A Theory-Based Transport Model with Comprehensive Physics

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DIII-D
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GENERAL ATOMICS

A Theory-Based Transport Model with Comprehensive 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 Was 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 (Kotschenrouther)

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

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

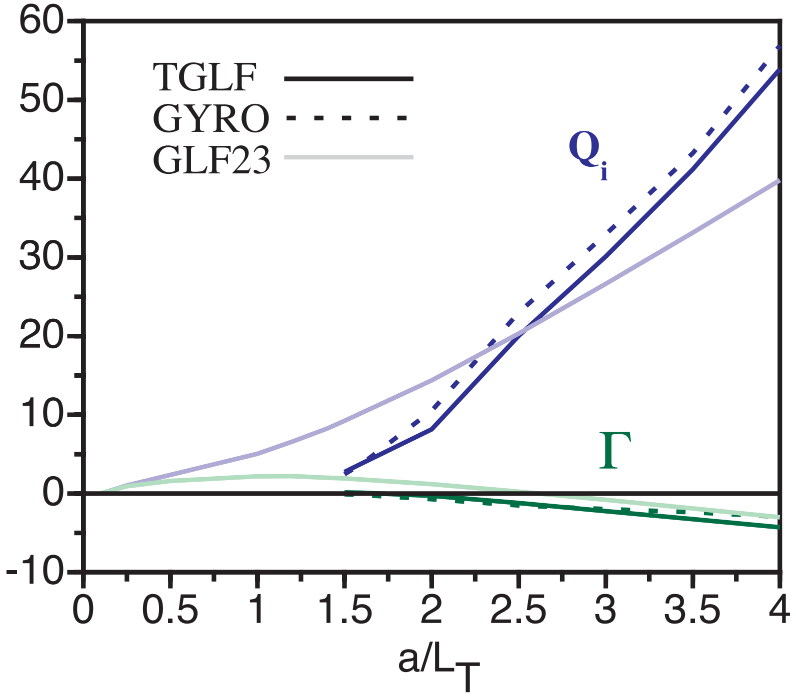
GLF23

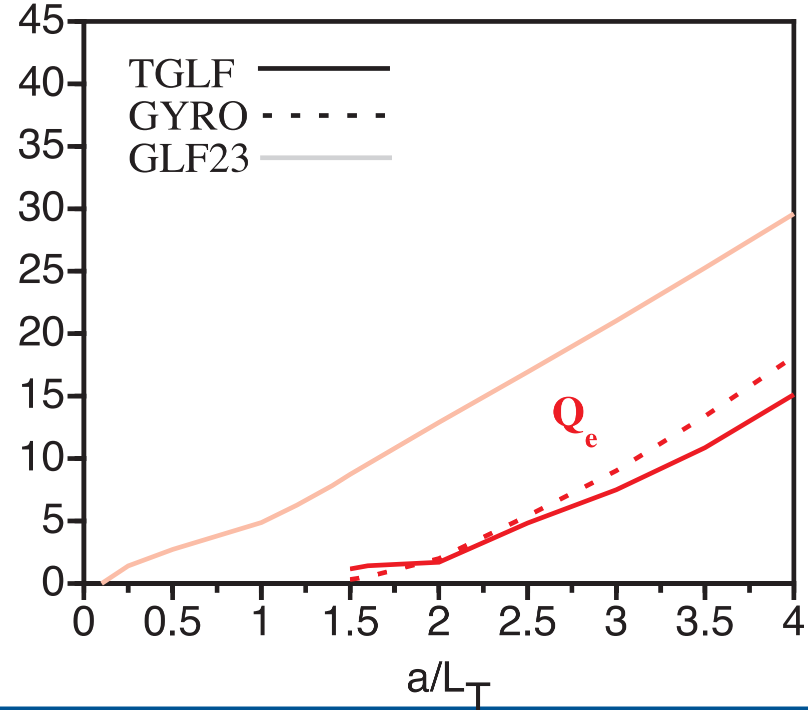
- Different equations for low-k (ITG,TEM) and high-k (ETG)
- FLR integrals used Pade approximation valid for low-k
- Parameterized single Gaussian trial wavefunction valid for a limited range of conditions
- Small trapped fraction required.
- Shifted circle (s-alpha) geometry
- Normally run electrostatic
- 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!

The New TGLF Transport Model is a More Accurate Fit to Gyro-Kinetic Turbulence Than GLF23

- TGLF fits GYRO well for all three channels
- GLF23 electron energy flux is systematically high
- GLF23 with trapped electrons misses critical temperature gradient
- GLF23 was fit to this same scan with adiabatic electrons

Temperature gradient scan with trapped electrons

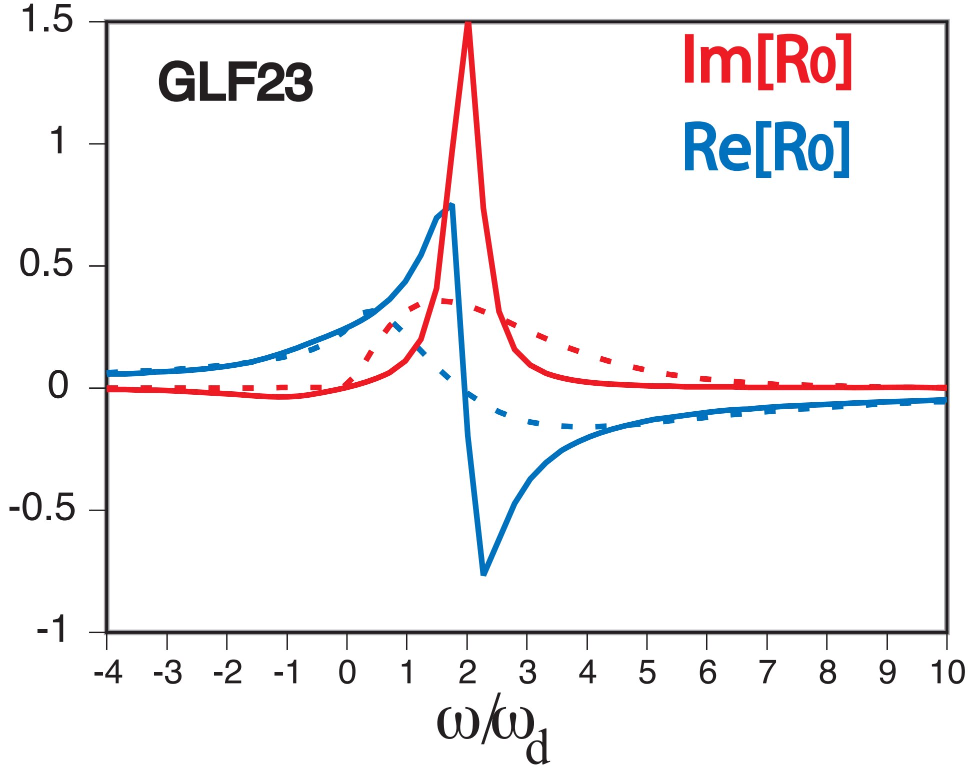




GLF23 has an Inaccurate Trapped Electron Model

- **The 2-moment GLF23 trapped electron model is a poor fit to the kinetic trapped density response function**

GLF23 (solid) and kinetic (dashed) trapped density response for 25% trapped fraction

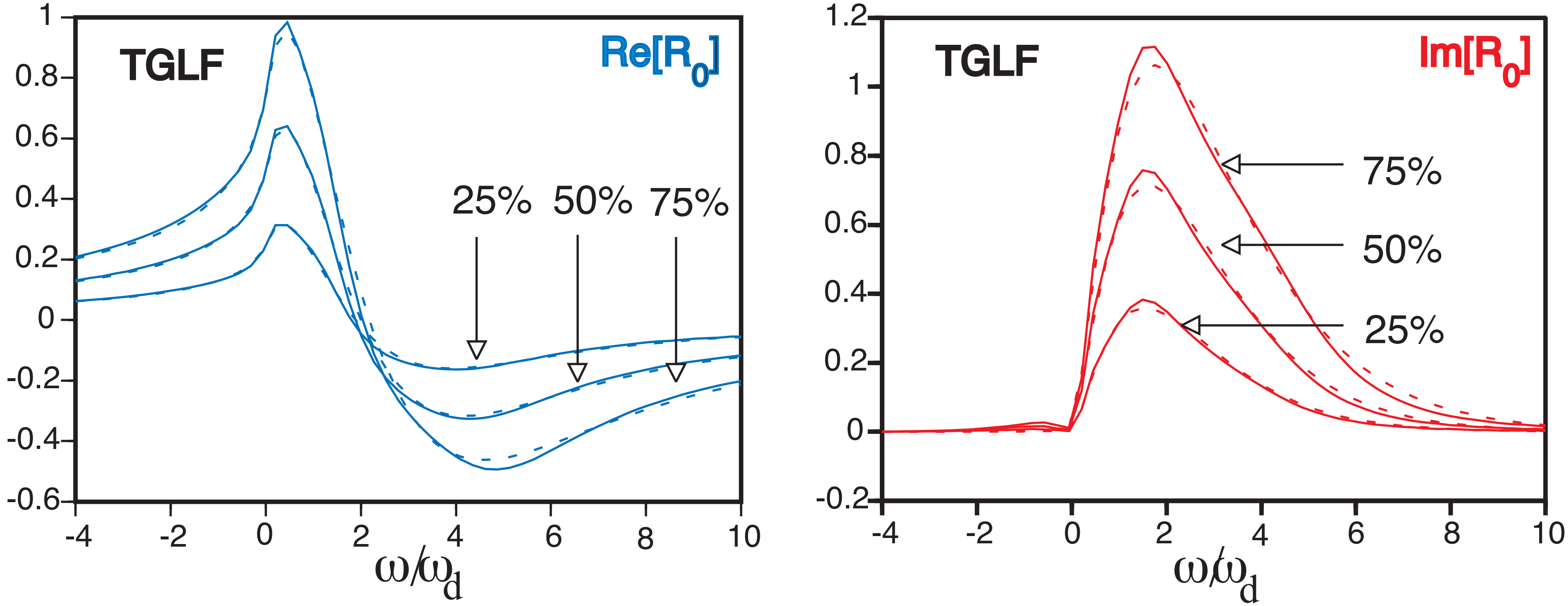


$$\tilde{N}^t = -\frac{e\tilde{\phi}}{T}\left(R_0 + \frac{\omega_*}{\omega_d}R_1 + \eta\frac{\omega_*}{\omega_d}R_2\right)$$

The TGLF Trapped Electron Model is Very Accurate

- **The 3-moment TGLF trapped electron model is an excellent fit to the kinetic trapped density response function**

TGLF (solid) and kinetic (dashed) trapped density response for 25%, 50%, 75% trapped fraction

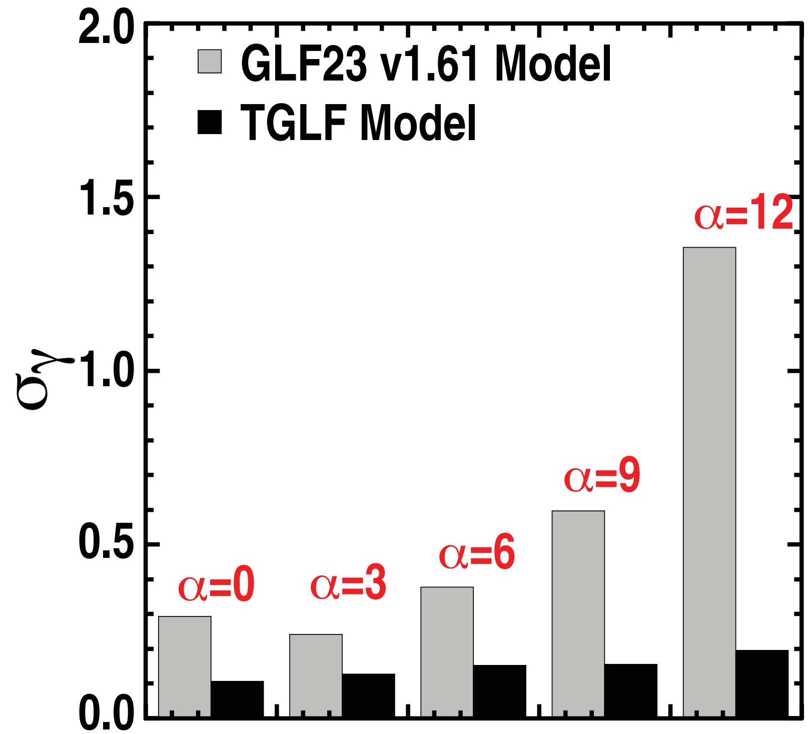


TGLF Has a Uniformly Good Accuracy Over a Wide Range of Plasma Conditions

- **Linear stability benchmarks in s-alpha geometry show that TGLF is an accurate approximation to gyro-kinetic calculations with GKS**
- **The average fractional deviation for the TGLF growth rate is 11.4% for the whole database of 1800 GKS runs**

$$\sigma_\gamma = \sqrt{\sum_i \left(\gamma_i^{\mathrm{TGLF}} - \gamma_i^{\mathrm{GKS}}\right)^2} \Big/ \sqrt{\sum_i \left(\gamma_i^{\mathrm{GKS}}\right)^2}$$

Each bar is the fractional deviation for a set of 80 pts varying shear and safety factor about the PED point over the range $1 \le \hat{s} \le 7, 3 \le q \le 7$

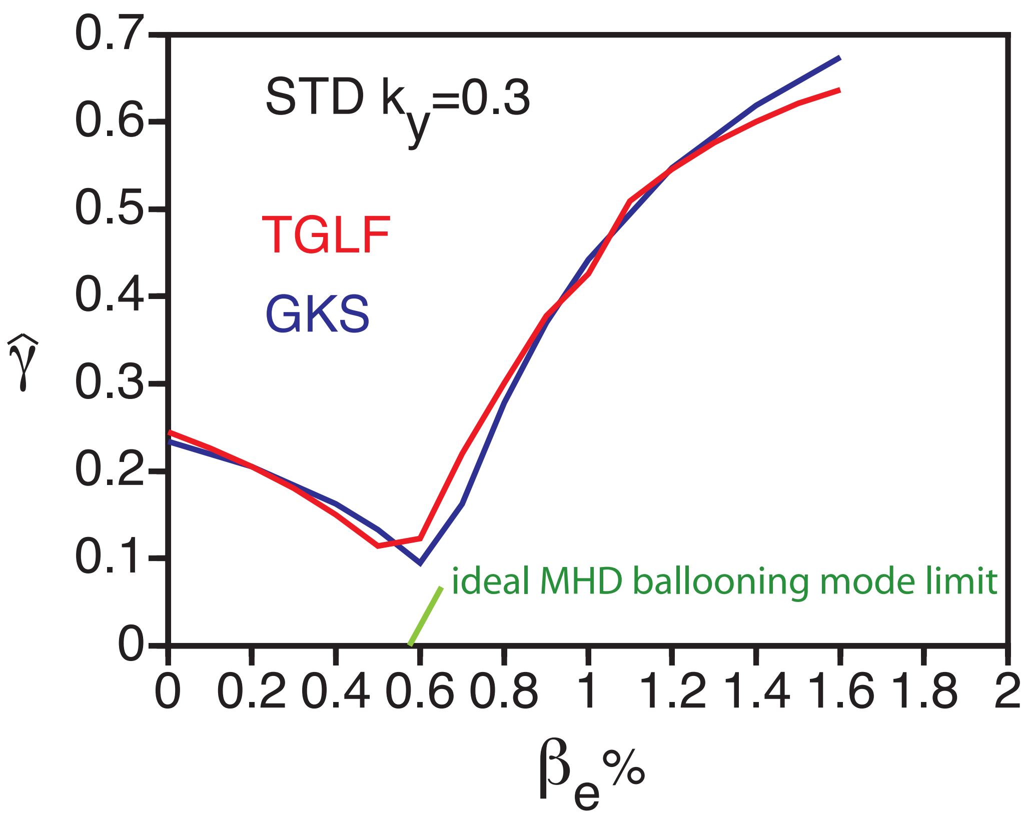


$$\mathrm{PED} = \left(a/L_{n_e} = a/L_{n_i} = 3,\ a/L_{T_e} = a/L_{T_i} = 10,\ T_i/T_e = 1,\ q = 4,\ \hat{s} = 3,\ \alpha = 5,\ k_y = 0.3,\ r/a = 0.5,\ R/a = 3.0\right)$$

Electromagnetic fluctuations give correct kinetic ballooning mode threshold

TGLF kinetic ballooning mode growth rates agree very well with GKS

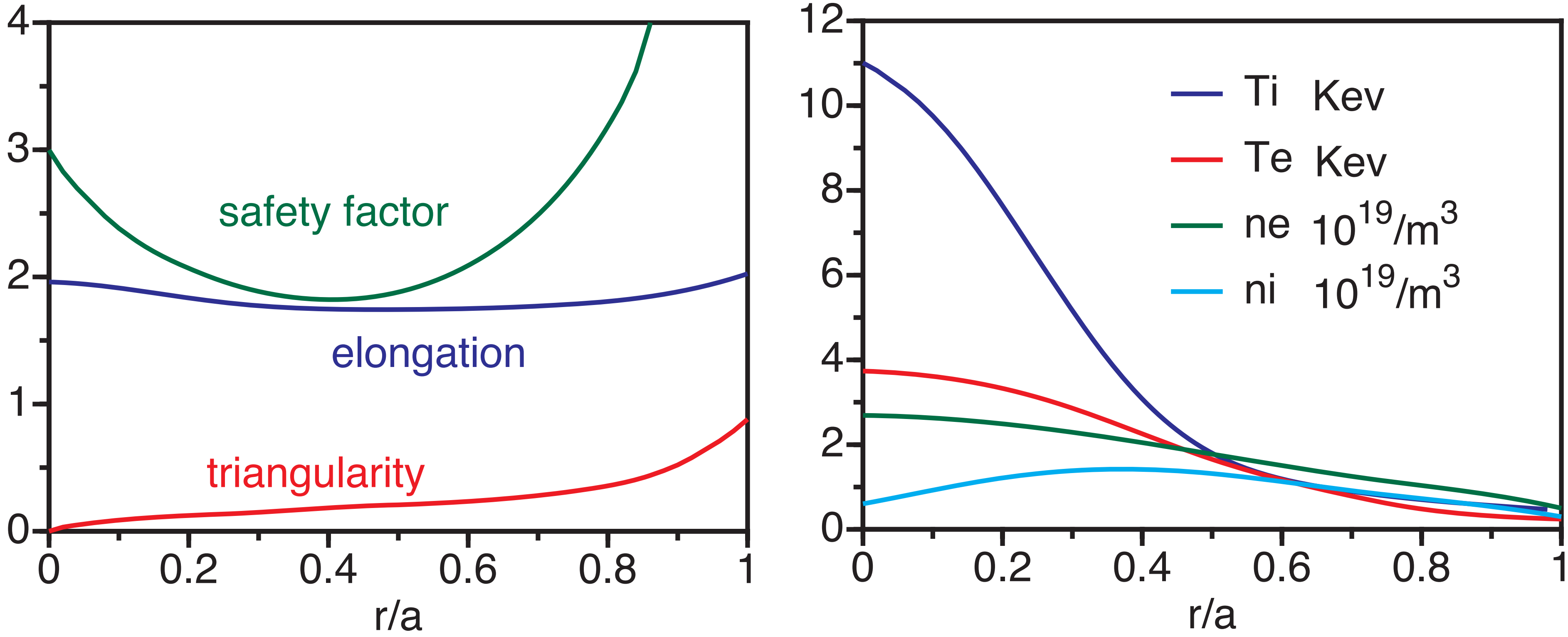
S-alpha geometry with only perpendicular magnetic fluctuations



TGLF is Now Being Used for Linear Stability Analysis of Experimental Data

- **As an illustration of the accuracy of TGLF with comprehensive physics an analysis of a DIII-D NCS discharge will be made**
- **The geometry and plasma profiles are shown below**
  - L. Lao et al. Phys. Plasmas 3 (1996) 1951

DIII-D NCS discharge 84736 at 1.3 s

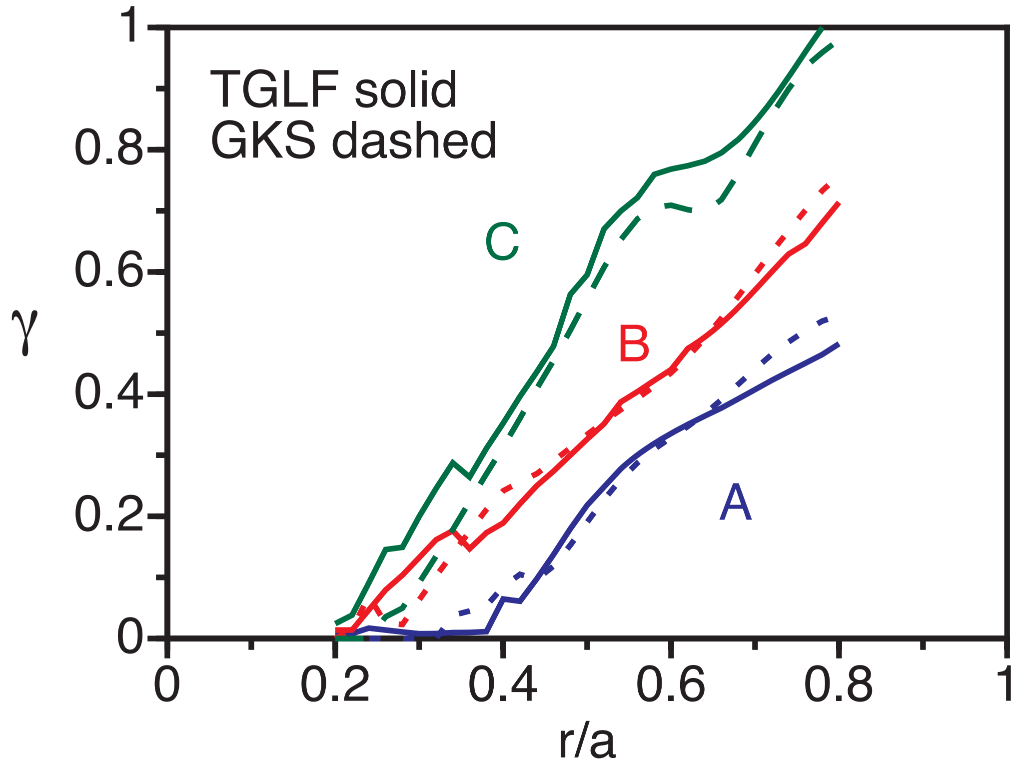


TGLF Linear Growth Rates Are Accurate for Real Experimental Conditions

- **The radial profile of the normalized linear growth rate for k_y = 0.3 and three different physics settings is shown**
  - (A) comprehensive physics
  - (B) collisionless, electrostatic
  - (C) s-alpha geometry dilution, collisionless, electrostatic

- **The TGLF code was 200× faster than GKS for (C)**
  (2.4 s vs 8.9 min on a 3 GHz CPU)

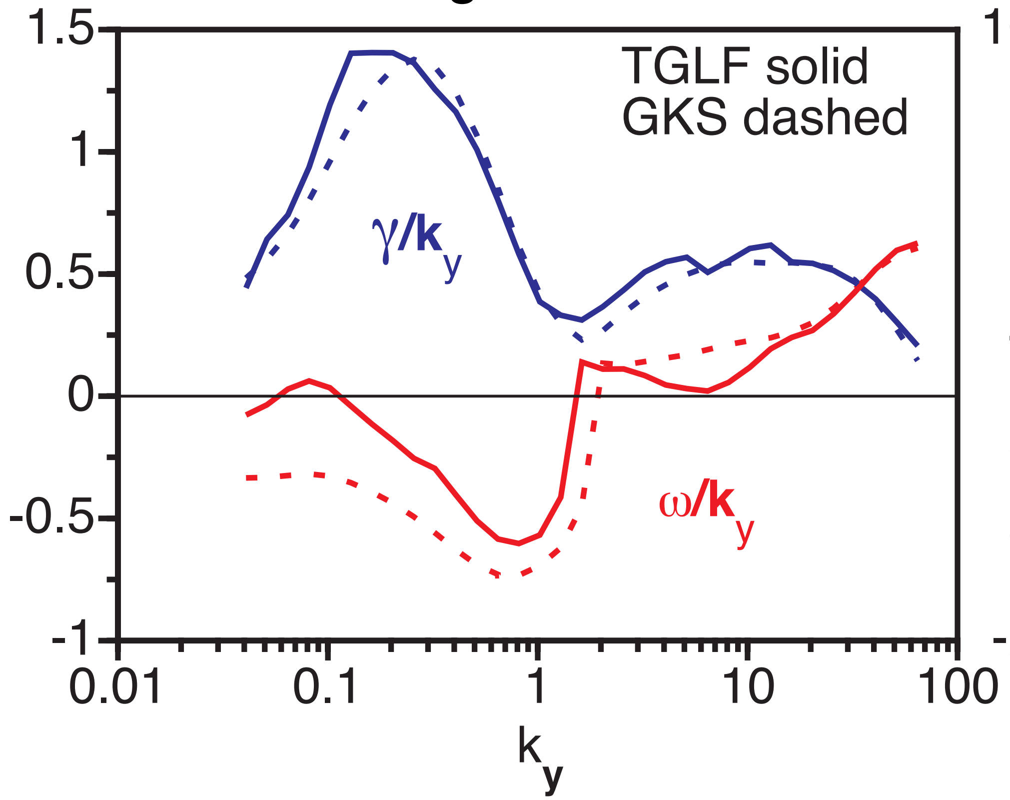
DIII-D NCS discharge 84736 at 1.3s

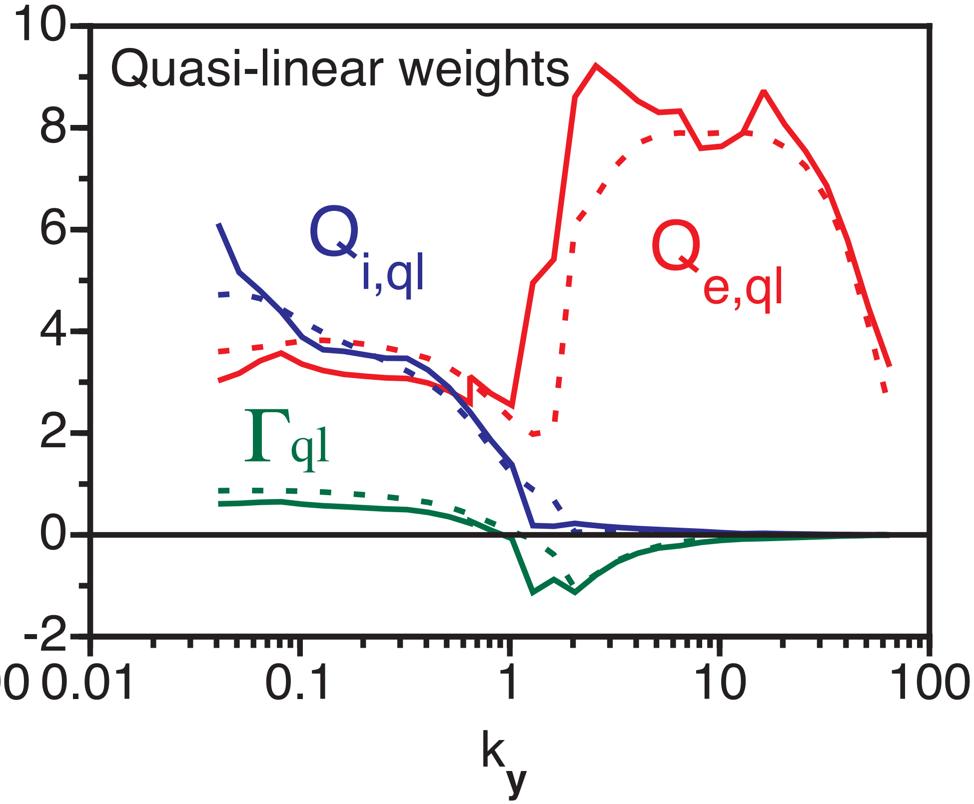


The Full Spectrum of Drift Wave Eigenmodes Can Be Computed With TGLF

- **k-spectrum with comprehensive physics at r/a=0.7 for DIII-D NCS discharge 84736 at 1.3 s**

Linear eigenmodes

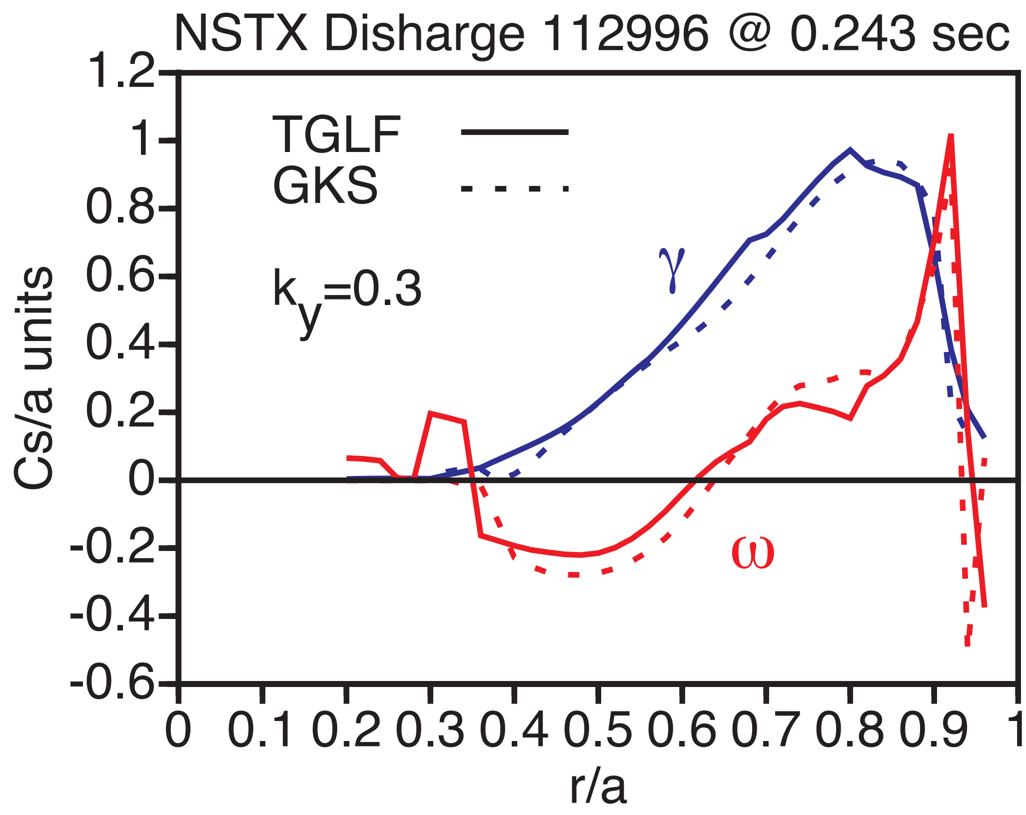




TGLF Works for Low Aspect Ratio

- 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)



TGLF Flux Model is Fit to a Large Database of NonLinear Gyro-kinetic Turbulence Simulations

The normalized TGLF fluxes are given by

$$\hat{Q}_i = c_{Q_i}\overline{\Phi}^2 Q_{i,ql} \qquad \hat{Q}_e = c_{Q_e}\overline{\Phi}^2 Q_{e,ql} \qquad \hat{\Gamma} = c_{\Gamma}\overline{\Phi}^2 \Gamma_{ql}$$

- **The coefficients are chosen to give zero off-set for the whole database of 86 non-linear GYRO turbulence simulations**
  - s-alpha geometry, kinetic electrons and ions, collisionless, electrostatic
- **The coefficients would all be the same if the ratios of the fluxes were exactly the quasi-linear ratios**

c_{Qi}	c_{Qe}	c_{Γ}
30.0	32.4	36.6

A Model for the Zonal Flow Shear is Included to Fit the Spectrum of the Turbulence

- **A model for the reduction of the growth rate by the ExB shear due to"zonal flows" γ_{ZF} and the equilibrium electric field γ_{ExB} is used to obtain an effective net growth rate used in the saturated intensity model.** $\overline{\Phi}^2(\overline{\gamma})$

$$\overline{\gamma} = \mathrm{Max}\left[\left(\hat{\gamma} - \alpha_E \hat{\gamma}_{ExB} - \alpha_{ZF}\hat{\gamma}_{ZF}\right)/\hat{\omega}_{d0}, 0\right] \quad \textbf{where} \quad \hat{\omega}_{d0} = k_y\left(a/R\right)$$

and

$$\hat{\gamma}_{ZF} = \hat{\omega}_{d0}\left(\mathrm{Max}\left[\hat{\gamma} - \alpha_E\hat{\gamma}_{ExB}, 0\right]/\hat{\omega}_{d0}\right)^{\beta_{z\gamma}} \Big/ \left(k_y^{\beta_{zk}} q^{\beta_{zq}}\right)$$

α_{ZF}	$\beta_{z\gamma}$	β_{zk}	β_{zq}
0.369	0.906	0.420	0.317

α_E
0.35

A Local Model for the Saturated Intensity is Sufficient for a Good Fit

The model for the saturated intensity of the potential fluctuations is local in both k_y and space. $\overline{\Phi}^2 = \tilde{\Phi}^2 / (\rho_s / a)^2$

$$\overline{\Phi}^2 = \Delta_{ky} \frac{\hat{\omega}_{d0}^2}{k_y^4} \Lambda \qquad \Lambda = \frac{\overline{\gamma}^{\beta_\gamma} \left[\alpha_{d0} + \left(\alpha_d \mathrm{Max}[\overline{\omega}_d, 0] \right)^{\beta_d} \right]}{\left[1 + \left(\alpha_\gamma \overline{\gamma} \right)^{\beta_\gamma} \right] \left[1 + \left(\alpha_d |\overline{\omega}_d| \right)^{\beta_d} \right] k_y^{\beta_k}}$$

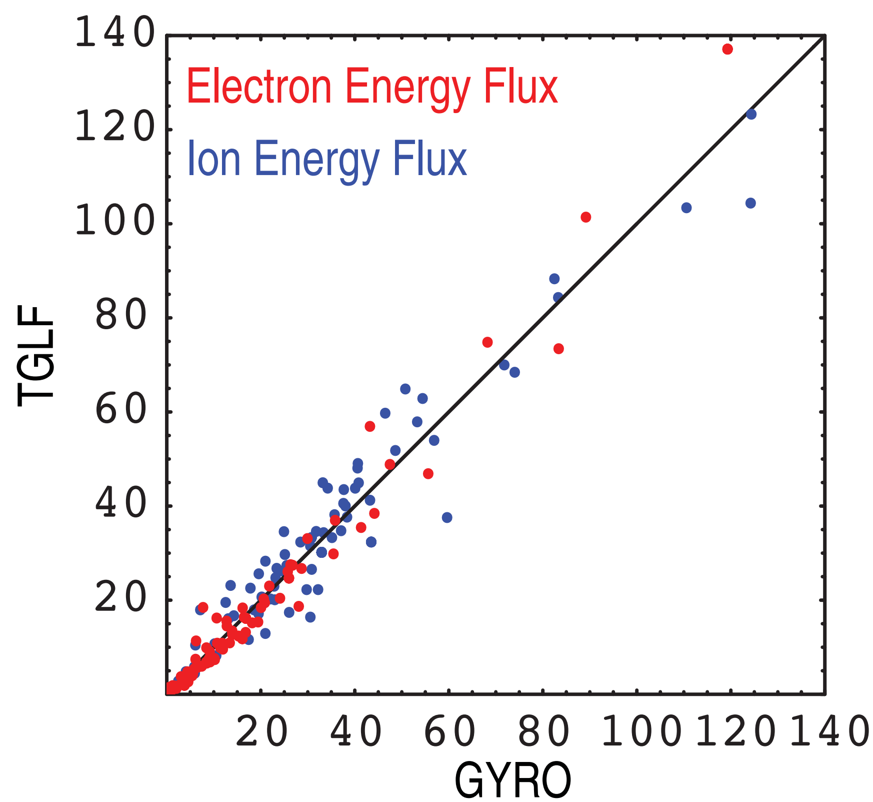
$\overline{\omega}_d = \langle \hat{\omega}_d \rangle / \hat{\omega}_{d0}$ **is the wavefunction average of the curvature drift.**

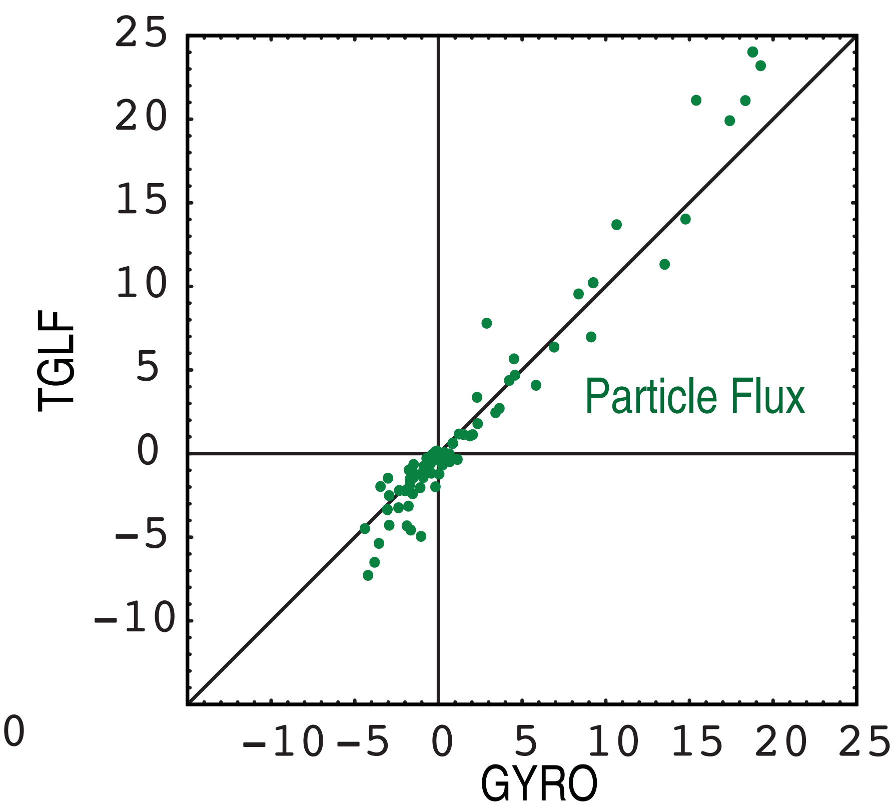
The intensity model has the weak turbulence limit: $\overline{\Phi}^2 \propto \overline{\gamma}^2$ for $\overline{\gamma} << 1$
and the strong turbulence limit: $\overline{\Phi}^2 \propto \hat{\omega}_{d0}^2$ for $\overline{\gamma} >> 1$

α_γ	β_γ	α_{d0}	α_d	β_d	β_k
0.893	1.98	0.072	2.55	1.94	0.933

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 :** $\sigma_{Q_i} = 16\%,\ \sigma_{Q_e} = 15\%,\ \sigma_{\Gamma} = 28\%$



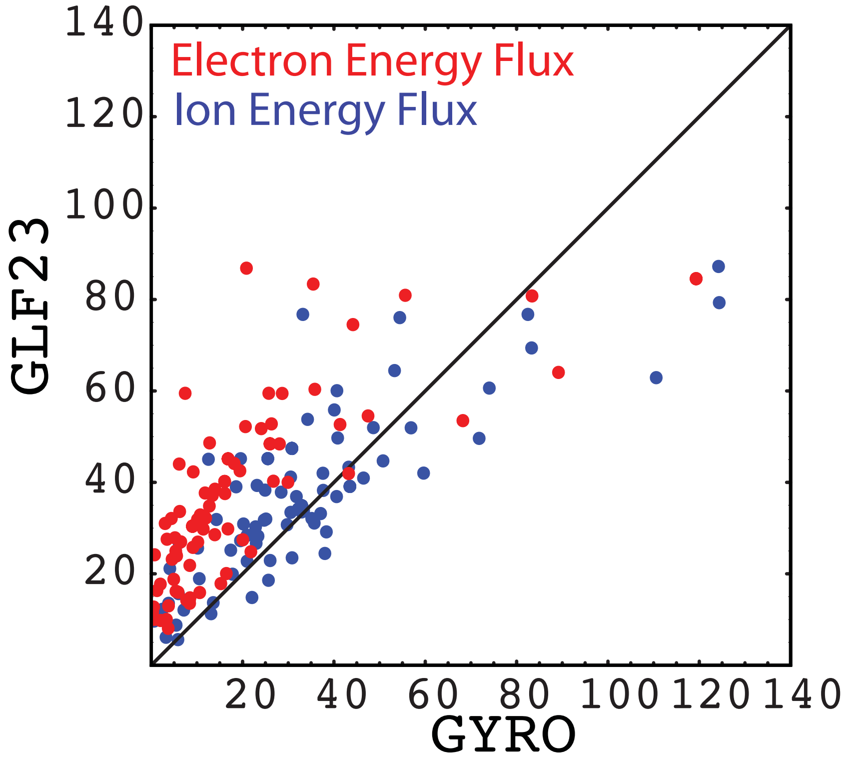


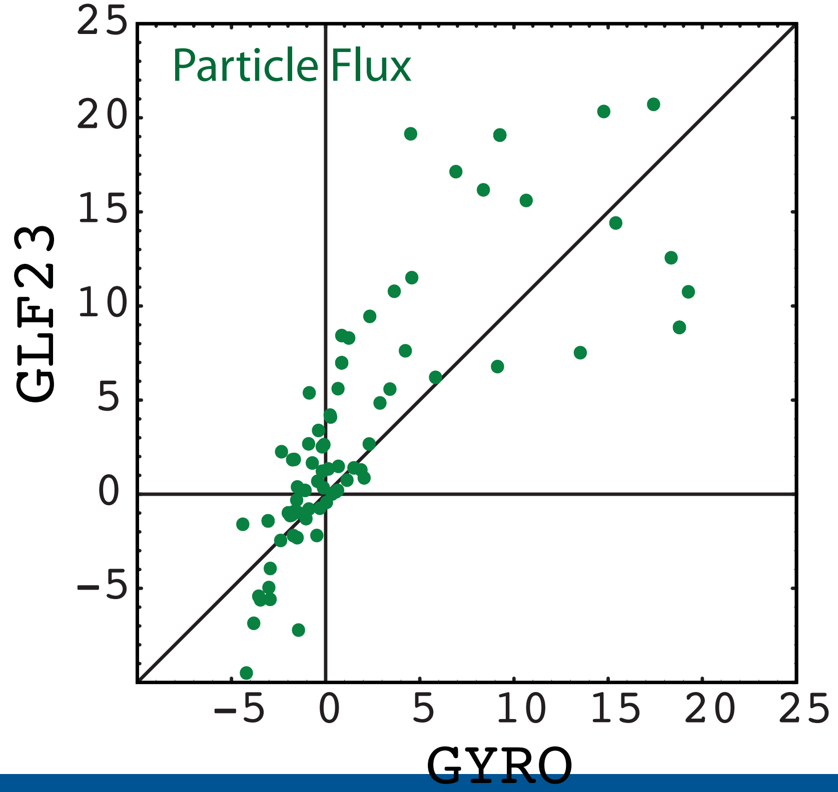
GLF23 Fluxes Are a Poor Fit to GYRO

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

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

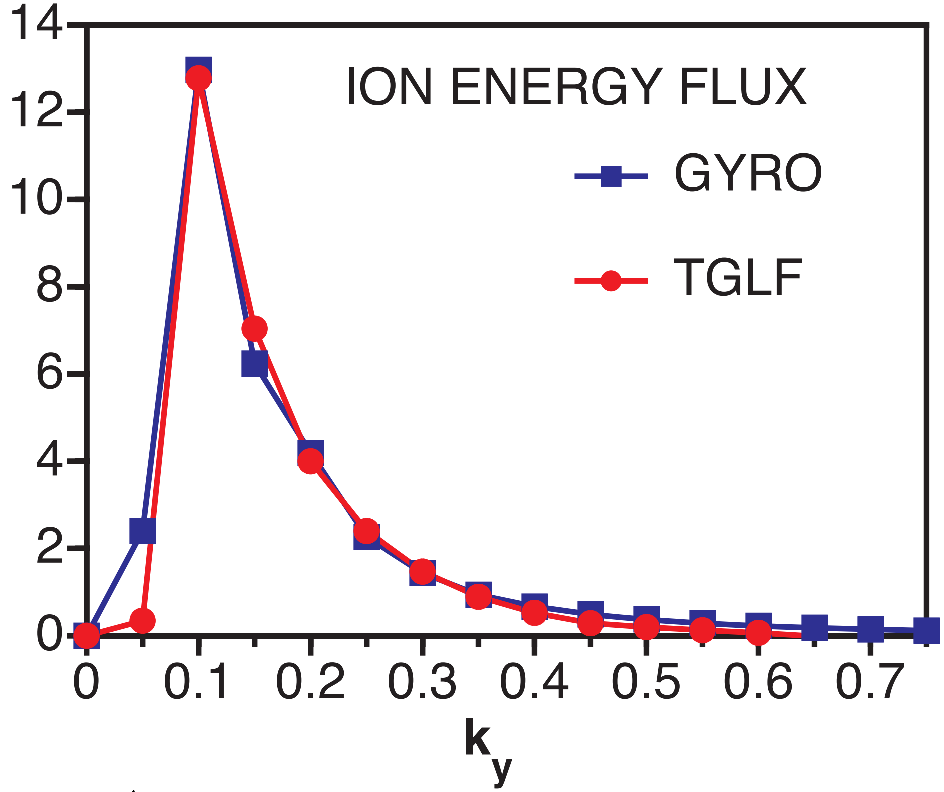
- **GLF23 is systematically high, especially for the electron energy flux**

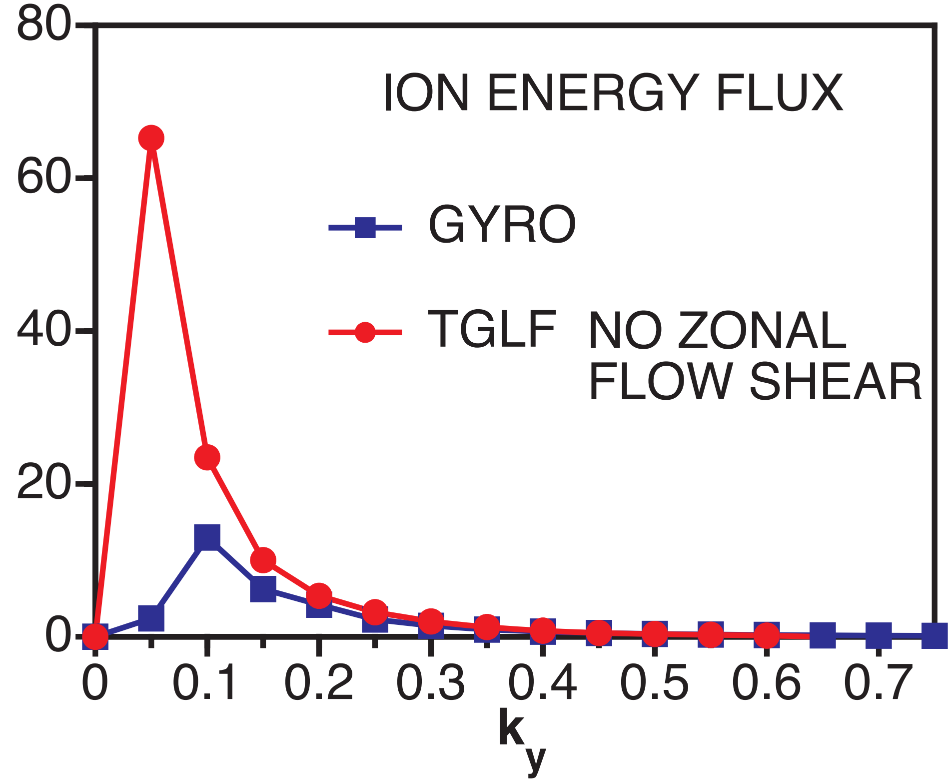




Quasi-linear TGLF Fits the GYRO Flux Spectrum Well

- The detailed shape of the ion energy flux spectrum is well fit by the TGLF model
- The lowest k_y modes are suppressed by the "zonal flow" shear model as can be seen below with $\alpha_{ZF} = 0$

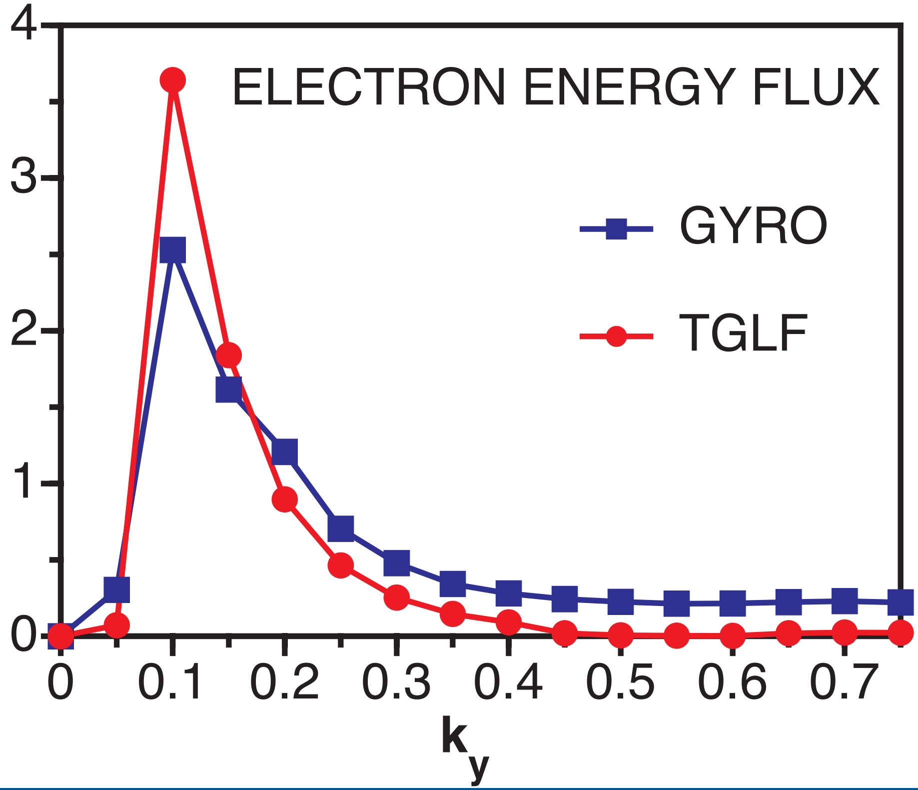


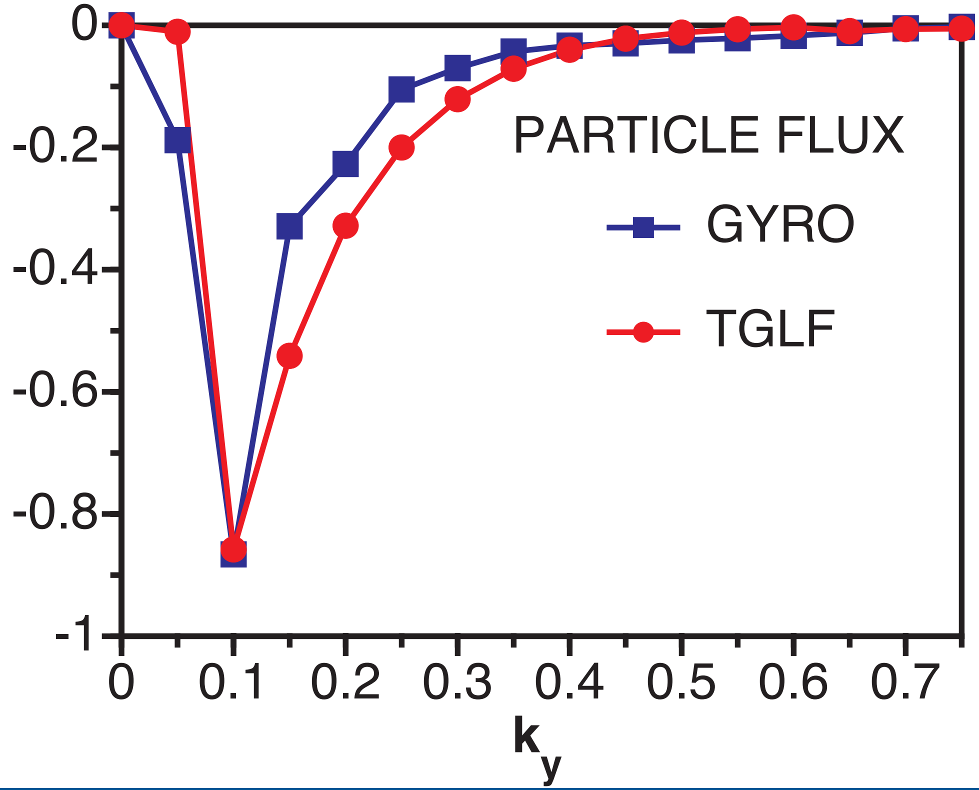


$$\mathrm{STD} = \left(a/L_{n_e} = a/L_{n_i} = 1,\ a/L_{T_e} = a/L_{T_i} = 3,\ T_i/T_e = 1,\ q = 2,\ \hat{s} = 1,\ \alpha = 0,\ r/a = 0.5,\ R/a = 3.0\right)$$

Spectral Fits Are Good for All Channels

- **The electron energy flux spectrum is generally fit about as well as the ion energy flux spectrum**
- **The particle flux spectrum is best fit when the particle flux is not close to zero**

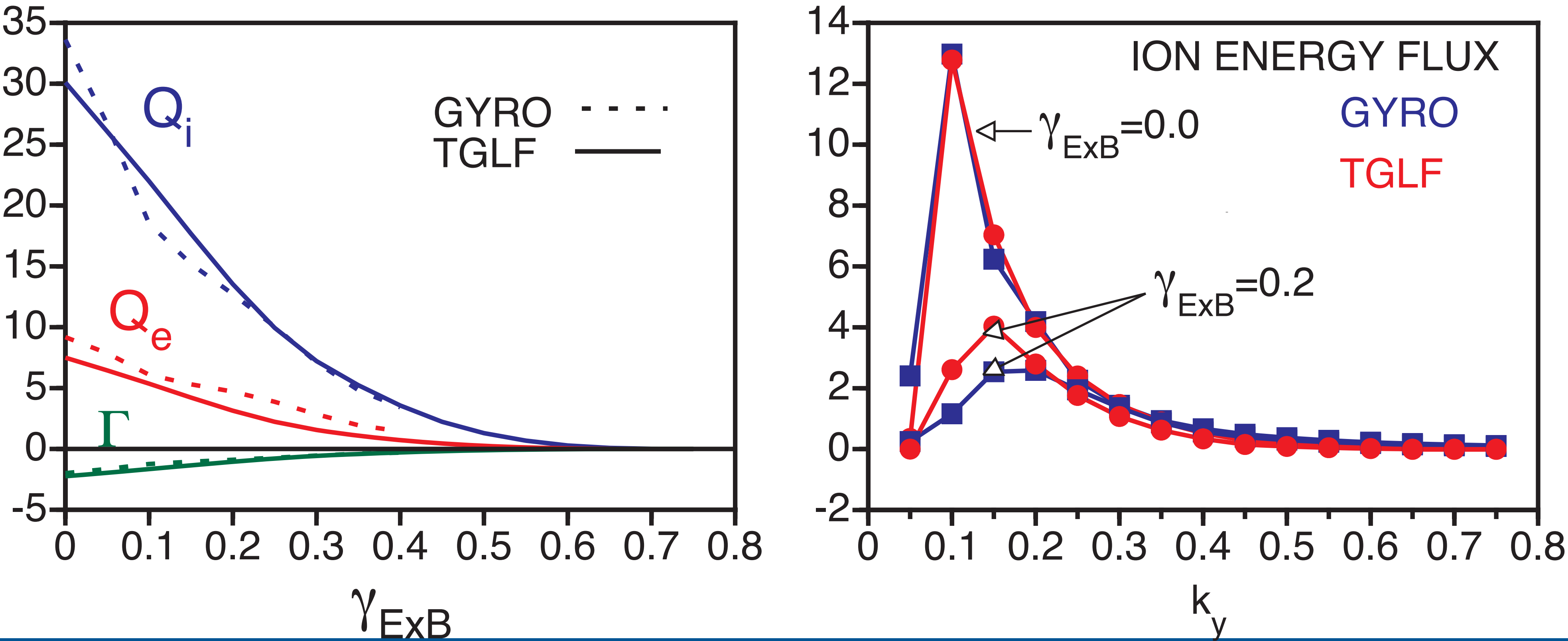




E×B Shear Quench Rule Agrees With GYRO

- **The linear subtraction of the ExB shear from the growth rate is a good model of the reduction in total flux**

- **Even the change in the flux spectrum is fairly well fit**



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TGLF is an Accurate Model of Gyro-Kinetic Theory

- **A new Trapped Gyro-Landau Fluid (TGLF) system of equations has been developed that yields a fast, accurate approximation to the linear eigenmodes of gyro-kinetic driftwave instabilities with comprehensive physics**
  - A TGLF eigenmode code is available for stability analysis of experimental discharges

- **A quasi-linear transport model using TGLF eigenmodes and a local model for the saturated fluctuation intensity achieves an excellent fit to a large database of non-linear gyro-kinetic turbulence simulations using the GYRO code**
  - Extension of the intensity model to high-k ETG modes will use the latest coupled ITG/TEM-ETG GYRO simulations. (Waltz and Candy)

Will TGLF Predict the Transport in Experiments?

- **Transport predictions of the TGLF transport model will be tested in conventional tokamaks, low aspect ratio spherical tori and the near separatrix region.**
  - This will be a true test of the first principles gyro-kinetic theory foundation of the TGLF model
  - Prediction of the pedestal width in H-mode is a high priority
  - Prediction of transport in ITER

- **Planned extensions of TGLF include:**
  - General geometry from numerical MHD equilibrium instead of the Miller model which is needed for the pedestal
  - Intensity models that include mode coupling (non-local in wavenumber) and turbulence spreading (non-local in space)
  - Inclusion of equilibrium parallel and ExB velocity shear in the linear eigenmodes (beyond the quench rule)