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

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EU-US TTF Meeting, San Diego
April 6, 2011

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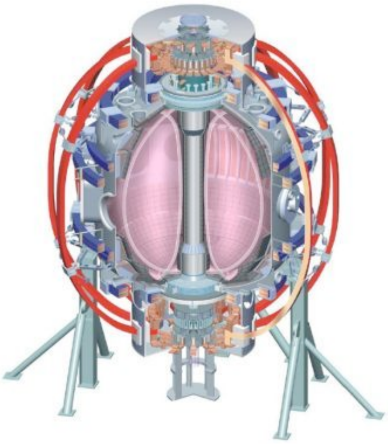

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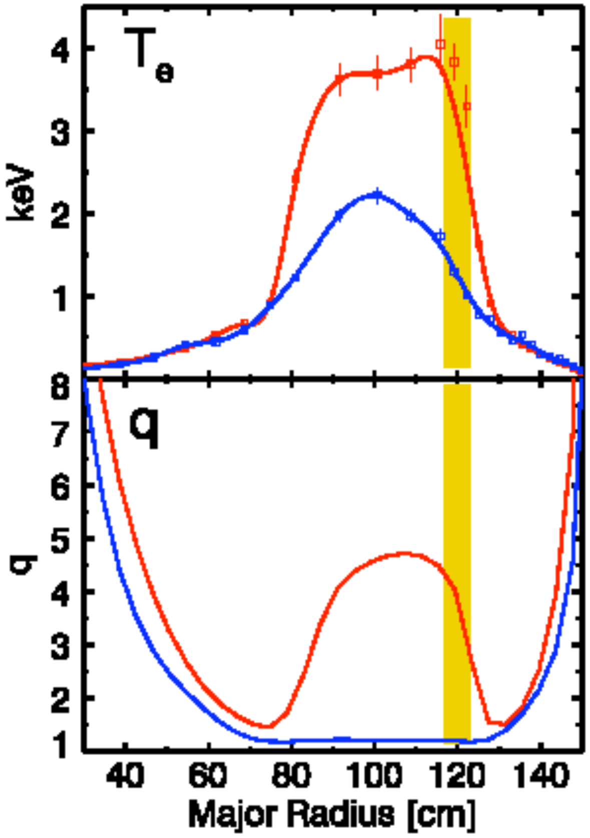
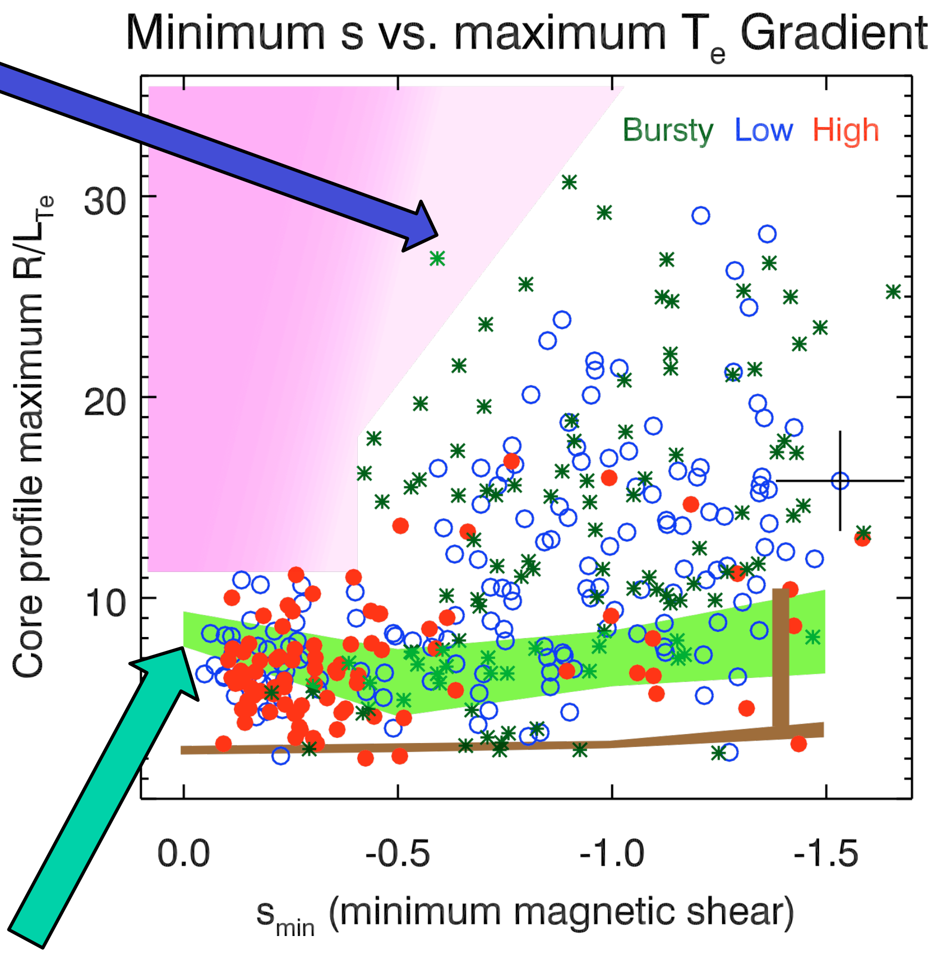
A Puzzle: Some NSTX plasmas violate profile stiffness.

Can heat some plasmas to very steep gradients.





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

Yuh et al PoP (2009)

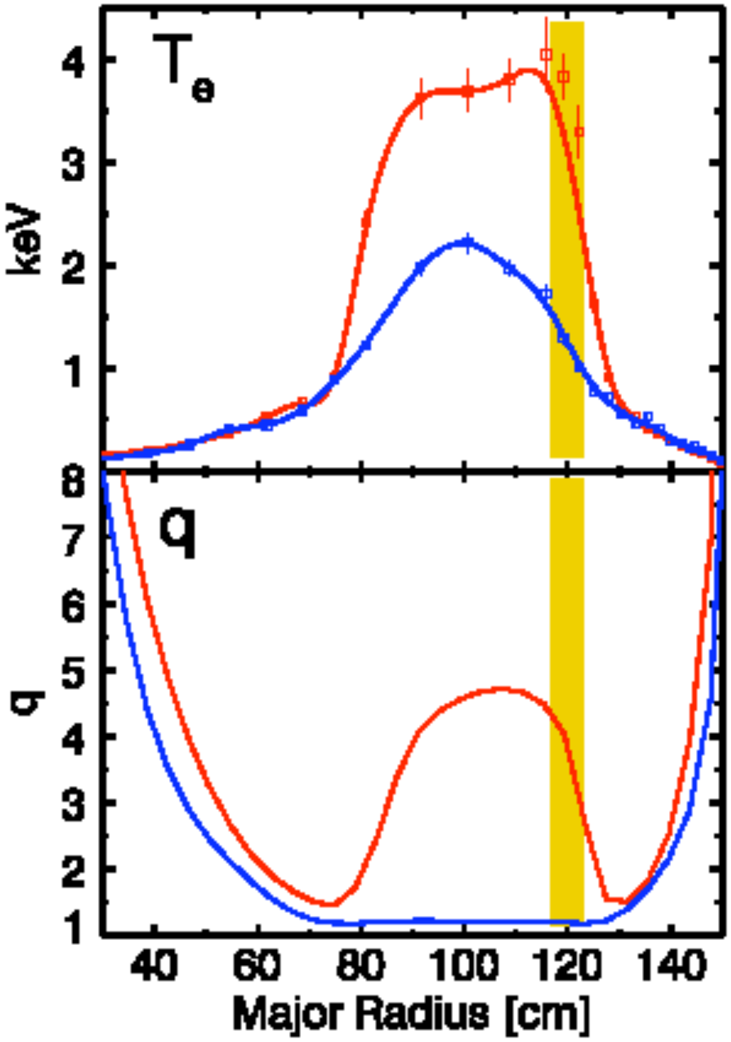
Goal of work: Understand NSTX behavior

- 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:

$$(R/L_{T_e})_{crit} \approx 4.5$$

$$(R/L_{T_e})_{xp} \approx 21.5 \pm 5$$

Physical Parameters

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

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

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

Simulation Plan: Probe Nonlinear Critical Gradient

- GYRO*
- Scan electron temperature gradient
- Nonlinear flux tube simulations
- Vary magnetic shear
- Electrostatic $\beta = 0$
- No background flow shear
- Electron-scale resolution
- ~ 100,000 CPU hours each at ORNL Cray XT
- ~ 5 million total CPU hours (10 weeks on 3000 processors)
  - ~ 40% of PPPL's 2010 INCITE CSPM allocation

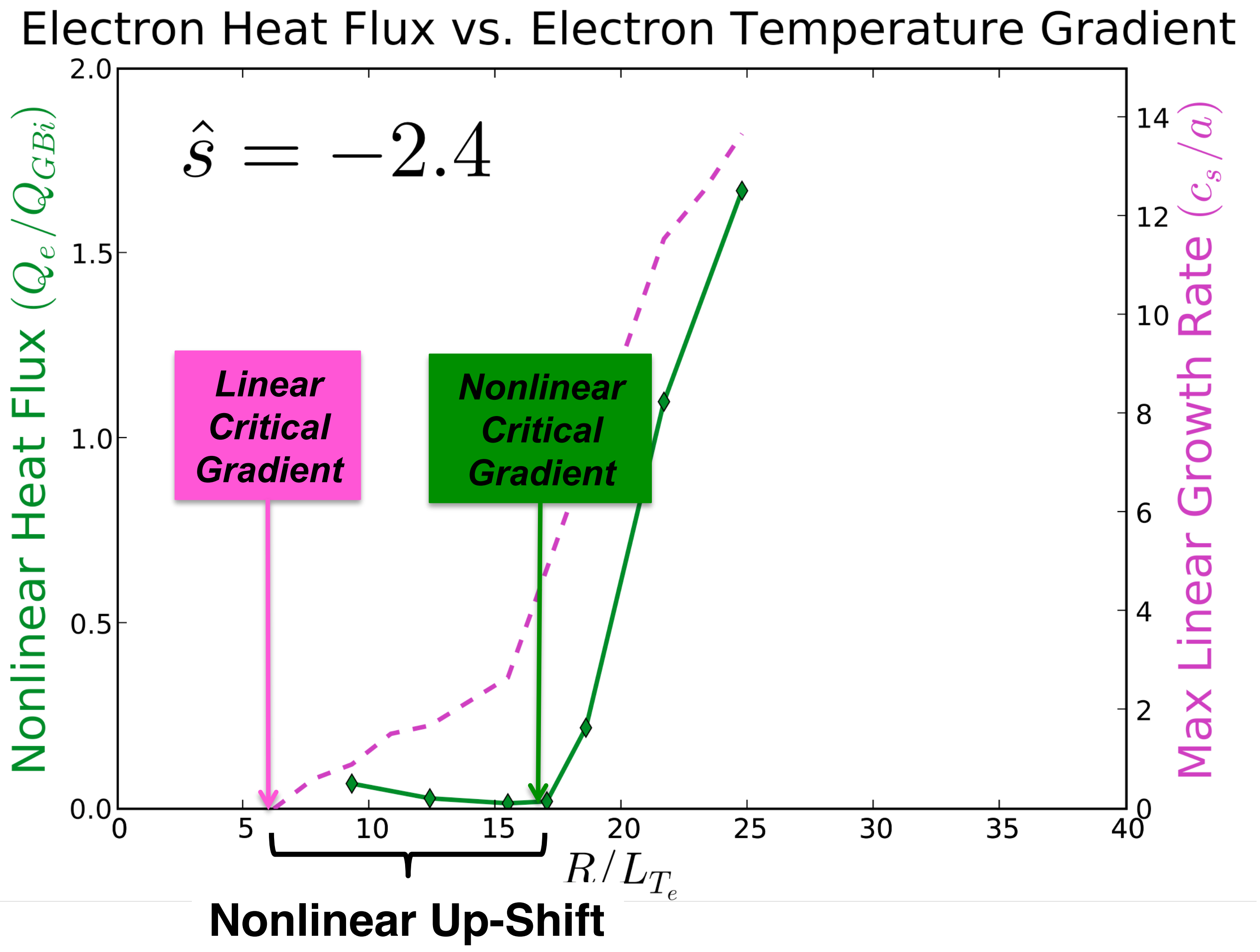
**** J. Candy and E.A. Belli, GYRO Technical Guide, General Atomics Report GA-A26818 (2010).***

Numeric Details

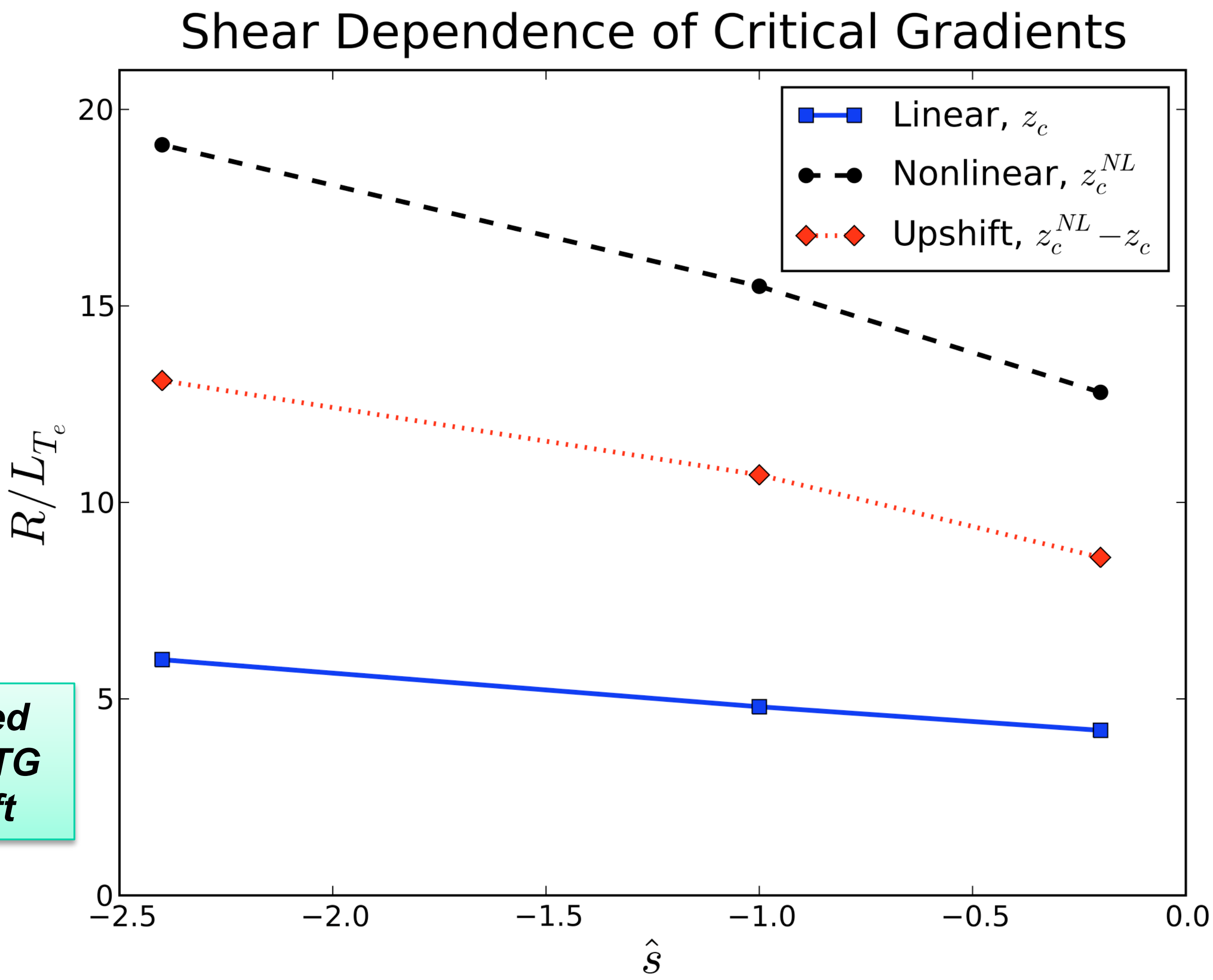
- All species gyrokinetic: electrons, deuterium
- 22 points per passing particle orbit
- 12 energy, 24 pitch angle grid points
- 24 toroidal modes
- Electron gyro-radius radial grid resolution

$$
\begin{aligned}
L_x \times L_y &= 4.26 \times 2.4\rho_s \qquad & k_\theta \rho_s &= [2.618, 60.21] \\
&= 255 \times 144\rho_e \qquad & k_\theta \rho_e &= [0.043, 1.004]
\end{aligned}
$$

The Nonlinear Up-Shift is very large for baseline negative shear.



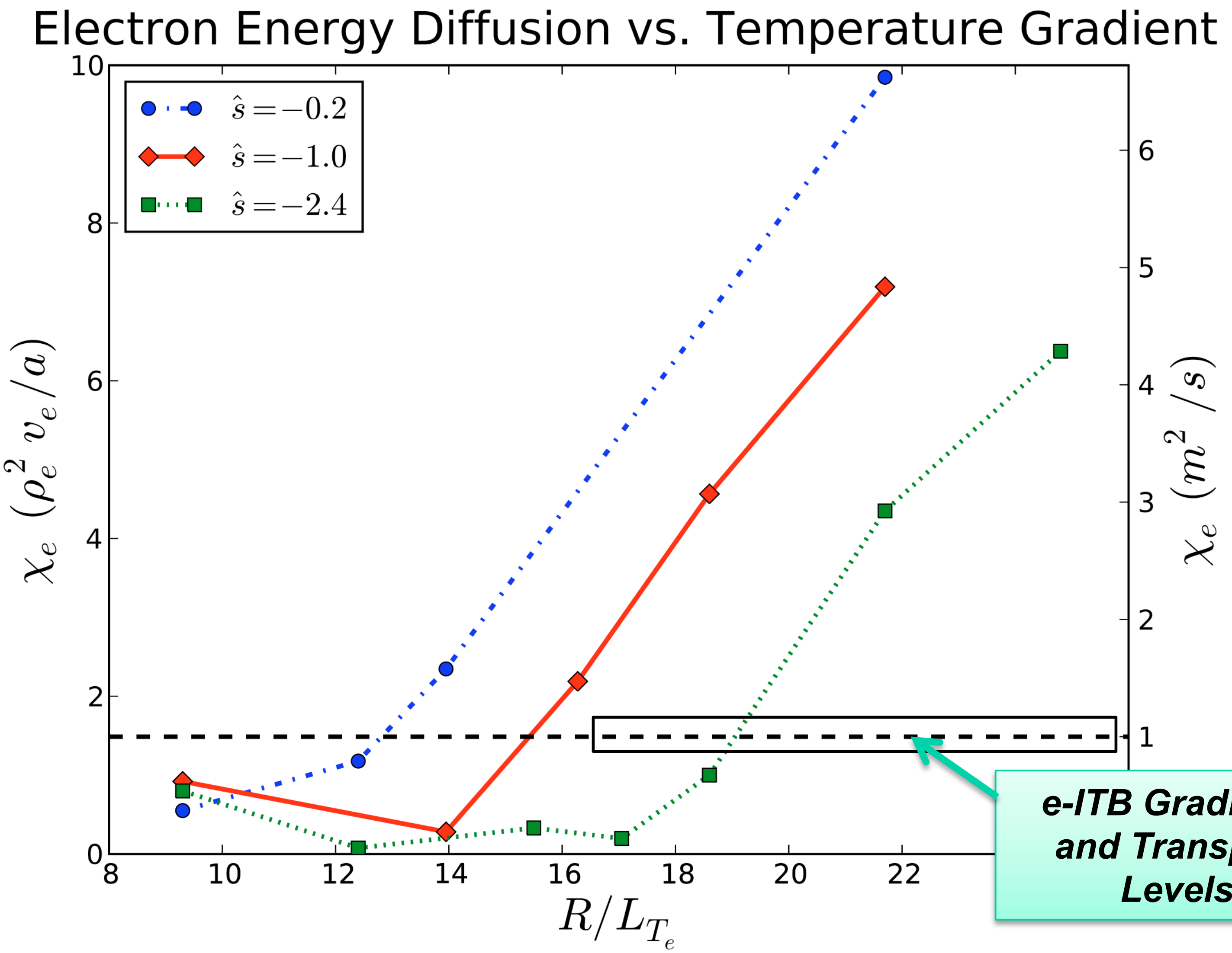
The up-shift strength depends upon magnetic shear.



Reversed Shear ETG Up-shift

Dimits ITG Up-shift

Transport Threshold Increases With Reversed Shear



e-ITB Gradients and Transport Levels

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

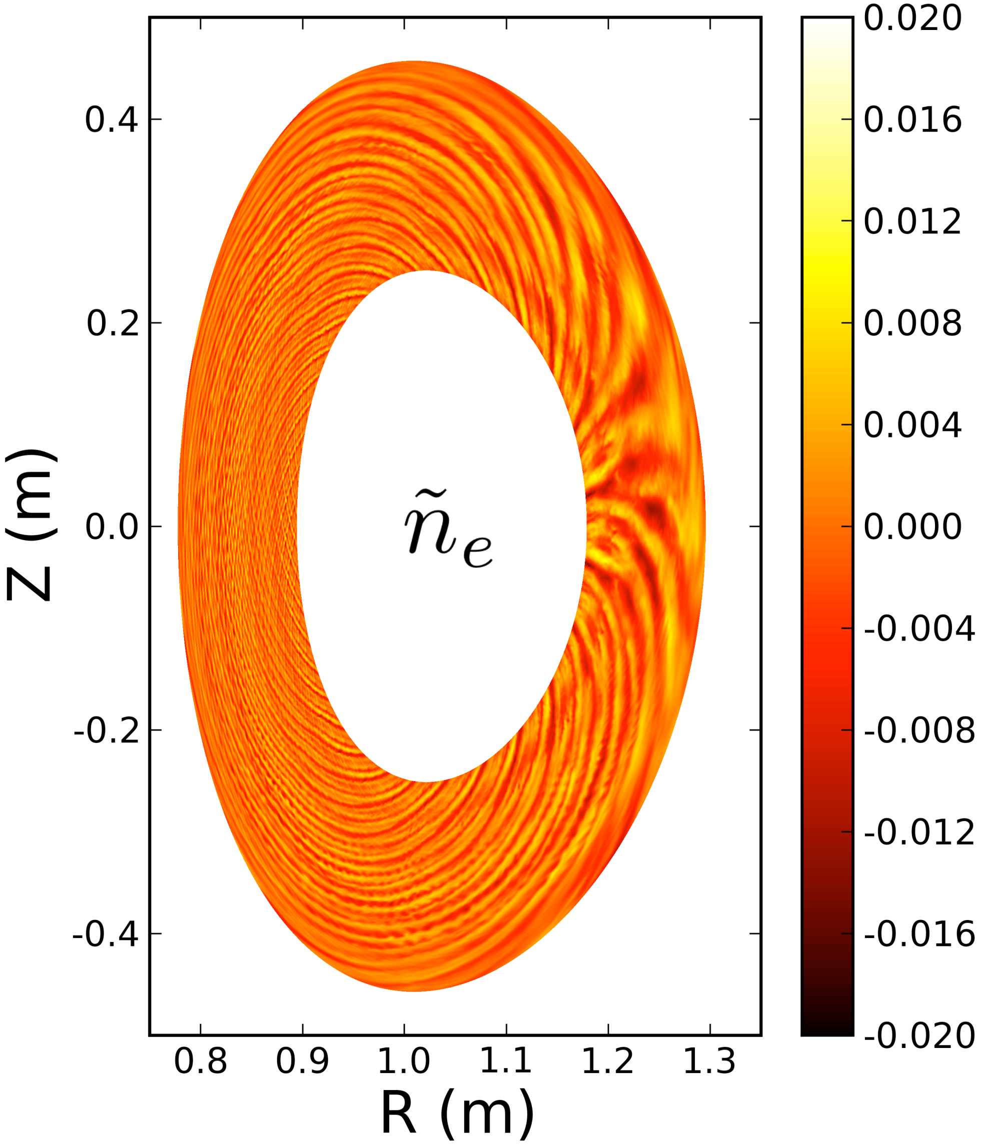
$$R/L_{T_e} \approx 9$$

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

$$max\,|\tilde{n}_e| = 1.3\%$$

Eddies Sheared, Saturate at Low Amplitude

Linearly Unstable, But Low Levels of Transport

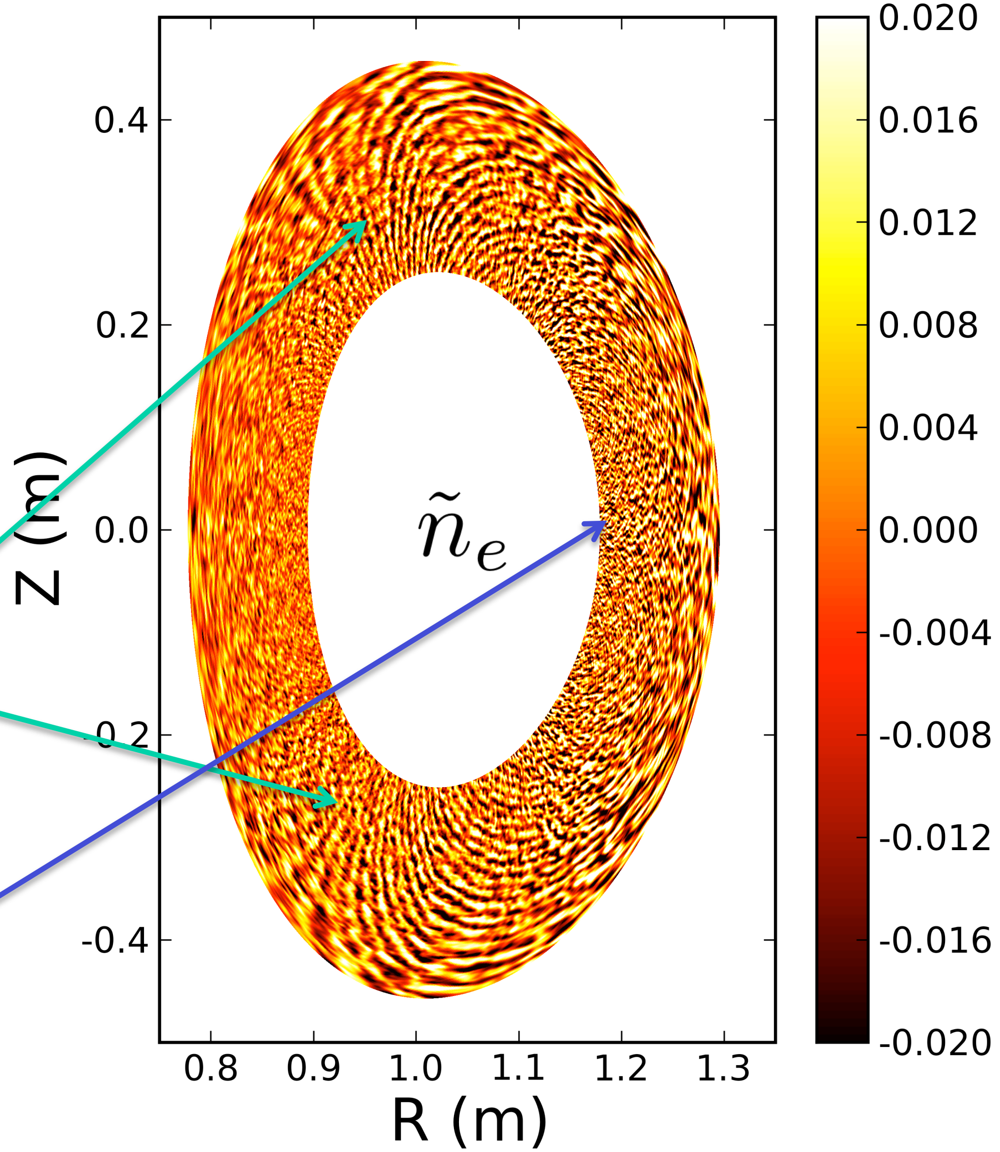


Above Nonlinear Critical Gradient Threshold: Streamers Not on Midplane, Large Transport

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

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

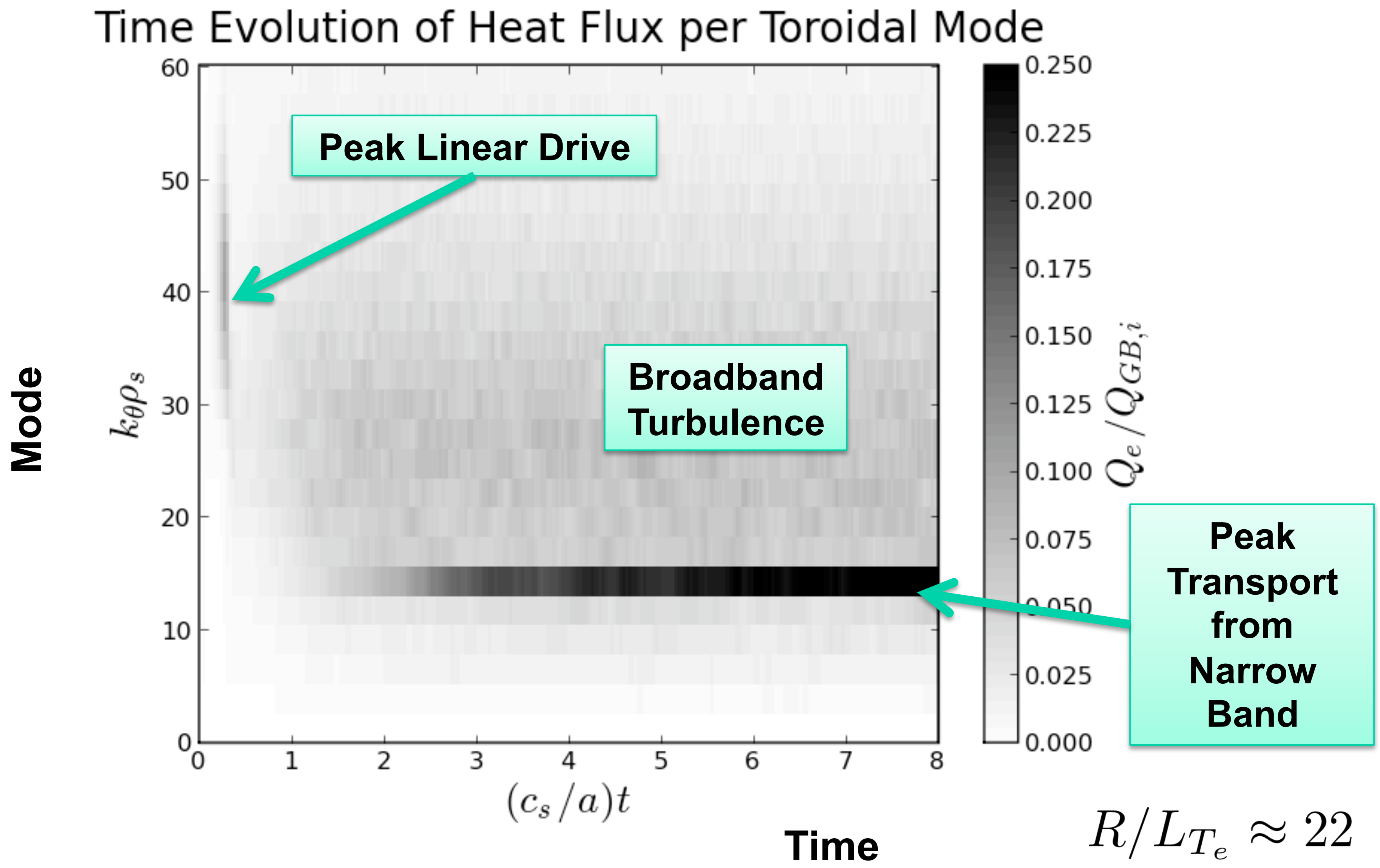
$$max\,|\tilde{n}_e| = 6.0\%$$



Radial Streamers out of Top and Bottom

Broadband Turbulence

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



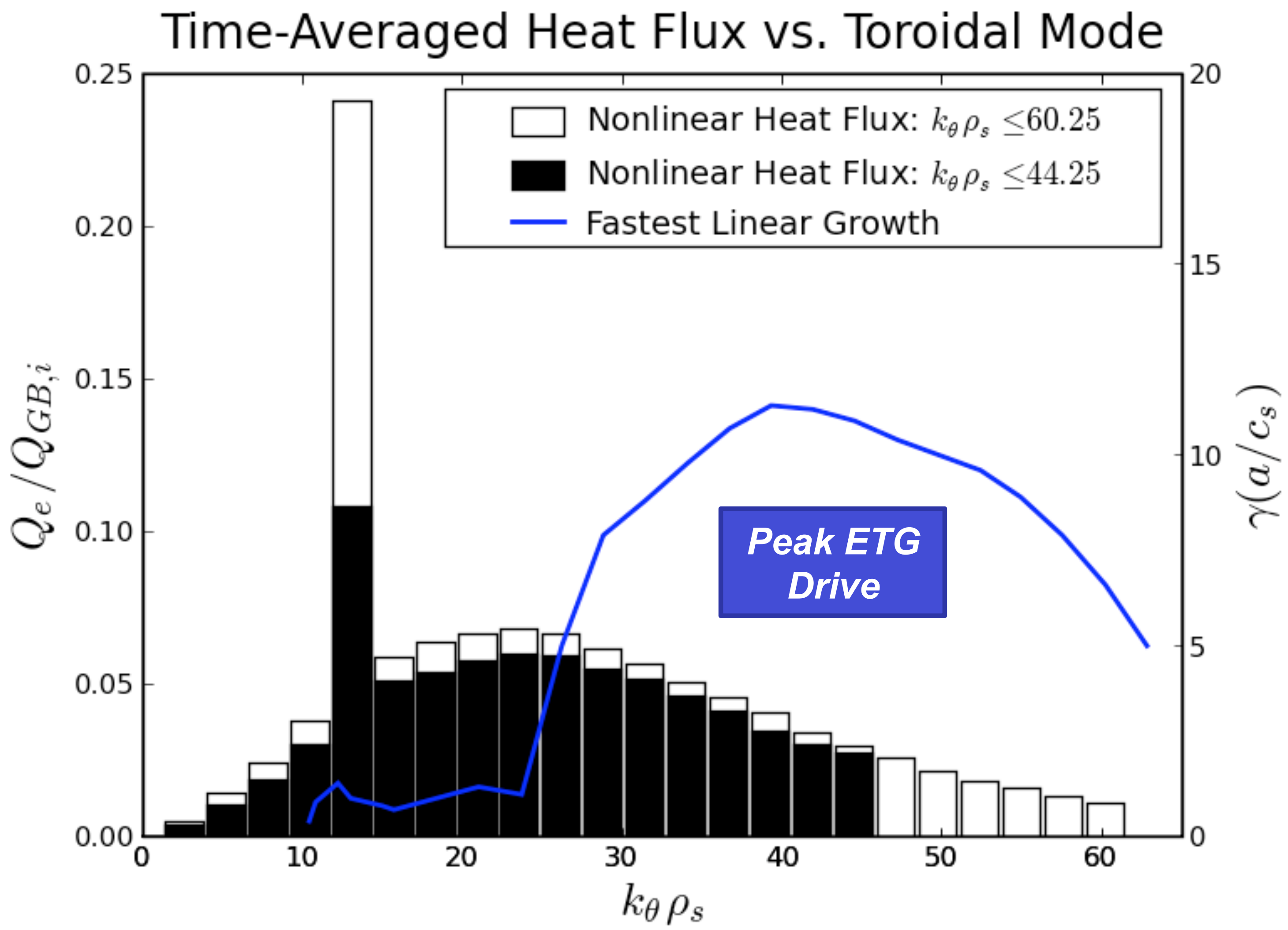
Peak Linear Drive

Broadband Turbulence

Peak Transport from Narrow Band

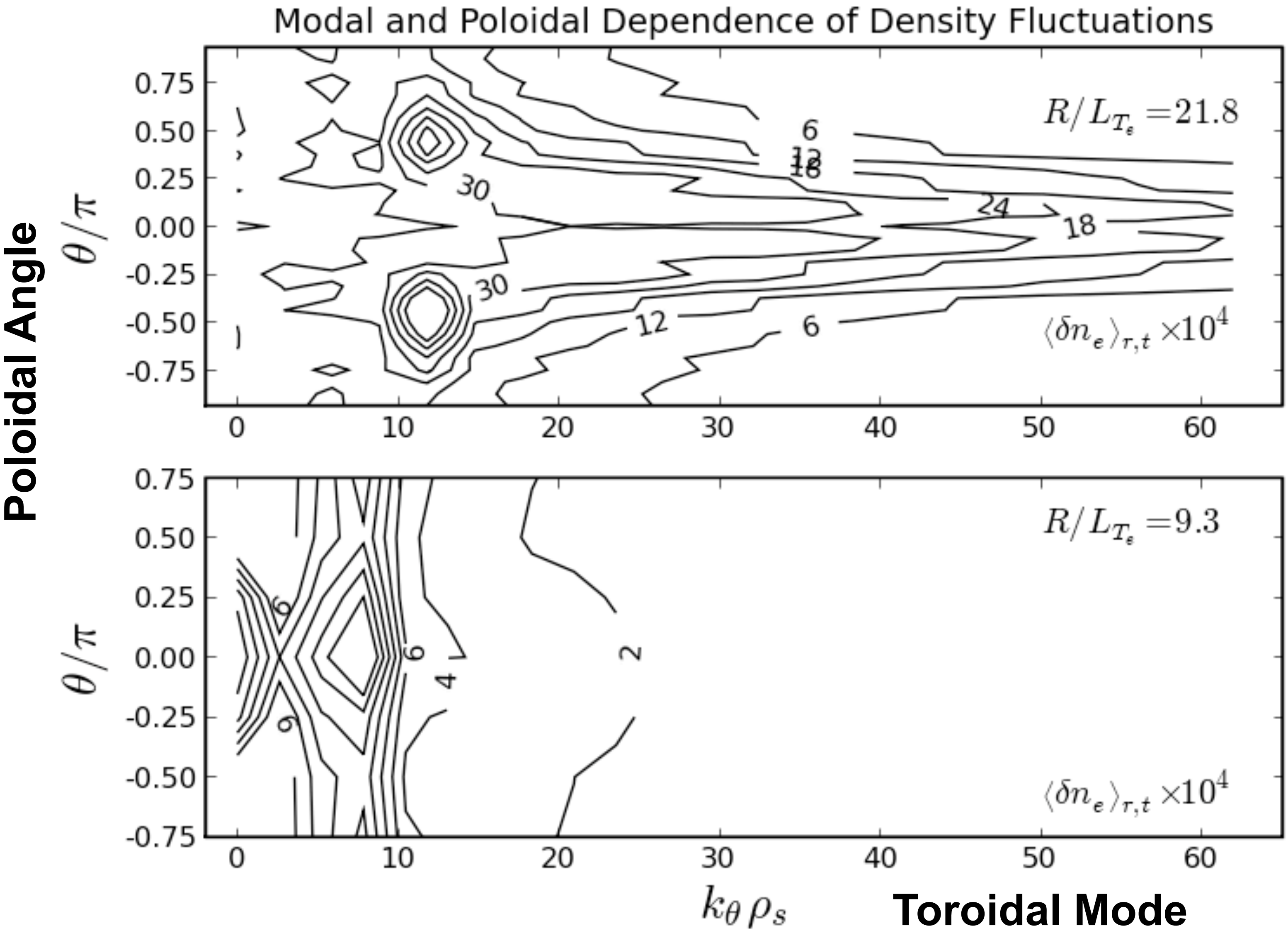
$R/L_{T_e} \approx 22$

Evidence of Energy Transfer to Narrow Band



- ***If include less of ETG drive, amplitude of spike drops.***

Strong transport peak comes from off-midplane streamers.



Above NL Critical Gradient

Below NL Critical Gradient

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 off midplane
  - xp planned for this run year
- Saturation relies on drive at $k_\theta \rho_s \sim 45$, transport at $k_\theta \rho_s \sim 15$
  - 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
    - No upshift found with adiabatic ion model: always low transport
- 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 energy flow is important.
- Additional 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

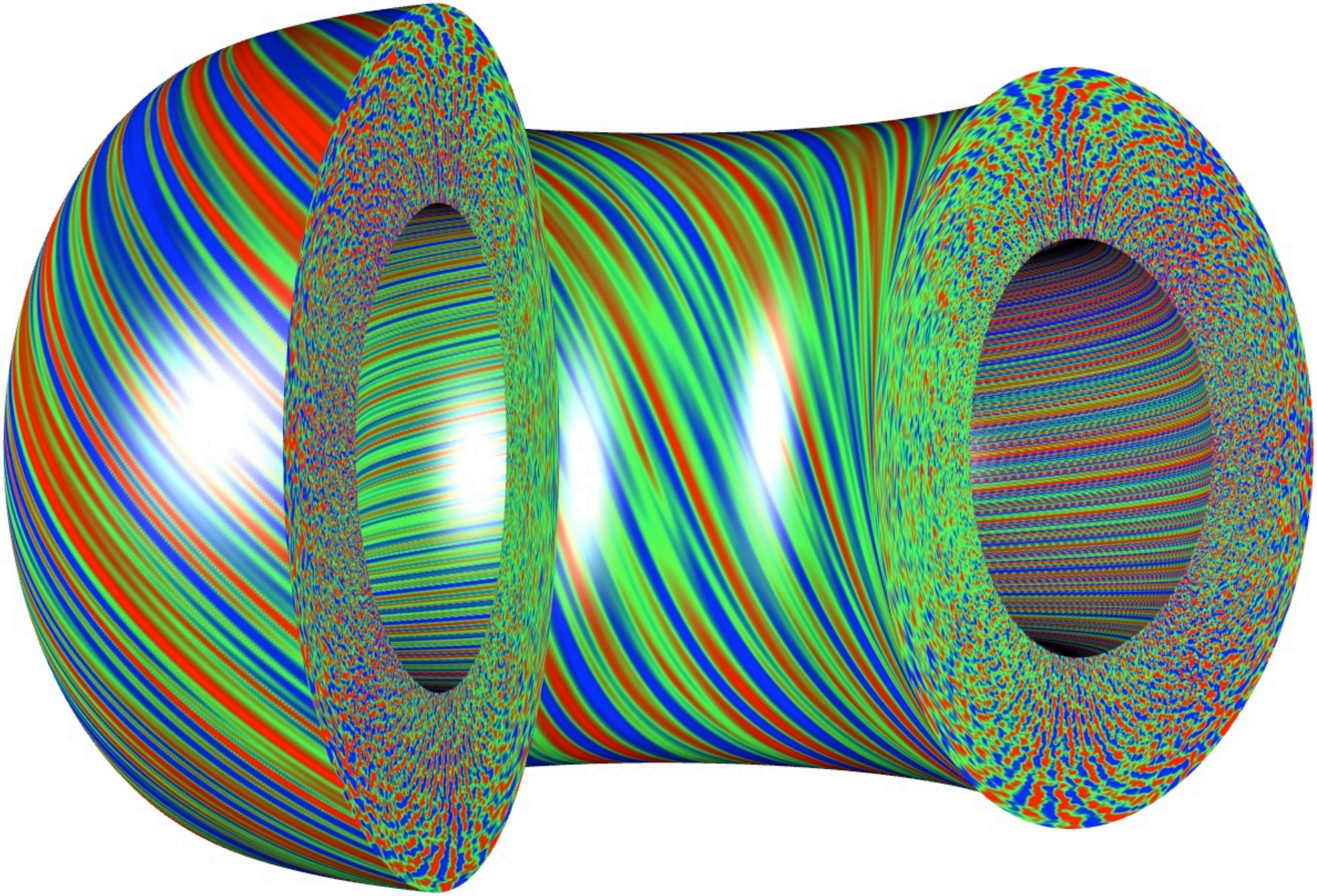
Acknowledgements

SciDAC Center for the Study of Plasma Microturbulence

National Center for Computational Sciences at Oak Ridge National Laboratory, DOE DE-AC05-00OR22725

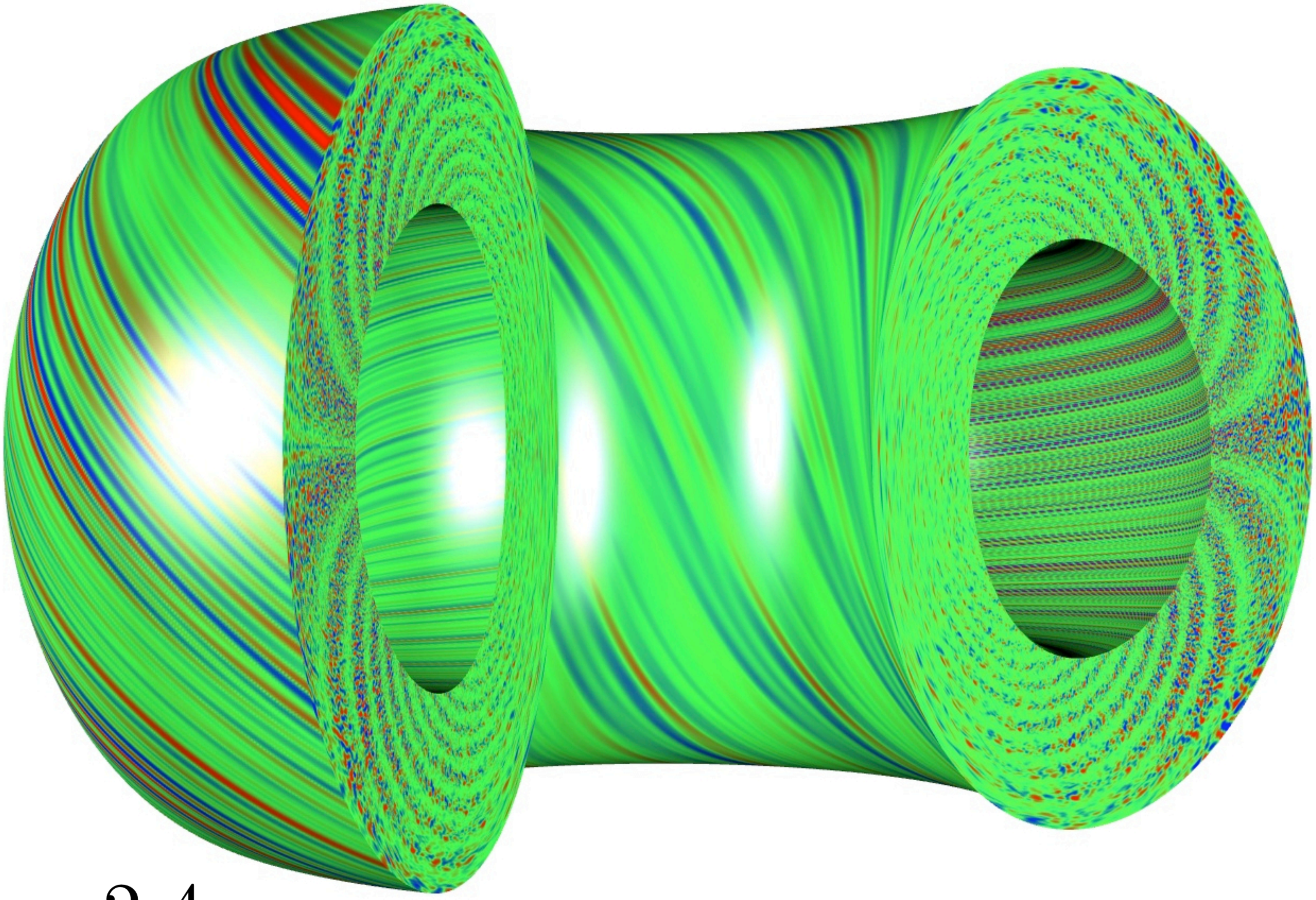
Princeton Plasma Physics Laboratory, Princeton University, DOE DE-AC02-09CH11466

Thank You



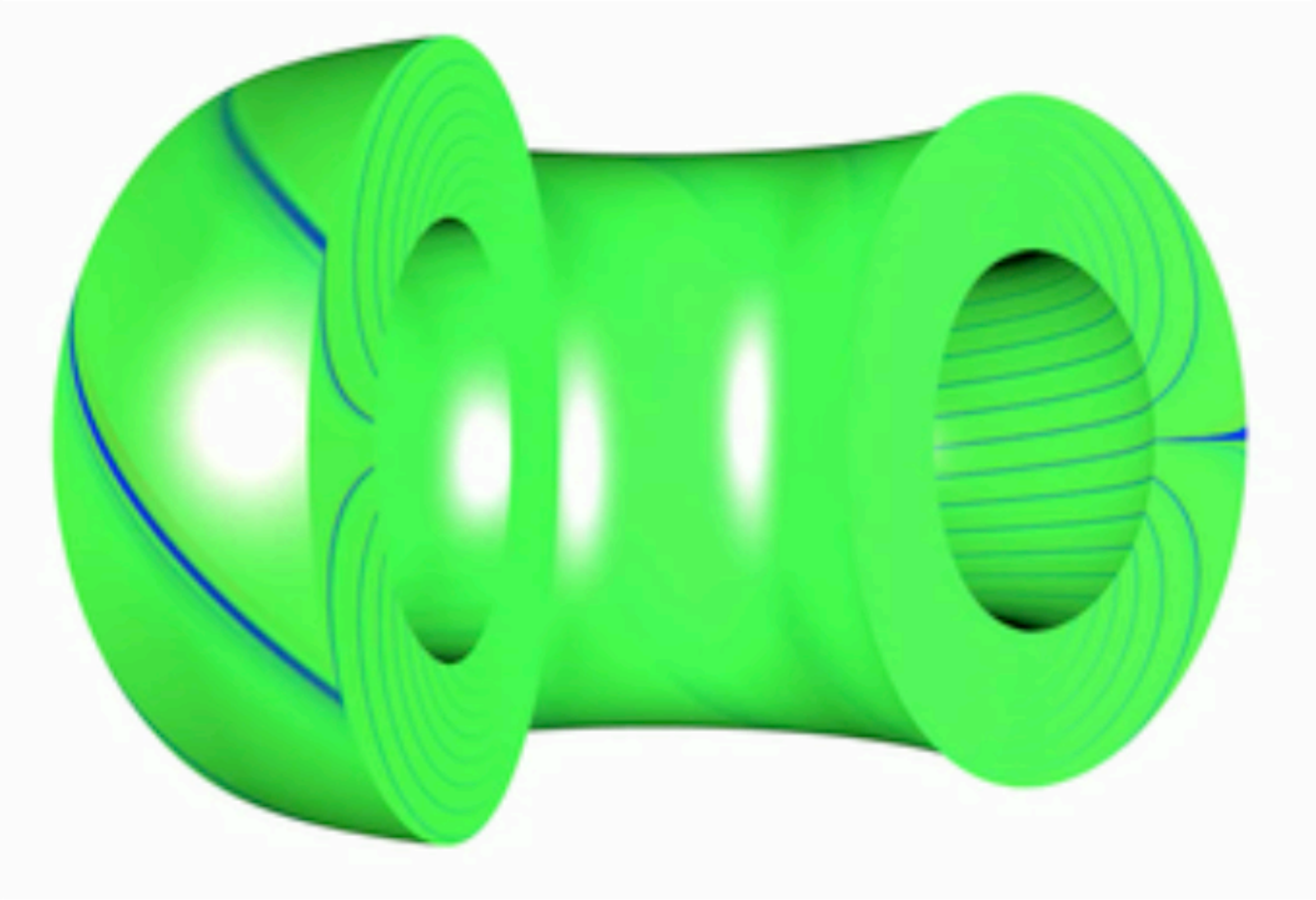
Extra Slides

Early Stage of Reversed Shear



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

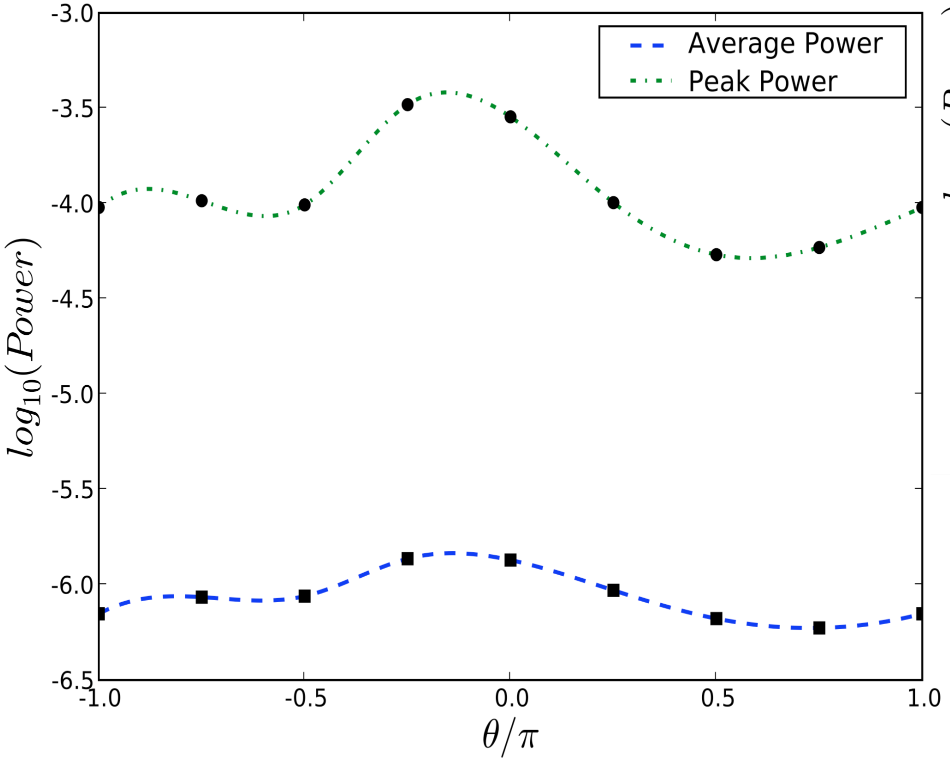
Density Fluctuation Evolution

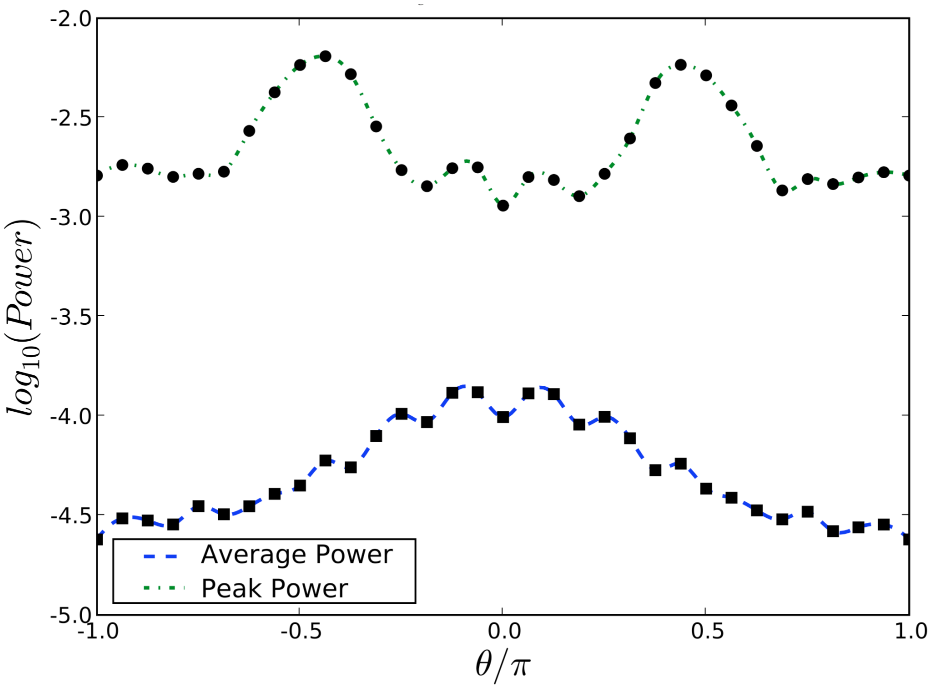


Movie at: http://www.pppl.gov/~jpeterso/documents/nstx_129354_LT14.mov

Poloidal Dependence of Power Spectra Amplitudes

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

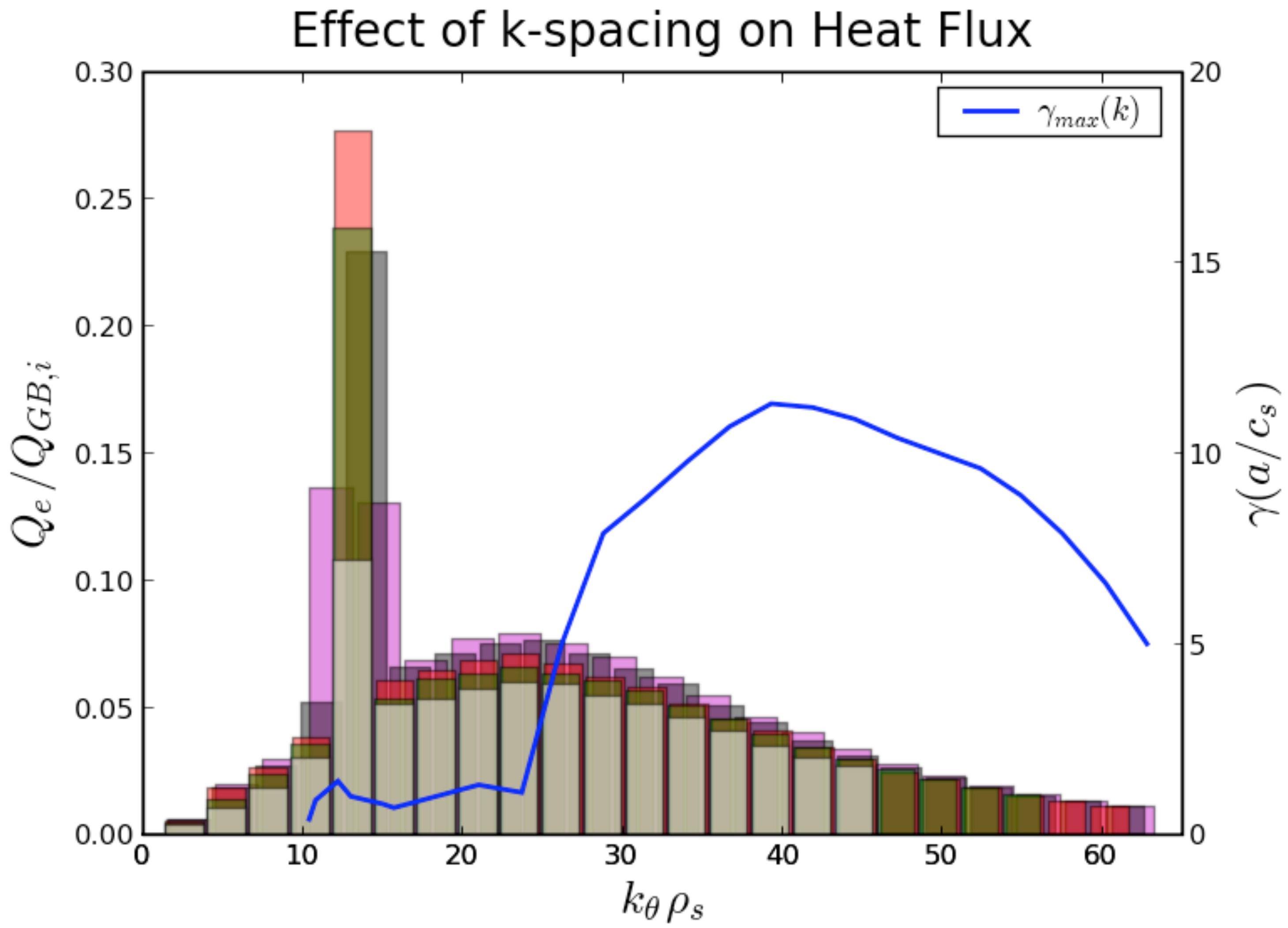




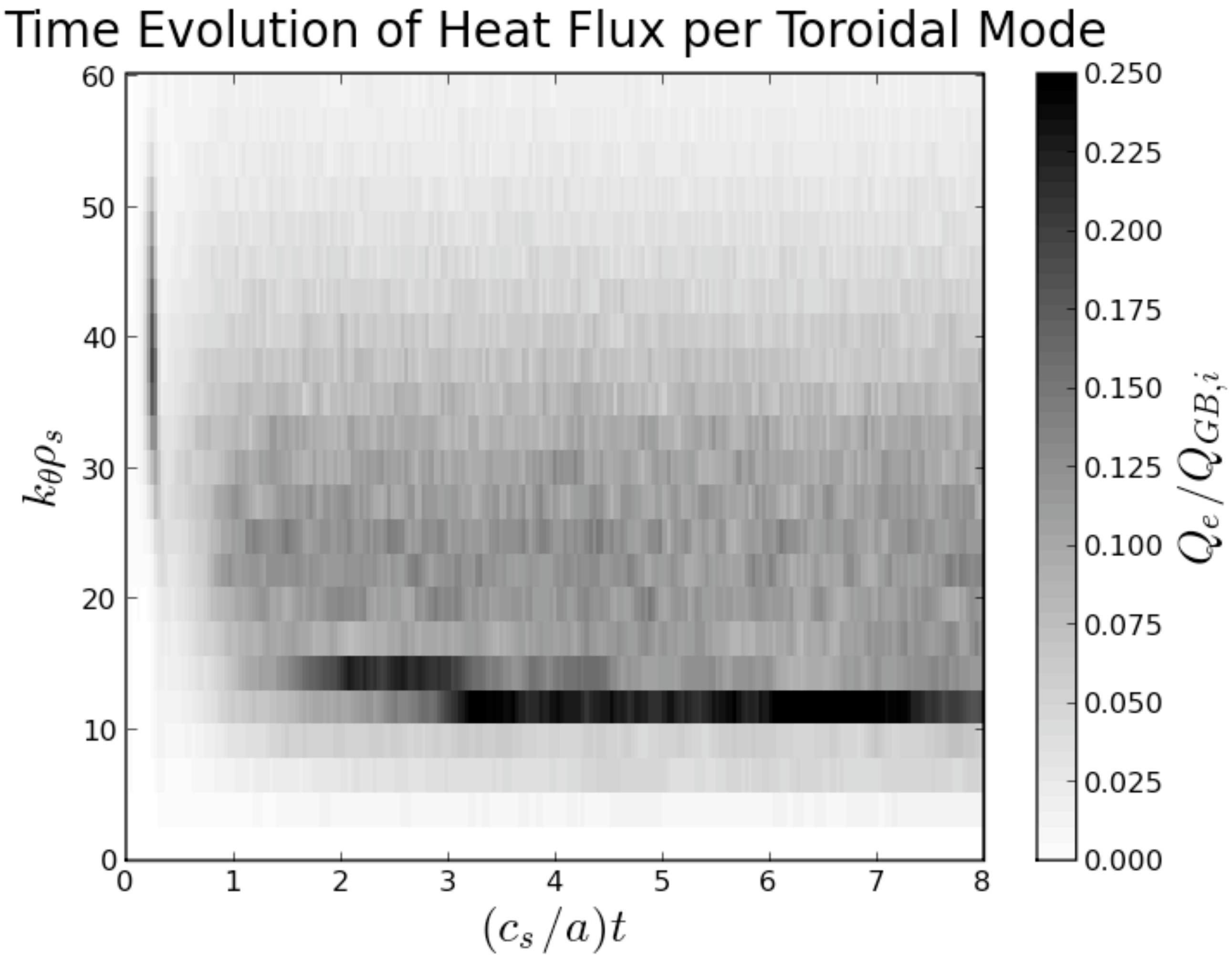
$$R/L_{T_e} \approx 22$$

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

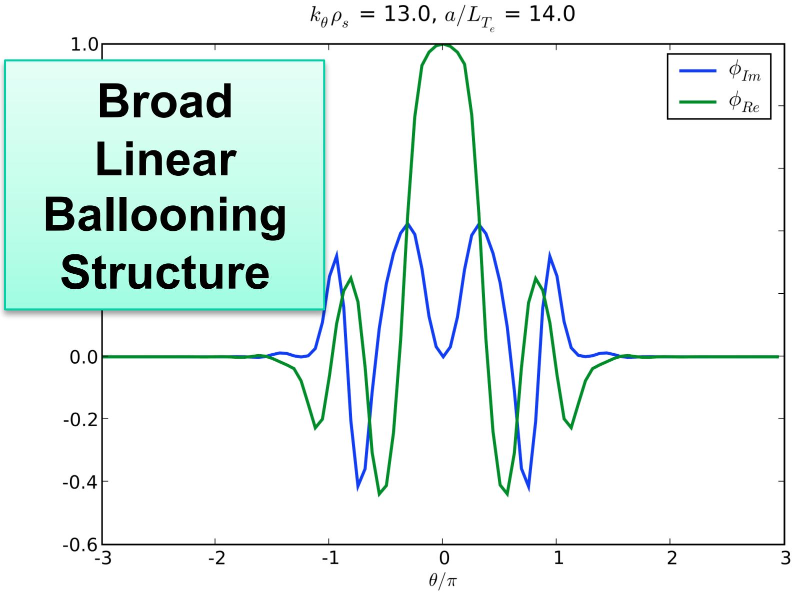
Box Variation Shows Robust Peak



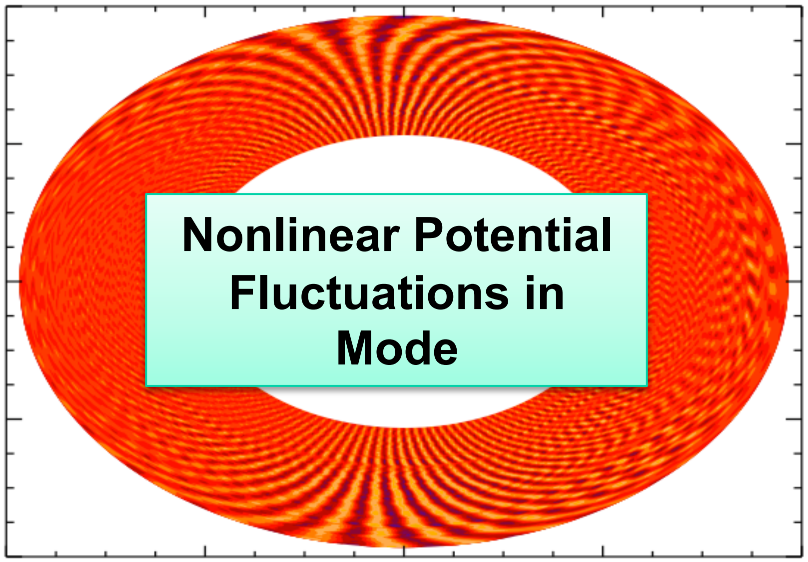
Spike, off-midplane streamers found at other gradients.



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



Broad Linear Ballooning Structure

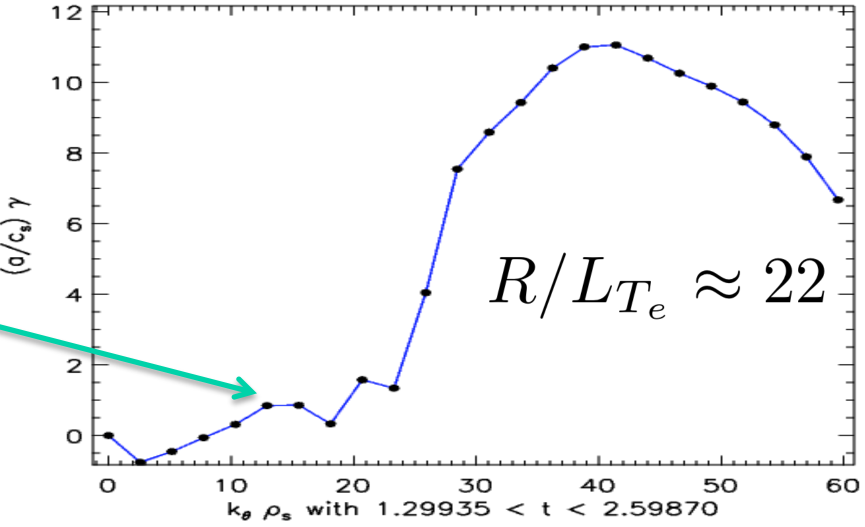


Nonlinear Potential Fluctuations in Mode

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

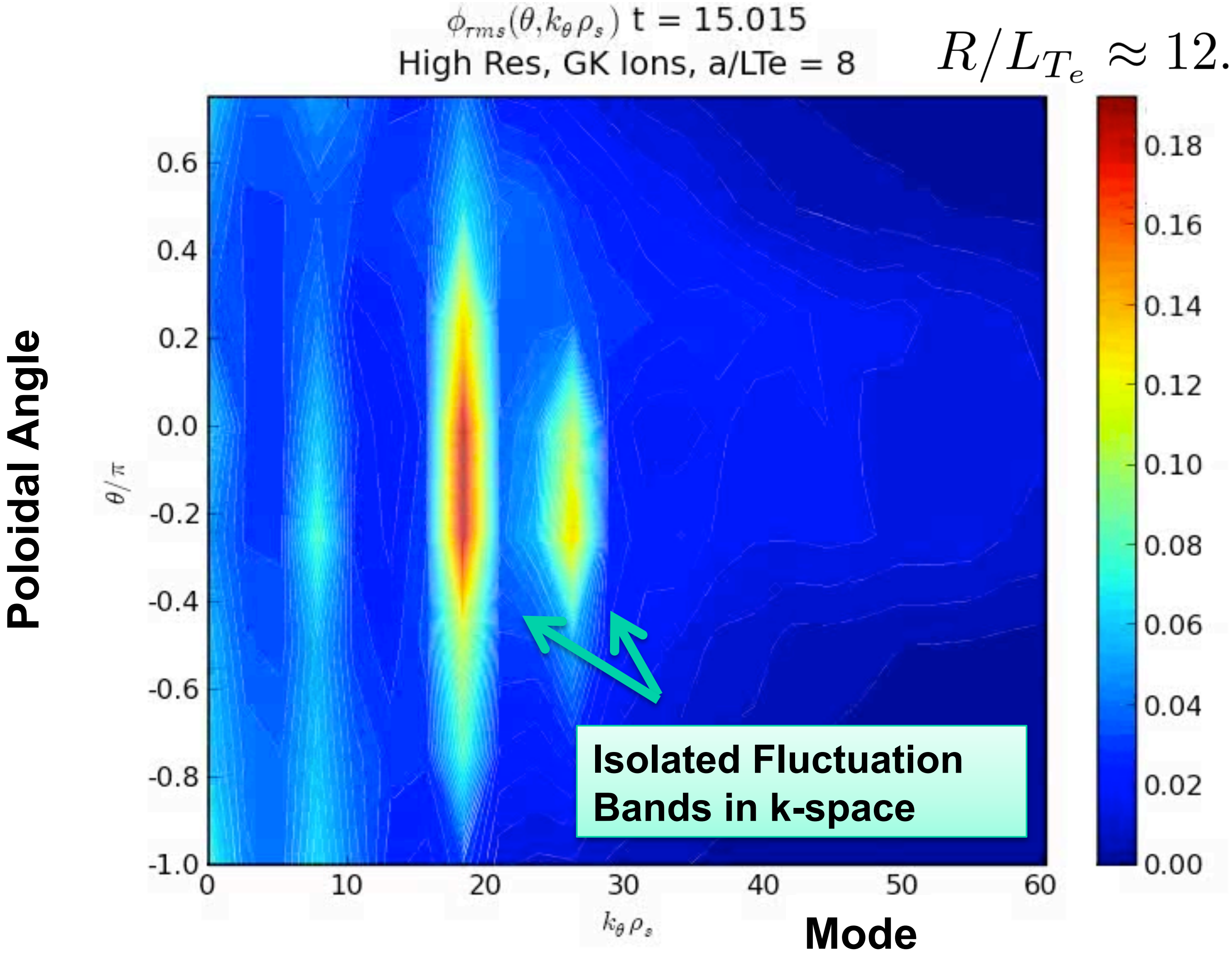
$$\omega = 25.19\ a/c_s$$

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



Low-transport modes centered on Midplane

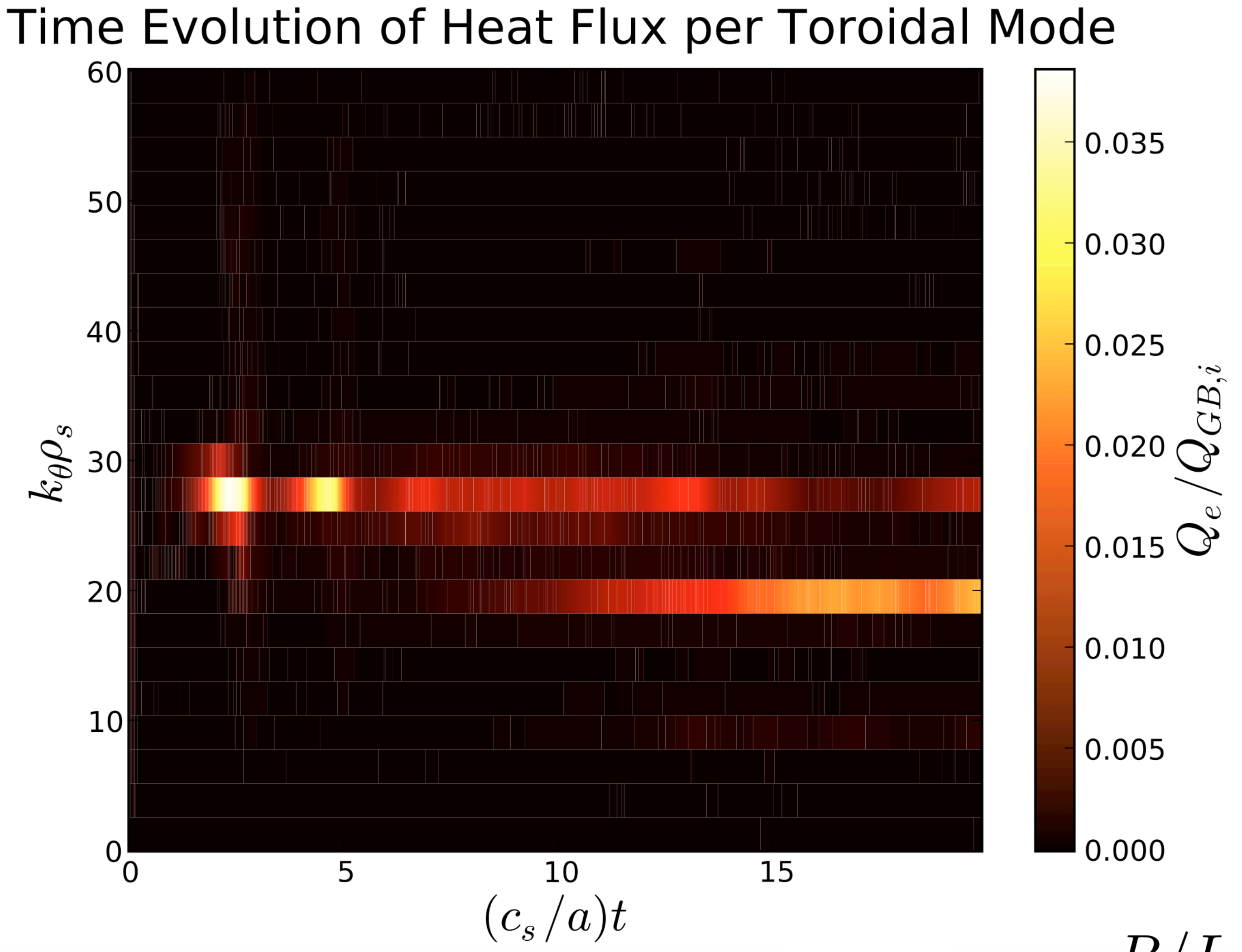
$R/L_{T_e} \approx 12.5$



Isolated Fluctuation Bands in k-space

Below nonlinear critical gradient, no broadband turbulence.

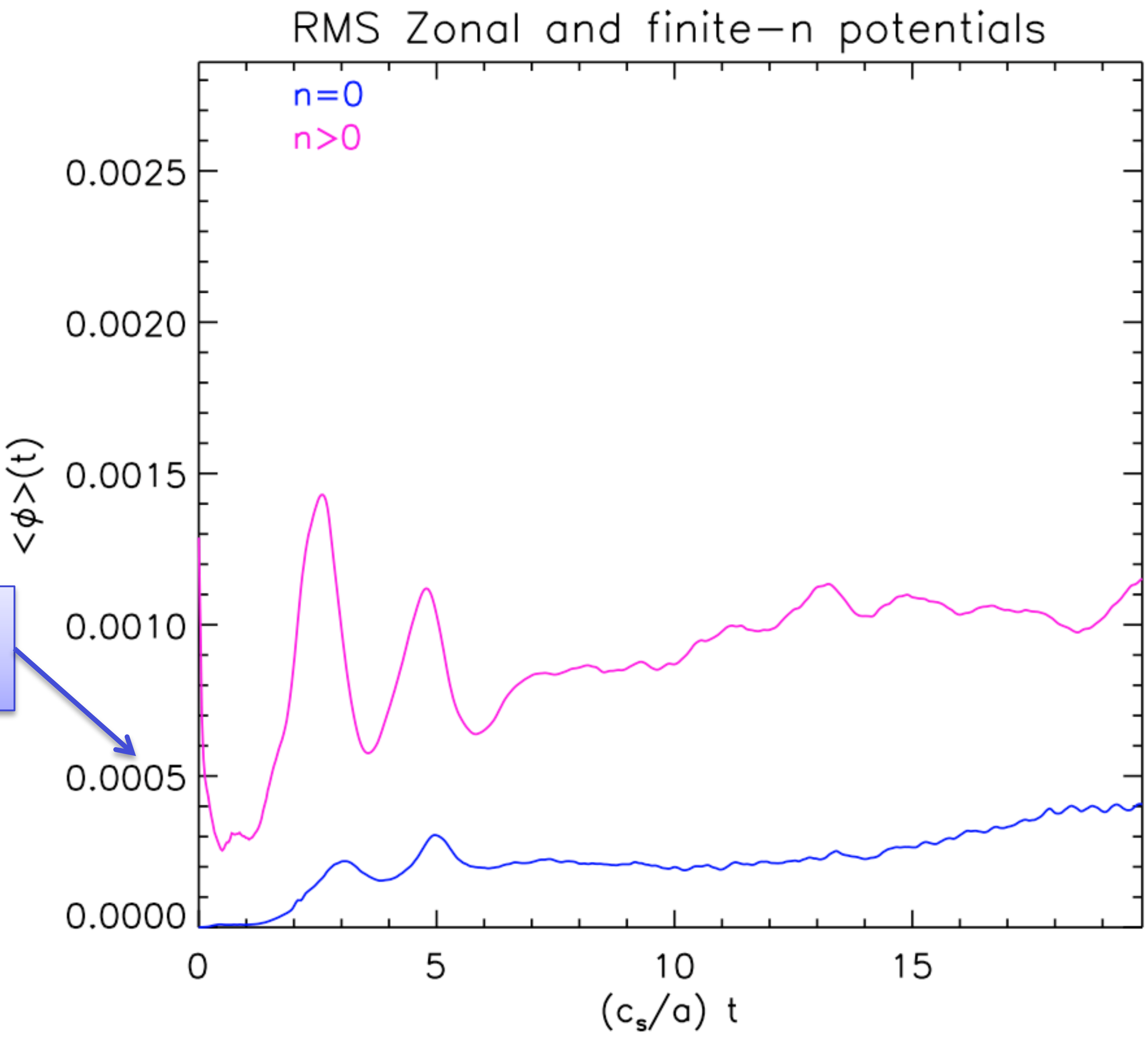
Mode



Time

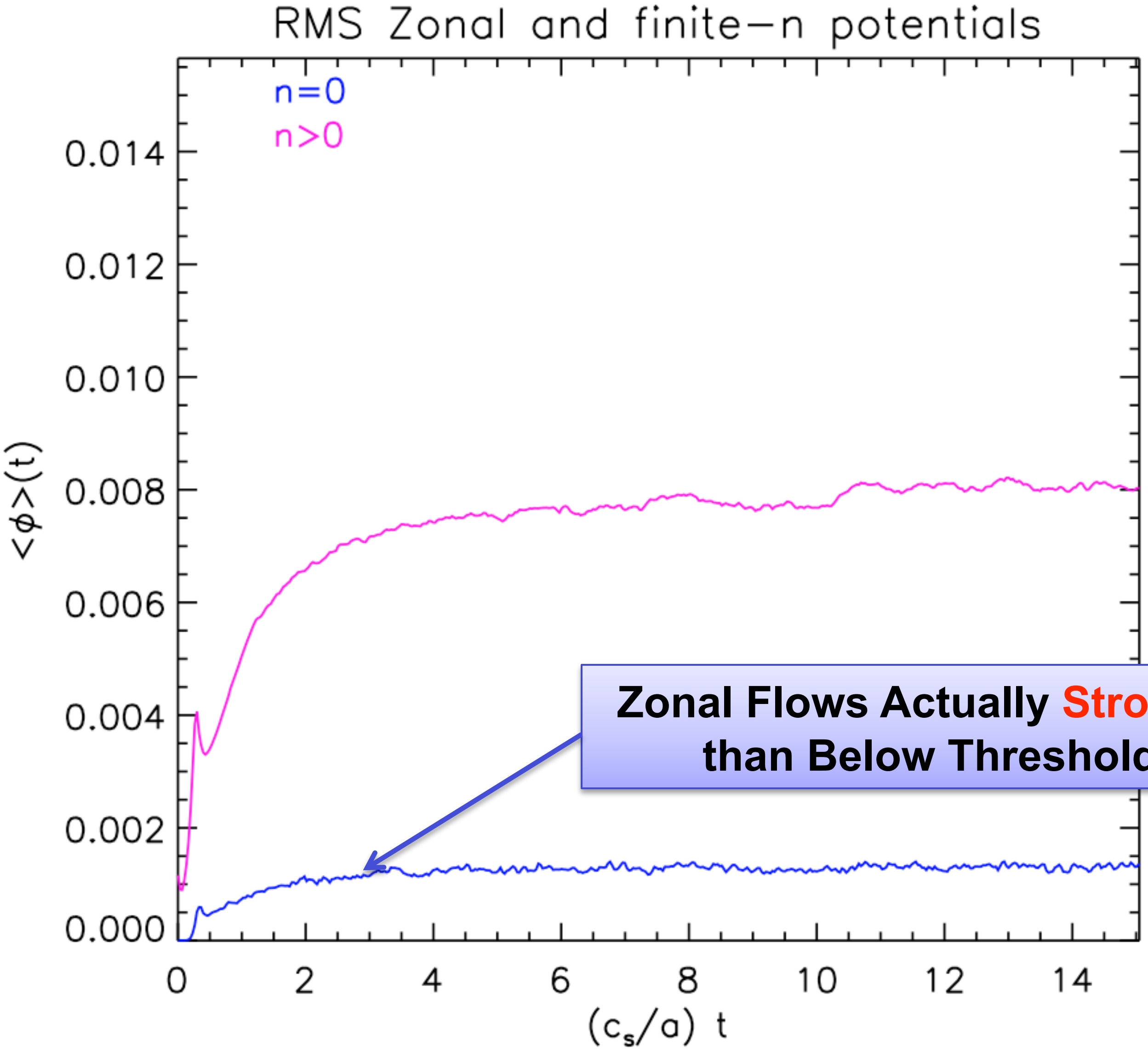
$$R/L_{T_e} \approx 12.5$$

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



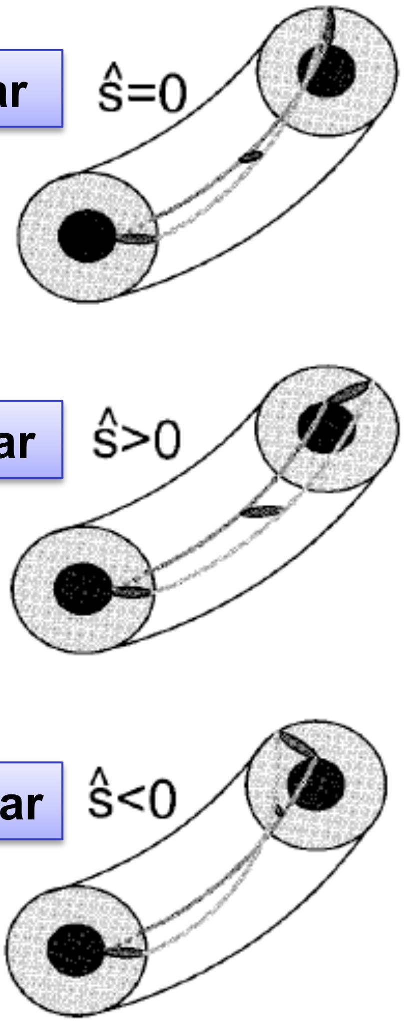
Low-magnitude

Above Nonlinear Critical Gradient, Quicker Saturation



Zonal Flows Actually Stronger than Below Threshold

The magnetic field shear can regulate turbulence.



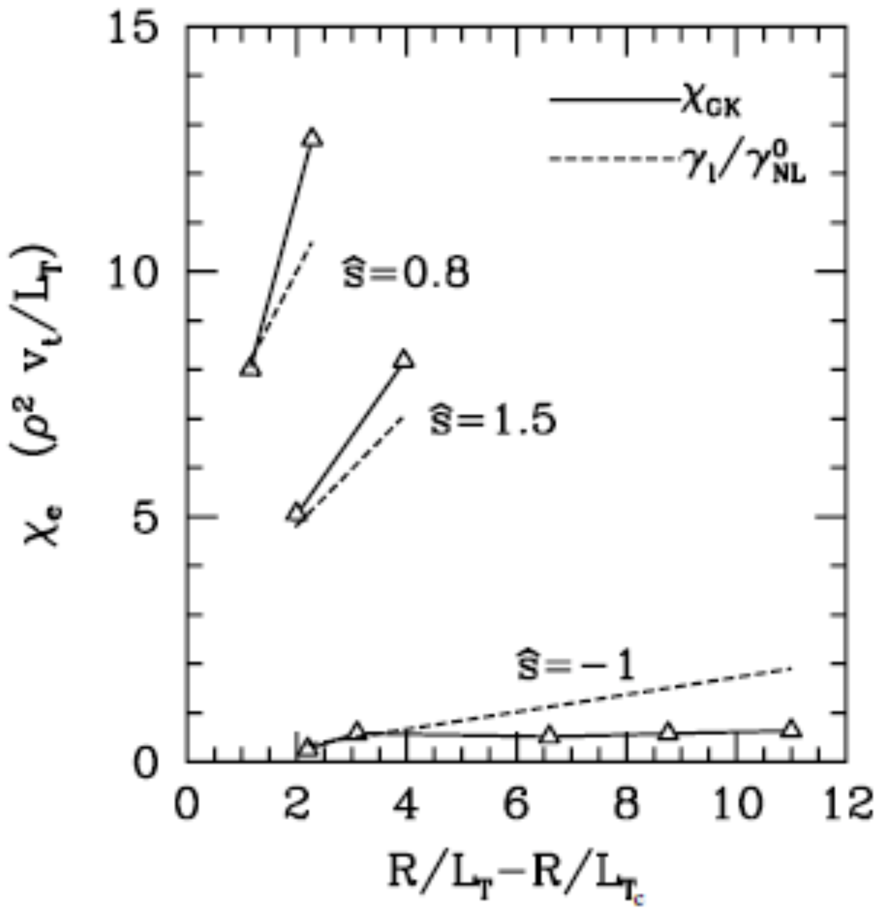
Zero Shear $\hat{s}=0$

Positive Shear $\hat{s}>0$

Negative Shear $\hat{s}<0$

Antonsen et al Phys. Plasmas (1996)

ETG Heat Diffusivity vs. Driving Gradient



Jenko and Dorland PRL (2002)