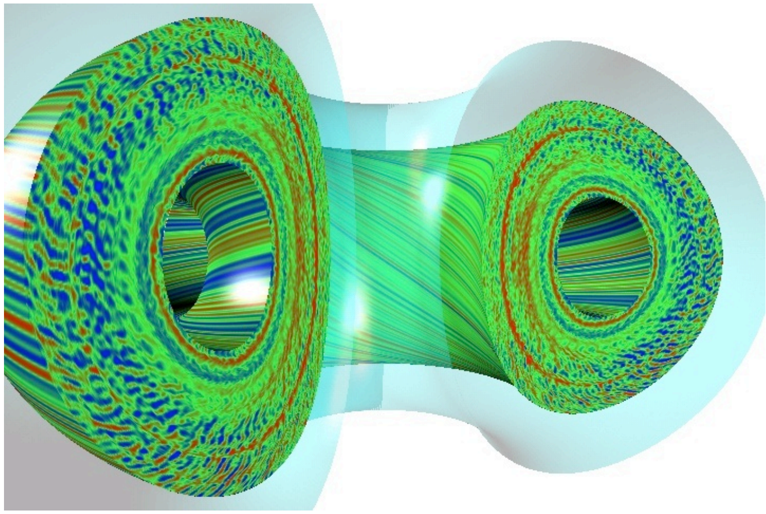
Testing the Trapped Gyro-Landau Fluid model with data from Tokamaks and Spherical Tori



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Summary of Results

- **Tokamaks:**
  - 96 L&H-mode time slices from DIII-D, JET and TFTR were used.
  - The predicted temperature and density profiles deviated from a curve fit through the data by only 15% for Ti, 16% for Te and 12% for Ne outside the q=1 surface (Kinsey APS07).
- **Spherical Tori:**
- **MAST:**
  - 8 L& H mode discharges from MAST were used.
  - The predicted temperature profile deviations outside the q=1 surface were 17% for Ti and 26% for Te.
  - 7 discharges had large sawtooth reqions with q=1 at r/a=0.4 to 0.5.
  - Ion neoclassical transport and high-k electron ETG transport were important. Electron-ion collisions were much higher than for the tokamaks, strongly reducing the trapped electron drive.
- **NSTX:**
  - 5 L&H mode discharges from NSTX were used.
  - All had q>1 everywhere but the driftwaves were linearly stable inside of r/a<0.4
  - Kinetic ballooning mode computed with TGLF were also stable.

What is The Trapped Gyro-Landau Fluid (TGLF) Model?

- **TGLF is a theory-based transport model with comprehensive gyro-kinetic physics.**

- **Comprehensive physics: shaped magnetic geometry, electron-ion collisions, fully electromagnetic, dynamic electrons, ions, and impurity ions**

- **Theory-based: model fit to first principles gyro-kinetic theory**

A More Accurate Transport Model With Comprehensive Physics Has Been Needed

- **The GLF23 transport model (Waltz, Staebler et.al.,1997) has been used successfully worldwide to predict core temperature profiles in tokamaks**

- **A new transport model has been developed using the same methodology as GLF23: the Trapped Gyro-Landau Fluid (TGLF) model**
  - TGLF has particularly improved the treatment of trapped particles compared to GLF23
  - TGLF includes the physics missing from GLF23
- **The TGLF linear stability code is being used for fast analysis of experiments**
  - Growth rates agree very well with gyro-kinetic linear stability codes
  - 100x faster for linear stability analysis of experimental discharges
- **The TGLF quasi-linear transport model is a better fit to non-linear gyro-kinetic turbulence simulations than GLF23**
  - 86 non-linear turbulence simulations over a wide range of parameters were used for the TGLF intensity model fit

Anatomy of a Quasi-Linear Transport Model

First Principles Theory

Non-Linear gyro-kinetic turbulence simulations
GYRO (Candy and Waltz)

Linear gyro-kinetic stability calculations
GKS (Kotschenreuther)

Model to compute approximate linear eigenmodes.
Trapped Gyro-Landau Fluid (TGLF)

Model for the saturated intensity of the turbulence constructed from the linear eigenmodes (growth rate, wavenumbers, etc)

Quasi-linear weight evaluated using linear eigenmodes

Dimensional factor

Particle flux:

$$\Gamma_e = \sum_{k_\theta} n_e \sqrt{\frac{T_e}{m_i}} \; \tilde{\Phi}^2_{Model} \; \frac{Re\langle i k_\theta \rho_s \tilde{\Phi}^* \tilde{n}_e \rangle}{\langle \tilde{\Phi}^* \tilde{\Phi} \rangle}$$

Similar models for electron and ion energy fluxes

TGLF is a Major Upgrade from GLF23

TGLF

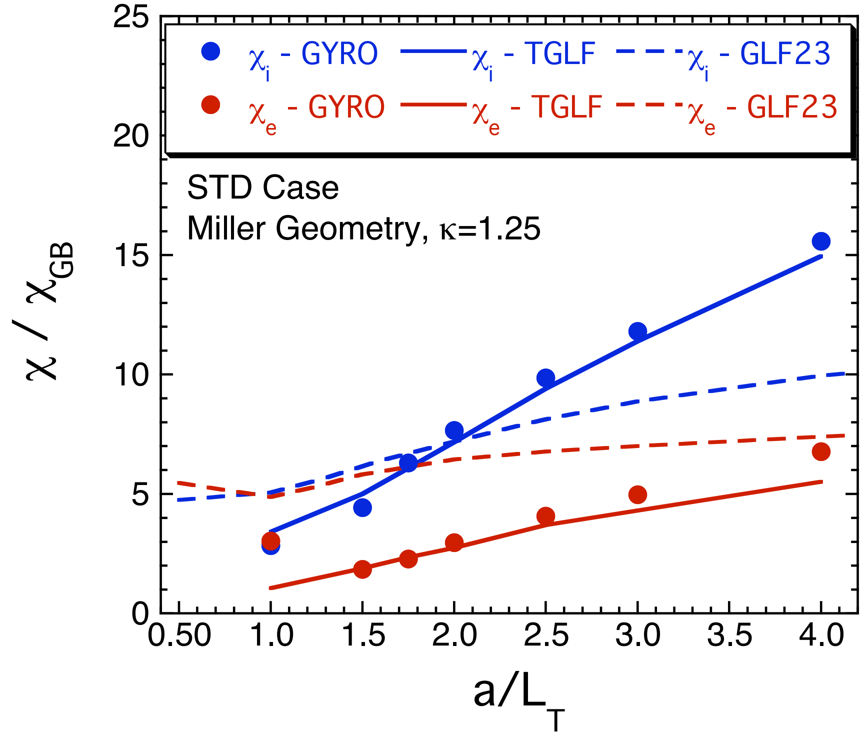
- TIM, ITG,TEM, ETG modes from a single set of equations
- Exact FLR integrals keep accuracy for high-k i.e. $k_\theta \rho_i > 1$
- Adaptive Hermite basis function solution method valid for the same range as the GK equations
- All trapped fractions
- Shaped geometry (Miller model)
- Fully electromagnetic $\left(\tilde{B}_\perp, \tilde{B}_\parallel\right)$
- New electron-ion collision model fit to pitch angle scattering
- Transport model fit to 86 GYRO runs with kinetic electrons
- 15 moment equations per species
- 10-30 times slower than GLF23

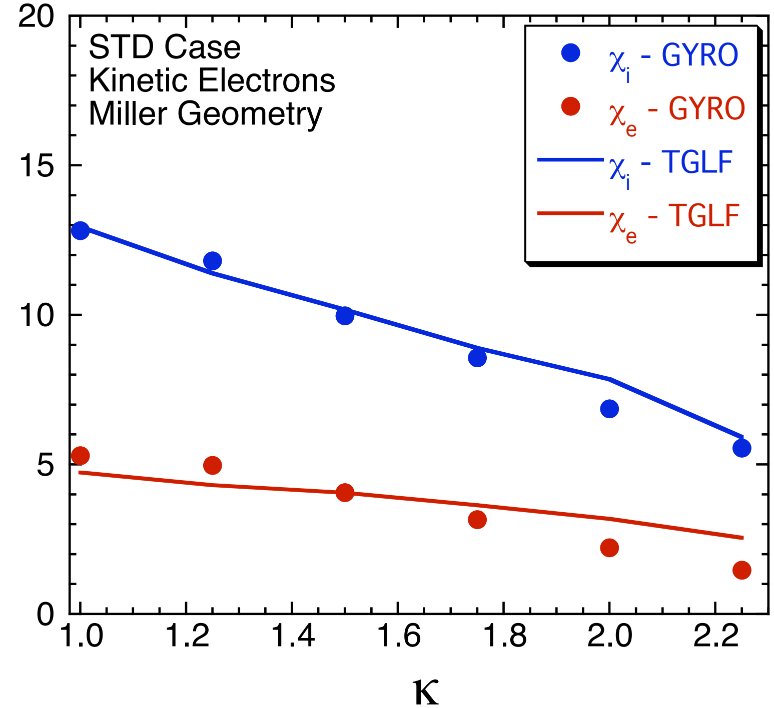
GLF23

- Different equations for low-k (ITG,TEM) and high-k (ETG)
- FLR integrals used Pade approximation valid for low-k
- Parameterized single Gaussian trial wavefunction valid for a limited range of conditions
- Small trapped fraction required.
- Shifted circle (s-alpha) geometry
- Normally run electrostatic
- Inaccurate electron-ion collision model only for low-k equations
- Transport model fit to a few GLF non-linear turbulence runs
- 4 moment equations per species
- Fast enough for 1997 computers!

TGLF demonstrates better agreement with GYRO nonlinear simulations than GLF23

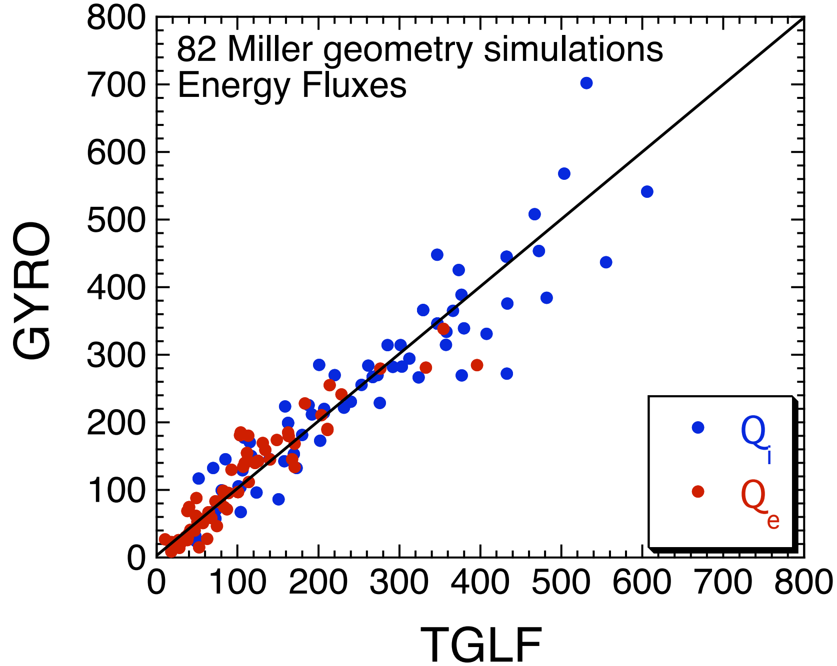
- **TGLF matches GYRO a/L_T scan around GA-STD case with Miller geometry**
  - STD case: $R/a=3$, $r/a=0.5$, $q=2$, $s=1$, $a/L_T=3$, $a/L_n=1$, $\kappa=1.0$, $\delta=0$, $\beta=0$, $\nu_{ei}=0$
- **GLF23 low-k electron energy transport is systematically too large (red dashed line) and misses critical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

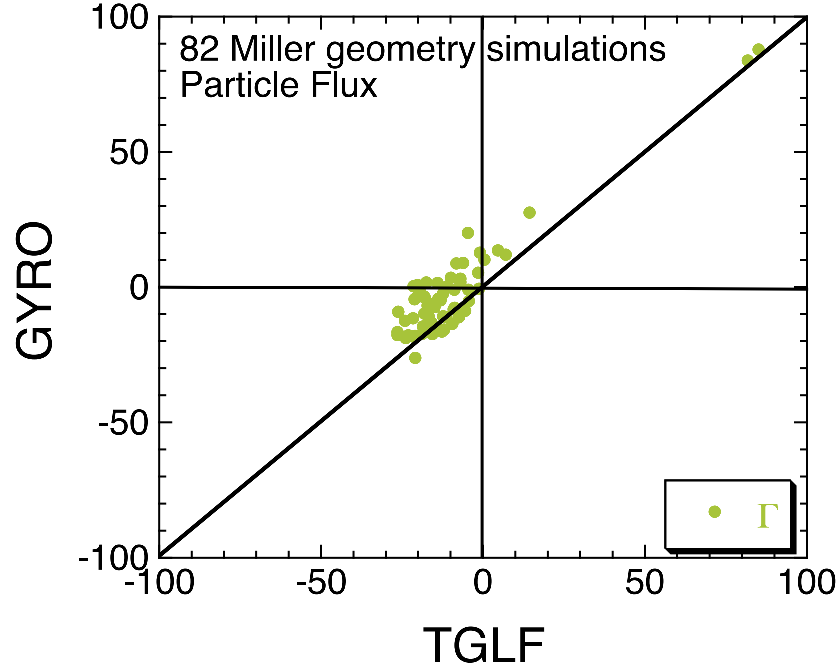




TGLF model fits the energy transport from 82 nonlinear GYRO Miller geometry simulations very well

- **GYRO scans w/ kinetic electrons, Miller shaped geometry, electrostatic, collisionless**
  - Also a version of TGLF fit to 84 shifted circle GYRO simulations
- **Use the 2 most unstable modes at each k_y**
- **Best fit has RMS errors of [17%, 20%] for [ion, electron] energy fluxes**

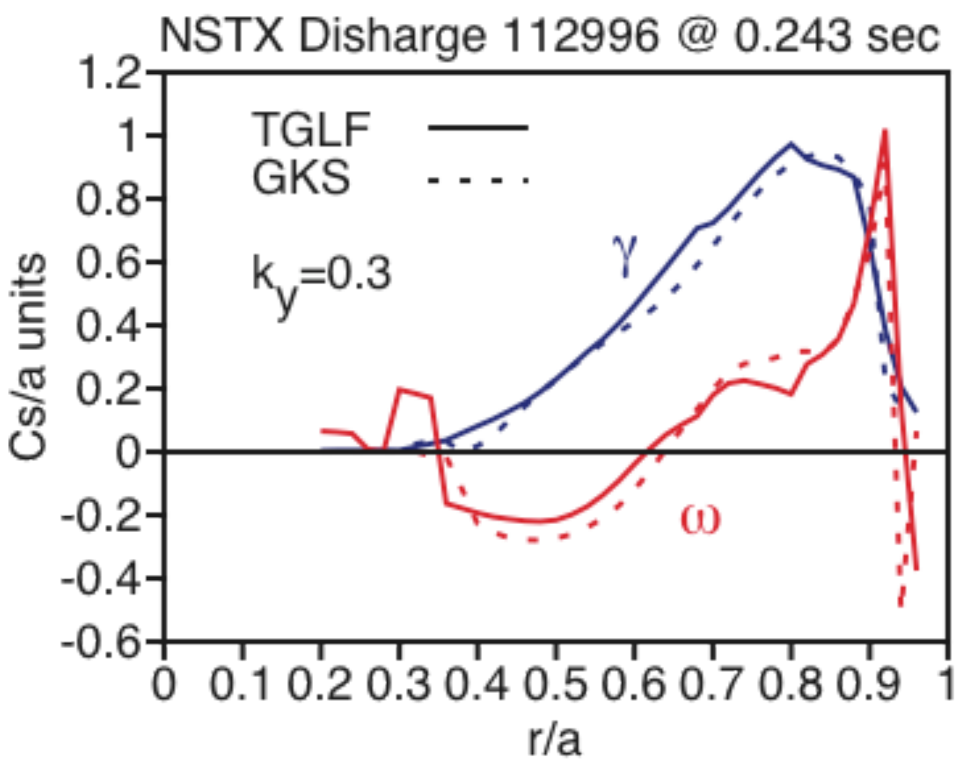




TGLF Works for Low Aspect Ratio

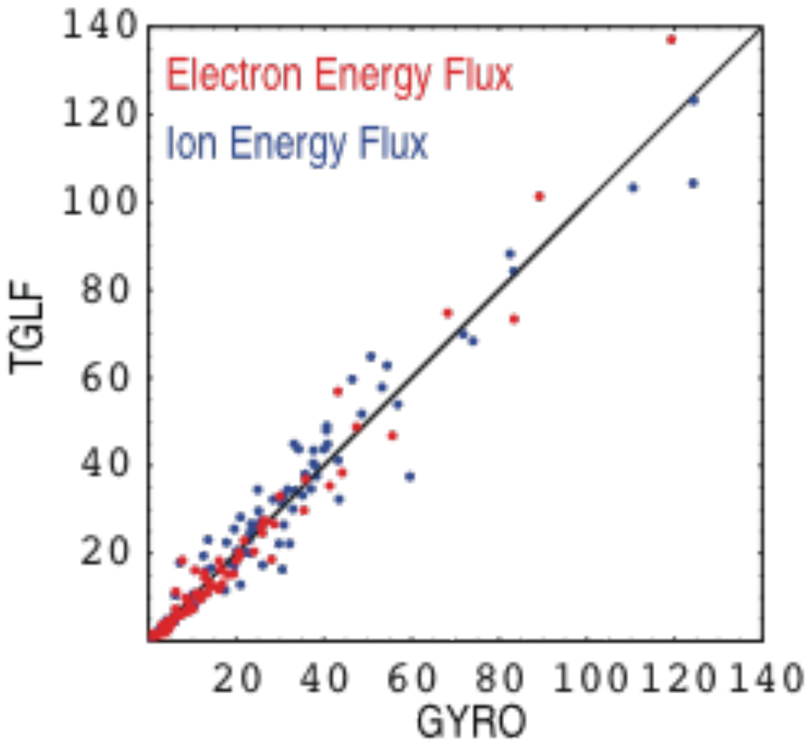
- **The good agreement between TGLF and GKS is maintained for the low aspect ratio spherical torus NSTX**

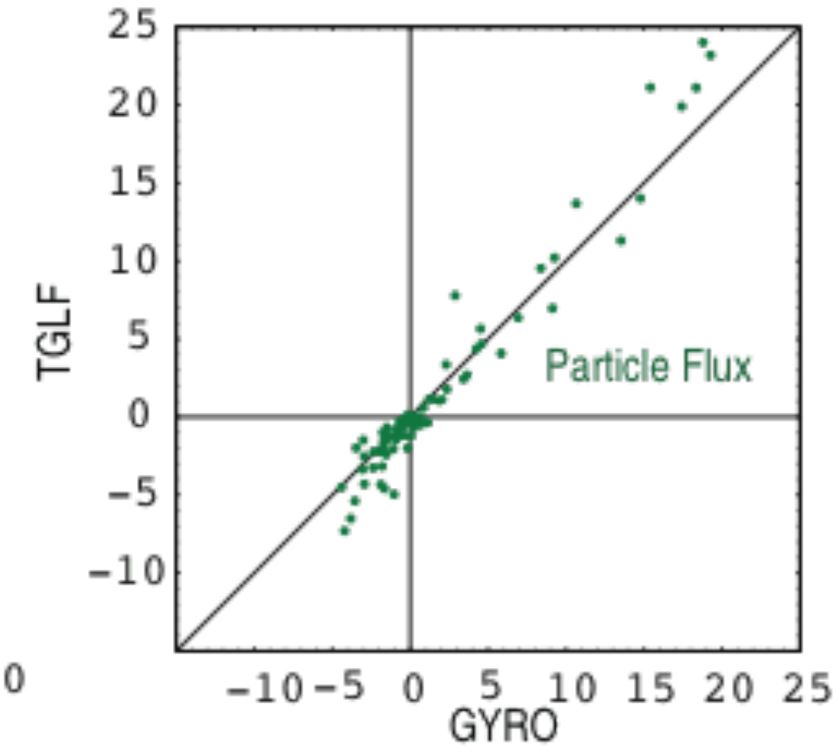
- **The NSTX data was measured and analyzed by Dan Stutman (Johns Hopkins), Stan Kaye, Ben LeBlanc and Ron Bell (PPPL)**



Quasi-Linear TGLF Fits Non-Linear GYRO Total Fluxes Well

- **The total fluxes for TGLF fit the database of 86 GYRO runs with fractional deviations of :** $\sigma_{Q_i} = 16\%,\ \sigma_{Q_e} = 15\%,\ \sigma_{\Gamma} = 28\%$



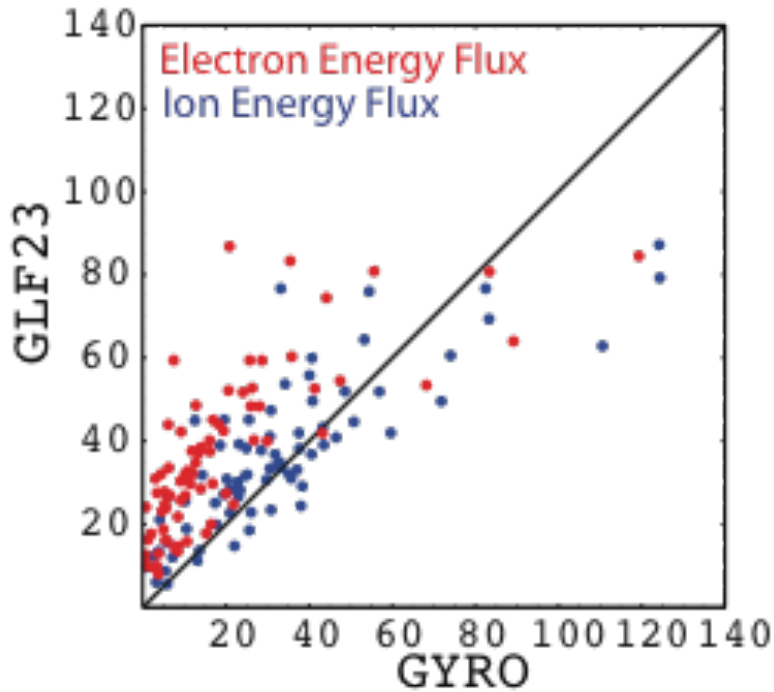


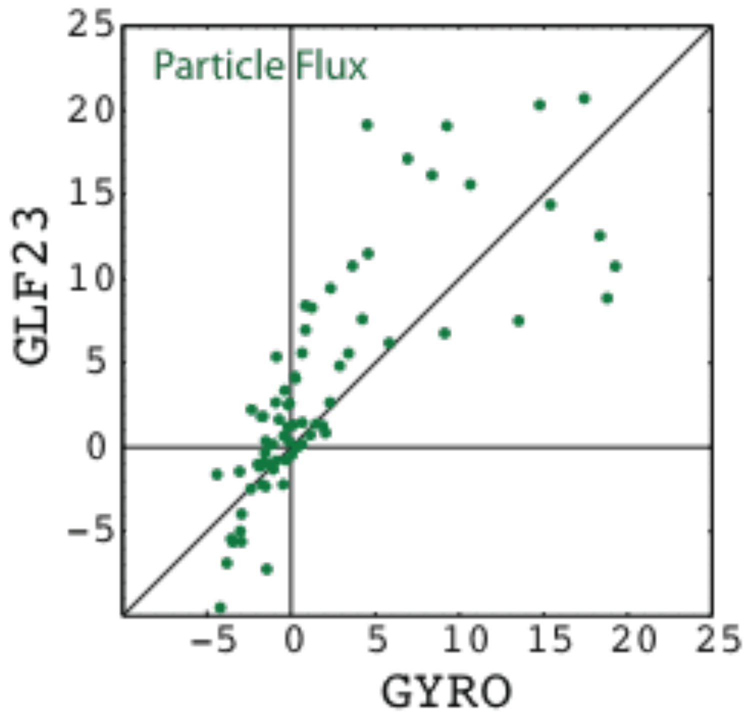
GLF23 Fluxes Are a Poor Fit to GYRO

- **The fractional deviation between GLF23 and GYRO for the 86 cases is**

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

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





A profile database of 96 Discharges from DIII-D, JET, and TFTR has been assembled for model testing

- **The database is comprised of conventional L- and H-mode discharges**
  - 25 DIII-D L-, 33 DIII-D H-, 22 JET H-, 16 TFTR L-mode discharges
  - Most of JET and all of TFTR discharges in ITPA Profile Database
  - Most discharges are from parameter scans including ρ^*,ν^*,β,q,Ti/Te,rotation
  - Only considered discharges with toroidal rotation data present
  - 96 shot database supplemented w/ DIII-D hybrid database (27 shots)
- **Simulation methodology**
  - TGLF and GLF23 run in the XPTOR transport code and treated equally with same solver and data
  - Predict core Te and Ti profiles for a single time-slice taking densities, toroidal rotation profiles, equilibrium, sources, sinks from experimental analyses
  - Boundary conditions enforced at ρ=0.84 for L-, H-modes
  - First TGLF runs are electrostatic with hydrogenic ions only
  - Toroidal rotation taken from data
  - Chang-Hinton neoclassical, neoclassical poloidal rotation for ExB shear
  - TGLF simulations performed on local Linux cluster usually with 40 processors 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

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

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

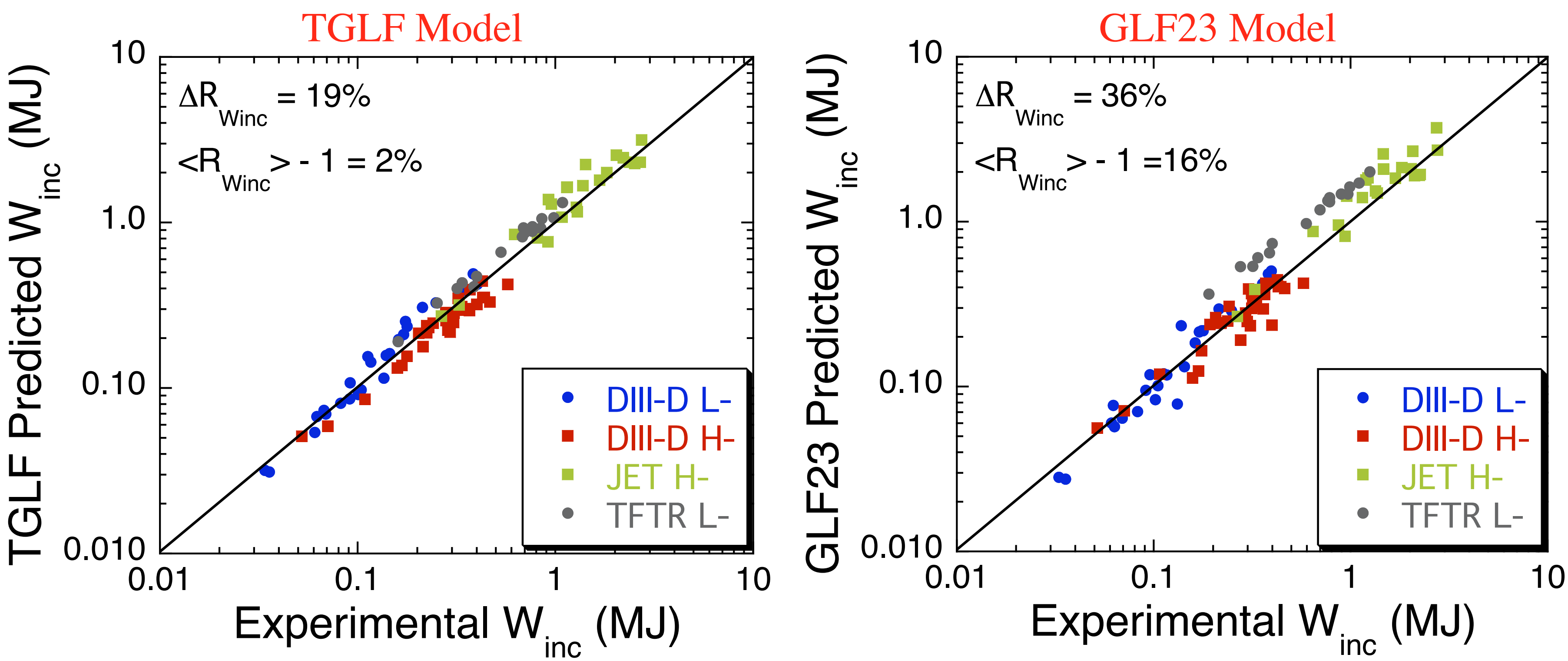
Deviation between simulation Temperature (T_s) and experimental (T_x)

Avg RMS and offset for each dataset

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

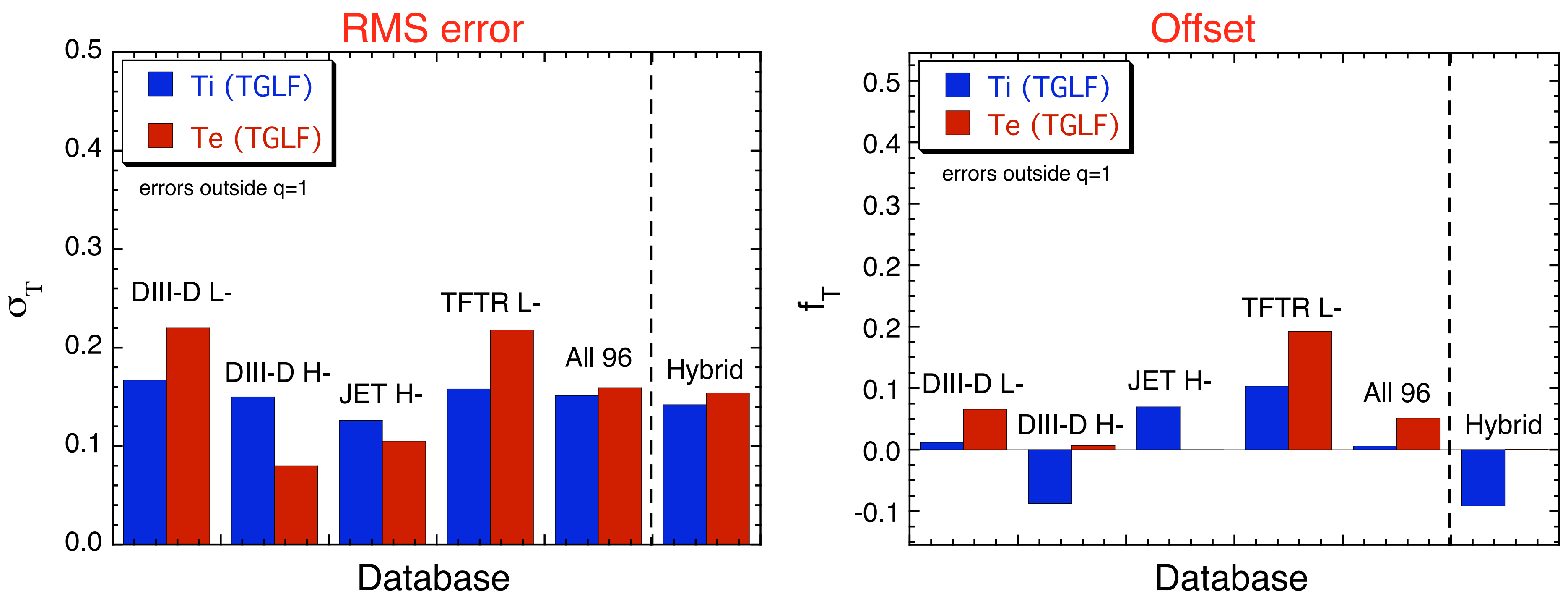
TGLF exhibits lower average global errors than GLF23 for a large L- and H-mode profile Database of 96 discharges

- **Database: 25 DIII-D L-,33 DIII-D H-, 22 JET H-, 16 TFTR L-mode discharges**
- **Avg RMS errors in W_{inc} is 19% for TGLF, 36% for GLF23**
- **Offset in W_{inc} much smaller for TGLF (2% vs 16%)**
- **Avg RMS error in W_{tot} is ΔR_{Wtot}=10% for TGLF, 20% for GLF23**



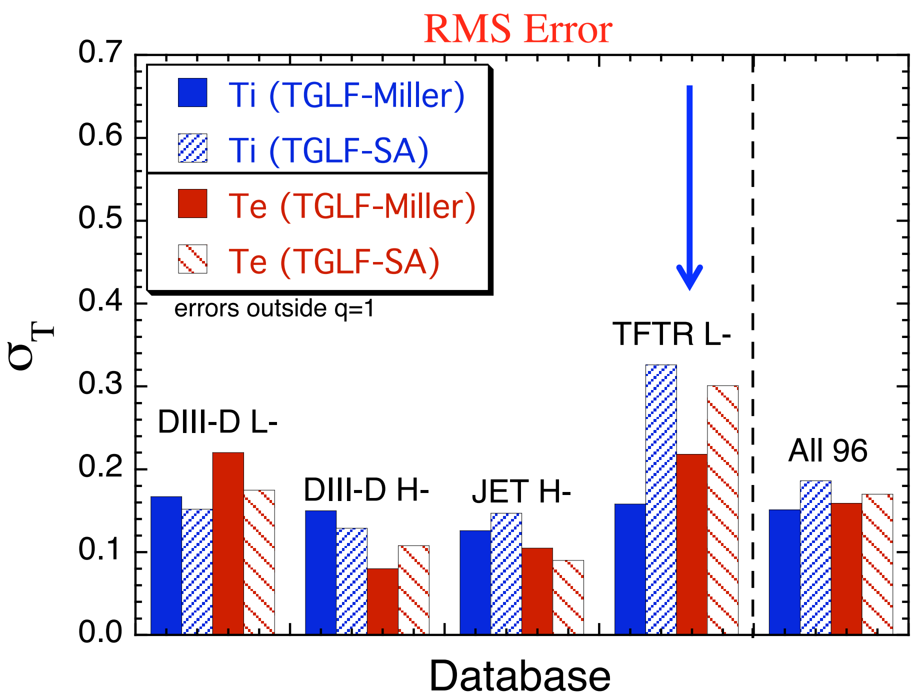
Local errors show TGLF model has fairly uniform agreement across DIII-D, JET, and TFTR discharges

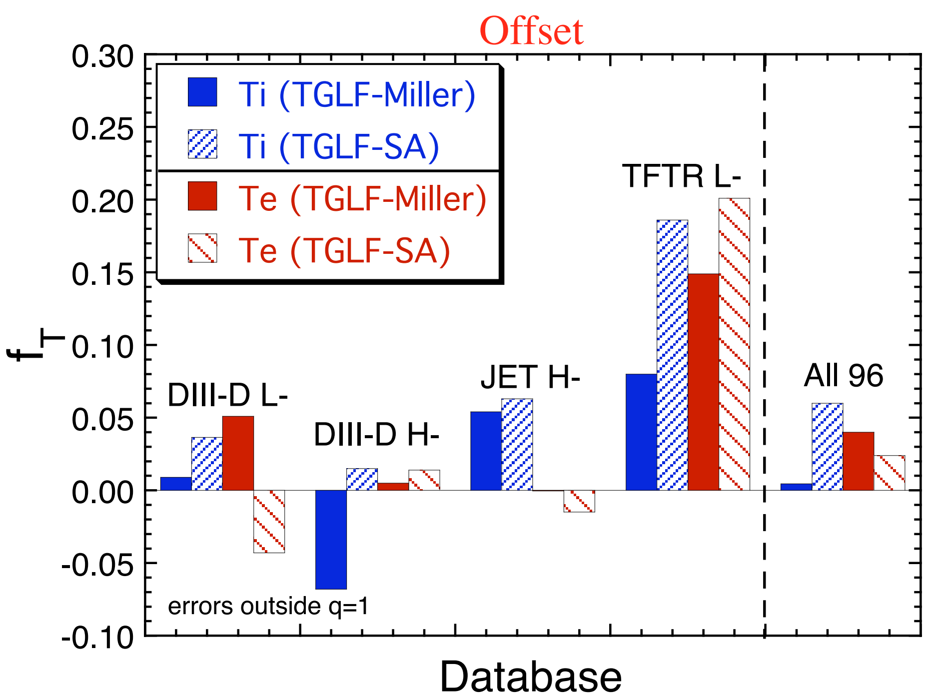
- **Avg RMS error for $[T_i,T_e]$ = [15%,16%]**
  - RMS errors in profiles computed outside q=1 to avoid influence by sawteeth
- **TGLF Avg RMS error for T_e smallest for H-modes, largest for DIII-D & TFTR L-modes**
- **TGLF has a small offset for DIII-D L- and H-modes and JET H-modes, but systematically overpredicts T_i,T_e for DIII-D and TFTR L-modes**



Sensitivity to Geometry: Miller geometry improves the agreement of TGLF with experimental profiles

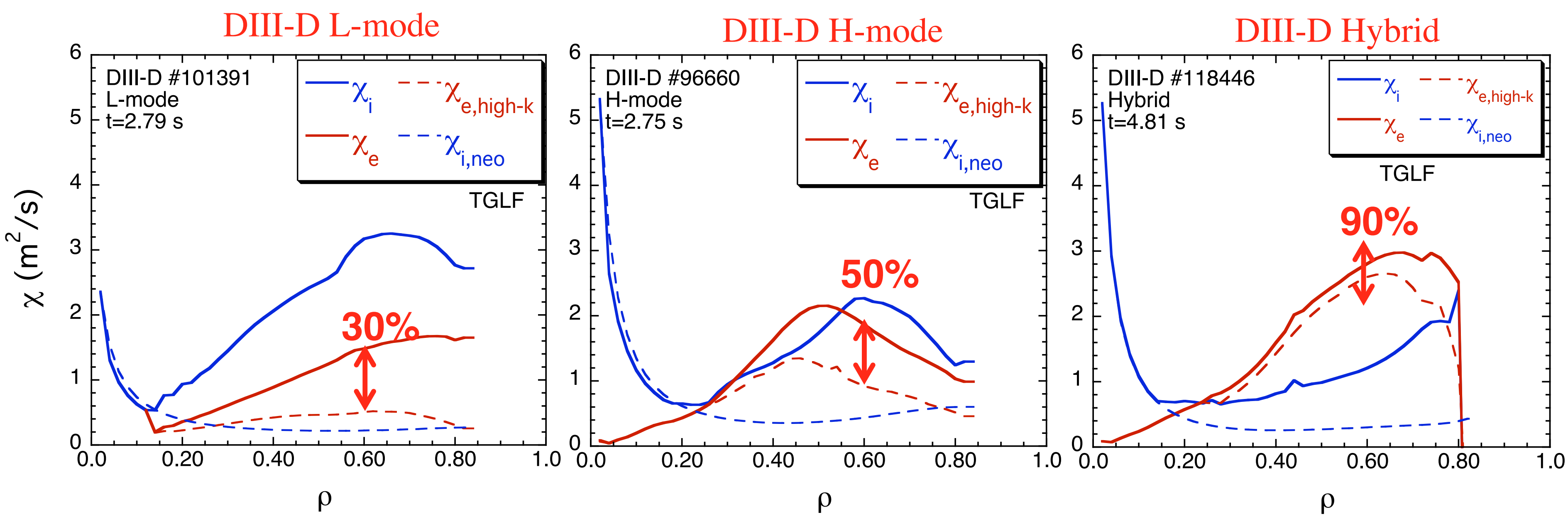
- **Miller geometry yields very little improvement for shaped tokamaks (DIII-D, JET) but yields surprisingly noticeable improvement for TFTR which is circular**
  - Finite aspect ratio in Miller geometry increases transport in TFTR compared to s-α but is compensated by elongation in shaped tokamaks (DIII-D, JET)





Sensitivity to High-k Modes: TGLF predicts high-k modes can dominate the electron transport in the plasma core

- **ETG coefficient in saturation rule determined by fitting GYRO simulation of GA STD case where $\chi_{e,high\text{-}k} / \chi_{e,total}$ = 11% (k_y > 1, μ=30)**
- **TGLF has lower low-k contribution to χ_e than GLF23**
- **Suppression of ITG/TEM transport by ExB shear results in high values of $\chi_{e,high\text{-}k} / \chi_e$ as χ_e approaches neoclassical**
  - Low q_{95} hybrids have largest $\chi_{e,high\text{-}k} / \chi_e$, L-modes have lowest $\chi_{e,high\text{-}k} / \chi_e$

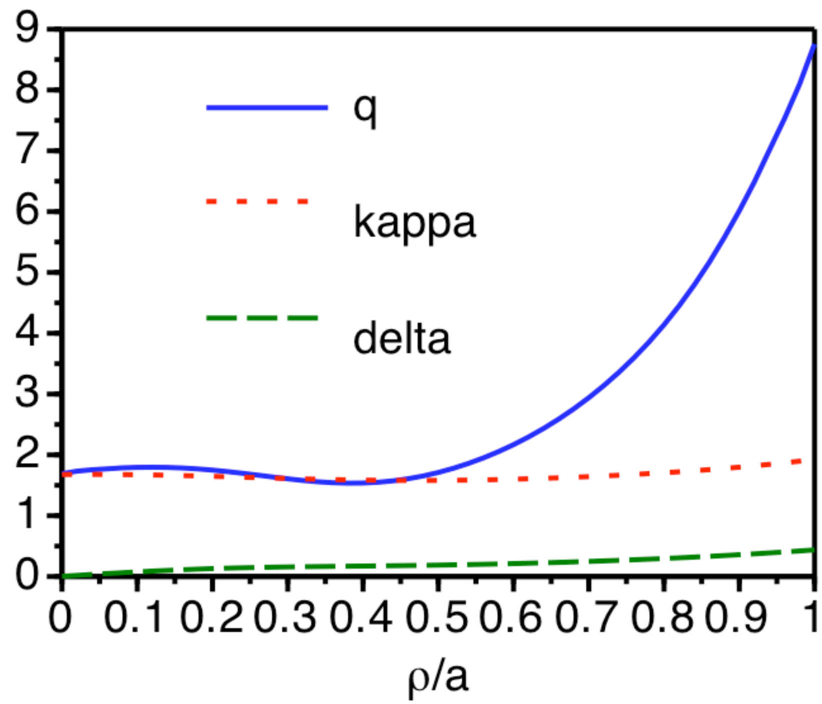


Spherical Tori Differ From Tokamaks

- **Low aspect ratio is only one difference between ST's and Tokamaks.**
- **The ratio of the beam velocity to the Alven velocity is much higher in present ST's.**
  - Beam driven instabilities are common and may contribute to transport.
- **Present ST's have a larger electron-ion collision frequency than present Tokamaks.**
  - Trapped electron drive is greatly suppressed.
- **Present ST's have a larger ratio of the ion gyroradius to major radius.**
  - Diamagnetic ExB velocity shear is more important in ST's
  - Neoclassical ion thermal transport is more important in ST's.
  - High-k ETG modes are more important in ST's because low-k modes are suppressed by ExB velocity shear.

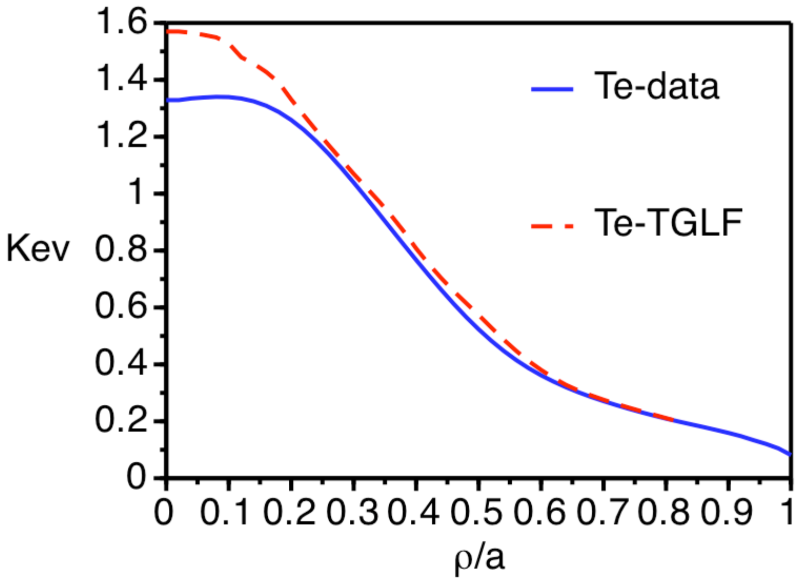
TGLF predictions for MAST

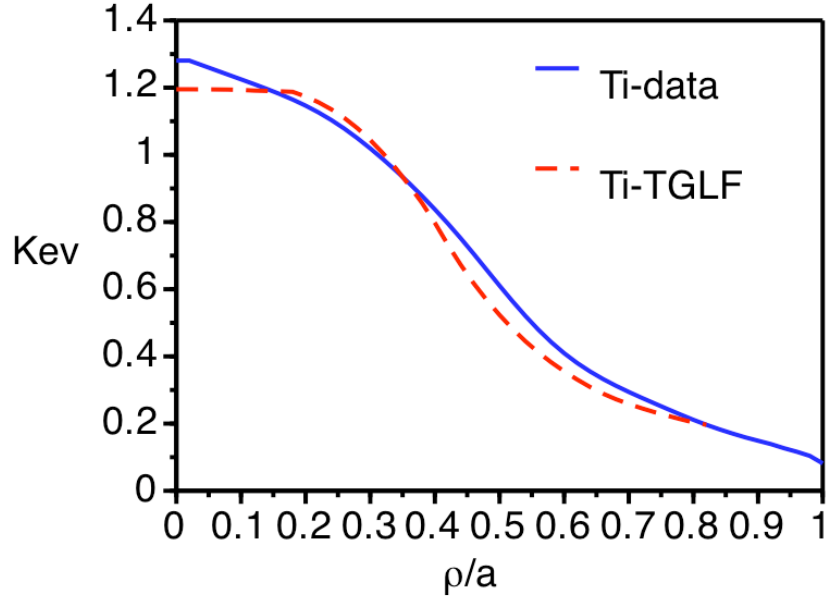
- **8 MAST discharges were selected for TGLF testing. One of these was free of sawteeth (q>1) H-mode discharge 8500.**
  - TGLF was run at the time of peak stored energy.



TGLF Temperature predictions are a good match for MAST Discharge 8500

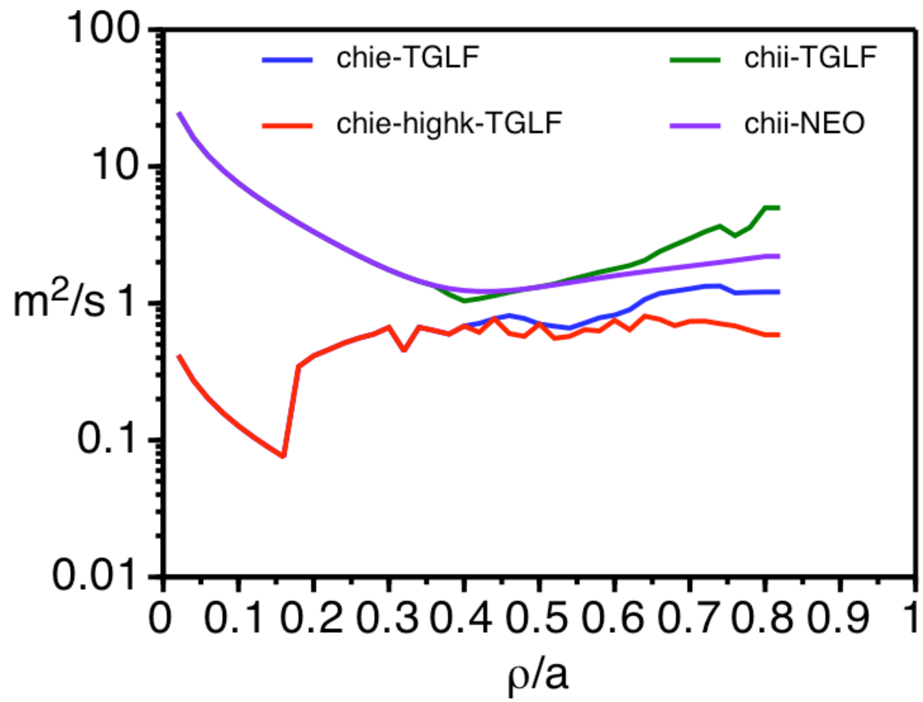
- **Both the TGLF predicted ion and electron temperature profiles agree with the data.**
  - The boundary of the simulation is at ρ/a=0.84





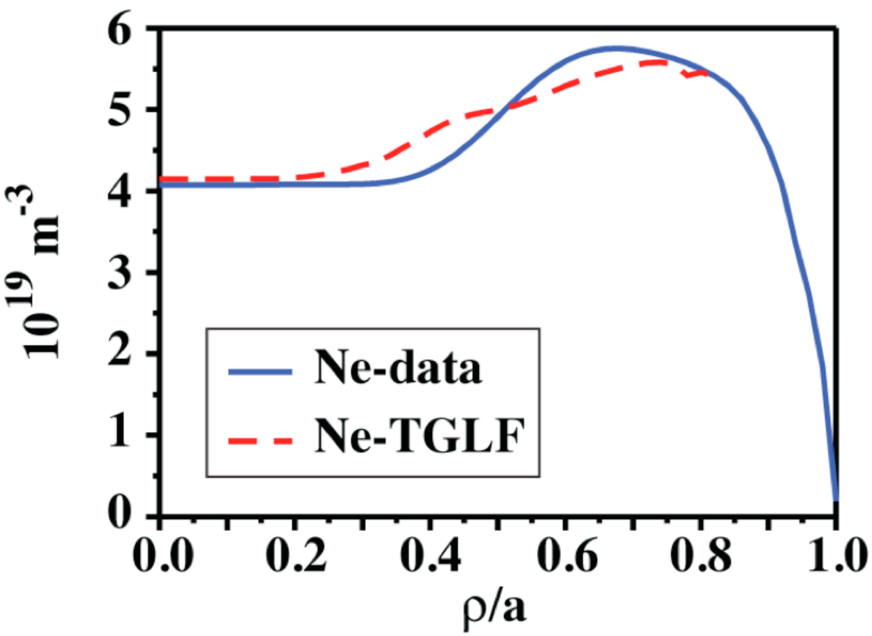
Transport in MAST 8500 is similar to DIII-D Hybrid

- The low-k ITG/TEM modes are dominant for $\rho/a>0.65$
- The ion energy transport is neoclassical for $\rho/a<0.5$
- The high-k TEM/ETG modes determine the electron energy transport for $\rho/a<0.65$
- The high-k modes generate an ion energy pinch for $0.35<\rho/a<0.5$
- The electron energy transport is electron neoclassical in the center $\rho/a<0.15$



TGLF Predicted Density Profile is also Good

- Transport code feedback on the edge particle source is used to try and match the line average density.
- This H-mode has an increasing density so the particle flux is negative in the core.



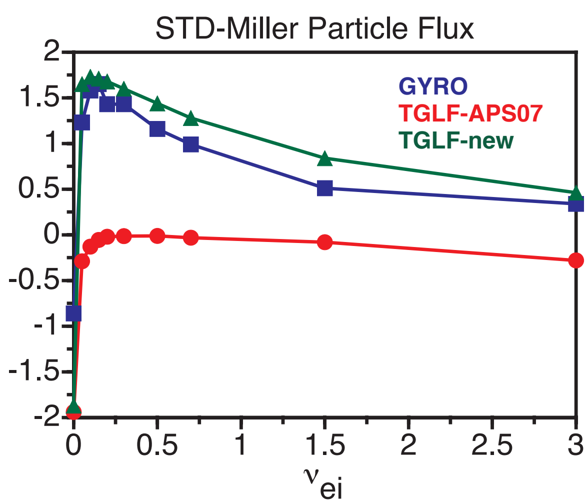
Electron-Ion Collisions are Important

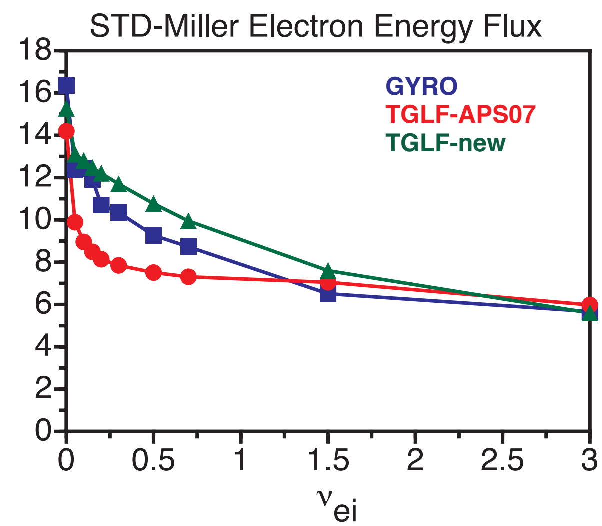
- **Since the APS07 version of TGLF was tested against tokamak data a new electron-ion collision model has been developed.**
- **The new TGLF collision model is fit to a local numerical solution of the gyro-kinetic equation with pitch angle scattering.**
- **The electron-ion collision frequency is typically an order of magnitude larger in MAST than in DIII-D discharges.**
- **The APS07 version of the collision model was fit to a database of linear growthrates. It is not as accurate as the new model.**
- **Since the ion energy transport is neoclassical over more than half of the profile for 8500 it is important to use the correct low-aspect ratio formula.**
  - Beli and Candy have shown that modifying the Chang-Hinton formula by using an effective magnetic field for low-aspect ratio shaped plasmas give a better result compared to a high accuracy numerical calculation.

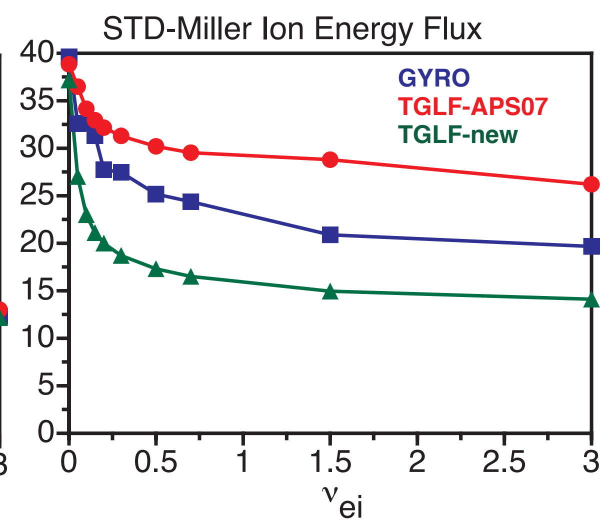
$$B\_unit = B_0 \, \rho / r \, d\rho / dr$$

The New Collision Model Improves the Agreement with GYRO

- **The electron energy and particle flux are improved for the new model**
  - The ion energy flux is too low

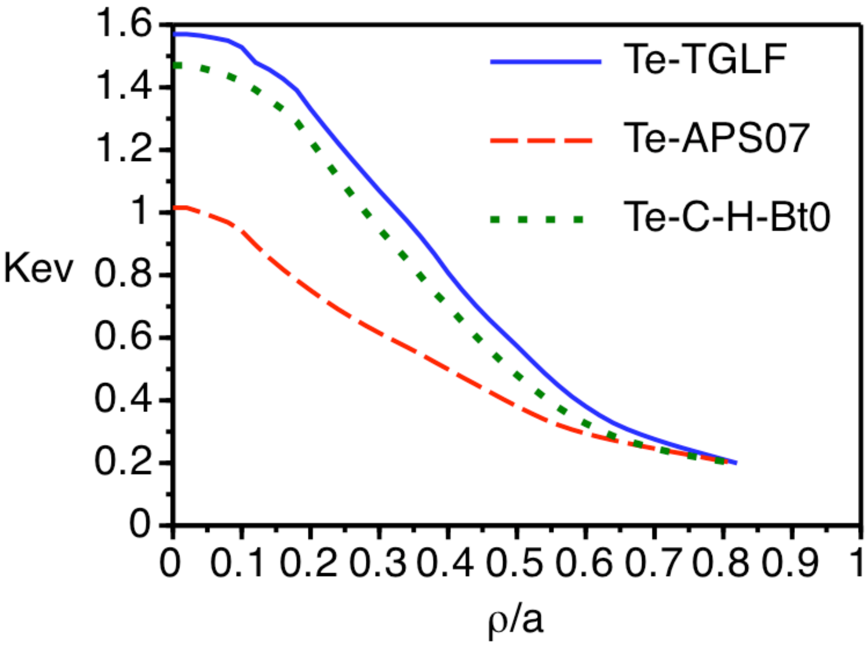


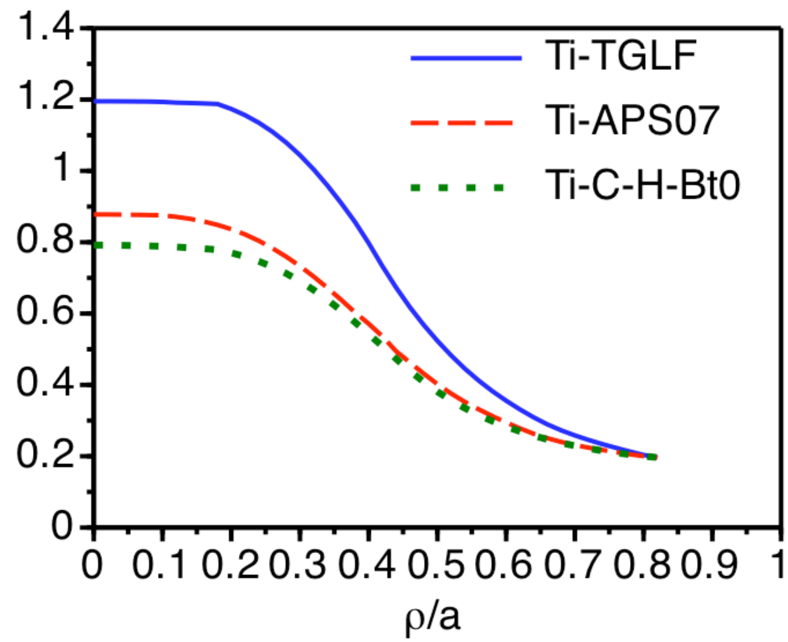




Neoclassical ion Energy Transport is important

- The APS07 collision model predicts colder ion and electron temperatures than the new model
- The Beli-Candy modified Chang-Hinton ion neoclassical formula gives hotter ions than using the conventional vacuum magnetic field.





MAST Temperatures for q > 1 are well predicted by TGLF

- All of the remaining 7 MAST discharges (not 8500) had q < 1 for r/a< 0.45
- The TGLF predicted temperature profiles outside of the q<1 region agree fairly well with the data.
- Inside of the q < 1 region the energy transport predicted by TGLF was far too weak indicating drifwaves are not the main transport mechanism in the MHD unstable region.

TABLE. 1: STATISTICS FOR MAST DISCHARGES.

MAST Discharge No.		Deviation-Ti	Deviation-Te	Offset-Ti	Offset-Te
8500	H-mode	0.057	0.104	–0.035	0.070
18571	H-mode	0.225	0.243	–0.125	–0.138
15021	H-mode	0.098	0.639	–0.056	0.353
8505	L-mode	0.219	0.050	–0.127	0.010
17661	L-mode	0.147	0.127	–0.003	0.003
17663	L-mode	0.291	0.267	0.050	0.042
17666	L-mode	0.133	0.307	0.053	0.186
17668	L-mode	0.171	0.300	-0.022	0.133
Average		0.167	0.255	-0.033	0.082

NSTX

- 5 NSTX discharges were used. The time of the peak in the stored energy was chosen like the MAST cases.
- The Newton-implicit solver in XPTOR was unable to converge for most of the NSTX cases.
- Linear stability analysis with TGLF shows that all driftwaves are stable for r/a<0.4 in these NSTX cases despite q>1 everywhere.
- The experimental electron temperature gradient is above the critical gradient for high-k ETG modes for r/a>0.4 drops well below the threshold in the deep core.
- Kinetic MHD ballooning modes are computed to be linearly stable with TGLF as well in this region (r/a<0.4).
- TGLF does not find tearing or interchange MHD modes.
- Previous work on ETG thresholds has found the when resistive interchange modes are unstable in negative magnetic shear tokamak discharges that the ETG threshold is high and erratic using Miller geometry. (Stallard APS 1998)

Summary of Tokamak and ST Results

- **The TGLF transport model was found to give about the same accuracy of temperature predictions in tokamaks and MAST (~20%) outside the sawtooth region (q>1).**
- **The MAST H-mode (8500) (weak shear q>1) was found to resemble a DIII-D hybrid regime (weak shear q>1).**
  - ExB shear reduces or quenches the low-k ITG/TEM modes
  - High-k ETG modes dominate electron thermal transport for r/a<0.6
- **The 5 NSTX discharges examined have a non-driftwave transport mechanism in the deep core (r/a<0.4).**
  - Kinetic MHD ballooning modes were also stable
- **Finite aspect ratio Miller geometry gave similar results as infinite aspect ratio s-alpha geometry for 8500.**
  - The strong shaping of 8500 reduces transport while finite aspect ratio increases it. DIII-D also exhibits near cancellation of these effects.
  - The circular tokmak TFTR show better agreement with Miller than with s-alpha geometry

Summary of Tokamak and ST Results

- **The Beli-Candy modified Chang-Hinton ion neoclassical thermal diffusivity was a good model of the ion energy transport.**
  - The ion neoclassical transport model makes a difference in the predicted ion temperatures. (a nice test of neoclassical theory)
- **An improved electron-ion collision model was needed for TGLF in order to model the high collision frequency of the ST's.**
  - Collision frequency in MAST is an order of magnitude higher than DIII-D.
  - The APS07 version of the TGLF electron-ion collision model gives too strong an ion thermal transport compared to GYRO for large collision frequency. The new collision model is too low for the ion energy flux compare to GYRO. Work is ongoing to improve the agreement with GYRO.