ASDEX Upgrade

Max-Planck-Institut für Plasmaphysik

Surprises in gyrokinetic turbulence simulations: Some recent GENE results

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Acknowledgements:

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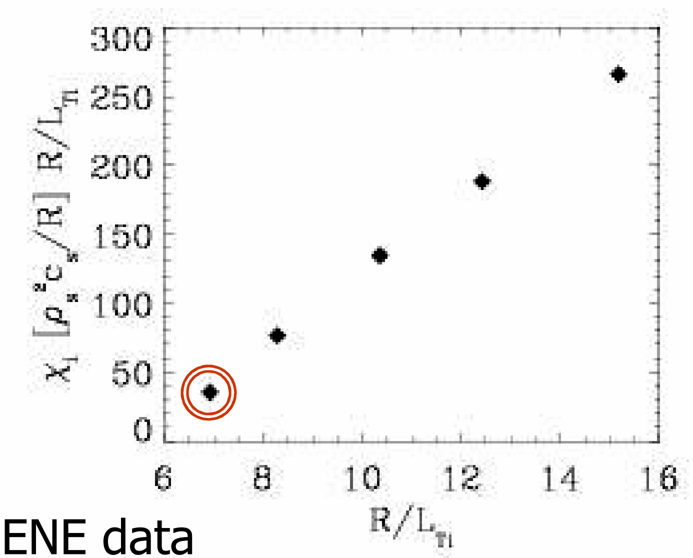
Adiabatic ITG turbulence in a simple tokamak

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
• ion heat flux is offset-linear
• nonlinear upshift of threshold

What about other transport channels, modes, and scales?
How generic is the adiabatic ITG s-α scenario?

Overview

- The tool: GENE
- The nature of (pure) TEM turbulence
- Nonlinear ITG-TEM(-ETG) interactions
- The role of magnetic geometry (NSTX, NCSX)

The tool: GENE

The nonlinear gyrokinetic equations

$$f = f(\mathbf{X}, v_{\|}, \mu; t)$$

Advection/Conservation equation

$$\frac{\partial f}{\partial t} + \dot{\mathbf{X}} \cdot \frac{\partial f}{\partial \mathbf{X}} + \dot{v}_{\|} \frac{\partial f}{\partial v_{\|}} = 0$$

X = gyrocenter position
$v_{\|}$ = parallel velocity
μ = magnetic moment

$$\dot{\mathbf{X}} = v_{\|}\mathbf{b} + \frac{B}{B_{\|}^{*}}\left(\frac{v_{\|}}{B}\bar{\mathbf{B}}_{1\perp} + \mathbf{v}_{\perp}\right)$$

$$\mathbf{v}_{\perp} \equiv \frac{c}{B^2}\bar{\mathbf{E}}_1 \times \mathbf{B} + \frac{\mu}{m\Omega}\mathbf{b} \times \nabla(B + \bar{B}_{1\|}) + \frac{v_{\|}^2}{\Omega}(\nabla \times \mathbf{b})_{\perp}$$

$$\dot{v}_{\|} = \frac{\dot{\mathbf{X}}}{m v_{\|}} \cdot \left(e\bar{\mathbf{E}}_1 - \mu\nabla(B + \bar{B}_{1\|})\right)$$

Appropriate field equations

$$\frac{n_1}{n_0} = \frac{\bar{n}_1}{n_0} - \left(1 - \|I_0^2\|\right)\frac{e\phi_1}{T} + \|x I_0 I_1\|\frac{B_{1\|}}{B}$$

$$\nabla_{\perp}^2 A_{1\|} = -\frac{4\pi}{c}\sum \bar{J}_{1\|}$$

$$\frac{B_{1\|}}{B} = -\sum \epsilon_{\beta}\left(\frac{\bar{p}_{1\perp}}{n_0 T} + \|x I_1 I_0\|\frac{e\phi_1}{T} + \|x^2 I_1^2\|\frac{B_{1\|}}{B}\right)$$

Current physics features of GENE

Treatment of particle dynamics

- Arbitrary number of gyrokinetic particle species, passing and trapped
- Can be active (feedback via field equations) or passive
- Non-Maxwellian (beam-type) equilibrium distributions
- Electromagnetic effects are included

Collisions

- Collisions between any pair of species are kept
- Pitch angle scattering *and* energy scattering are retained
- Momentum and energy conserving terms are implemented

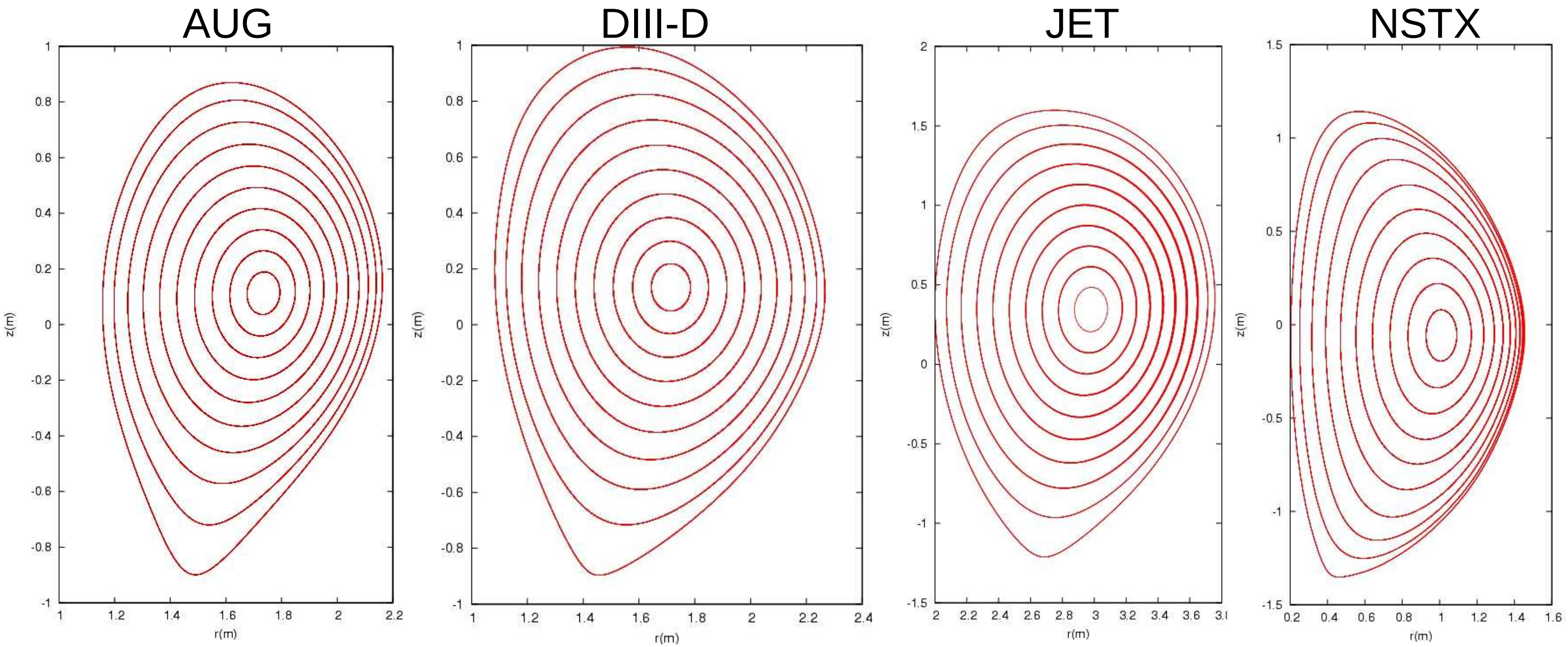
General geometry

- Interface to CHEASE MHD equilibrium code
- Interface to other MHD codes: TRACER

The TRACER code

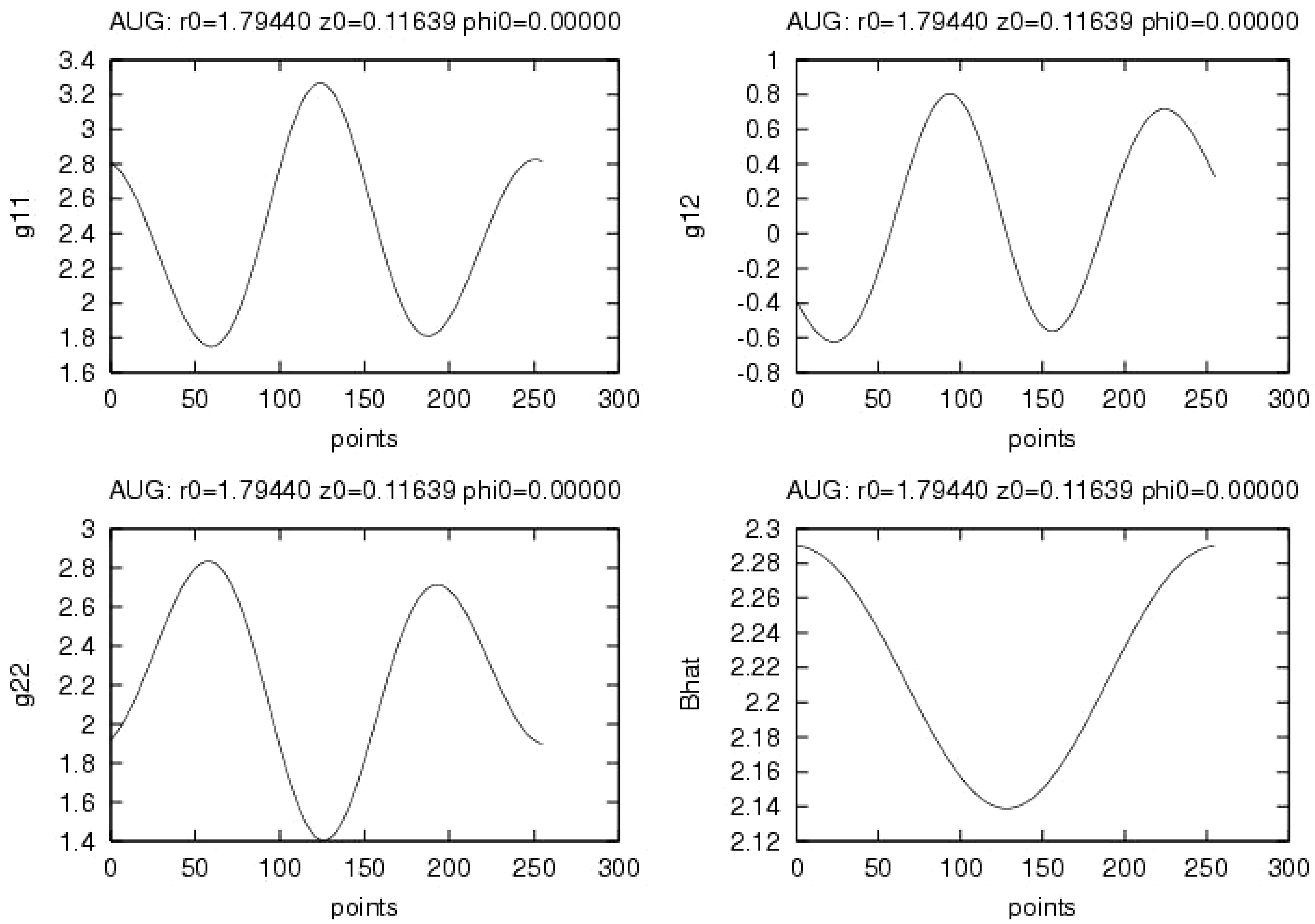
Description

- Numerical generation of a **Clebsch system** via field line tracing
- No assumptions on the existence or properties of flux surfaces
- Flexibility in construction of flux surface label
- Coupling to plasma parameter databases



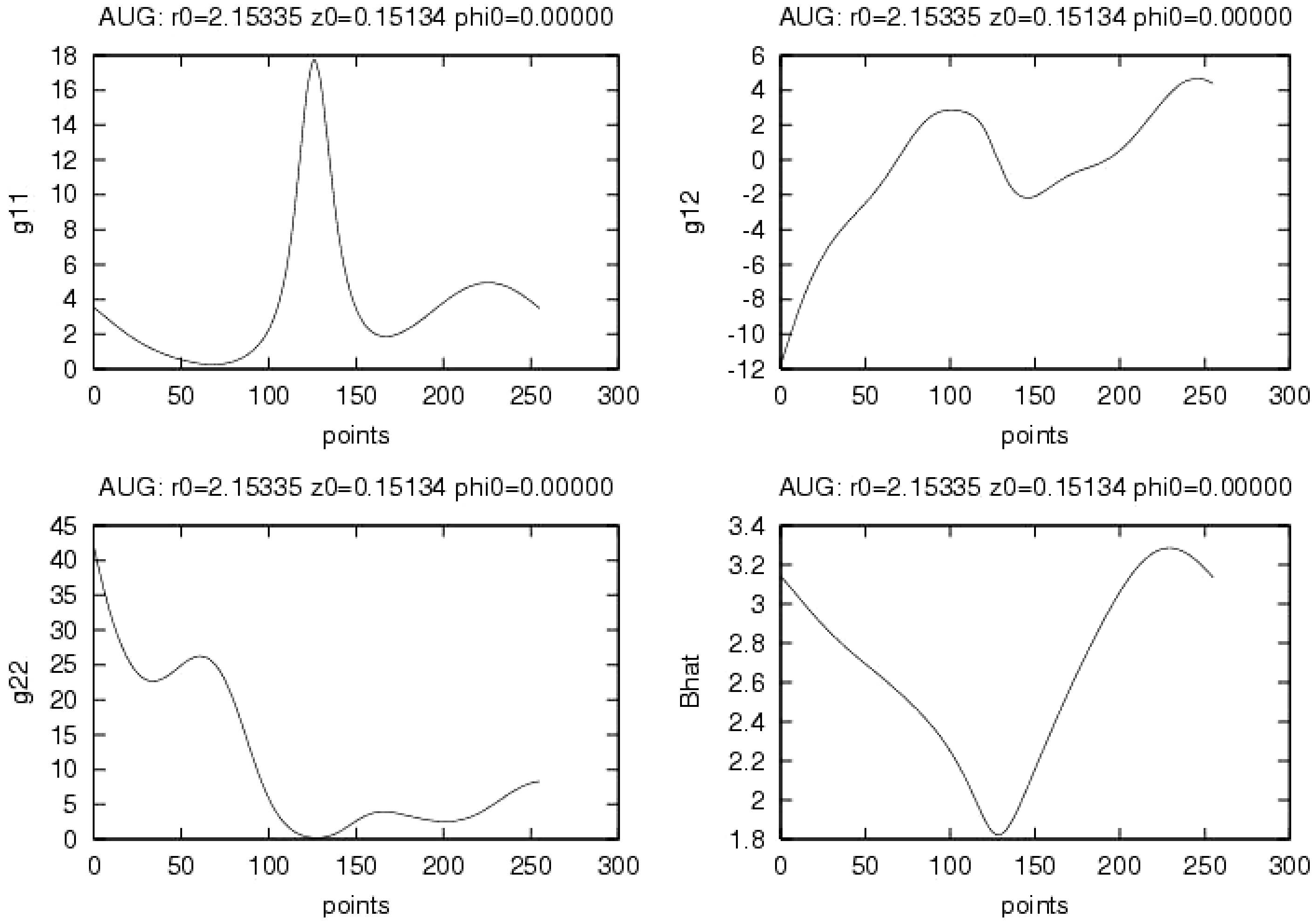
The TRACER code (cont'd)

Some metric coefficients for AUG at ρ_{tor} = 0.1



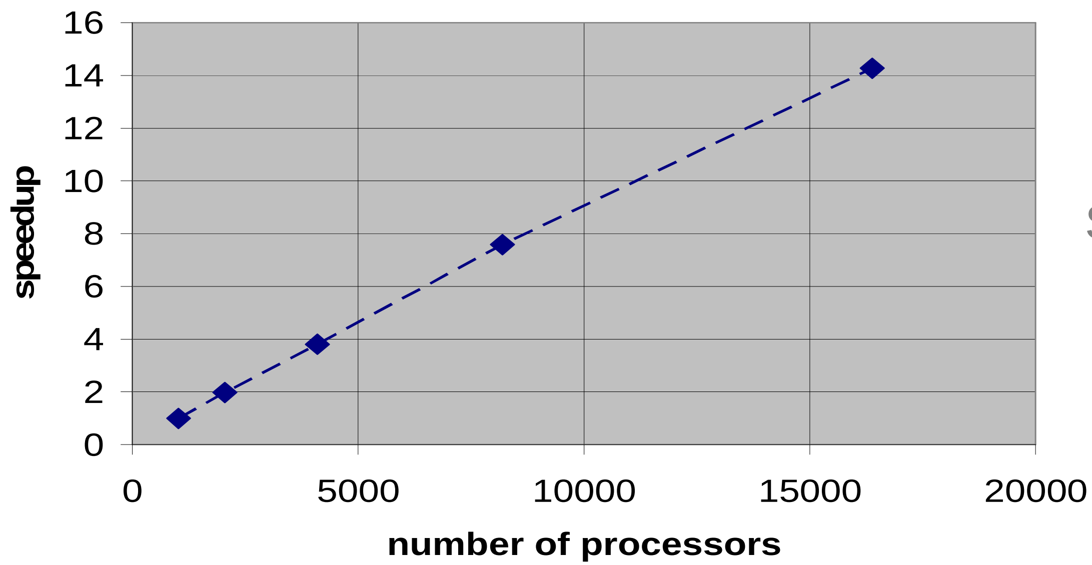
The TRACER code (cont'd)

Some metric coefficients for AUG at $\rho_{tor} = 0.95$



Hyperscaling of GENE

- GENE runs very efficiently on a large number of parallel platforms
- Example: IBM BlueGene/L @ Watson Research Center



Speedup: 14.2 / 16

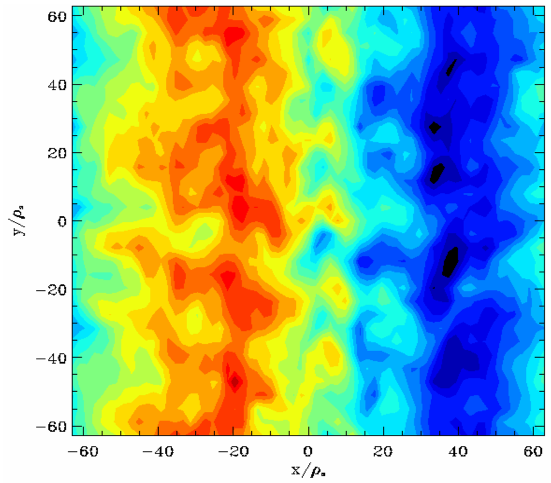
Strong scaling (fixed problem size) – from 1k to 16k cores

The nature of (pure) TEM turbulence

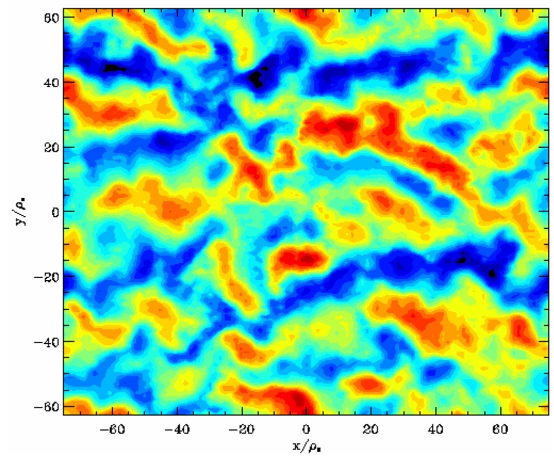
Questions concerning TEM turbulence

- Established result for ITG turbulence: Nonlinear saturation via zonal flows
- In plasmas with strong electron heating, TEM turbulence can be dominant: What is the nonlinear saturation mechanism?
- When ITG modes and TEMs coexist, how do they interact nonlinearly?
- In the following, we will tend to concentrate on collisionless, temperature gradient driven TEM turbulence away from linear thresholds

Φ ITG



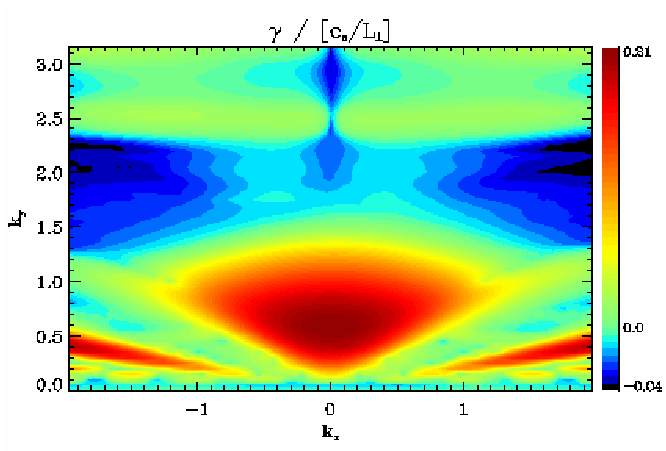
Φ TEM

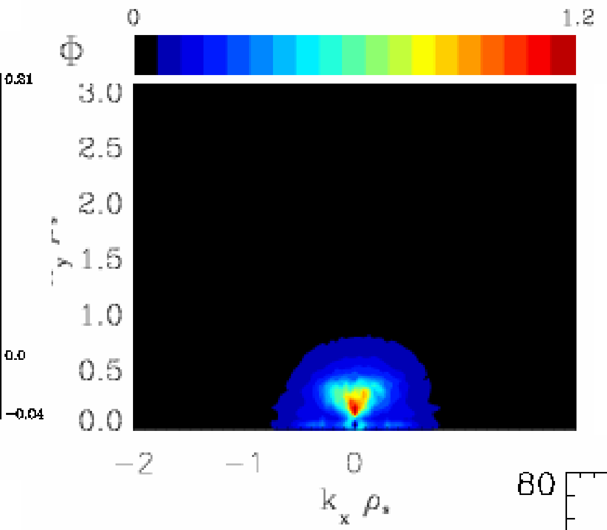


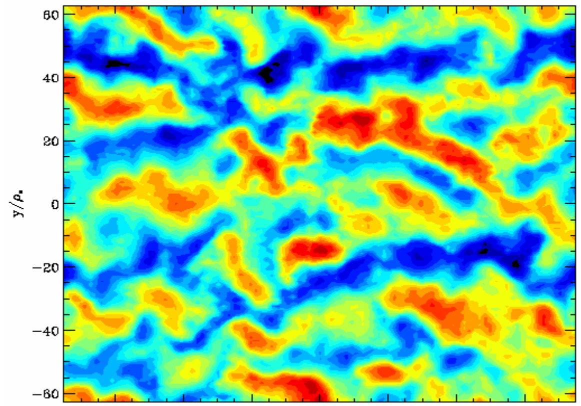
Characteristics of TEM turbulence

In the saturated phase, TEM turbulence often exhibits:

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

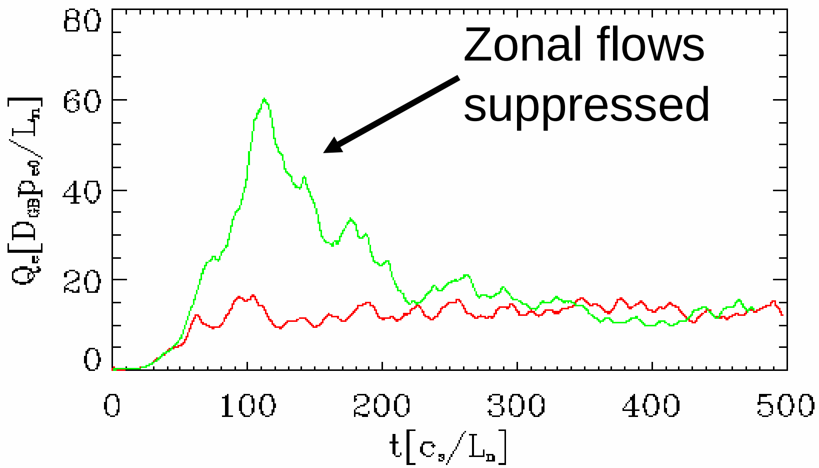






– no dependence of transport level on (intrinsically nonlinear) zonal flows

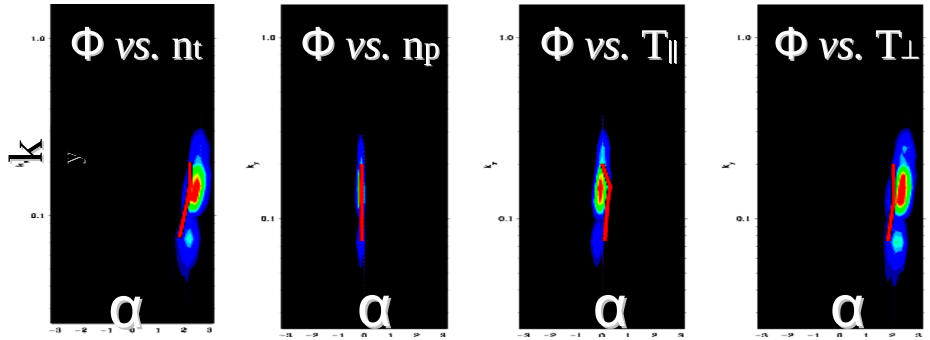
[Dannert & Jenko, PoP 2005]

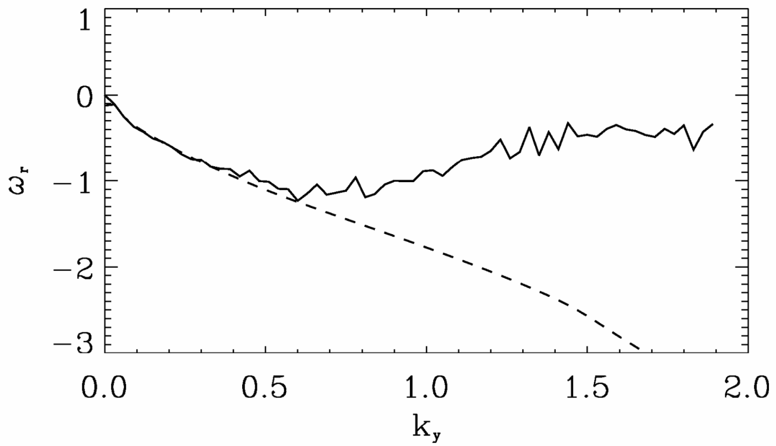


Characteristics of TEM turbulence (cont'd)

– 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

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

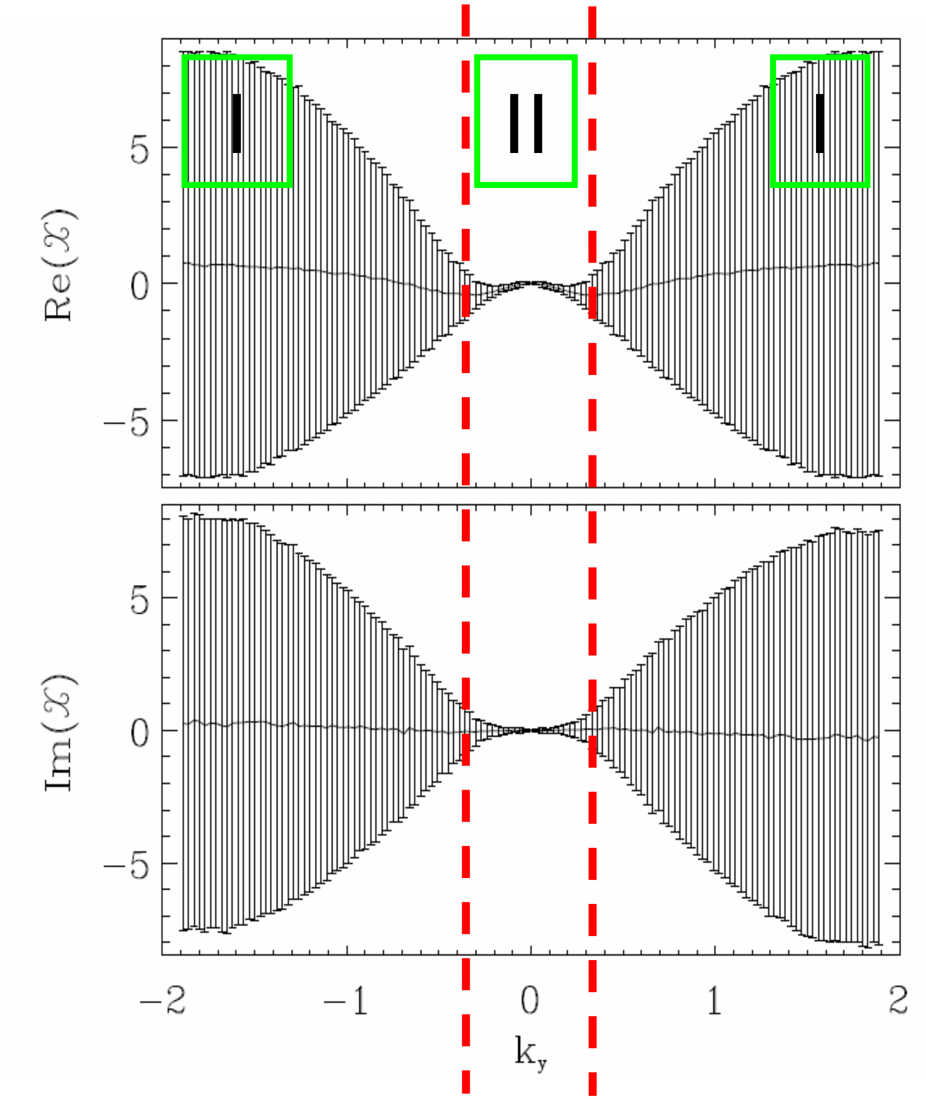
- $\mathcal{N}l[g]$ and g are fluctuating quantities; to get an estimate for the complex proportionality constant *X=X(k$_x$,k$_y$,z,spec)*, we minimize the model error $\langle|\mathcal{N}[g] - \mathcal{X}g|^2\rangle$

- 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)

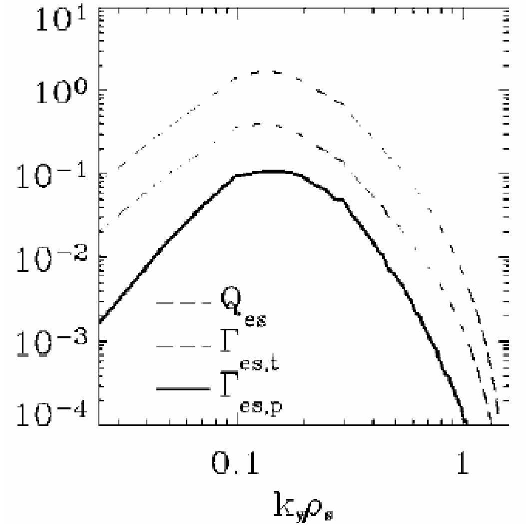
Structure of the nonlinearity

- 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



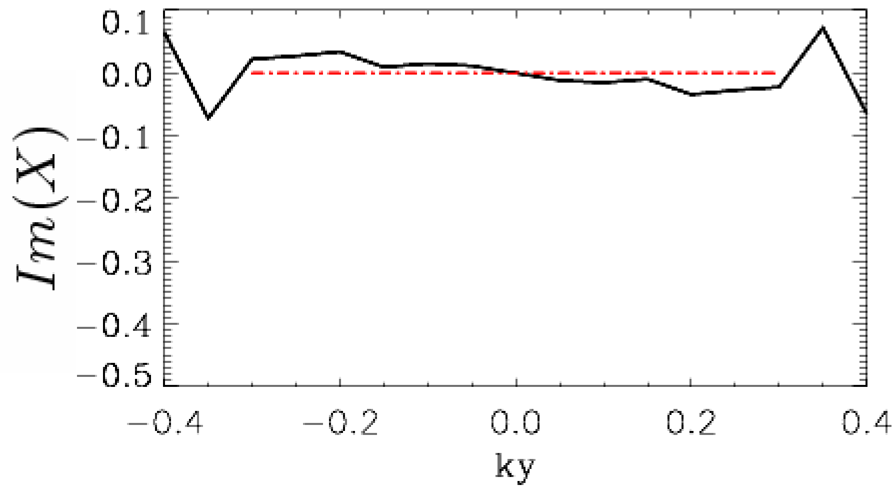
Region II: Transport relevant ky range

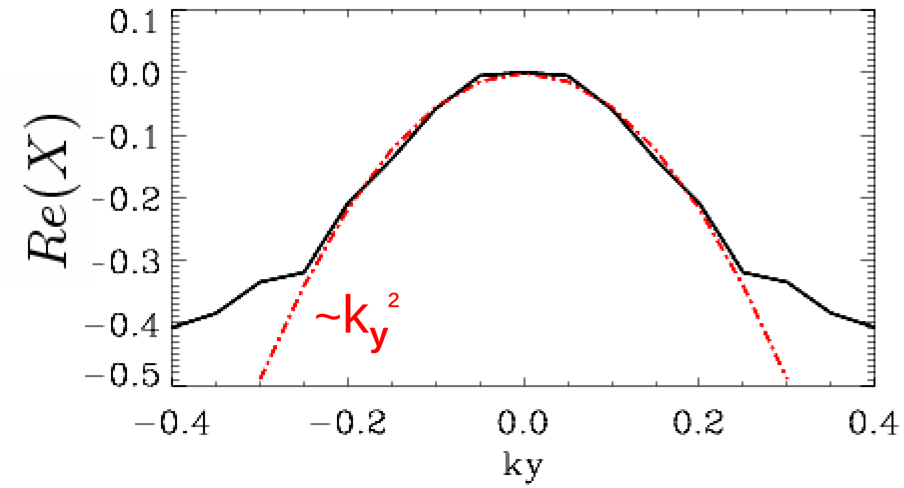
- The ky range where fluctuations are small coincides with the ky range relevant for transport



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

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

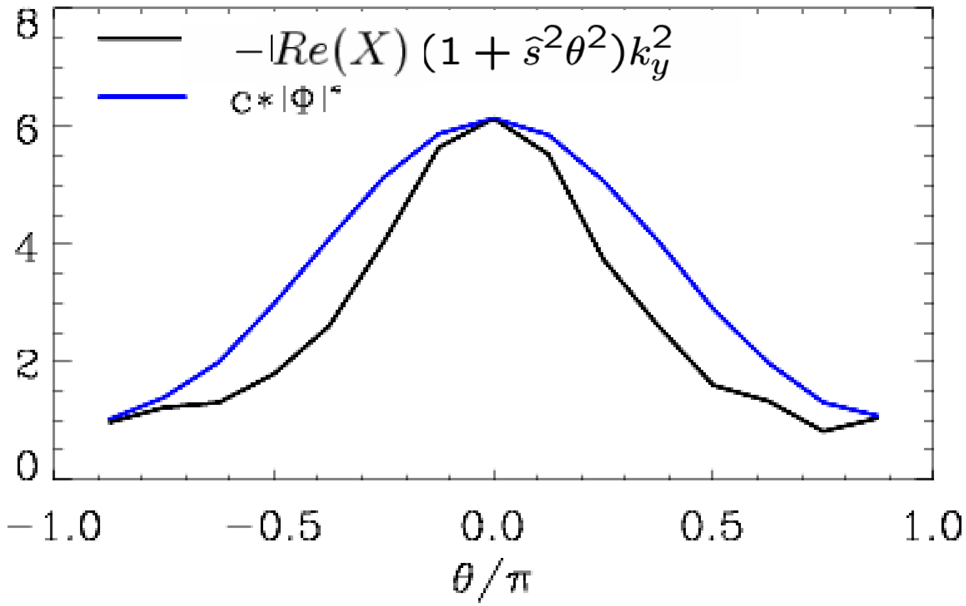




Cp. Resonance Broadening Theory (Dupree), MSR formalism (Krommes), Dressed Test Mode Approach (Itoh) in long wavelength, low frequency limit

Region II: Parallel structure of diffusivity

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



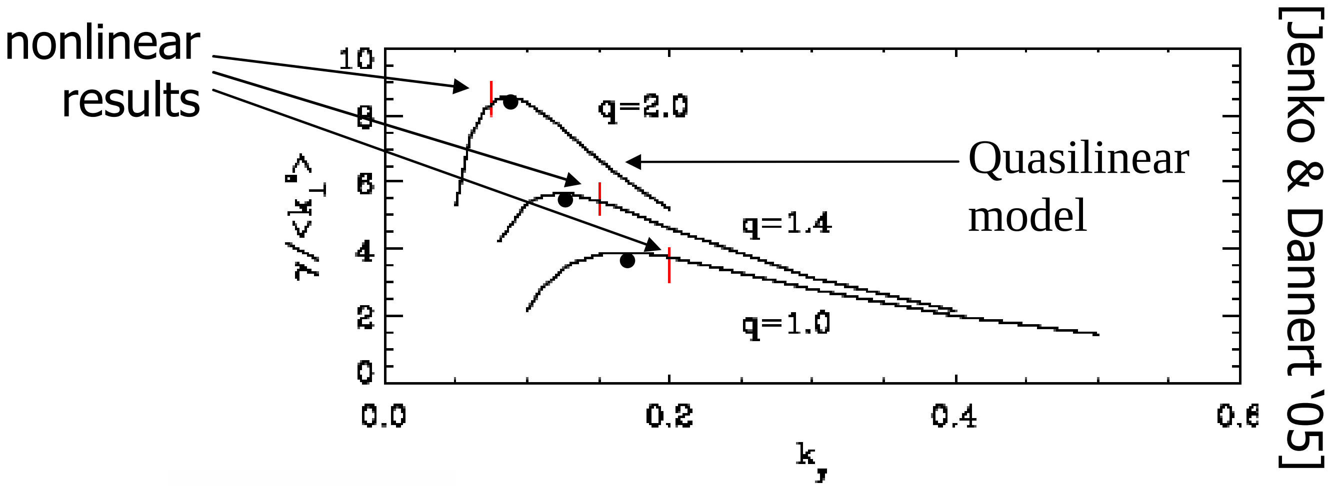
- Integration with parallel weighting yields effective wave number $\langle k_\perp^2 \rangle := \int d\theta D(\theta) k_\perp^2 \simeq c \int d\theta \left|\Phi^2(\theta)\right| k_\perp^2$

- 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 $Q_e \propto \max_{k_y} \left[\frac{\gamma}{\langle k_\perp^2 \rangle} \right] \frac{R}{L_{T_e}}$
- Application: q dependence of TEM-induced transport

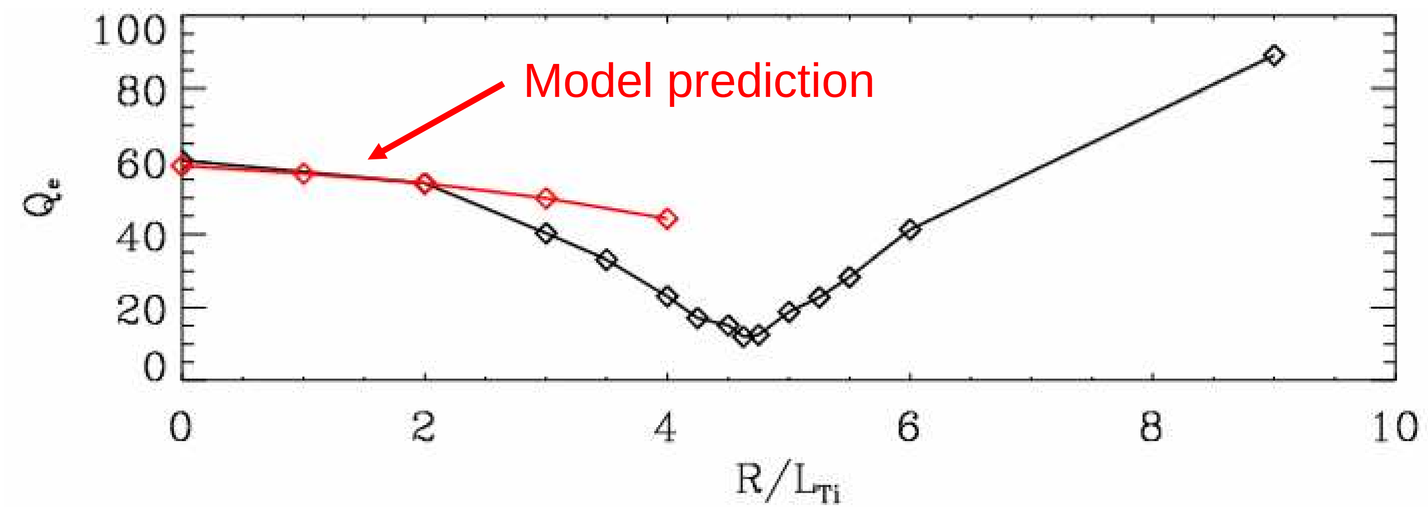


- Scaling: $Q_e \propto q^\nu$
- The quasilinear model captures the q-dependence seen in nonlinear simulations (here $\nu \approx 1.7$) and in experiments ($\nu = 1 - 2$)

Nonlinear ITG-TEM interactions

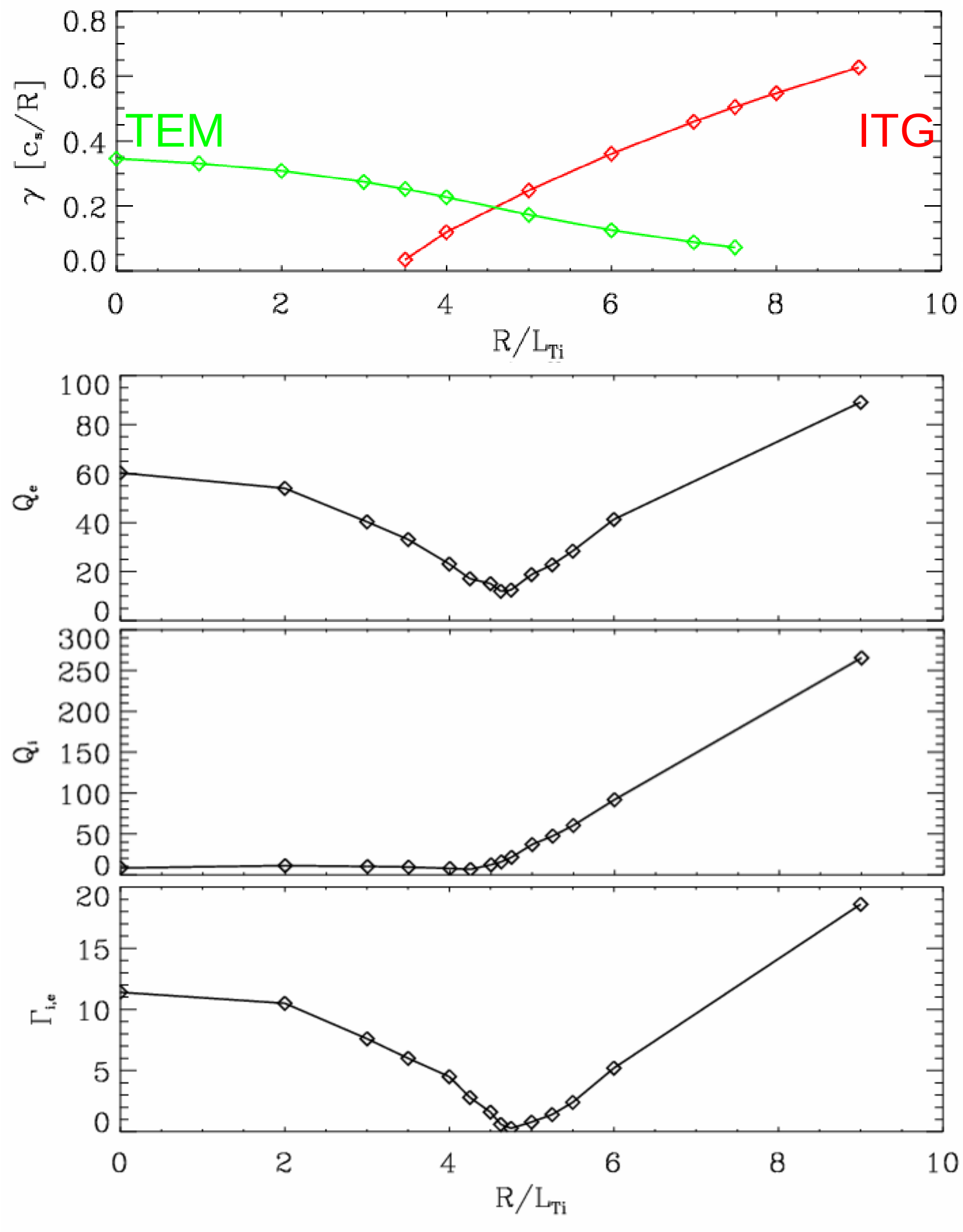
TEM-ITG turbulence transition

- In the following, R/L_{Te} is held constant at 4.5
- Increasing R/L_{Ti} finally leads to a breakdown of the quasilinear model and transition to ITG dominated turbulence

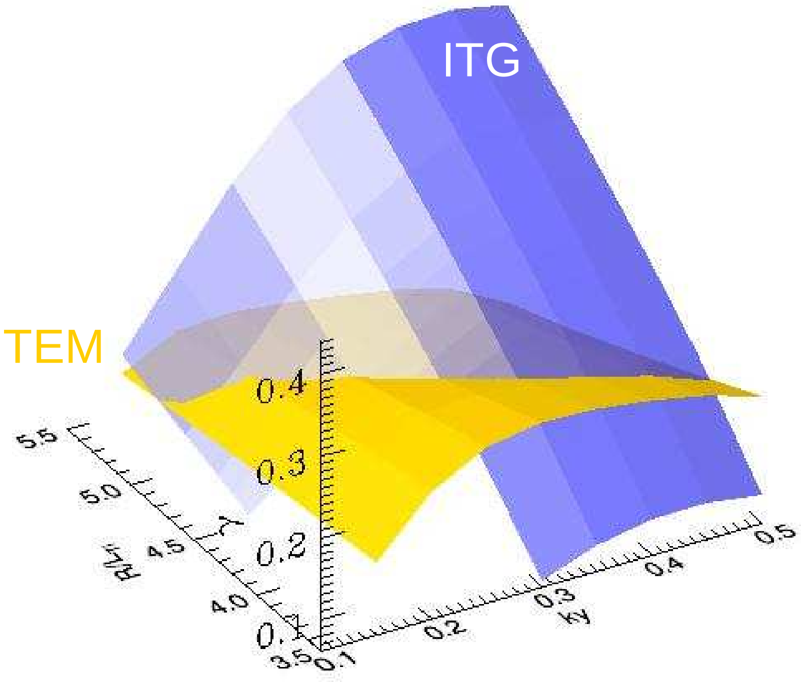


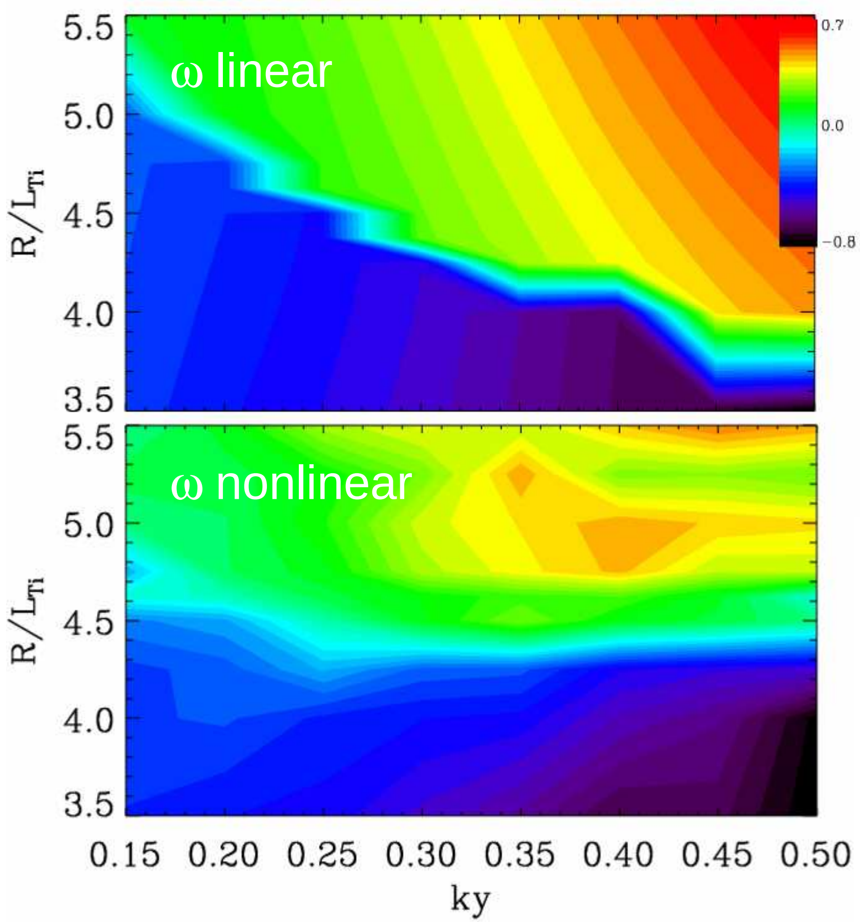
TEM-ITG turbulence transition (cont'd)

- Linear growth rates (k_y=0.25): smooth transition
- Subdominant modes are present (GENE as eigenvalue solver)
- With the additional instability, heat and particle fluxes are suppressed instead of increased
- ITG branch: Nonlinear upshift of critical R/L_{Ti}



Nonlinear frequency spectrum

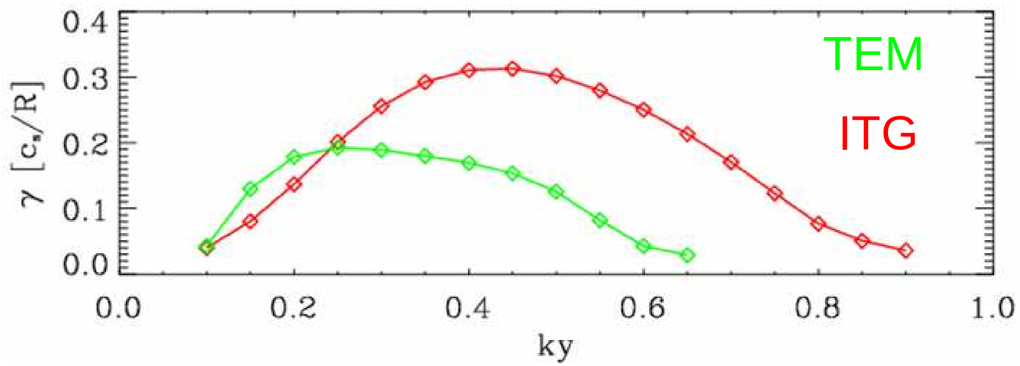


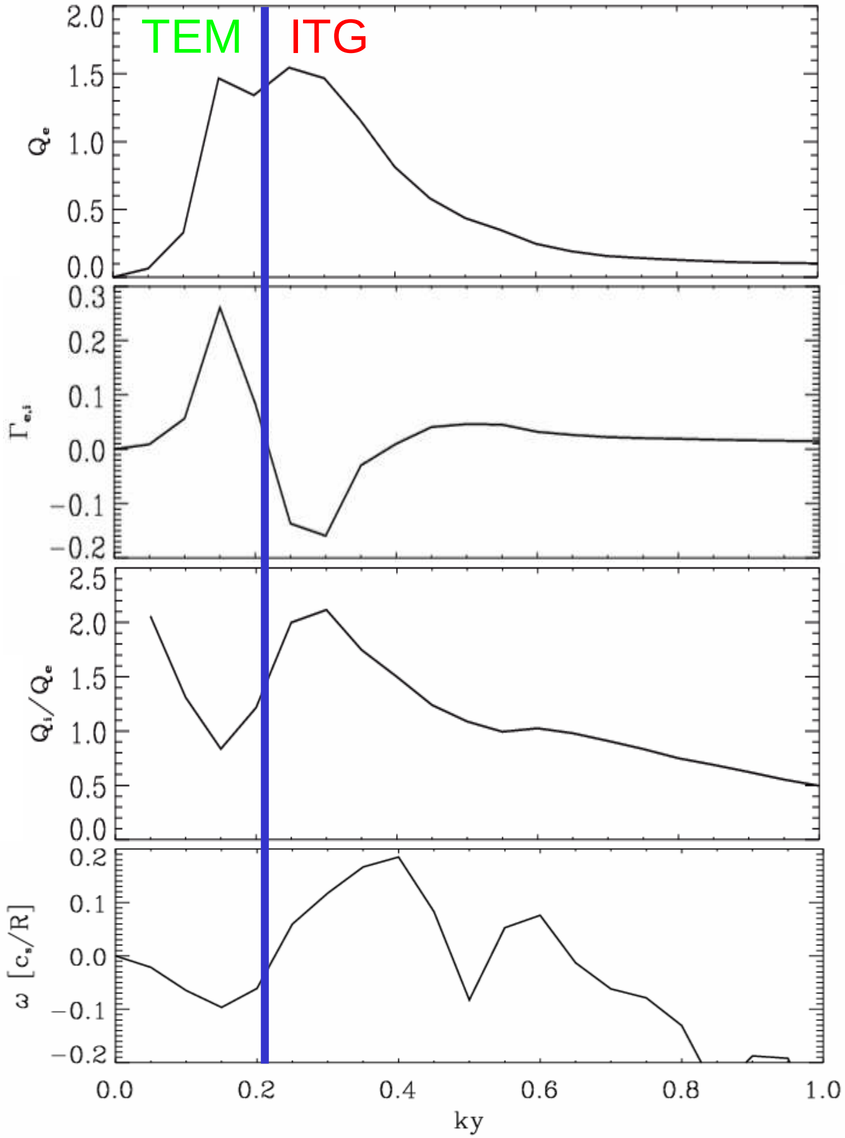


- Even though the linear growth rates can differ significantly, the k_y dependence of critical R/L_{Ti} is strongly flattened
- The nonlinear frequencies show rather abrupt transition in R/L_{Ti}; there is only a relatively small R/L_{Ti} interval with both signs

Coexistence near critical R/L_{Ti}

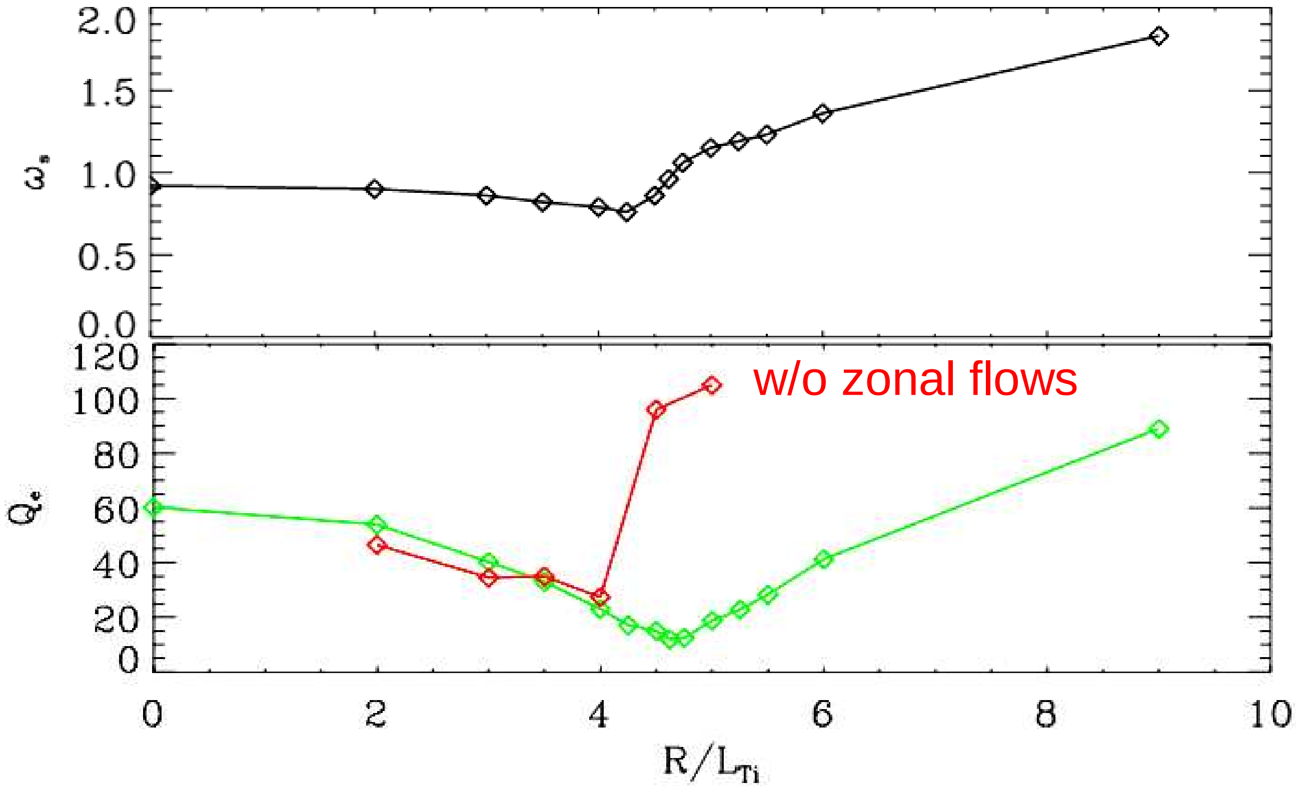
- In the (narrow) transition region (R/L_{Ti}=4.6): Different kinds of turbulence coexist at different k_y
- Turbulence properties (nonlinear frequency, transport ratio, ..) are consistent at a given k_y
- The spectral distribution of TEM and ITG turbulence roughly corresponds to the linear result





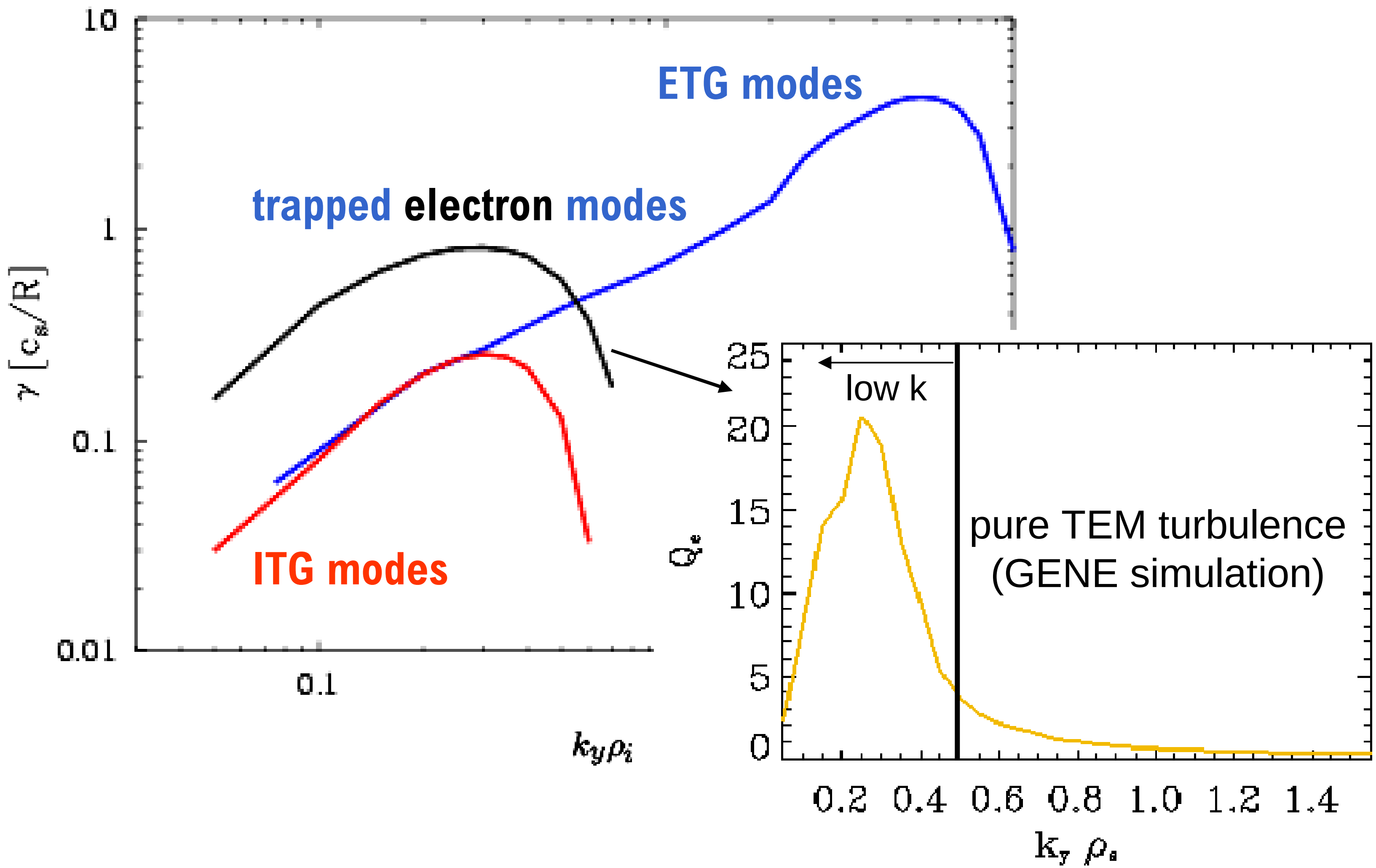
Zonal flow behavior

- TEM-ITG transition changes the role of zonal flows ($k_y=k_{||}=0$)
- Relatively sharp transition seen in the value of the ExB shearing rate ω_s and in simulations where zonal flows have been artificially suppressed



Nonlinear ITG-TEM-ETG interactions

Plasma microturbulence: Multiple scales

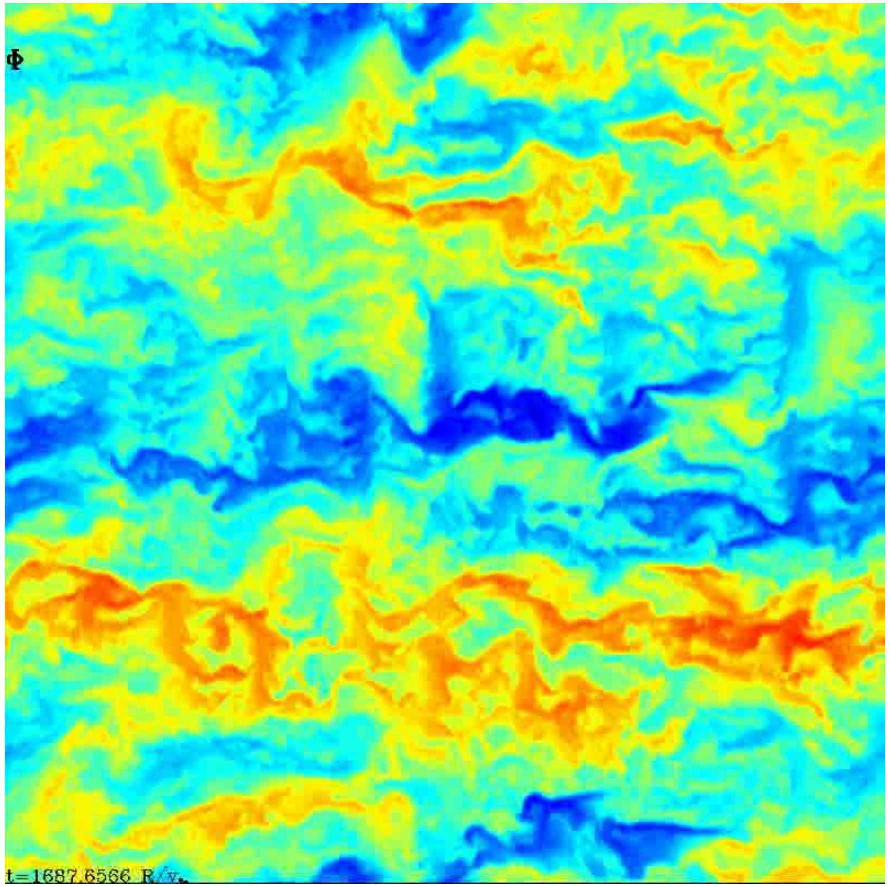


Question to theory: What is the role of high wavenumbers?

TEM-ETG turbulence (Φ contours)

Here: electrostatic, collisionless, s-α model equilibrium; Cyclone-like parameters, reduced mass ratio

Case I: ITG is turned off



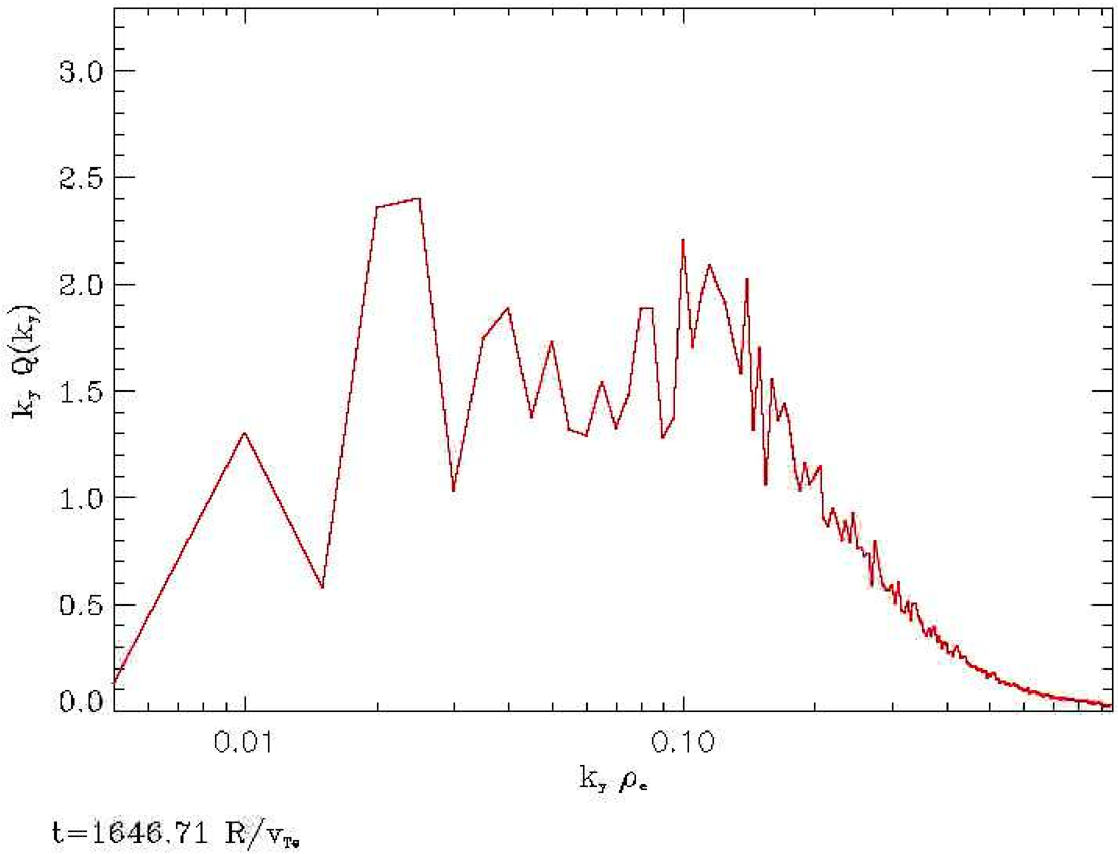
~ 100,000 CPUh / run

box size:
64 ion gyroradii

resolution:
~2 electron gyroradii

ETG streamers and TEM streamers coexist

TEM-ETG turbulence (transport spectrum)



$$Q = \sum_{k_y} Q(k_y) \propto \sum_{k_y} k_y\, Q(k_y)\, \Delta(\log k_y)$$

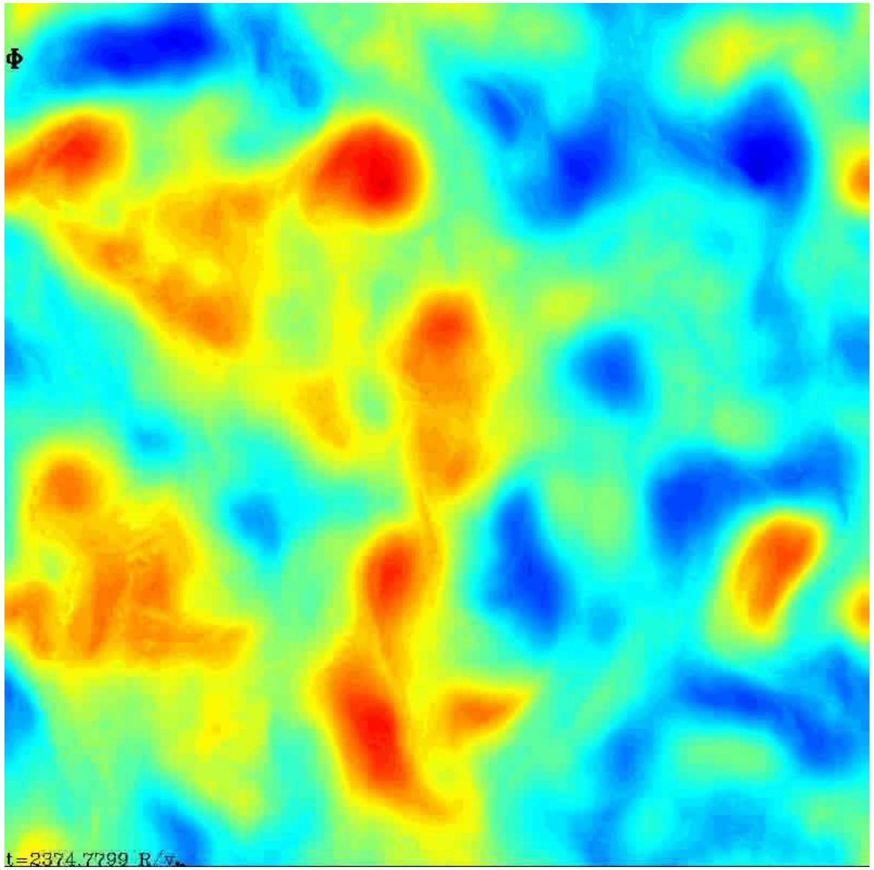
ETG transport level is in line with pure ETG simulations

75% of the electron heat transport is in the $k\rho_i$>0.5 regime

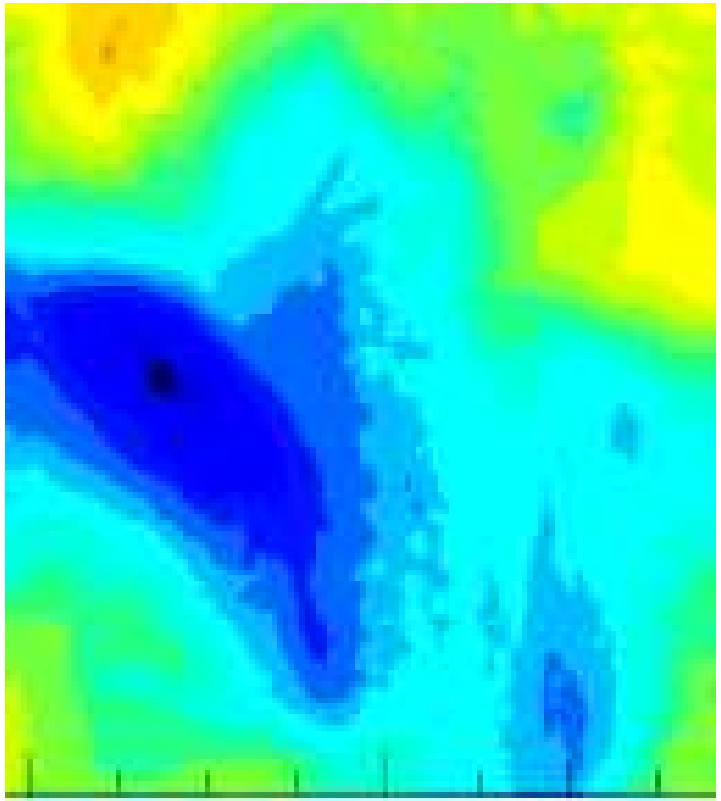
ITG/TEM-ETG turbulence (Φ contours)

Note: For R/LTi = 6.9, one obtains χ_i ~ 50 m^2/s (!) and a fairly small ETG fraction; therefore, we use R/LTi = 5.5

Case II: ITG is dominant

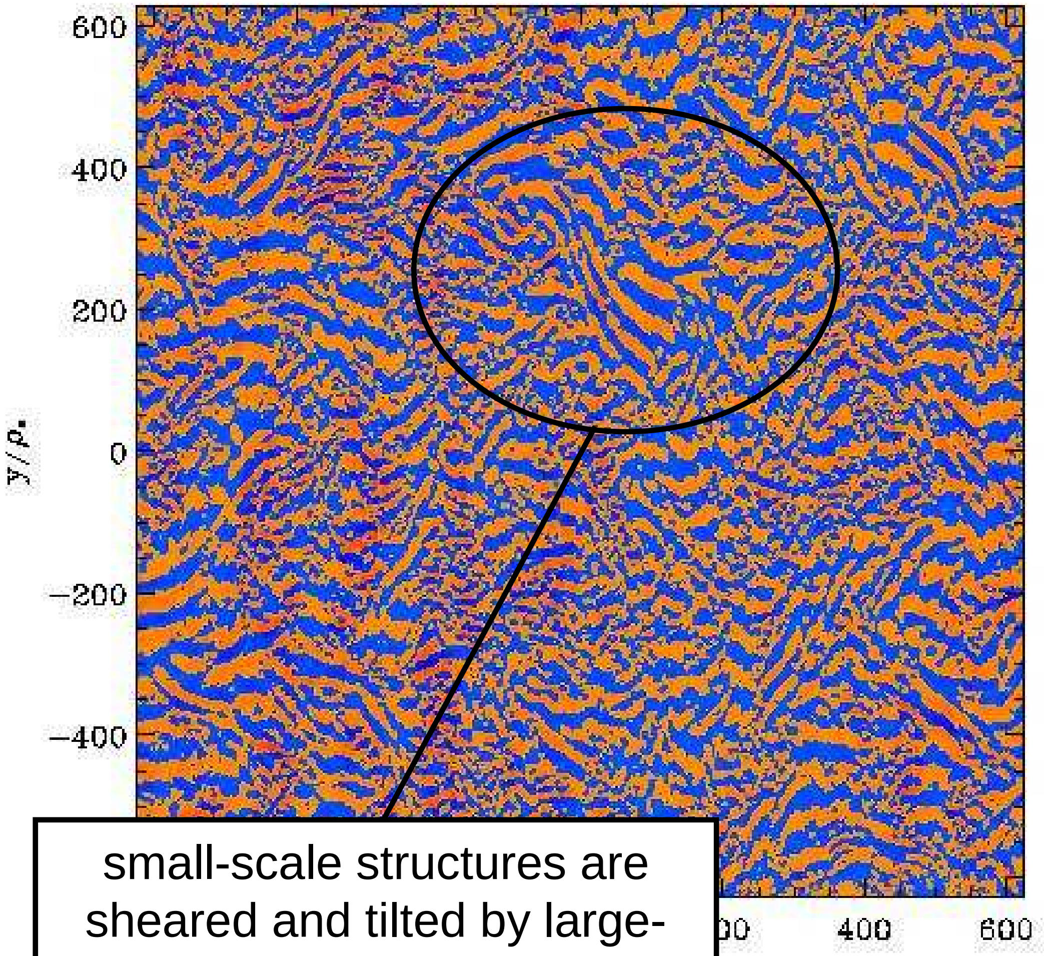


small-scale streamers are subject to large-scale vortex shearing



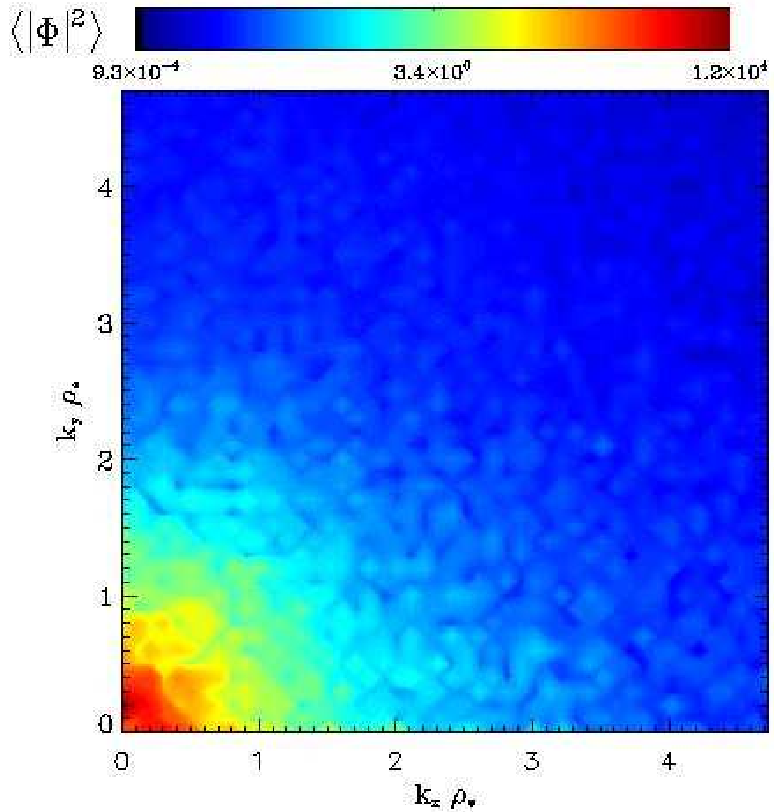
ITG/TEM-ETG turbulence (cont'd)

Filter: Set modes with $k_y \rho_s < 2$ to zero

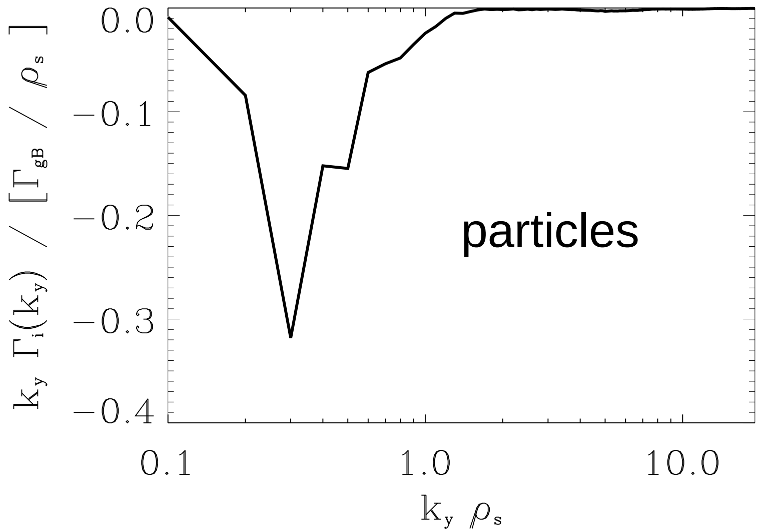


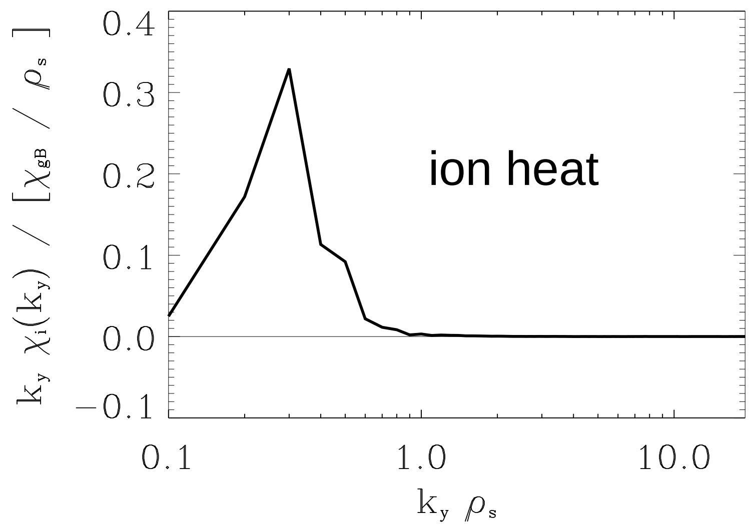
small-scale structures are sheared and tilted by large-scale vortices

Isotropic density spectrum



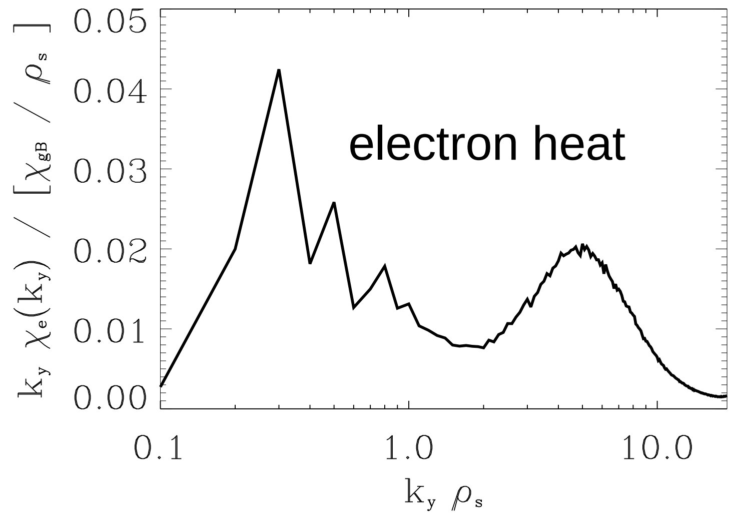
ITG/TEM-ETG turbulence (cont'd)





Ion heat flux is still too large, but > 50% of the *electron* heat transport is in the $k\rho_i$ > 0.5 regime

ETG even more pronounced in presence of ExB shear: NSTX



The role of magnetic geometry

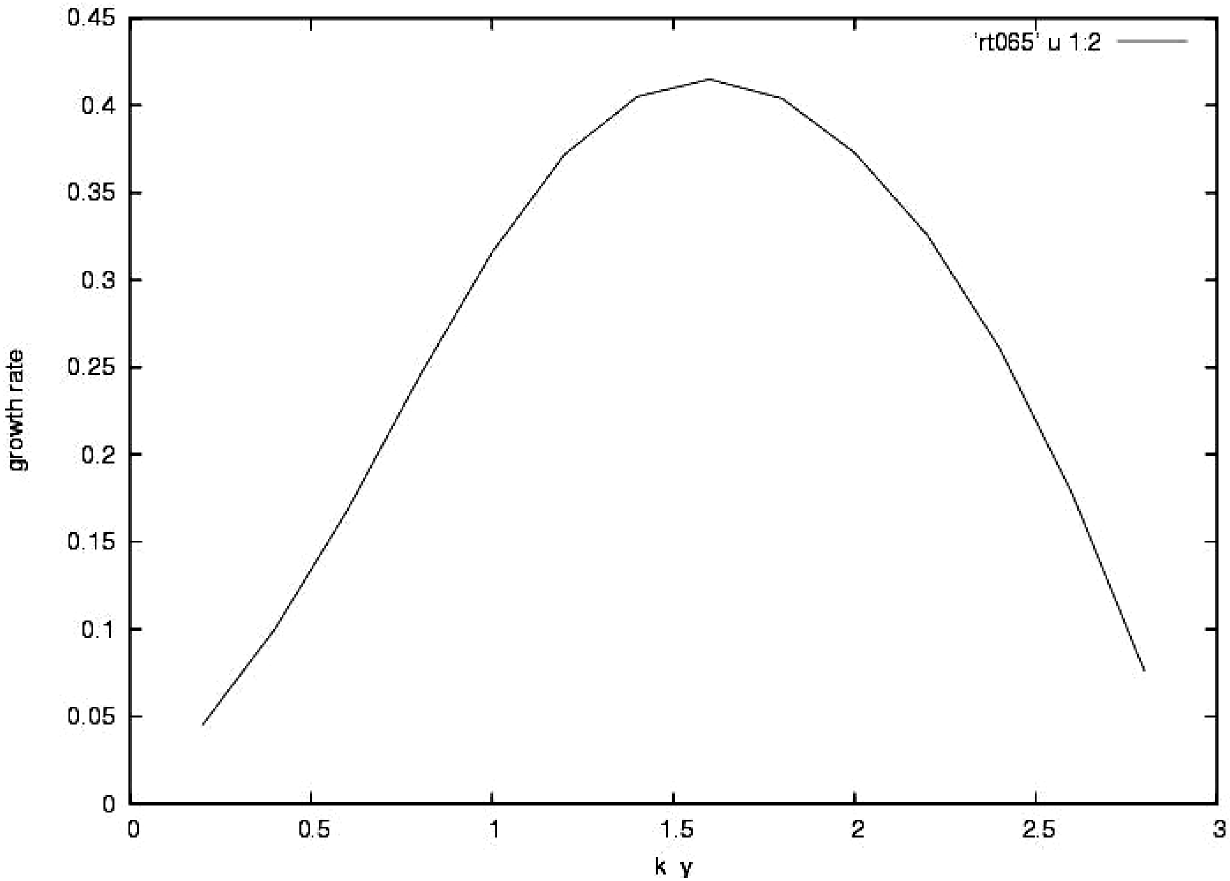
µtearing modes in the high-beta spherical tokamak NSTX

µtearing modes: A brief overview

- Finite beta modes with “tearing parity”; may induce substantial electron heat transport due to magnetic flutter
- First wave of theoretical papers in the 1970s and 1980s; have received renewed interest in the last few years
- Generally thought to be unimportant in (the core of) tokamaks, but found to be relevant in the core of NSTX (M. Redi *et al*.)
- Nonlinear simulations are extremely challenging, and even the linear properties are not yet fully understood
- Test case: NSTX #120967 (t=0.49s, r/a=0.65)

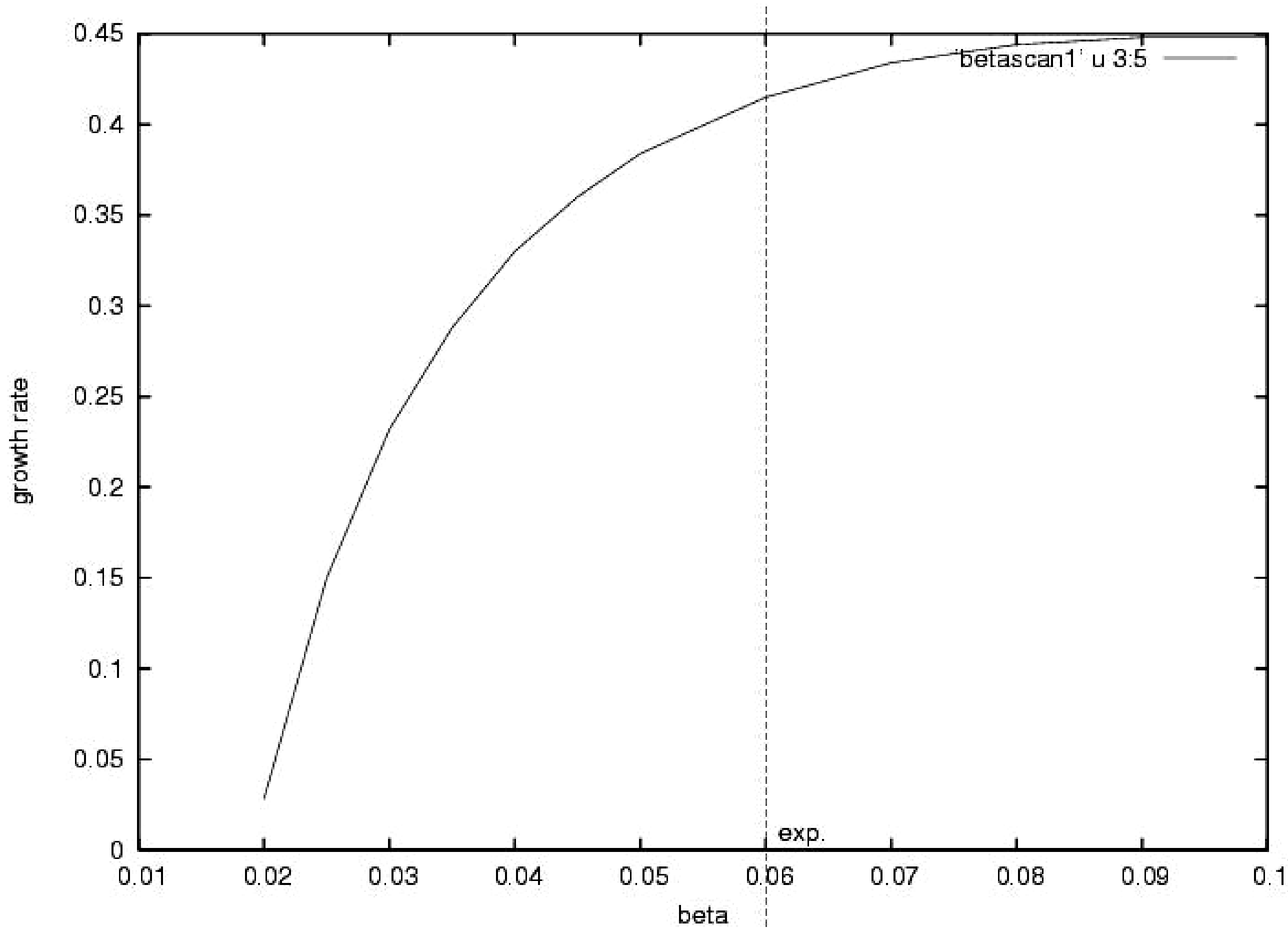
NSTX #120967 (t=0.49s, r/a=0.65)

Dominant microinstability: µtearing mode



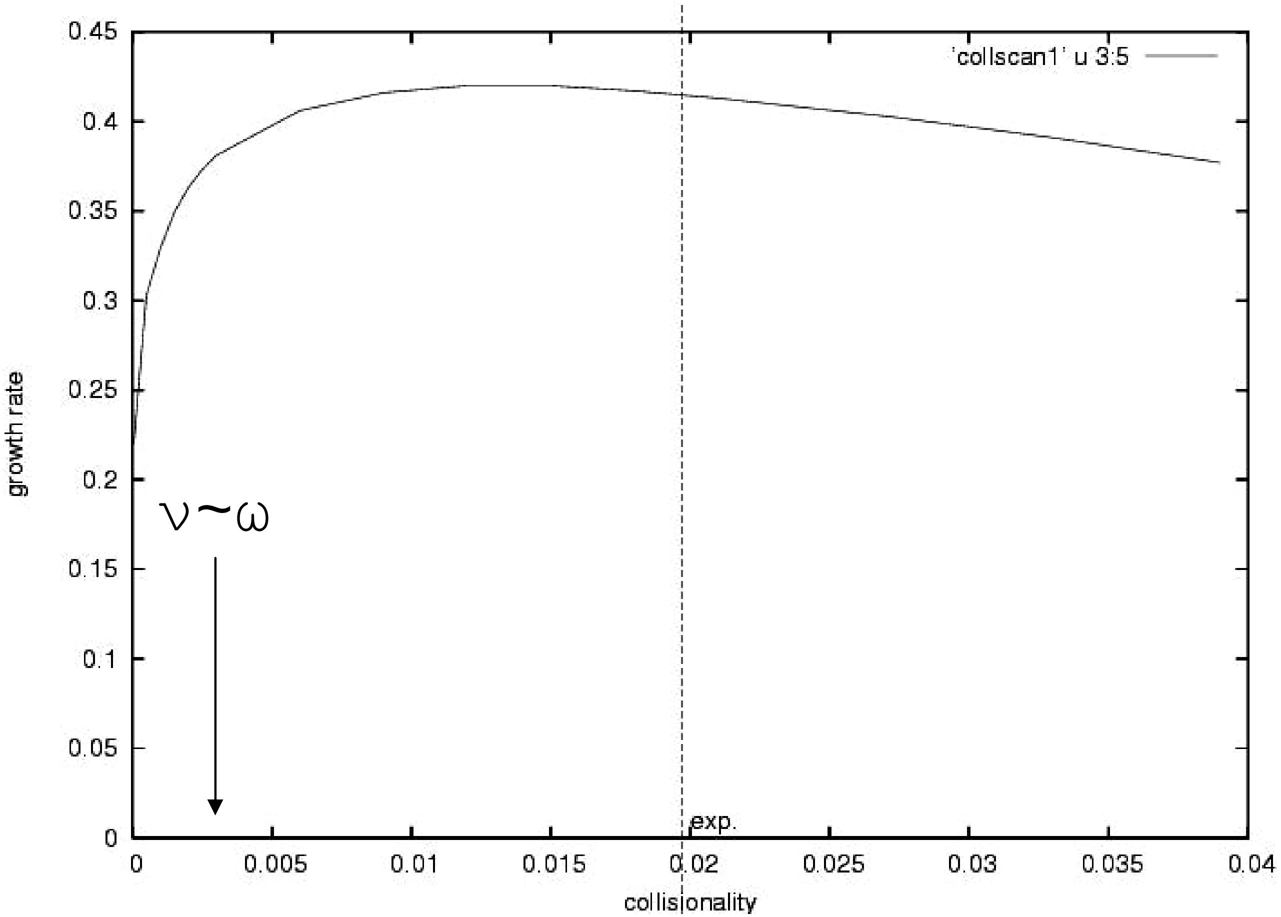
µtearing modes in NSTX: γ(β)

Critical beta value is exceeded by a factor of 3.



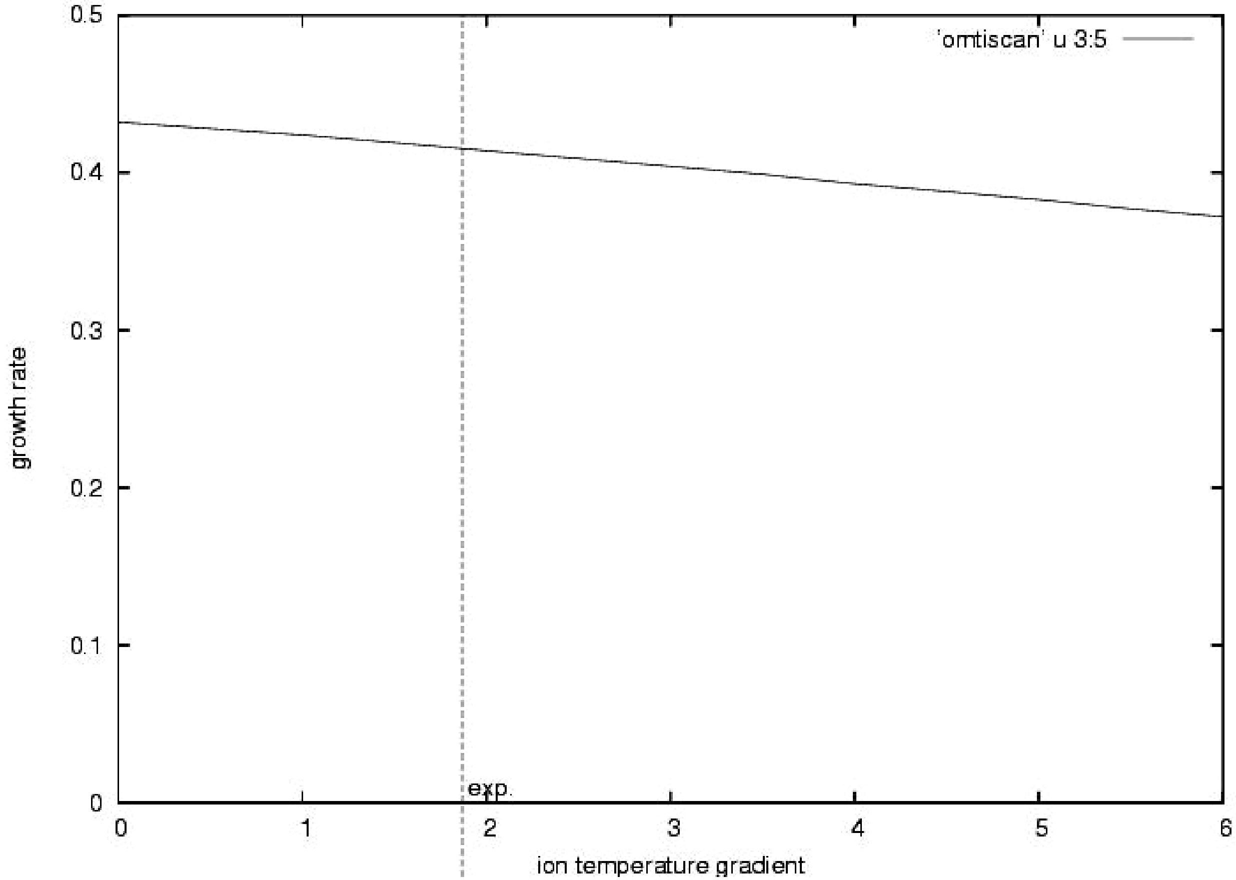
µtearing modes in NSTX: γ(ν)

The modes are deep in the collisional regime.



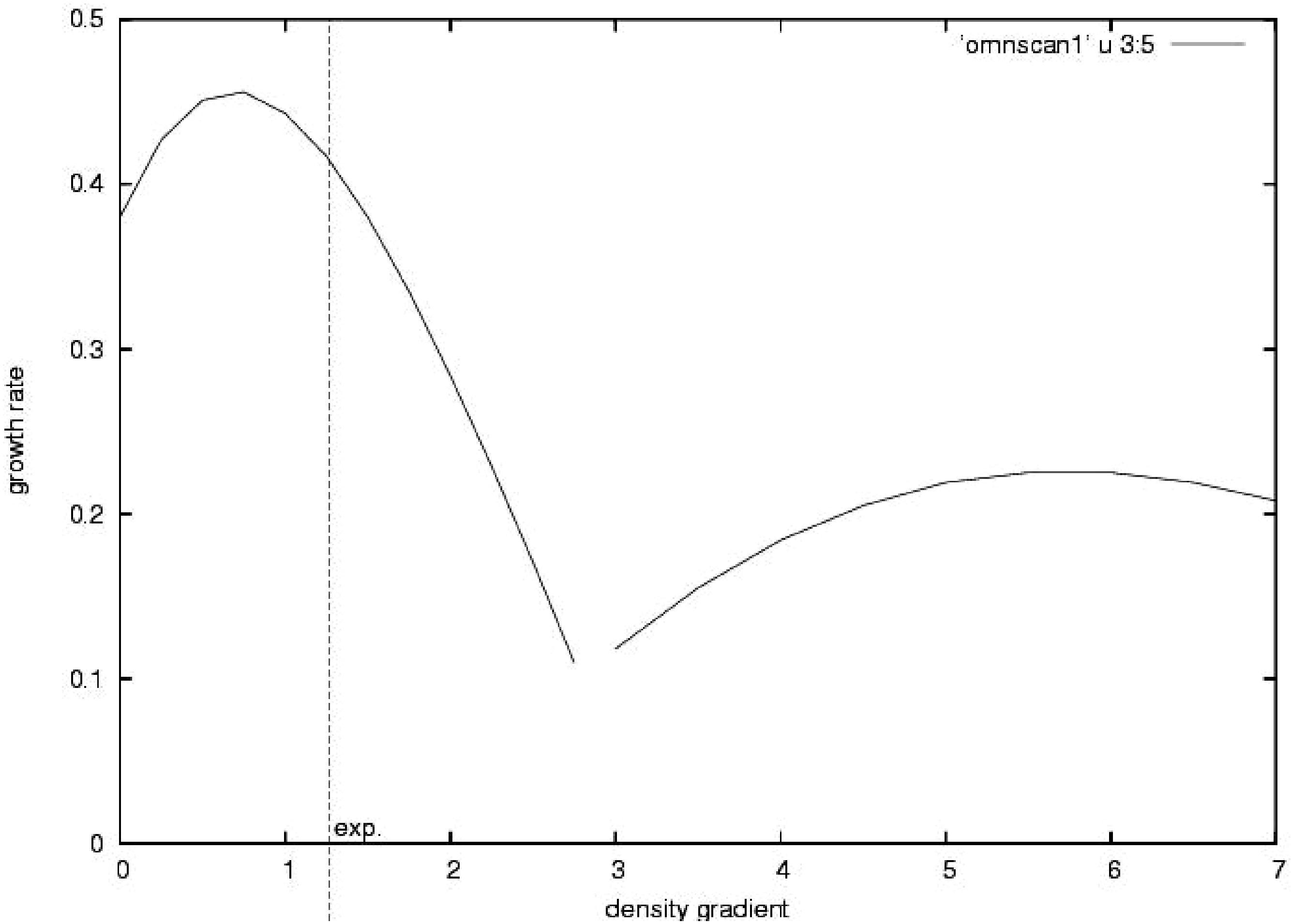
μtearing modes in NSTX: γ(R/LTi)

Weak dependence on the ion temperature gradient.



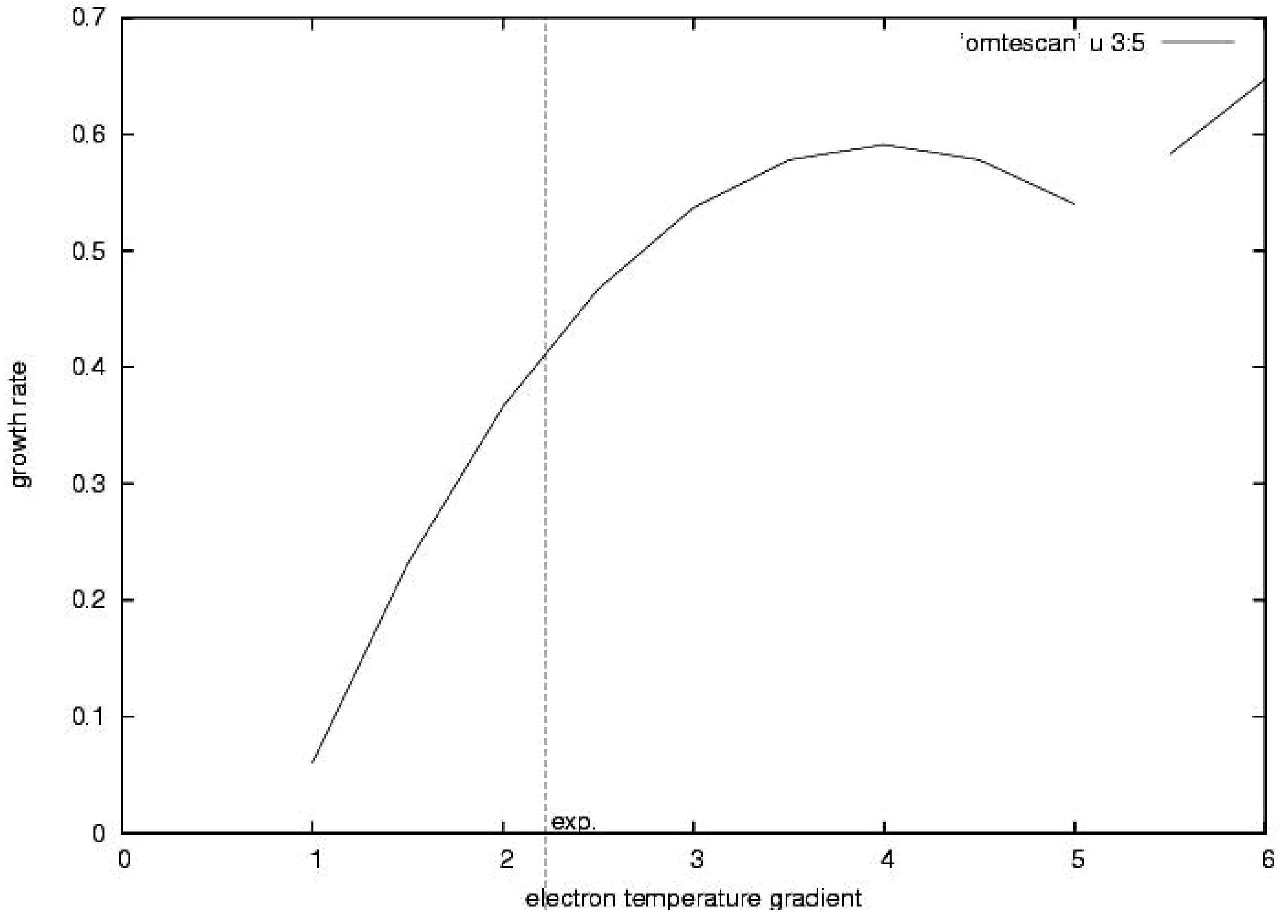
µtearing modes in NSTX: γ(R/Ln)

Density gradient dependence is rather complex.



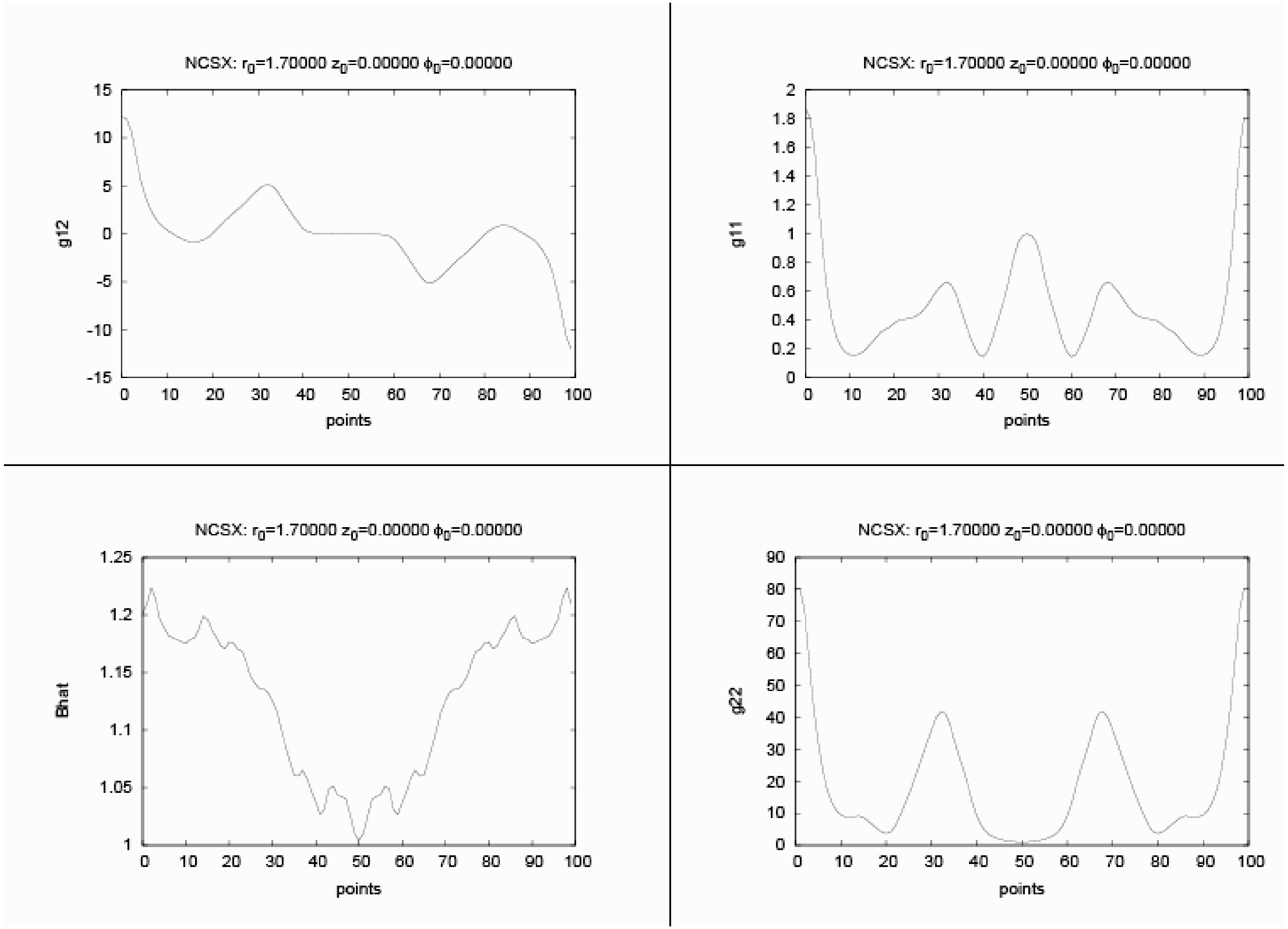
µtearing modes in NSTX: $\gamma(R/L_{Te})$

Critical electron temperature gradient is clearly exceeded.



Adiabatic ITG turbulence in the NCSX stellarator

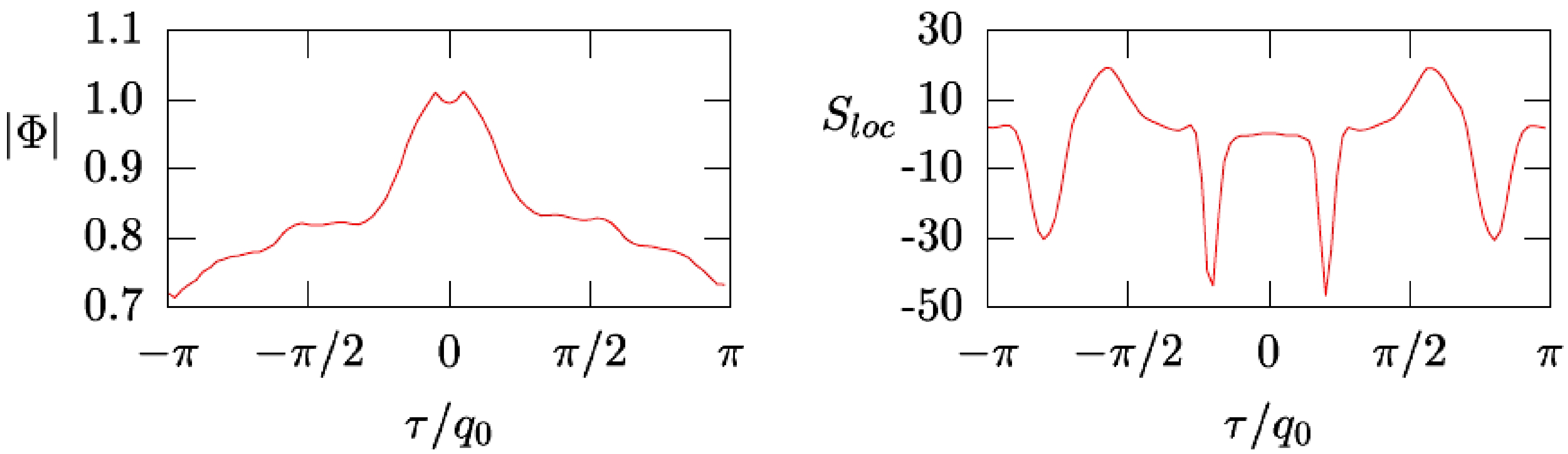
Geometric coefficients from TRACER



Nonlinear ITG parallel mode structure

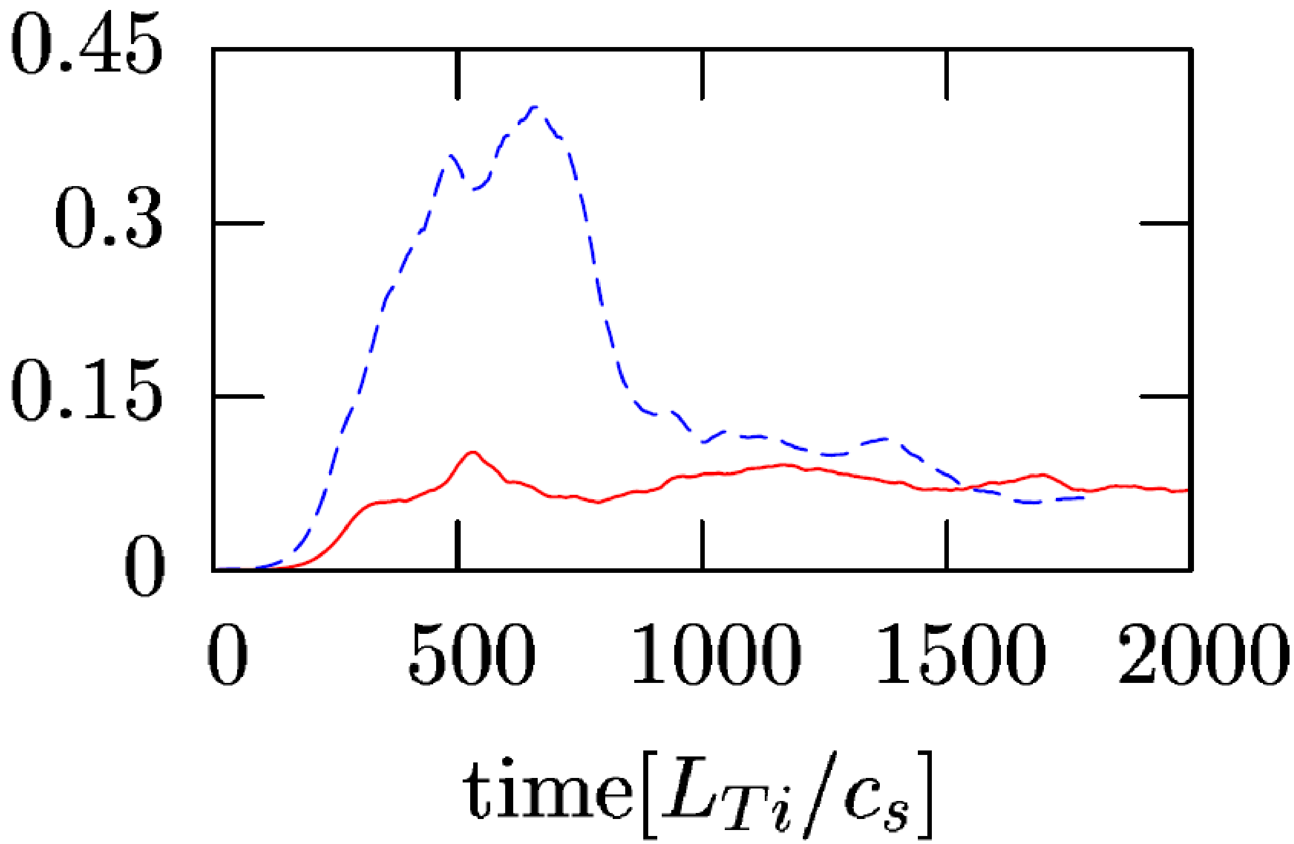
NCSX exhibits strong ballooning controlled by strong local shear regions

Example (*nonlinear* GENE simulation):



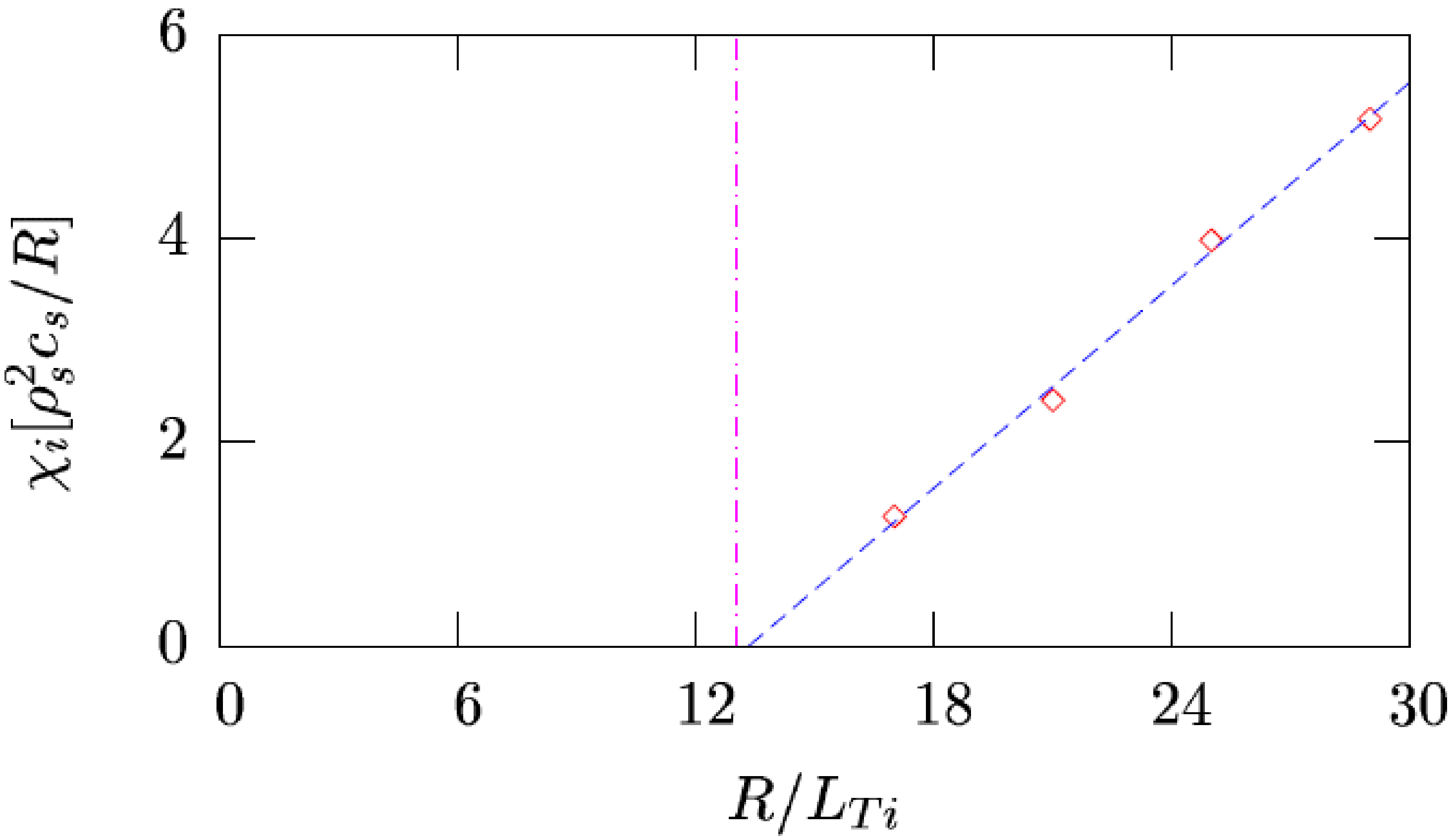
Zonal flow effects

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



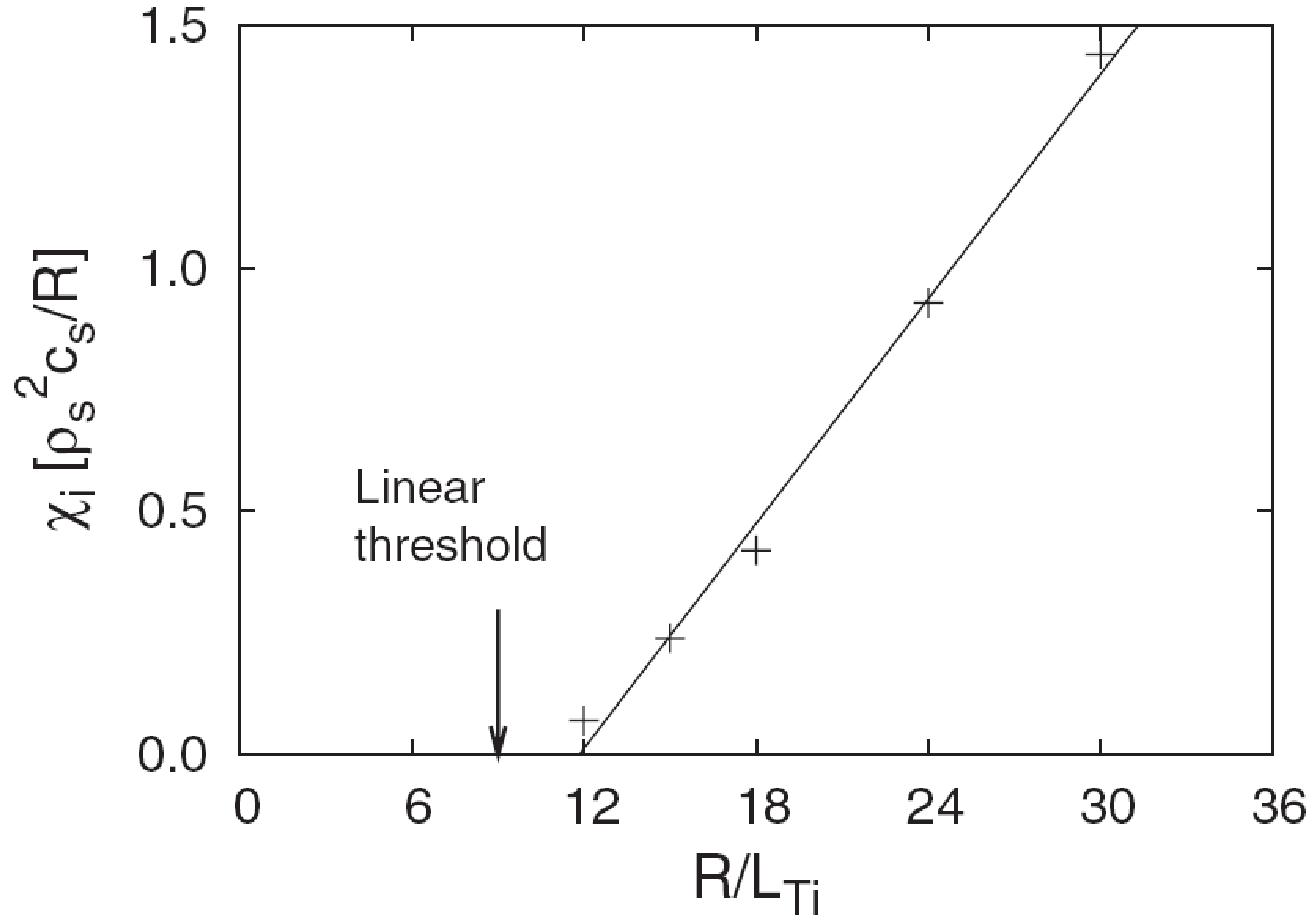
Flux-gradient relationship (adiabatic ITG modes)

- Offset-linear scaling for χ – not Q
- Moderate transport levels (profile stiffness)
- No Dimits shift, but large threshold



Comparison: ITG turbulence in W7-X

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



Conclusions

Our theoretical understanding of plasma microturbulence is still rather fragmentary, and the adiabatic ITG scenario is not universal

GENE simulations show:

- Nonlinear TEM saturation due to perpendicular particle diffusion: F. Merz and F. Jenko, PRL **100**, 035005 (2008)
- Coexistence with ITG modes only in a transitional regime; significant nonlinear, TEM-induced upshift of critical R/L_{Ti}
- Scale separation between ion and electron heat transport for realistic plasma parameters
- Interesting magnetic geometry effects (e.g., NSTX, NCSX)

More information and papers:

www.ipp.mpg.de/~fsj