Progress Report from the Cyclone Project

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Cyclone began whirling in December, 1996, and consists of:

S. Parker, **Colorado** (Leader)
C. Bolton, **DOE/OFES**
D. Boucher, **ITER**
G. Bateman, A. Kritz, A. Redd, **Lehigh U.**
R. Sydora, **UCLA**
J. Kinsey, L. Lao, **GA**
J. Mandrekas, **Georgia Tech**
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A. Dimits, W. M. Nevins, D. Shumaker, B. Cohen, **LLNL**
M. A. Beer, G. W. Hammett, S. D. Scott, **PPPL**

Overview

- What is Cyclone?
- Test Cases for Turbulence Codes
- Comparisons of Turbulence Codes
    1. Heat fluxes
    2. Fluctuation Levels
- R/L_T Scan
- Other Parameter Scans
- Suspected Causes of Differences
- Linear Theory
- HRW Effect
- Particle Noise
- Physics Basis and Reliability of IFS/PPPL Model
- Multi-Mode Model

What is Cyclone?

- Purpose: To provide information on the **physics basis** and the **reliability** of the transport models most widely used for predicting ITER performance.
  - *We need to know why transport models disagree.*
- Codes/models that have been or eventually will be considered in detail:
  - Flux-tube gyrofluid turbulence simulations
  - Flux-tube gyrokinetic turbulence simulations
  - Global gyrokinetic turbulence simulations
  - Linear 1D high-n eigenmode and initial value calculations
  - IFS/PPPL model
  - Multi-Mode model
- Participation is voluntary.

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Transport Models Examined by Cyclone

- IFS/PPPL model has been focus of group activity so far.
- Primary activity has been comparison of flux-tube gyrofluid and flux-tube gyrokinetic ITG turbulence simulations.
- Performed in close coordination with the "Numerical Tokamak Turbulence Project," a US-DOE Grand Challenge project.
- Several hundred hours of supercomputer CPU time charged so far.

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Gyrofluid/Gyrokinetic Comparison Test Cases

- Test cases use simplified physics:
  1. Circular, unshifted, $\beta = 0$, high aspect ratio equilibrium
  2. Electrostatic, adiabatic electron response
  3. Single species of ions, Z = 1.
  4. $T_i = T_e$
  5. Collisionless
  6. No sheared flows
- Simplified physics chosen because:
  1. Significant differences evident at this basic level
  2. Inclusion of less sophisticated models desirable
- All models stripped to this limit for comparisons
- Remaining parameters inspired by experimental data from DIII-D and TFTR, and from 15 gyrokinetic simulations in Dimits, *et al.*, PRL, **77**, 71 (1996).

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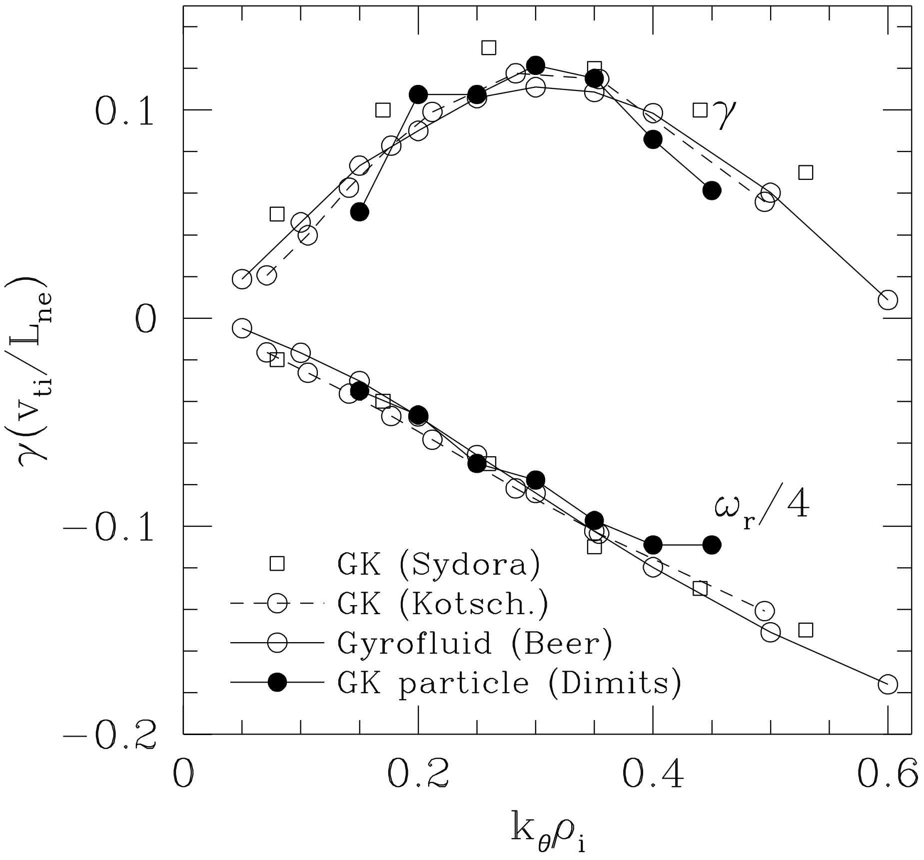
Test Case Parameters

Case	R/L_T	R/L_n	q	$\hat{s}$	r/R
Cyclone	6.9	2.2	1.4	0.8	0.18
NTTP	10	2.5	2.4	1.6	0.21
PRL	10	2.5	1.2	0.8	0.21

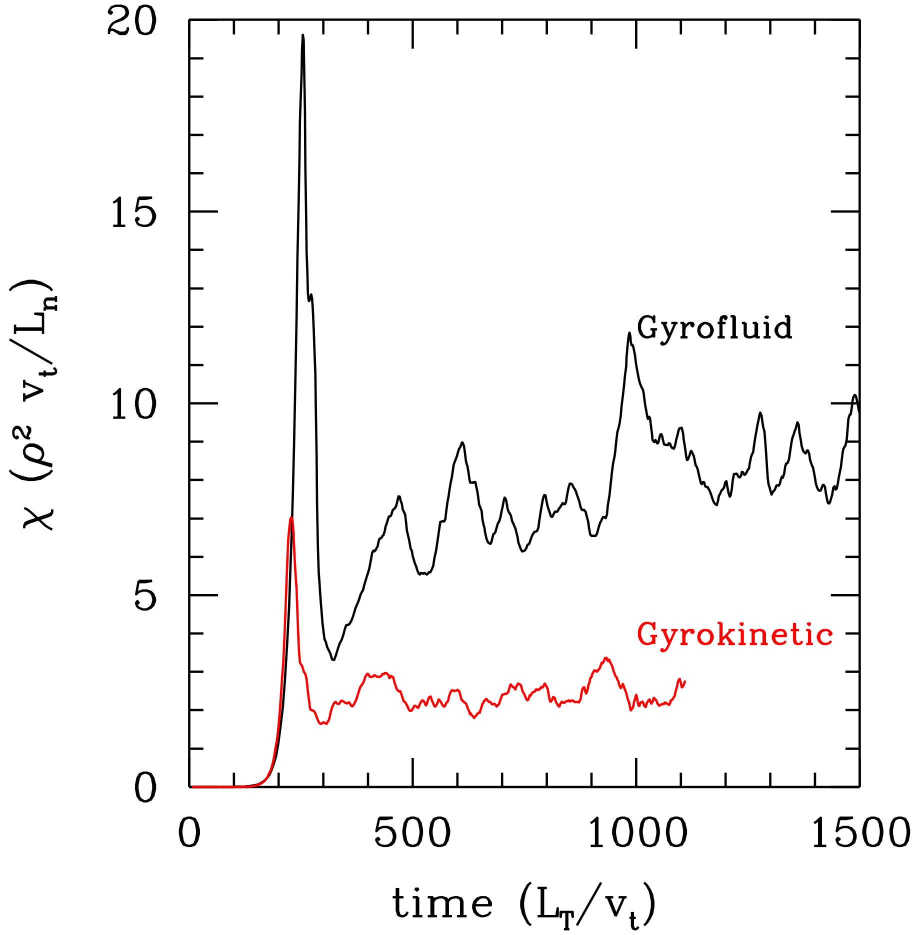
- Cyclone test case inspired by parameters from the half-radius of a DIII-D H-mode from the ITER profile database, #81499.
- NTTP test case inspired by parameters from the half-radius of a TFTR L-mode, #41309.
- PRL test case parameters from Dimits, *et al.*, PRL, **77**, 71 (1996).
- Cases differ in q, $\hat{s}$, and R/L_T, but are otherwise almost identical.
- Scaling of predicted χ_i with R/L_T investigated by varying R/L_T of the Cyclone case with other parameters held fixed.
- Importance of self-generated sheared poloidal flows investigated by suppressing them, and by varying r/R and q in the flux-tube simulations.

Linear comparisons: Cyclone Base Case



- Good agreement in measured frequencies. Plan to focus on low $k_\theta\rho_i$ in future.

Comparison of Nonlinear Simulations: Cyclone Base Case Results



- Gyrokinetic heat flux is lower than gyrofluid heat flux by a factor of 3.3.

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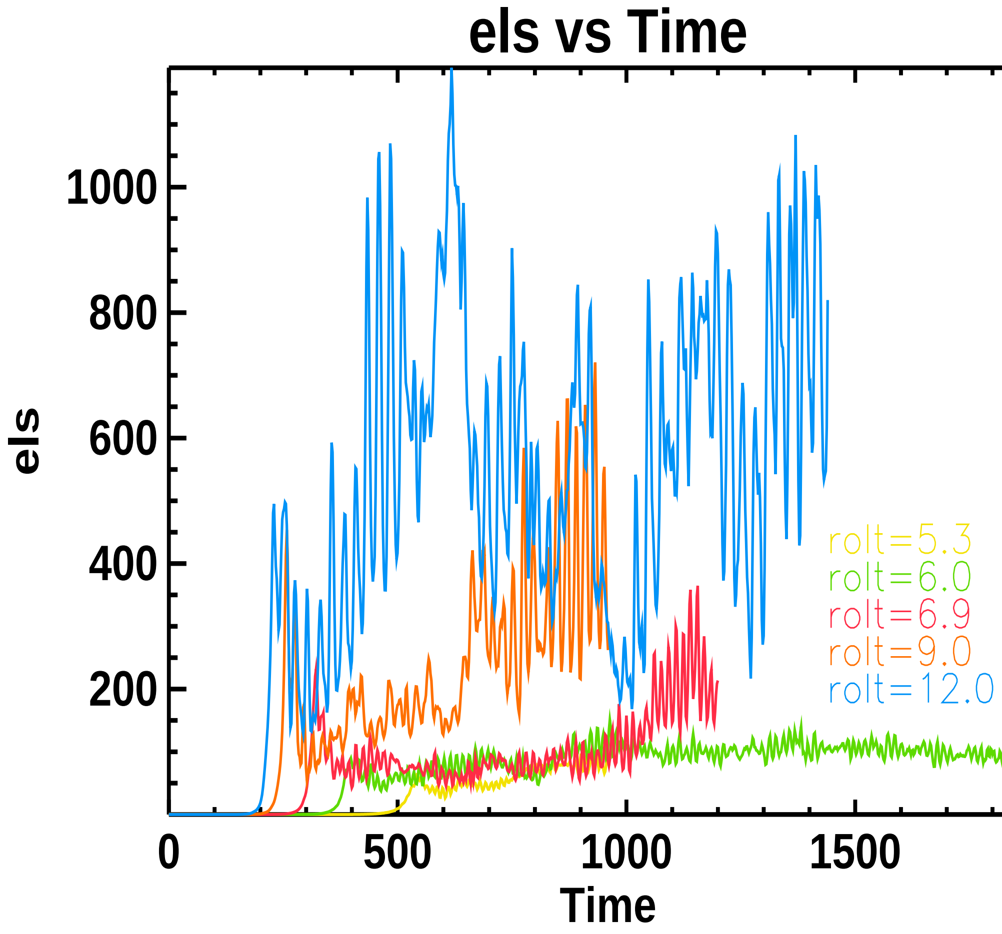
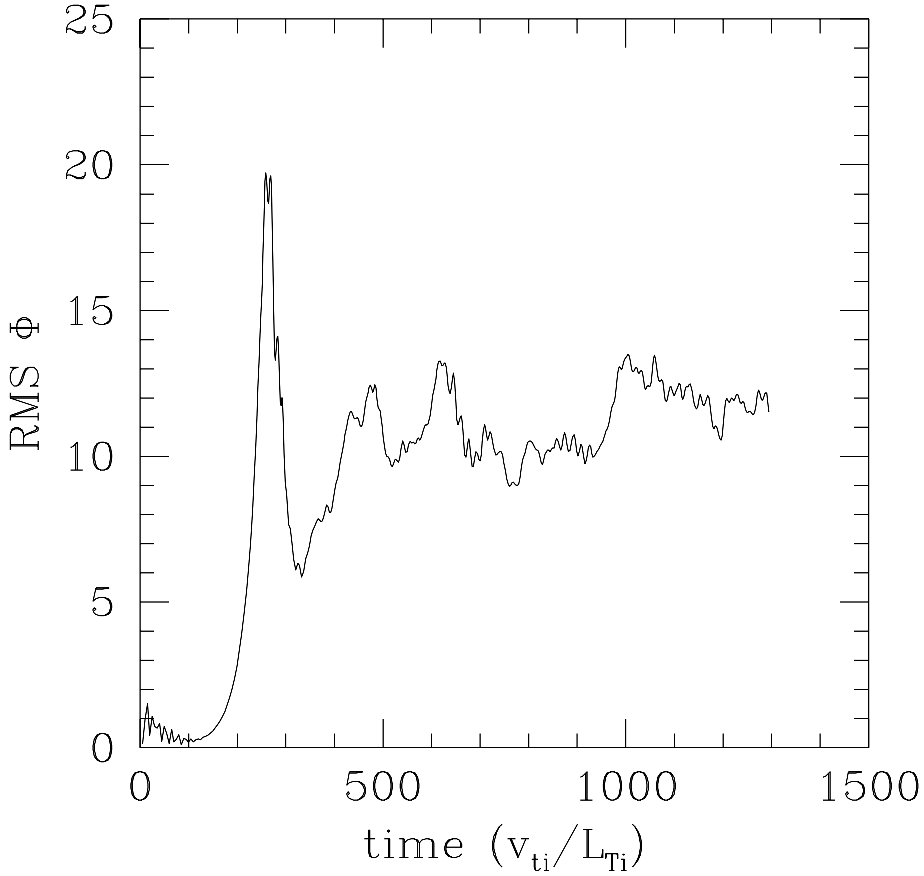
Gyrokinetic Volume-Averaged Φ^2

- Cyclone base case R/L_T scan.

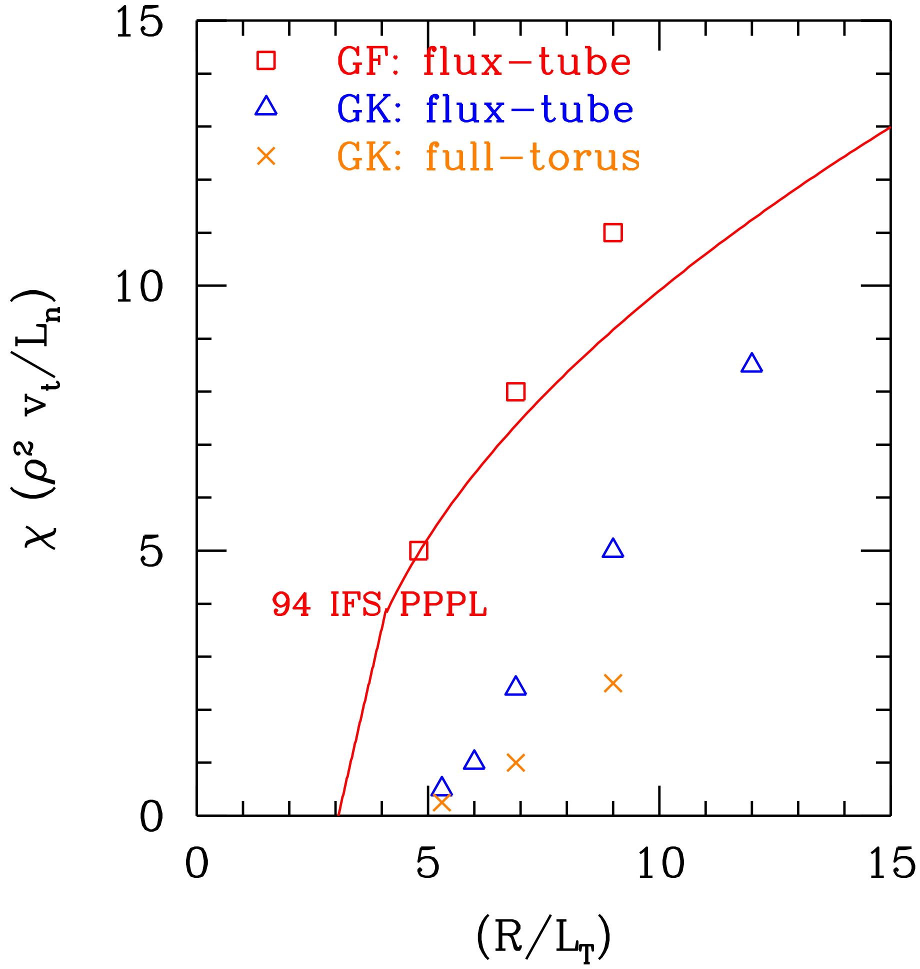


Gyrofluid Volume-Averaged $\sqrt{\Phi^2}$

- Cyclone base case results.



Comparison of Nonlinear Simulations: R/L_T Scan



- Differences in predictions evident
- IFS/PPPL agrees reasonably well with GF simulations.

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Global Gyrokinetic Code Results

- Global code heat flux is lower than flux-tube gyrokinetic heat flux by a factor of 2.4.
- Long-wavelength sheared flows are stationary in time.
- Difference may be due to boundary conditions: global codes use $\Phi = 0$ at $r/a = 1$, whereas flux-tube codes use periodic boundary conditions.
- Global codes subject of future Cyclone focus.

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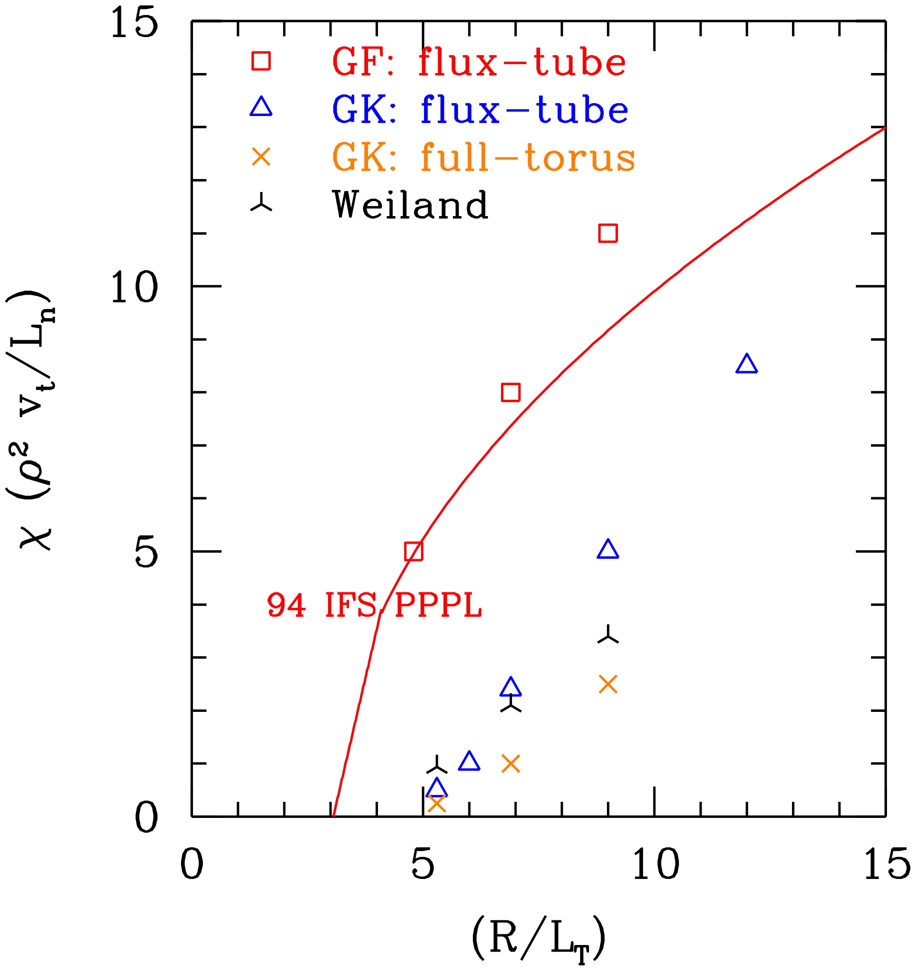
Comparison of Models and Simulations



- Weiland model χ closer to GK results
- Note: MMM implementation of Weiland model has factor of $1/\kappa^4$. These comparisons have $\kappa = 1$.

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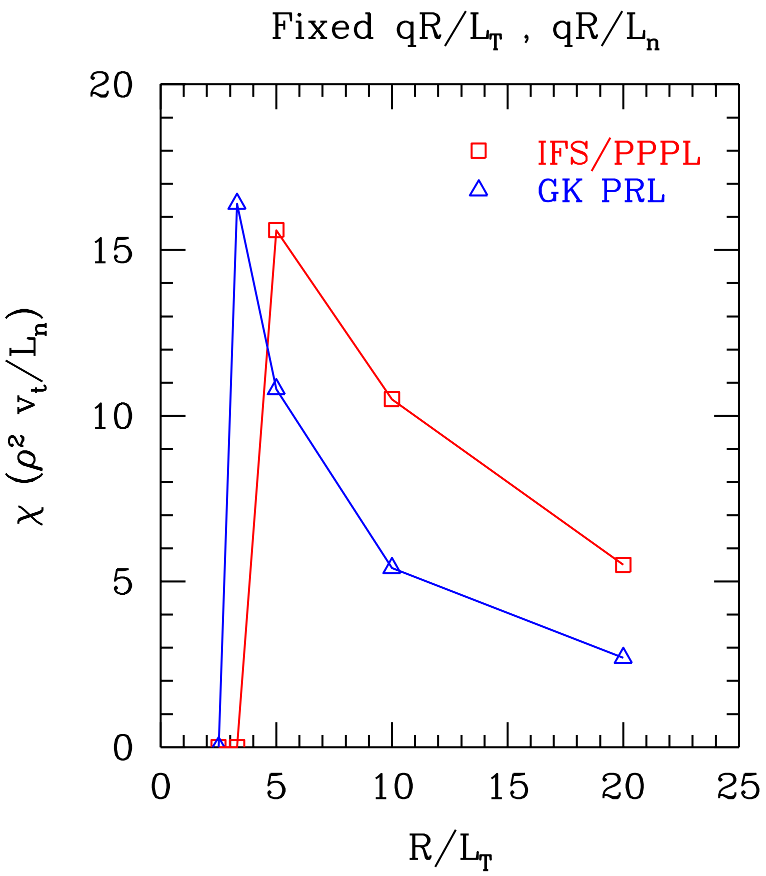
More GF/GK Comparisons: Behavior Near Threshold

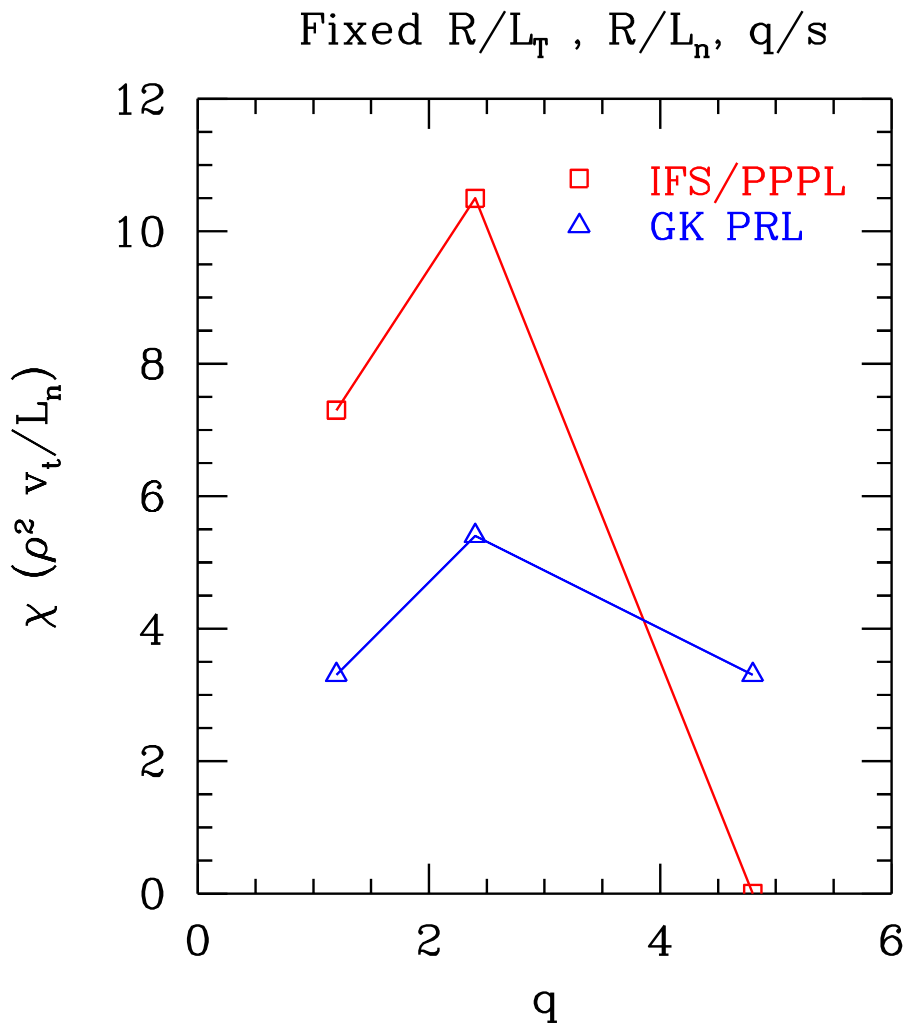
- 15 GK simulations in PRL by Dimits, it et al., compared here and in following slides to IFS/PPPL model
- PRL GK simulations show large flux near marginal stability for some parameters



- Here, $qR/L_T = 24$, $L_n/L_T = 4$, $\hat{s} = 1.6$, $r/R = 0.2$, $T_i = T_e$.

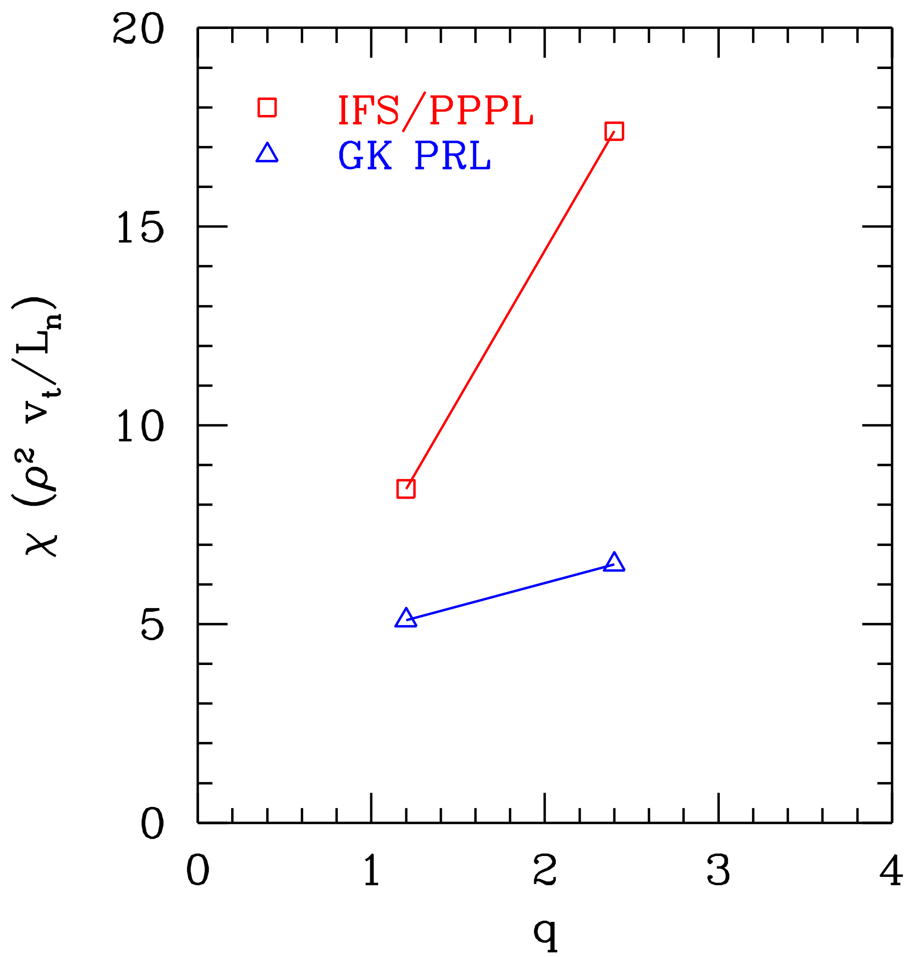
GF/GK Comparisons

- Factor of two difference typical of PRL cases



GF/GK Comparisons: q Scaling

- Gyrofluid model predicts stronger q scaling.
- Inconsistent with expectations from HRW effect.



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Differences Between GK and GF Flux-Tube Simulations

1. Particle noise
2. Hinton-Rosenbluth-Waltz effect
3. Excessive GF damping of flow at high k_r
4. GF equations missing nonlinear wave-particle effects
5. Differences in linear theory
6. Box size convergence issues (may not be relevant to Cyclone comparisons)

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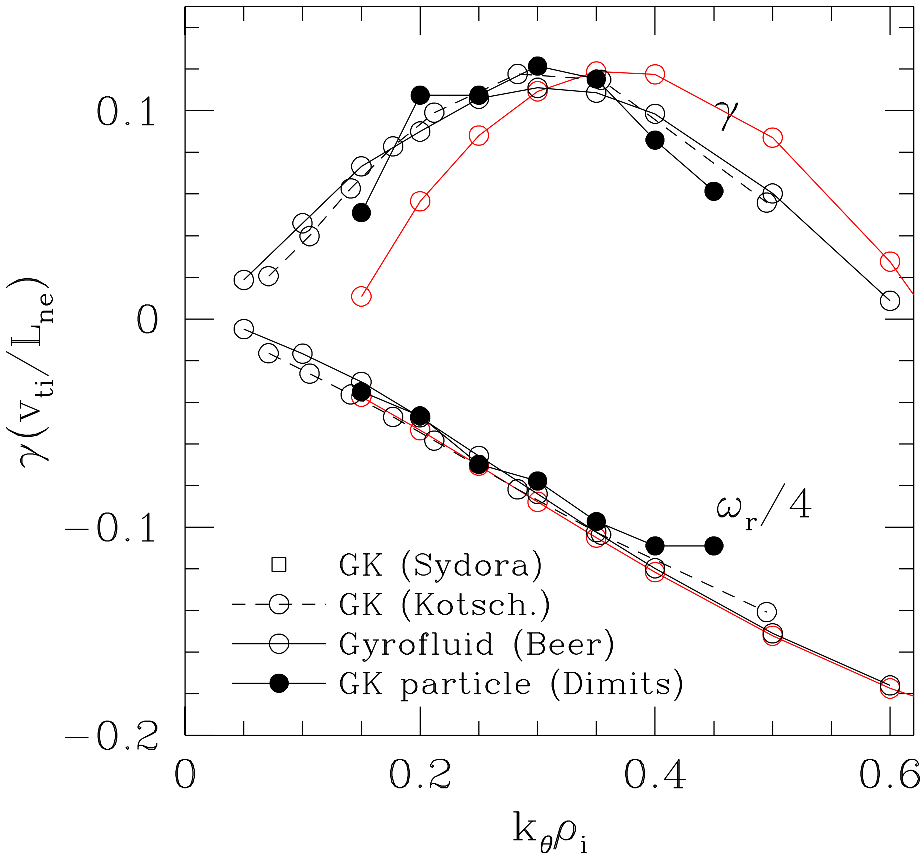
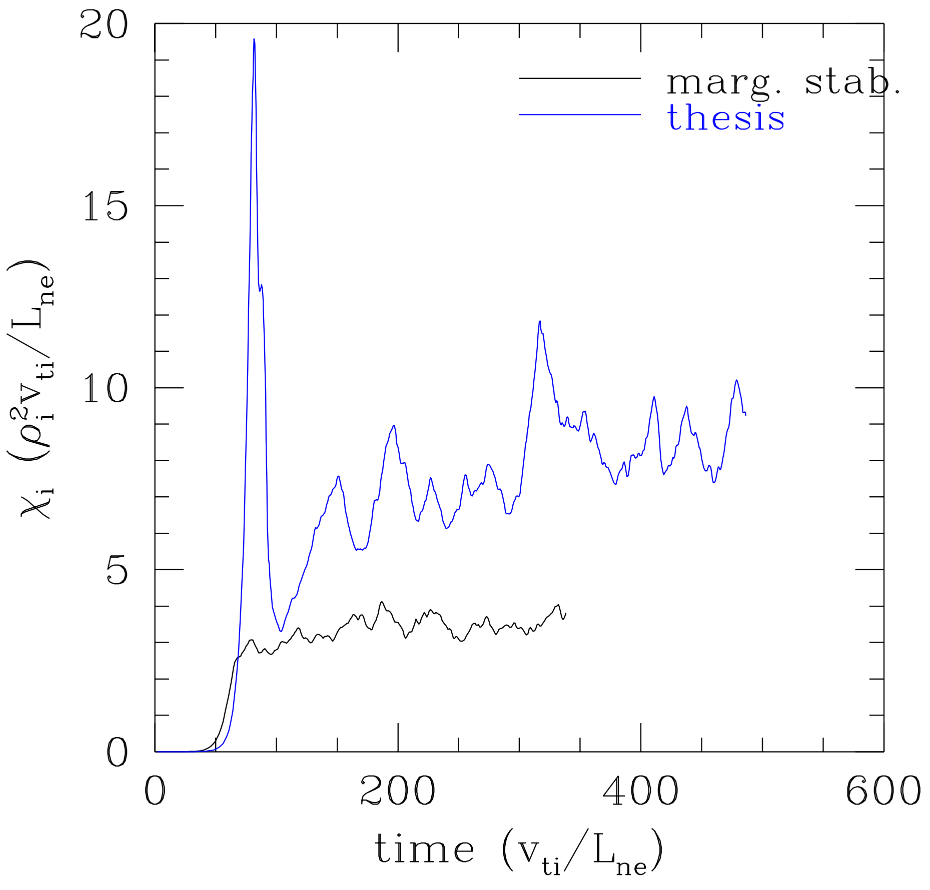
Impact of Small Difference in Linear Theory

- Beer varied closure coefficients to change γ *vs.* $k_\theta \rho_i$.



Impact on Heat Flux

- Nonlinear heat flux affected strongly by differences at low $k_\theta \rho_i$.



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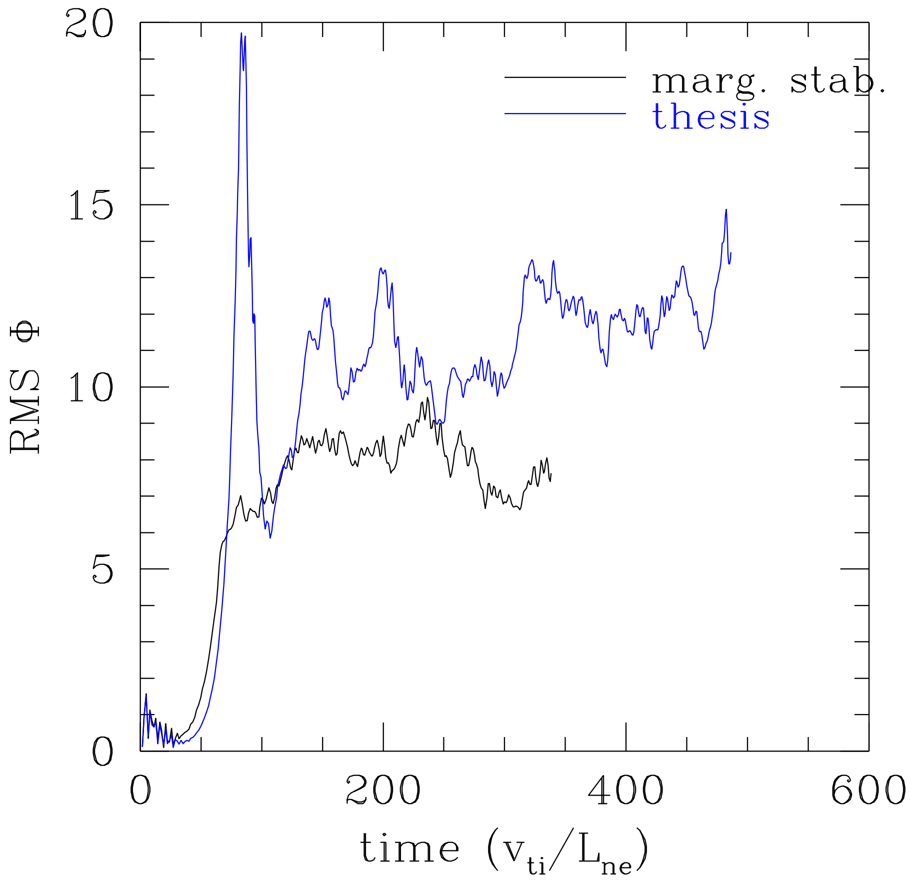
Impact on Fluctuation Level

- Volume-averaged Φ smaller.



IFS/PPPL Model

- Objectives: Use simulations to predict ion and electron temperature profiles, given some boundary temperature and experimentally measured or inferred density, net heating, and current profiles.
- Emphasis is on model that has strong theoretical foundations – there are no parameters fit to experimental data.
- Agrees reasonably well with large amount of experimental data, including transient transport experiments and steady state L and H-mode experiments on multiple tokamaks.
- Describes transport from ITG mode only.
- Relies heavily upon interpolated simulation results. GLF23 (Waltz) is example of how to improve upon IFS/PPPL model.
- Adequately describes current scaling in circular and elongated discharges (given experimental temperature near edge as boundary condition).

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Physics Basis, Reliability of IFS/PPPL Model

- IFS/PPPL model based on nonlinear gyrofluid simulations and linear gyrokinetic calculations
- There are significant differences between gyrofluid and gyrokinetic simulation results.
- We have not determined the source of the disagreement:
  - Differences in linear theory not completely ruled out.
  - Tests so far indicate HRW effect not likely cause of discrepancy.
  - Further GK PIC noise tests remain to be done.
  - Existence (or effects) of nonlinear wave-particle effects that are not described by the gyrofluid equations has not been investigated within Cyclone.
  - Size and effect of high k_r damping in GF simulations have not been investigated within Cyclone.
- No firm conclusions regarding the IFS/PPPL model.

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Implications of Present Differences for ITER

- Cyclone base case GK flux is one-third of GF flux
- With density 1.5 times the Greenwald limit, no sawteeth, 100 MW of ion heating on axis, and a pedestal temperature of 1.5 keV, this difference would increase predicted Q from 2 to 9.3.
- Less impact if pedestal temperature is lower.
- Similar results obtained from changing functional dependence of χ on R/L_T.
- Detailed sensitivity studies using gyrokinetic simulation results not undertaken.

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Multi-Mode Transport Model

- Objectives:
  - Predict experimentally measured T_i, T_e, n_e, n_Z, q, ...
  - Used combination of the best theories available in 1995 when MMM was last frozen
  - Emphasis is more on developing a model that agrees with experimental data and less on theoretical foundations
- Relative weights of model components were calibrated empirically in 1995 using fewer than 10 discharges from TFTR, DIII-D and JET
  - Resulting MMM matches more than 60 L- and H-mode discharges to within 15%

Multi Mode Transport Model

- Weiland drift wave transport model (ITG, TEM, ...)
  - includes impurities, finite β, collisions, ...
  - quasilinear transport model based on Braginskii equations
  - does not include sheared flows
  - never intended to compute spectrum ($\gamma(k_\theta)$)
  - assumed $k_\theta \rho_s = 0.316 \Longrightarrow$ gyro-Bohm transport model
    (this gyro-Bohm model yields agreement with non-gyro-Bohm L-mode and H-mode experimental data)

Multi-Mode Transport Model

- Guzdar-Drake resistive drift ballooning mode
  - small near the center of hot plasmas
  - linear dependence on collision frequency provided best model available when MMM was frozen in 1995
  - collisionality and q dependence of this model found to be important in obtaining good agreement with data in current and ρ_* scans
  - it is important to predict transport out to plasma edge
- MMM also includes neoclassical and kinetic ballooning mode thermal and particle transport

Multi-Mode Transport Model

- Elongation scaling
  - empirically, $\tau_E \propto (1+\kappa^2)^2/(q^2 n T)$
  - no one has completely explained this scaling yet
  - transport theories were derived for only circular plasmas when the MMM was last frozen in 1995 — authors had no theoretical guidance on effect of high elongation
  - authors found empirically that $\chi \propto \kappa^{-4}$ used in MMM allows them to:
    1. match a wide range of experimental data
    2. produce the observed asymptotic scaling
  - local elongation κ is used in MMM (typically local κ is smaller near magnetic axis)

Summary

- Cyclone project is quite active.
- So far primarily looking at differences between flux-tube gyrofluid and gyrokinetic ITG simulations.
- From a theoretical perspective, the order-of-magnitude agreement between the gyrofluid and gyrokinetic turbulence simulations is encouraging.
- Existing differences significant to experimental comparisons and to ITER projections.
- No firm conclusions to date.

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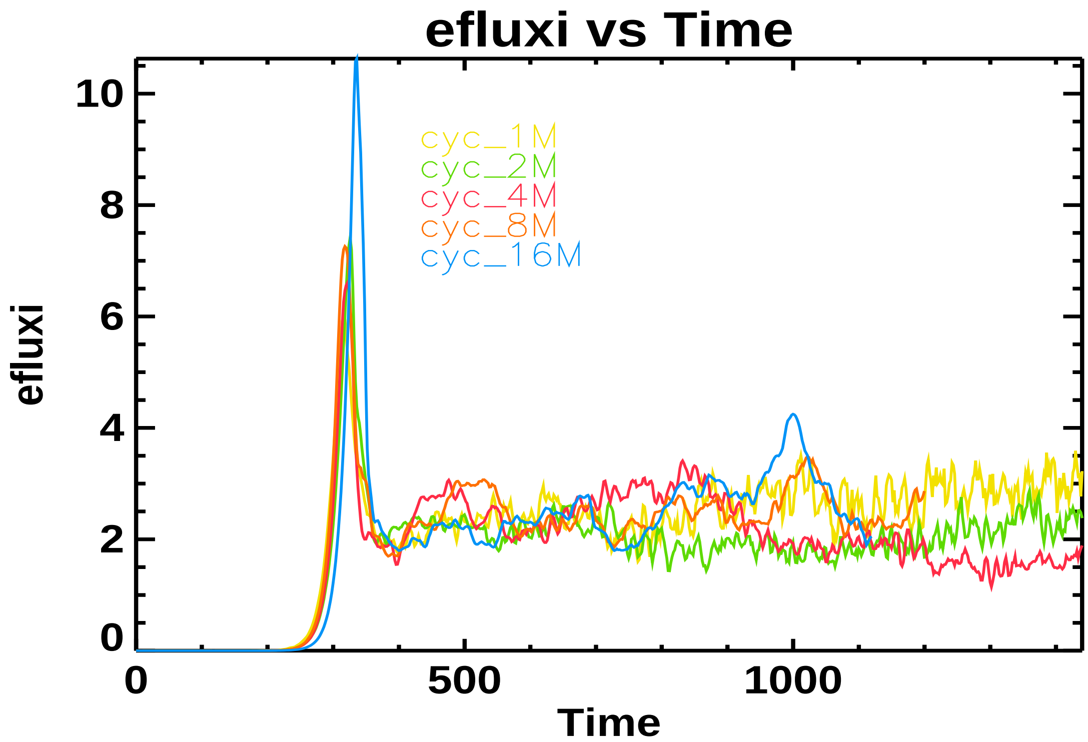
Particle Convergence Studies: χ

- Extensive particle convergence studies undertaken for base case.
- Particle number varied by a factor of 16, with no effect on predicted heat flux.
- This evidence suggests that the gyrokinetic particle simulations have enough particles to extract a signal from the particle noise.



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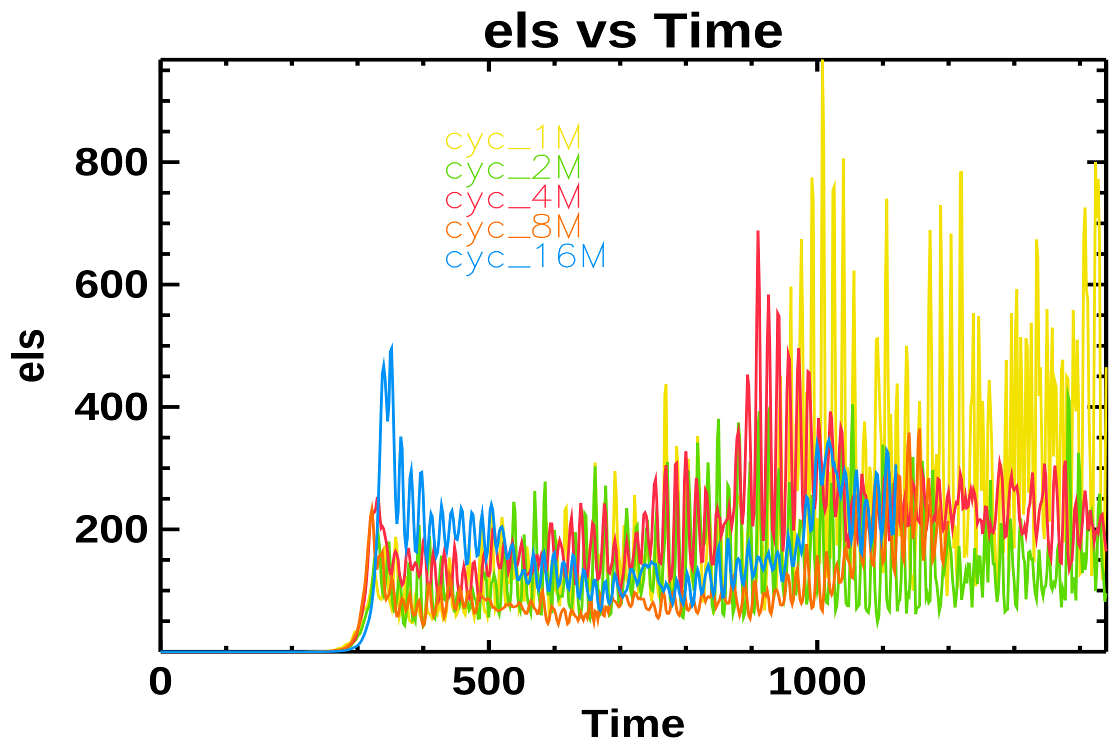
Particle Convergence Studies: Φ

- High frequency oscillations observed in volume averaged Φ^2; growing in time.
- Origin of this behavior not yet understood, and shows a lack of a true steady state.
- More work is need to understand this phenomenon.



Noise in δf PIC Simulations

- Principal inaccuracy of δf PIC algorithm arises from calculation of moments of continuum distribution function with finite number of particles.

- Well-known (Monte Carlo) formulas exist for these errors, which decrease with $1/\sqrt{N}$, but increase in time in the presence of diffusion.

- In typical applications, noise causes diffusion.

- Toroidal microinstabilities have novel features: "radial" modes are easily excited to large amplitudes, and turbulence is highly anisotropic.

- Noise in the radial modes:

  1. Does not cause radial transport (only poloidal)
  2. Suppresses other modes through $\mathbf{E}\times\mathbf{B}$ shear stabilization

- Nonlinear gyrokinetic and gyrofluid flux-tube simulations' predictions of heat flux are sensitive to radial mode dynamics: With no self-generated flows allowed, flux increases by factor of 5–10.

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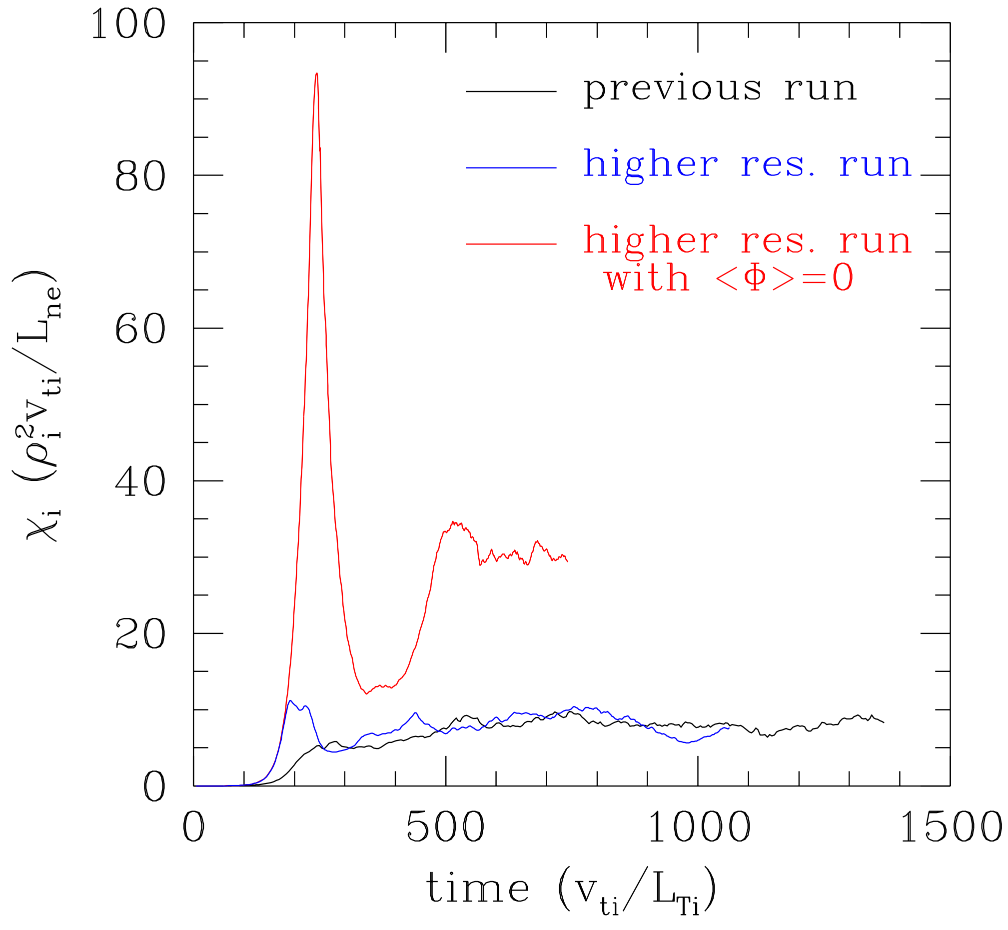
Turbulent Flux Larger Without Radial Modes



- Results from gyrofluid simulations

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Noise in δf PIC Simulations Grows

- Perturbed distribution function represented by weighted markers, $\delta f(x, v, t)$.
- RMS value of weights increases in time, as long as there is radial diffusion in the system:

$$\delta f(x_i, v_i, t) = -\left(x_i(t) - x_0\right) \frac{\partial f}{\partial x}$$

- A radial mode Fourier component of density is given by:

$$\rho_k = \frac{\int d^3v\, d^3x\, e^{ikr_i} \delta f(x, v) f_M}{\int d^3x\, d^3v\, f_M} \simeq \sum_{i=1}^{N} e^{ikr_i} \delta f(x_i, v_i)/N$$

- Neglecting dielectric effects, the error (noise) can be estimated by

$$\delta^2 \simeq \frac{\sum_{i=1}^{N} \left[e^{ikr_i} \delta f(x_i, v_i)\right]^2 /N - \left[\sum_{i=1}^{N} e^{ikr_i} \delta f(x_i, v_i)/N\right]^2}{N}$$

- Thus, noise grows in time. For any N, there is a time beyond which the solution is noise dominated.

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Measuring Noise in δf PIC Simulations

- Two measures of noise (in addition to particle convergence studies) agreed upon by the group:

  1. Calculate Φ using sub-populations of particles. Measure correlations in any standard way. Low noise should correspond to high correlation. Dielectric effects may make this test somewhat more stringent than expected.
  2. Record the radial mode information for Φ. Stop the simulation and scramble the weights. This removes the signal, and leaves only the noise. Lower the gradients to just below threshold, and restart the simulation. Run for a few bounce times, to allow the neoclassical shielding to set in. Compare the resulting $\mathbf{E}\times\mathbf{B}$ shearing rates and spectra of Φ to level found before scrambling.

- Tests will be completed for the base case.

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Hinton-Rosenbluth-Waltz Effect: Background

- Linear collisionless damping of poloidal rotation calculated by HRW.
- Stated that poloidal rotation is not damped by collisionless magnetic pumping or transit time damping.
- Suggested that gyrofluid simulations in error, overpredicting the heat flux from ITG turbulence.
- Suggested that nonlinear coupling of poloidally varying sources also likely wrong in gyrofluid model.
- Suggested that one should expect to find build-up of stabilizing poloidal flow in low collisionality experiments and simulations, with a commensurate decrease in heat flux.

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Hinton-Rosenbluth-Waltz Effect: Cyclone Response

- Residual flows correctly predicted by HRW calculation.
  - For initial value problem, ratio of residual flow to initial flow is proportional to $\sqrt{\epsilon}/q^2$.
  - In turbulent system, flow could build up, as suggested.
  - Gyrofluid linear response is in general not accurate.
  - Beer varied linear response to measure significance.

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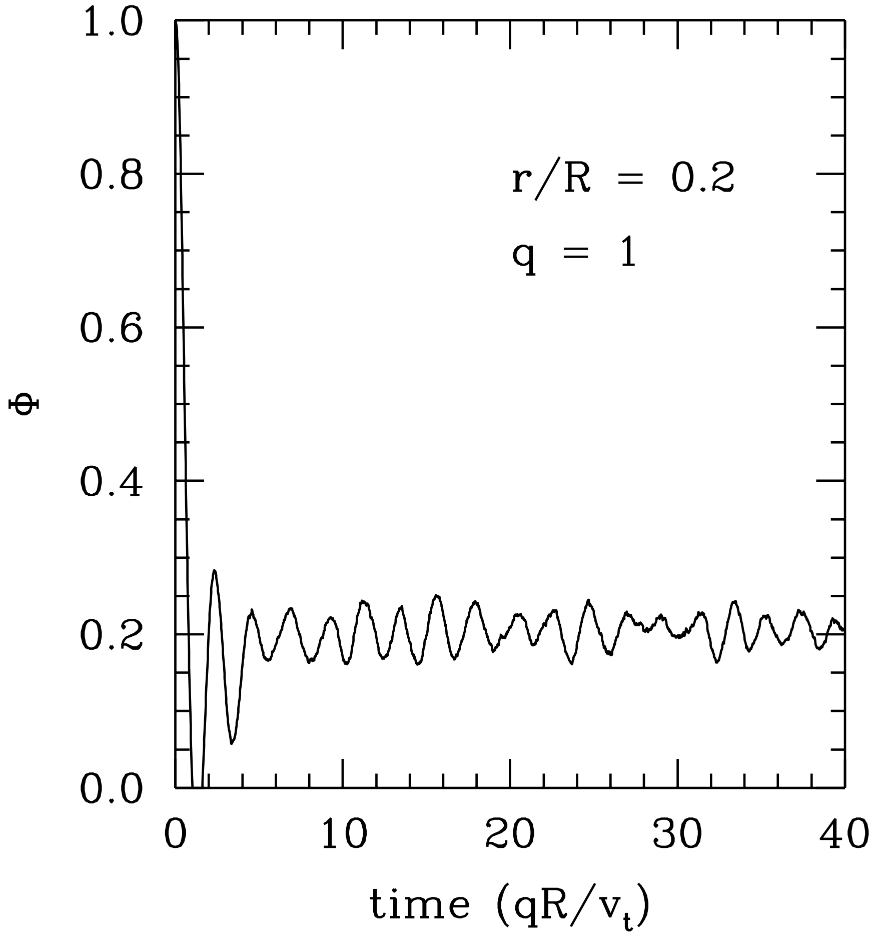
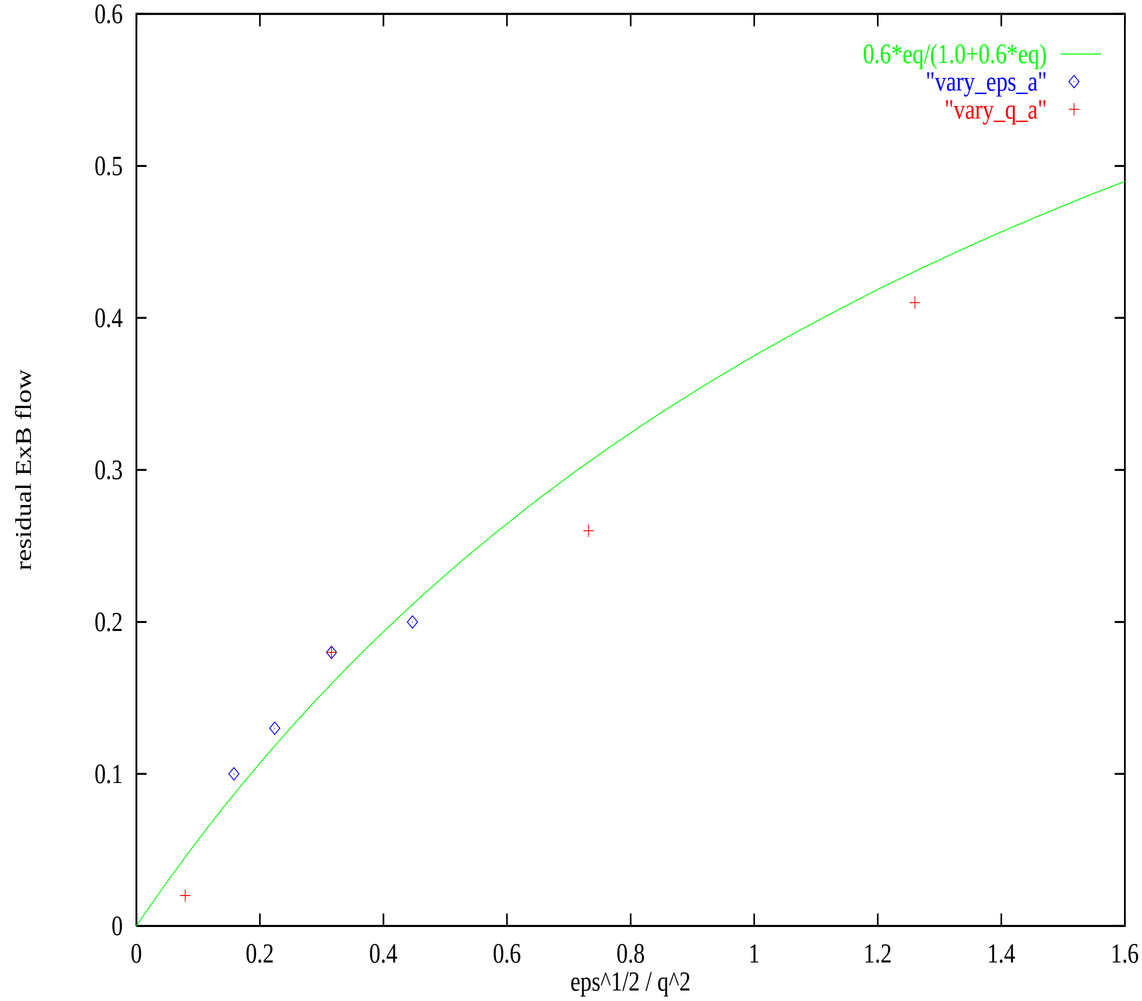
Gyrokinetic Initial Value Test

- Perturbation damps to residual level on bounce time-scale.
- HRW calculation predicts final value of 0.21.



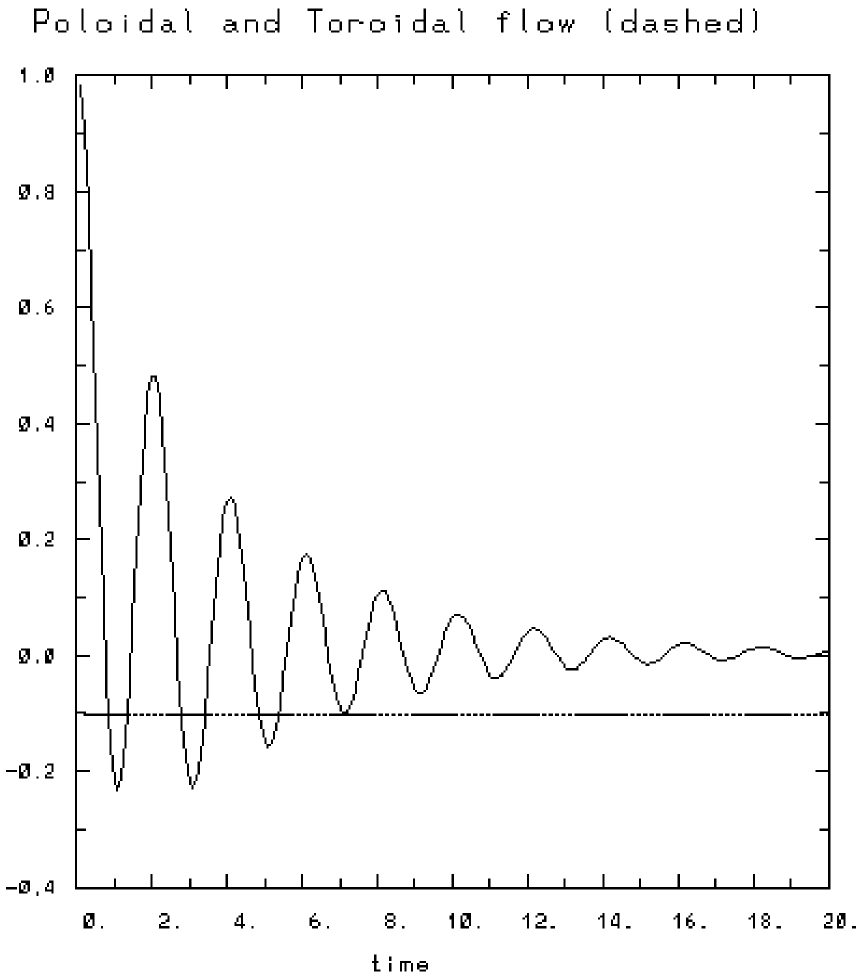
Residual Flow from Gyrokinetic Code

- With Maxwellian initial distribution plus small electrostatic potential, Dimits found that the residual $\mathbf{E}\times\mathbf{B}$ flow scaled as predicted by HRW.



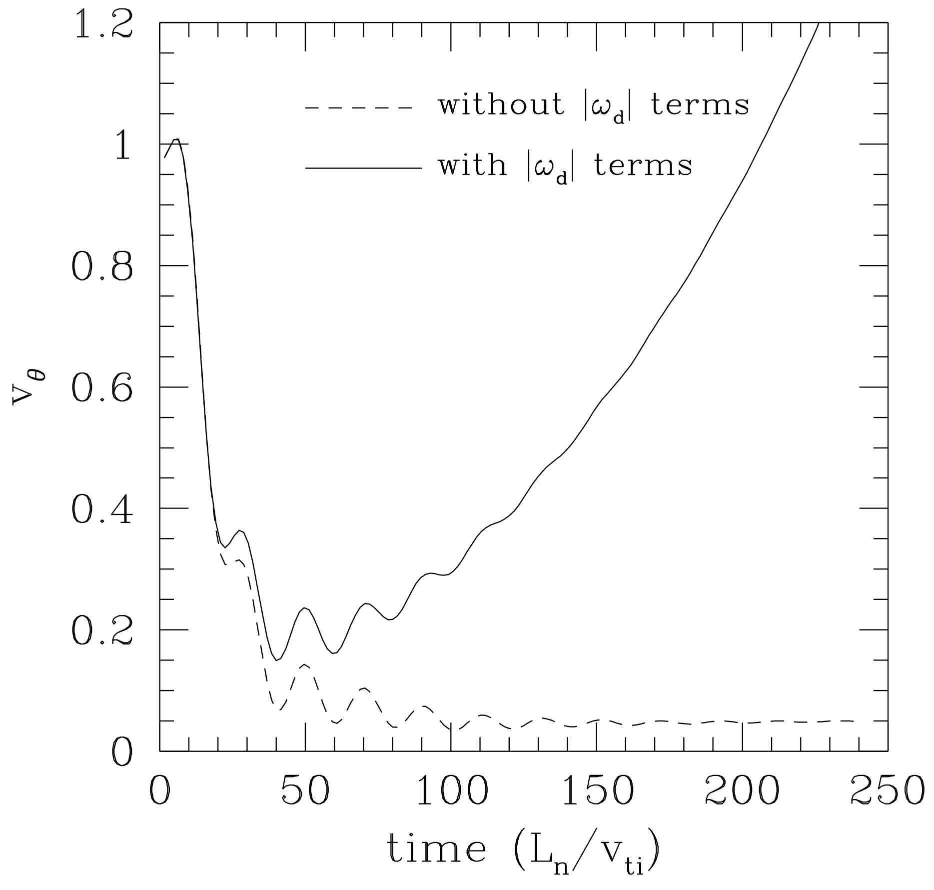
Residual Flow from Gyrofluid Code

- With same initial conditions, gyrofluid code does not produce correct residual flow. Flow is damped to zero in some cases.



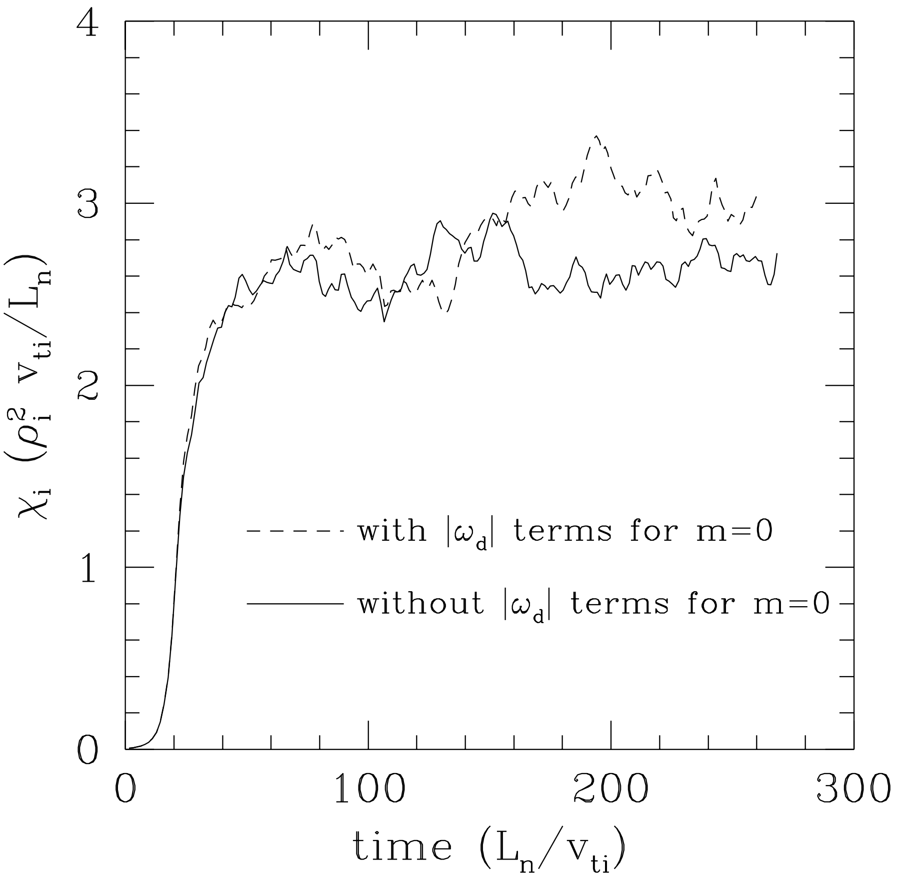
Importance of Linear Response

- Gyrofluid closure coefficients can be varied to change linear response.
- Beer found set of coefficients which caused a weak long-wavelength instability in the flow without significantly affecting description of growing modes.



Varying Linear Response in Nonlinear Simulations

- Nonlinear simulations with weak flow instability gives similar results to case with flow damped to zero.



- Suggests that long-time linear response may not be significant when turbulent damping is significant.

Hinton-Rosenbluth-Waltz Effect: Cyclone Response

- HRW emphasized nonlinear *source* of flow more than nonlinear *sink*.
  - Because of uncertainty over details of the nonlinear response, nonlinear simulations undertaken to vary control parameter, look for differences between GF and GK results. None found to date.
  - Plan to look at time correlation functions to sort out time scales in nonlinear systems, particularly close to marginal stability.
- Consensus of Cyclone is that although the gyrofluid equations have the incorrect linear response, tests done to date indicate that the HRW effect is not likely to explain the differences between gyrofluid and gyrokinetic turbulence simulations. More work needs to be done to make this result solid.

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Comparisons with Nonlinear Gyrokinetic Simulations

- HRW calculation suggests that the level of poloidal flow shear, which is stabilizing, is determined by the long-time linear response, and therefore increases with $\sqrt{r/R}/q^2$.
- If this is related to the difference between gyrofluid and gyrokinetic simulation predictions, one would expect this to be reflected in an r/R or q scan.
- We undertook two r/R scans at two values of q.
- Expected to find difference in scalings of χ with r/R.

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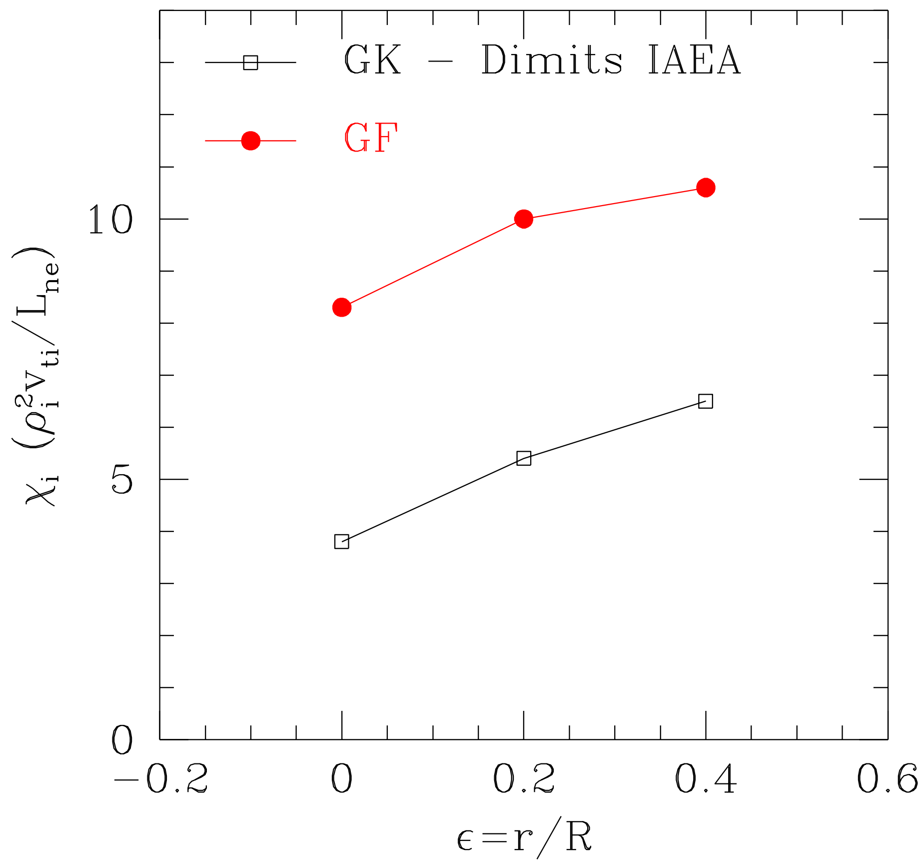
Gyrofluid and Gyrokinetic r/R Scans

- At $q = 2.4$, no difference in r/R scaling is observed.



- Similar results obtained for $q = 1.4$.

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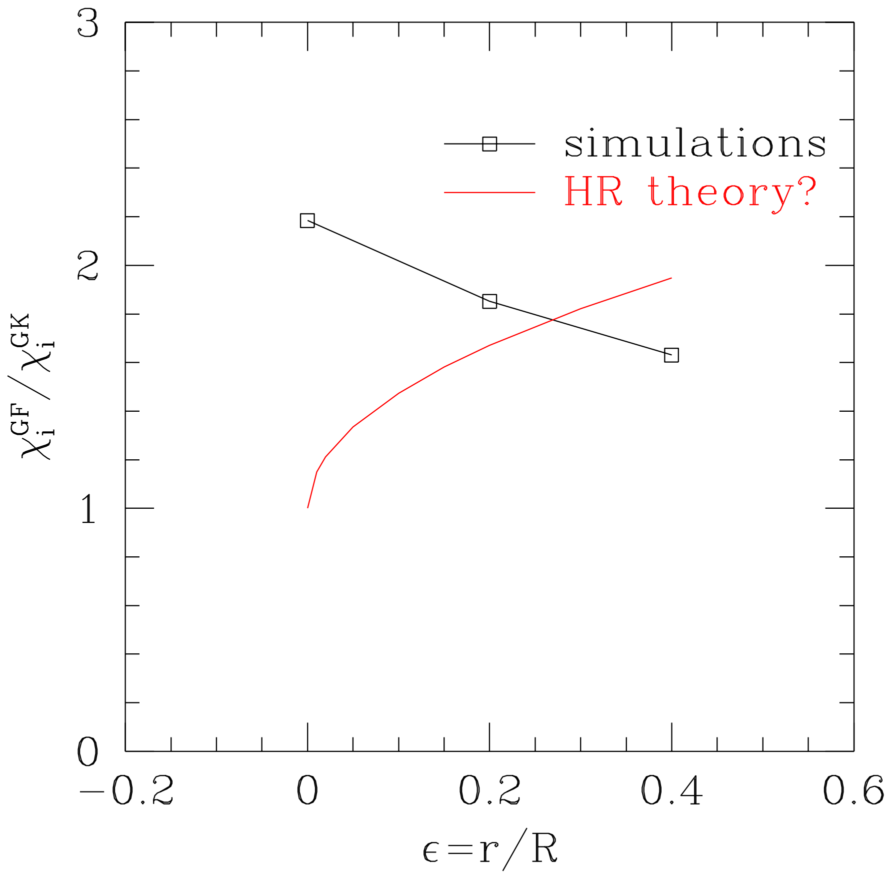
Difference Persists at $r/R = 0$

- One might expect the ratio $\chi^{\mathrm{GF}}/\chi^{\mathrm{GK}}$ to approach unity as r/R approaches zero if the HRW effect were the explanation of the difference between the two.
- The detailed functional form of $\chi^{\mathrm{GF}}/\chi^{\mathrm{GK}}$ that one might expect is not known. The red curve in the figure is only a cartoon.



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