Advances in Validating Gyrokinetic Turbulence Models Against L and H-Mode Plasmas

by

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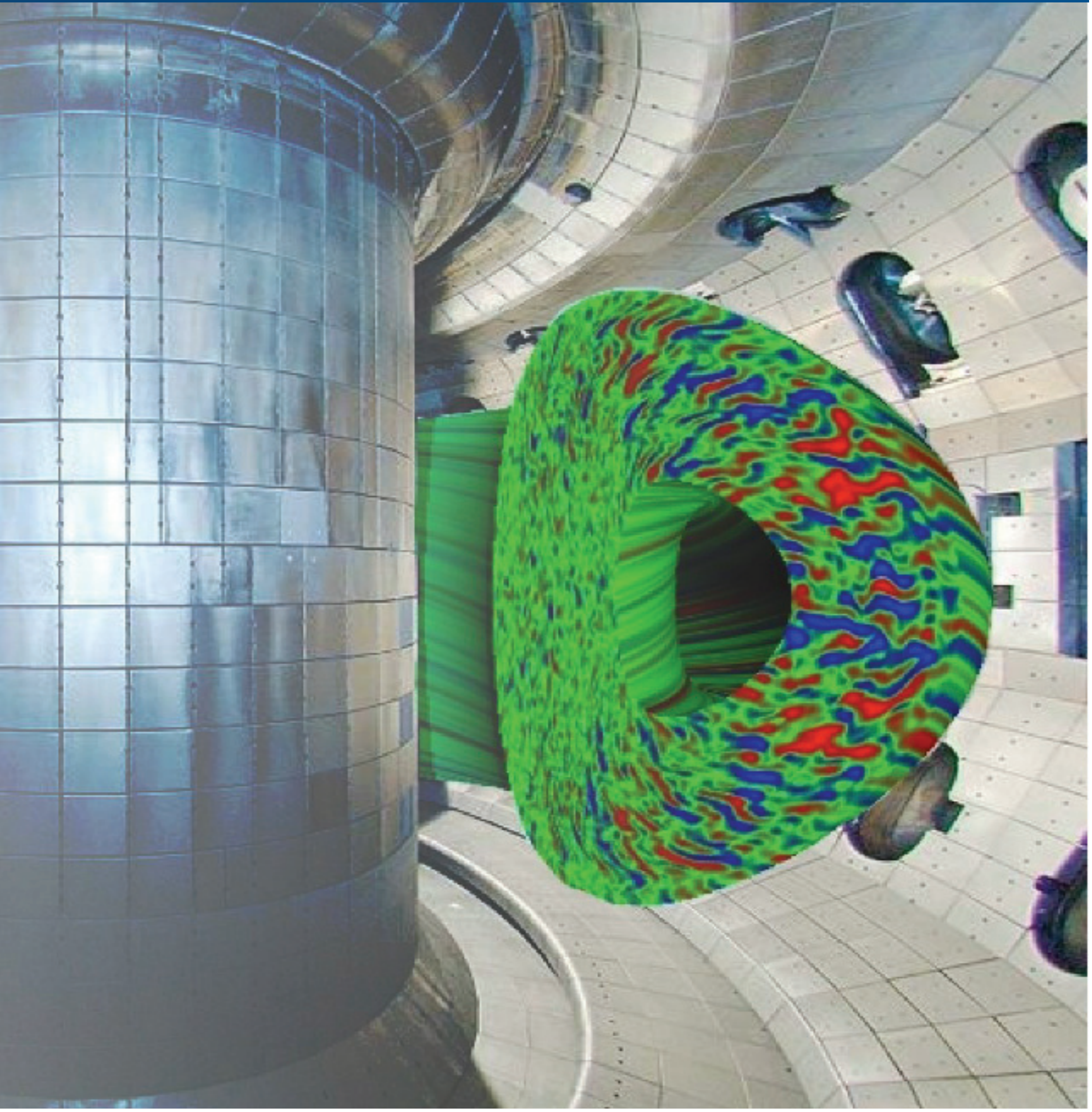

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Introduction

- **The development of validated turbulent transport models is essential for predicting the performance of ITER and other future reactor devices with confidence**
- **Robust validation requires that the model(s) being considered be tested against experiment at multiple levels, across a range of conditions**
  - For turbulent transport, need to test predictions of underlying turbulence characteristics such as amplitudes and spectral shapes, not just fluxes
- **Towards this end, a series of detailed experiments have been performed at the DIII-D facility**
  - Each experiment has focused on not just measuring turbulent quantities, but also their scalings with key parameters: plasma elongation, T_e/T_i, heating power, etc.
- **In this talk, results of two representative cases are presented:**
  - A L-mode elongation scaling experiment
  - A quiescent H-mode (QH-mode) electron power scan experiment

Outline

1. **Comparison of model predictions against an L-mode elongation experiment**

2. **Addressing systematic uncertainties via transport solution profiles**

3. **Initial results of GYRO simulations of a QH-mode electron power scan**

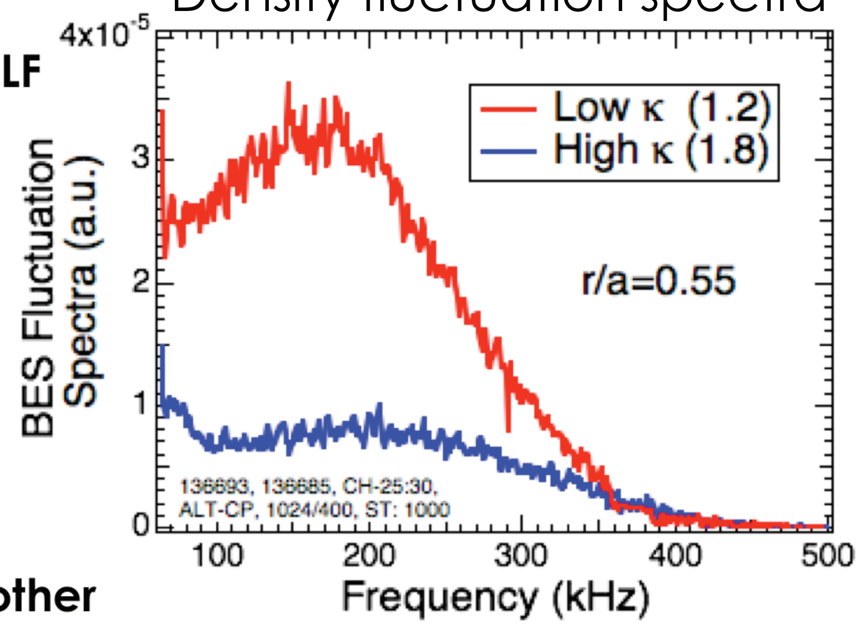
Experimental Motivation: Testing Elongation Scaling Predicted by TGLF and GYRO Studies

- Kinsey *et al* [2007 PoP] found that use of Miller geometry representation led to GYRO and TGLF turbulent diffusivities χ roughly scaling with elongation κ as

$$\chi \propto \kappa^{-1/3} s_\kappa^{-2/3}$$

$$s_\kappa = r d \ln \kappa / dr$$

Density fluctuation spectra

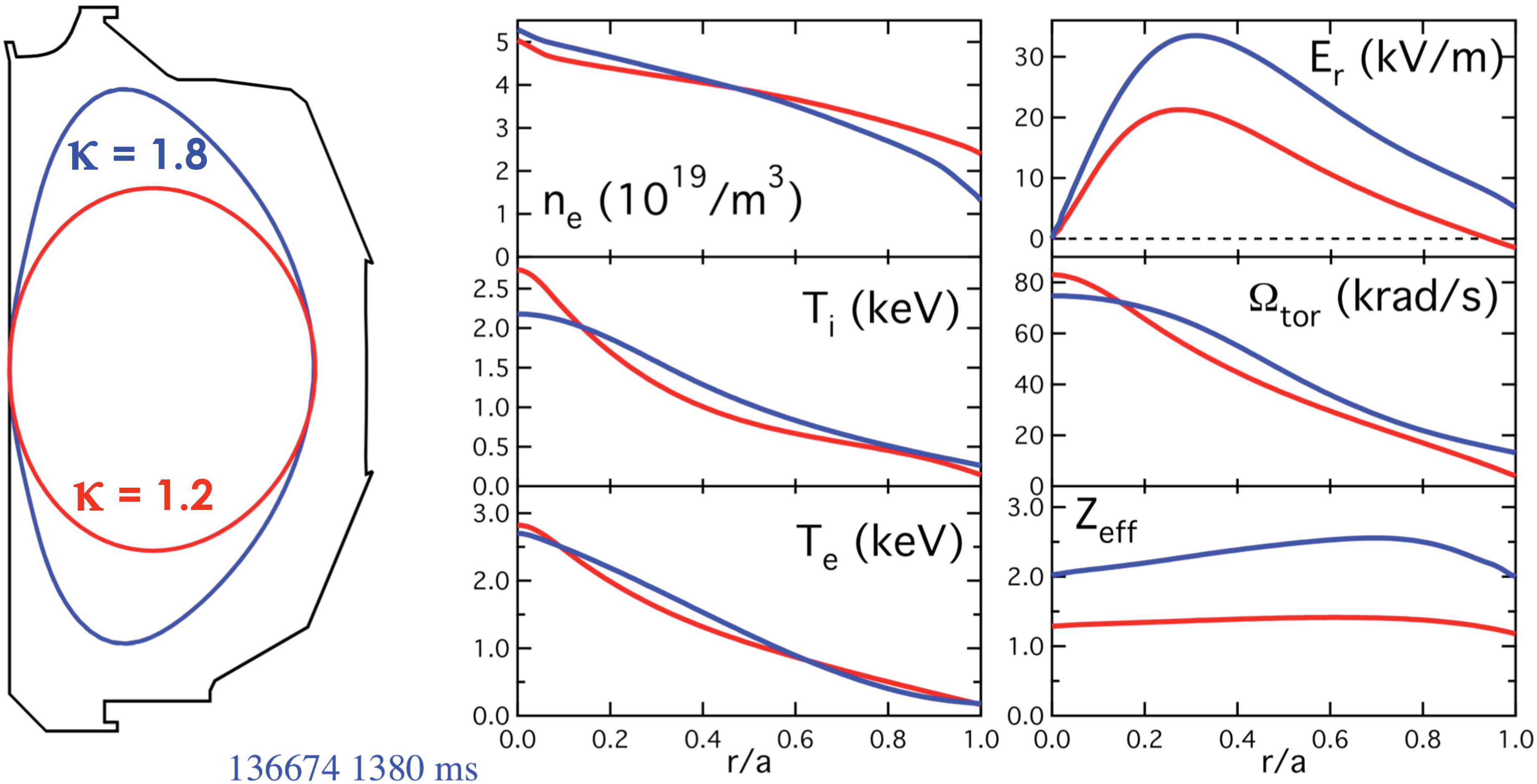


- Since this was a strong effect not included in other models which used a simple s-α representation, an experiment was designed in 2008 to measure a broad spectrum of turbulence quantities at various elongations

- Experimentally observed order of magnitude increase in fluctuation power and 50% decrease in confinement time with a 50% decrease in κ, qualitatively consistent with model predictions

Obtain Relatively Well-matched Equilibrium Profiles with 50% Variation in κ

- Obtaining this level of profile matching required twice the heating in the low κ case as for high κ
- Profiles of density and T_e fluctuations measured across outer half of each plasma



136674 1380 ms
136693 1380 ms
$B_T = 2.1$ T

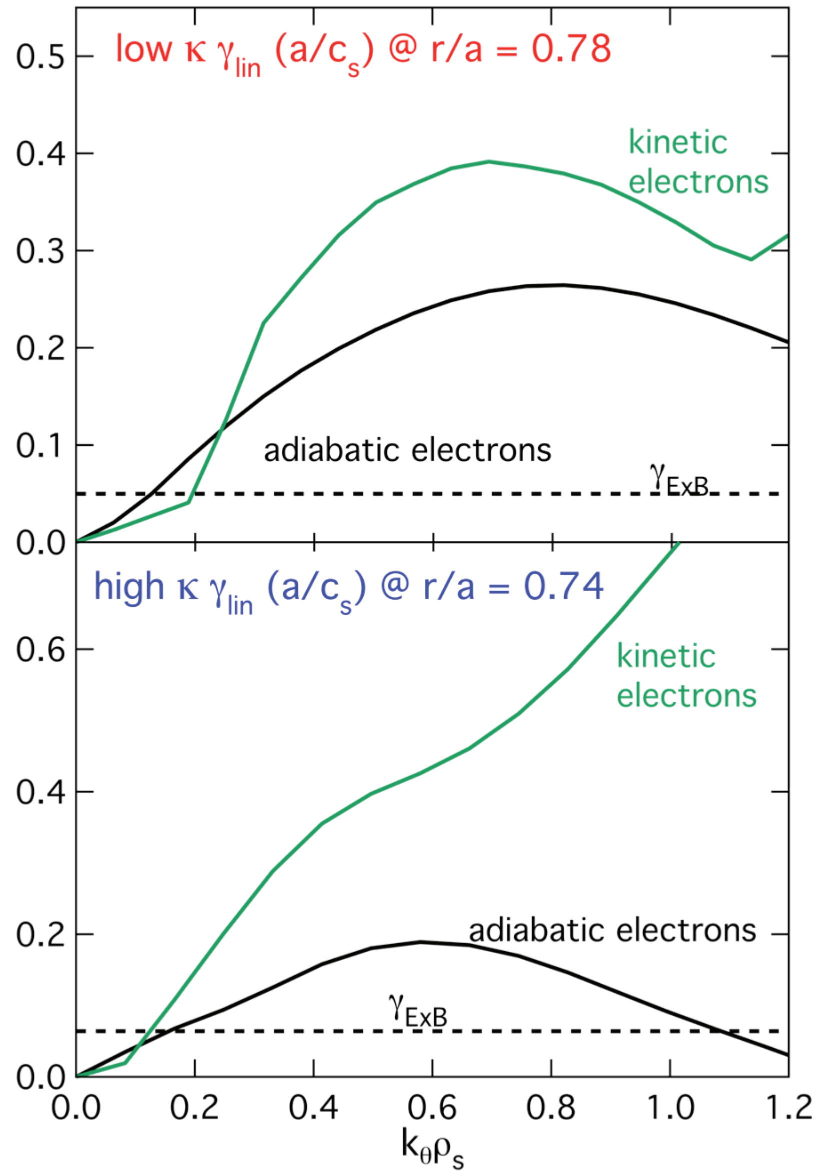
Predict Turbulence and Transport Statistics with the Nonlinear Gyrokinetic Code GYRO

- **GYRO is a δf initial value Eulerian (continuum) 5D gyrokinetic code**
  - Documentation at: http://fusion.gat.com/theory/Gyro
- **Implements the (minimal) necessary ingredients for quantitatively accurate core transport predictions in real plasmas**
  - takes measured experimental profiles as inputs
  - equilibrium sheared ExB and toroidal rotation profiles
  - shaped geometry (Miller formulation)
  - trapped and passing electrons
  - electron pitch angle scattering collisions
  - finite β effects (magnetic fluctuations)
- **Results presented in this talk are from local GYRO simulations unless otherwise noted**
  - Solve rigorous limit $\rho_s/a \to 0$ limit of gyrokinetic-Maxwell equations
  - **Physical picture:** turbulence properties at a given radius only depend upon the local dimensionless parameters at that radius

Identify Key Physics Components for Validation Via Examination of Linear Growth Rates

- **Growth rates calculated via identification of fastest growing modes in GYRO**

- **Typically find that kinetic electrons will can increase low k_θ growth rates by factor of 2 or more relative to adiabatic electron case**



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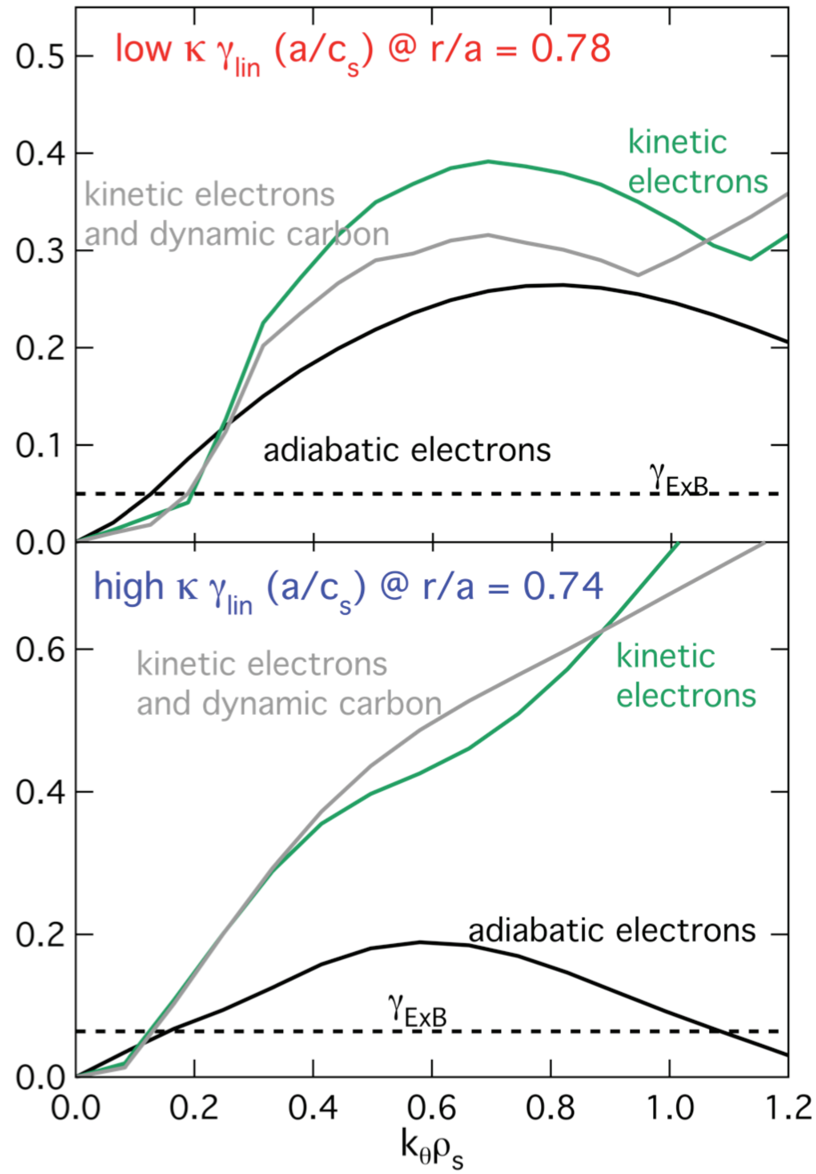
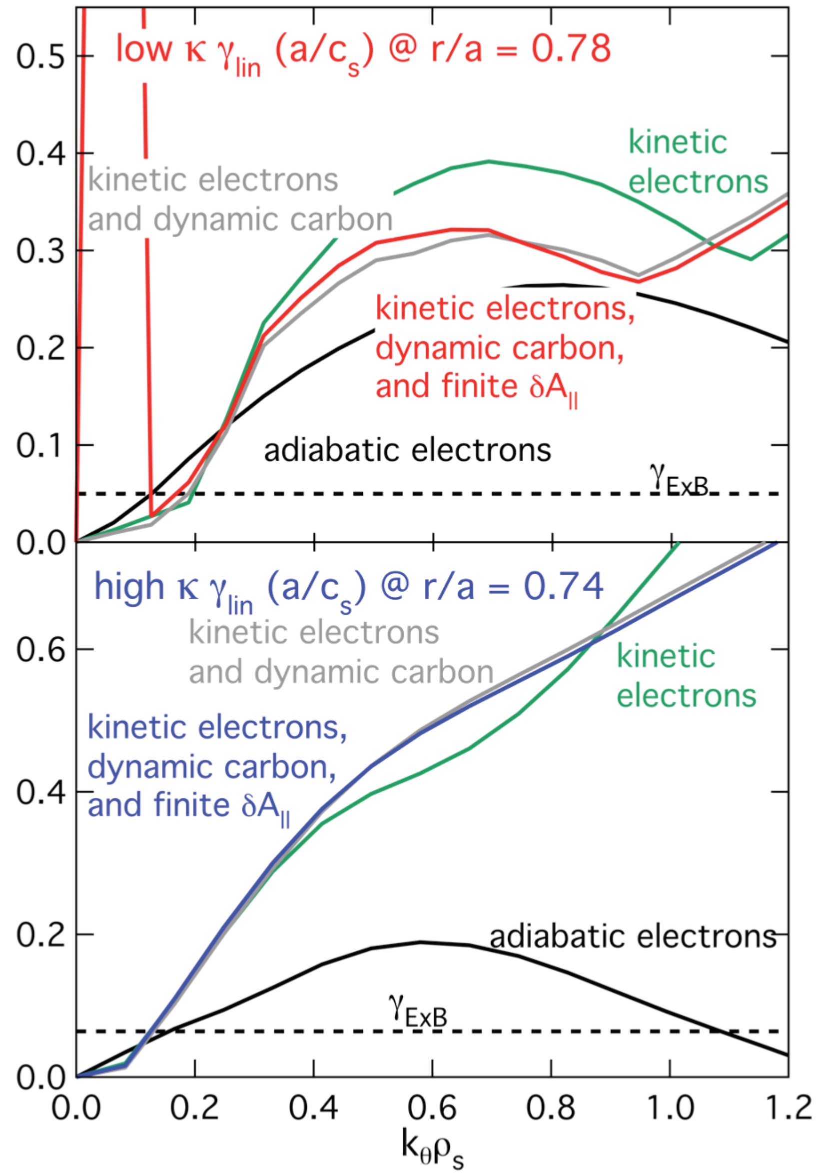
Identify Key Physics Components for Validation Via Examination of Linear Growth Rates

- **Growth rates calculated via identification of fastest growing modes in GYRO**
- **Typically find that kinetic electrons will can increase low k_θ growth rates by factor of 2 or more relative to adiabatic electron case**
- **Inclusion of dynamic carbon ions can significantly stabilize ITG modes (low κ), destabilize long-wavelength TEM modes (high κ)**



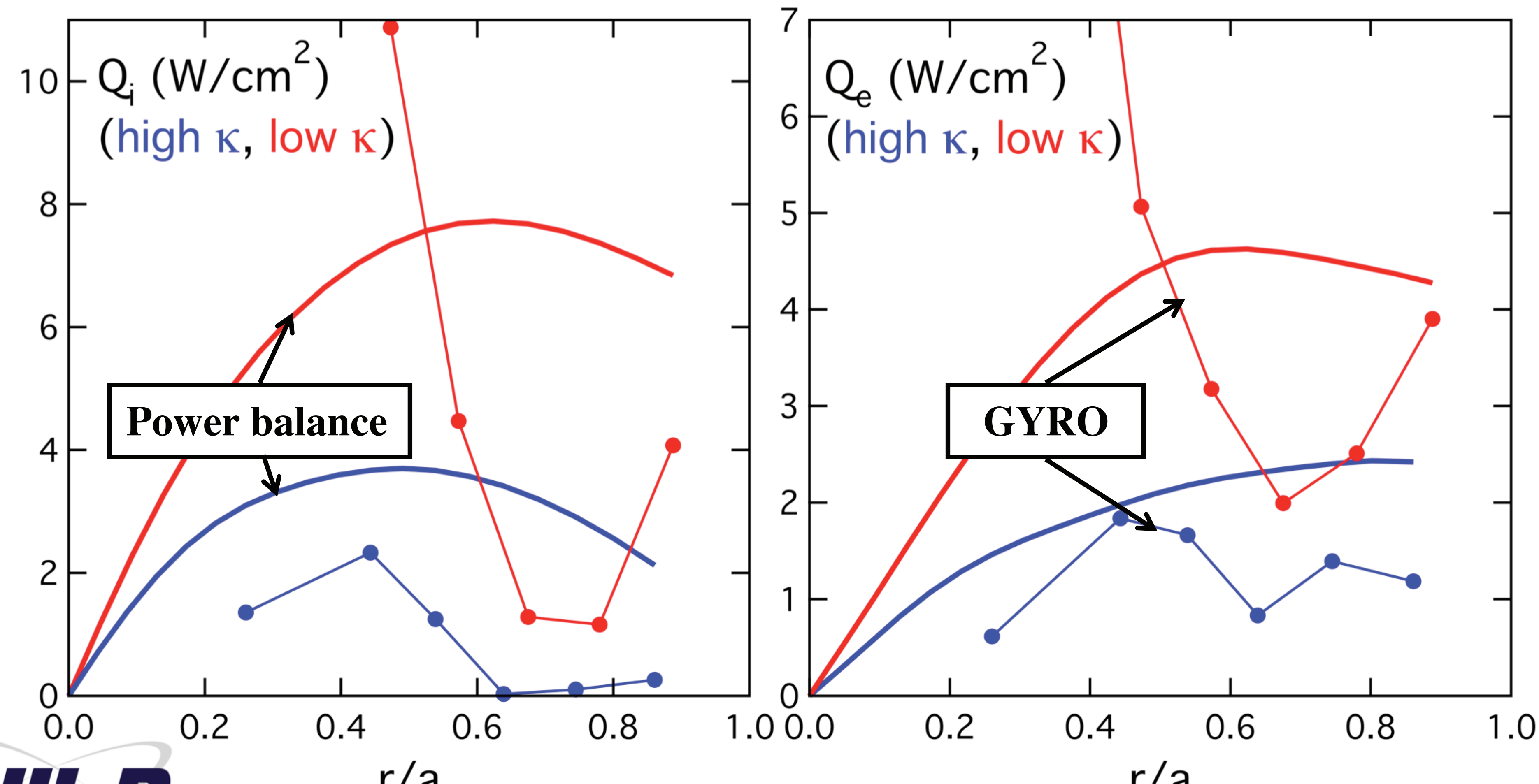
Identify Key Physics Components for Validation Via Examination of Linear Growth Rates

- **Electromagnetic (finite $\delta A_{||}$) effects generally only make a small impact at large r/a on linear growth rates, but can lead to numerical issues for standard resolutions**
  - **ex: spike at $k_\theta\rho_s$ = 0.07 in low κ scan is a numerical instability caused by interaction of EM physics + collisions**
  - Numerical issues can be resolved by increasing collision operator grid resolution
  - Finite EM can have stronger effect at smaller r/a (stabilizes core ITG modes)
- **Simulations results presented in this talk include dynamic carbon ions but not EM effect**



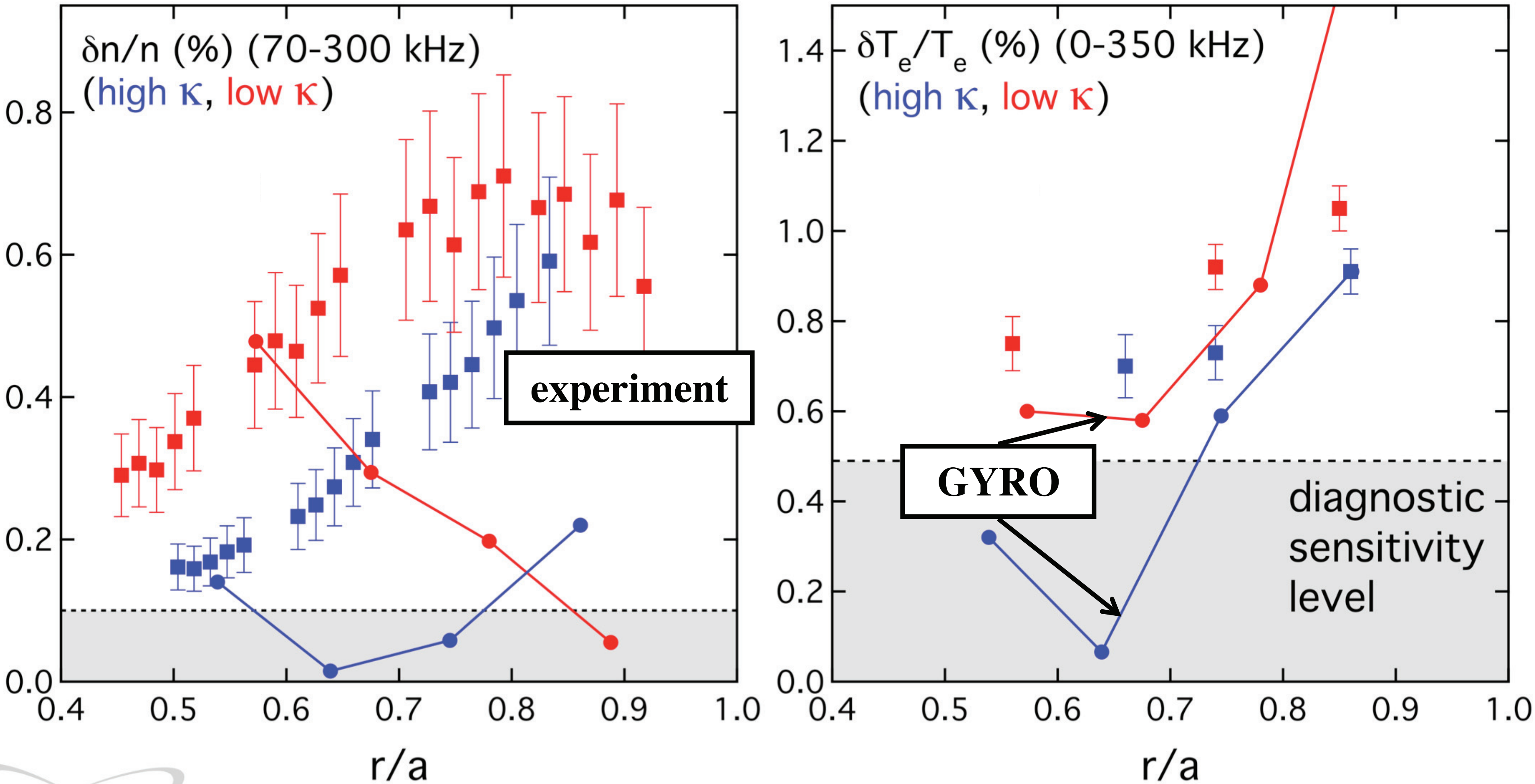
GYRO Flux Predictions Consistent With Global Experimental κ Scaling, But Not Trends in r/a

- **High κ simulations systematically underpredict fluxes**
  - Transition from ion to electron mode dominated at r/a =0.62
- **Low κ simulation at r/a = 0.25 predicts $\{Q_i,Q_e\} = \{50.9,17.1\}$ W/cm²**



Gyro-predicted Fluctuations Exhibit Similar Trends As Corresponding Fluxes

- **GYRO results are full synthetic BES and CECE calculations to include spot size effects and finite frequency integration ranges**



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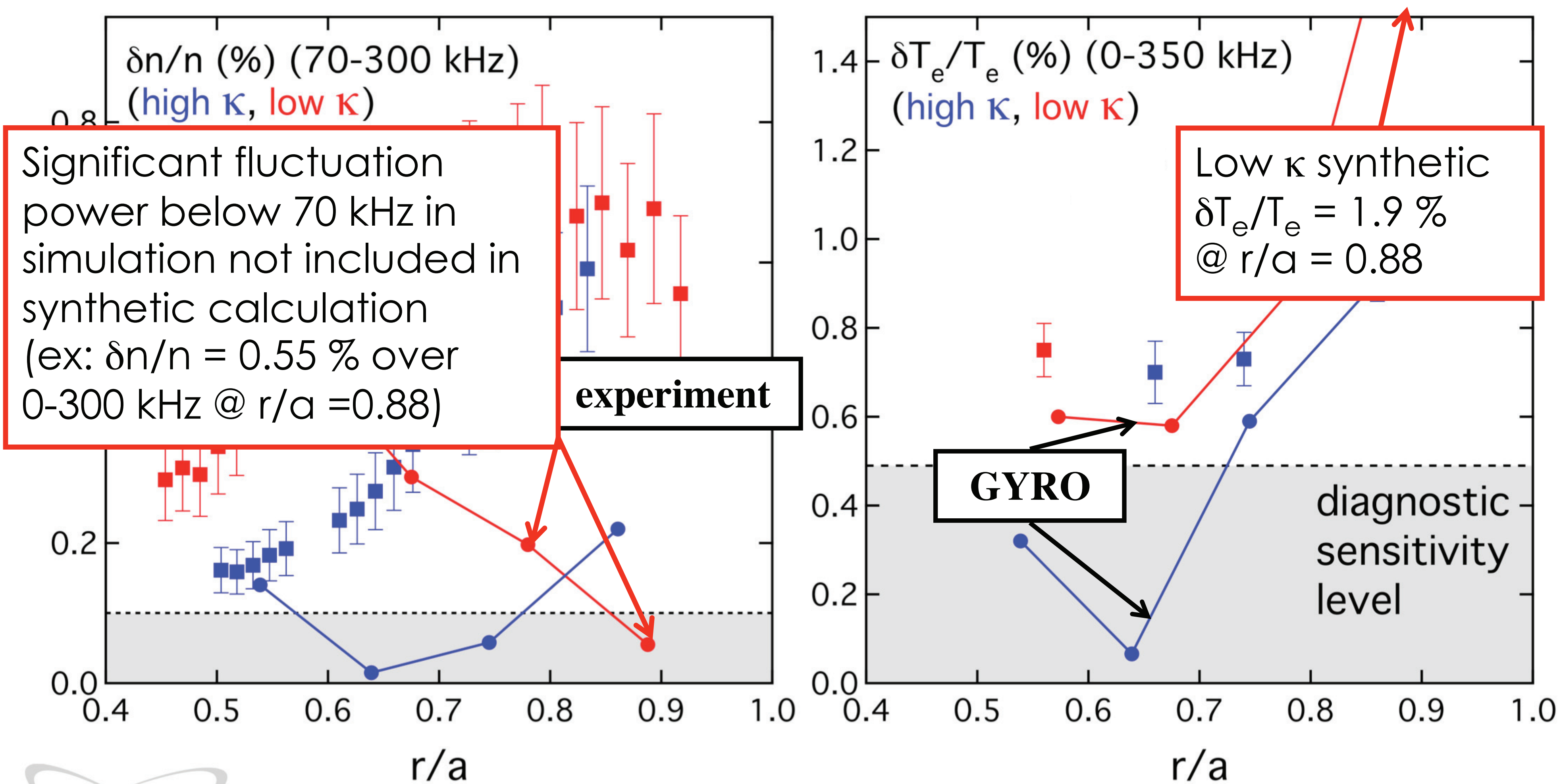

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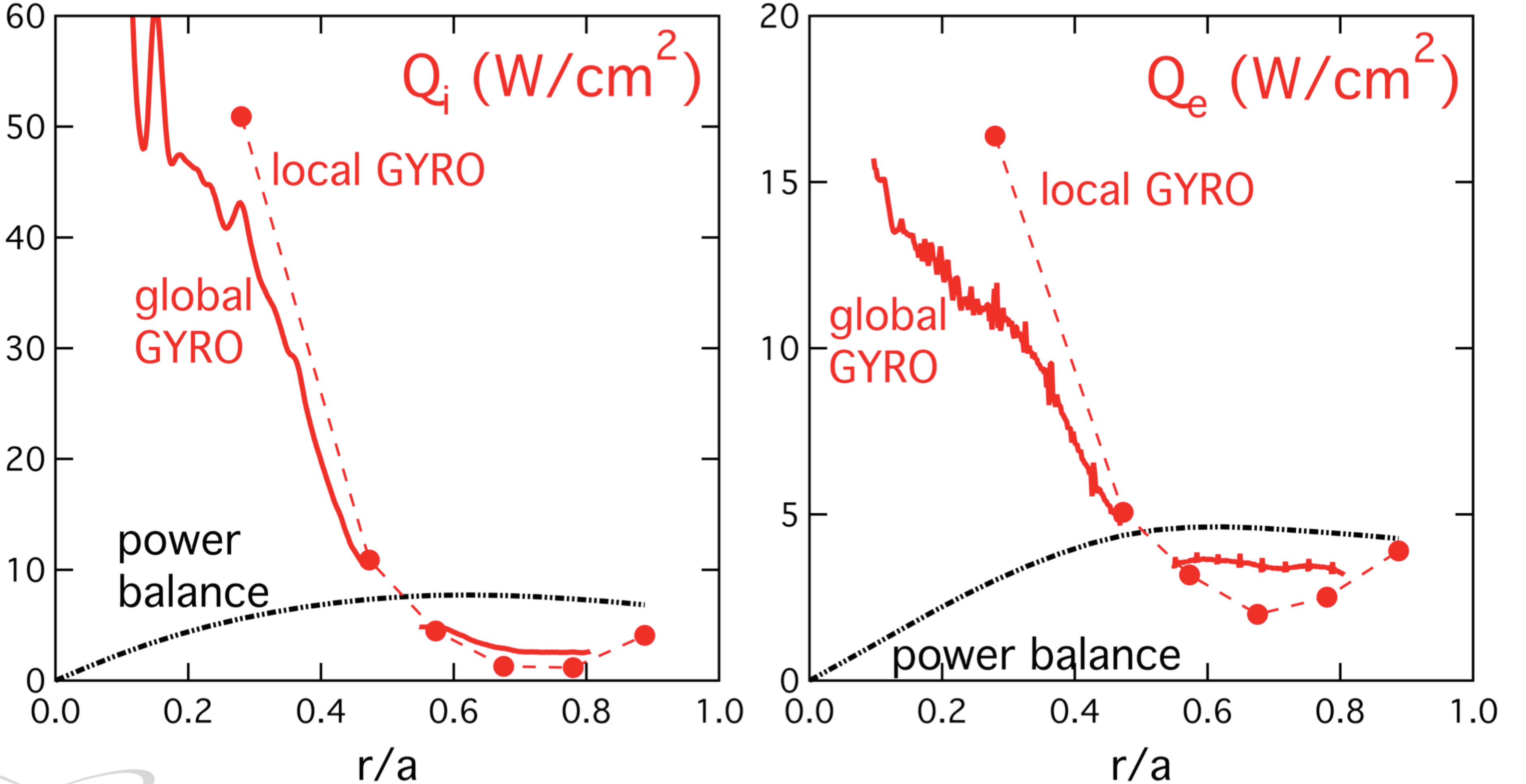
Nonlocal Effects Do Not Appear To Resolve Discrepancies of Low κ Transport Predictions

- **Preliminary** electrostatic single-ion global simulations yield similar magnitudes, trends in r/a as local simulations



Systematic and Bias Uncertainties Dominate Statistical Uncertainties in Well-posed Validation Analysis

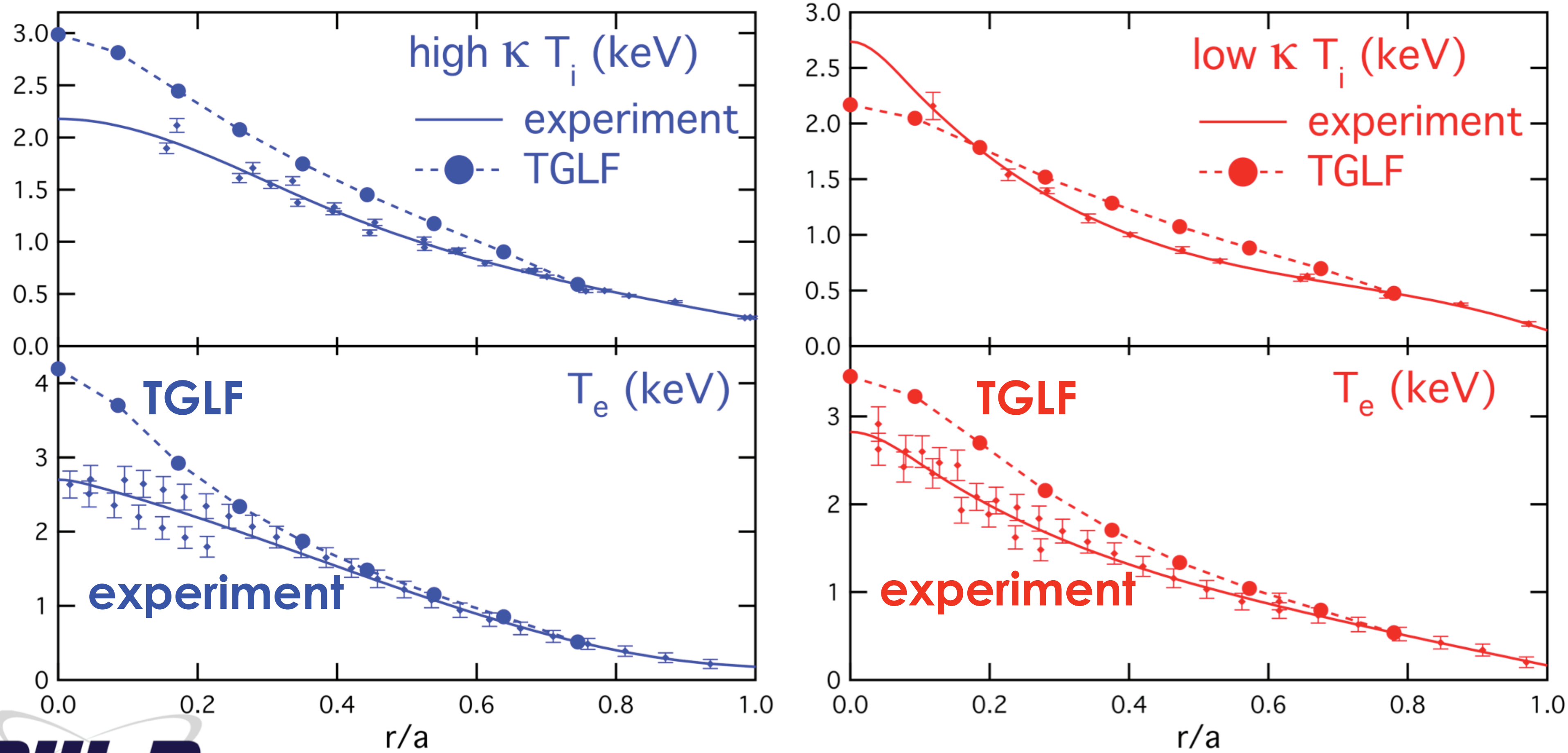
- **Statistical uncertainties in model results arise from**
  - Finite time-averages of initial value simulations
  - Propagation of statistical uncertainties of input parameters (e.g. experimental profiles) into model output
  - Both can be minimized by use of appropriate averaging windows

Examine Systematic and Bias Uncertainties by Using TGLF-calculated Transport Solution Profiles

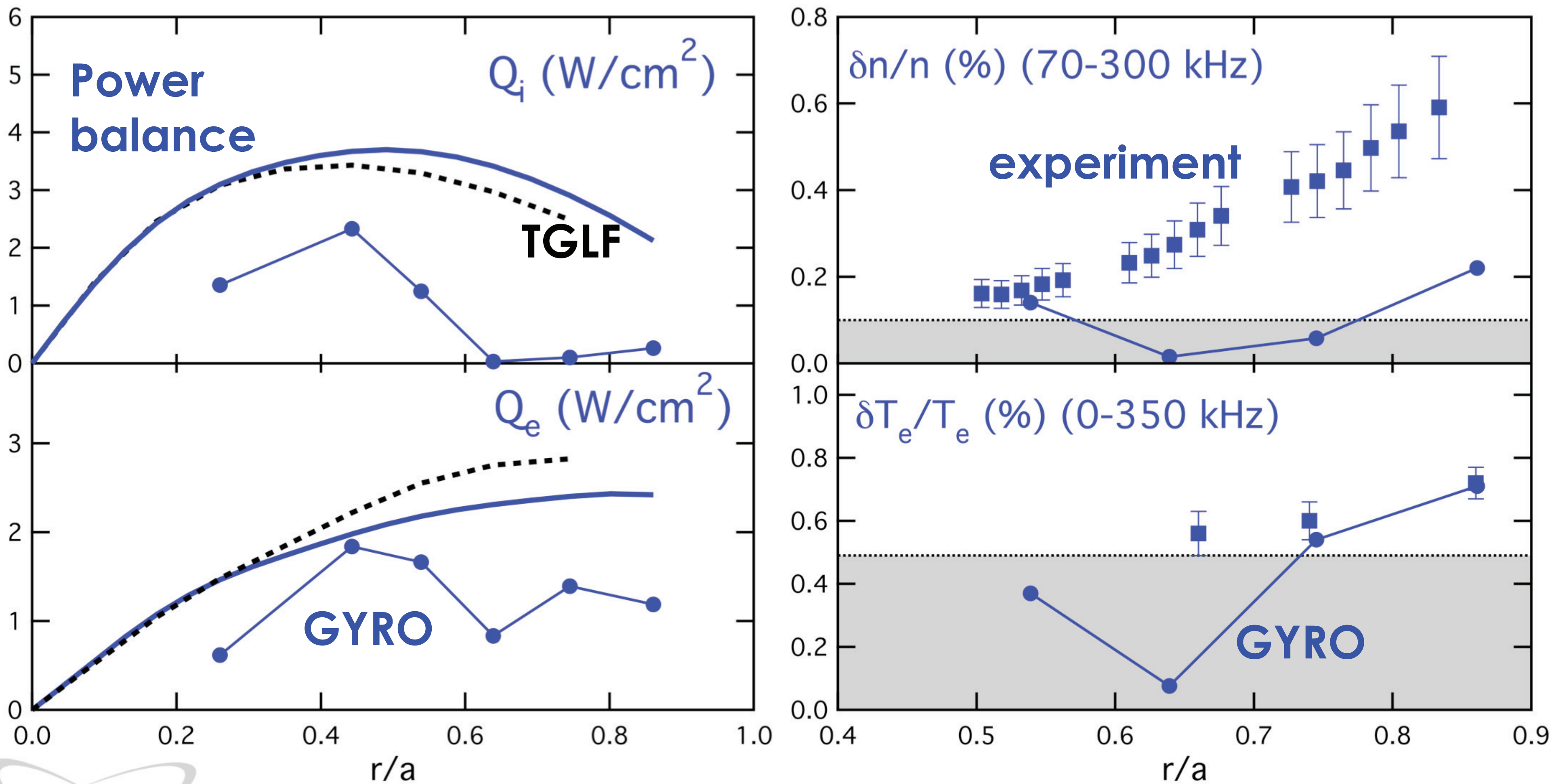
- **To quantify impact of systematic or bias uncertainties in model inputs on model output, we repeat the comparisons using transport solutions calculated with the quasilinear TGLF transport model**
  - Transport solutions are those profiles which when input to a transport model yield predicted transport profiles equal to those calculated via power balance analysis
  - Use the TGLF model here because it is designed to be a computationally efficient tool for calculation of turbulent fluxes which has been verified against a large database of GYRO simulations
  - TGLF ((T)rapped (G)yro-(L)andau Fluid Model) is a quasilinear model which combines cross-phases calculated via linear theory with a nonlinear staturation role derived via a fit to a large database of nonlinear GYRO runs
  - TGLF transport predictions have been verified against nonlinear GYRO simulations over a wide range of parameters with good agreement
  - For clarity, only predict T_i and T_e profiles; hold density and rotation profiles fixed

Calculate Transport Solutions With TGLF Model To Assess Impact Of Profile Stiffness on Comparison

- **Find that TGLF predictions diverge from experiment on-axis, but generally do not strongly differ from experiment at outer radii**
  - Unable to obtain convergence at r/a > 0.8 due to systematic underprediction of fluxes, consistent with previous studies



TGLF Flux Predictions Differ From Power Balance Because of Self-consistent Changes to Collisional Exchange Source Term



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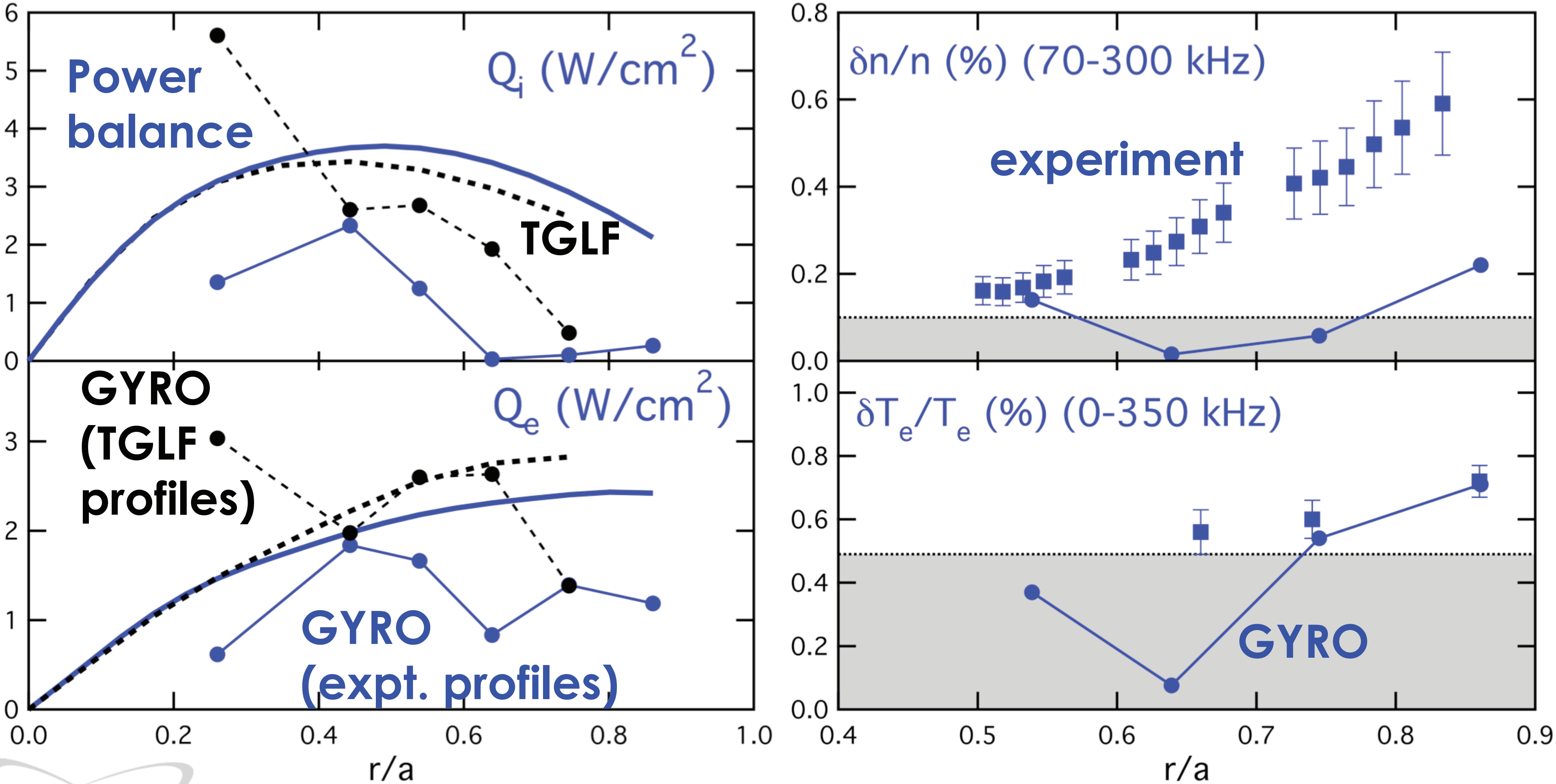
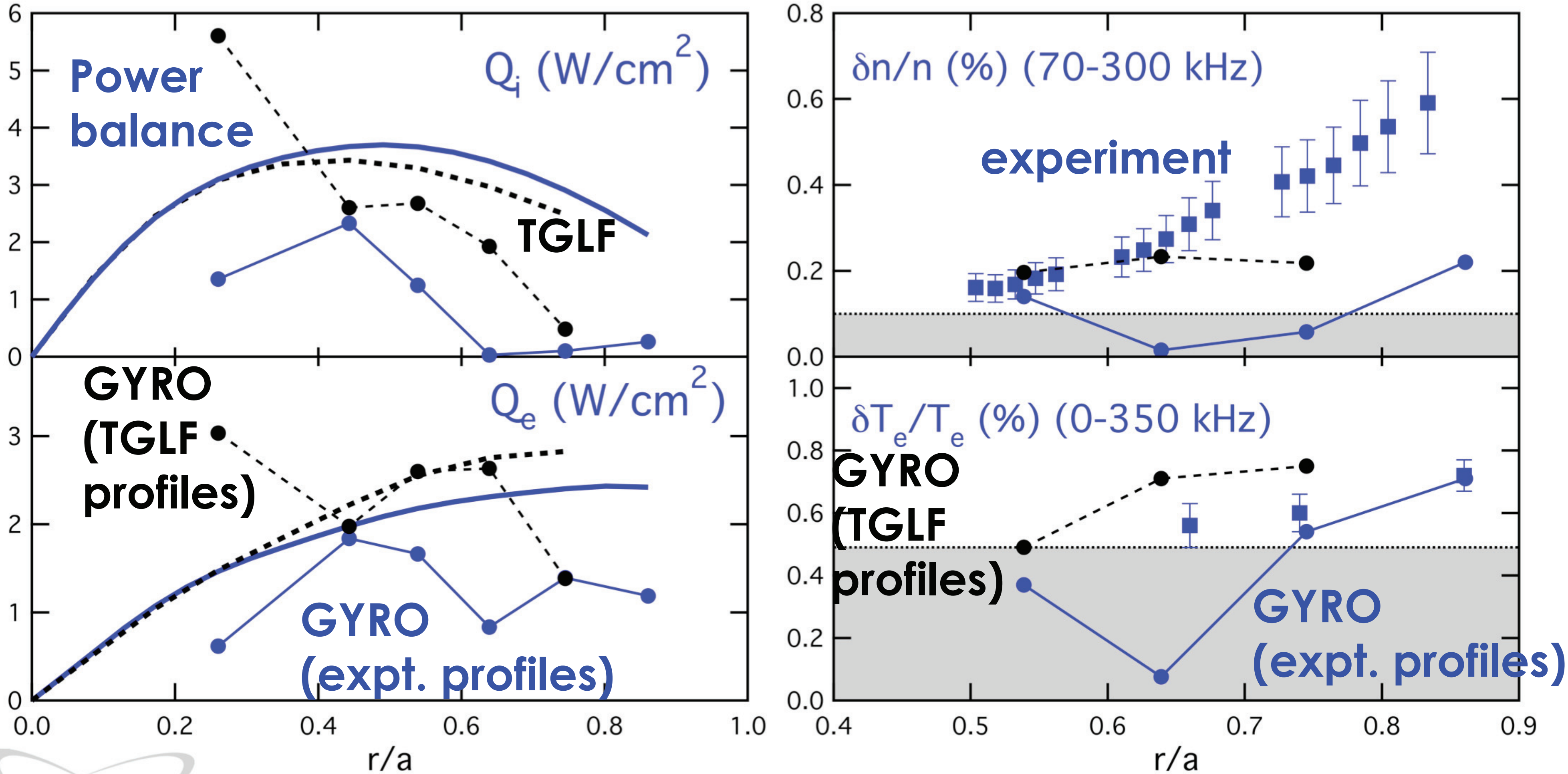
High κ GYRO Predictions Exhibit Increased Agreement with Experiment when Using TGLF Predictions

- Go from underprediction to overprediction at r/a = 0.25
- Good agreement between GYRO and TGLF inside r/a = 0.75
- Surprisingly small response at r/a = 0.75



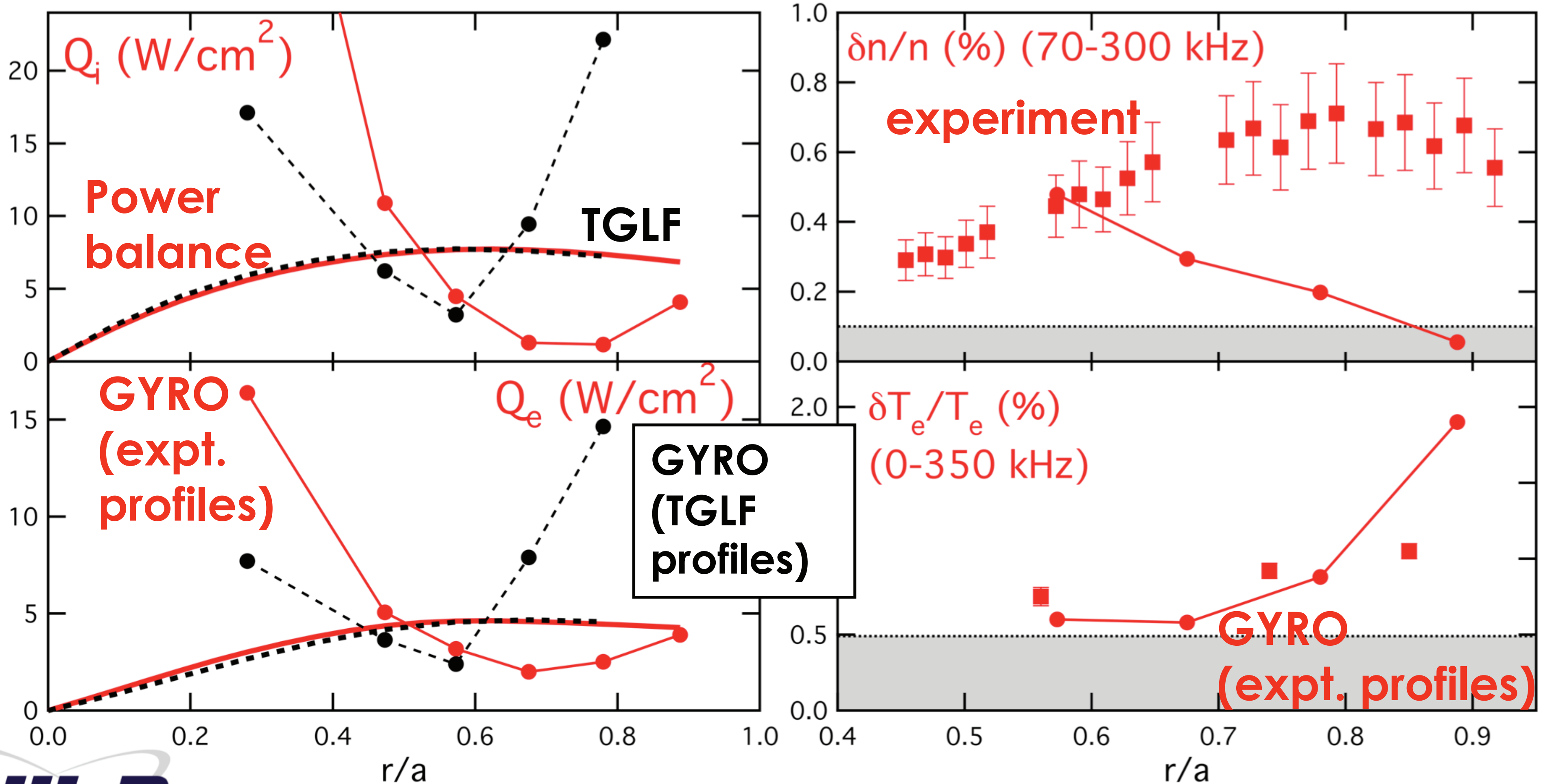
Magnitude and Trend of Predicted Fluctuation Response Follow Flux Response for r/a < 0.75

- **Unclear why δT_e overpredicted, but δn, Q_i, and Q_e underpredicted at r/a = 0.75**
  - Not shown: significant inward pinch predicted for transport solution profiles vs. ~0 particle transport predicted with experimental profiles



Low κ GYRO Simulations Exhibit Significantly Different Responses to Profile Changes than TGLF

- Fluxes reduced but still to high at r/a = 0.25
- Underprediction becomes overprediction at larger r/a
- Little change at mid-radii (where agreement was best using expt. profiles)



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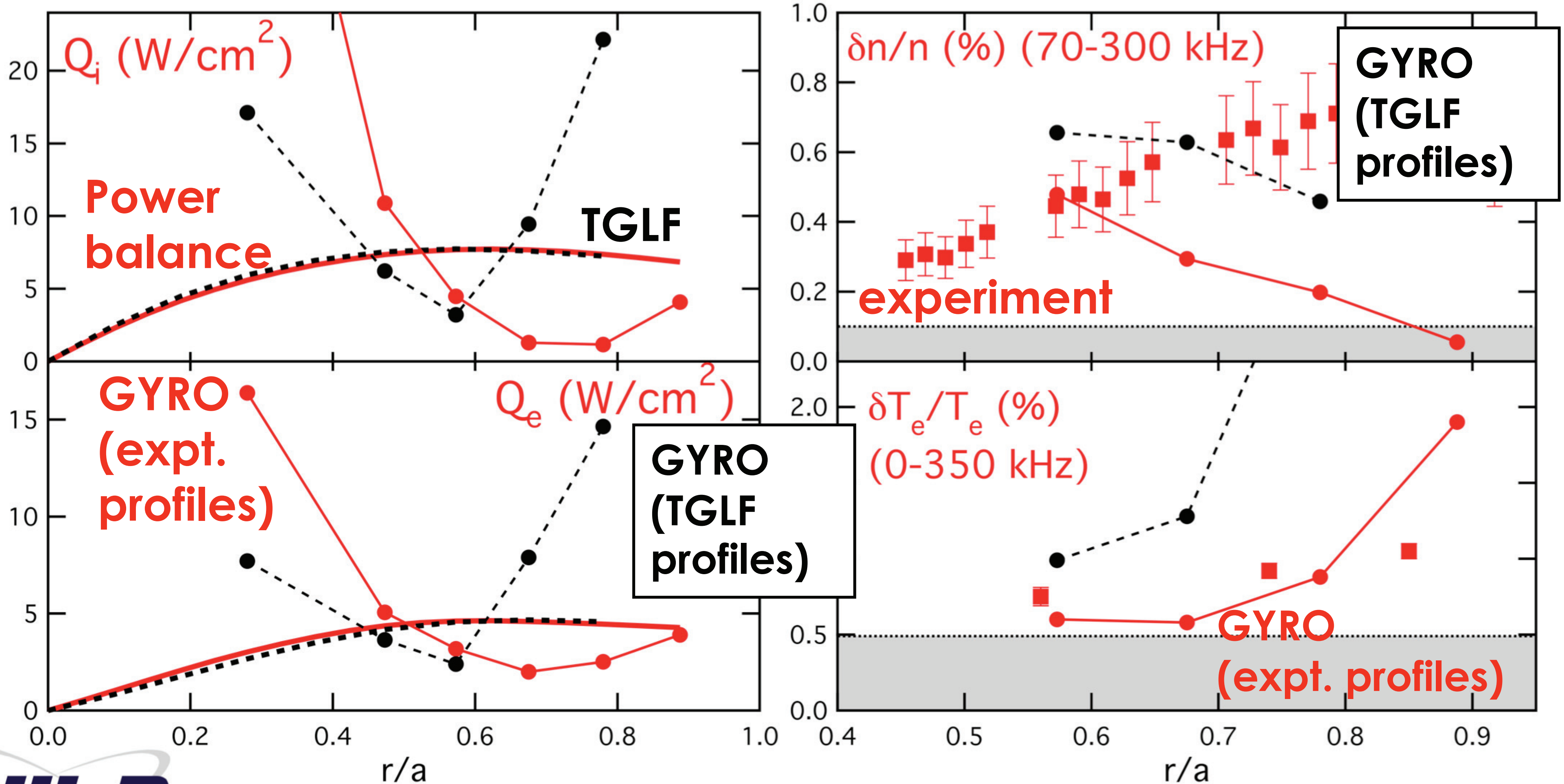
Observe Interesting Anticorrelation Between Density Fluctuation and Energy Flux Responses

- **Temperature fluctuations show similarly large response as fluxes**
  - GYRO predicts $\delta T_e/T_e$ = 3.3% at r/a = 0.78 using flux-matching profiles
- **Further motivation for looking into particle transport**



The Results Presented Here are Only the First Steps of the Full Range of Planned Validation Exercises

- **We find that there are systematic discrepancies between GYRO predictions of turbulence and transport levels and experiment, which cannot be resolved by using TGLF-calculated transport solution profiles**

- **While the results presented here yield some intriguing and hard-won lessons in model validation, much more work remains:**
  - Calculating self-consistent transport solutions with GYRO instead of TGLF (and comparing to both experiment and TGLF)
  - Testing predictions of particle and momentum transport on equal-footing with energy fluxes
  - Exploring relative sensitivities of density, temperature fluctuations in greater detail
  - Assessing the impact of electromagnetic effects
    - Linear theory suggests they should be small, but numerics of nonlinear simulations remains challenging

Testing Transport Predictions in Qh-mode Plasmas

- **Most previous validation studies using nonlinear turbulence simulations have focused upon Ohmic and L-mode conditions**
  - Generally exhibit high turbulence levels with high signal-to-noise, little to no MHD activity which can complicate analysis

- **However, in order to extrapolate to ITER or other future reactor-scale devices with confidence, assessing the fidelity of current models in H-mode plasmas is essential**

- **Towards this end, an initial H-mode validation experiment was performed using quiescent H-mode (QH-mode) plasmas**
  - Chose QH-mode plasmas because they are very stationary plasmas with no ELMs or sawteeth; EHO is localized to $r/a > 0.8$
  - Performed an electron power scan by adding 2.8 MW on-axis ECH power to a standard NBI-heated QH-mode discharge

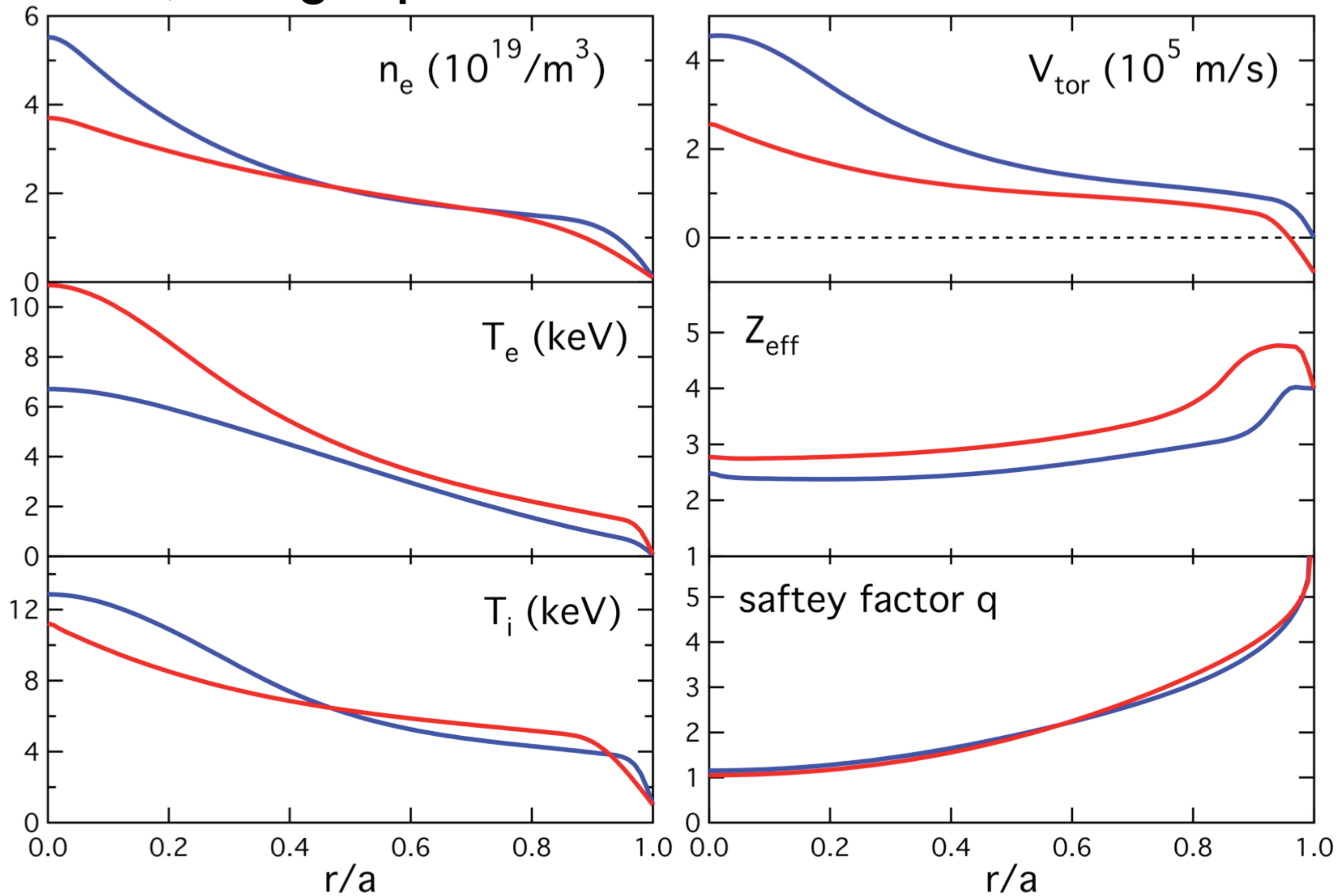
Addition of ECH To Qh-mode Allows for On-axis $T_e \approx T_i \approx 11$ Kev

- **Initial local simulations performed at r/a = 0.6**
- **Linear scans exhibit similar sensitivities as L-modes: very weak sensitivity to EM effects, strong impact of kinetic electrons and impurities**

Injected Power

141397 4125 ms
6.9 MW NBI

141407 4125 ms
6.9 MW NBI
2.8 MW ECH



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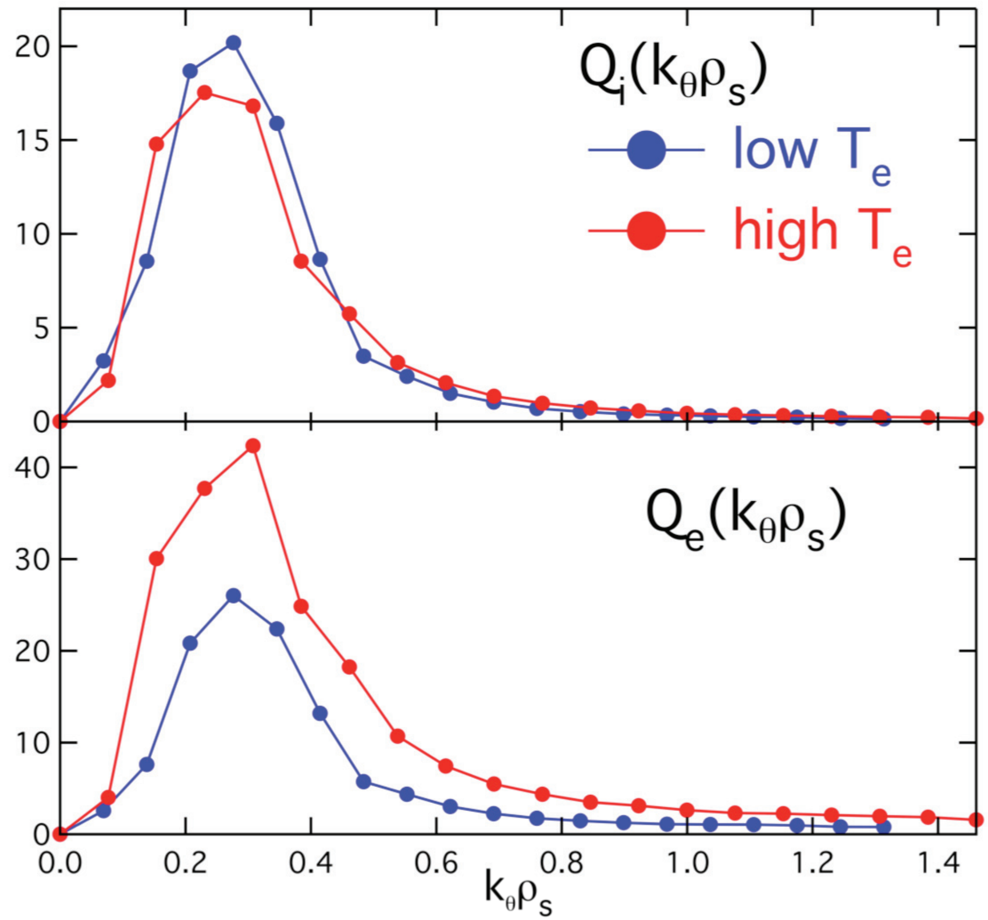
GYRO Simulations Significantly Overpredict Transport in Both Discharges by 1-2 Orders of Magnitude

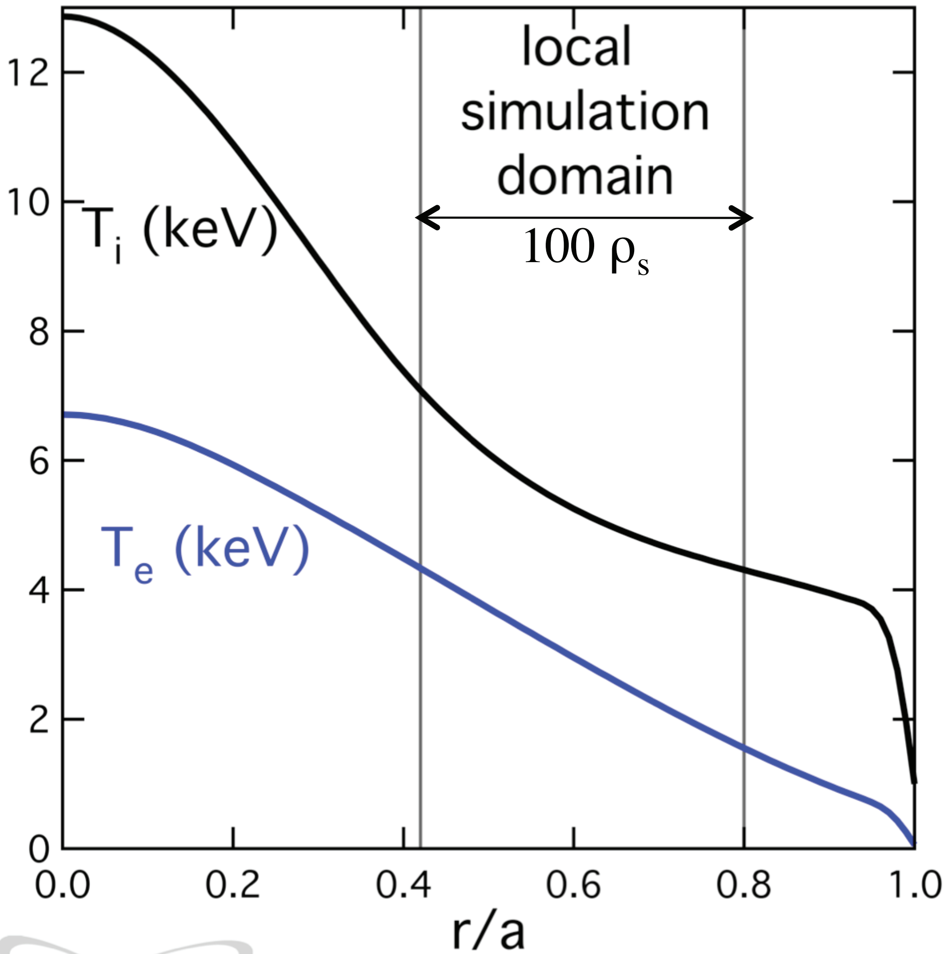
- GYRO-predicted RMS midplane $\delta n_e/n_e$ = 2-3%, $\delta T_e/T_e$ = 5-6%, both 10x larger than observed levels even if diagnostic spatial integration volumes accounted for
- Transport peaks at low $k_\theta \rho_s$ ~ 0.3 equivalent to toroidal mode numbers *n* = 20-30

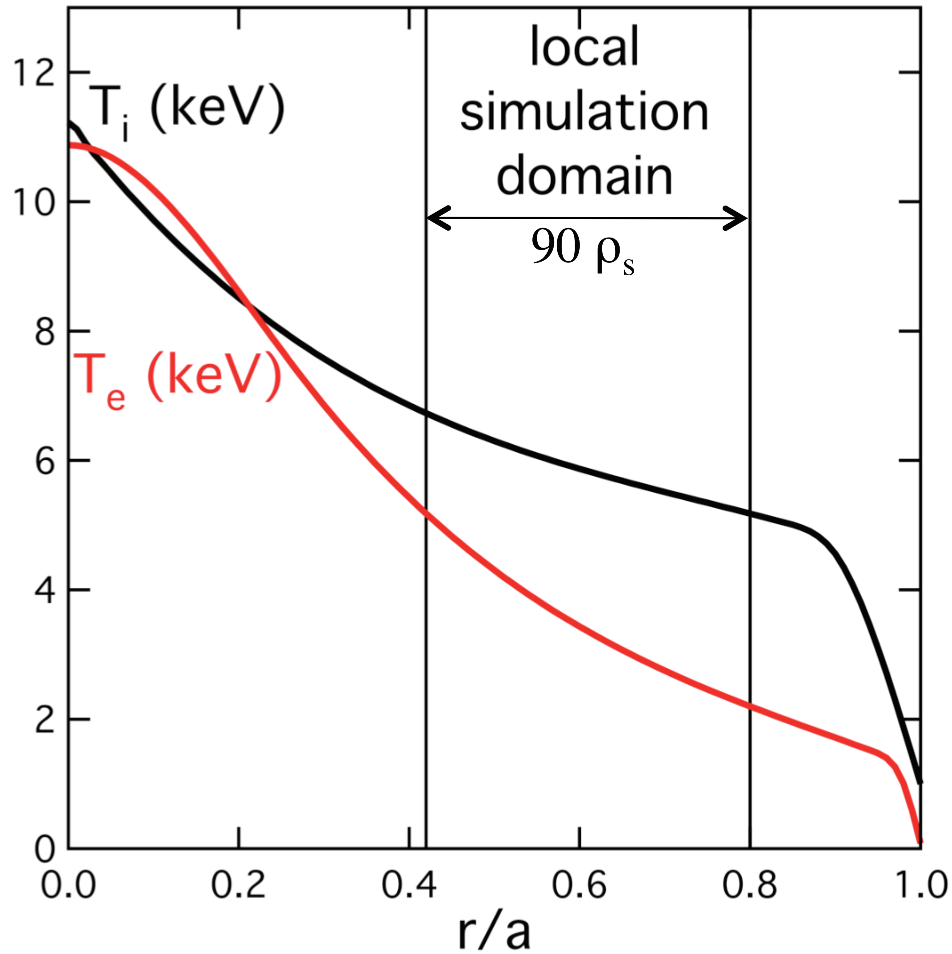
Q (W/cm^2)	GYRO	Expt.
Q_i (low T_e)	87	8.5
Q_i (high T_e)	76	7
Q_e (low T_e)	119	1.7
Q_e (high T_e)	206	9



Nonlocal Effects Likely to Play Significantly Stronger Role in these Plasmas

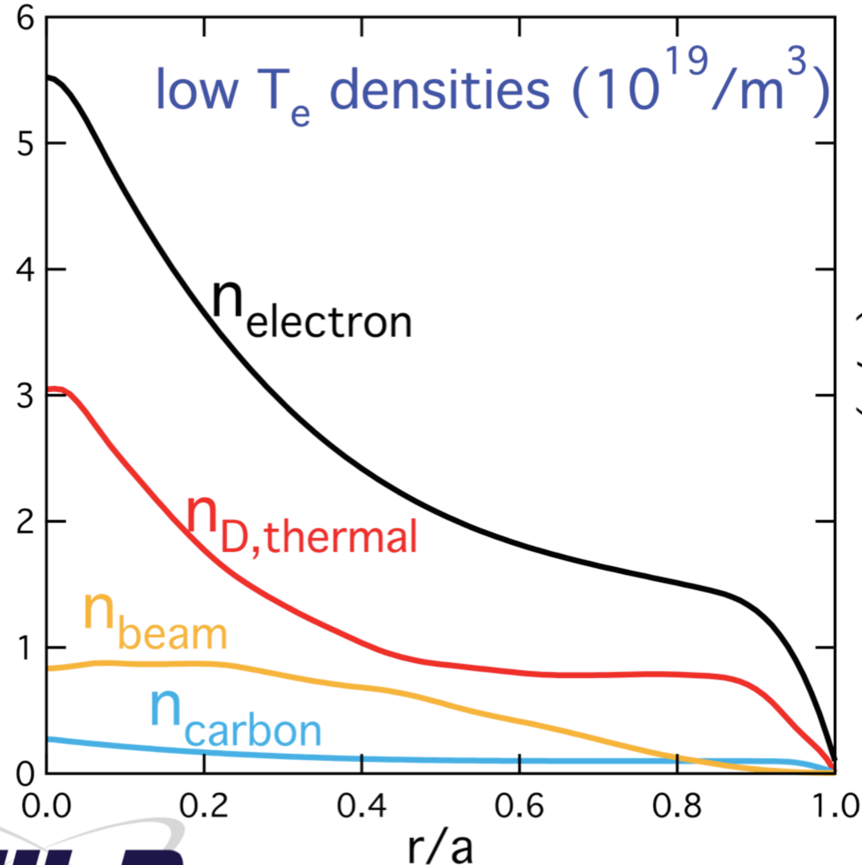
- **Performing these global simulations will be the next step**
  - Initial attempts indicate global runs will be 10x more computationally expensive

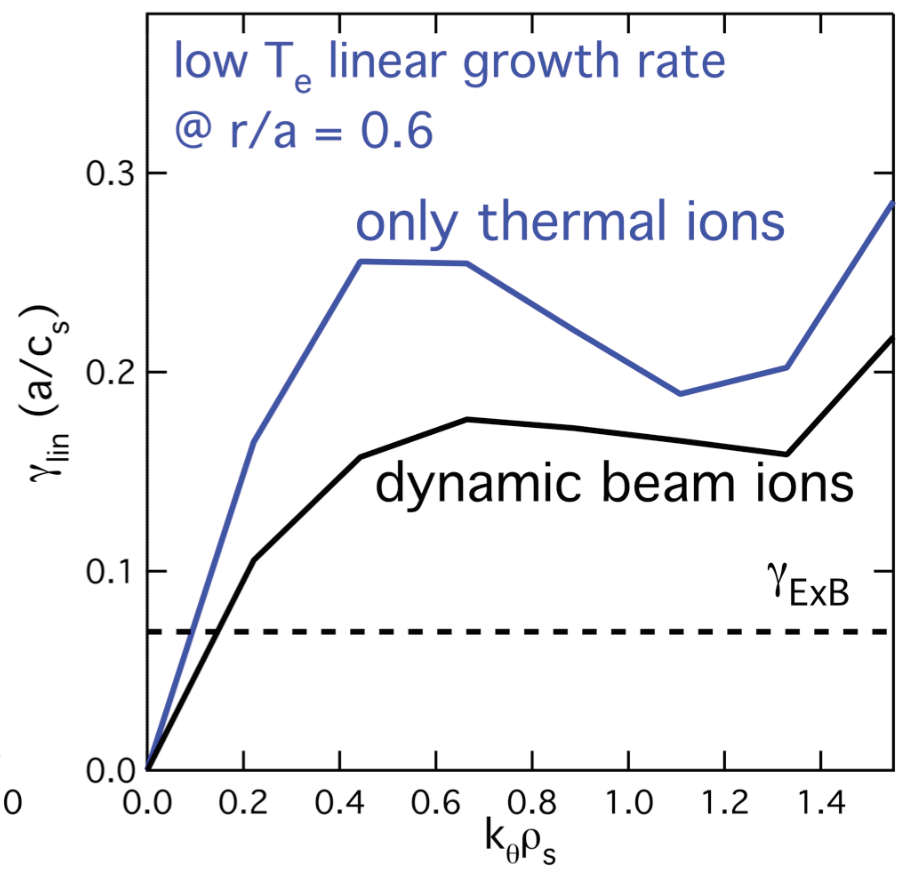




Improved Treatment of Energetic Beam Ions is Strongly Stabilizing

- **Initial simulations treat beam ions as thermal particles, but beam ion density is significant fraction of total ion density**
- **A simple treatment of beam ion distribution as Maxwellian with high T_{beam} derived from NUBEAM-calculated pressure yields strong linear stabilization for both cases**
  - Inclusion of these dynamics may add another order of magnitude to computational cost





A Series of Validation Experiments Has Been Performed on DIII-D to Better Quantify Model Fidelity in L-mode and H-mode Plasmas

- **We find that GYRO reproduces "zeroth-order" prediction of increasing transport with decreased elongation in L-mode plasmas, but clear differences with experiment at any given point**
  - Turbulence (both transport and fluctuation levels) magnitudes at larger r/a is systematically underpredicted, consistent with previous studies
  - The responses of GYRO and TGLF to profile changes exhibited strong point-to-point variation, limiting the utility of assessing systematic uncertainties in GYRO with flux-matching profiles calculated with TGLF
  - Future work should focus on improved assessments of model sensitivities (e.g. flux-matching profiles calculated with GYRO) particle and momentum transport, and EM effects

- **Validation in H-mode conditions will require even greater computation resources**
  - Initial local simulations over predicted transport by factor of 10-100
  - Both nonlocal and energetic particle effects likely necessary for accurate QH-mode modeling

QH-mode Growth Rates Exhibit Similar Physical Sensitivities as L-mode Discharges

- Low T_e case modes require kinetic electrons to be unstable, but are still ion modes (in that they propagate in V^*_i direction)
- High T_e modes propagate in V^*_e direction
- As in κ scan, only use ES simulations to avoid possible numerical issues