ITER Predictions Using The GYRO Verified and Experimentally Validated TGLF Transport Model

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in collaboration with
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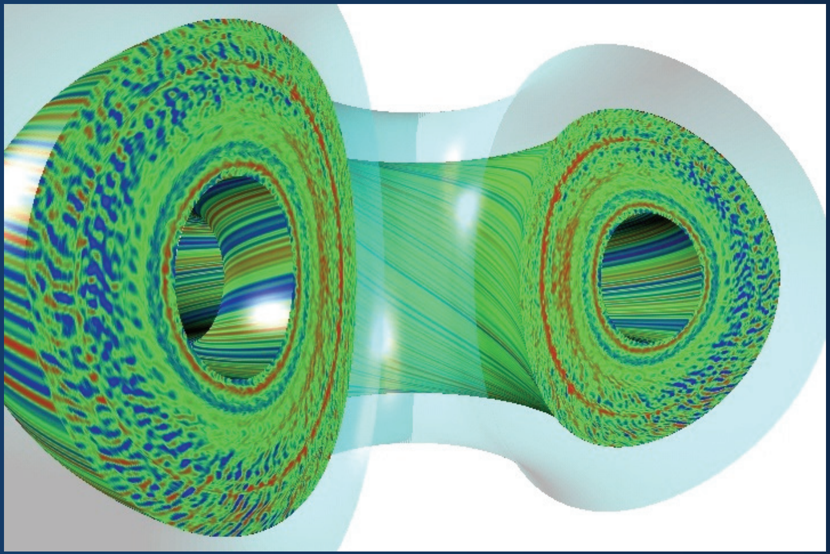
General Atomics



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GENERAL ATOMICS

Overview

- **A comprehensive driftwave model has been developed for predicting the turbulent transport in tokamak**
  - Trapped Gyro-Landau-Fluid (TGLF) quasilinear transport model
  - TGLF philosophy:
    - ✓ VERIFY by comparing TGLF to gyrokinetic linear and nonlinear simulations
    - ✓ VALIDATE TGLF using experimental data

- **TGLF has been well verified against gyrokinetic simulations**
  - TGLF energy diffusivities are within 20% of GYRO results for 191 nonlinear simulations

- **TGLF has been well validated against experimental data**
  - TGLF shows better agreement than GLF23 model for T_e & T_i profiles from a database of 133 discharges from DIII-D, JET, TFTR

- **TGLF is now being used to predict the performance in ITER for the conventional H-mode scenario**

Overview (ITER Projections)

- **Realistic finite aspect ratio shaped geometry reduces the predicted fusion power compared to the s-α model**
  - Predictions from TGLF (Miller shaped geometry) are less optimistic than from GLF23 (infinite aspect ratio s-α geometry)
- **ITER fusion projections are characteristically stiff**
  - Fusion Q $\propto P_{aux}^{-0.8}$
  - Fusion power $\propto \beta_{ped}^2$, so any pedestal optimization has a large payoff
- **Synergistic effects of density peaking, finite β, and ExB shear due to small toroidal rotation are found to be significant**
  - Together they yield a 60% increase in fusion power above the simplified ITER base case (flat density, no rotation, electrostatic)
  - Individually they are small effects (5%)
  - **With all 3 ingredients, TGLF predicts Q=15 and P_{fusion}=450 MW near the maximum pedestal β**
- **TGLF results are confirmed using nonlinear GYRO transport runs**

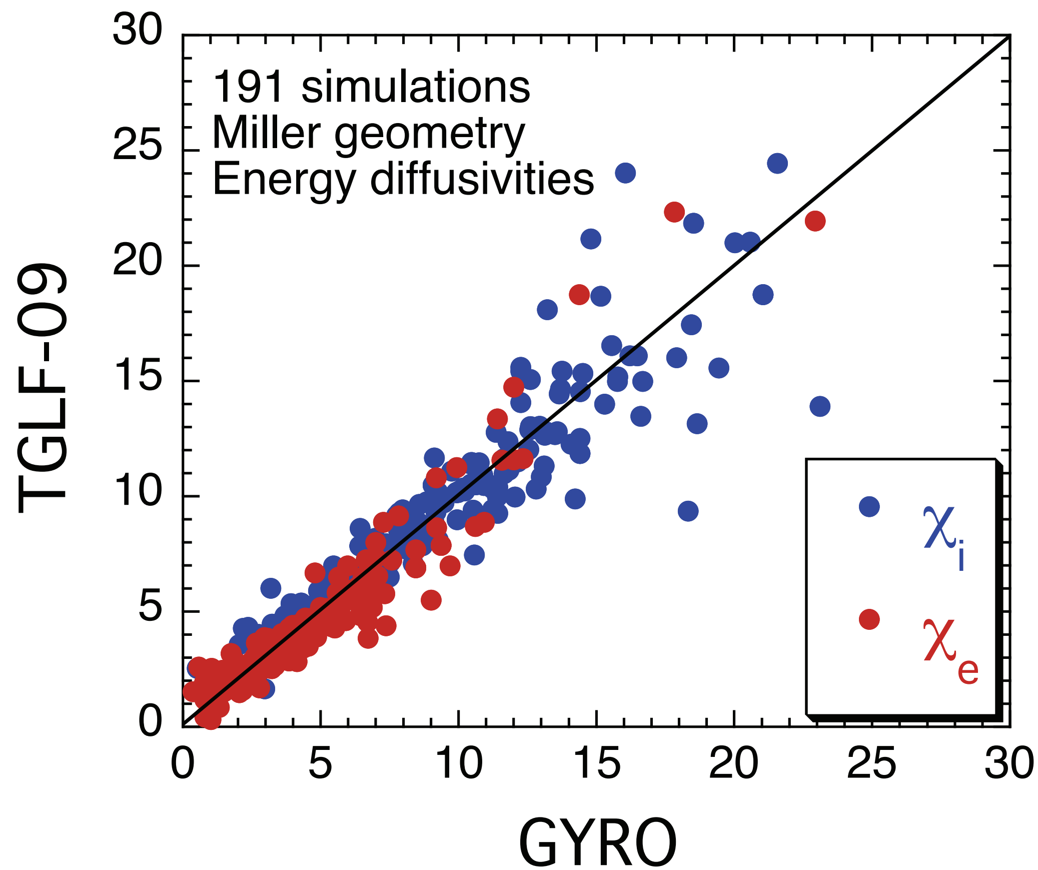
The TGLF Gyro-Landau-Fluid Transport Model

- **TGLF is the next generation GLF model with improved comprehensive physics compared to its predecessor, GLF23**
  - Model valid continuously from low-k ITG/TEM to high-k ETG
  - Extended range of validity
  - Valid for shaped geometry using Miller local equilibrium which replaces the s-α infinite aspect ratio shifted circular geometry
  - Solves set of 15-moment gyro-fluid equations for linear driftwave eigenmodes
  - Computationally more intensive than GLF23
- **Was tested against a database of 1800 linear growth rates and frequencies computed using the GKS gyrokinetic code**
  - Avg σ (γ) = 11% for TGLF, 38% for 1997 GLF23
- **A model for the nonlinear saturation levels was found using the net linear mode growth rates (with ExB shear) and nonlinear GYRO simulations with Miller shaped geometry**
- **Results shown here use TGLF with improved collision model (TGLF-09)**

Verification of the TGLF transport model Against GYRO nonlinear simulations

The TGLF Quasilinear ITG/TEM Energy Diffusivities Agree Very Well with 191 Nonlinear GYRO Miller Geometry Simulations

- **TGLF saturation rule was fit to 83 nonlinear GYRO Miller geometry collisionless simulations**
- **TGLF saturation rule has now been compared against 108 new GYRO cases with collisions**
  - 108 cases NOT included in saturation rule fitting
  - Total GYRO transport database is now 191 simulations
- **Quasilinear theory works amazingly well**
  - RMS errors for [χ_i, χ_e] = [13%, 16%]
- **Many of the GYRO cases are far above ITG threshold**



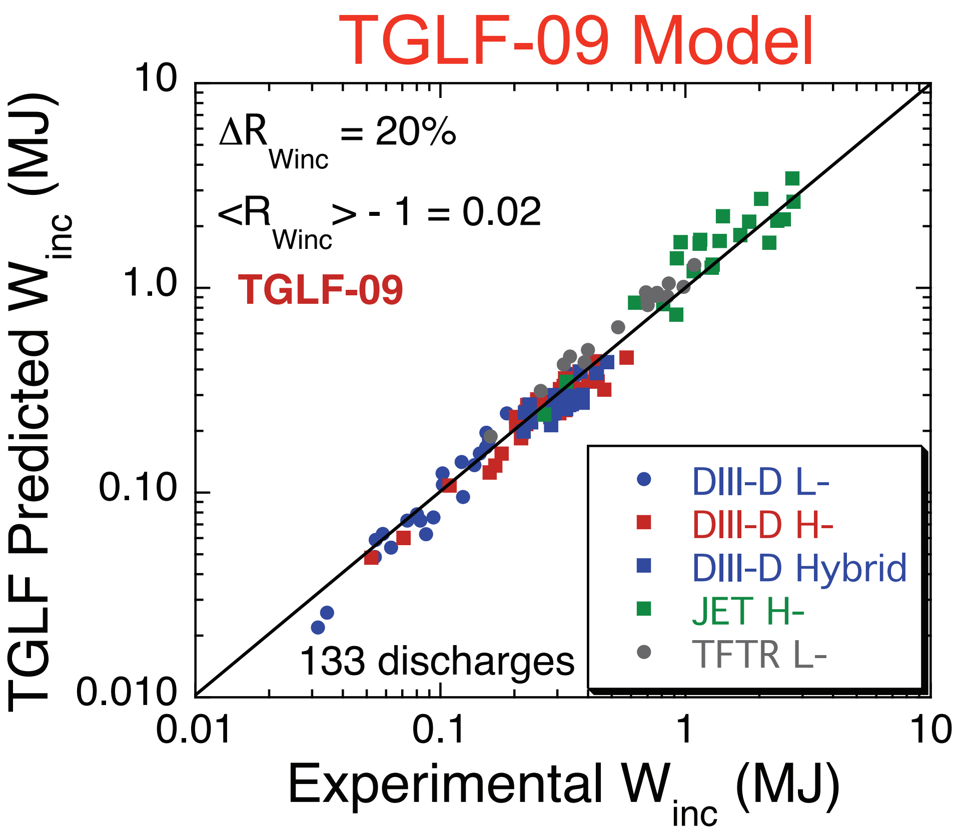
χ's are normalized: χ / χ_{GB}

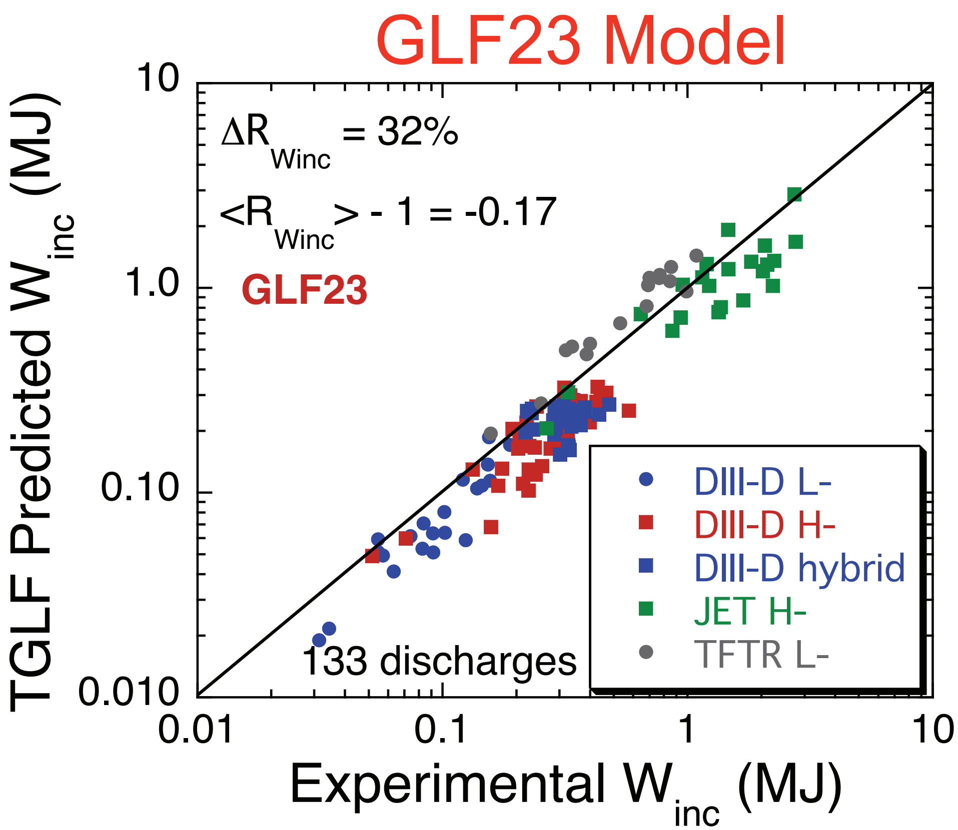
Validation of the TGLF transport model against experimental profile database

"Model testing is meant to demonstrate
that developers have correctly understood
the underlying physics and have made
the right set of choices." – Greenwald, PoP 2010

TGLF Exhibits Lower Average Global & Local Errors than GLF23 for a Large Profile Database of 133 Discharges

- **25 DIII-D L-, 40 DIII-D H-, 30 DIII-D hybrid, 22 JET H-, and 16 TFTR L-mode discharges**
- **Avg RMS error in incremental stored energy (W_{inc}): 20% for TGLF, 32% for GLF23**
- **Offset in W_{inc} much smaller for TGLF (+2% vs -17%)**
- **Avg RMS error for [T_i,T_e] profiles: TGLF = [14%,15%], GLF23 = [21%,22%]**



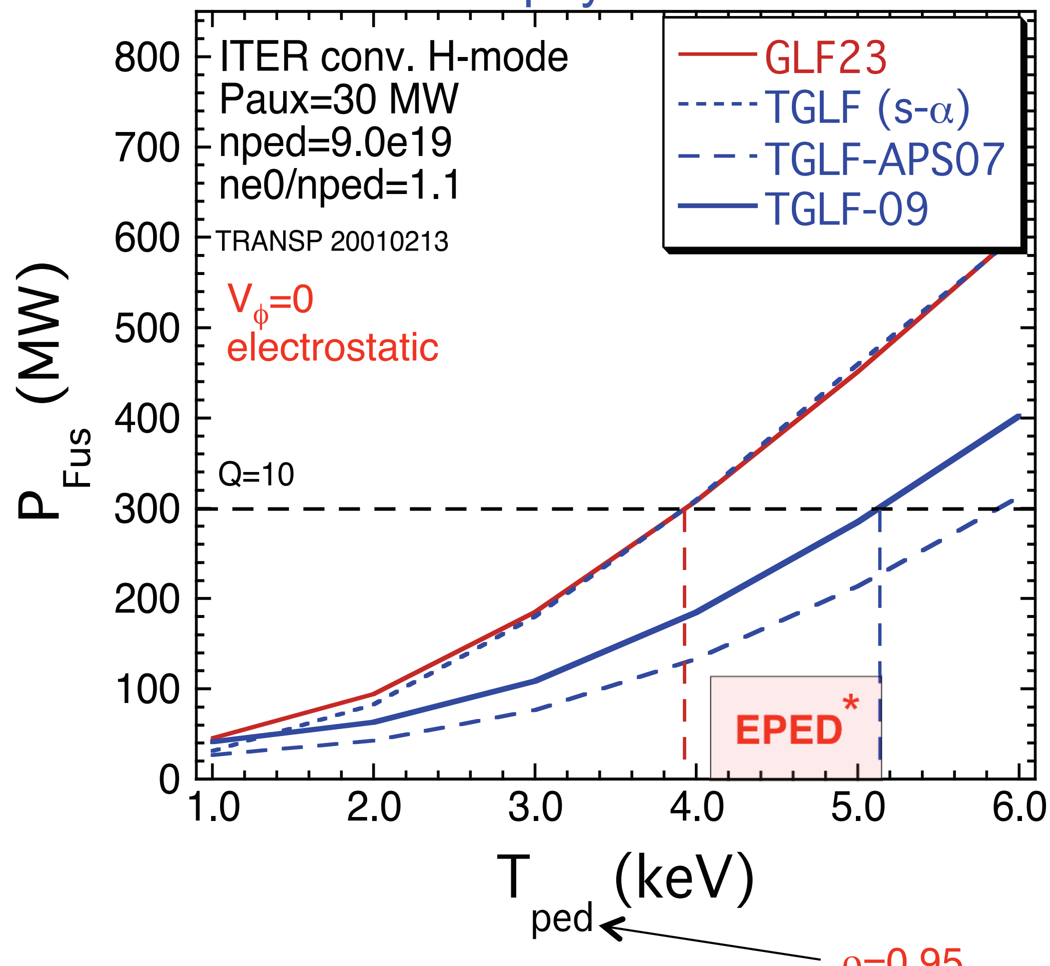


ITER Predictions Using TGLF

Realistic Finite Aspect Ratio Shaped Geometry Reduces the Predicted Fusion Power Compared to the s-α Model

- **TGLF uses finite aspect ratio Miller geometry and has larger transport than with s-α geometry**
- **TGLF with shifted circle geometry agrees with GLF23 shifted circle (s-α) results**
- **ITER predictions sensitive to collision model in TGLF**
  - TGLF with new collision model (TGLF-09) leads to more optimistic predictions than TGLF-APS07 version
  - Mostly impacts very low-k modes which survive in ITER since ExB shear effects are small

Reduced physics base case†

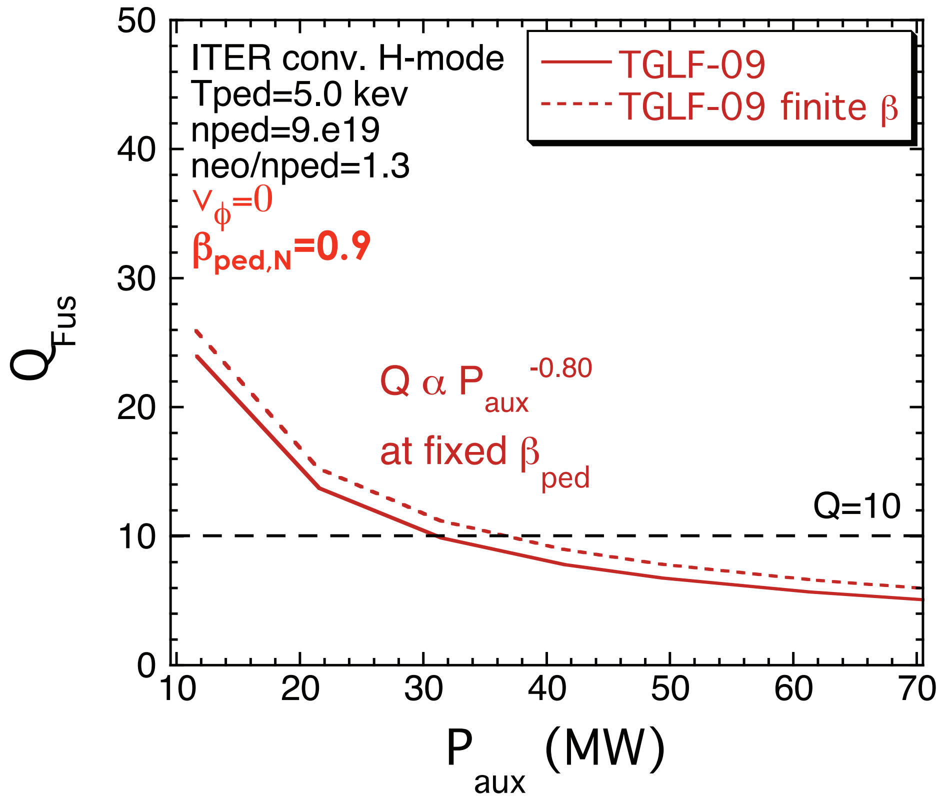


* **Snyder THS/1-1 :**Peeling-ballooning + KBM pedestal model range of predictions

† Base case: flat density, v_ϕ=0, electrostatic, n_e/n_{GW}=0.8

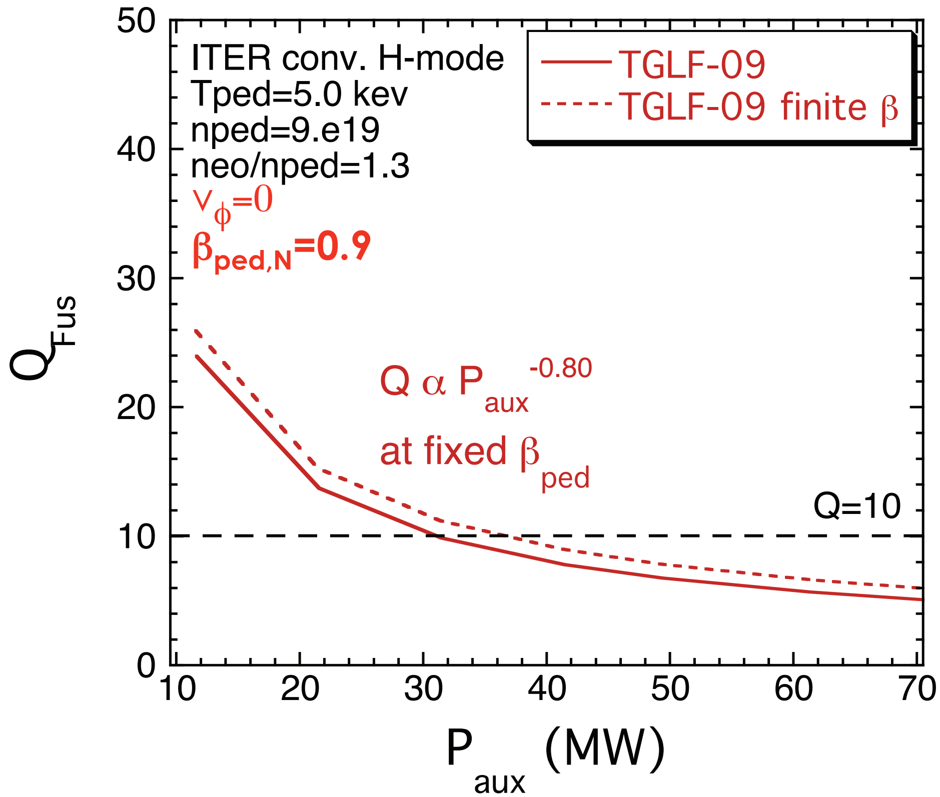
TGLF Fusion Projections Exhibit Stiff Transport Characteristics: *Fusion Gain Q is Sensitive to Auxiliary Heating Power*

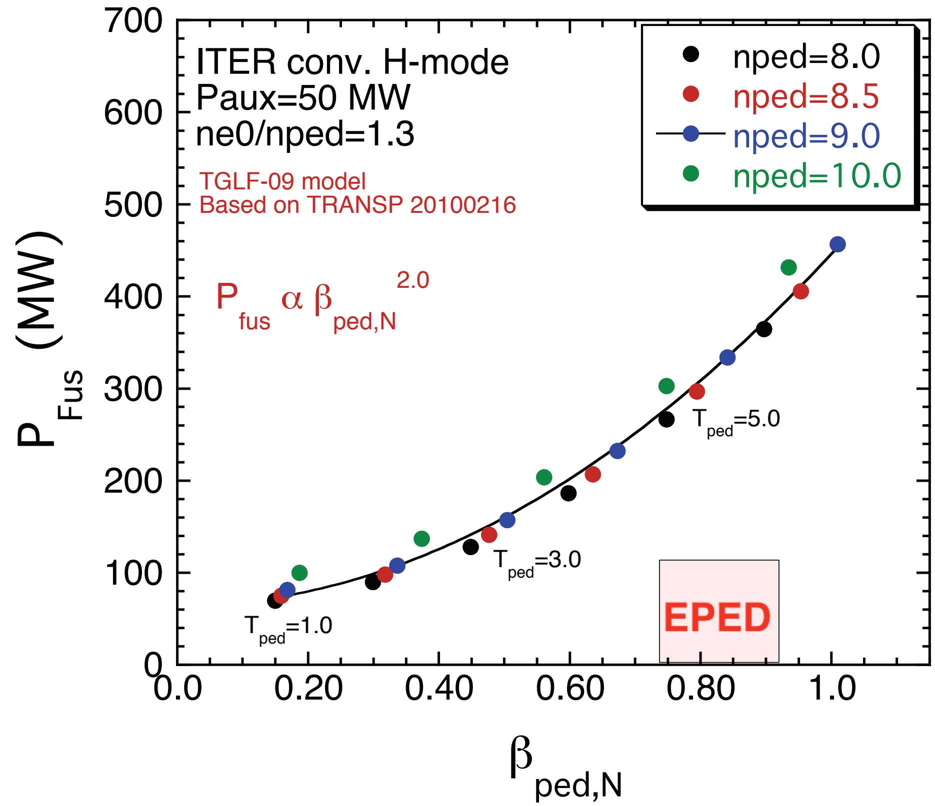
- **Fusion Q sensitive to auxiliary heating, scales like $P_{aux}^{-0.8}$ at fixed β_{ped}**
  - $Q=P_{fusion}/P_{aux}$ larger at low auxiliary power
  - Temperature profiles insensitive to P_{aux}



TGLF Fusion Projections Exhibit Stiff Transport Characteristics: *Pedestal Optimization Essential*

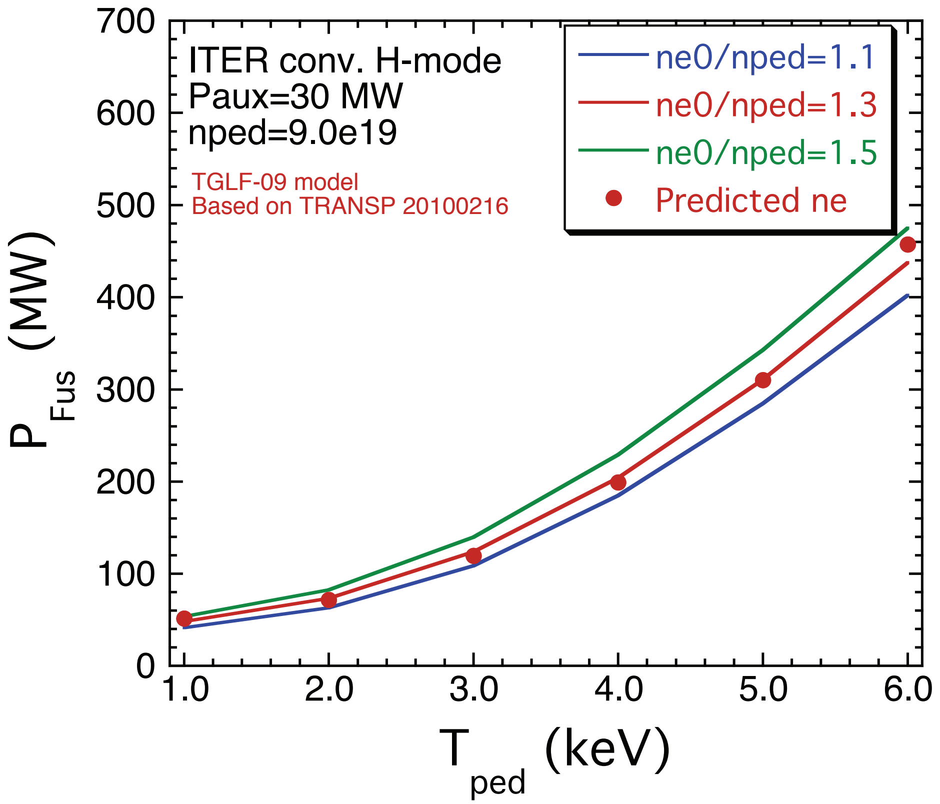
- **Fusion Q sensitive to auxiliary heating, scales like $P_{aux}^{-0.8}$ at fixed β_{ped}**
  - $Q=P_{fusion}/P_{aux}$ larger at low auxiliary power
  - Temperature profiles insensitive to P_{aux}
- **Fusion power scales like $\beta_{ped,N}^{2}$**





TGLF Predicts a Density Peaking Factor of n_{e0}/n_{ped}=1.3 for ITER

- **Density peaking has been observed in low collisionality JET, AUG, and C-Mod discharges**
  - Weisen (2005), Angioni (2007), and Greenwald (2007)
- **Predictions compared for ITER conventional ELMy H-mode case using TGLF**
  - T_e & T_i predicted using prescribed density profiles with various peaking factors (lines)
  - n_e, T_e, T_i predicted using TRANSP beam source (dots)
  - Z_{eff} held fixed for all cases
- **Density peaking of n_{e0}/n_{ped}=1.3 increases fusion power by 5% above simplified base case with a flat density profile**



Lines = cases with prescribed ne profiles
Dots = TGLF predicted density profiles

Base case: v_ϕ=0, electrostatic, n_e/n_{GW}=0.8

Synergistic Effects of Density Peaking, Finite β, and ExB Shear due to Low Toroidal Rotation can Significantly Increase Fusion Power

- Studied 3 effects using a ITER conventional H-mode case with a fusion Q near 10: P_{aux}=30 MW, $\beta_{ped,N}$=0.90*
- Each effect has only a 5% increase in the predicted fusion power

Scenario variation	P_{fus} (MW)	
Base case with prescribed n_e ($n_{e0}/n_{ped} = 1.1$)	285	(reduced physics)
Predicted density with $n_{e0}/n_{ped} = 1.3$	310	
Finite β with prescribed n_e ($n_{e0}/n_{ped} = 1.1$)	311	

- Synergistic effect of 3 ingredients yields a 59% increase in the fusion power

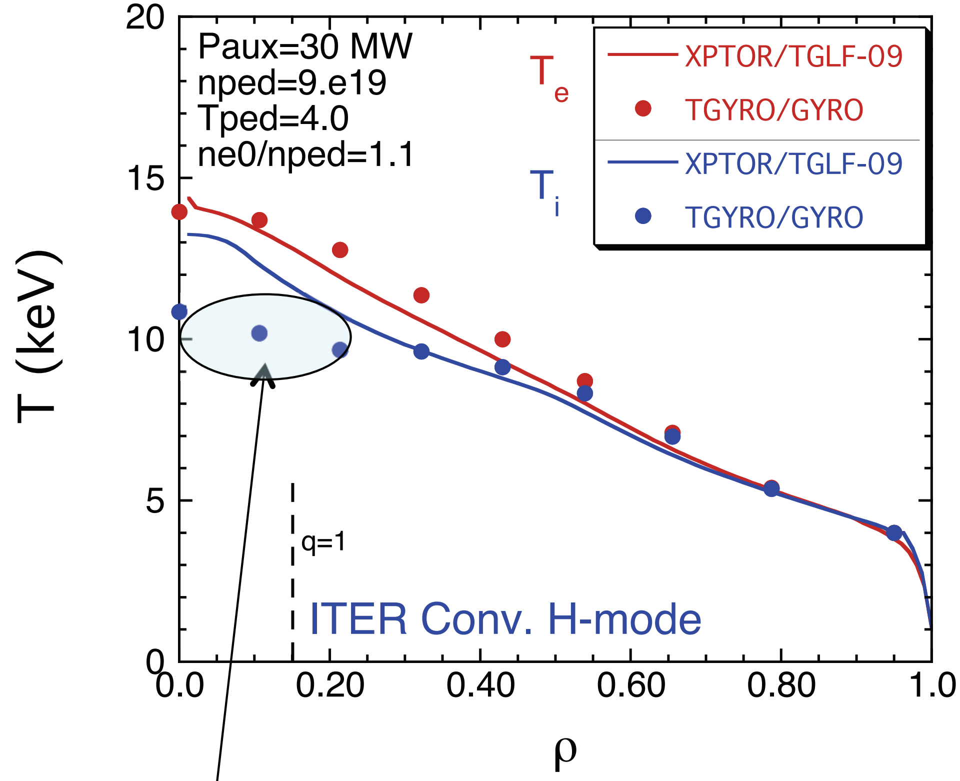
Scenario variation	P_{fus} (MW)	
Predicted $n_{e0}/n_{ped} = 1.3$, Finite β	373	
Predicted $n_{e0}/n_{ped} = 1.3$, Finite β, $v_{\phi,0} = 0.5 \times 10^5$ (m/s)	452+	(Q=15)

+ P_{fus}=350 MW (Q=12) at $\beta_{ped,N}$=0.74 (unoptimized EPED limit)

* EPED model predicts a max $\beta_{ped,N}$ = 0.74-0.92 depending on n_{ped}, global β

Nonlinear GYRO Transport Predictions Confirm TGLF Results for ITER

- **GYRO was used for the energy transport within the TGYRO code***
  - ITER conventional H-mode simplified base case with $\beta_{ped,N}$=0.9, v_ϕ=0
  - 8 radial zones, 8 toroidal modes with k_y <= 0.70, $[L_x,L_y]$=[64,64]
  - Electrostatic, low-k modes only (no ETG)
  - Convergence of the TGYRO/GYRO results difficult since the profiles reside near threshold, zonal flows are bursty
  - 6 hrs using 4608 cores on Jaguar at ORNL



TGYRO predictions are unreliable-transport is bursty, convergence is difficult

* Candy, et al., Phys. Plasmas **16**, 060704 (2009)

Outstanding Issues

- **Outstanding challenges for transport models remain**
  - Need experimental validation of core stiffness
  - More V&V needed for ITER relevant plasma conditions (e.g. low v_ϕ, low nustar)
  - Momentum transport needs validation (recently implemented in TGLF)
  - Electromagnetic effects need studying (TGLF,GYRO)
  - Verification & Validation is ongoing work !
- **Aspects of ITER modeling that need future study**
  - Does treating D and T ion species separately change the transport ?
  - Are helium ash effects important ?
  - Equilibrium and sources not consistent with predicted profiles
- **ITER results appear to be sensitive to various mechanisms near threshold**
  - Need to understand synergistic effects
- **Core/pedestal ITER predictions have not been optimized together**
  - Further iterations between core & pedestal interaction needed

Summary

- **Quasilinear saturation rule in TGLF shows remarkable agreement with large GYRO transport database of 191 simulations with Miller geometry**

- **TGLF has good agreement with temperature profiles for a database of 133 discharges from DIII-D, JET, and TFTR, avg RMS error for $[T_i,T_e]$ = [14%,15%]**

- **TGLF is less optimistic than previously obtained s-α results for ITER due to finite aspect ratio effects**

- **TGLF fusion projections exhibit stiff core transport characteristics**
  - Fusion Q scales like $P_{aux}^{-0.8}$ at fixed β_{ped}
  - Fusion power scales like β_{ped}^{2} **-> pedestal optimization essential**

- **Synergistic effects of density peaking, finite β, and ExB shear driven by small toroidal rotation are significant, P_{fusion} increases by 60%**
  - **Can achieve P_{fus}= 450 MW (Q=15) at $\beta_{ped,N}$=0.90 (near maximum pedestal β)**

- **TGLF ITER results have been confirmed using nonlinear GYRO transport runs**

Extra slides

Future Work

- **Near term future work**
  - Explore observed synergistic effects in ITER simulations in more detail
  - Test momentum transport (recently implemented)
  - Study finite beta effects in TGLF including magnetic flutter transport and compare to GYRO nonlinear simulations
  - Perform GYRO ETG simulations with shaped geometry, compare to TGLF
  - Include small effect of turbulent exchange
  - Examine possible data issues: MHD activity, time derivative terms, fast ion losses, beam deposition, dilution
- **Longer term future work**
  - Replace ExB shear rule with rotational ballooning mode net linear growth rate model; χ vs γ_E curve changes shape with aspect ratio
  - Study near edge turbulence and extend modeling toward edge
  - Add nonlocal transport effects, broken gyro-Bohm scaling
  - Test impurity dynamics

TGLF Saturation Rule was Fit to GYRO Nonlinear ITG/TEM Simulations Using Miller Geometry

- **Transport fluxes are computed using the 2 most unstable modes at each k_y & a saturation rule with the magnitude of the total eigenvector**

$$\Gamma = \sum_{k_y} nc_s \left[\frac{\mathrm{Re}\left\langle i\hat{k}_y \tilde{\Phi}^* \tilde{n} \right\rangle}{\tilde{V}^* \tilde{V}} \right] \overline{V}^2 \qquad Q = \frac{3}{2} \sum_{k_y} pc_s \left[\frac{\mathrm{Re}\left\langle i\hat{k}_y \tilde{\Phi}^* \tilde{p}_T \right\rangle}{\tilde{V}^* \tilde{V}} \right] \overline{V}^2$$

[ ] = quasilinear weight

$$\overline{V}^2 = C_{norm} \left(\frac{\rho_s \hat{\omega}_{d0}}{a} \right)^2 \left(1 + \frac{T_e}{T_i} \right)^2 \left(\frac{1}{\hat{k}_y^{c_k}} \right) \left[\frac{\hat{\gamma}_{net}^{c_1} + c_2 \hat{\gamma}_{net}}{\hat{k}_y^4} \right]$$

Model for saturated intensity

$$C_{norm} = 32.5 \qquad c_1 = 1.55 \qquad c_2 = 0.534 \qquad \alpha_E = 0.3\sqrt{\kappa} \qquad 0.1 \le \hat{k}_y \le 24$$ (21 modes)

$$\tilde{\mathrm{V}} = \left(\tilde{\mathrm{n}}, \tilde{\mathrm{u}}_{||}, \tilde{\mathrm{p}}_{||}, \tilde{\mathrm{p}}_{\mathrm{T}}, \tilde{\mathrm{q}}_{||}, \tilde{\mathrm{q}}_{\mathrm{T}} \right) \qquad \hat{\gamma}_{net} = Max\left[\left(\hat{\gamma} - \alpha_E \hat{\gamma}_E \right) / \hat{\omega}_{d0}, 0 \right] \qquad \hat{\omega}_{d0} = \hat{k}_y \frac{a}{R}$$

- **Coefficients & exponents in the saturation rule were found by minimizing the error between TGLF & GYRO energy fluxes for 83 nonlinear GYRO ITG/TEM simulations**

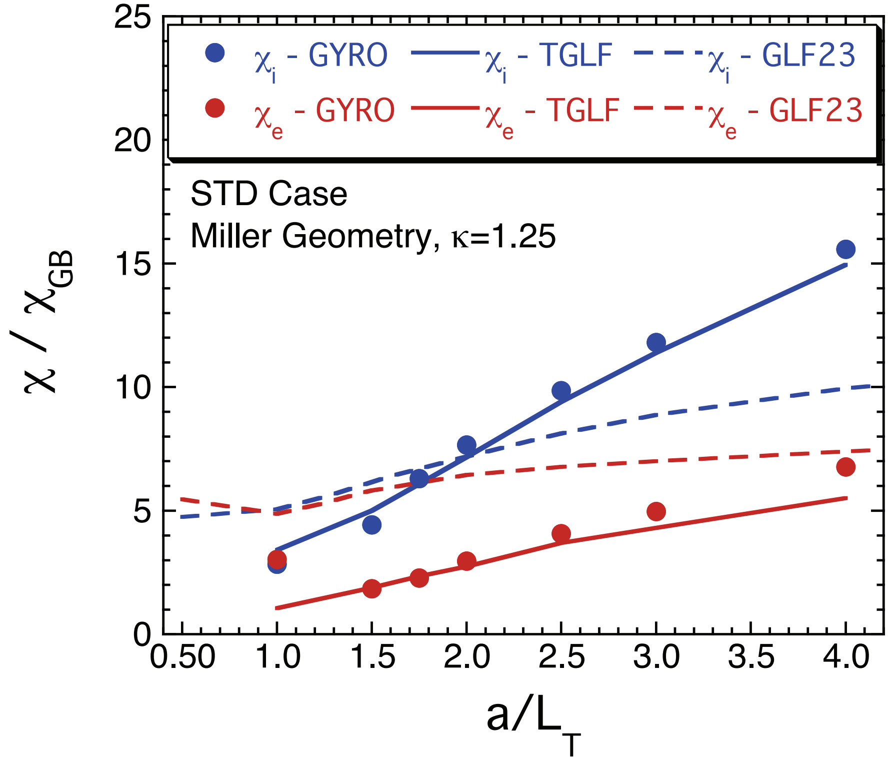
$$c_k = 0.0 \quad for \quad \hat{k}_y < 1$$

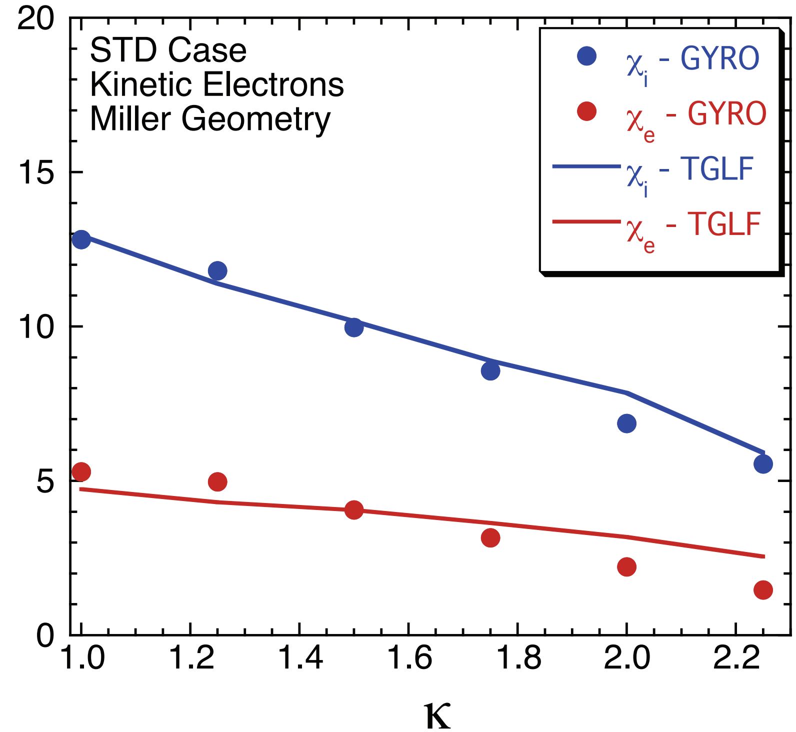
- **The high-k ($\hat{k}_y > 1$) part of the electron energy flux is adjusted to fit one GYRO coupled ITG/TEM-ETG simulation of the GA STD case with Miller geometry by modifying the $\hat{k}_y$ exponent**

$$c_k = 1.25 \quad for \quad \hat{k}_y \ge 1$$

TGLF Demonstrates Better Agreement with GYRO Nonlinear Simulations than GLF23

- **TGLF matches GYRO a/LT scan around GA-STD case with Miller geometry**
  - STD case: $R/a=3$, $r/a=0.5$, $q=2$, $s=1$, $a/L_T=3$, $a/L_n=1$, $\kappa=1.0$, $\delta=0$, $\beta=0$, $\nu_{ei}=0$
- **GLF23 low-k electron energy transport is systematically too large (red dashed line) and misses the critical temperature gradient**
- **TGLF reproduces stabilizing effect of elongation seen in GYRO simulations**

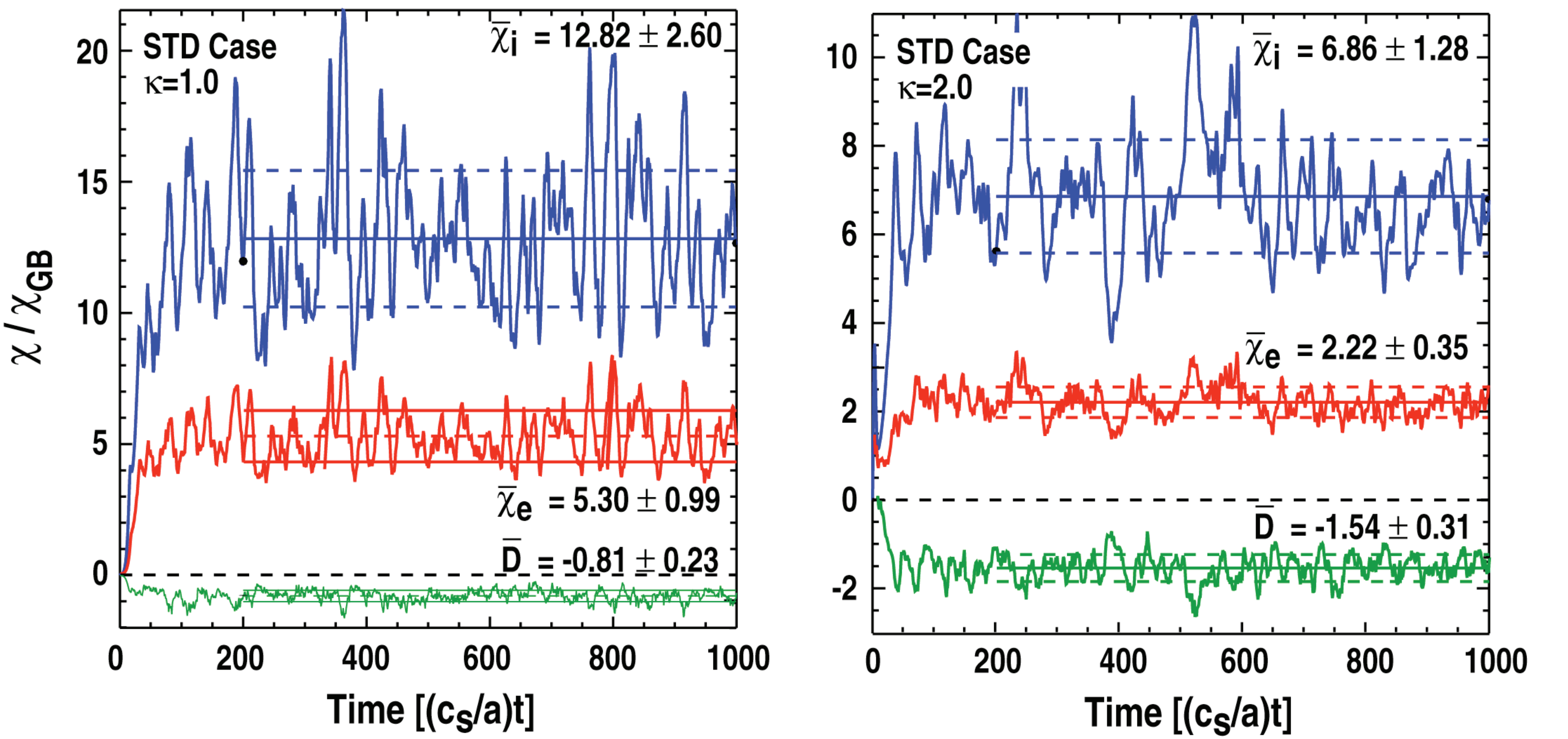




GENERAL ATOMICS

GYRO Simulations Show Elongation Stabilizes Transport

- **Local elongation and κ-shear varied around GA STD case**
  - Miller geometry with kinetic electrons, collisionless, electrostatic



Linear ExB Shear Quench Rule in TGLF and Shows Good Agreement with GYRO Simulations Including Elongation

- **TGLF compared to GYRO ExB shear scans for STD case with Miller geometry, different values of κ, δ=0, low-k only, kinetic electrons***
- **ExB shear rate with multiplier α_E is subtracted from maximum growth rate at each $k_\theta \rho_s$**

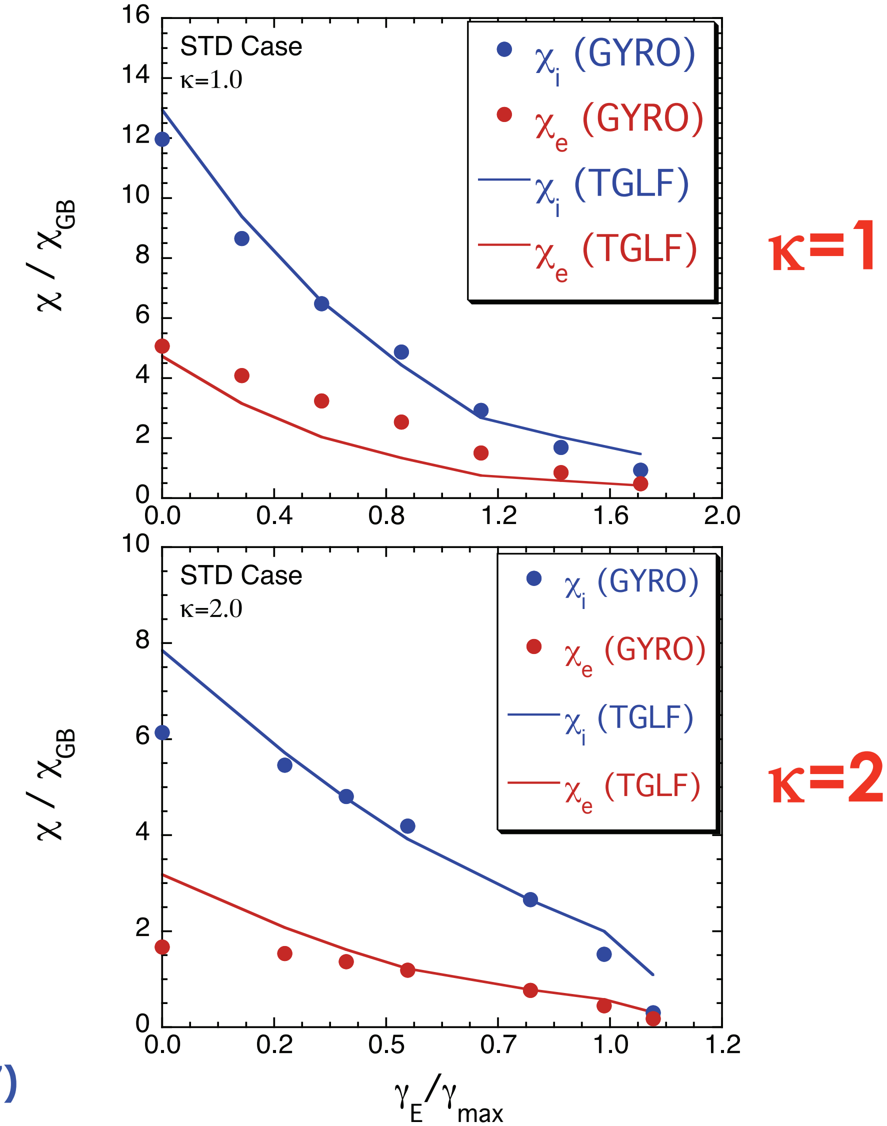
$$\hat{\gamma}_{net} = Max\left[\left(\hat{\gamma} - \alpha_E \hat{\gamma}_E\right)/\hat{\omega}_{d0}, 0\right]$$

Here,

$$\alpha_E = 0.3\sqrt{\kappa}$$

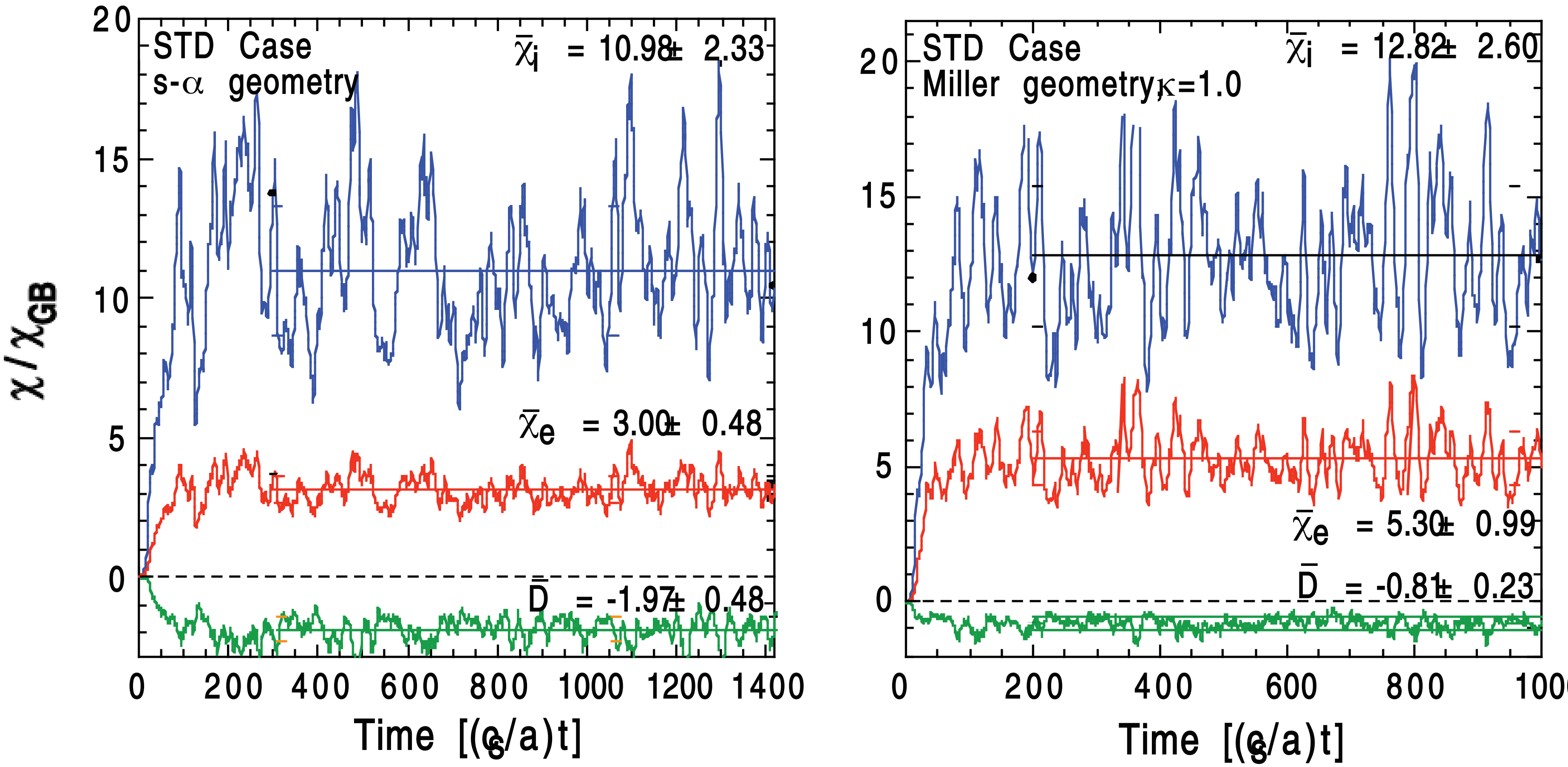
gives a good fit to GYRO ExB shear simulations with Miller geometry

See Kinsey, et al., Phys. Plasmas 14, 102306 (2007)



GYRO Simulations Show Electron Transport Increases Significantly Going from s-α Geometry to Miller Geometry with κ=1

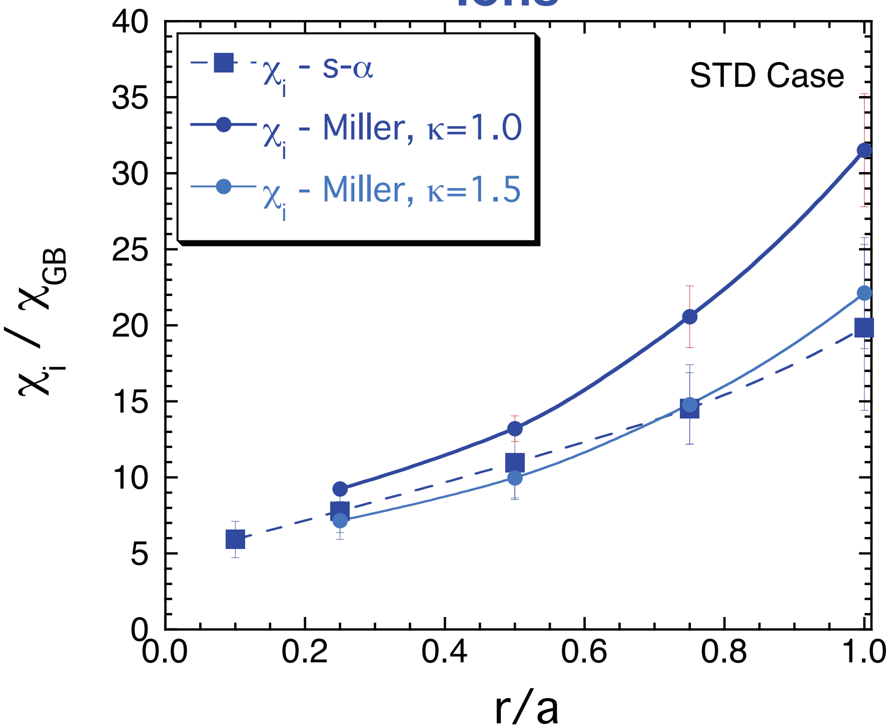
- **Geometry varied for GA STD case with kinetic electrons, collisionless**
  - STD case: $R/a=3$, $r/a=0.5$, $q=2$, $s=1$, $a/L_T=3$, $a/L_n=1$, $\kappa=1.0$, $\delta=0$, $\beta=0$, $\nu_{ei}=0$
  - s-α model is infinite aspect ratio, circular geometry



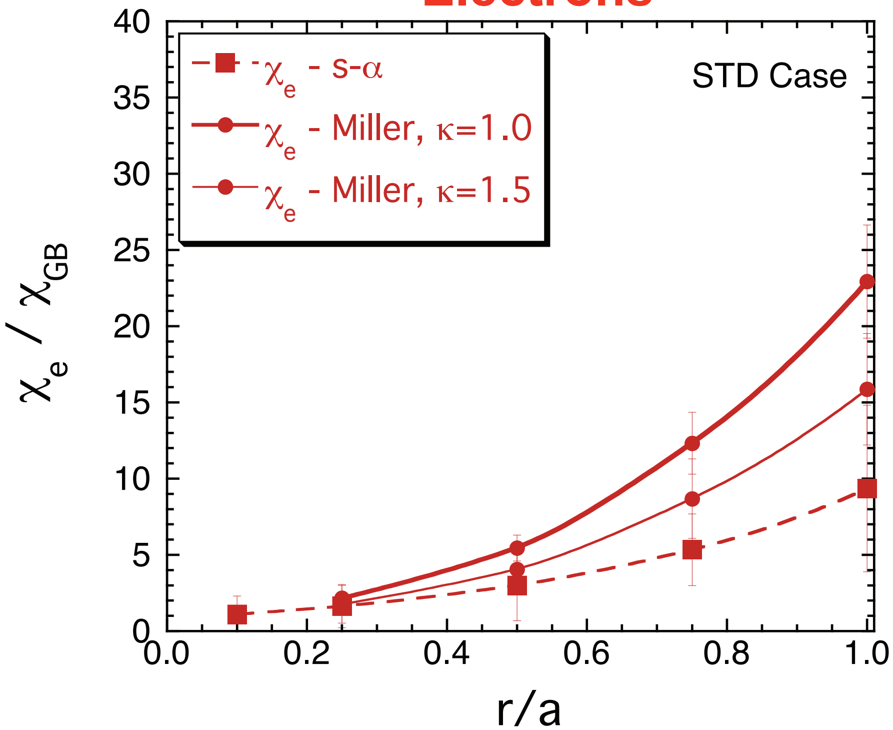
GYRO Shows that Transport is Significantly Higher Going from s-α Geometry to Miller Geometry for the GA STD Case

- **GYRO simulations varying r/a for STD case show larger χ's with Miller finite aspect ratio geometry compared to infinite aspect ratio s-α geometry**
  - Elongation shear (and elongation) stabilization compensates for this in DIII-D
  - GYRO κ=1.5 results for χ_i close to s-α result, χ_e still higher than s-α
  - Assumed $s_\kappa=(\kappa-1)/\kappa$ for elongation shear

Ions

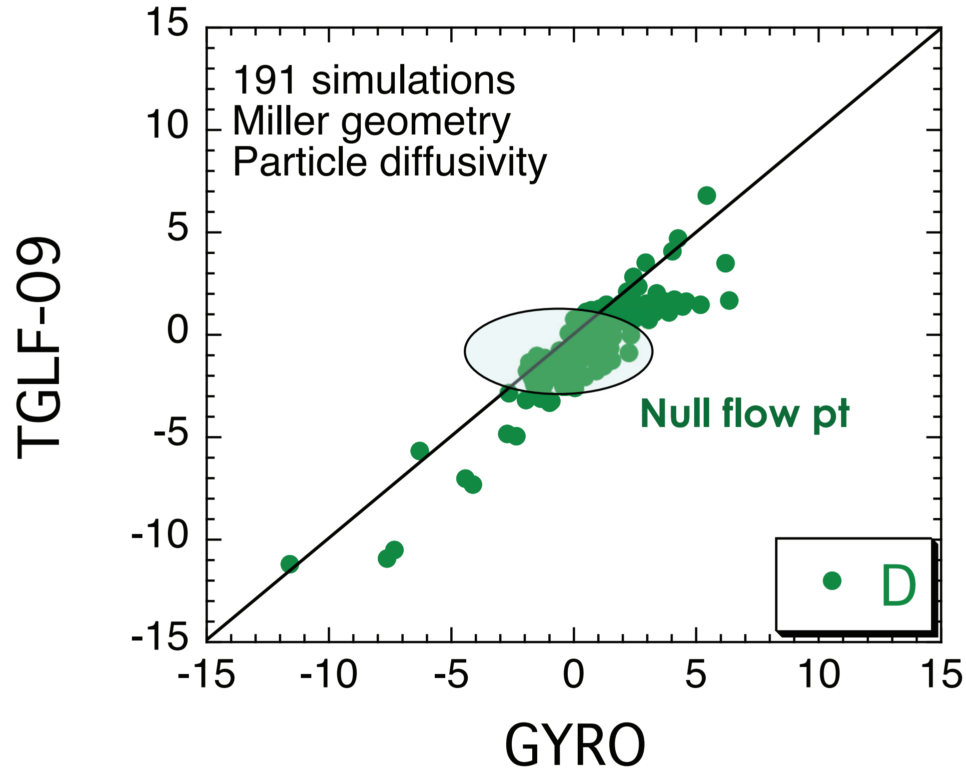


Electrons



TGLF Fit to191 Nonlinear GYRO ITG/TEM Particle Diffusivities More Challenging than Energy Diffusivities

- **Most of the GYRO simulations were close to a null flow point**
  - Some modes driving an inward flow, some an outward flow
  - A challenge for quasi-linear models
- **RMS error in D = 78% compared to [13%, 16%] for TGLF-09 [ion, electron] energy diffusivities**

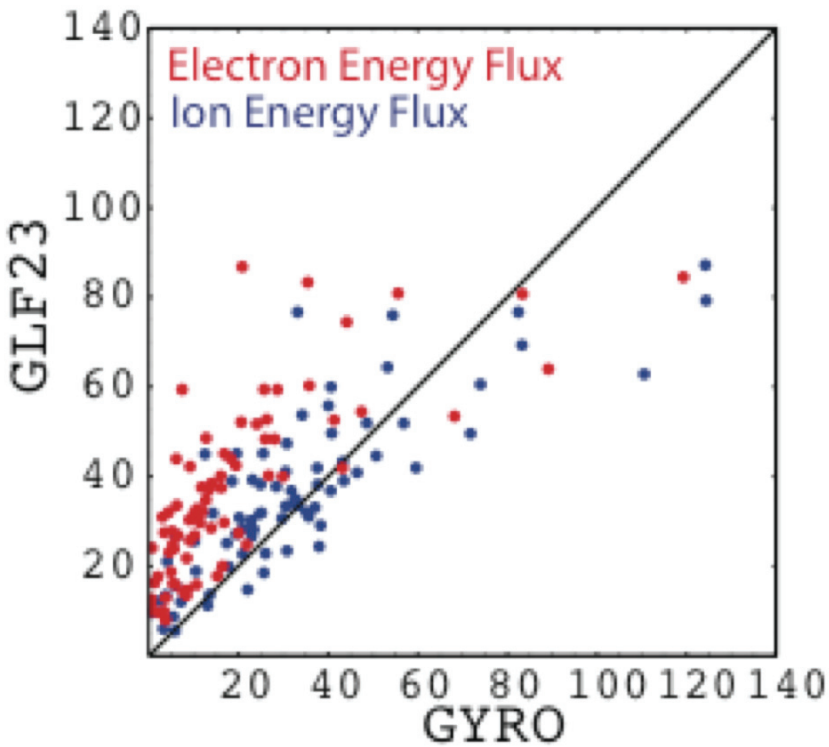


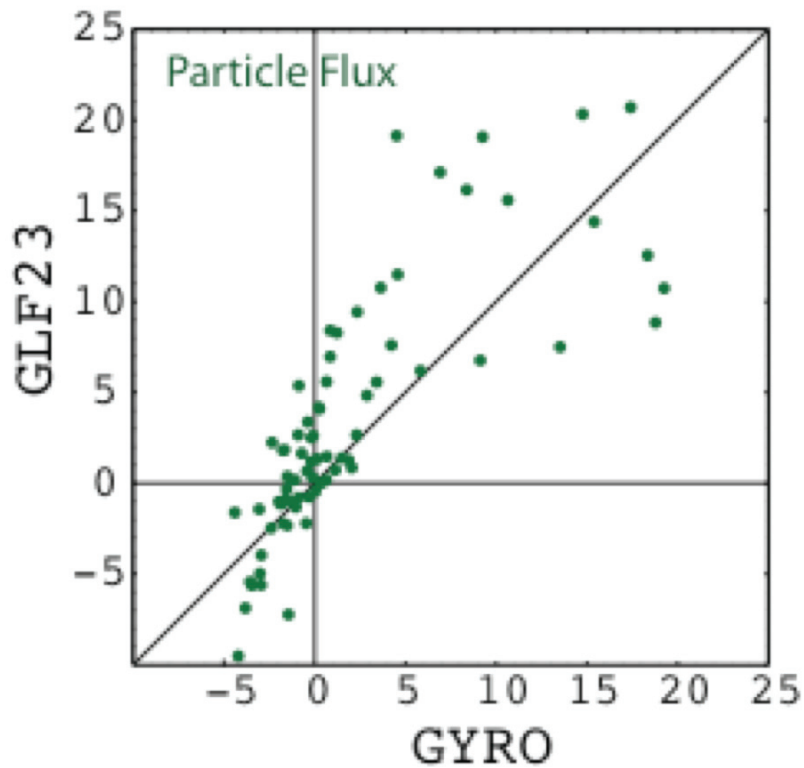
GLF23 Fluxes are a Poor Fit to GYRO Nonlinear Shifted Circle Simulations

- **RMS errors between GLF23 and GYRO for the 86 shifted circle cases are**

$$\sigma_{Q_i} = 42\%,\ \sigma_{Q_e} = 78\%,\ \sigma_{\Gamma} = 78\%,$$

- **GLF23 is systematically high, especially for the electron energy flux**





Simulation Methodology

- **TGLF is run in the XPTOR parallel transport code**
- **Data taken from TRANSP or ONETWO analyses**
- **Predict core T_e and T_i profiles for a single time-slice taking densities, toroidal rotation profiles, equilibrium, sources, sinks from experimental analyses**
- **In cases where density is evolved, we dynamically adjust the wall source while attempting to match the experimental line average density**
- **Boundary conditions enforced at ρ=0.84 for H-modes**
- **Chang-Hinton neoclassical, neoclassical poloidal rotation for ExB shear**
- **TGLF is computationally more demanding than GLF23**
  - Solves a 120x120 matrix per grid pt for the eigenvalues instead of an 8x8 matrix (GLF23)

    CPU time ≈ 10 mins for 40 grid pts, 40 processors

Figures of Merit

- **Quantitative agreement measured by global and local figures of merit**

Avg. and RMS in incremental stored energy W_{inc} for i^{th} discharge

$$\langle R_W \rangle = 1/N \sum_i W_{s,i} / W_{x,i} \qquad \Delta R_W = \sqrt{1/N \sum_i \left(W_{s,i} / W_{x,i} - 1 \right)^2}$$

RMS and offset for temperature T profile at each j^{th} radial pt for i^{th} discharge

$$\sigma_{T,i} = \sqrt{\sum_j \varepsilon_j^2} \Big/ \sqrt{\sum_j T_{x,i}^2} \qquad f_{T,i} = \frac{1}{N} \sum_j \varepsilon_j \Big/ \sqrt{\frac{1}{N} \sum_j T_{x,j}^2}$$

$$\varepsilon_j = T_{x,j} - T_{s,j}$$

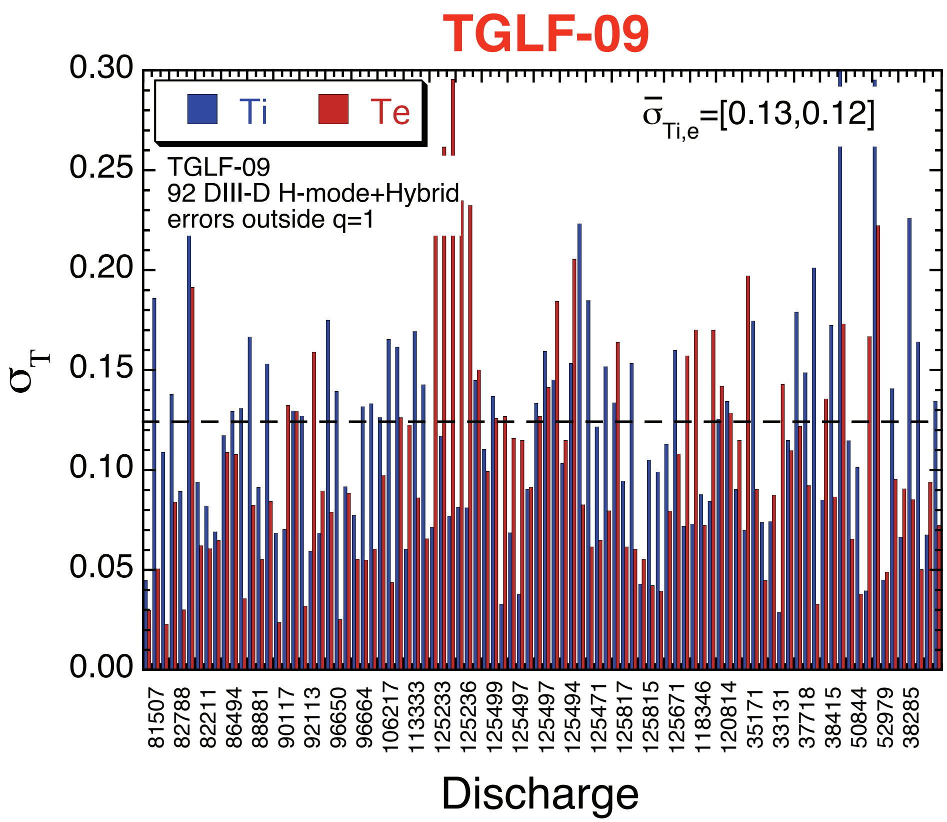
Deviation between Exp. Temp (T_x) and Simulation (T_s)

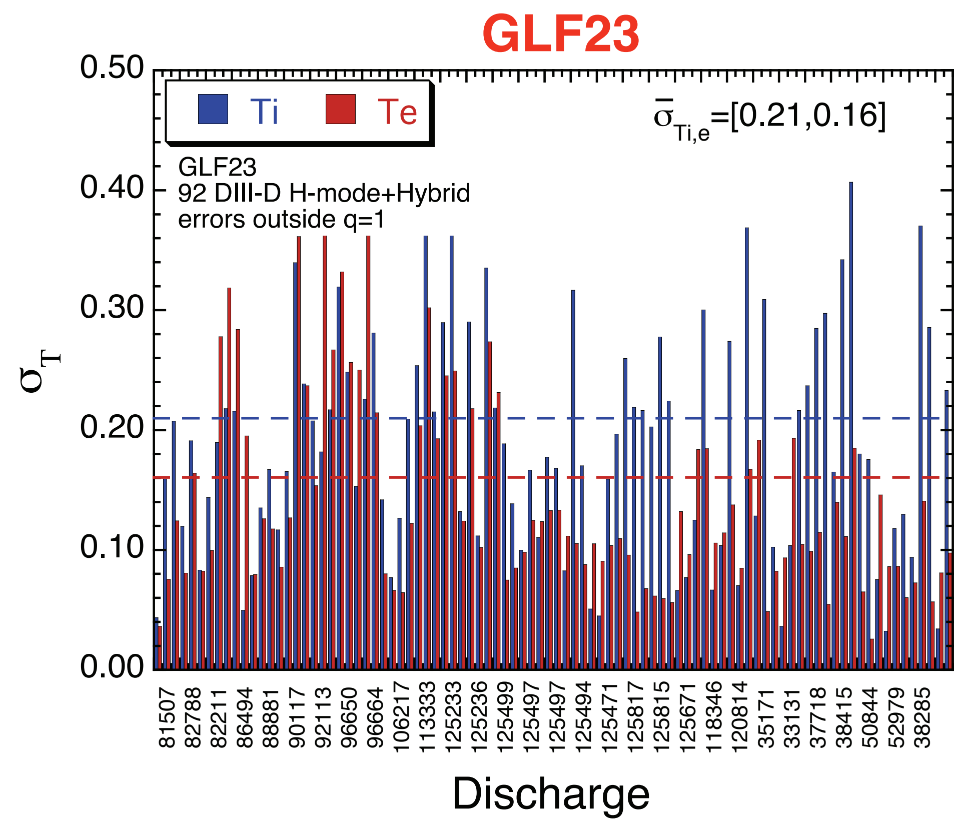
Avg RMS and offset for each dataset

$$\bar{\sigma}_T = \sqrt{\frac{1}{N} \sum_i \sigma_{T,i}^2} \qquad \bar{f}_T = \frac{1}{N} \sum_i f_{T,i}$$

TGLF-09 Model Shows Improved Agreement with Ion and Electron Temperature Profiles Compared to GLF23 Model

- **RMS errors and offsets averaged over 92 DIII-D and JET H-mode & hybrid discharges**
  - $[\sigma_{Ti}, \sigma_{Te}]$= [0.13, 0.12] for TGLF-09, [0.21, 0.16] for GLF23
  - $[f_{Ti}, f_{Te}]$= [-0.012, -0.003] for TGLF-09, [+0.003, -0.083] for GLF23



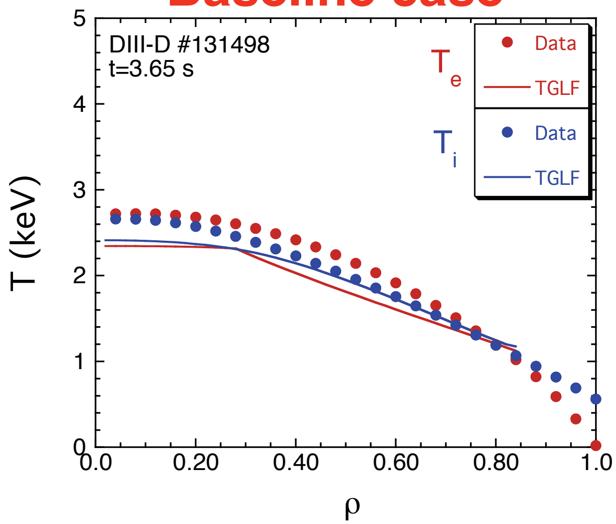


XPTOR code, ρ_{BC}=0.84, density profile fixed, self-consistent ExB shear

TGLF also Shows Good Agreement with Recent DIII-D ITER Demonstration Discharges

- **DIII-D has evaluated various leading ITER scenarios matching the ITER shape, aspect ratio, I/aB**
  - Baseline or conventional sawtoothing H-mode scenario
  - Advanced inductive scenario
  - Hybrid scenario
  - Steady-state scenario

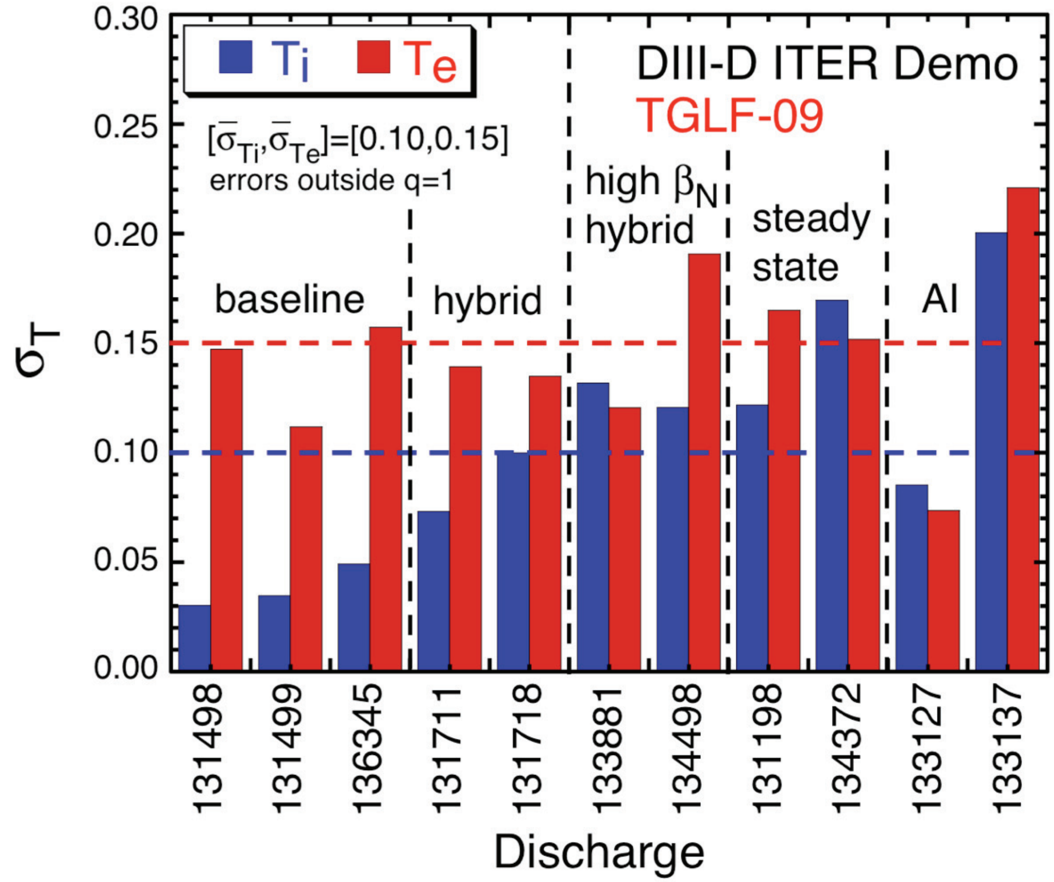
Baseline case



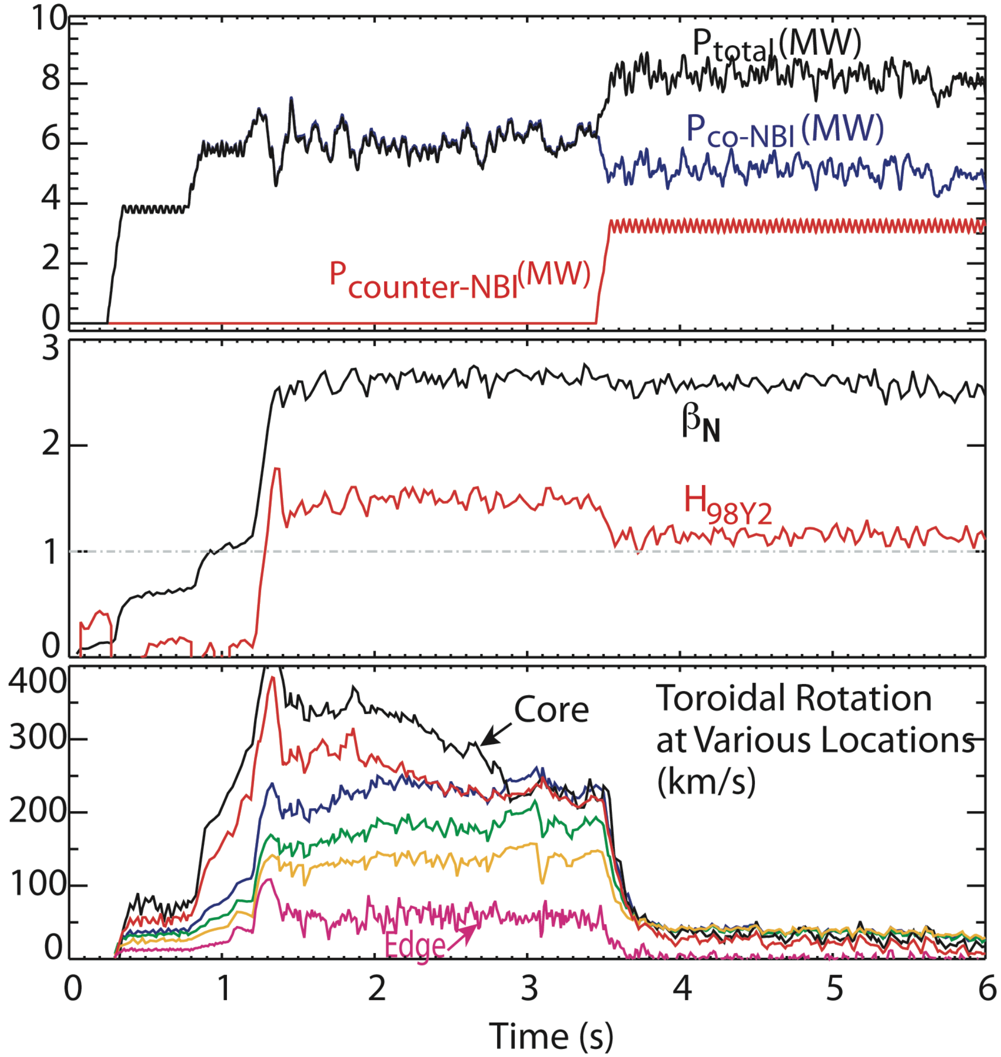
*** χ_i at neoclassical level**

- **RMS errors comparable to previous H-mode results**

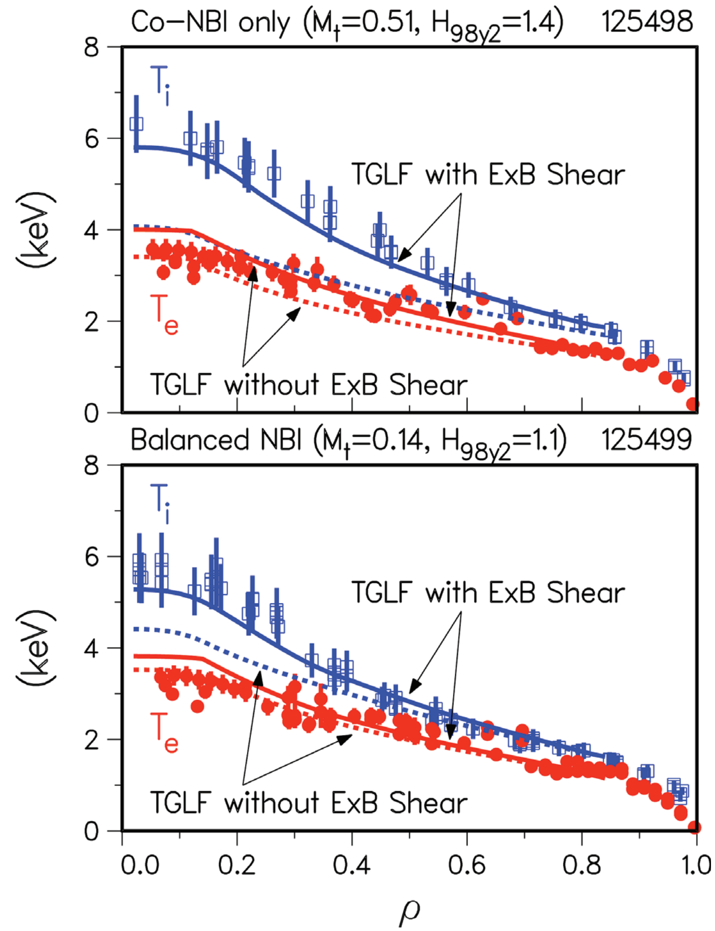
$\overline{\sigma}_{Ti}$=10% and σ_{Te}=15%



On DIII-D, Reduced Rotation Rate Leads to Increased Transport, but Hybrid Confinement Remains Good



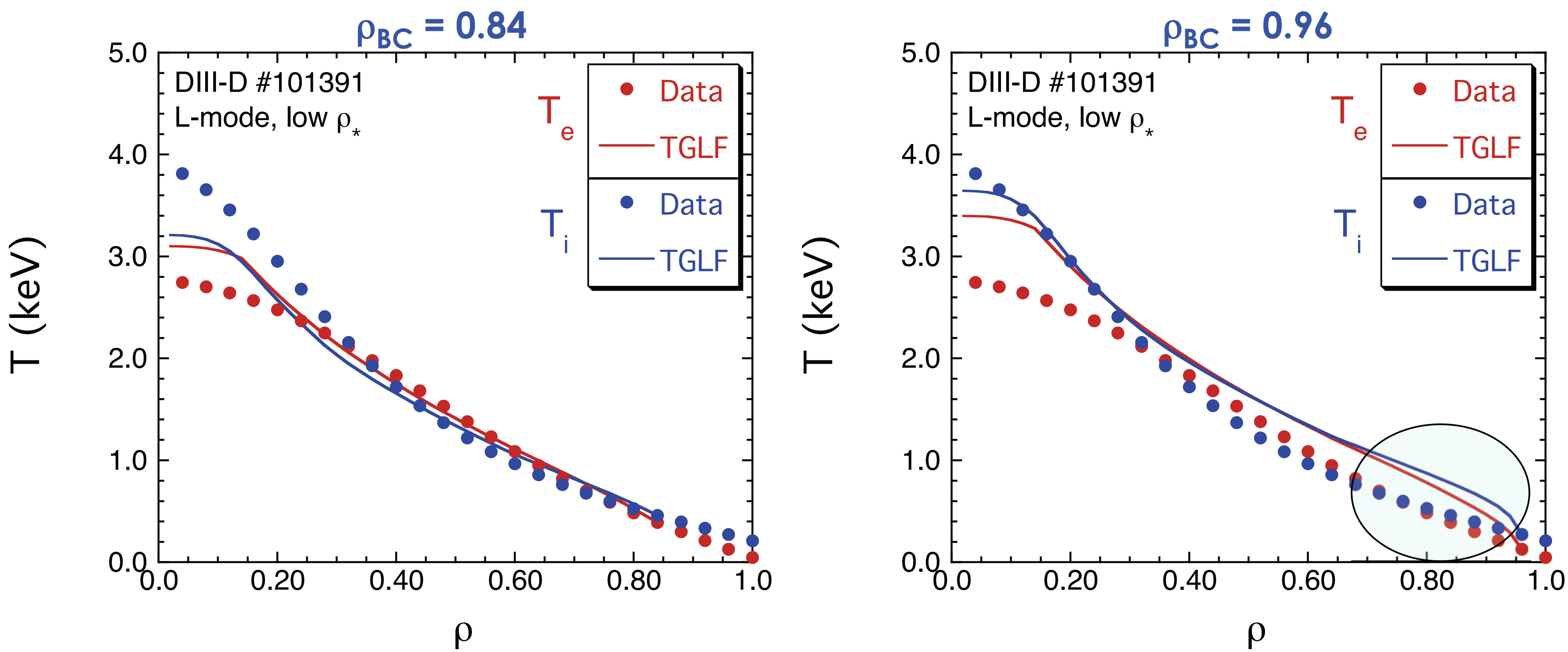
- Changes in ExB shear can explain the effect of torque on energy transport



GENERAL ATOMICS

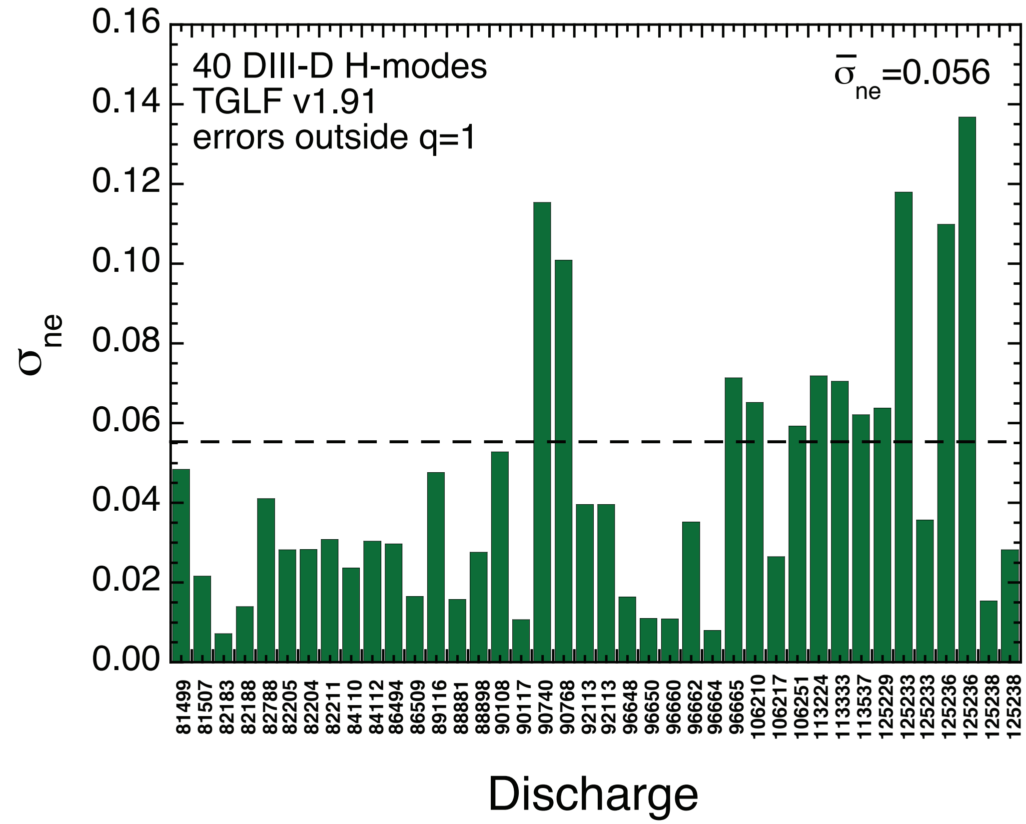
TGLF Typically Underestimates Energy Transport in Near Edge Simulations of DIII-D L-mode Discharges

- **Boundary conditions have been extended to ρ=0.96 with T_e, T_i predicted**
  - Nearly a dozen DIII-D L-mode discharges modeled
  - Predicting the density also for #101391 did not alter the temp. profile predictions
- **More TGLF and GYRO comparisons needed for L-mode edge conditions**



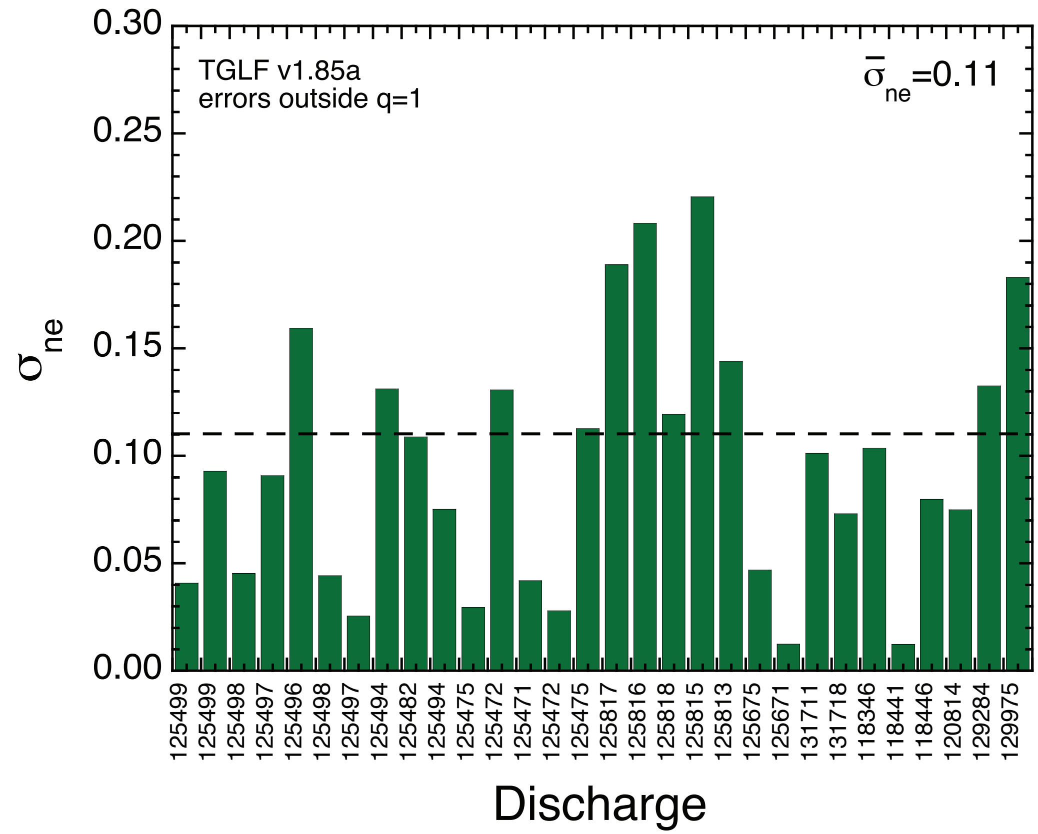
TGLF Show Good Agreement with DIII-D H-mode Density Profiles with Little Change in Predicted Temperature Profiles

- **Avg RMS error in electron density profiles is 5.6% for 40 DIII-D H-mode cases**
  - Largest errors for cases with χ_i close to neoclassical
  - Wall source varied in an effort to match experimental line average electron density
  - Beam source taken from exp. analysis
  - Impurity and fast ion density profiles also taken from exp. analysis
  - Very little change in RMS errors for temperature profiles observed



Sensitivity to Particle Transport: TGLF Show Good Agreement with Hybrid Density Profiles with Little Change in Predicted Temperature Profiles

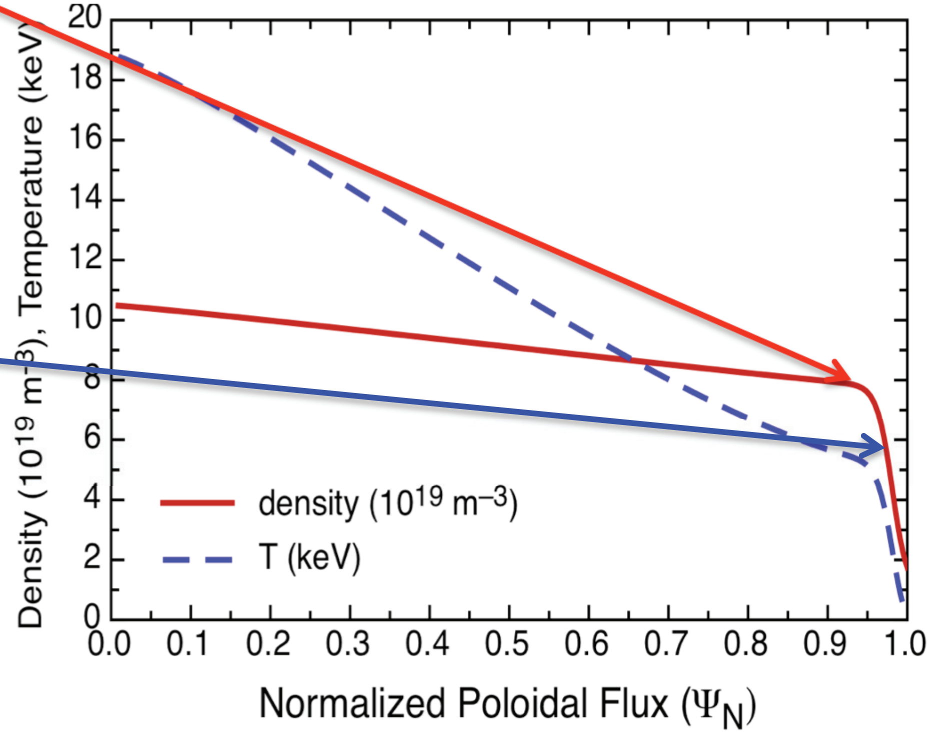
- **Avg RMS error in electron density profiles is 11% for 30 hybrid cases**
  - Largest errors for cases with χ_i close to neoclassical
  - Wall source varied in an effort to match experimental line average electron density
  - Beam source taken from exp. analysis
  - Impurity and fast ion density profiles also taken from exp. analysis
  - Very little change in RMS errors for temperature profiles observed



Pedestal Boundary Conditions for ITER

- XPTOR transport runs set the boundary conditions at the location were density flattens out, ρ=0.95
- For ITER baseline, the EPED1 model predicts a pedestal height of $\beta_{N,ped}$~0.6 and a width of Δ_ψ~0.04 (~4.4 cm)
  - This "pedestal" location is still in the steep ne gradient region
  - At "Top" location (ρ=0.95), the max $\beta_{N,ped}$ is in the range of 0.74-0.92

EPED1 ITER profiles

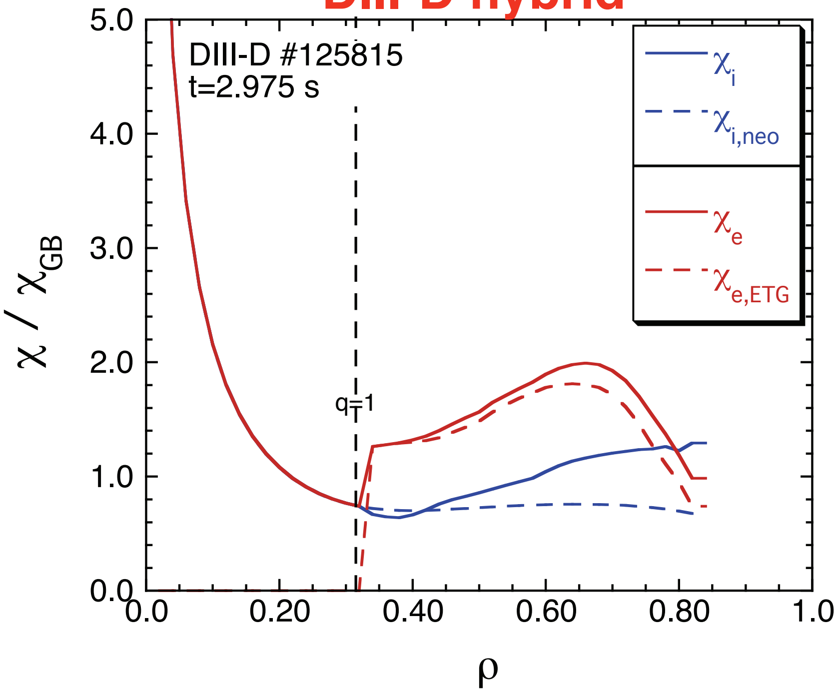


see Snyder THS/1-1

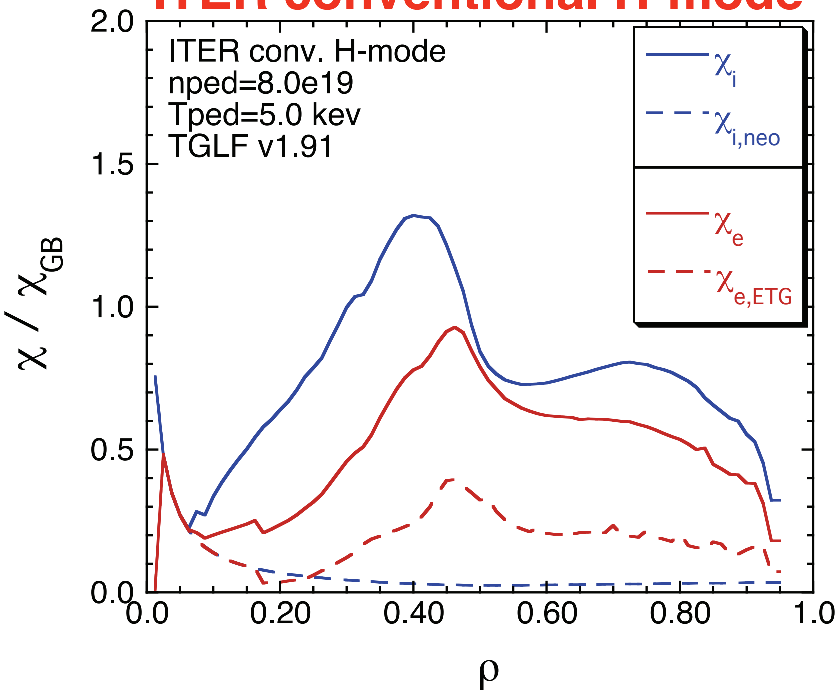
TGLF Shows that ITER Predictions are Insensitive to ETG Transport

- **TGLF predicts that ETG modes often dominate the electron energy transport in DIII-D hybrids**
  - ExB shear effects in DIII-D hybrids are much larger than in ITER conventional H-mode scenario with low toroidal rotation
- **ETG modes contribute 30% of electron transport**
  - But TGLF shows fusion predictions are insensitive ETG fraction ($\chi_{high\text{-}k} / \chi_{low\text{-}k}$)

DIII-D hybrid

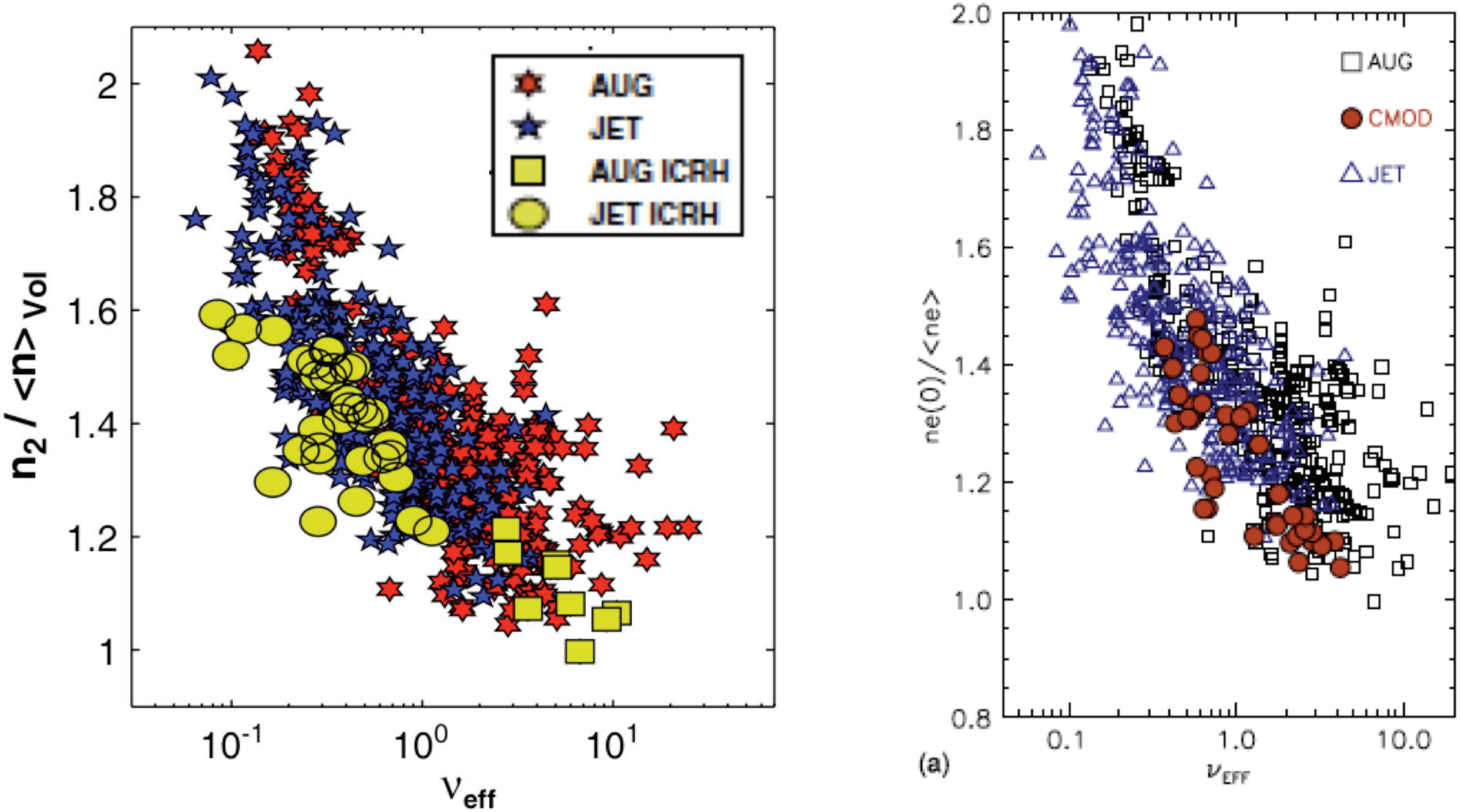


ITER conventional H-mode



Density Peaking has been Observed in Low Collisionality JET, AUG, and C-Mod H-mode Discharges with NBI and ICRH Heating

- **Nucl. Fusion papers by Greenwald et al. (2007), Angioni et al. (2007) and Weisen et al. (2005):**



GENERAL ATOMICS