A Comprehensive Study of the Parametric Dependencies of Transport Using Gyrokinetic Simulations

Presented by
J. Kinsey, R. Waltz, J. Candy

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LEHIGH
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GENERAL ATOMICS

Over 320 Nonlinear Gyrokinetic Simulations Have Been Performed Using The GYRO Code

- **A nonlinear simulation database has been created for benchmarking and transport model development**

  http://fusion.gat.com/comp/parallel

- **Scans in R/a, r/a, q, $\hat{s}$, α, a/L_n, a/L_T, ν, β, T_i/T_e, κ, δ, dilution, and ExB shear with and without kinetic electrons (most runs w/ kinetic electrons)**
- **Simulations around several reference cases assuming $\hat{s}$-α geometry, electrostatic (except for β scan), and flat profiles across annulus, zero boundary conditions**
  - **GA Standard Case (STD):** R/a=3, r/a=0.5, q=2, $\hat{s}$=1, α=0, a/L_T=3, a/L_n=1, T_i/T_e=1, ν=0, β=0
  - **TEM1 Case:** STD w/ a/L_n=2, a/L_T=2
  - **TEM2 Case:** STD w/ a/L_n=3, a/L_T=1
- **Miller geometry used for κ and δ scans**
- **Diffusivities shown are time-averaged values and are normalized to the gyro-Bohm diffusivity, $\chi_{GB}=c_s\rho_s^2/a$**

Nonlinear Database Comprised of Parameter Scans

- **Temperature and density gradient scans : 25 kinetic electron simulations (plus 6 kinetic electron Cyclone simulations, J. Candy)**
- **Safety factor and magnetic shear scans :123 kinetic electron simulations** *J.E. Kinsey, R.E. Waltz, J. Candy, submitted to Phys. Plasmas*
- **Aspect ratio and minor radius scans : 12 kinetic electron simulations**
- **Collisionality and Ti/Te scans :10 kinetic electron simulations**
- **Elongation and triangularity scans : 5 adia. electron + 34 kinetic electron simulations**
- **ExB velocity shear scans: 84 adia. electron and kinetic electron simulations**

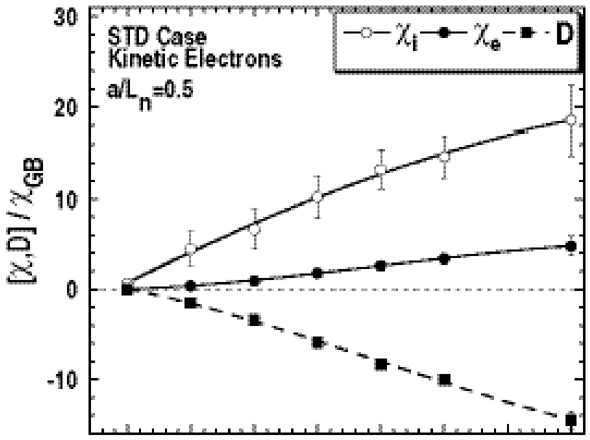
  J.E. Kinsey, R.E. Waltz, J. Candy, Phys. Plasmas ***12****, 022305 (2005).*
- **Beta scans (J. Candy) : 14 kinetic electron EM simulations**

  J. Candy, Phys. Plasmas ***12****, 072307 (2005).*
- **He dilution scans (C. Estrada) : 19 kinetic electron simulations**

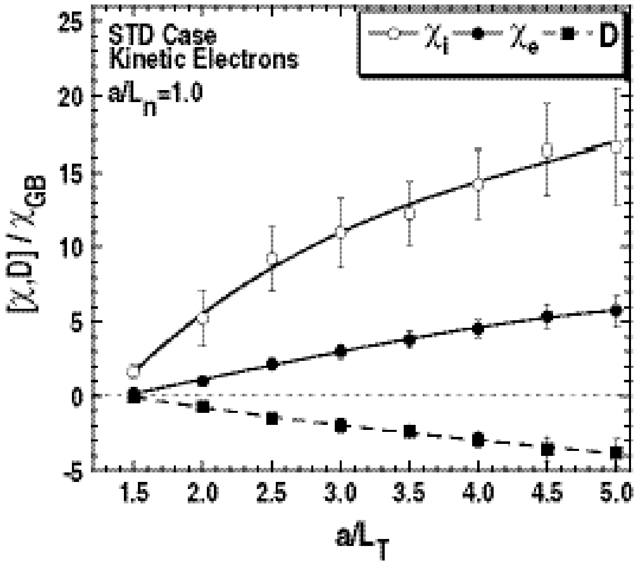
  C. Estrada-Mila, J. Candy, R.E. Waltz, Phys. Plasmas ***12****, 022305 (2005).*

Temperature Gradient Scan for STD Case Including Kinetic Electrons

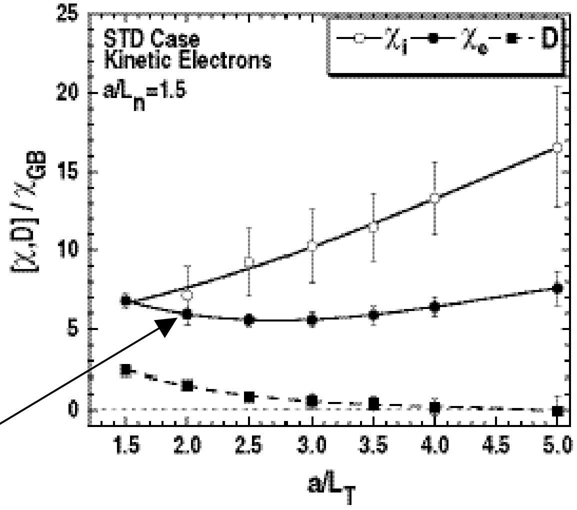
- STD case scans in a/L_T w/ a/L_n=0.5, 1.0, and 1.5
- Transport not as stiff at low gradients for peaked density (a/L_n=1.5)



Flat Density



STD Case



Peaked Density

TEM

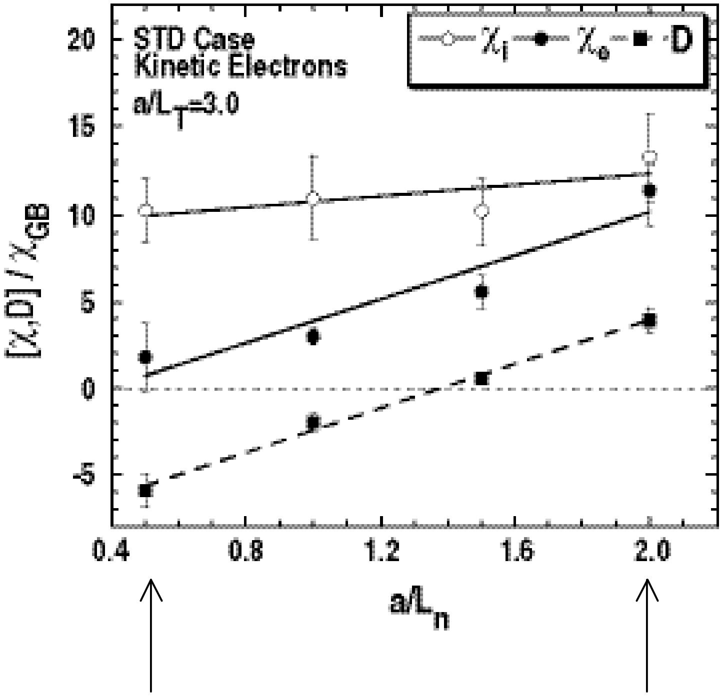
$\chi_{GB} = c_s \rho_s^2 / a$

* Note: error bars on plots are a measure of intermittency and NOT uncertainty

Density Gradient Scan for STD Case

- **STD case a/L_n scan with a/L_T=1.0**
  - Ion and electron density gradient varied together
- **Particle diffusivity changes from negative (inward) to positive (outward) as density gradient is increased**
  - $D=D_e=D_i$ due to ambipolarity
- **Electron energy and particle transport show stronger dependence on a/L_n than ion energy transport**

STD Case



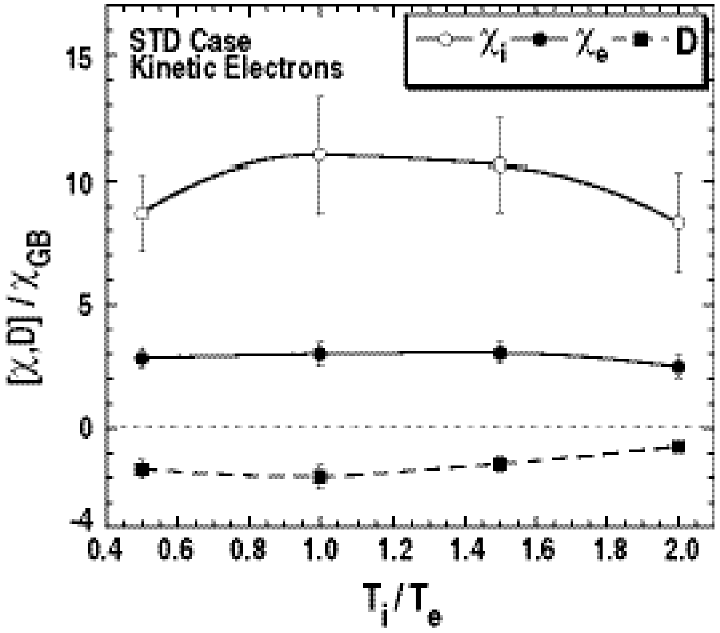
Flat density

Peaked density

Temperature Ratio Scan for STD Case

- STD case T_i/T_e scan at fixed a/L_T
- Ion energy diffusivity modestly reduced going from T_i/T_e =1 to T_i/T_e =2
- Electron energy transport fairly insensitive to T_i/T_e
- Particle pinch somewhat reduced as T_i/T_e is increased
- Linear stability of spectrum for T_i/T_e =2 shows ITG modes below $k_\theta\rho_s$=0.3 and TEM modes above $k_\theta\rho_s$=0.3

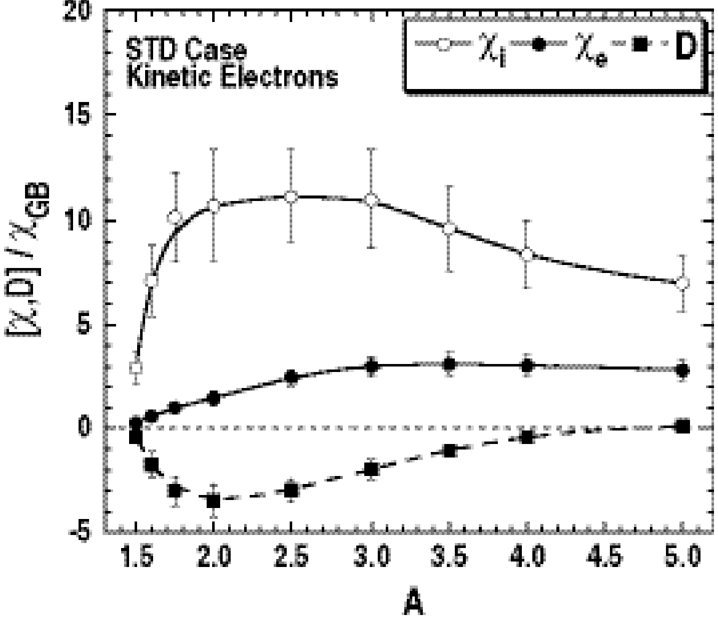
STD Case



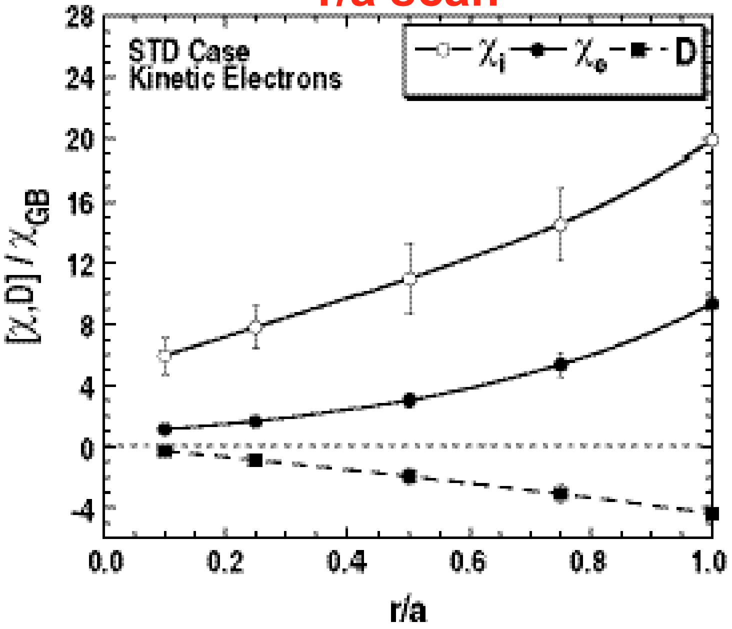
Aspect Ratio and Minor Radius Scans for STD Case

- Scans in R/a and r/a for STD parameters with kinetic electrons
- Strong reduction in transport below A=2 which is consistent with previous linear gyrokinetic studies (e.g. Rewoldt)
- Nearly linear increase in transport with increasing r/a at fixed R/a

R/a scan



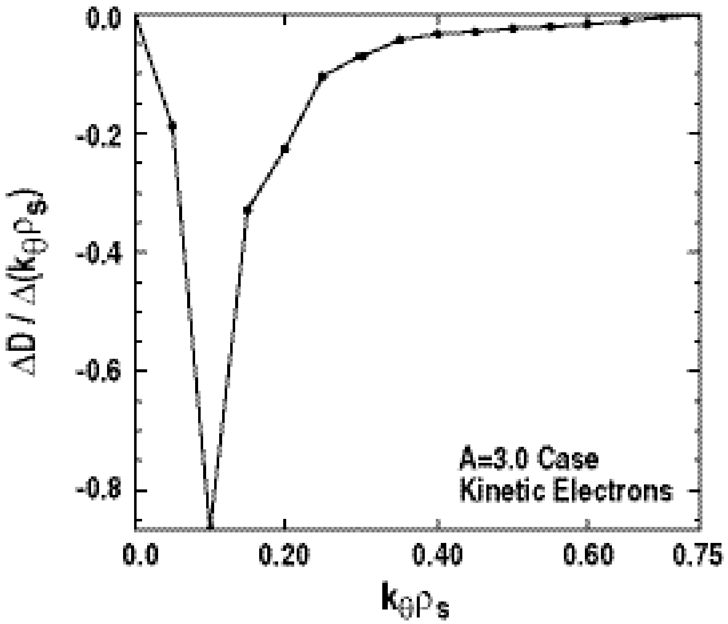
r/a scan



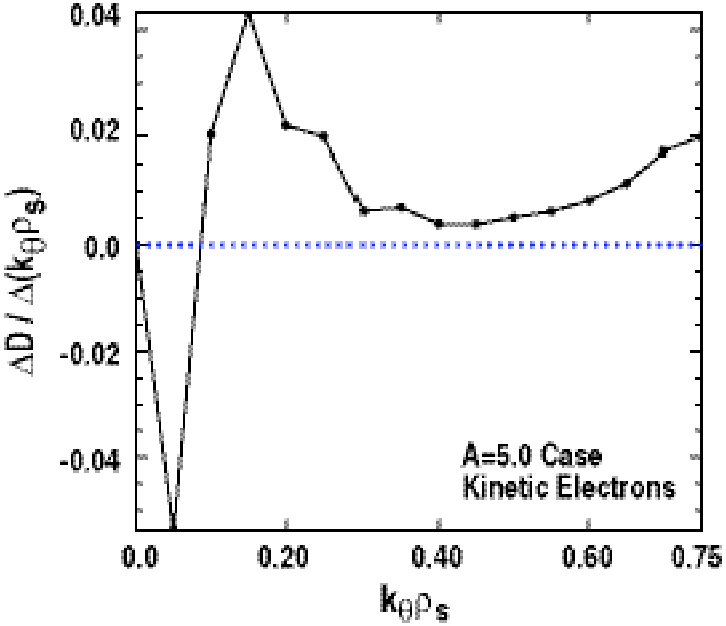
Shorter Wavelength Modes Drive Outward Flow at High Aspect Ratio

- **Particle pinch predicted at low-medium aspect ratio**
  - At A=R/a=3.0, all modes in spectrum drive a pinch
- **Null flow point near A=5.0**
  - Modes above $k_\theta \rho_s$=0.15 drive an outward flow

A=3.0

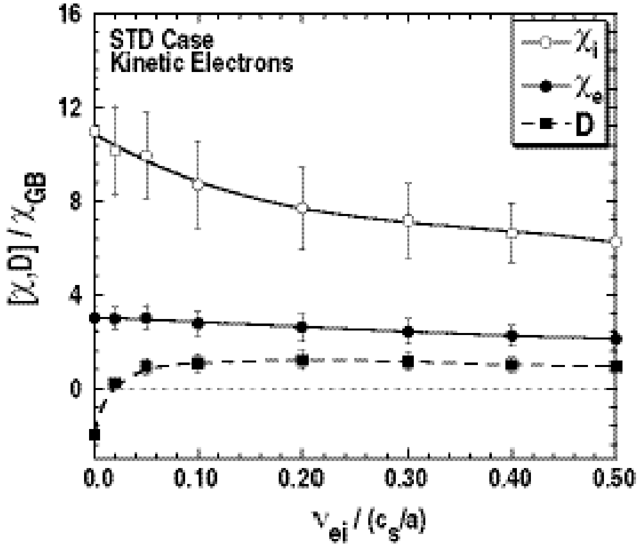


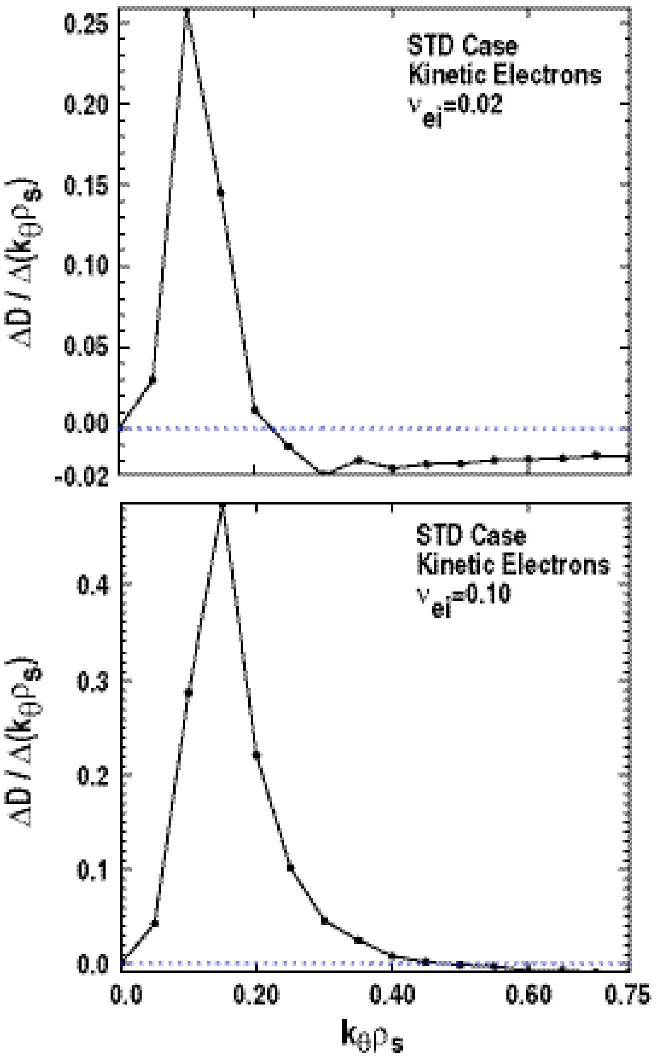
A=5.0



Particle Pinch Strongly Impacted By Collisions

- Particle pinch predicted for STD case w/o collisions
- Addition of collisions increasingly eliminates particle pinch driven by low k_y modes
- Electron energy transport insensitive to collisions



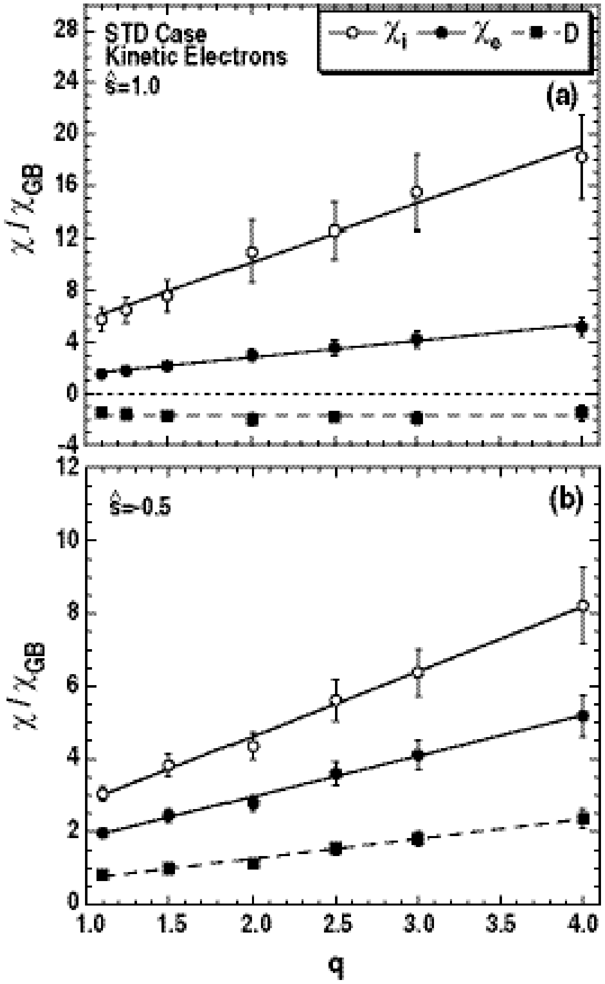


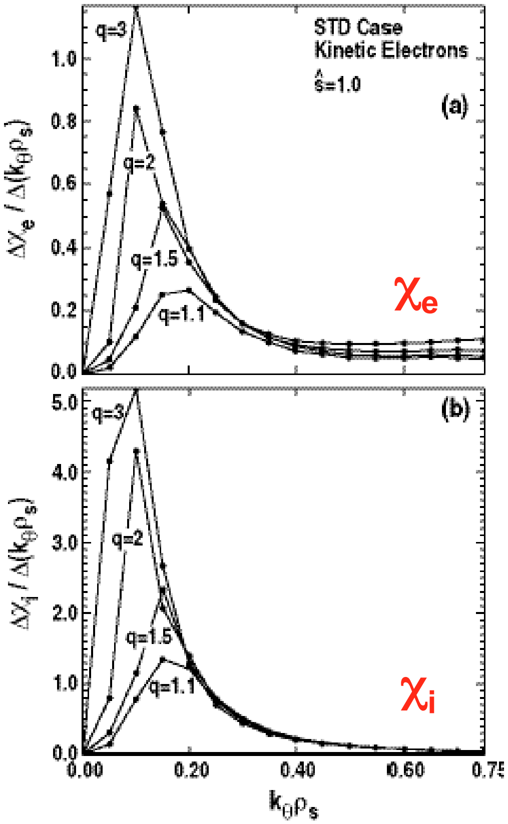
ν=0.02

ν=0.10

Ion and Electron Transport Exhibits Linear q Dependence in STD Case Kinetic Electron Simulations

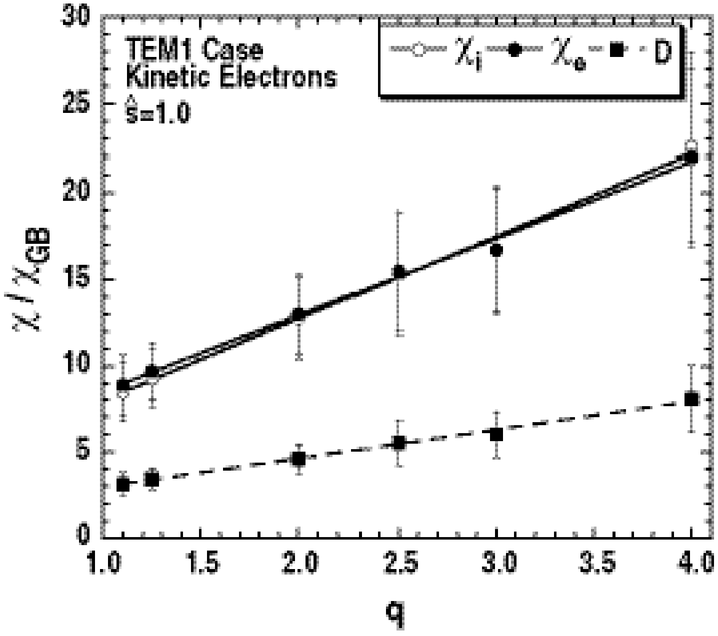
- **Energy transport exhibits linear q dependence for both positive and negative shear**
  - D also follows linear q dependence if D is positive
  - Spectral downshift w/ decreasing q is evident
  - Small contribution to χ_e from higher $k_\theta \rho_s$ modes
- **Particle transport insensitive to q for s=1.0 case where D is negative**
  - Passing electron contribution to D changes sign near q=2
  - D_{pass}/D_{total} small (0.1-0.2) but large enough to impact q scaling

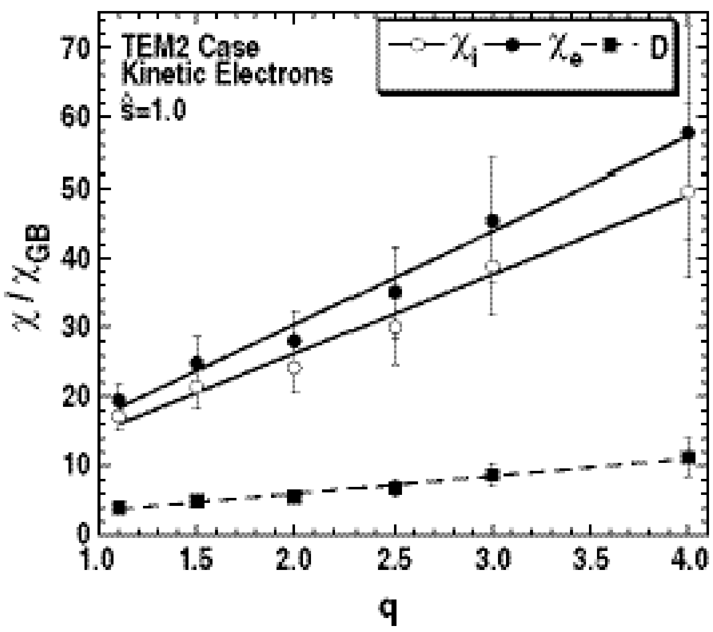




TEM Cases Also Exhibit Linear q Dependence

- **TEM1: STD parameters w/ a/L_T=2, a/L_n=2**
  (half of modes in ion direction, others in electron direction)
- **TEM2: STD parameters w/ a/L_T=3, a/L_n=1**
  (All modes in electron direction)





GAM Amplitude Increases With Increasing q

- **Geodesic Acoustic Modes evident at n=0 at $\omega(a/c_s) = \pm 0.75$**

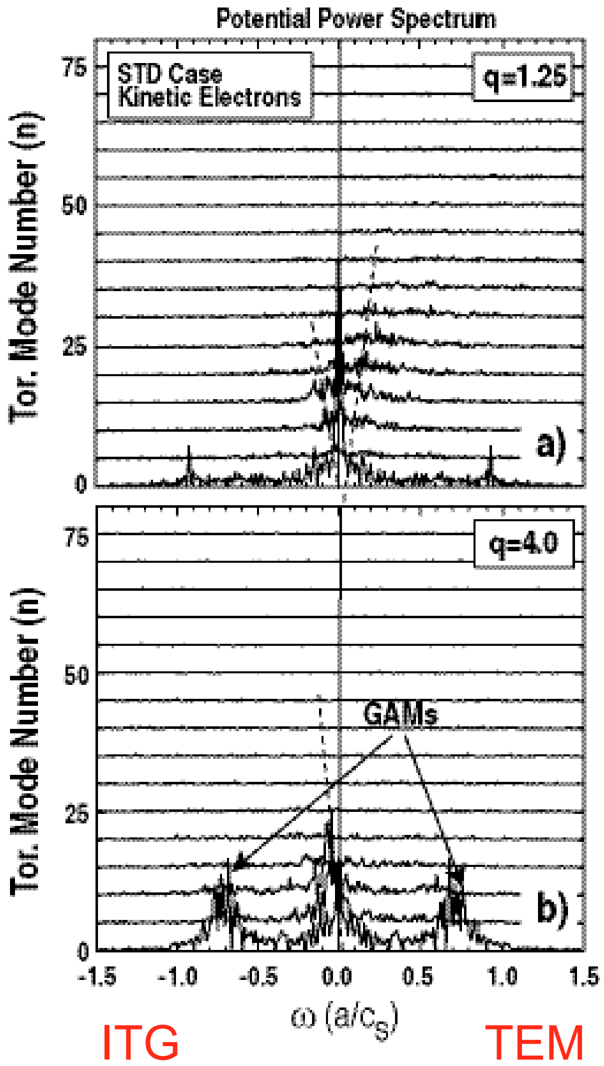
- **Amplitude in simulations is consistent with q scaling of GAM damping rate:**

  $$\gamma_G = -\,\omega_G \exp(-q^2)$$

  where ω_G is the GAM frequency (Hinton, 1999)

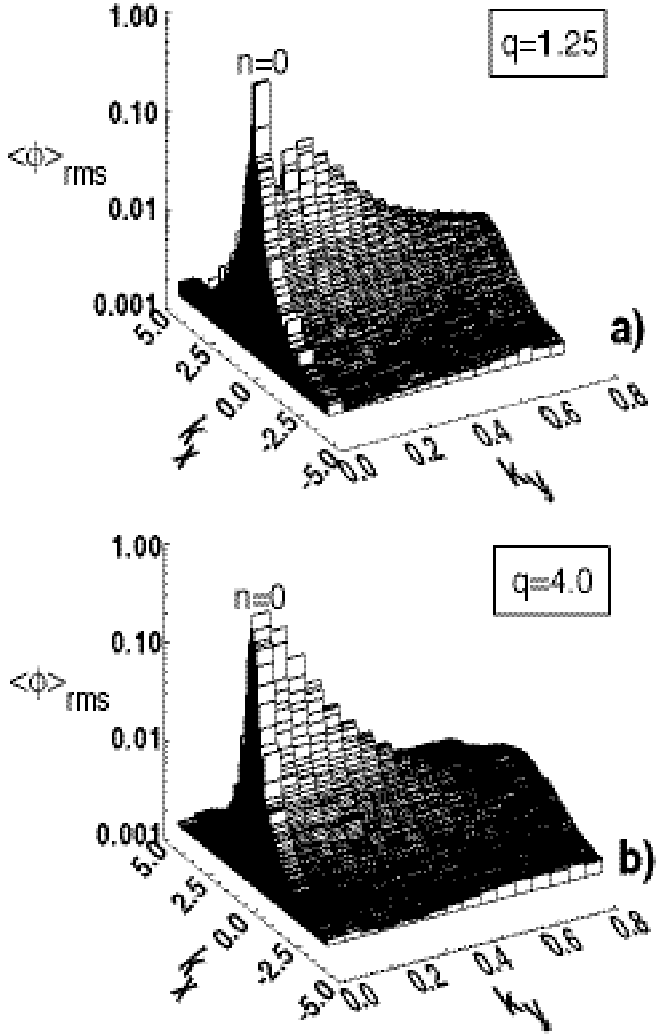
- **Fluctuations ITG dominated in q=4 case with 1 peak at negative $\omega(a/c_s)$**

- **Spectrum shows both ITG and TEM peaks for q=1.25 case**



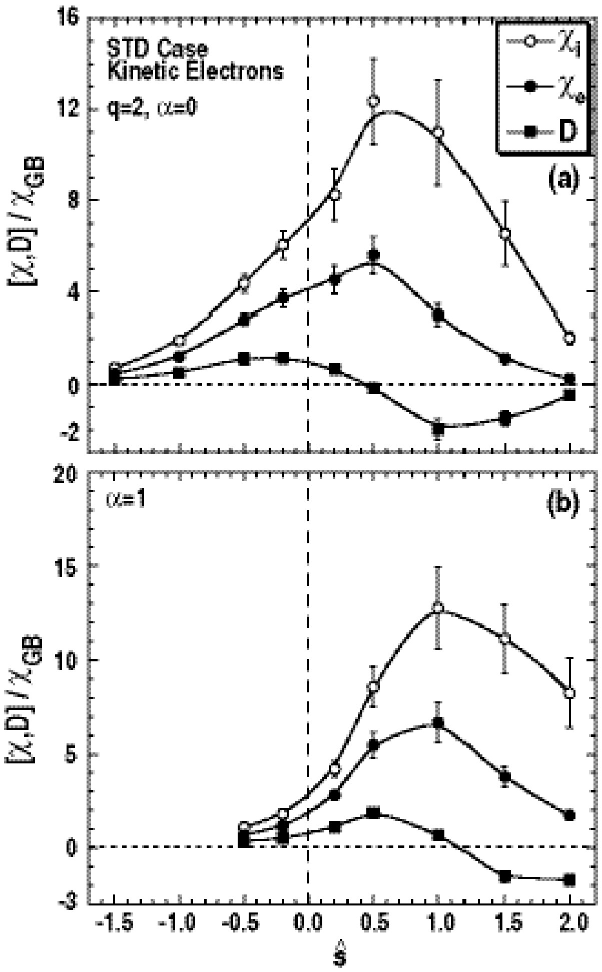
At Low q, n=0 Amplitude Larger Than Neighboring n > 0 Mode Amplitudes

- **Time-averaged RMS spectral intensity of the potential fluctuations compared for STD case w/ q=1.25 and q=4.0**
- **Spectral intensity shown in (k_x,k_y) plane where $k_x=k_r\rho_s$ and $k_y=k_\theta\rho_s$**
- **Also evident that higher k_y modes contribute more to transport at low q compared to high q**



Particle Diffusivity Can Change Sign As Magnetic Shear Is Varied

- **Magnetic shear $\hat{s}$ varied at fixed q for α=0 and α=1**
- **For STD case, null flow point found at $\hat{s}$=0.5 for α=0**
  - D negative for $\hat{s}$ > 0.5
  - D positive for $\hat{s}$ < 0.5
- **Alignment of null point with maximum in χ particular to STD parameters**
- **Alpha stabilizing for negative shear (e.g. $\hat{s}$=-0.5), and destabilizing for positive shear (e.g. $\hat{s}$=2)**

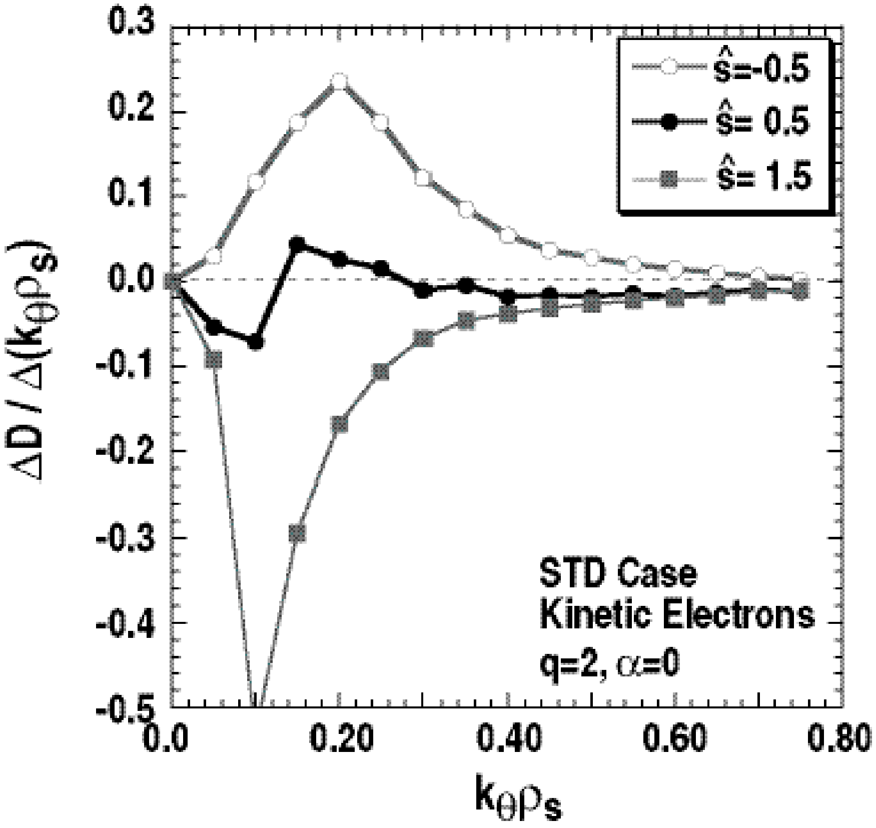


α=0

α=1

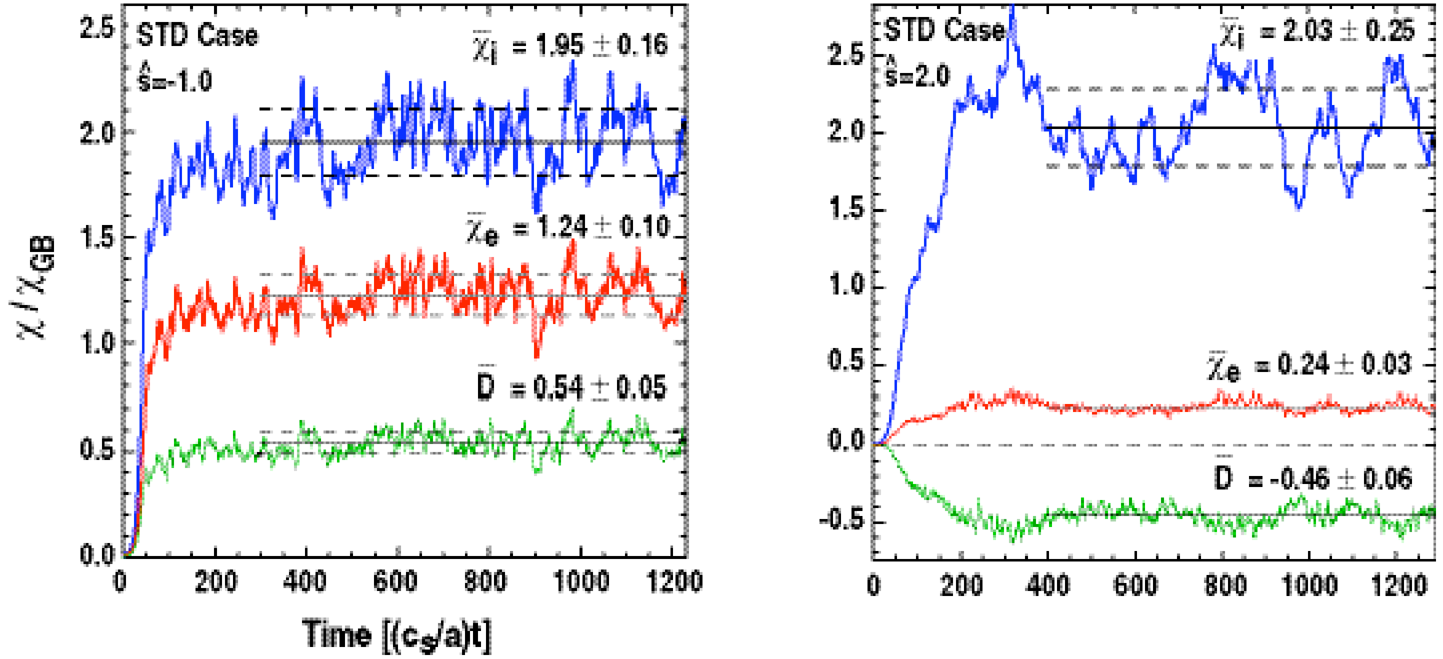
Spectral Analysis at Null Point Shows Some Modes Drive A Negative Flow With Other Modes Drive A Positive Flow

- **Spectrum includes 16 toroidal mode numbers with a maximum $k_\theta\rho_s$=0.75**
- **Null flow point at $\hat{s}$=0.5**
  - Linear stability shows transition from ITG to TEM above $k_\theta\rho_s$=0.65
- **Time-average particle diffusivity is negative for $\hat{s}$=1.5 and positive for $\hat{s}$=-0.5**
  - Linear stability shows TEM above $k_\theta\rho_s$=0.50 for $\hat{s}$=1.5
  - Linear stability shows TEM above $k_\theta\rho_s$=0.65 for $\hat{s}$=-0.5



Ratio Of Ion to Electron Energy Transport Changes Dramatically With Magnetic Shear

- **For STD case, ratio of χ_i/χ_e changes significantly with shear**
  - **At $\hat{s}=2$, $\chi_i/\chi_e=9.7$**
  - **At $\hat{s}=1$, $\chi_i/\chi_e=3.4$**
  - **At $\hat{s}=-1$, $\chi_i/\chi_e=1.6$**



The Effects Of Elongation and Triangularity On Turbulent Transport Have Been Investigated Using The Miller Equilibrium Model

- **Nine parameters are required to describe the local equilibrium using Miller geometry[1]: κ (elongation), δ (triangularity), q, $\hat{s}$ (magnetic shear), α (normalized pressure gradient) , $A=R_0/r$, $\partial_r R_0$, along with gradient factors of κ and δ (s_κ and s_δ)**
- **For D-shaped plasmas, the shape of a flux surface is specified in terms of the major radius R and height Z as a function of the poloidal angle θ:**

$$R = R_0 + r\cos[\theta + (\sin^{-1}\delta)\sin\theta]$$
$$Z = \kappa\, r \sin\theta$$

- **Systematic nonlinear scans in κ and δ were performed for the STD case with $\partial_r R_0=0$, $\alpha=0$, $\beta=0$**
  - For κ scans, we also varied $s_\kappa=(r/\kappa)\partial_r\kappa \approx (\kappa-1)/\kappa$
  - For δ scans, we also varied $s_\delta=(r/(1-\delta^2)^{0.5})\partial_r\delta \approx \delta/(1-\delta^2)^{0.5}$

[1] *R. L. Miller, et al, Phys. Plasmas 5, 973 (1998).*

Adiabatic Electron Simulations Show The Ion Energy Transport Decreasing Linearly With Increasing Elongation

- **κ varied from 1 to 2 for STD case using Miller geometry**
  - kappa gradient factor s_κ varied along with κ
  - GYRO results for $\chi_{natural}$ where

    $\chi_{natural} = <|\nabla r|^2> \chi_{ITER}$

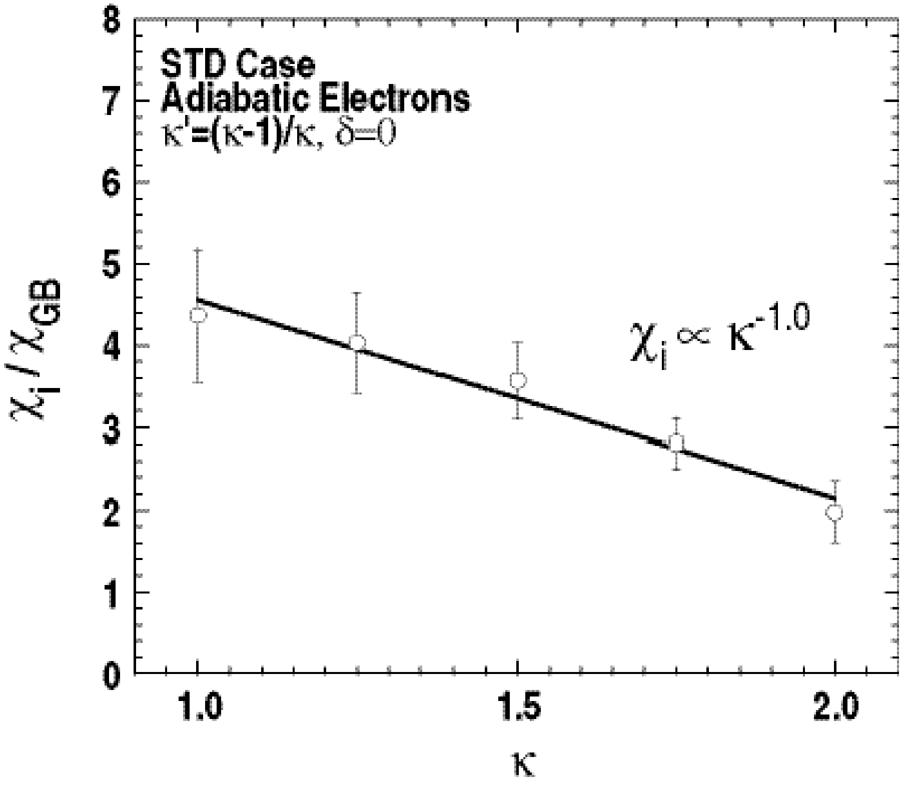
    For concentric ellipses where “r” is the midplane minor radius:

    $<|\nabla r|^2> = (1+\kappa^2)/(2\kappa^2)$

    $B_{unit} = (\rho/r)(d\rho/dr)B_0 \approx \kappa^2 B_0$, so

    $\chi_{ITER} \approx 2/(1+\kappa^2)\ \chi_{natural}$
- **Previous NL gyrofluid simulations by Waltz[1] showed no κ dependence for $\chi_{natural}$ at q=2 (and q=3)**

Adiabatic Electrons
STD case w/ a=2. δ=0



$\chi_{natural} = \chi / \chi_{GB}$ where $\chi_{GB} = c_s \rho_s^2 / a$

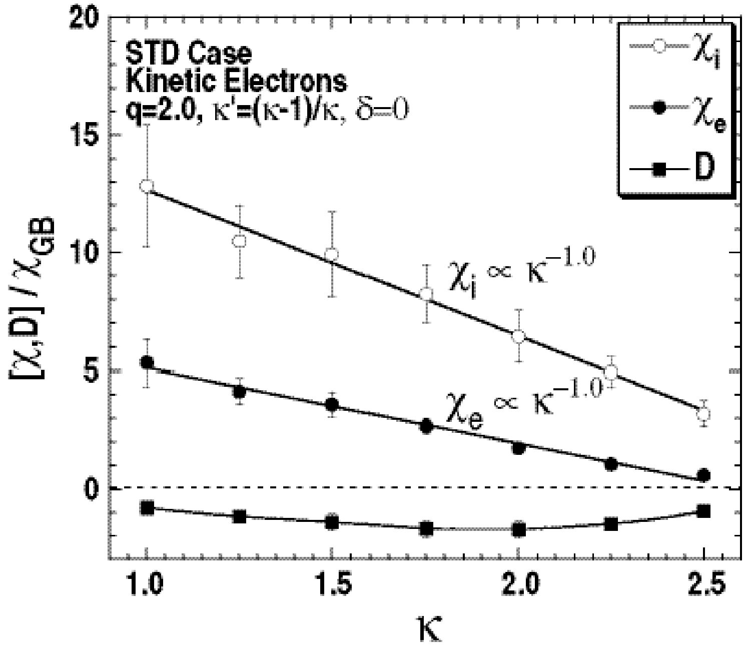
[1] R. E. Waltz, and R.L. Miller, Phys. Plasmas 6, 4265 (1999).

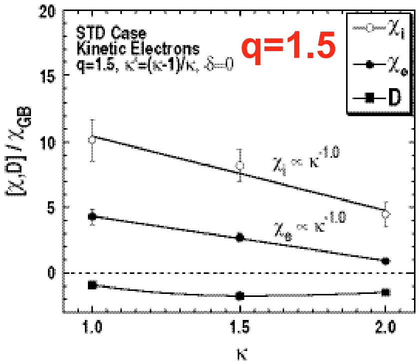
Kinetic Electron Simulations Also Shows Energy Transport Decreases Linearly With Increasing Elongation

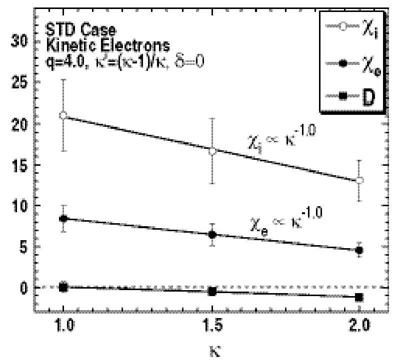
- **Linear decrease in both χ_e and χ_i valid for κ scans at different safety factors**
  - κ varied from 1.0 to 2.0 for different q values and for different shear values using STD parameters with $\hat{s}=1.0$
  - Miller geometry with $\delta=0$; kappa gradient factor $s_\kappa=(\kappa-1)/\kappa$ varied along with κ
  - Offset linear gives best fit to NL results. Growth rate at $k_\theta\rho_s=0.3$ shows same dependence
  - Particle transport shows little or no κ dependence

    Caveat: D is small and negative

    -> follows κ^{-1} dependence if D is positive (see shear scan)



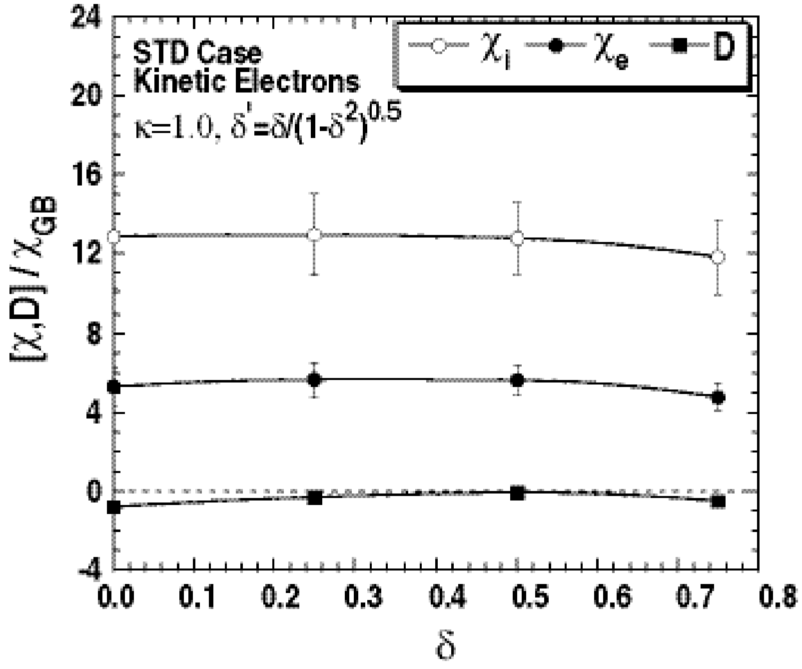




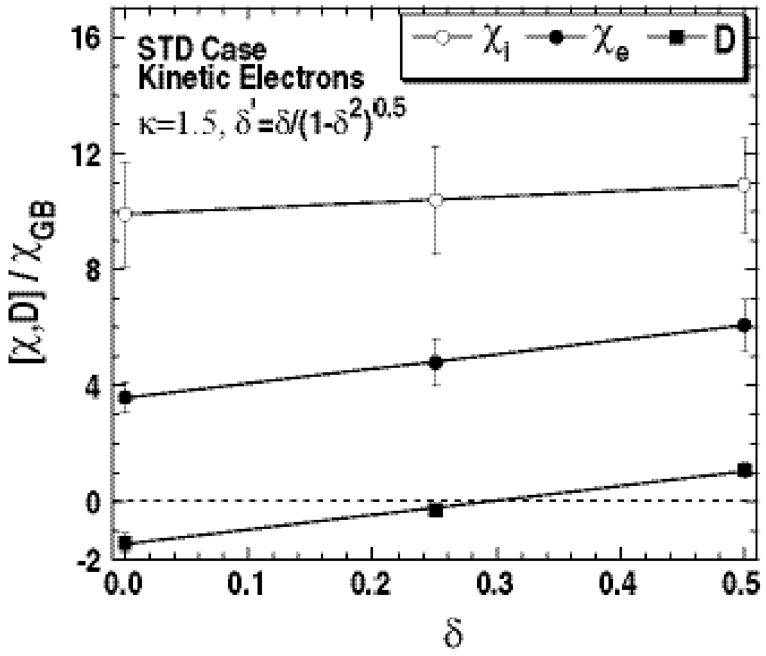
Dependence of Transport on Triangularity Weak For Circular Plasmas, Stronger For Elongated Plasmas

- **δ varied for κ=1.0, 1.5, and 2.0 using STD parameters**
  - Miller geometry, delta gradient factor s_δ varied along with δ
- **Stronger δ dependence for κ=1.5, 2.0 cases compared to κ=1.0 case**
  - δ destabilizing, especially for χ_e and D, going from δ=0.0 to δ=0.5

κ=1.0



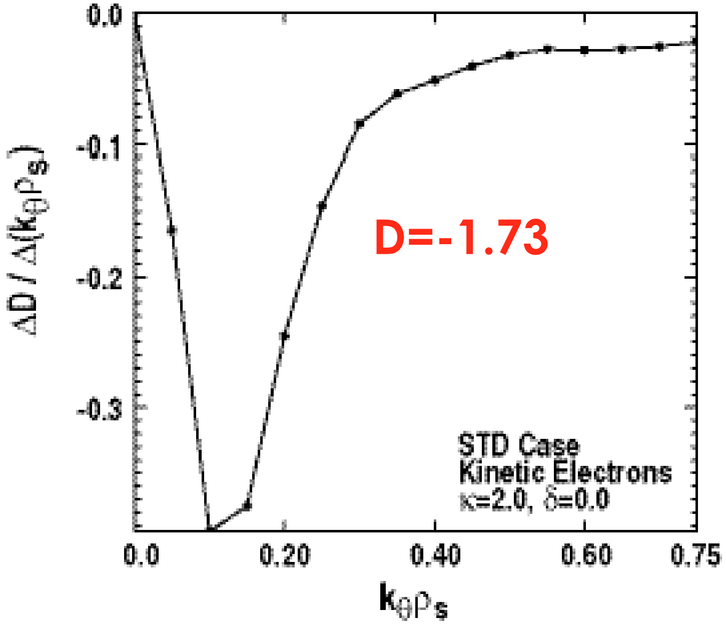
κ=1.5



Triangularity Strongly Impacts Particle Transport Spectrum For Elongated Plasmas

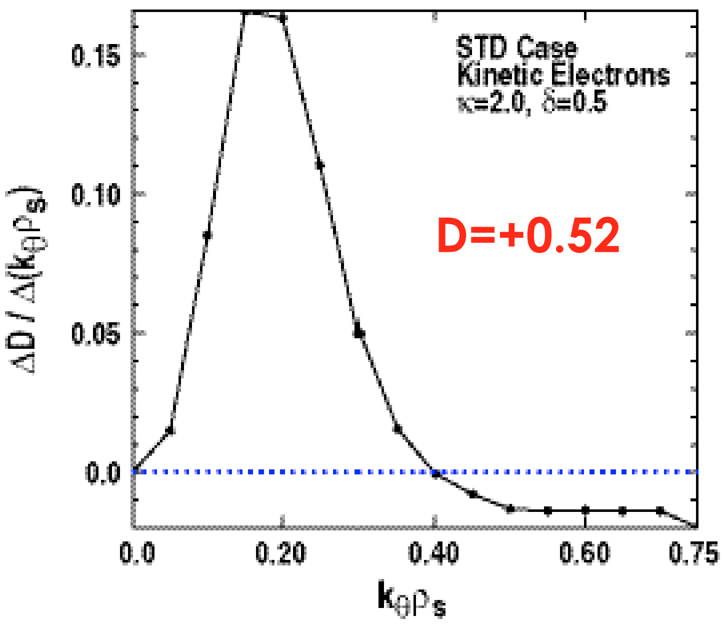
- **δ varied from 0.0 to 0.5 for STD case w/ κ=2.0**
- **Particle transport changes from $D/D_{GB}=-1.73$ to $D/D_{GB}=+0.51$**
  - Transport from low k modes changes sign
  - Less of an effect at κ=1.0 ($D/D_{GB}=-0.8$ -> $D/D_{GB}=-0.1$ when δ=0.0 -> 0.5)

δ=0.0



D=-1.73

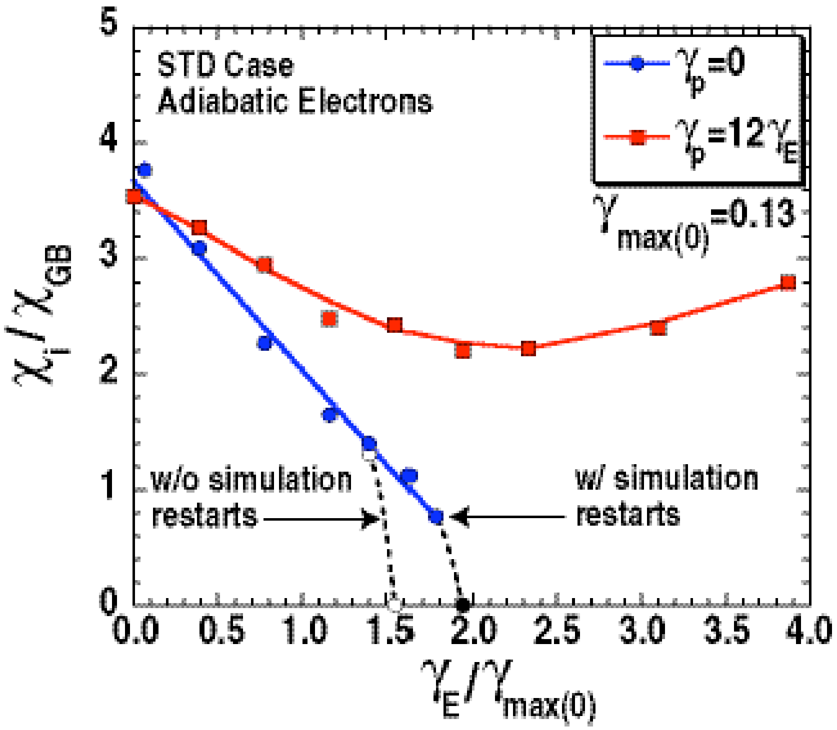
δ=0.5



D=+0.52

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

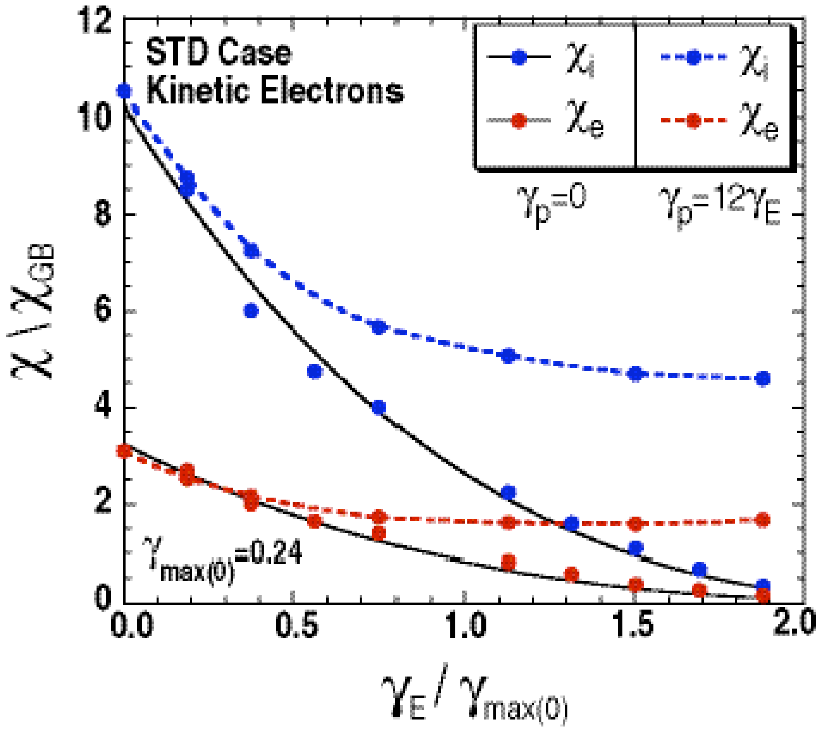
- **ExB shear quench rule originally developed from gyrofluid ITG simulations which showed a quench point at γ_E=γ_{max}**
- **Using GYRO with no parallel velocity shear (γ_p =0), two quench points can be found depending on how the ExB shear is applied in the simulations**
  - ITG transport quenches at γ_E=1.6γ_{max} when γ_E applied at onset of simulation
  - Quench point higher near γ_E=2γ_{max} when γ_E applied in a restart from simulation without γ_E included



- **Purely toroidal rotation case with γ_p =(Rq/r)γ_E=12γ_E shows that transport not quenched by any level of γ_E**

ExB Shear Quench Rule Remains Valid With Addition Of Kinetic Electrons In Nonlinear Gyrokinetic Simulations

- **ExB shear quench point near $\gamma_E=2\gamma_{max}$ for ions and electrons**
  - Same quench point found for the adiabatic electron case
  - Also valid for TEM cases (e.g. STD case w/ $a/L_n=3$, $a/L_T=1$) and for negative shear (e.g. STD case w/ $s=-0.5$)



- **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 when parallel velocity shear included (assuming purely toroidal rotation with $\gamma_p = (Rq/r)\,\gamma_E = 12\gamma_E$**

16 modes
$k_\theta \rho_s <= 0.75$
$\gamma_{max0} = 0.27$

Summary

- **A large database of over 320 nonlinear GYRO gyrokinetic simulations has been created comprising of various parameter scans around several reference cases**
  - Scans in R/a, r/a, q, s, α, a/L_n, a/L_T, ν, β, T_i/T_e, κ, δ, dilution, and ExB shear with and without kinetic electrons (most runs w/ kinetic electrons)
- **Aspect ratio scan shows strong reduction in transport below A=2, weak reduction going from A=3 to A=5**
  - Strong particle pinch near A=2
  - At high A, low-k modes drive a pinch while higher-k modes drive an outward flow
- **Safety factor scans show that the Ion and energy transport exhibits linear q dependence for both ITG and TEM dominated cases**
  - Spectral downshift with increasing q which contributes to most of q^{-1} dependence of transport
  - D also exhibits linear q dependence if D is positive. If D is negative (pinch), then overall q dependence weak due to change in sign of passing electron contribution as q is varied
  - GAM amplitude increases with increasing q; amplitude and frequency consistent with analytic calculations by Hinton, et al.
  - n=0 amplitude greater than neighboring n>0 amplitudes at low q, comparable amplitudes at higher q values

Summary (cont.)

- **Magnetic shear scans show that particle diffusivity can change sign as shear is varied**
  - At null flow point, some modes drive a pinch while other modes drive an outward flow
  - Ratio of ion to electron transport changes dramatically with shear (χ_i/χ_e largest for large positive shear, smallest for negative shear)
- **Adiabatic and kinetic electron simulations robustly show that $\chi_{natural}$ exhibits an inverse linear dependence on elongation**
  - Unlike previous gyrofluid ITG simulations by Waltz, we find κ^{-1} regardless of q and s values
  - Particle transport also exhibits κ^{-1} dependence if D is positive
- **Dependence on triangularity strongest for highly elongated plasmas, weak effect for circular shaped plasmas**
  - Triangularity destabilizing for both energy and particle transport
  - Triangularity has significant impact on particle transport spectrum at high elongation; transport from low-k modes can change sign as δ is varied
- **ExB shear quench rule remains valid in the presence of kinetic electrons with a quench point at $\gamma_E=2\gamma_{max}$ for ions and electrons**
  - Quench rule valid for both ITG and TEM cases
  - Transport may not be quenched at higher q values if parallel velocity shear included in simulations