Coupled ITG/TEM-ETG Gyrokinetic Simulations

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Coupled ITG/TEM-ETG Transport

Motivation and What's New

- Is energy transport from **electron-temperature-gradient** (ETG) modes significant?
  - Is it a large fraction of the total χ_e?
  - Could it account for residual electron transport in an ITB?
  - How do we define it, since its only part of χ_e?
- GYRO is well-suited (scalable, efficient) to study this problem.
- This work was supported by a DOE INCITE computer-time award.
- First simulations to resolve both electron-scale and ion-scale turbuence.

Let's define χ_e^{ETG} as that which arises from $k_\theta \rho_i > 1.0$

Coupled ITG/TEM-ETG Transport

Summary of main results

- The **adiabatic-ion** model of ETG is **poorly-behaved**.
  - Transport becomes **unbounded** for some parameters.
  - Using the **kinetic ion response** cures the problem.
- Ion-temperature-gradient (ITG) transport is **insensitive** to ETG.
- Increased ITG drive can **reduce** ETG transport.
  - Unclear how much of the effect is **linear** and how much is **nonlinear**.
- What fraction of χ_e is χ_e^{ETG}?
  - Only **10% to 20%** in the absence of $\mathbf{E}\times\mathbf{B}$ shear (this talk).
  - Up to **100%**, as ITG/TEM is quenched by $\mathbf{E}\times\mathbf{B}$ shear (Waltz).

The ETG-ai Model

The minimal model of ETG, but is it sensible?

- Basis of **original studies** by Jenko and Dorland.
- Take **short-wavelength limit** of the ion response:

$$\frac{\delta f_i}{n_i F_M} = -\frac{z_i e\, \delta\phi(\mathbf{x},t)}{T_i} \quad .$$

- **Nearly isomorphic** to usual adiabatic-electron model of ITG.
- Computationally simple – ion time and space scales removed.
- The **physics of zonal flows** is dramatically altered.

Electron-ion Scale Separation

Parameterized by the electron-to-ion mass ratio

- Turbulence extends from **electron** (ρ_e) scales to **ion** (ρ_i) scales:

$$\frac{(L_x)_i}{(L_x)_e} \sim \mu \qquad \frac{(L_y)_i}{(L_y)_e} \sim \mu$$

- Characteristic times are **short for electrons** and **long for ions**:

$$\frac{\tau_i}{\tau_e} \sim \frac{a/v_e}{a/v_i} \sim \mu$$

- Critical parameter is the **root of the mass-ratio**:

$$\mu \doteq \sqrt{\frac{m_i}{m_e}} \simeq 60$$

Three Ways to Treat Ion Dynamics

1. **ETG-ai** = **adiabatic ion model of ETG** **(CHEAP)**

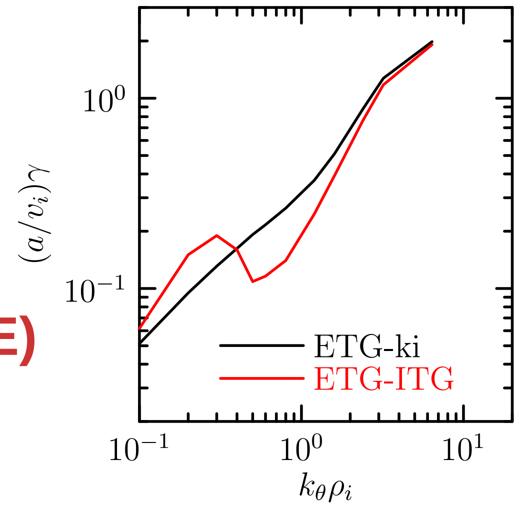
   ion scales do not enter

2. **ETG-ki** = **kinetic ion model of ETG** **(EXPENSIVE)**

   (no ion drive) $\longrightarrow a/L_{Ti} = 0.1, \;\; a/L_{ni} = 0.1$

3. **ETG-ITG** = **kinetic ion model of ETG** **(EXPENSIVE)**

   (ion drive) $\longrightarrow a/L_{Ti} = a/L_{Te}, \;\; a/L_{ni} = a/L_{ne}$



Other parameters taken to match the **Cyclone base case**:

$$q = 1.4, \;\; s = 0.8, \;\; R/a = 2.78, \;\; a/L_{Te} = 2.5, \;\; a/L_{ne} = 0.8$$

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Reduced Mass Ratio for Computational Efficiency

A crucial method to cut corners

- Can deduce essential results using $\mu < 60$.
- Fully-coupled simulations, as shown, use **light kinetic ions**:

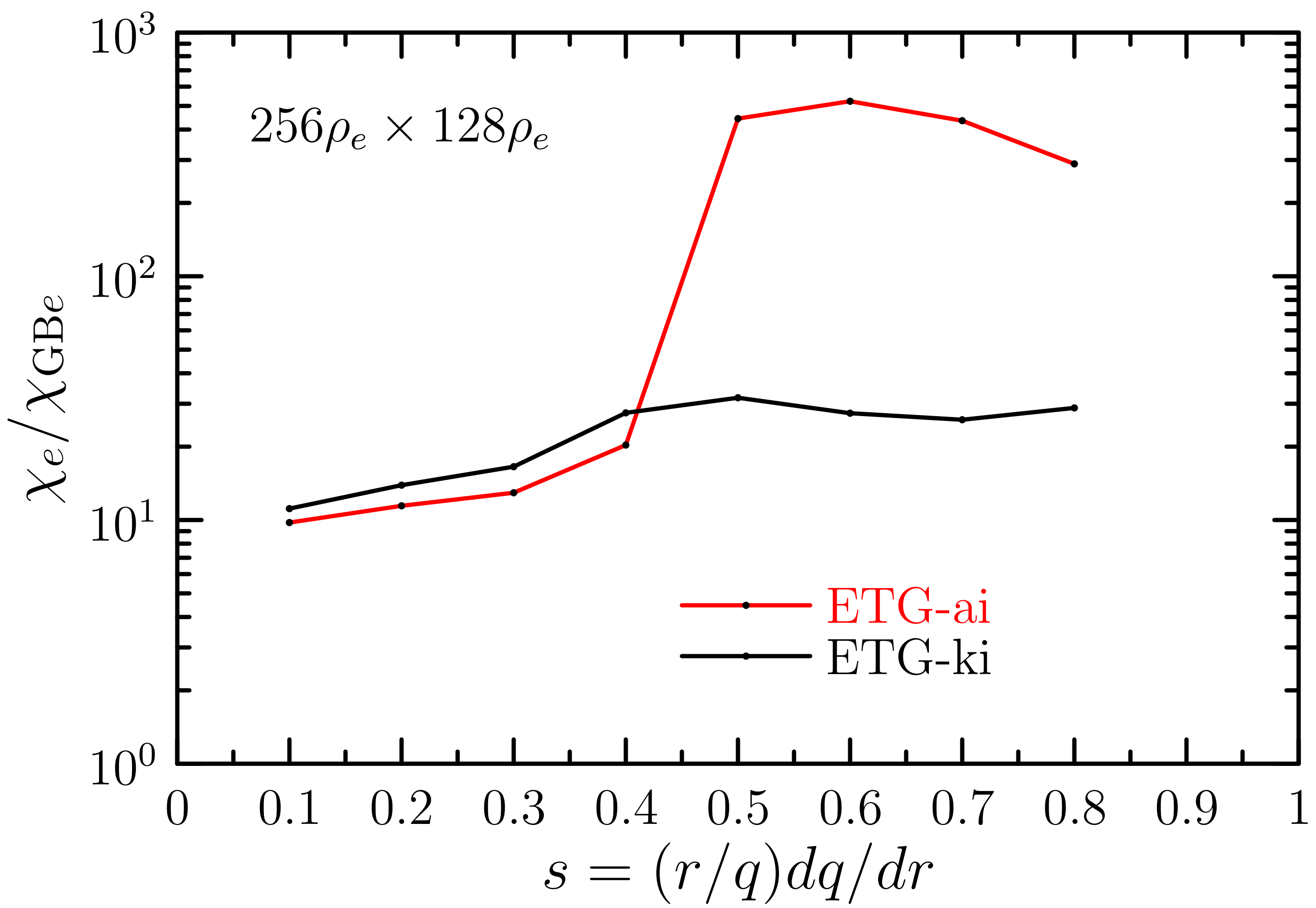
$$\mu \doteq \sqrt{\frac{m_i}{m_e}} = 20, 30 \quad .$$

- Simulation cost scales roughly as $\mu^{3.5}$: $\left(\frac{30}{20}\right)^{3.5} \simeq 4$.

$\mu = 20$	5 days on Cray X1E (192 MSPs)
$\mu = 30$	5 days on Cray X1E (720 MSPs)

ETG-ai Model FAILS for Cyclone Base Case

Lacks long-wavelength ion response of robust ETG-ki model



Red curve (ETG-ai) is unphysical for $s > 0.4$.

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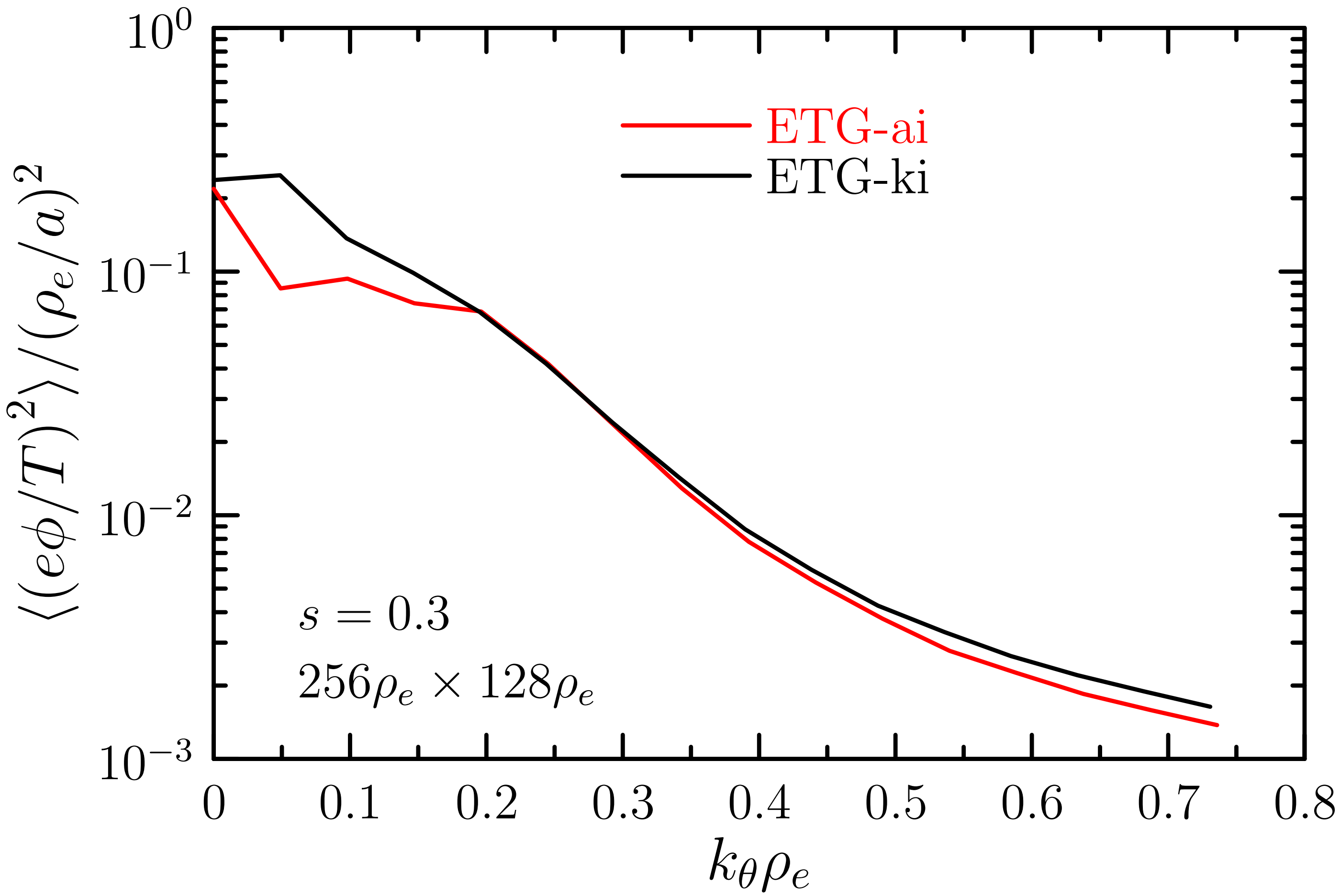
Toroidal Power Spectrum Comparison

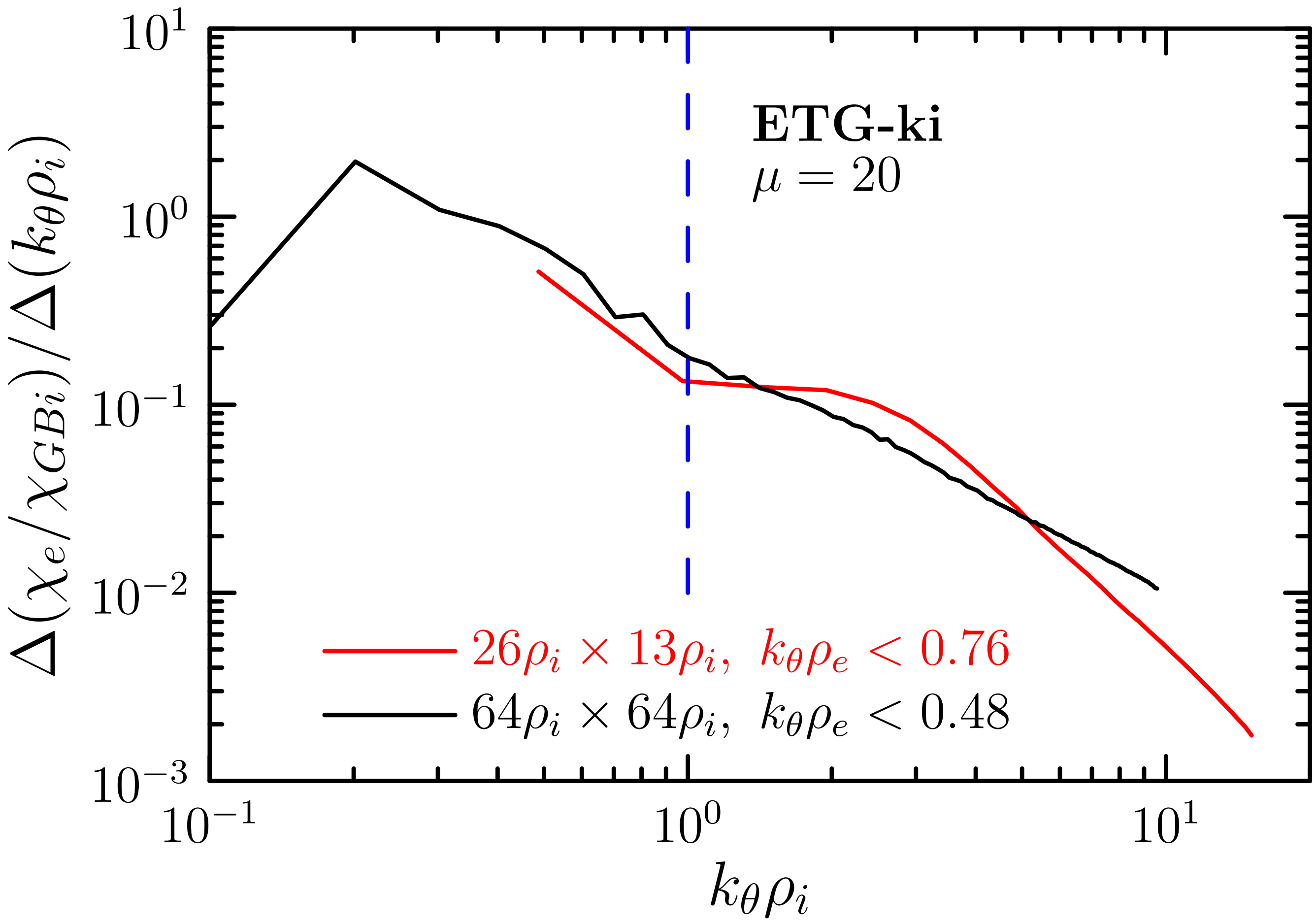
ETG-ki model modifies long-wavelength dynamics only



Red curve (ETG-ai) exhibits spectral pile-up at $k_\theta \rho_e = 0$.

Comparison of ETG-ki Simulations

Spectral overlap is obtained between *large-box* and *small-box* simulations



Red curve simulation too small to contain most-unstable ITG/TEM modes.

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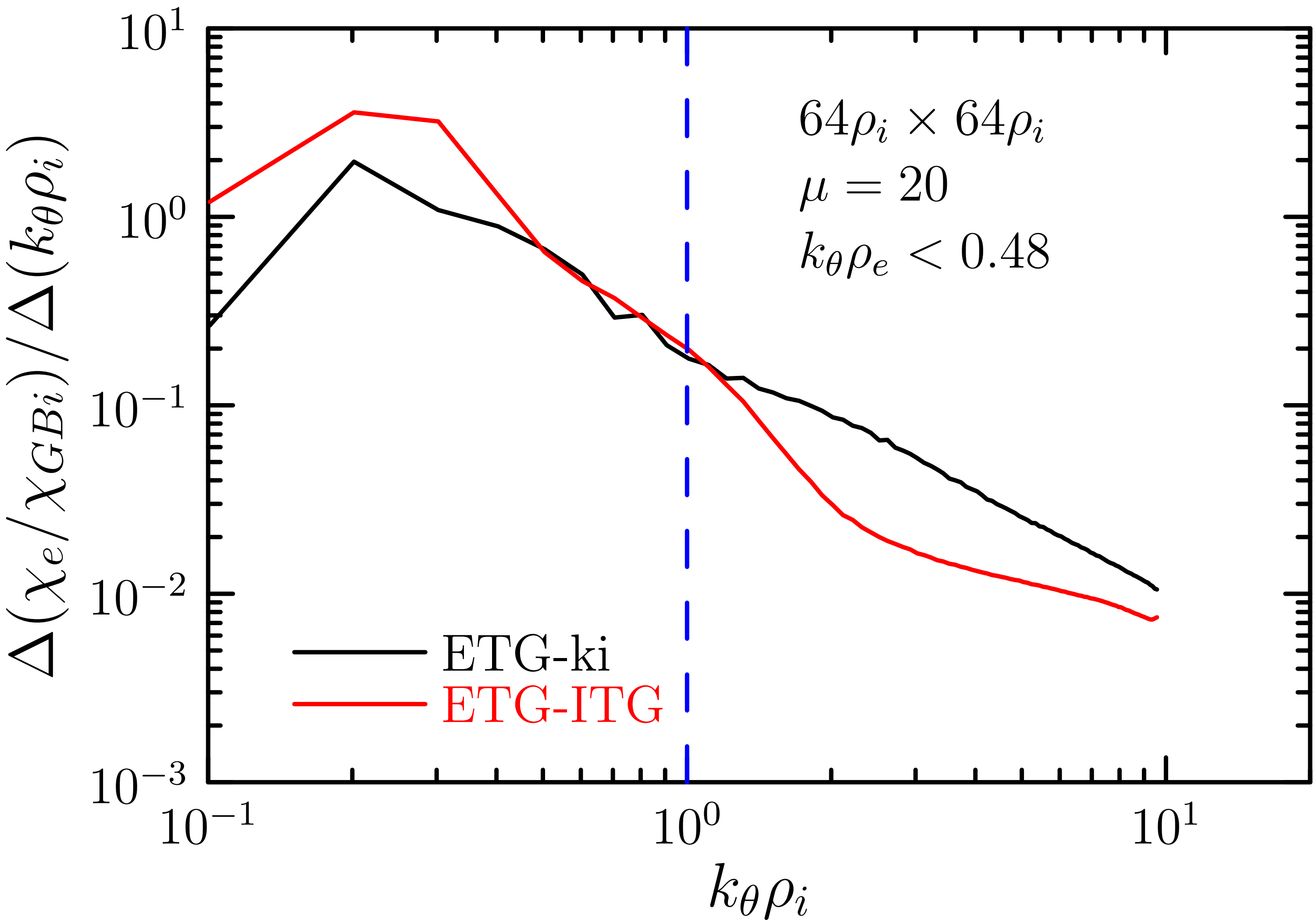
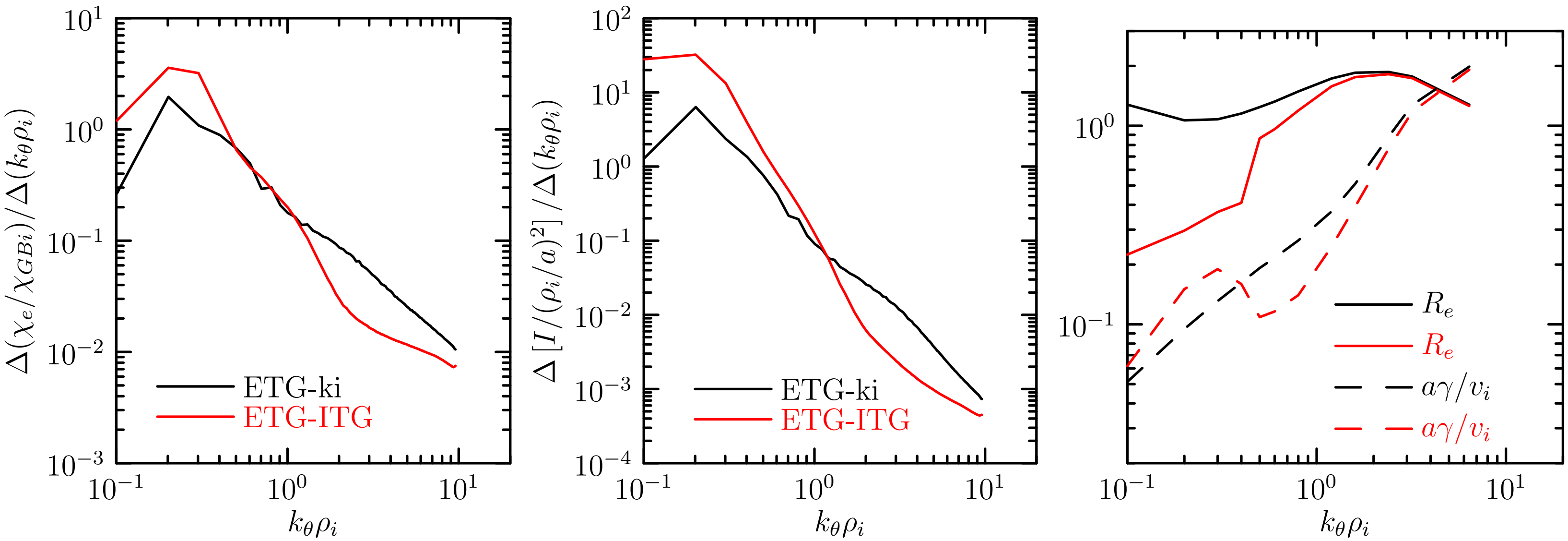
The Effect of Ion Gradients: ETG-ITG versus ETG-ki

Finite ion gradients reduce χ_e^{ETG}



Understanding the Effect of Ion Gradients

What is the dominant physical mechanism for this reduction?



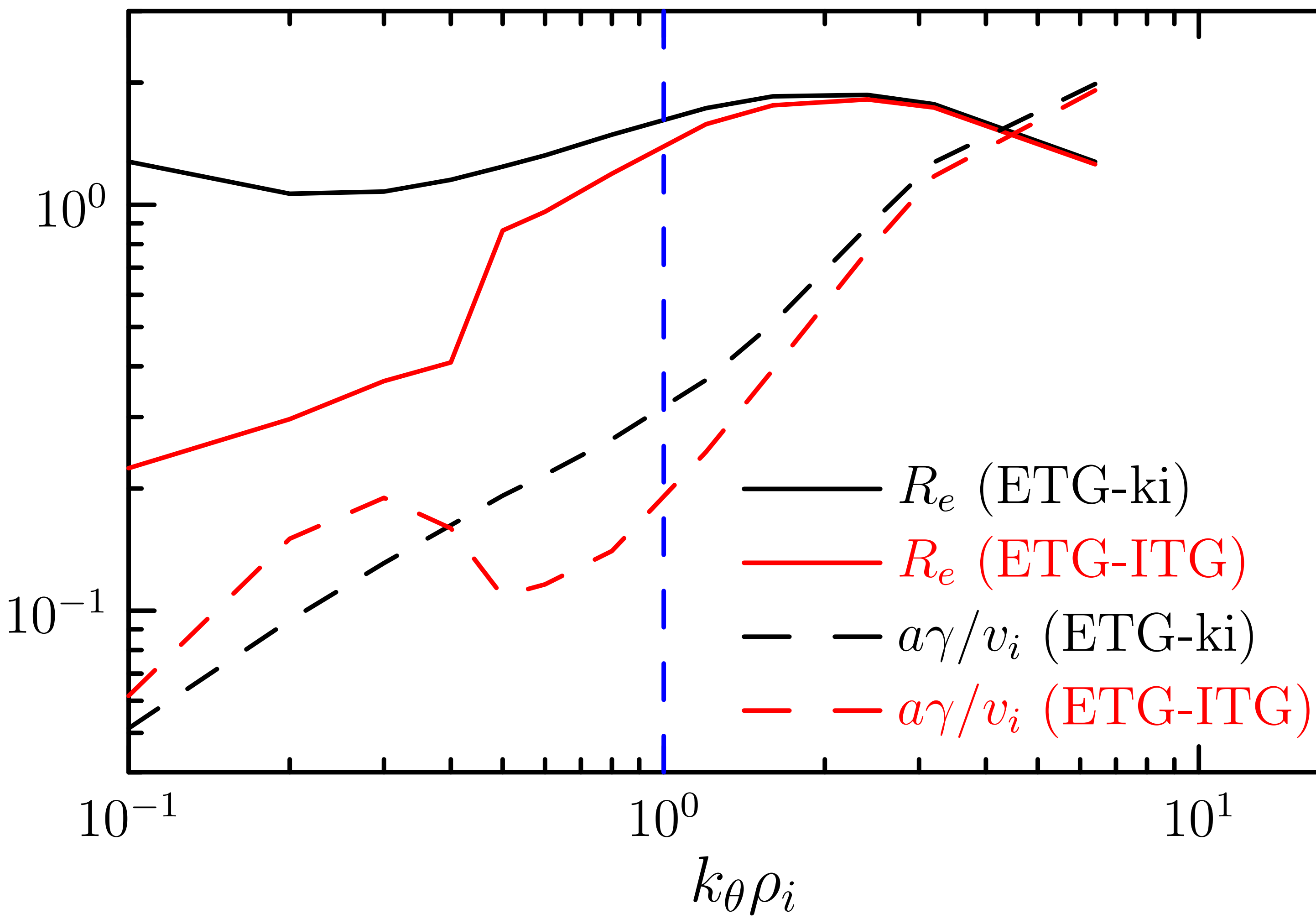
$$(I)_{k_\theta} = \left| \frac{e\phi_{k_\theta}}{T} \right|^2$$ is the **intensity**

$$(R_e)_{k_\theta} = \frac{(Q_e)_{k_\theta}}{k_\theta \rho_i (I)_{k_\theta} n_e T_e}$$ is the **quasilinear response function**.

$$a\gamma/v_i$$ is the **linear growth rate**.

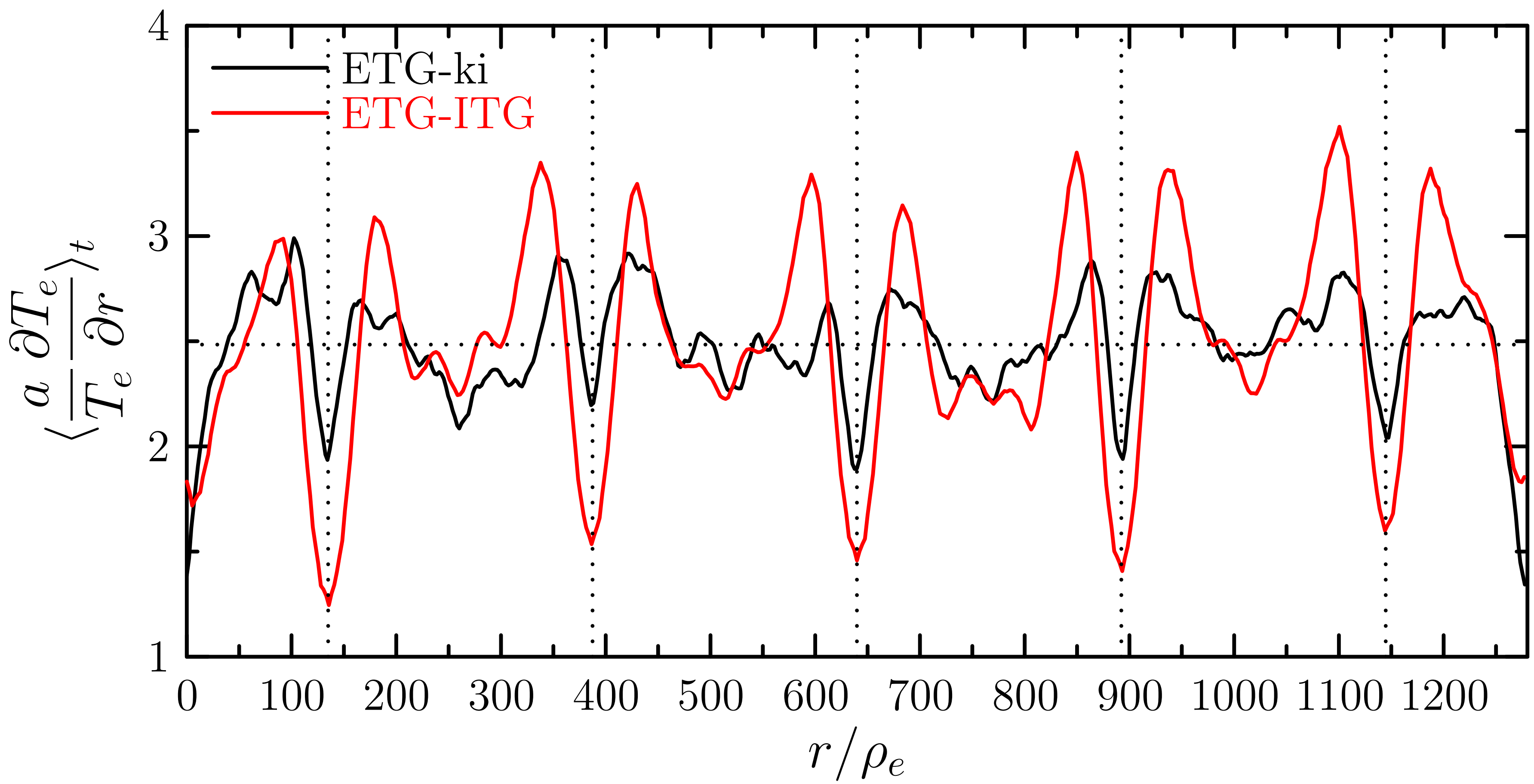
Linear Effect of Ion Gradients

Some correlation between linear and nonlinear results



Electron Temperature Profile Corrugations Develop

This is a real phenomenon, tied to rational surfaces



Are corrugations connected with the reduction in χ_e^{ETG}?

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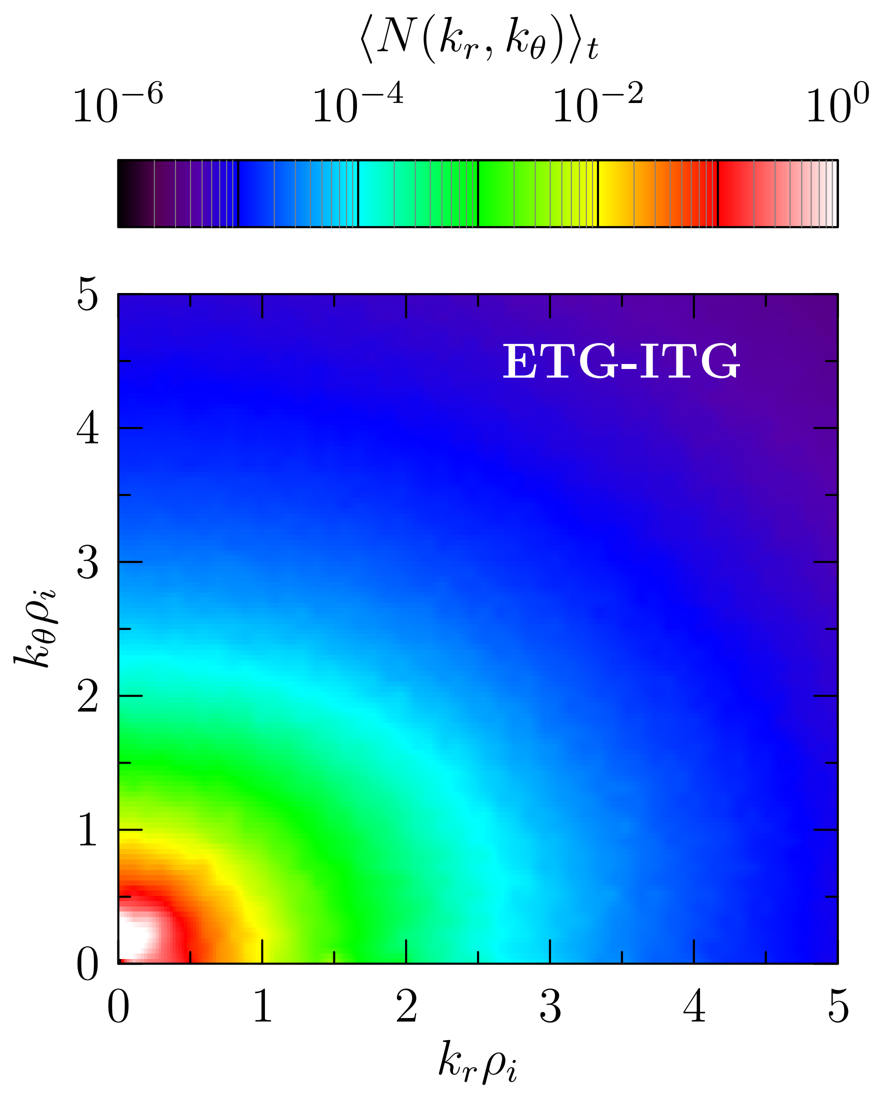
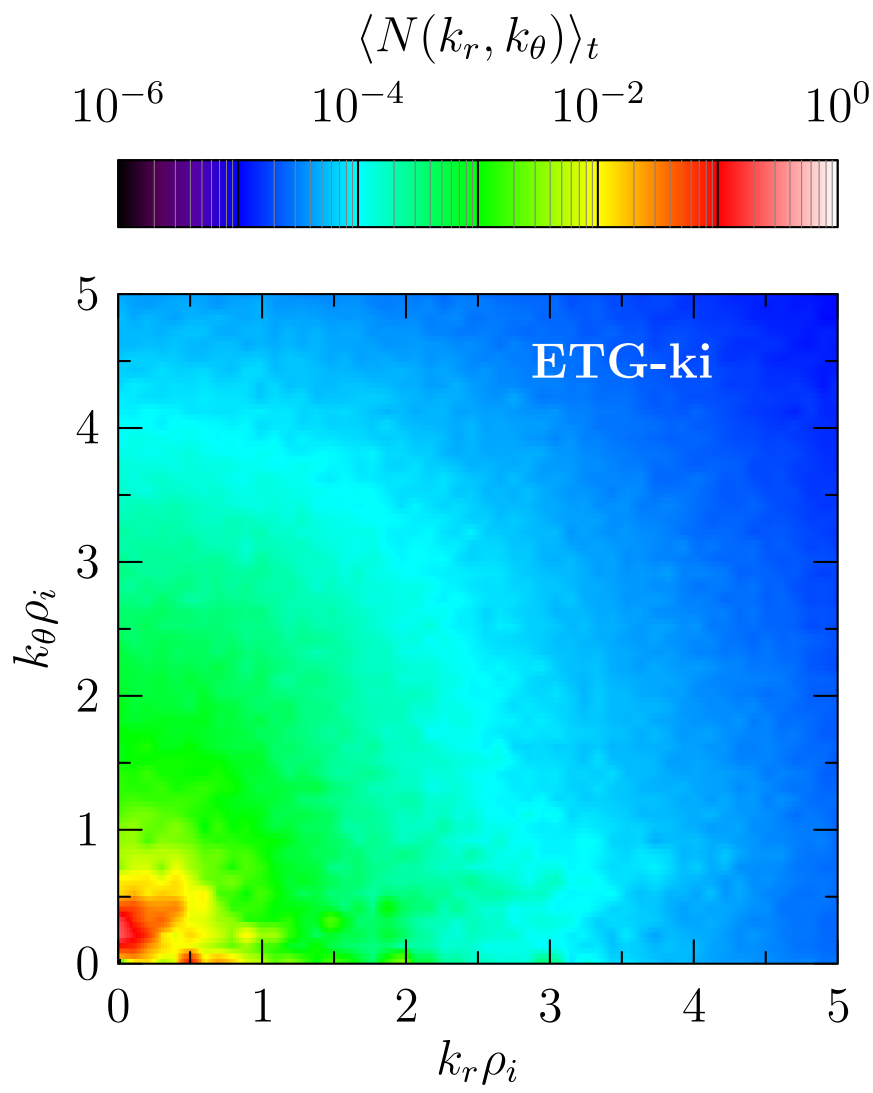
Perpendicular Spectral Intensity of Density Fluctations

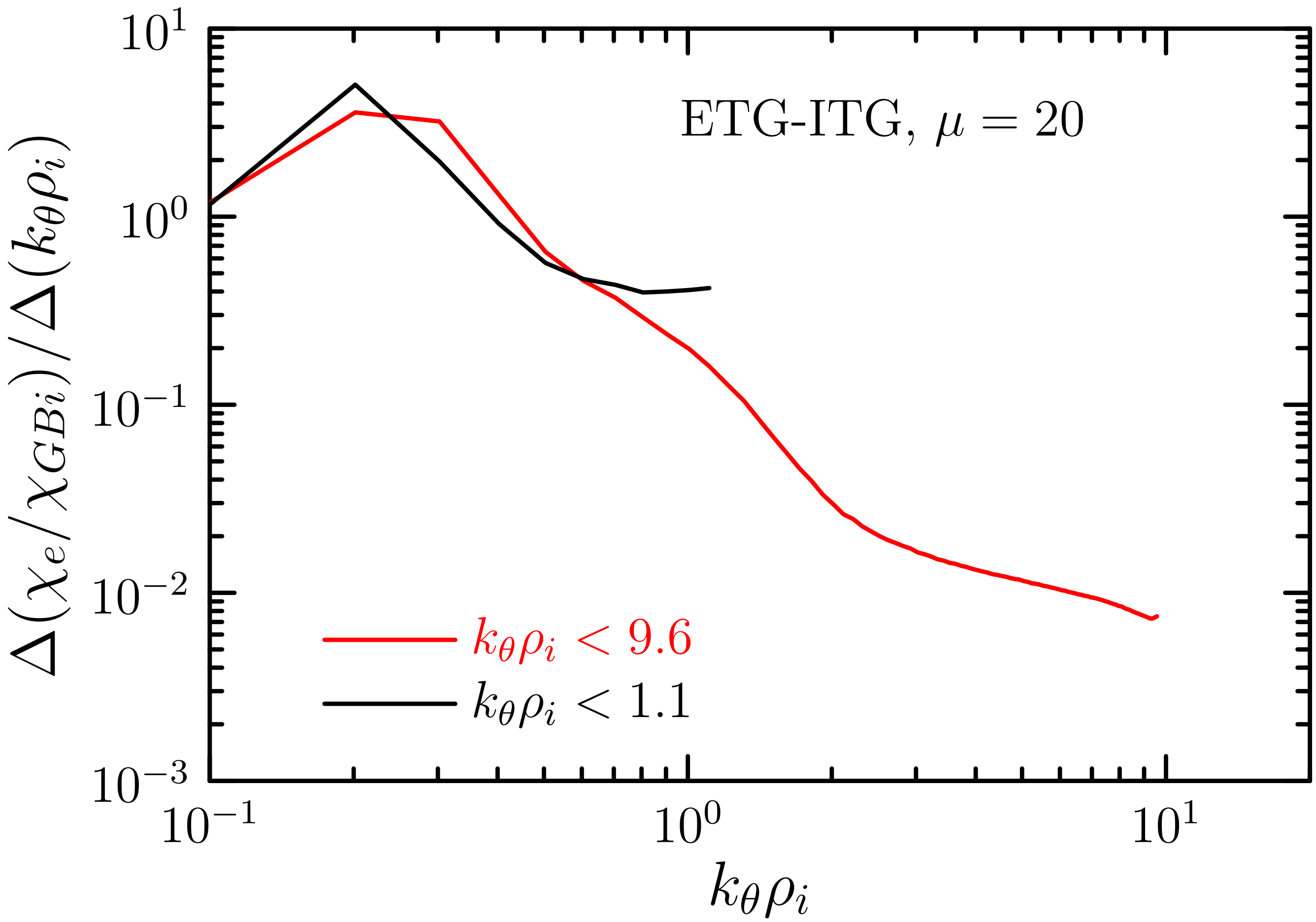
ETG-ITG spectrum is highly isotropic for $k_\perp \rho_i > 0.5$





Effect of Reduced Spatial Grid Size

Resolving only up to $k_\theta \rho_i < 1.1$ approximates total electron transport



Traditional simulation (black) gives a good approximation of χ_e.

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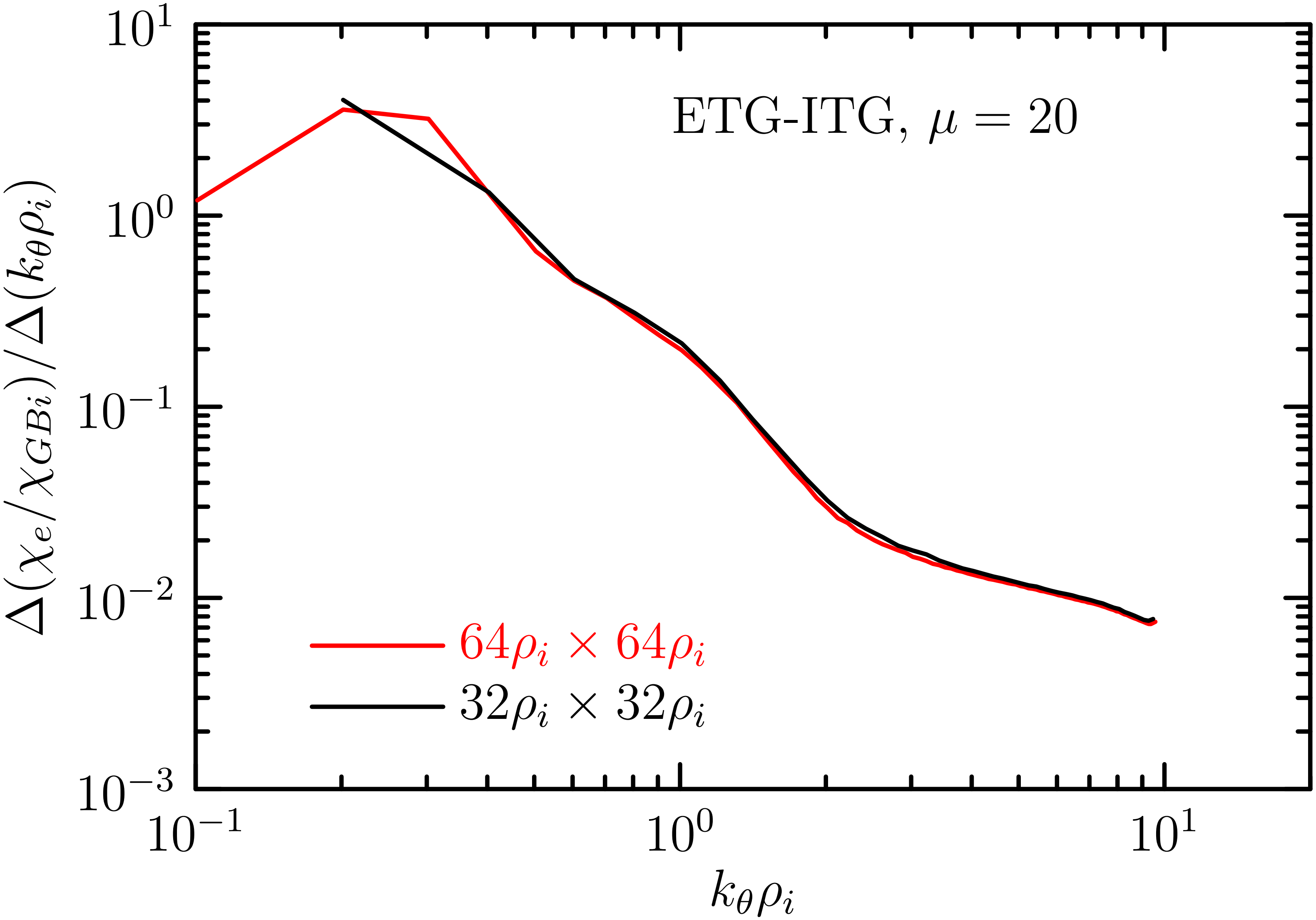
Effect of Reduced Perpendicular Box Size

A $32\rho_i \times 32\rho_i$ box is enough to capture the physics for $k_\theta \rho_e > 0.1$.



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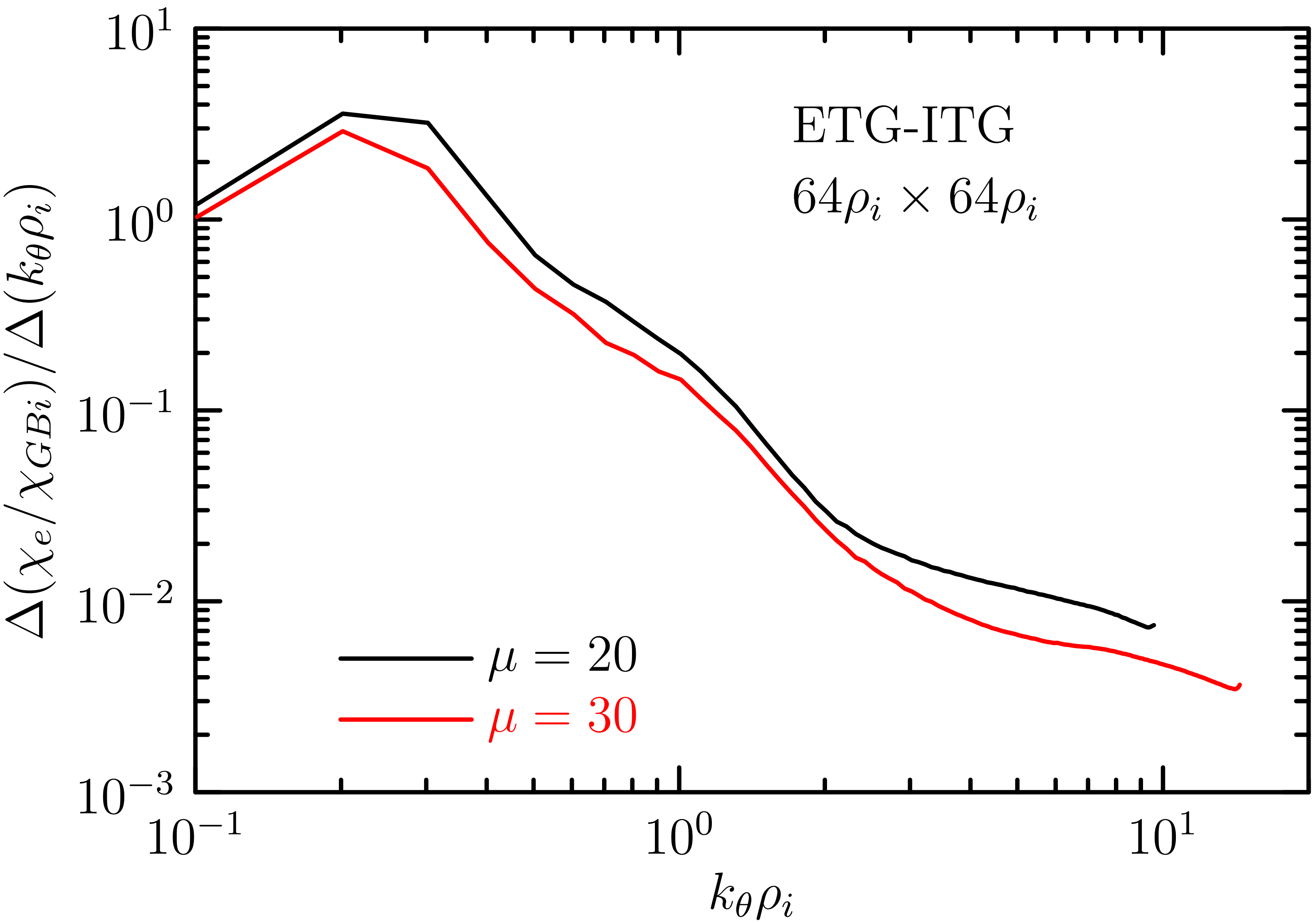
Mass-ratio Comparison in Ion Units

Transport overestimate for $\mu = 20$ is well-known



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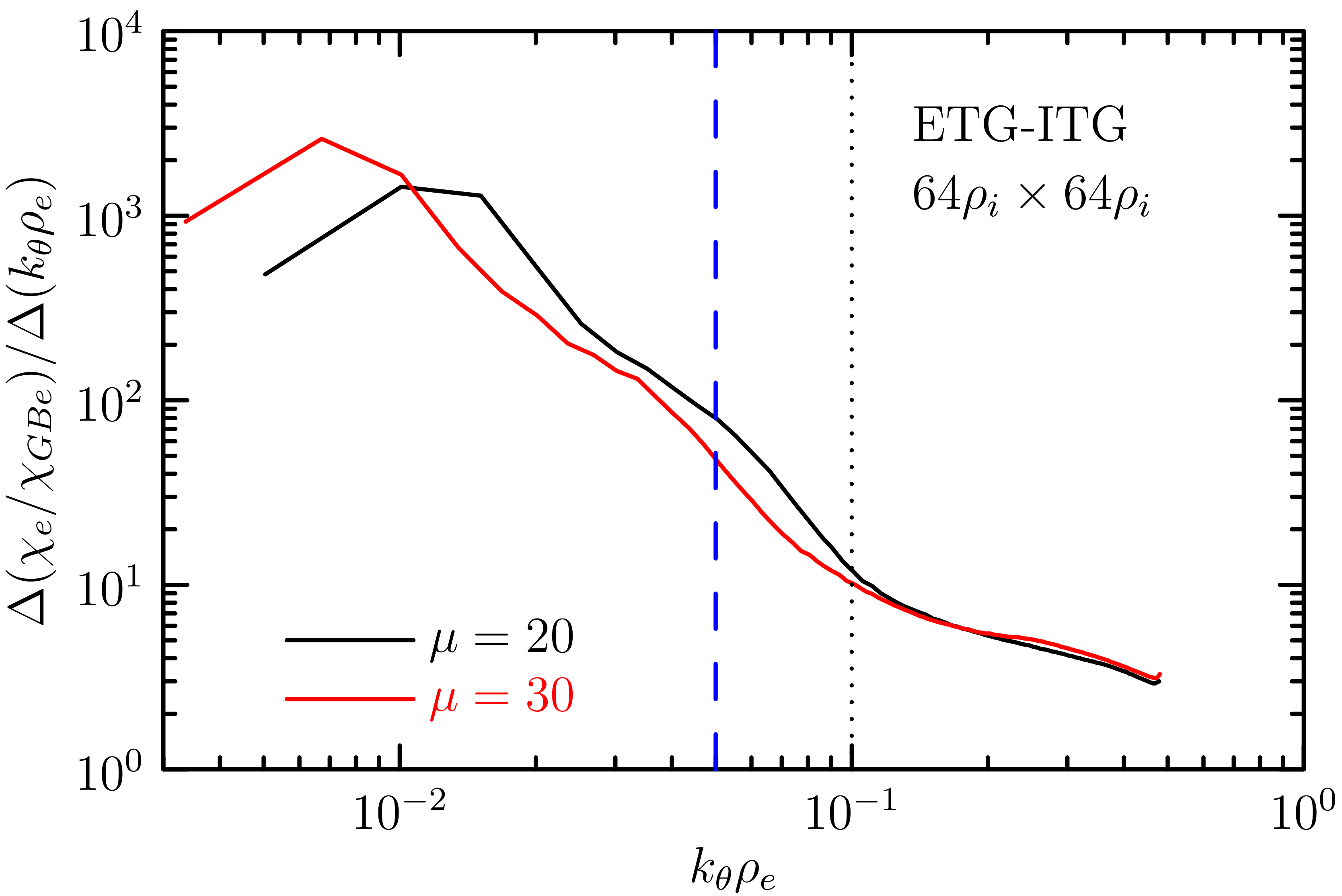
Mass-ratio Comparison in Electron Units

Curve approaches universal shape at short wavelength ($k_\theta \rho_e > 0.1$)



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Electron Transport Result Matrix

About 16% (8%) of electron transport comes from $k_\theta\rho_i > 1$ ($k_\theta\rho_i > 2$)

	μ	$k_\theta\rho_i < 1$	$k_\theta\rho_i > 1$	$k_\theta\rho_i > 2$	$k_\theta\rho_e > 0.1$
$\chi_i/\chi_{\mathrm{GB}i}$	20	7.378	0.054	0.011	
	30	7.754	0.043	0.009	
$\chi_e/\chi_{\mathrm{GB}i}$	20	2.278	0.367	0.183	
	30	1.587	0.296	0.157	
$D/\chi_{\mathrm{GB}i}$	20	-0.81	0.134	0.009	
	30	-1.60	0.074	0.010	
$\chi_e/\chi_{\mathrm{GB}e}$	20				3.67
	30				3.76

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