Validation of Gyrokinetic Transport Simulations Using DIII-D Core Turbulence Measurements

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Motivation and Overview

- **The development of validated transport models is essential for predicting the performance of ITER and other future reactor devices with confidence**

- **Comparisons of turbulent transport predictions against "experimental" energy and particle flows are only weakly discriminating**
  - the "experimental" flows are calculated via a power balance model with its own assumptions and limitations (e.g. for fast ion transport)

- **Much better are comparisons against directly measured characteristics of the underlying turbulence (e.g. spectra and correlation functions)**

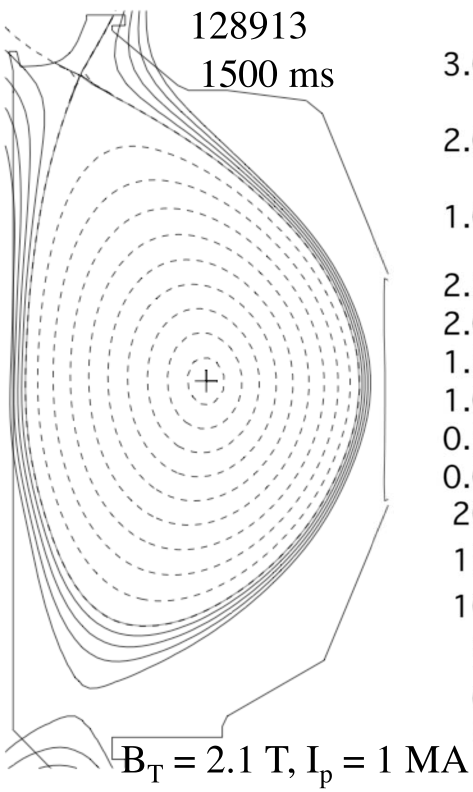
- **In this study, use the GYRO code to model a basic L-mode DIII-D discharge, and compare both predicted energy flows and fluctuation characteristics against experiment**

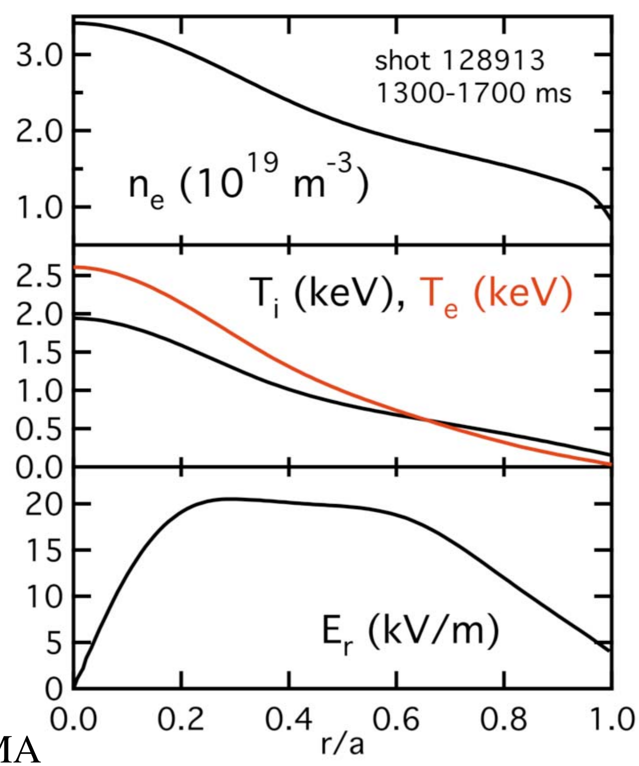
Summary of Results

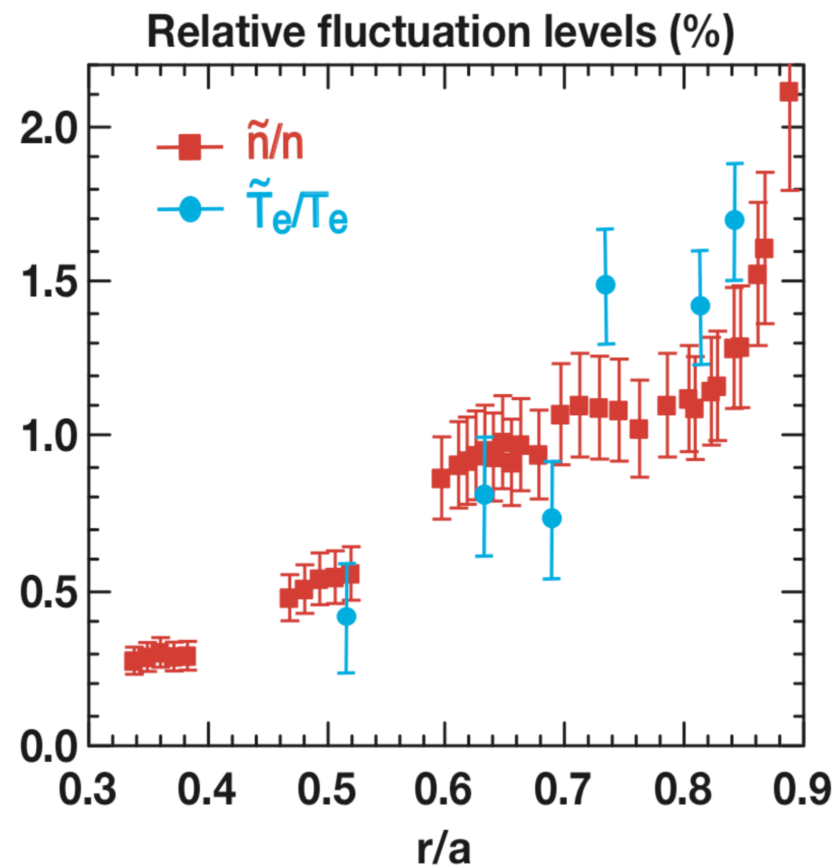
- Local GYRO simulations match ion and electron energy flows at r/a < 0.6, but underpredict the flows at larger r/a
- Local and global GYRO simulations give nearly identical predictions for the energy flows across the entire plasma
- Using synthetic diagnostics, the GYRO-predicted fluctuation spectra are shown to agree well with experimental measurements at r/a = 0.5
- At r/a = 0.75, GYRO underpredicts fluctuation amplitudes by an amount consistent with the underprediction of the energy flows, but still achieves relatively good agreement in the density correlation functions
- Using the quasilinear TGLF transport model in conjunction with the new TGYRO transport code, the ability to perform nonlinear, predictive fixed-flow transport modeling is now available

Use Data From a Steady, Sawtooth-Free L-Mode Plasma for This Study

- **Obtain profiles of long wavelength density and electron temperature fluctuations at outboard midplane via beam emission spectroscopy (BES) and correlation electron cyclotron emission (CECE) radiometry**





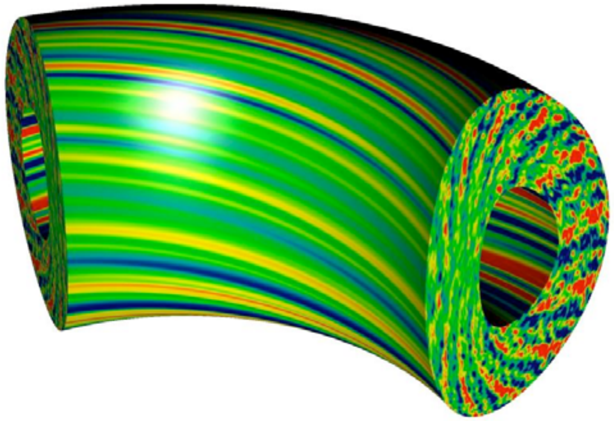


Use GYRO Code to Predict Turbulent Fluctuations and Transport

- **GYRO is an initial value Eulerian (continuum) 5D gyrokinetic δf code**
  - Documentation at: http://fusion.gat.com/theory/Gyro

- **GYRO can be run in a local (flux-tube) or nonlocal (global) mode:**
  - **Local:** This case corresponds to the $\rho^* = \rho_s/a \rightarrow 0$ limit of the GK equations, in which each equilibrium profile and gradient is taken to have a fixed (and independent) value across the box
  - **Nonlocal:** spatial variation of equilibrium profiles (and their gradients) is retained

- **Believed to contain the necessary ingredients for quantitatively accurate core transport predictions**
  - takes measured experimental profiles as inputs
  - equilibrium sheared ExB and toroidal rotation profiles
  - realistic geometry (Miller formulation)
  - trapped and passing electrons
  - e-i pitch angle collisions
  - finite beta (magnetic fluctuations)



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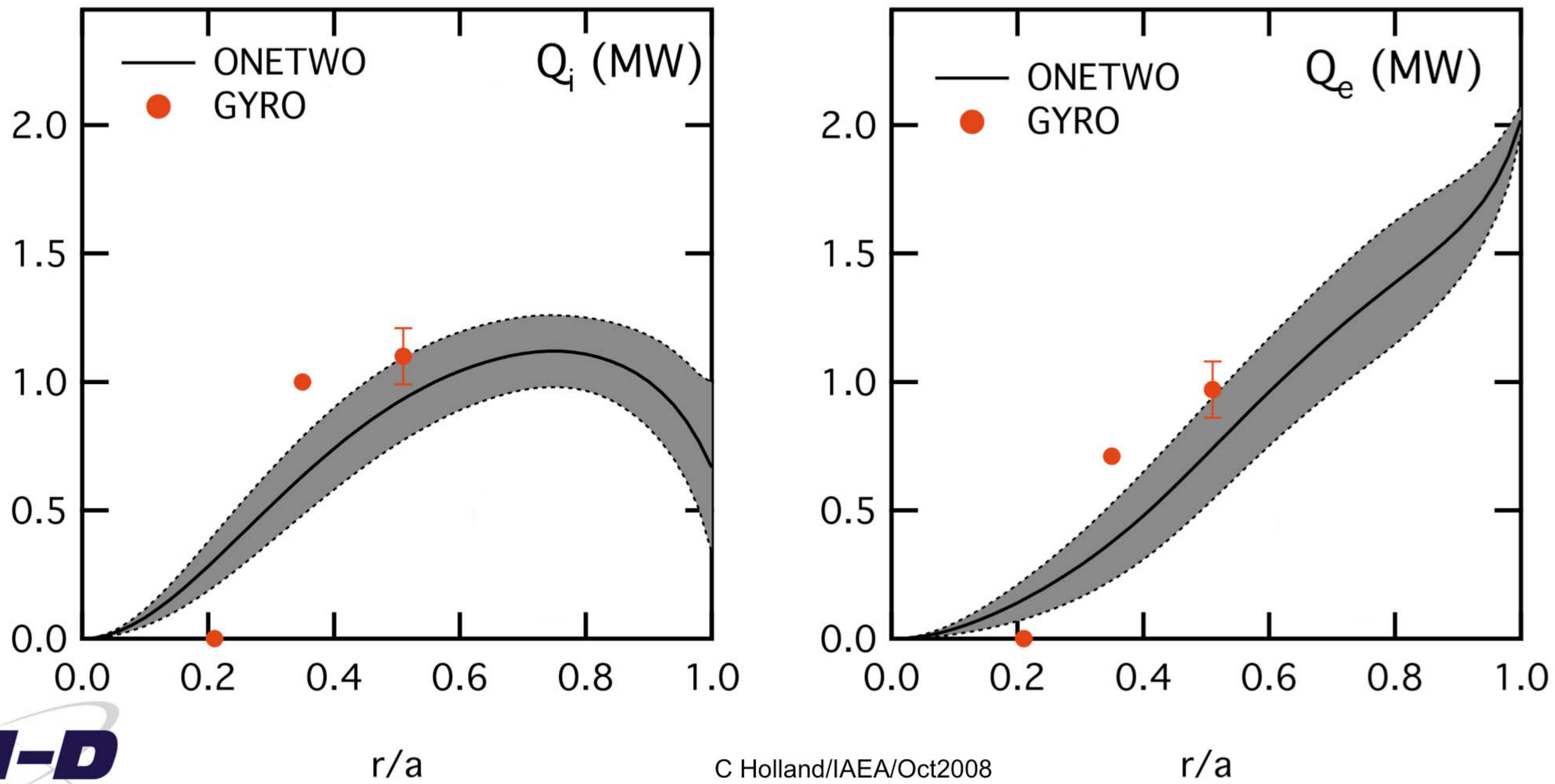
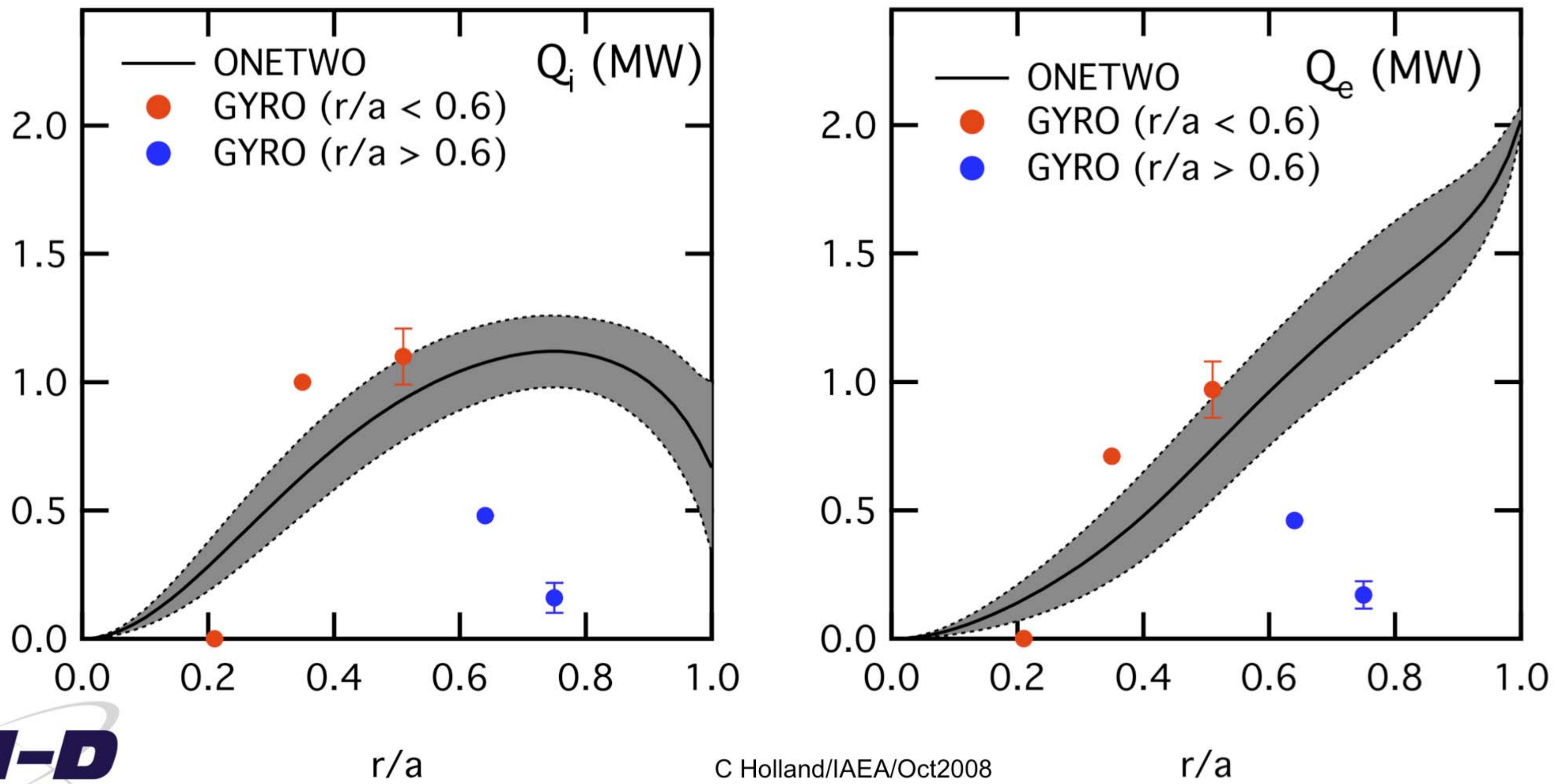
Local GYRO Simulations Approximately Match Energy Flows for r/a ≤ 0.6 In Magnitude and Trend With Radius

- **Use the ONETWO code to calculate ion and electron energy flows Q_i and Q_e**
  - GYRO error bar shows magnitude of response to 20% change in γ_{ExB}
  - ONETWO error bar shows magnitude of response to using different fits to Thomson electron density profile measurements



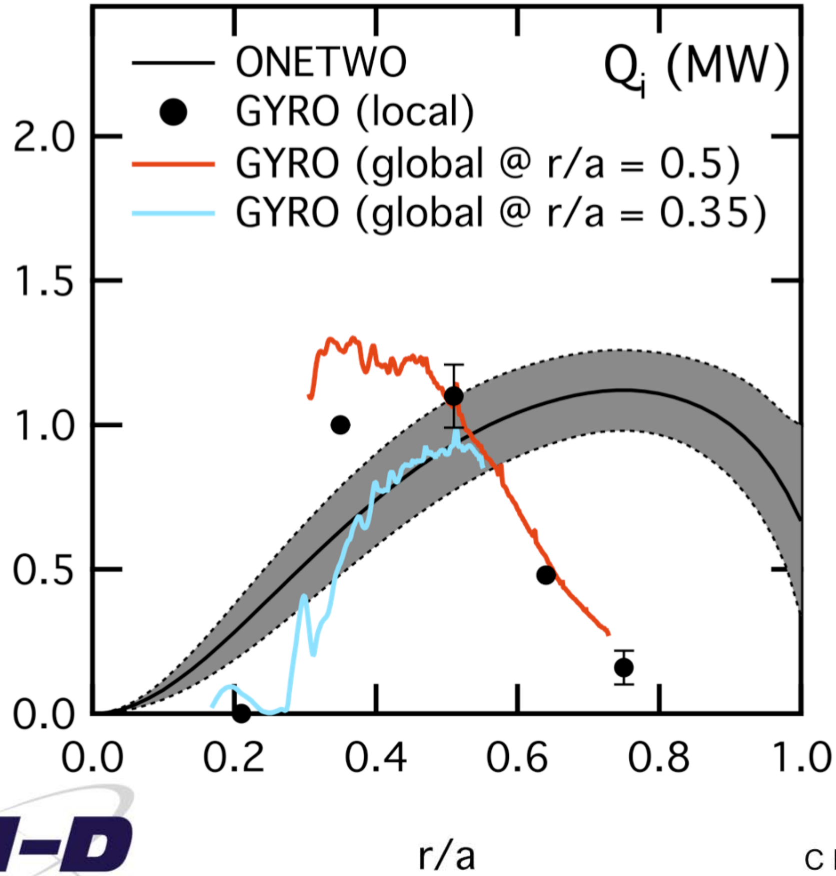
Local GYRO Simulations Systematically Underpredict Energy Flows for r/a > 0.6 in This Discharge

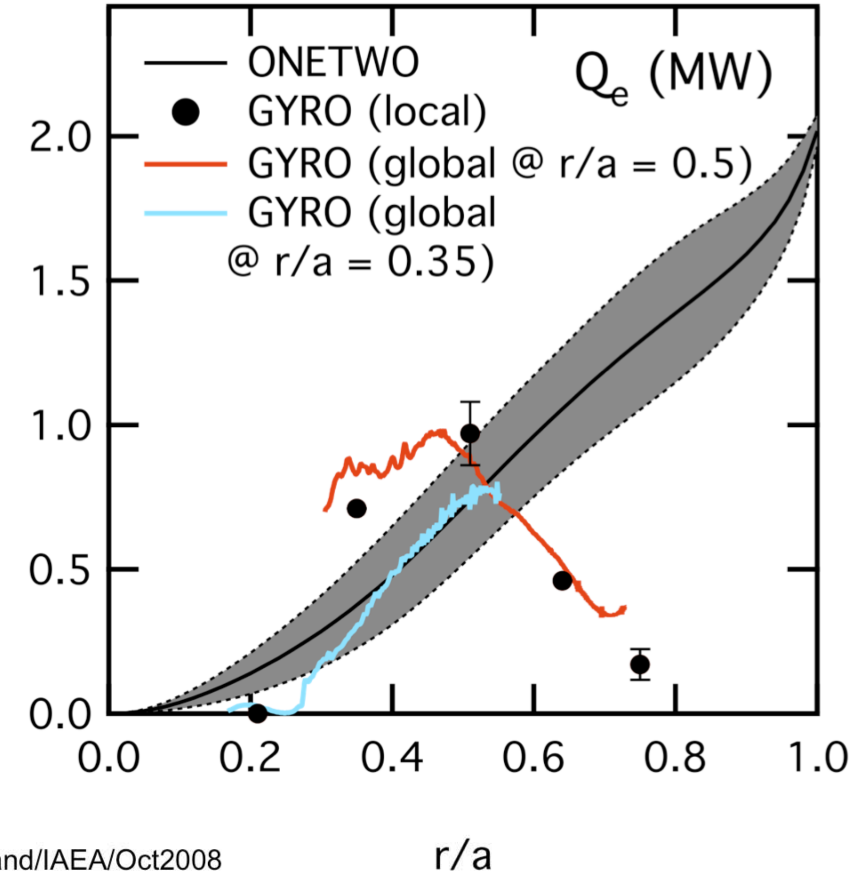
- **Mismatches at r/a > 0.6 are too large to be reconciled with plausible uncertainties of local gradients**
- **Cause of mismatch at larger radii unknown at this time**



Local GYRO Simulations in Very Good Agreement With Global Simulation Results Everywhere but r/a = 0.35

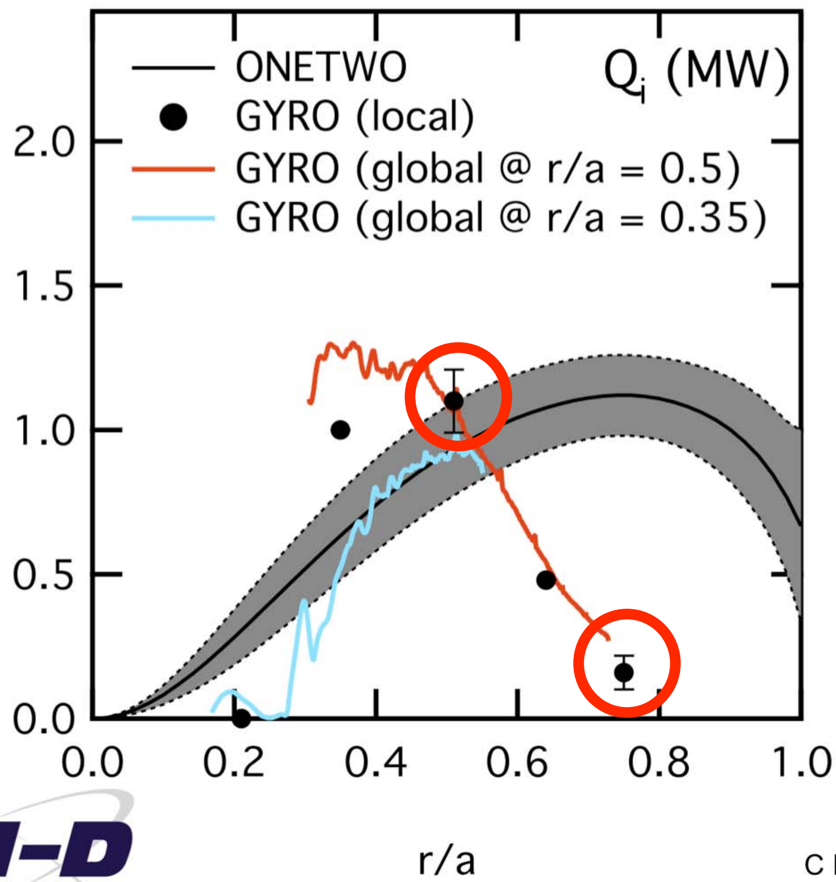
- **Red global simulation centered at r/a = 0.5 (local ρ^* = 0.0026)**
- **Blue global simulation centered at r/a = 0.35 (local ρ^* = 0.0033)**
- **Nonlocality leads to reduction of local r/a = 0.35 predictions, but does not meaningfully impact other local results**
  - Decrease likely arises from proximity to inner stable region

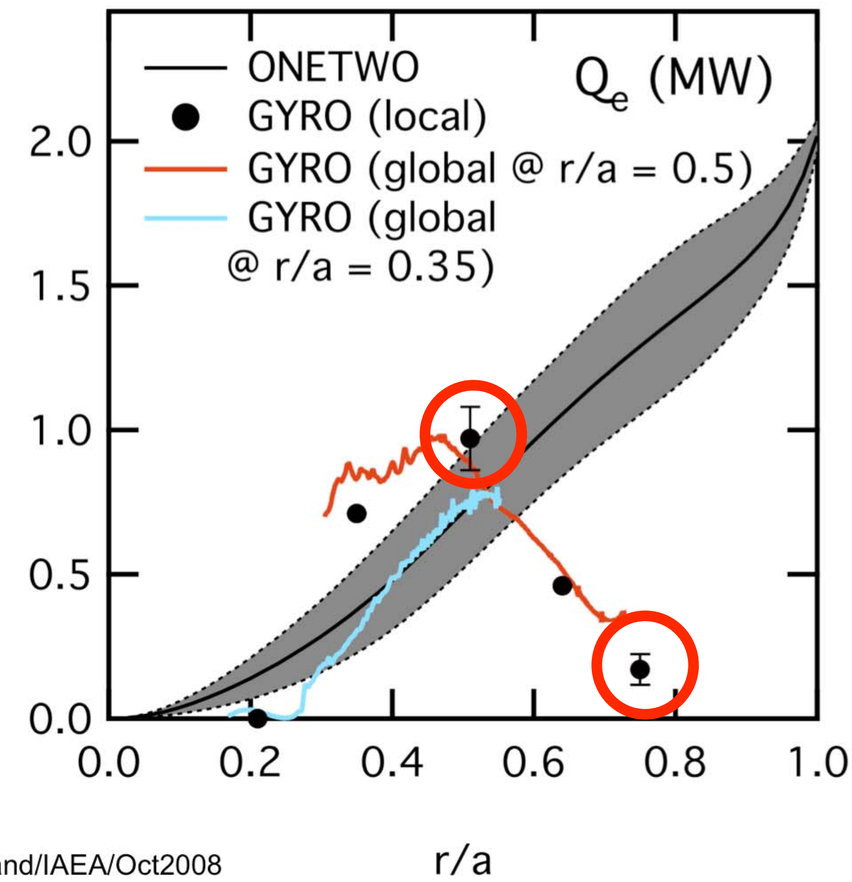




Next Step: Compare Predicted Fluctuation Characteristics at r/a = 0.5 and 0.75 Against Experimental Measurements

- **Use local GYRO simulation results for these comparisons**

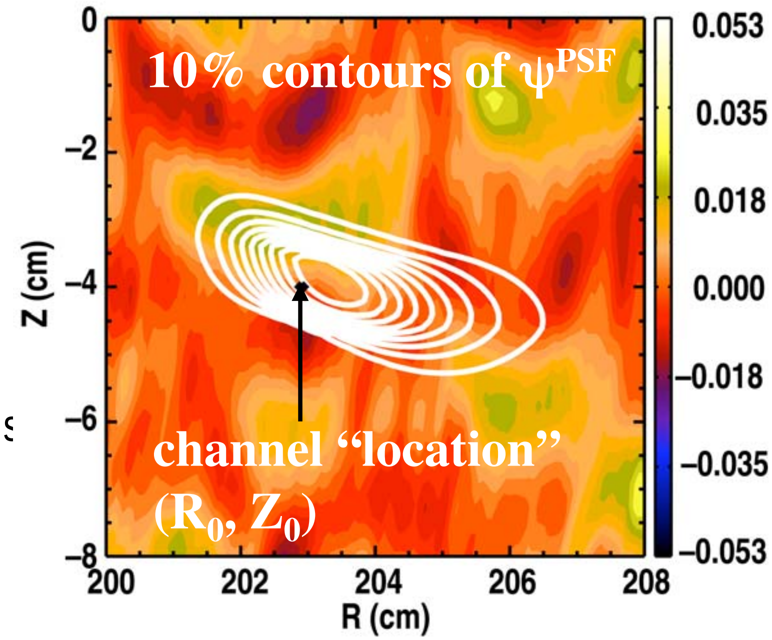




Comparing Fluctuation Characteristics at r/a = 0.5

Synthetic Diagnostics are an Essential Component of Quantitative Code-Experiment Comparisons

- **In order to do "apples-to-apples" comparisons of simulation and experiment, need to not just model the turbulence, but also how a given diagnostic "sees" the turbulence**



- **This is done by creating a synthetic diagnostic which models what the diagnostic would have seen had it observed the simulation fluctuations**
  - For the BES and CECE systems, this modeling is done by convolving point-spread functions (PSFs) that describe the spatial sensitivity of each diagnostic with the fluctuation fields

- **For a synthetic diagnostic which measures fluctuations at (R_0,Z_0,φ_0), record at each timestep in steady-state portion of simulation:**
  - A "unfiltered" reference signal $\delta X_{GYRO}(R_0, Z_0, \varphi_0, t)$
  - A synthetic signal $\delta X_{synthetic}(t) = \dfrac{\int d^2r\ \psi^{PSF}(R-R_0, Z-Z_0)\delta X_{GYRO}(R-R_0, Z-Z_0, \varphi_0, t)}{\int d^2r\ \psi^{PSF}(R-R_0, Z-Z_0)}$

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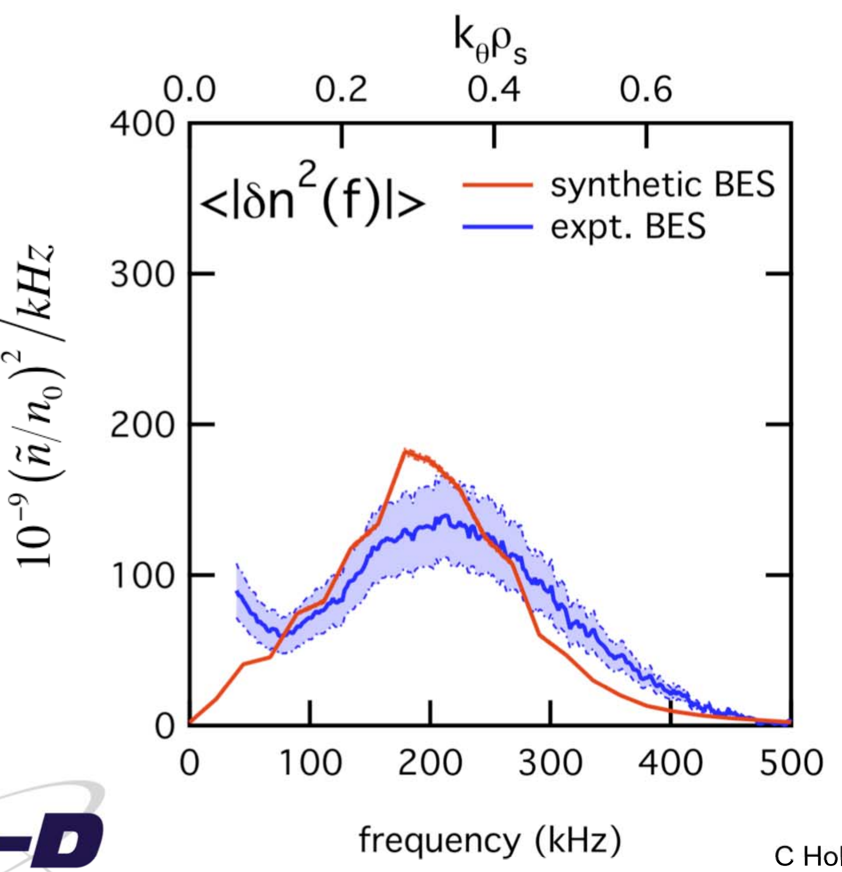
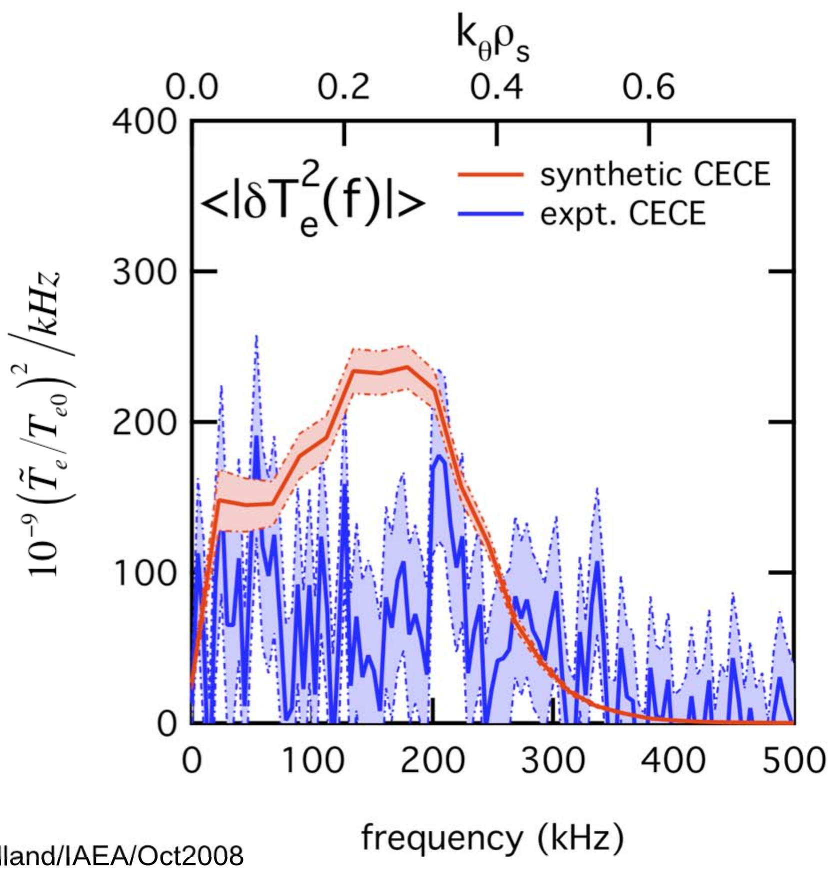
Lab-Frame Spectra Comparisons Show GYRO in Excellent Agreement With BES (δn_e), Overpredicts CECE (δT_e) at r/a = 0.5

- **Agreement between synthetic and experimental spectra requires that GYRO accurately reproduces both the fluctuation amplitudes and the poloidal mode spectra**
  - Lab-frame frequency spectra is essentially Doppler-shifted poloidal mode spectrum
  - In this talk, always refer to normalized fluctuation levels $\delta X \equiv \tilde{X}/X_0$





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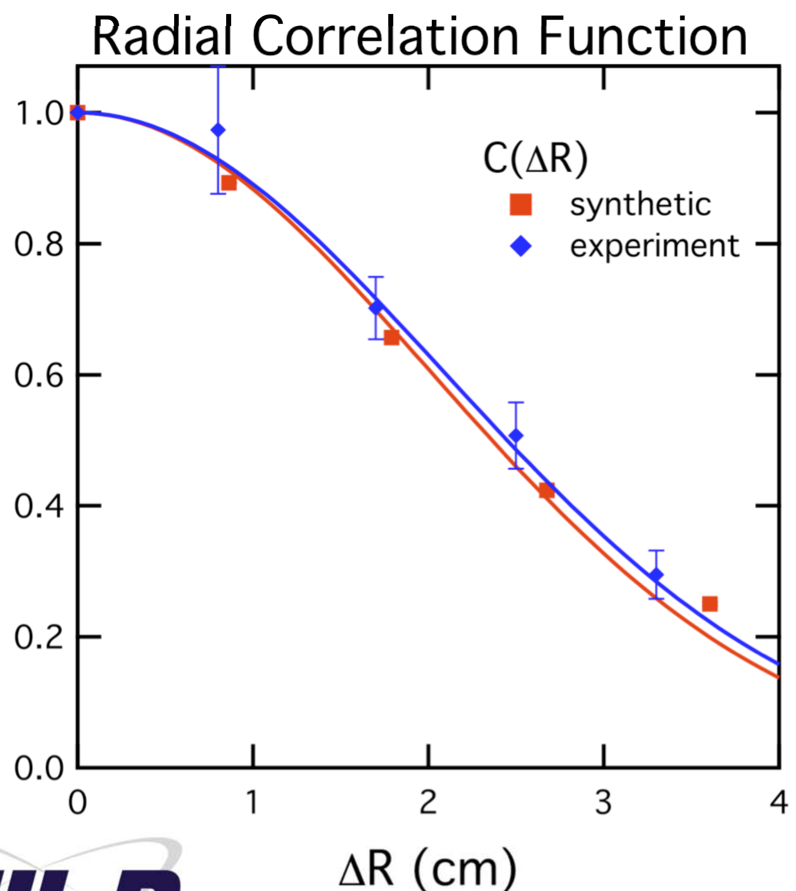
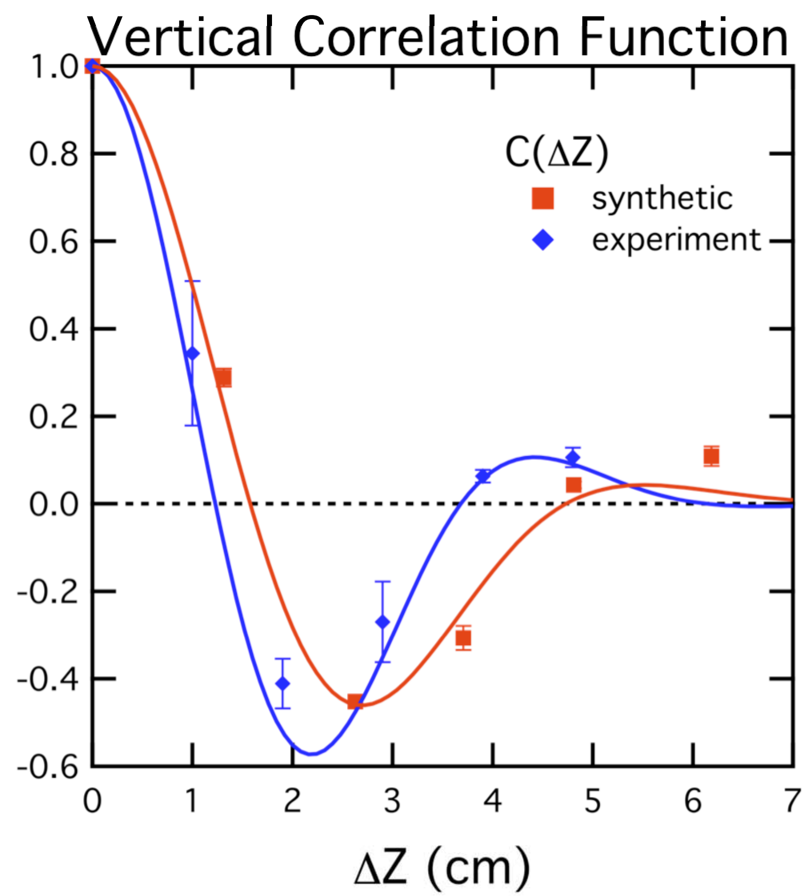
Very Good Agreement is Found Between Synthetic and Experimental Density Correlation Functions at r/a = 0.5

- **Agreement in vertical correlation function C(ΔZ) consistent with agreement in lab-frame power spectra**
- **Solid lines are Gaussians fit to experimental BES and synthetic BES**





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Comparing Fluctuation Characteristics at r/a = 0.75

Synthetic Spectra Consistently Underpredict Experimental Measurements at all Frequencies at r/a = 0.75

- **Magnitude of underprediction consistent with generic scaling of Q ∝ δX^2**

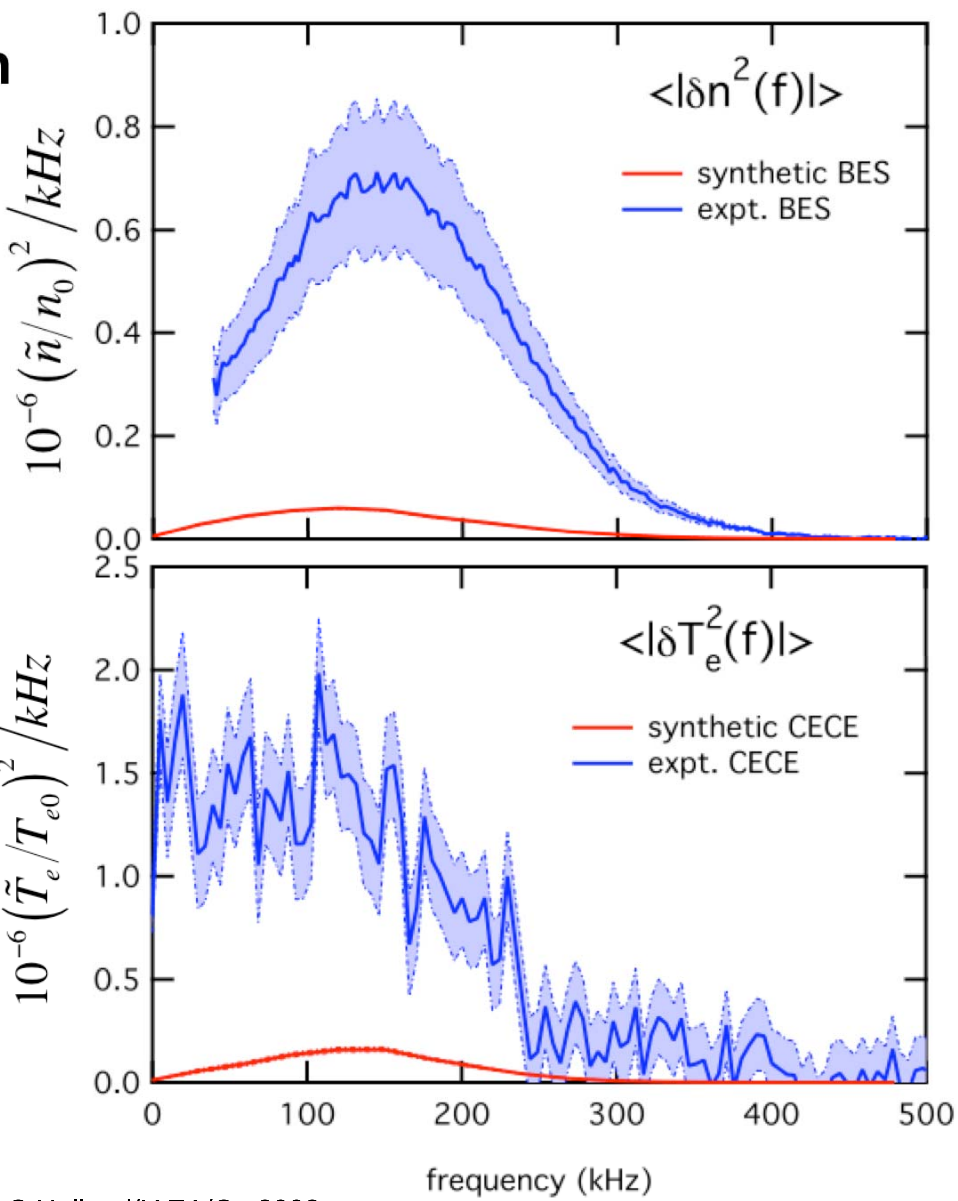
- **Use** $\delta X_{RMS}^2 = \int_{40\,kHz}^{400\,kHz} df \left\langle |\delta X(f)|^2 \right\rangle$ **to find**

$$\sqrt{Q_i^{PB}/Q_i^{GYRO}} = 2.7$$

$$\sqrt{Q_e^{PB}/Q_e^{GYRO}} = 2.7$$

$$\delta n^{BES}/\delta n^{syn} = 3.3$$

$$\delta T_e^{CECE}/\delta T_e^{syn} = 3.2$$



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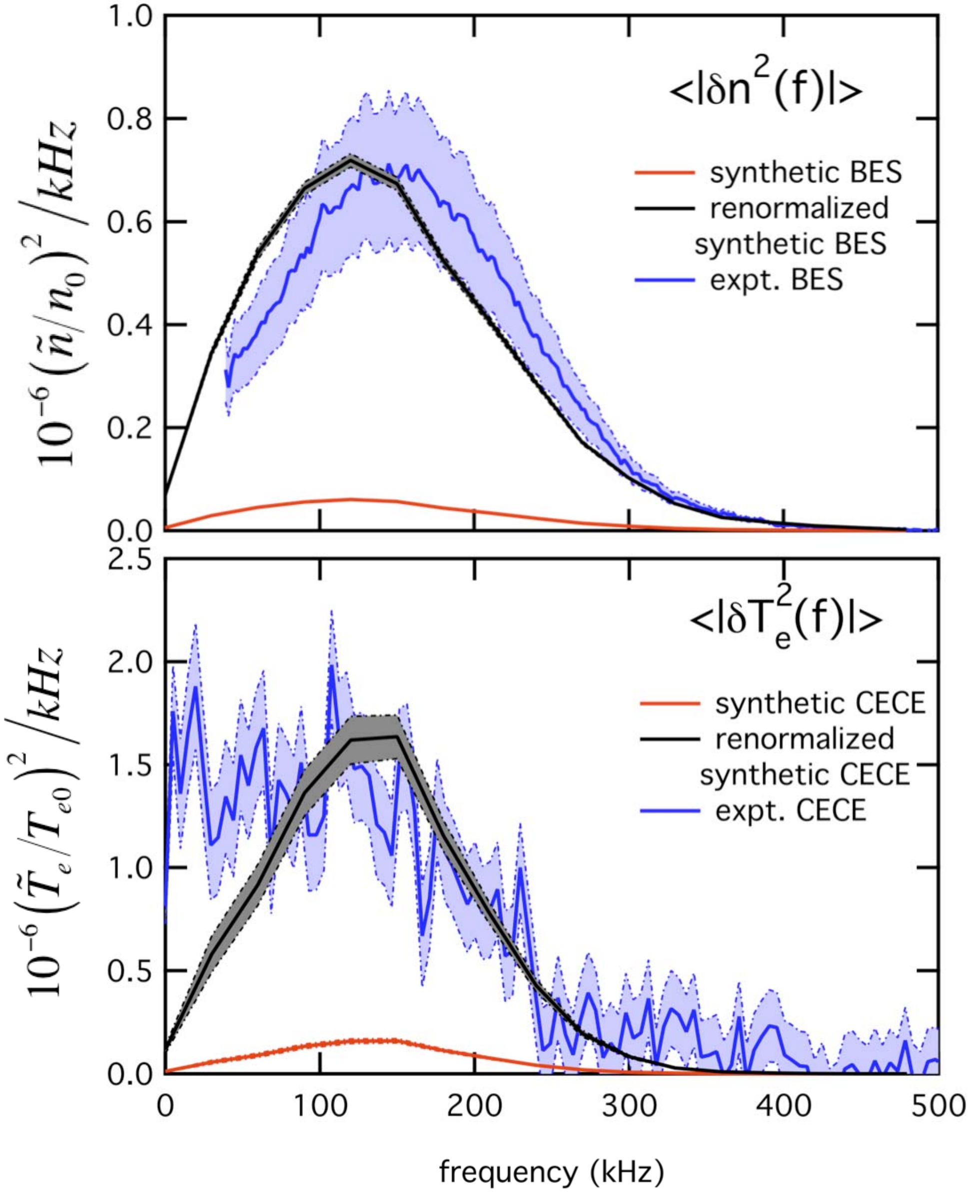
Synthetic Spectra Match Experiment In Shape But Not Magnitude at r/a = 0.75

- **If synthetic spectra are renormalized to contain same power as corresponding experimental spectra, find good agreement with measured BES and CECE spectral shapes over 40-400 kHz**
  - Source of mismatch in δT_e spectra below 40 kHz unknown

- **Is spectral shape more robust than magnitude?**



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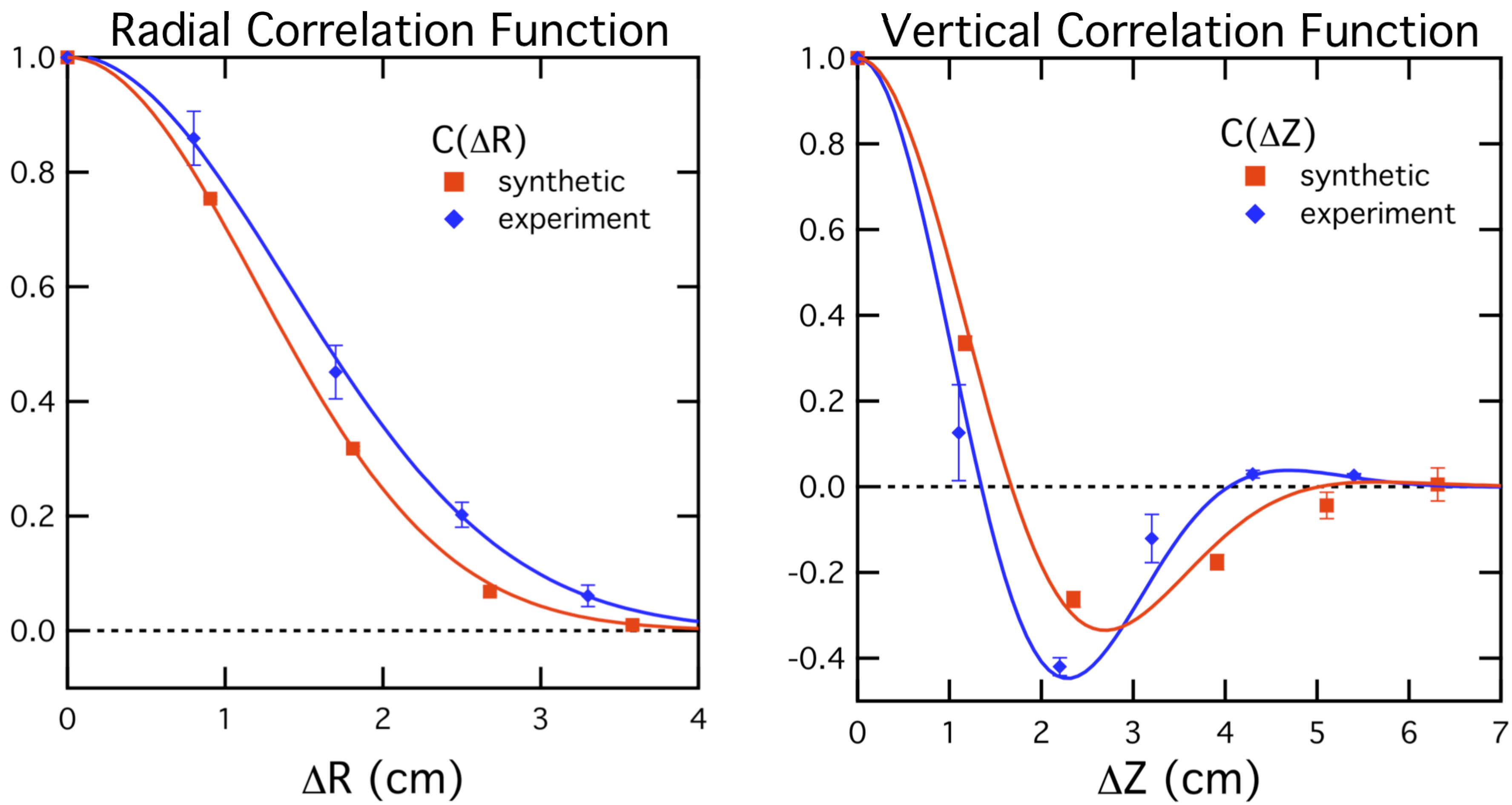
Synthetic Density Correlation Functions at r/a = 0.75 Exhibit Similar Behavior and Agreement With Experiment as at r/a = 0.5



Addressing Profile Uncertainties Via Fixed-Flow Simulations

Stiff Transport Magnifies Gradient Uncertainties, Necessitating Flow-Matching Simulations

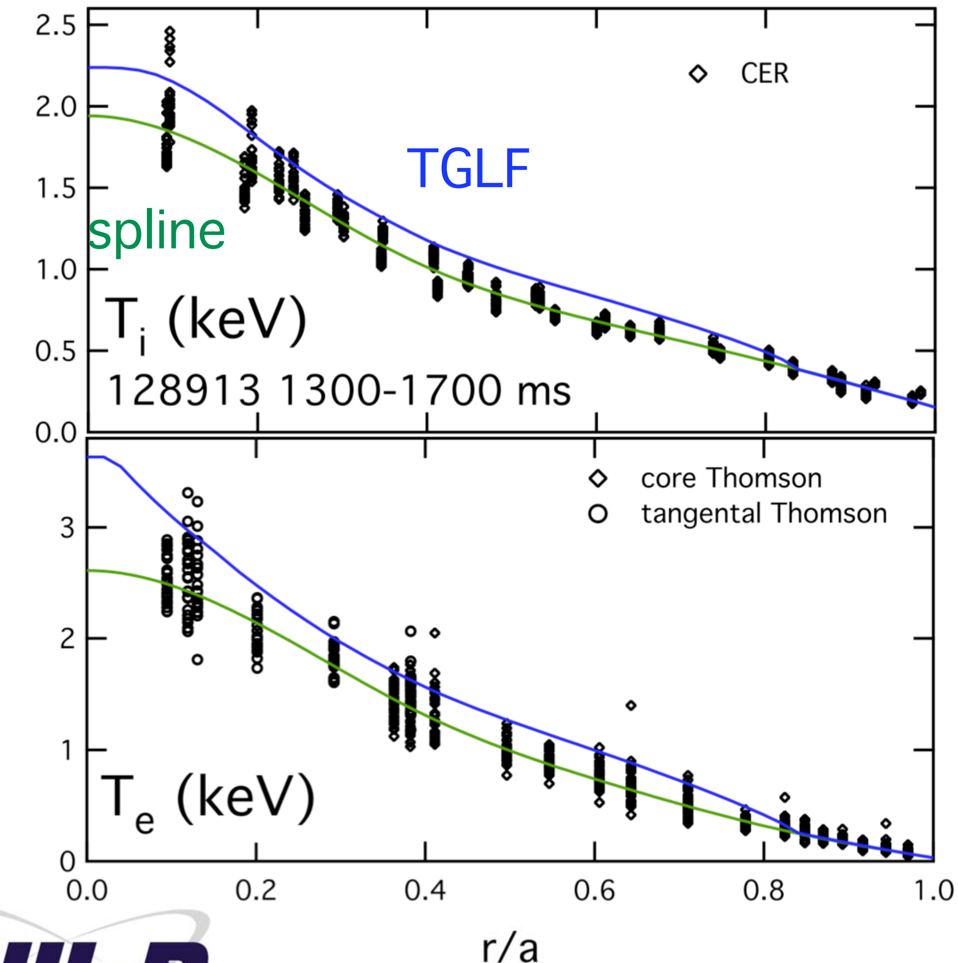
- **Systematic uncertainties in fitting equilibrium profiles create large uncertainties in local equilibrium gradients, which are magnified further when the stiff turbulent flows are calculated**
  - Ex: fitted profiles rely on diagnostic calibrations, analyst's selection of a non-unique fitting function

- **One way of addressing this issue is to predict a set of profiles needed to match the energy flows calculated via power balance, and compare these predicted profiles against measurements**
  - Because flows are volume integrals of (computed) sources, they have in general less uncertainty than local gradients

- **Caveat:** this approach assumes one has accurate models of the relevant sources

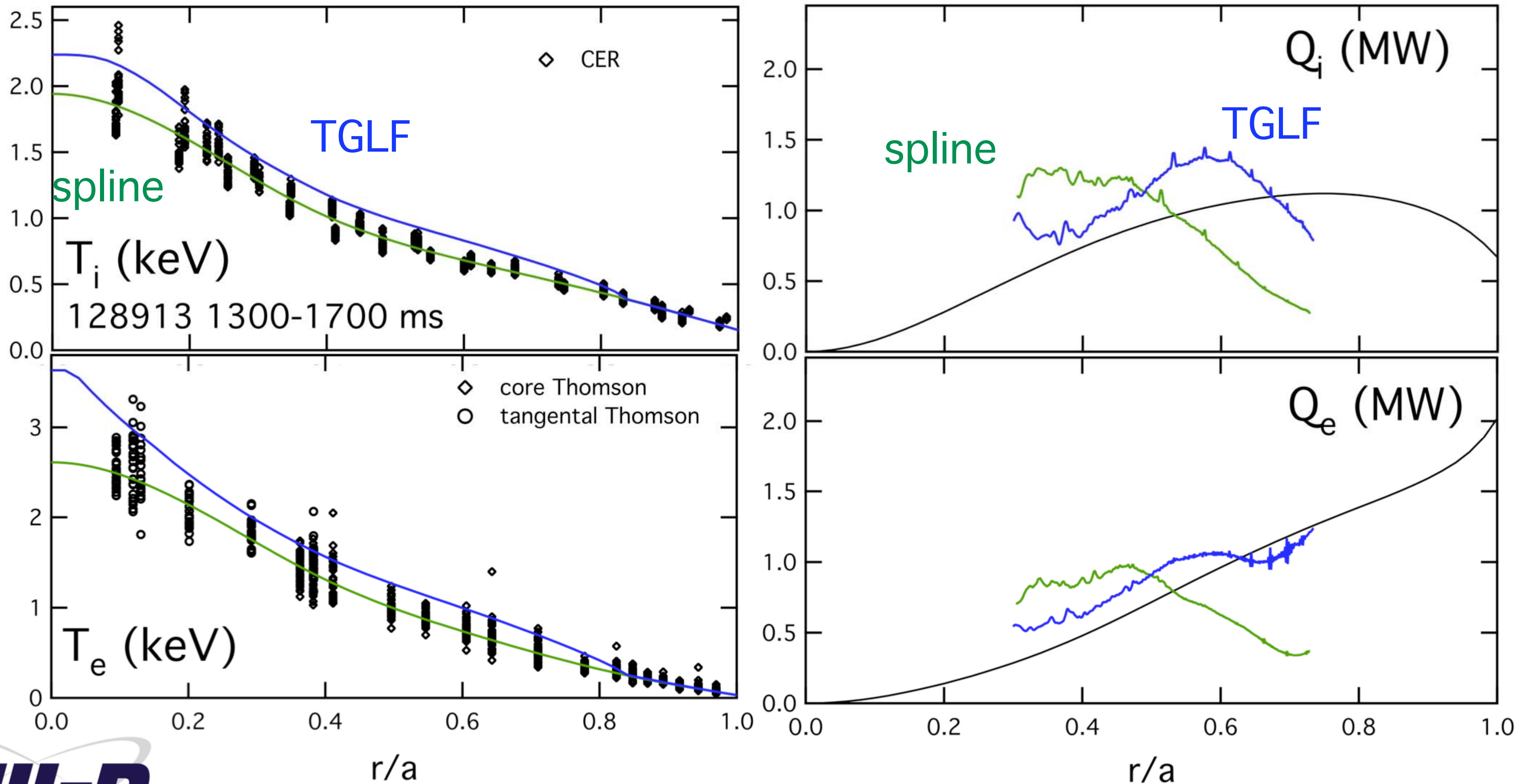
Use the TGLF Model to Make Initial Profile Predictions

- **TGLF is a quasilinear transport model fit against > 80 nonlinear GYRO runs**
- **TGLF predictions are outside statistical uncertainties of initial spline fit, but systematic uncertainties remain**



Global GYRO Simulation Using the TGLF Predicted Profiles Yields Significantly Improved Agreement with ONETWO Calculation

- **Using TGLF profiles, improved agreement with ONETWO results achieved at all r/a, particular at r/a > 0.6**



Next Step: Flow-Matching Calculations Using the TGYRO Transport Driver Code

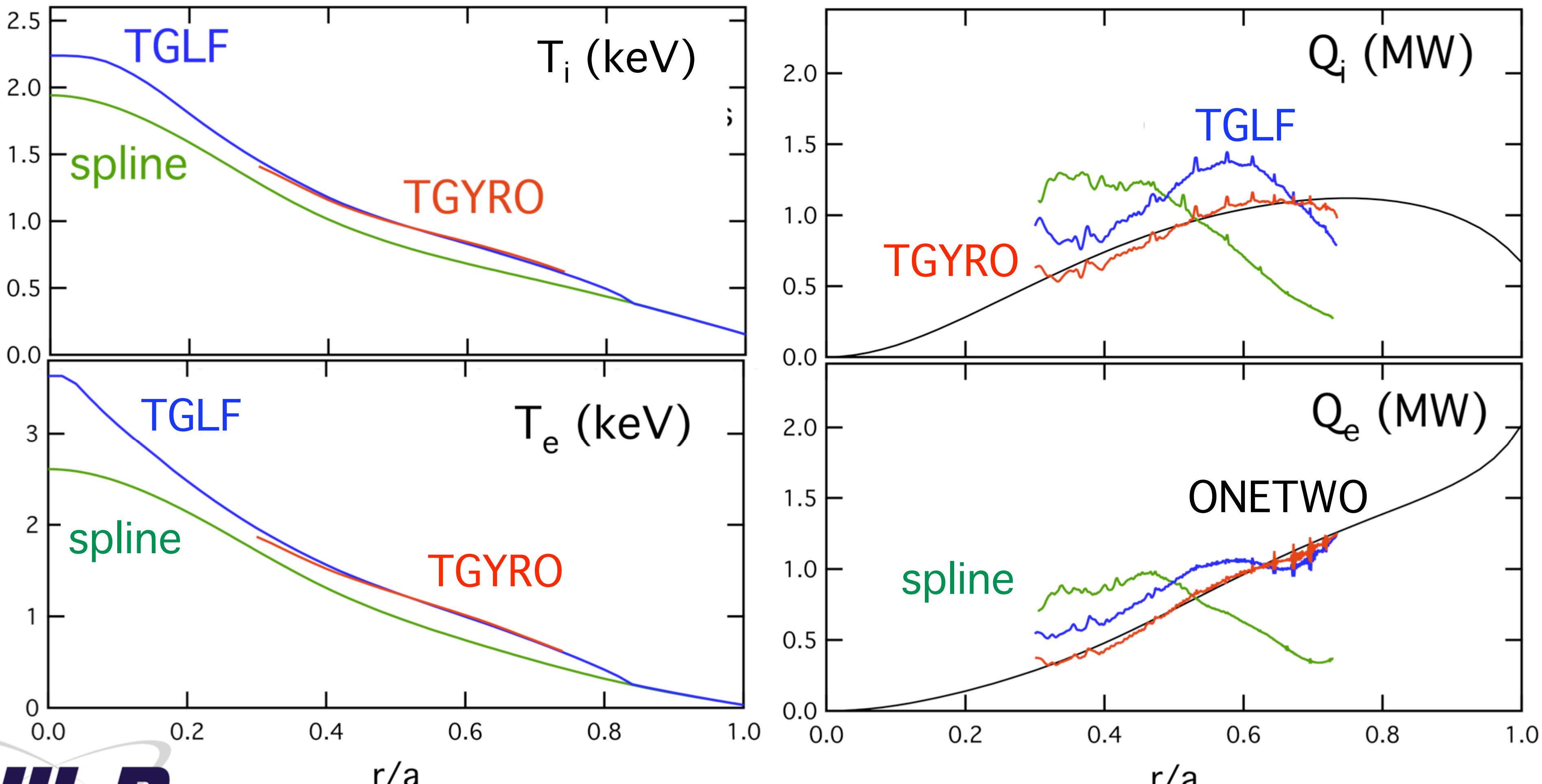
- **A new TGYRO transport code has been development to predict flow-matching profiles using either a global GYRO or combination of multiple local GYRO and TGLF simulations in parallel**

- **Basic global simulation algorithm: every a/c_s, adjust local scale lengths by an amount proportional to difference between GYRO simulation and power balance flows at each radial location**
  - Example: $\Delta(a/L_{Ti}) \propto (Q_i^{GYRO} - Q_i^{PB})$
  - Keep T_i and T_e at center of simulation fixed, and pivot profiles about this point. Contrasts with traditional approach of specifying pivot at some large r/a near top of pedestal.

- **First results from the local TGYRO algorithm for ITER plasmas available at this conference in poster TH/P8-28 by Nordman and Candy**

Tiny Changes to TGLF Profile Predictions by TGYRO Yield Exact Matches to Power Balance Flows

- **Small but finite changes to local values of TGLF profile gradients by TGYRO translate into essentially equivalent temperature profile predictions**



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Summary of Results

- **Local long-wavelength ($k_\perp \rho_s < 1$) GYRO simulations of this particular discharge match ion and electron energy flows calculated via ONETWO at r/a < 0.6 within experimental uncertainties, but underpredict the flows at larger r/a.**
  - Define flow as total amount of energy crossing a flux surface, specified in MW

- **Local and global GYRO simulations give nearly identical predictions for the energy flows, with the only meaningful difference at r/a = 0.35.**

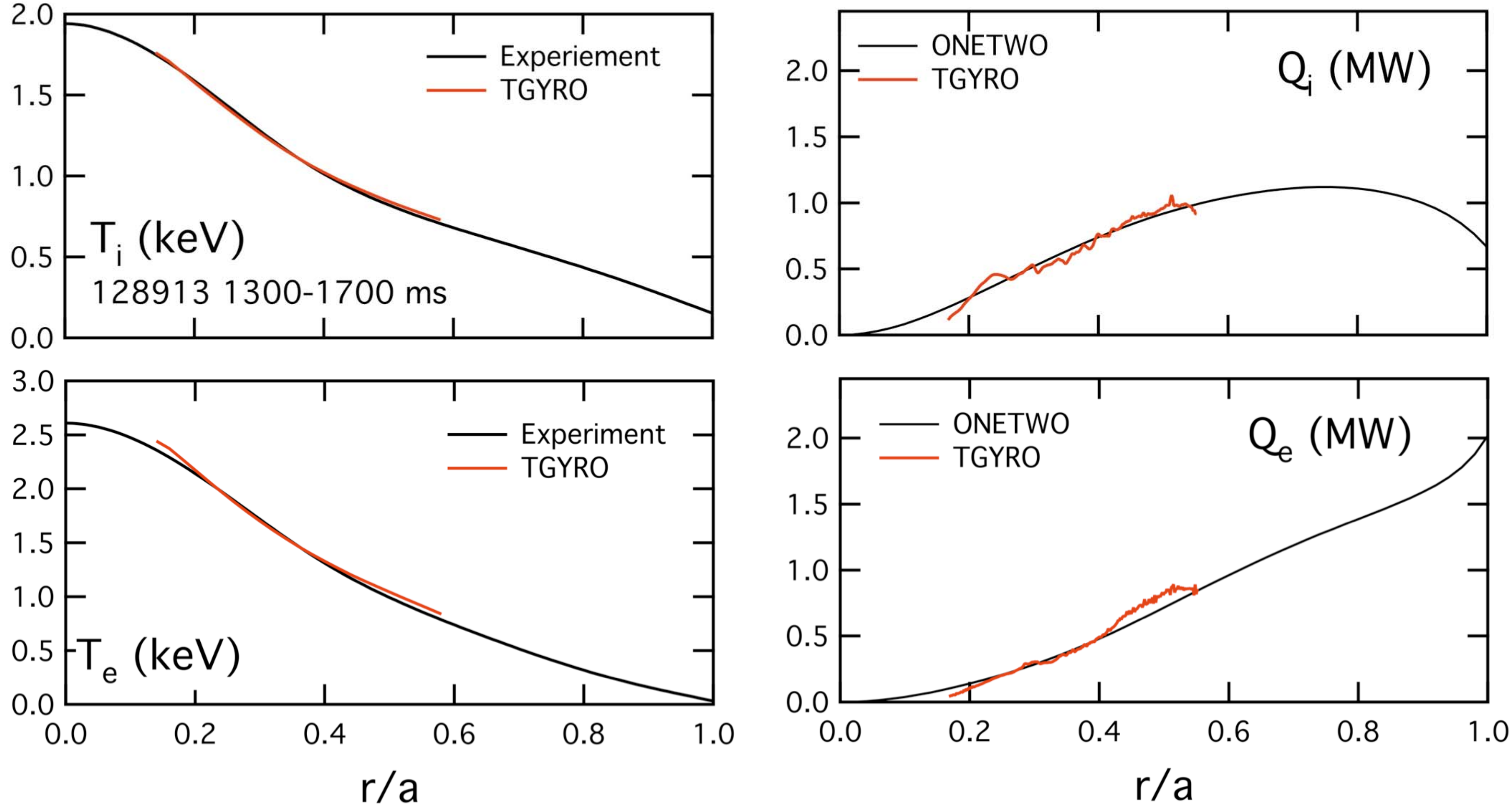
- **Using synthetic diagnostics, the GYRO-predicted density and electron temperature fluctuation spectra are shown to agree well with experimental measurements at r/a = 0.5.**
  - Good agreement is also found for the density correlation functions.

- **At r/a = 0.75, GYRO underpredicts fluctuation amplitudes by an amount consistent with the underprediction of the energy flows, but still achieves relatively good agreement in the density correlation functions.**

- **Using the quasilinear TGLF transport model in conjunction with the new TGYRO transport code, the ability to perform nonlinear, predictive fixed-flow transport modeling is now available**

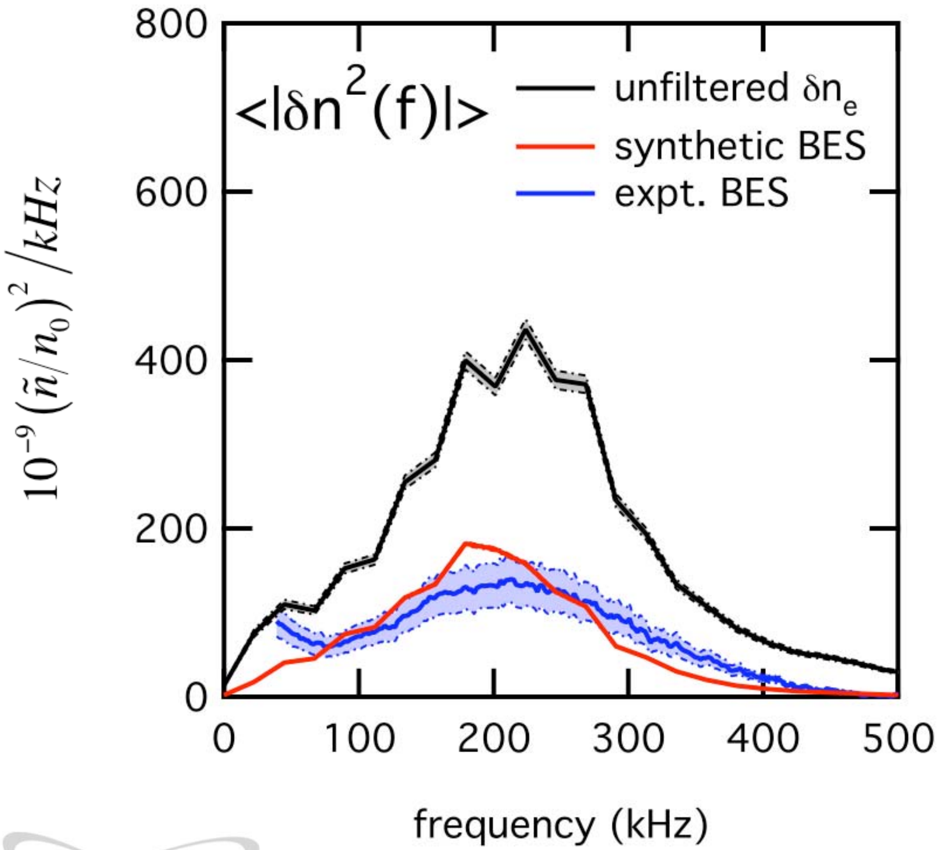
Backups

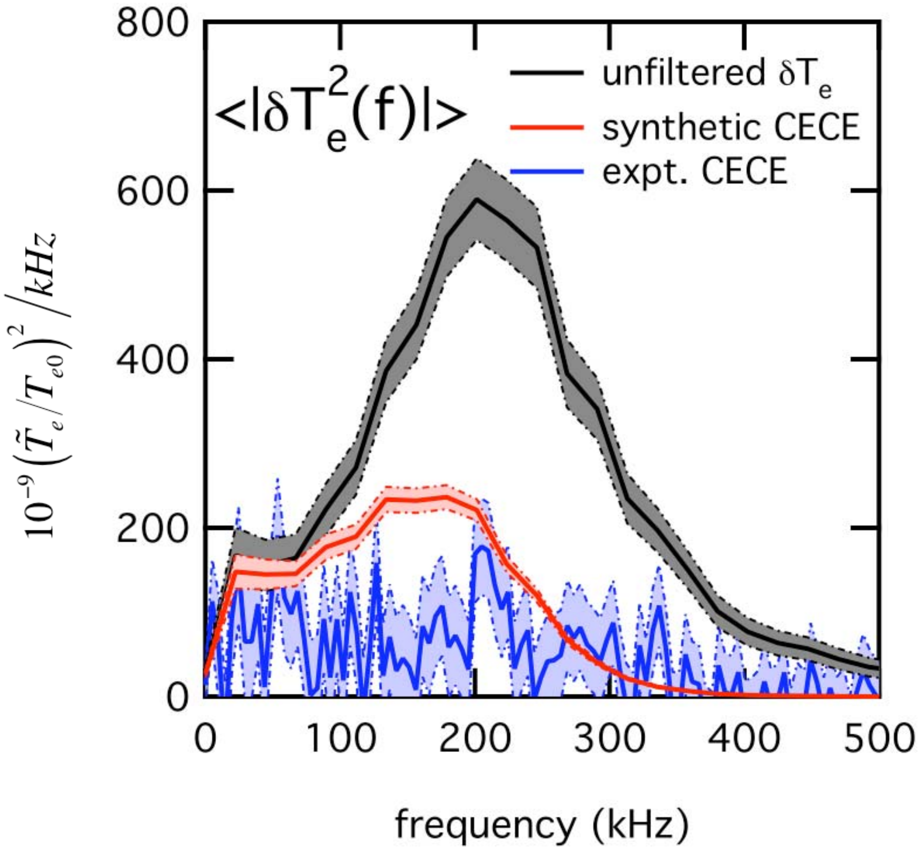
Need Only Small Changes to Fitted Profiles Inside r/a = 0.6 to Match ONETWO Energy Flows



Finite Wavenumber Sensitivities of Each Diagnostic Have Significant Impact on Measured Spectra

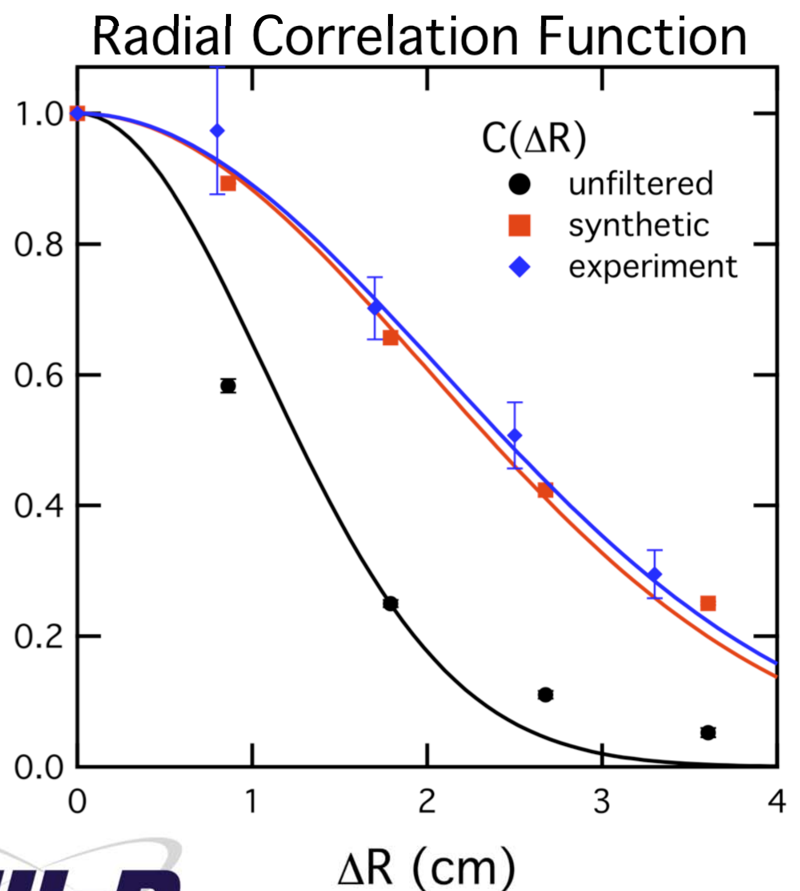
- **Observe a 40%-50% attenuation of fluctuation amplitudes for both diagnostics**

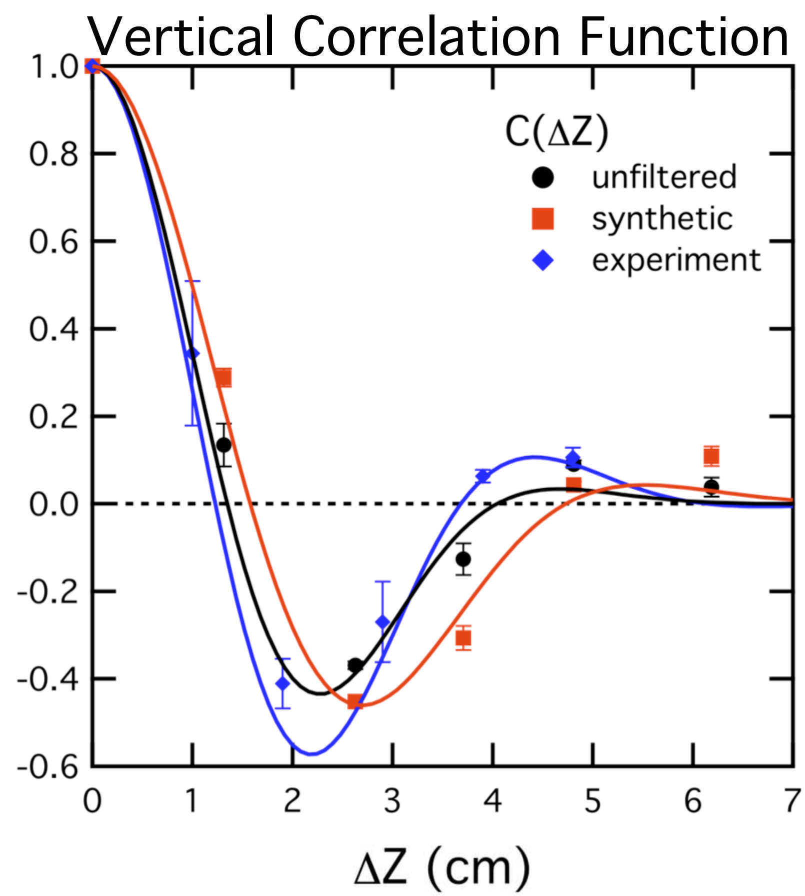




Primary Impact of PSF Appears in Radial Correlation Function

- **Agreement in vertical correlation function C(ΔZ) consistent with agreement in lab-frame power spectra**
- **Solid lines are Gaussians fit to experimental BES, synthetic BES, and unfiltered signals**





Synthetic Spectra Consistently Underpredict Experimental Measurements at all Frequencies at r/a = 0.75

- **Magnitude of underprediction consistent with generic scaling of Q ∝ δX^2**

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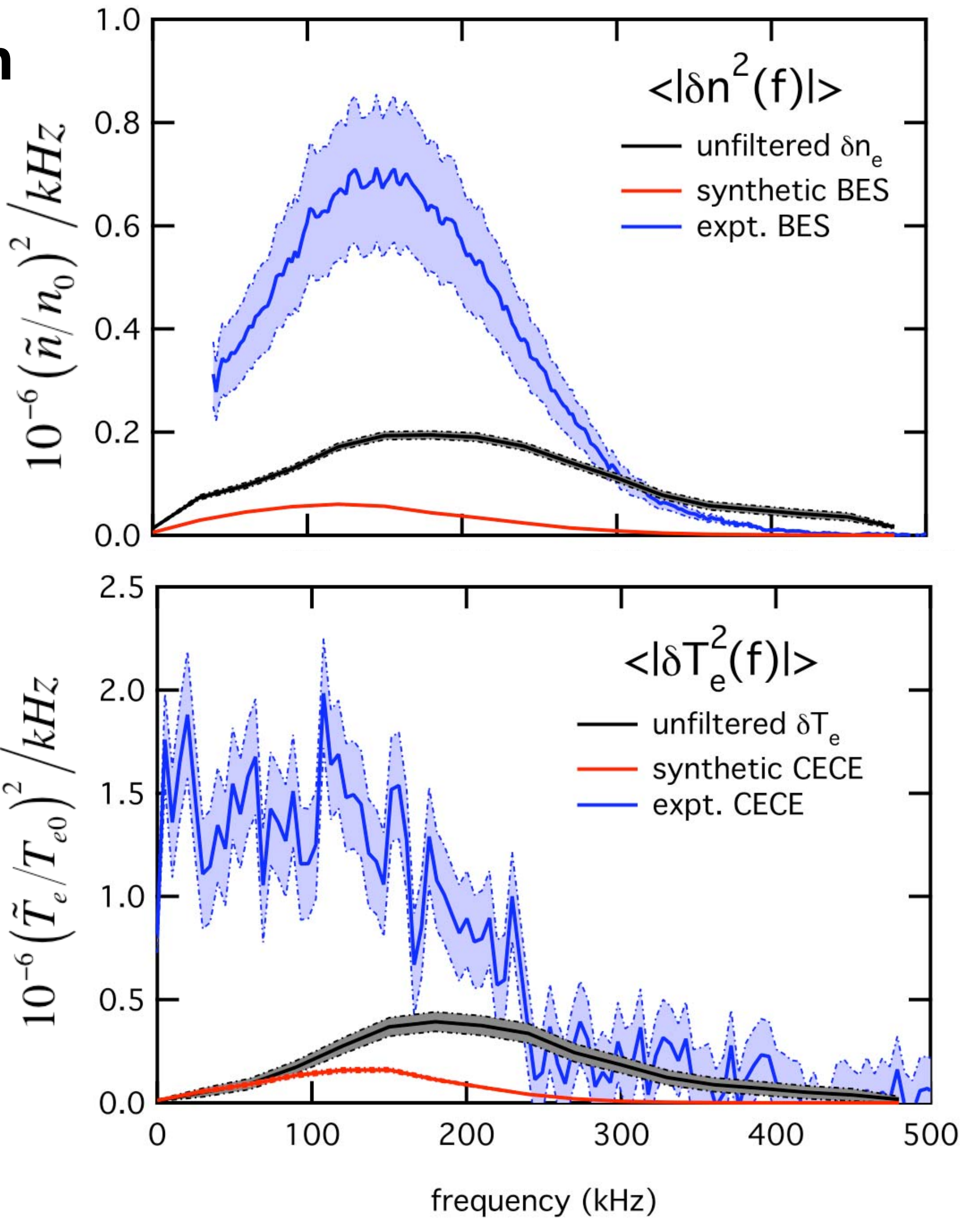

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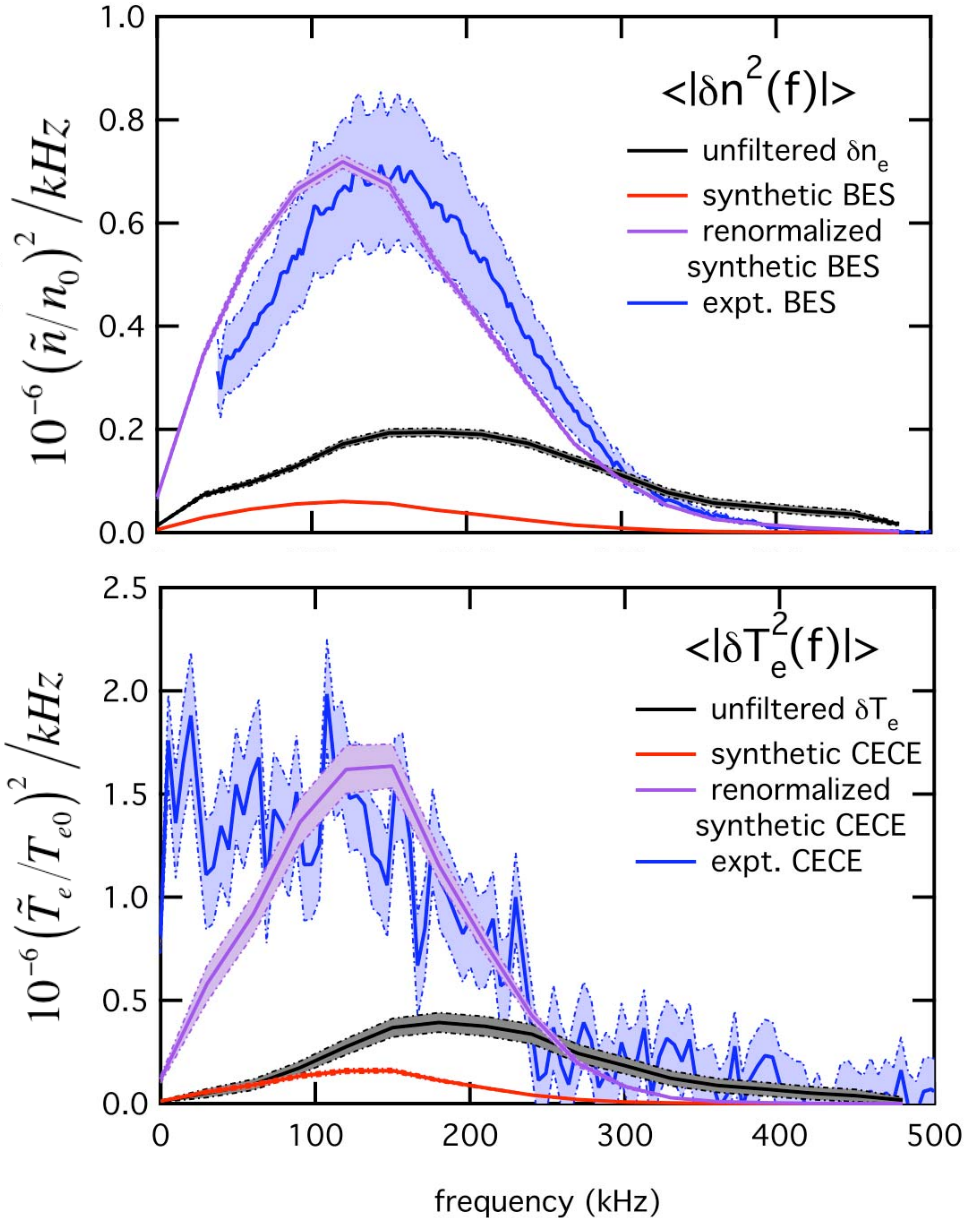

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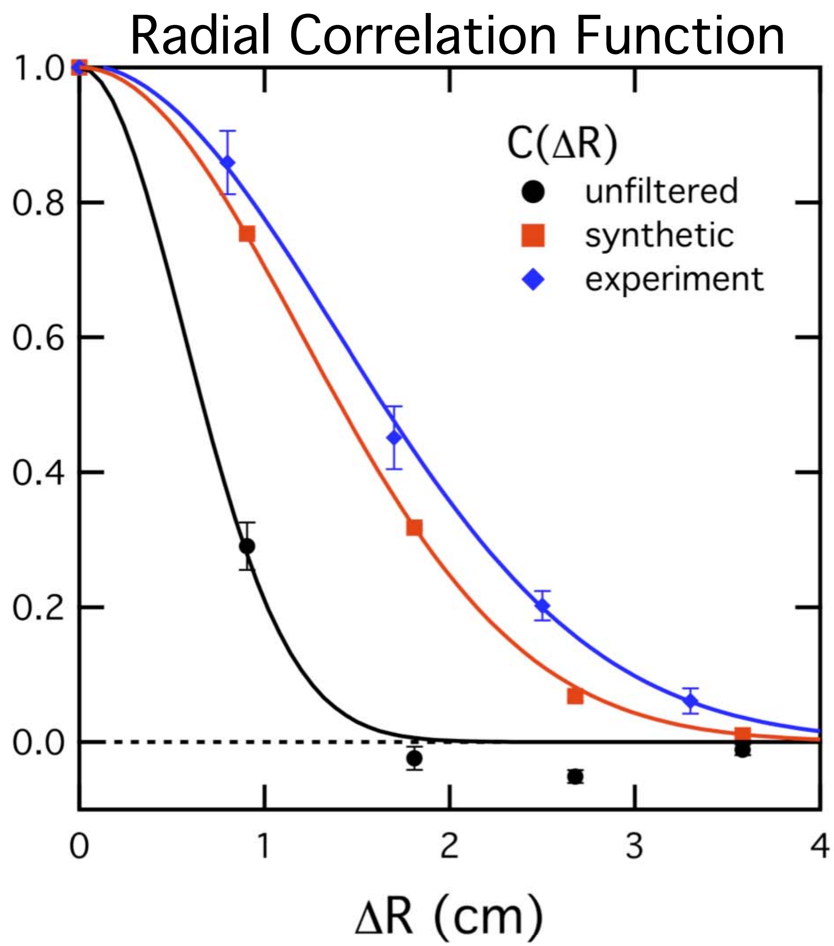
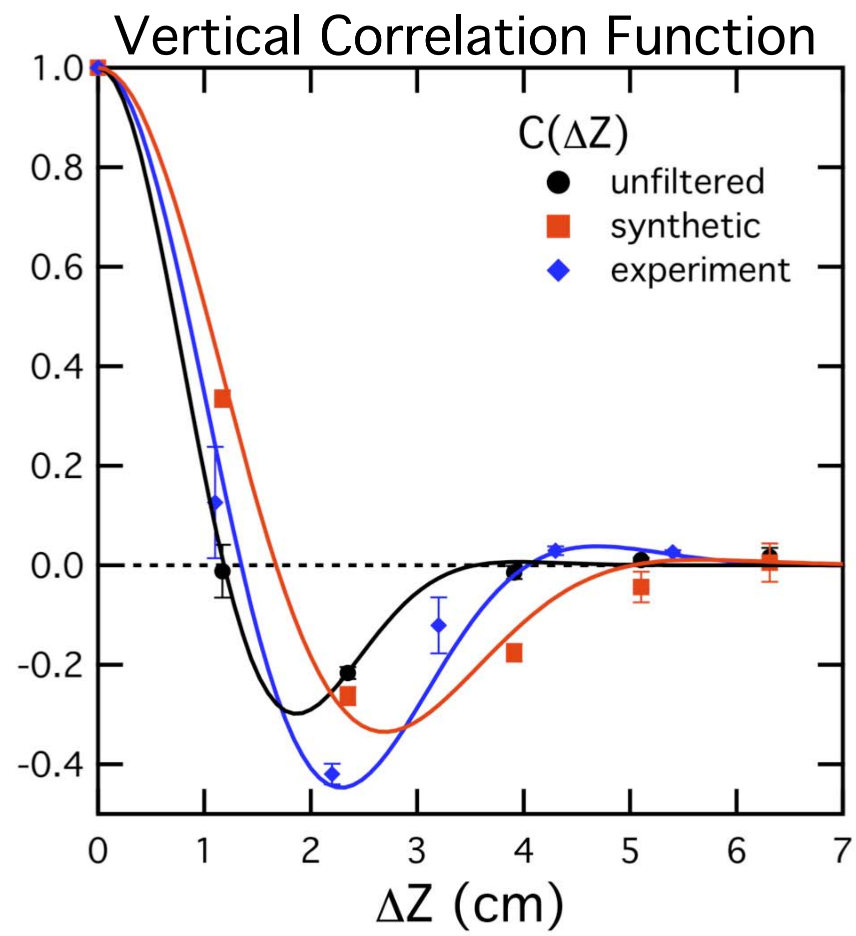
Synthetic Density Correlation Functions at r/a = 0.75 Exhibit Similar Behavior and Agreement with Experiment as at r/a = 0.5



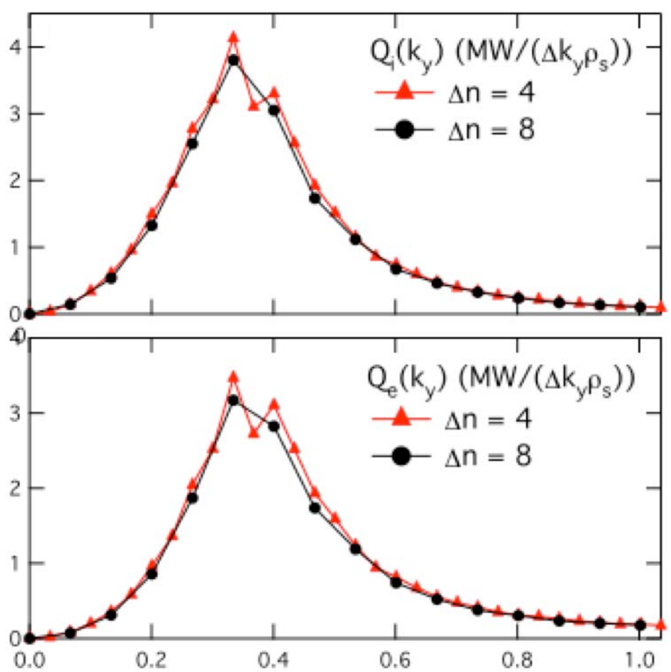


Simulations Exhibit Excellent Convergence in D*n*

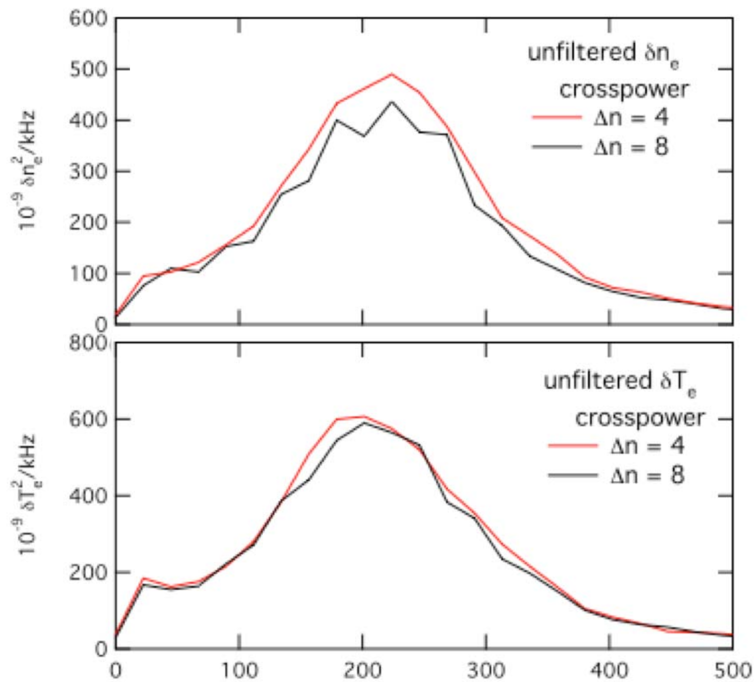
- **A 32-mode simulation with $\Delta n = 4$ exhibits excellent agreement with 16-mode $\Delta n = 8$ results**
  - Agreement in spectral shape as well as net flow and fluctuation levels

$Q_i(k_y)$

$Q_e(k_y)$



$k_y r_s$



frequency (kHz)

$\left\langle \left|\delta n(f)\right|^2 \right\rangle$

$\left\langle \left|\delta T_e(f)\right|^2 \right\rangle$

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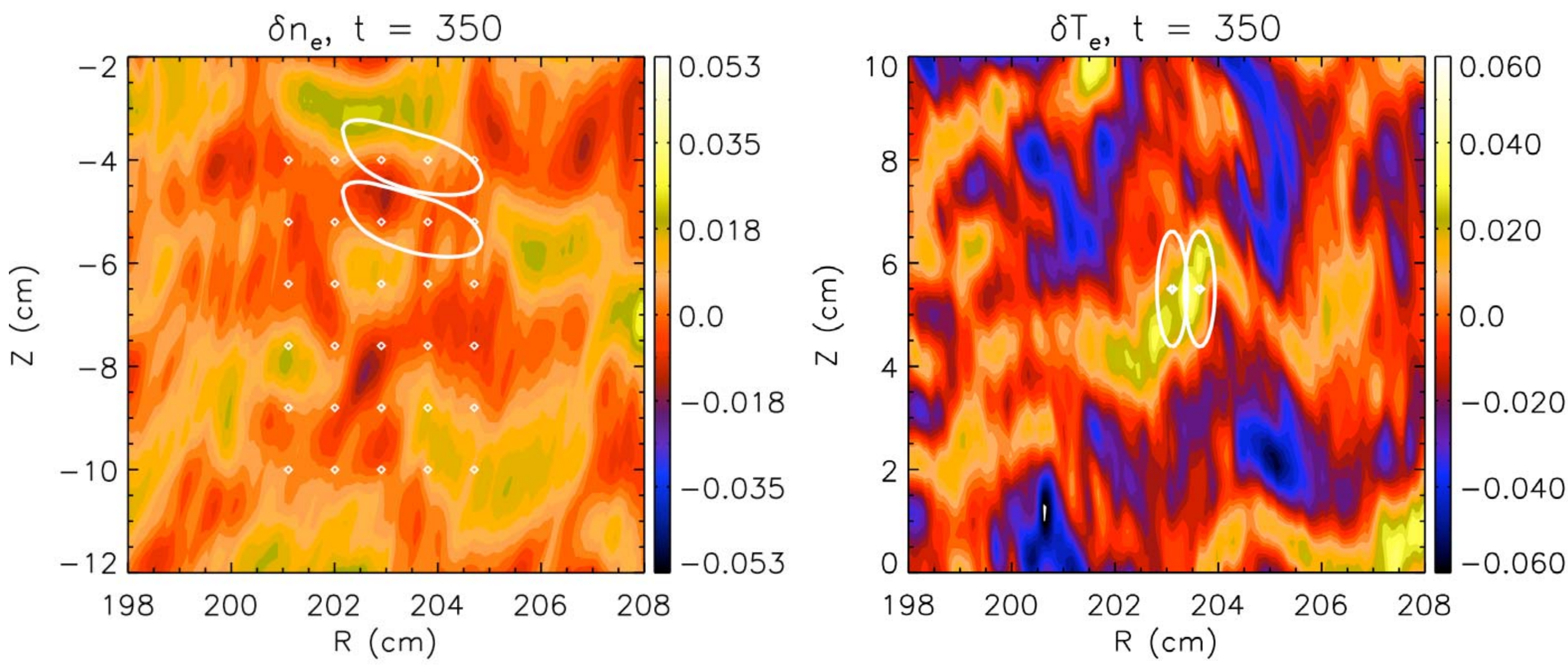
BES and CECE Fluctuation PSF Visualizations in (R,Z) Plane Overlaid on Local r/a = 0.5 Fluctuations

- **In this talk, always refer to normalized fluctuations labeled via** $\delta X \equiv \tilde{X}/X_0$



50% contours of BES and CECE PSFs

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Quasilinear TGLF Model Gives Quick and Accurate Approximations to Full GYRO Calculations

- **TGLF ((T)rapped Gyro-Landau-Fluid) model uses a combination of linear phase information and a semi-analytic saturation rule to quickly predict turbulent flows**
  - Model calculates linear eigenvalues for set of 15-moment gyro-fluid equations (per species)
  - Uses a mixing-length type saturation rule for fluctuation intensity $\overline{V_k^2}$ which is fit to database of > 80 nonlinear GYRO runs
  - Includes both long-wavelength ITG/TEM transport and short-wavelength ETG-driven transport
  - By combining TGLF flow predictions with experimentally measured sources, one can predict a set of profiles necessary to match experimental flows
  - See G. Staebler's poster TH/P8-42 for latest info

- **Simple approach: use TGLF to predict a set of steady-state flow-matching temperature profiles, then use those profiles in the GYRO calculation**

$$\Gamma = n\sum_{k_y}\rho_s c_s\left[\frac{\mathrm{Re}\left\langle ik_y\tilde{\phi}_k^*\tilde{n}_k\right\rangle}{\tilde{V}_k^*\tilde{V}_k}\right]\overline{V_k^2}$$

$$Q = \frac{3}{2}p\sum_{k_y}\rho_s c_s\left[\frac{\mathrm{Re}\left\langle ik_y\tilde{\phi}_k^*\tilde{p}_{T,k}\right\rangle}{\tilde{V}_k^*\tilde{V}_k}\right]\overline{V_k^2}$$

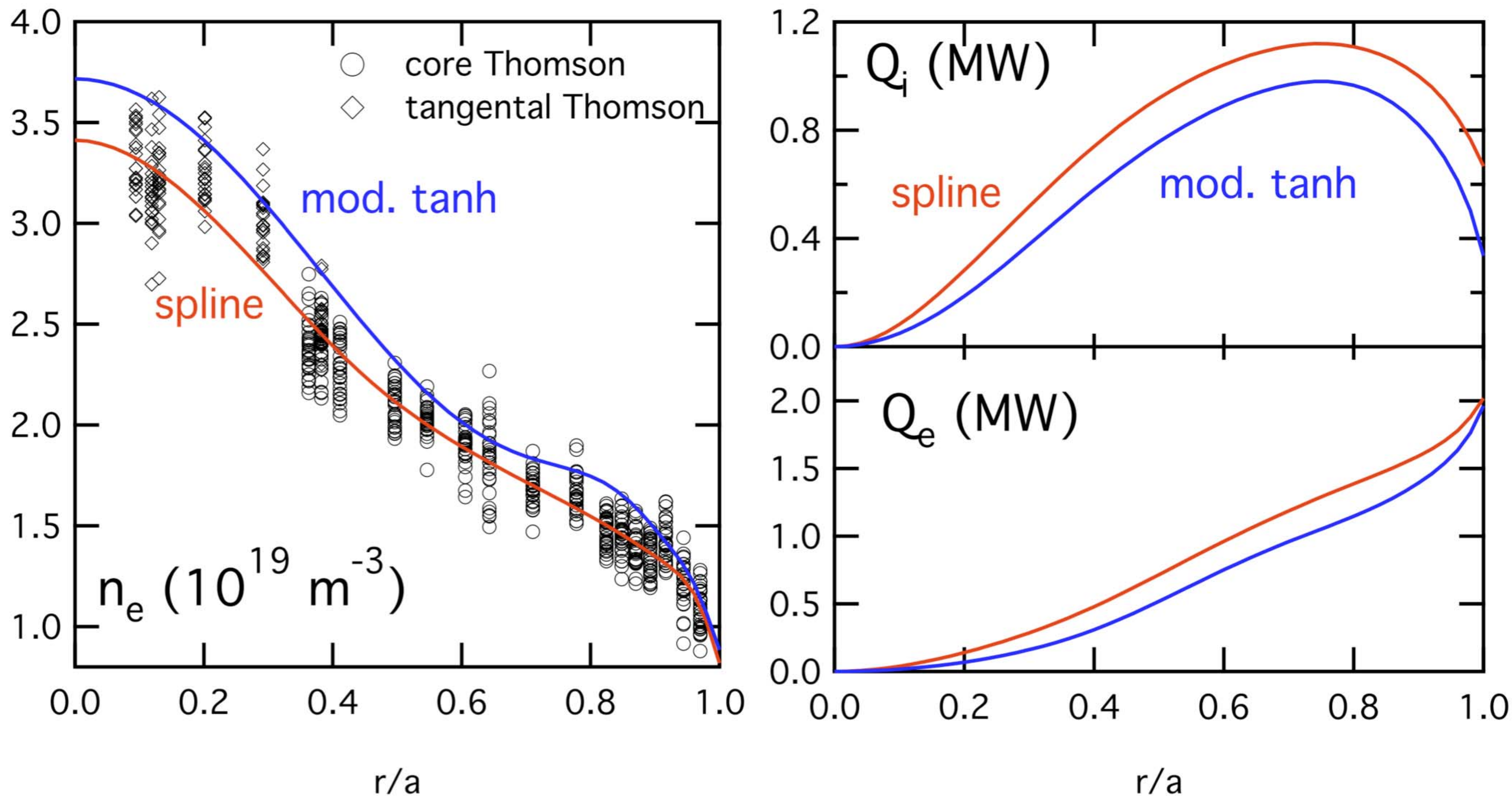
$$\tilde{V}_k = \left(\tilde{n}_k,\tilde{u}_{\parallel,k},\tilde{p}_{\parallel,k},\tilde{p}_{T,k},\tilde{q}_{\parallel,k},\tilde{q}_{T,k}\right)$$

$$\frac{\partial n}{\partial t}+\frac{1}{V'}\frac{\partial}{\partial r}\left(V'\Gamma\right)=S_n$$

$$\frac{\partial}{\partial t}\left(\frac{3}{2}nT\right)+\frac{1}{V'}\frac{\partial}{\partial r}\left(V'Q\right)=S_W$$

G. M. Staebler, J. E. Kinsey, and R. E. Waltz,
Phys. Plasmas **12** 102508 (2005), **14** 055909 (2007), **15** 055908 (2008)

Impact of Different Fit Choices to Electron Density on ONETWO Results



Sensitivity Studies Indicate Only "Moderate" Stiffness of Transport at r/a = 0.5

- All simulations used a 20% too large γ_{ExB} value
- As for previous simulations, each column required ~3000 cpu-hours
- All diffusivities normalized to χ_{gB} = 0.866 m^2/s

			a/L_{Ti}			a/L_{Te}			a/L_{ne}			box size		
	Expt.	base	+5%	-5%	-10%	+5%	-5%	-10%	+5%	-5%	-10%	N_n=32 Δ_n = 4	N_n=64 Δ_n = 2	N_n=20 (max ky +25%)
χ_i	4.5	4.74	5.35	4.23	4.05	4.83	5.00	4.87	4.72	5.30	5.47	5.18	5.26	5.74
χ_e	2.1	2.38	2.67	2.17	2.05	2.46	2.53	2.42	2.49	2.56	2.52	2.63	2.72	2.84
D_{ne}	0.05	0.75	0.89	0.64	0.58	0.71	0.87	0.90	0.77	0.84	0.87	0.86	0.88	0.92

$$Q = \frac{3}{2}\left\langle \tilde{p}\tilde{V}_r \right\rangle = -n\chi \frac{dT}{dr} \qquad \Gamma = \left\langle \tilde{n}\tilde{V}_r \right\rangle = -D\frac{dn}{dr}$$

Parameter Scans Show r/a = 0.75 Results Are Numerically Robust

- **Each row used >= 4096 processor-hours on Jaguar**
- **No ExB shear used in these cases**

	χ_i/χ_{gB}	χ_e/χ_{gB}	D_{ne}/χ_{gB}
expt	**22.5**	**15.5**	**0.25**
base	9.24 ± 0.40	4.79 ± 0.15	-0.46± 0.083
Inc. grad-Ti 10%	11.5	5.5	0.36
Half Δt (short run)	11.3	5.3	0.31
μ=40	9.77	5.43	-.45
EM effects on	10.3	5.36	0.12
Inc. max k_y 25%, Δx 33%, red. Δt 50%	9.69	4.72	0.11
Double max ky, half binormal box size	10.98	5.07	0.47
Inc. ORBIT_GRID	10.8	5.58	-0.76
Inc. ENERGY_GRID	9.84	5.04	-0.28
Inc. radial box size 50%	9.79	5.08	-0.39

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