ASDEX Upgrade

Max-Planck-Institut für Plasmaphysik

Co-existence and interference of multiple modes in plasma turbulence:

Some recent GENE results

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Acknowledgements:

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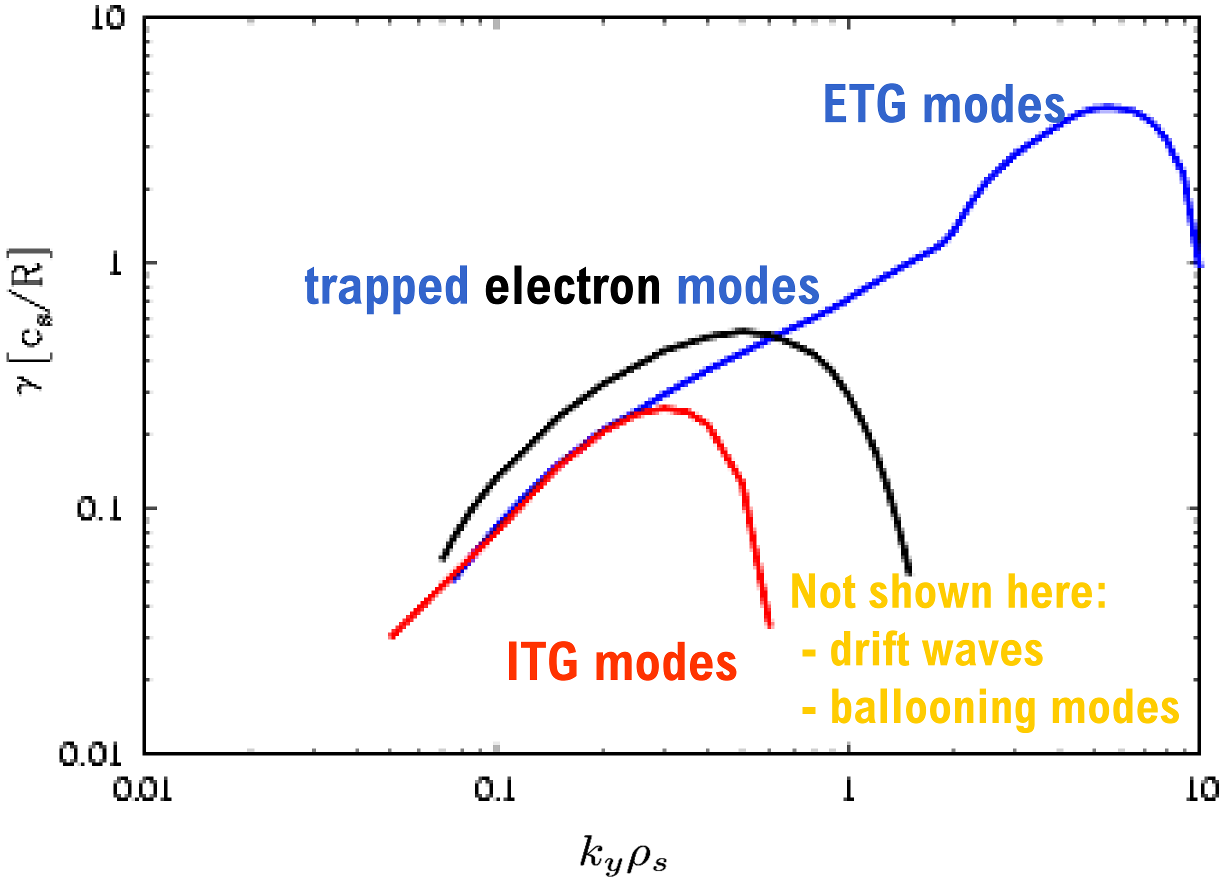
Microinstabilities driving plasma turbulence



How do these modes co-exist or interfere with each other?

Overview

- The tool: GENE
- New insights into linear gyrokinetics
- Turbulence in the stellarator W7-X
- Interference in ITG/TEM turbulence
- Nonlinear ITG/TEM-ETG interactions

The tool: GENE

The nonlinear gyrokinetic equations

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

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

Advection/Conservation equation

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

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

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

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

Appropriate field equations

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

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

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

The GENE code

Treatment of particle dynamics

- Arbitrary number of gyrokinetic particle species, passing and trapped
- 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

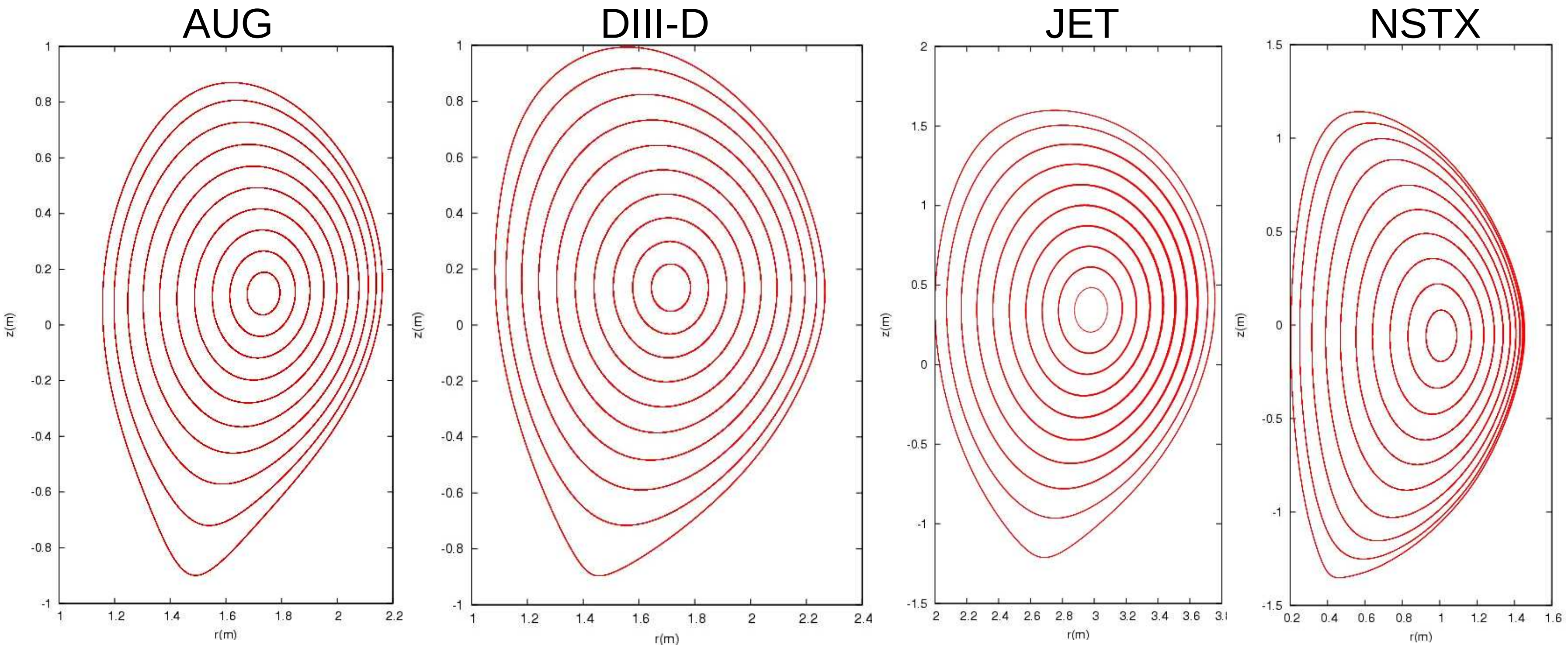
Different modes of operation

- GENE can be used as initial value solver or as eigenvalue solver

The TRACER code

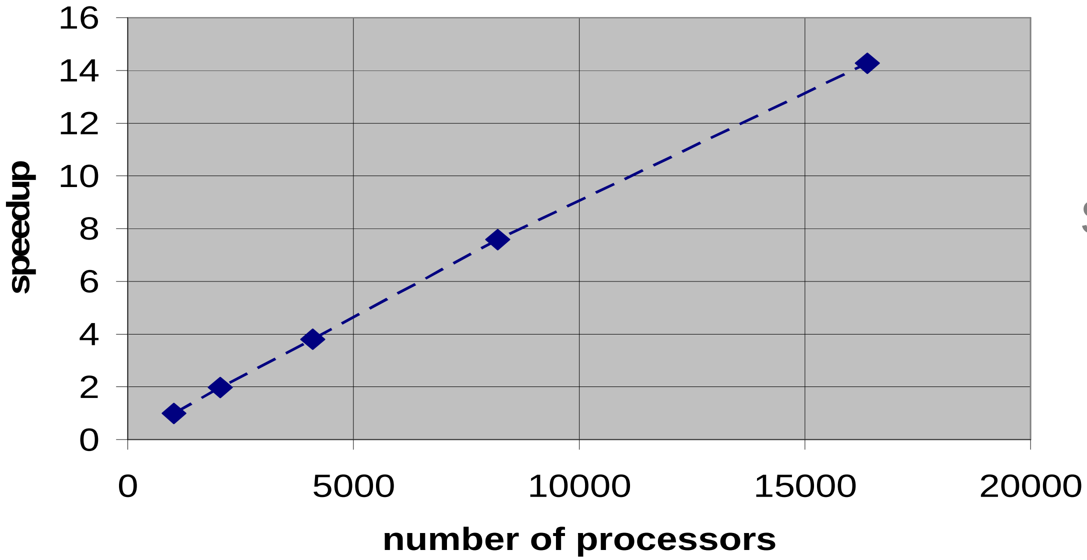
Description

- 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



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

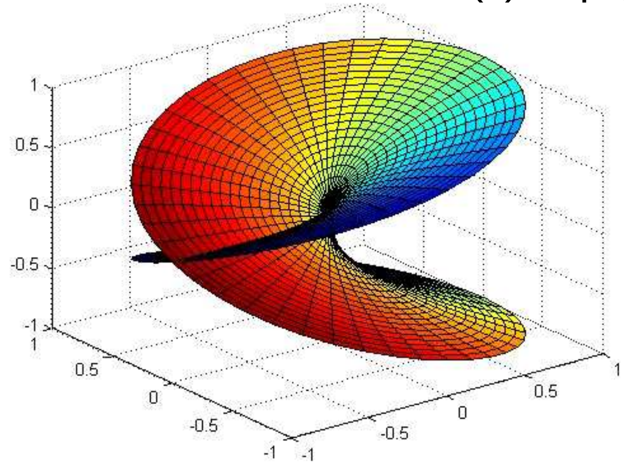
New insights into linear gyrokinetics

Exceptional points

Kammerer, Merz, and Jenko,
Phys. Plasmas 15, 052102 (2008)

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

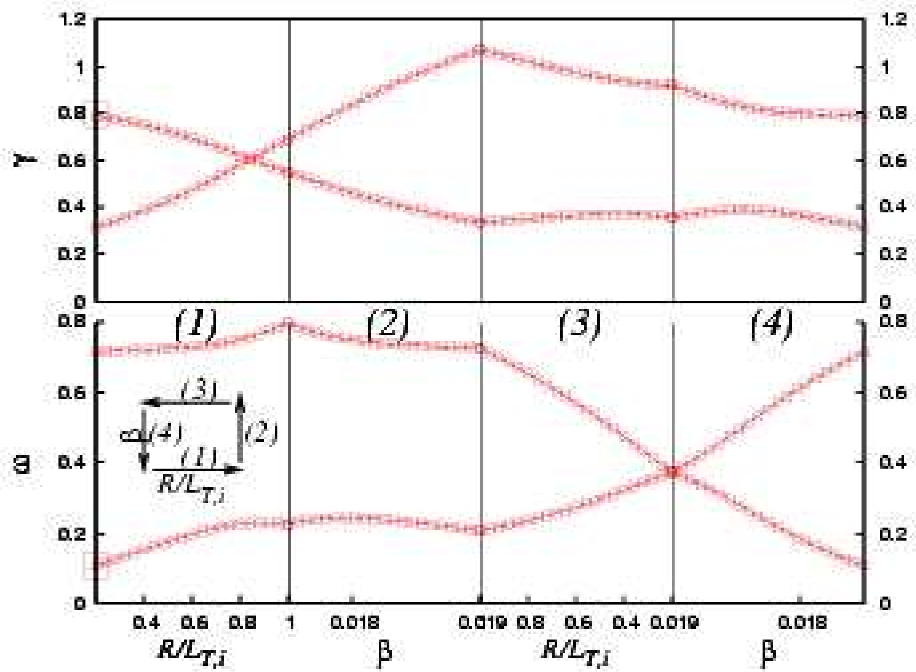
Riemann surface of f(z)=sqrt(z)



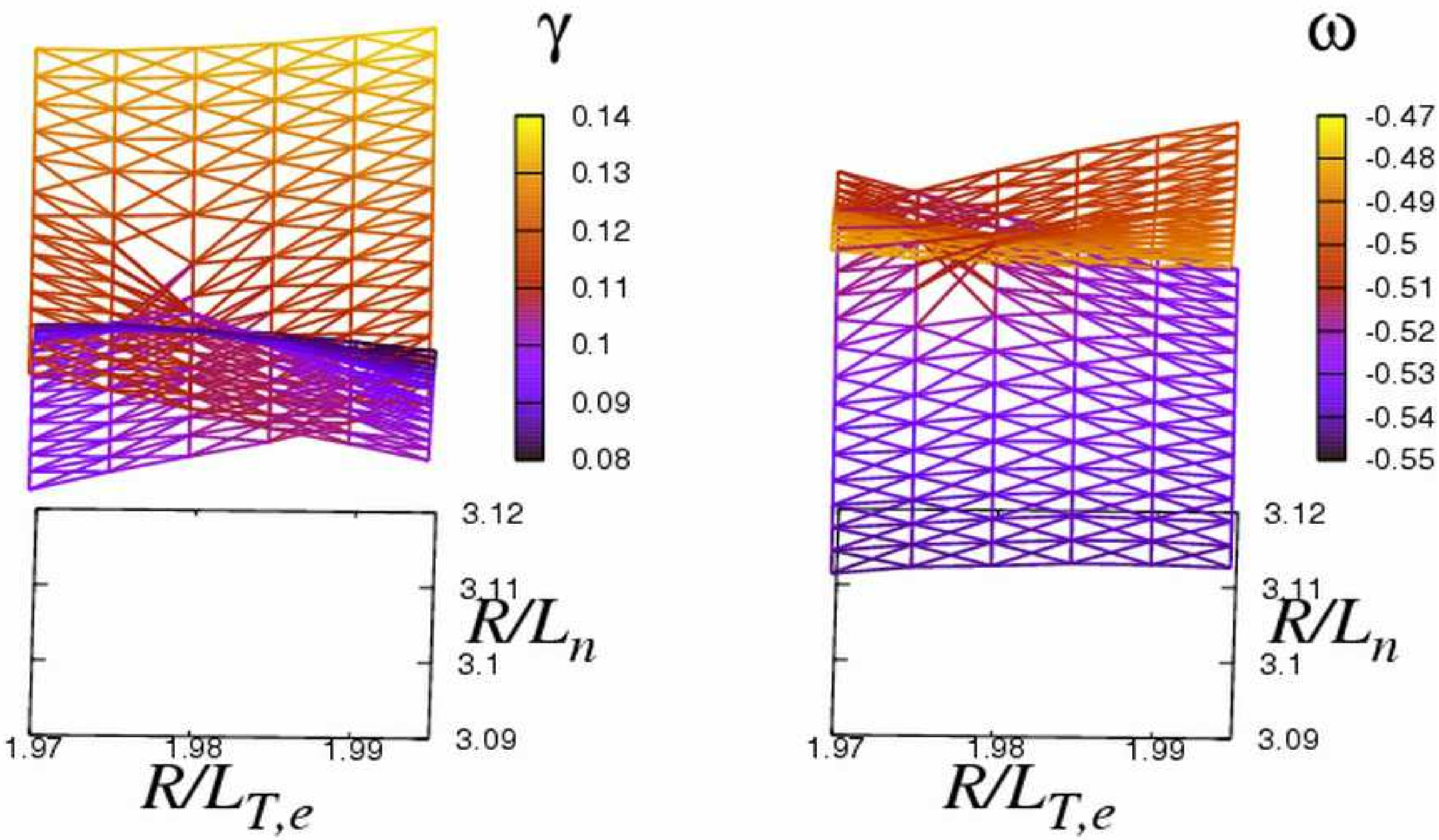
The non-Hermiticity of the linear gyrokinetic operator leads to *Exceptional Points*.

Here, both eigenvalues *and* eigenvectors are identical.

Similar: quantum physics etc.



Exceptional points (cont'd)

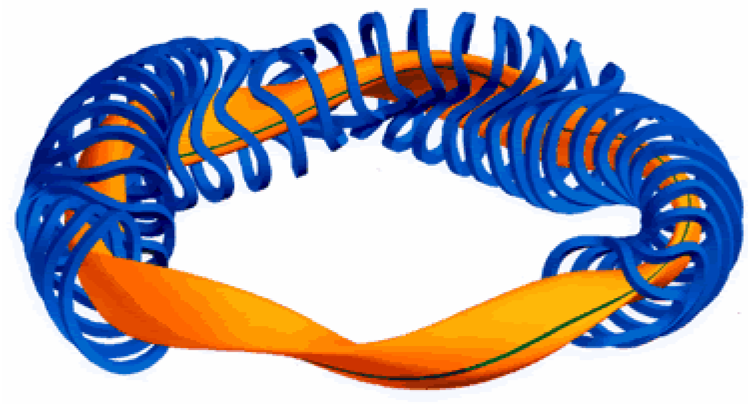


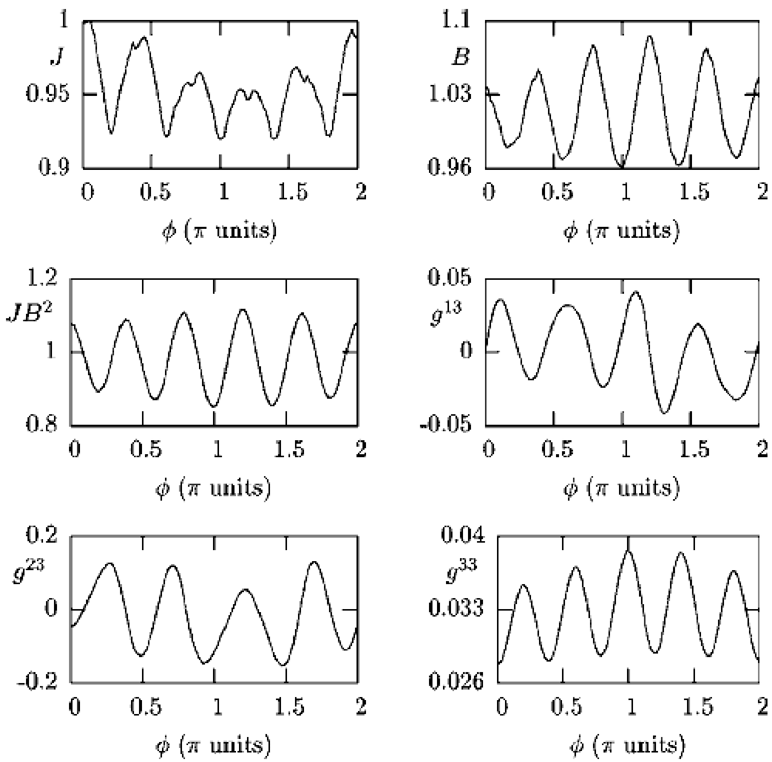
Turbulence in the stellarator W7-X

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

GENE simulations for W7-X

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





- Geometric coefficients are calculated by means of a field line tracing procedure [Xanthopoulos & Jenko, PoP 2006]

- Complicated parallel structure

  ➡ numerically expensive simulations

  (>100 points in parallel direction)

Coexistence of ITG and trapped ion modes

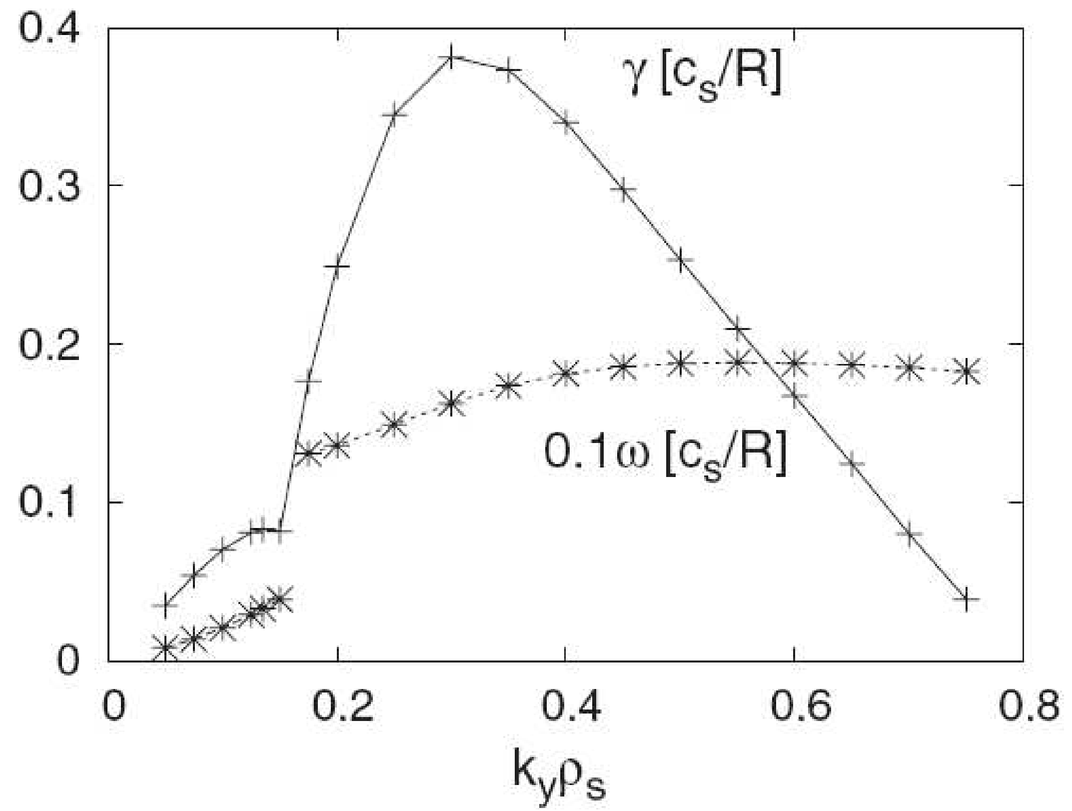


FIG. 5. k_y spectrum of the linear frequency and growth rate. The dominant microinstabilities are ITG modes (at $k_y\rho_s > 0.15$) and trapped ion modes (at $k_y\rho_s < 0.15$).

Nonlinear coexistence of two kind of modes

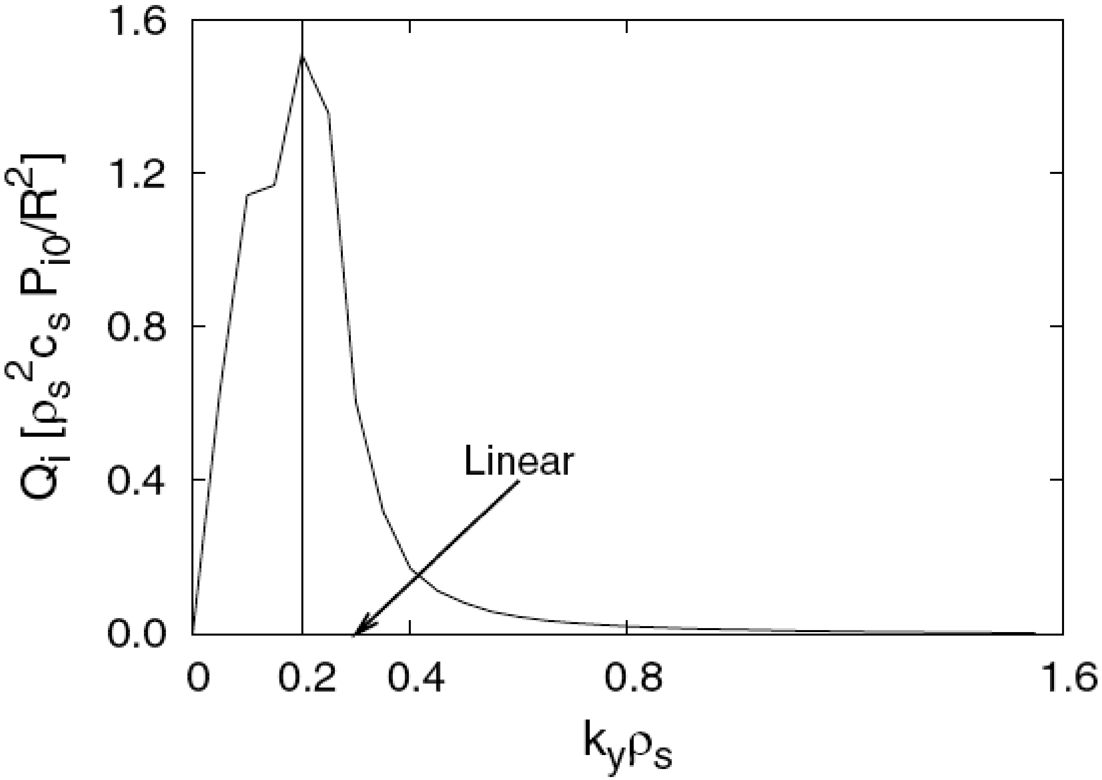
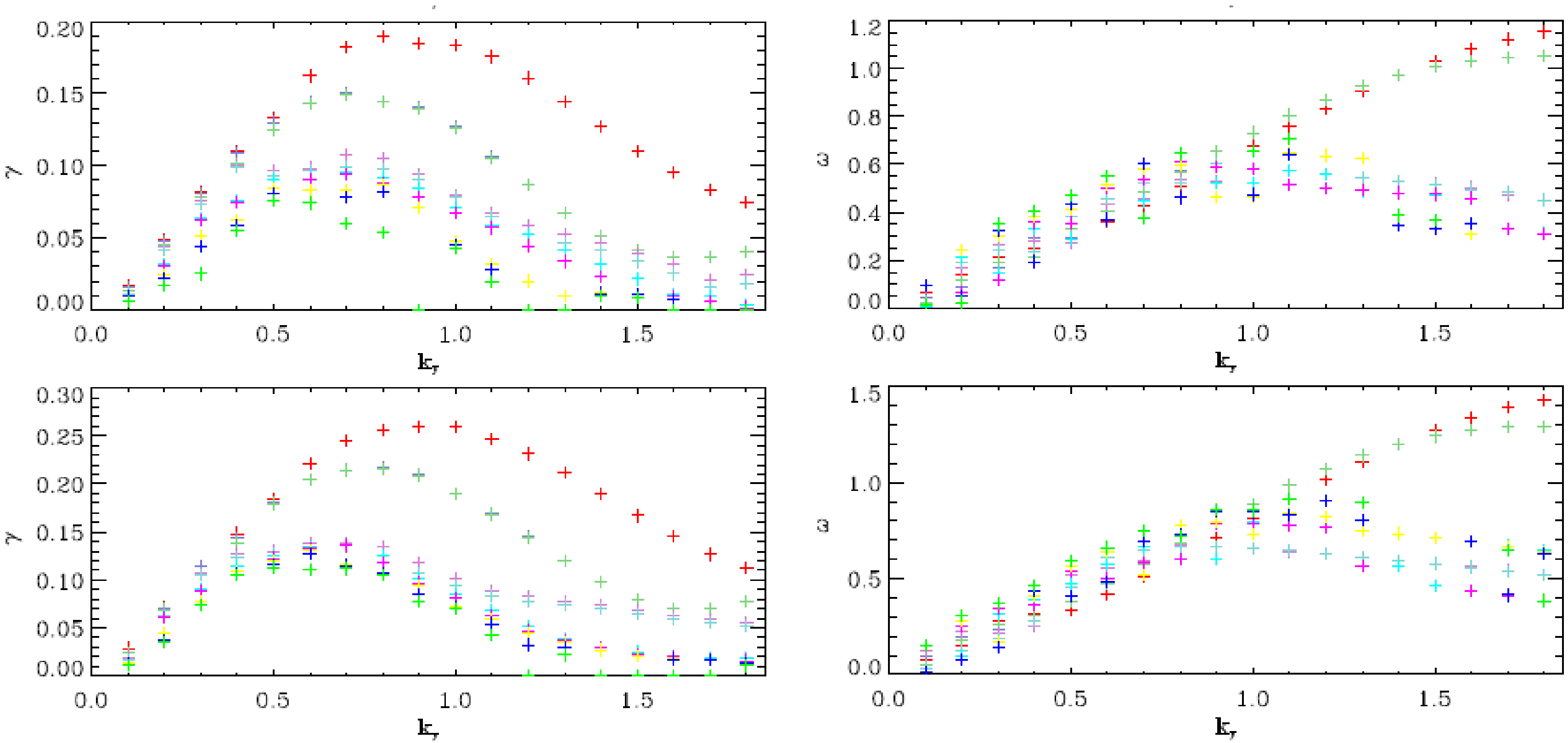


FIG. 4. k_y spectrum of the ion heat flux, exhibiting the coexistence of ITG modes (at $k_y\rho_s \sim 0.2$) and trapped ion modes (at $k_y\rho_s \sim 0.1$) in the saturated turbulent state.

Coexistence of multiple linear modes

W7-X, ITG modes with adiabatic electrons

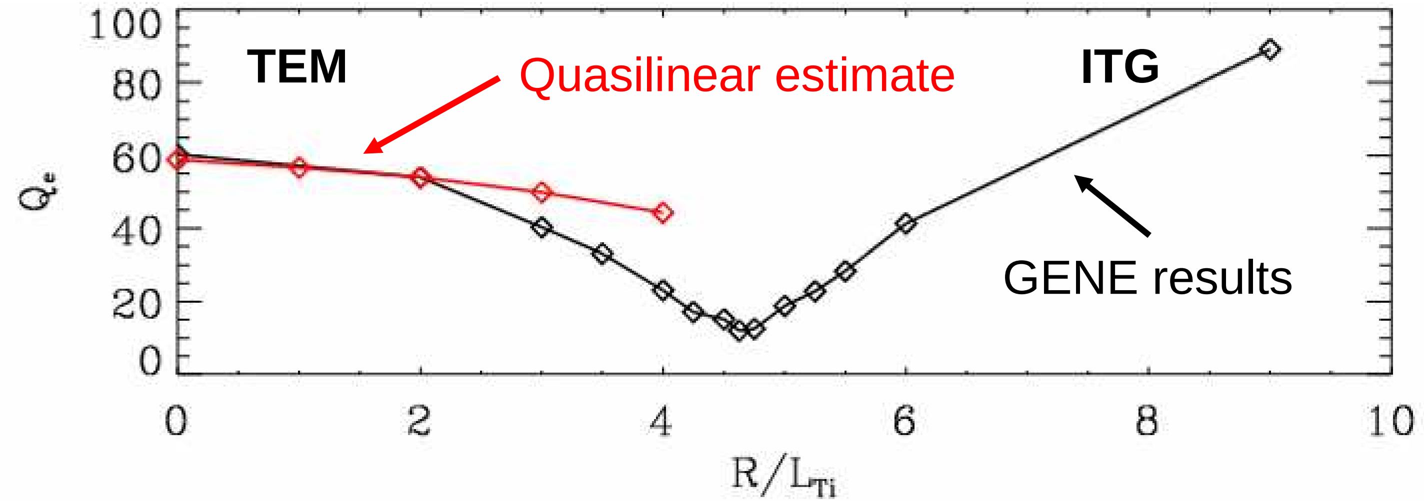


Interference in ITG/TEM turbulence

See also: Poster by Florian Merz

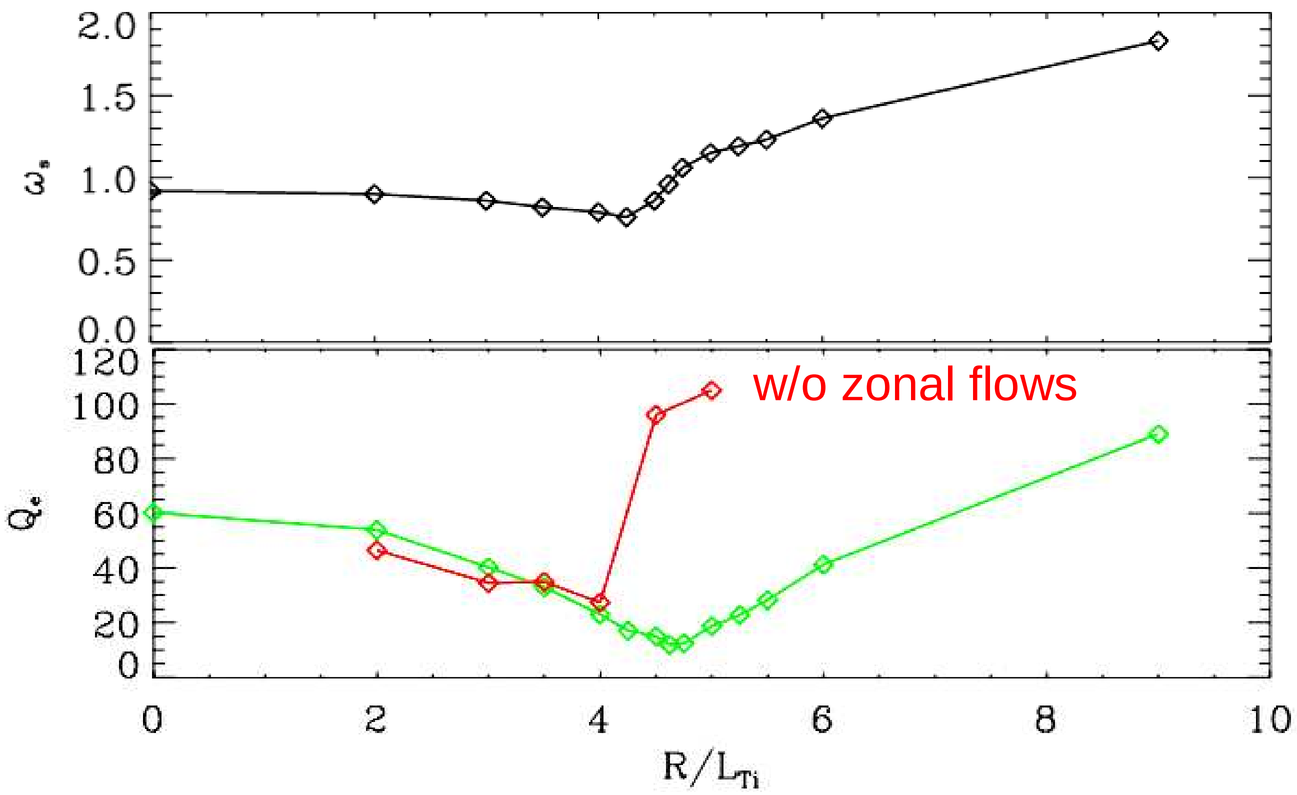
TEM-ITG turbulence transition

- R/L_{Te} is held constant at 4.5
- Increasing R/L_{Ti} finally leads to a deviation from the quasilinear model and a transition to ITG dominated turbulence at R/L_{Ti} ~ 4.5



Zonal flow behavior

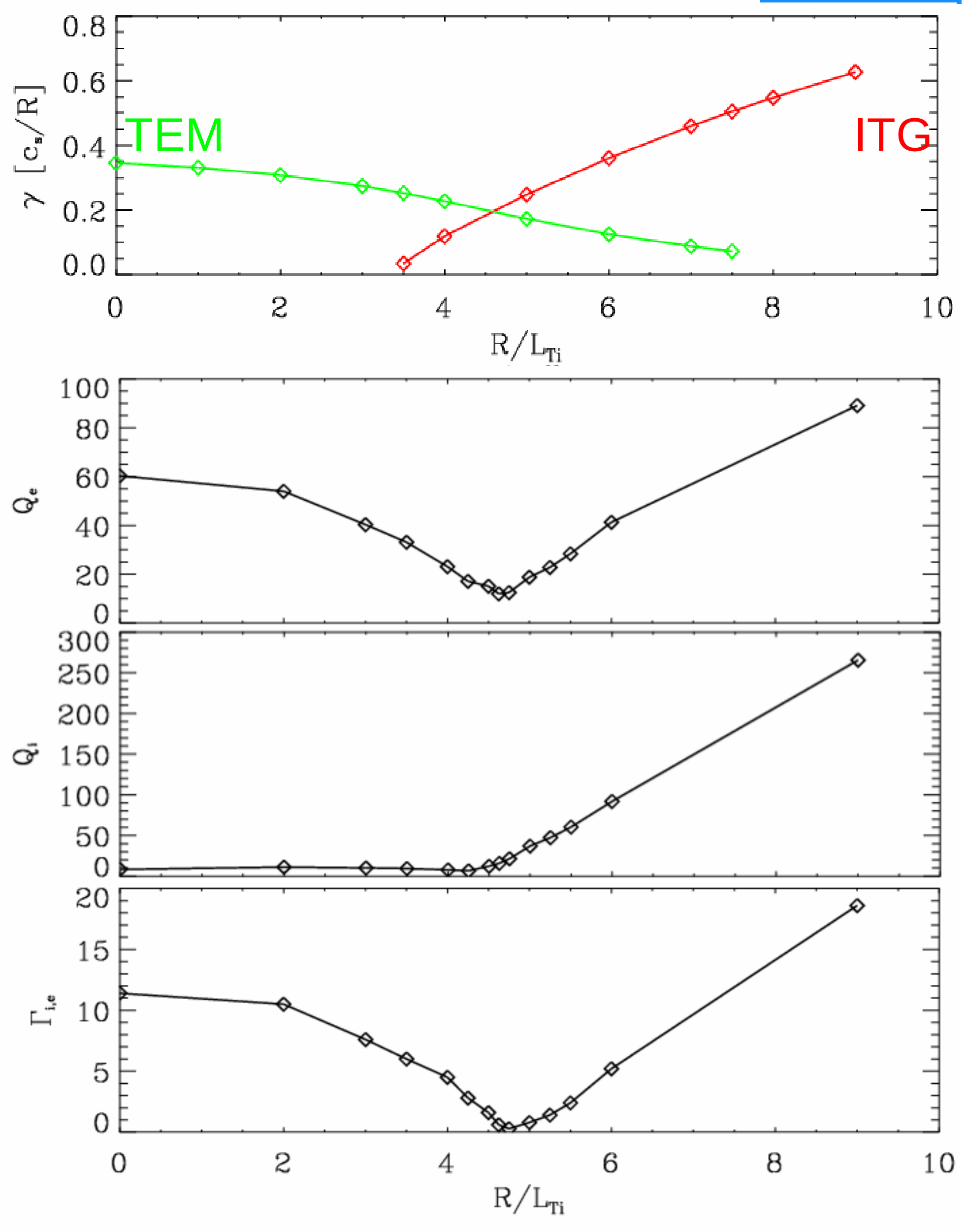
- TEM-ITG transition also changes the role of zonal flows
- Relatively sharp transition seen in the value of the ExB shearing rate ω_s and in simulations where zonal flows have been suppressed



TEM-ITG turbulence near the transition

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

Destructive interference!



Nonlinear and linear frequency spectra

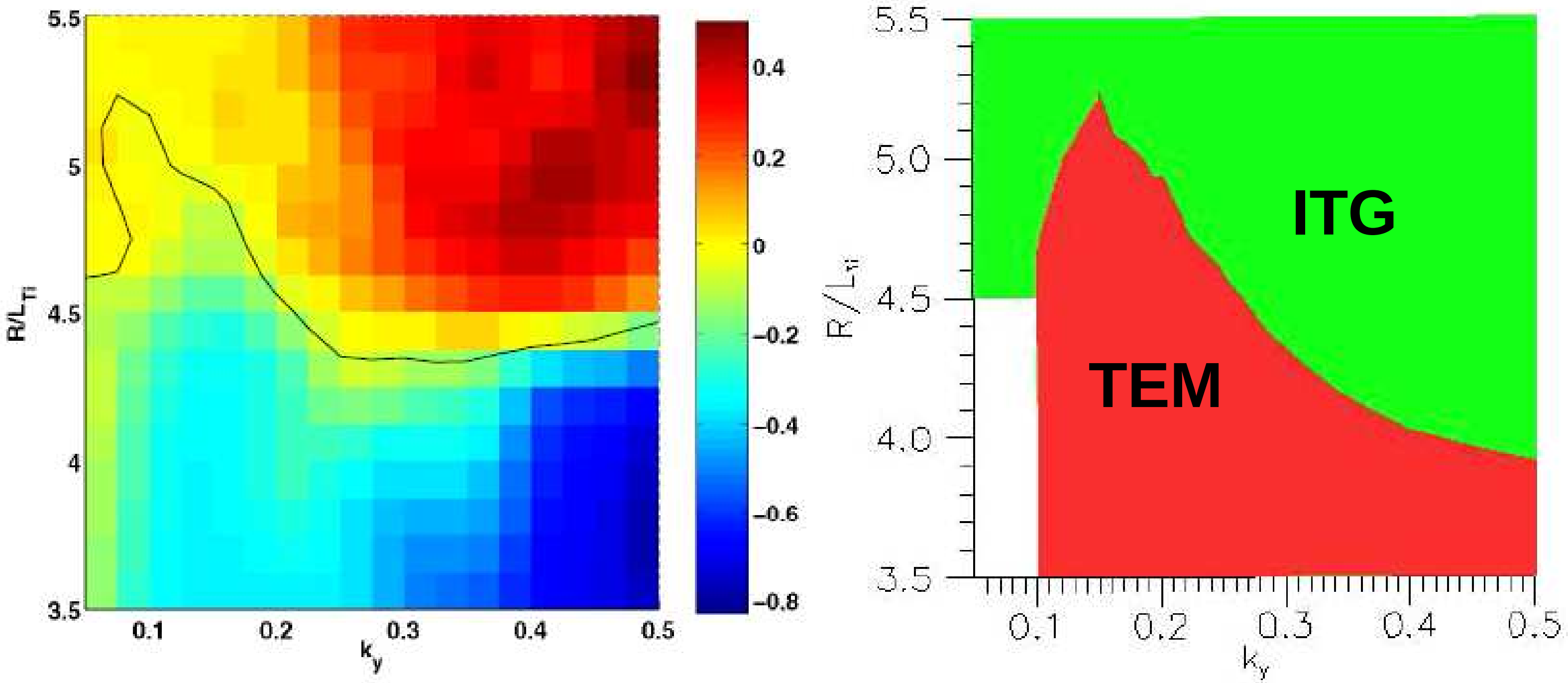
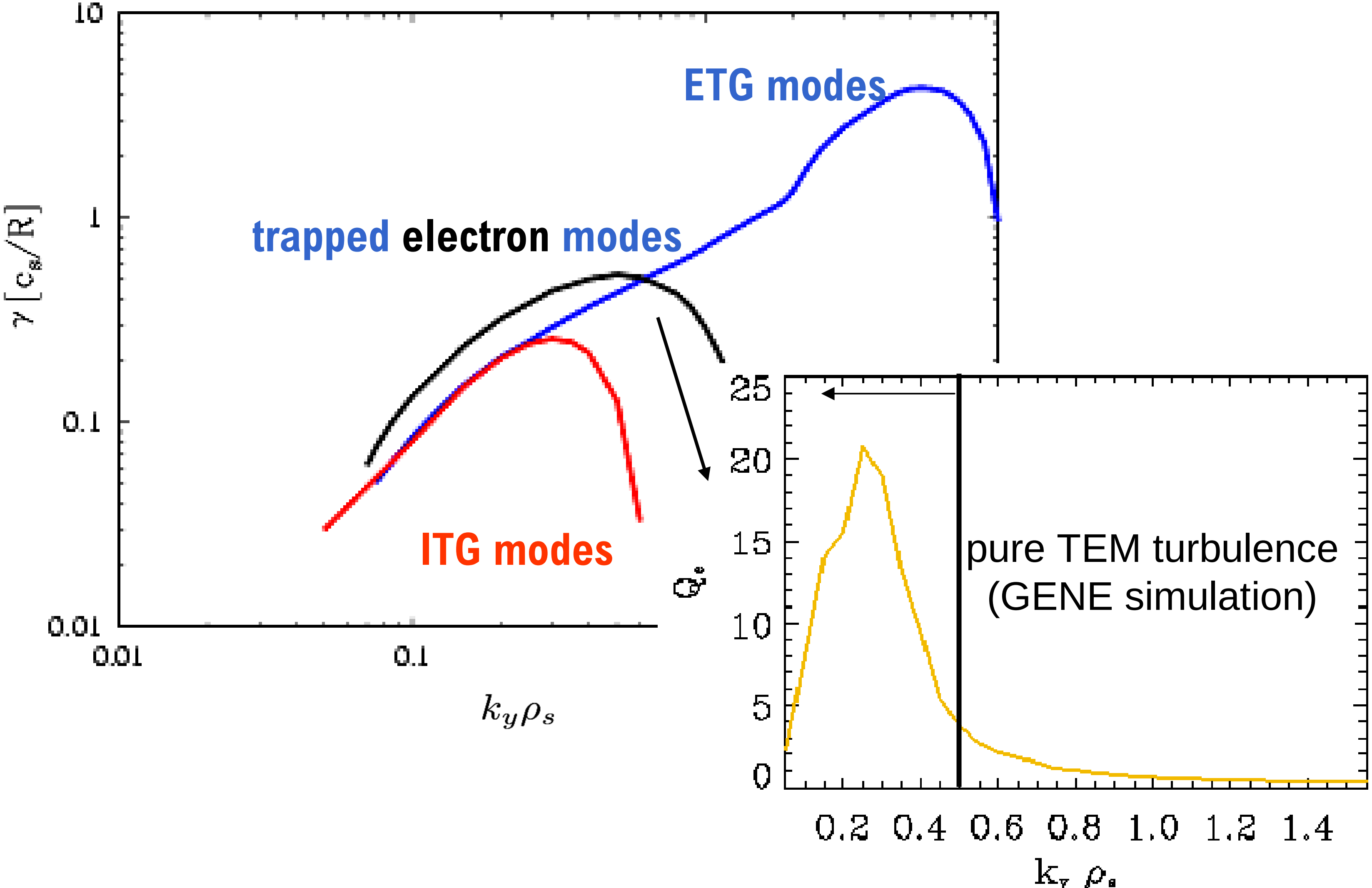


Figure 6.7.: Left: First moment of the nonlinear frequency distribution (color coded), the $\omega = 0$ contour line (black) may be used to mark the TEM-ITG transition. Right: The areas where the dominant microinstability is TEM/ITG are coloured red/green.

Nonlinear ITG/TEM-ETG interactions

See also: Poster by Tobias Görler

Plasma microturbulence: Multiple scales

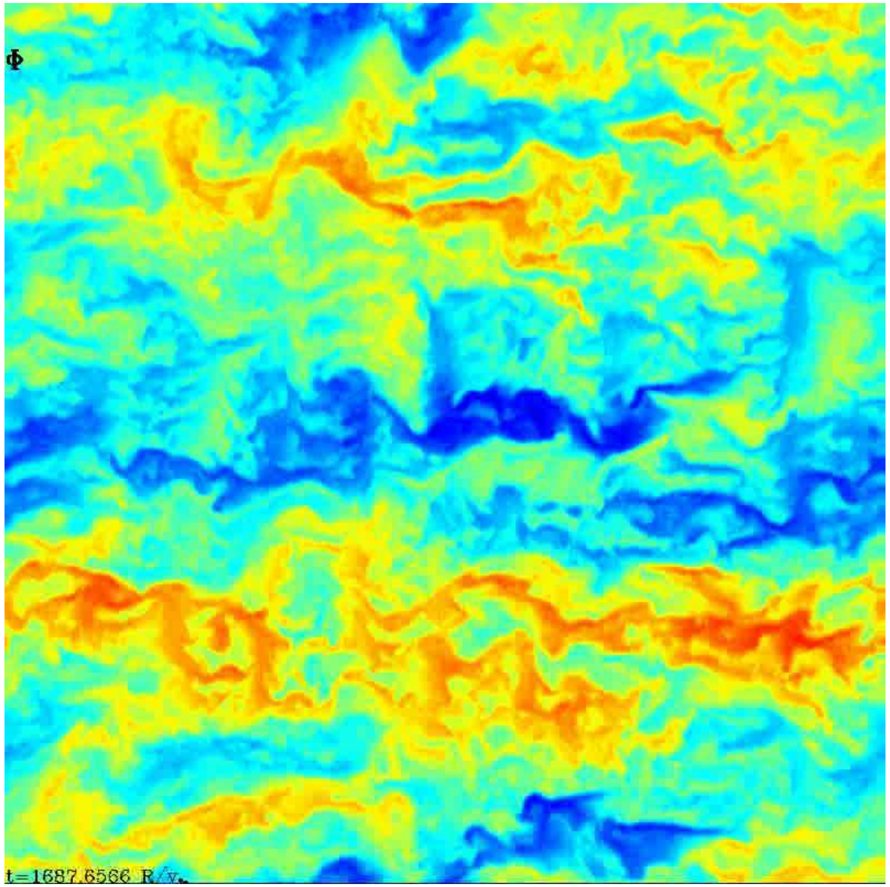


Nonlinear coexistence of ITG/TEM and ETG modes?

TEM-ETG turbulence (Φ contours)

Here: electrostatic, collisionless, s-α model equilibrium;
Cyclone-like parameters, reduced mass ratio (of 400)

Case I: ITG is turned off



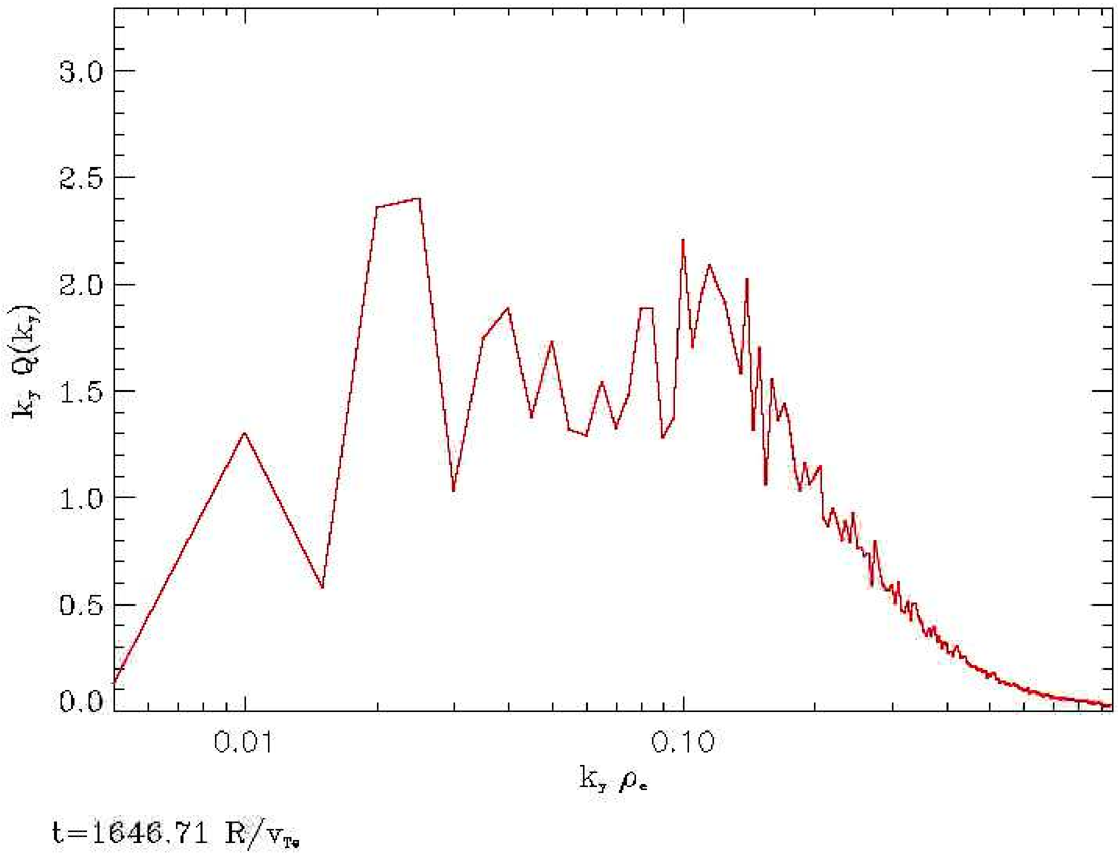
~ 100,000 CPUh / run

box size:
64 ion gyroradii

resolution:
~2 electron gyroradii

ETG streamers and
TEM streamers coexist

TEM-ETG turbulence (transport spectrum)

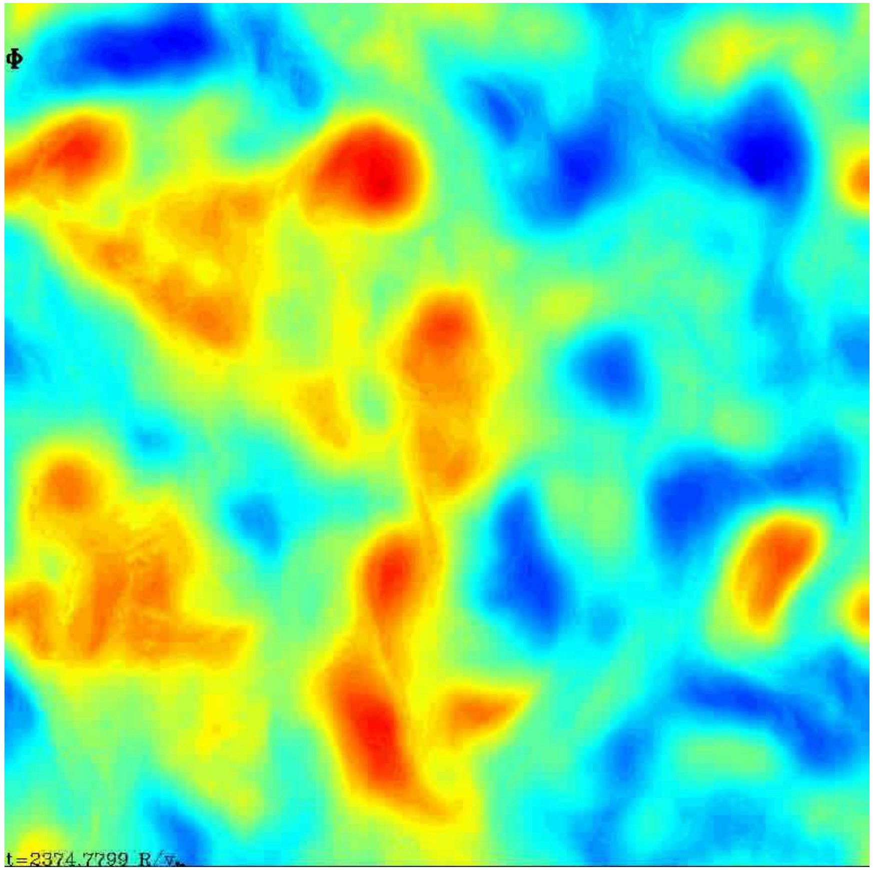


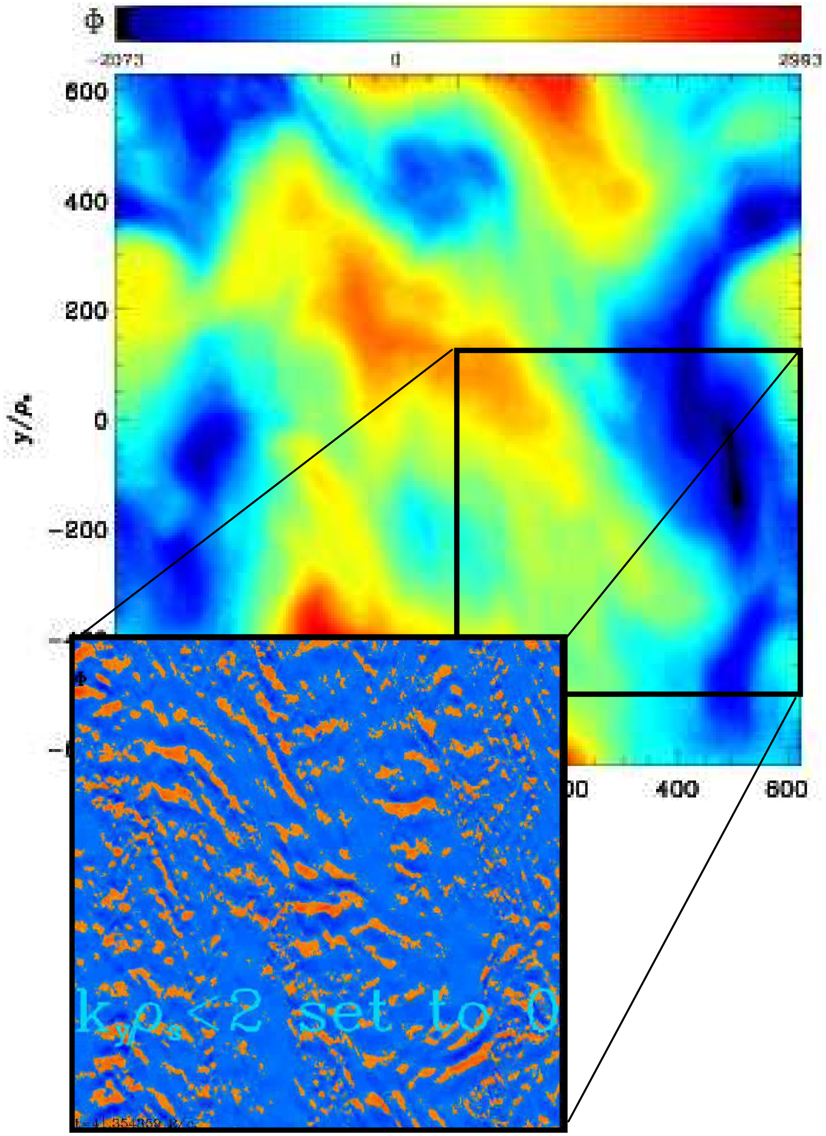
$$Q = \sum_{k_y} Q(k_y) \propto$$

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

Transport is evenly distributed over a wide k range;
ETG transport level is in line with pure ETG simulations

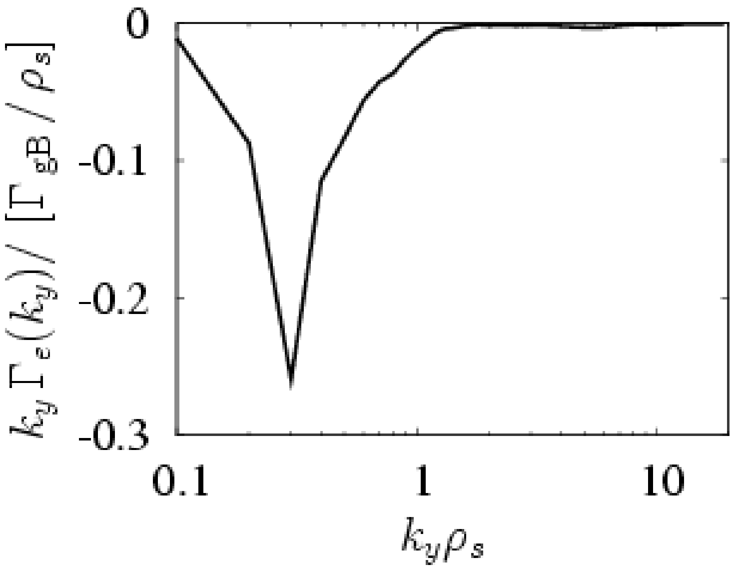
ITG/TEM-ETG turbulence (Φ contours)

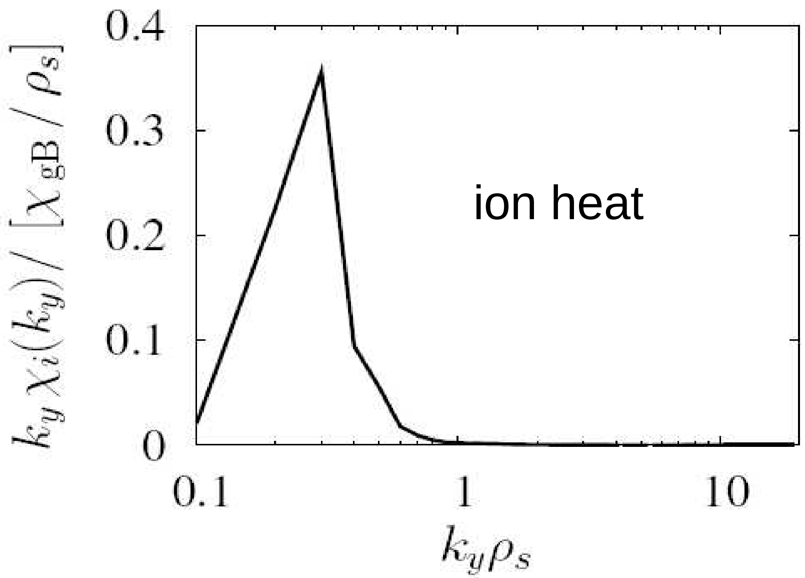




small-scale structures are sheared and tilted by large-scale vortices

ITG/TEM-ETG turbulence (cont'd)

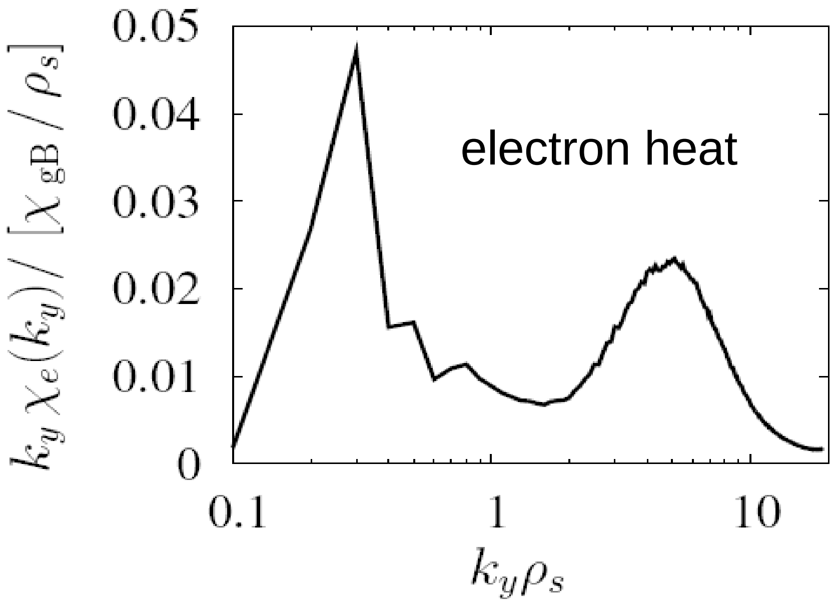




Scale separation of electron and ion heat fluxes

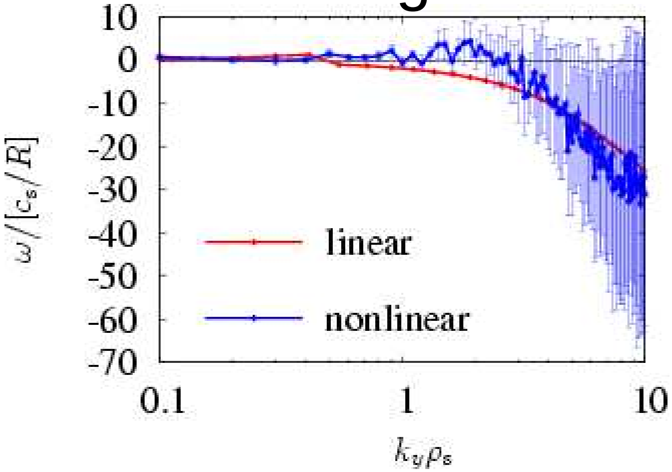
ETG even more pronounced in the presence of ExB shear, high beta, dominant electron heating

No "superposition principle"

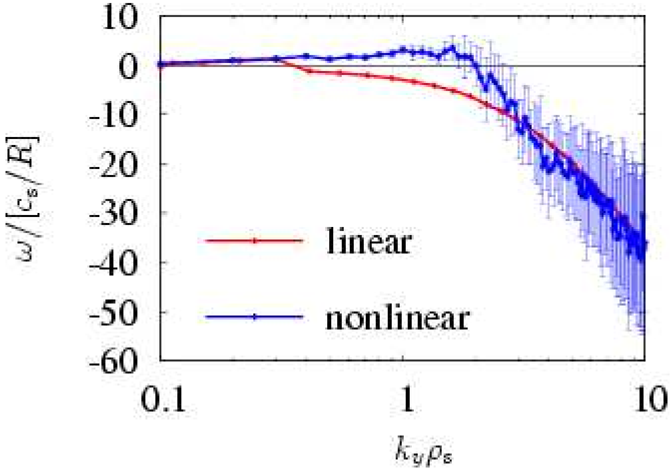


Frequency spectra

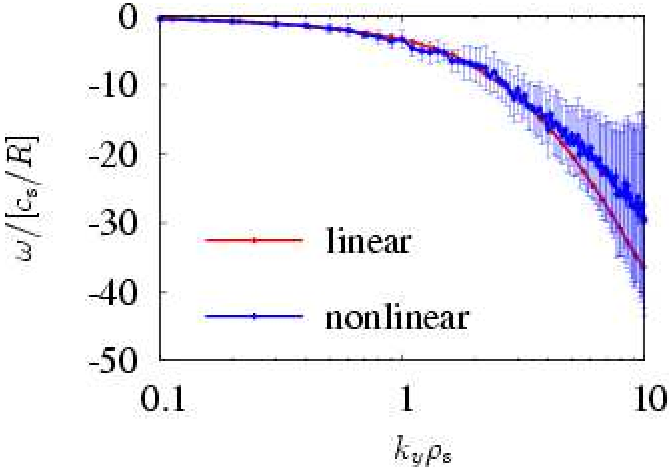
Strong ITG



Moderate ITG



No ITG

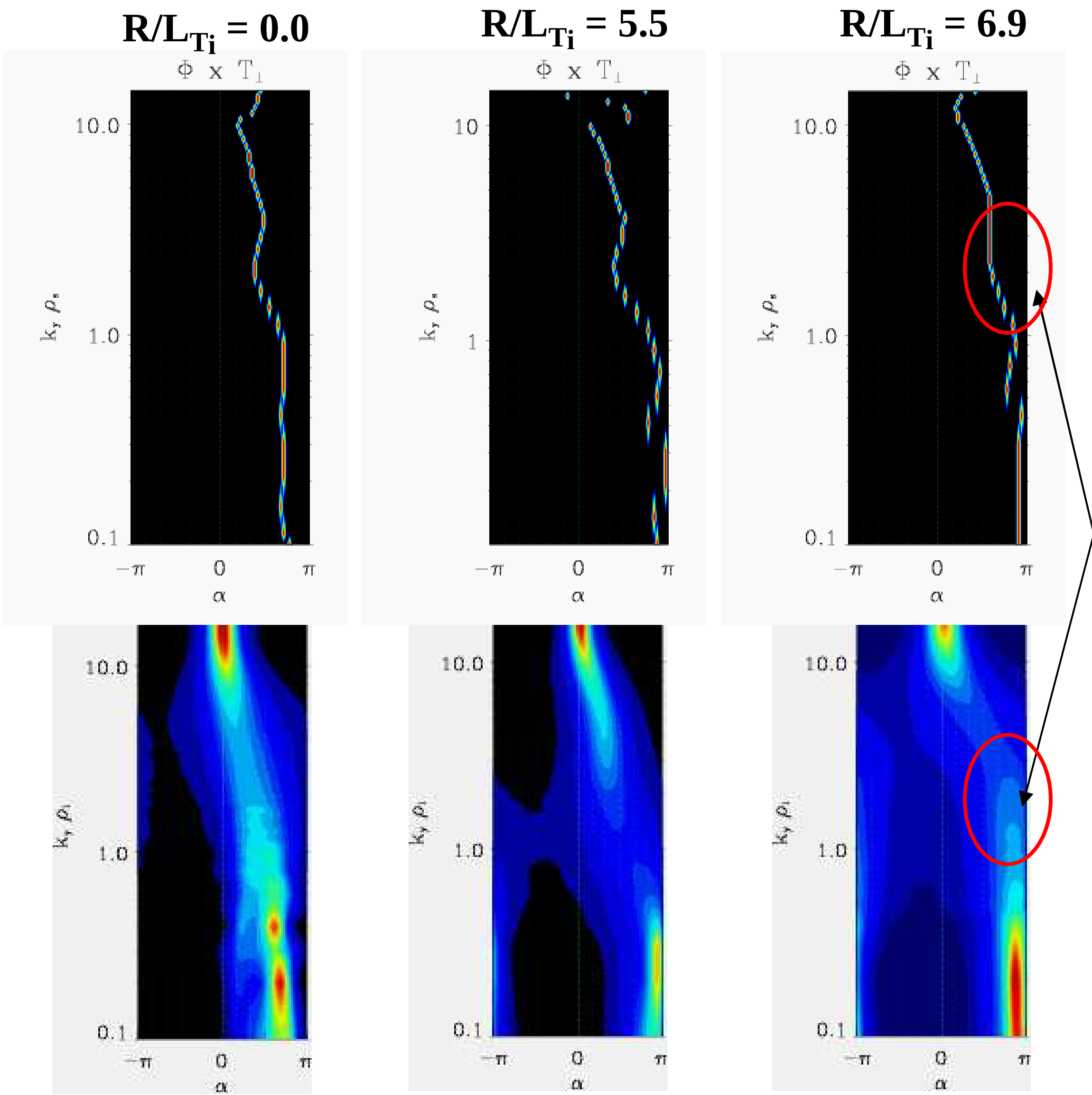


Nonlinear and linear frequencies match over a wide range except for transition regime from dominant ITG to TEM/ETG

Cross phases (Tperp vs phi)

Linear

Nonlinear



nonlinear spread of ITG features

Conclusions

Our theoretical understanding of plasma microturbulence is still rather fragmentary, and, in particular, the interactions of various microinstabilities need to be studied further

GENE simulations show:

- Often, multiple linear modes coexist (esp. in stellarators)
- Due to the existence of Exceptional Points, such coexisting linear modes can be strongly coupled
- ITG modes and TIMs/TEMs can coexist also nonlinearly, sometimes inducing destructive interference effects
- Nonlinear coupling between ion and electron scales can violate "superposition principle"

More information and papers:

www.ipp.mpg.de/~fsj