# Coexistence and transitions in TEM/ITG turbulence

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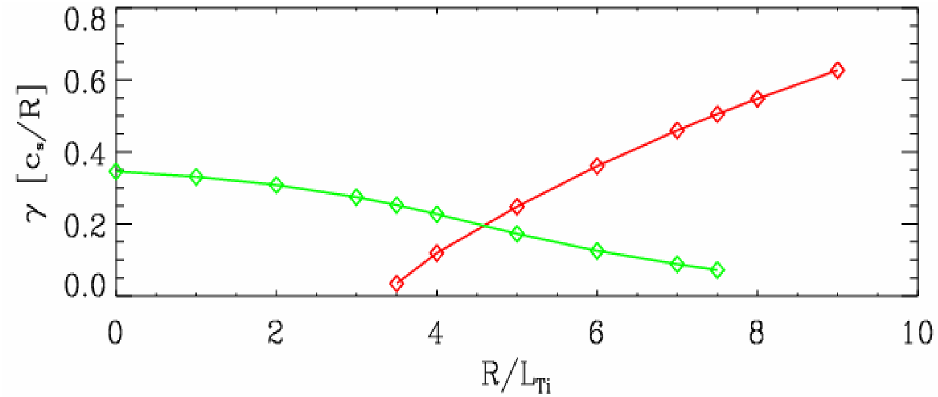
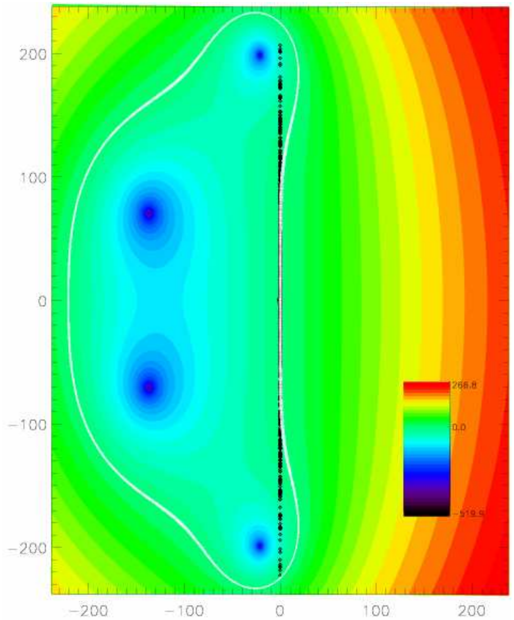
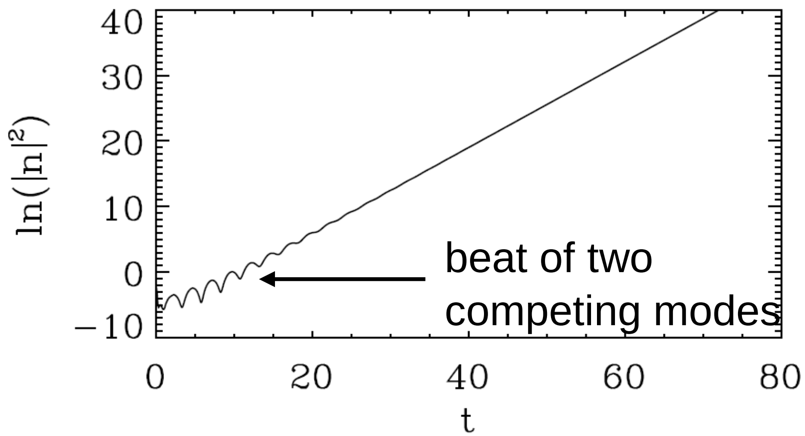
# GENE: Initial value + eigenvalue solver

- The plasma turbulence code GENE uses an eigenvalue solver
  - To compute the linear time step limit for explicit time stepping schemes
  - To investigate the nature of subdominant modes and mode transitions



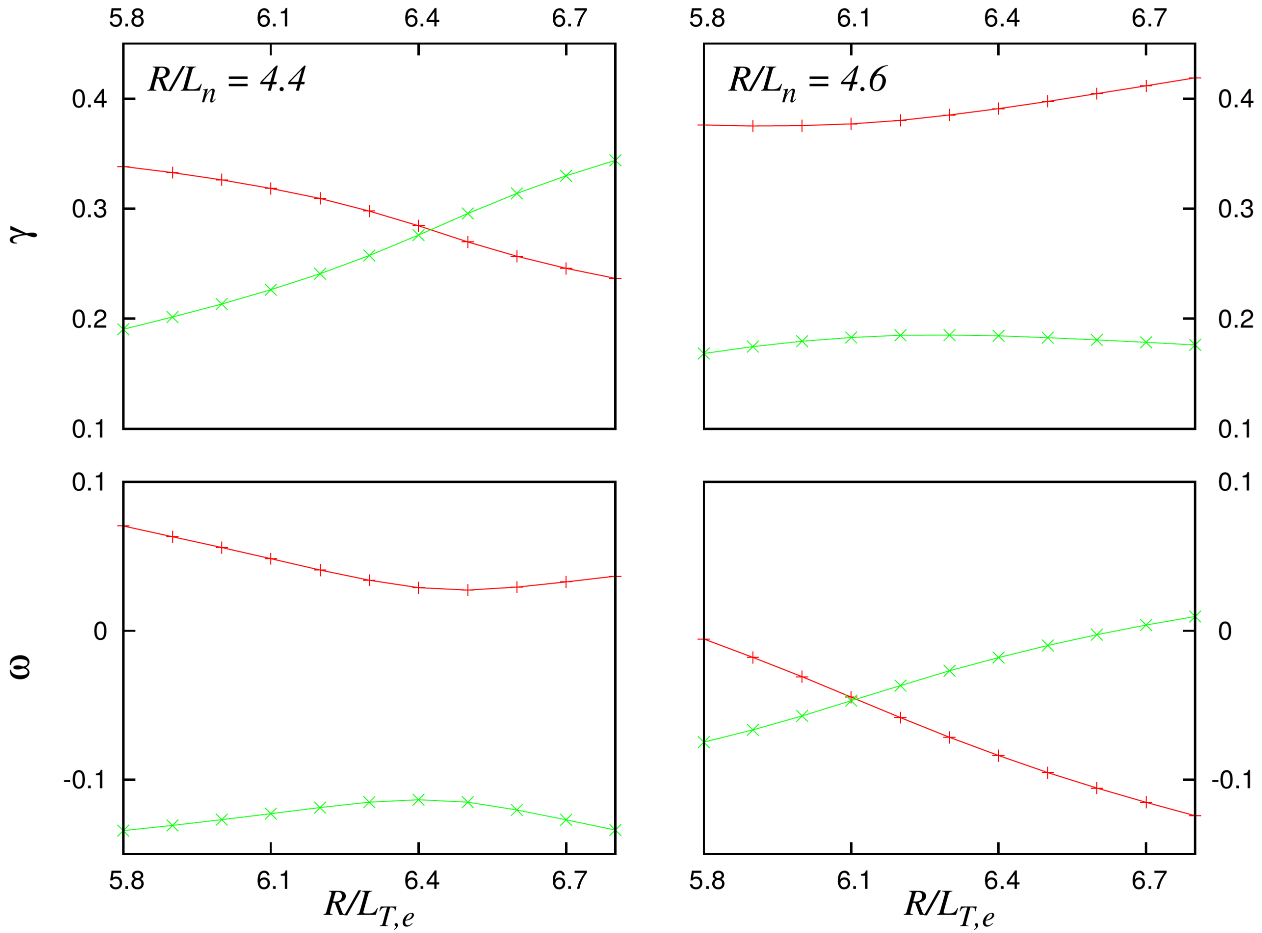

- The eigenvalue solver doesn't have the problems of the initial value solver at mode transitions



# Linear mode transitions

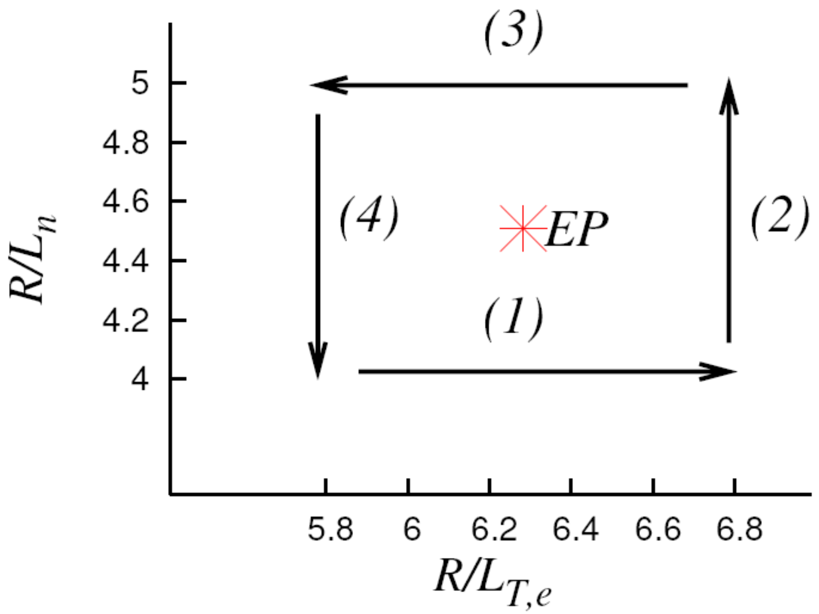
- Observation: The qualitative parameter dependence of the eigenmodes on one parameter can depend sensitively on the value of a second parameter.

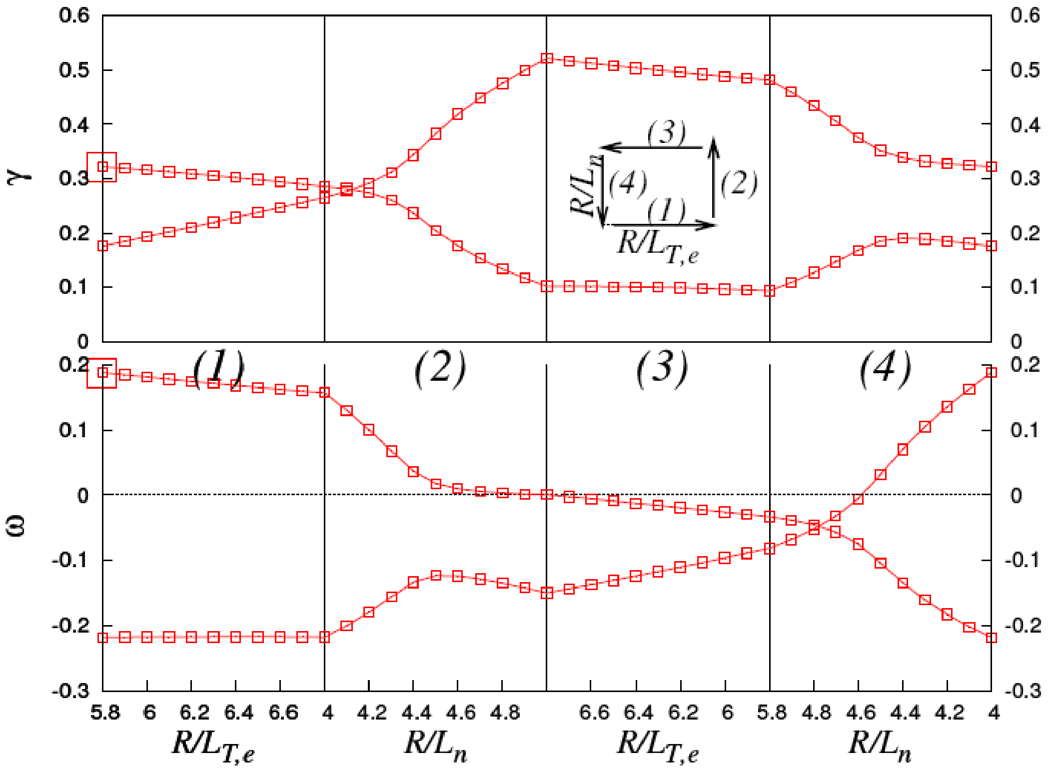
- Two unstable modes can show
  - A clear transition
  - „Mixing“ or „hybridization“



# Linear mode transitions II

- Connection of the two 1D scans in parameter space: closed scan along a rectangle in the 2D parameter space ($R/L_{Te}$,$R/L_n$)

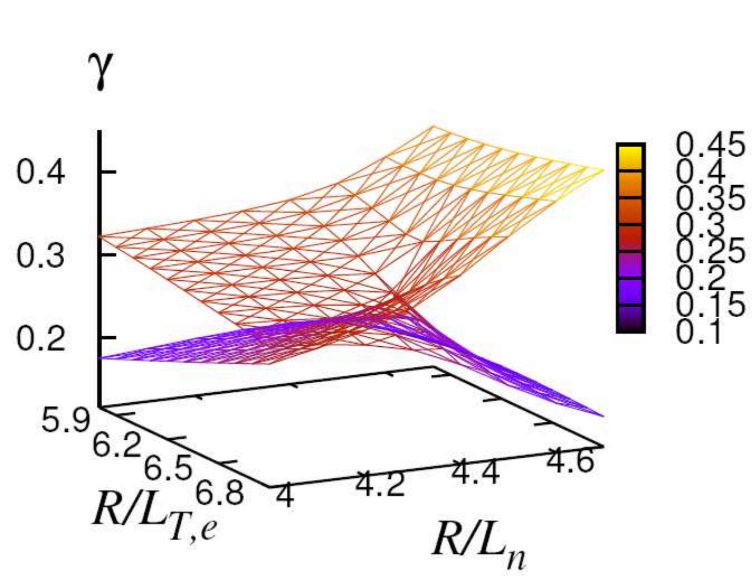


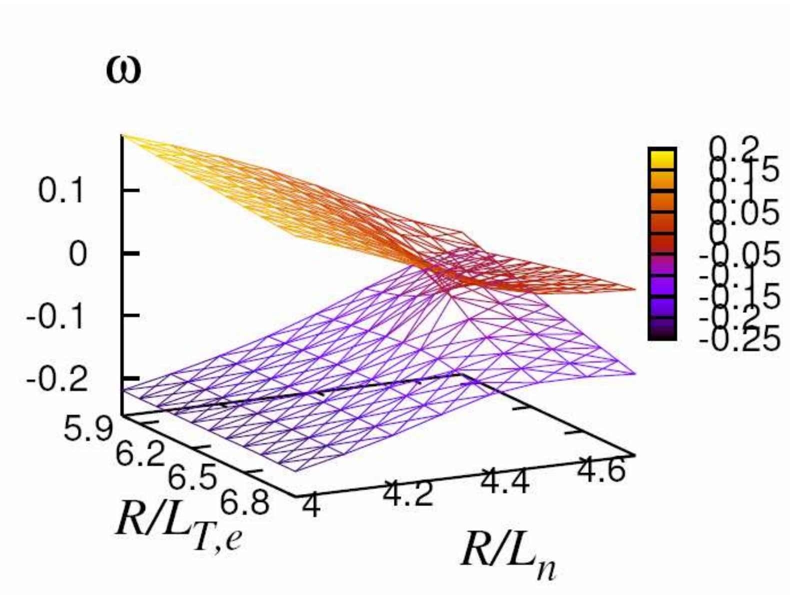




The modes are connected!

# Non-Hermitian degeneracies

- A full 2D scan reveals the nontrivial topology of the eigenvalue surface in the ($R/L_{Te}$,$R/L_n$) plane:




- Reason: a non-Hermitian degeneracy / Exceptional Point in the center

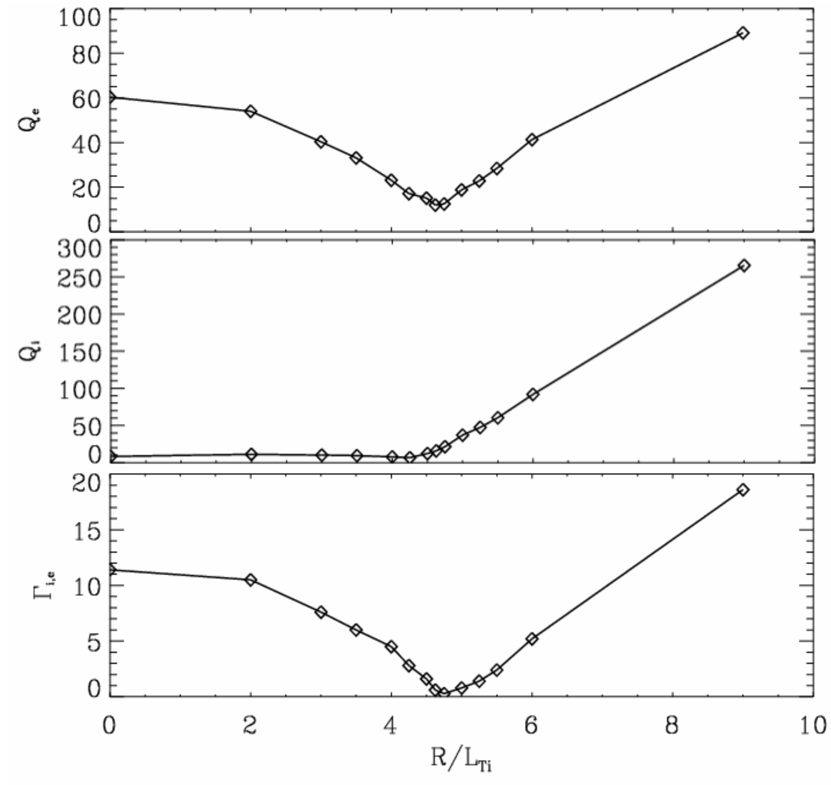
# Non-Hermitian degeneracies II

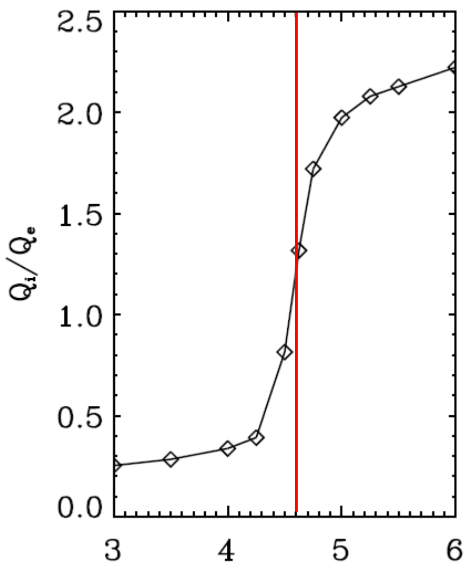
- The non-Hermiticity of the linear operator creates the instabilities also and also leads to the degeneracies
- Non-Hermitian degeneracies have codimension 2 in the gyrokinetic parameter space and are therefore encountered frequently
- Further scans revealed pairwise connections between ITG, ETG, KBM, temperature/density gradient driven TEMs, so that all relevant microinstabilities can be transformed into each other by continuous parameter variations (see M. Kammerer, F. Merz, and F. Jenko, PoP **15,** 2008)

⇒ A strict distinction of microinstabilities is impossible, traditional naming should be avoided close to exceptional points

# Nonlinear TEM-ITG transition

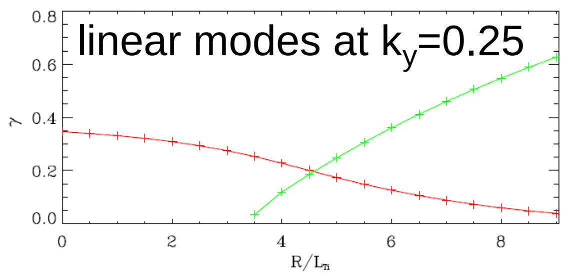
- Parameter scan far from non-Hermitian degeneracies
- With the additional instability, heat and particle fluxes are suppressed instead of increased
- ITG branch: Nonlinear upshift of critical $R/L_{Ti}$

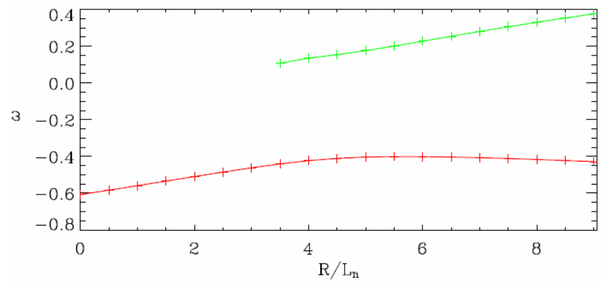



Transition at $R/L_{Ti}$=4.63

linear modes at $k_y$=0.25



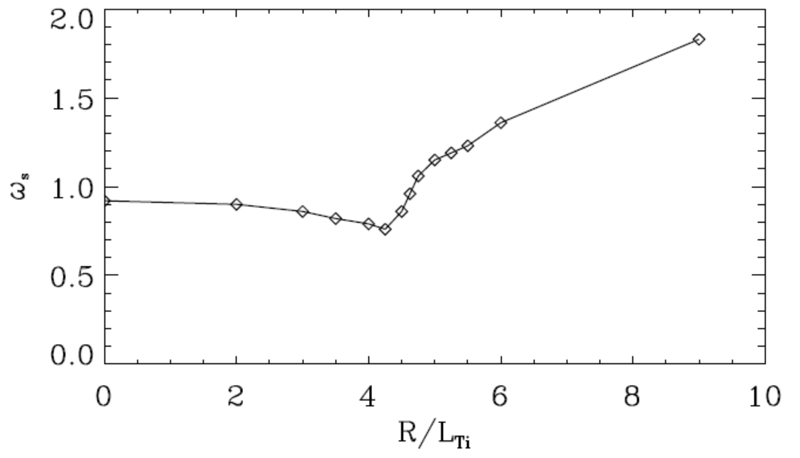



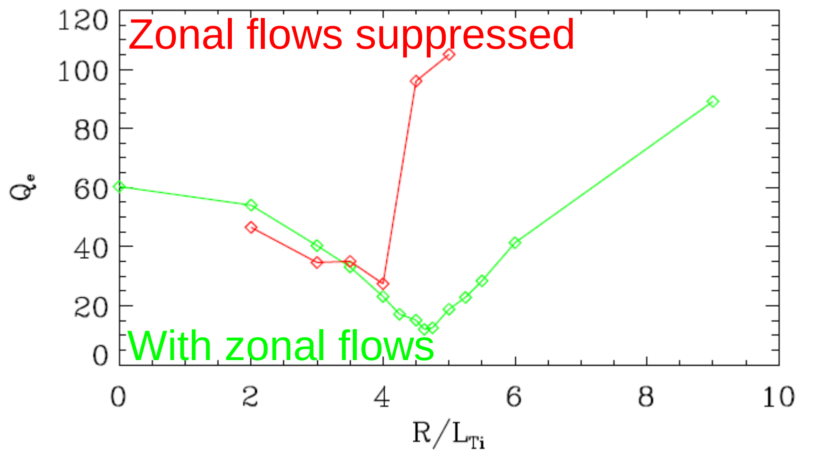
# Nonlinear TEM-ITG transition: zonal flows

- Shearing rate shows a jump at the transition

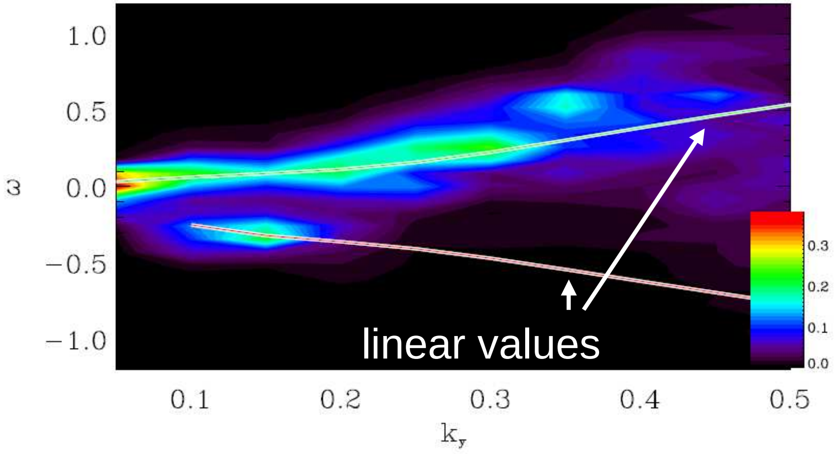
- Zonal flow suppression shows almost no effect in TEM regime but large increase of transport for ITG regime

- Nonlinear upshift of critical $R/L_{Ti}$ also observable for ITG saturation mechanism (linearly $R/L_{Ti}$=3.3 to $R/L_{Ti}$=4.5 nonlinearly)

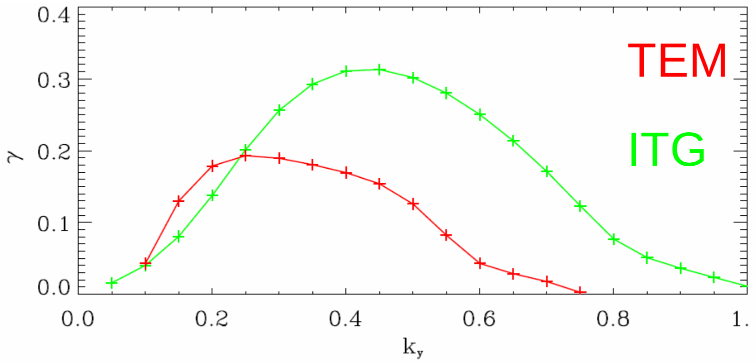


# Spectral decomposition at the transition

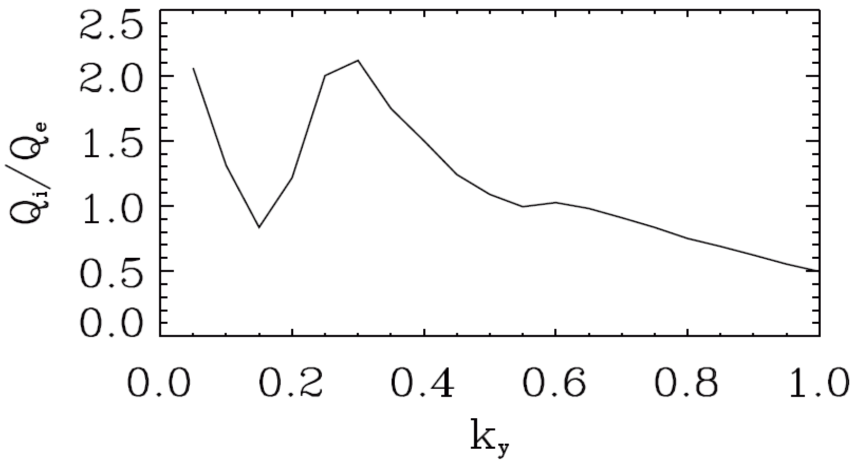



- Nonlinear frequency distribution shows coexistence of TEM and ITG at different wave numbers and even at the same wave number



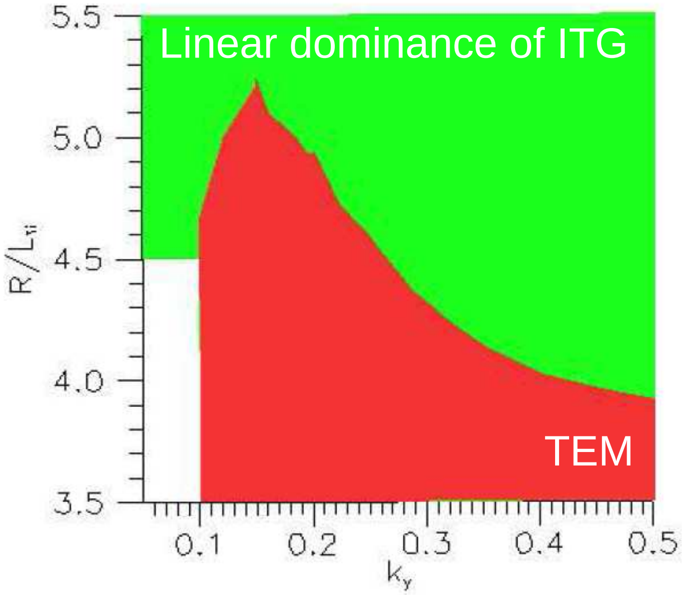

- Dominant mode is determined by linear growth rate

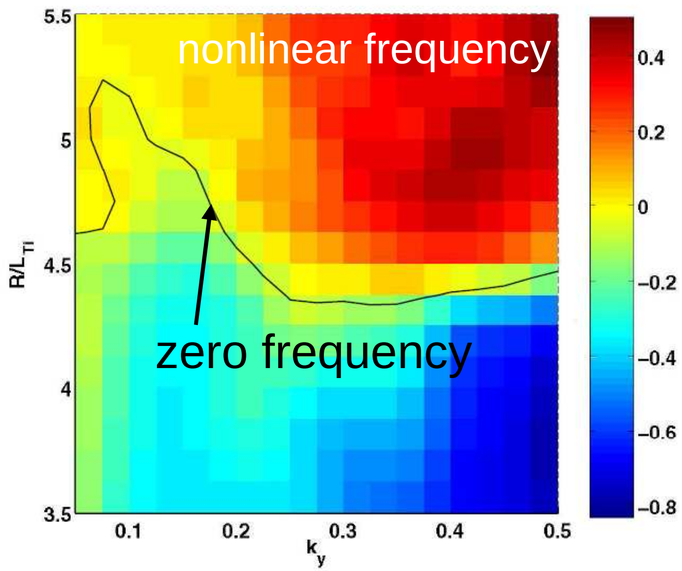
- Spectral dependence is confirmed by other TEM/ITG specific properties like the flux ratios

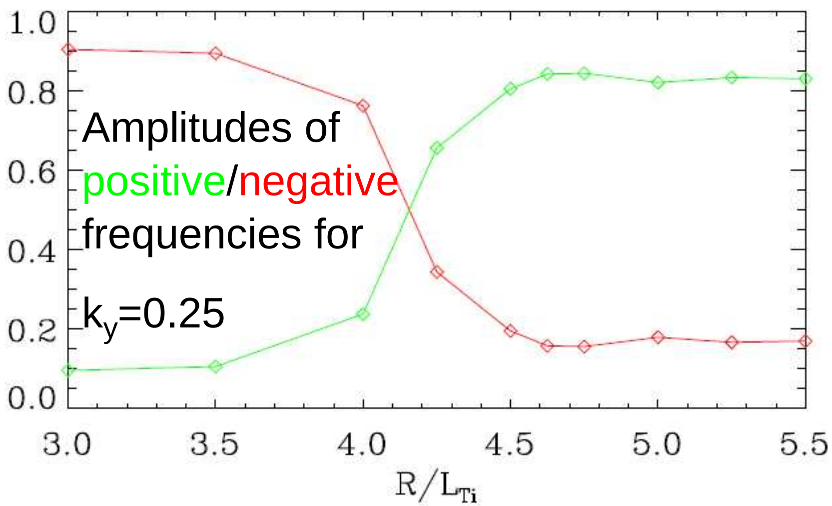


# Spectral dependence of the regimes

- Dominant microinstability depends nontrivially on gradient and wave number
- Nonlinearly, the normalized sum of amplitudes of positive/negative frequencies (ITG/TEM contributions) shows a steep transition
- The average of the nonlinear frequency distribution can be used to determine the nature of the turbulence

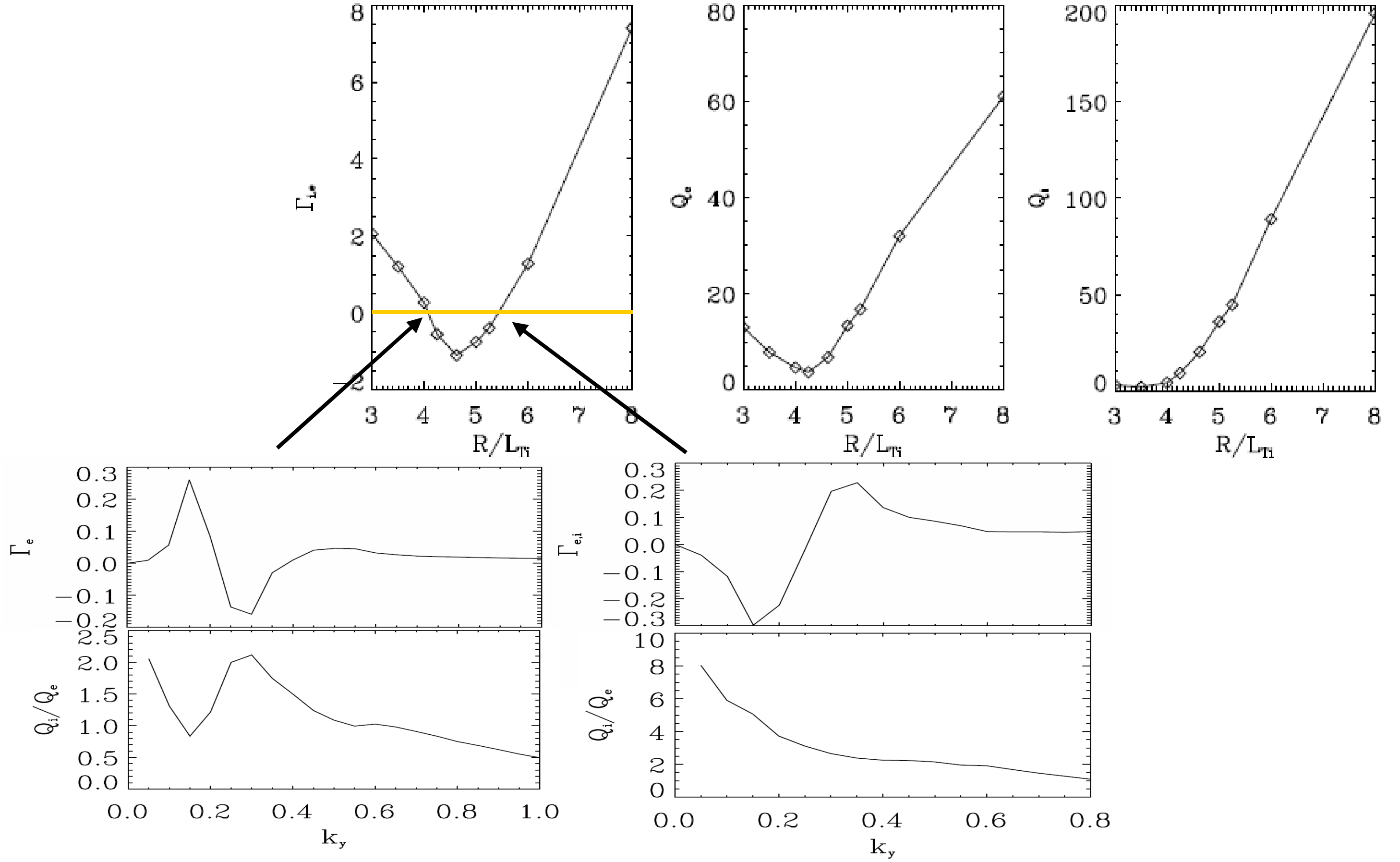


# Particle transport at the TEM-ITG transition

- Zero crossings of the particle transport important for quasistationary state in actual experiments

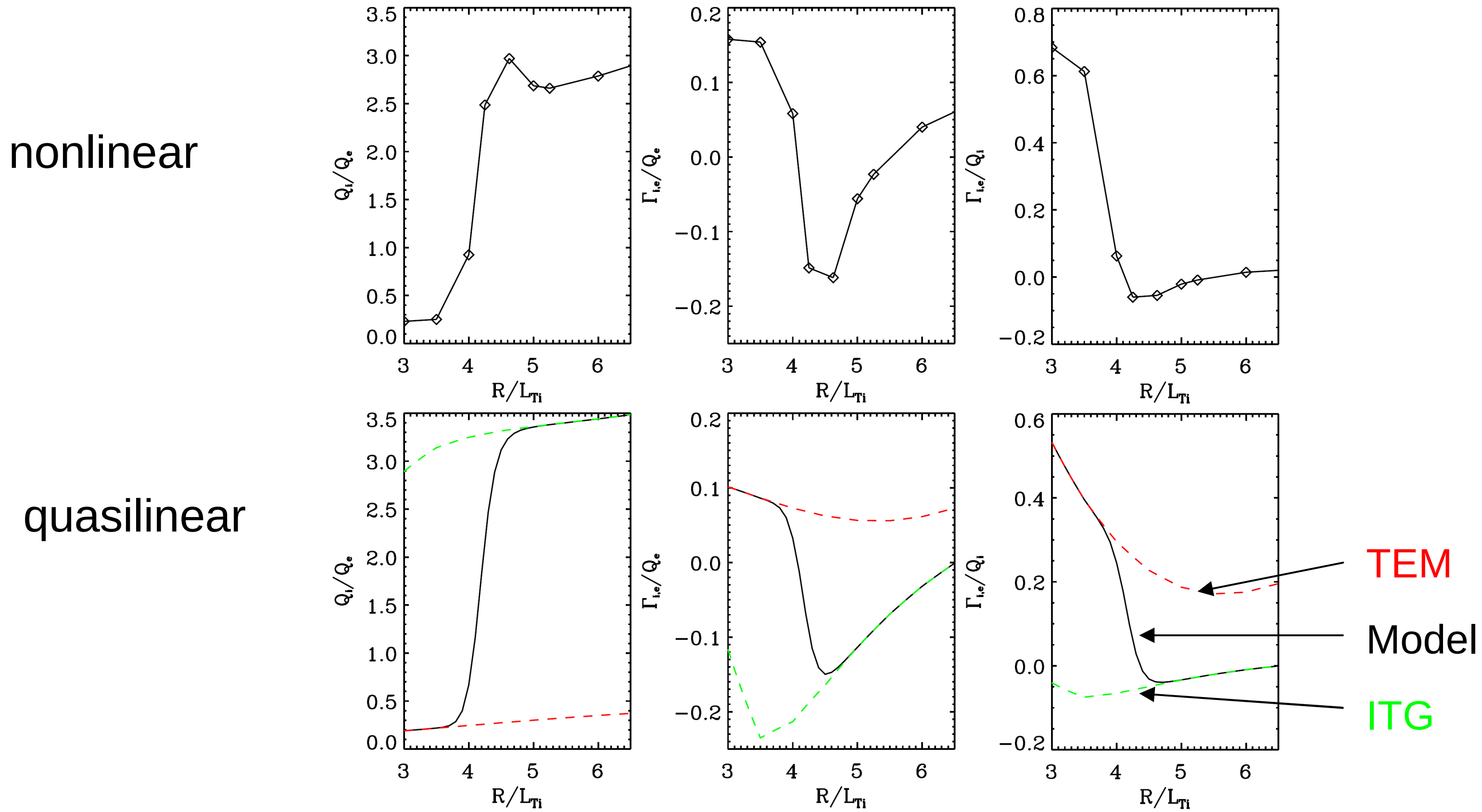



- Mechanisms: spectral balance of an ITG pinch with either TEM- or ITG induced outward transport at a different scale

# Simple quasilinear model for the flux ratios

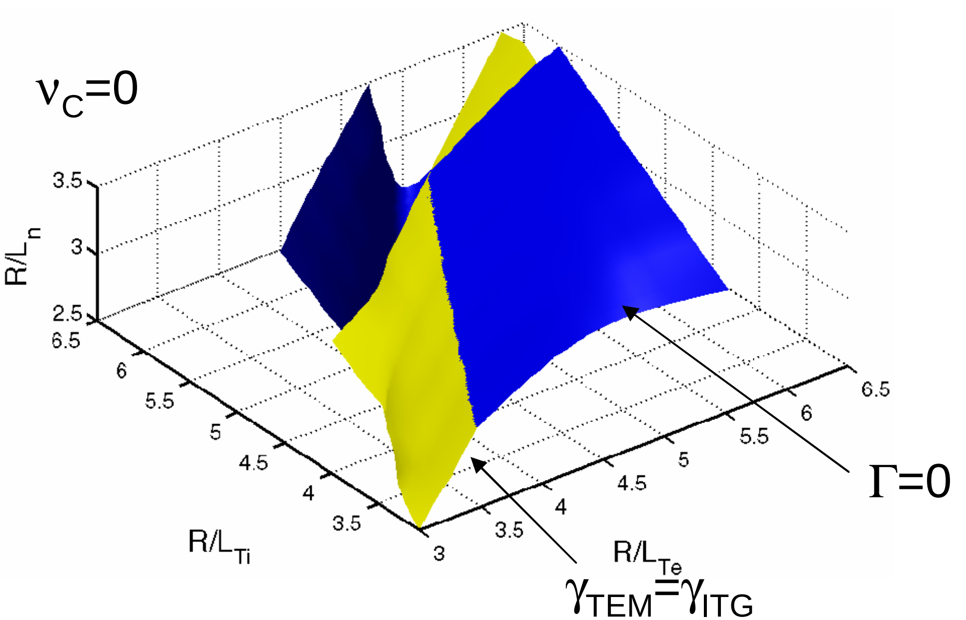
- Flux ratios can be determined from linear computations and are enough to determine $\Gamma$=0
- Only one 'central' $k_y$=0.25 to describe the whole spectrum
- Average of the two microinstabilities via $R_m = \frac{\gamma^p_{\rm TEM} R_{\rm TEM} + \gamma^p_{\rm ITG} R_{\rm ITG}}{\gamma^p_{\rm TEM} + \gamma^p_{\rm ITG}}$

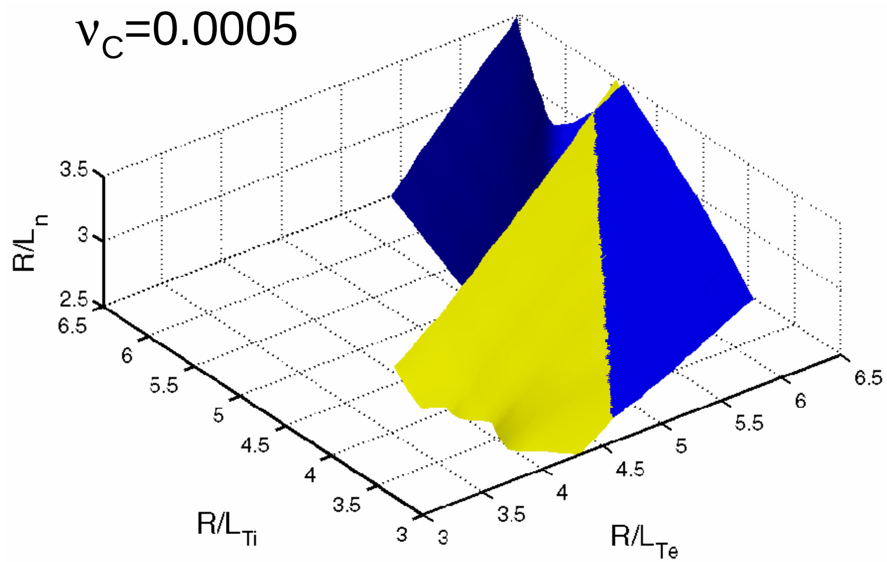
  with $R = (Q_i/Q_e, \Gamma/Q_e, \Gamma/Q_i)$, p=10



# Application of the quasilinear model

- The simplicity of the model allows for higher dimensional investigations of the $\Gamma$=0 hypersurface. The most important parameters are the gradients
- Example: dependence of the $\Gamma$=0 surface in gradient space on the collisionality



# Conclusions

- **Linear gyrokinetics**: non-Hermitian degeneracies connect different microinstabilities, close to the degeneracies, the traditional naming is misleading

- **TEM/ITG turbulence**: in the transition region, one finds
  - Spectral coexistence of TEM- and ITG-like turbulence and even remnants of both modes at the same wavenumber
  - A significant upshift of critical $R/L_{Ti}$ of ITG turbulence due to nonlinear TEM-ITG interaction
  - A determining role of the linear physics for the nonlinear behaviour
  - Zero particle flux by spectral balance of ITG pinch and outward transport by either TEM or ITG, which can be approximated by a simple quasilinear model to study higher dimensional parameter dependencies