Capturing electron-scale effects in tokamak turbulence

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GENERAL ATOMICS

Drift waves and tokamak plasma turbulence

Role in the context of fusion research

- **Plasma performance**:

  In tokamak plasmas, performance is limited by turbulent radial transport of both energy and particles.

- **Gradient-driven**:

  This turbulent transport is caused by drift-wave instabilities, driven by free energy in plasma temperature and density gradients.

- **Unavoidable**:

  These instabilities will persist in a reactor.

- **Various types (asymptotic theory)**:

  ITG, TIM, TEM, ETG . . . + Electromagnetic variants (AITG, etc).

Fokker-Planck Theory of Plasma Transport

Comprehensive series of papers by Sugama and coworkers

The Fokker-Planck (FP) equation provides the **fundamental theory** for **plasma equilibrium**, **fluctuations**, and **transport**:

$$\left[\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla + \frac{e_a}{m_a}\left((\mathbf{E}+\hat{\mathbf{E}}) + \frac{\mathbf{v}}{c}\times(\mathbf{B}+\hat{\mathbf{B}})\right)\cdot\frac{\partial}{\partial \mathbf{v}}\right](f_a + \hat{f}_a)$$
$$= C_a(f_a + \hat{f}_a) + S_a$$

$f_a \longrightarrow$ **ensemble-averaged distribution**

$\hat{f}_a \longrightarrow$ **fluctuating distribution**

$S_a \longrightarrow$ **sources (beams, RF, etc)**

$C_a = \sum_b C_{ab}(f_a + \hat{f}_a, f_b + \hat{f}_b) \longrightarrow$ **nonlinear collision operator**

Fokker-Planck theory

Comprehensive, consistent framework for equilibrium profile evolution

The general approach is to separate the FP equation into **ensemble-averaged**, $\mathcal{A}$, and **fluctuating**, $\mathcal{F}$, components:

$$\mathcal{A} = \left.\frac{d}{dt}\right|_{\rm ens} f_a - \langle C_a \rangle_{\rm ens} - D_a - S_a \ ,$$

$$\mathcal{F} = \left.\frac{d}{dt}\right|_{\rm ens} \hat{f}_a + \frac{e_a}{m_a}\left(\hat{\mathbf{E}} + \frac{\mathbf{v}}{c} \times \hat{\mathbf{B}}\right) \cdot \frac{\partial}{\partial \mathbf{v}}(f_a + \hat{f}_a) - C_a + \langle C_a \rangle_{\rm ens} + D_a \ ,$$

where

$$\left.\frac{d}{dt}\right|_{\rm ens} \doteq \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla + \frac{e_a}{m_a}\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right) \cdot \frac{\partial}{\partial \mathbf{v}} \ ,$$

$$D_a \doteq -\frac{e_a}{m_a}\left\langle \left(\hat{\mathbf{E}} + \frac{\mathbf{v}}{c} \times \hat{\mathbf{B}}\right) \cdot \frac{\partial \hat{f}_a}{\partial \mathbf{v}} \right\rangle_{\rm ens} \ .$$

▷ D_a is the **fluctuation-particle interaction operator**.

Fokker-Planck theory

Space- and time-scale expansion in powers of $\rho_* = \rho_s/a$

Ensemble averages are expanded in powers of ρ_* as

$$
\begin{aligned}
f_a &= f_{a0} + f_{a1} + f_{a2} + \ldots \;, \\
S_a &= \phantom{f_{a0} + f_{a1} +} S_{a2} + \ldots \; \textbf{(transport ordering)}, \\
\mathbf{E} &= \mathbf{E}_0 + \mathbf{E}_1 + \mathbf{E}_2 + \ldots \;, \\
\mathbf{B} &= \mathbf{B}_0 \;.
\end{aligned}
$$

Fluctuations are also expanded in powers of ρ_* as

$$
\begin{aligned}
\hat{f}_a &= \hat{f}_{a1} + \hat{f}_{a2} + \ldots \;, \\
\hat{\mathbf{E}} &= \hat{\mathbf{E}}_1 + \hat{\mathbf{E}}_2 + \ldots \;, \\
\hat{\mathbf{B}} &= \hat{\mathbf{B}}_1 + \hat{\mathbf{B}}_2 + \ldots \;.
\end{aligned}
$$

Built-in assumption about scale separation **hard to escape**.

Fokker-Planck theory

Lowest-order conditions for flow and gyroangle independence

Lowest-order Constraints

The lowest-order ensemble-averaged equation gives the **constraints**

$$\mathcal{A}_{-1} = 0 : \qquad \mathbf{E}_0 + \frac{1}{c}\mathbf{V}_0 \times \mathbf{B} = 0 \qquad \text{and} \qquad \frac{\partial f_{a0}}{\partial \xi} = 0$$

where ξ is the gyroangle.

Large mean flow

The only **equilibrium flow** that persists on the fluctuation timescale is

$$\mathbf{V}_0 = R\,\omega_0(\psi)\mathbf{e}_\varphi \quad \text{where} \quad \omega_0 \doteq -c\frac{\partial \Phi_0}{\partial \psi} \ .$$

[F.L. Hinton and S.K. Wong, Phys. Fluids **28** (1985) 3082].

Fokker-Planck theory

Equilibrium equation is a formidable nonlinear PDE

Equilibrium equation

The gyrophase average of the zeroth order ensemble-averaged equation gives the **collisional equilibrium** equation:

$$\int_0^{2\pi} \frac{d\xi}{2\pi} \mathcal{A}_0 = 0 : \qquad \left(\mathbf{V}_0 + v_\parallel' \mathbf{b} \right) \cdot \nabla f_{a0} = C_a(f_{a0})$$

where $\mathbf{v}' = \mathbf{v} - \mathbf{V}_0$ is the velocity in the rotating frame.

Equilibrium distribution function

The exact solution for f_{a0} is a **Maxwellian in the rotating frame**, such that the centrifugal force causes the density to vary on the flux surface:

$$f_{a0} = n_a(\psi, \theta) \left(\frac{m_a}{2\pi T_a} \right)^{3/2} e^{-m_a (v')^2 / 2T_a} \ .$$

Fokker-Planck theory

Equations for neoclassical transport and turbulence at $\mathcal{O}(\rho_*)$

Drift-kinetic equation

Gyroaverage of first-order $\mathcal{A}_1$ gives expressions for **gyroangle-dependent ($\tilde{f}_{a1}$)** and **gyroangle-independent ($\bar{f}_{a1}$)** distributions:

$$\int_0^{2\pi} \frac{d\xi}{2\pi} \mathcal{A}_1 = 0 : \qquad f_{a1} = \tilde{f}_{a1} + \bar{f}_{a1} \; , \quad \tilde{f}_{a1} = \frac{1}{\Omega_a} \int^{\xi} d\xi \, \widetilde{\mathcal{L} f_{a0}}$$

▷ Ensemble-averaged $\bar{f}_{a1}$ is determined by the **drift kinetic equation (NEO)**.

Gyrokinetic equation

Gyroaverage of first-order $\mathcal{F}_1$ gives an expression for **first-order fluctuating distribution ($\hat{f}_{a1}$)** in terms of the distribution of the gyrocenters, $h_a(\mathbf{R})$:

$$\int_0^{2\pi} \frac{d\xi}{2\pi} \mathcal{F}_1 = 0 : \qquad \hat{f}_{a1}(\mathbf{x}) = -\frac{e_a \hat{\phi}(\mathbf{x})}{T_a} + h_a(\mathbf{x} - \rho)$$

▷ Fluctuating $\hat{f}_{a1}$ is determined by the **gyrokinetic equation (GYRO)**.

Drift-Kinetic Equation for Neoclassical Transport

NEO gives complete solution with full kinetic e-i-impurity coupling

$$v_\parallel' \mathbf{b} \cdot \nabla \bar{g}_a - C_a^L(\bar{g}_a) = \frac{f_{a0}}{T_a} \left[-\frac{1}{N_a} \frac{\partial N_a T_a}{\partial \psi} W_{a1} - \frac{\partial T_a}{\partial \psi} W_{a2} + c \frac{\partial^2 \Phi_0}{\partial \psi^2} W_{aV} + \frac{\langle B E_\parallel^A \rangle}{\langle B^2 \rangle^{1/2}} W_{aE} \right]$$

$$\bar{g}_a \doteq \bar{f}_{a1} - f_{a0} \frac{e_a}{T_a} \int^\ell \frac{dl}{B} \left(B E_\parallel - \frac{B^2}{\langle B^2 \rangle} \langle B E_\parallel \rangle \right) \; ,$$

$$W_{a1} \doteq \frac{m_a c}{e_a} v_\parallel' \mathbf{b} \cdot \nabla \left(\omega_0 R + \frac{I}{B} v_\parallel' \right) \; ,$$

$$W_{a2} \doteq W_{a1} \left(\frac{\varepsilon}{T_a} - \frac{5}{2} \right) \; ,$$

$$W_{aV} \doteq \frac{m_a c}{2 e_a} v_\parallel' \mathbf{b} \cdot \nabla \left[m_a \left(\omega_0 R + \frac{I}{B} v_\parallel' \right)^2 + \mu \frac{R^2 B_p^2}{B} \right] \; ,$$

$$W_{aE} \doteq \frac{e_a v_\parallel' B}{\langle B \rangle^{1/2}} \; .$$

Gyro-Kinetic Equation for Turbulent Transport

GYRO gives complete solution with full $(\phi, A_\parallel, B_\parallel)$ electromagnetic physics.

$$\frac{\partial h_a(\mathbf{R})}{\partial t} + \left(\mathbf{V}_0 + v_\parallel' \mathbf{b} + \mathbf{v}_{da} - \frac{c}{B}\nabla\hat{\Psi}_a \times \mathbf{b}\right)\cdot\nabla h_a(\mathbf{R}) - C_a^{GL}\left(\hat{f}_{a1}\right)$$
$$= f_{a0}\left[-\frac{\partial \ln(N_a T_a)}{\partial\psi}\hat{W}_{a1} - \frac{\partial \ln T_a}{\partial\psi}\hat{W}_{a2} + \frac{c}{T_a}\frac{\partial^2\Phi_0}{\partial\psi^2}\hat{W}_{aV} + \frac{1}{T_a}\hat{W}_{aT}\right]$$

$$\hat{W}_{a1}(\mathbf{R}) \doteq -\frac{c}{B}\nabla\hat{\Psi}_a \times \mathbf{b}\cdot\nabla\psi\ ,$$

$$\hat{W}_{a2}(\mathbf{R}) \doteq \hat{W}_{a1}\left(\frac{\varepsilon}{T_a} - \frac{5}{2}\right)\ ,$$

$$\hat{W}_{aV}(\mathbf{R}) \doteq -\frac{m_a R c}{B}\left\langle(\mathbf{V}_0 + \mathbf{v}')\cdot\mathbf{e}_\varphi\nabla\left(\hat{\phi} - \frac{1}{c}(\mathbf{V}_0 + \mathbf{v}')\cdot\hat{\mathbf{A}}\right)\times\mathbf{b}\cdot\nabla\psi\right\rangle_\xi\ ,$$

$$\hat{W}_{aT}(\mathbf{R}) \doteq e_a\left\langle\left(\frac{\partial}{\partial t} + \mathbf{V}_0\cdot\nabla\right)\left(\hat{\phi} - \frac{1}{c}(\mathbf{V}_0 + \mathbf{v}')\cdot\hat{\mathbf{A}}\right)\right\rangle_\xi\ .$$

$$\hat{\Psi}_a(\mathbf{R}) \doteq \left\langle\hat{\phi}(\mathbf{R}+\boldsymbol{\rho}) - \frac{1}{c}(\mathbf{V}_0 + \mathbf{v}')\cdot\hat{\mathbf{A}}(\mathbf{R}+\boldsymbol{\rho})\right\rangle_\xi$$
$$\to J_0\left(\frac{k_\perp v_\perp'}{\Omega_a}\right)\left(\hat{\phi}(\mathbf{k}_\perp) - \frac{\mathbf{V}_0}{c}\cdot\hat{\mathbf{A}}(\mathbf{k}_\perp) - \frac{v_\parallel'}{c}\hat{A}_\parallel(\mathbf{k}_\perp)\right) + J_1\left(\frac{k_\perp v_\perp'}{\Omega_a}\right)\frac{v_\perp'}{c}\frac{\hat{B}_\parallel(\mathbf{k}_\perp)}{k_\perp}\ .$$

Gyro-Kinetic Equation for Turbulent Transport

GYRO gives complete solution with full $(\phi, A_\parallel, B_\parallel)$ electromagnetic physics.

Must also solve the electromagnetic field equations on the **fluctuation scale**:

$$\frac{1}{\lambda_D^2}\left(\hat{\phi}(\mathbf{x}) - \frac{\mathbf{V}_0}{c}\cdot\hat{\mathbf{A}}\right) = 4\pi\sum_a e_a \int d^3v\, \hat{h}_a(\mathbf{x}-\boldsymbol{\rho}) \ ,$$

$$-\nabla_\perp^2 \hat{A}_\parallel(\mathbf{x}) = \frac{4\pi}{c}\sum_a e_a \int d^3v\, \hat{h}_a(\mathbf{x}-\boldsymbol{\rho}) v_\parallel' \ ,$$

$$\nabla \hat{B}_\parallel(\mathbf{x}) \times \mathbf{b} = \frac{4\pi}{c}\sum_a e_a \int d^3v\, \hat{h}_a(\mathbf{x}-\boldsymbol{\rho}) \mathbf{v}_\perp' \ .$$

▷ Can one compute equilibrium-scale potential Φ_0 from the Poisson equation?

▷ Practically, no; need higher-order theory and extreme numerical precision.

▷ All codes must take care to avoid **nonphysical potential** at long wavelength

▷ TGYRO gets $\omega_0(\psi) = -c\partial_\psi \Phi_0$ from the **momentum transport equation**.

Transport Equations

Flux-surface-averaged moments of Fokker-Planck equation

$$\left\langle \int d^3v\, \mathcal{A} \right\rangle_\theta$$ **density**

$$\left\langle \int d^3v\, \varepsilon \mathcal{A} \right\rangle_\theta$$ **energy**

$$\sum_a \left\langle \int d^3v\, m_a v'_\varphi \mathcal{A} \right\rangle_\theta$$ **toroidal momentum**

Only terms of order ρ_*^2 survive these averages

$$\rho_*^{-1} = 10^3 \quad \rho_*^0 = 1 \quad \rho_*^1 = 10^{-3} \quad \rho_*^2 = 10^{-6}$$

Transport Equations

Flux-surface-averaged moments of Fokker-Planck equation to $\mathcal{O}(\rho_*^2)$

$$n_a(r): \quad \frac{\partial \langle n_a \rangle}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial r}(V'\Gamma_a) = S_{n,a}$$

$$T_a(r): \quad \frac{3}{2}\frac{\partial \langle n_a T_a \rangle}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial r}(V'Q_a) + \Pi_a \frac{\partial \omega_0}{\partial \psi} = S_{W,a}$$

$$\omega_0(r): \quad \frac{\partial}{\partial t}(\omega_0 \langle R^2 \rangle \sum_a m_a n_a) + \frac{1}{V'}\frac{\partial}{\partial r}(V' \sum_a \Pi_a) = \sum_a S_{\omega,a}$$

$$S_{n,a} = S_{n,a}^{\text{beam}} + S_{n,a}^{\text{wall}} \quad \text{and} \quad \Gamma_a = \Gamma_a^{\text{GV}} + \Gamma_a^{\text{neo}} + \Gamma_a^{\text{tur}}$$

$$S_{W,a} = S_{W,a}^{\text{aux}} + S_{W,a}^{\text{rad}} + S_{W,a}^{\alpha} + S_{W,a}^{\text{tur}} + S_{W,a}^{\text{col}} \quad \text{and} \quad Q_a = Q_a^{\text{GV}} + Q_a^{\text{neo}} + Q_a^{\text{tur}}$$

$$\Pi_a = \Pi_a^{\text{GV}} + \Pi_a^{\text{neo}} + \Pi_a^{\text{tur}}$$

RED: TGYRO GREEN: NEO BLUE: GYRO

GENERAL ATOMICS

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**:

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

GENERAL ATOMICS

Coupled ITG/TEM-ETG Transport

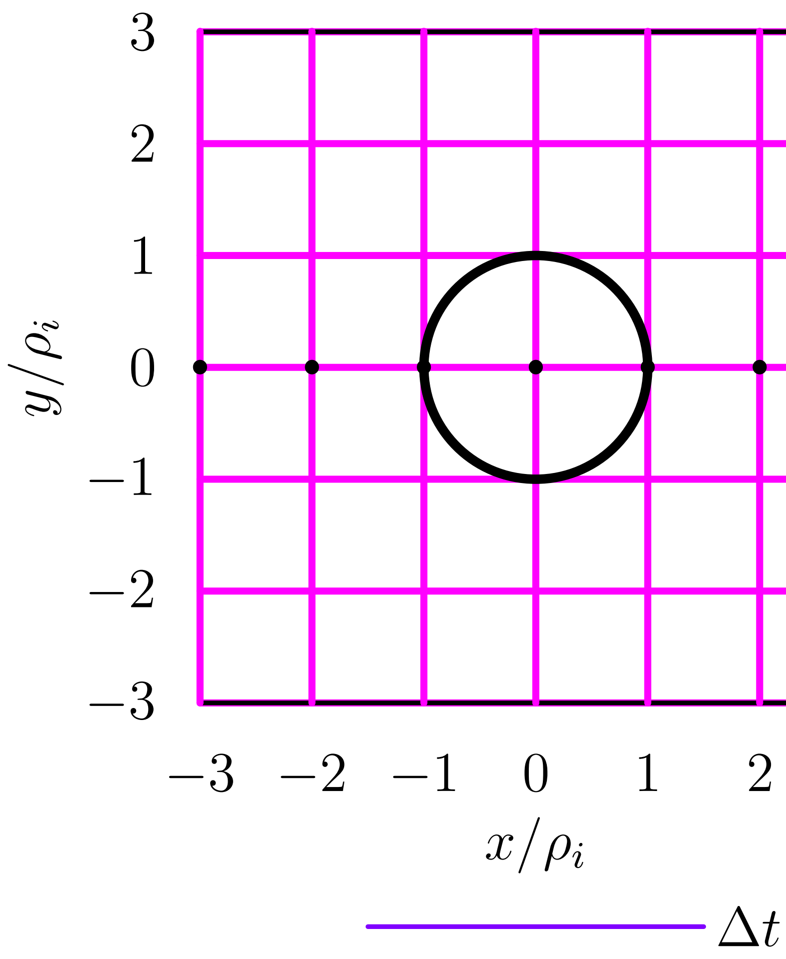
Motivation and What's New

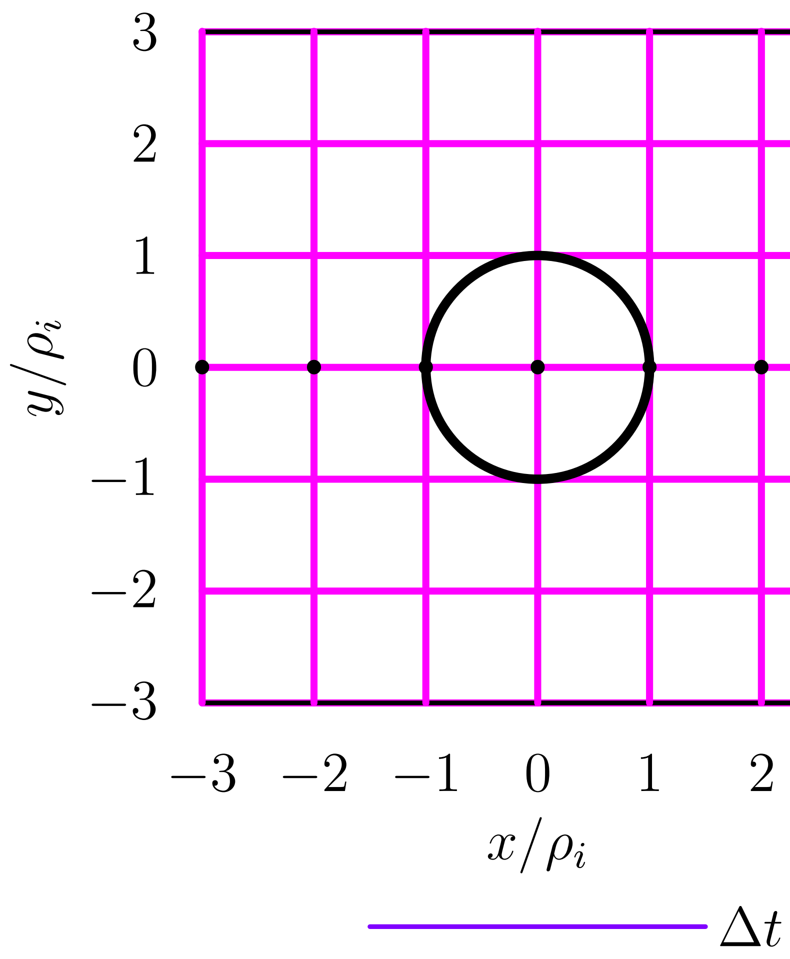
- Is energy transport from **electron-temperature-gradient** (ETG) modes significant?
  - Is it a large fraction of the total χ_e?
  - Could it account for **residual electron transport** in an ITB?
  - How do we define it, since its only part of χ_e?
- GYRO is well-suited (scalable, efficient) to study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

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

Multi-scale simulations require spatial grid refinement

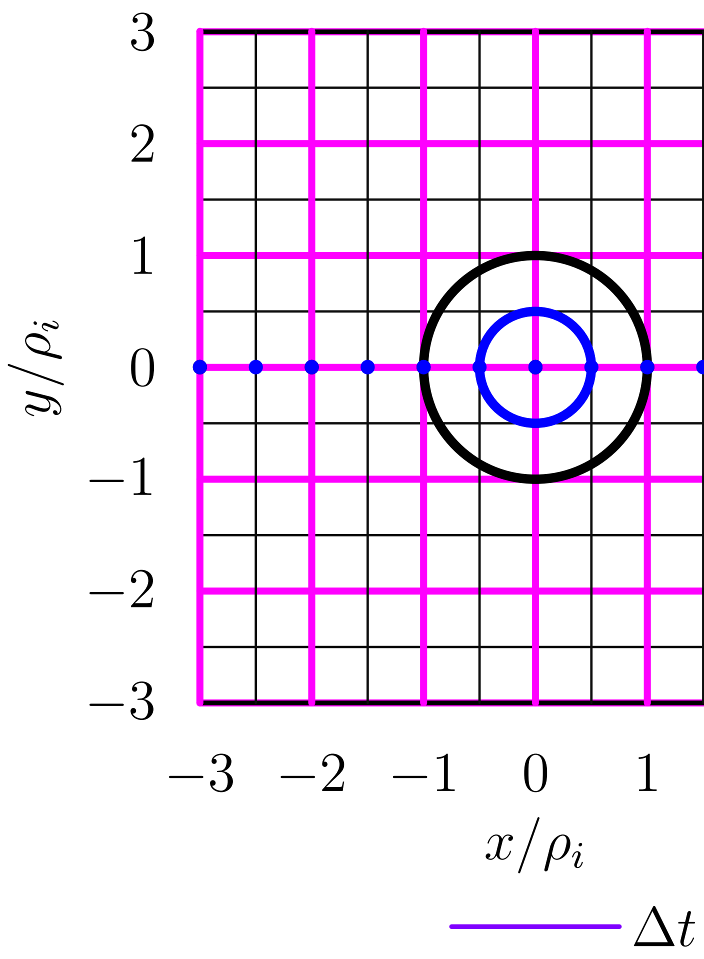
$\mu = 1,\ k_\theta \rho_i \leq 1$

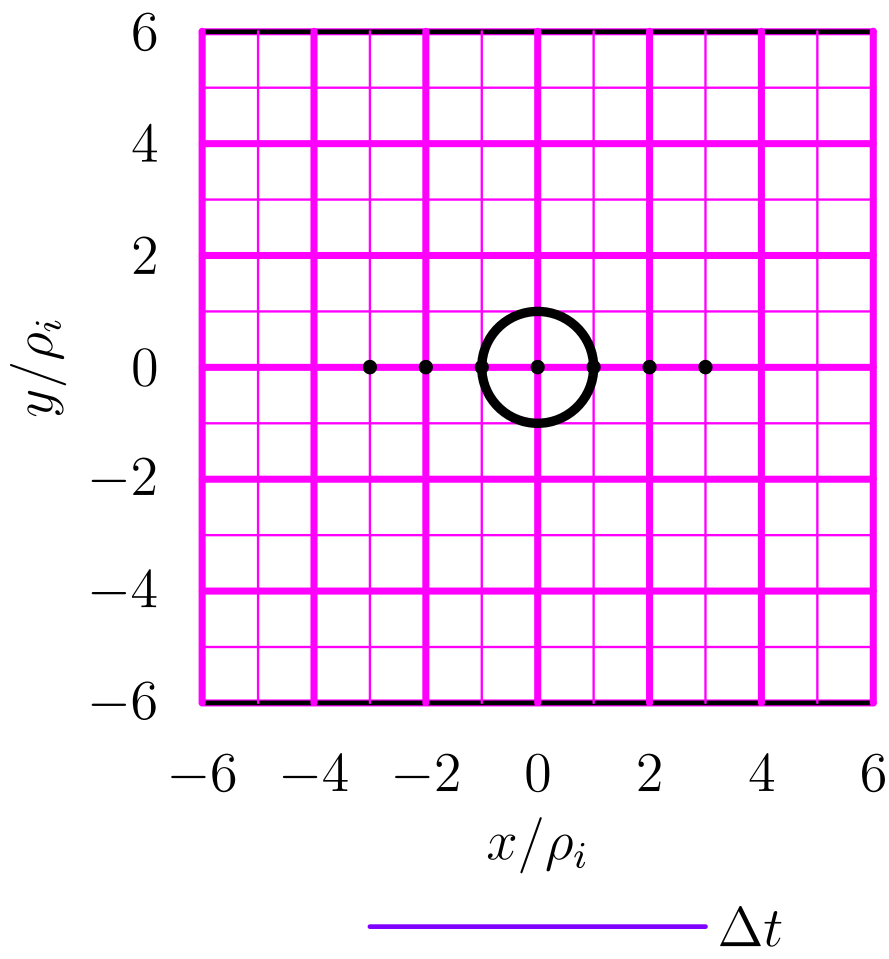




Multi-scale simulations require spatial grid refinement

$\mu = 2,\ k_\theta \rho_i \leq 2$

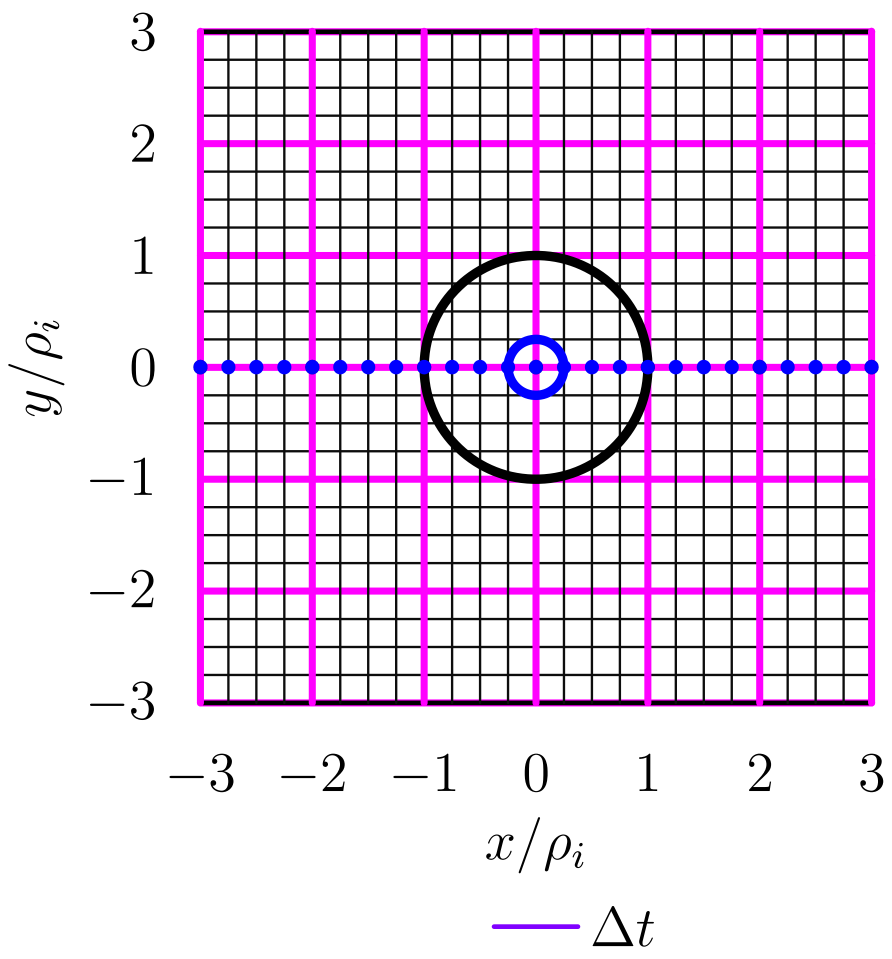


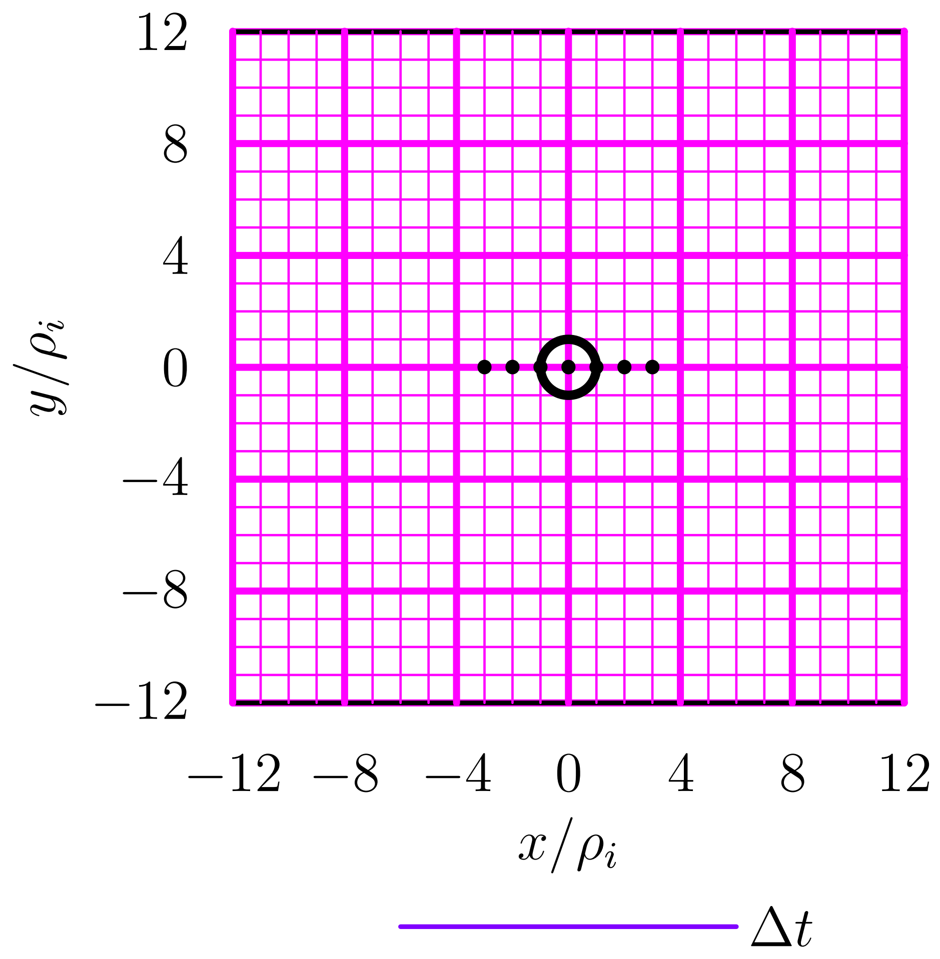


GENERAL ATOMICS

Multi-scale simulations require spatial grid refinement

$\mu = 4,\ k_\theta \rho_i \leq 4$

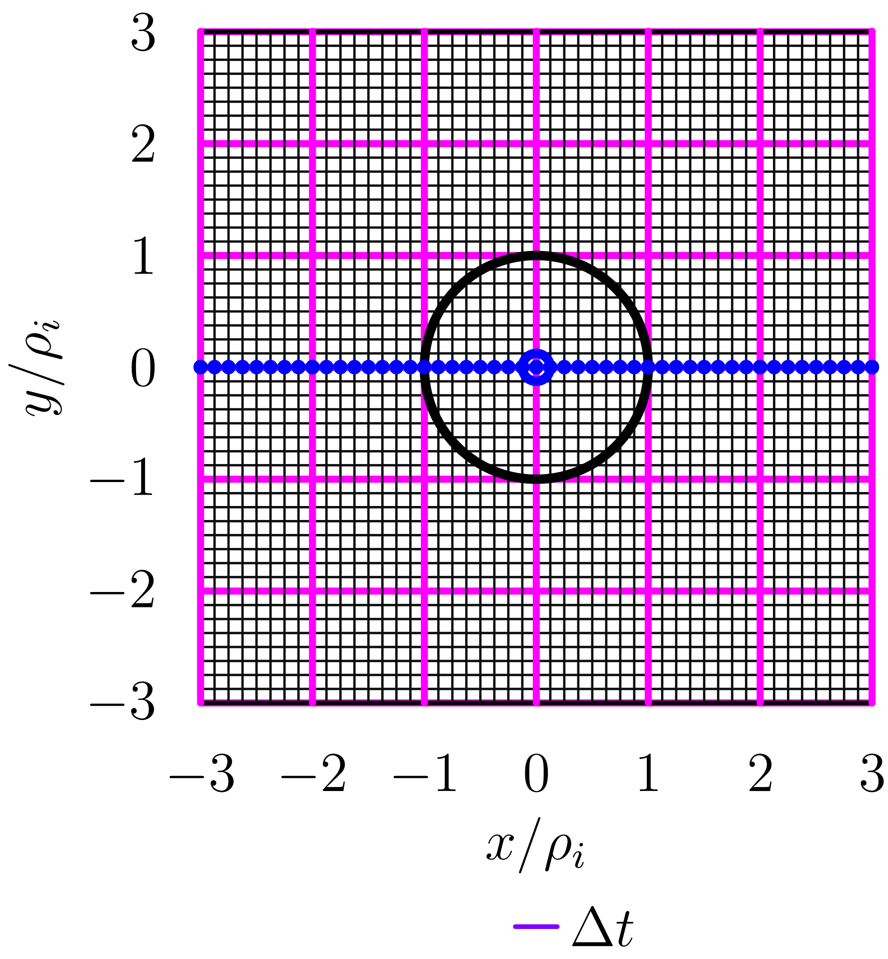


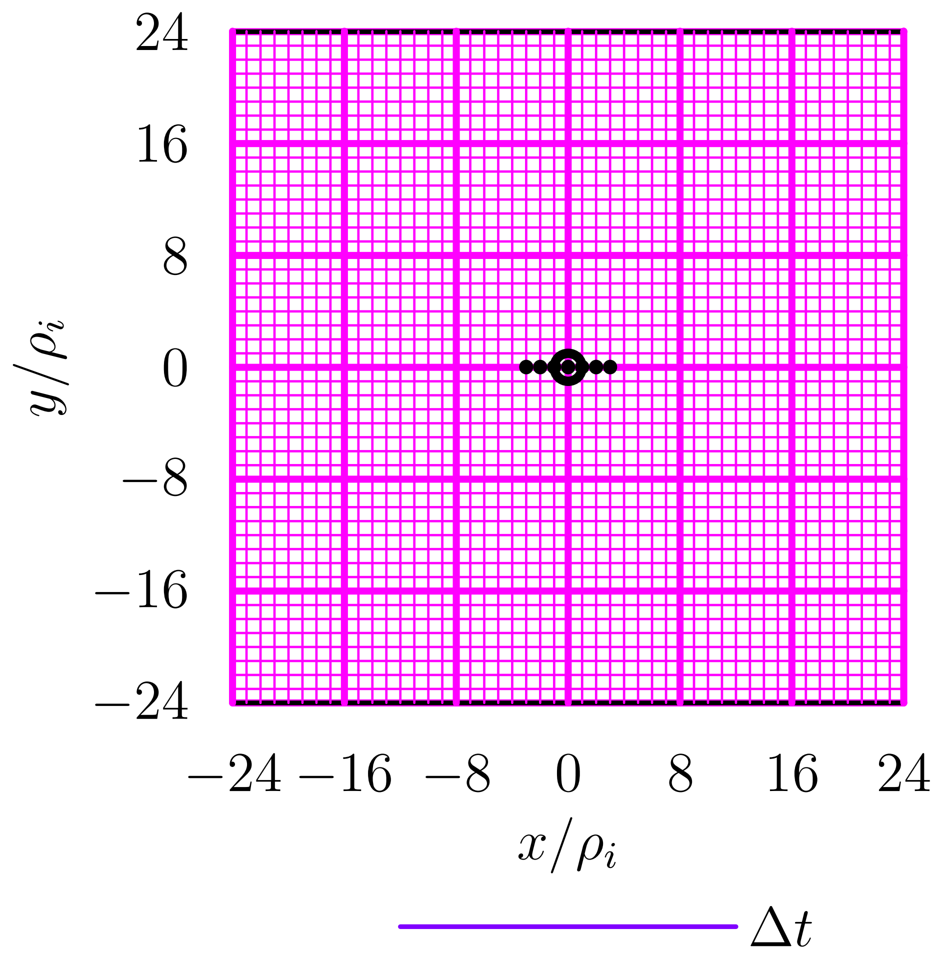


GENERAL ATOMICS

Multi-scale simulations require spatial grid refinement

$\mu = 8,\ k_\theta \rho_i \leq 8$





GENERAL ATOMICS

Three Ways to Treat Ion Dynamics

Definitions

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) $\rightarrow a/L_{Ti} = 0.1, \;\; a/L_{ni} = 0.1$

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

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

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

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

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:

$$\delta f_i(\mathbf{x}, \mathbf{v}, t) \rightarrow -n_0 \, F_M(|\mathbf{v}|) \, \frac{e \, \delta\phi(\mathbf{x}, t)}{T_i} \quad .$$

- **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.

Three Ways to Treat Ion Dynamics

Comparison of linear growth rates

1. **ETG-ai**

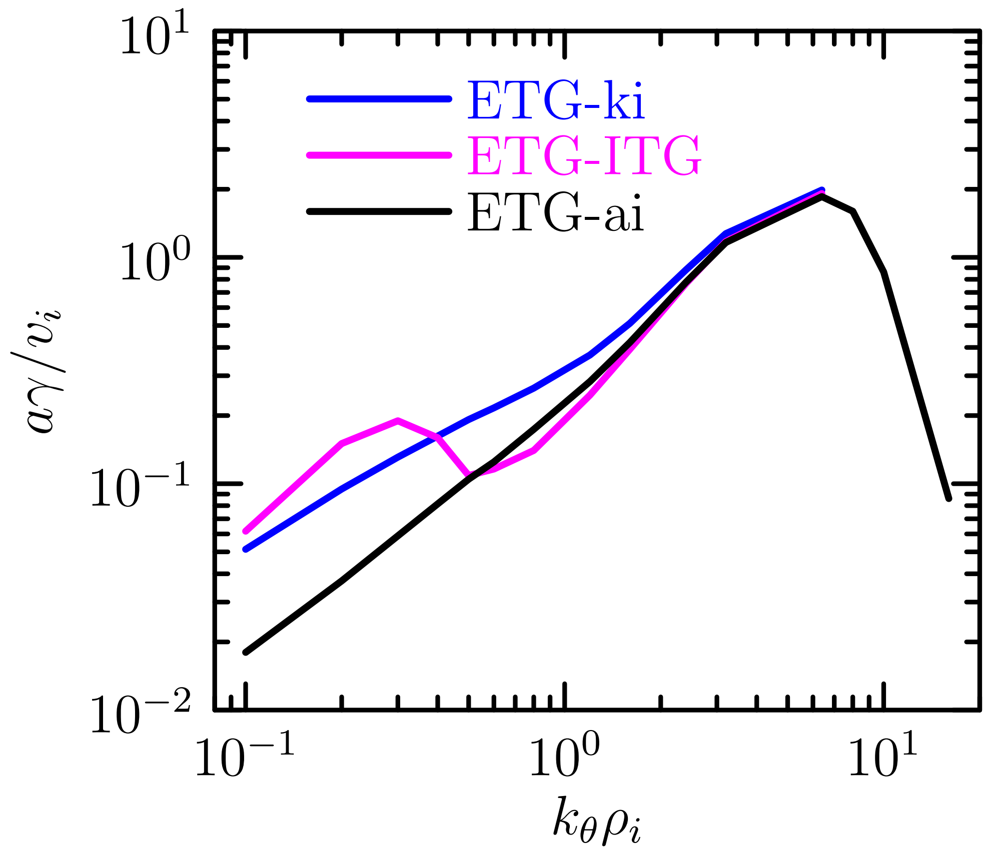
   adiabatic ion model of ETG

2. **ETG-ki**

   kinetic ion model of ETG

3. **ETG-ITG**

   kinetic ion model of ETG



$k_\theta = \frac{nq}{r}$ where n is the toroidal **eigenmode** number.

GENERAL ATOMICS

Reduced Mass Ratio for Computational Efficiency

A crucial method to cut corners (for ETG-ki and ETG-ITG models)

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

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

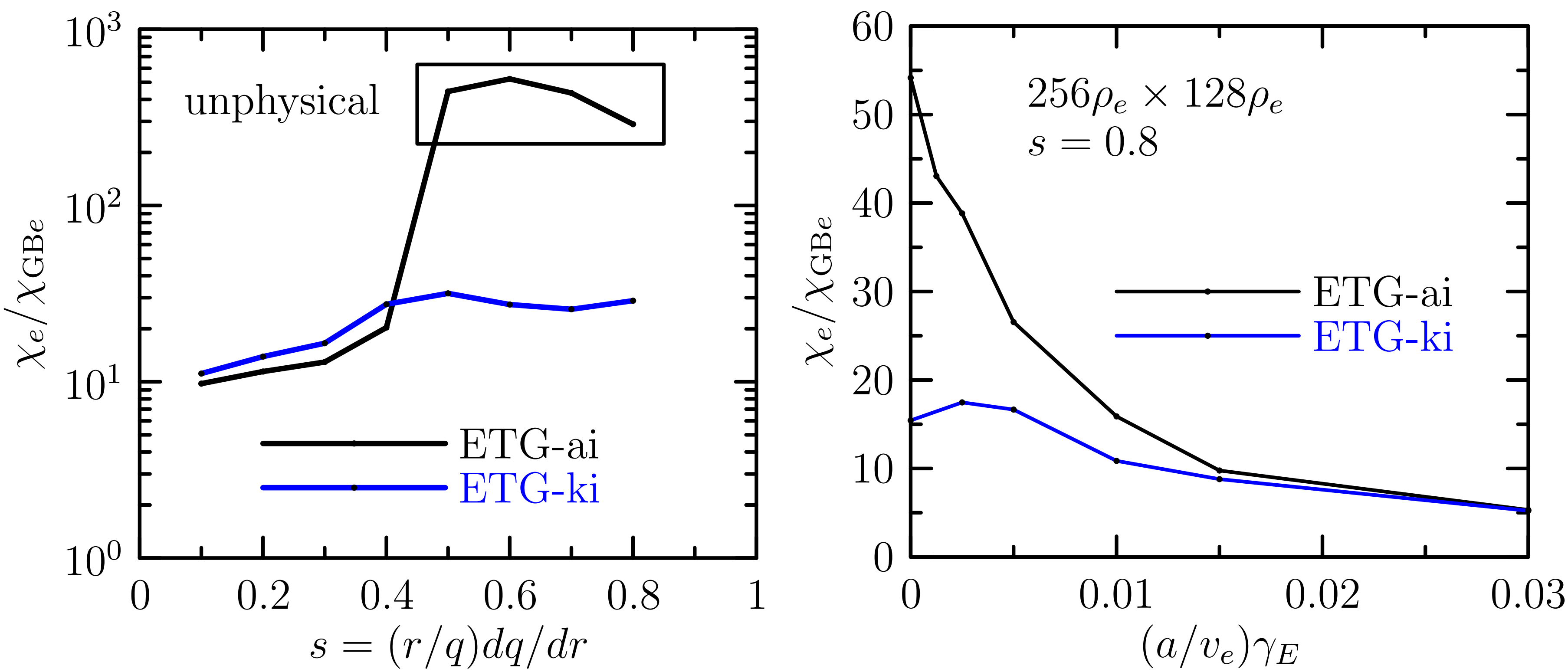
- Simulation cost scales roughly as $\mu^{3.5}$: $\left(\frac{30}{20}\right)^{3.5} \simeq 4$.

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

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

The failure of the ETG-ai model

Can illustrate the divergence by parameter variation

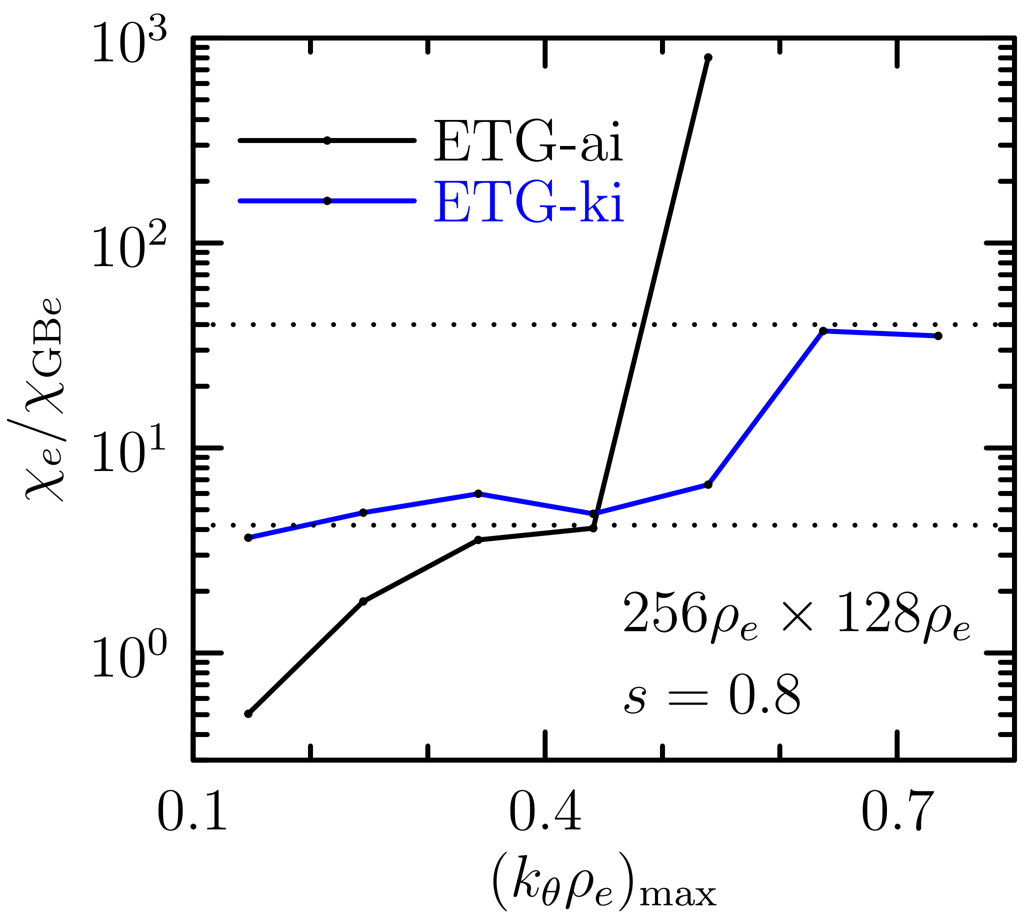


$E \times B$ shearing rate: γ_{E}

The ETG Cyclone Base Case **DOES NOT SATURATE PHYSICALLY**

The failure of the ETG-ai model

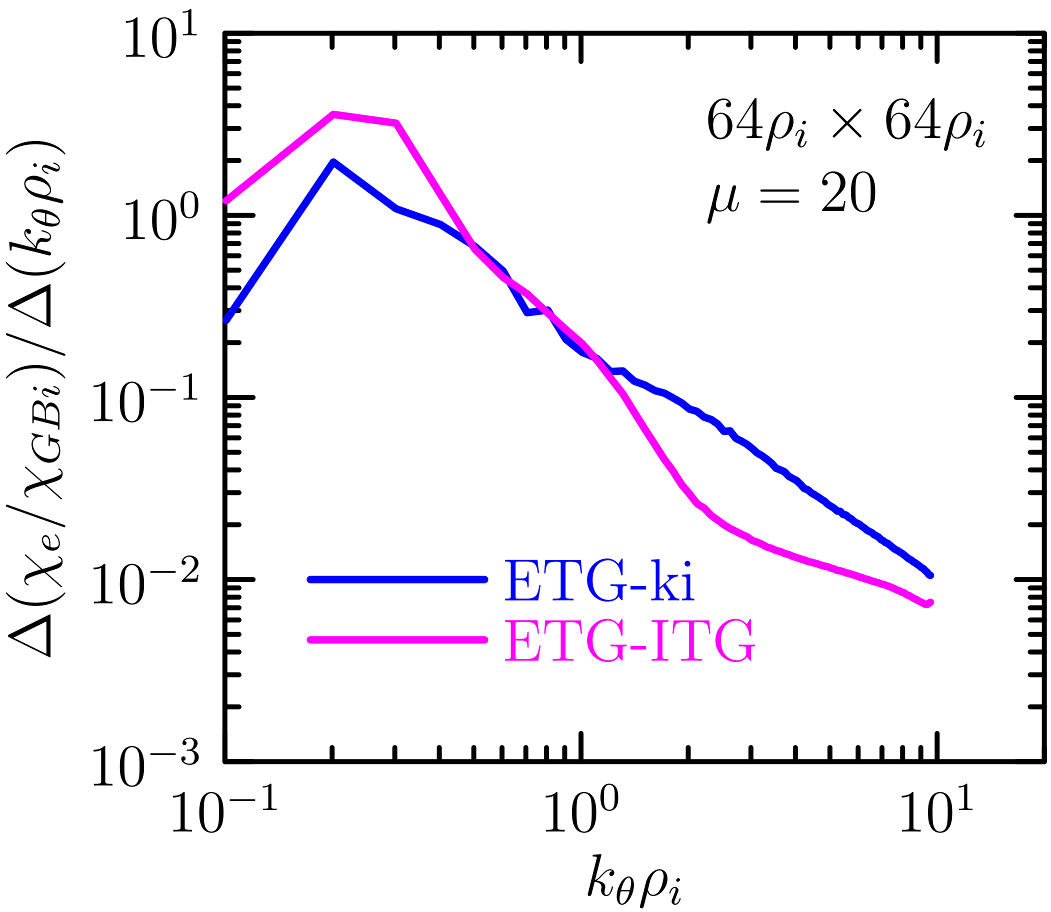
A false asymptote occurs if short-wavelength modes are underresolved



Two wrongs don't make a right.

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

Finite ion gradients reduce χ_e^{ETG}



The reduction in ETG-ITG short-wavelength transport is not fully understood; probably the result of **strong long-wavelength shearing**.

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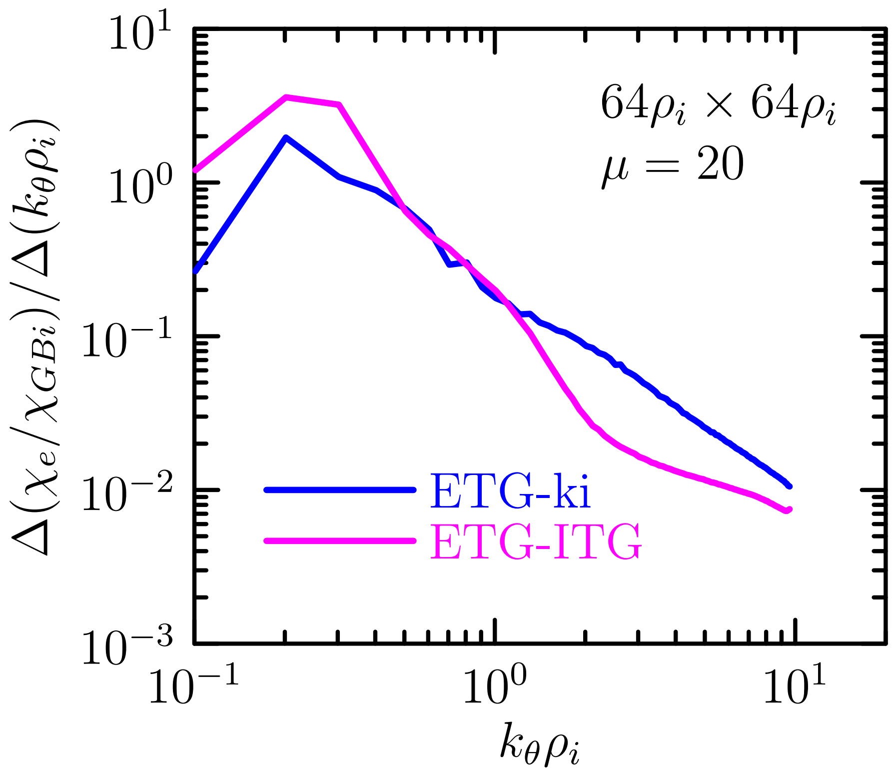
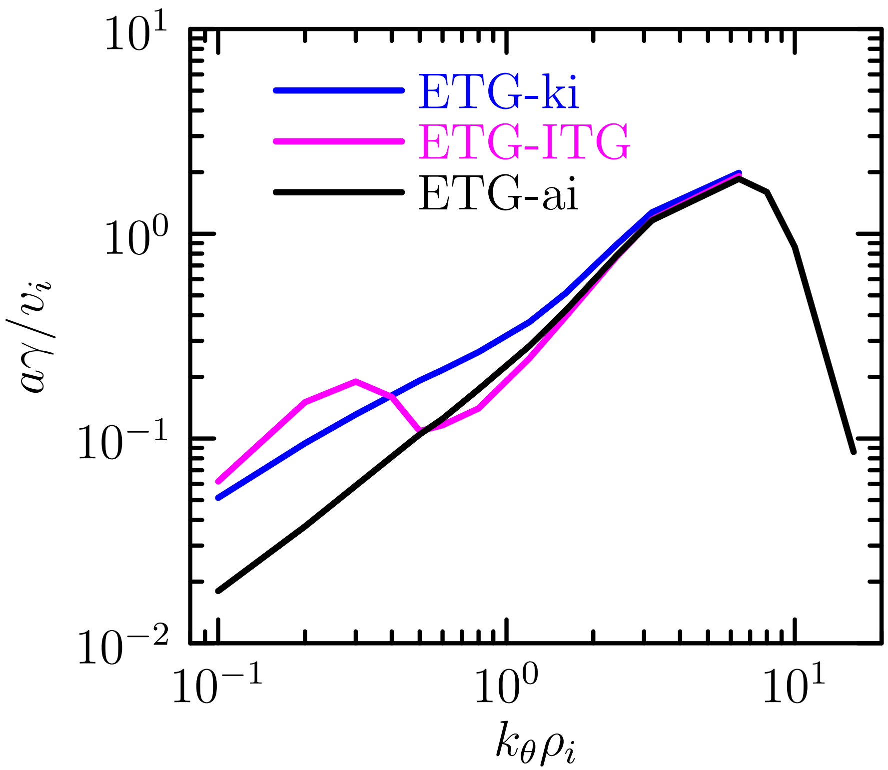
Understanding the Effect of Ion Gradients

What is the dominant physical mechanism for this reduction?





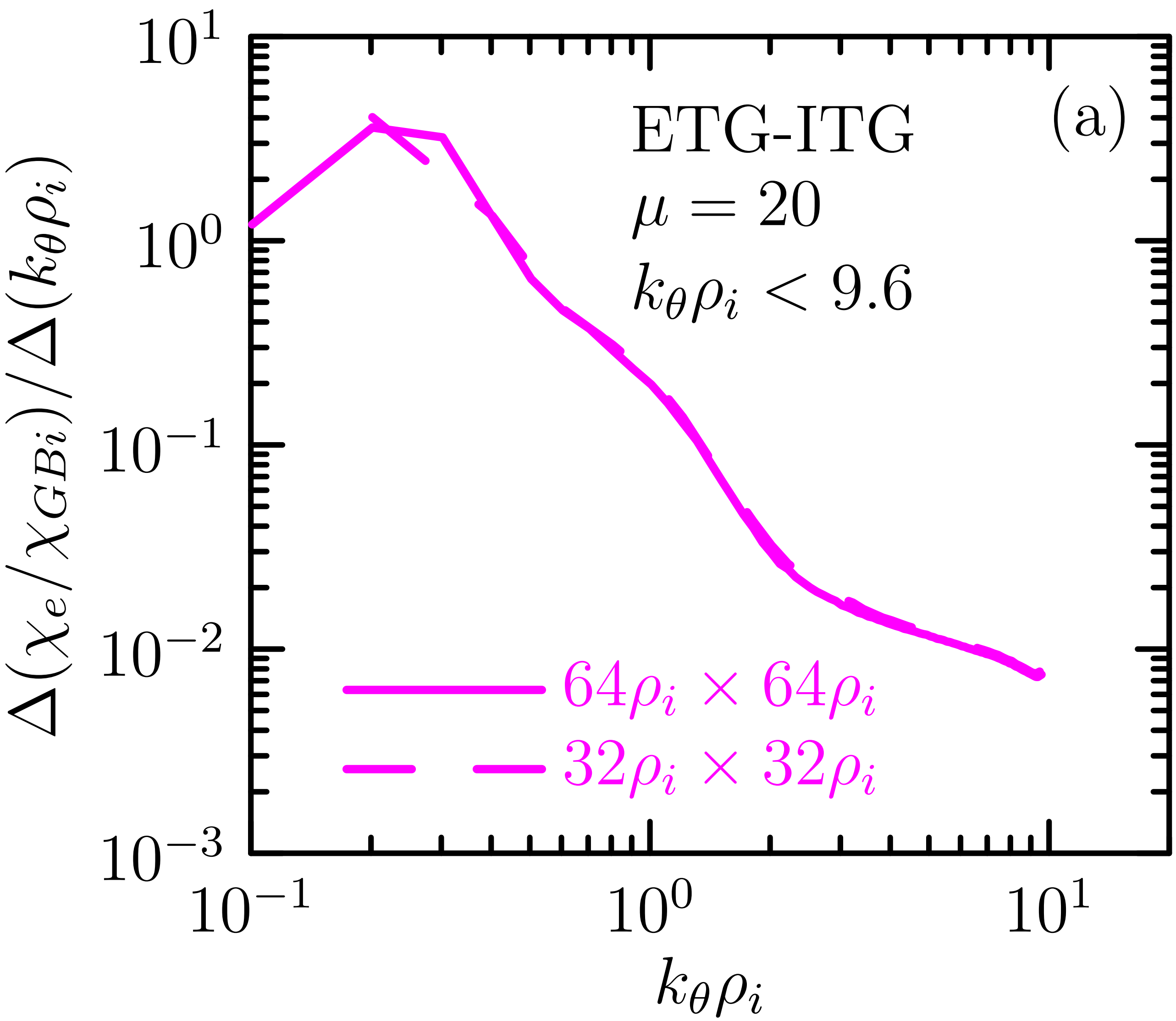
χ_e is the **nonlinear electron heat flux**.

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

GENERAL ATOMICS

Effect of Reduced Perpendicular Box Size

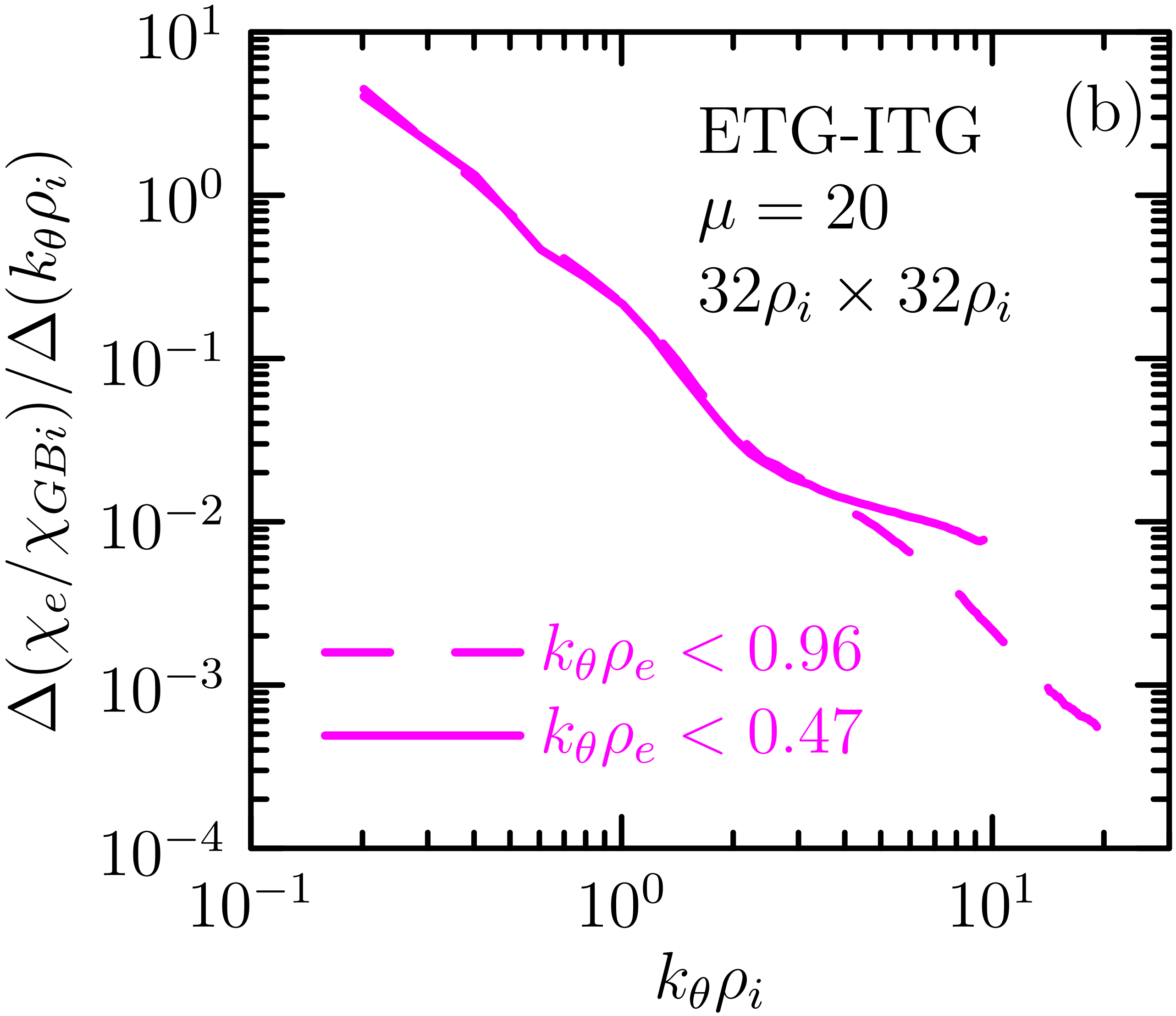
A $32\rho_i \times 32\rho_i$ box is enough to capture the physics for $k_\theta \rho_e > 0.1$.



GENERAL ATOMICS

Effect of perpendicular grid refinement

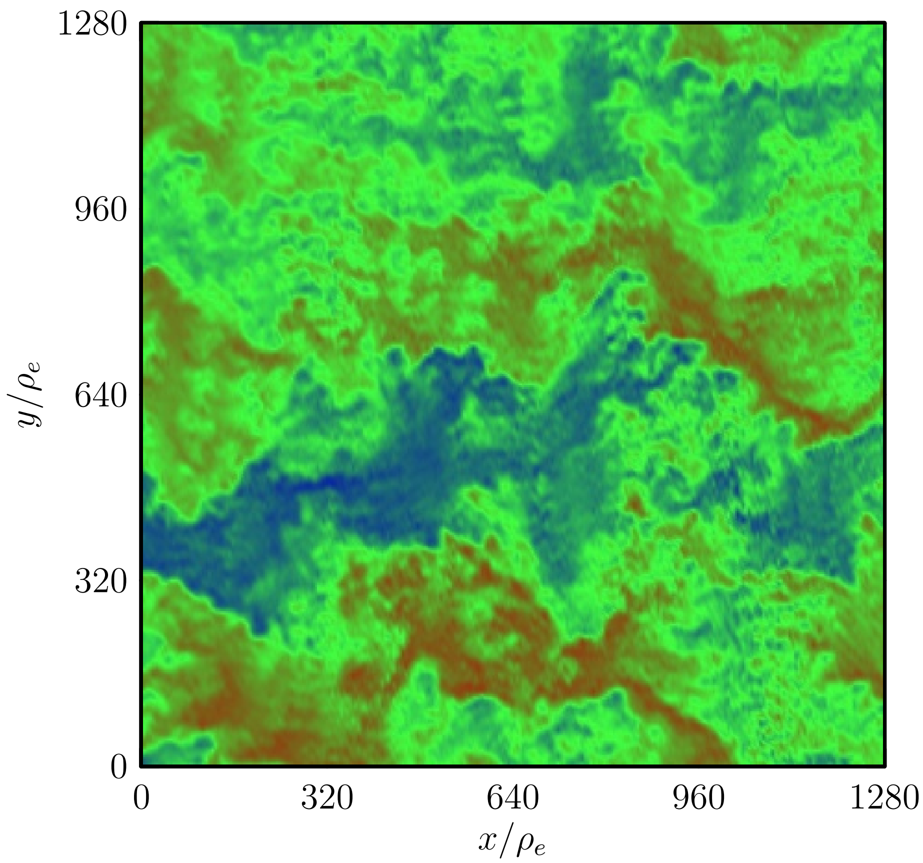
Remove spectral lip (4 days on 1536 XT3 CPUs, courtesy M. Fahey)

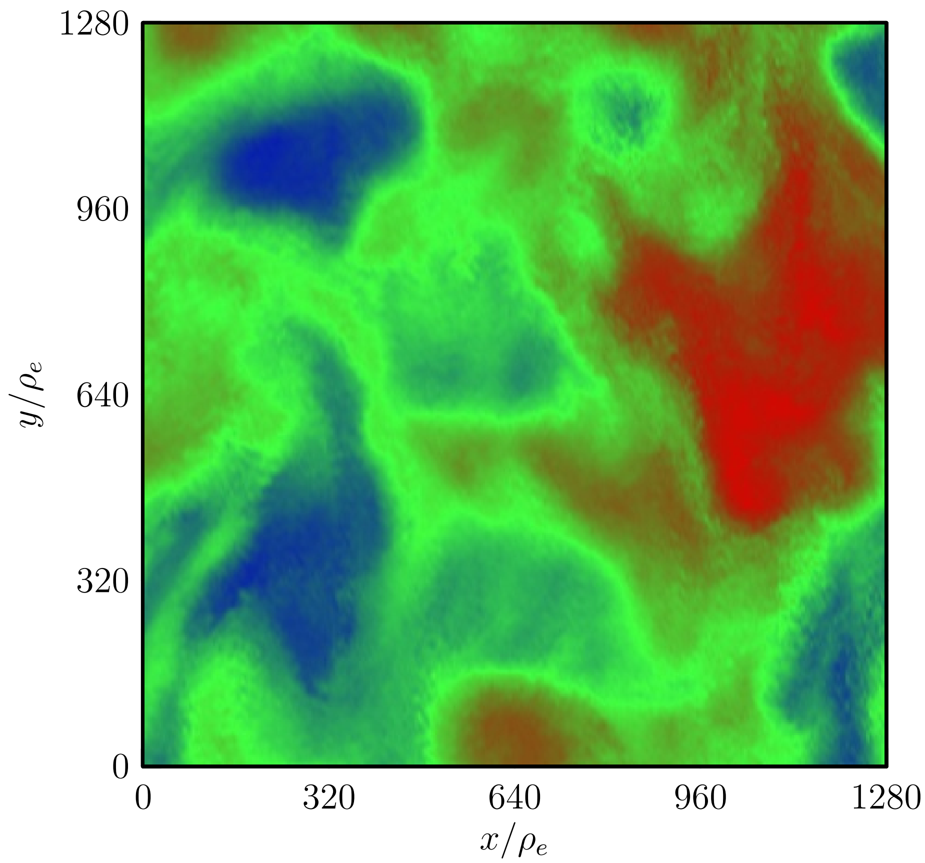


GENERAL ATOMICS

Perpendicular Spectral Intensity of Density Fluctations

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



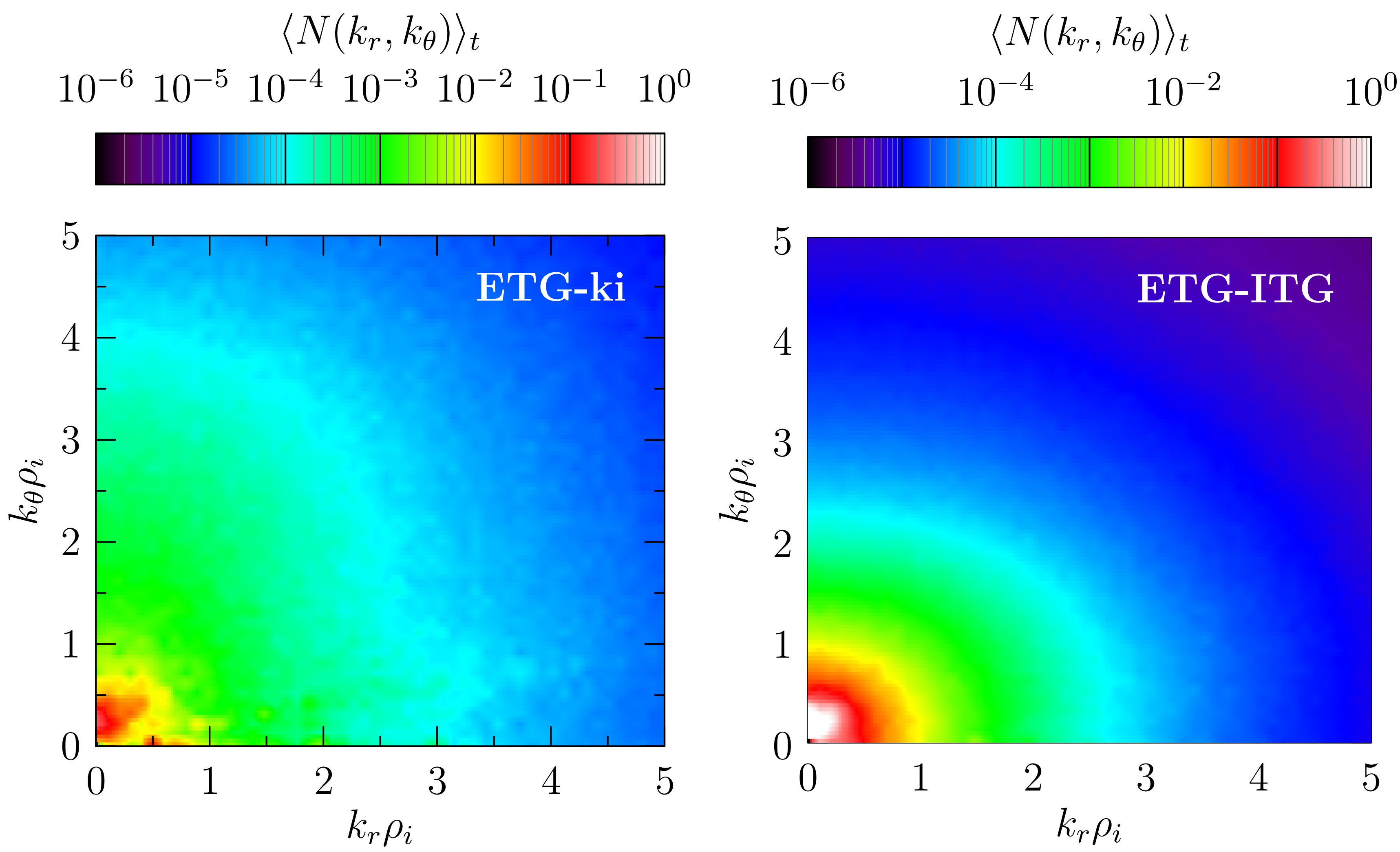


Electron-scale eddies apparent in ETG-ki (left) simulation.

GENERAL ATOMICS

Perpendicular Spectral Intensity of Density Fluctuations

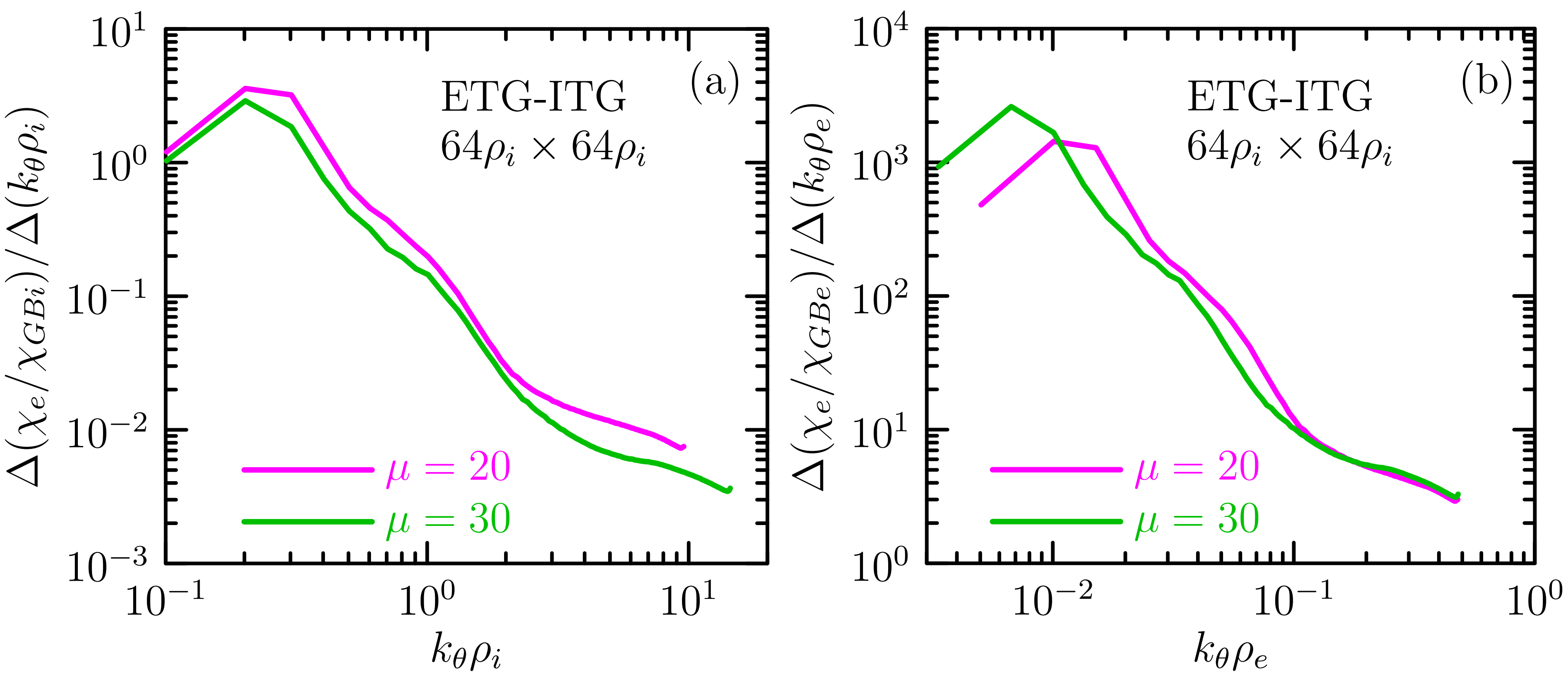
ETG-ITG spectrum is highly isotropic (streamerless) for $k_\perp \rho_i > 0.5$



GENERAL ATOMICS

Mass-ratio Comparison in Electron Units

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



GENERAL ATOMICS

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**

GENERAL ATOMICS

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.
  - Up to **100%**, as ITG/TEM is quenched by $\mathbf{E}\times\mathbf{B}$ shear.

Resolving electron transport in spherical tokamaks

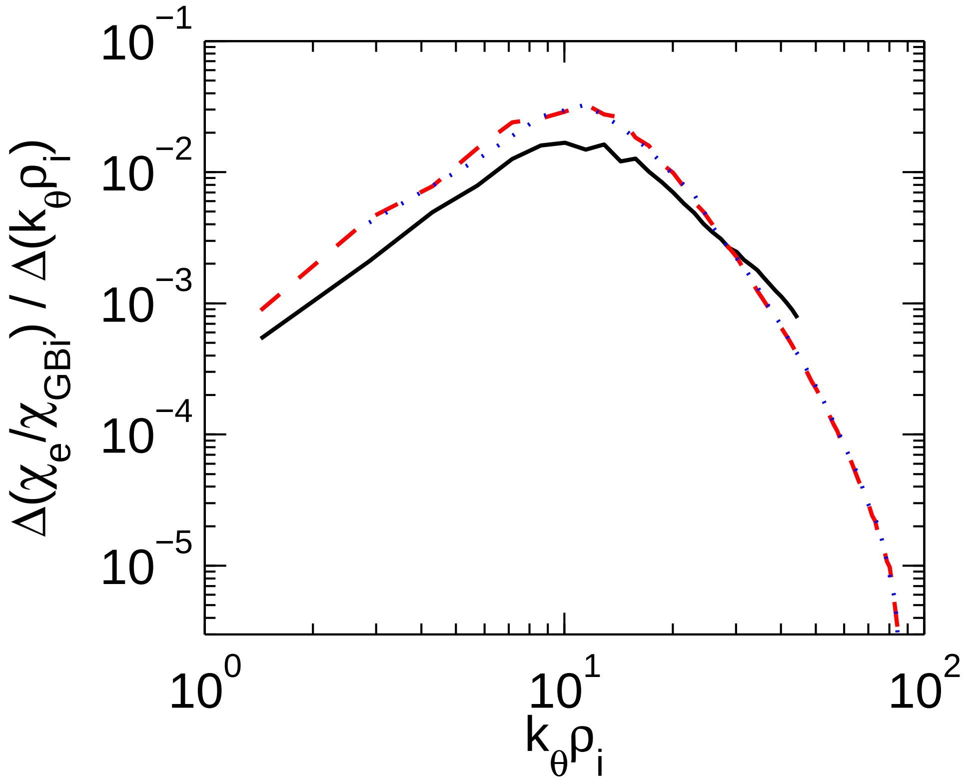
Simulations by Guttenfelder based on MAST parameters

- Strong toroidal flow and flow shear in spherical tokamaks (STs) tend to suppress ion-scale turbulence
- Possibility to use small spatial simulation domains because flow provides physical long-wavelength cut-off
- Artificial mass ratio can be used, subject to certain limitations.
- Adiabatic ions often generate transport collapse and should not be used.
- Guttenfelder and Candy, Phys. Plasmas **18**, 022506 (2011)

GENERAL ATOMICS

Resolving electron transport in spherical tokamaks

Must resolve full electron tail: $k_\theta \rho_e \sim 1.5$



$L_y = 260\rho_e, k_\theta \rho_e < 0.74$ (solid black)

$L_y = 260\rho_e, k_\theta \rho_e < 1.5$ (dashed red)

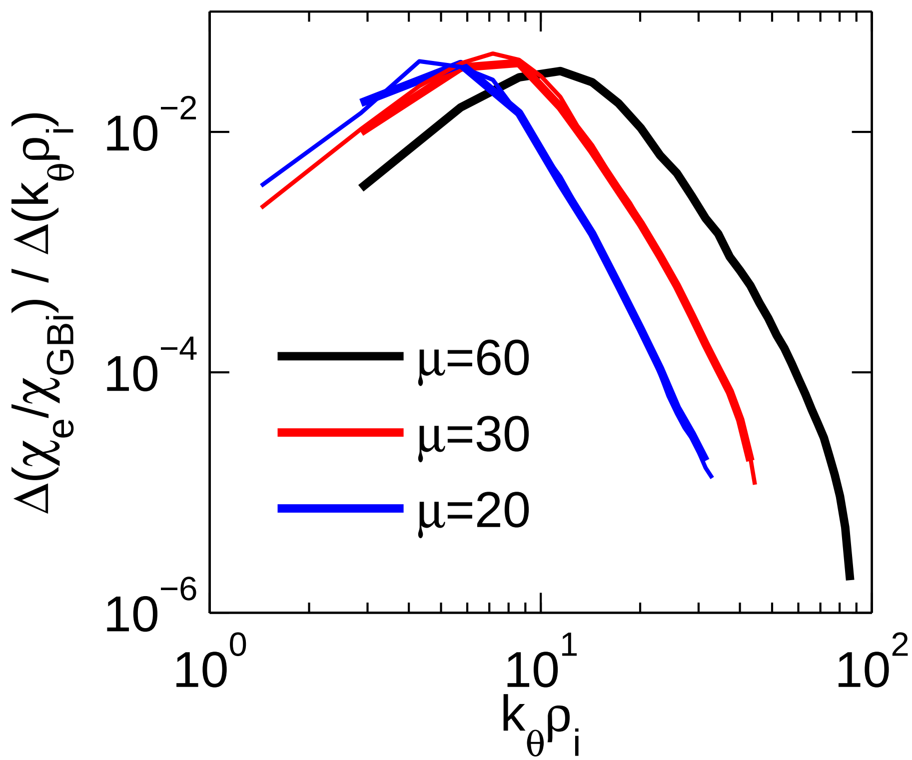
$L_y = 130\rho_e, k_\theta \rho_e < 1.5$ (dotted blue).

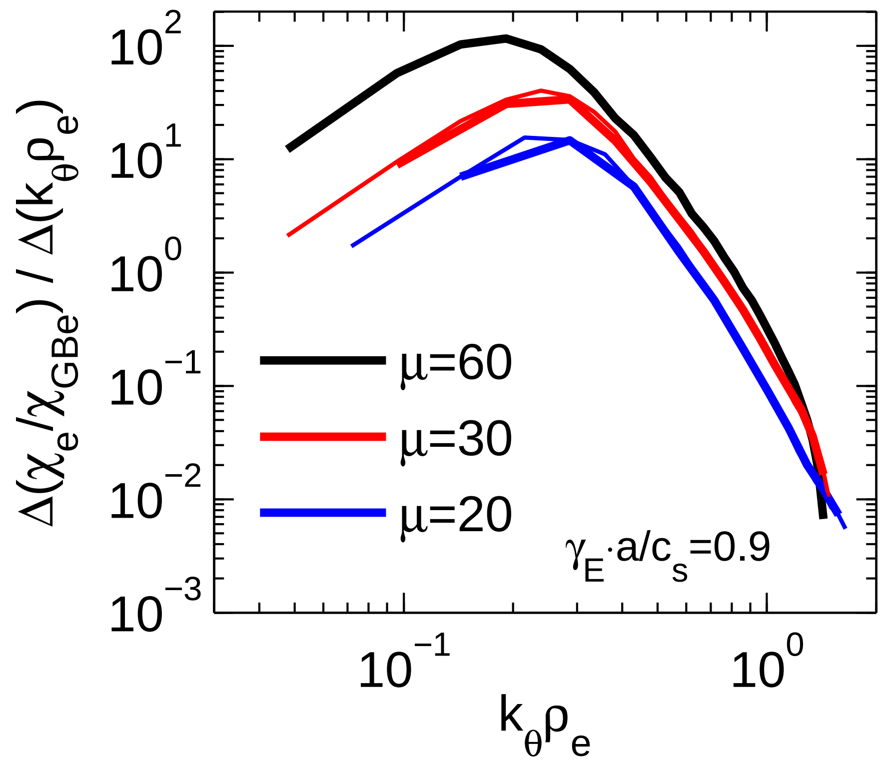
GENERAL ATOMICS

Resolving electron transport in spherical tokamaks

Is reduced mass ratio a viable approach?

Simulations with fixed shearing rate in **ion units**: $\gamma_E(a/c_s) = 0.9$



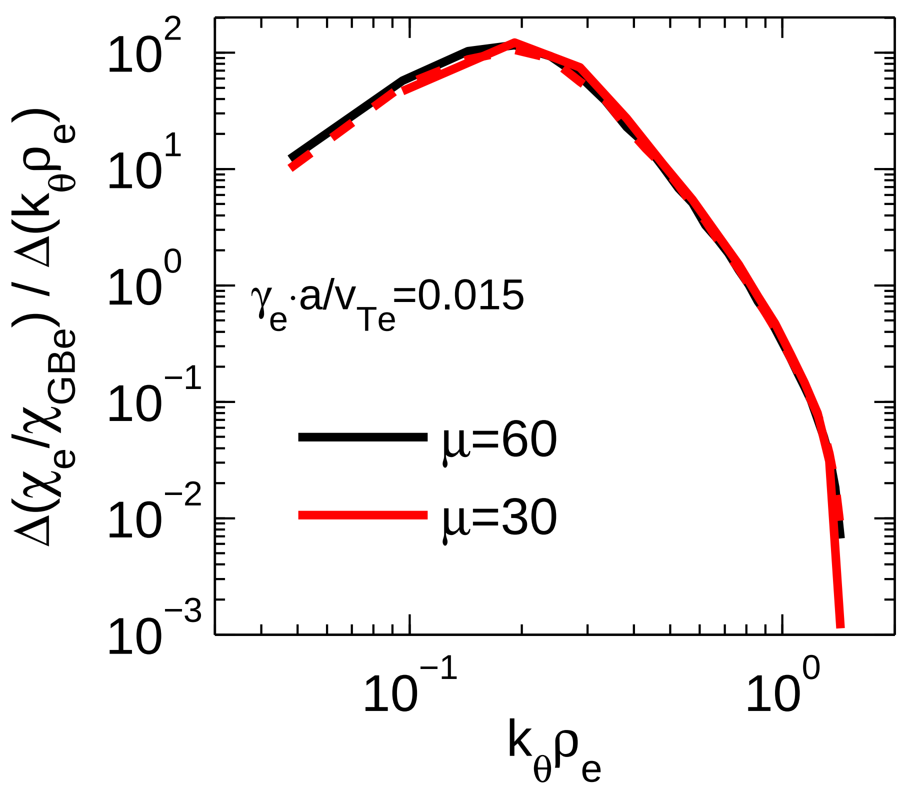


Results plotted in ion units (left) and electron units (right).

Resolving electron transport in spherical tokamaks

Electron-scale self-similarity requires fixed shear in e-units

Simulations with fixed shearing rate in **ion units**: $\gamma_E(a/v_{te}) = 0.015$



Results plotted in electron units.

GENERAL ATOMICS

Electron-scale transport in DIII-D H-mode plasmas

Massive simulation effort by experimentalist (L. Schmitz)

- Attempt to understand electron transport in DIII-D H-mode
- Low overall transport with spectrum experimentally observed to increase past $k_\theta \rho_i = 1.0$ at $r/a = 0.6$.
- This is in contrast to typical L-mode simulations, which have spectrum decaying rapidly for $k_\theta \rho_i > 1.0$
- L. Schmitz, C. Holland, T. Rhodes, *et al.*, Nucl. Fusion **52**, 023003 (2012)

Electron-scale transport in DIII-D H-mode plasmas

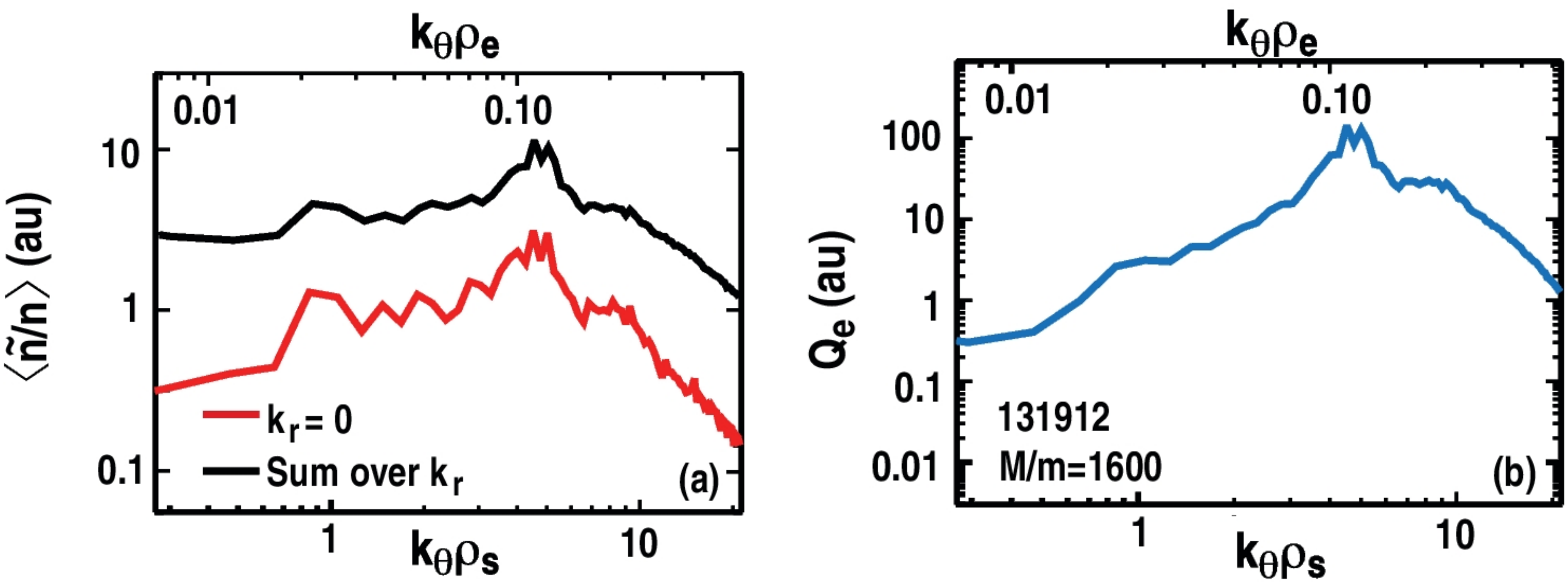
Massive simulation effort by experimentalist (L. Schmitz)

- 90,000 CPU-hours for single run with experimental H-mode profiles/shape
- Huge dynamic range: $0 \leq k_\theta \rho_s \leq 21.3$
- Small radial domain acceptable: $L_x = 39.1\rho_s = 840\rho_e$.
- Reduced mass ratio: $\mu = 40$.
- Flow shear stabilizes long-wavelength turbulence

Electron-scale transport in DIII-D H-mode plasmas

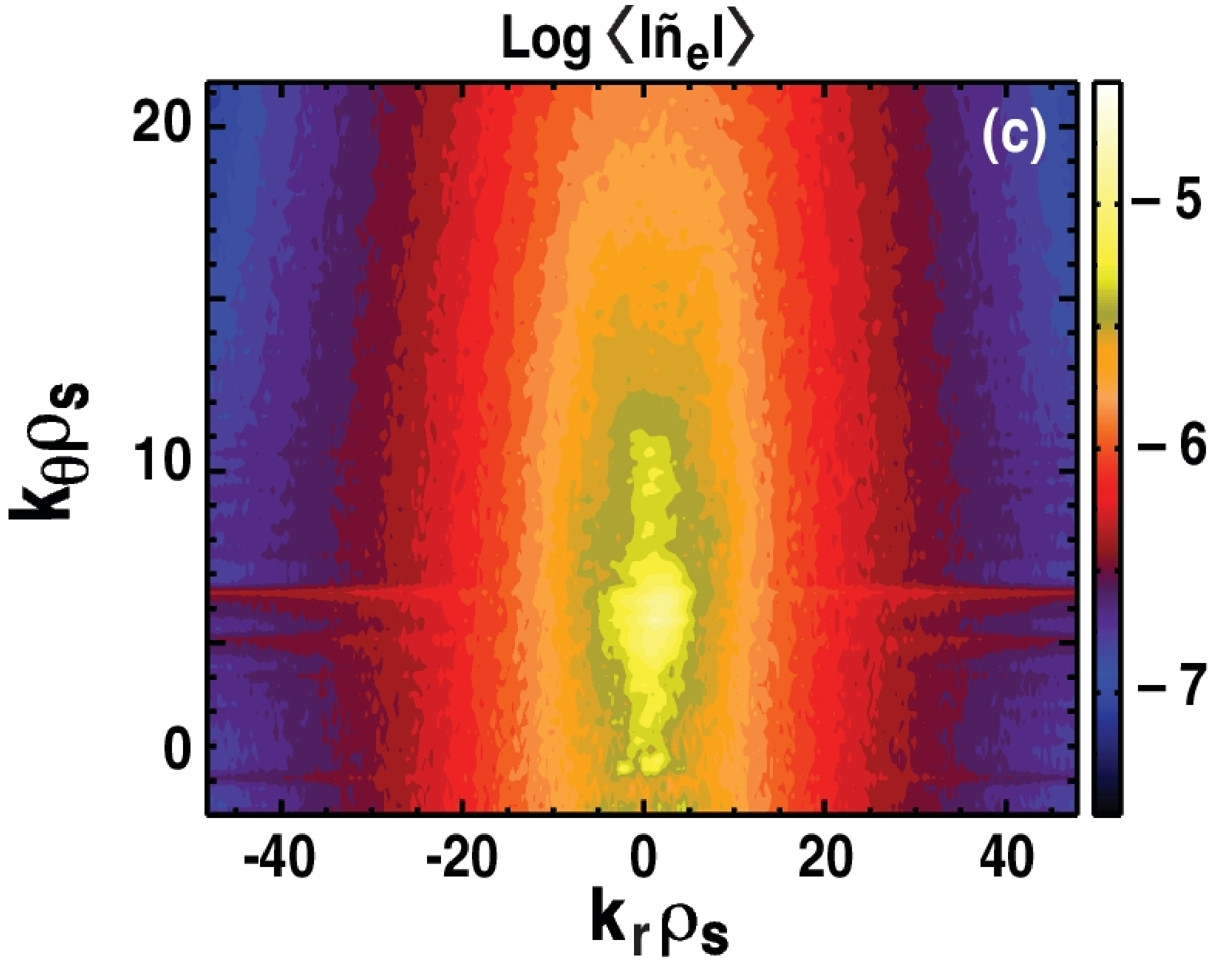
Qualitative agreement with experimental spectral shape

- Results show spectrum increasing up to $k_\theta \rho_e \sim 5$



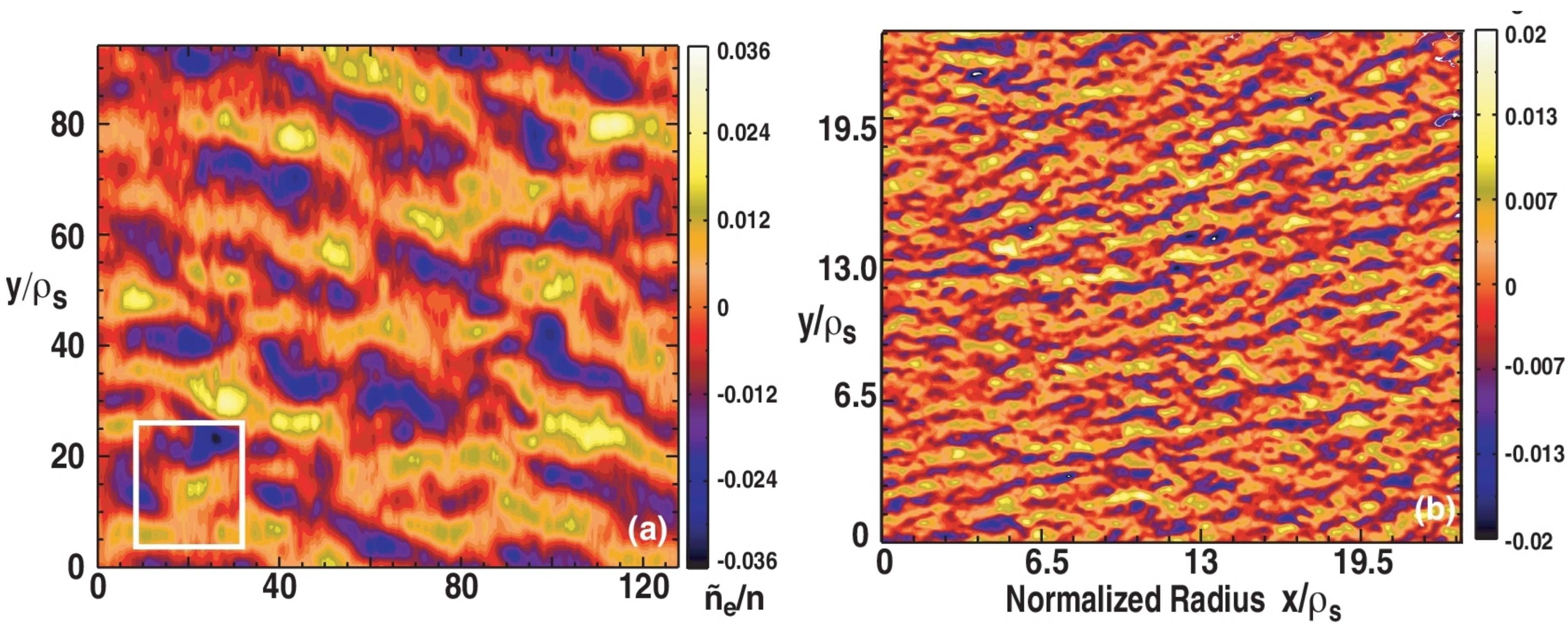
Electron-scale transport in DIII-D H-mode plasmas

2D (radial-binormal) fluctuation spectrum



Electron-scale transport in DIII-D H-mode plasmas

L-mode (128915) versus H-mode (131912)



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