Nonlinear Gyrokinetic Simulations of Electron Internal Transport Barriers in the National Spherical Torus Experiment

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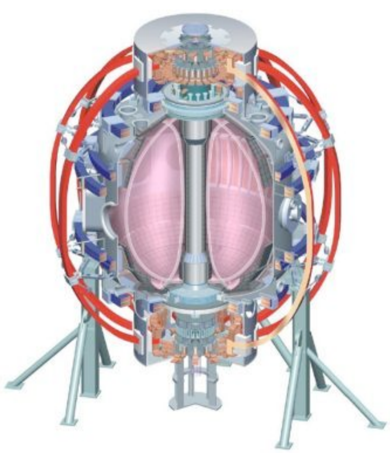

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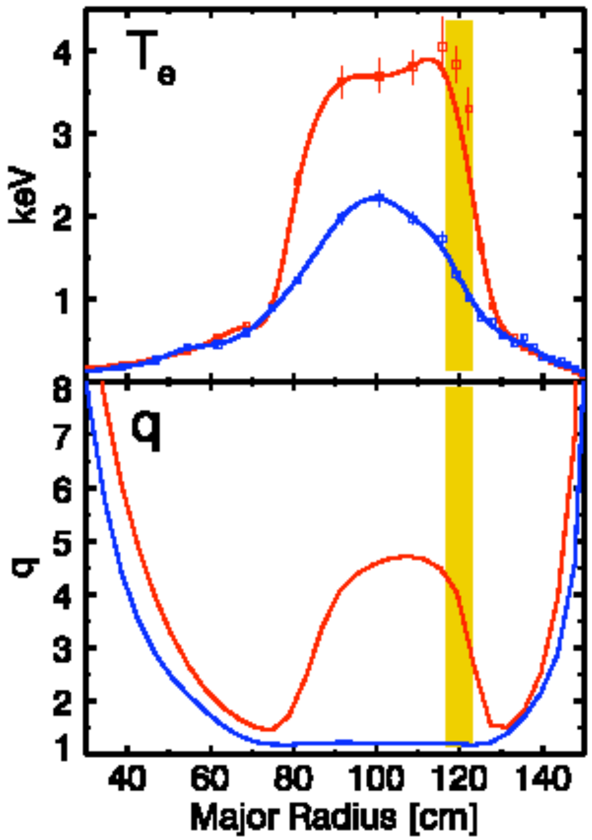
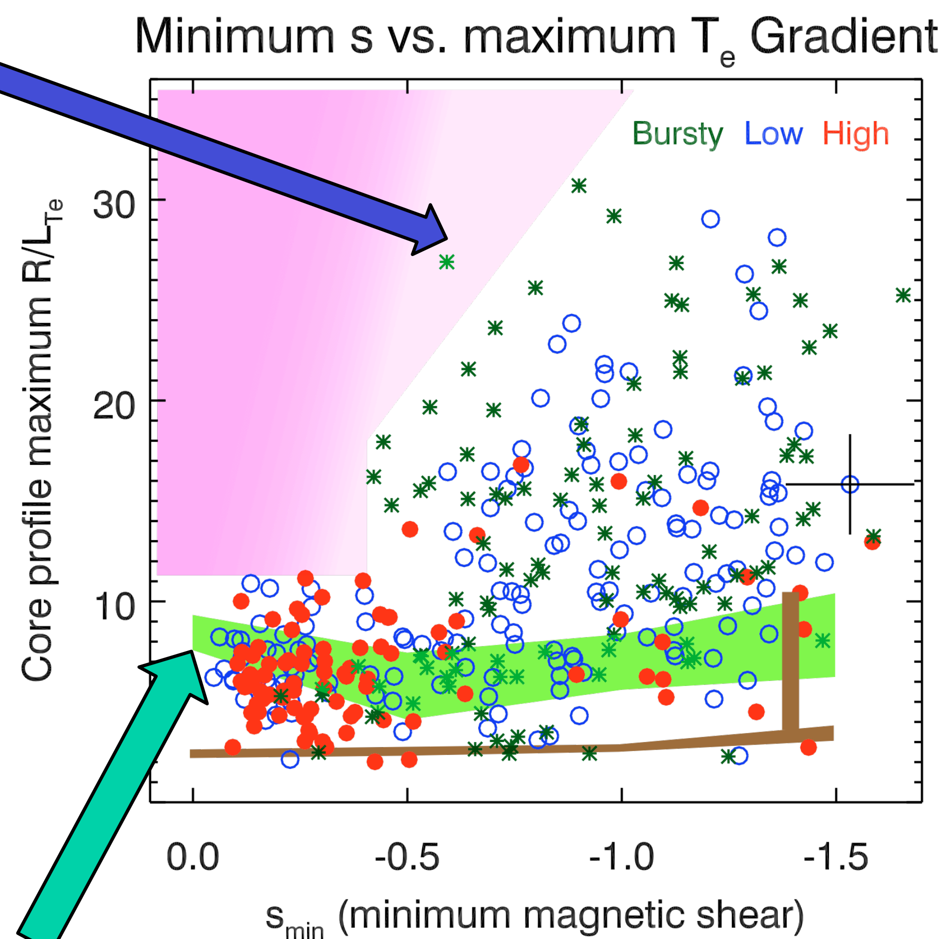
A Puzzle: Some NSTX plasmas violate profile stiffness.

Can heat some plasmas to very steep gradients.





Should be unstable to electron temperature gradient (ETG) turbulence.

Yuh et al PoP (2009)

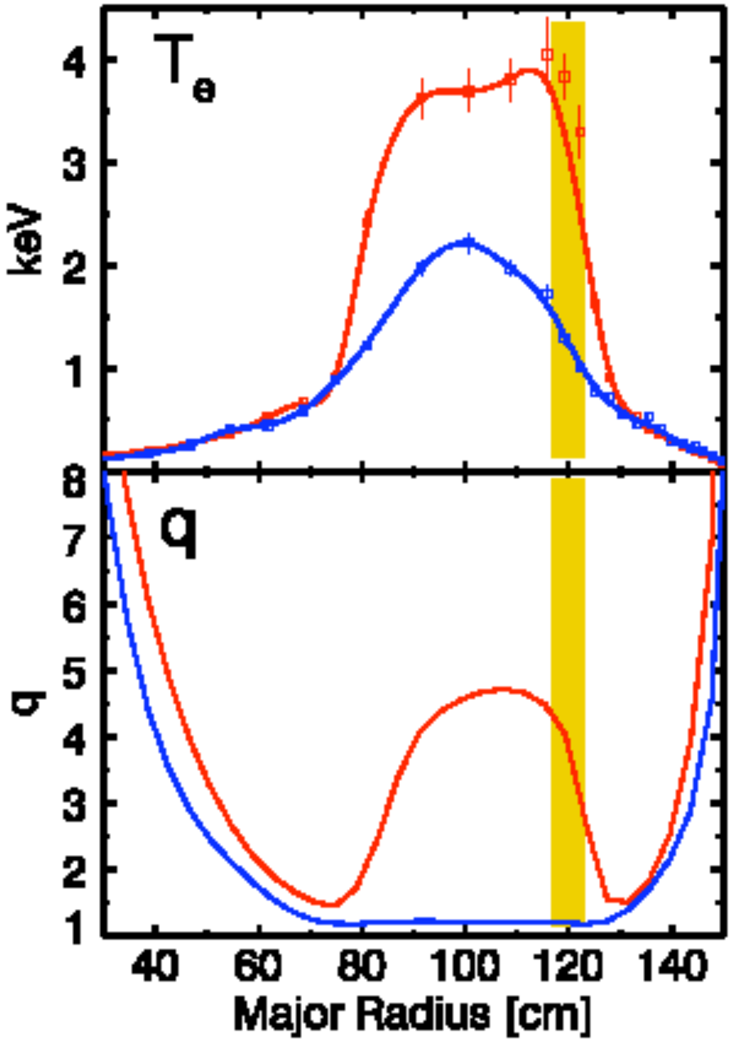
Goal of work: Understand NSTX behavior

- Can trigger electron Internal Transport Barriers (e-ITB) that push past ETG stiffness threshold
- Coincides with lowering of electron-scale density fluctuations
- Electron transport seems to drop as well
- Shear in the magnetic field geometry seems to be important

Can numerical simulations help shed light on the experimental observations?

- What is the connection between electron turbulence and transport during these e-ITB phases?
- What role does magnetic shear play in the suppression of ETG turbulence and/or the formation of e-ITBs?

Baseline NSTX Reversed Shear Discharge #129354 @ 232 ms



- e-ITB during strong reversed shear
- RF heat drives high electron temperature
- ETG unstable: $(R/L_{T_e})_{crit} \approx 4.5$

Physical Parameters

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

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

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

Simulation Plan: Probe Nonlinear Critical Gradient

- GYRO*
- Scan electron temperature gradient
- Nonlinear flux tube simulations
- Vary magnetic shear
- Electrostatic
- No background flow shear
- Electron-scale resolution
- ~100,000 CPU hours each at ORNL Cray XT
- ~3 million total CPU hours

*** J. Candy and E.A. Belli, GYRO Technical Guide, General Atomics Report GA-A26818 (2010).***

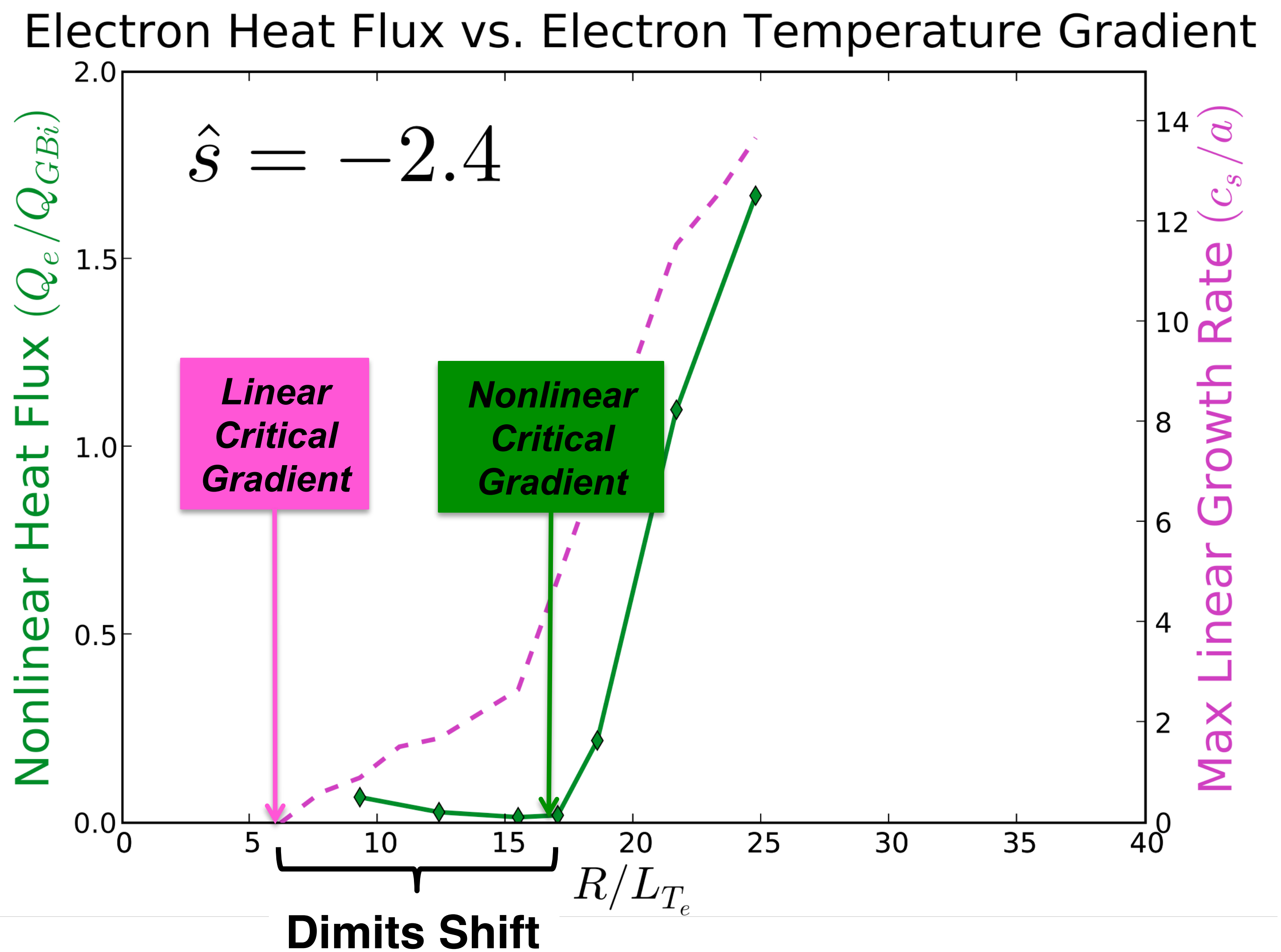
Numeric Details

- All species gyrokinetic: electrons, deuterium
- 22 points per passing particle orbit
- 12 energy, 24 pitch angle grid points
- 24 toroidal modes
- Electron gyro-radius radial grid resolution

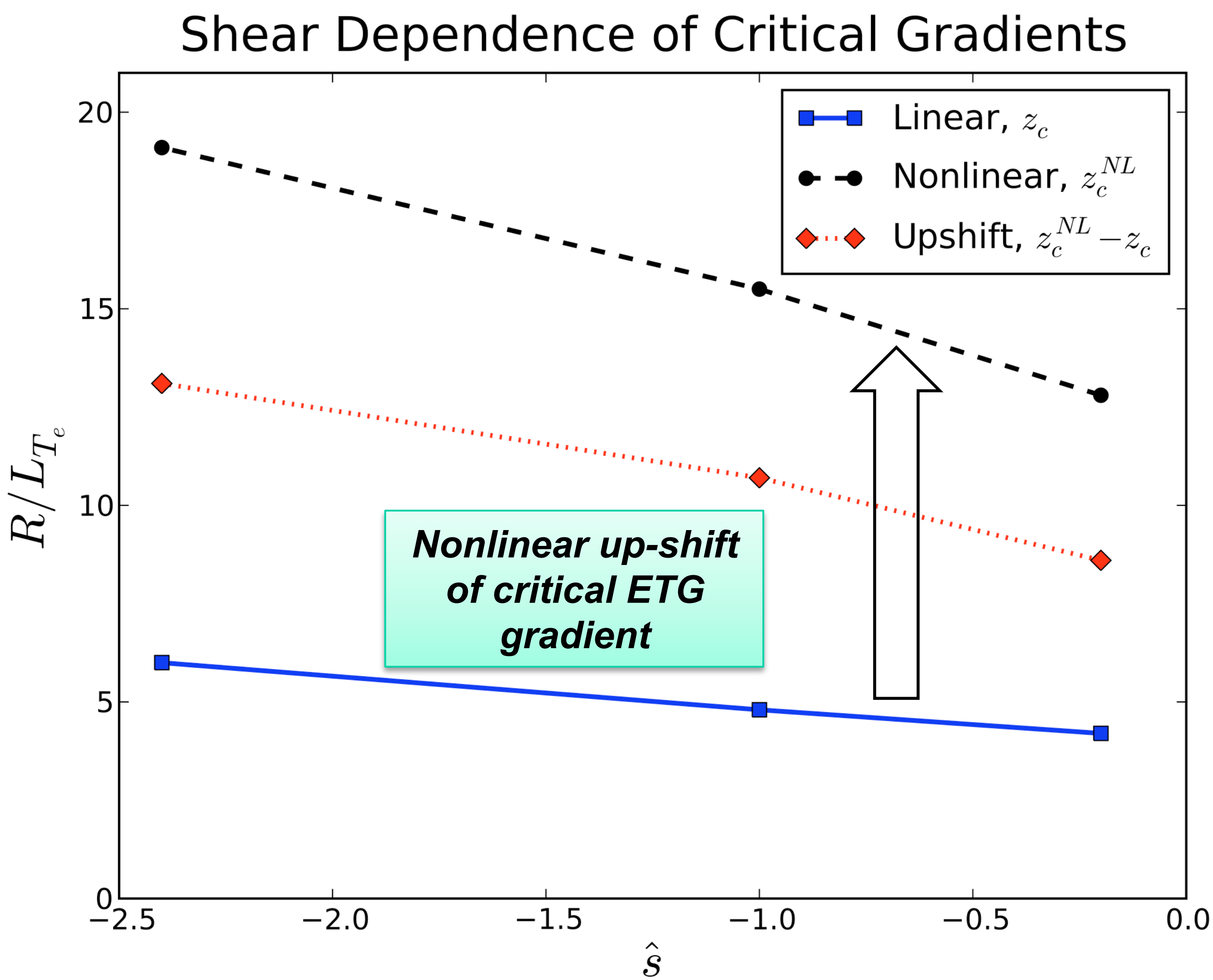
$$L_x \times L_y = 4.26 \times 2.4\rho_s \qquad k_\theta \rho_s = [2.618, 60.21]$$

$$= 255 \times 144\rho_e \qquad k_\theta \rho_e = [0.043, 1.004]$$

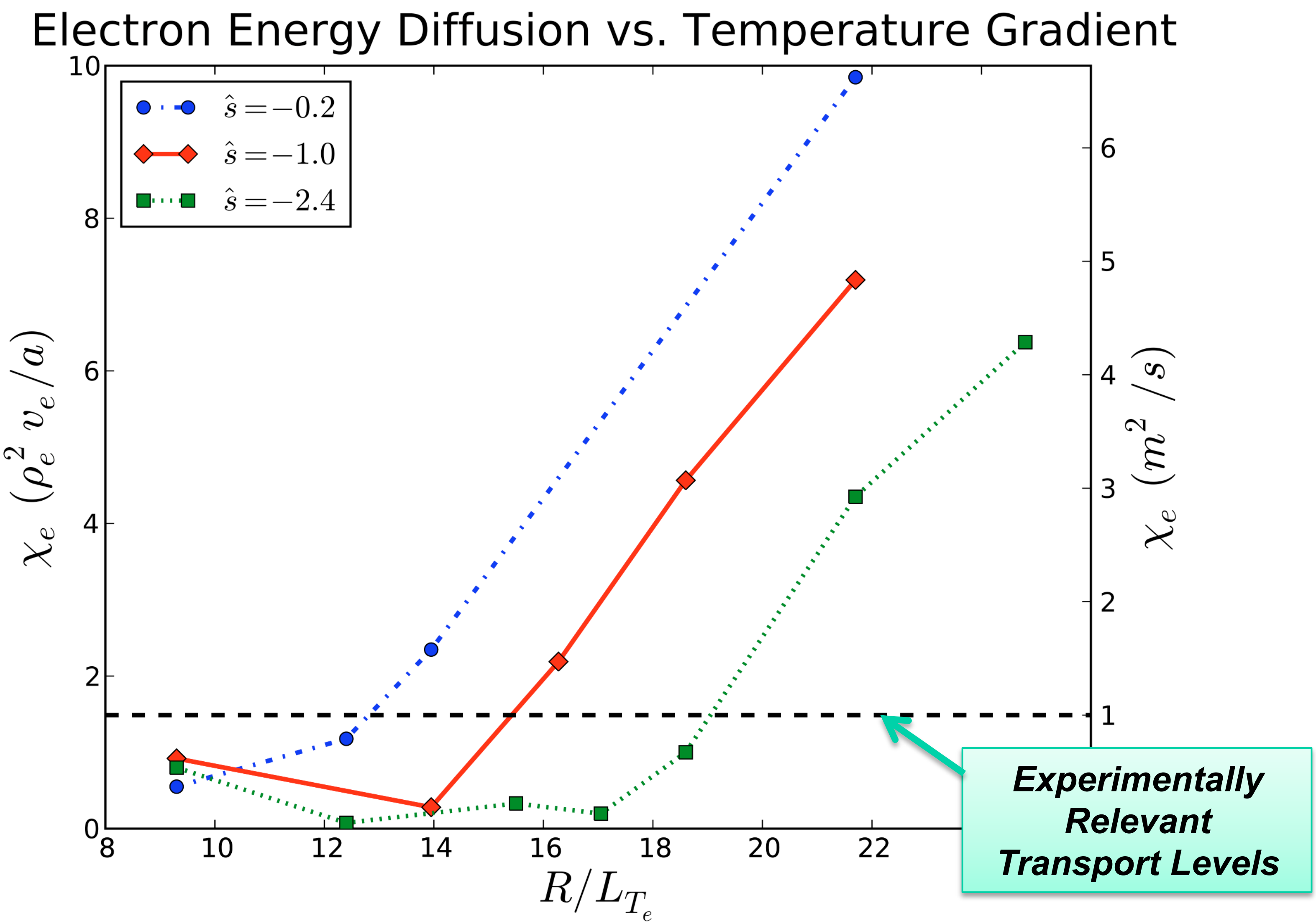
The Dimits Shift is <u>very large</u> for baseline negative shear.



The up-shift strength depends upon magnetic shear.



Stiff Profile Threshold Increases With Reversed Shear



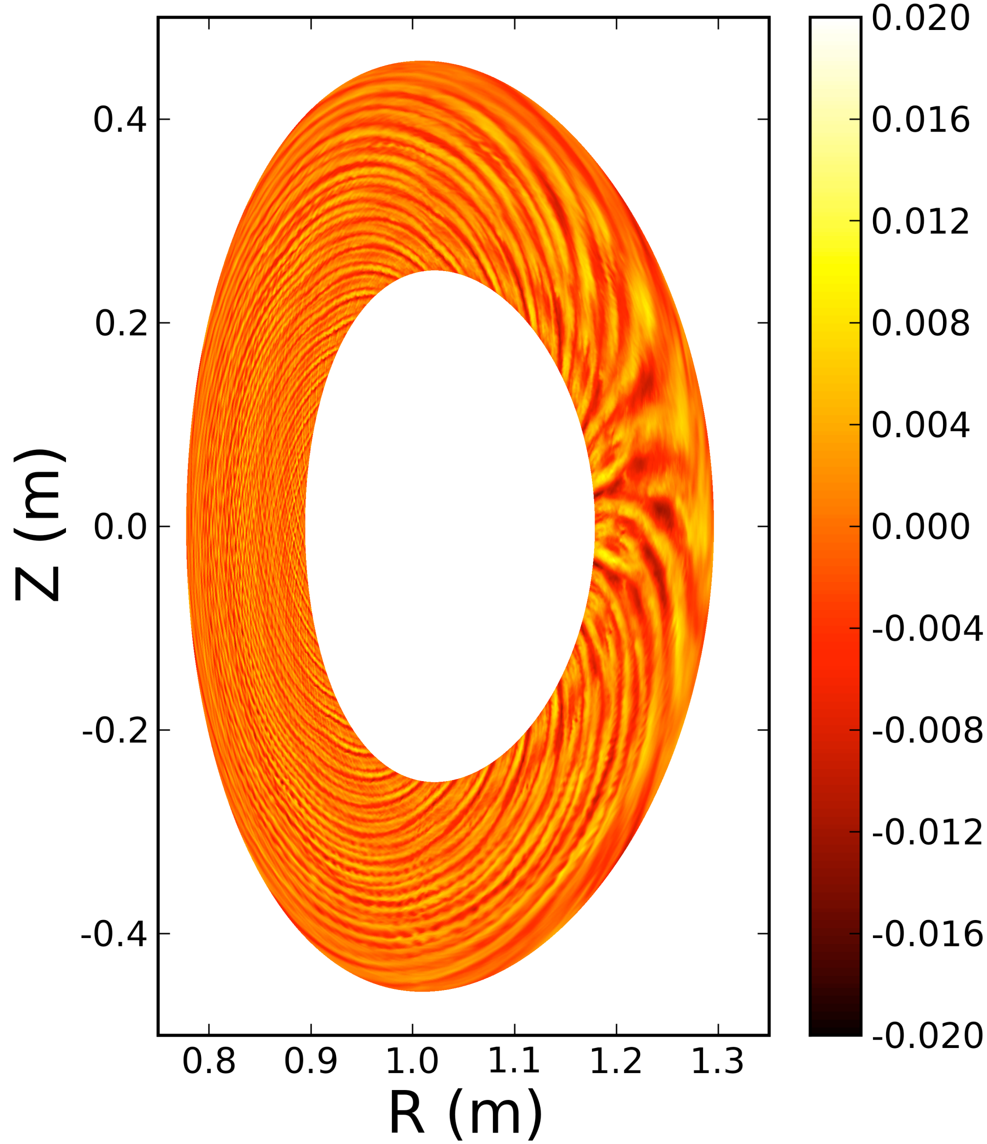
Below Nonlinear Critical Gradient Threshold: Streamers Sheared Apart, Low Transport

$$R/L_{T_e} \approx 9$$

$$\langle \tilde{n}_e \rangle_{rms} \approx 0.3\%$$

Eddies Sheared, Saturate at Low Amplitude

Linearly Unstable, But Low Levels of Transport



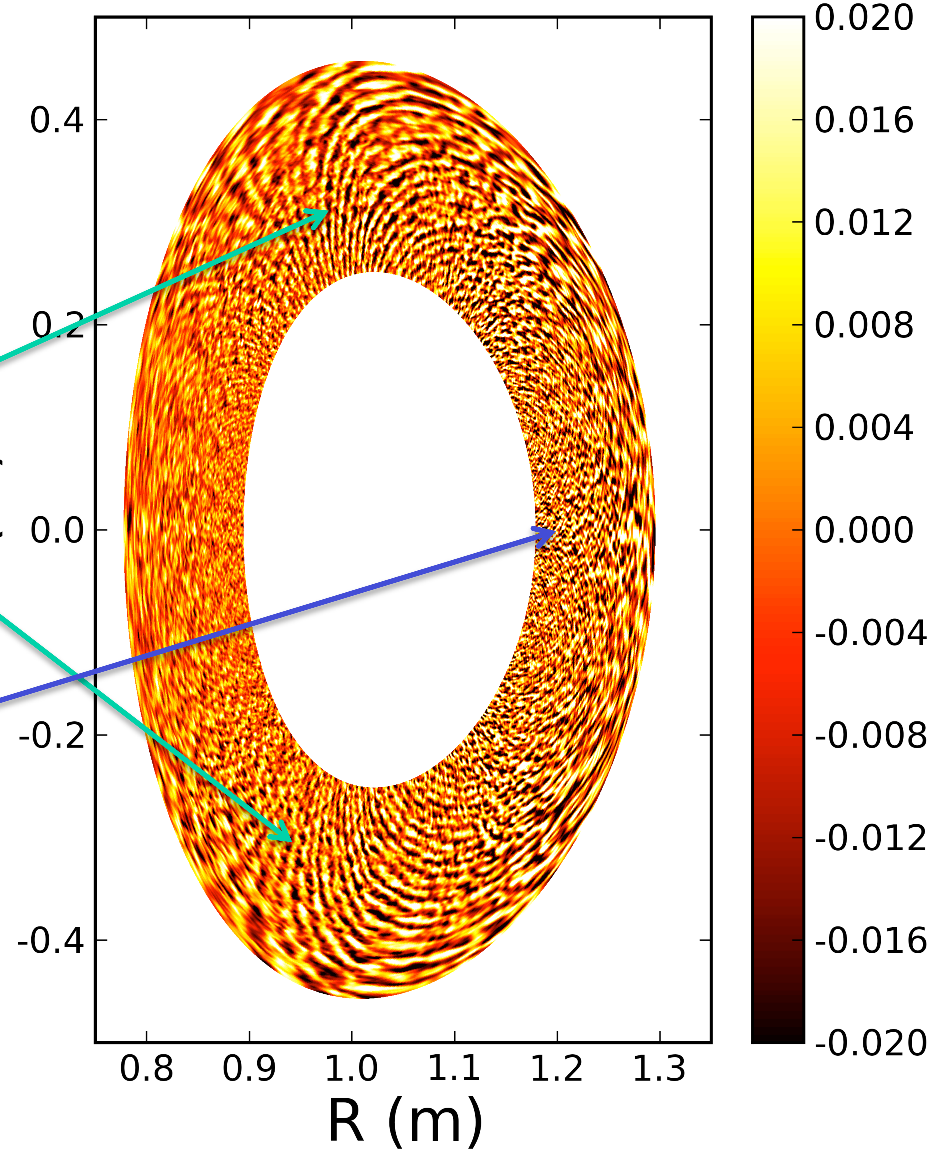
Above Nonlinear Critical Gradient Threshold: Streamers Not on Midplane, Large Transport

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

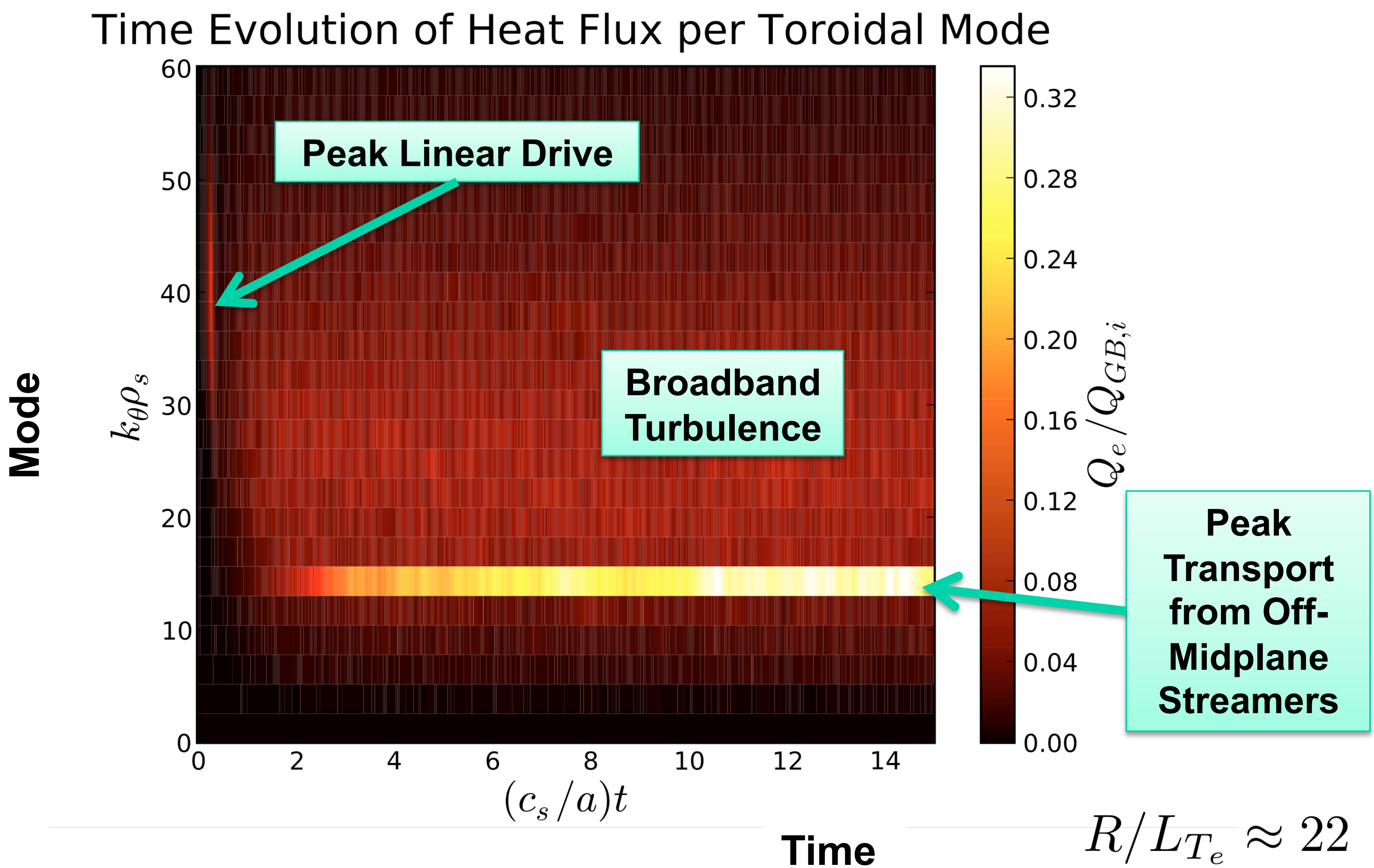
$$\langle \tilde{n}_e \rangle_{rms} \approx 1.1\%$$

Radial Streamers out of Top and Bottom

Broadband Turbulence

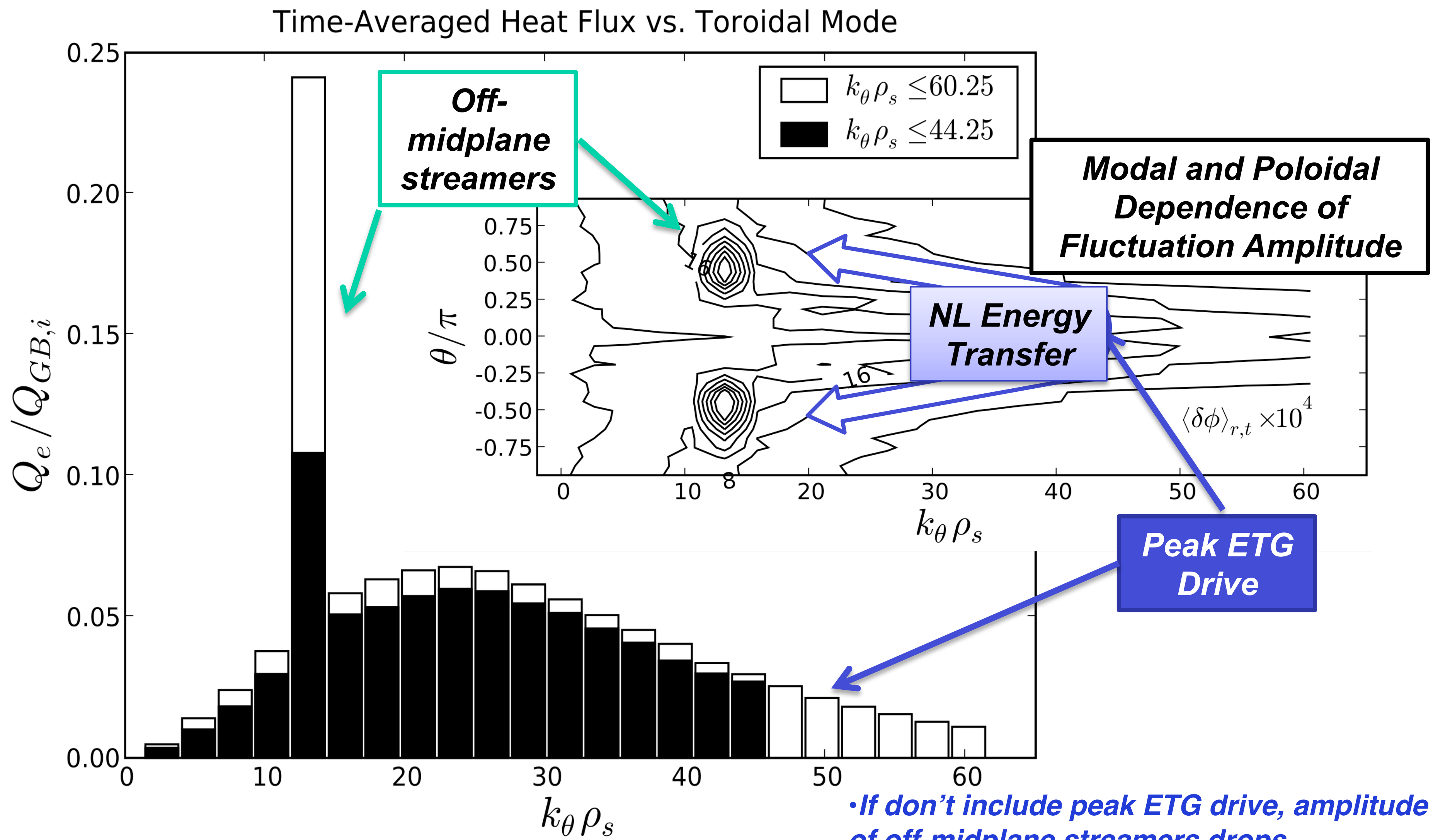


Above nonlinear critical gradient, broadband turbulence and linearly subdominant peak of transport.



$R/L_{T_e} \approx 22$

Evidence of Energy Transfer to Off-Midplane Streamers



•If don't include peak ETG drive, amplitude of off-midplane streamers drops.

Some Testable (?) Speculations

- Performance of e-ITBs is limited by nonlinear critical gradient for transport.
  - Map out critical gradient as function of shear, compare with xp data
  - New validation experiment on NSTX
- Reversed shear discharges can still have significant ETG turbulence off the midplane.
  - Move high-k, look for difference / stronger fluctuations away from midplane
- Transport relies on interplay between very high-k and high-k.
  - Energy transport diagnostics in simulation
  - Map out linear stability properties of both modes, compare w/ nonlin.
- "Bursty" turbulence is characteristic of turbulence near nonlinear critical gradient.
  - Synthetic diagnostics

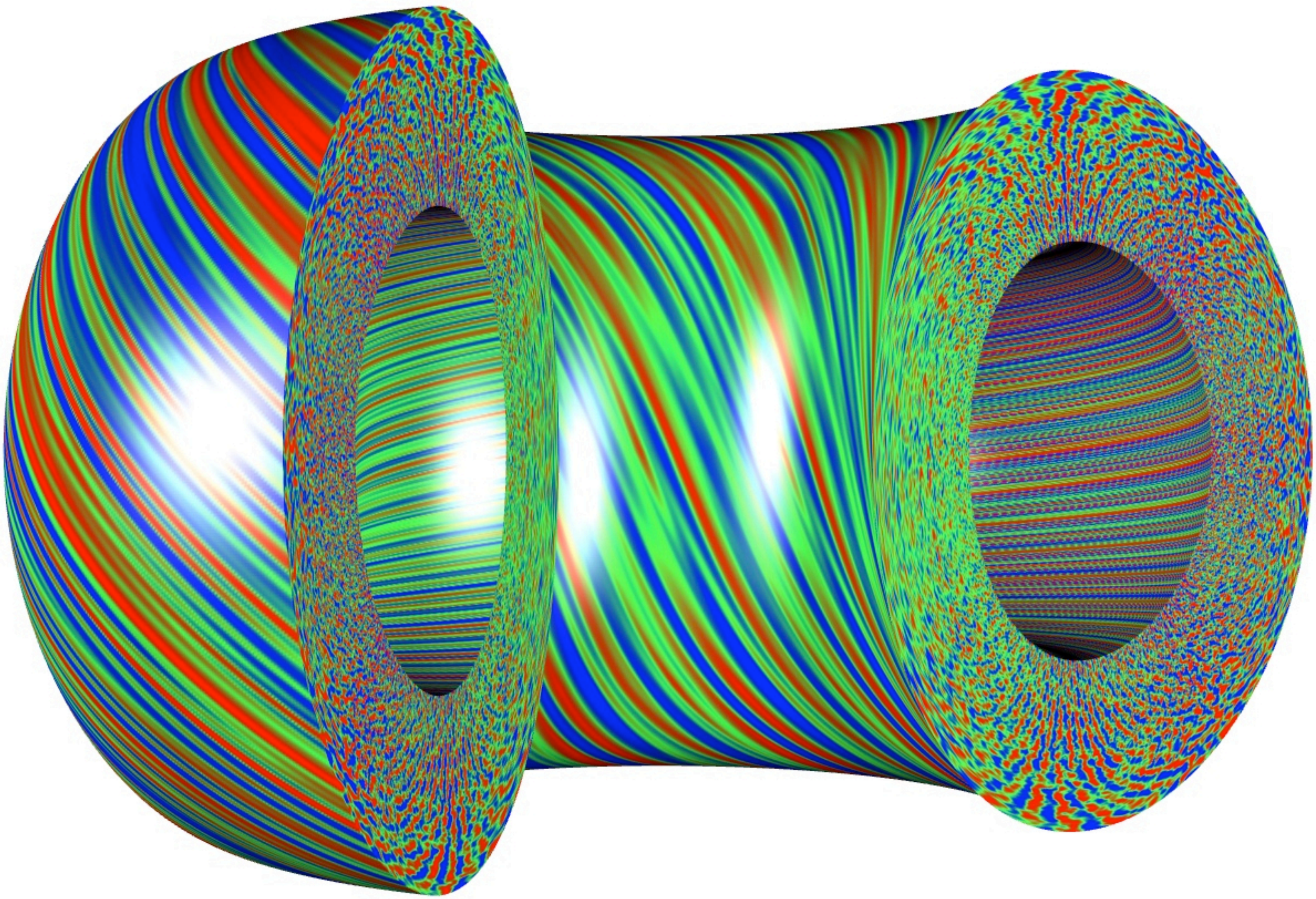
Future Work

- Thorough analysis of high-transport case
  - Goal: investigate nonlinear gradient threshold, top/bottom streamers
- Apply mag. shear to gyrokinetic secondary instability theory
  - Goal: investigate how strength of ETG damping changes with shear
  - Goal: investigate GK vs. adiabatic ions
- 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 top/bottom mode is important.
- Numerical convergence studies

Conclusions

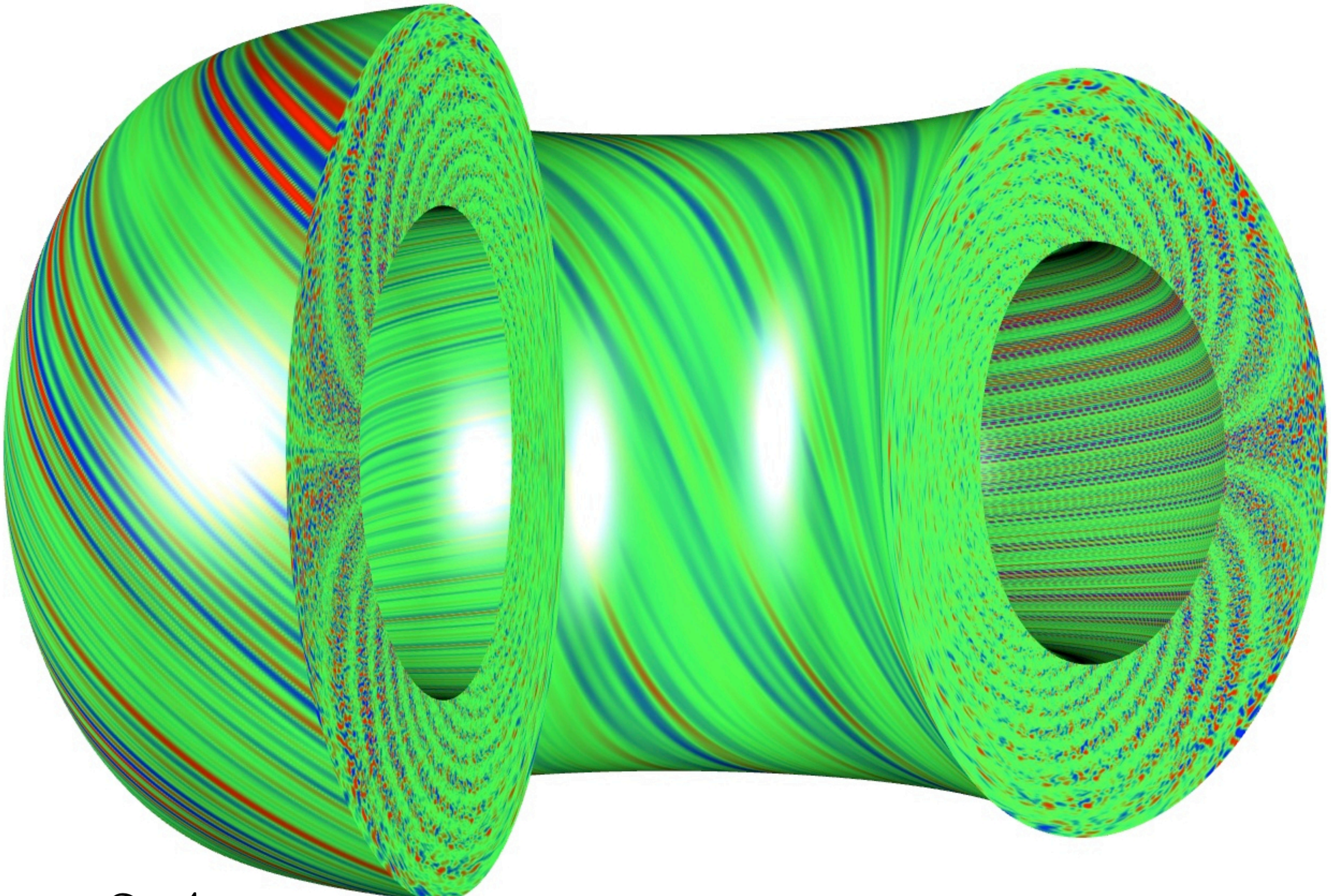
- Reversed shear temperature gradient scans find a second-instability threshold for electron transport.
  - ~ 3x the linear critical gradient
- Nonlinear critical gradient is consistent with observations of maximum attainable gradients in NSTX reversed shear discharges.
- Above threshold, a slow-growing mode saturates with highest amplitude, causes large amount of transport.
  - Nonlinearly driven by peak ETG drive
  - **Streamers out of top and bottom**: midplane streamers sheared

Thank You



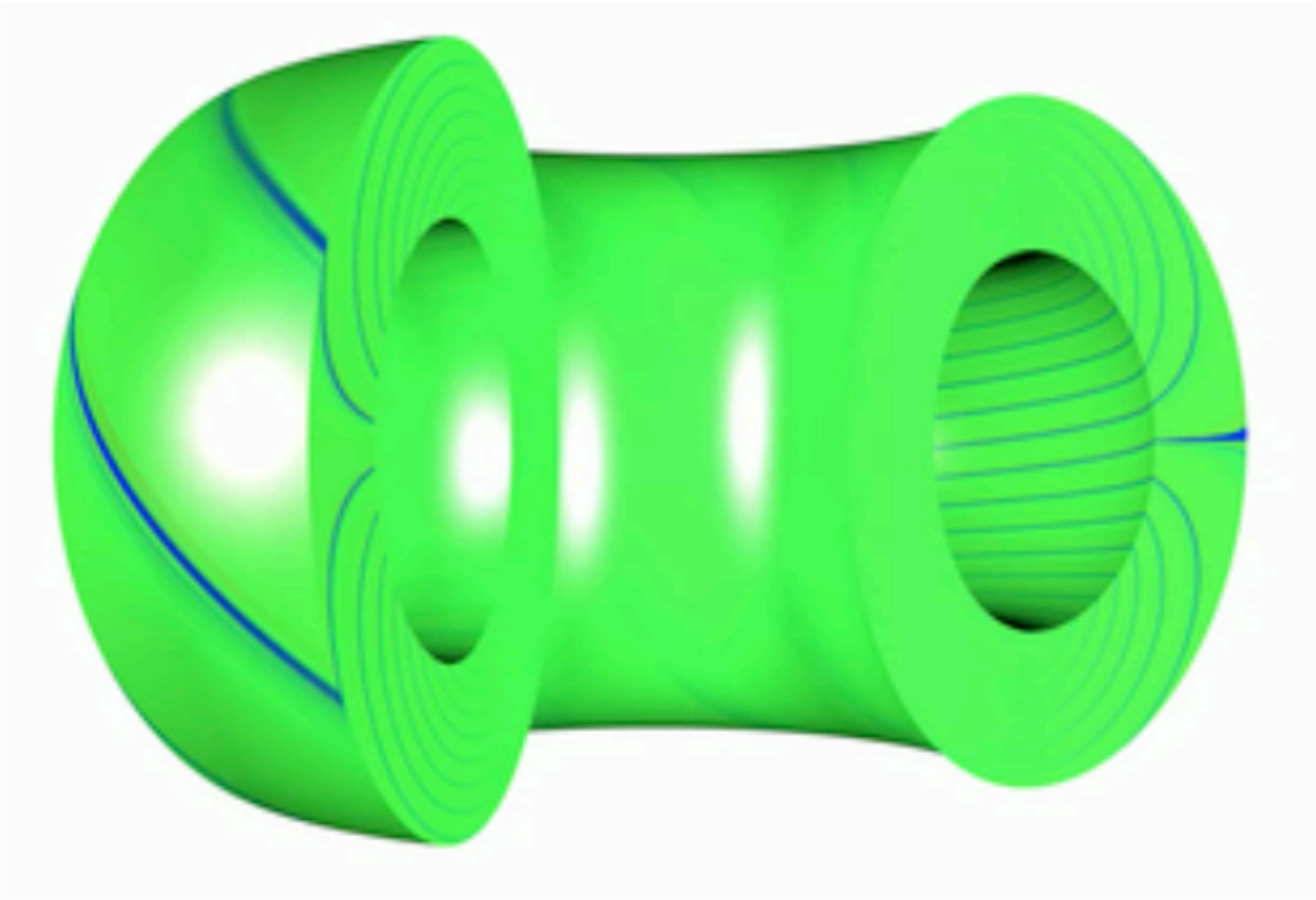
Extra Slides

Early Stage of Reversed Shear



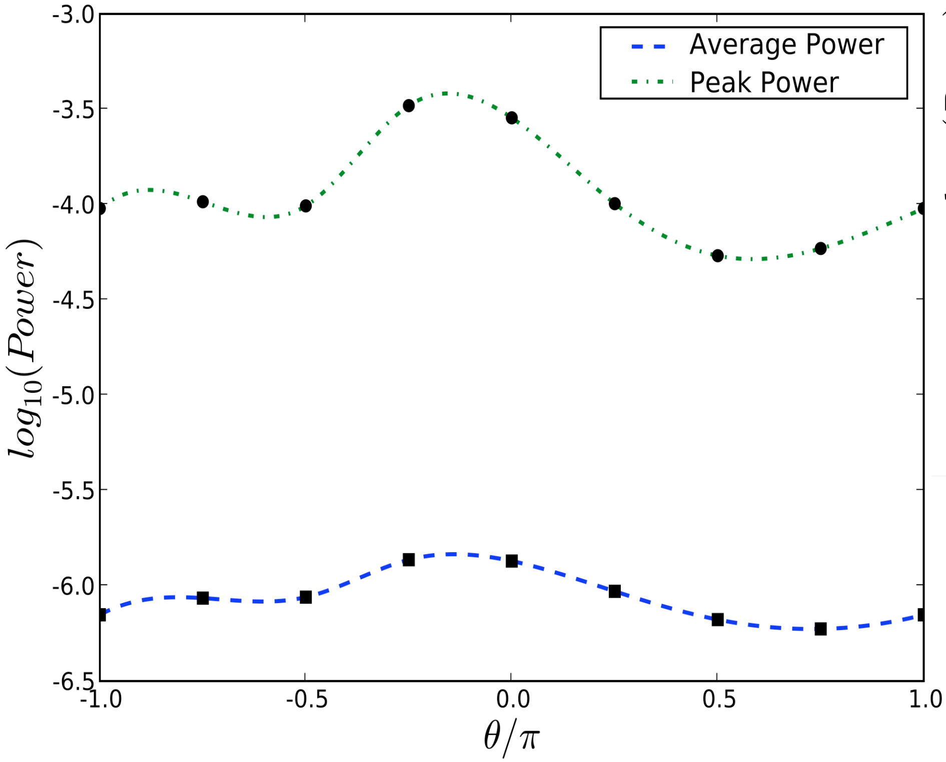
$$\hat{s} = -2.4$$

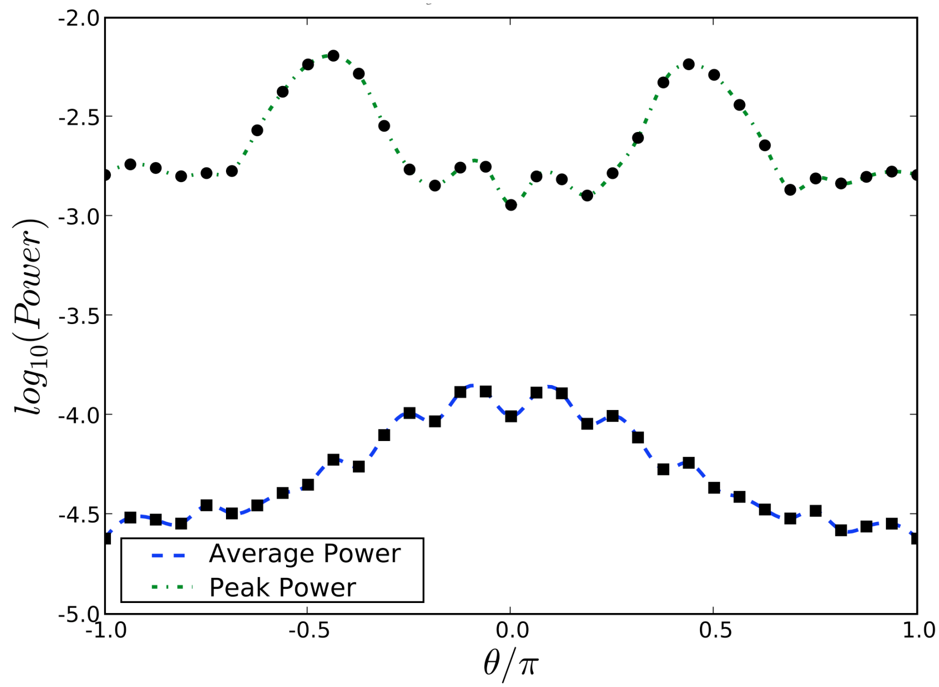
Density Fluctuation Evolution



Poloidal Dependence of Power Spectra Amplitudes

$R/L_{T_e} \approx 12.5$



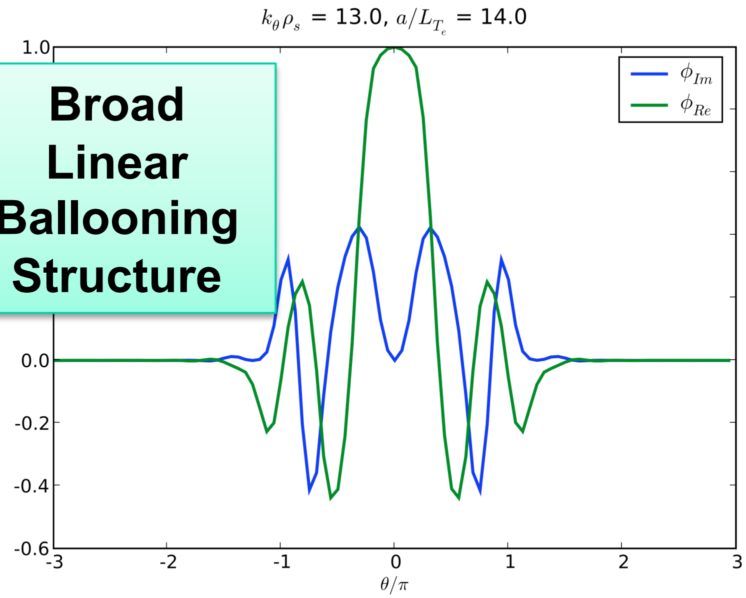


$R/L_{T_e} \approx 22$

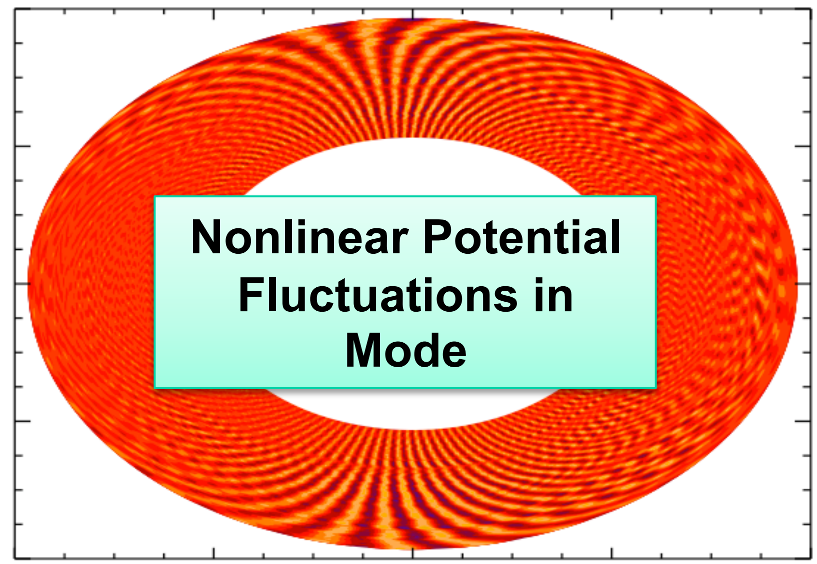
$$\hat{s} = -2.4$$

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

Broad Linear Ballooning Structure



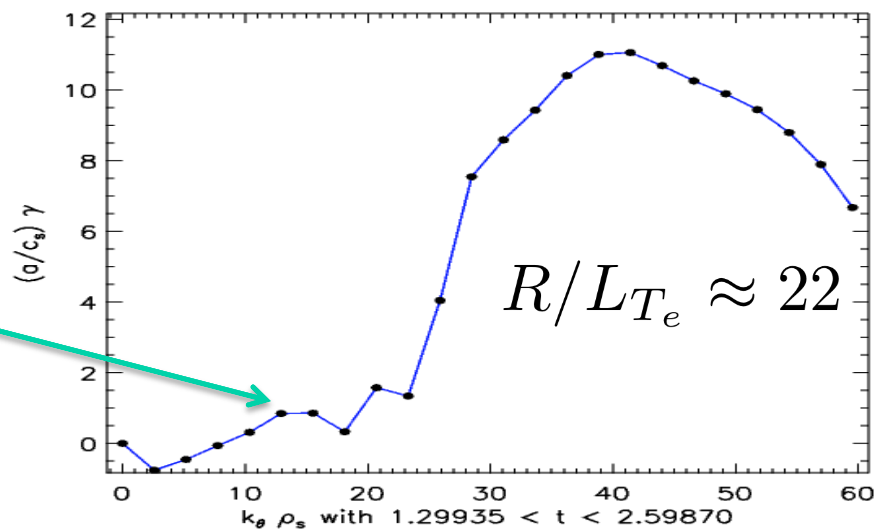
Nonlinear Potential Fluctuations in Mode



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

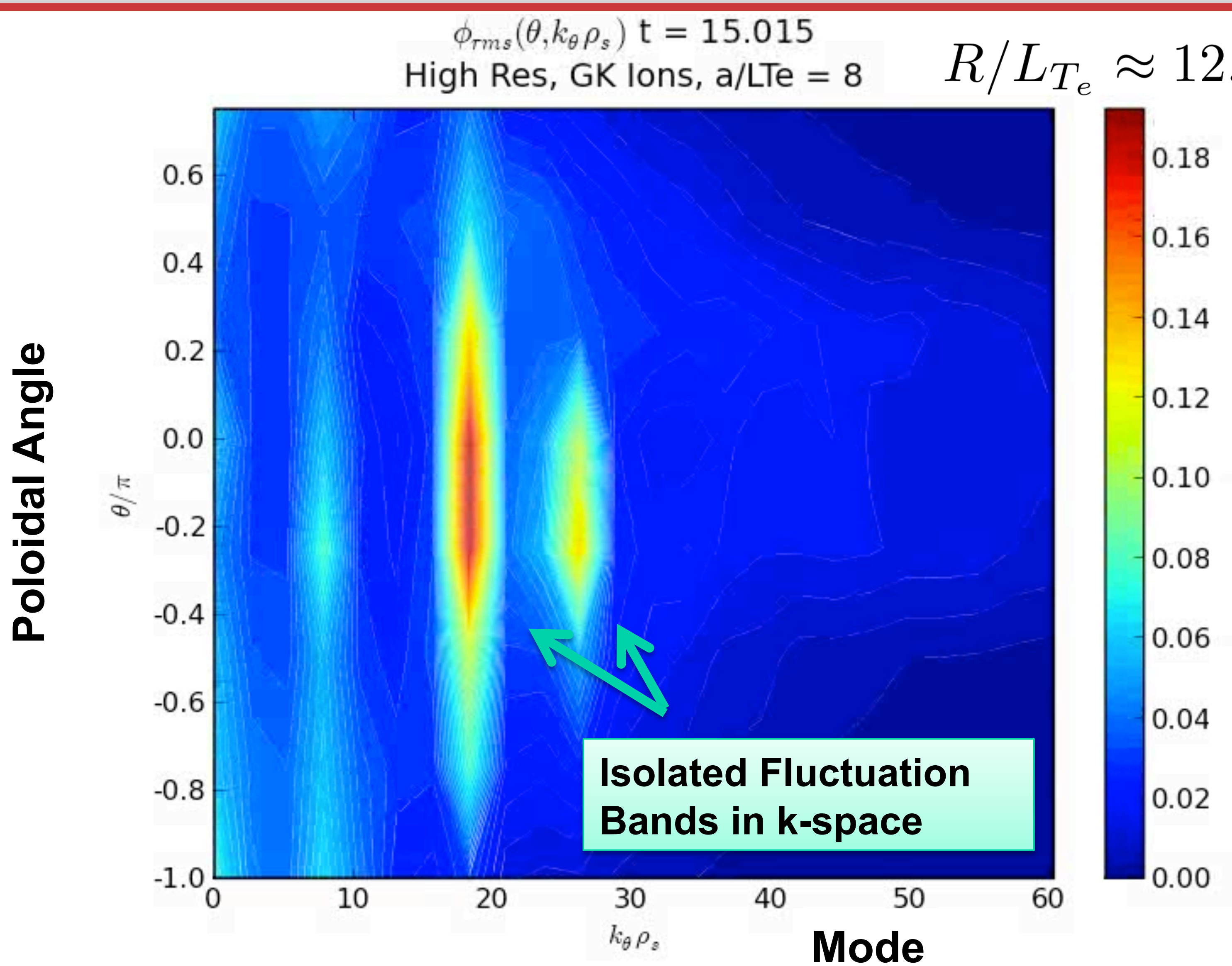
$$\omega = 25.19\ a/c_s$$

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

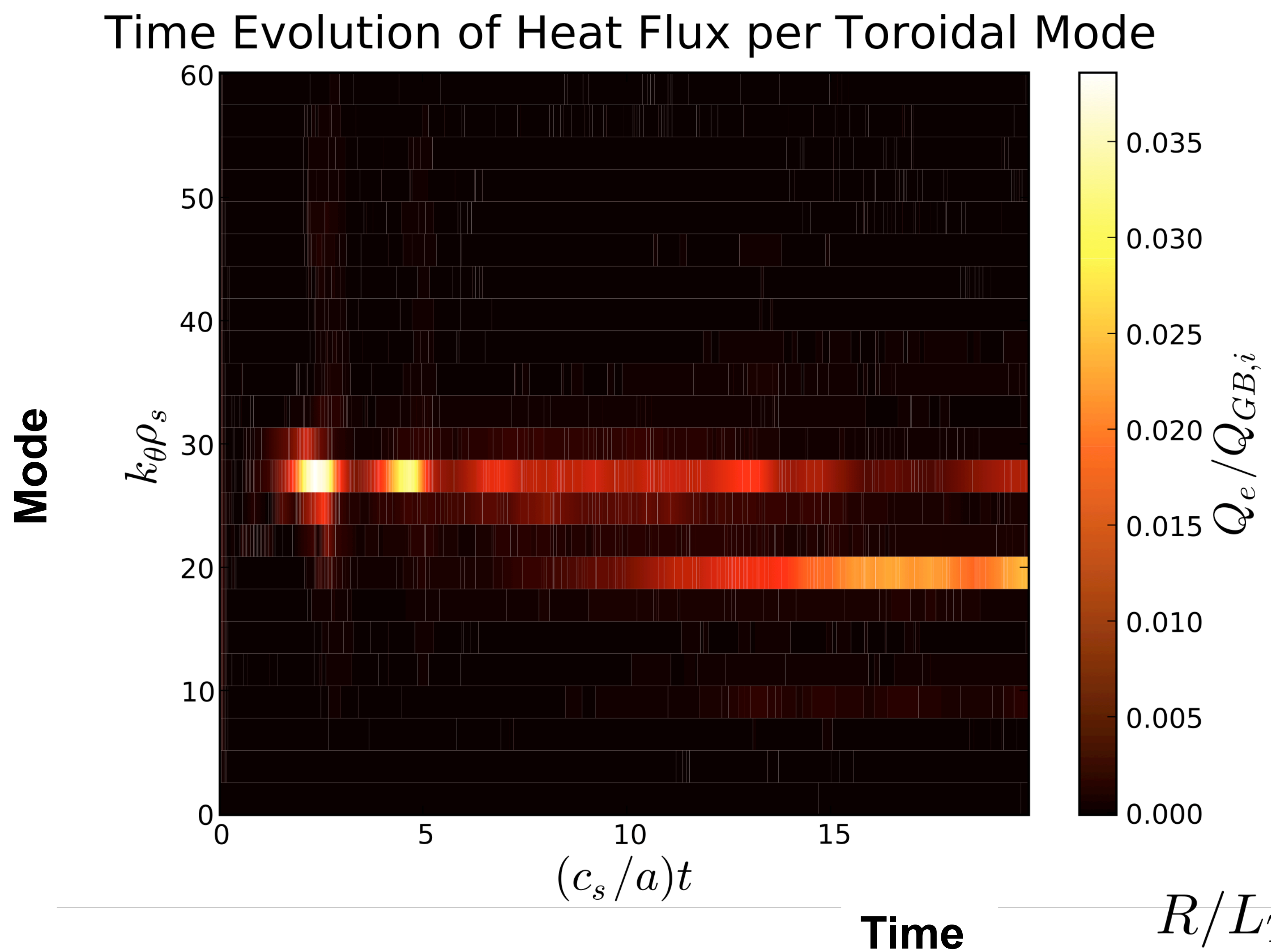


Low-transport modes centered on Midplane

$R/L_{T_e} \approx 12.5$

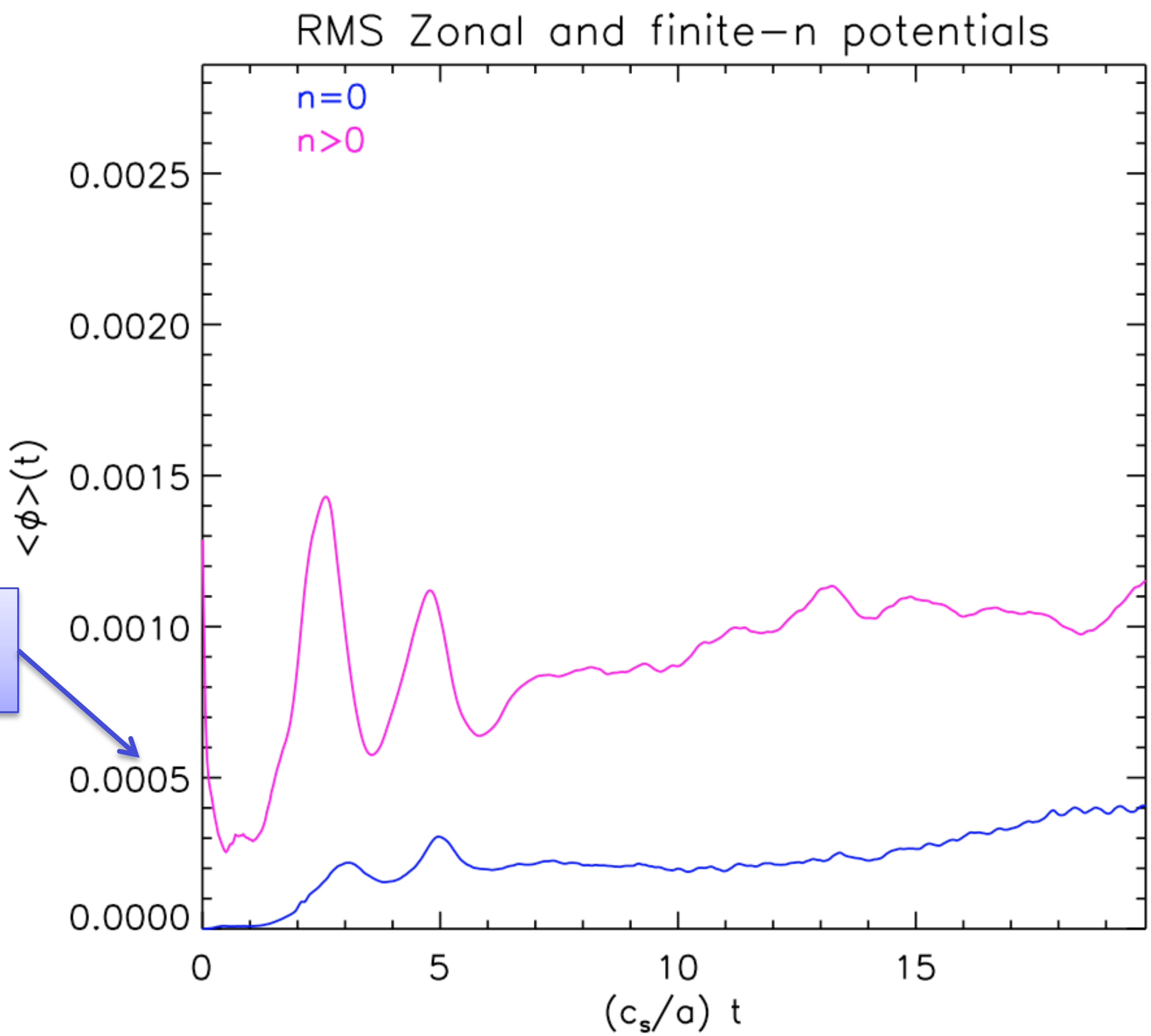


Below nonlinear critical gradient, no broadband turbulence.



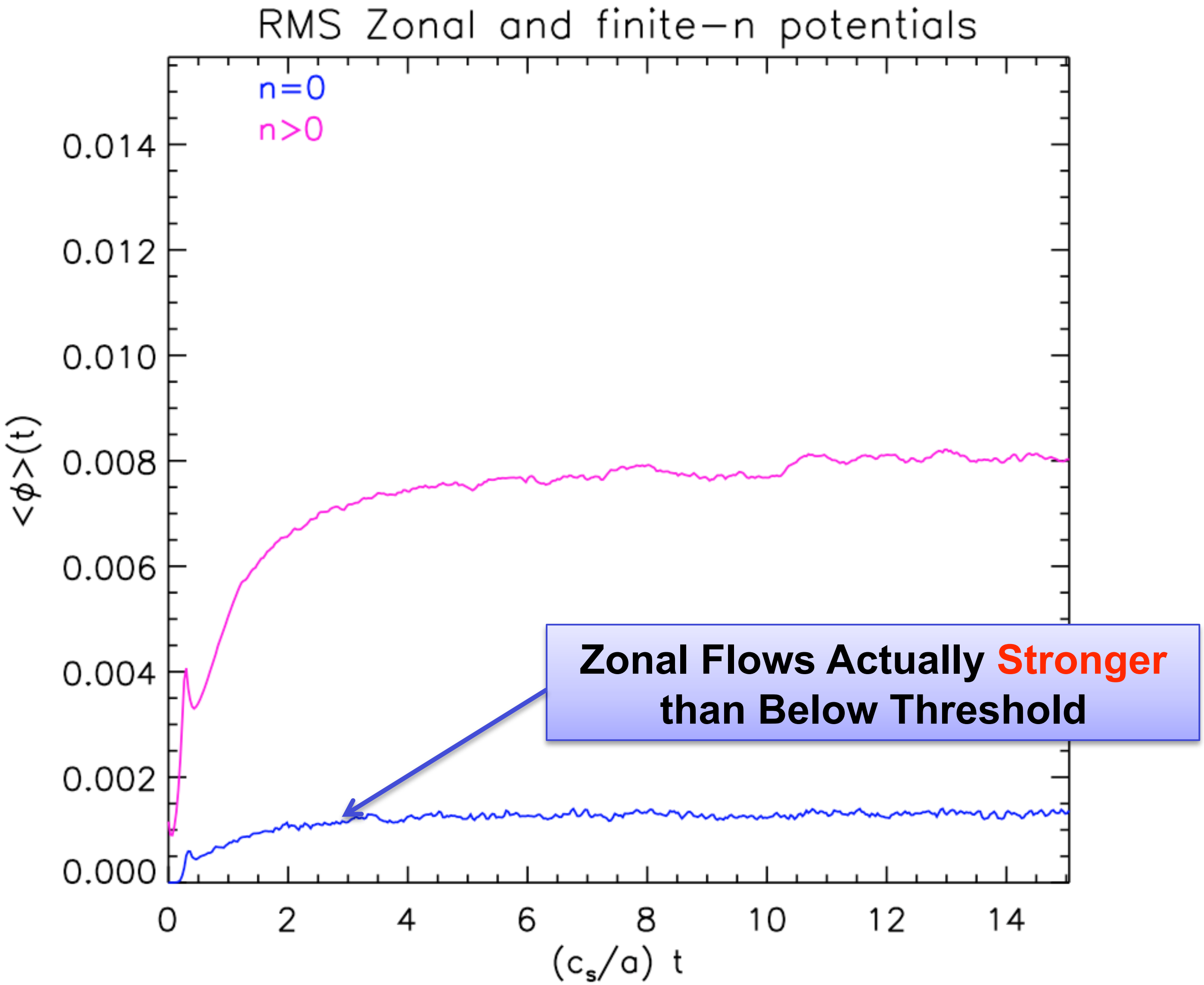
$R/L_{T_e} \approx 12.5$

Zonal Flows Appear Correlated with Finite-n Potential Fluctuations Below Critical Gradient

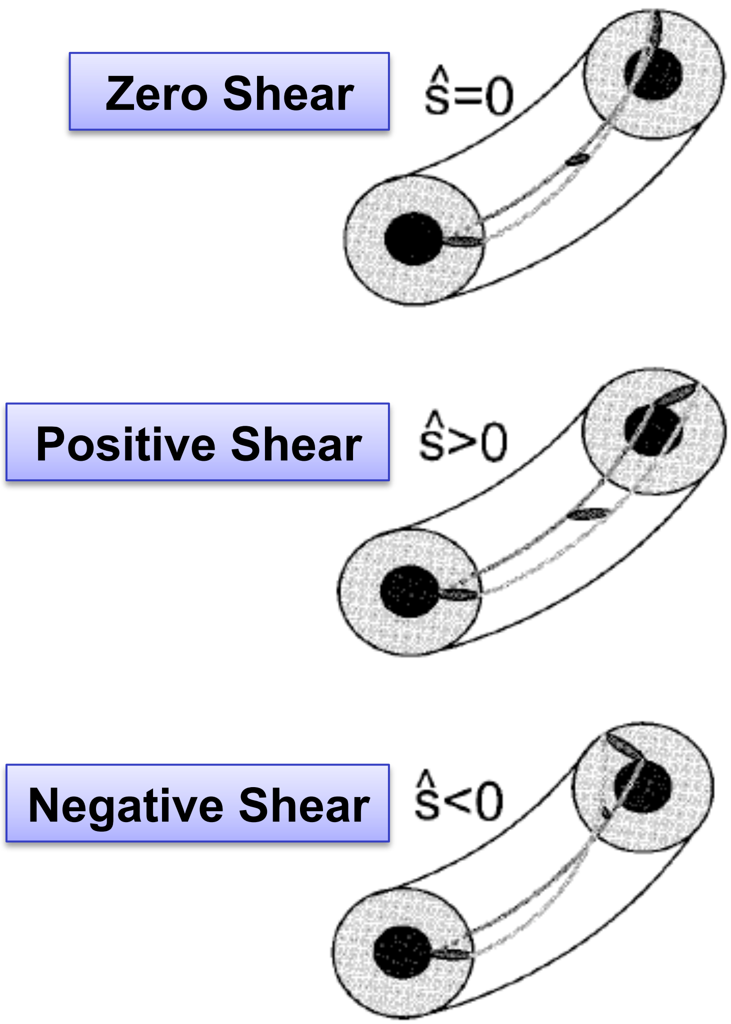


Low-magnitude

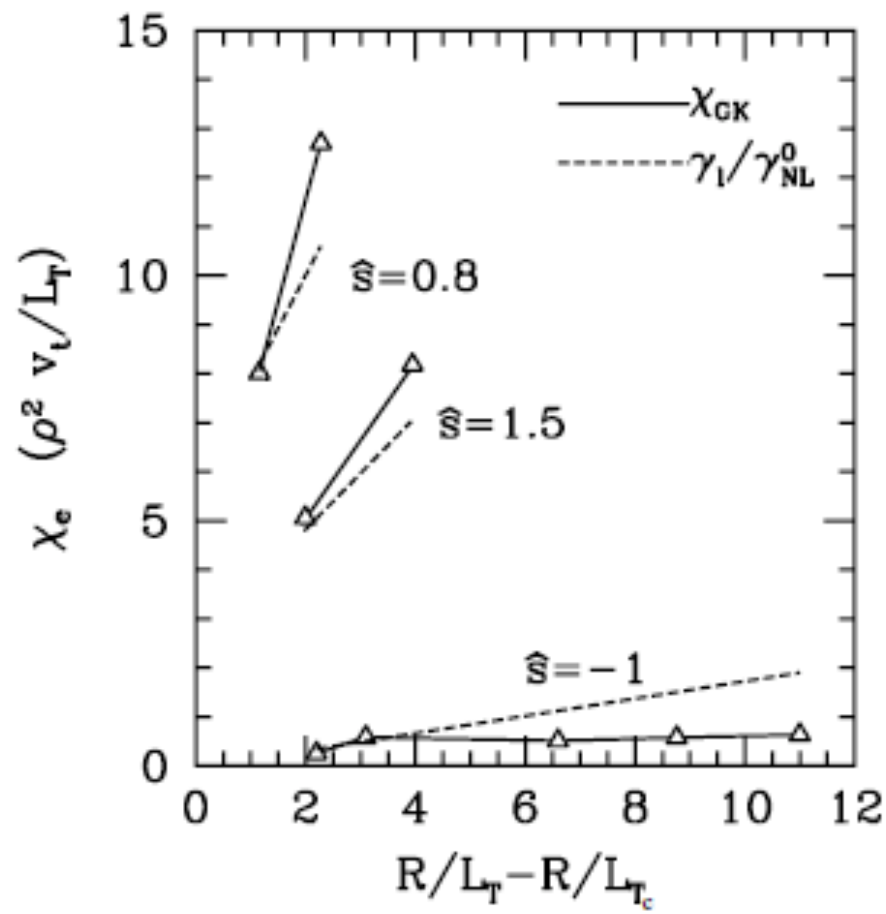
Above Nonlinear Critical Gradient, Quicker Saturation



The magnetic field shear can regulate turbulence.



ETG Heat Diffusivity vs. Driving Gradient



Antonsen et al Phys. Plasmas (1996)

Jenko and Dorland PRL (2002)