# From electron to ion scales – nonlinear gyrokinetic multiscale simulations

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**EURATOM Assoziation**

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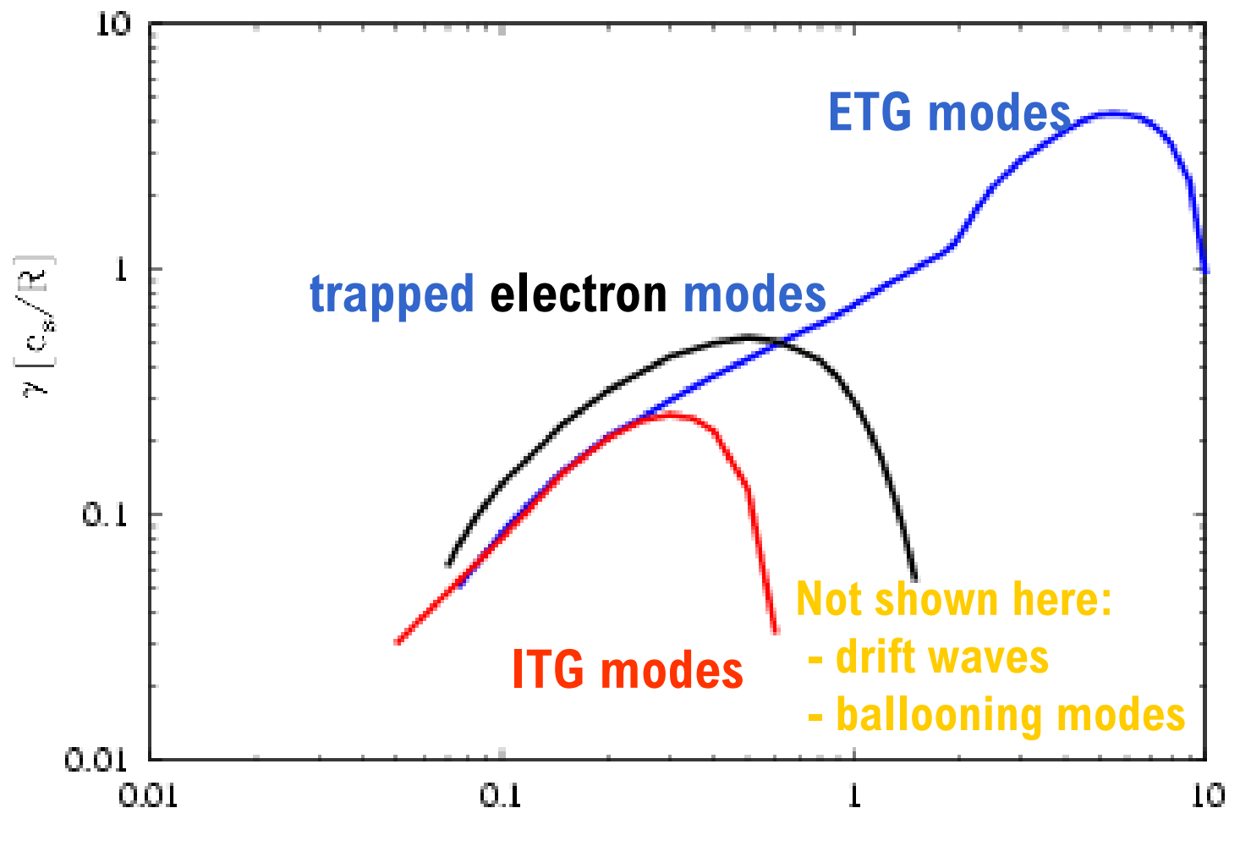
## I. Multiple scales in plasma microturbulence

- Examples: ITG/TEM and ETG modes
- Spatio-temporal separation defined by square root of ion-electron mass ratio (> 40)
- Covering both scales is computationally very demanding since high resolution in space and time is essential
- Therefore simulations are usually restricted to ion or electron gyroradius scale thus neglecting possible cross-scale coupling



*Linear growth rates of ITG/TEM and ETG modes, clearly a spatial-temporal separation can be seen between maxima*

### Role of sub-ion scales?

- **Theory:**
  - Nonlinear (pure) ETG simulations
    $\chi_e^{\mathrm{ETG}} \gg \frac{\rho_e^2 v_{te}}{L_{T_e}}$ is possible *(Jenko, Dorland et al., PoP/PRL 2000)* - confirmed in *(Nevins et al., PoP 2006) and (Bottino et al., PoP 2007)*
  - ETG in concert with longer wavelength turbulence (ITG, TEM, etc.)
    - first gyrokinetic multiscale simulations (with the GENE code): transport in the tokamak edge *(Jenko, J Plasma Fus Res 2004)*
    - recent core turbulence simulations *(Waltz et al., PoP 2007)* show small high-k (kρs>1) contribution
- **Experiment:**
  - ETG assumed to be present in several experiments
    - high frequency component present
    - evidence for transport contribution from high-k (at DIII-D)
  - Existence confirmed recently: *E. Mazzucato et al, PRL 2008*

## II. GENE – a nonlinear gyrokinetic Vlasov code

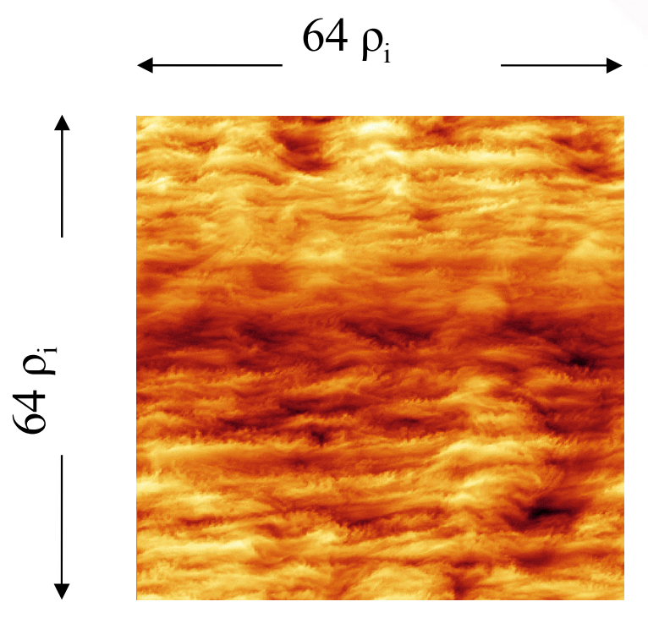
- Eulerian approach: fixed grid in phase space (no numerical noise)
- Local (flux tube) simulations in arbitrary geometries
- Time-explicit, finite difference and pseudo-spectral methods
- Massively parallelized

- Fully gyrokinetic electrons and ions
- Fully electromagnetic fluctuations
- Realistic collision operators
- Initial value and Eigenvalue solver (allowing for investigation of subdominant modes) implemented

**References:**
F. Jenko, W. Dorland, M. Kotschenreuther, and B. N. Rogers, Phys. Plasmas **7**, 1904 (2000)
T. Dannert and F. Jenko, Phys. Plasmas **12**, 072309 (2005)
M. Kammerer, F. Merz, and F. Jenko, Physics of Plasmas **15**, 052102 (2008)
F. Merz, "Gyrokinetic simulation of multimode plasma turbulence" (PhD dissertation, Westfälische Wilhelms-Universität Münster , 2008)

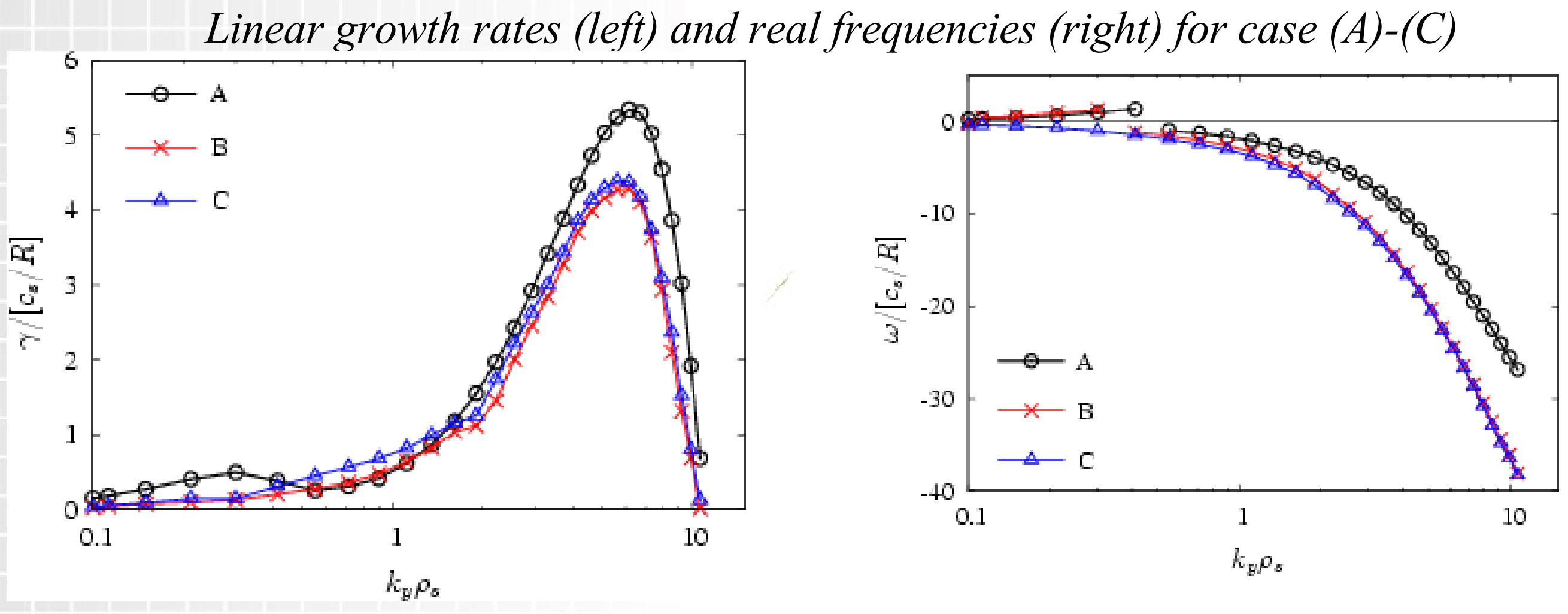
## III. Simulation details

- Physical model & parameters
  - Cyclone-like – except for profile gradients:
    **A) $R/L_{T_i} = 6.9$, $R/L_{T_e} = 6.9$, $R/L_n = 2.2$**
    **B) $R/L_{T_i} = 5.5$, $R/L_{T_e} = 6.9$, $R/L_n = 0.0$**
    **C) $R/L_{T_i} = 0.0$, $R/L_{T_e} = 6.9$, $R/L_n = 0.0$**
  - For simplicity: *electrostatic, collisionless, s-α-model equilibrium*
- Numerical parameters
  - perpendicular *box size*:
    64 x 64 ion gyroradii
  - perpendicular *resolution*:
    1.5 x 3 electron gyroradii
- **Reduced** mass ratio: from $m_i/m_e = 1836$ to $m_i/m_e = 400$
  - computational effort lowered by one order of magnitude:
    $T_{CPU} \sim (m_i/m_e)^{3/2}$
  - Still more than 100,000 CPUh / simulation



## IV. Linear results

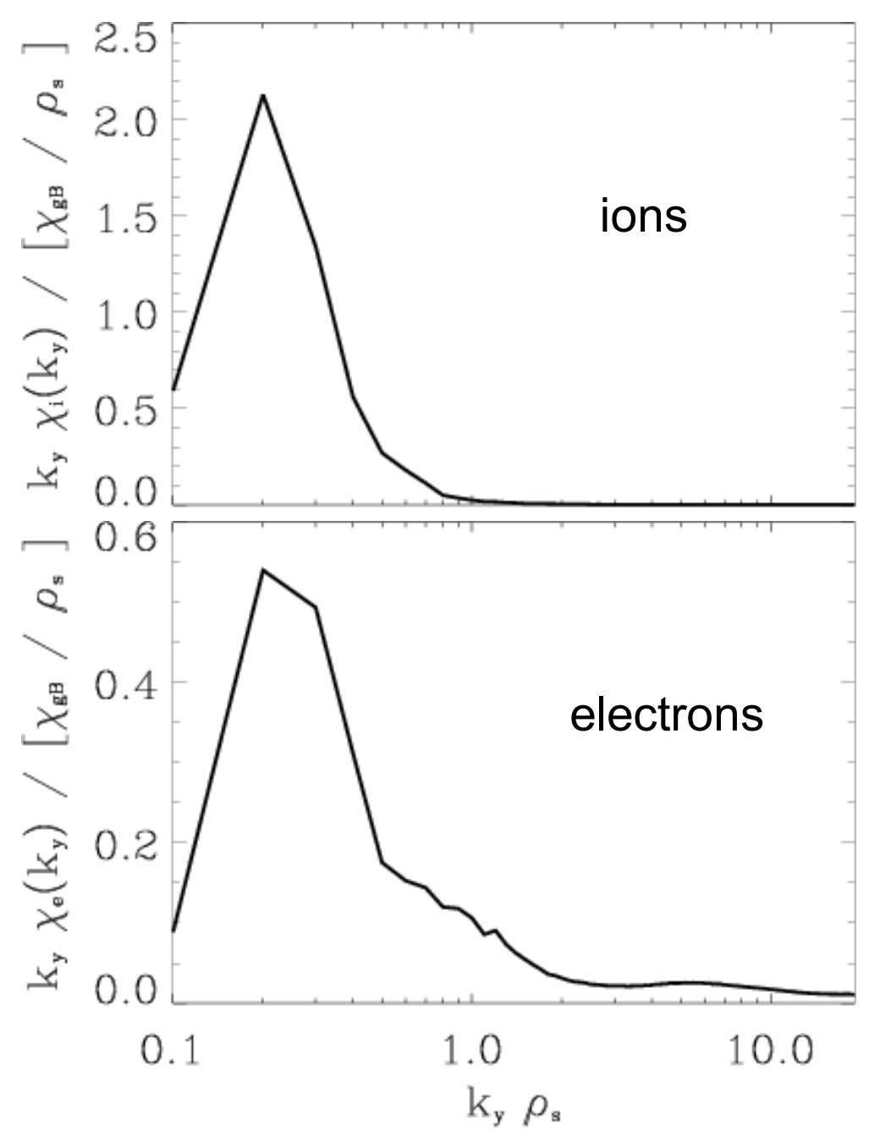
*Linear growth rates (left) and real frequencies (right) for case (A)-(C)*



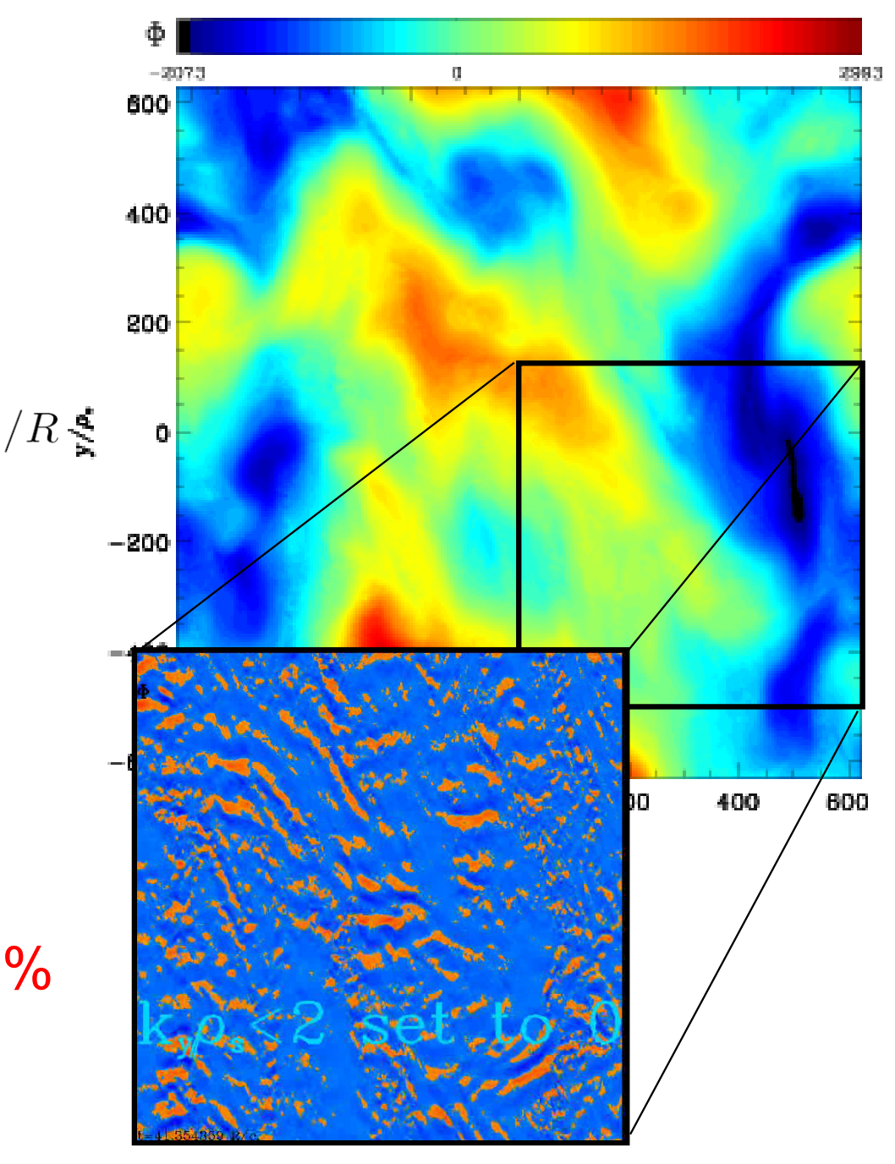
- In case (A) and (B) dominant ITG mode at low-k, afterwards a TEM can be seen which transitions smoothly into an ETG mode

## V. Nonlinear results – case A

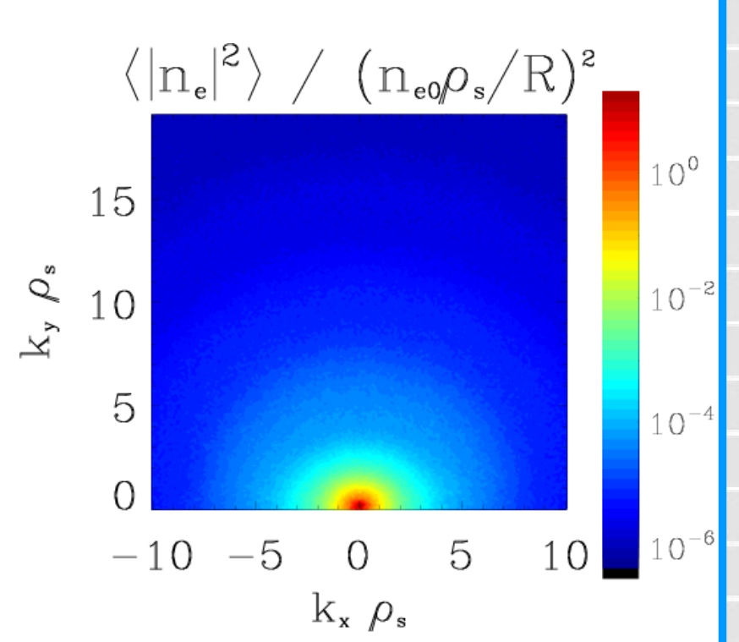
**Case A:** $R/L_{T_i}$=6.9,$R/L_{T_e}$ = 6.9, $R/L_n$ = 2.2 – **strong ITG**



- ion heat transport
  - localized at low-k
  - **unrealistically high:**
    $\chi_i^{\mathrm{sim}} \sim 23.7\, c_s\rho_s^2/R \gg \chi_i^{\mathrm{exp}} \sim 0.36\, c_s\rho_s^2/R$
- Electron heat transport
  - ETG nonlinearly present
  - 'high-k' contribution to electron heat transport ~10%
  - ETG streamer evolution hampered by large-scale vortex shearing



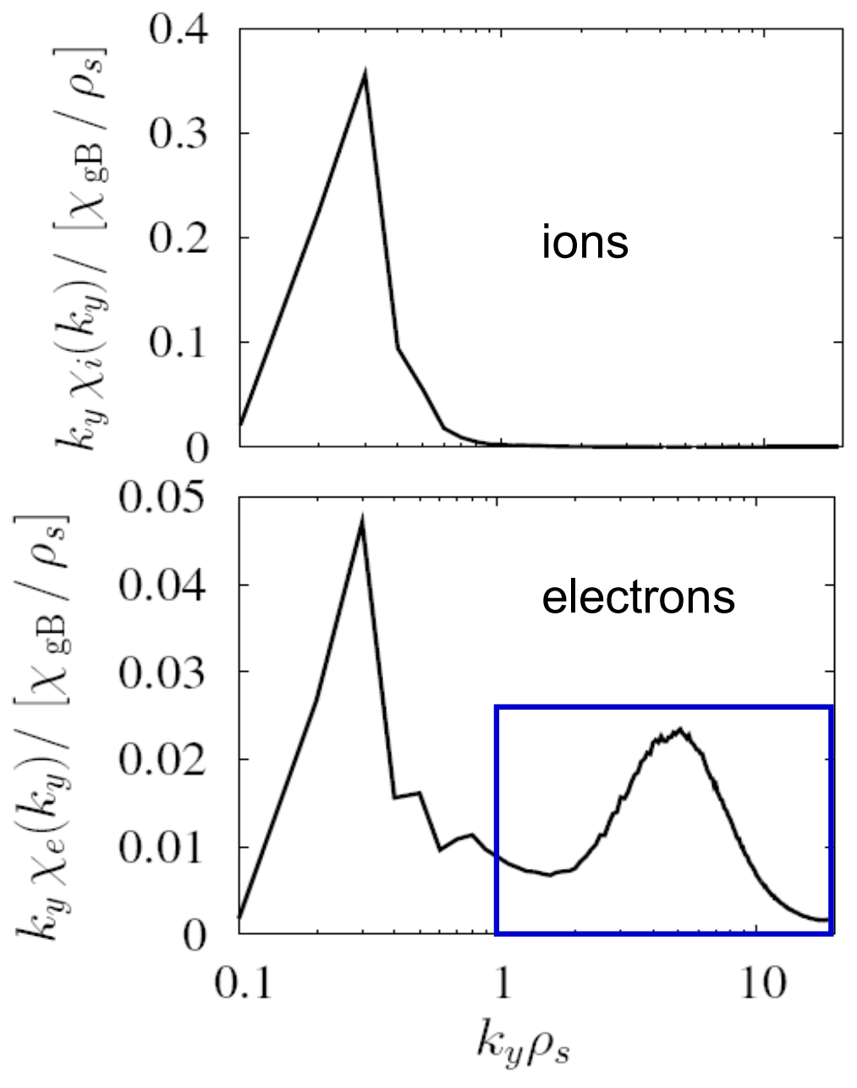
*Potential contour at outboard midplane together with a filtered detail*



*Squared density fluctuations isotropic*

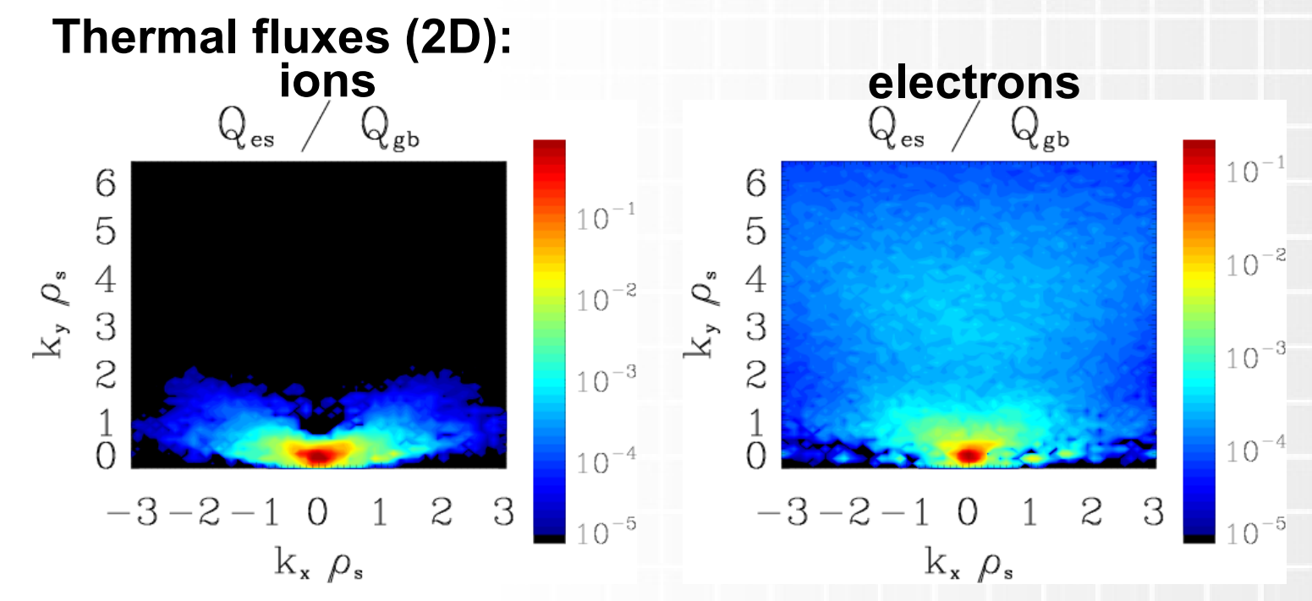
## VI. Nonlinear results – case B

**Case B:** $R/L_{T_i}$=5.5,$R/L_{T_e}$ = 6.9, $R/L_n$ = 0.0 – **weak ITG**

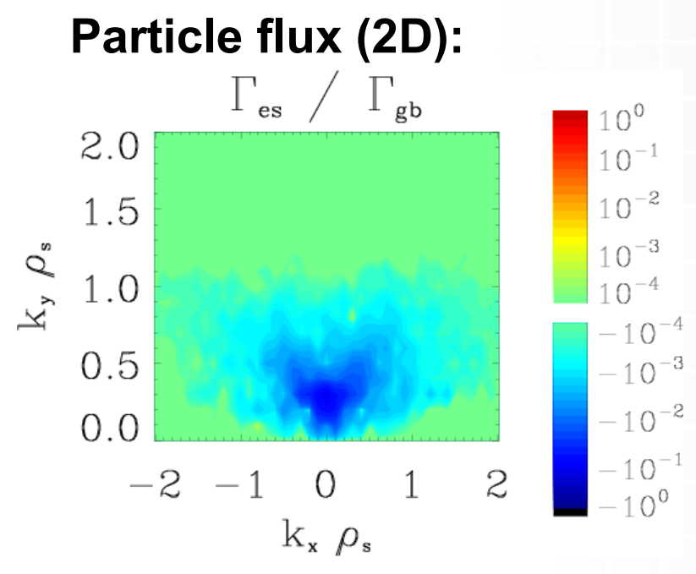


- ion heat transport still dominat but reduced by one order of magnitude
- more than 40% of the electron heat transport is in the 'high-k' regime!

Scale separation between ion and electron heat transport



→ high-*k* transport anisotropy which has been absent in case A

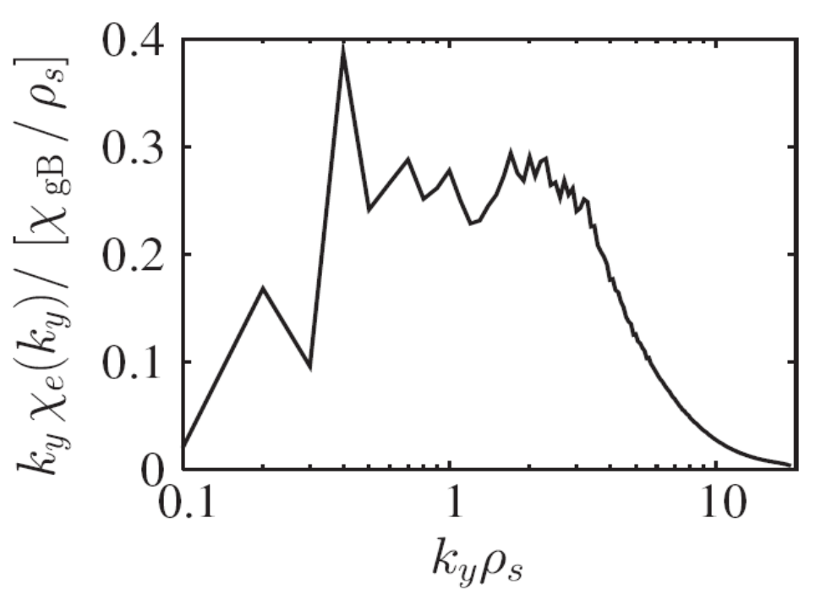


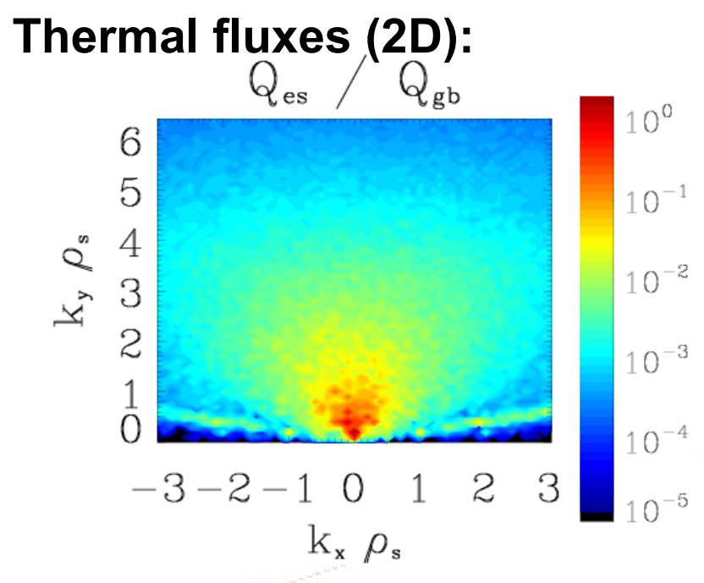
Particle flux

- similar to case A (not shown)
- negative (pinch)
- restricted to low-k due to increasing ion "adiabaticity" at higher wavenumbers

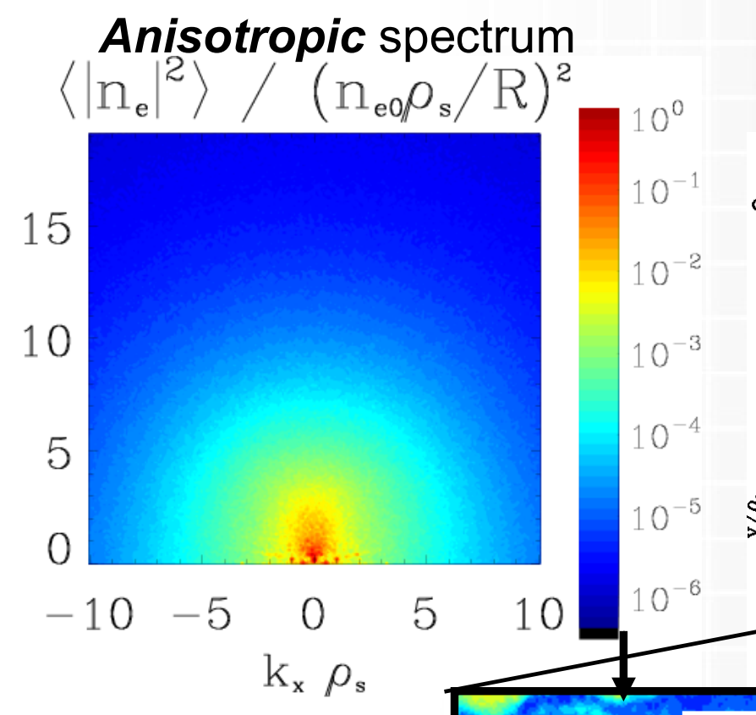
## VII. Nonlinear results – Case C

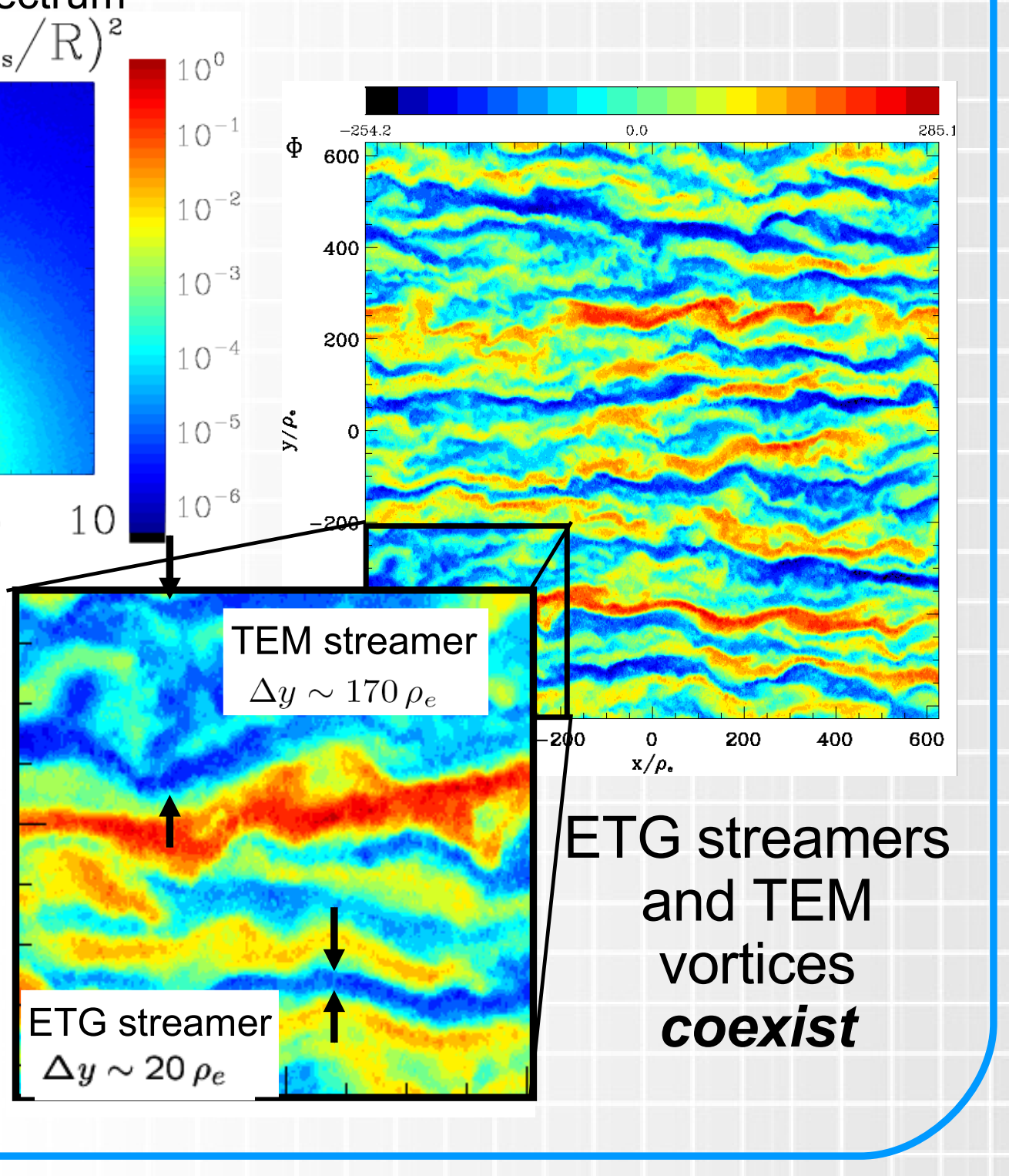
**Case C:** $R/L_{T_i}$=0.0,$R/L_{T_e}$ = 6.9, $R/L_n$ = 0.0 – **no ITG**





- Ion heat flux negligible
- Only TEM and ETG modes unstable (dominant electron heating, high beta values, substantial equilibrium ExB shear, ITBs)
- More than 50% of the electron heat transport is in the 'high-k' regime!
- ETG transport level ($\chi_e > 10\,\frac{\rho_e^2 v_{te}}{L_{T_e}}$) is in line with pure ETG simulations
- Transport fraction:
  - $k_y\rho_s > 1$: ~50%
  - $k_x\rho_s > 1$: ~30%
  - → high-*k* transport anisotropic

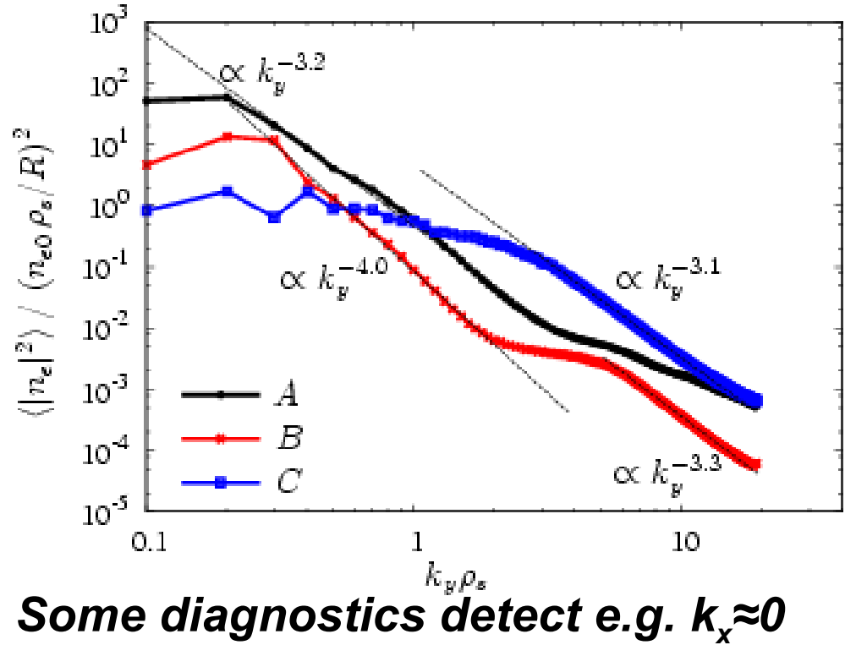




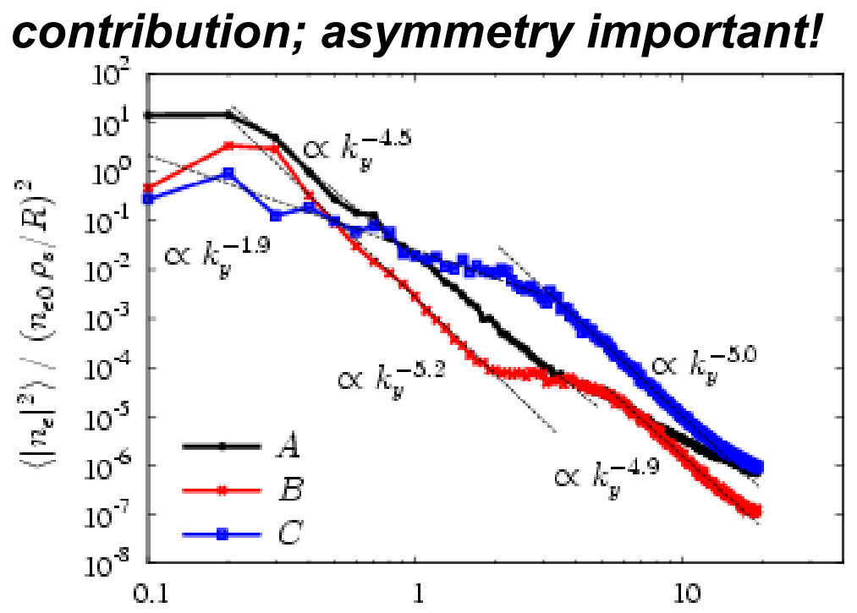
ETG streamers and TEM vortices ***coexist***

## VIII. Density and frequency spectra

*Squared density spectra*

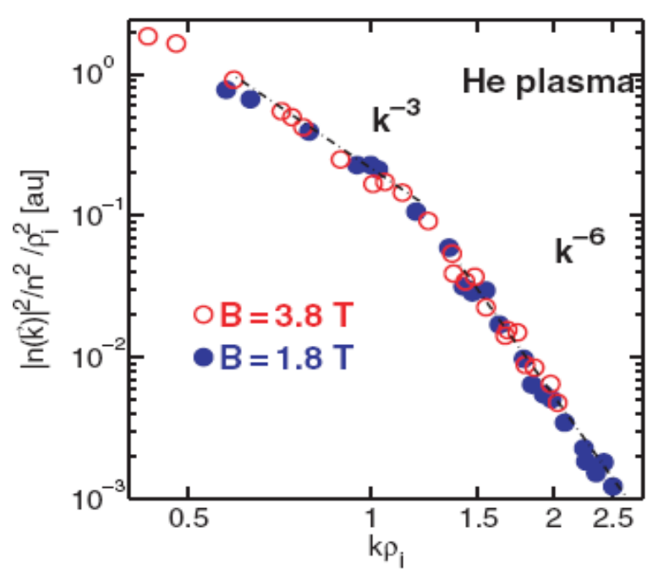


***Some diagnostics detect e.g. $k_x$≈0 contribution; asymmetry important!***



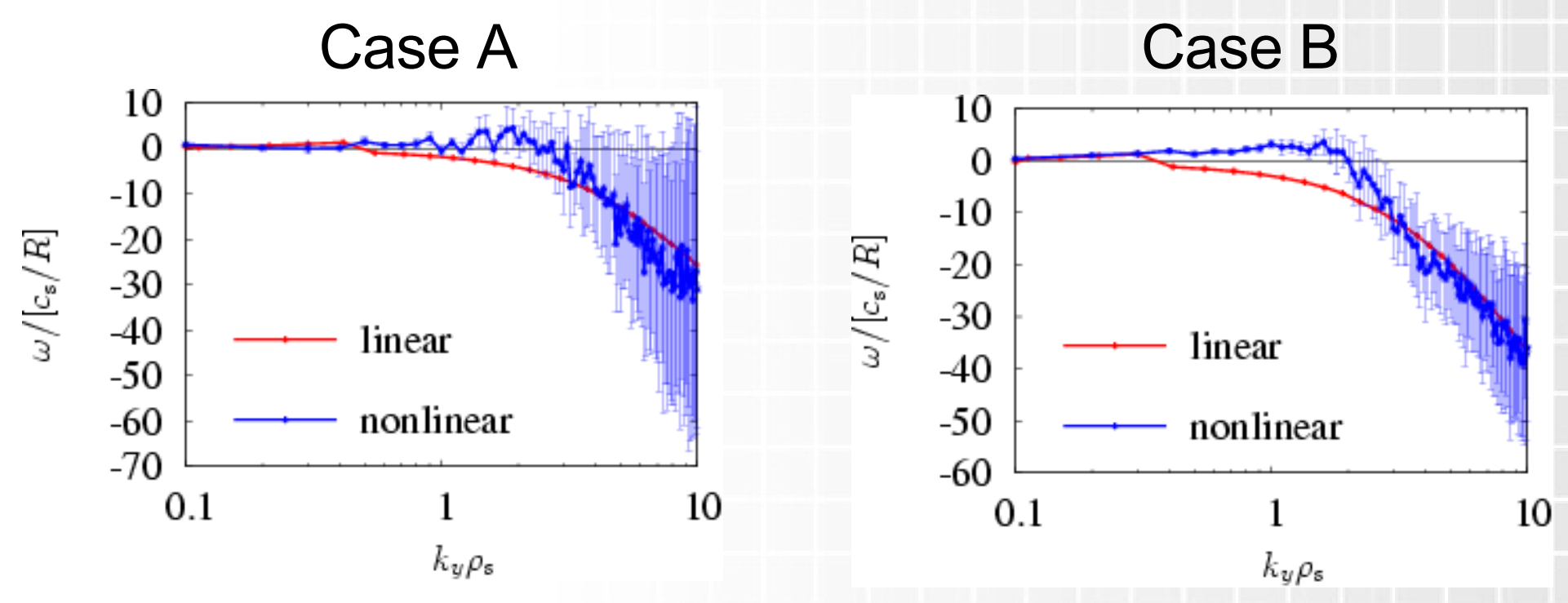
- **A second 'knee' is observed in multiscale simulations**
- **Power laws in pure and mixed turbulence sims: $\langle|n_e|^2\rangle \sim k_y^{-\alpha}$ with α~3.5**
- **Disagreement with experimental results (α~6)?**

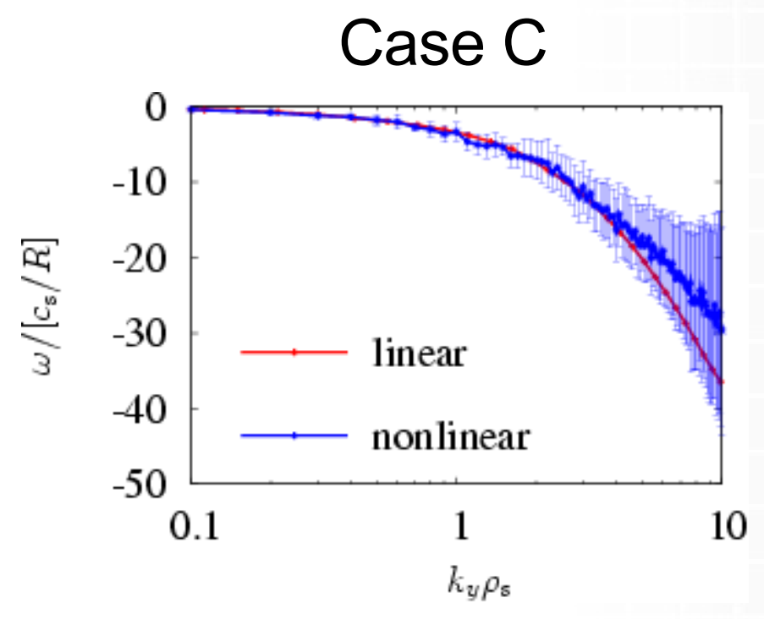
***Exp. Results (P.Hennequin et al., PPCF 46, B121)***



- **Power laws steeper at $k_x$=0, closer to experiment**
- **Similarities between blue (TEM/ETG) curve and exp. results**
- **High power law exponent (case C: α~5) does not imply negligible transport contribution**

*Frequency spectra*





- **Nonlinear and linear frequencies match over a wide range except for transition regime from dominant ITG to TEM/ETG**
- **Phase velocity on the order of $v_{ph} < 5\, c_s\rho_s/R$**

## IX. Summary and Conclusion

- If ETG modes are unstable
  – there tends to be a scale separation between ion and electron heat transport (the latter can exhibit substantial or even dominant high-k contributions) [*T. Görler and F. Jenko, PRL 100, 185002 (2008)*]
    - discharges with dominant electron heating, high beta, large equilibrium ExB shear
    - residual electron heat fluxes in transport barriers
  – density spectra tend to be anisotropic at higher k and may exhibit a flat region or modified power laws at $k_y\rho_e$~0.15-0.25 ($k_y\rho_s$~9-15 for D plasmas)
- Linear features (like cross phases or frequencies) tend to survive in the nonlinear simulations; deviations most pronounced in mode-transitional regimes