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# On the Nature of Plasma Core Turbulence.

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# On the Nature of Plasma Core Turbulence

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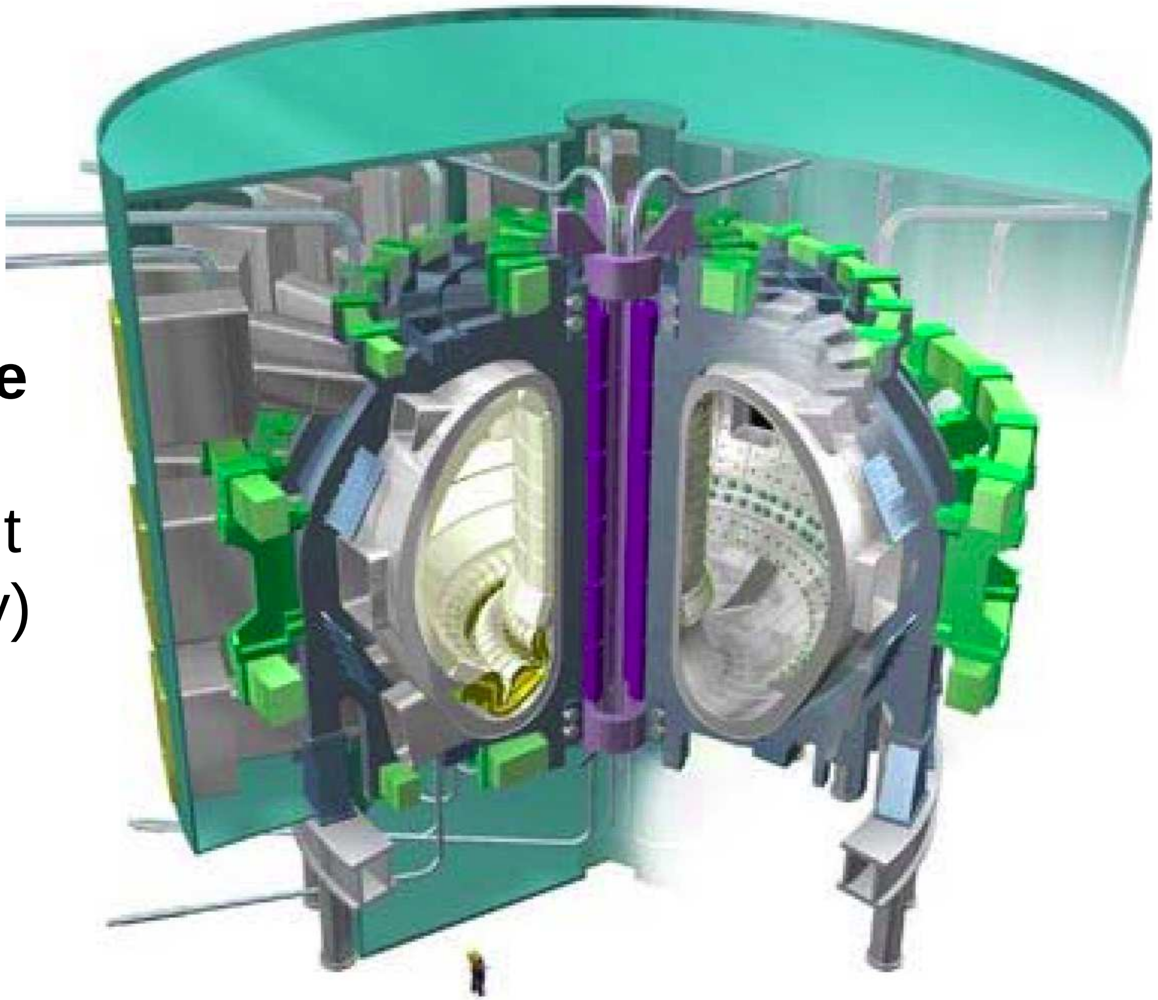
Acknowledgements:
F. Merz, T. Görler

ICTP Trieste, 23 July 2008

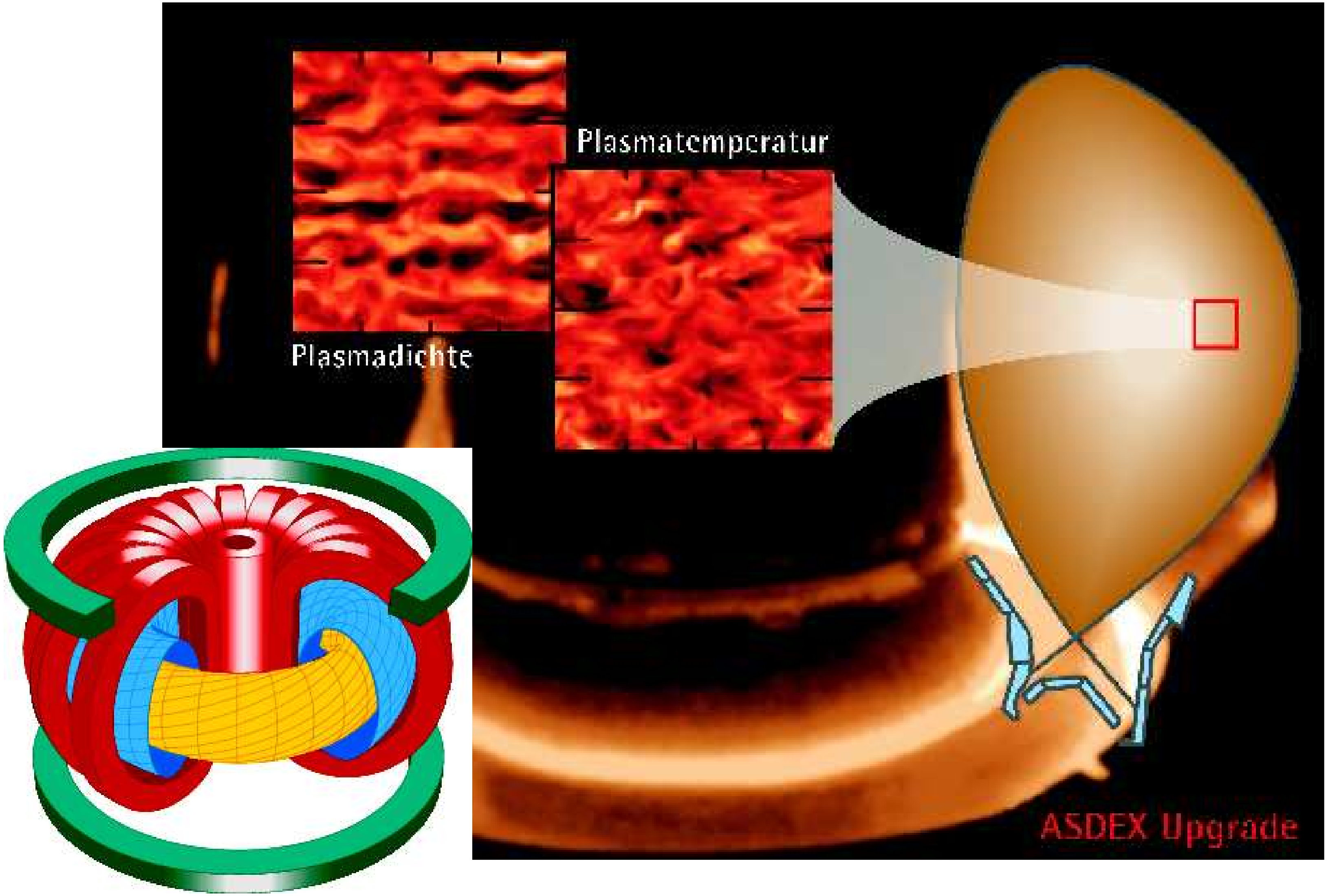
# The next step for magnetic fusion: ITER

**Plasma turbulence** will determine the energy confinement time (and efficiency) of ITER



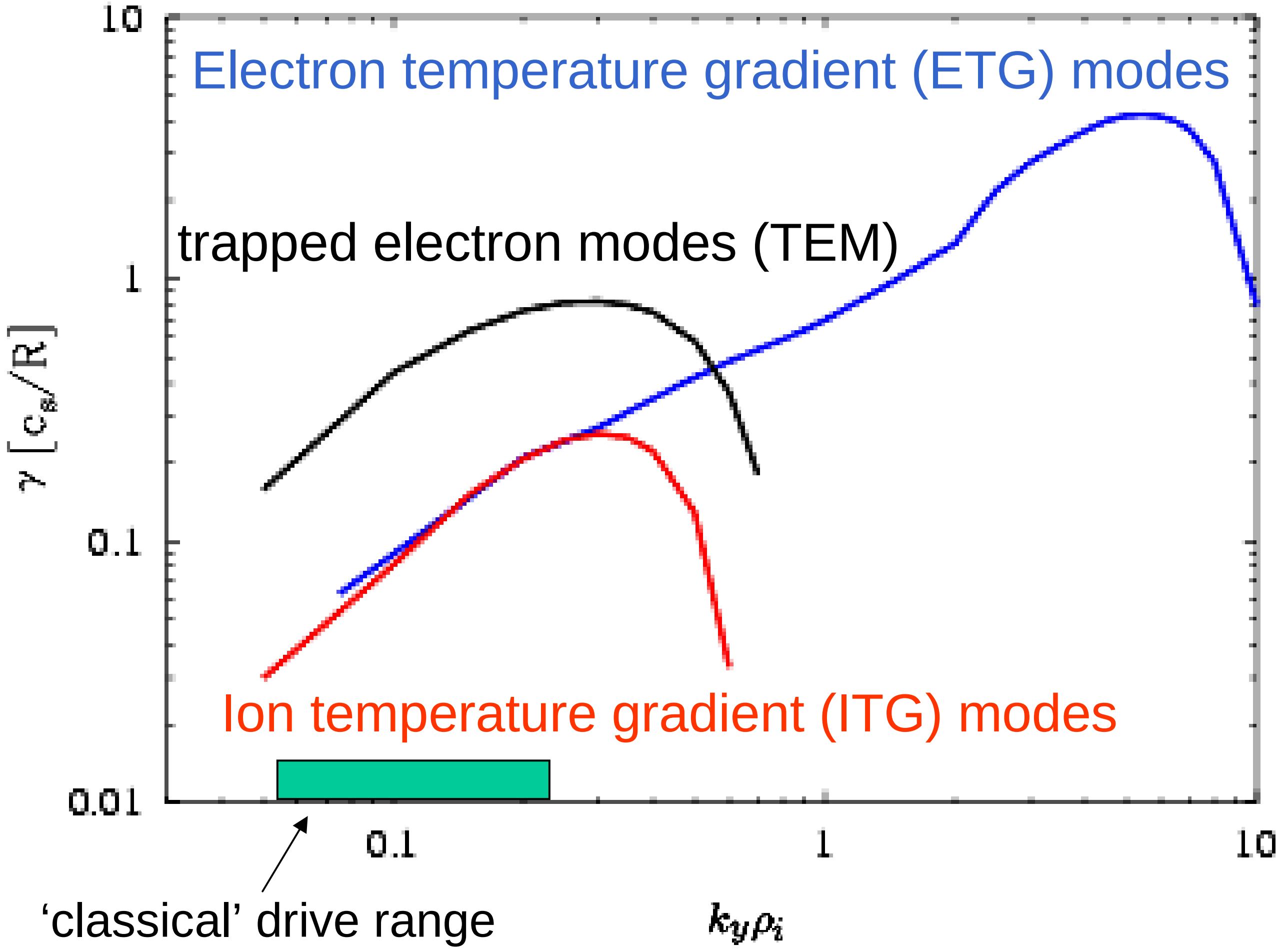
www.iter.org

# Turbulent mixing in a tokamak



gradients → microinstabilities → fluctuations → transport

# Plasma turbulence is driven by different kinds of linear microinstabilities



‘classical’ drive range

Central importance:

**drive (= transport) range** – rather than the inertial range

The drive range may extend over 2-3 orders of magnitude

DR physics is itself a **multiscale problem**

# Exceptional points

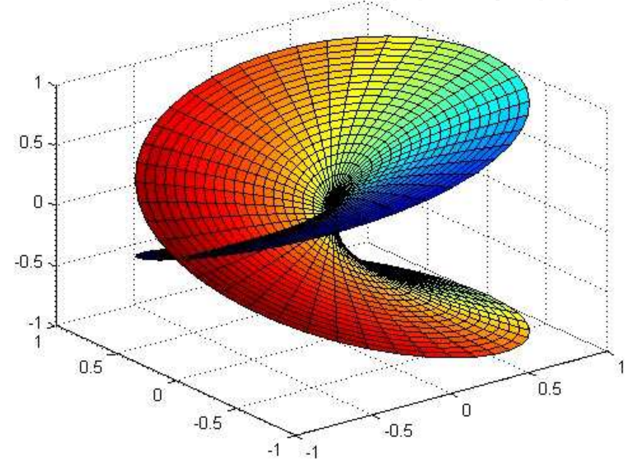
Different microinstabilites (usually considered as separated) can be transformed into each other via continuous parameter changes.

The non-Hermiticity of the linear gyrokinetic operator leads to *Exceptional Points*.

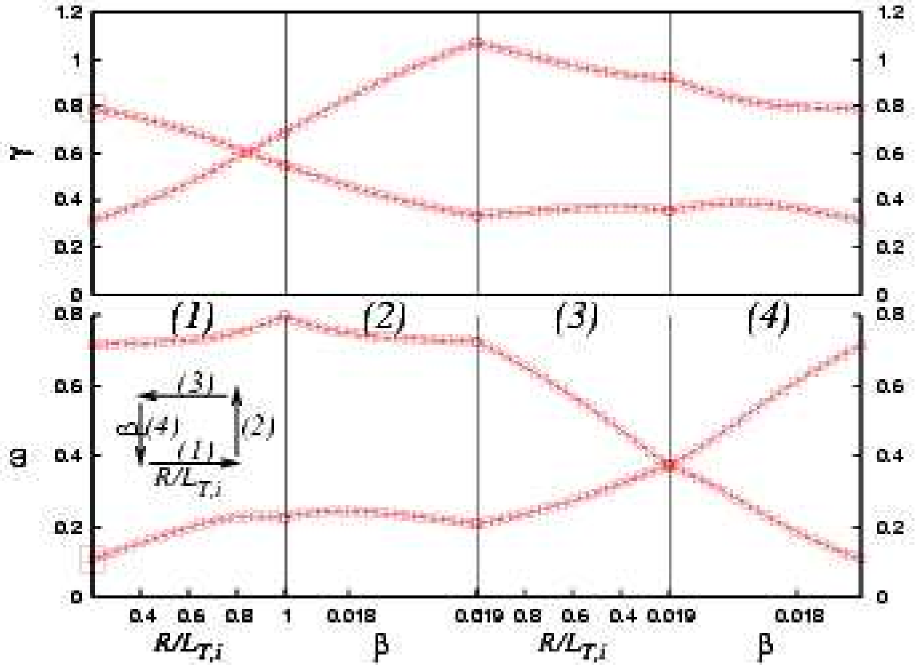
Here, both eigenvalues *and* eigenvectors are identical.

Similar: quantum physics etc.

Riemann surface of f(z)=sqrt(z)



Kammerer, Merz & Jenko, PoP 2008



# Turbulent transport and structures

## ExB drift velocity

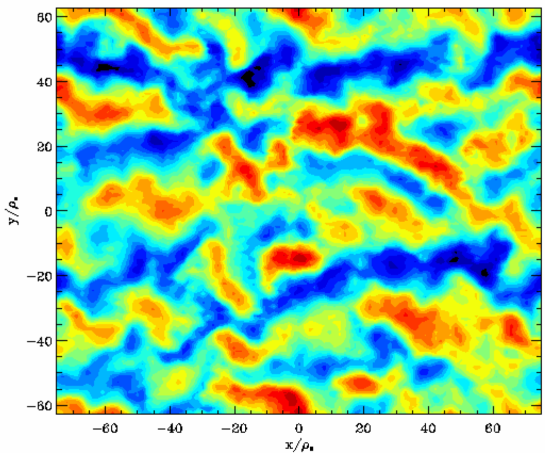
$$\tilde{\mathbf{v}}_E = \frac{c}{B^2}\mathbf{B}\times\nabla\tilde{\phi}$$

$$\mathbf{Q} \equiv \frac{3}{2}\langle\tilde{p}\,\tilde{\mathbf{v}}_E\rangle = -n\chi\nabla T$$

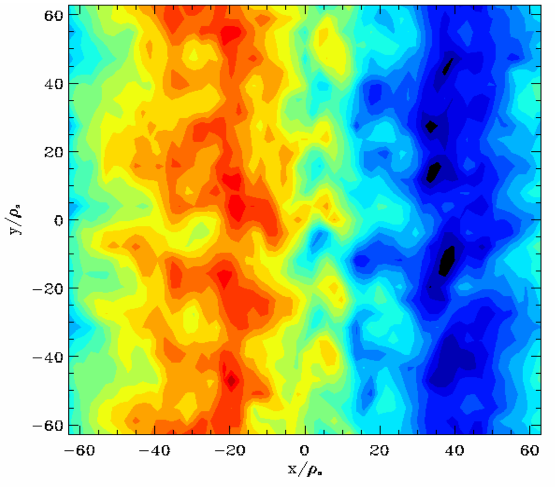
$$\chi \sim \frac{(\delta x)^2}{\delta t} \sim \frac{\rho^2 v_t}{L_T}$$

(random walk/mixing length estimates)

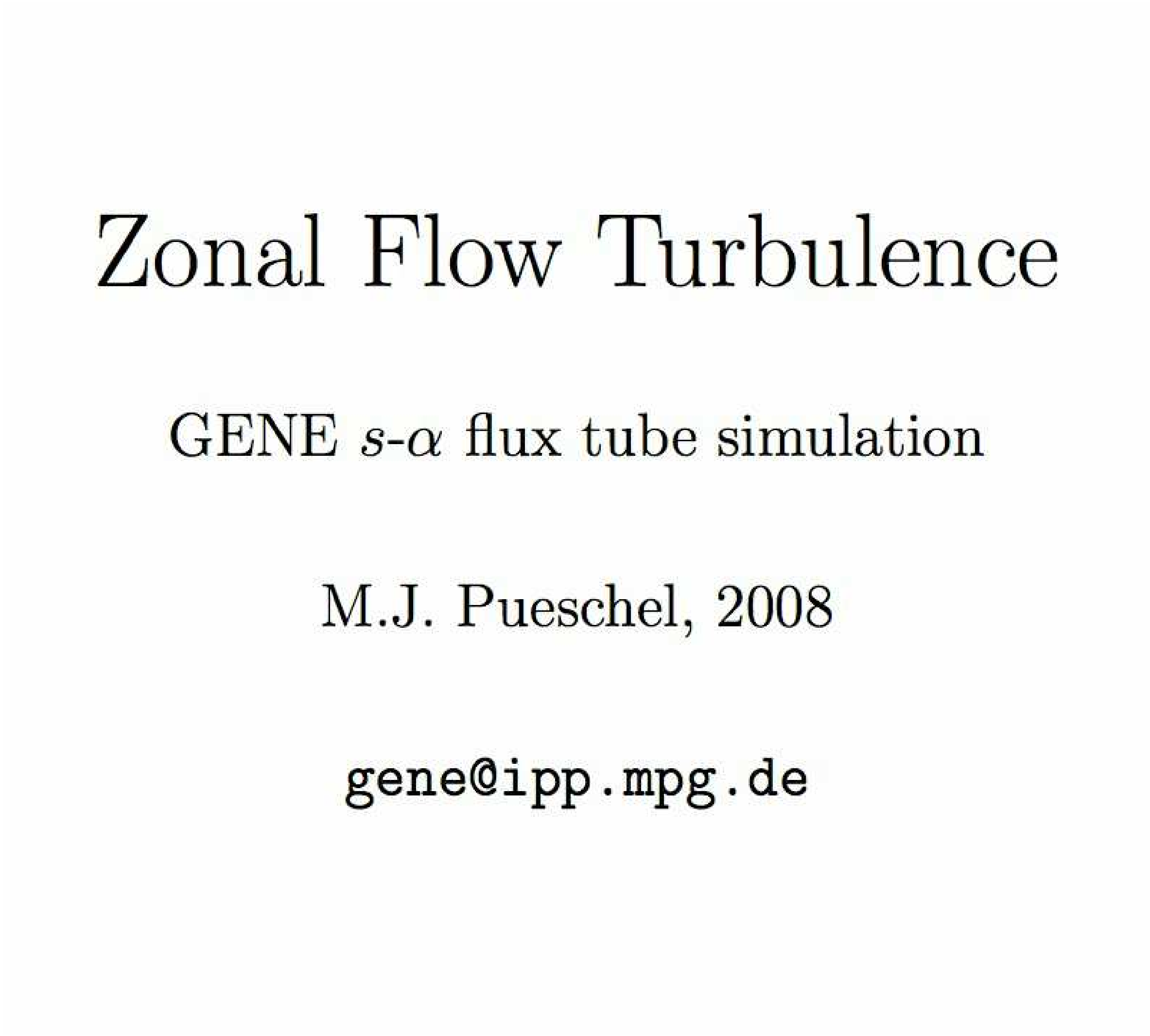
Streamers
(ETG,TEM)



Zonal flows
(ITG)



# Saturation of ITG modes: zonal flows



Zonal Flow Turbulence

GENE $s$-$\alpha$ flux tube simulation

M.J. Pueschel, 2008

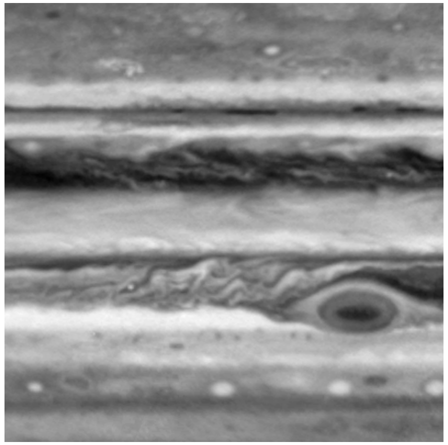
gene@ipp.mpg.de

**Structure formation**

Emergence of **zonal ExB flows** (due to symmetry breaking!)

They are linearly neutrally stable but excited nonlinearly

Zonal flows in geo-/astrophysics



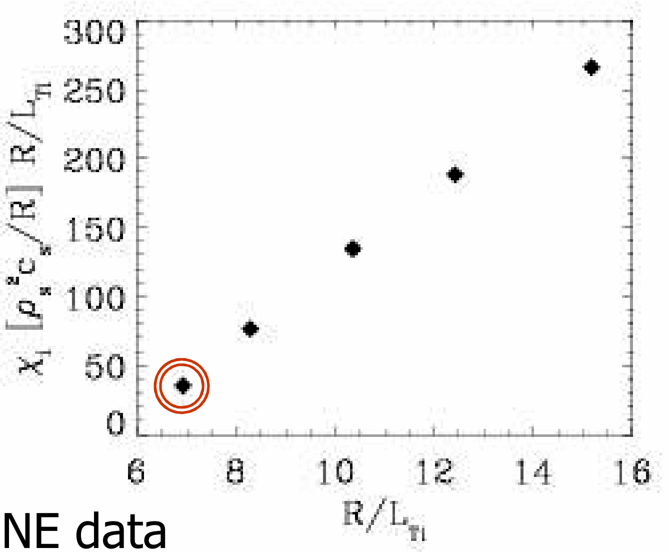
**Effect on turbulent transport**

Zonal flows may reduce or even suppress the turbulent transport

# 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?

# The remainder of this talk

- The tool: GENE

- The nature of (pure) TEM turbulence

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

- Nonlinear ITG-TEM-ETG interactions

  T. Görler & F. Jenko, PRL **100**, 185002 (2008)

# The nonlinear gyrokinetic equations

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

## Advection/Conservation equation

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

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

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

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

**X** = gyrocenter position
$v_\parallel$ = parallel velocity
μ = magnetic moment

## Appropriate field equations

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

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

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

# 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

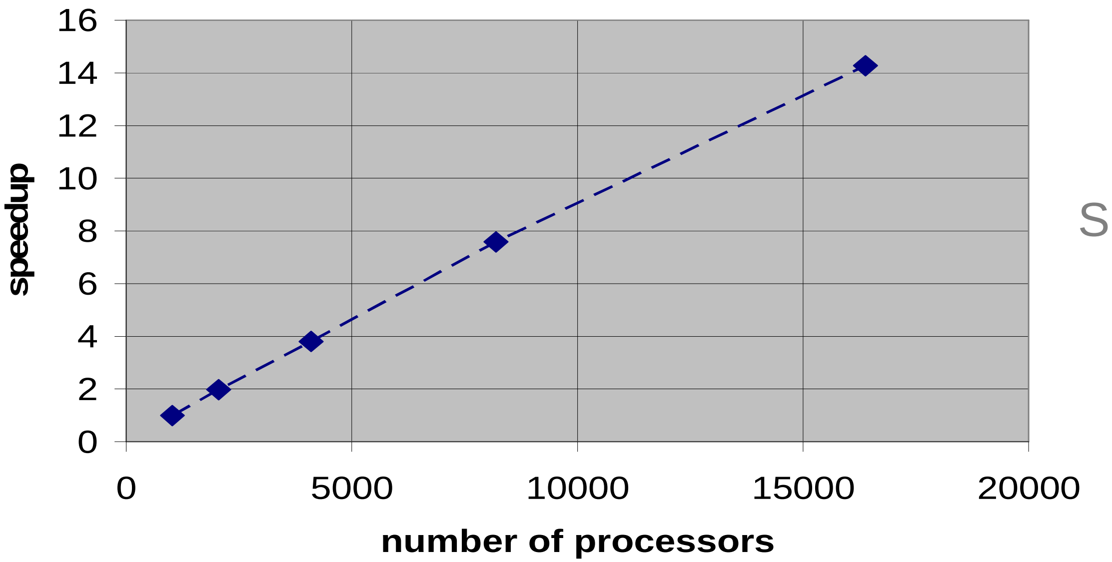
- Collisions between any pair of species are kept
- Pitch angle scattering *and* energy scattering are retained
- Momentum and energy conserving terms are implemented

## General geometry

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

# 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

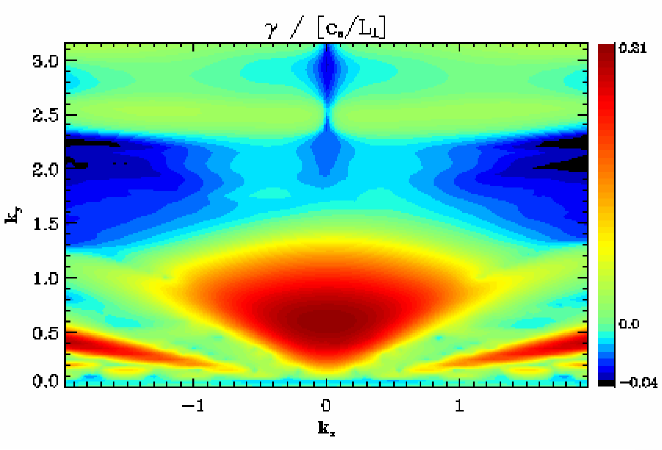
**Strong scaling (fixed problem size) – from 1k to 16k cores**

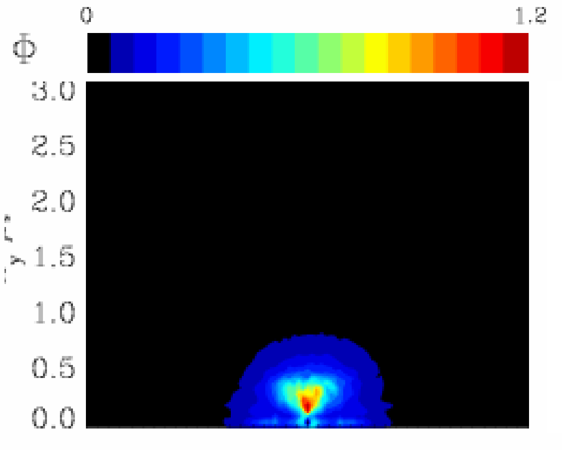
# The nature of (pure) TEM turbulence

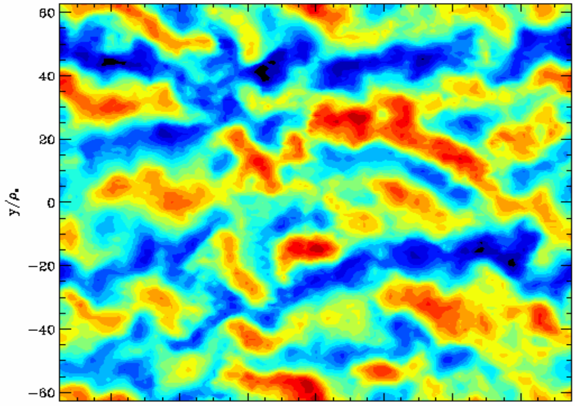
# Characteristics of TEM turbulence

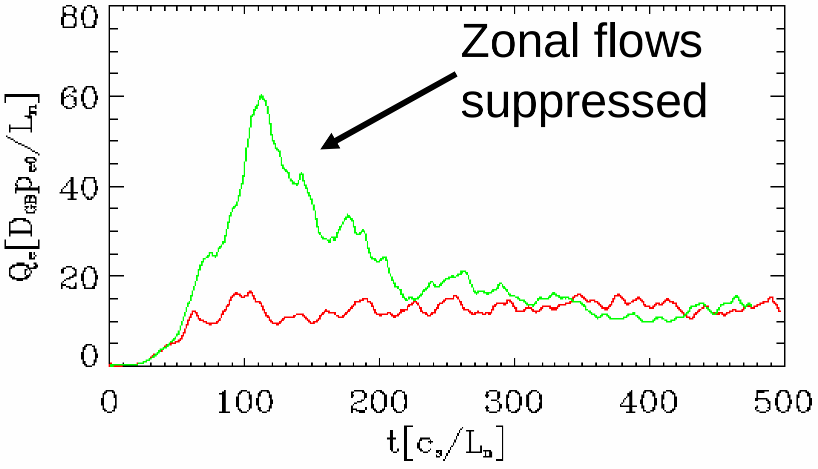
In the saturated phase, TEM turbulence often exhibits:

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









Zonal flows suppressed

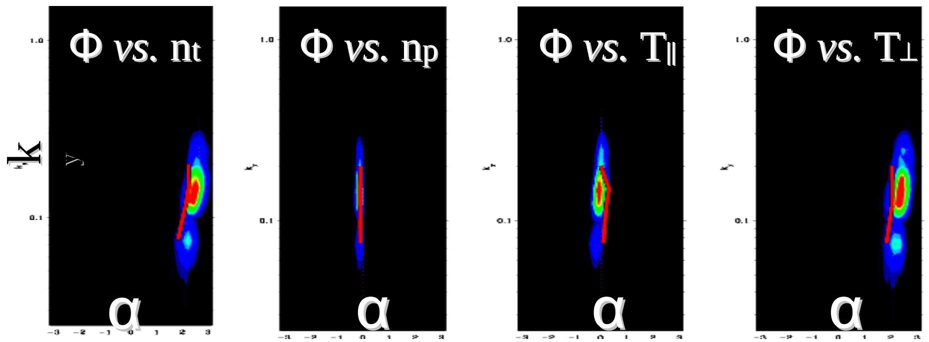
- no dependence of transport level on (intrinsically nonlinear) zonal flows

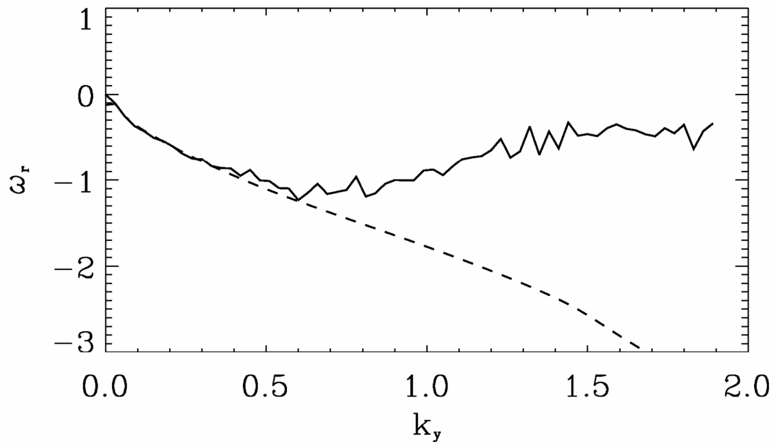
  [Dannert & Jenko, PoP 2005]

# 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?

# Quasilinear ansatz

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

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

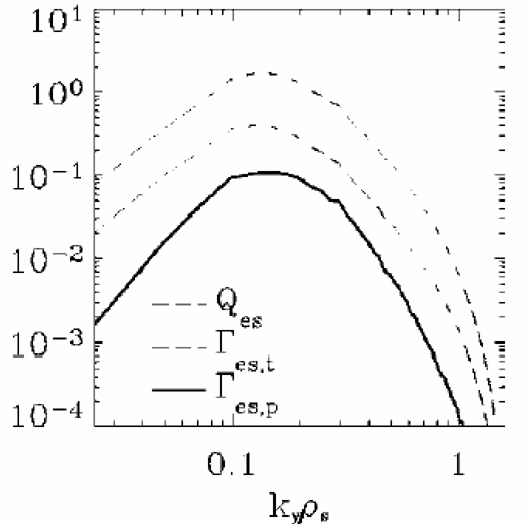
- $\mathcal{N}l[g]$ and $g$ are fluctuating quantities; to get an estimate for the complex proportionality constant $X=X(k_x,k_y,z,spec)$, we minimize the model error $\langle|\mathcal{N}[g] - \mathcal{X}g|^2\rangle$

- 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)

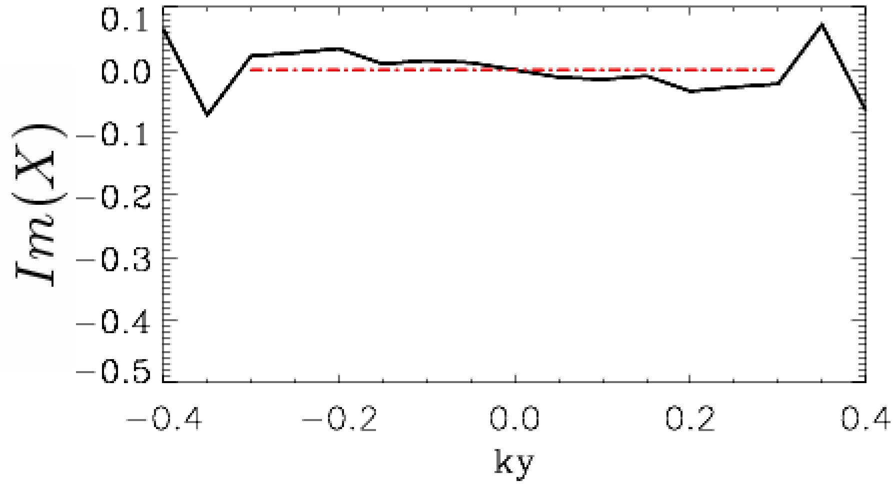
# Transport relevant ky range

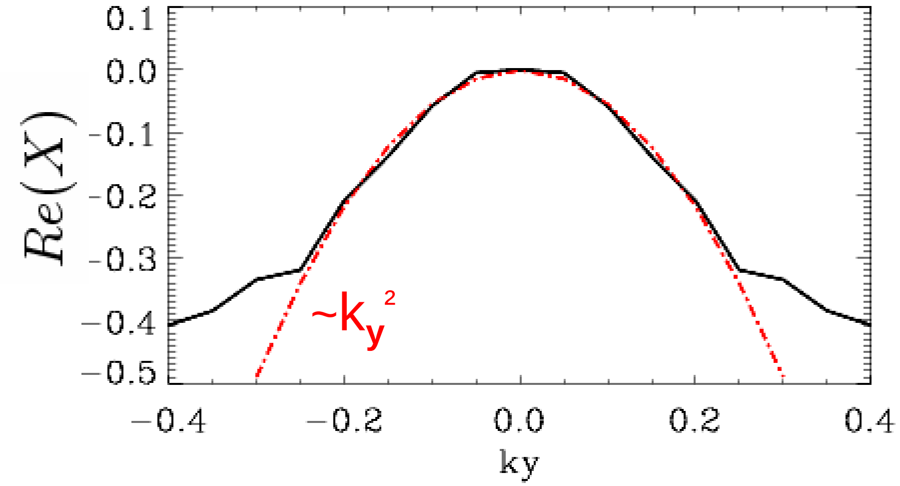
- The ky range where fluctuations are small coincides with the ky range relevant for transport



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

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

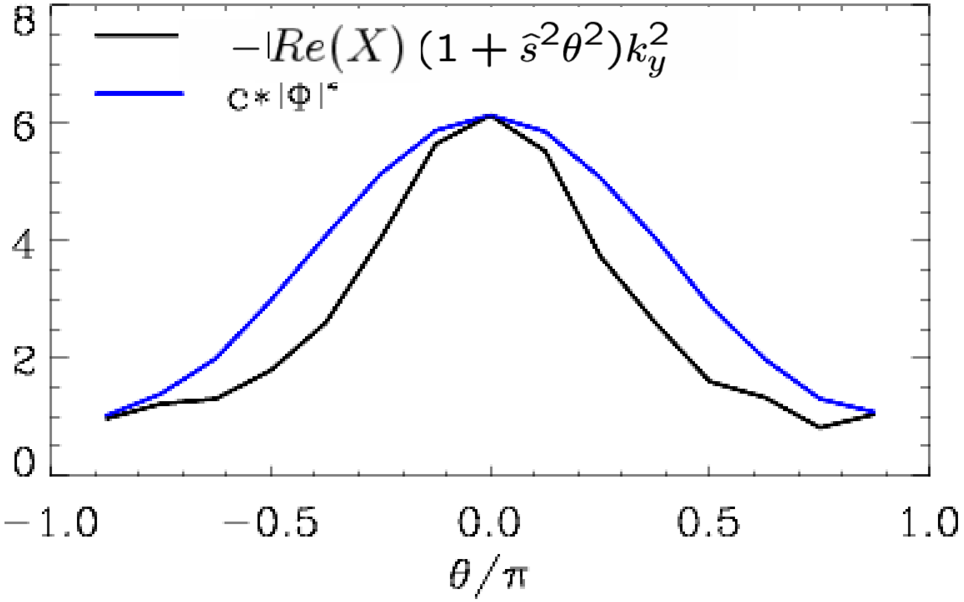




Cp. Resonance Broadening Theory (Dupree), MSR formalism (Krommes), Dressed Test Mode Approach (Itoh) in long wavelength, low frequency limit

# Parallel structure of diffusivity

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



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

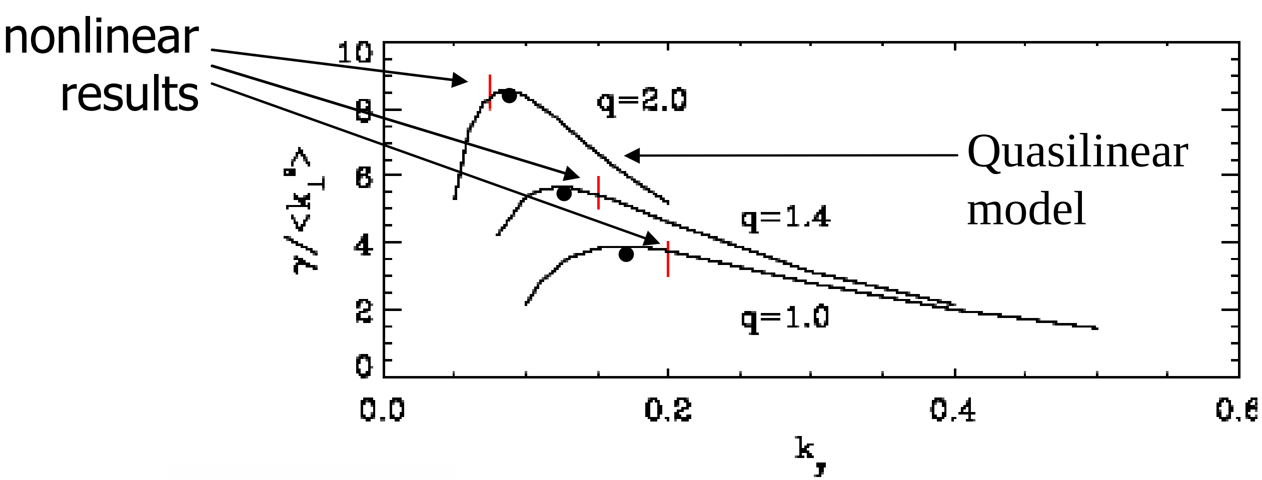
- Quasilinear equation: $\frac{\partial g}{\partial t} = \mathcal{L}g + \mathcal{N}l[g] \simeq (i\omega_r + \gamma - D_0 \langle k_\perp^2 \rangle)g$

- 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

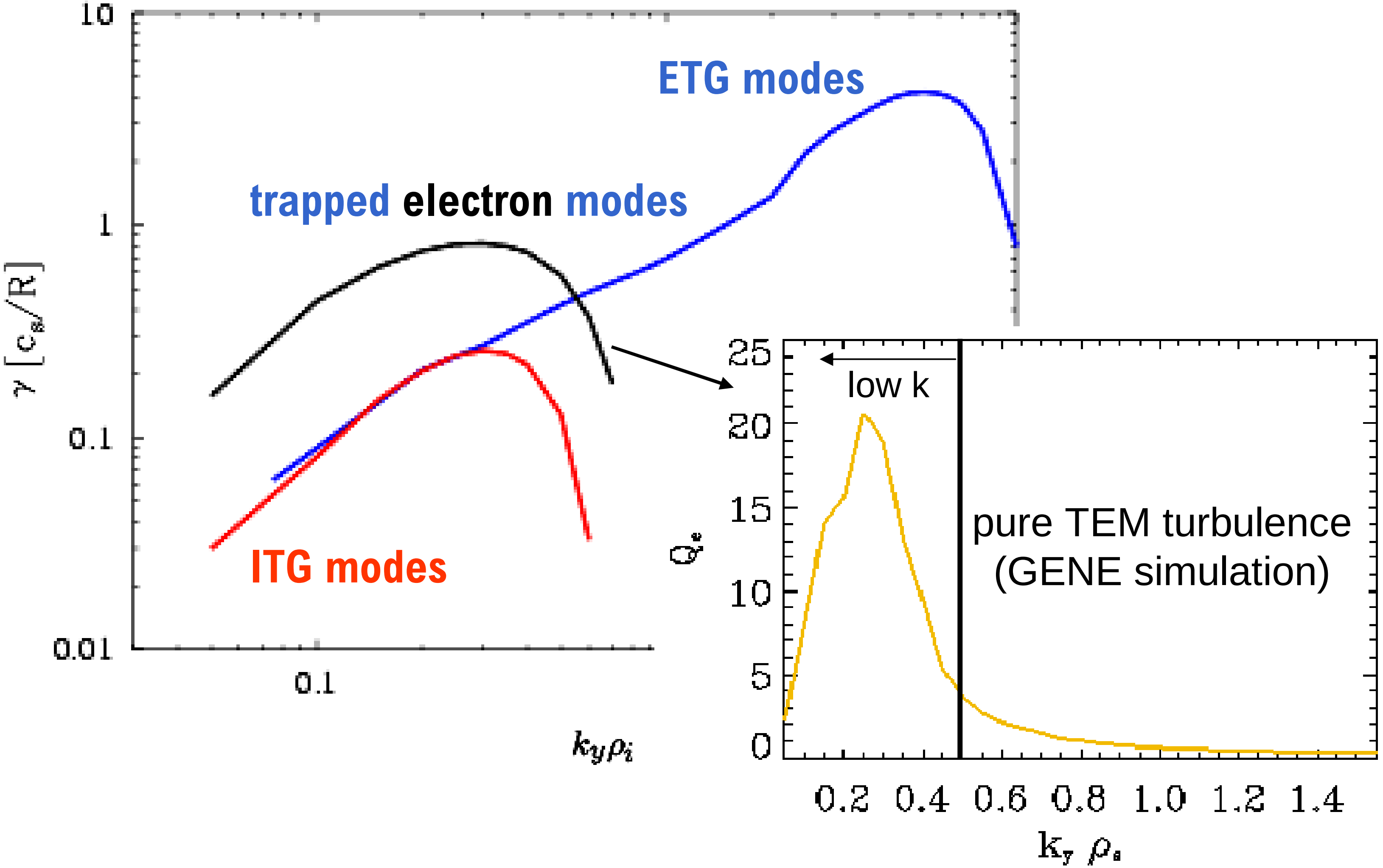


[Jenko & Dannert ‘05]

- 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 ($\nu = 1-2$ )

# Nonlinear ITG-TEM-ETG interactions

# Plasma microturbulence: Multiple scales



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

# A brief history of high-k turbulence simulations

## (Pure) ETG turbulence can induce significant electron heat transport:

$\boxed{\chi_e^{\mathrm{ETG}} \gg \frac{\rho_e^2 v_{te}}{L_{T_e}} \text{ is possible}}$ (Jenko, Dorland, Rogers & Kotschenreuther, PoP/PRL 2000)

For comparison: $\chi_i^{\mathrm{ITG}} \approx 0.7 \frac{\rho_s^2 c_s}{L_{T_i}}$ (Cyclone base case)

Confirmed, e.g., by (Idomura *et al*., NF 2005), (Nevins *et al.*, PoP 2006), and (Bottino *et al.*, PoP 2007)

## ETG turbulence in concert with longer wavelengths (ITG, TEM, etc.):

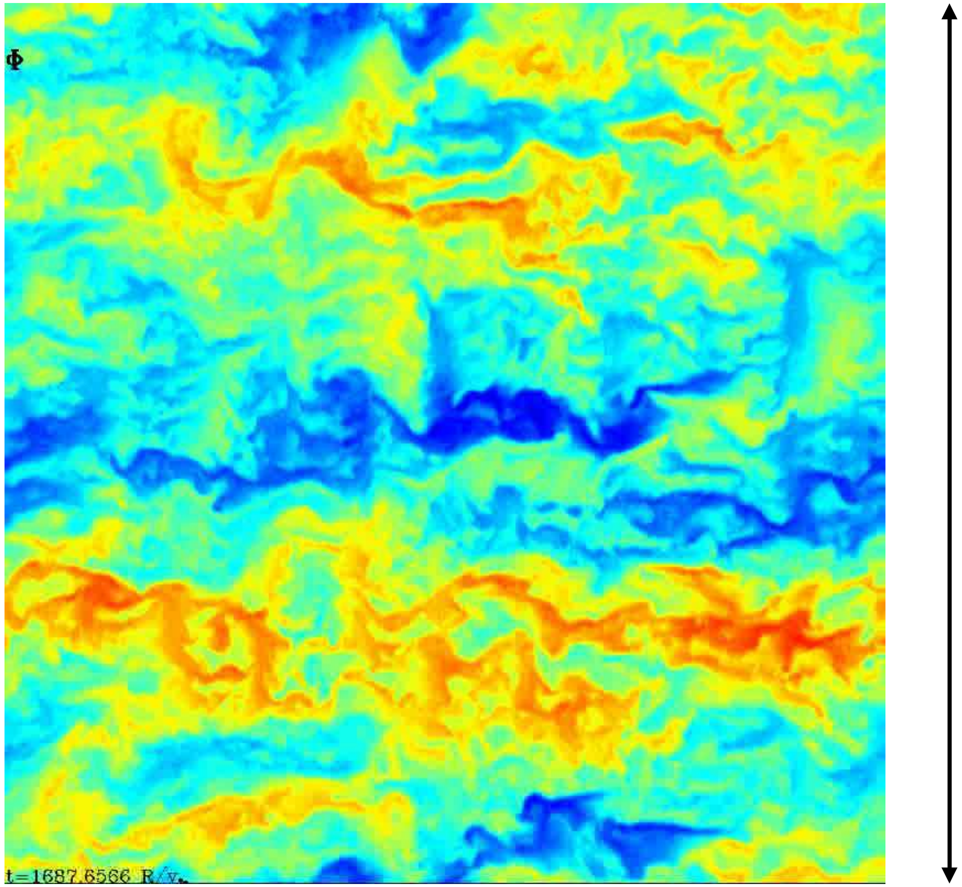
First gyrokinetic multiscale simulations (with GENE): Transport in the tokamak edge (Jenko, J Plasma Fus Res 2004)

Recently: Similar work for core parameters by Candy and Waltz

# TEM-ETG turbulence (Φ contours)

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

Case I: ITG is turned off



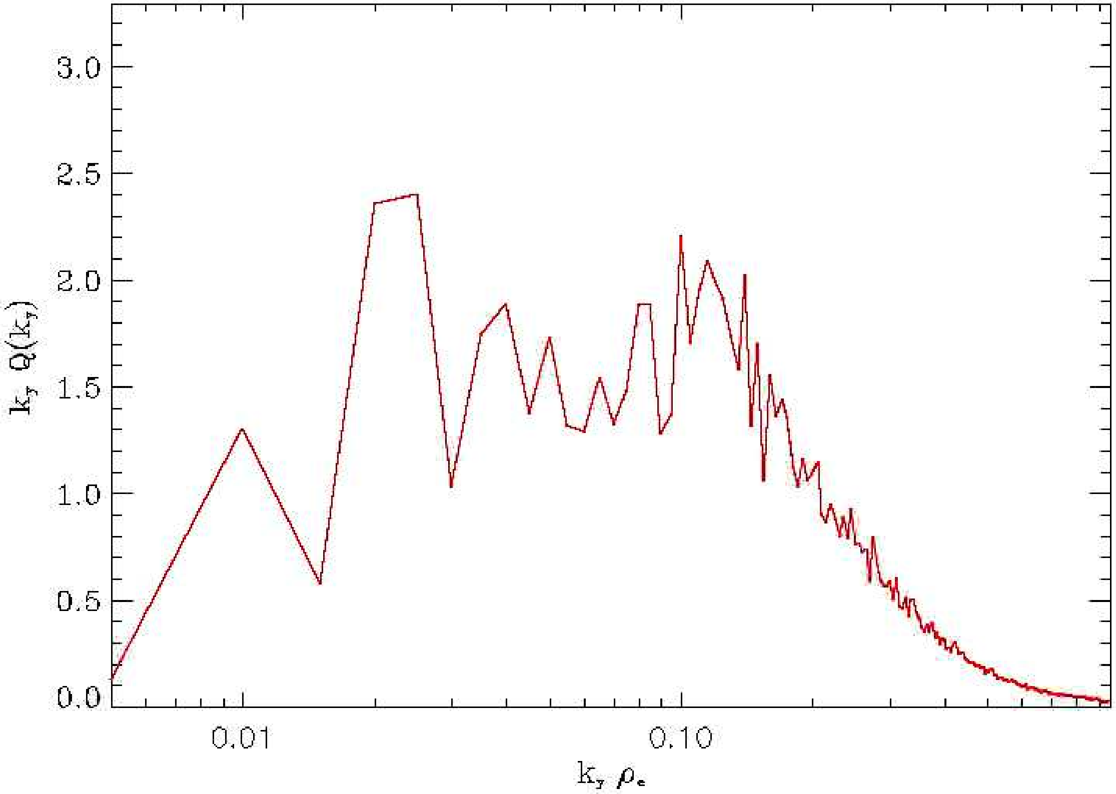
~ 100,000 CPUh / run

box size:
64 ion gyroradii

resolution:
~2 electron gyroradii

ETG streamers and
TEM streamers coexist

# TEM-ETG turbulence (transport spectrum)



$t=1646.71\ R/v_{Te}$

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

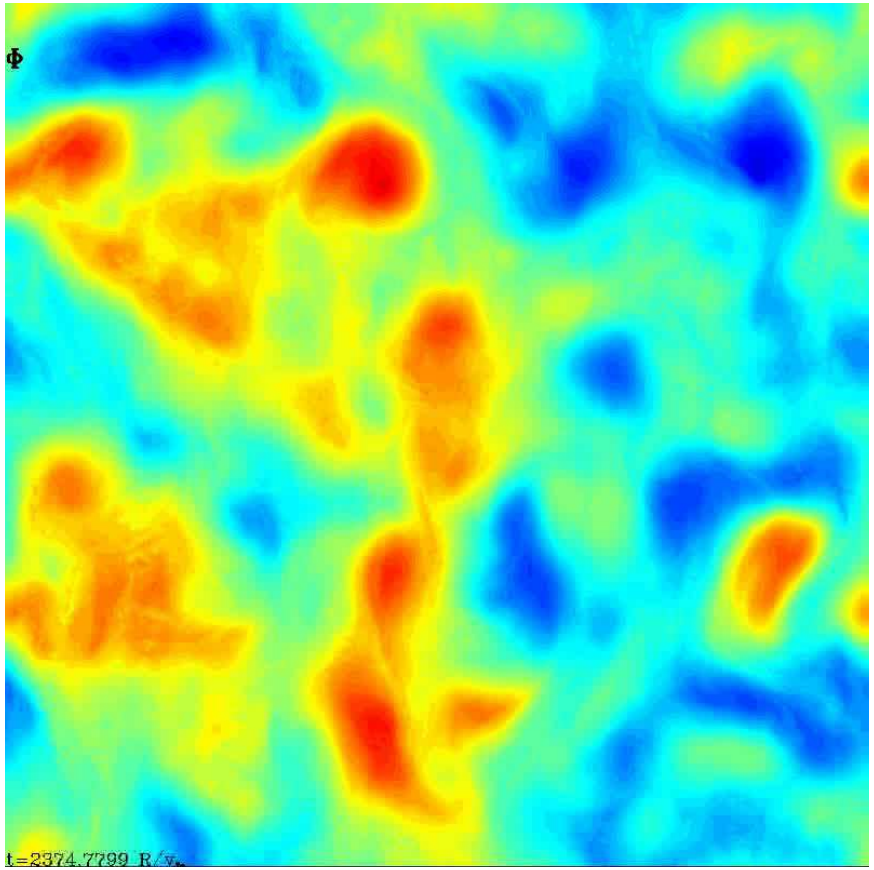
ETG transport level is in line with pure ETG simulations

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

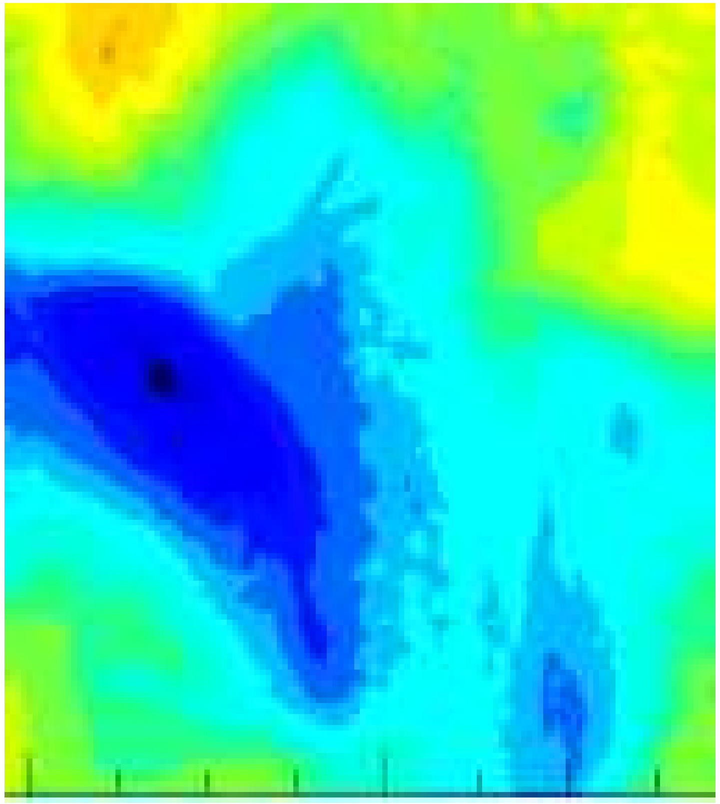
# ITG/TEM-ETG turbulence (Φ contours)

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

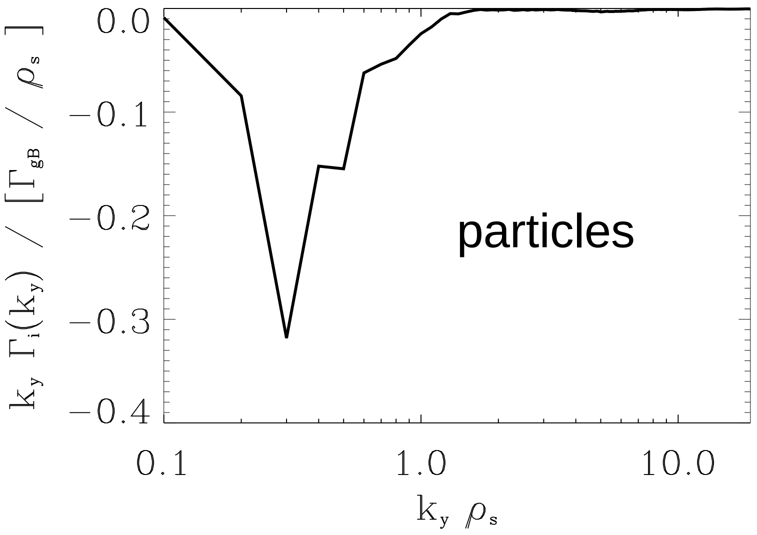
Case II: ITG is dominant

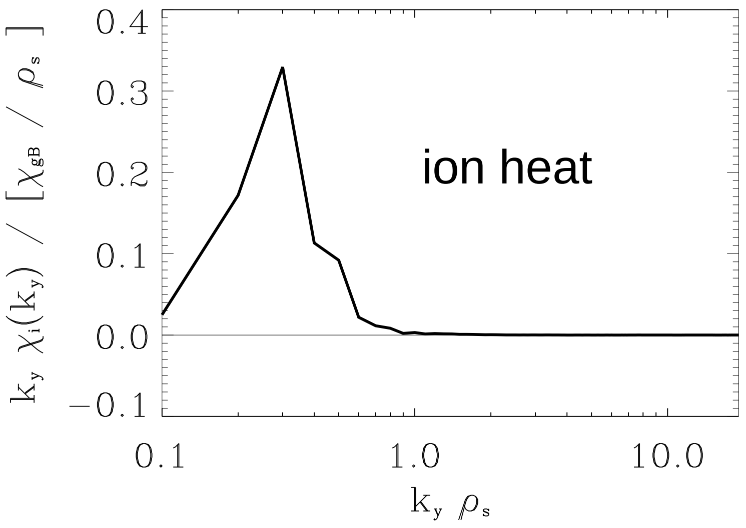


small-scale streamers are subject to large-scale vortex shearing



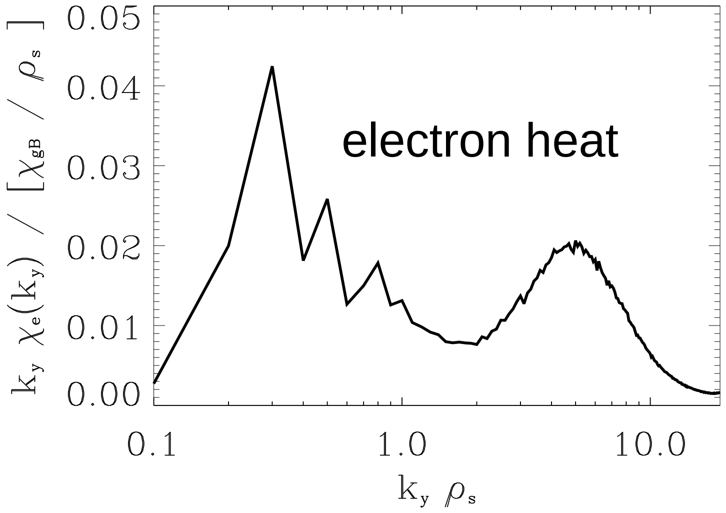
# ITG/TEM-ETG turbulence (cont'd)





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

ETG even more pronounced in presence of ExB shear: NSTX



# Conclusions

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

*GENE simulations show:*

- Nonlinear TEM saturation due to turbulent eddy viscosity:
  F. Merz & F. Jenko, PRL **100**, 035005 (2008)
- Scale separation of ion/electron heat transport for realistic plasma parameters: T. Görler & F. Jenko, PRL **100**, 185002 (2008)

**A lot remains to be discovered – by you?!**

More information and papers:

www.ipp.mpg.de/~fsj