Nonlinear gyrokinetic simulations including ion- and sub-ion-scale dynamics

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GYROKINETICS FOR ITER
workshop

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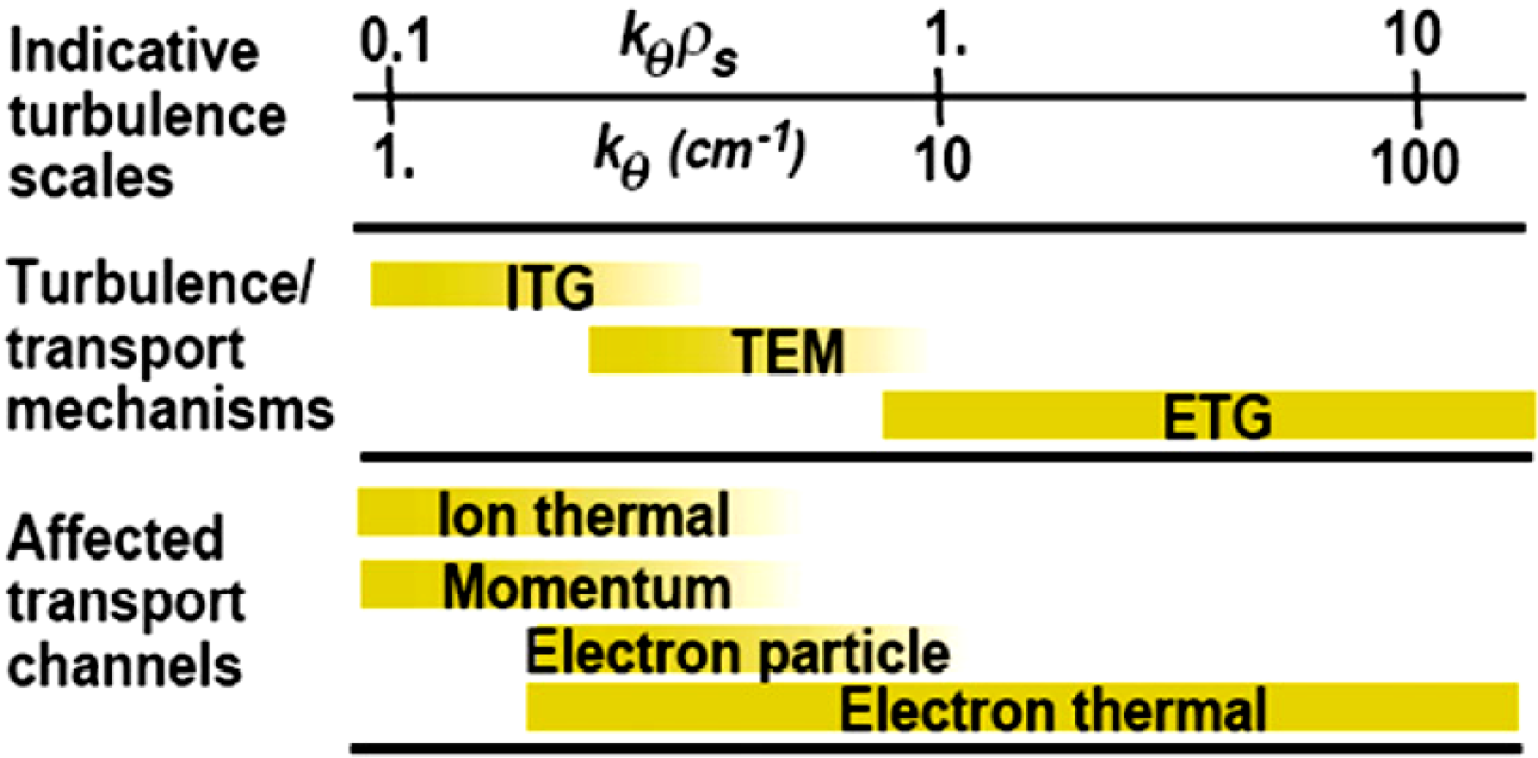
Multiple scales in Plasma microturbulence



Doyle et al.

- **ITG/TEM and ETG scales separated by** $\sqrt{\frac{m_i}{m_e}}$
- **TEM may transition smoothly to ETG**

Role of sub-ions scales?

- Significant transport contributions?
- Modeling possible? (→ group 7)
- Power laws? Cascades?

High-k turbulence simulations

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

$\chi_e^{\mathrm{ETG}} \gg \frac{\rho_e^2 v_{te}}{L_{T_e}}$ is possible (Jenko, Dorland, Rogers & Kotschenreuther, PoP 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.):

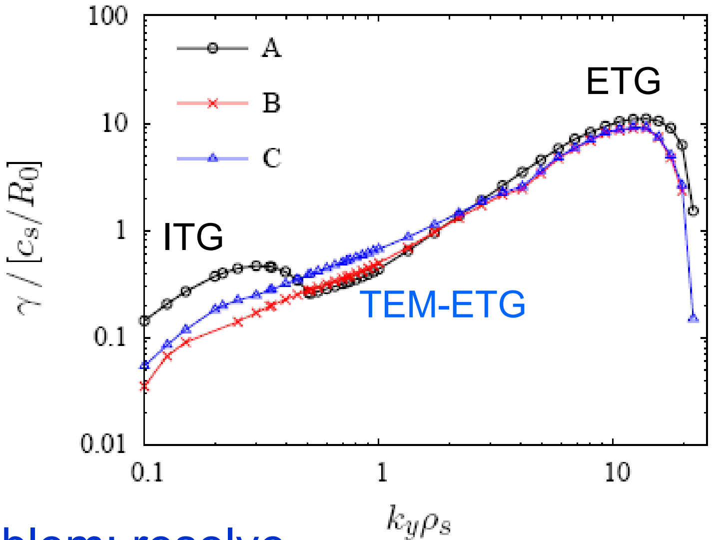
First gyrokinetic multiscale simulations:

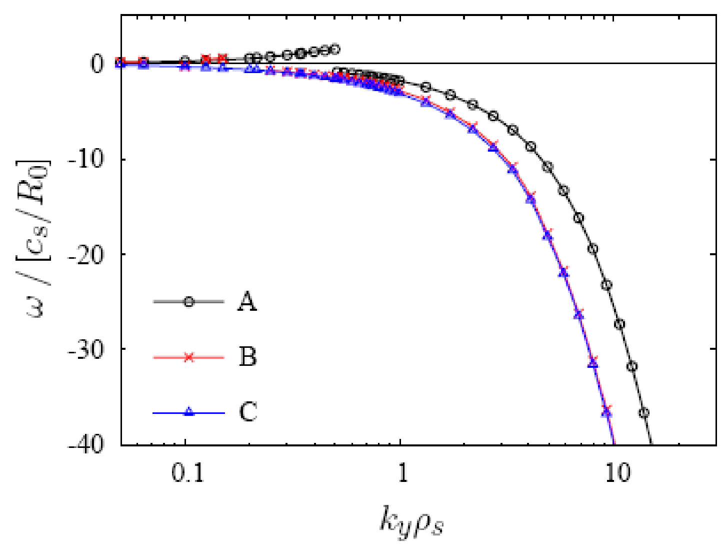
Transport in the tokamak edge (Jenko, J Plasma Fus Res 2004)

Similar work for core parameters by Candy and Waltz

Multiscale simulations with GENE

- Physical scenario
  - Coupled ITG/TEM, and ETG mode turbulence; three prototypical cases: **strong**, **weak**, and **no** ITG modes; *electron temperature gradient is kept fixed*
  - Cyclone-like – except for profile gradients; electrostatic, collisionless, s-α geometry





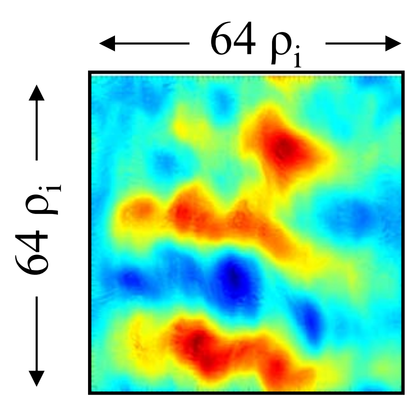
- Problem: resolve
  - Small electron gyroradius scales → many grid points in perp. directions
  - Large ion-scale turbulence → large perp. simulation box size
  - Fast electron dynamics → small time step
  - Slow ion dynamics → long simulation time

Multiscale simulations: parameters

- Numerical parameters (minimum set)
  - at least 800 radial (x), 400 binormal (ky), and 16 parallel (z) grid points
  - about 32 x (8-16) grid points in velocity space
  - two-species distribution function ~ 20 GB
  - computational time ~ several 10^6 CPUh for one(!) simulation

reduced mass ratio $m_i/m_e = 400$
$T_{CPU} \sim (m_i/m_e)^{3/2} \sim$ few 100k CPUh/sim.

- Final parameter choice:
  - perpendicular *box size*:
    64 x 64 ion gyroradii
  - perpendicular *resolution*:
    1.5 x 3 electron gyroradii



Heat transport spectra

Case A: strong ITG

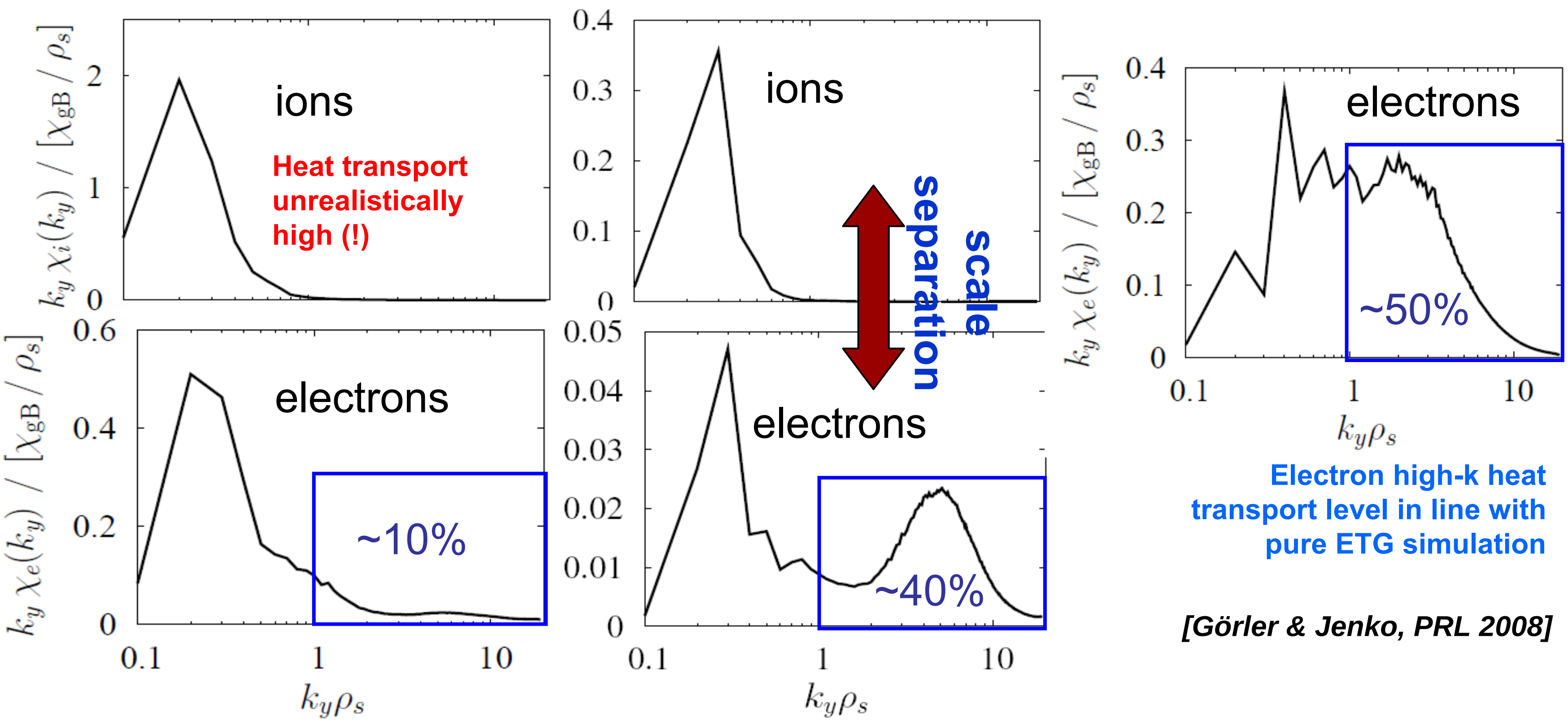
R/LTi=R/LTe=6.9, R/Ln=2.2

Case B: weak ITG

R/LTi=5.5, R/LTe=6.9, R/Ln=0.0

Case C: no ITG

R/LTi=0.0, R/LTe=6.9, R/Ln=0.0



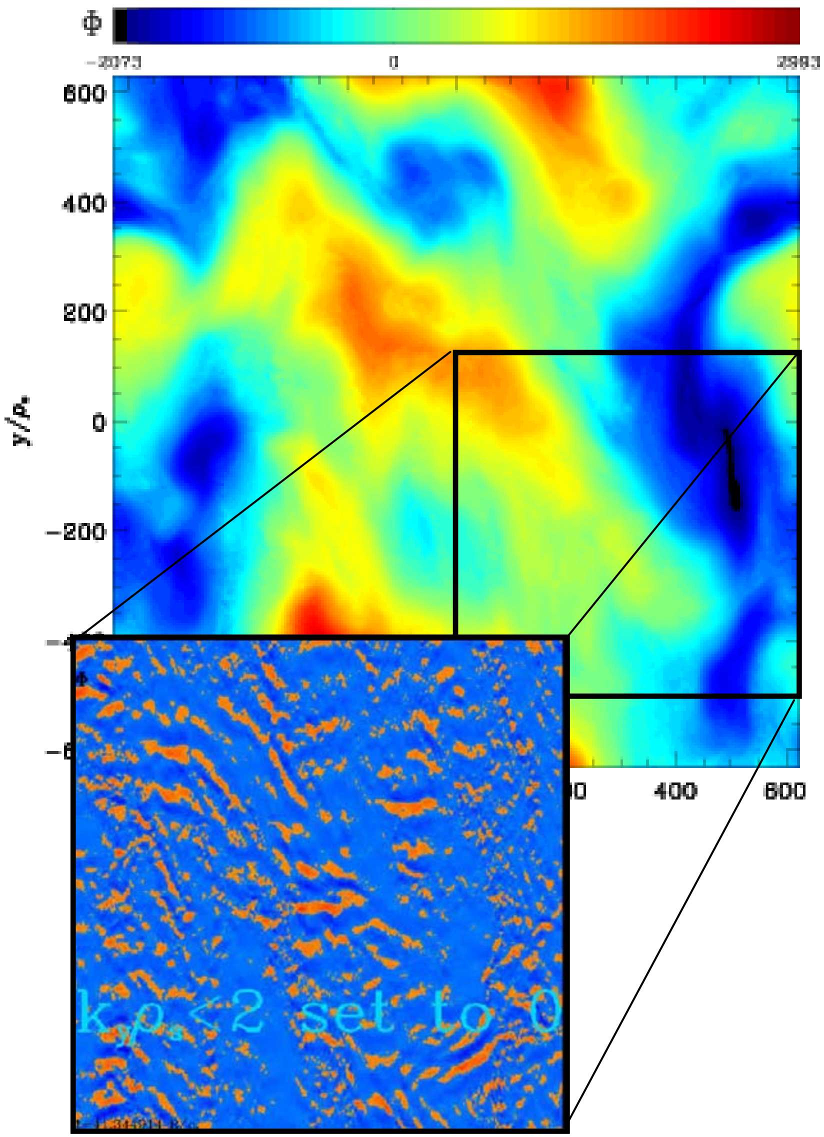
Electron high-k heat transport level in line with pure ETG simulation

[Görler & Jenko, PRL 2008]

<u>ITG/TEM/ETG turbulence</u>: large fraction of electron heat transport can be carried by electron scales (cmp. recent experiments)

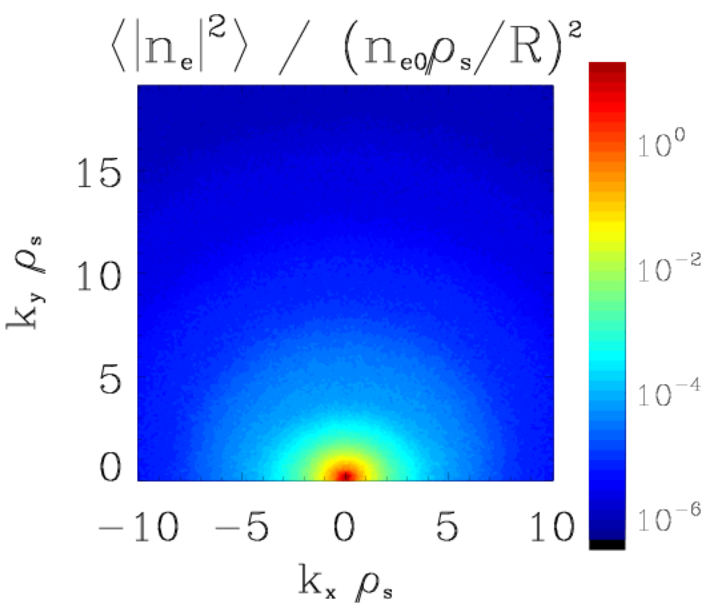
Possible explanations?

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



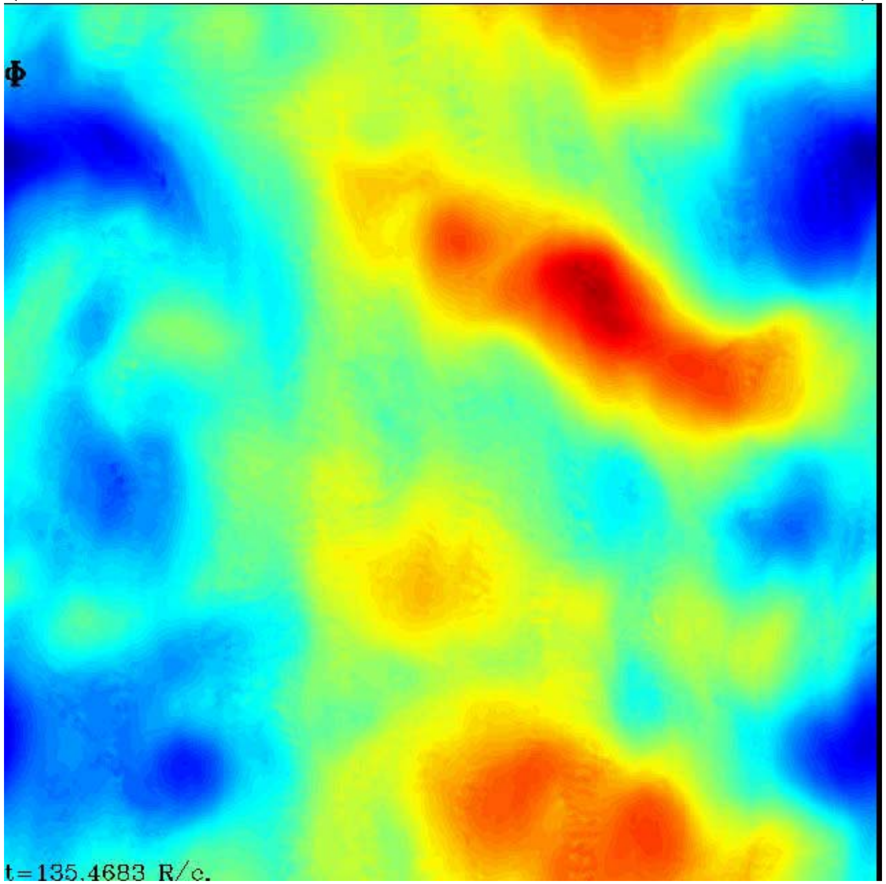
small-scale streamers are subject to large-scale vortex shearing

Isotropic **spectrum**



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

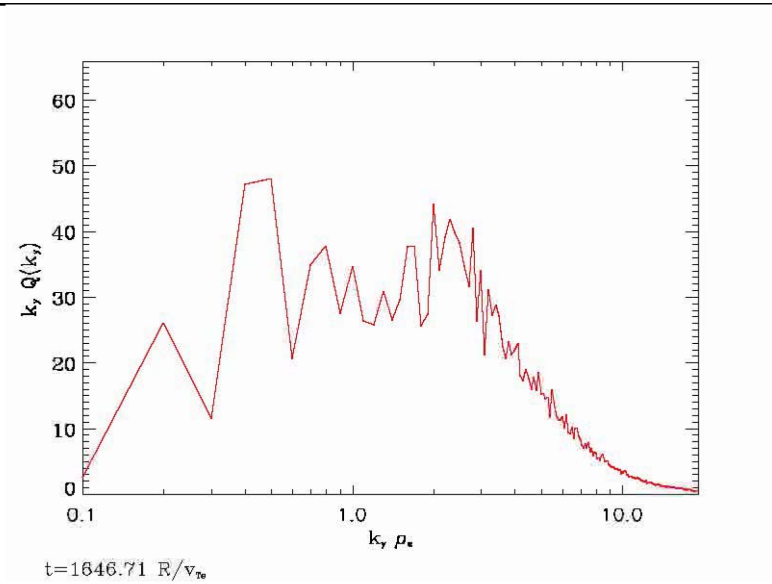
box size: ~64 ρ_i resolution: ~2ρ_e

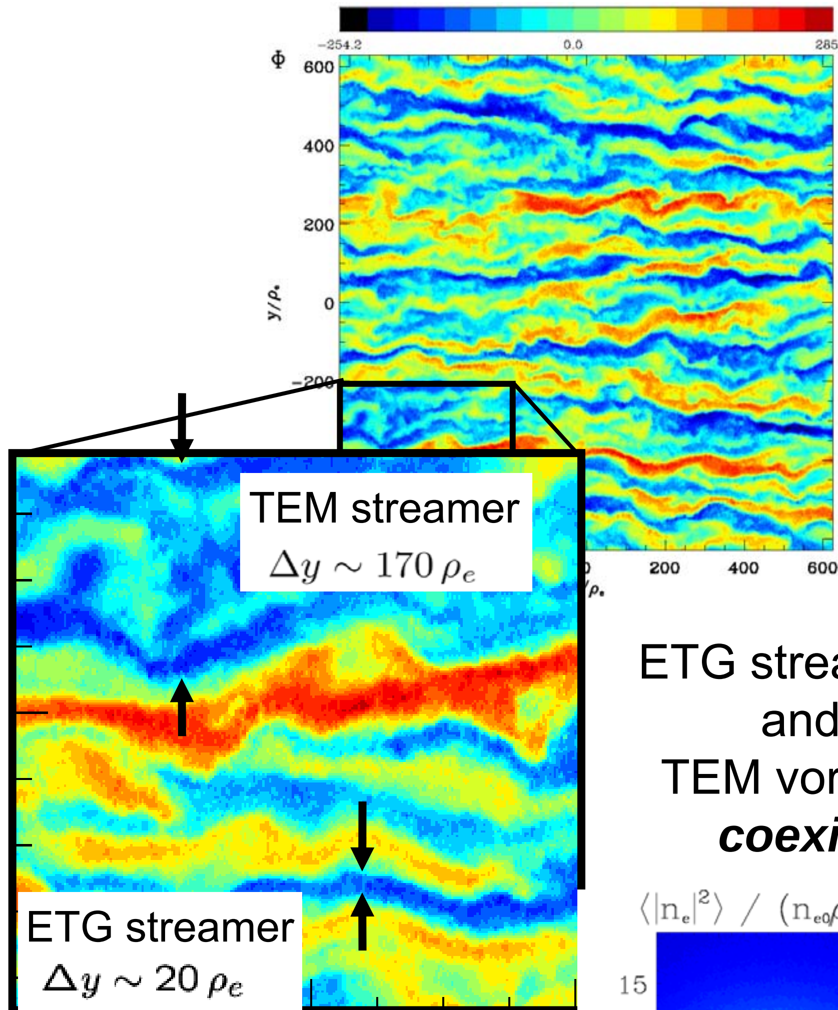


Small-scale structures with opposite drift direction observed

↔ high-k suppression weaker

Case C: R/L_{Ti}=0.0, R/L_{Te} = 6.9, $R/_{Ln}$ = 0.0 – **no ITG**

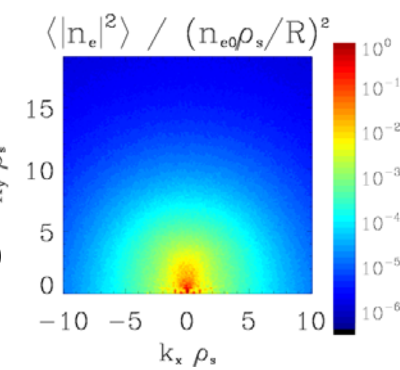




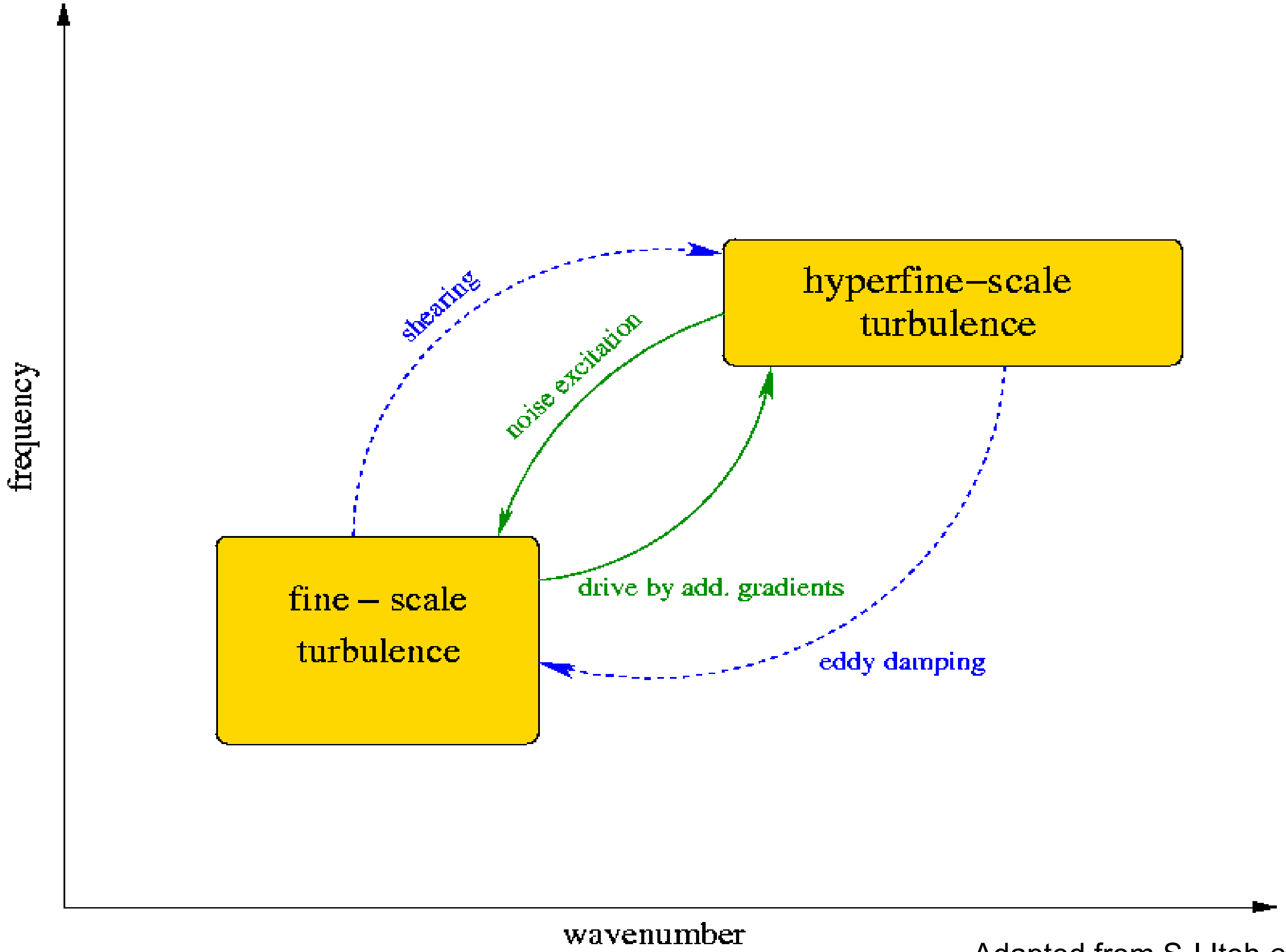
- Only TEM and ETG modes unstable
- More than 50% of the electron heat transport is in the 'high-k' regime!
- ETG transport level ($\chi_e > 10\,\frac{\rho_e^2 v_{te}}{L_{T_e}}$) is in line with pure ETG simulations

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

streamer → anisotropic spectrum (!)



Further examples for direct coupling mechanisms

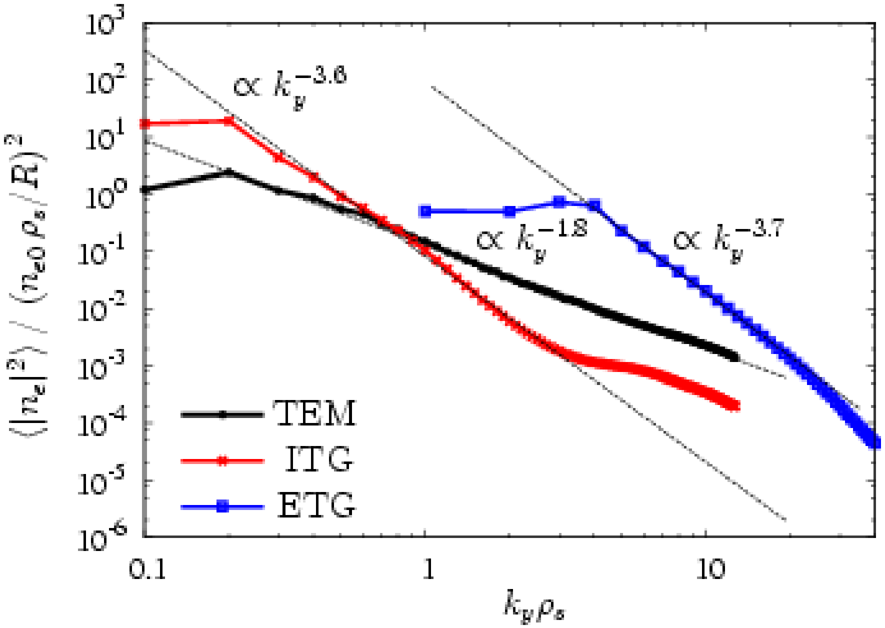


Adapted from S-I Itoh *et al.* (2001-2003)

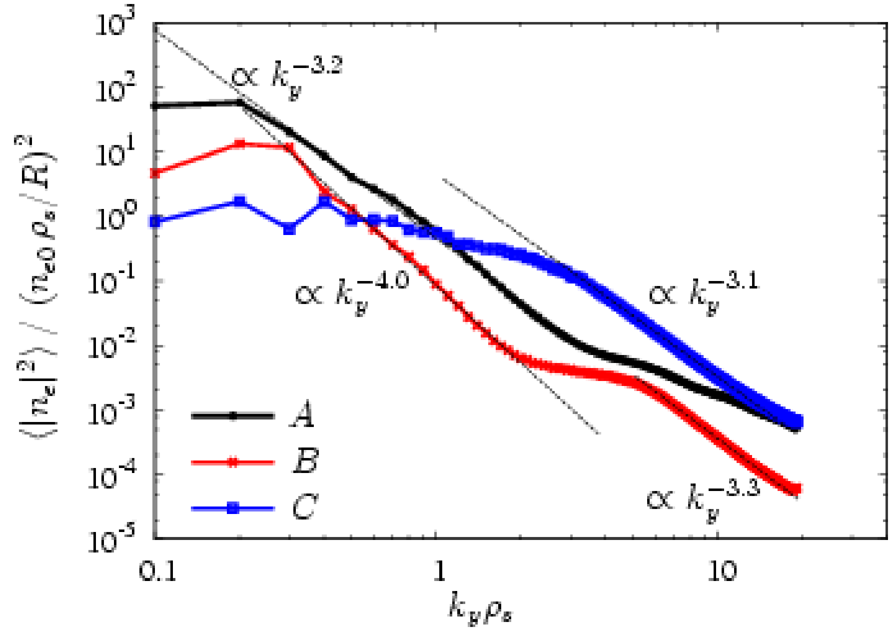
Density and frequency spectra

Comparison: Density spectra ((x,z,t) average)

(Linearly) *Pure* ITG, TEM and ETG simulation results



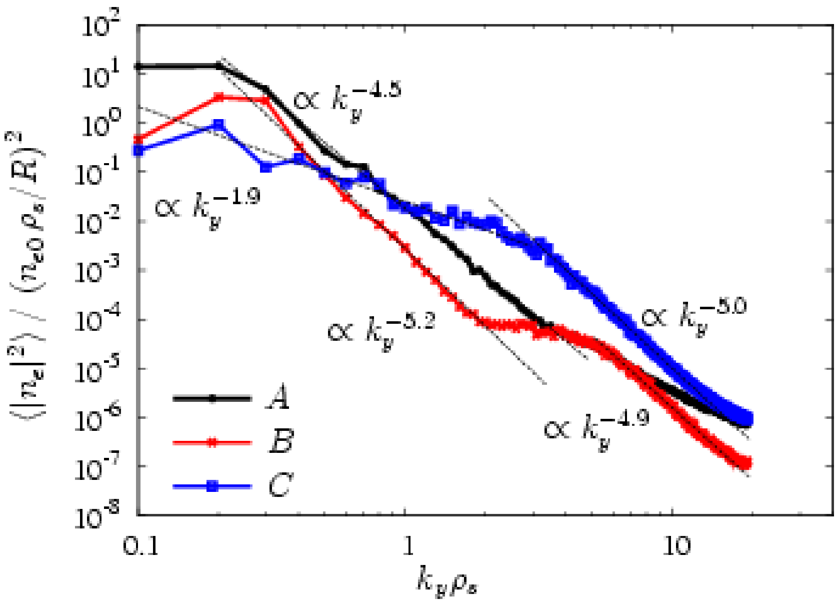
Multiscale simulation results



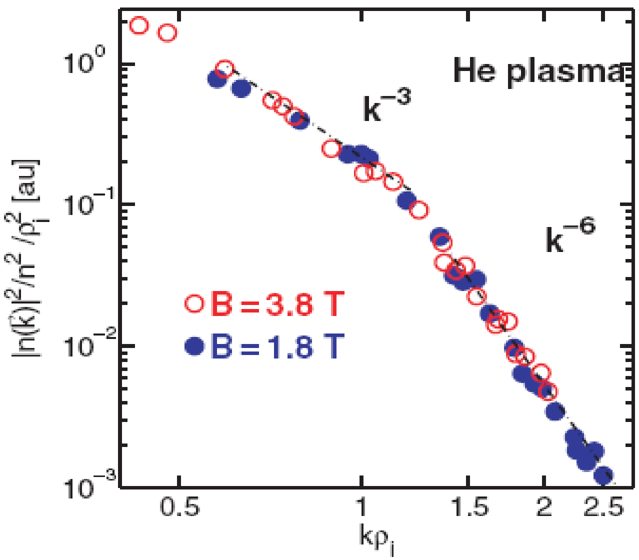
- **A second ‘knee’ is observed in multiscale simulations**
- **Power laws in pure and mixed turbulence sims: $<|n_e|>^2 \sim k_y^{-\alpha}$ with $\alpha \sim 3.5$**
- **Disagreement with experimental results ($\alpha \sim 6$)?**

Comparison: Density spectra (k_x=0, (z,t) avg.)

Some diagnostics detect e.g. $k_x \approx 0$ contribution; asymmetry important!



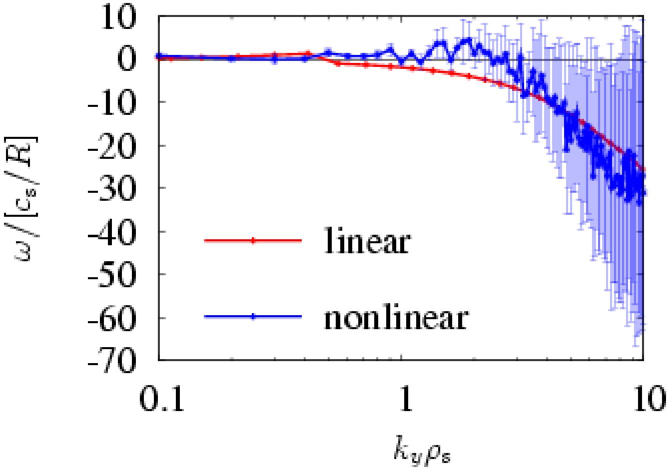
Exp. Results
(P.Hennequin et al., PPCF 46, B121)



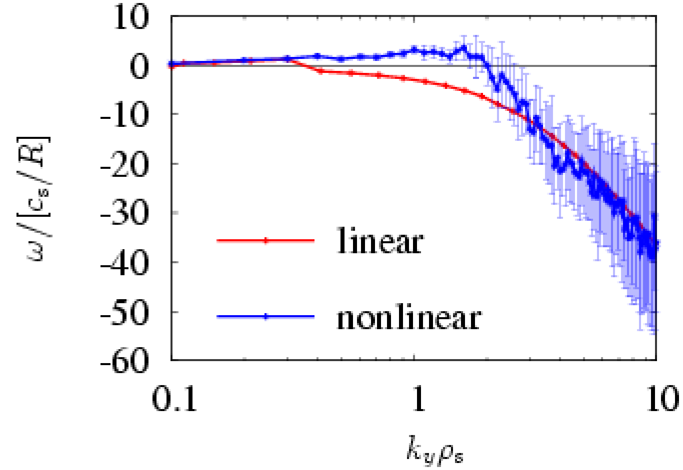
- **Power laws steeper at k_x=0, closer to experiment**
- **Similarities between blue (TEM/ETG) curve and exp. results**
- **High power law exponent (case C: α~5) does not imply negligible transport contribution**

Comparison: Frequency spectra

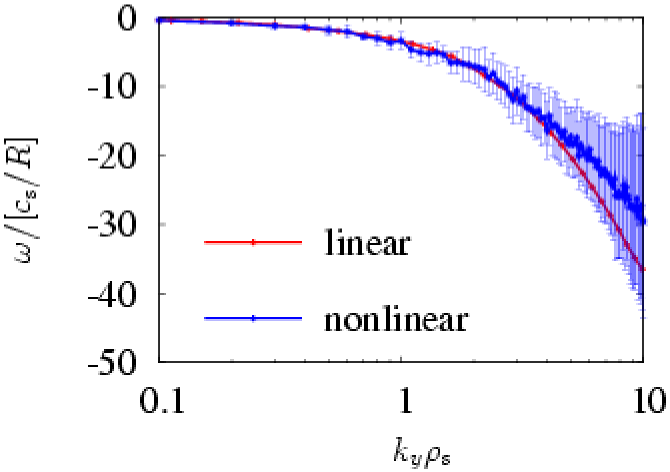
Case A



Case B

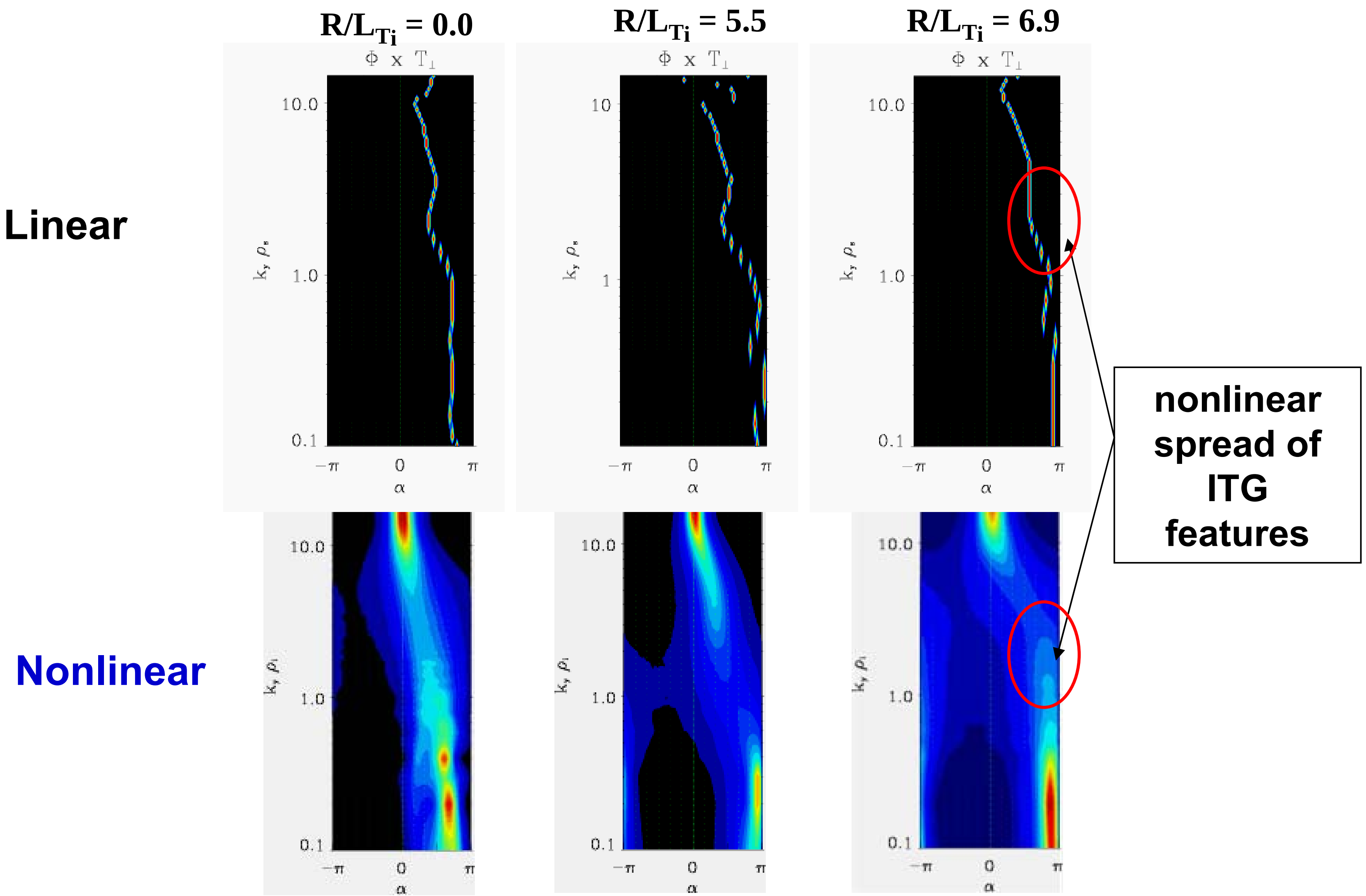


Case C



- **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 $v_{ph} \lesssim 5\ c_s\rho_s/R$**

Linear and nonlinear cross phases $\Phi \times T_{\perp}$



Summary: Multiscale features in nonlin. GK

- 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 [see group 3]
    - residual electron heat fluxes in transport barriers [see, e.g., *D. Told's talk*]
  - 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) [*T. Görler and F. Jenko, PoP 15, 102508 (2008)*]

- Linear features (like cross phases or frequencies) tend to survive in the nonlinear simulations; deviations most pronounced in mode-transitional regimes

Open questions

- Application to parameters adapted to specific experiments?
  - realistic geometry
  - realistic mass ratio
  - collisions, magnetic fluctuations, …
  - equilibrium ExB shear

- Further parameter scans required
  - Identify critical parameters where high-k modes become important

- Efficient sub-grid models for cases with minor high-k contributions (in order to avoid strange pile-ups in the spectra)

- **Link to phase-mixing results?**