NSTX

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Nonlinear Gyrokinetic Turbulence Simulations of the NSTX Spherical Torus

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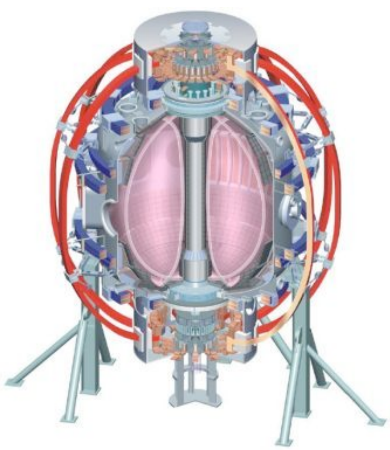

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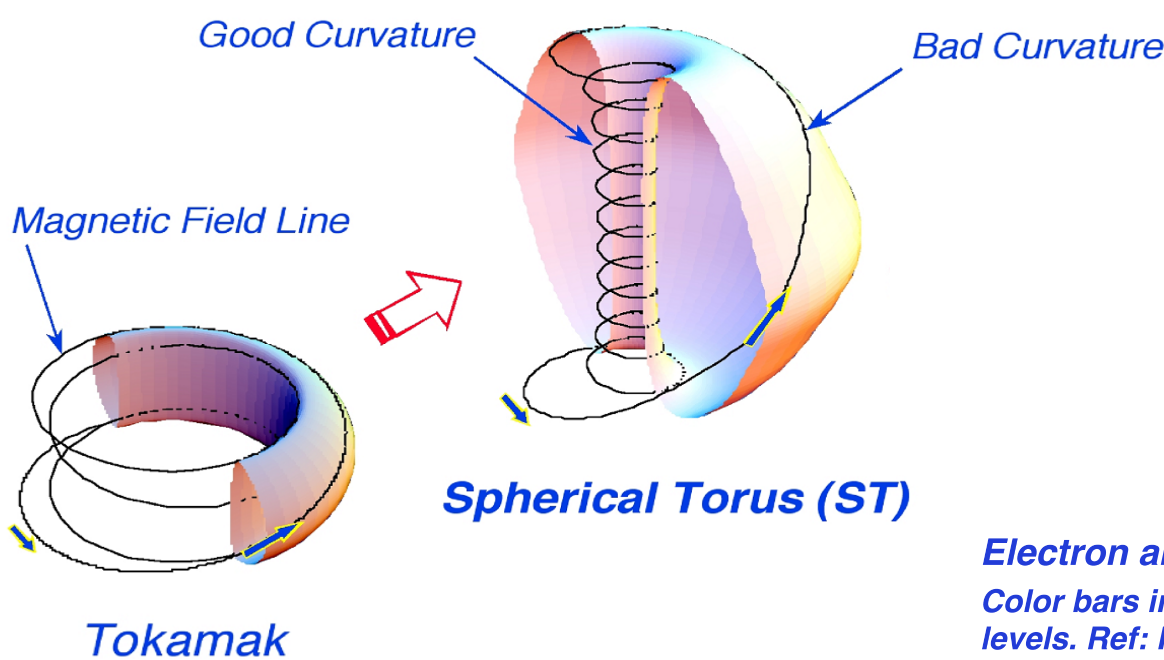
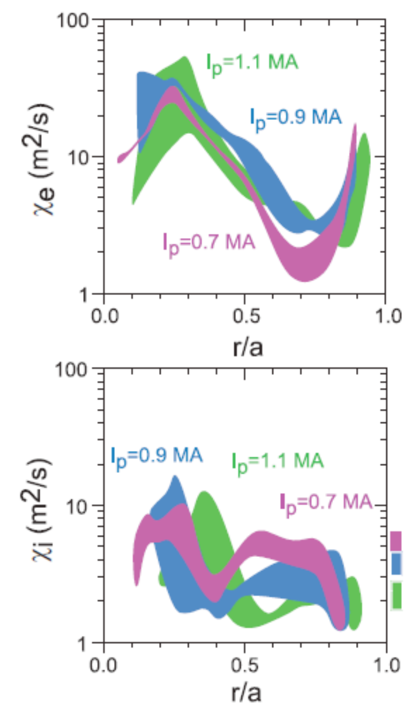
Summary

- Nonlinear gyrokinetic simulations of NSTX RF discharges show electron temperature gradient driven turbulence.
- This ETG turbulence can account for at least 50% of measured experimental electron heat flux.
- Reversed magnetic shear suppresses this turbulence.
- We have discovered a stronger nonlinear up-shift of the critical gradient for transport at negative magnetic shear.
- A mode unaffected by magnetic shear may cause transport at high gradients.
- High-k scatting measurements miss the peak of ETG turbulence spectrum.
- An improved TGYRO transport solver can more robustly and more quickly predict plasma temperature profiles.

NSTX is a Unique Laboratory for Studying Electron Losses

- Low aspect Ratio ST, Neutral Beam Power, Strong Sheared Flows, High β_N , Strong Reversed Shear, Good Curvature
- Ion transport in NSTX near neoclassical levels
  - Electrons are dominant loss mechanism
  - Kaye et al. PRL 98, 175002 (2007)

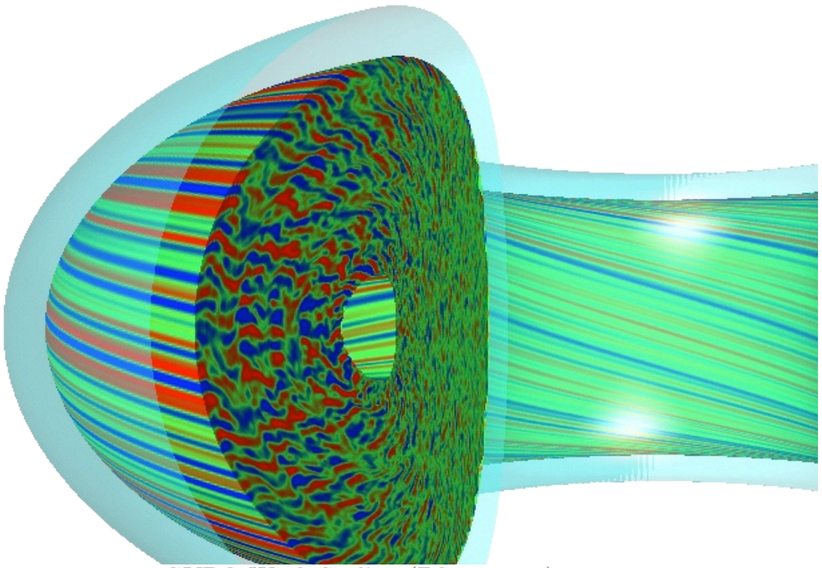




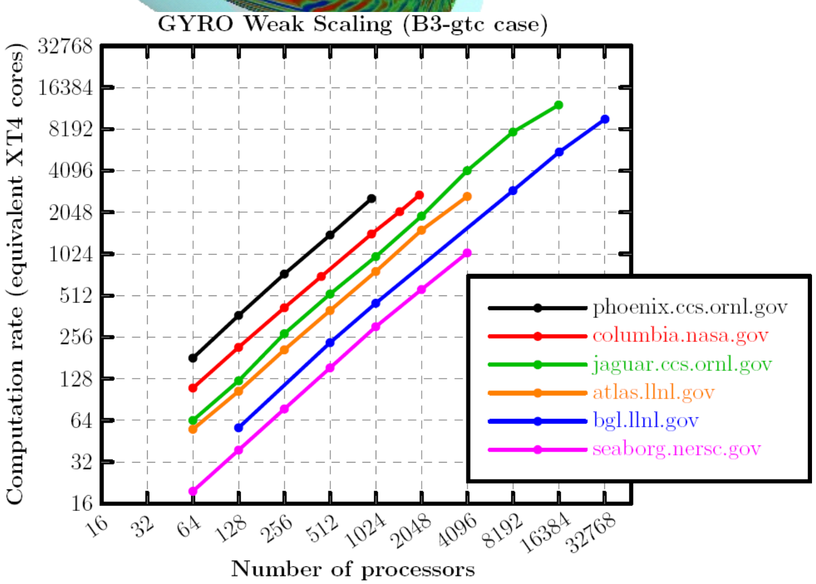
Electron and Ion Thermal Diffusivities in NSTX.

Color bars indicate calculated neoclassical transport levels. Ref: Kaye et al 2007.

GYRO is a 5D Eulerian Global Continuum Non-Linear Gyrokinetic Simulation Tool

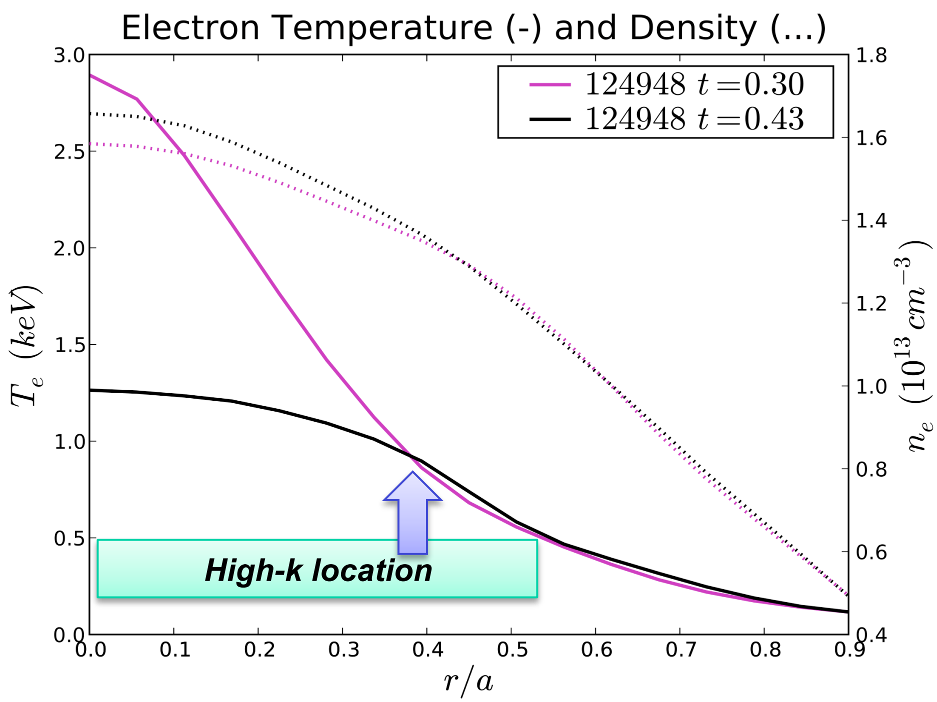


- Uses advanced numerical techniques to obtain higher accuracy with lower resolution
- Flux tube or global
- Adiabatic Ions, Adiabatic Electrons, Kinetic Electrons and full GK compatibility
- ExB shear flow compatibility
- Highly parallelizable

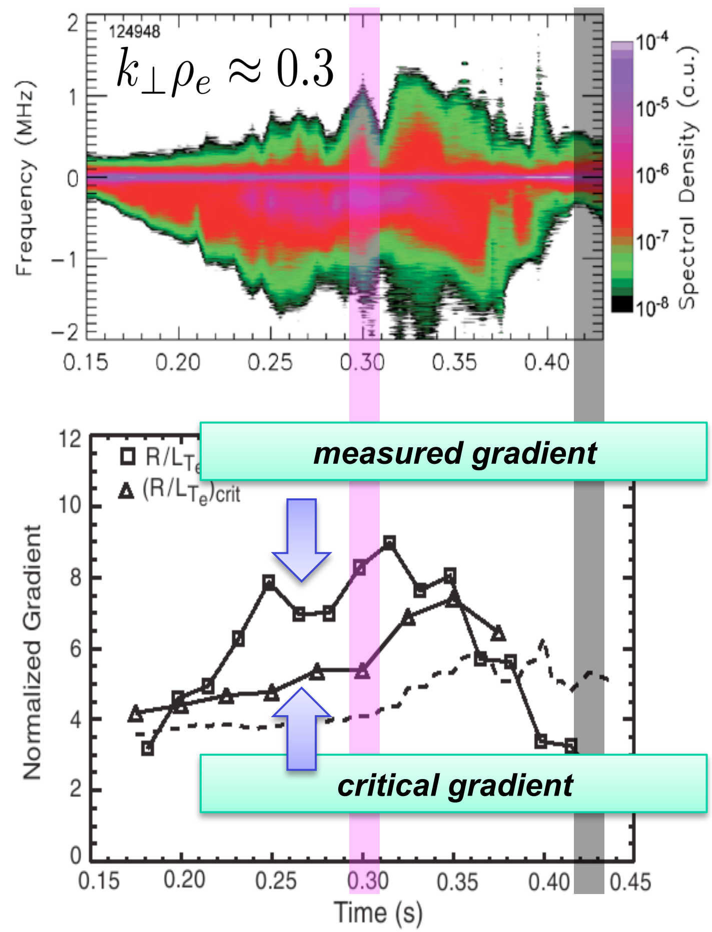


J Candy, R. E. Waltz et al. J. Phys Conf Ser 78, 012008 (2007)

Electron-scale fluctuations in NSTX appear during NSTX #124948 when linearly unstable to ETG



$$\left(\frac{a}{L_{T_e}}\right)_{crit}(t=0.3\ s)\approx 3.3$$



•*Mazzucato et al PRL (2008)*

Simulating NSTX Discharge #124948 @ 300 ms

- Low Magnetic Shear
- Low ExB Flow Shear
- RF Heating Gives Peaked Electron Temperature Profile
- Global Simulations @ Reduced Mass Ratio

$$\mu = \sqrt{\frac{m_i}{m_e}} = 20.0$$

- Only Simulate Electron Scales

$$k_\theta \rho_s = [1.225, 18.37]$$

$$k_\theta \rho_e = [0.06125, 0.9185]$$

Some physical parameters for NSTX 124948 @ 300 ms

r_0/a	0.373
R_0/a	1.502
κ	1.859
δ	0.129
q	3.113
$\hat{s}$	-0.127
ρ_*	0.007
n_i/n_e	1.0
T_i/T_e	0.833

Z_{eff}	2.50
$\gamma_E(a/c_s)$	-5.6×10^{-3}
λ_D/a	9.4×10^{-5}
$\nu_{ei}(a/c_s)$	0.087
$\nu_{ii}(a/c_s)$	0
a/L_n	0.628
a/L_{T_i}	1.302
a/L_{T_e}	4.71
$\beta_{e,unit}$	6.1×10^{-3}

Data from TRANSP/TORIC analysis of RF shot with NBI blips, extracted with transp2gyro

TRANSP2GYRO
Tool Converts Experimental Data to Simulation Input

TRANSP stores XP data on server

Experimental data and analysis

Data stored on MDS+ server fusiongrid

transp2gyro extracts and converts time slice

trxpl

Extracts plasmastate file from MDS+ server

iterdb2gyro

Converts plasmastate to INPUT_profiles

TGYRO Suite reads time slice

TGYRO

Transport Driver

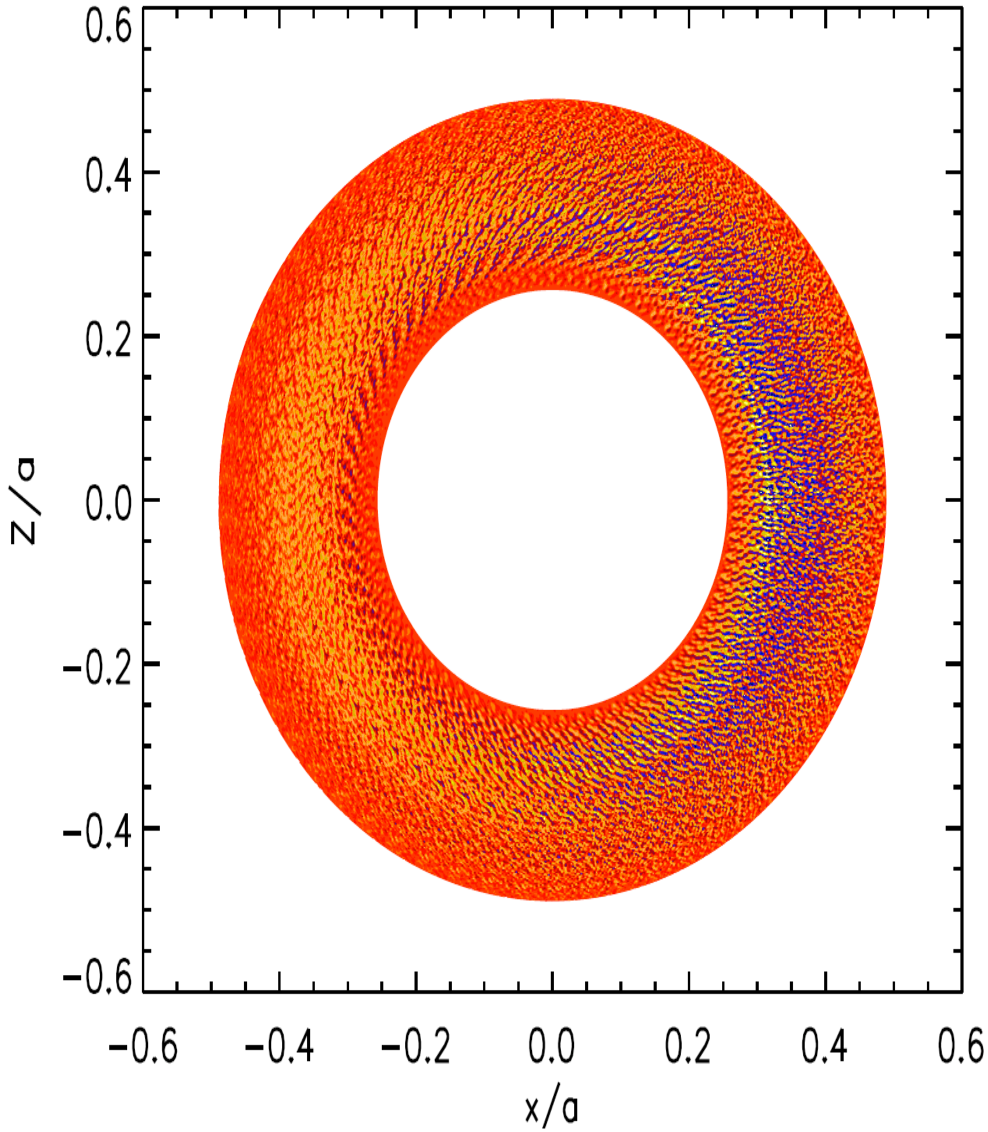
GYRO and TGLF

Turbulent Fluxes

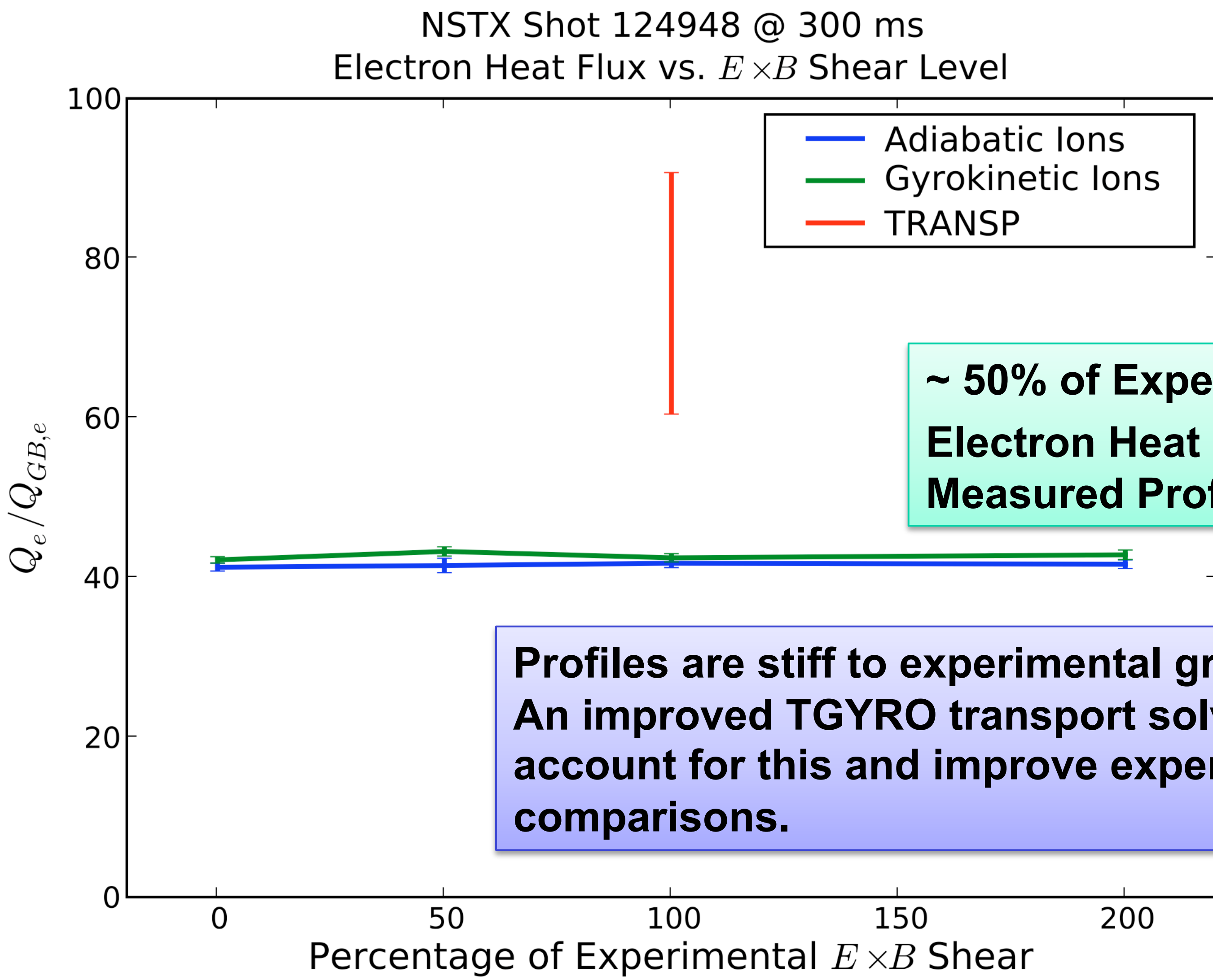
NEO

Neoclassical Fluxes

Potential Fluctuations Strongest on Outboard Side.



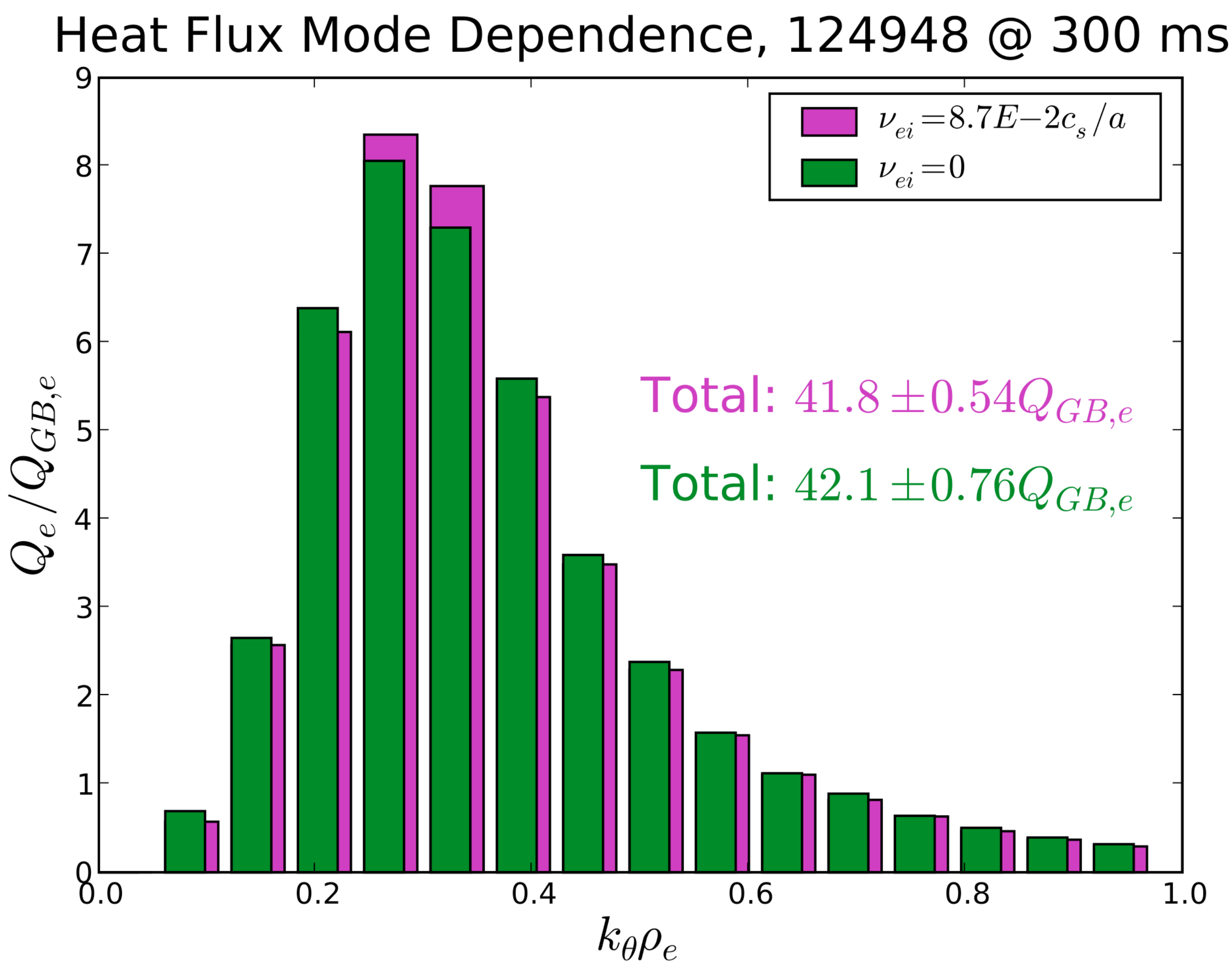
Adiabatic and Kinetic Ions Agree for Range of ExB Shears



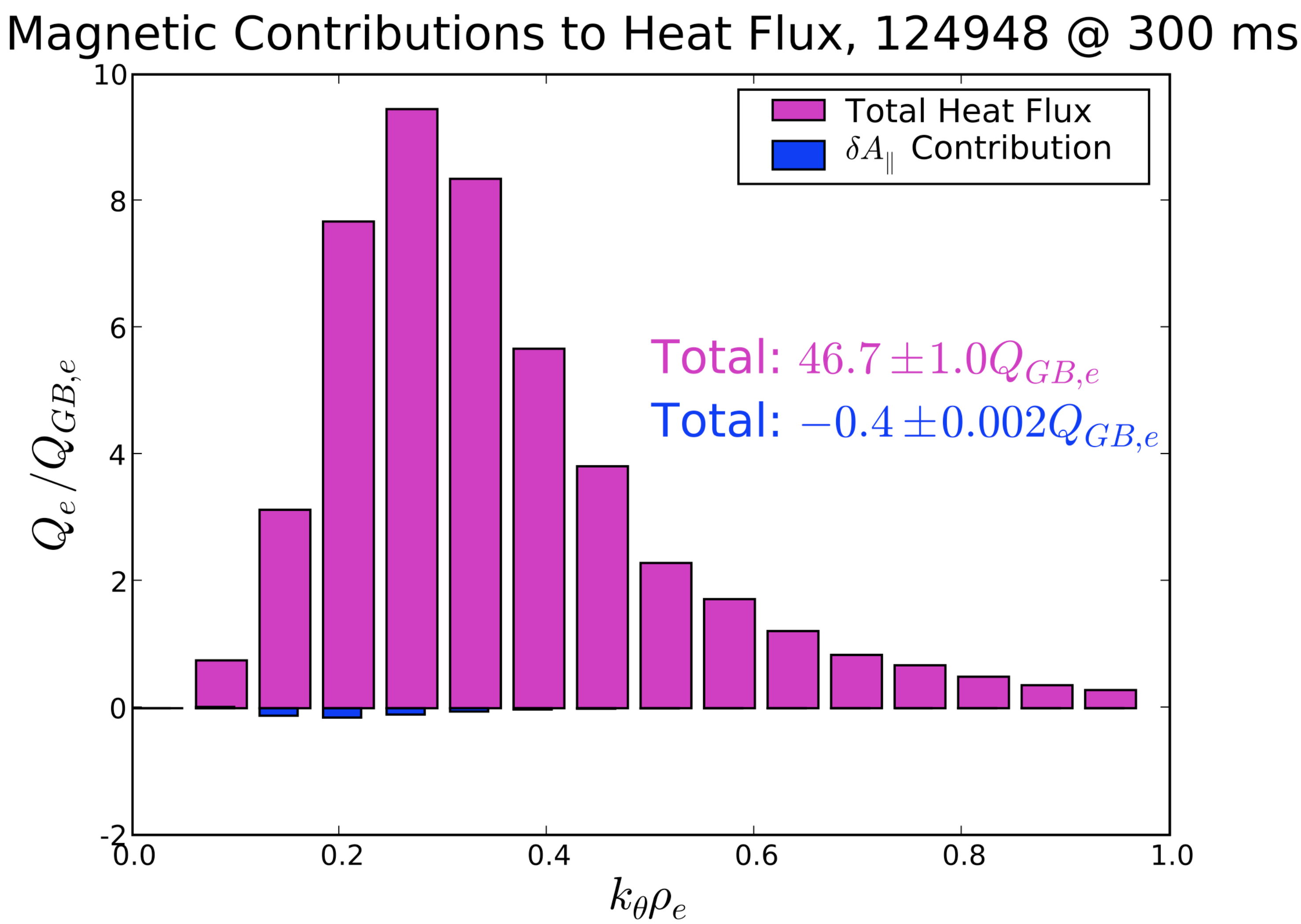
~ 50% of Experimental Electron Heat Flux Using Measured Profiles

Profiles are stiff to experimental gradients. An improved TGYRO transport solver could account for this and improve experimental comparisons.

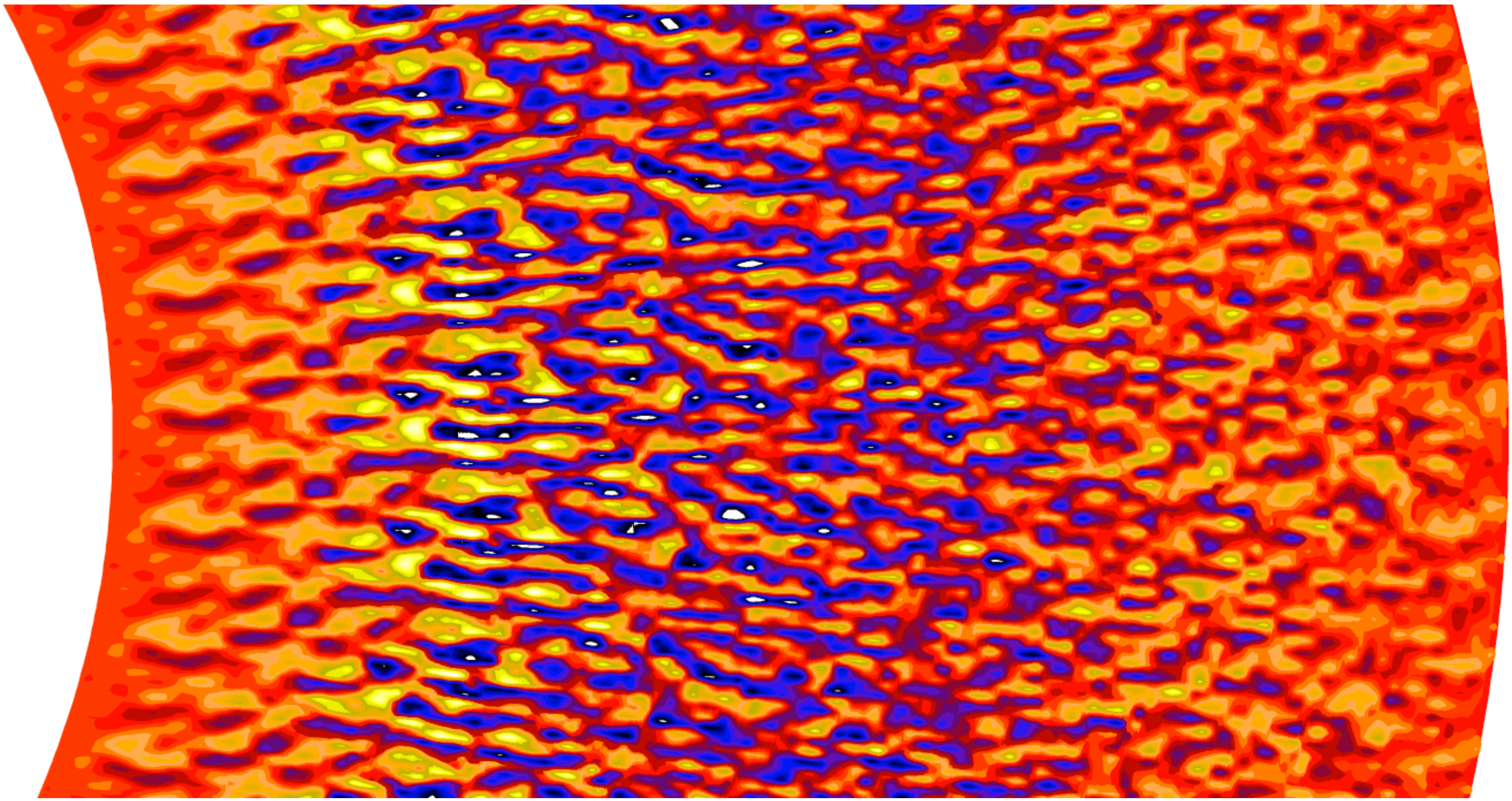
Removing electron-ion collisions has little effect on heat transport.



Adding magnetic fluctuations has slight effect at longer wavelengths.



Poloidal cross-section shows elongated streamers.

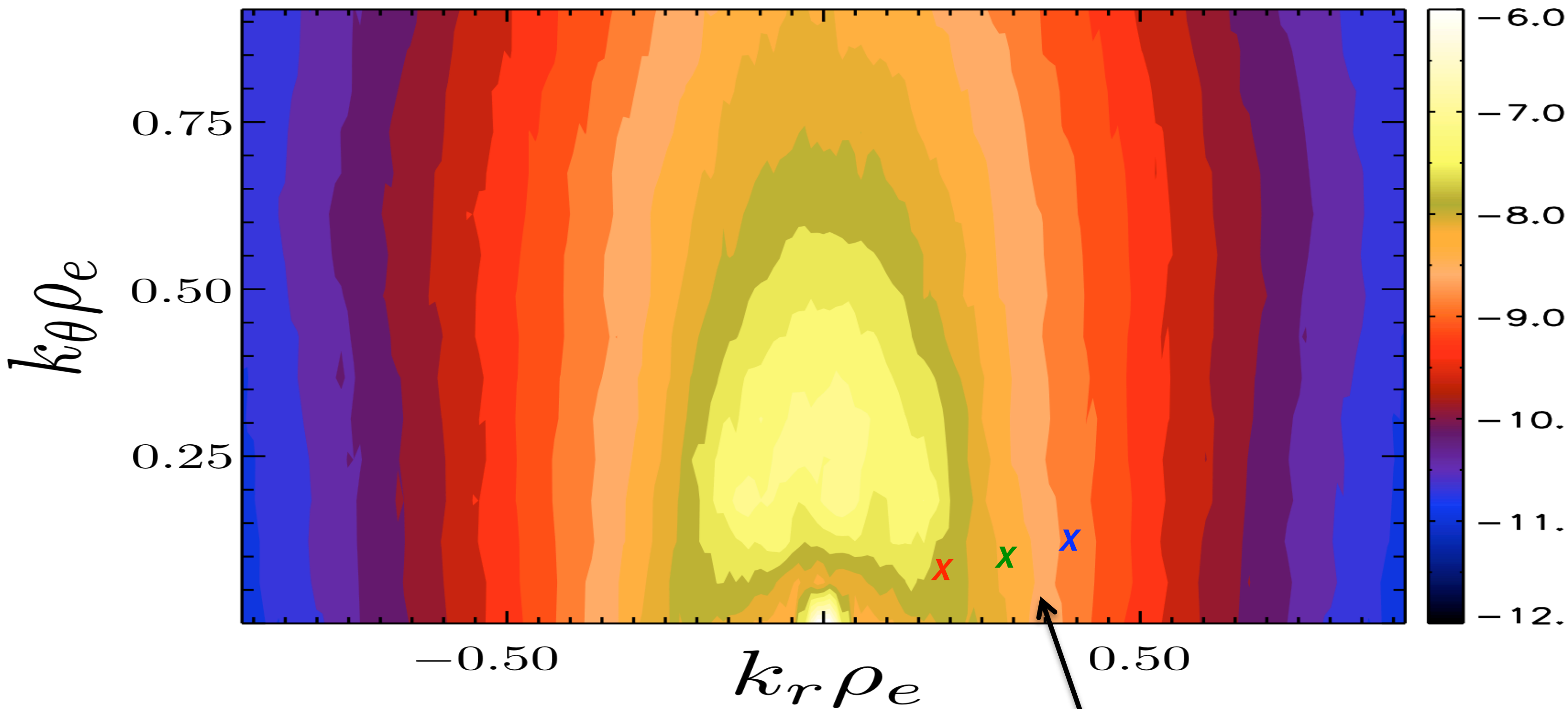


$640\rho_e$

Radial direction

Anisotropic electron density power spectrum has implications for experimental comparison.

Logarithmic Electron Density Power Spectrum



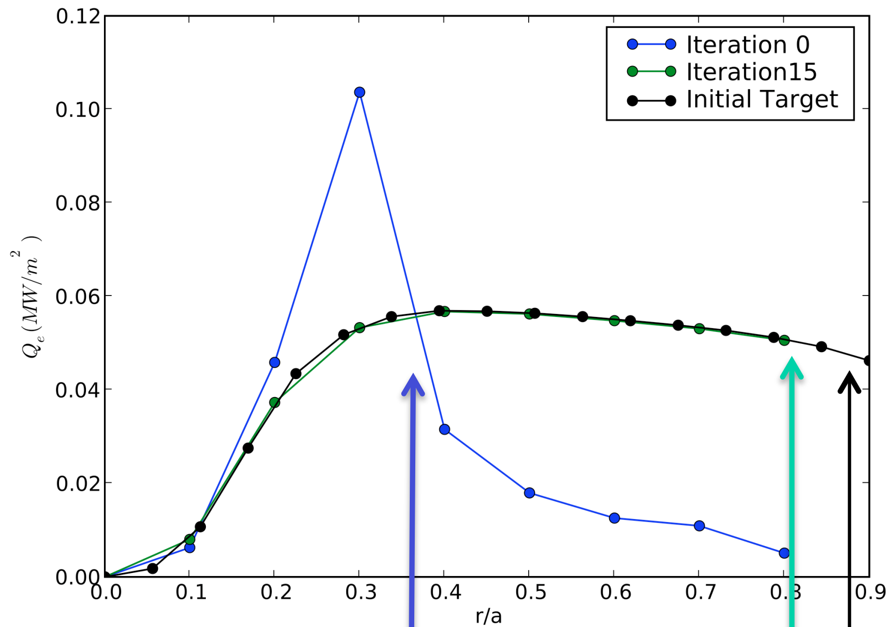
As high-k scattering diagnostic misses the ETG peak, synthetic diagnostics become more important.

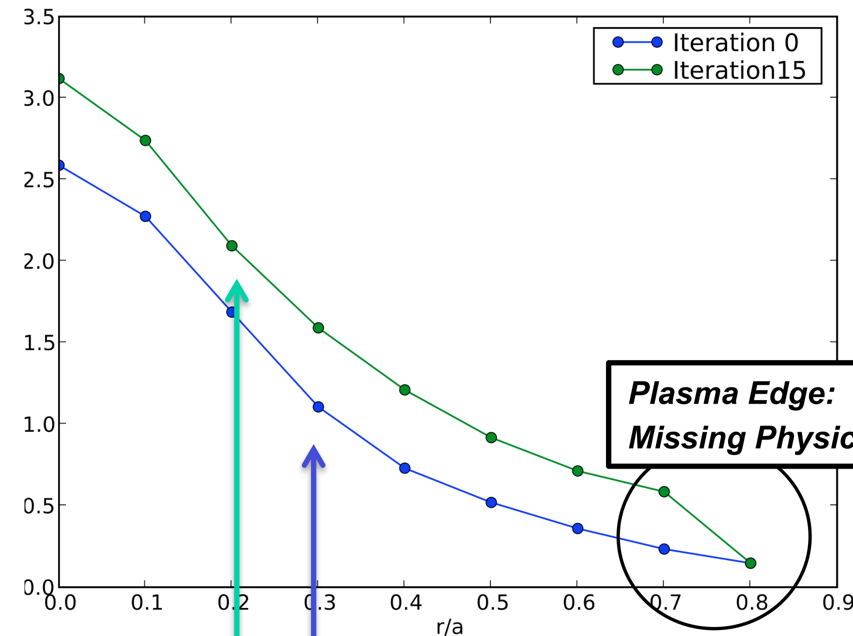
Approx. high k locations:

Ch. 3 Ch. 4 Ch. 5

TGYRO-TGLF Predicts Te for Low-Shear NSTX Discharge

$$Q_e \rightarrow T_e$$





Plasma Edge: Missing Physics

Qe using Measured Te Profile

Measured Te Profile

Qe using Predicted Te Profile

Predicted Te Profile

Measured Qe Profile

New Algorithm: Convergence in under 15 iterations
Old Algorithm: No Convergence after 200 iterations

Improved TGYRO Algorithms Allow for More Robust, Faster Convergence

- Based on Levenberg-Marquardt Residual Minimization

$$\left[\mathcal{J}^T\mathcal{J} + \alpha \mathrm{diag}\left(\mathcal{J}^T\mathcal{J}\right)\right] \cdot \delta\vec{z} = \mathcal{J}^T \cdot \vec{F}\left(\vec{z}_0\right)$$

$$\alpha \rightarrow 0 : \text{Full Newton Step}$$

$$\alpha \rightarrow \infty : \text{Full Steepest Descent Step}$$

Travel in a direction that combines steepest descent and Newton directions to robustly progress towards root.

- Combined with Search Direction Backtracking to only take a step that reduces the error in the solution

$$\vec{z}_{n+1} = \vec{z}_n + \lambda\delta\vec{z}_n \qquad 0 < \lambda \leq 1$$

Find location along search direction with lowest global residual.

- With TGLF, can robustly reduce difference in target and transport fluxes to machine precision in half the calls to TGLF

Simulating Strongly Reversed Magnetic Shear: NSTX Discharge #129534 @ 232 ms

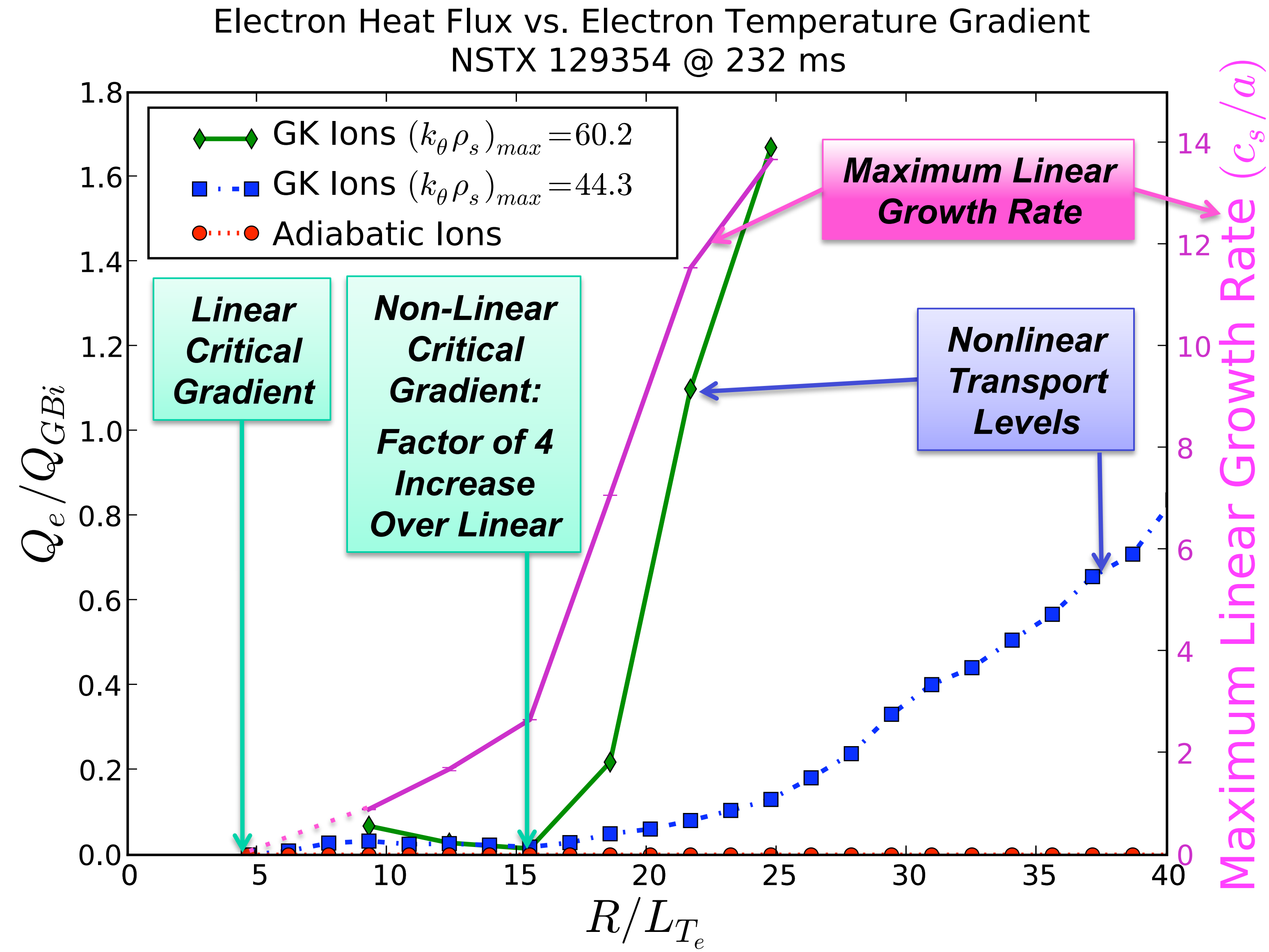
- RF-Driven Electron Temperature Gradient
  - All linearly unstable $(R/L_{T_e})_{crit} \approx 4.5$
- Scan Electron Temperature Gradient
- 70 Nonlinear Flux Tube Simulations
- 16 or 24 Modes, electron-scale resolutions (see below)
- Gyrokinetic electrons, gyrokinetic or adiabatic ions
- Electrostatic, No ExB Flow Shear
- ~2,000,000 total CPU hours @ ORNL XT5 (Jaguar)

$$R/L_{n_e} = 1.74 \qquad \hat{s} = -2.4$$

$$Z_{eff} = 3.39 \qquad q = 2.4$$

$$\mu_e = 60.0 \qquad \nu_{ei} = 0.16\ (a/c_s)$$

The Nonlinear Up-shift of the Critical Gradient for Transport is Very Strong in Reversed Shear



Key Observations About Nonlinear Critical Gradient

- Both kinetic ion resolutions see nonlinear critical gradient threshold for transport at same location.
- This transport threshold is ~ 4x linear instability threshold.
- Nonlinear critical gradient is consistent with observations of maximum attainable gradients in NSTX reversed shear discharges. (H. Yuh)
- Increased transport with additional modes is consistent with other benchmarking work on ETG. (Nevins et al PoP 2006)
- Adiabatic Ion simulations, while linearly unstable, do not show significant transport, even for R/LTe > 50, consistent with earlier ETG observations. (Jenko & Dorland PRL 2002)

Parameters For Nonlinear Reversed Shear Flux Tube Simulations

16 Modes

$$L_x \times L_y = 2.13 \times 2.13\rho_s$$
$$= 128 \times 128\rho_e$$
$$k_\theta \rho_s = [2.95, 44.25]$$
$$k_\theta \rho_e = [0.043, 0.738]$$

- Adiabatic Ions
- Kinetic Ions

$$R/L_{T_e} = [4.6, 52.6]$$

24 Modes

$$L_x \times L_y = 4.26 \times 2.4\rho_s$$
$$= 255 \times 144\rho_e$$
$$k_\theta \rho_s = [2.618, 60.21]$$
$$k_\theta \rho_e = [0.043, 1.004]$$

- Kinetic Ions

$$R/L_{T_e} = [9.28, 34.75]$$

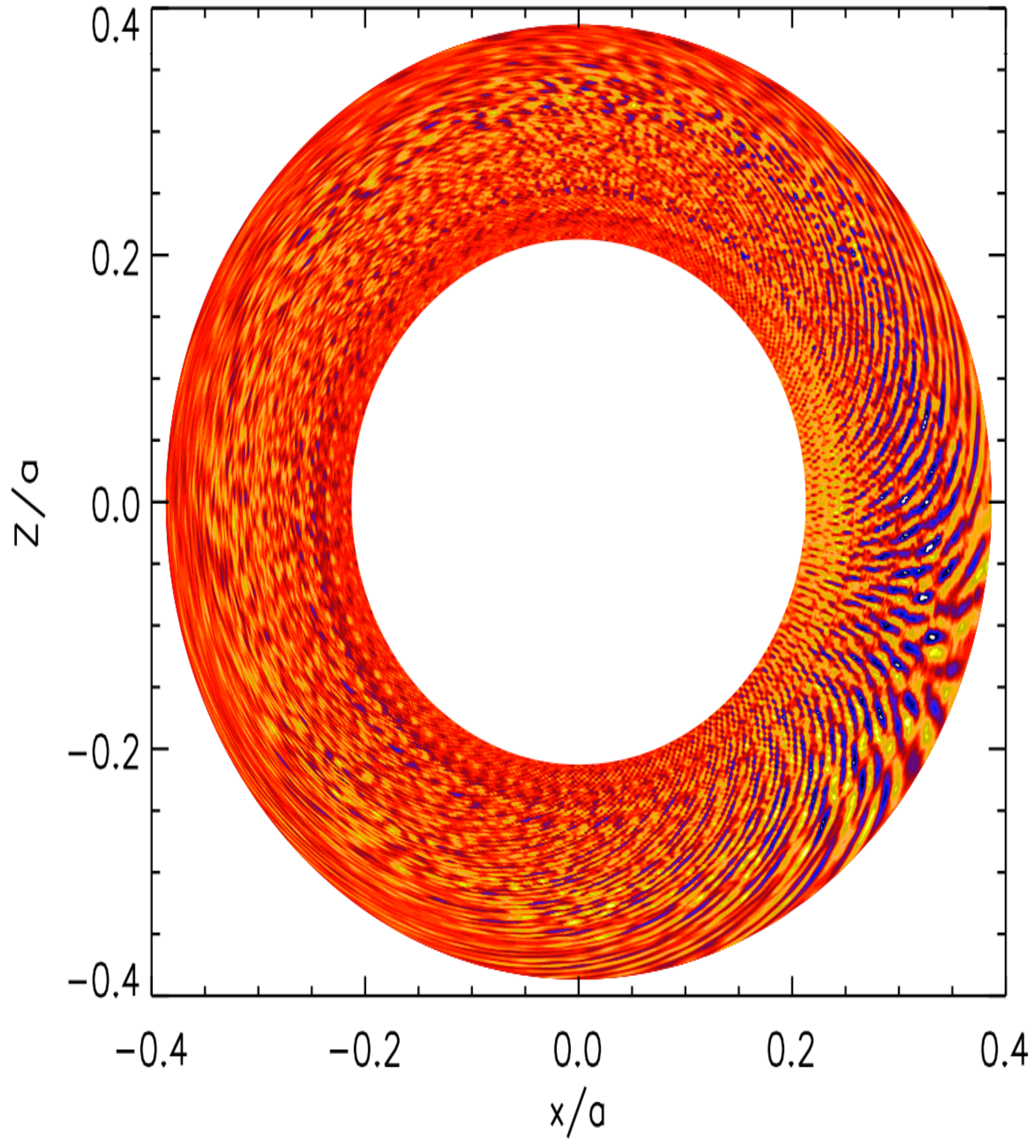
Below Nonlinear Critical Gradient Threshold: Streamers Sheared Apart, Low Transport

$$R/L_{T_e} \approx 12.5$$

$$Q_e/Q_{GB,i} = 0.028 \pm 0.01$$

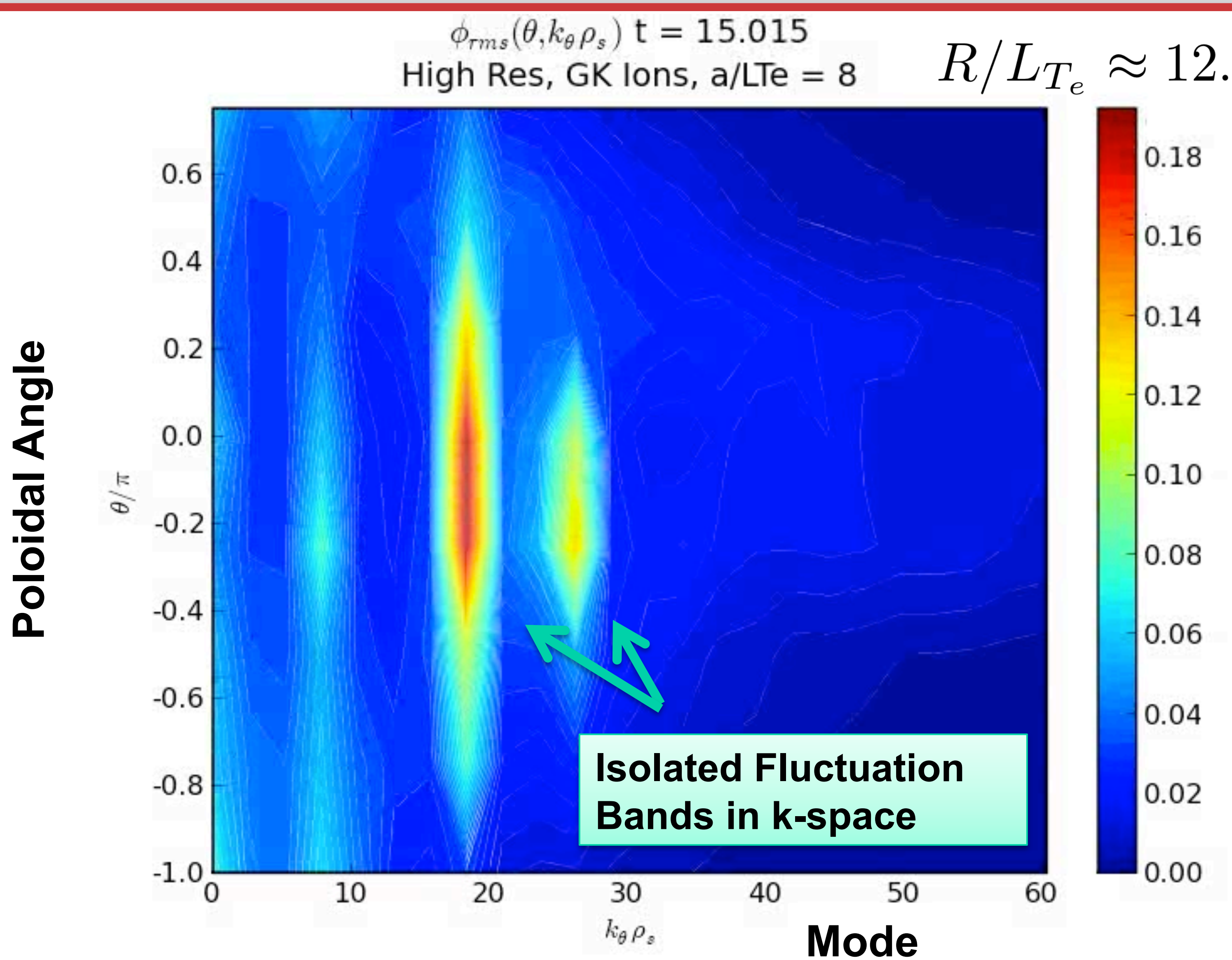
Eddies Sheared, Saturate at Low Amplitude

Linearly Unstable, But Low Levels of Transport



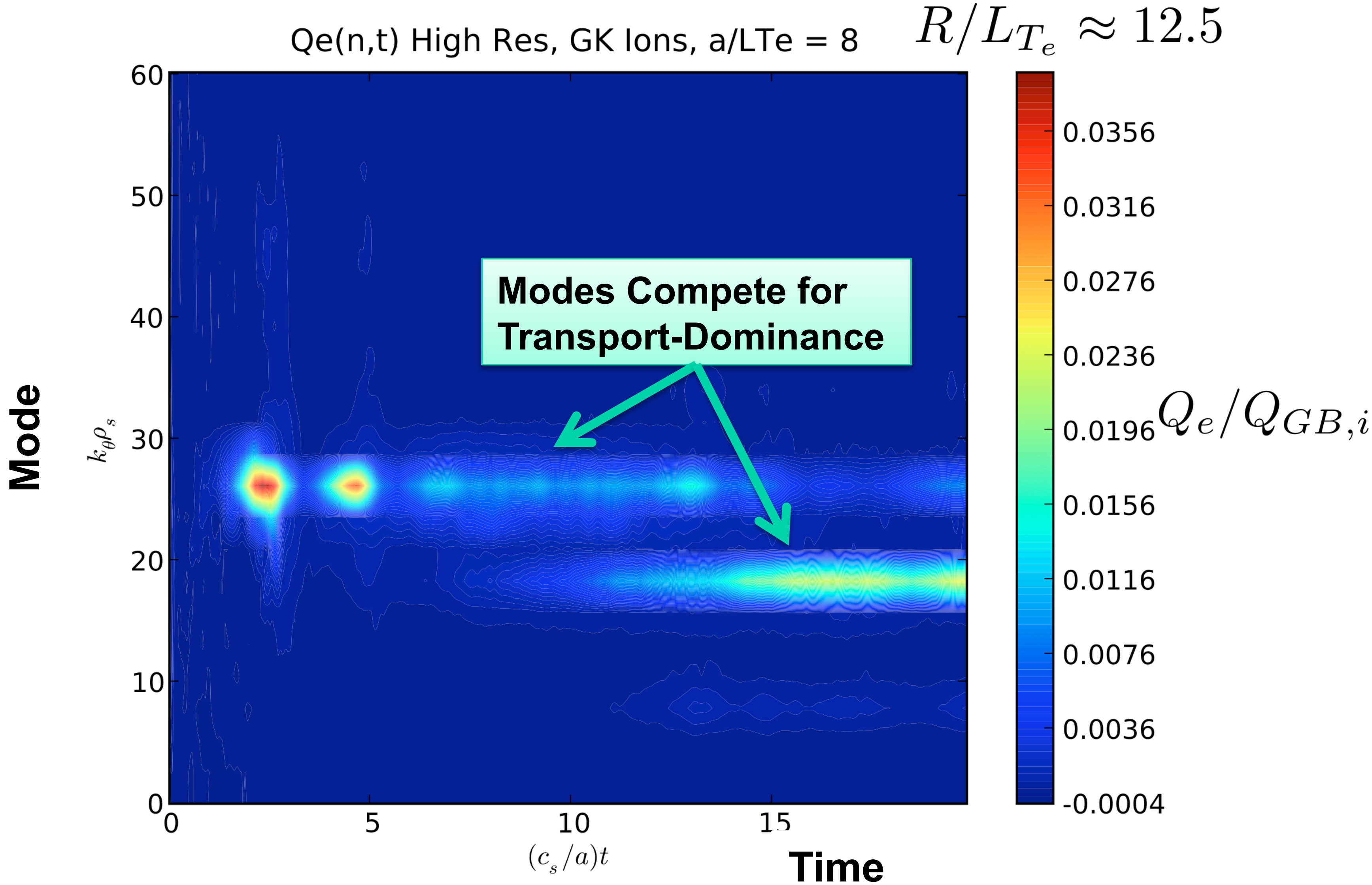
Low-transport modes centered on Midplane

$R/L_{T_e} \approx 12.5$

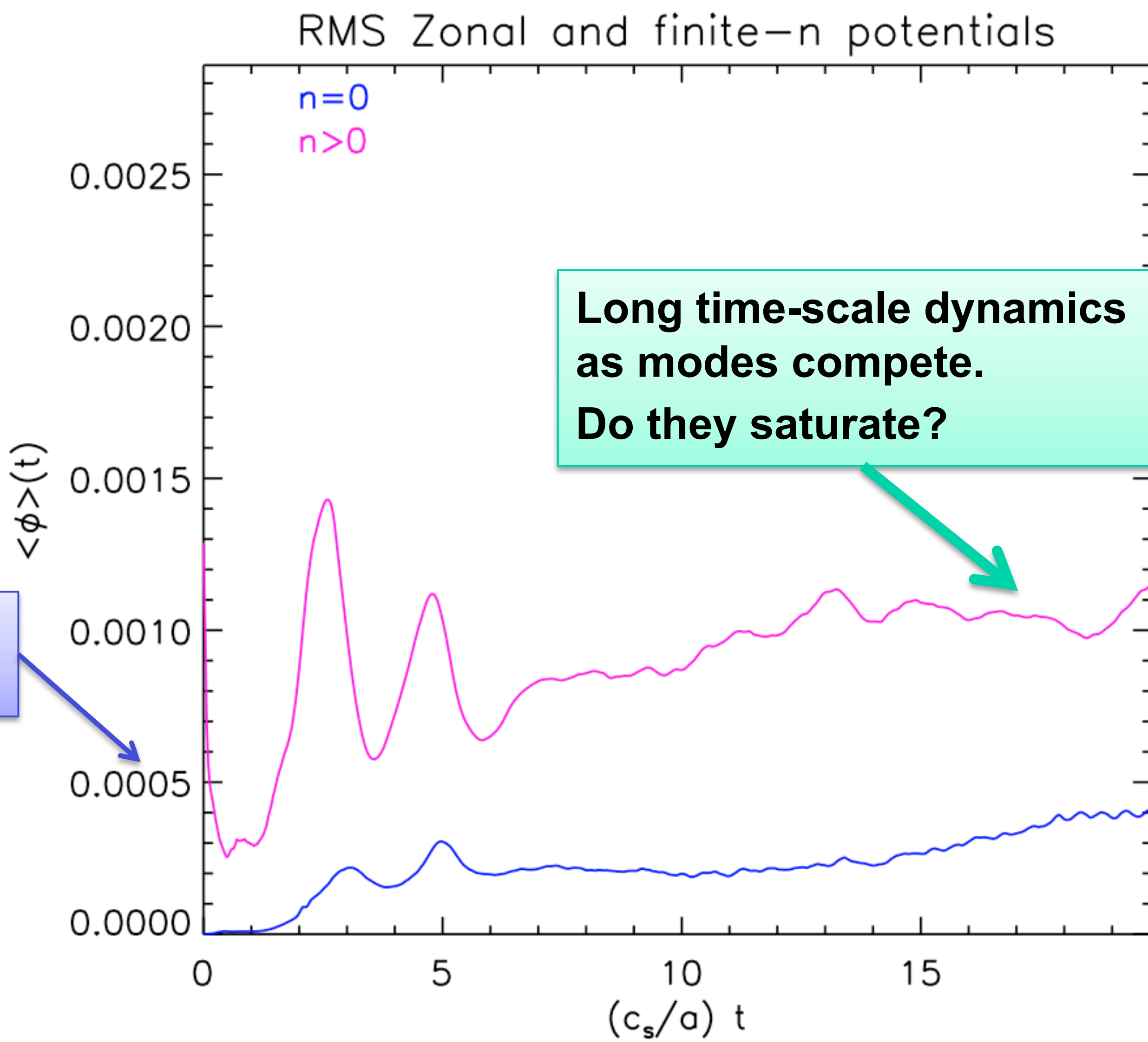


No Single Mode Dominates in Shear-Suppressed Regime

$R/L_{T_e} \approx 12.5$



Zonal Flows Appear Correlated with Finite-n Potential Fluctuations



Long time-scale dynamics as modes compete.

Do they saturate?

Low-magnitude

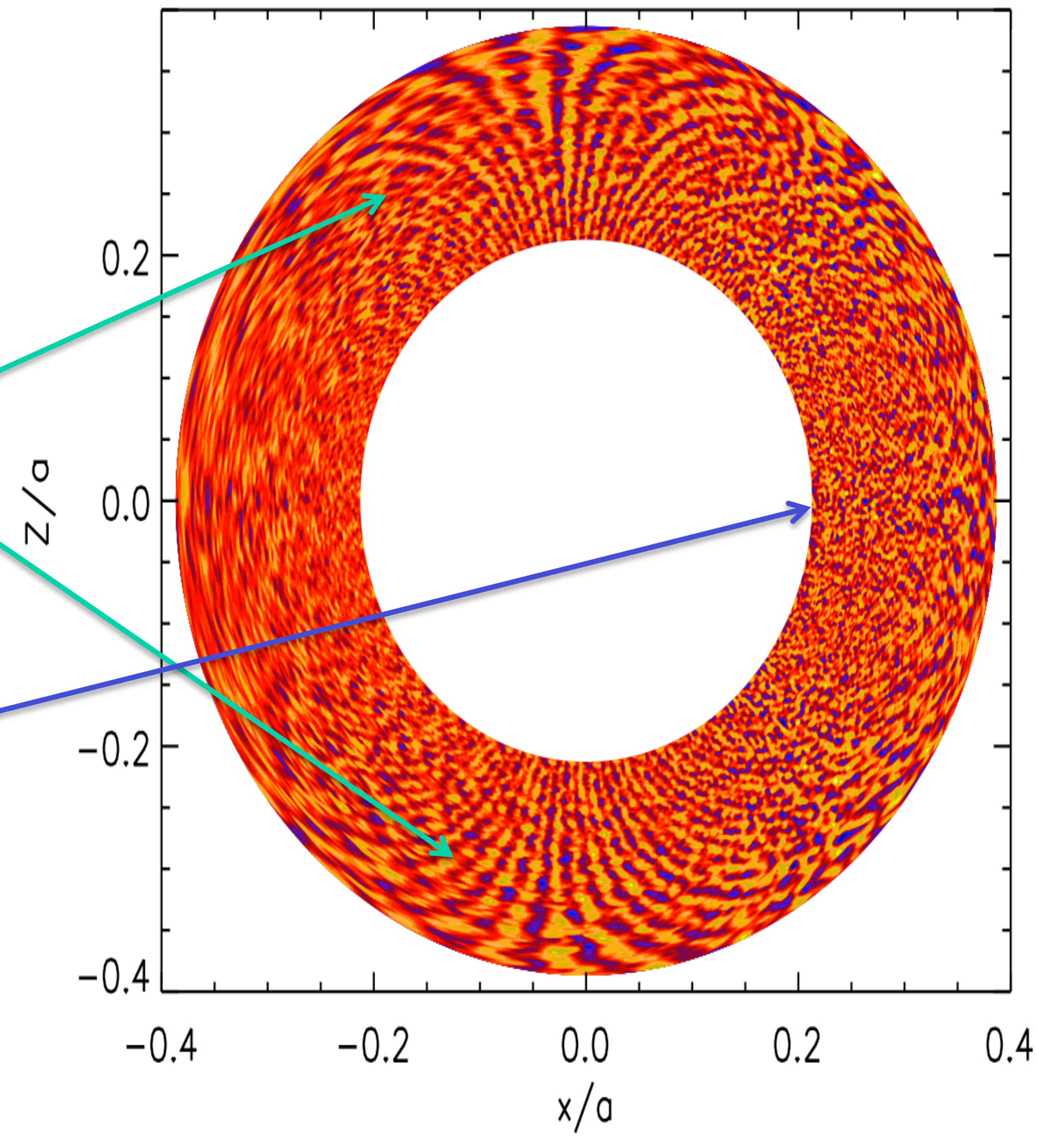
Above Nonlinear Critical Gradient Threshold: Streamers Not on Midplane, Large Transport

$$R/L_{T_e} \approx 22$$

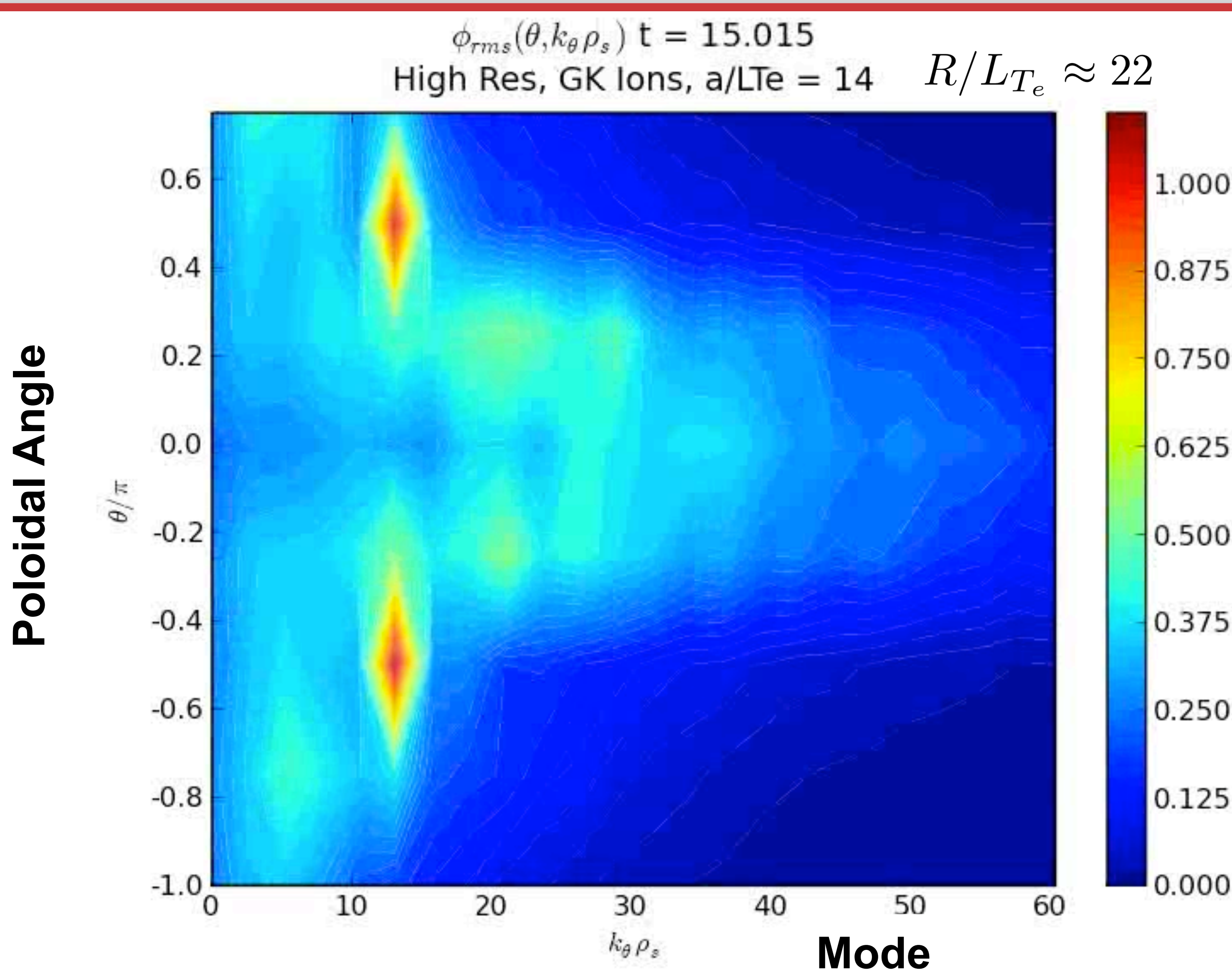
$$Q_e/Q_{GB,i} = 1.136 \pm 0.013$$

Radial Streamers out of Top and Bottom

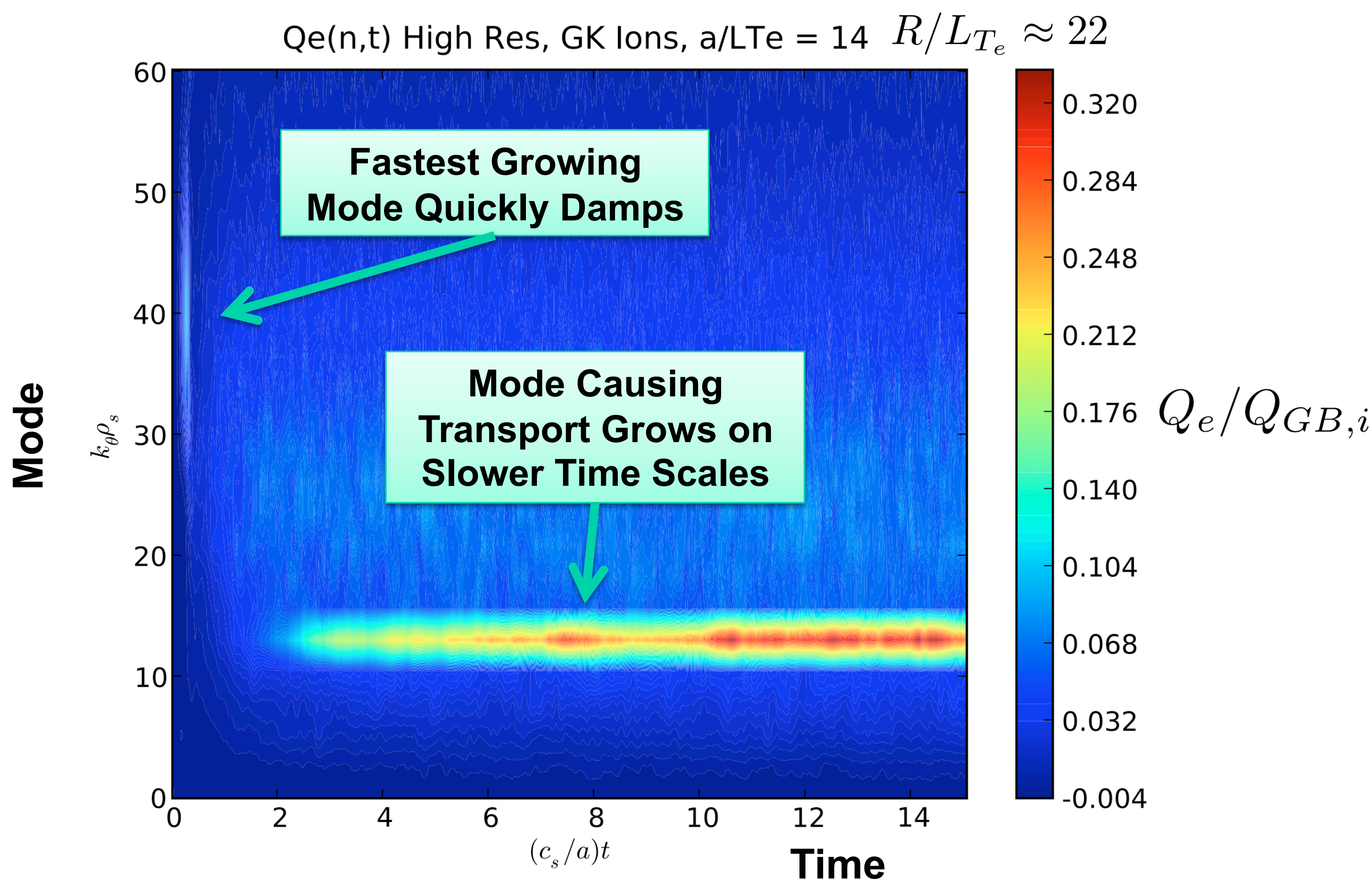
Midplane Eddies Sheared Apart, Even at High Driving Gradient



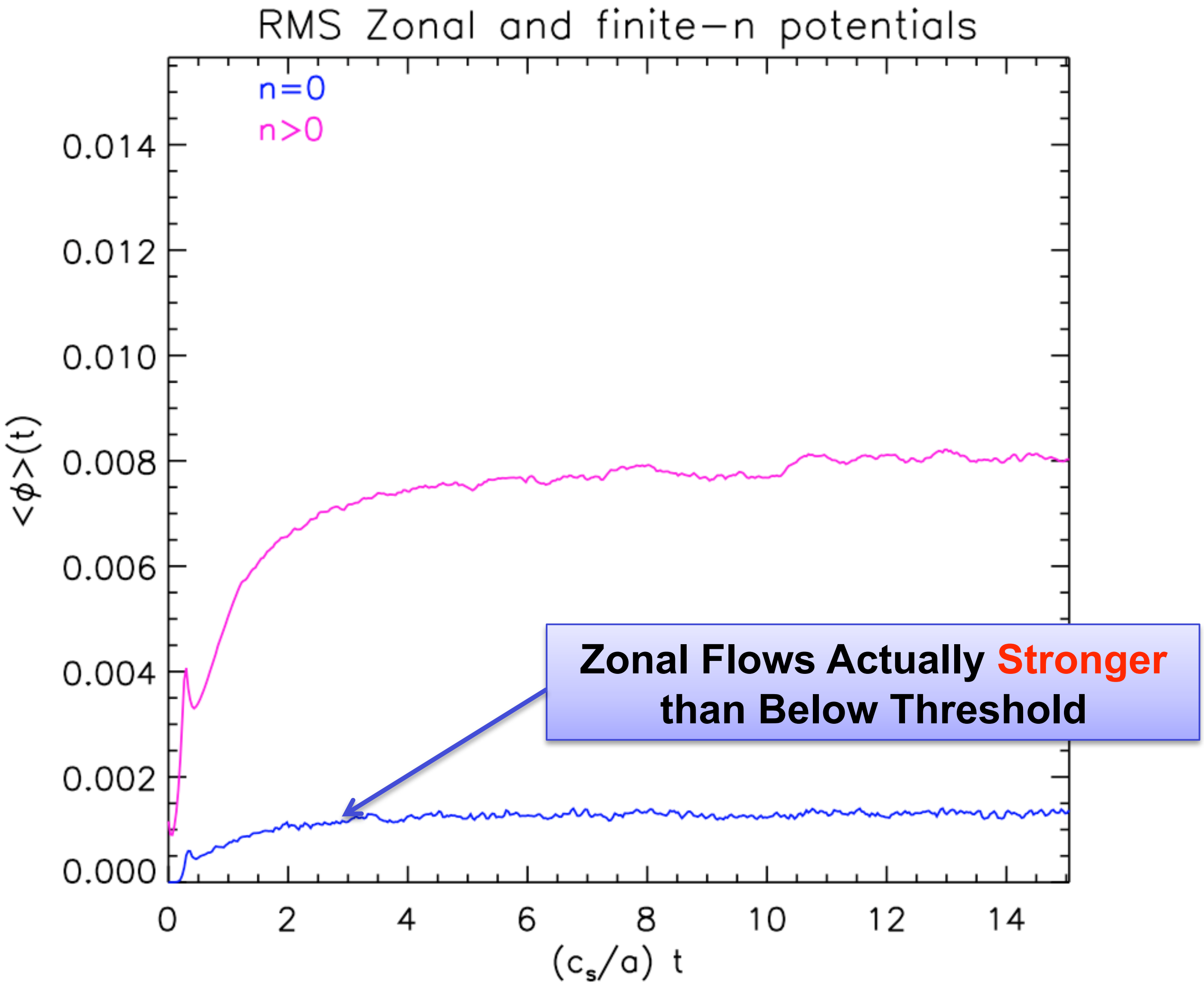
Transport-Causing Mode is Strongest Off Midplane



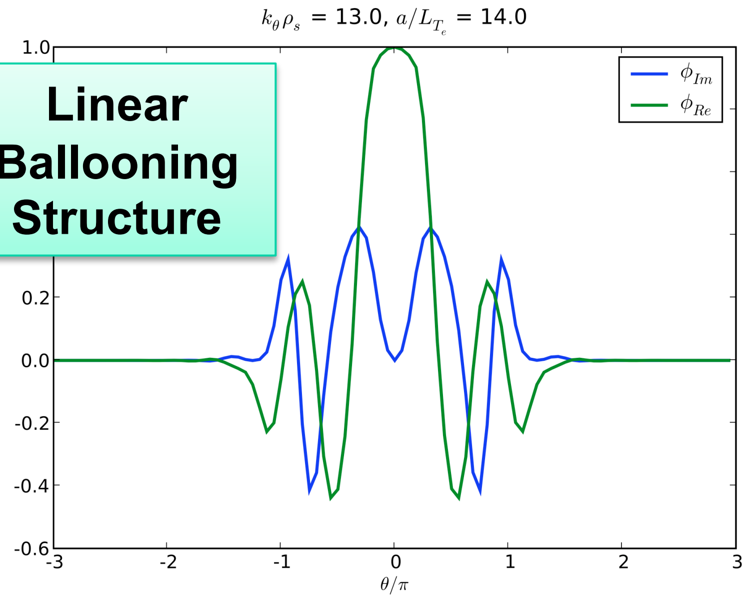
The Fastest Growing Dies Away, Not Responsible for Transport



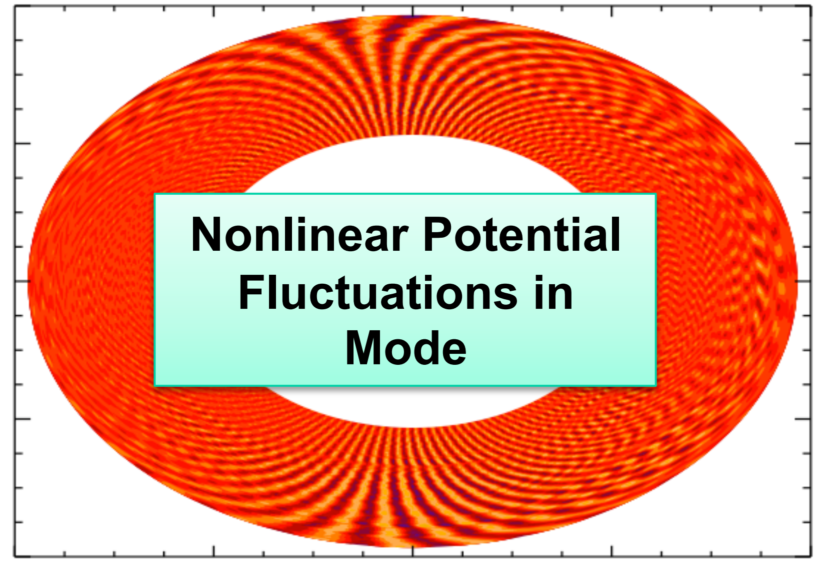
Above Nonlinear Critical Gradient, Quicker Saturation



Transport Causing Mode Found With Both Linear Initial Value and Field Eigenmode Solvers



Linear Ballooning Structure

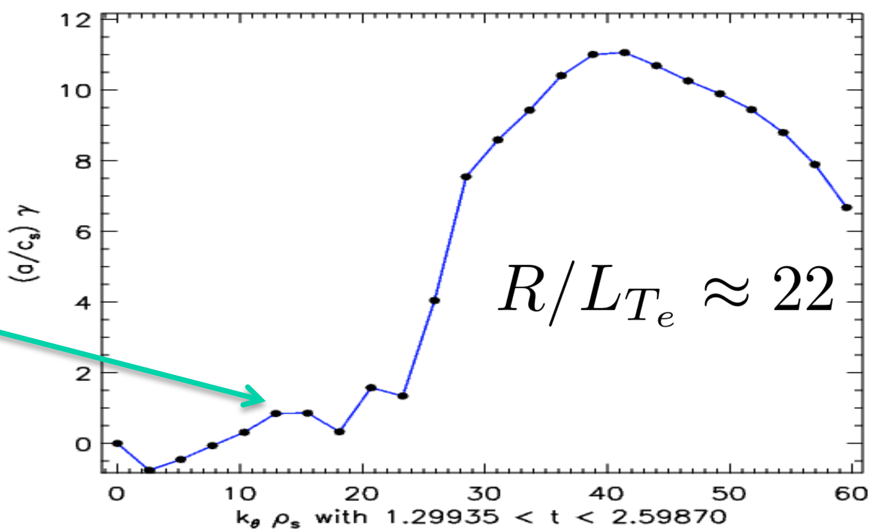


Nonlinear Potential Fluctuations in Mode

Sub-dominant Linear Growth Rate, Nonlinearly Saturates at Highest Amplitude

$$\omega = 25.19\ a/c_s$$

$$\gamma = 0.838\ a/c_s$$



Conclusions

- Global Nonlinear Simulations of NSTX RF-heated discharges in both low and strongly reversed magnetic show turbulence driven by the electron temperature gradient
  - Low-shear case: can account for roughly half of observed transport
- Improved TGYRO algorithms allow for robust, quicker profile predictions, account for stiff profile transport problem
  - Error reduced to machine precision in half the calls to TGLF
- Reversed Shear temperature gradient scans find a second-instability threshold for transport
  - ~ 4x the linear critical gradient, only seen with kinetic ion simulations
- Above threshold, a slow-growing mode saturates with highest amplitude, causes majority of transport
  - Linearly sub-dominant, nonlinearly dominant
  - **Streamers out of top and bottom**: midplane streamers sheared

Future Work

- Thorough analysis of transport causing mode’s linear properties
  - Goal: investigate second-instability threshold, top/bottom streamers
- Use gyrokinetic parameter scans around reversed shear discharge as benchmark for TGLF
  - Goal: more robust and accurate ST TGLF/TGYRO transport predictions
- Calculate synthetic high-k spectra based on these GK simulations
  - Goal: comparison with high-k experimental data
  - Goal: investigate “bursty” high-k signals in this regime
- Multi-scale nonlinear simulations
  - Goal: link ion and electron scales, especially if this intermediate-k transport causing mode is important.

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