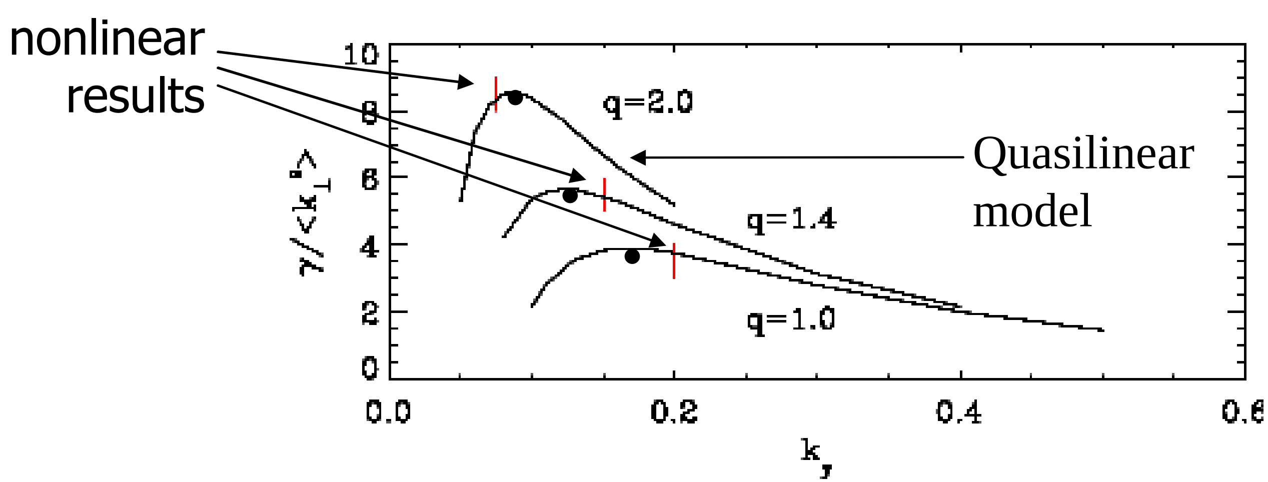
- Integration with parallel weighting yields effective wave number $\langle k_\perp^2 \rangle := \int d\theta D(\theta) k_\perp^2 \simeq c \int d\theta \left|\Phi^2(\theta)\right| k_\perp^2$

- Quasilinear equation: $$\frac{\partial g}{\partial t} = \mathcal{L}g + \mathcal{N}l[g] \simeq (i\omega_r + \gamma - D_0\langle k_\perp^2\rangle)g$$

- Stationarity implies $$D_0 \sim \frac{\gamma}{\langle k_\perp^2 \rangle}$$

Quasilinear transport model

- Fick's law $Q \sim D_0 \frac{R}{L_{Te}}$ gives $\boxed{Q_e \propto \max_{k_y} \left[\frac{\gamma}{\langle k_\perp^2 \rangle} \right] \frac{R}{L_{T_e}}}$
- Application: q dependence of TEM-induced transport



[Jenko & Dannert '05]

- Scaling: $Q_e \propto q^\nu$
- The quasilinear model captures the q-dependence seen in nonlinear simulations (here $\nu \approx 1.7$) and in experiments ($\nu = 1 - 2$)

Conclusions (for part II)

- There exist regimes in which nonlinear TEM saturation is *not* due to ZFs (confirmed by Parker et al.)
- Careful statistical analysis: Saturation due to perpendicular particle diffusion (or eddy diffusion)
- Explains near-linear properties of TEMs in the saturated turbulent state
- Motivates quasilinear transport model which is in good agreement with nonlinear simulations