Gyrokinetic simulations of microturbulence in DIII-D near-edge L-mode plasmas

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DIII-D NATIONAL FUSION FACILITY

PSTI UCLA Plasma Science and Technology Institute

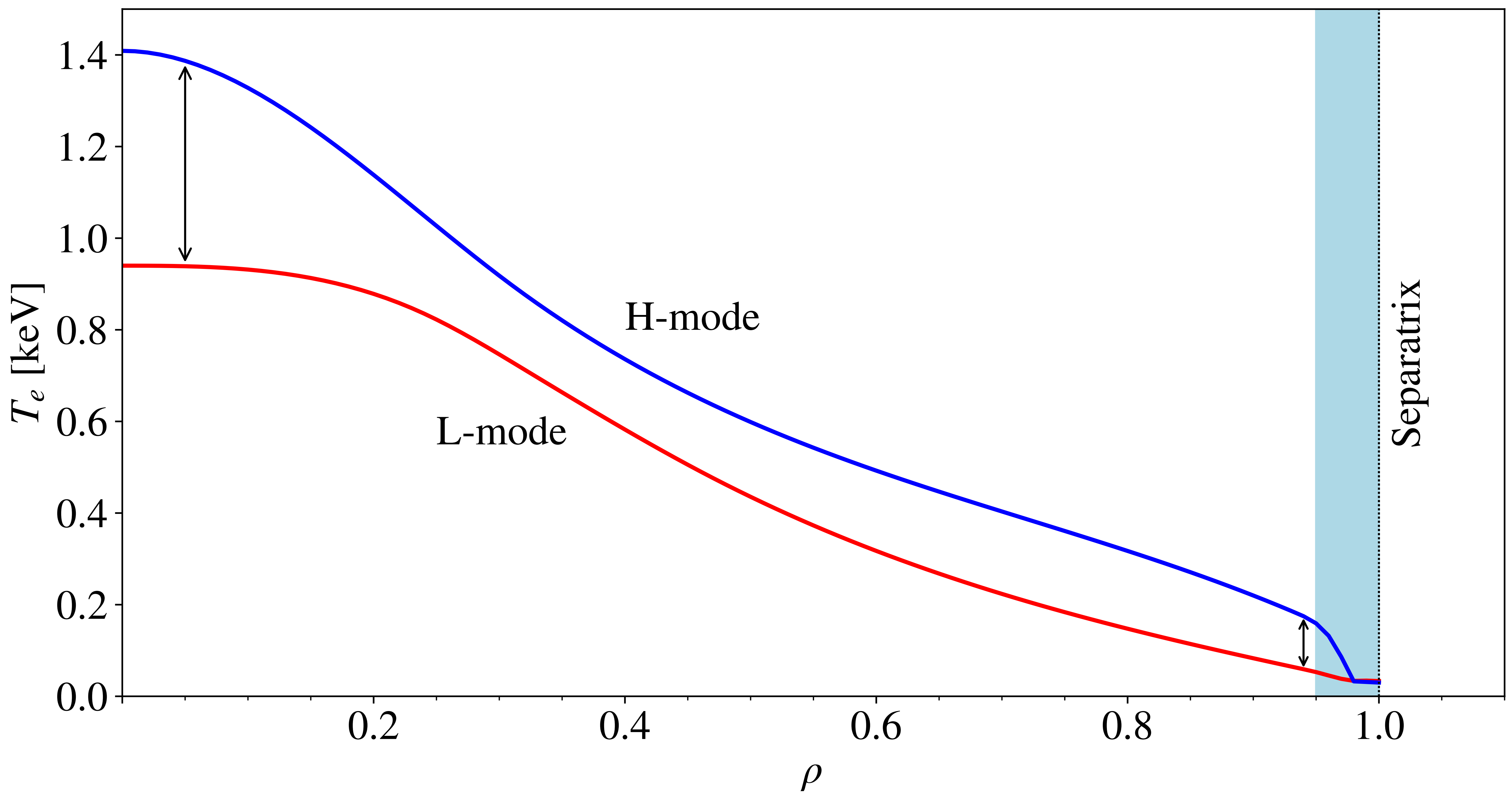
NERSC

Tokamaks are one of the most promising tools on the path towards commercial nuclear fusion

To go from post-diction to prediction, simulations must match experiment

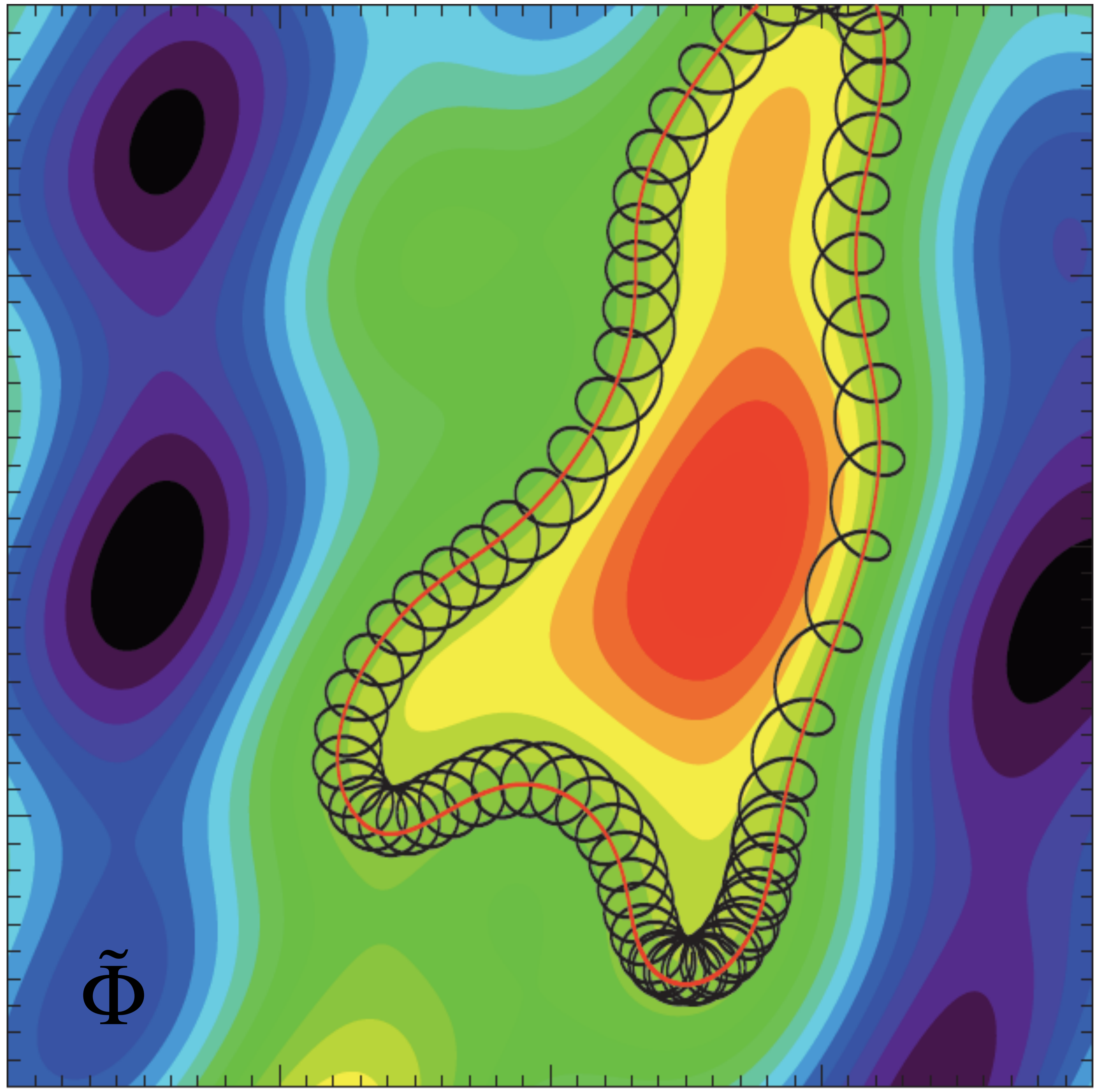
L-mode plasmas serve as initial condition for the L-H transition and are important for vertical stabilization during current ramp phases in ITER.

Near-edge ($0.80 \leq \rho \leq 0.95$) is testing ground for edge, where development of edge pedestal affects core parameters like a 'tail wagging the dog' [Snyder, Colloquium, 2009]

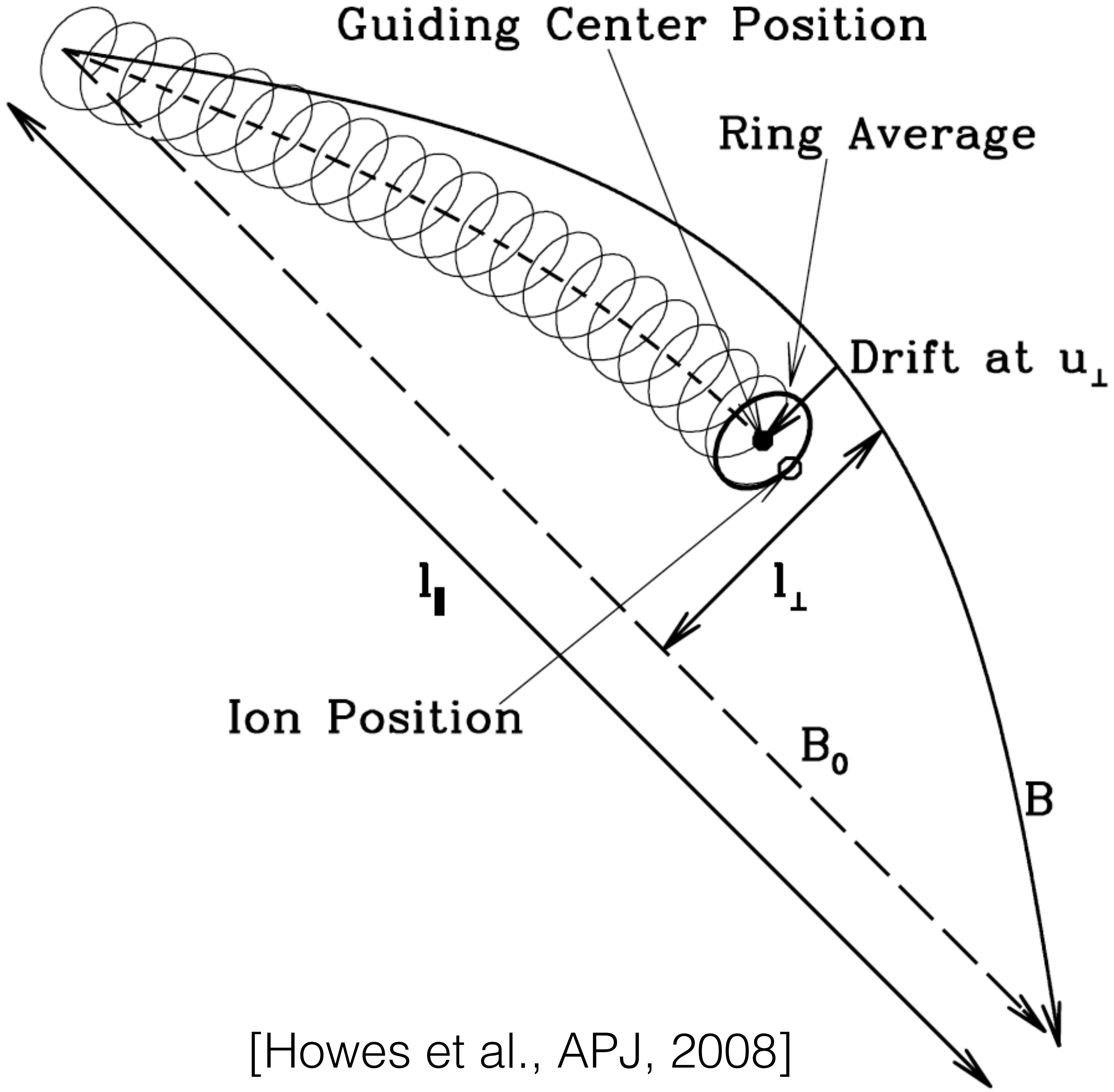


This work studies microinstabilities, multi-scale effects and the role of ExB shear in near-edge

Particle motion = fast gyration around a “guiding center” + relatively slow g.c. drift



[Jenko, HEPP Guest Lecture, IPP, 2013]



[Howes et al., APJ, 2008]

Gyrokinetic approximation makes realistic modeling of fusion plasmas possible

Six-dimensional distribution function:

$$f(\mathbf{x}, \mathbf{v}; t)$$

Kinetic equation:

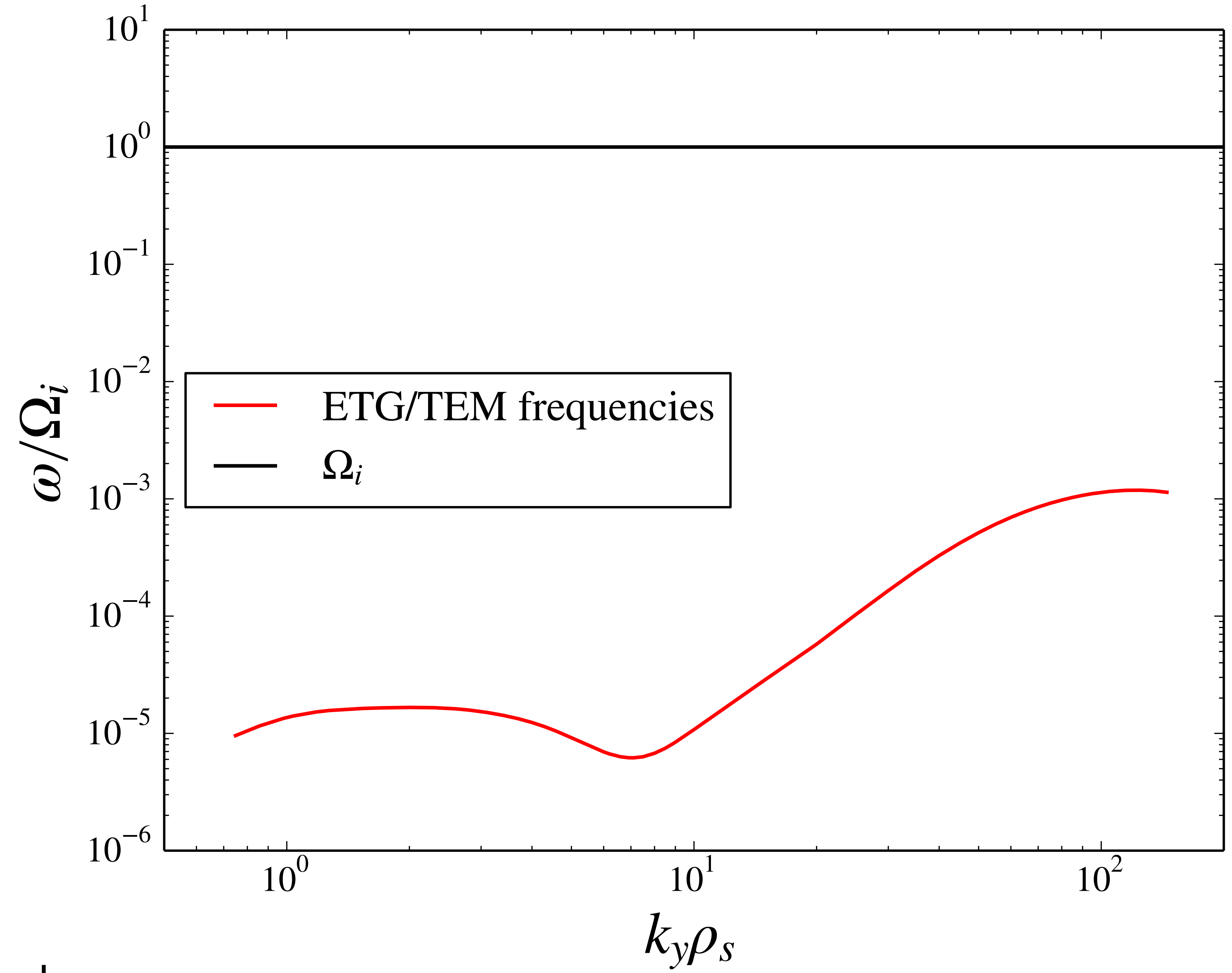
$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla_{\mathbf{x}} f + \frac{q}{m}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \nabla_{\mathbf{v}} f = \left(\frac{\partial f}{\partial t}\right)_c$$

Perturbation:

$$f = f_0 + \delta f$$

Gyrokinetic ordering:

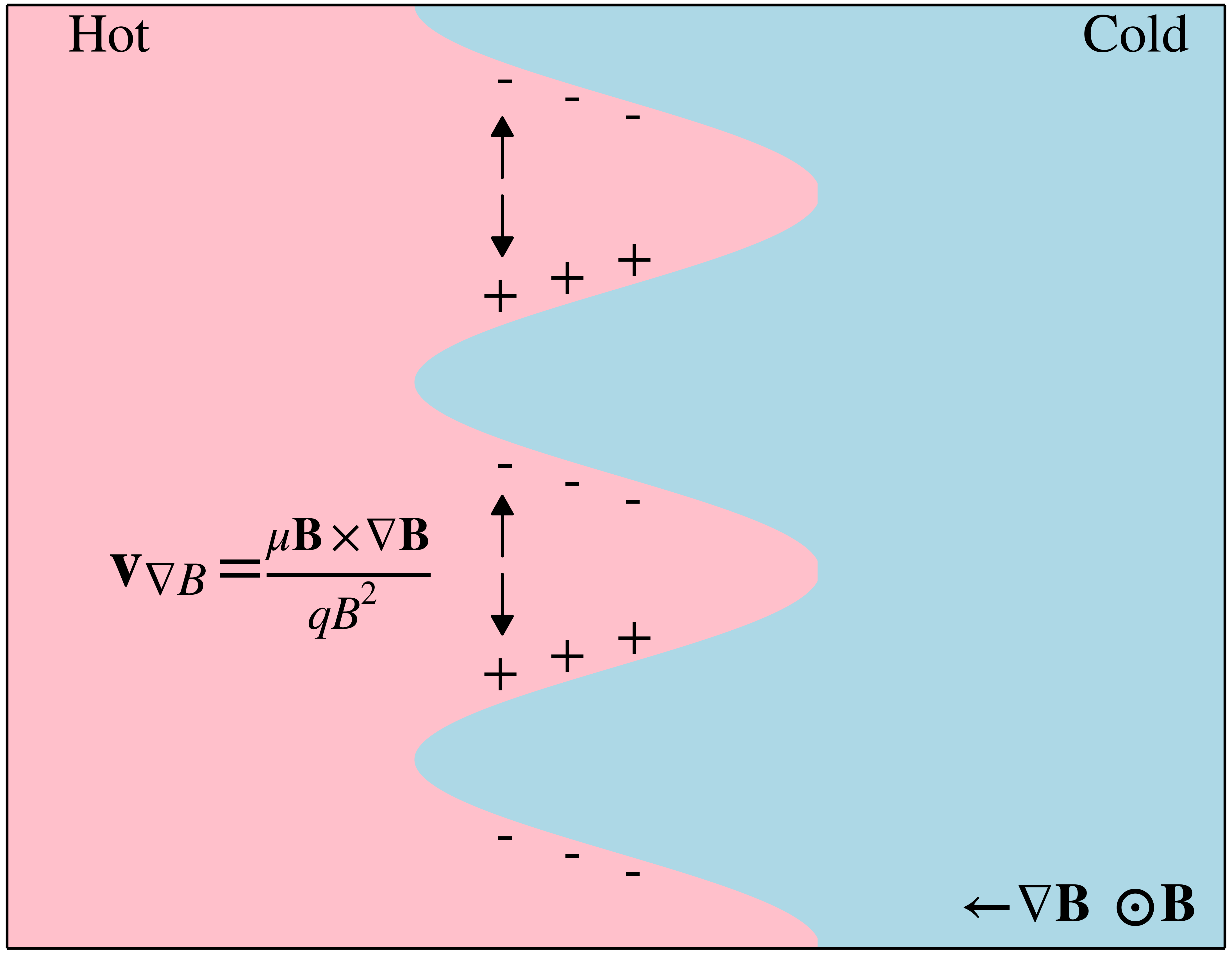
$$\frac{\omega}{\Omega_i} \sim \frac{\delta f}{f_0} \sim \frac{q\delta\phi}{T_0} \sim \frac{\delta n}{n_0} \sim \frac{\delta T}{T_0} \sim \frac{|\delta \mathbf{B}|}{\mathbf{B}_0} \sim \frac{\rho_{i,e}}{R} \sim \frac{k_{\parallel}}{k_{\perp}} \sim \epsilon \ll 1 \sim k_{\perp}\rho_{i,e}$$

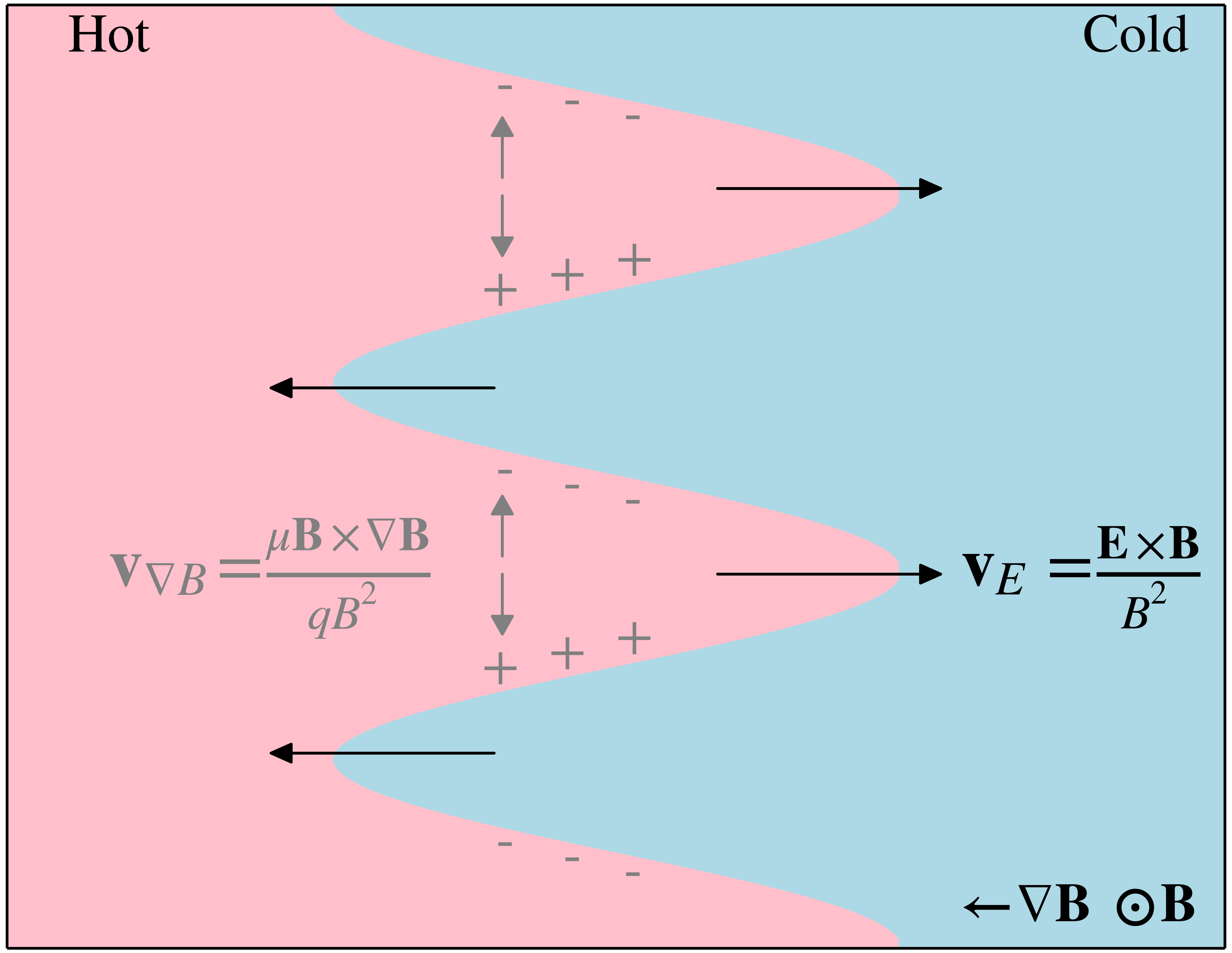


Approximations give a reduced 5D distribution function of charge rings that computers can evolve more readily:

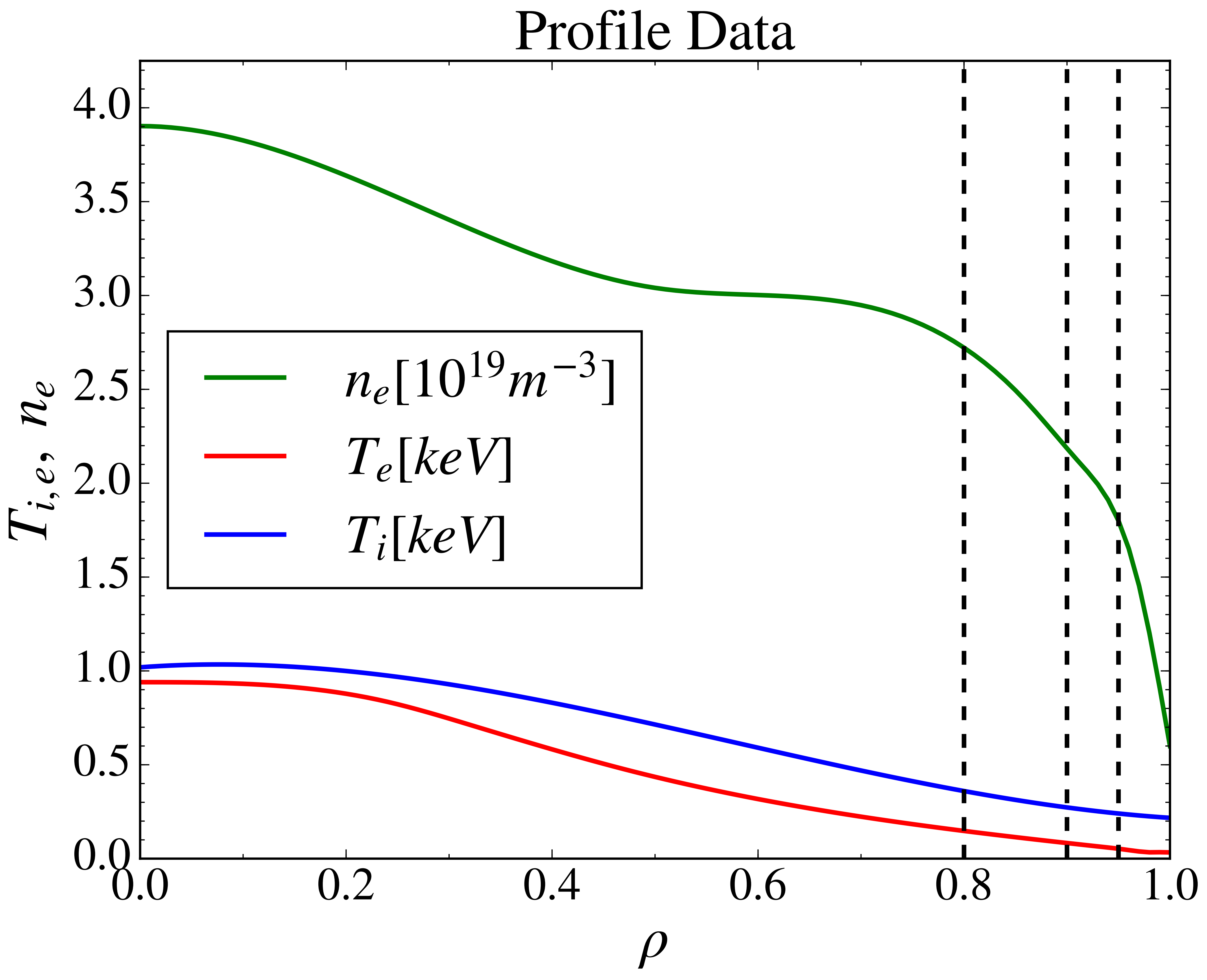
$$f(\mathbf{X}, v_{\parallel}, \mu; t)$$

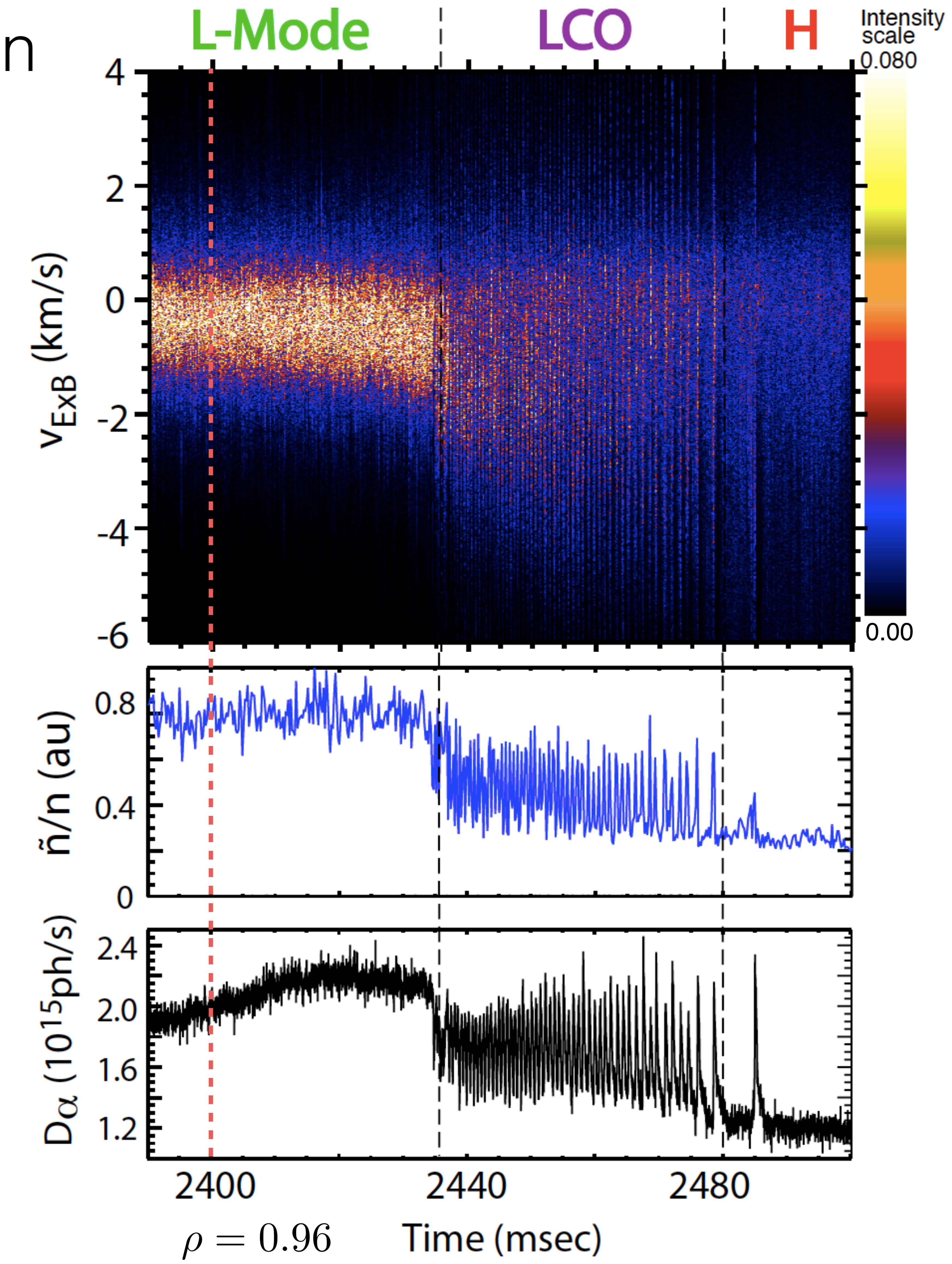
The ITG/ETG instability arises in the low-field or “bad curvature” region of a tokamak





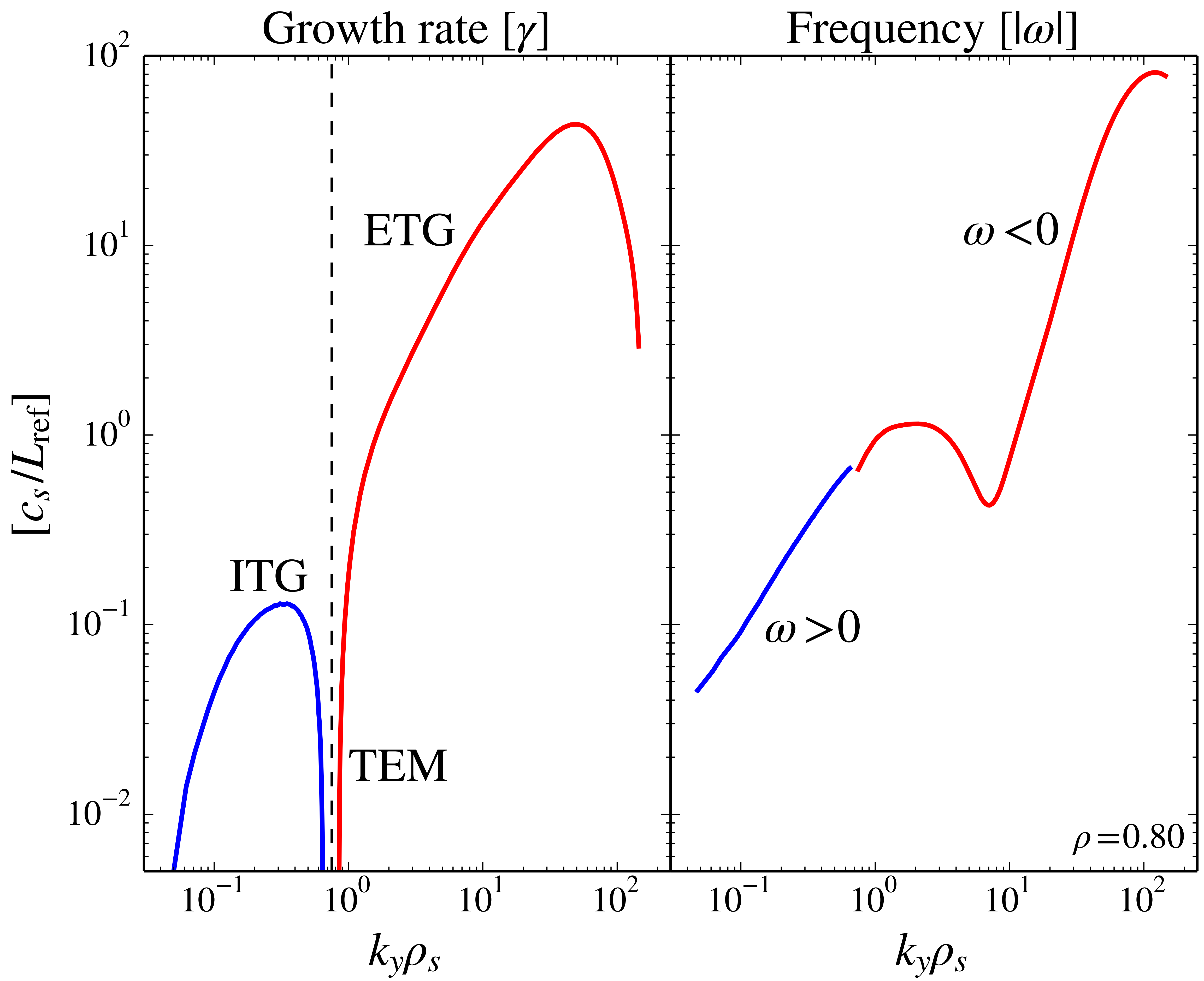
To characterize a near-edge L-mode plasma before an L-H transition, we will study DIII-D shot #153624 at rho=0.80, 0.90 and 0.95, and t=2400 ms.

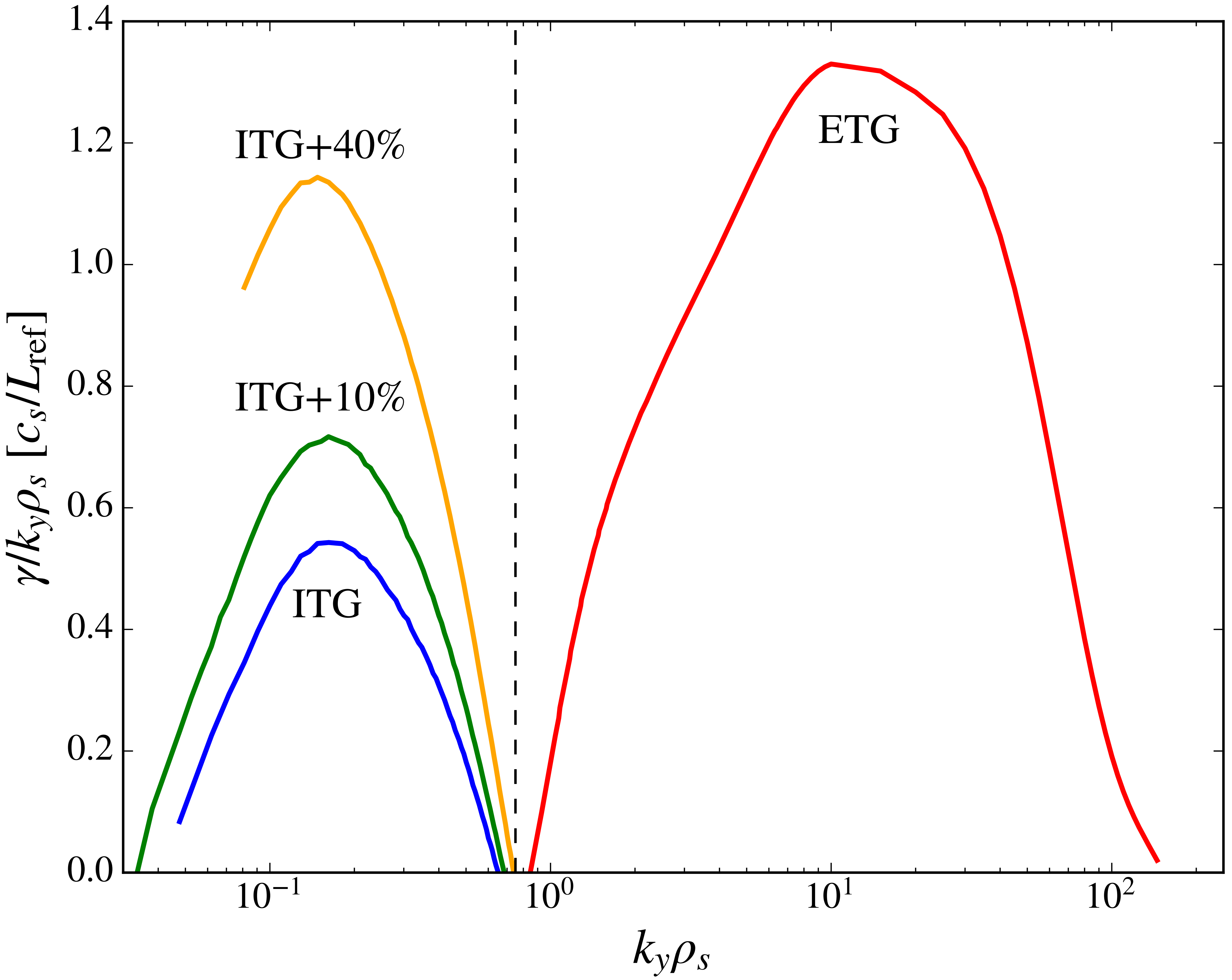




[see Schmitz et al., PRL, 2012]

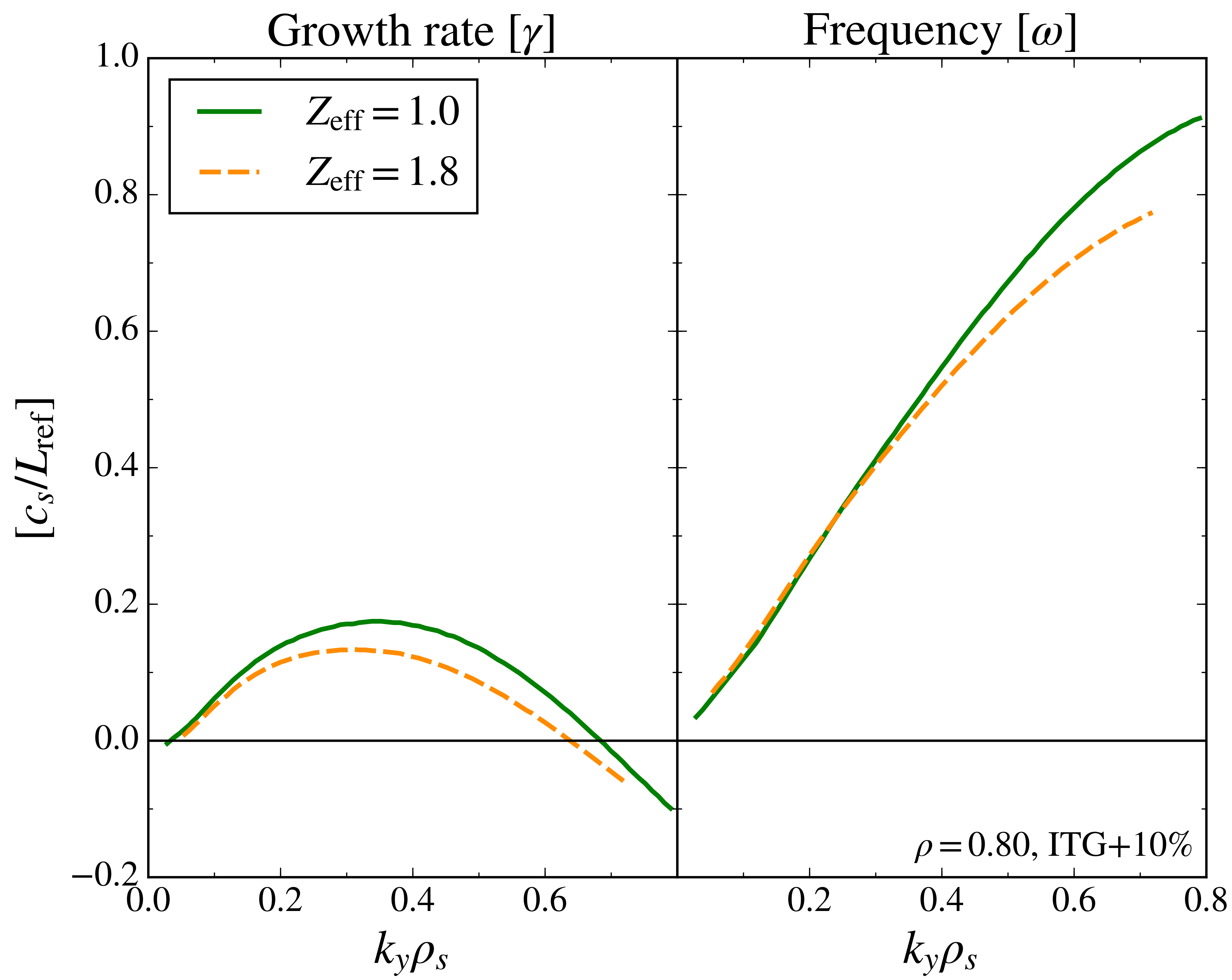
At **rho=0.80**, linear ITG and ETG growth rate spectra are separated by a stable region: invites two single-scale simulation domains, but cross-scale coupling is possible





$\mathrm{Max}\left(\gamma_{\mathrm{ETG}}/\mathrm{k_y}\right) \geq \mathrm{Max}\left(\gamma_{\mathrm{ITG+40\%}}/\mathrm{k_y}\right)$ [Staebler et al., NF, 2017]

Sensitivity study: Carbon impurities have a small effect on the linear growth rates at rho=0.80, and will be ignored in nonlinear simulations for simplicity

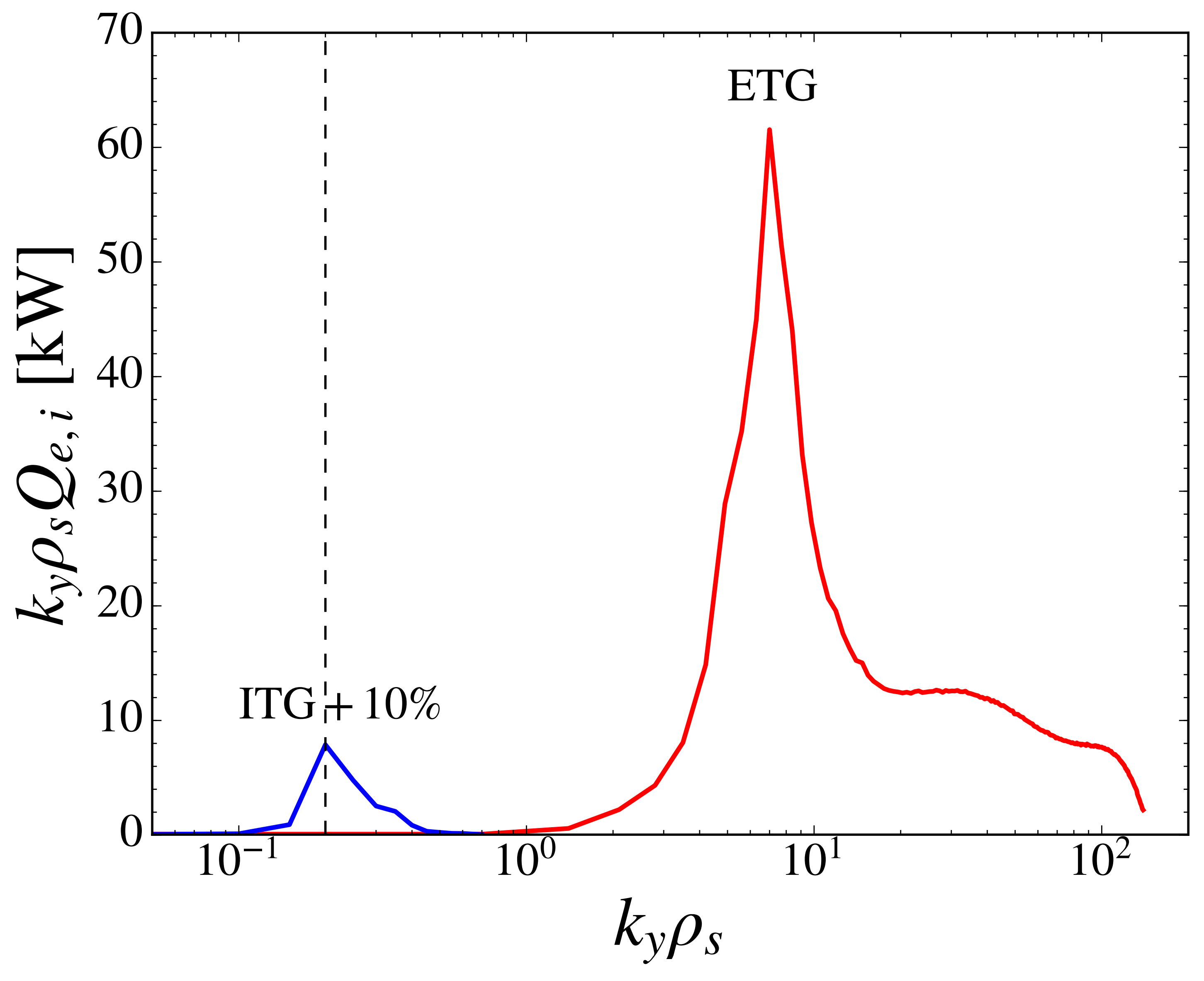


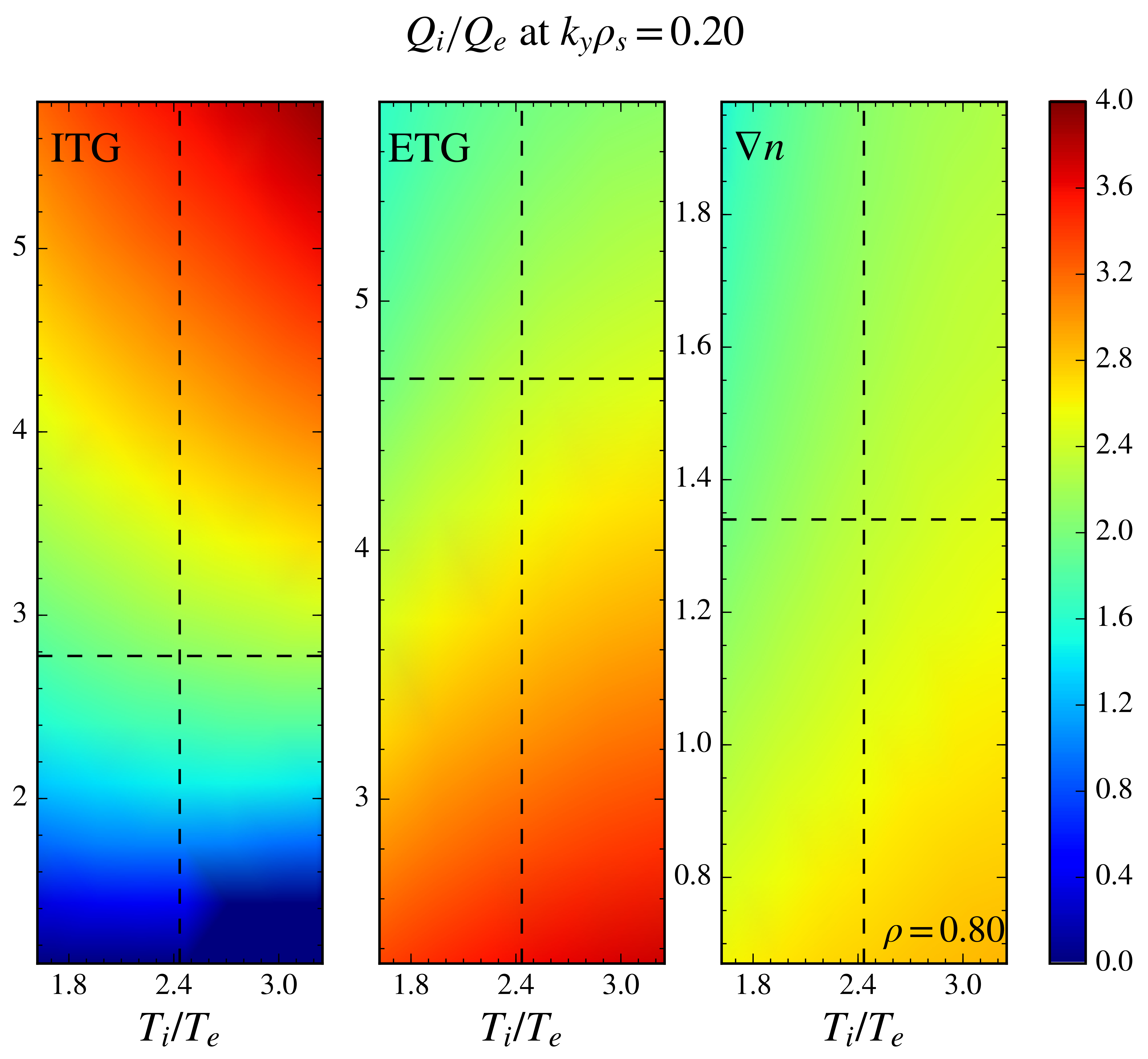
Ion-scale heat flux is reduced due to strong poloidal zonal flow (causing Dimits shift), not matching experiment with nominal parameters

Sensitivity study: Linear simulations can indicate the ratio of nonlinear fluxes; quasi-linear study suggests higher ITG is most likely to increase flux ratio

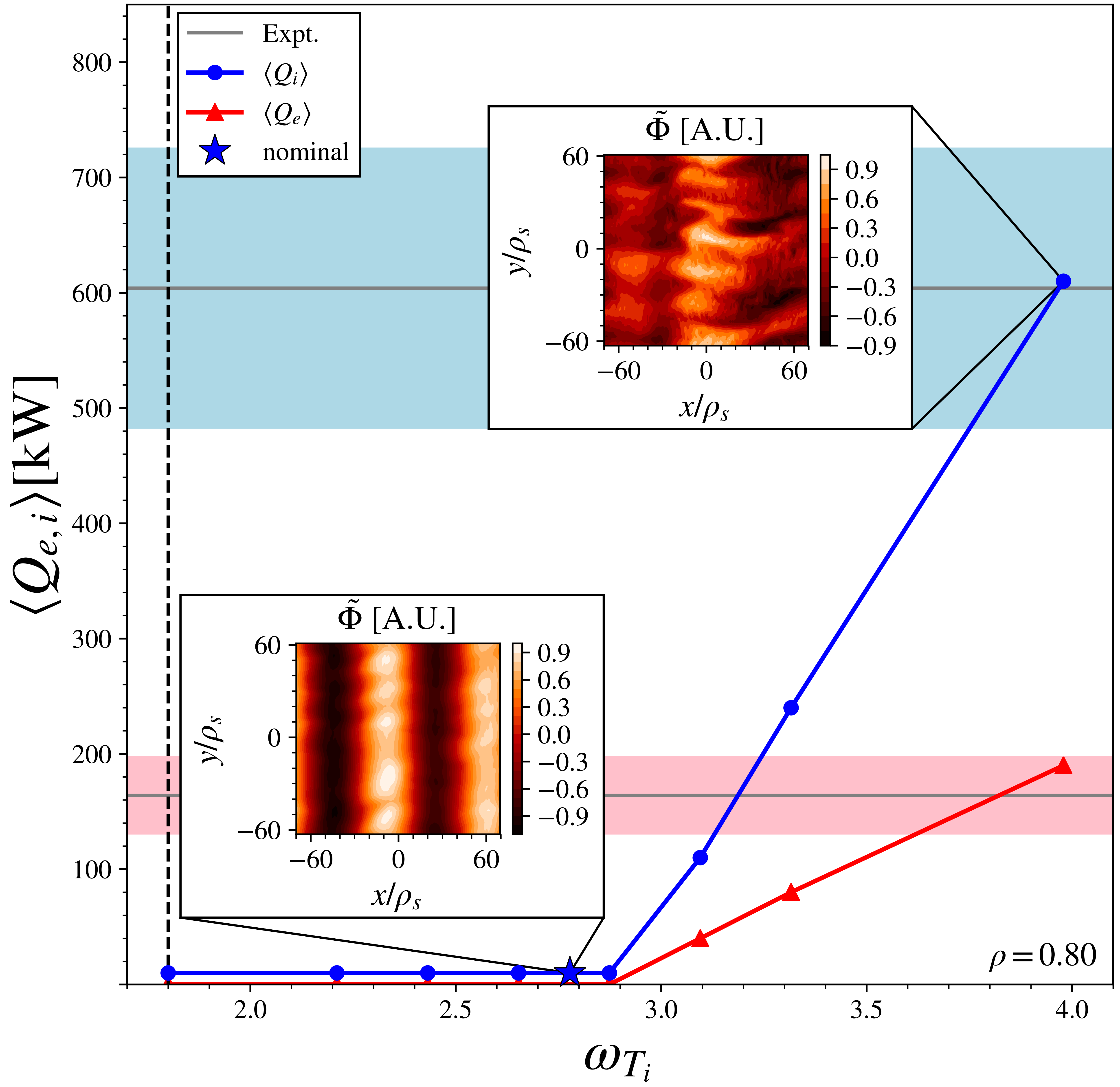
Experimental flux ratio: $Q_i / Q_e = 3.68 \pm 0.74$

Most ion-scale flux is carried at $k_y \rho_s = 0.2$:

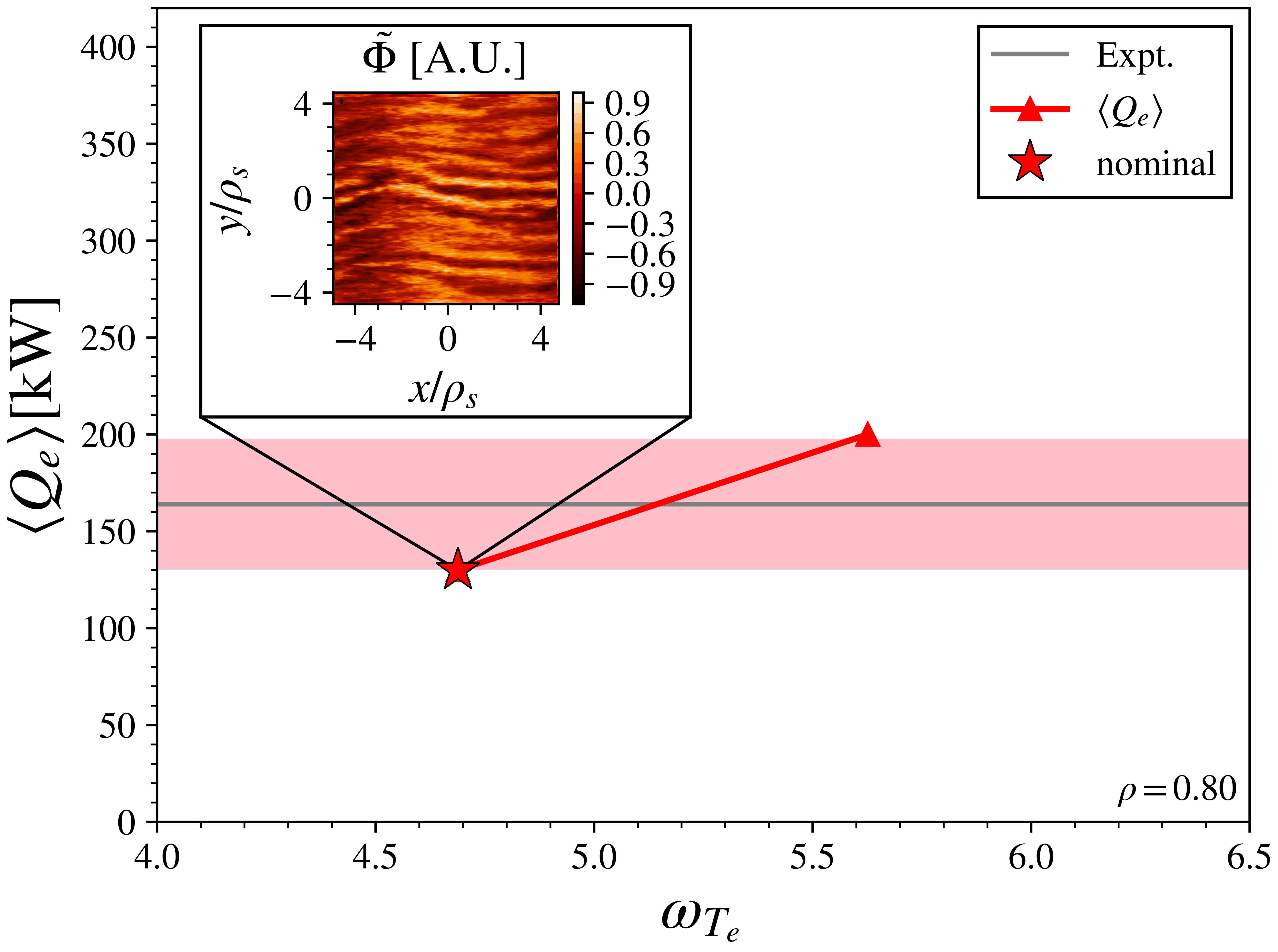




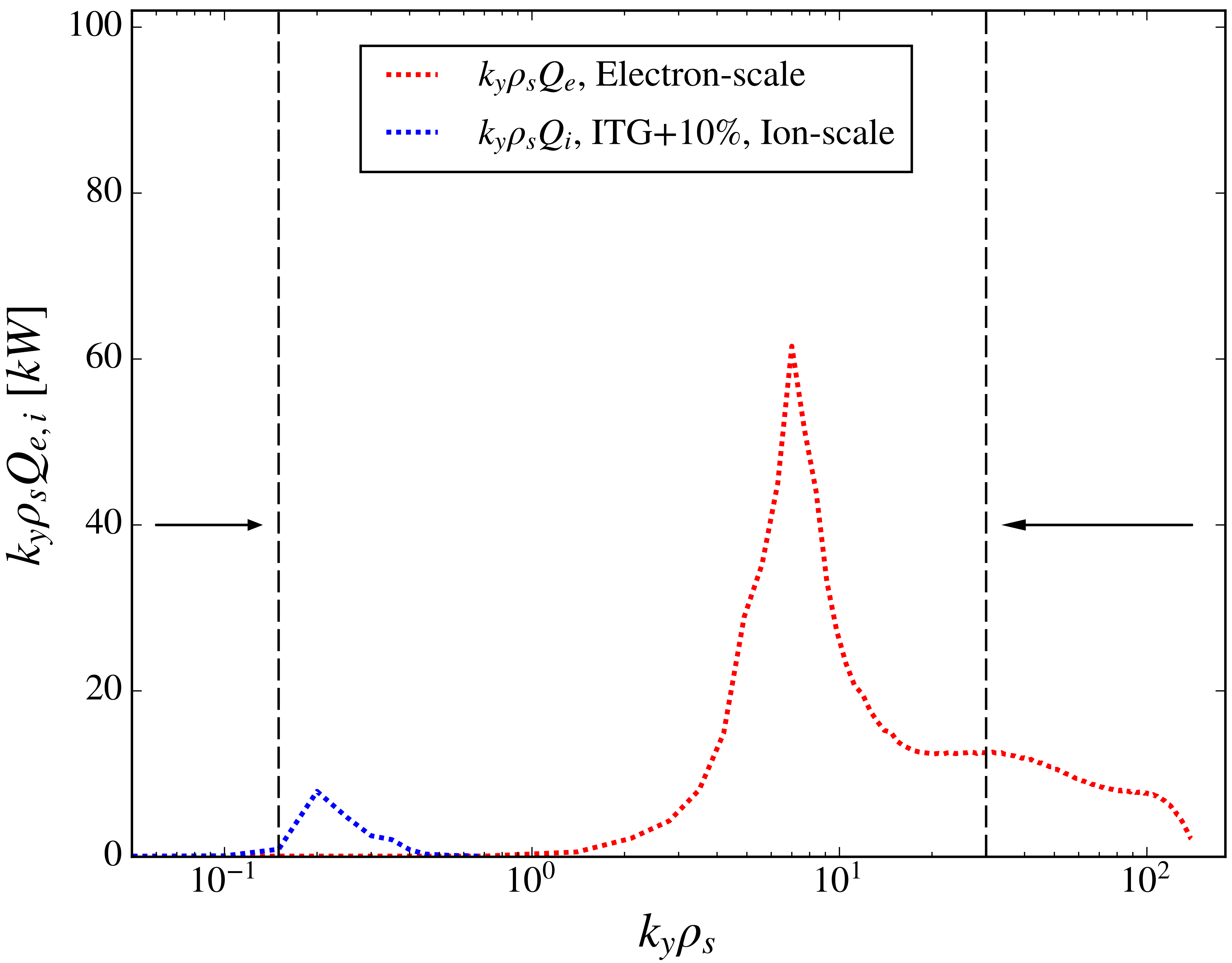
Increasing the ion temperature gradient by 40% gives good agreement with experiment, matching heat transport in both ion and electron channels



Electron-scale simulations show large electron heat flux carried by ETG streamers at high-k: possibility of multi-scale interactions between electron-scales and ion-scales

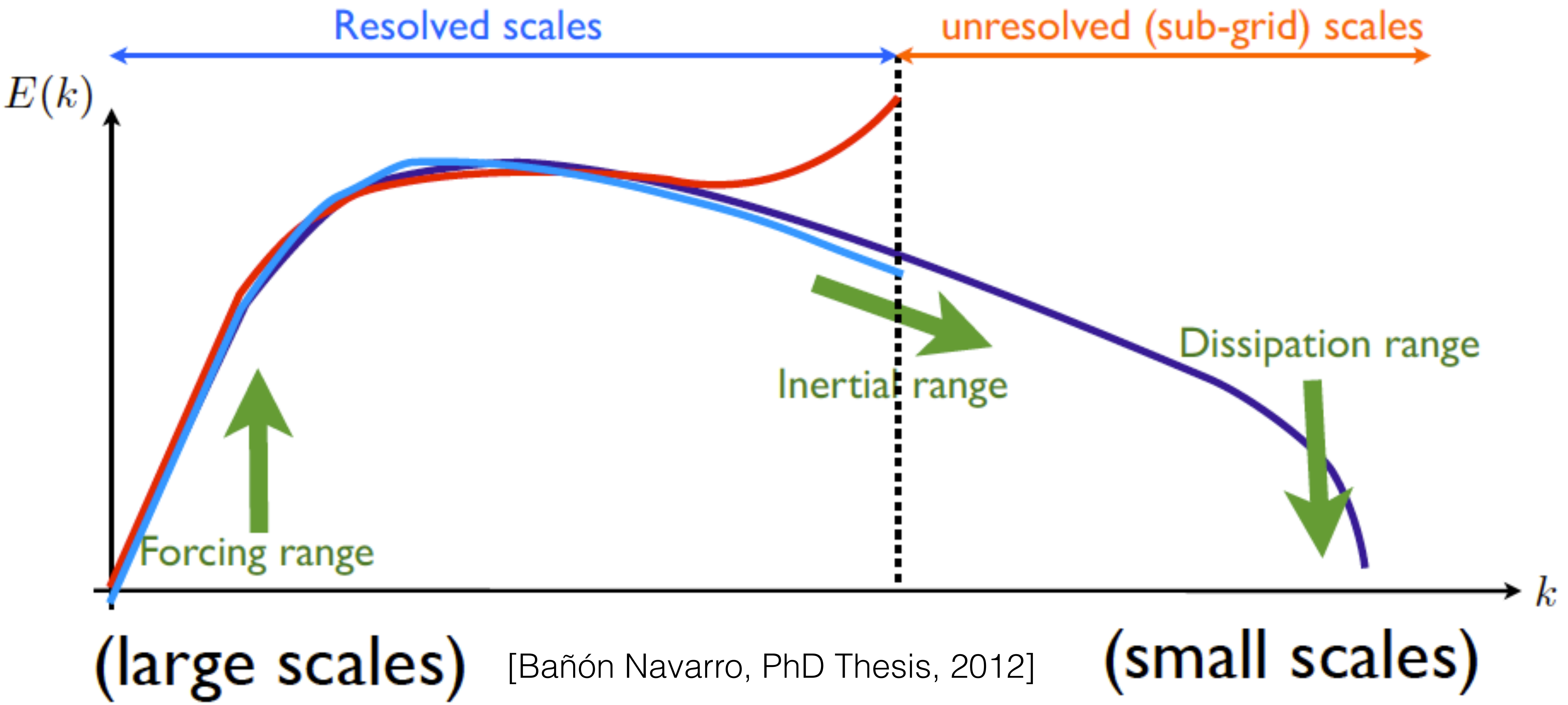


Multi-scale: Carefully reduce the simulation box under preservation of all qualitative and most quantitative features



$k_{y,\min}\rho_s = 0.15$ $k_{y,\max}\rho_s = 30.0$

Multi-scale: Large Eddy Simulation (LES) feature models unresolved dissipation, greatly reducing cost

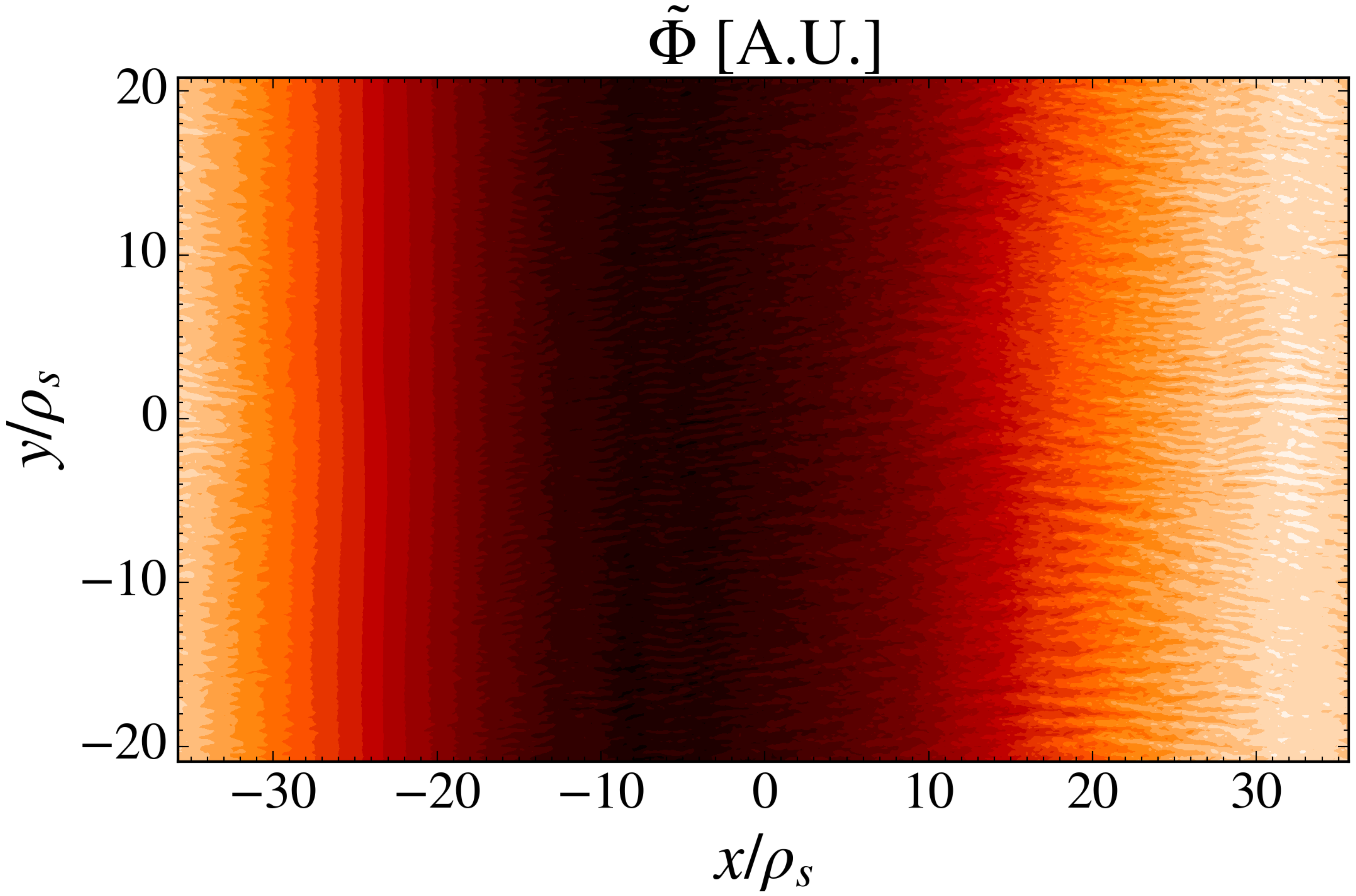


[Bañón Navarro, PhD Thesis, 2012]

While not resolving smallest scale dynamics, resolved spectrum remains physical

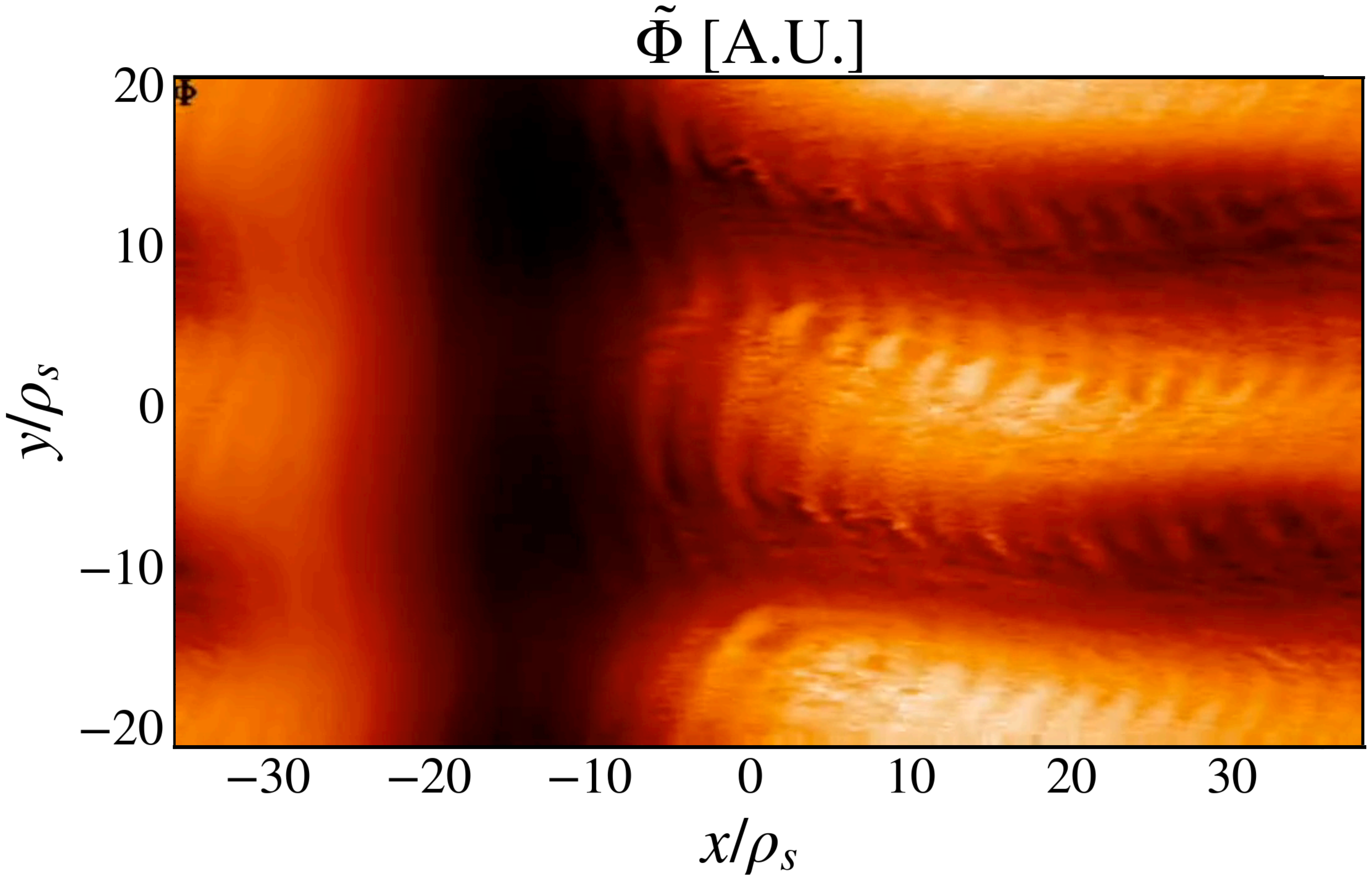
Multi-scale simulations ($0.15 \leq k_y \rho_s \leq 30.0$) are conducted using GyroLES feature in GENE

ITG nominal:



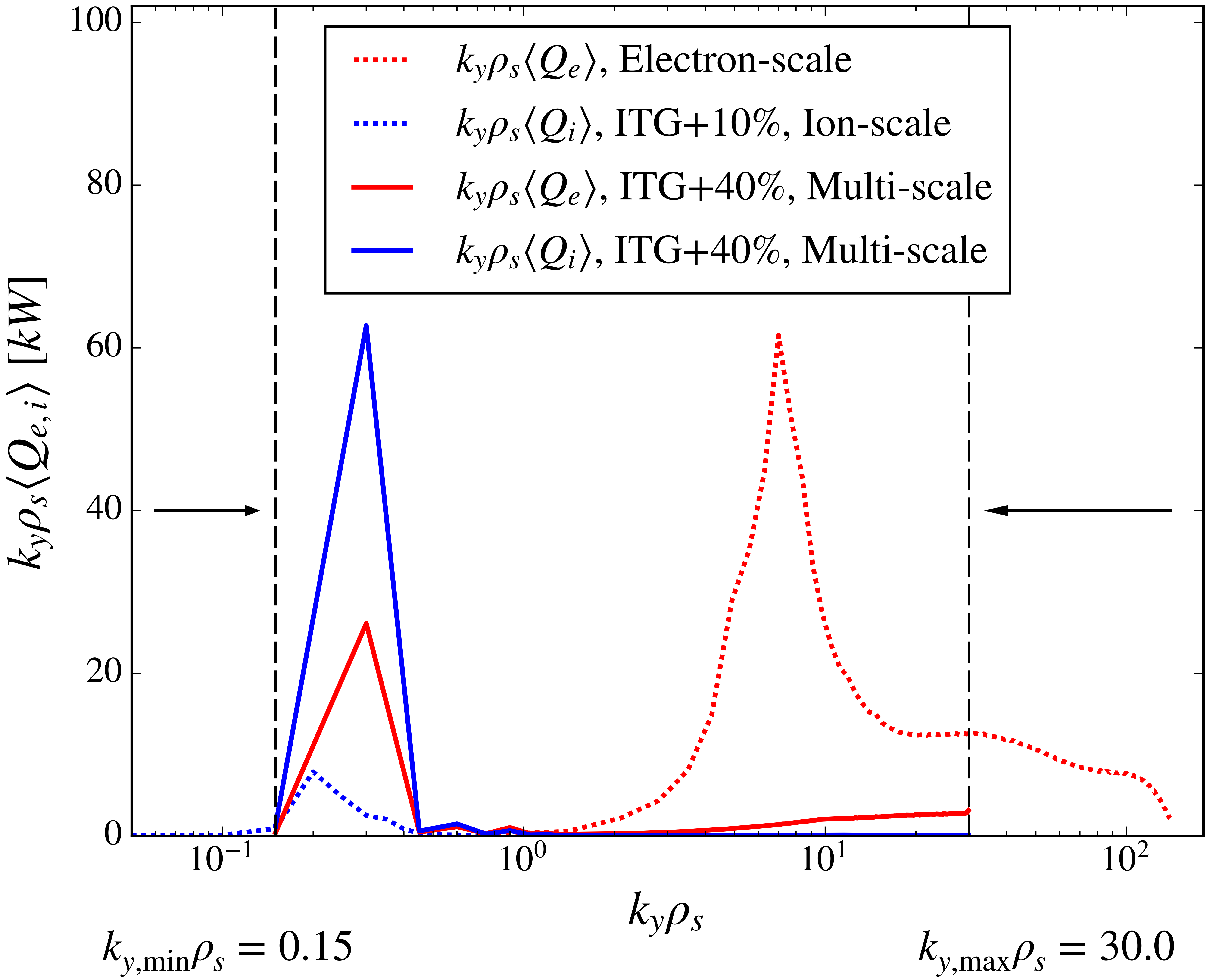
Strong ETG-driven streamers coexist with ion-scale zonal flow, consistent with [N. Howard, TTF, 2017]

ITG+40%:

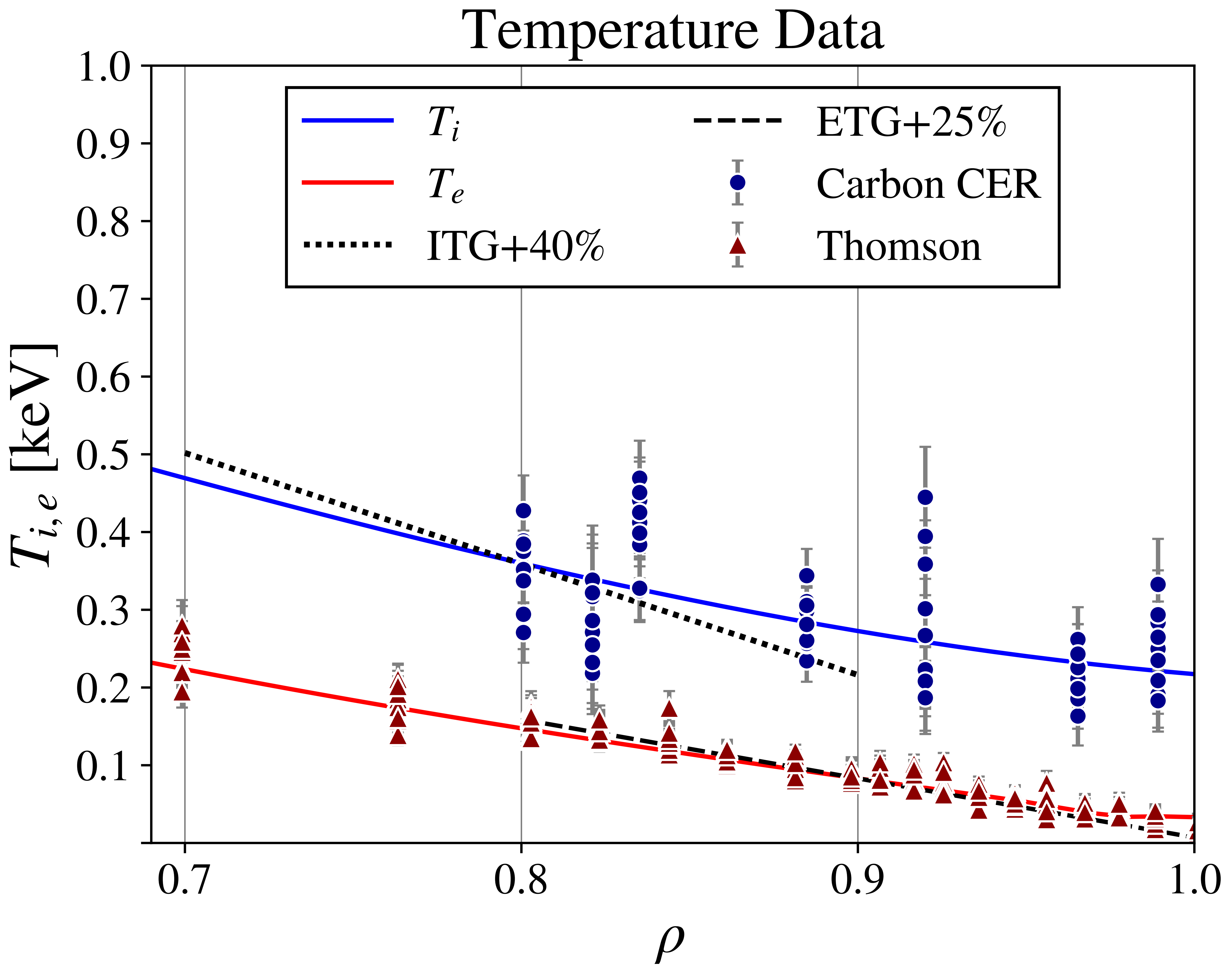


Streamers are sheared apart by ITG modes, vertical structures are currently being studied

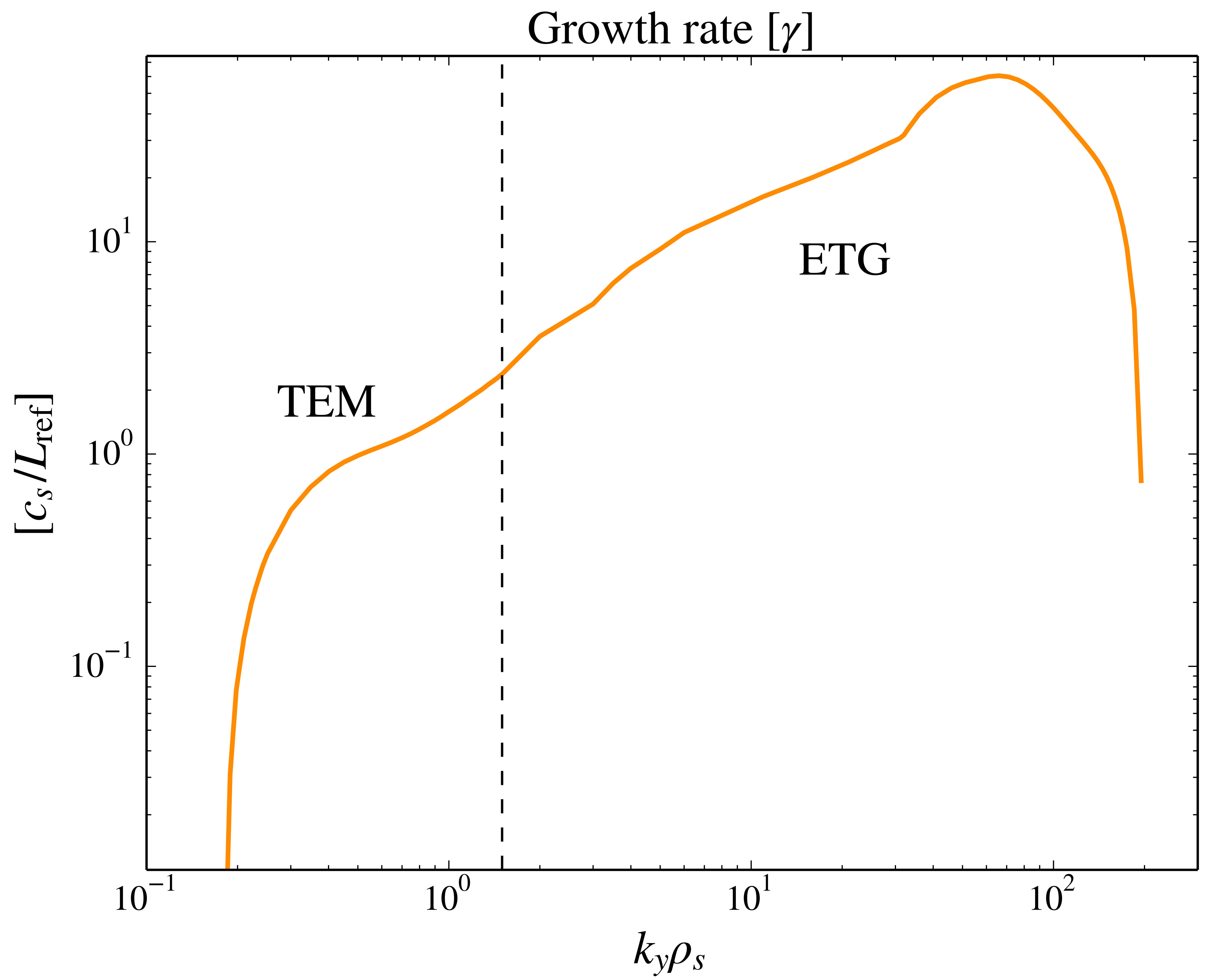
Multi-scale simulations qualitatively show that ITG modes are driven sufficiently unstable by an increase in ITG of ~40%, such that little electron-scale heat flux survives. Therefore flux-matched ion-scale simulations appear trustworthy

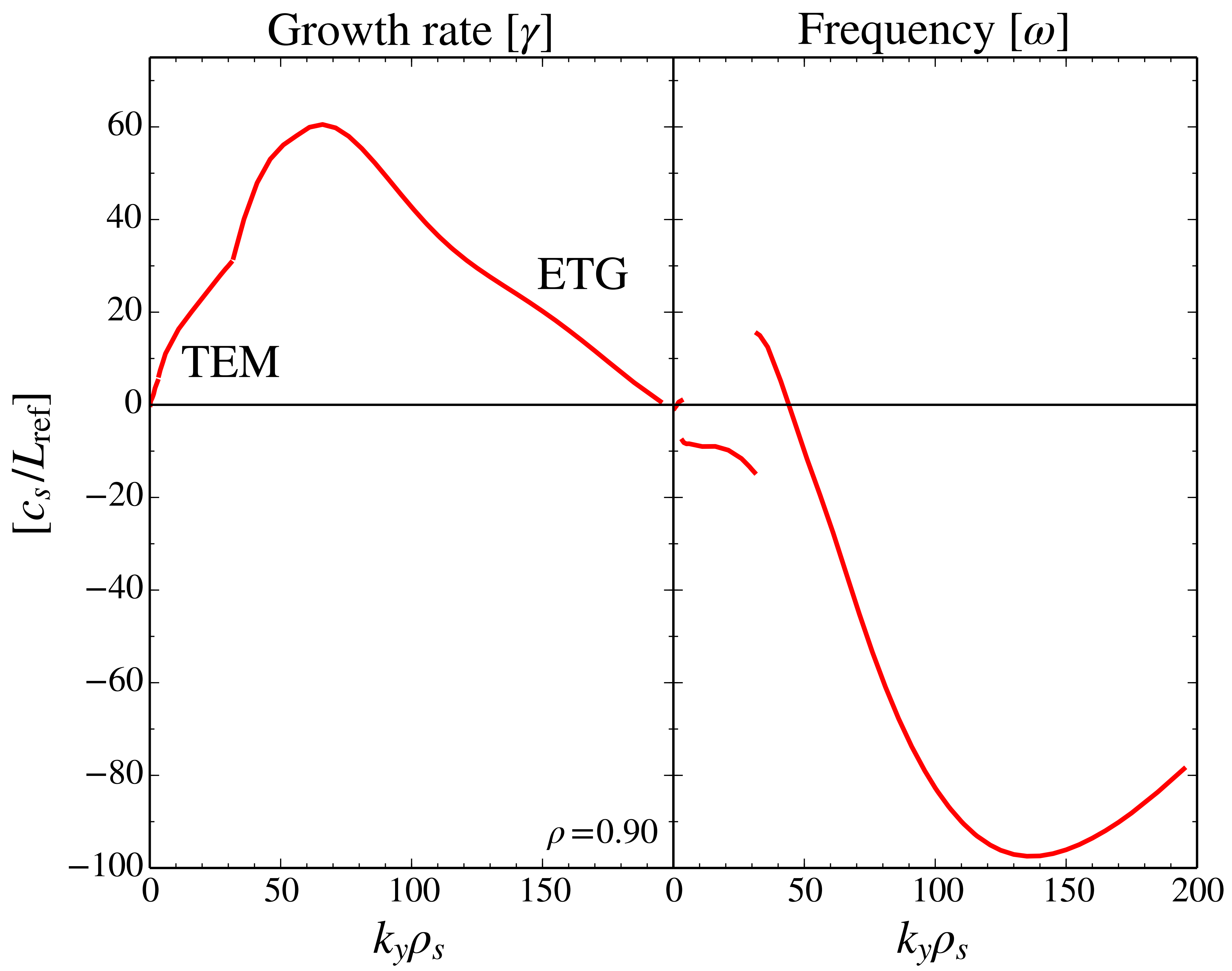


At **rho=0.80**, impurity ion CER data is consistent with ~40% increase in ITG at the1.6σ level, likely due to low Carbon density

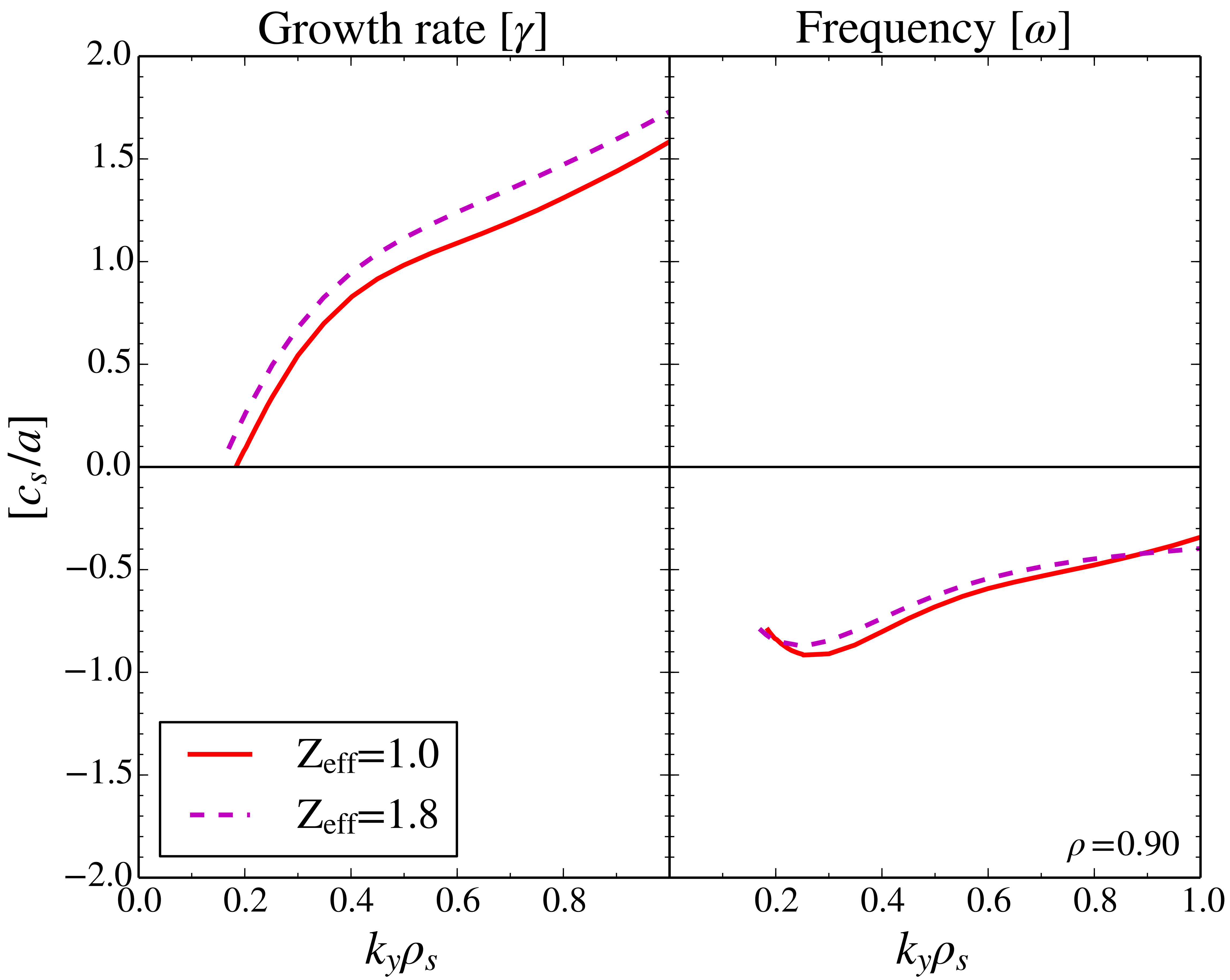


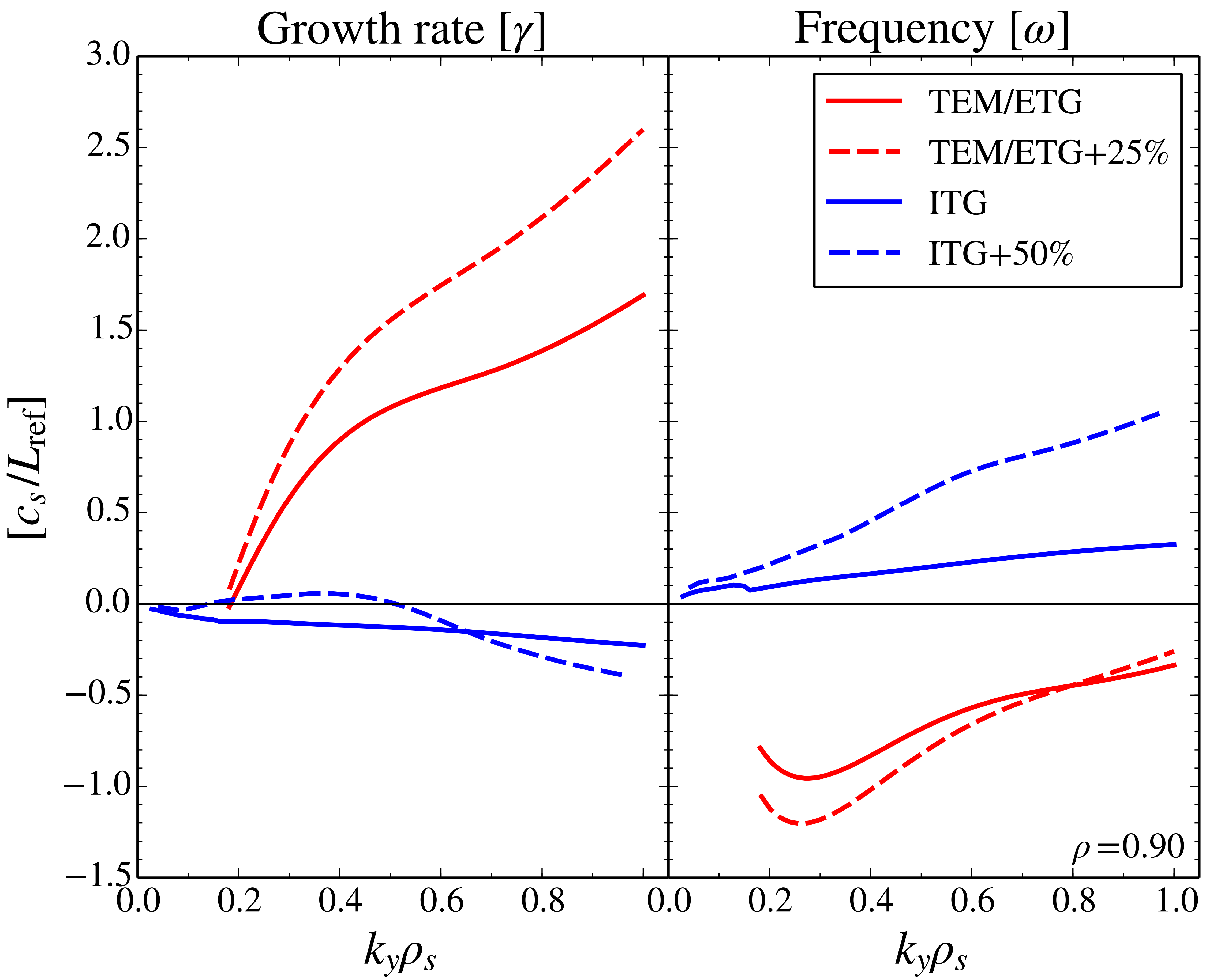
At **rho=0.90**, linear simulations show no clear scale-separation, and a TEM/ETG dominated mode spectrum



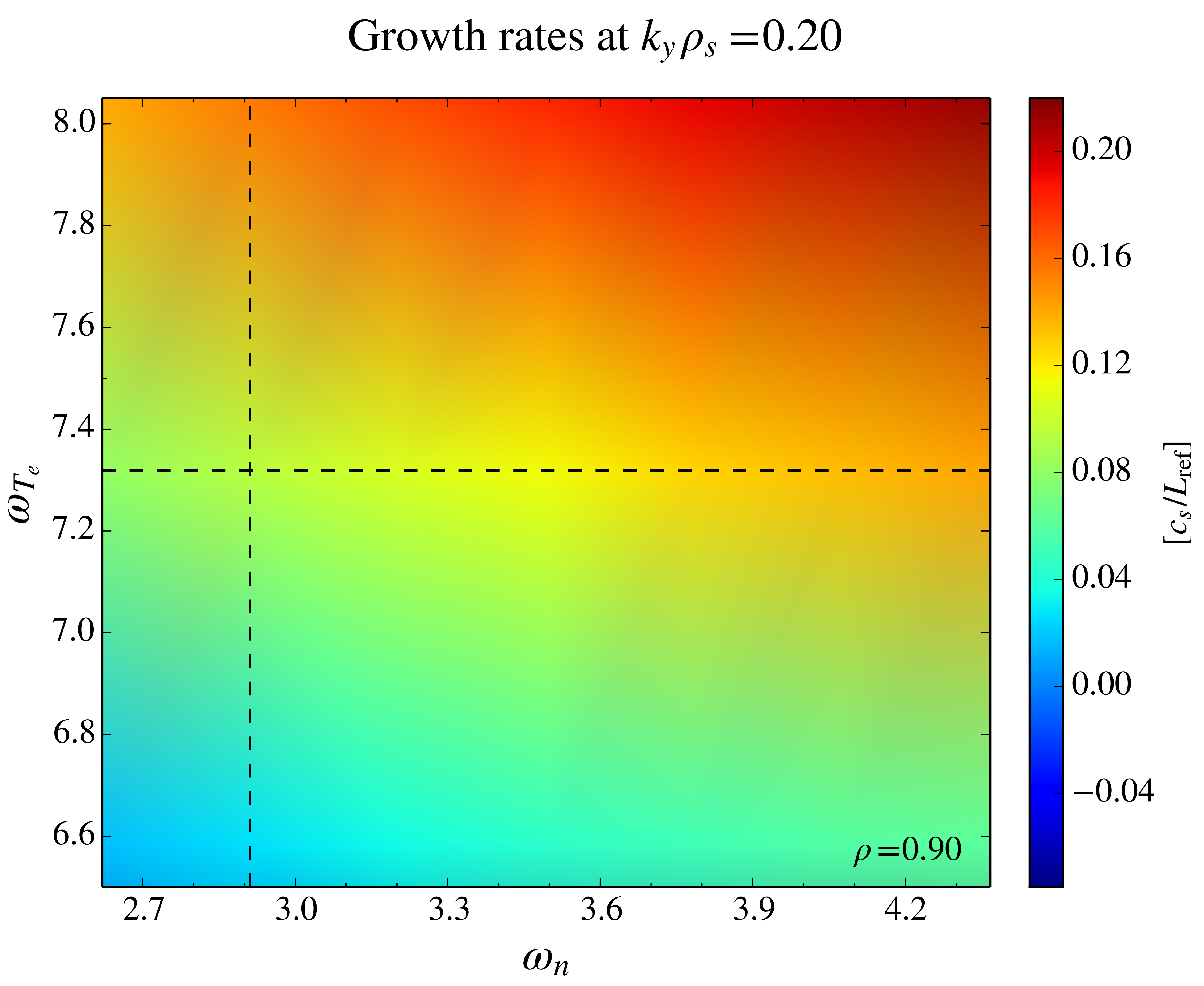


Sensitivity study: Limited effect of Carbon & existence of sub-dominant stable ITG branch



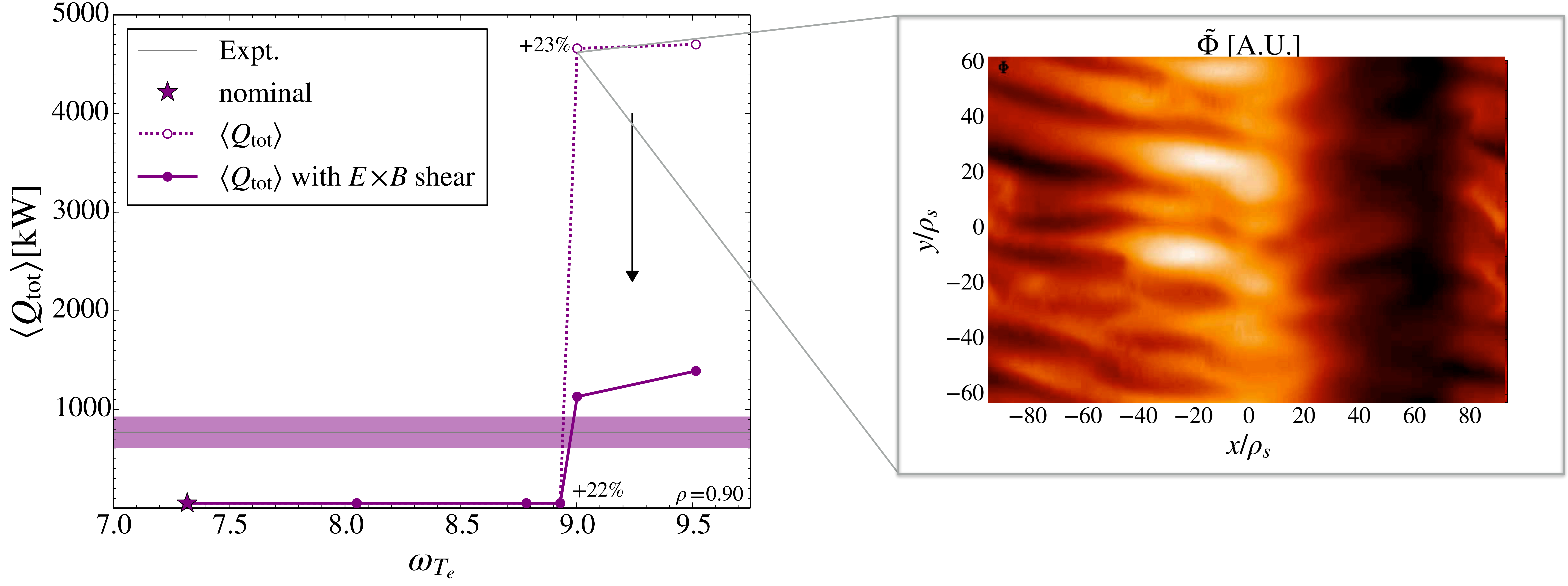


Sensitivity study: Linear growth rates are most sensitive to changes in ETG



No large changes in growth rates occur with changes in T_i/T_e , n_e , ω_{T_i}

Observable at rho=0.90 is the total heat flux, due to difficulty resolving heat channels



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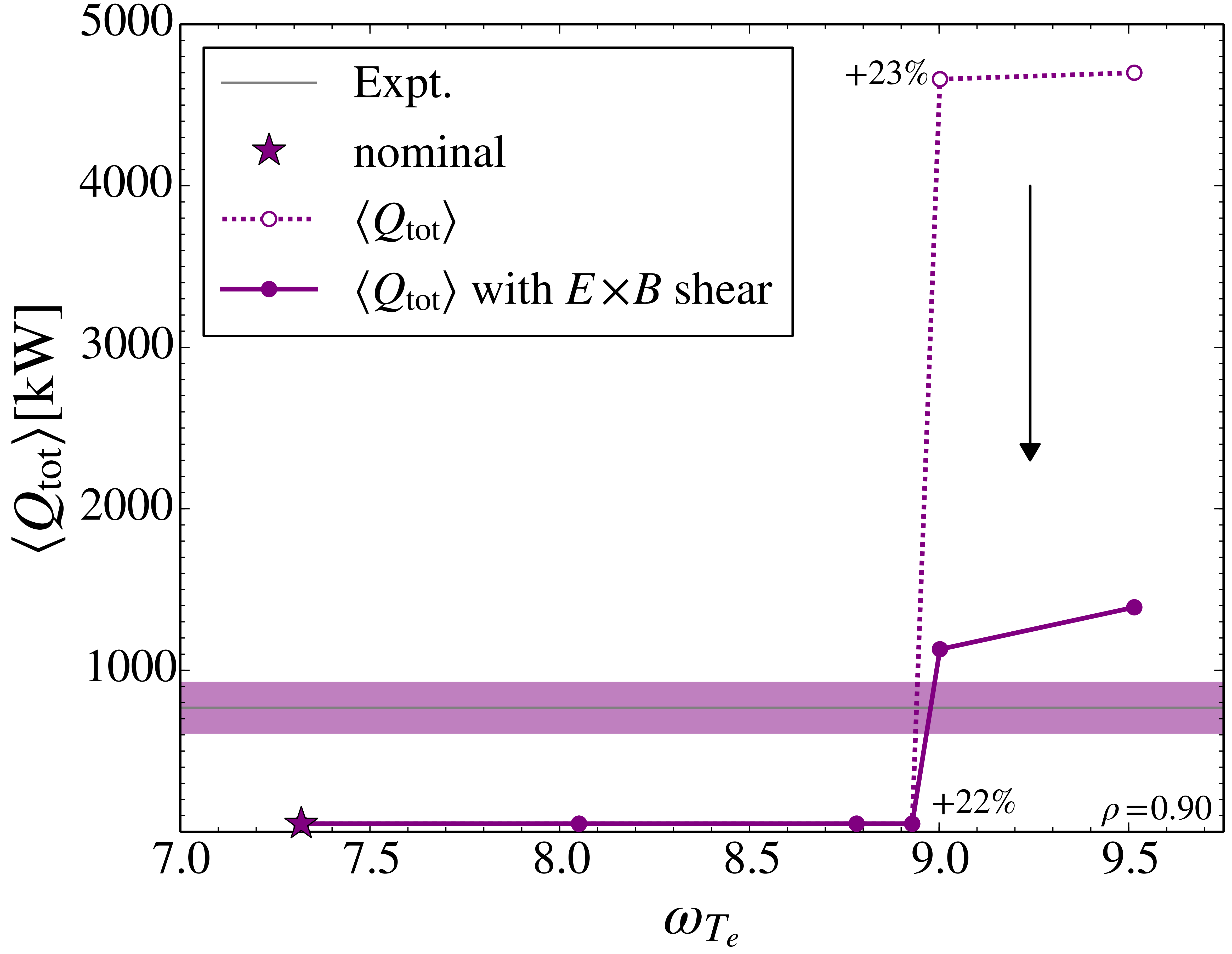
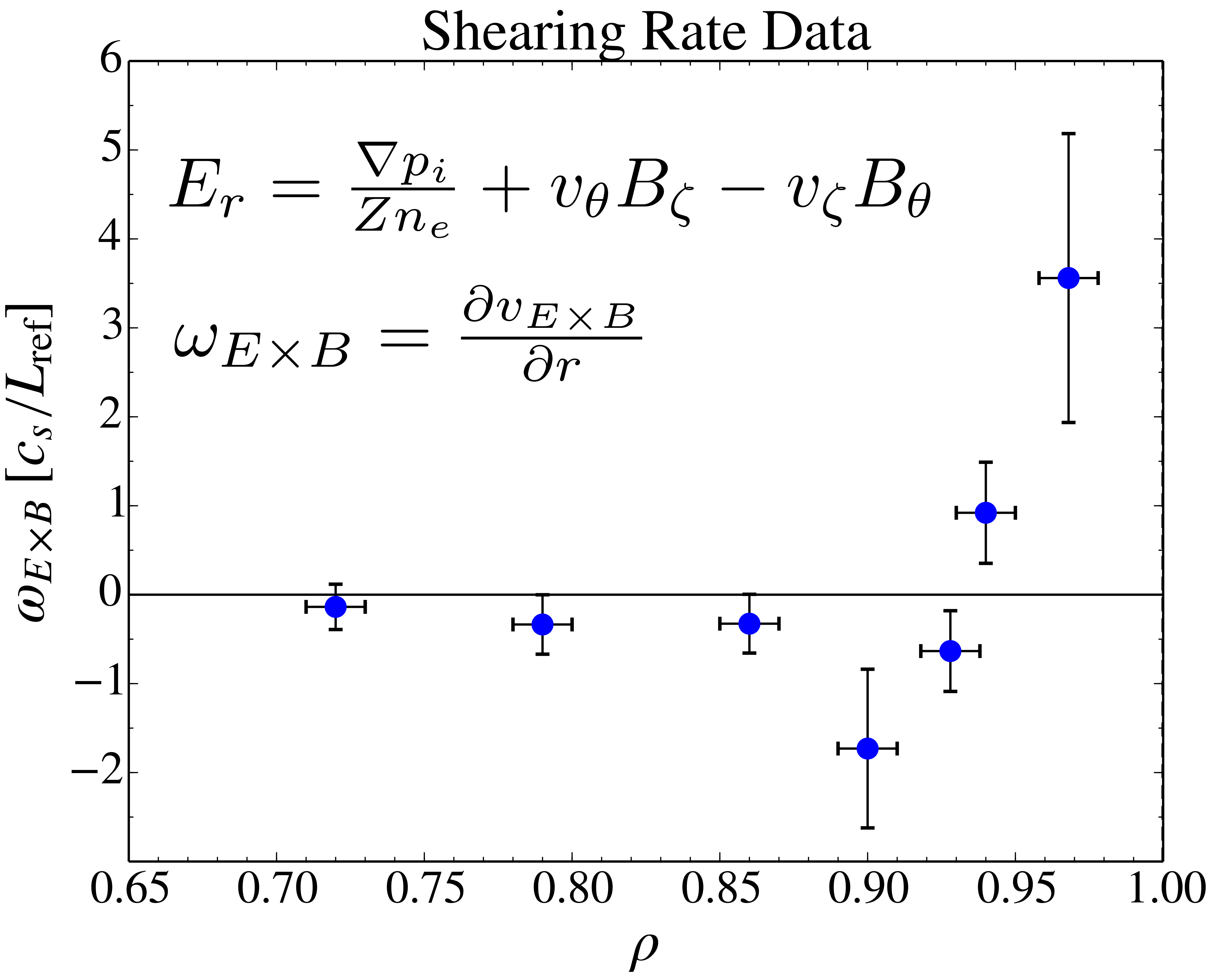
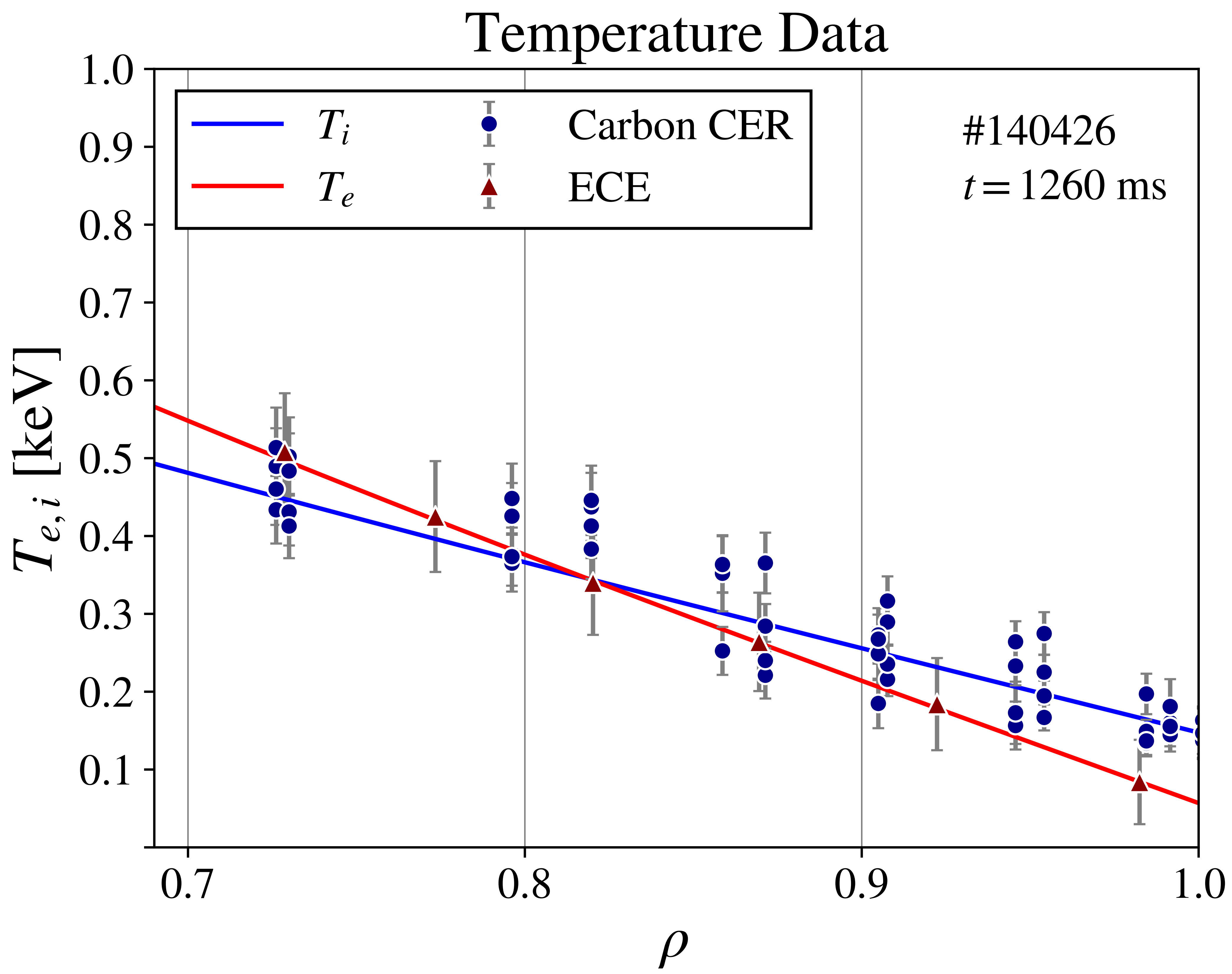
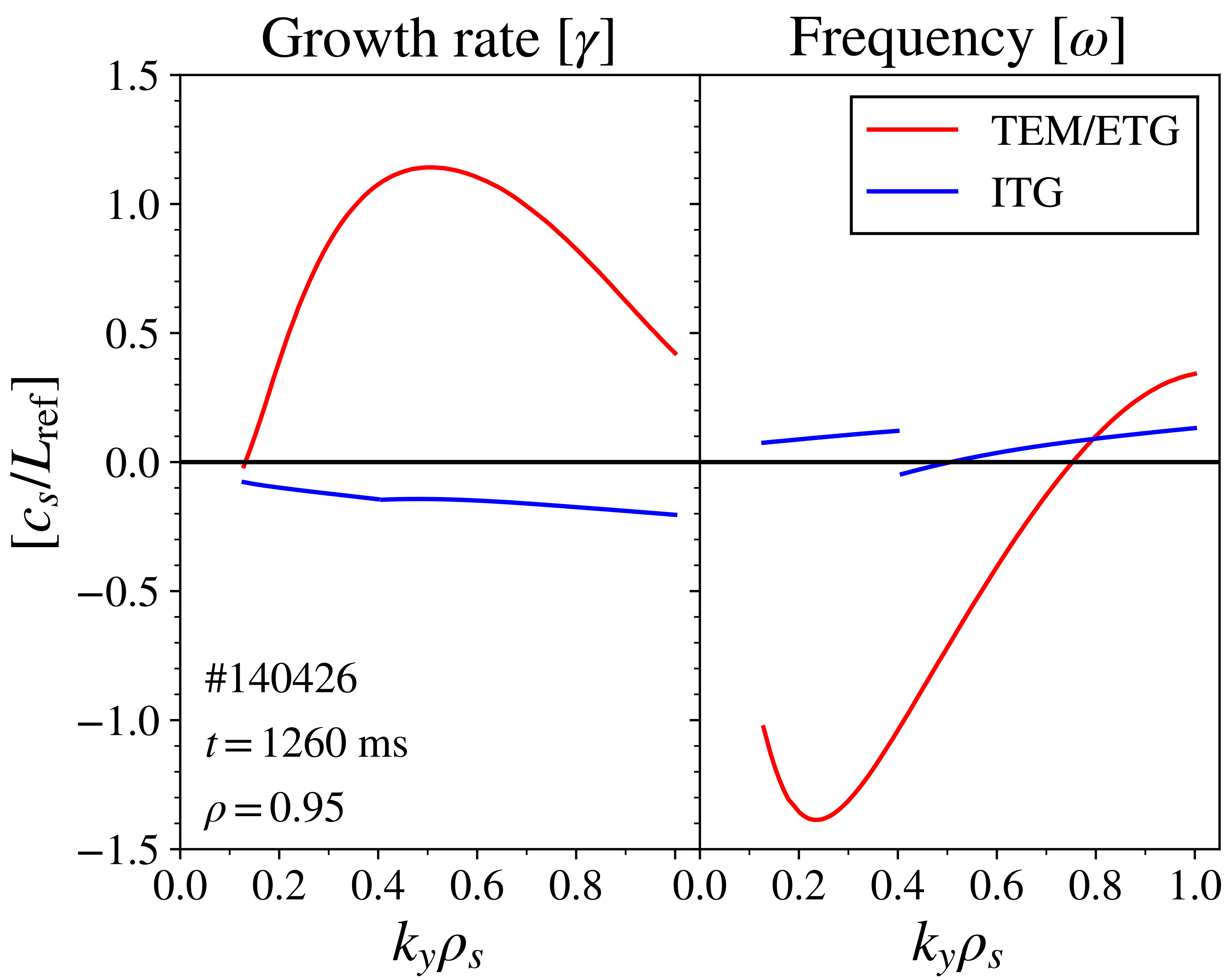




ExB shearing rate is already important for flux-match at rho=0.90 with ETG+25%, and is known to become increasingly important when moving into the edge region

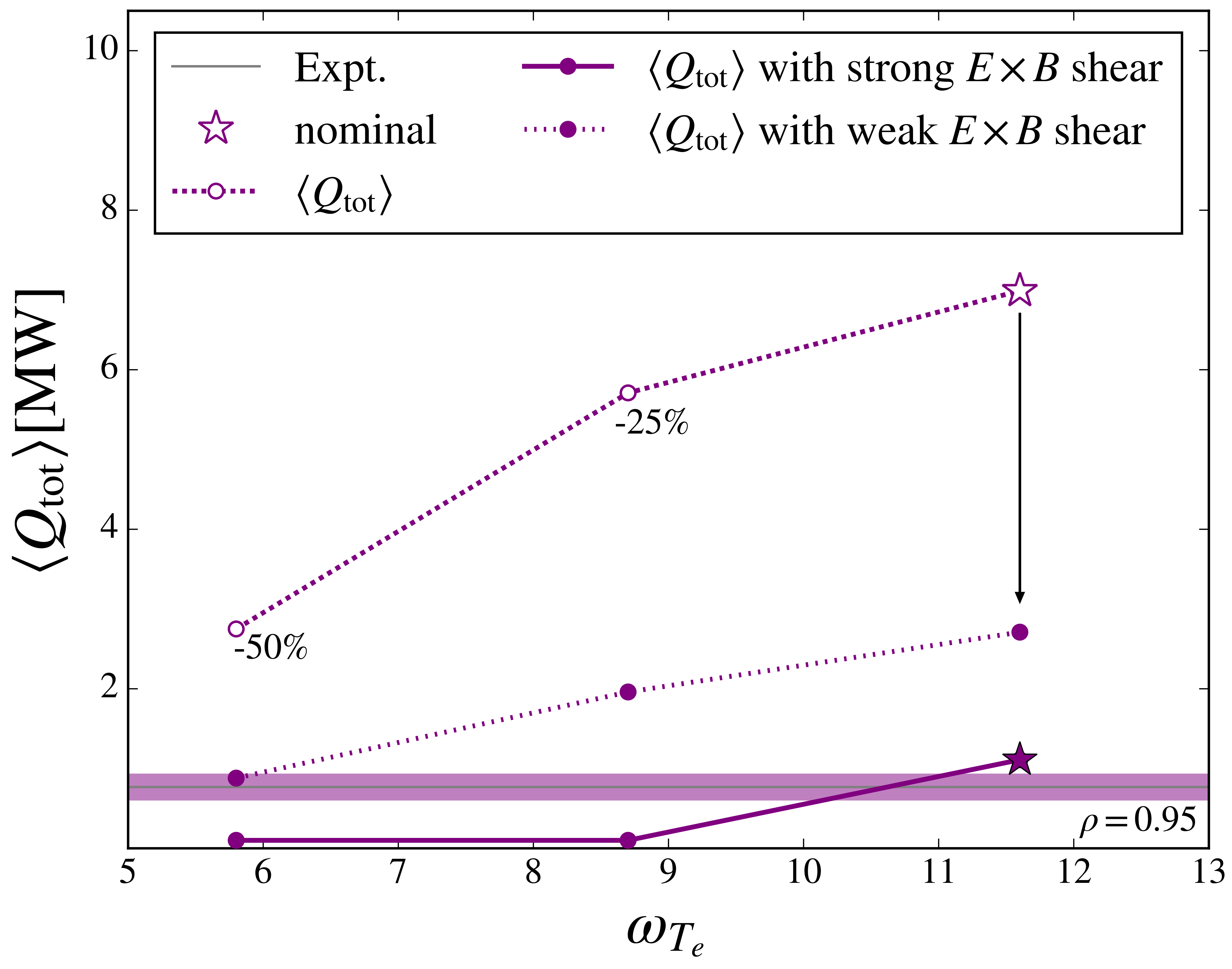
At **rho=0.95**, the possible need for global study (e.g. to capture RBMs) invites using similar discharge with higher quality CER data





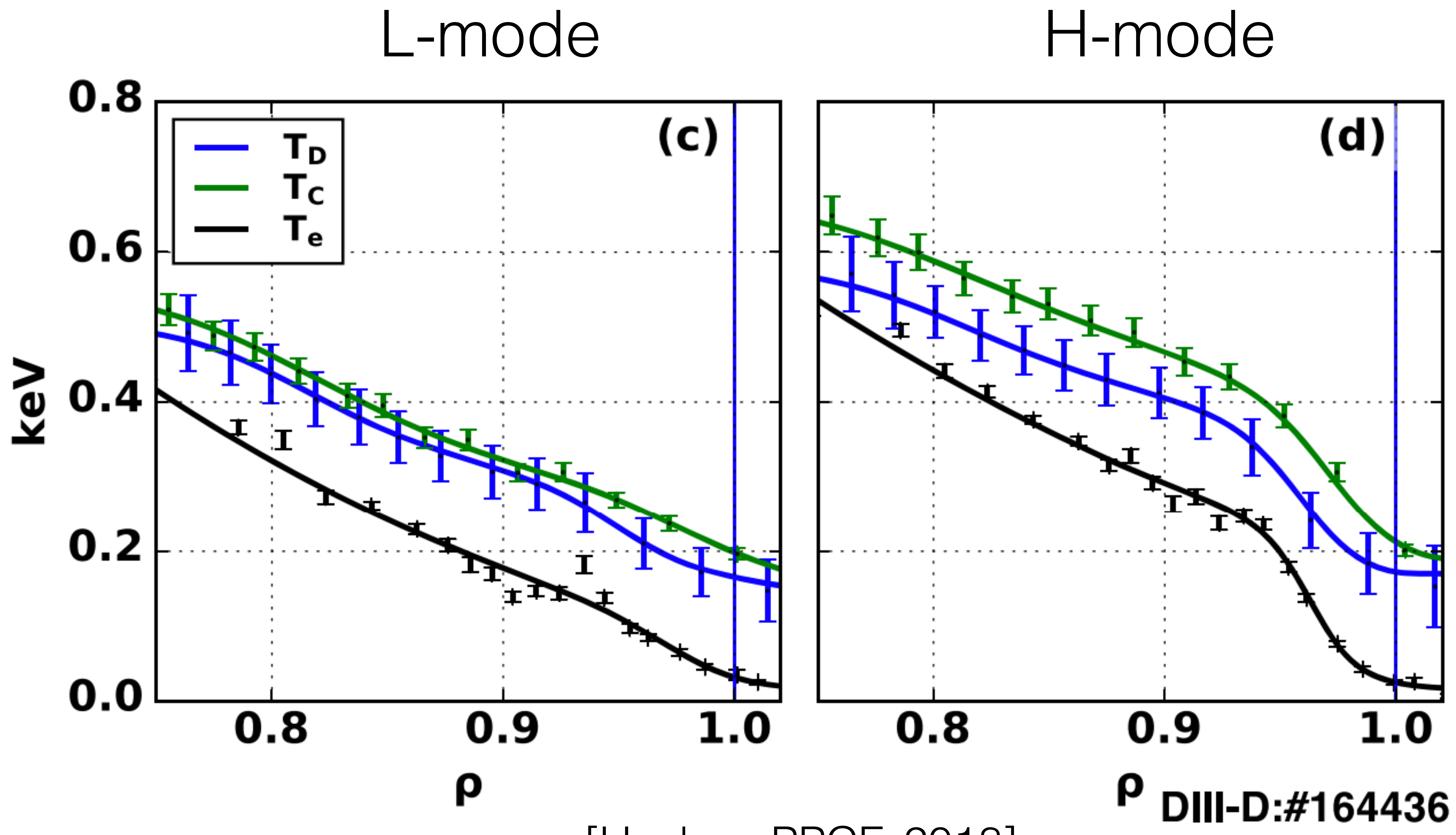
Linear mode spectrum is TEM/ETG dominated with stable ITG (comparable to $\rho = 0.90$).

At **rho=0.95**, preliminary nonlinear simulations show less heat flux stiffness than at $\rho = 0.90$

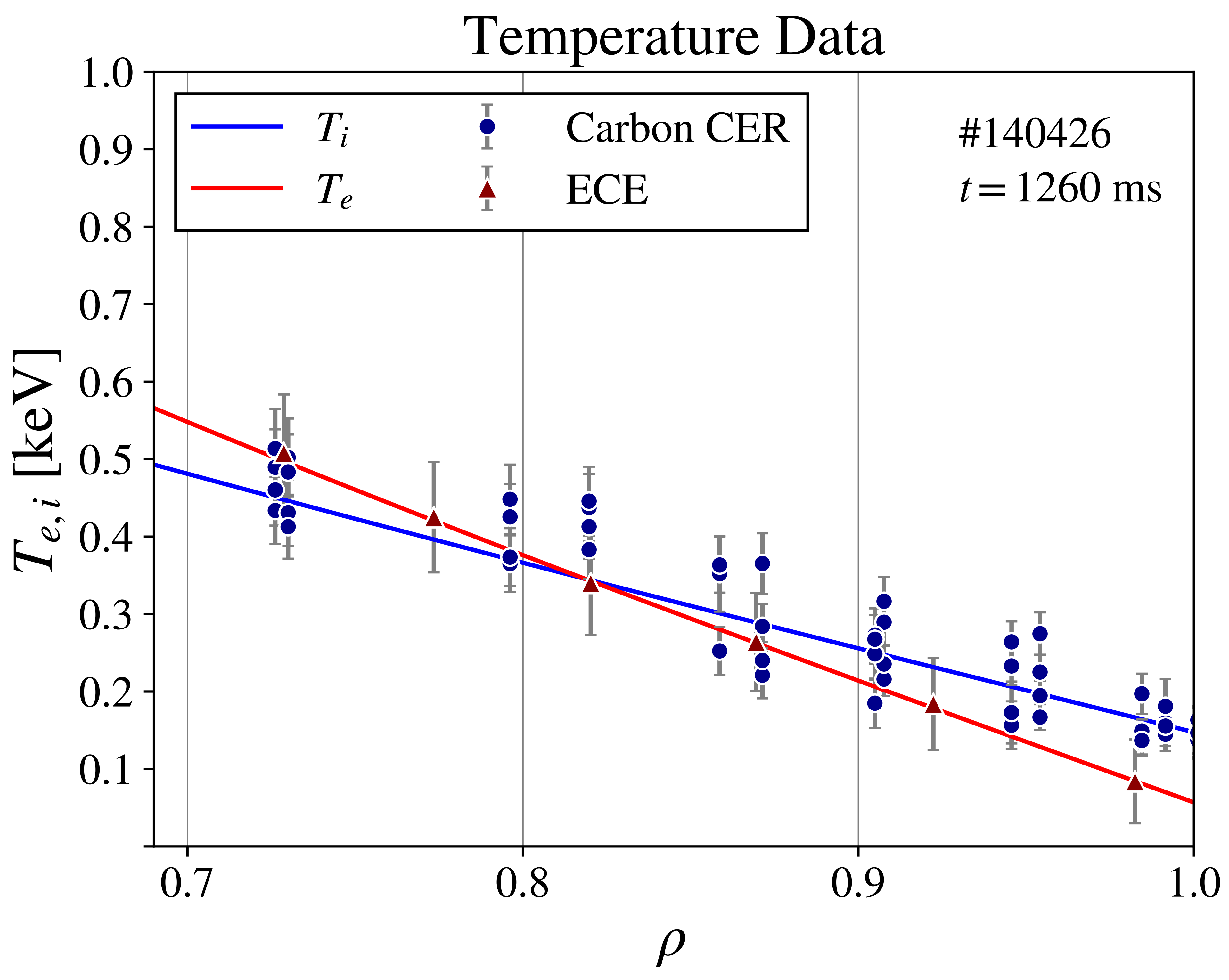


Flux-match appears possible with ExB shear and **nominal** parameters

DIII-D now has a main ion charge exchange diagnostic, which can aid in validation of future gyrokinetic simulations



[Haskey, PPCF, 2018]

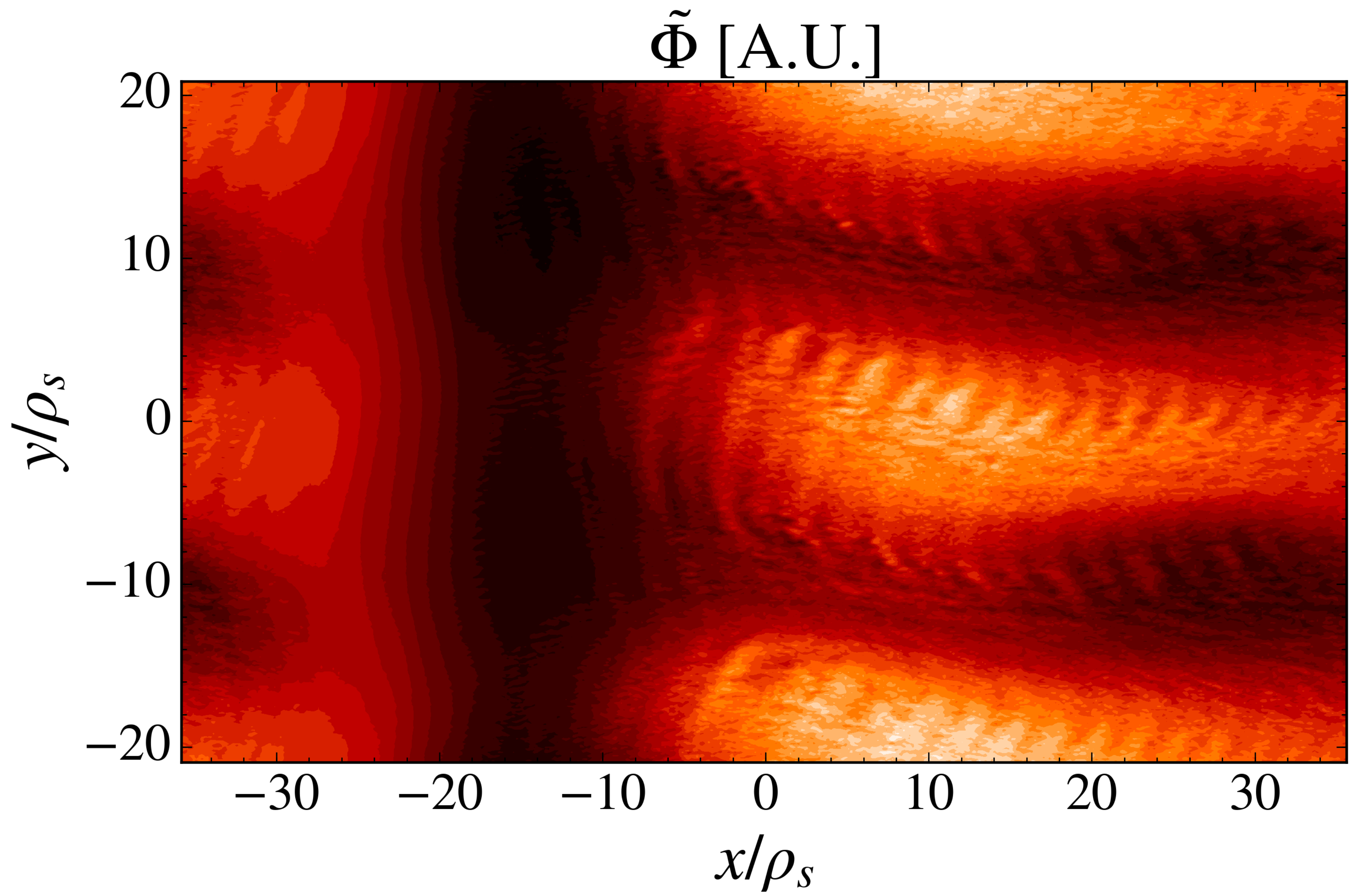


Summary

- At **rho=0.80**, flux-match with ~40% increase in ITG is consistent with impurity ion CER data at the 1.6σ level. Multi-scale simulations are carried out in near-edge (rho=0.80) for the first time. Flux-match within experimental uncertainty can be tested in future work with recently installed *main ion* CER diagnostic on similar discharge.

- At **rho=0.90**, gyrokinetic simulations match the experimental heat flux with the inclusion of ExB shear effects and a ~25% increase in ETG. This is within experimental uncertainty of Thomson scattering data.

- At **rho=0.95**, linear simulations of similar discharge show mode spectrum comparable to rho=0.90. Ongoing work indicates that heat flux stiffness is less pronounced. Flux-match appears possible with ExB shear and nominal parameters.



See arXiv:1808.06607 for details of this work

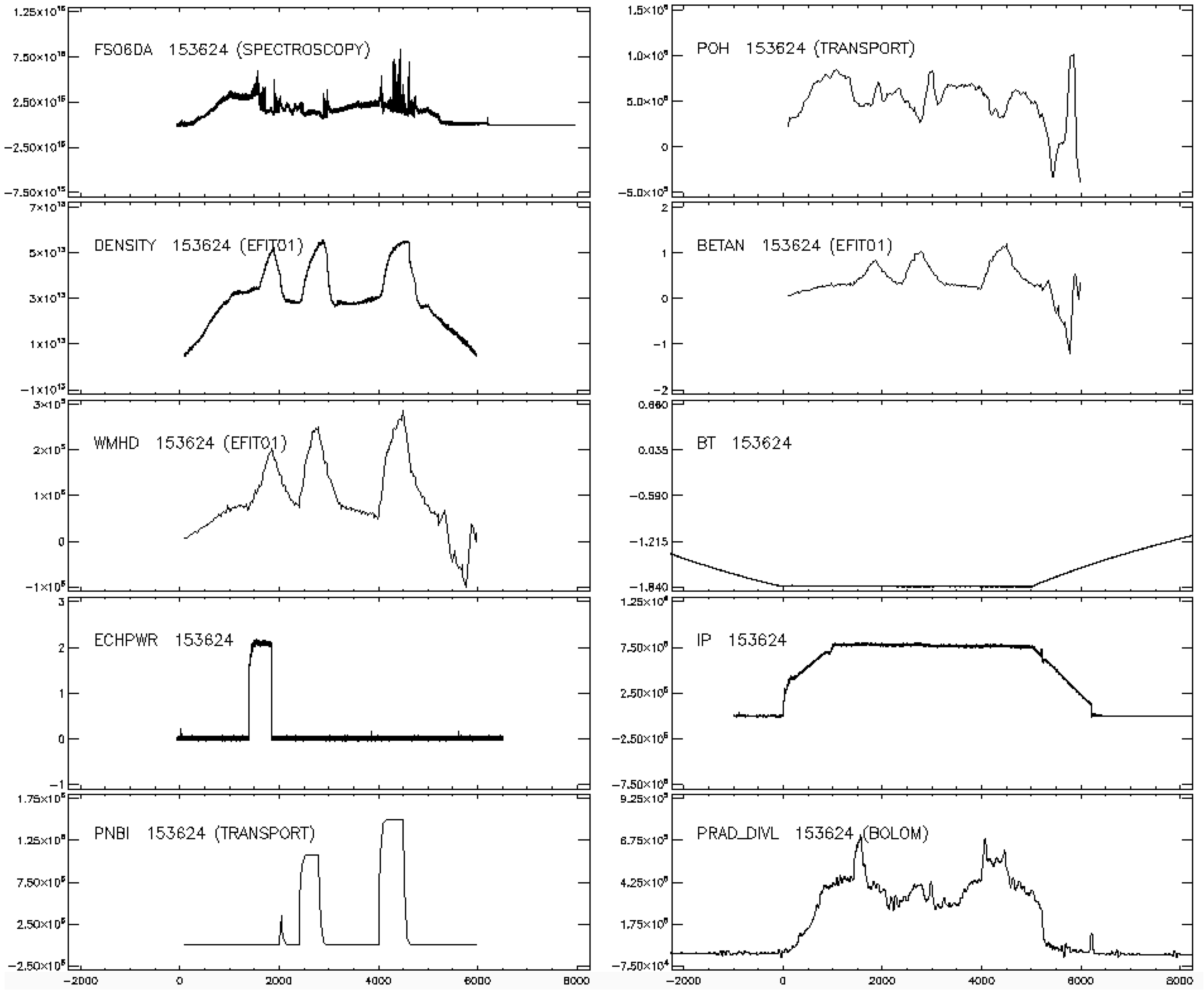
Backup Slides

Experimental Parameters

ρ	0.80	0.85	0.90	0.95
Time [s]	2.40	2.40	2.40	2.40
$\hat{s}$	1.41	1.98	2.98	5.18
q	2.86	3.15	3.69	4.47
ω_{T_i}	2.78	2.80	2.68	2.32
ω_{T_e}	4.69	5.62	7.32	13.51
ω_{n_e}	1.34	2.21	2.91	7.05
β_e [%]	0.056	0.0396	0.0252	0.0132
T_i [keV]	0.360	0.320	0.281	0.244
T_e [keV]	0.148	0.119	0.0831	0.0531
$n_e\,[10^{19}\,\mathrm{m}^{-3}]$	2.72	2.68	2.19	2.12
Z_{eff}	1.80	1.80	1.80	1.80
$\nu_{ei}[c_s/L_{\mathrm{ref}}]$	7.28	10.9	17.8	35.21
B_{ref} [T]	1.70	1.70	1.70	1.70
L_{ref} [m]	0.770	0.770	0.770	0.770
ρ_s [cm]	0.103	0.0927	0.0775	0.0619
$n\,[k_y\rho_s]$	208	224	242	264

Table 1: Physical parameters for radial positions in the near-edge region

Time traces of experimental parameters for #153624



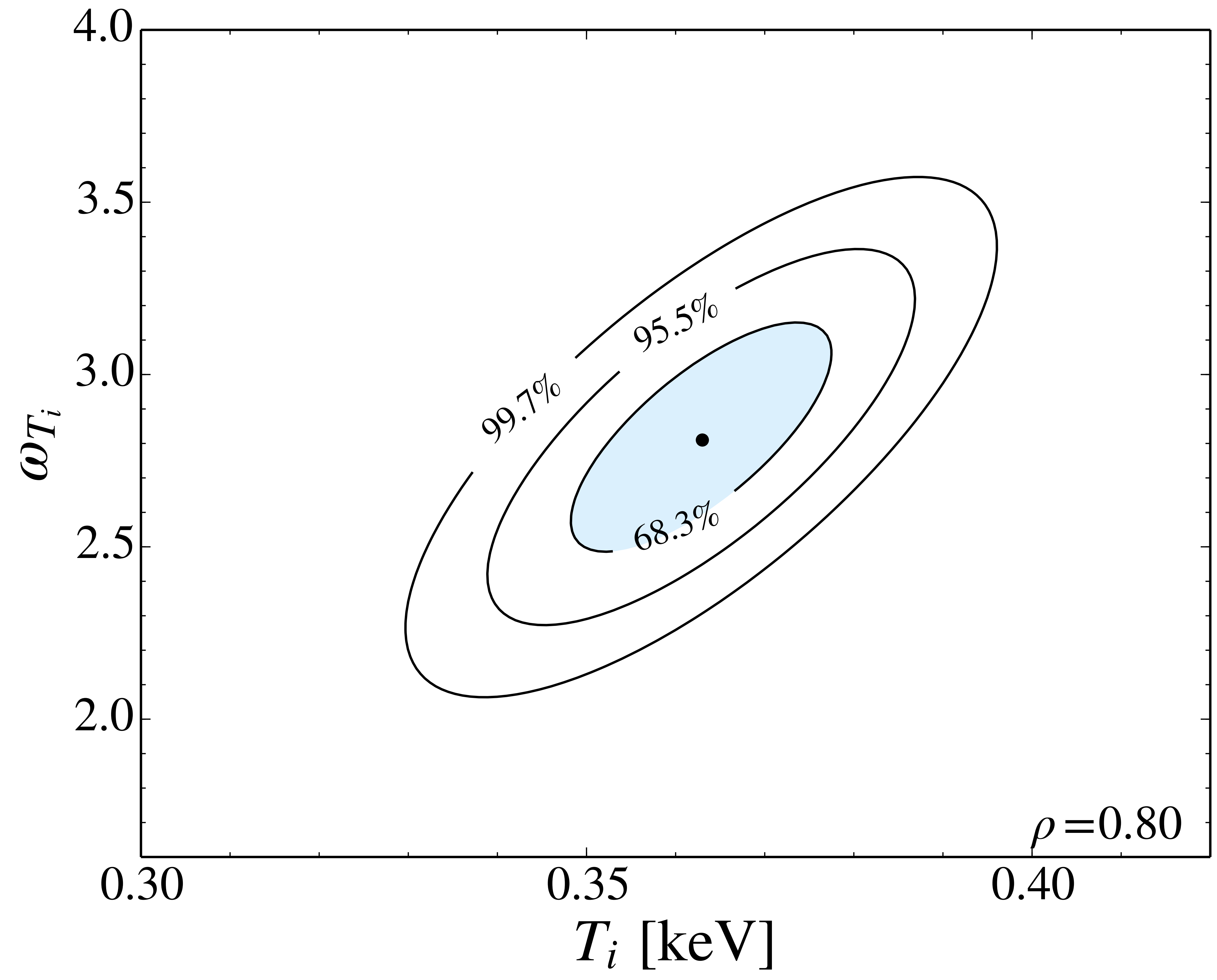
Quantify uncertainty with global model

Use polynomial model of lowest order that is able to pass through all data points:

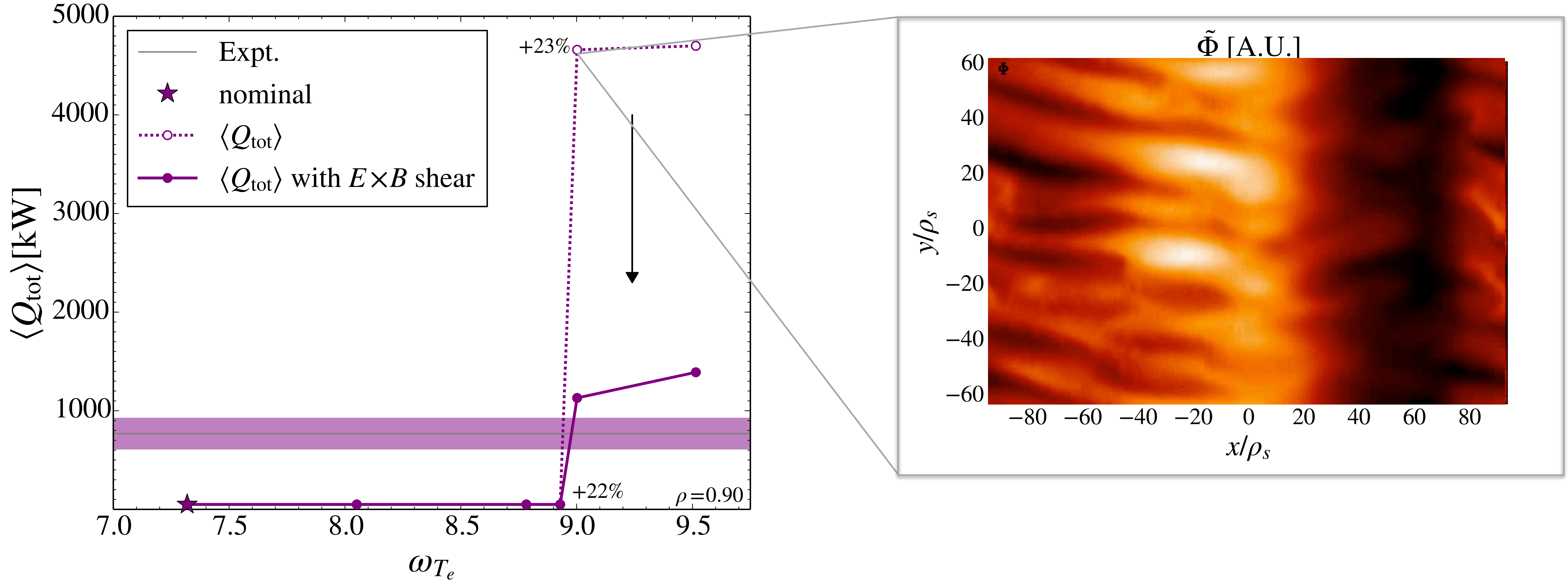
$$T_{i,\mathrm{th}}(\rho) = a(\rho - 0.80)^3 + b(\rho - 0.80)^2 + c(\rho - 0.80) + T_{i,0}(0.80)$$

Finds χ^2 minimum slightly better than gaprofiles, and fewer degrees of freedom

$$\chi^2(a, b, c, T_{i,0}) = \sum_i \frac{\left[T_{i,\mathrm{th}}(\rho_i) - T_{i,\mathrm{exp}}(\rho_i)\right]^2}{\sigma_i^2}$$



Observable at rho=0.90 is the total heat flux, due to difficulty resolving heat channels



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