Nonlinear Gyrokinetic Simulations of ExB Shear Quenching & Update on GLF23 Transport Model

Jon Kinsey

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in collaboration with R. Waltz, J. Candy, and G. Staebler

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Outline

- Overview of nonlinear ExB shear simulations with GYRO code
- Main results of ExB shear study
  - Quench point amazingly robust w/ and w/o kinetic electrons for cases where modes rotating in ion or electron direction
  - Quench point approximately $\gamma_E \approx 2\ \gamma_{max}$ when γ_p=0

    (2x larger than gyrofluid result)
  - Transport may not be quenched when γ_p included

    Pure toroidal rotation example: $\gamma_P = (Rq/r) = 12\gamma_E$

    (R/a=3,r/a=0.5,q=2)
- Update on GLF23 transport model
  - Overview of next generation GLF model being developed
  - Response function comparisons
  - Comparisons of GLF growth rates, frequencies with GKS gyrokinetic values

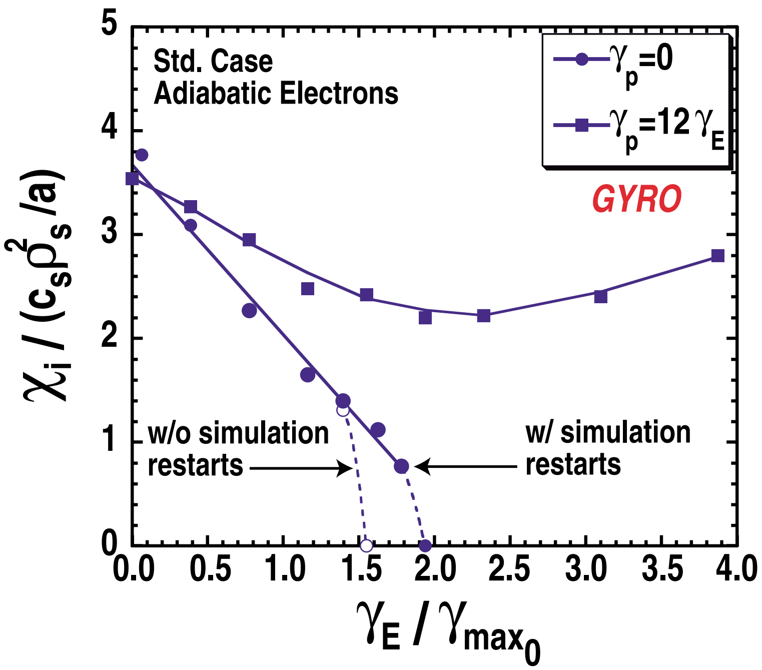
GYRO ExB Shear Simulations

- Motivation for revisiting ExB shear effects
  - Previously published results focused on ExB shear effects on ITG modes rotating in ion direction
  - Gyrofluid ITG simulations by Waltz, et al found that transport quenched at $\gamma_E=\gamma_{max}$ -> development of ExB shear quench rule
  - Since then, uncertainty in the validity of the quench rule when kinetic electrons are included and also for cases where the modes are rotating in electron direction

- Here, we investigate validity of ExB shear quench rule using the GYRO gyrokinetic code
  - Non-periodic boundary conditions utilizing benign boundary layers to eliminate boundary effects
  - Scans in ExB shear around standard case:
    $R/a=3, r/a=0.5, q=2, s=1, \alpha=0, a/L_T=3, a/L_n=1, T_i/T_e=1, \nu=0, \beta=0$
    plus cases w/ std parameters + $a/L_T=2, a/L_n=2$ or $a/L_T=1, a/L_n=3$
  - s-α geometry, electrostatic
  - Scans with and without kinetic electrons
  - Also, with and without parallel velocity shear, γ_p

Nonlinear Gyrokinetic Simulations With Adiabatic Electrons Show Higher ExB Shear Quench Point Compared to Gyrofluid Simulations

- With γ_p =0, two possible states near quench point at a critical γ_E
  - ITG transport quenches at γ_E=1.6γ_{max} when γ_E applied at onset of simulation rule
  - Quench point higher near γ_E=2γ_{max} when γ_E applied in a restart from simulation without γ_E included
- Purely toroidal rotation with γ_p =(Rq/r)γ_E=12γ_E shows that transport not quenched by any level of γ_E



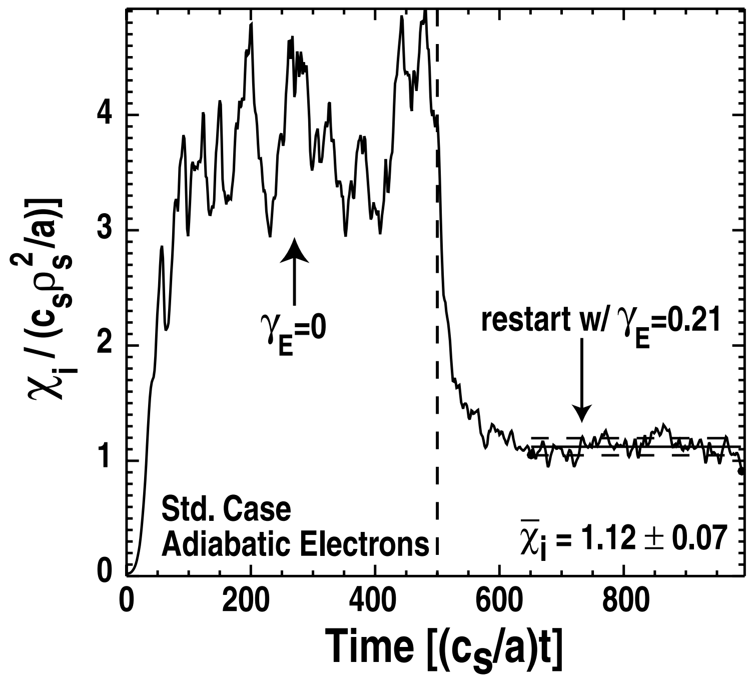
16 modes
k_y <= 0.8

R/a=3, r/a=0.5
q=2

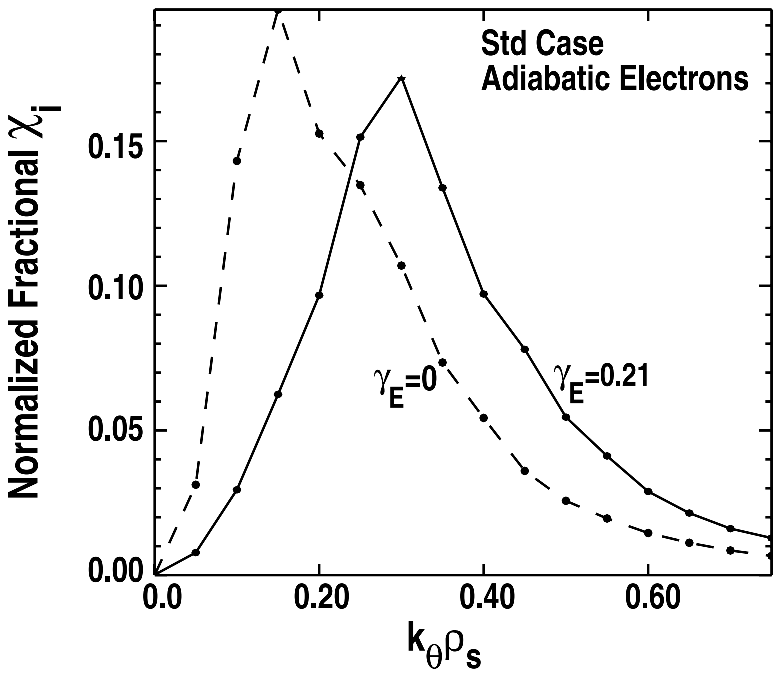
γ_{max0} = 0.13

Nonlinear ExB Shear Gyrokinetic Simulations of Standard Case With Adiabatic Electrons

- Time evolution of γ_E restart simulation of $\gamma_E / \gamma_{max} = 1.63$ case w/ $\gamma_P = 0$

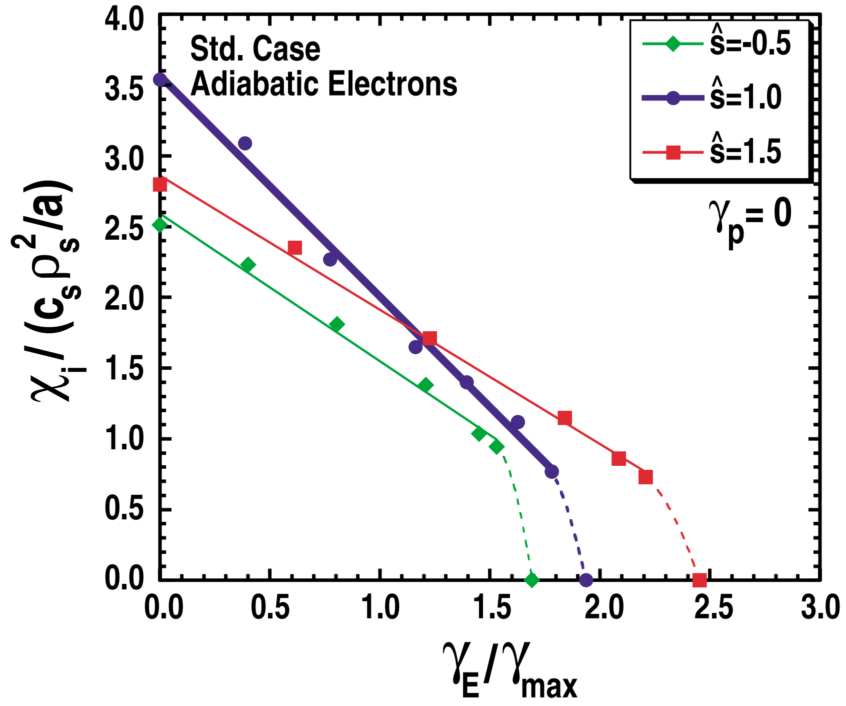


- Peak in spectrum shifts to higher $k_\theta\rho_s$ with γ_E



Quench Point Exhibits Some Dependence on Magnetic Shear

- A 20-30% variation in the quench point is observed for ExB shear scans at magnetic shear values of $\hat{s}=-0.5$, 1.0, and 1.5
- More simulations needed to determine if there a clear dependence on $\hat{s}$
  - Is slope is consistently weaker as the magnetic shear varies from the value at which the peak in the transport occurs ($s-\alpha=1/2$) ?



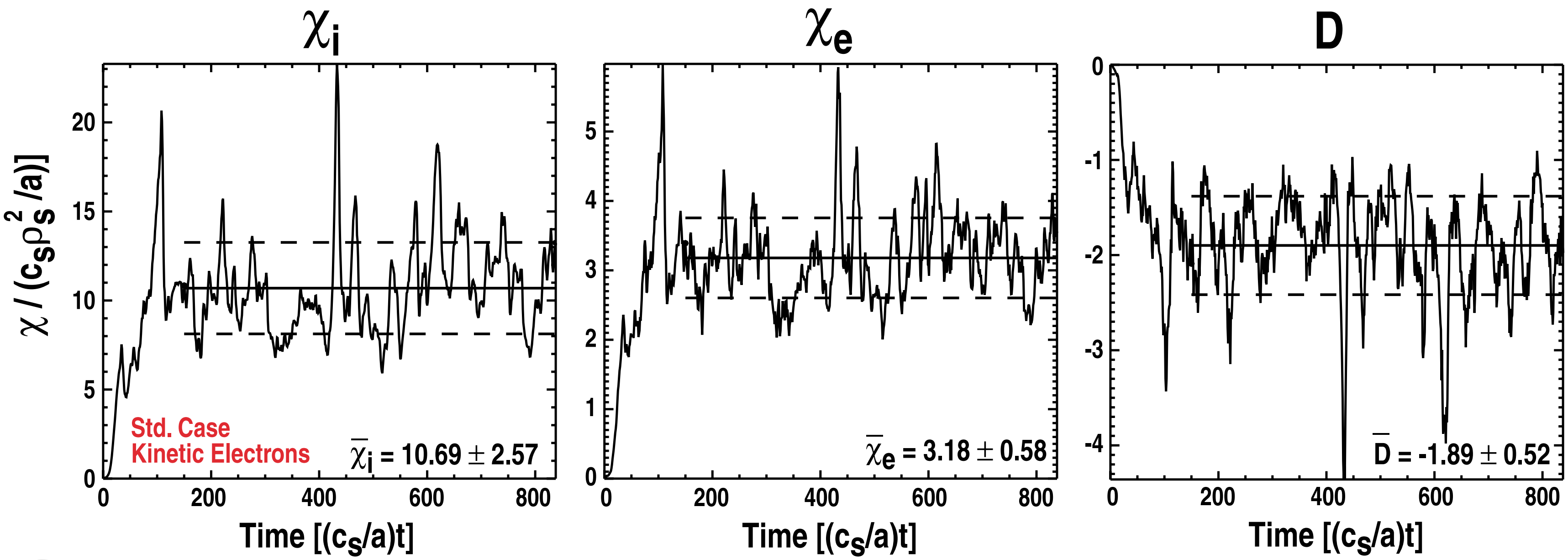
16 modes

$k_y <= 0.8$

$\gamma_p = 0$

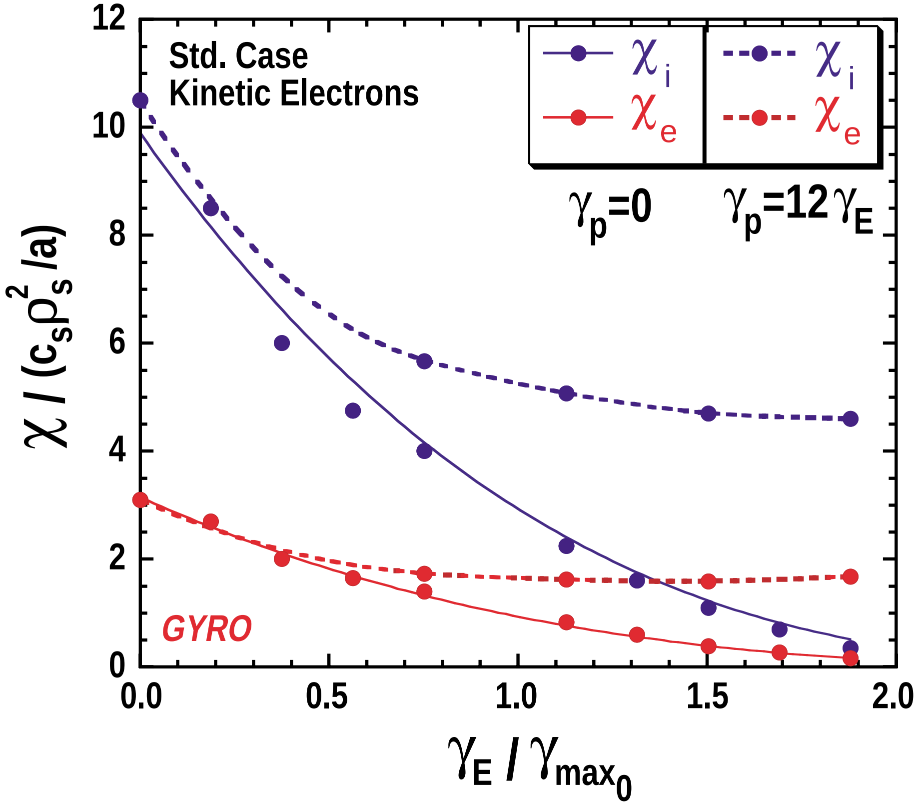
GYRO Simulation of Standard Case with Kinetic Electrons

- Ratio of $\chi_i/\chi_e \approx 3.3$
- Particle pinch predicted
- 16 modes, $k_\theta\rho_s \leq 0.75$, 125 gyroradii, $\gamma_{max}=0.27$, $\gamma_E=0$, $\gamma_p=0$
- Transport peaks at $k_\theta\rho_s = 0.1$
- Higher $k_\theta\rho_s$ modes contribute very little to χ_i , D and some to χ_e however, 32 mode simulation w/ $k_\theta\rho_s \leq 1.55$ yields χ,s only 7% larger



ExB Shear Quench Rule Remains Valid in Nonlinear Gyrokinetic Simulations with Kinetic Electrons

- **ExB shear quench point near $\gamma_E=2\gamma_{max}$ for ions and electrons very close to quench point for adiabatic electron case !**
- **Gradual reduction to zero transport near quench point - sharp drop in χ near quench point seen in adiabatic runs not seen with kinetic electrons**
- **Transport not quenched for purely toroidal rotation w/ $\gamma_p=(Rq/r)\gamma_E=12\gamma_E$**



transport quenched at $\gamma_{Ex}/\gamma_{max} = 1.9\text{-}2.0$ for $\gamma_{max} = 0$

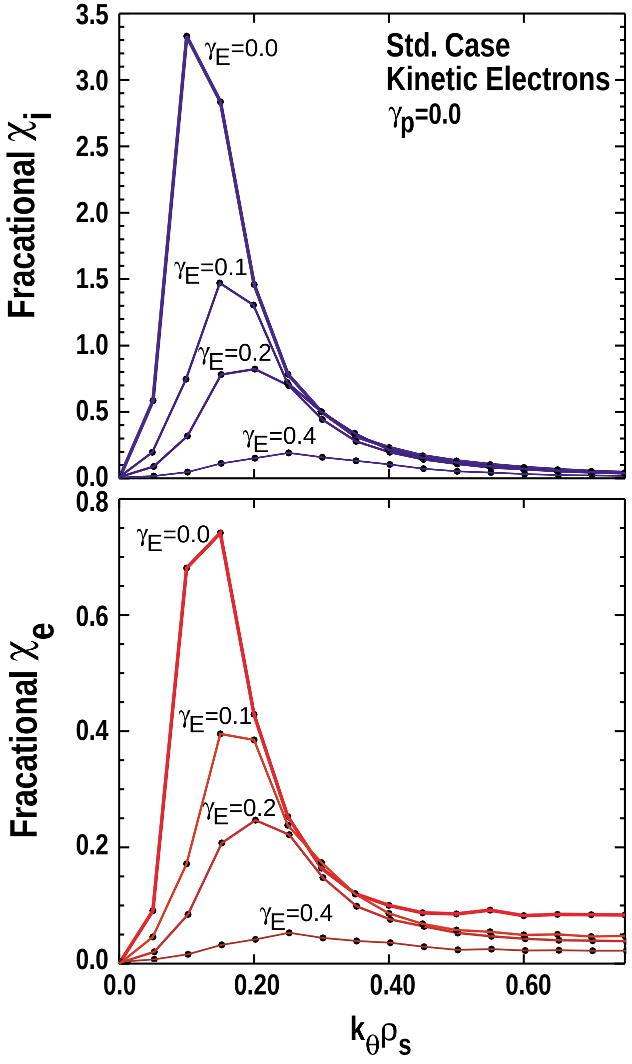
reduction in χ not linear

16 modes
$k_y <= 0.8$
$\gamma_{max0} = 0.27$

ExB Shear Impact on Spectral Contributions to Heat Diffusivity

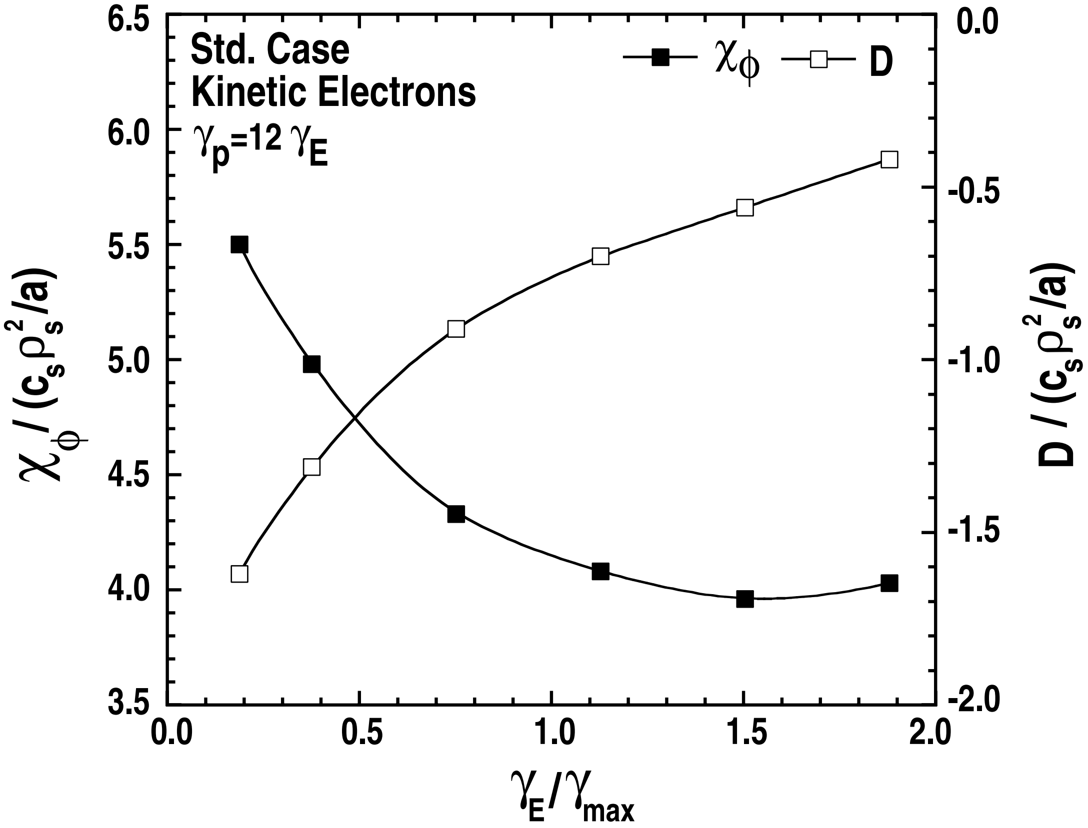
- All 16 modes in spectrum in ion direction for standard case
- Higher $k_\theta\rho_s$ modes contribute more to χ_e than χ_i
- ExB shear impacts all modes in spectrum up to k_y=0.75
- Peak in transport shifts from $k_\theta\rho_s$=0.10 at γ_E=0.0 to

  $k_\theta\rho_s$=0.25 at γ_E=0.4



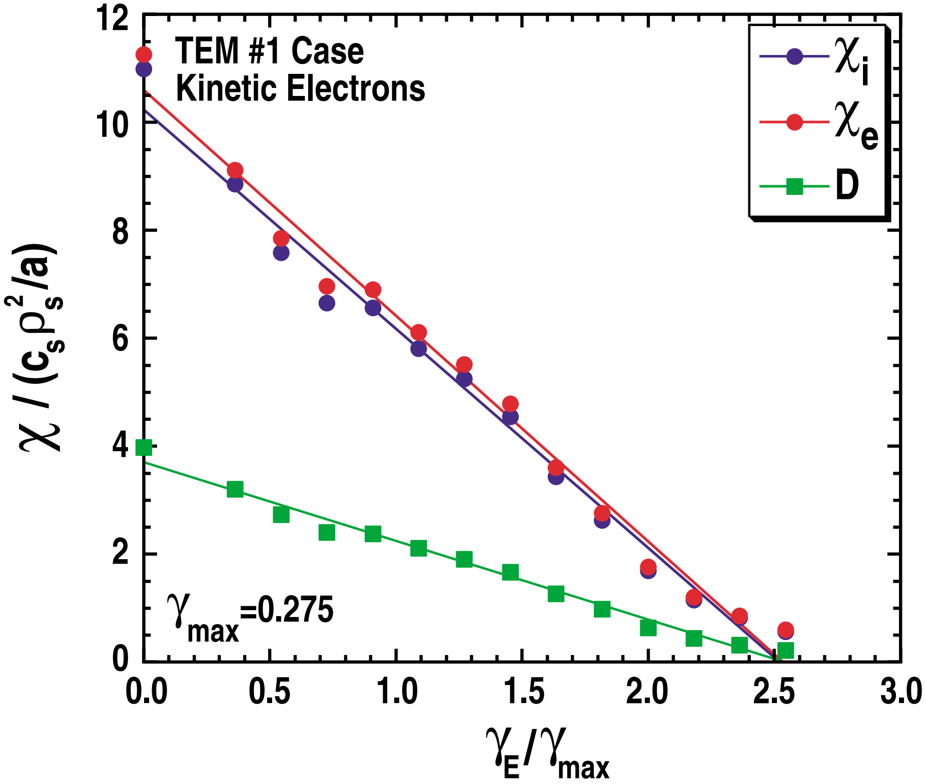
Toroidal Momentum and Particle Transport Versus ExB Shear In Kinetic Electron Simulations with Parallel Velocity Shear

- Ion particle pinch for std case - becomes less negative as γ_E increases
- Toroidal momentum transport follows reduction in χ as γ_E increases
  - χ_ϕ begins to increase near γ_E / γ_{max}=1.5



ExB Shear Quench Point Somewhat Higher For Peaked Density Case with Modes Primarily in Electron Direction

- Std parameters w/ $a/L_n=2$, $a/L_T=2$ (Note: std case has $a/L_n=1$, $a/L_T=3$)
- ExB shear quench point somewhat higher at $\gamma_E=2.5\gamma_{max}$
- Ion and electron heat diffusivities are comparable
- Particle transport in outward direction (std case was negative)

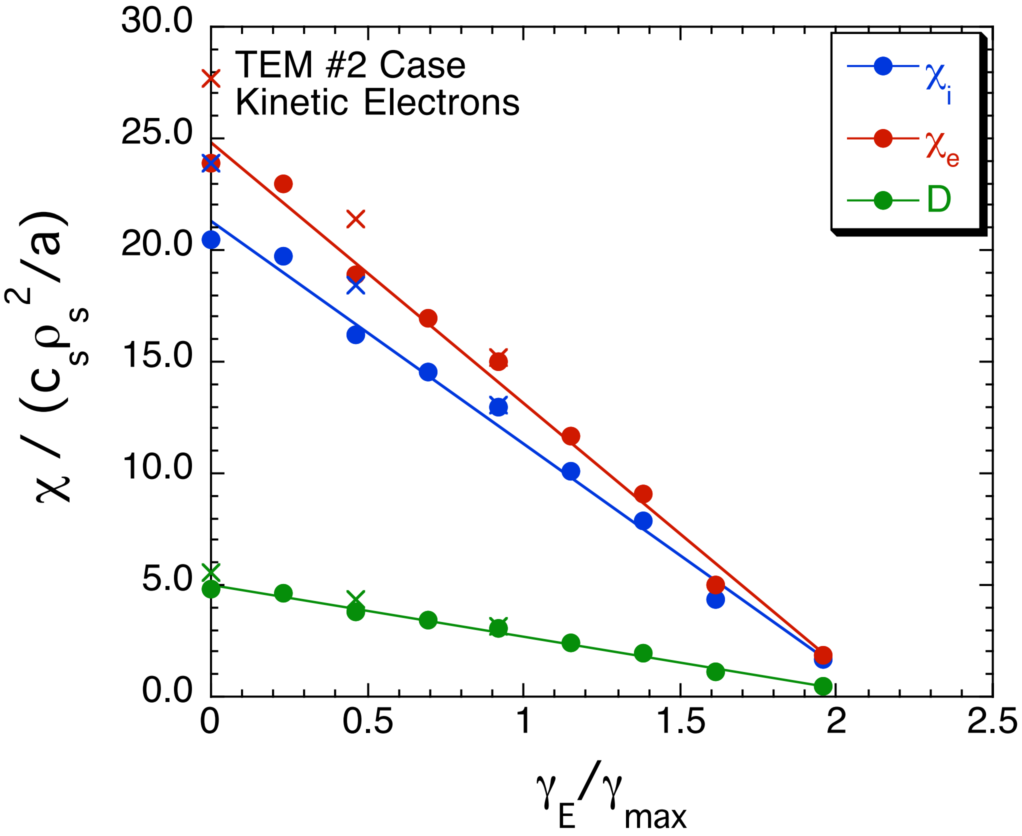


reduction in χ linear w/ γ_E

16 modes
k_y <= 0.8
γ_p=0

ExB Shear Quench Point For TEM Case #2

- Std parameters w/ a/L_n=3, a/L_T=1 (std case: a/L_n=1, a/L_T=3)
- ExB shear quench point approximately $\gamma_E=2.1\gamma_{max}$
- Ion and electron heat diffusivities are comparable w/ χ_e slightly higher than χ_i

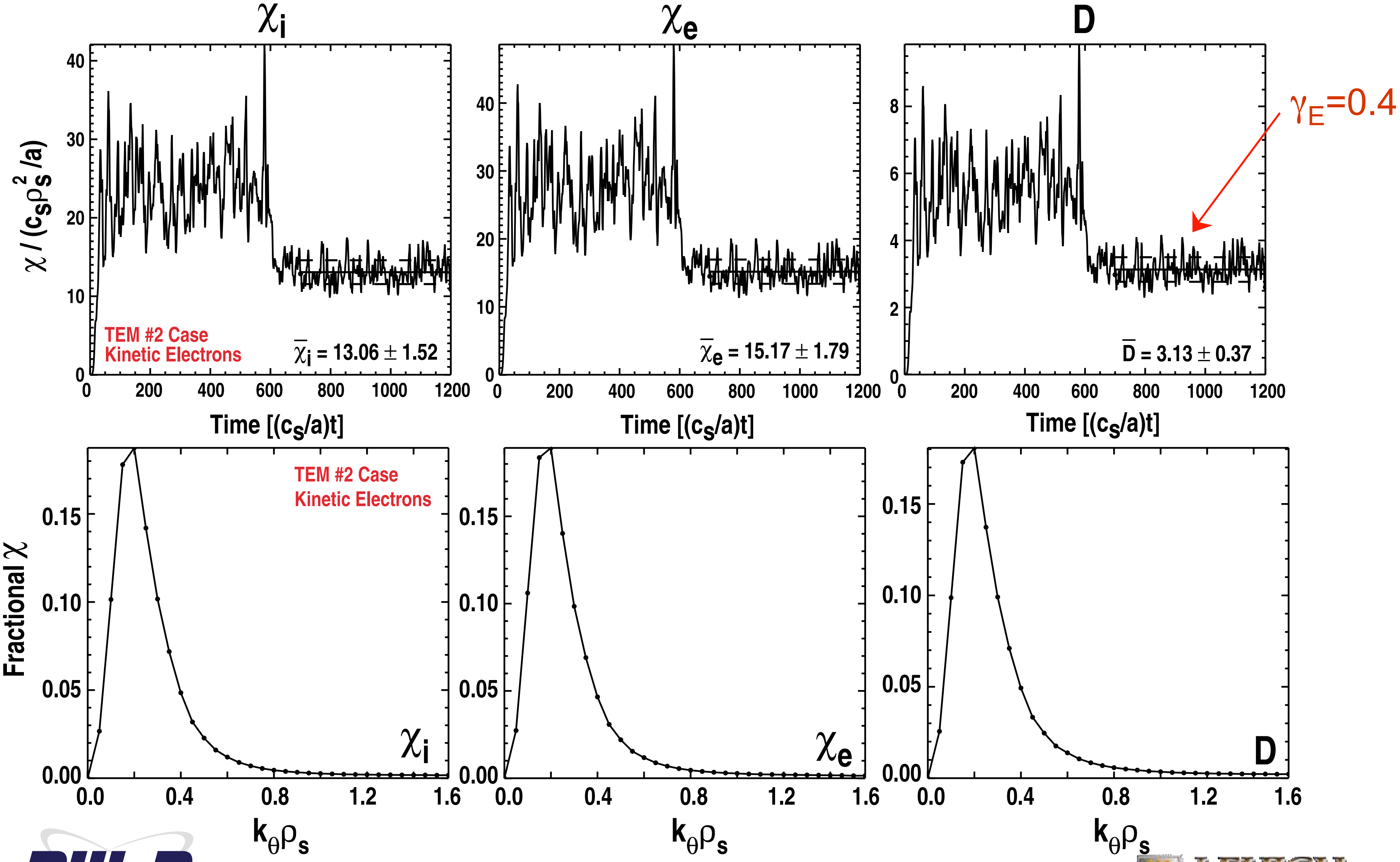


reduction in χ linear w/ γ_E

X = 32 mode simulations $k_\eta\rho_s \leq 1.55$

16 modes
k_y <= 0.8
γ_p=0

Higher $k_\theta \rho_s$ Modes Contribute Little to Transport in TEM Case #2



γ_E=0.4

Update on GLF23 Transport Model

A New Gyro-Landau-Fluid (GLF) Model is Being Developed

- Gyro-Landau fluid (GLF) models give an accurate approximation to the kinetic linear growth rates of drift-ballooning modes in tokamaks.
- Some inadequacies in the original GLF23 model:
  - ETG modes assumed to be decoupled from the ions (adiabatic ions).
  - ITG/TEM spectrum limited to $k_y<0.5$
  - Growth rates and frequencies don't agree with gyrokinetic results for NCS parameters with large α, pedestal parameters, low q, and Ti/Te > 1.5.
- A new set of GLF equations is needed in order to treat the coupling between ETG modes and ions. The new model has three moments for trapped particles and twelve for passing particles of each species. The closure of the highest moments is done by fitting coefficients to minimize the error between the GLF and kinetic response functions. In the new model these closure coefficients become functions of the trapped fraction.
- A model for the loss of bounce averaging and the return of Landau damping for trapped particles was developed enabling the GLF model to seamlessly cover the wavenumber range from the lowest trapped ion modes to the highest ETG modes.
- A code to solve the new GLF model as an eigenvalue problem has been written using Hermite basis functions.

New GLF Somewhat Different Than Beer 6-moment Model

- New GLF model takes moments of J_0F; Beer used F
  - No approximation needed for FLR terms, but have to approximate explicit Linsker terms $[\nabla_{II}, J_0]$
- In the closures, Beer has $P_\perp - n$

  we use $P_\perp - (H_{P\perp} / H_n)n$ where $H_{P\perp}$, H_n are moments of J_0F_0

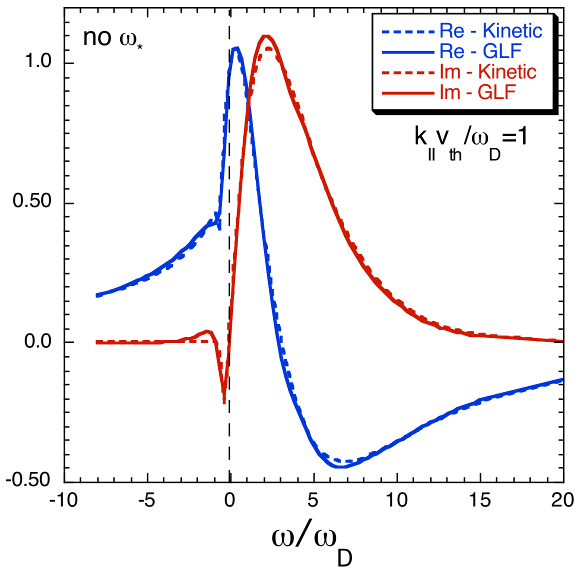
  This retains the correct adiabatic (zero frequency) limit as $P_\perp \text{->} H_{P\perp}$ and $n \text{->} H_n$
- We also take moments over a wedge in velocity space

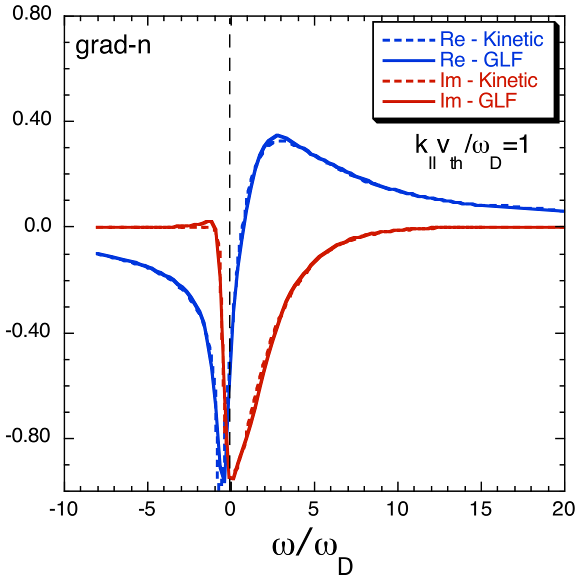
$$-f_t < v_{II}/v < f_t$$

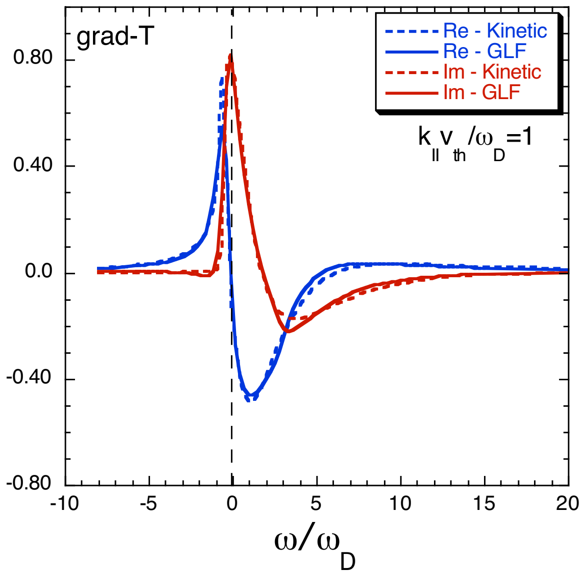
circulating particle density is $N_c = N(f_t - 1) - N(f_t)$

Comparison of GLF With Kinetic Response

- Using methodology of Beer et al. to determine the best closure coefficients, an excellent fit to the density response function is obtained

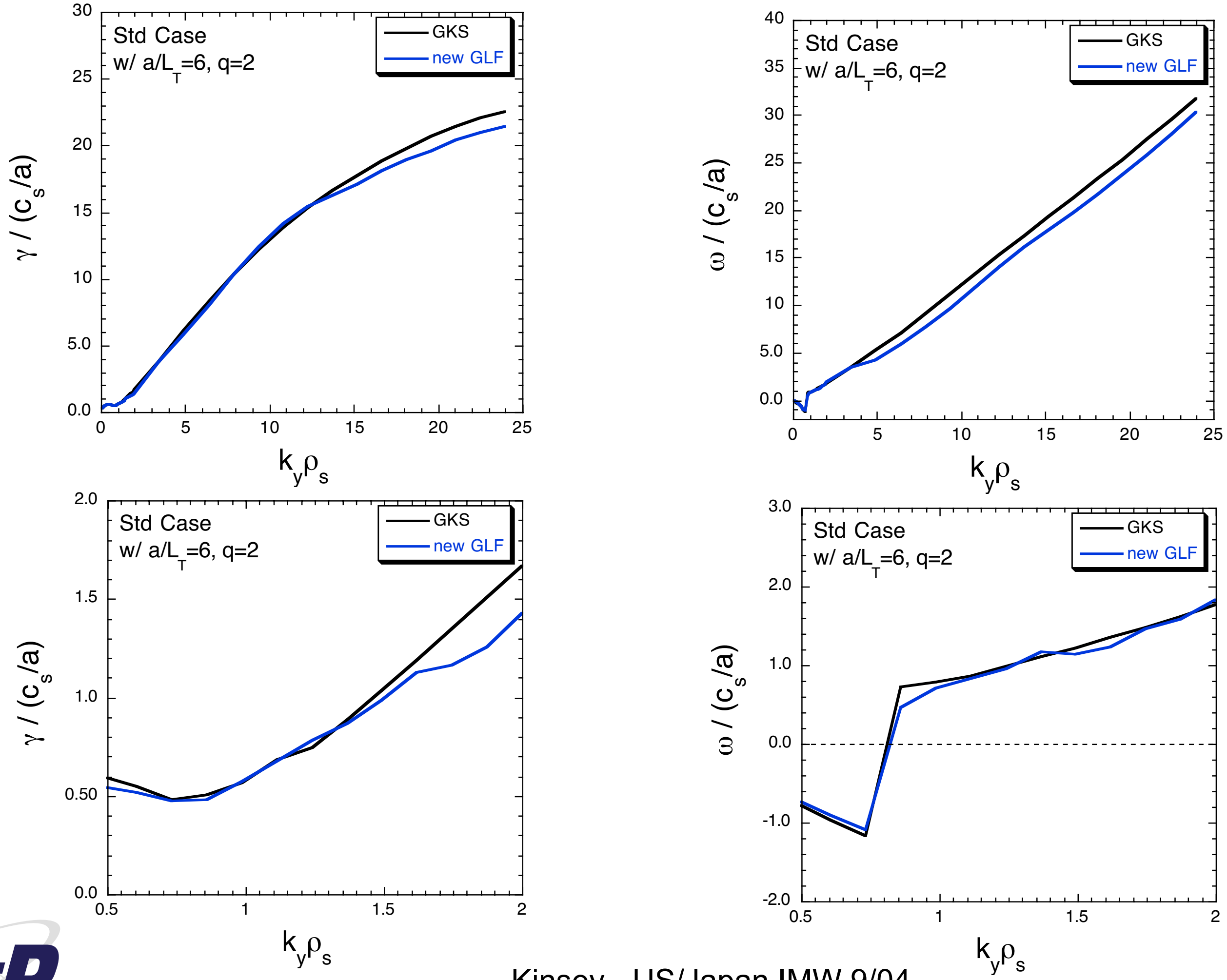






New GLF Model Shows Agreement With GKS Growth Rates & Frequencies for Entire ITG/TEM/ETG Mode Spectrum

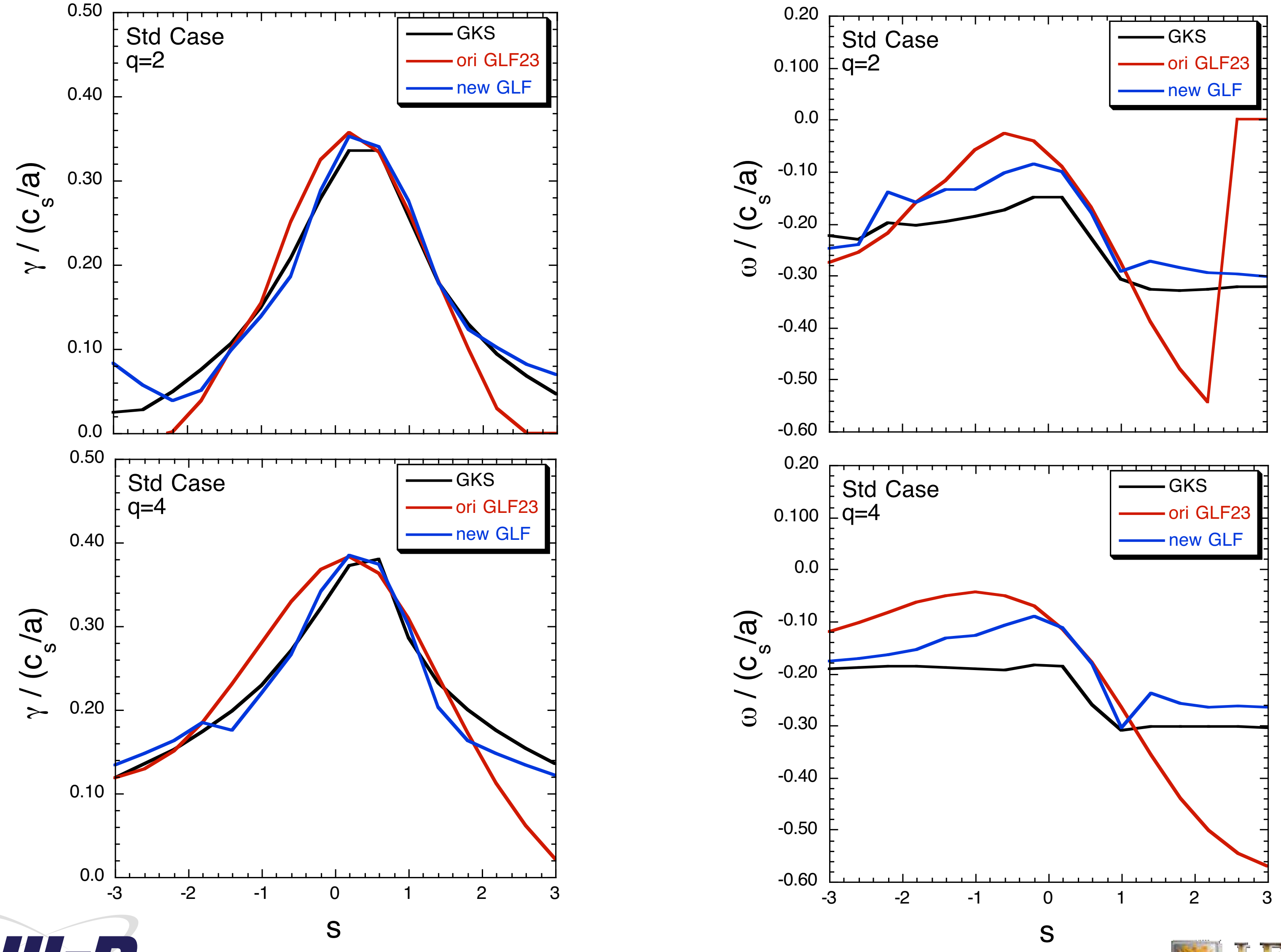
- Original GLF23 model limited to $k_\theta\rho_s$ <= 0.5 (ETG γ's scaled from ITG γ's)
- New GLF applies to entire range from low-k ITG/TEM to high-k ETG modes



low-k
to high-k

med-k

New GLF Model Shows Agreement With GKS Growth Rates & Frequencies for Shear Scan Around Standard Parameters

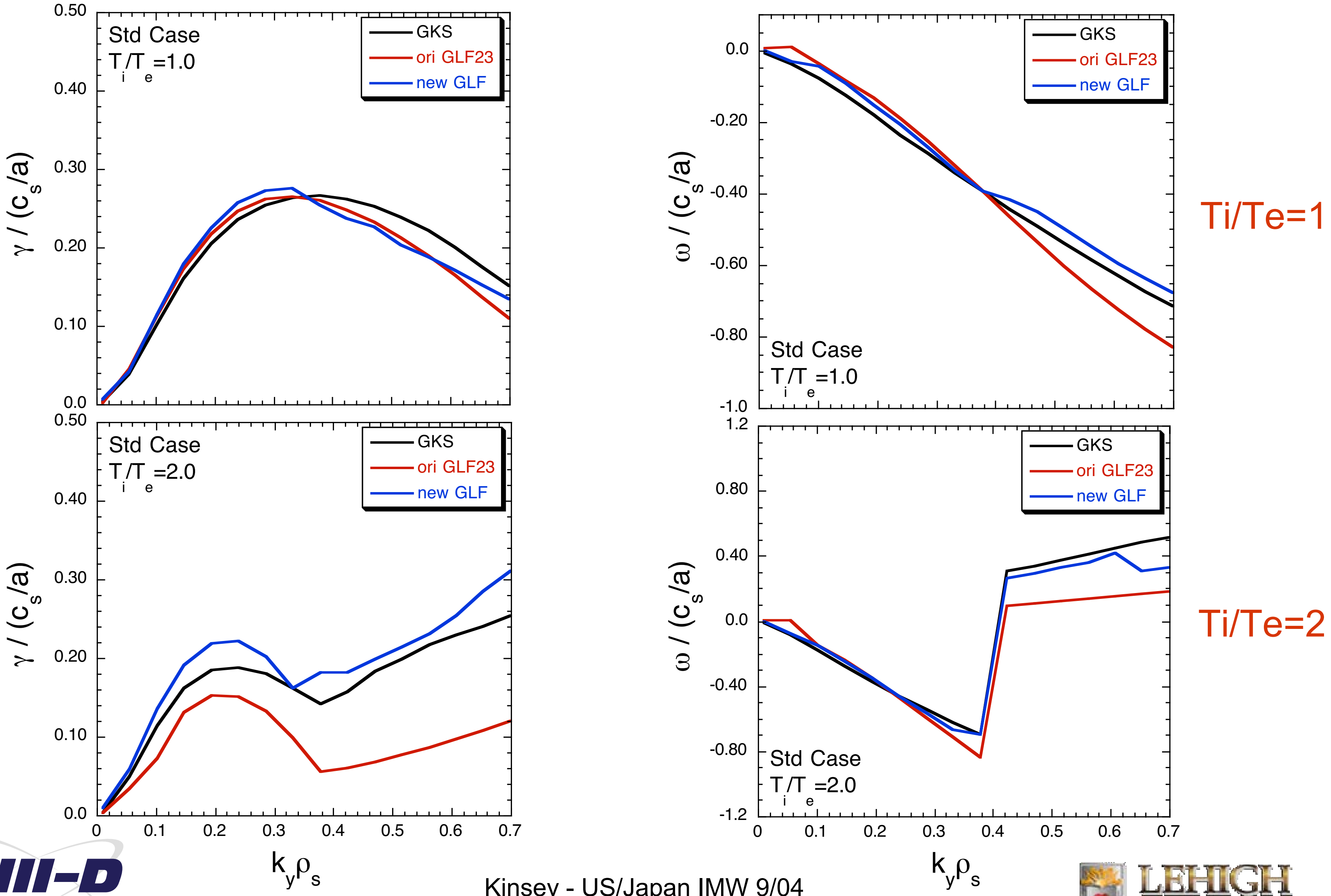


q=2

q=4

New GLF Model Shows Improved Agreement For High Ti/Te

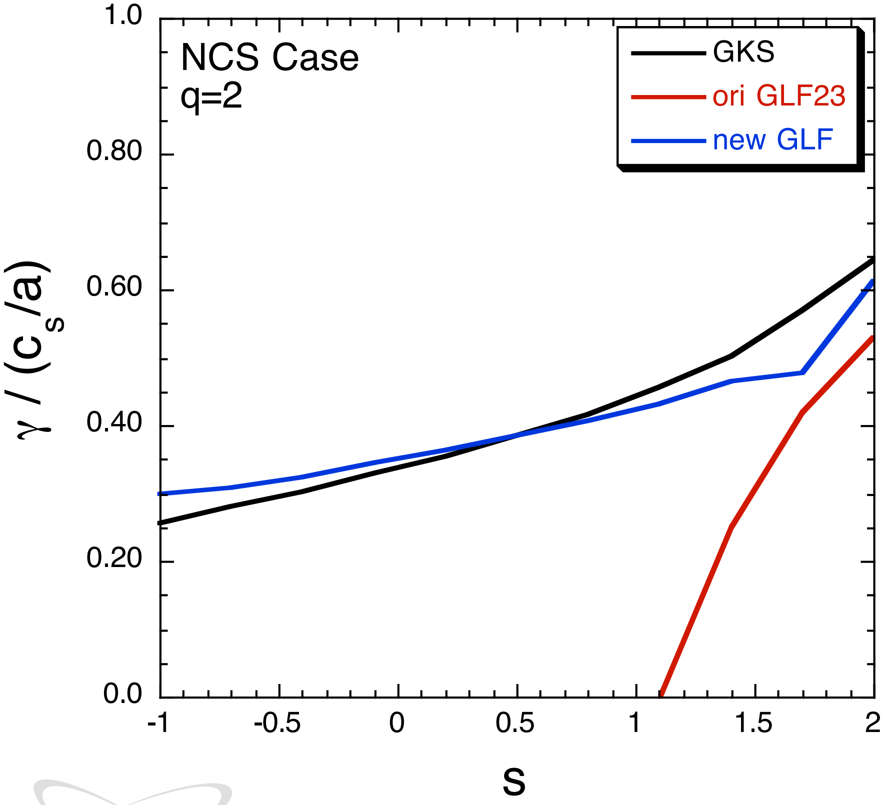
- **Similar agreement for ori GLF23, new GLF models with GKS for Ti/Te=1**



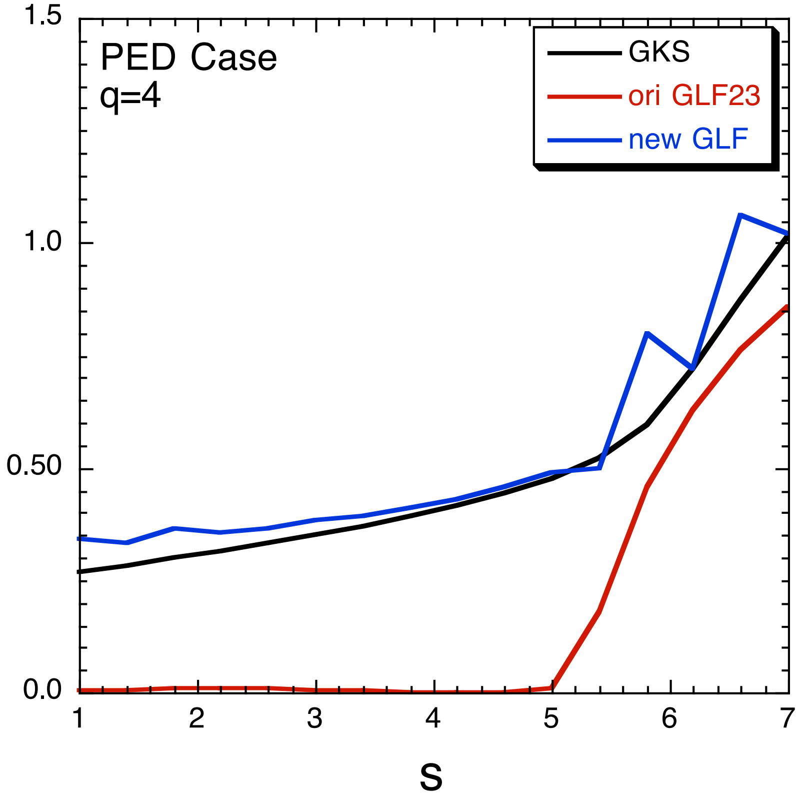
New GLF Model Significantly Better For NCS and Pedestal Parameters

- **Original GLF23 model does not describe growth rates and frequencies for large |s-α|**
- **New GLF model agrees with GKS for both NCS and pedestal cases with large shear and alpha**

NCS case:
STD+a/L_{Ti}=10, a/L_{Ti}=4,α=3



Pedestal case:
STD+r/a=0.75, a/L_n=3, $a/L_{Ti,e}$=10, α=9



Summary

- GYRO ExB shear scans show that
  - Quench point amazingly robust w/ and w/o kinetic electrons for cases where modes rotating in ion or electron direction
  - Quench point approximately $\gamma_E \approx 2\ \gamma_{max}$

    (2x larger than gyrofluid result)
  - Transport may not be quenched when γ_p included

    Pure toroidal rotation example: $\gamma_P = (Rq/r) = 12\gamma_E$

    (R/a=3,r/a=0.5,q=2)
  - Real geometry gyrokinetic simulations needed

    gyrofluid ITG simulations by Waltz found that $\gamma_E \approx 0.5\ \gamma_{max}$
- Next generation 6-moment GLF eigenvalue model is being developed
  - Agreement with GKS growth rates, frequencies is excellent over a wide range of parameters
  - Some fine tuning needed in Hermite basis function solution algorithm
  - Need to simplify GLF to make it computationally efficient enough to make a viable transport model