# TURBULENCE IN MAGNETICALLY CONFINED PLASMAS

## - LESSONS FROM 100 TERABYTES OF FLUCTUATION DATA -

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*University of Wisconsin-Madison*

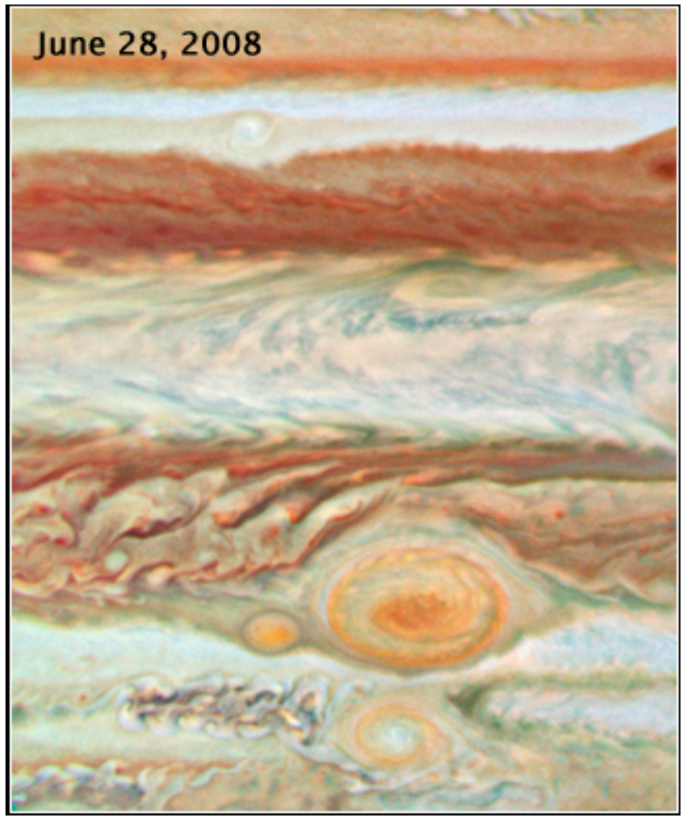
*54th Annual Meeting of the*
*American Physical Society-Division of Plasma Physics*

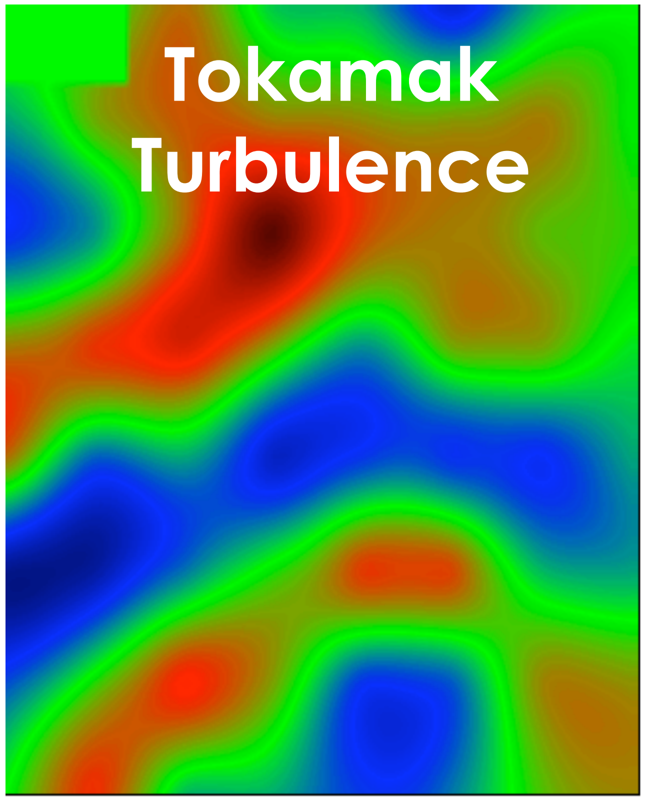
*Providence, Rhode Island*
*October 29-November 2, 2012*

THE UNIVERSITY *of* WISCONSIN
MADISON

# Plasma Turbulence is a Compelling Scientific Problem and a Challenge for the Development of Fusion Energy

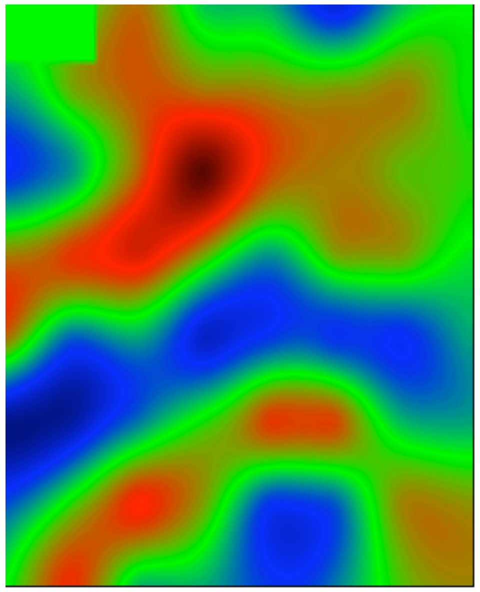
- **Highly complex and strongly nonlinear dynamics across multiple spatial and temporal scales**
  - Strong connection to related research fields
  - Magnetized plasma turbulence is largely 2D in nature
  - Multiple "fluids" (electron, ion, impurity)
- **Understanding turbulence and turbulent transport is critical to the development of fusion energy systems:**
  - Drives transport of energy, particles & momentum
  - Sets global energy confinement time
  - Determines size (and cost) of fusion reactors


June 28, 2008



# Goals for Plasma Turbulence Research

- **Understand the behavior, properties and dynamics of turbulence in magnetically confined plasmas**
  - What is the nature of fully saturated turbulence?
  - How does it affect plasma performance?
  - Can we control turbulence?
- **Develop experimentally validated turbulent transport simulations**
  - Essential to extrapolating our understanding to fusion energy systems

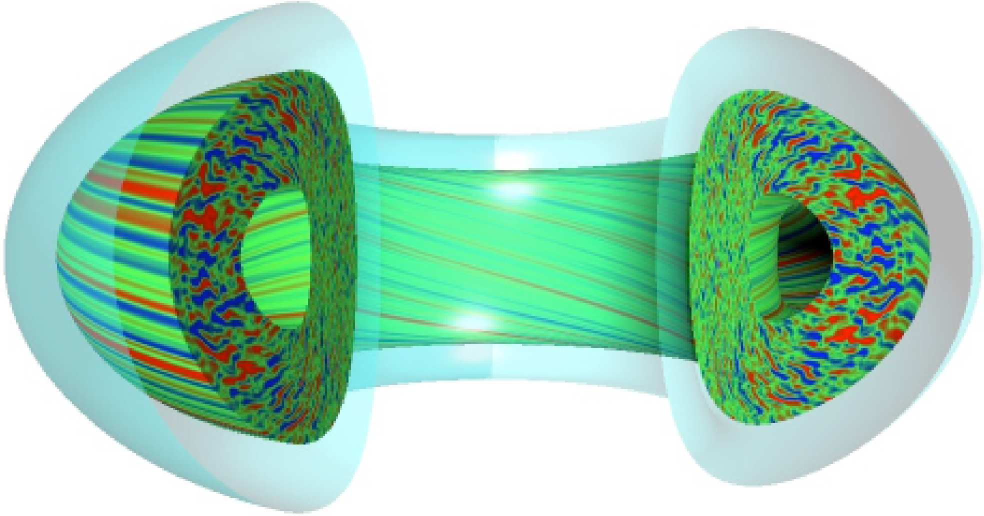


**Experiment**

**Analytic Theory**

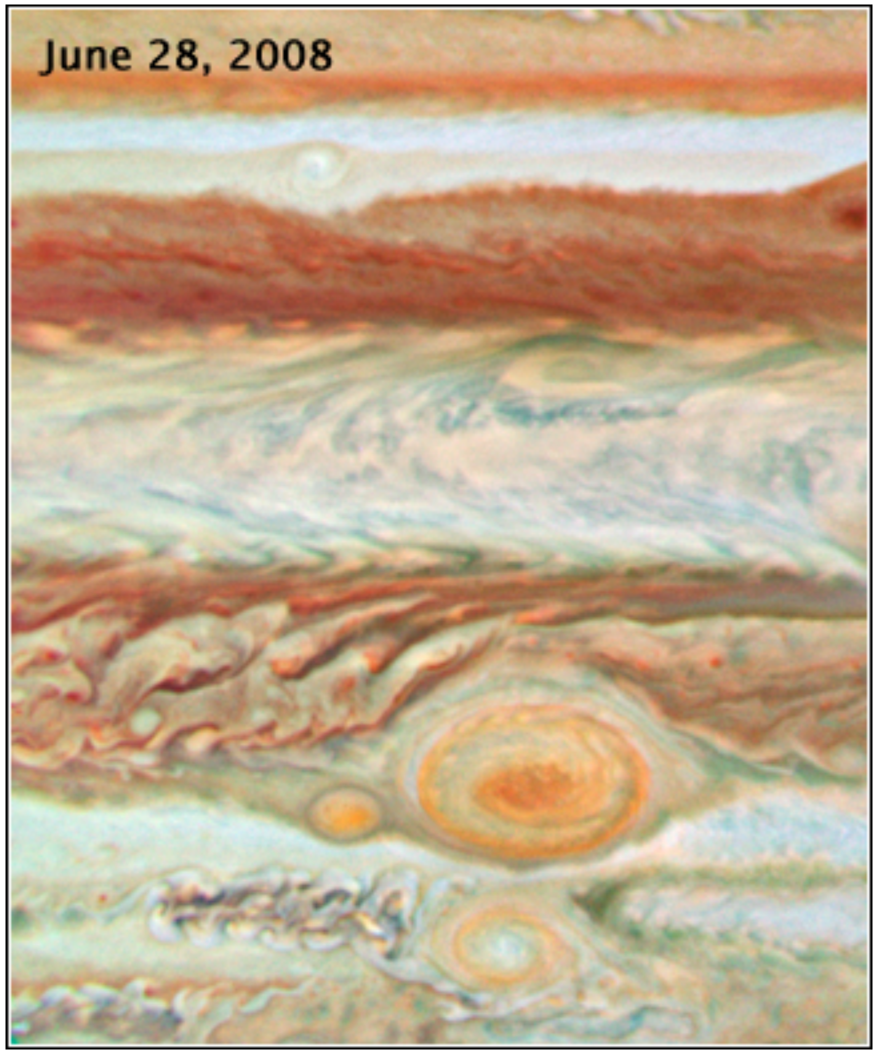
$$\frac{\partial \bar{f}}{\partial t} + \left(v_{\parallel}\hat{\mathrm{b}} + \mathrm{v}_E + \mathrm{v}_d\right)\cdot\nabla\bar{f} + \left(\frac{q}{m}E_{\parallel} - \mu\nabla_{\parallel}B + v_{\parallel}\left(\hat{\mathrm{b}}\cdot\nabla\hat{\mathrm{b}}\right)\cdot\mathrm{v}_E\right)\frac{\partial\bar{f}}{\partial v_{\parallel}} = 0$$

**Nonlinear Simulations**



# Turbulence in Geophysical Fluids and Magnetized Plasmas Exhibit a Many Common Physical Features

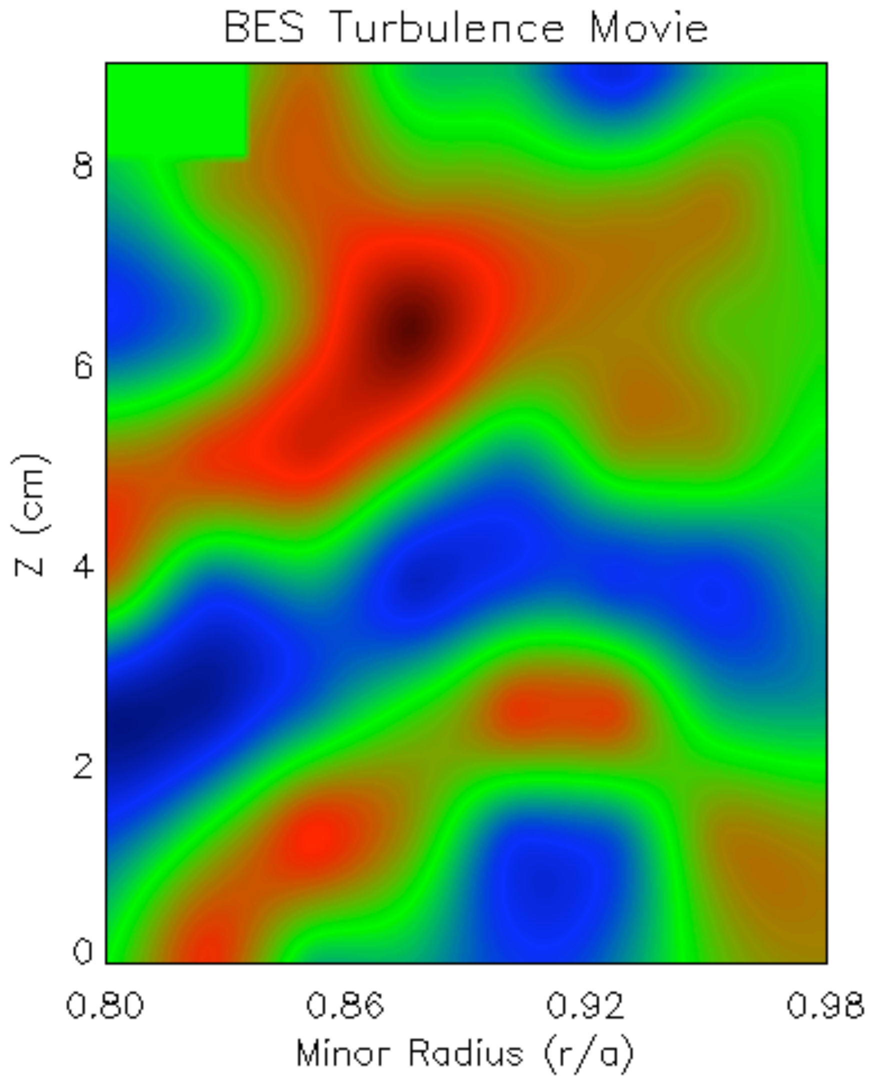
## Planetary Atmosphere



**2-Dimensional**
**∇P-driven turbulence**

**Inverse Energy Cascades**

## Plasma Turbulence



DIII–D (University of Wisconsin/General Atomics), 142369,1500ms

**Coriolis Force ⟷ Rotation Source ⟷ Lorentz (vxB)**
**Equatorial (Solar) ⟷ Energy Source ⟷ Central (Ohmic, NB, Fusion)**
**Polar Regions ⟷ Energy Sink ⟷ Divertor**
**Charney-Okukhov ⟷ Equations ⟷ Hasegawa-Mima**
**Rossby Waves ⟷ Waves ⟷ Drift Waves**
**Jet Stream ⟷ Large-Scale Flows ⟷ Zonal Flows**

# Outline and Major Themes

- **Introduction, Motivation and Measurement of Turbulence**
- **Turbulence Characteristics Consistent with Theory**
  - Spatial structure exhibit strong radial-poloidal asymmetry
  - Relation to radial transport
  - Saturation via self-driven Zonal Flows and dissipation
- **Behavior and Dependence on Plasma Transport Parameters**
  - Amplitudes and spatiotemporal characteristics scale with gyrokinetic parameters (ion gyroradius, gyrokinetic time scale, $a/c_s$)
  - Dominant instabilities depend on plasma collisions
  - Consistent with predicted linear instabilities
- **Testing, Challenging and Validating Nonlinear Simulations**
  - Quantitative comparisons show generally good agreement
  - Cases of disagreement leading to refinement of physics models
- **Controlling turbulence offers potential to improve performance**

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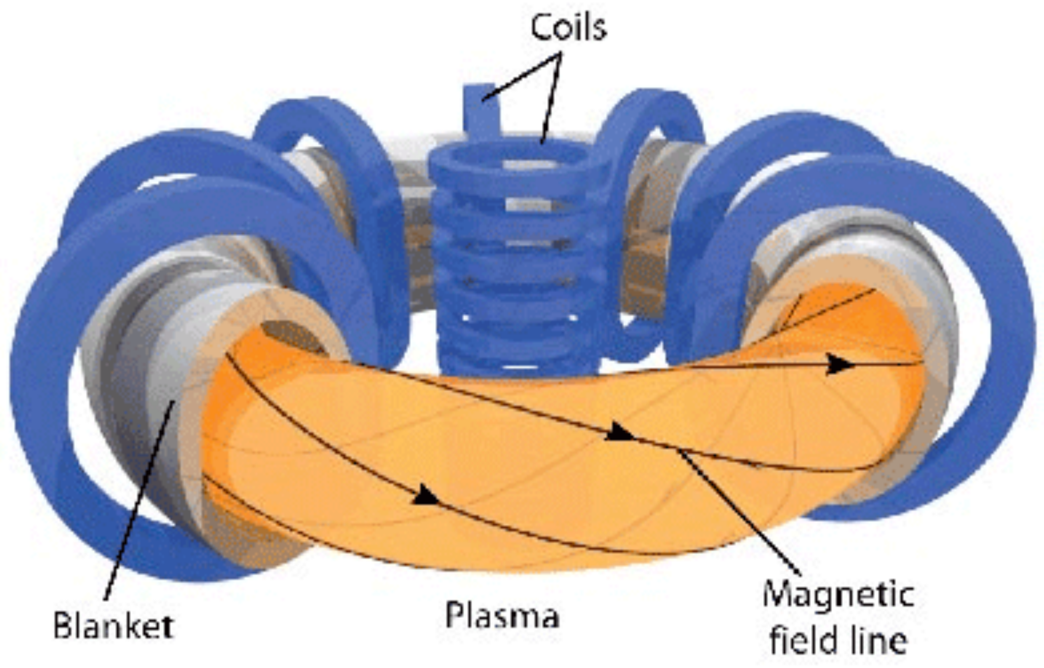
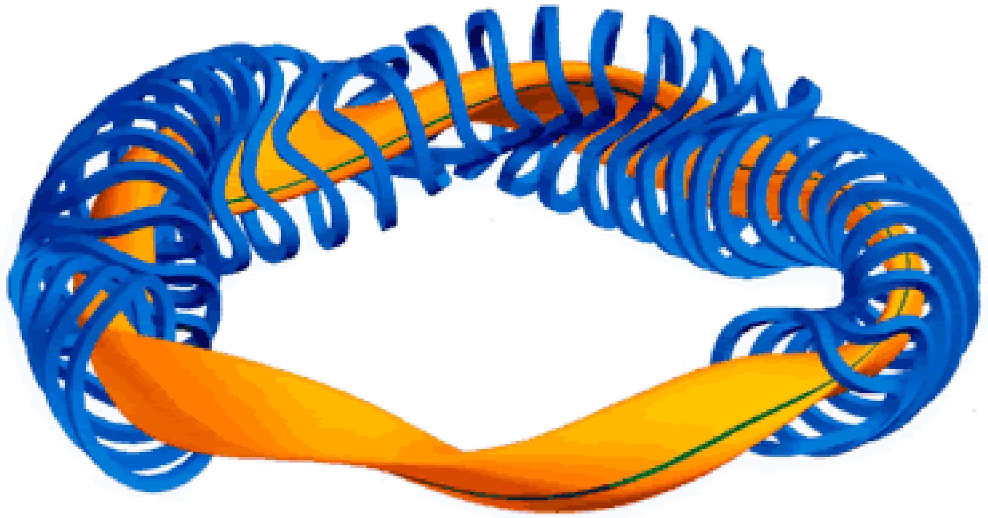
# Toroidal Magnetic Devices Generate Closed Magnetic Flux Surfaces that Confine High-Temperature Plasmas

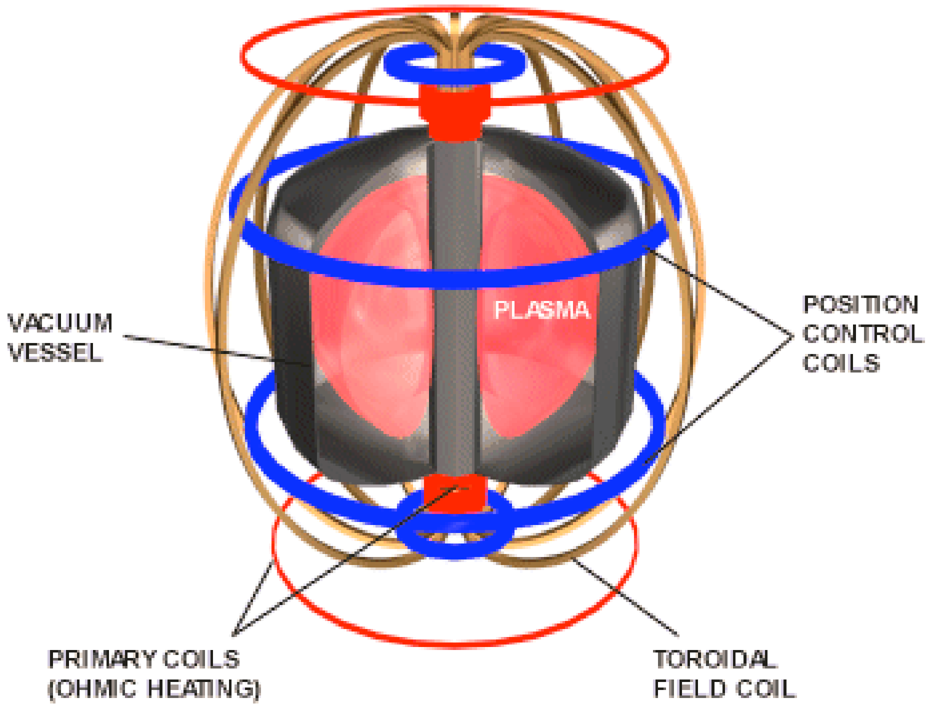
## Tokamak



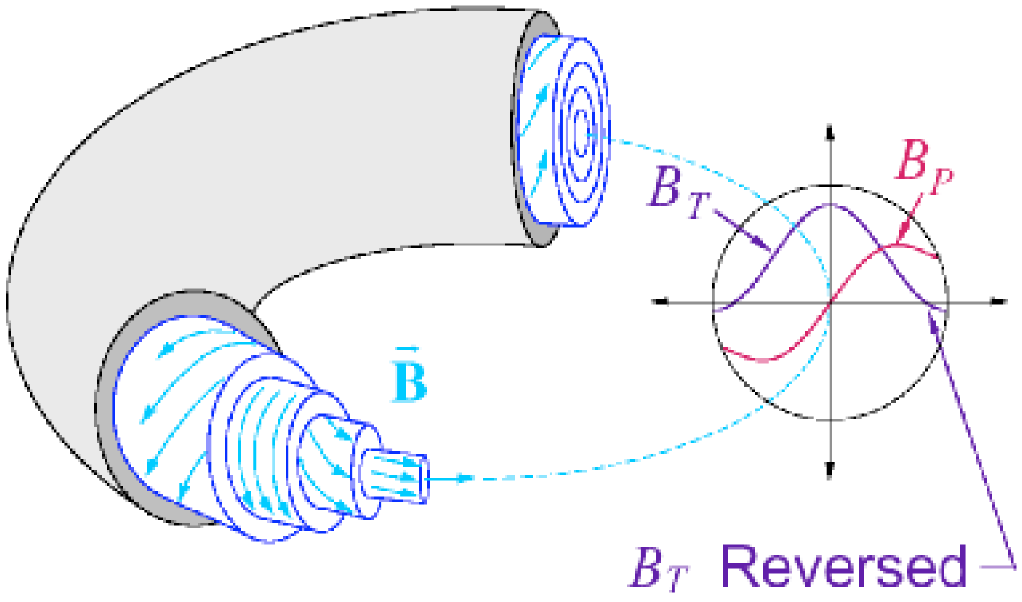
## Stellarator



## Spherical Tokamak



## Reversed-Field Pinch



- **Particle orbits confined to closed magnetic flux surfaces**

# Toroidal Magnetic Devices Generate Closed Magnetic Flux Surfaces that Confine High-Temperature Plasmas

**Tokamak**

**Stellarator**

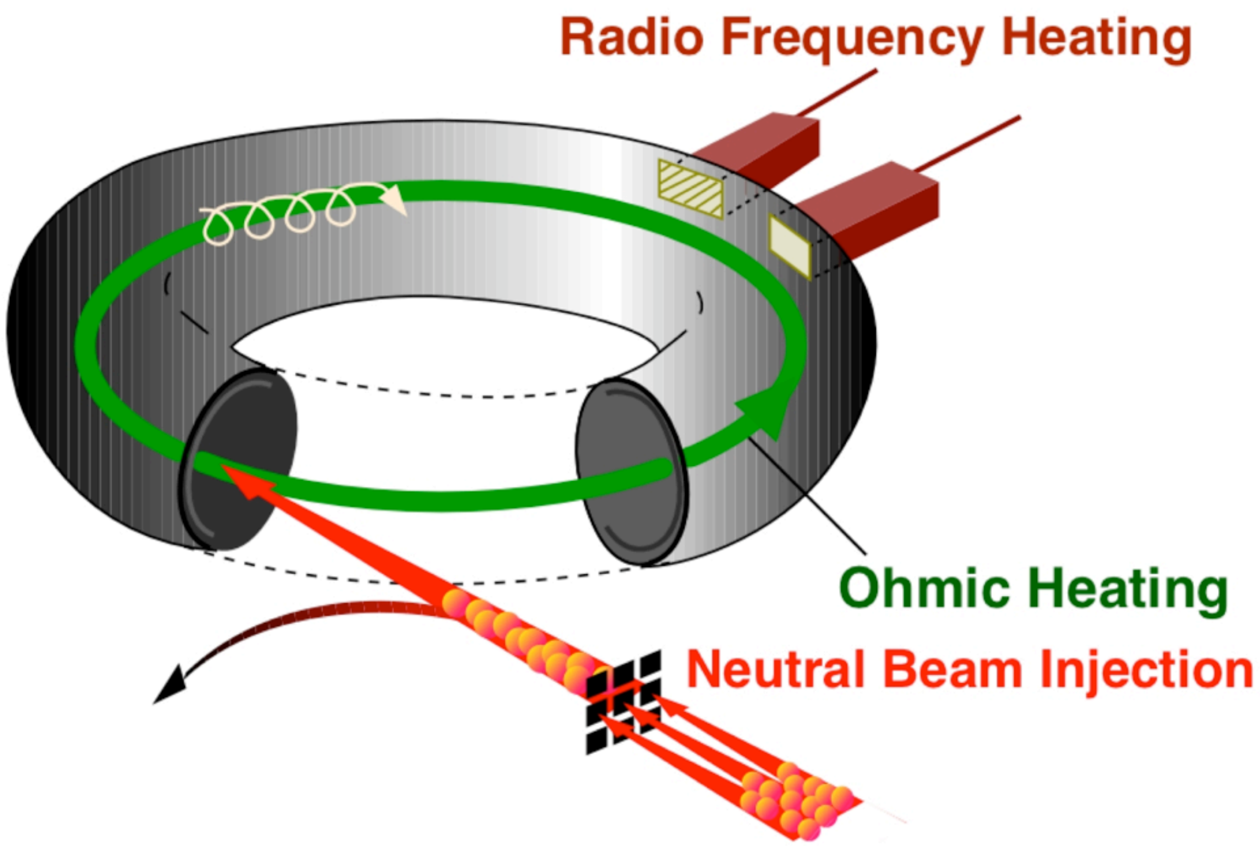
**Spherical Tokamak**

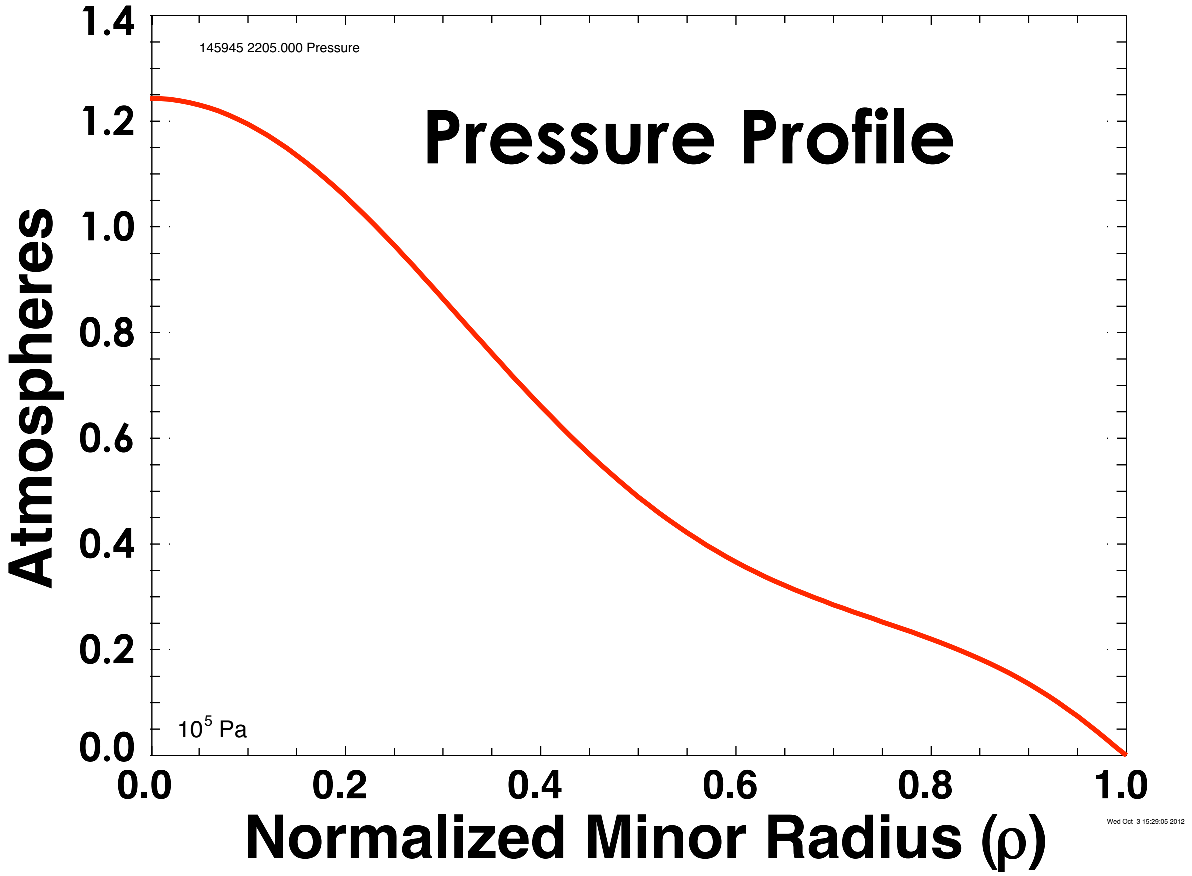
**Reversed-Field Pinch**

- **Particle orbits confined to closed magnetic flux surfaces**

# $\nabla$P-Driven Turbulence Drives Cross-Field Transport of Particles, Energy, and Momentum in Magnetically-Confined Plasmas

- **Multiple systems heat plasmas to temperatures required for fusion**
  - Ohmic, neutral beams, radio frequency & electron cyclotron heating
- **Resulting equilibrated pressure profiles provide a free-energy source for driving turbulence**





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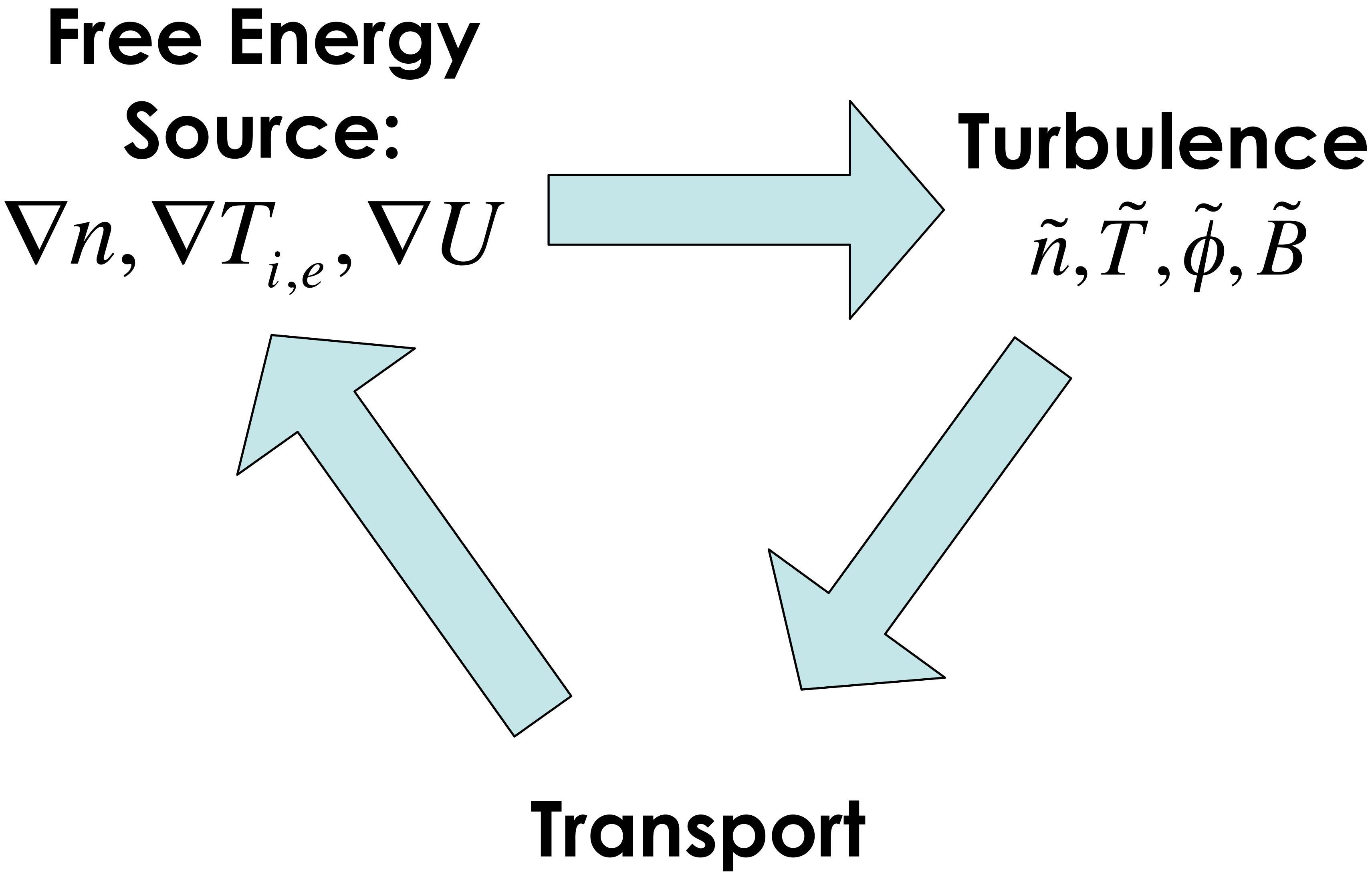


**Free Energy Source:**

$\nabla n, \nabla T_{i,e}, \nabla U$

**Turbulence**

$\tilde{n}, \tilde{T}, \tilde{\phi}, \tilde{B}$

**Transport**

**Particle Flux:** $\Gamma = \boxed{\langle \tilde{n}\tilde{v}_r \rangle} - \boxed{\dfrac{\langle \tilde{J}_{\|}\tilde{B}_r \rangle}{eB_\phi}}$

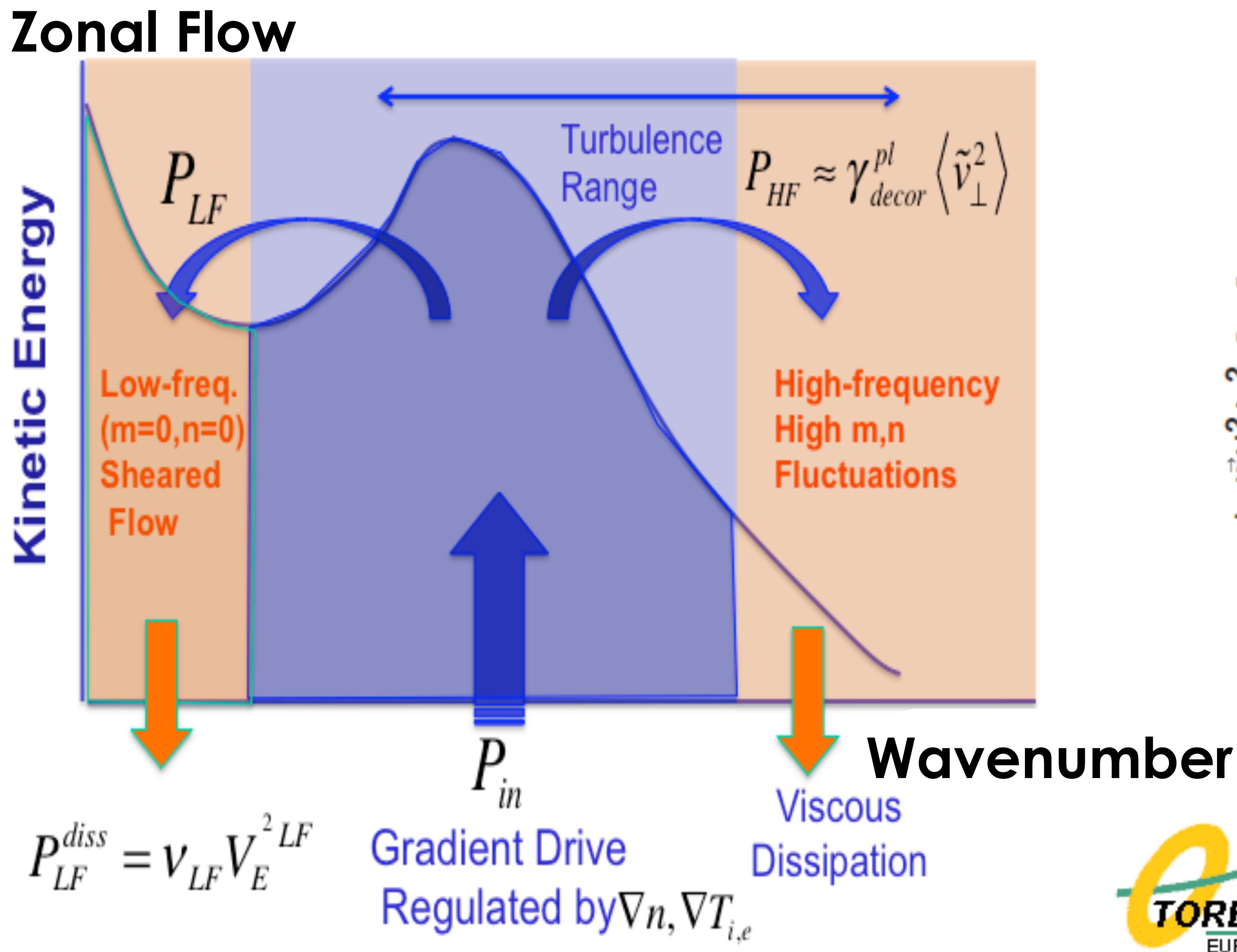
**Heat Flux:** $Q = \boxed{n\langle \tilde{v}_r\tilde{T} \rangle + T\langle \tilde{n}\tilde{v}_r \rangle} + \boxed{\dfrac{\langle \tilde{Q}_{\|}\tilde{B}_r \rangle}{B_\phi}}$

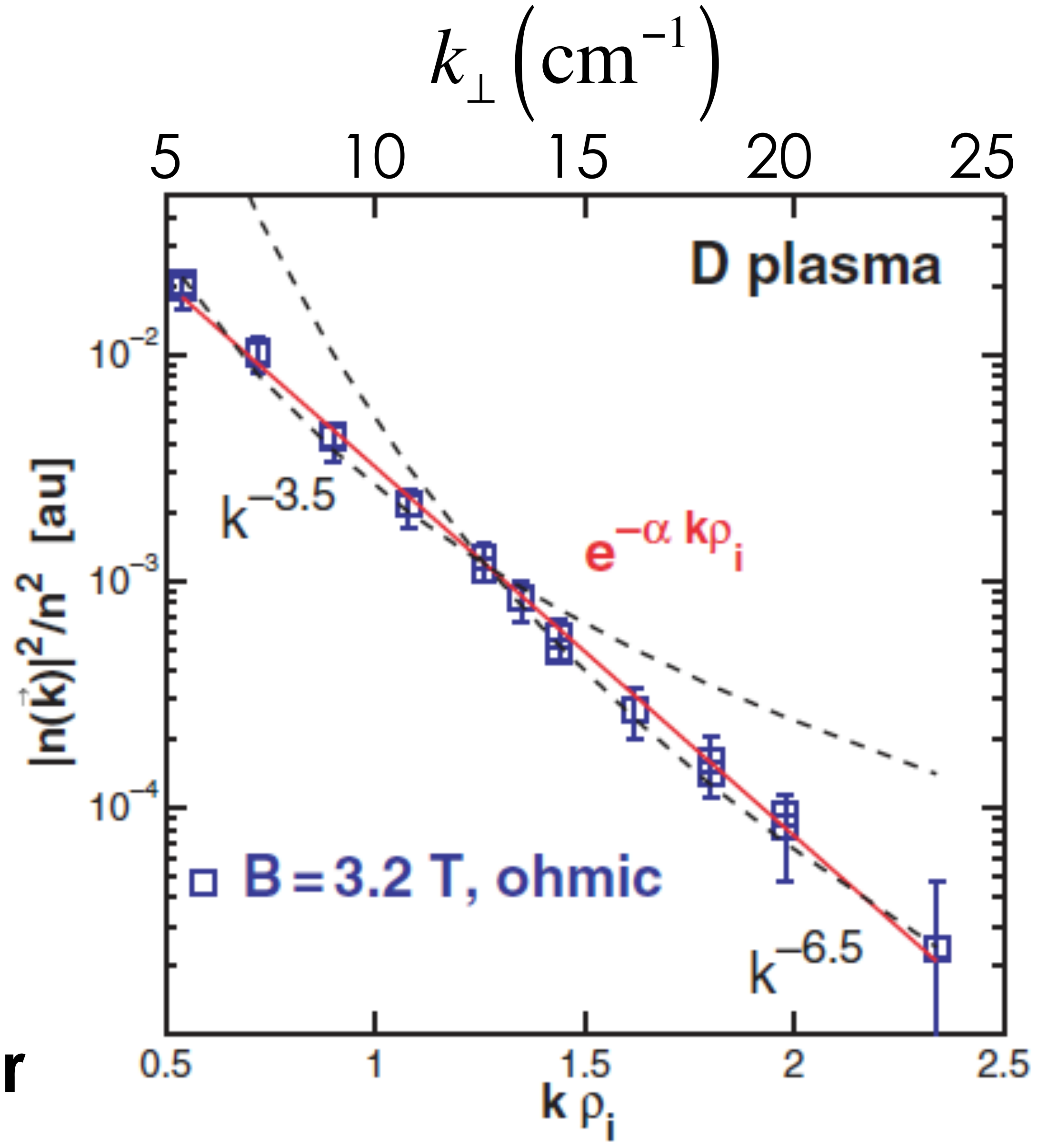
🟦 **Electrostatic**

🟥 **Electromagnetic**

# Plasma Turbulence Driven Unstable over Broad Range of Spatial Scales

- **Power injected at gyroradius scales**
- **Saturates via 3-wave nonlinear interactions**
  - Small spatial scales: (dissipation)
  - Large spatial scales: sheared "zonal flows" (2D feature)



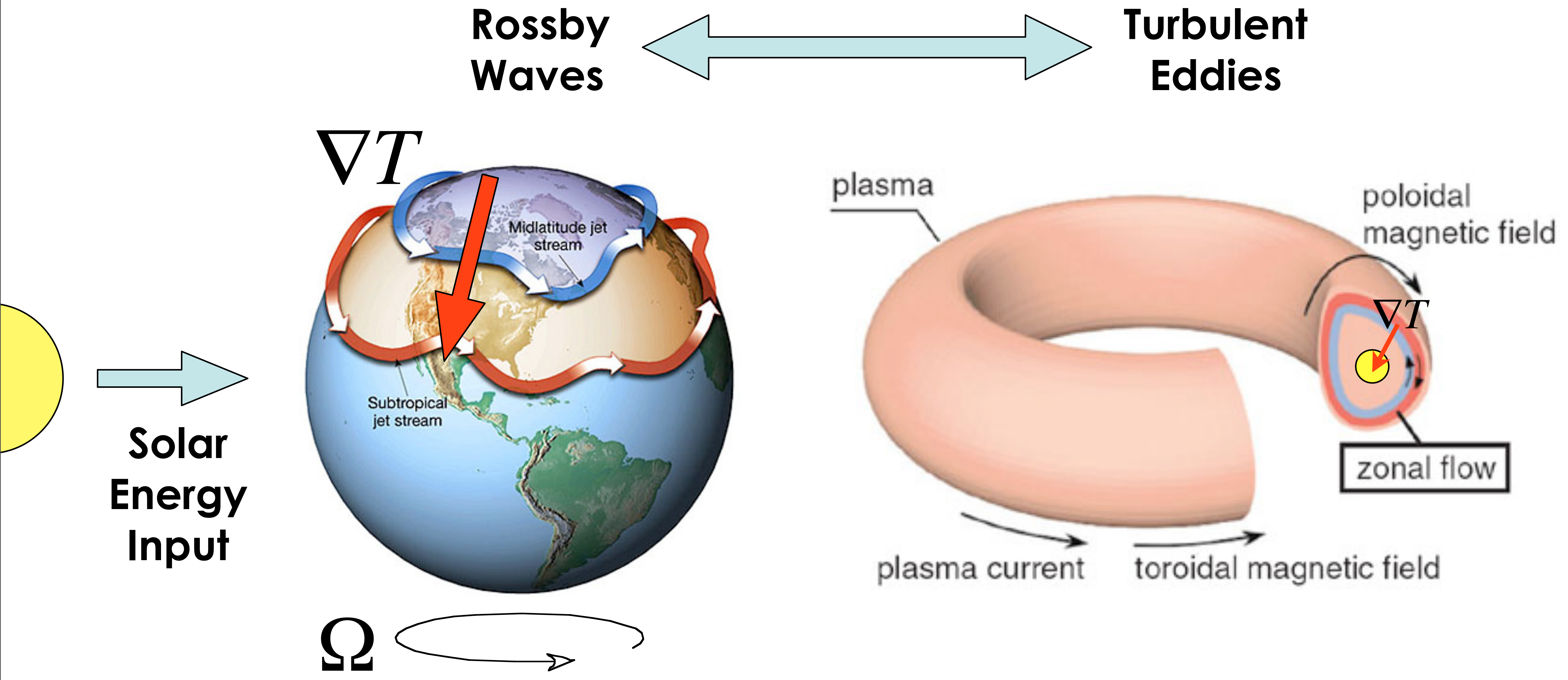


TORE SUPRA EURATOM-CEA

*P. Hennequin, Plasma Phys. Control. Fus.* ***46****, B121 (2004)*

# Geophysical Atmospheres and Toroidal Plasmas Exhibit Several Analogous Physical Features

- **Pressure gradients and rotation drive small scale instabilities**
  - Rossby Waves in atmospheres, drift waves in plasmas
- **Relatively small-scale instabilities generate large scale flows (2-D)**
  - Jet Stream in atmosphere
  - Zonal Flows in Plasmas



**Rossby Waves**

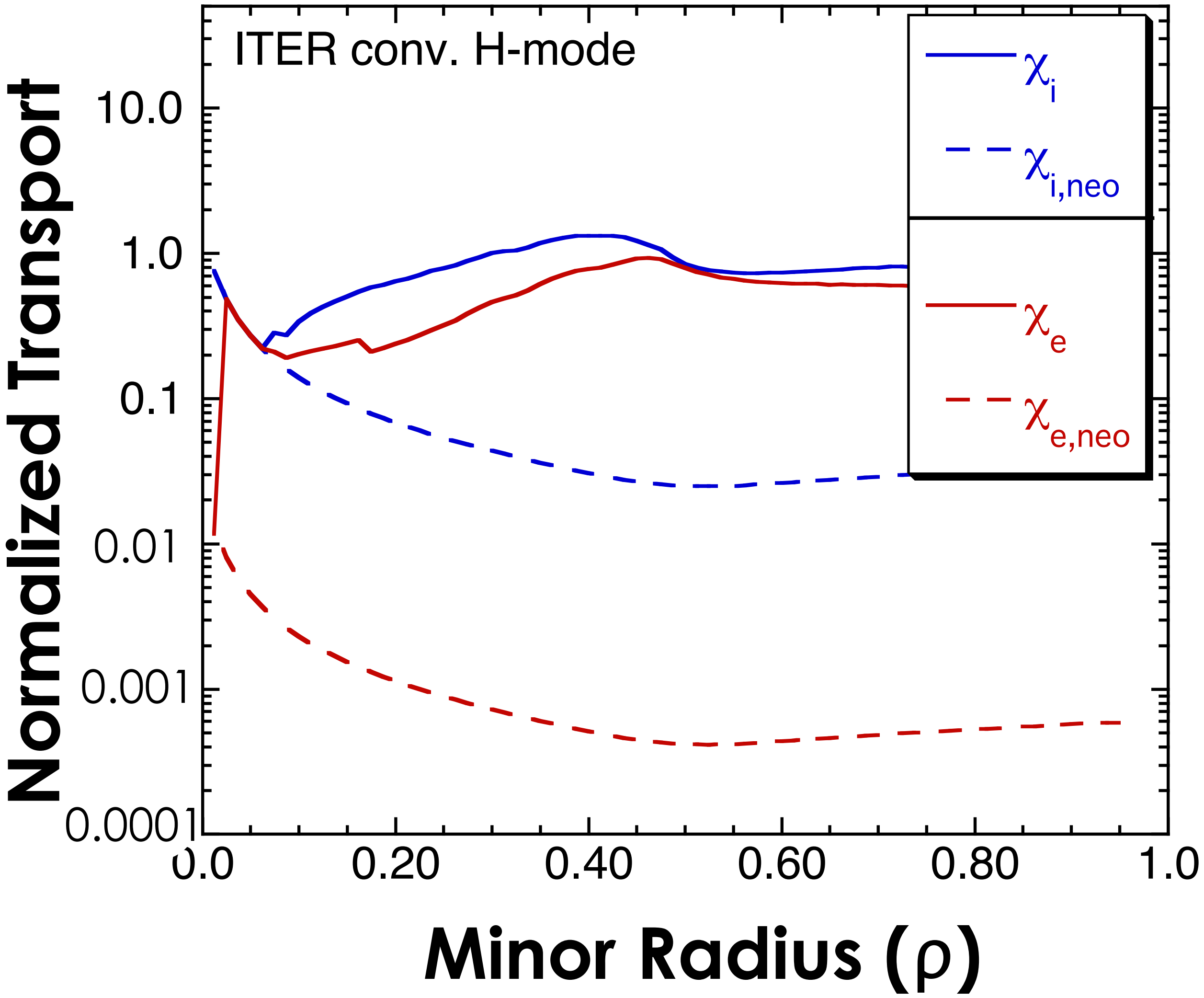
**Turbulent Eddies**

**Solar Energy Input**

# Without Turbulence, "Neoclassical" Collisional Transport Would Allow for "Small" Fusion Energy Systems

- **Initial projections decades ago indicated that fusion energy could be achieved with modest size and modest field systems**
- **Early experiments demonstrated that confinement was far worse than anticipated**

**Calculated Turbulent Transport for Reactor-Scale Plasma**



$$\Gamma = D\left(-\nabla n\right)$$

$$Q = \chi\left(-\nabla T\right)$$

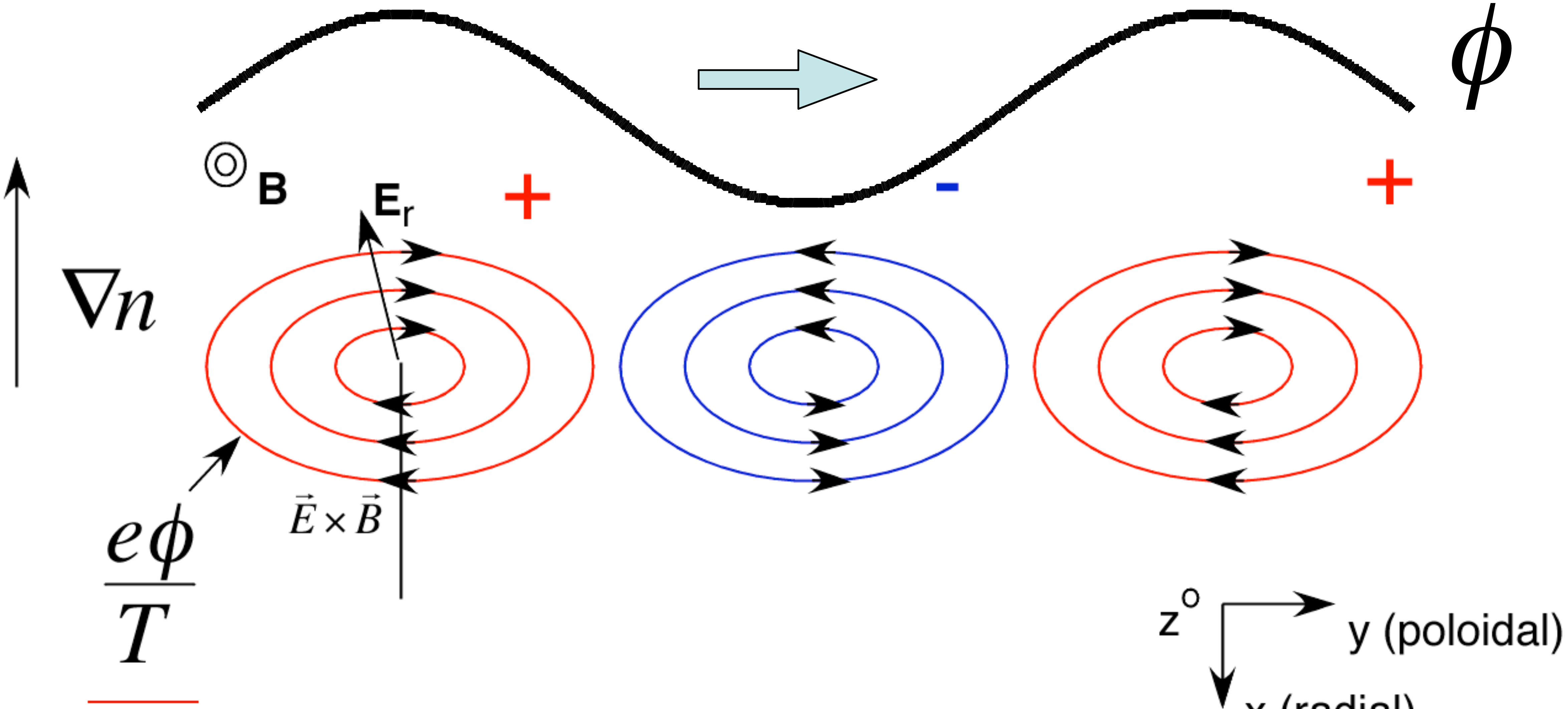
*- Ion thermal energy transport is one to two orders of magnitude higher than collisional (neoclassical) transport*

*- Electron transport several orders of magnitude higher (~2000*)*

*J. Kinsey, Nucl. Fusion* ***51****, 083001 (2011)*

# Drift-Wave Turbulence Drives Cross-Field Transport

- "Universal Instability" in plasmas with density & temperature gradients



- ***$E_r$x$B_T$*** **rotation about electrostatic potential structures**
- **Finite phase shift, $\delta\phi$, between density and potential fluctuations leads to** ***net outward radial flux of particles***

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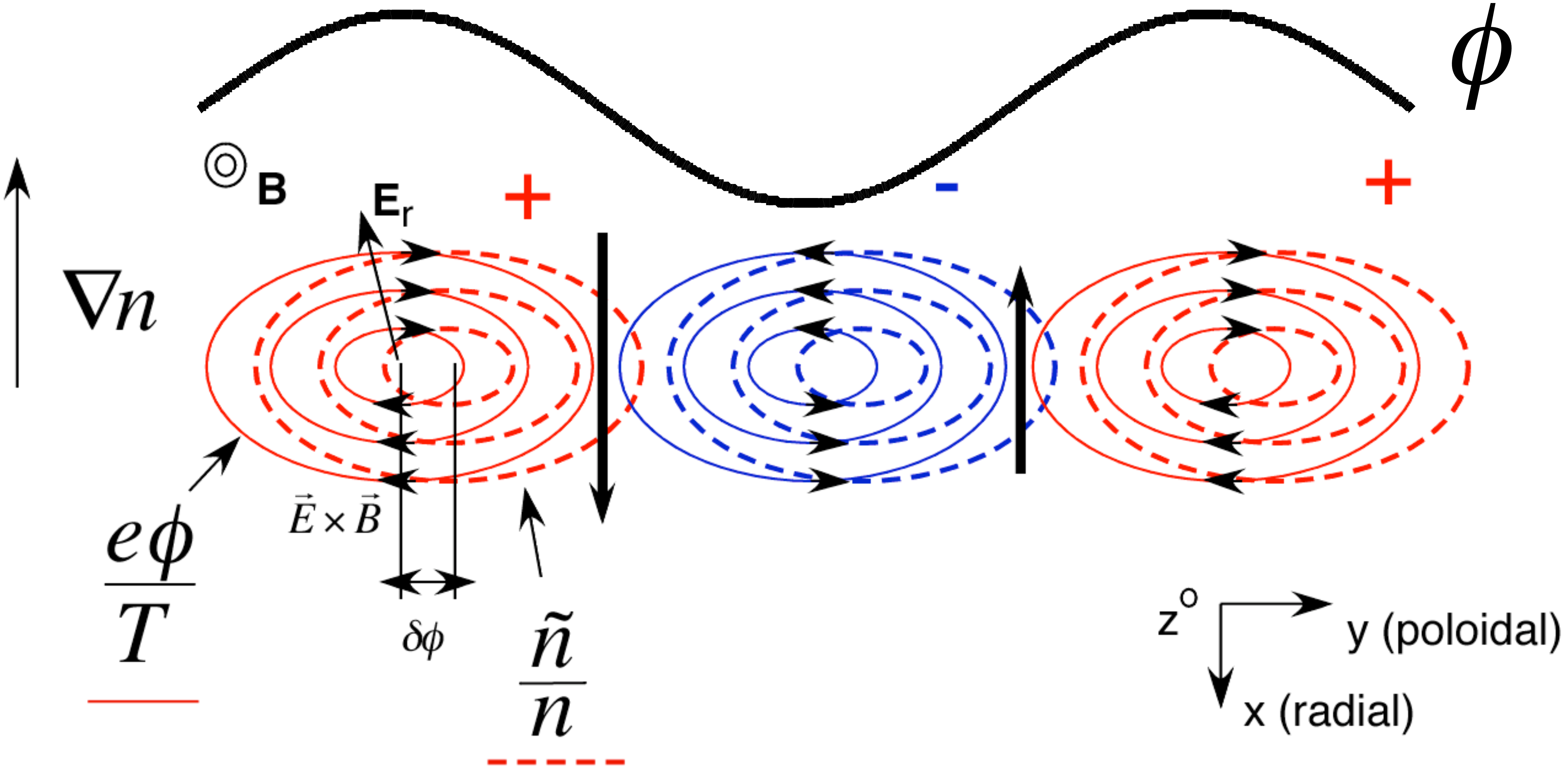
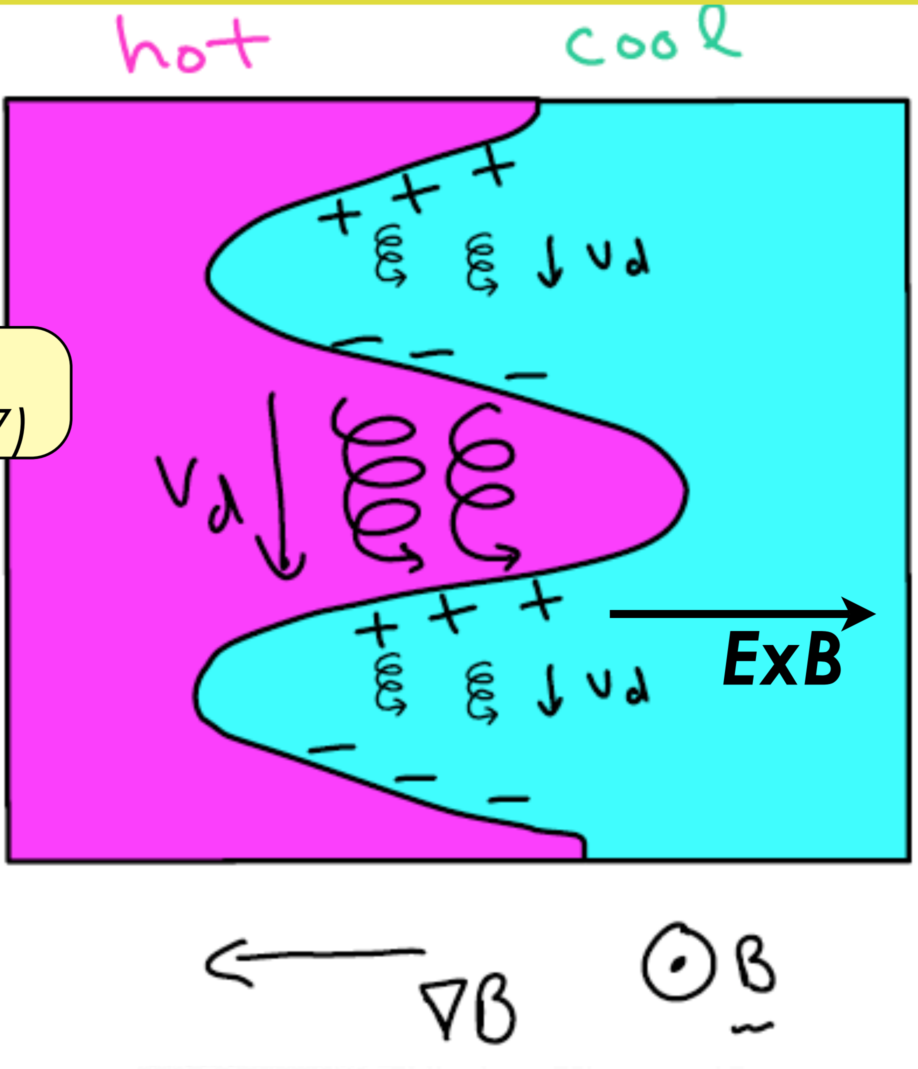


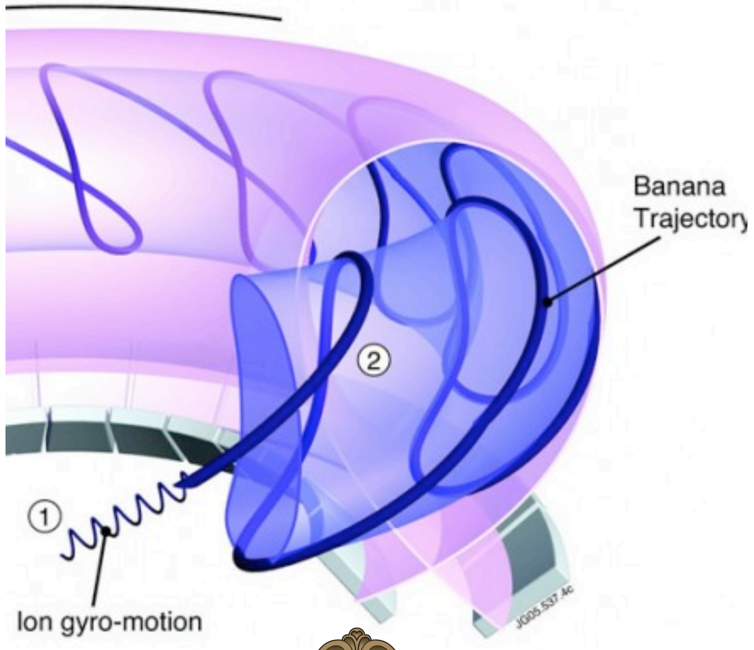
- ***E**$_r$**xB**$_T$* **rotation about electrostatic potential structures**
- **Finite phase shift, δ ϕ , between density and potential fluctuations leads to *net outward radial flux of particles***

# Several Linear Instabilities have been Theoretically Identified that Underly Observed Turbulence

- **Ion-Temperature Gradient-driven modes (ITG)**
  - Ion charge-separation, electric field, ExB drift
  - Driven by $\nabla T_i$
  - 5-10 ion gyroradii ($k_\perp \rho_i \sim 0.1$-$0.5$)
  - Ion diamagnetic direction: $V_{ph} \sim V_{d,i}$
- **Trapped-Electron Modes (TEM)**
  - Wave-particle resonance between toroidal precession of trapped electrons and parallel velocity of drift wave
  - Driven by $\nabla T_e$, $\nabla n$
  - 1-10 ion gyroradii ($k_\perp \rho_i \sim 0.3$-$1$)
  - Electron diamagnetic direction: $V_{ph} \sim V_{d,e}$
- **Electron-Temperature Gradient modes (ETG)**
  - Driven by $\nabla T_e$
  - Electron diamagnetic direction, $V_{ph} \sim V_{d,e}$
  - Spatial scale: ~ electron gyroradii ($k_\perp \rho_i \sim 1$-$10$)



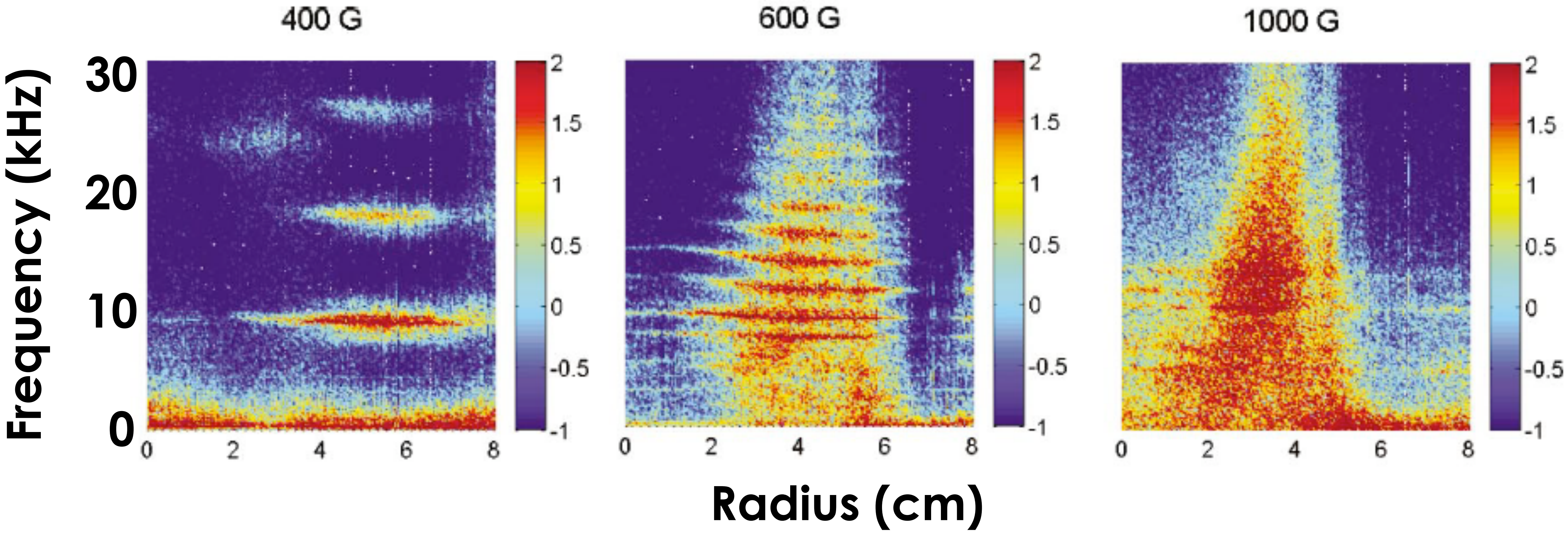
*G. Hammett, APS-Review (2007)*



# Basic Plasma Experiment Reveal Transition from Linear Drift Modes to Saturated Turbulence

- **As axial field is increased, broadband (nonlinear) turbulence develops**
  - Fluctuations Identified as Drift Wave Instabilities
- **Basic plasma physics experiments have provided a wealth of data on turbulence behavior**

**Electrostatic Potential Fluctuations, $\tilde{\phi}$**



**Linear Modes** → **Developed Turbulence**

**CSDX@UCSD**

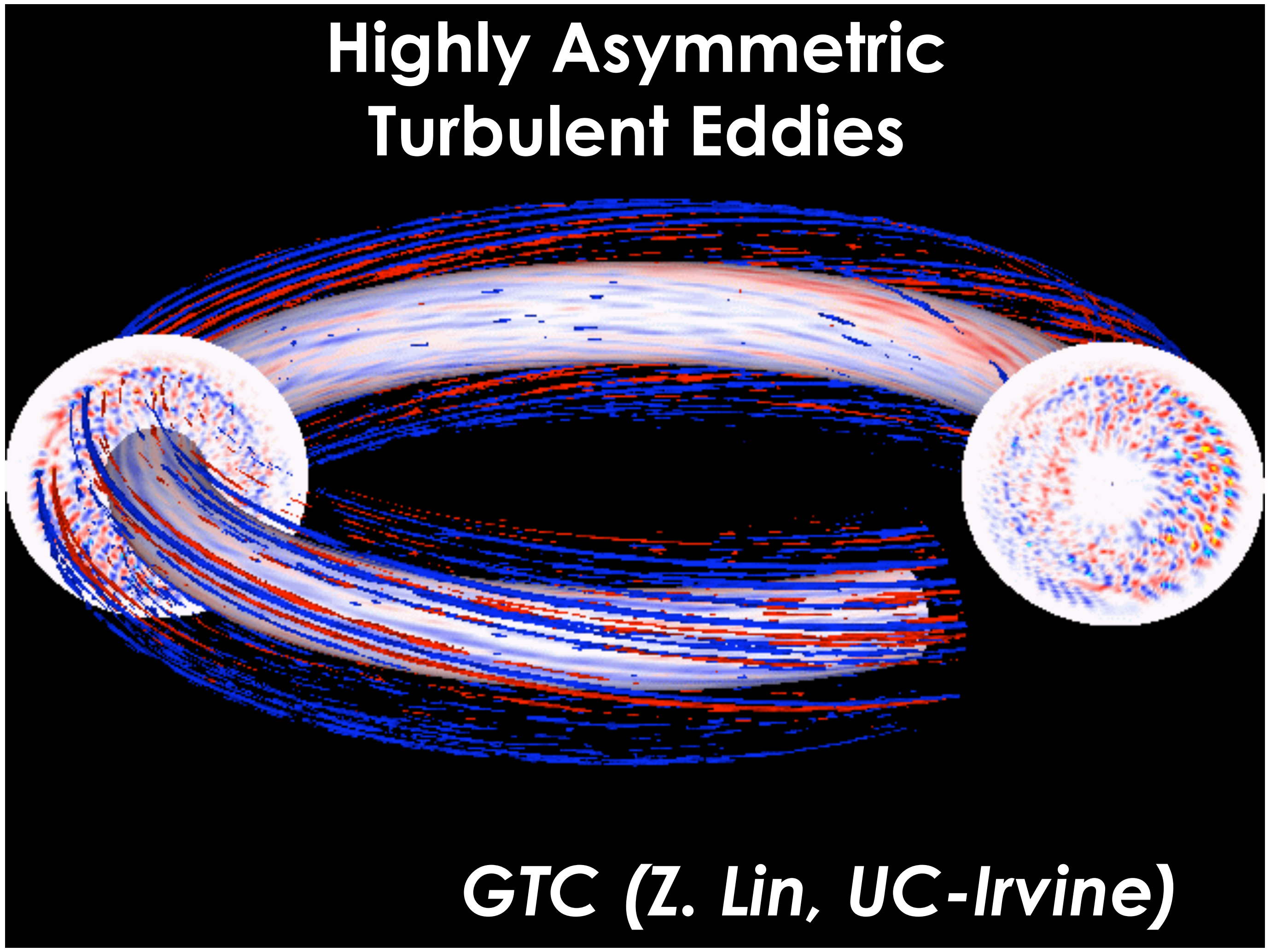
*M. Burin, Phys. Plasmas **12**, 052320 (2005)*

# Characteristics of Plasma Turbulence Challenge Diagnostics

- **Fluctuations in multiple fields:**

$$n, T_e, T_I, \tilde{\phi}, B$$

- **Spatial scales**
  - Long-wavelength ($k_\perp \rho_I < 1$): ~1 cm
  - Short-wavelength ($k_\perp \rho_e < 1$): <1 mm
- **Temporal scales**
  - Gyrokinetic time scale: $a/c_s \sim 10\ \mu s$
  - $\omega_{Lab} = \omega_{plasma} + k \cdot v$: 10 kHz - 10 MHz
- **Magnitude: 0.01% < ñ/n < 20%**
  - Wide dynamic range
- **Phase relationships**
  - Turbulent flux requires correlated measurements
- **Adequate signal-to-noise**
  - Noise sources: electronic, photon,...



**Highly Asymmetric Turbulent Eddies**

*GTC (Z. Lin, UC-Irvine)*

**Eddy Scales**

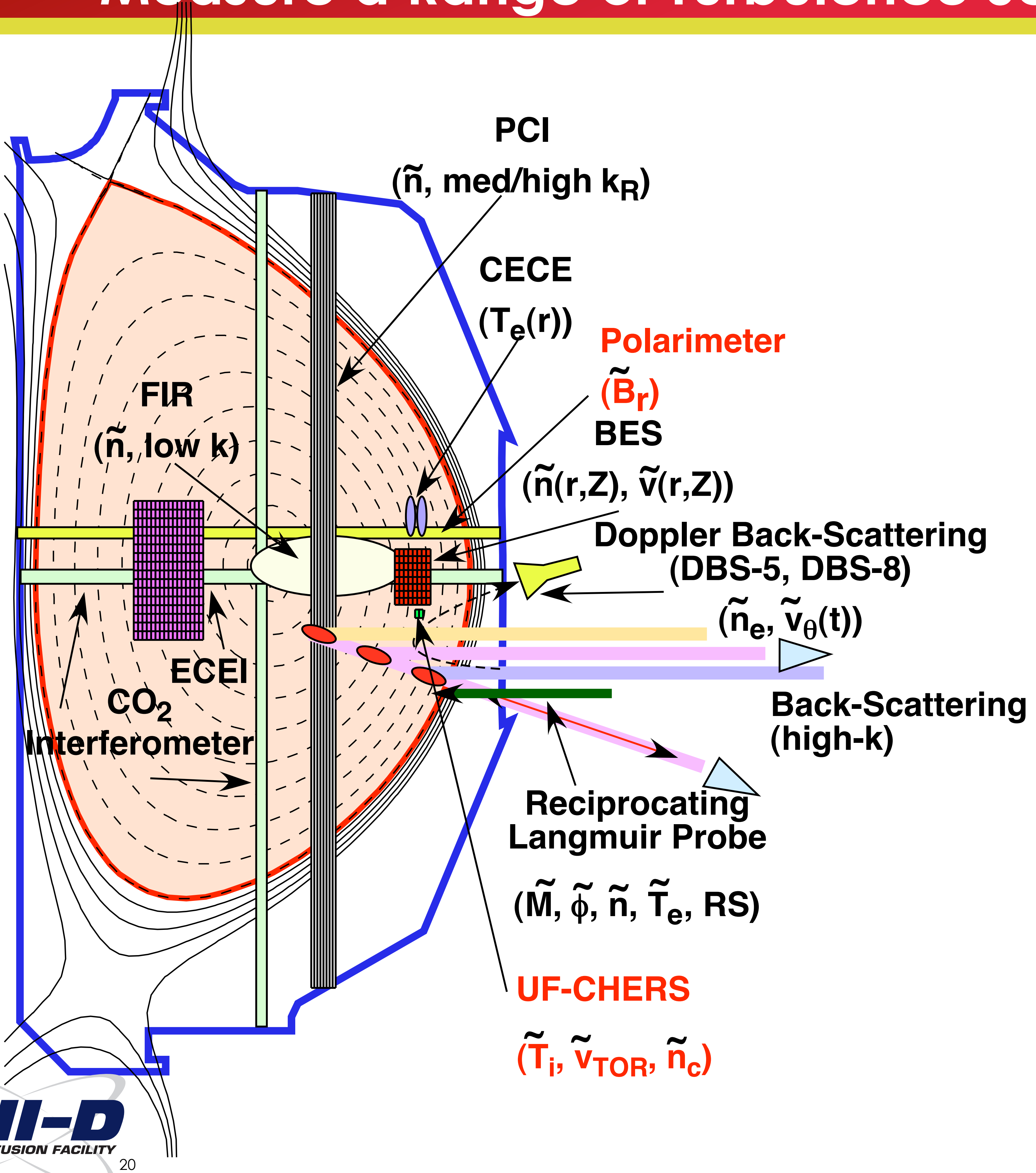
$$L_{\parallel} \sim qR \sim 10m$$
$$L_{\perp} \sim 10\rho_I \sim 1cm$$
$$\tau_c \sim a/c_s \sim 10\mu s$$

# Multiple Diagnostics & Measurement Techniques Developed to Measure Fluctuations in High-Temperature Plasmas

- **Microwave-based**
  - Correlation Reflectometry (ñ, $L_{c,r}$)
  - Doppler-Back Scattering (ñ, $\tilde{v}_\theta$ )
  - High-wavenumber backscattering (ñ)
  - Correlation Electron Cyclotron Emission/ECEI $\left(\tilde{T}_e\right)$
  - Polarimetry ( $\tilde{B}$ )
- **Laser**
  - Phase Contrast Imaging (ñ)
- **Beam**
  - Heavy Ion Beam Probe $\left(\tilde{n},\tilde{\phi}\right)$
- **Optical**
  - Beam Emission Spectroscopy $\left(\tilde{n},L_c,2\mathrm{D}\right)$
  - High-Frequency Charge Exchange Recombination Spectroscopy $\left(\tilde{T}_I\right)$
  - Gas Puff Imaging $\left(\tilde{n},L_c,2\mathrm{D}\right)$
- **Each views a component of multi-dimensional fluctuation "space"**

*N. Bretz, Rev. Sci. Instrum.* ***68****, 2927 (1997)*

# Experiments Employ a Suite of Fluctuation Diagnostics to Measure a Range of Turbulence Scales and Fields



**PCI**

**$(\tilde{n}, \text{med/high } k_R)$**

**CECE**

**$(T_e(r))$**

**Polarimeter**

**$(\tilde{B}_r)$**

**BES**

**$(\tilde{n}(r,Z), \tilde{v}(r,Z))$**

**Doppler Back-Scattering (DBS-5, DBS-8)**

**$(\tilde{n}_e, \tilde{v}_\theta(t))$**

**FIR**

**$(\tilde{n}, \text{low } k)$**

**ECEI**

**$CO_2$ Interferometer**

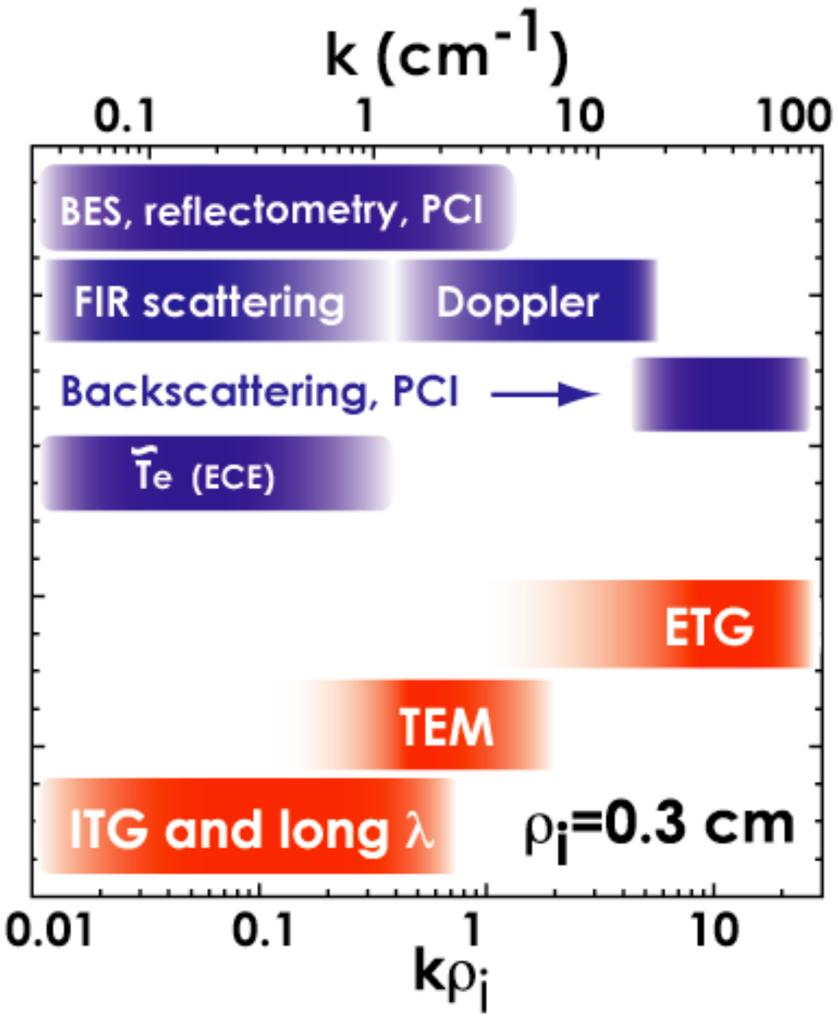
**Back-Scattering (high-k)**

**Reciprocating Langmuir Probe**

**$(\tilde{M}, \tilde{\phi}, \tilde{n}, \tilde{T}_e, \text{RS})$**

**UF-CHERS**

**$(\tilde{T}_i, \tilde{v}_{TOR}, \tilde{n}_c)$**



**Multiple fields:**

$\tilde{n}$ - BES, DBS, FIR, PCI

$T_e$ - CECE, ECEI

n-$T_e$ cross-phase (CECE-DBS)

$T_i$ - UF-CHERS*

v - DBS, BES, UF-CHERS

$\phi$ - Reciprocating probe

$B_r$ - Polarimeter*

***Under development**

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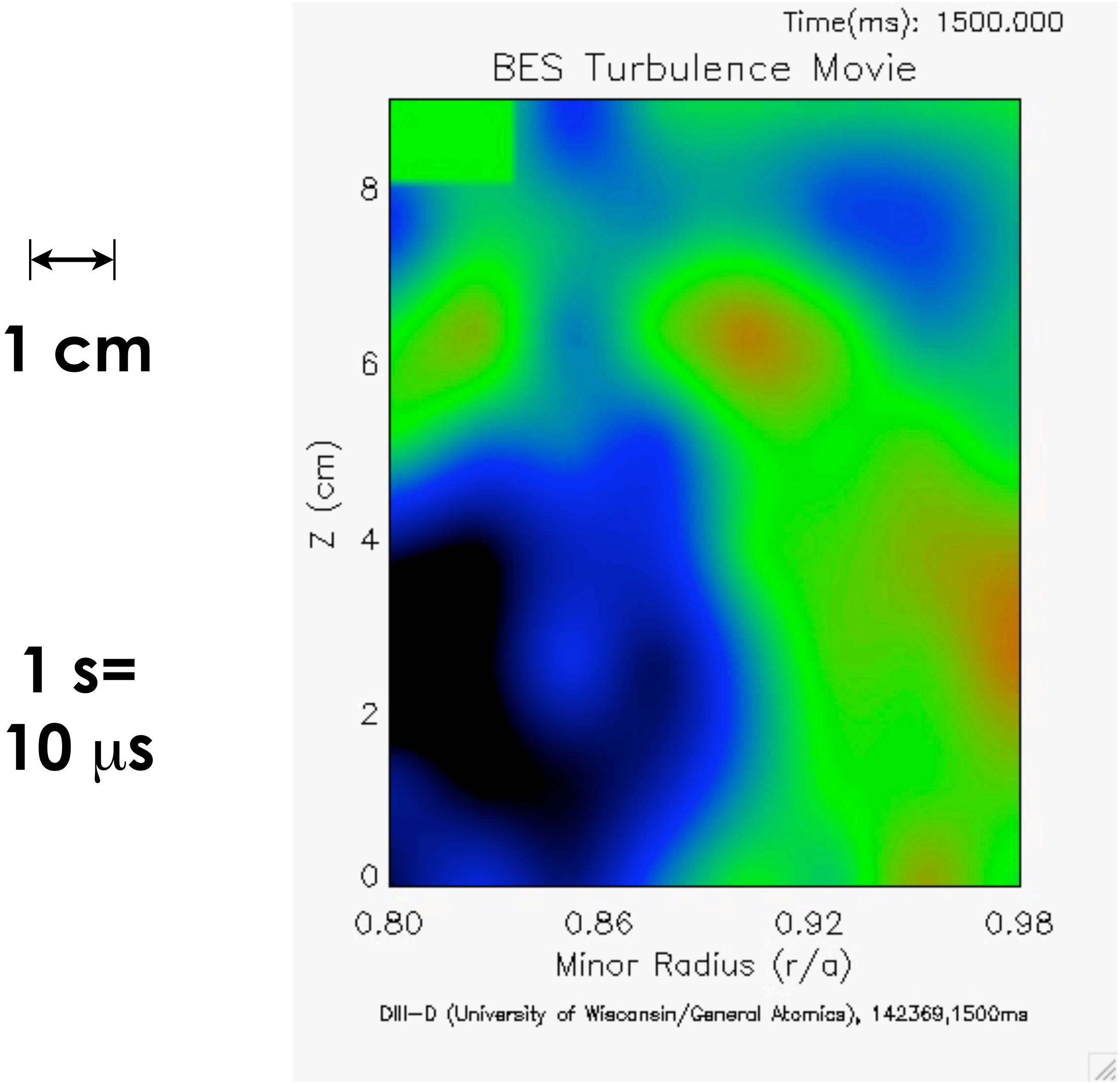
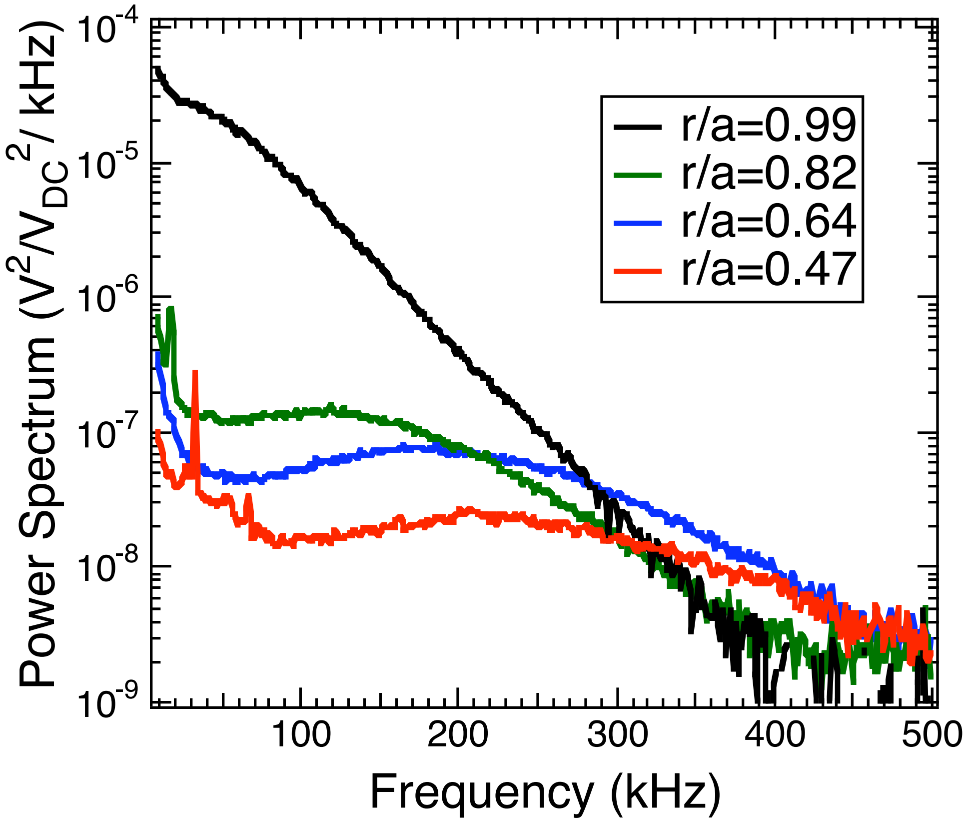
# Temporal Behavior of Low-k Fluctuations Reveals Dynamics; Ensemble-averaging Provides Descriptive Parameters



**Data**

- **Broadband**
- **Spatially coherent**
- **~2 cm eddy size**

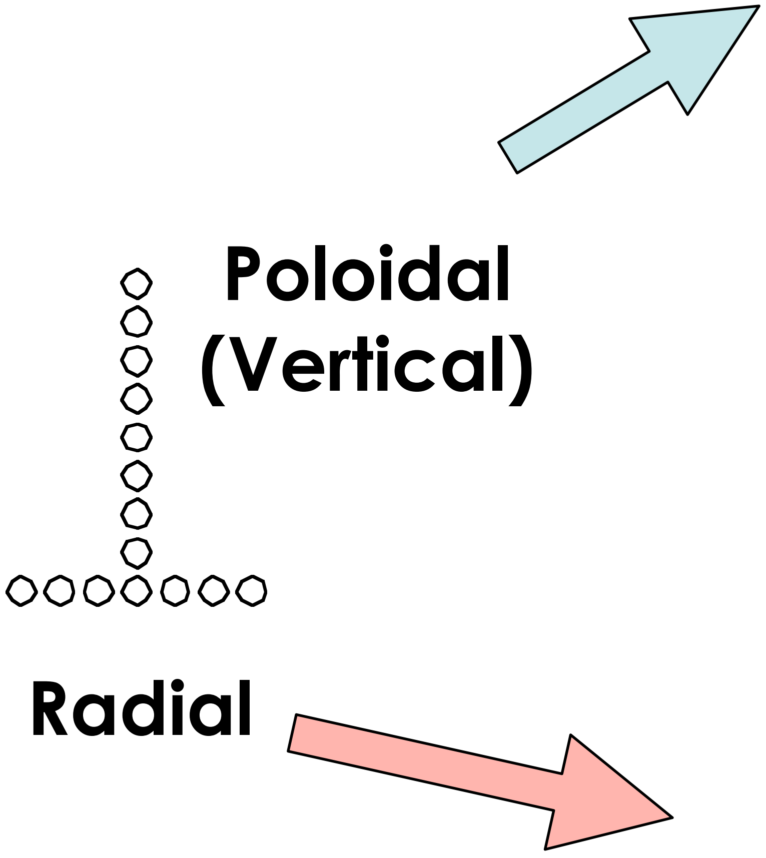
## Fluctuation Spectra at Several Radii



- **Ensemble-averaged spectral characteristics useful for comparisons with simulation**

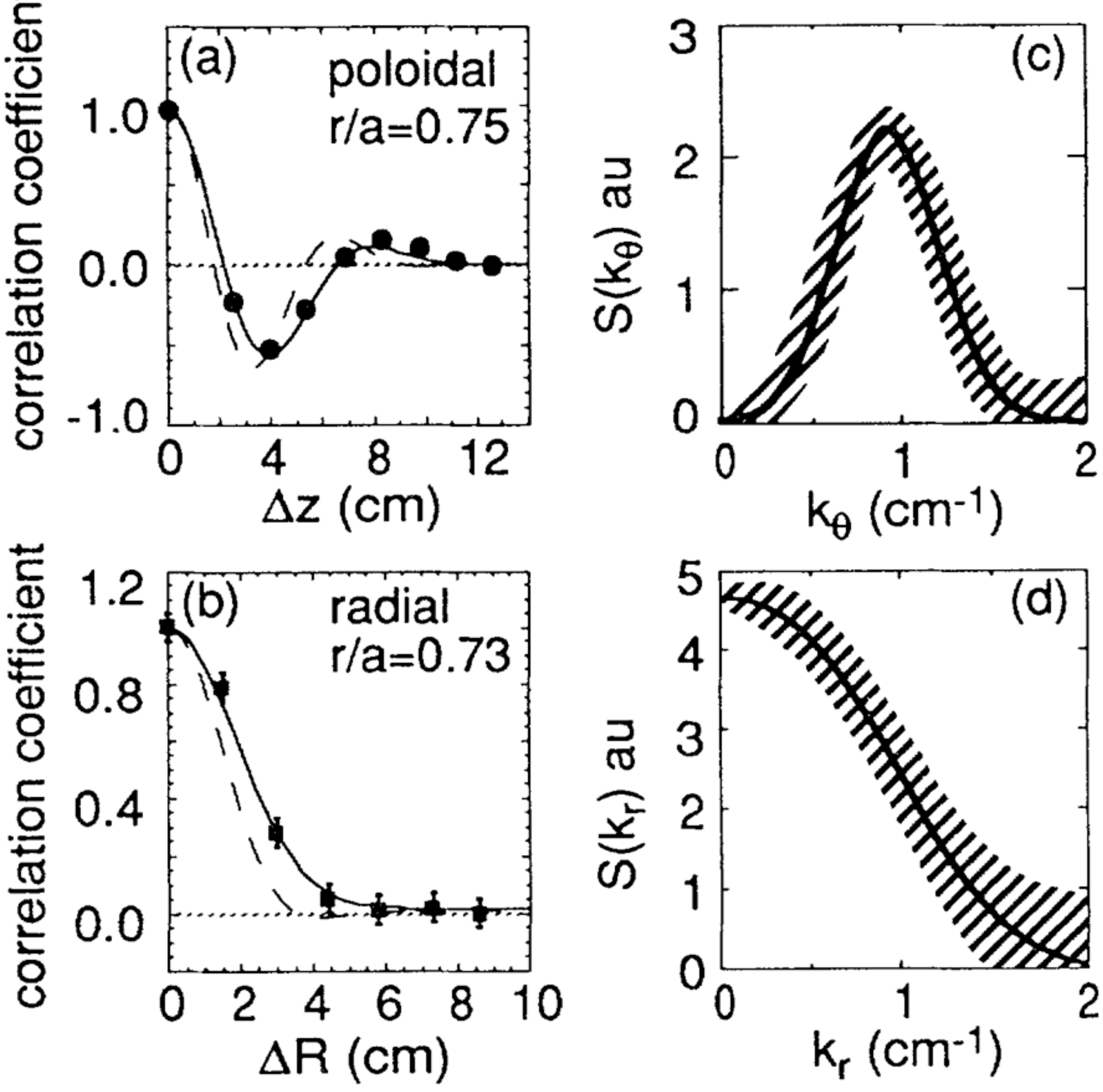
*Z. Yan, this meeting*

# Turbulence Exhibits a Spatial Asymmetry: Spectra peak at Finite Poloidal Wavenumber and Zero Radial Wavenumber



**Spatial Correlations**

**Spatial Transform**



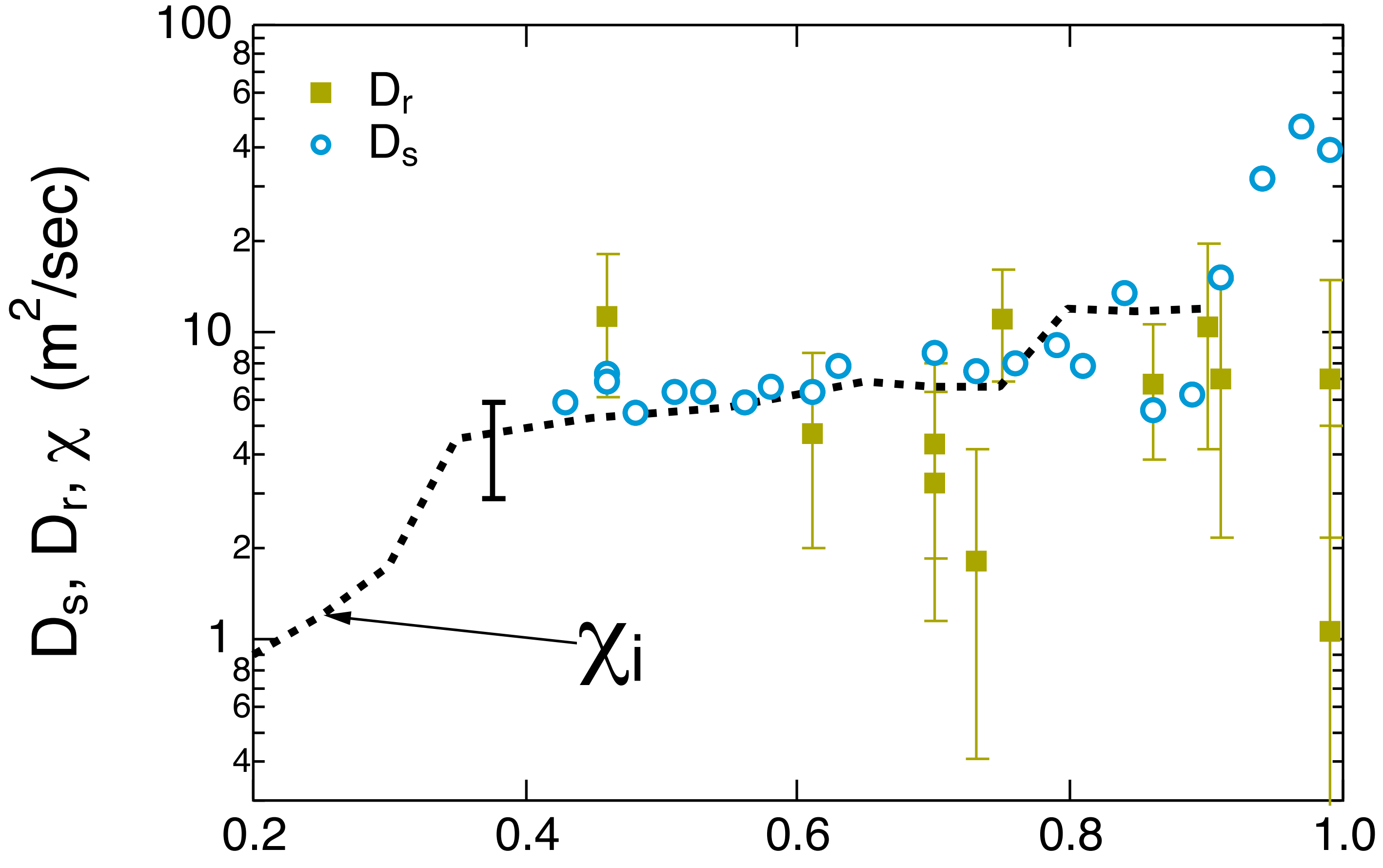
**BES**

**TFTR**

*R. Fonck, Phys. Rev. Lett.* ***70****, 3736 (1993)*

# Inferred Turbulent Transport is Similar to Measured Heat Transport Coefficients

## “Power Balance” Transport and Turbulent Transport Models



**BES**

## Random Walk

$$D_r = \frac{L_{c,r}^2}{\tau_c}$$

## Strong Turbulence:

$$D_s = \left(\frac{\tilde{n}}{n}\right)\frac{kT_e}{eB}$$

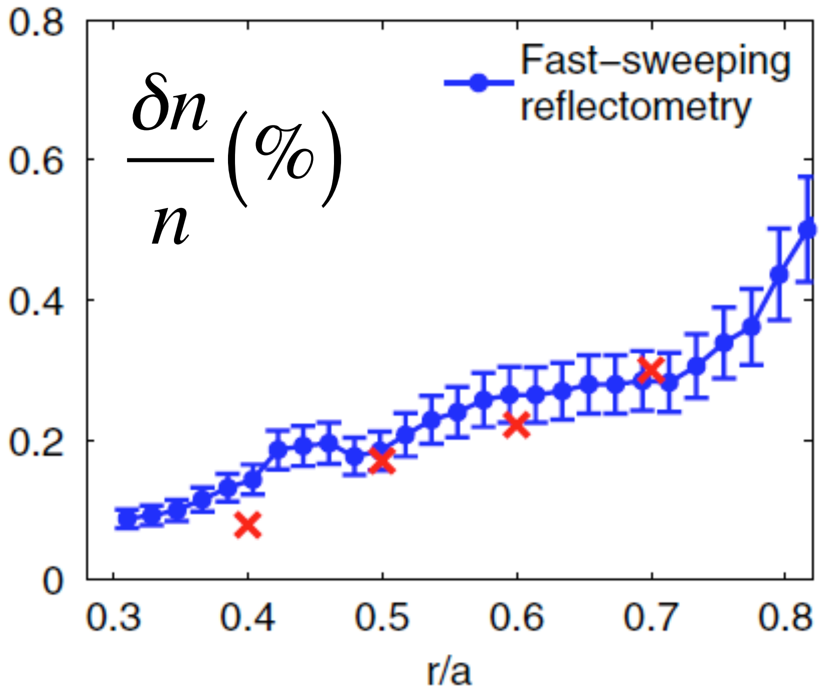
*R. Fonck, Phys. Rev. Lett.* ***70****, 3736 (1993)*

**Measured Turbulence Quantities:** $\frac{\tilde{n}}{n}, L_{c,r}, \tau_c$

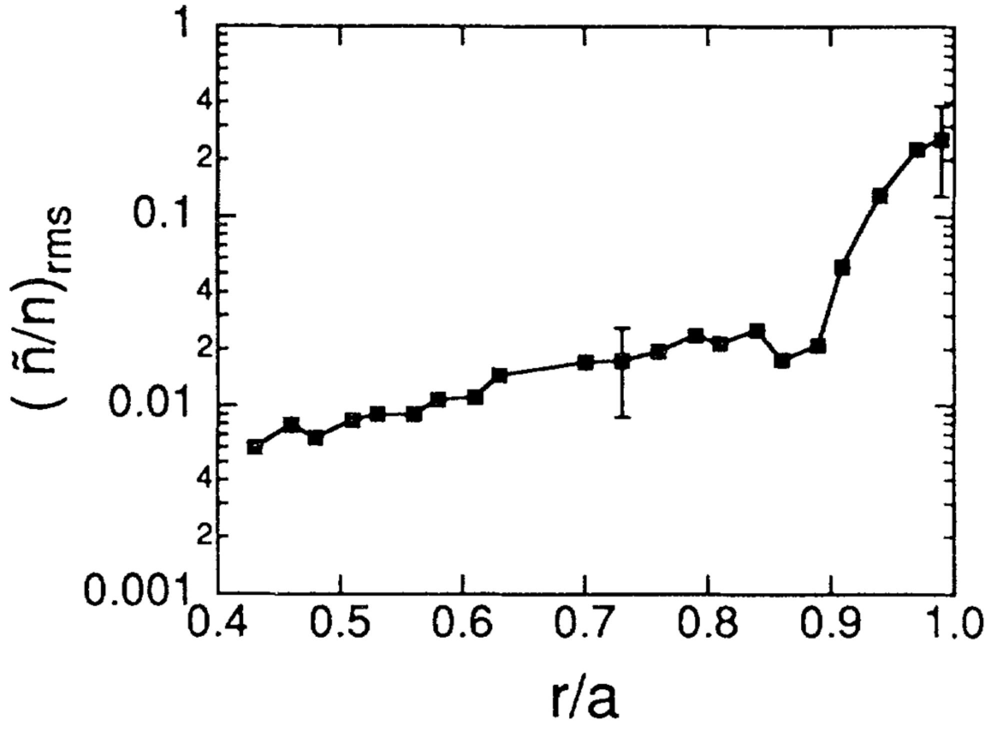
**TFTR**

# Density Fluctuation Amplitude Exhibits Similar Behavior on Multiple Tokamak Experiments

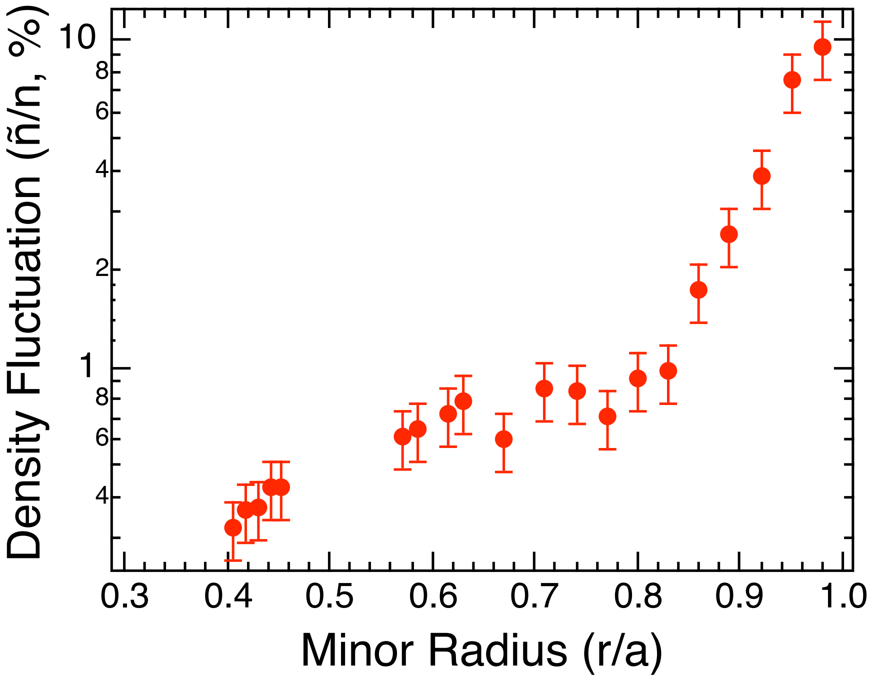
**Tore Supra**



**TFTR**



**DIII-D**

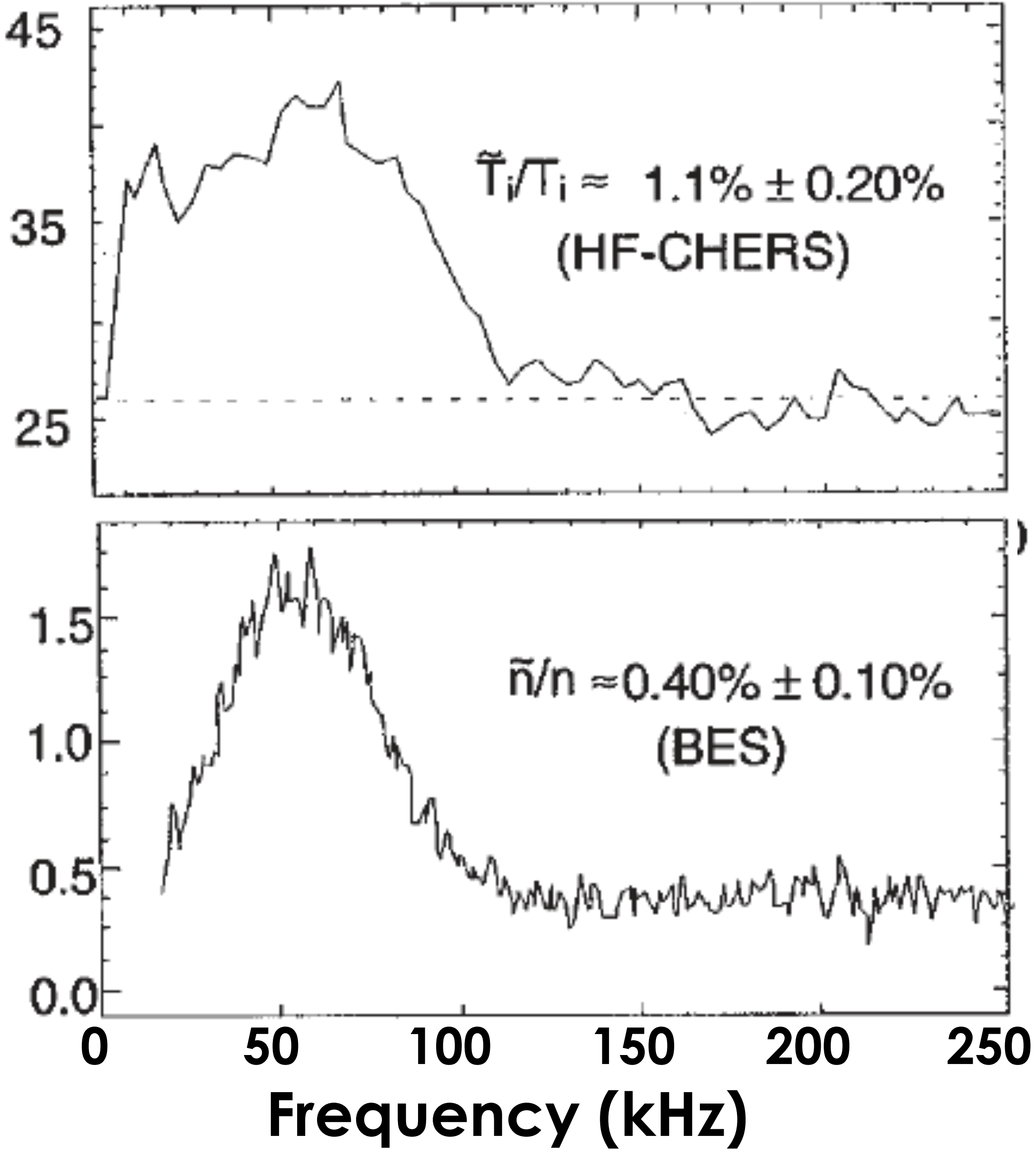


- **Intense edge fluctuations routinely observed in many plasmas**
  - Origin is uncertain

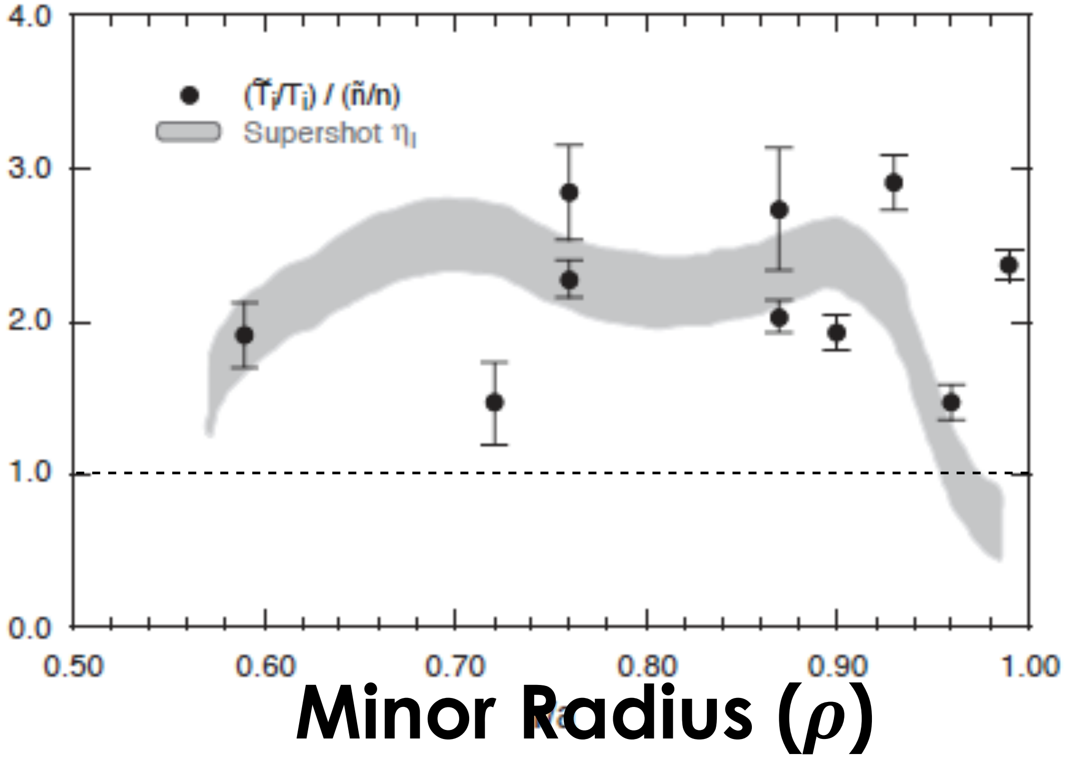
# Ion Temperature Fluctuation Measurements Suggest Ion Temperature Gradient-Driven Turbulence

- **Ion-Temperature-Gradient turbulence predicted to have larger normalized $T_I$ fluctuations than $\tilde{n}$ fluctuations**

$\tilde{T}_I / T_I$ **Spectrum**



$$\left(\frac{\tilde{T}_I}{T_I}\right) \Big/ \left(\frac{\tilde{n}}{n}\right)$$



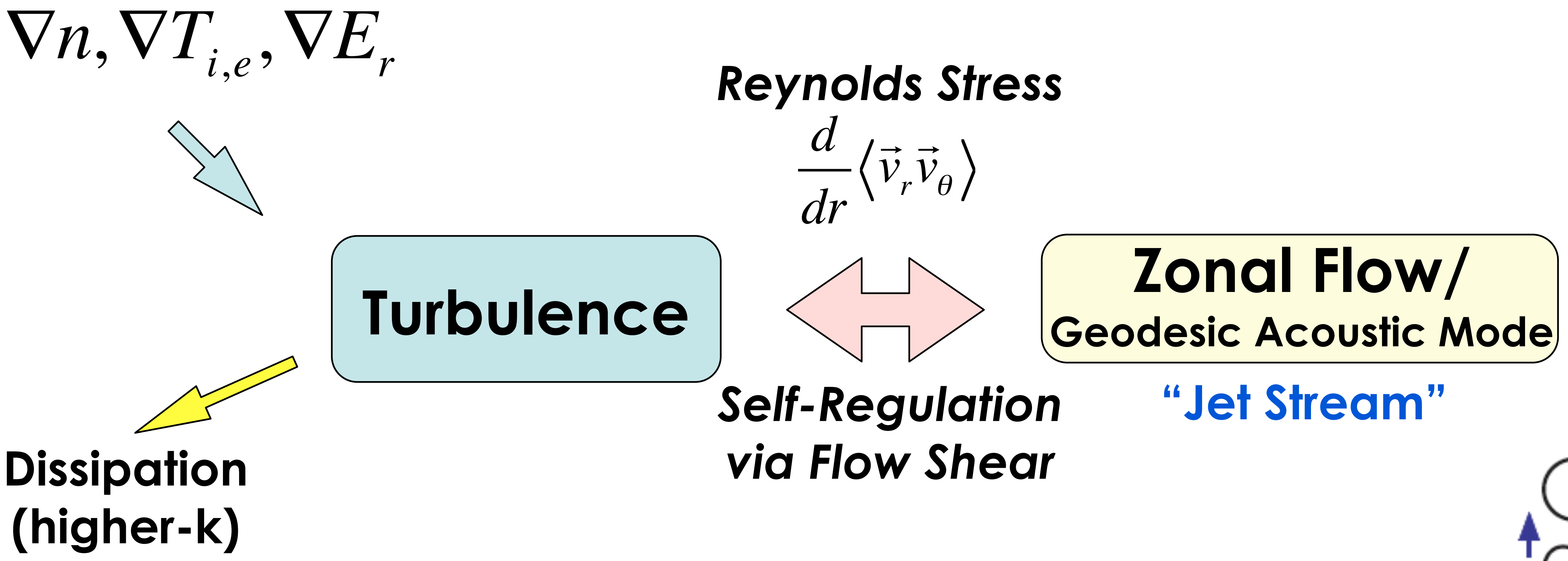
**HF-CHERS on TFTR**

$$\boxed{\frac{\tilde{T}_I}{T_I} > \frac{\tilde{n}}{n}}$$

*H. Evensen, Nucl. Fusion* ***38****, 237 (1998)*

**TFTR**

# Turbulence is Regulated via Self-Generated Zonal Flows



$\nabla n, \nabla T_{i,e}, \nabla E_r$

**Reynolds Stress**

$$\frac{d}{dr}\langle \vec{v}_r \vec{v}_\theta \rangle$$

**Turbulence**

**Zonal Flow/**
**Geodesic Acoustic Mode**

**“Jet Stream”**

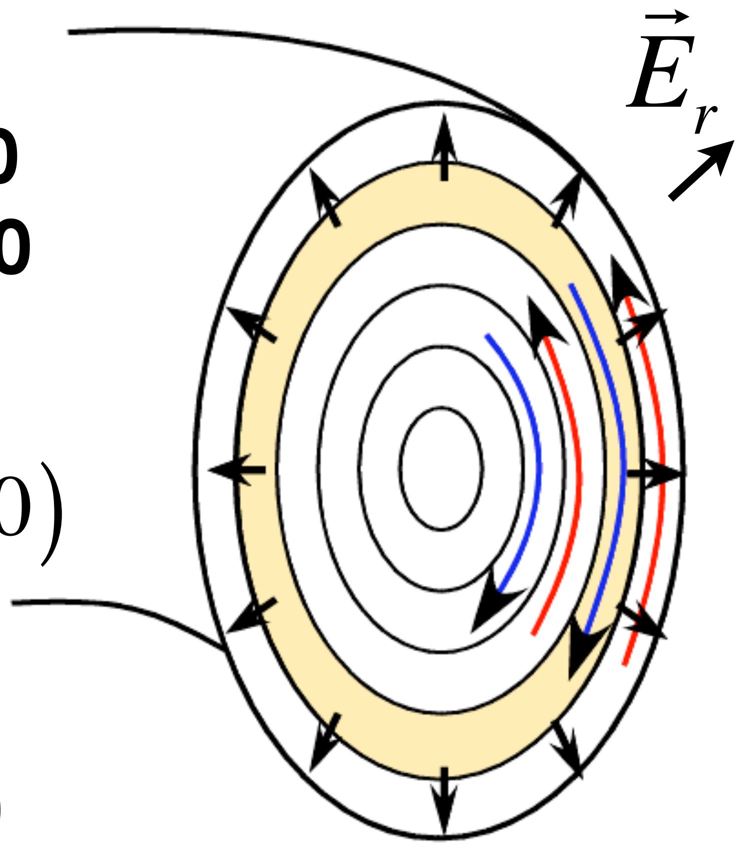
**Self-Regulation via Flow Shear**

**Dissipation (higher-k)**

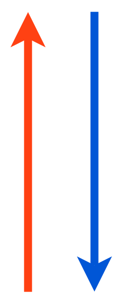
**n=0**
**m=0**

$\tilde{\phi}$

$(\tilde{n} \sim 0)$



$\vec{E}_r$



$\vec{E}_r \times \vec{B}_T$

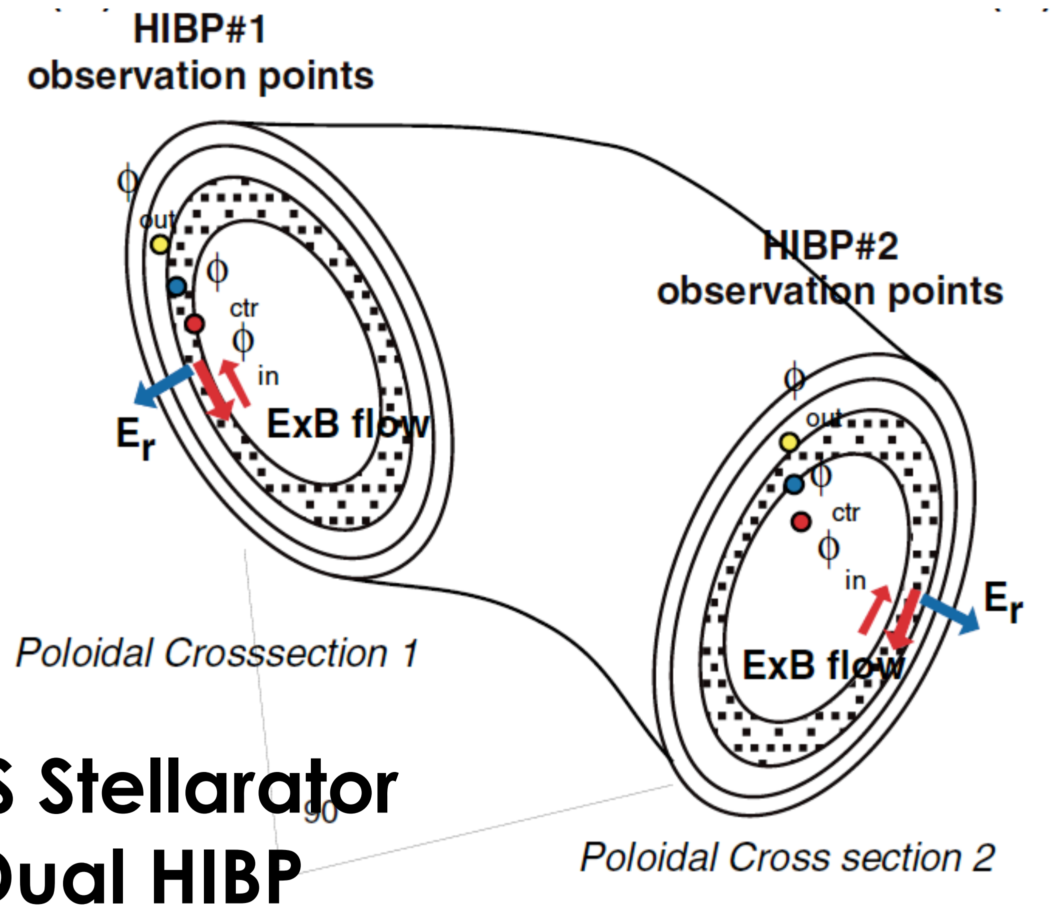
**Flow**

**Eddy Shearing**

*P. Diamond, Plasma Phys. Control. Fusion* **47**, *R35 (2005)*

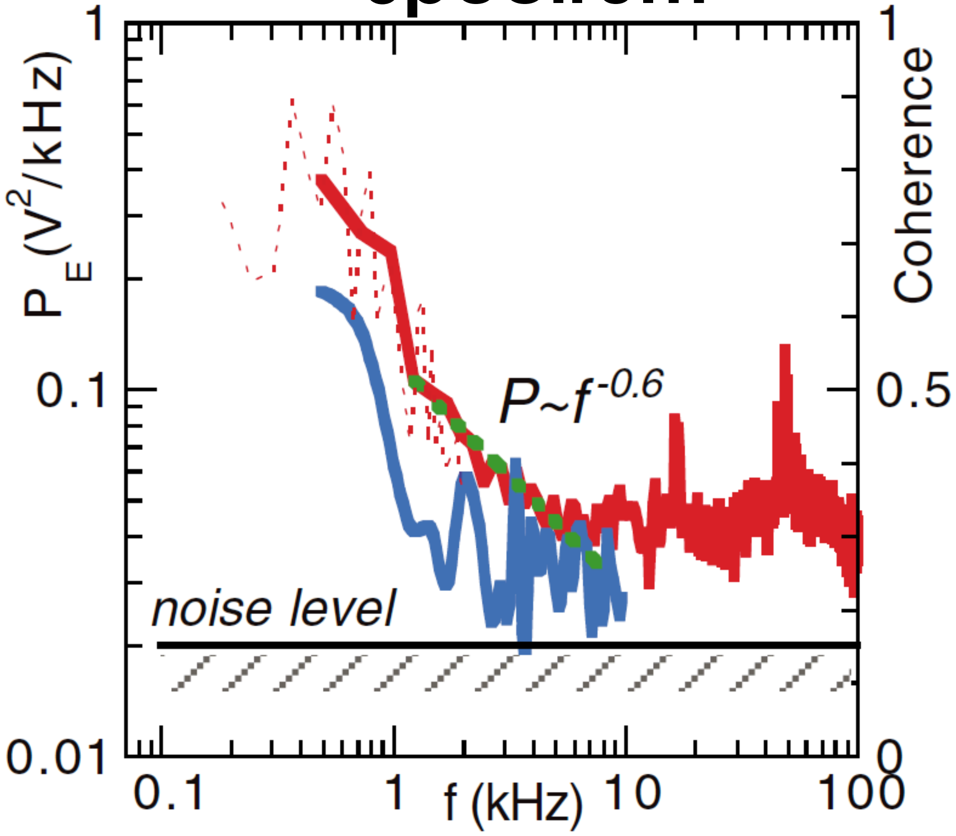
# Electrostatic Structures with Zonal Flows Features Observed in CHS Stellarator with Dual Heavy Ion Beam Probe

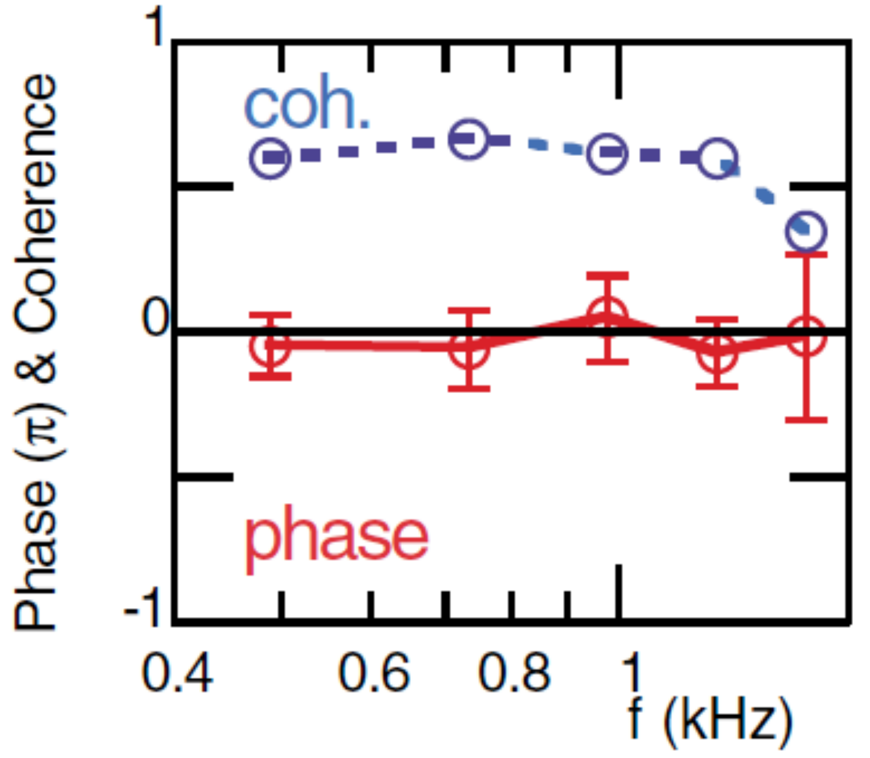
- **Measured characteristics:**
  - n=0 (axisymmetric)
  - Highly coherent over toroidal separation
  - Low frequency (0.3-2 kHz, ion collisions?)
  - Radially-localized (~2 cm wide)



**CHS Stellarator**
**Dual HIBP**

## Potential Fluctuation Spectrum

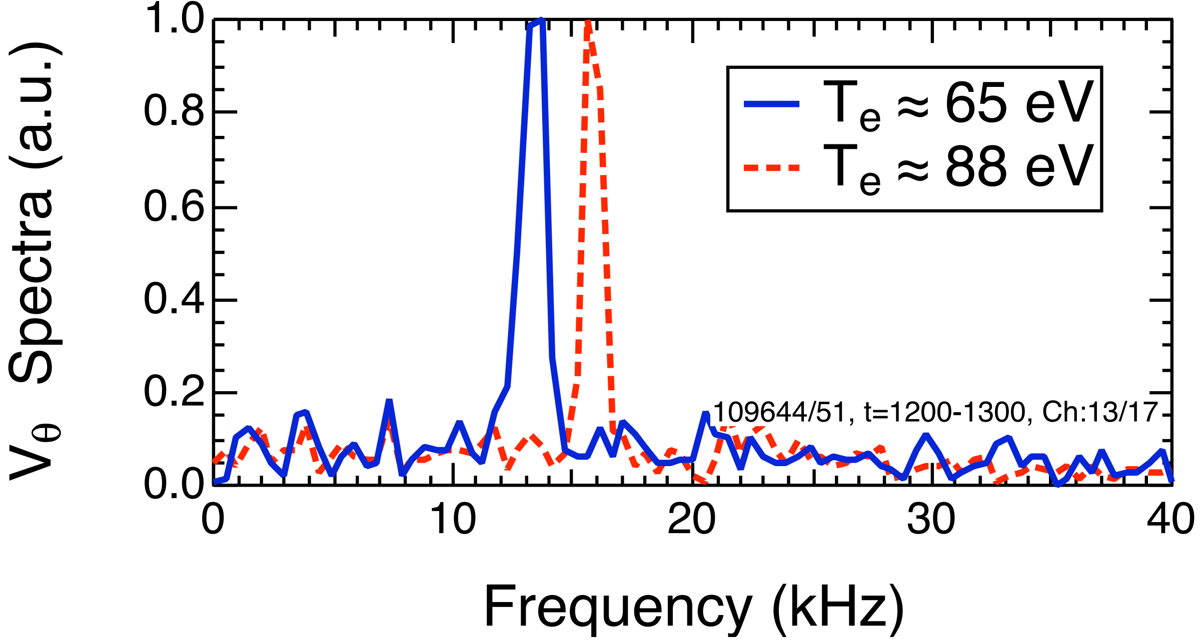




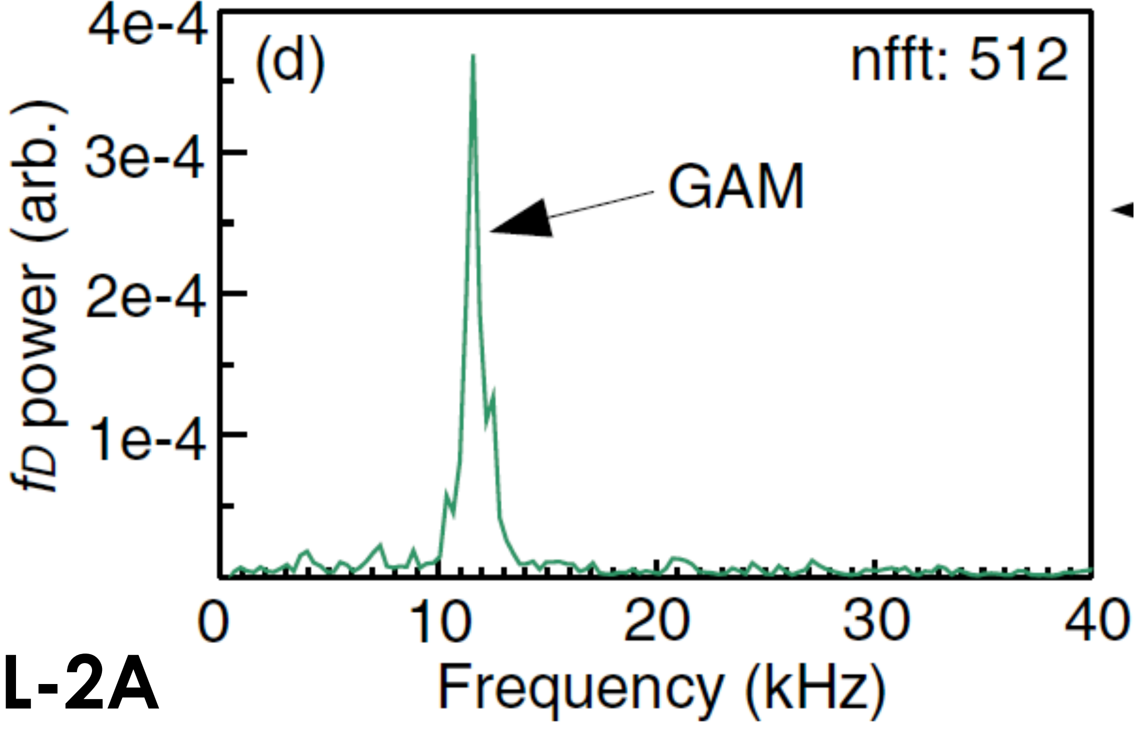
**CHS** *A. Fujisawa, Phys. Rev. Lett.* ***93****, 165002 (2004)*

# Search for Zonal Flows Reveals "Geodesic Acoustic Mode" in Outer Region of Toroidal Plasmas

## Coherent Poloidal Velocity Oscillations (BES on DIII-D)

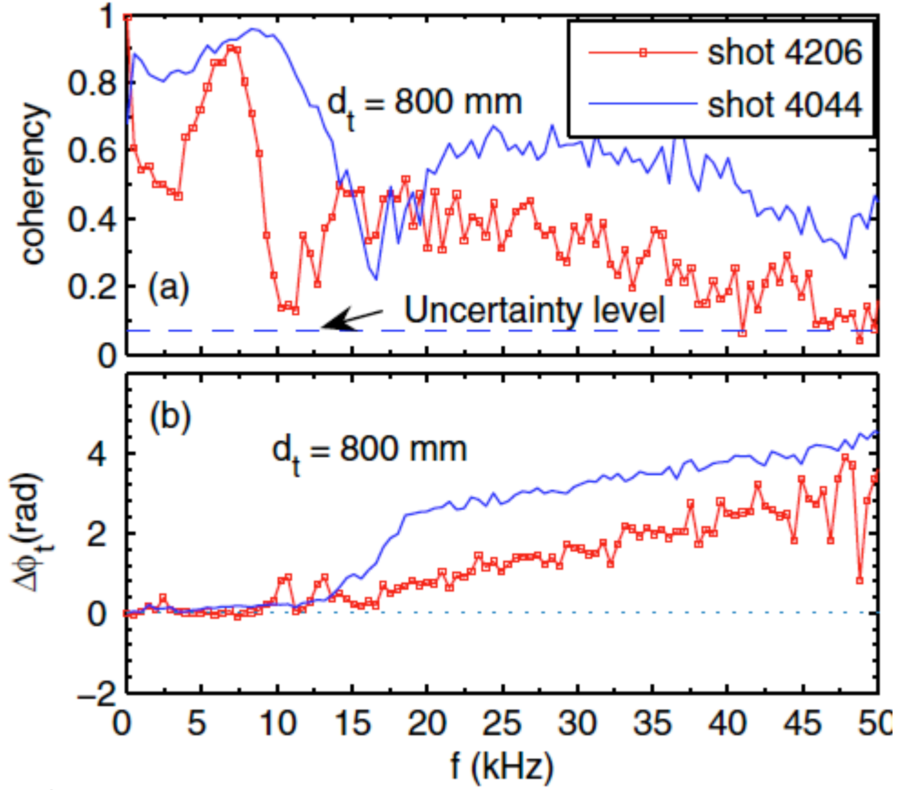


## Doppler Backscattering on ASDEX-U

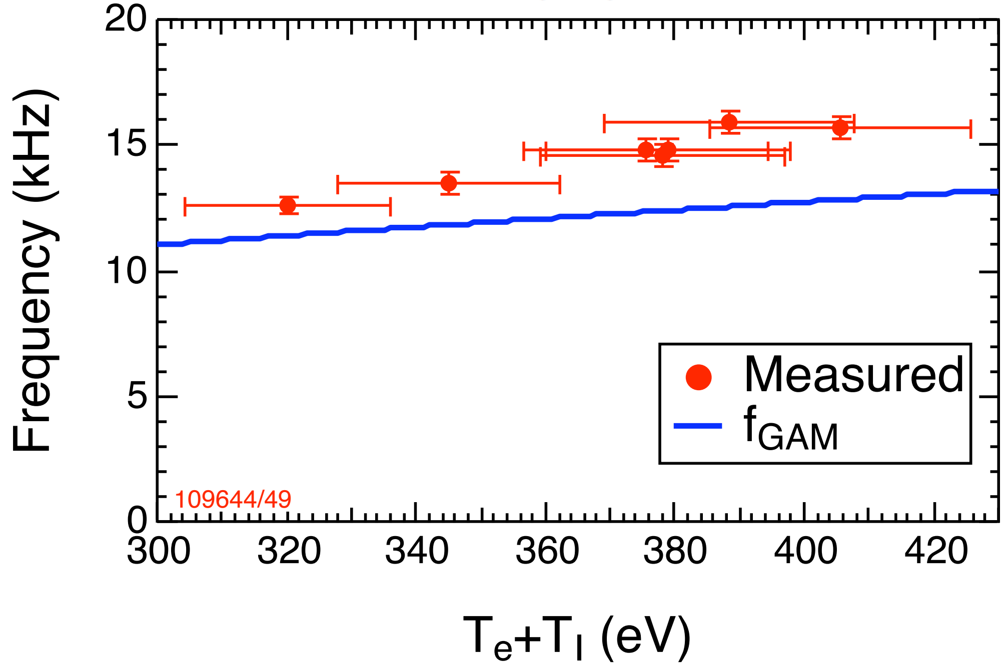


**HL-2A**

## Probes (HL-2A) show toroidal symmetry, n=0 structure



**GAM**



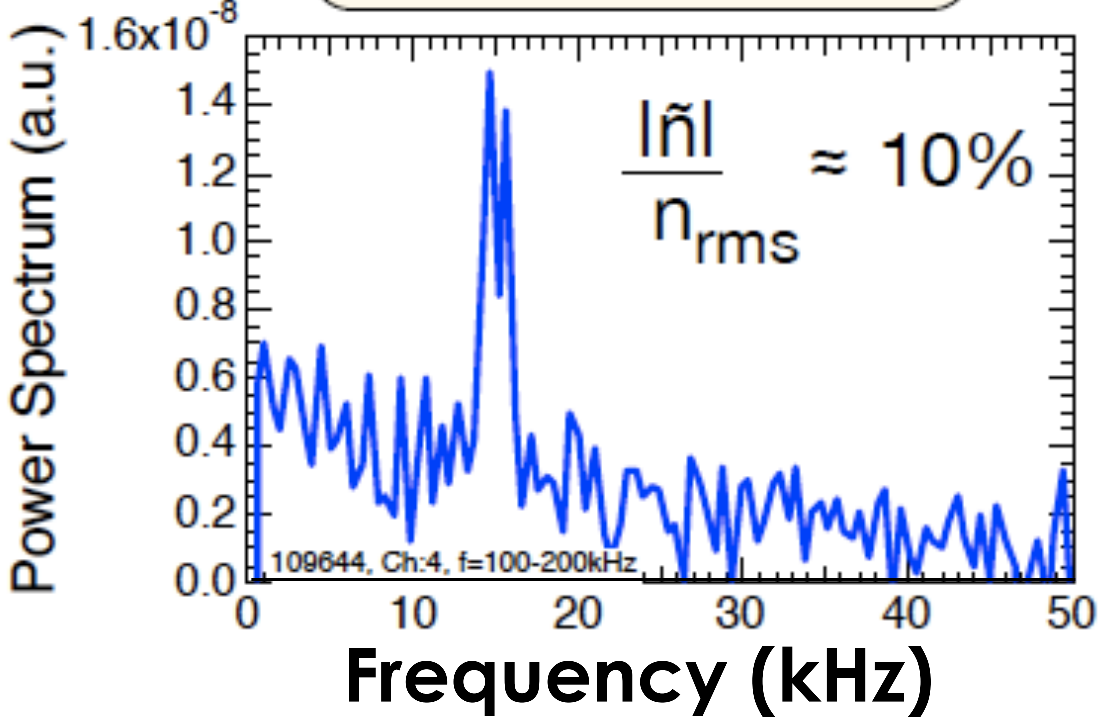
*G. McKee, Phys. Plasma* ***10****, 1712 (2003)*
*G. Conway, Plasma Phys. Control. Fusion* ***47****, 1165 (2005)*
*K.J. Zhao, Phys. Rev. Lett.* ***96****, 255004 (2006)*

DIII-D NATIONAL FUSION FACILITY

IPP Max-Planck-Institut für Plasmaphysik

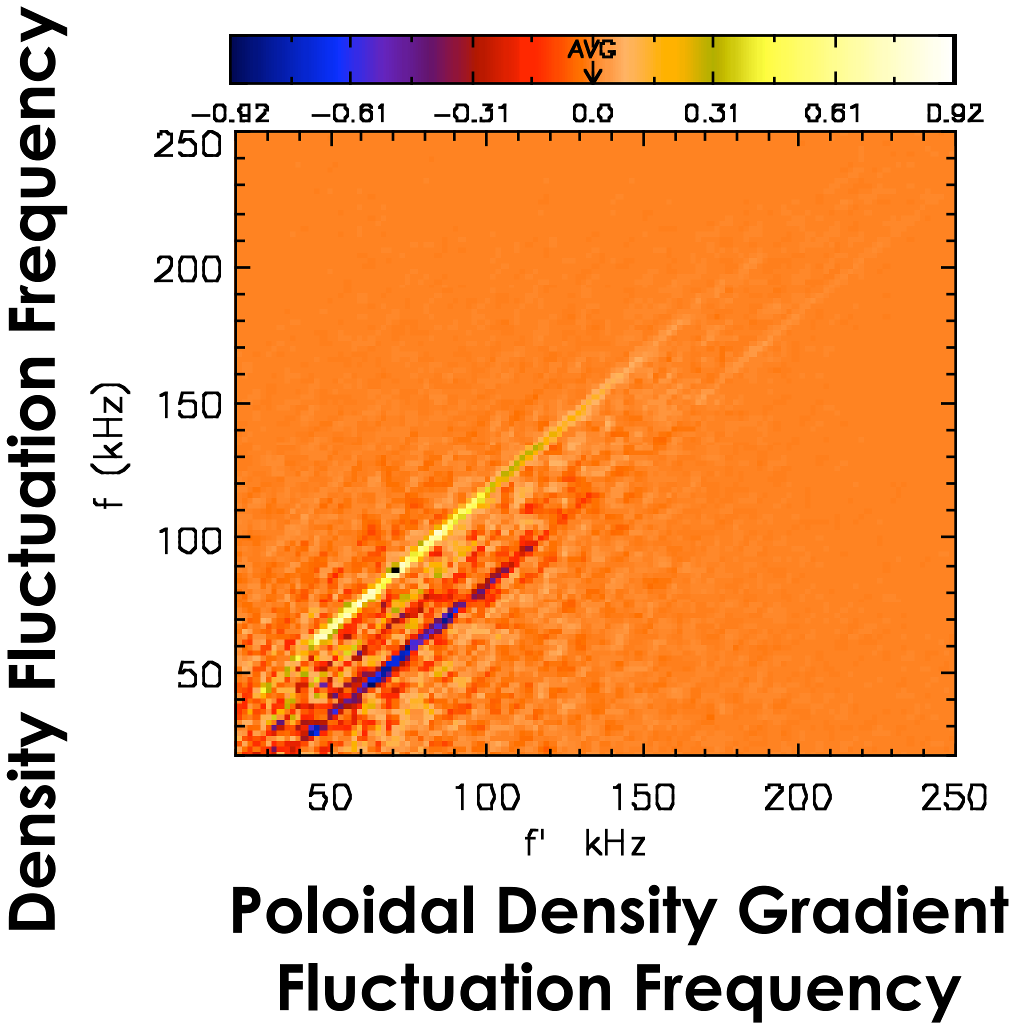
# GAM Modulates Turbulence Amplitude and Mediates Transfer of Internal Energy from Lower to Higher-Wavenumber

Power Spectrum of Fluctuation Envelope



**Energy Transfer measured via Bispectrum of ñ, dñ/dy, $V_\theta$ fluctuations**

$$T_n^Y(f',f) = -\mathrm{Re}\left\langle n^*(f)\,V_y(f-f')\,\frac{\partial n}{\partial y}(f')\right\rangle$$



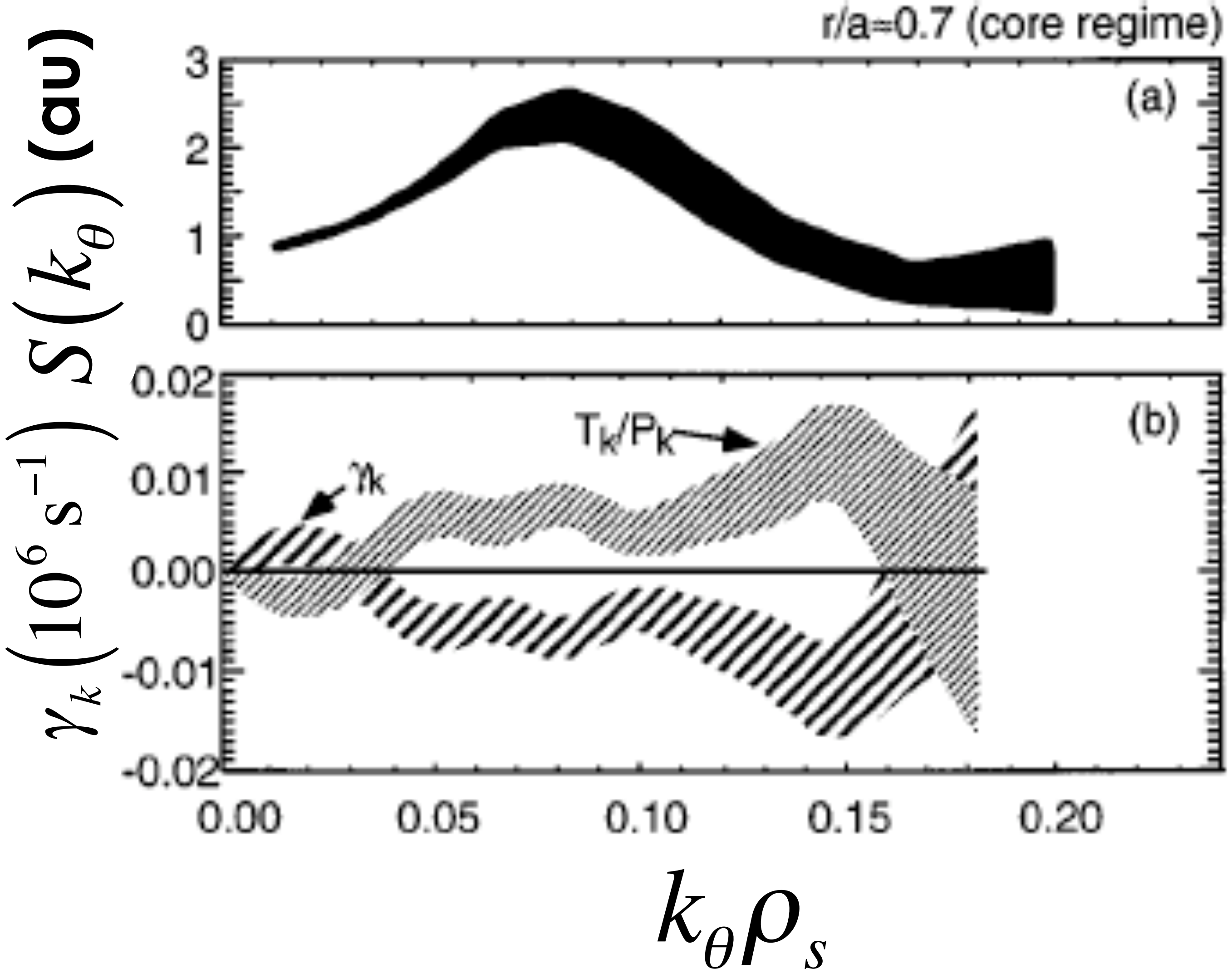
*C. Holland, Phys. Plasmas* ***14****, 056112 (2007)*
*G. McKee, Phys. Plasmas* ***10****, 1712 (2003)*

# Nonlinear Analysis Demonstrates Energy Transfer to Higher-Wavenumber Dissipation Region

- **Calculation of energy transfer via bispectral analysis technique**
  - Modified "Ritz" Method:

$$\frac{\partial\varphi(k,t)}{\partial t}=\Lambda_k^L\varphi(k,t)+\frac{1}{2}\sum_{\substack{k_1,k_2\\k=k_1+k_2}}\Lambda_k^Q(k_1,k_2)\varphi(k_1,t)\varphi(k_2,t)$$

- **Peak growth rate *not* at spectral peak**



**BES@TFTR**

n, *Phys. Rev. Lett.* ***79****, 841 (1997)*

# Outline and Major Themes

- Introduction, Motivation and Measurement of Turbulence
- Turbulence Characteristics Consistent with Theory
  - Spatial structure exhibit strong radial-poloidal asymmetry
  - Relation to radial transport
  - Saturation via self-driven Zonal Flows and dissipation
- **Behavior and Dependence on Plasma Transport Parameters**
  - Amplitudes and spatiotemporal characteristics scale with gyrokinetic parameters (ion gyroradius, gyrokinetic time scale, $a/c_s$)
  - Dominant instabilities depend on plasma collisions
  - Consistent with predicted linear instabilities
- Testing, Challenging and Validating Nonlinear Simulations
  - Quantitative comparisons show generally good agreement
  - Cases of disagreement leading to refinement of physics models
- Controlling turbulence offers potential to improve performance

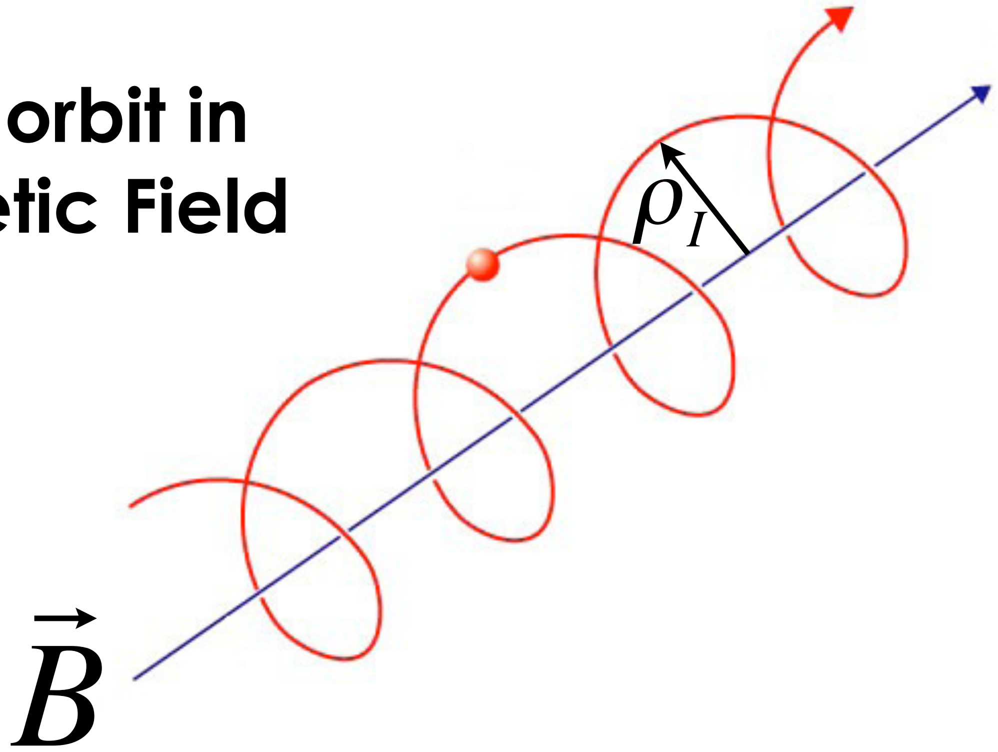
# $\rho$ * Dependence of Turbulence Characteristics

$\rho$ - ion gyroradius,  a - minor radius of toroidal plasma

$\rho$ *= $\rho_I$/a is a dimensionless size scaling parameter

$\rho$ *: experiments do not achieve reactor scale values; large extrapolation required

**Gyro-orbit in Magnetic Field**



**Theory predicts:**

$$L_{c,r} \sim \rho_I$$

$$\tau_c \sim a/c_s$$

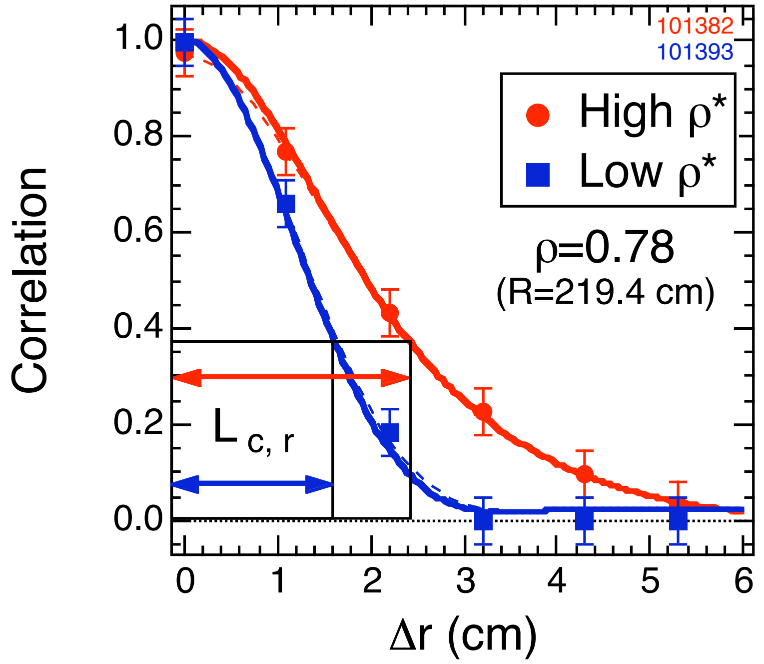
$$\tilde{n}/n \sim \rho^*$$

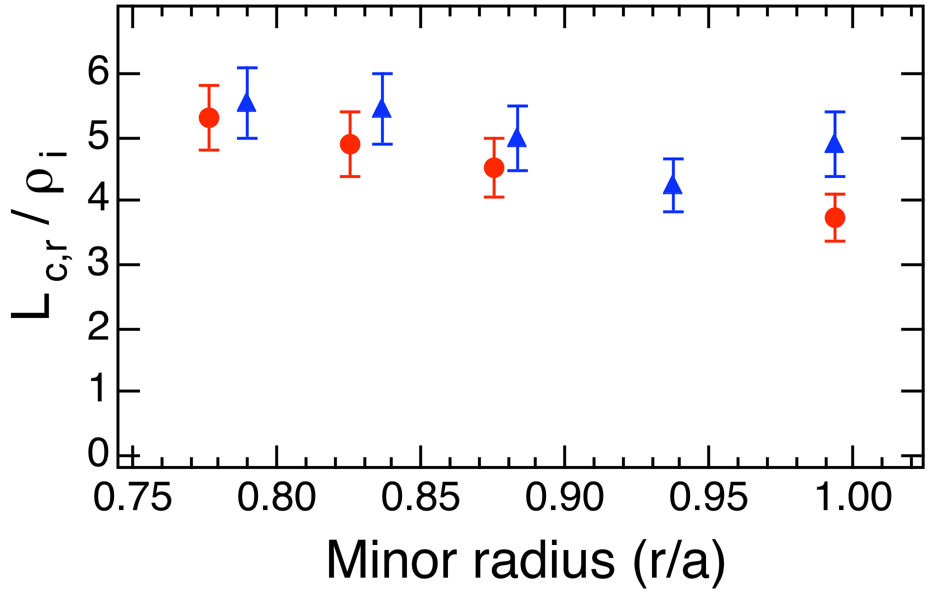
$$\Gamma \sim \left(\rho^*\right)^2$$

$\rho_I$, $\rho_e$ expected to set fundamental turbulence length scales

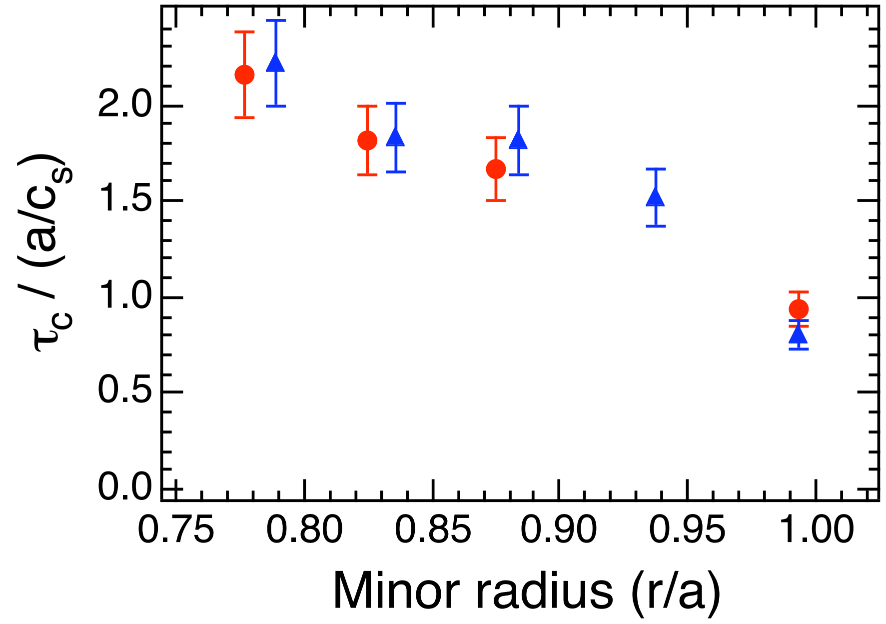
# Radial Correlation Length Scales with Ion Gyroradius Decorrelation Time Scales as Gyrokinetic Time Scale (a/c$_s$)

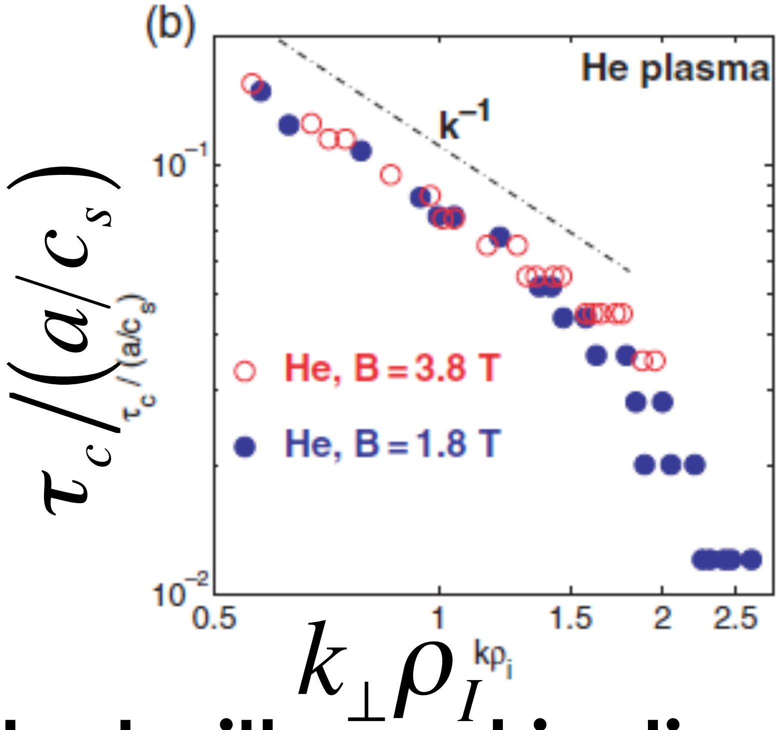
## Radial correlation length





## Correlation Time





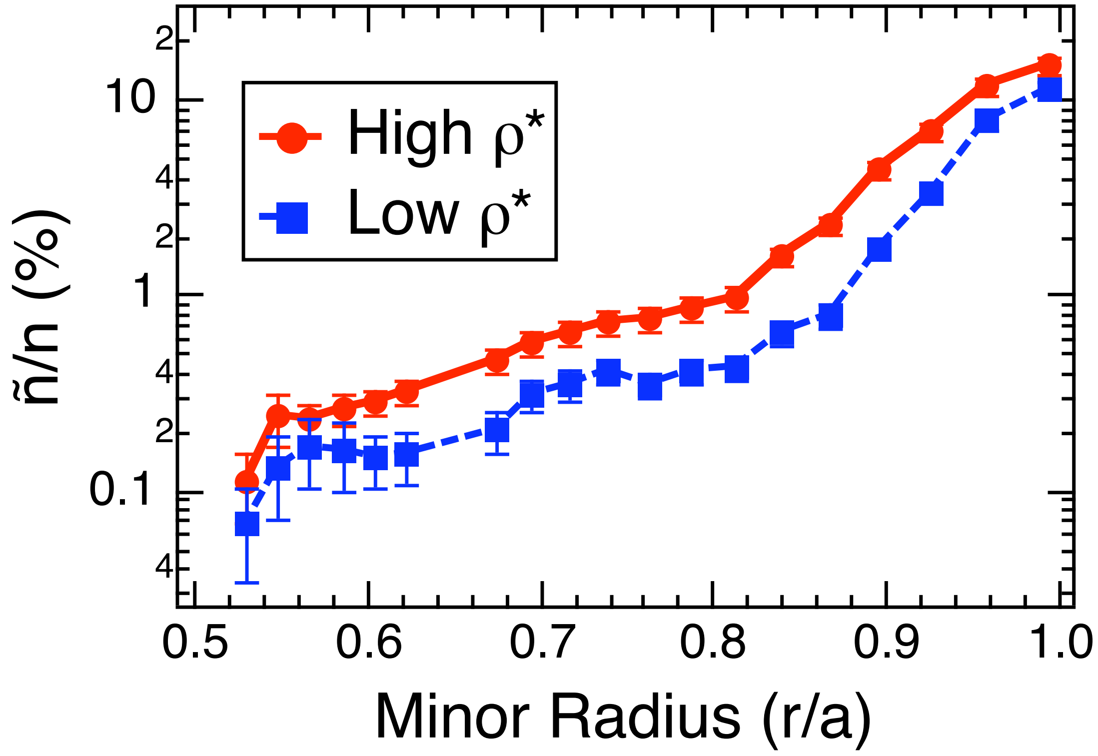
$$\tau_c \sim a/c_s$$

- **Spatiotemporal characteristics consistent with gyrokinetic equations**

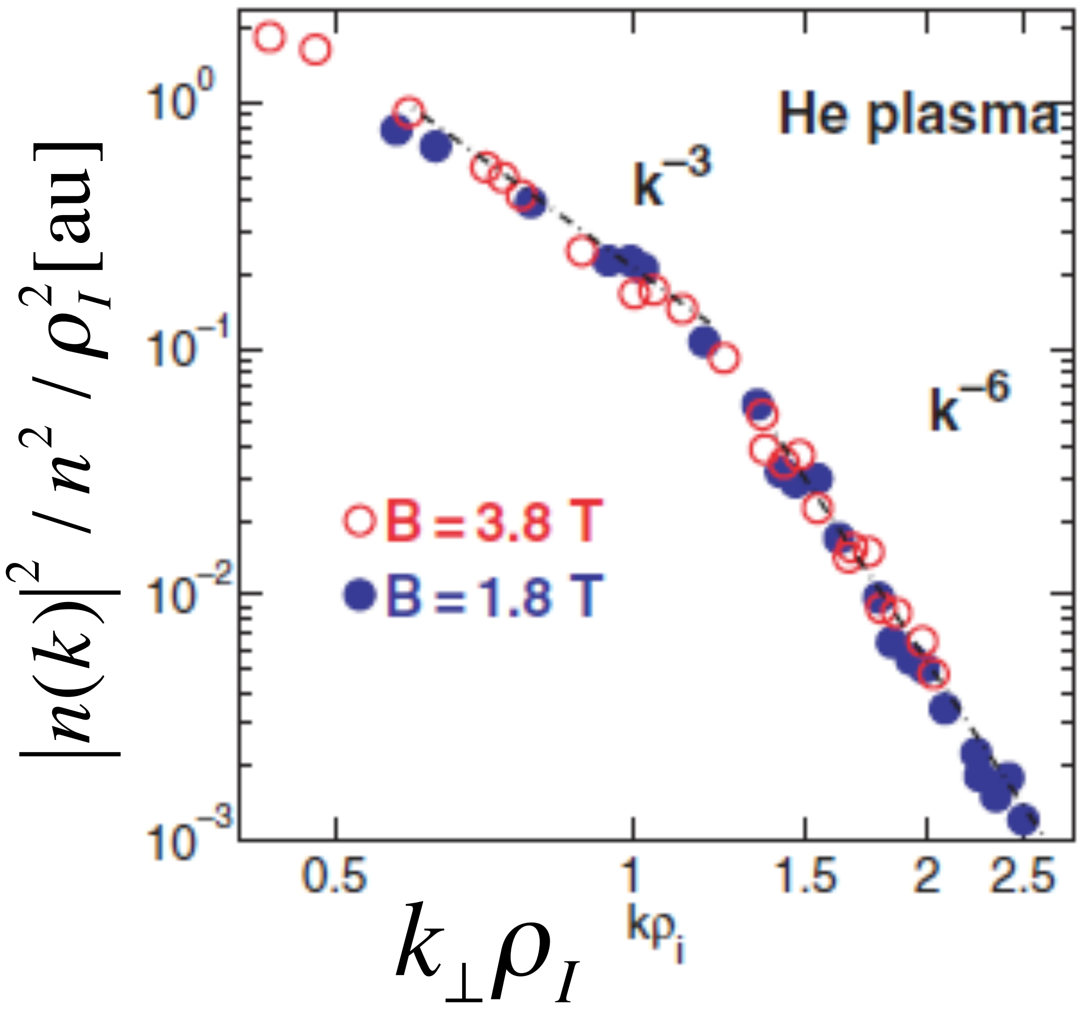
*G. McKee, Nuclear Fusion* ***41****, 1235 (2001)*
*P. Hennequin, Plasma Phys. Control. Fus.* ***46****, B121 (2004)*

# Turbulence Amplitude Profile and Wavenumber Spectra scale with Ion Gyroradius ( $\rho_I^*$)

**$\rho$ * Scaling of ñ/n**



**Wavenumber Spectra at two toroidal fields**



- **Taken together, these measurements show quantitative agreement with scaling predictions of gyrokinetic equations**

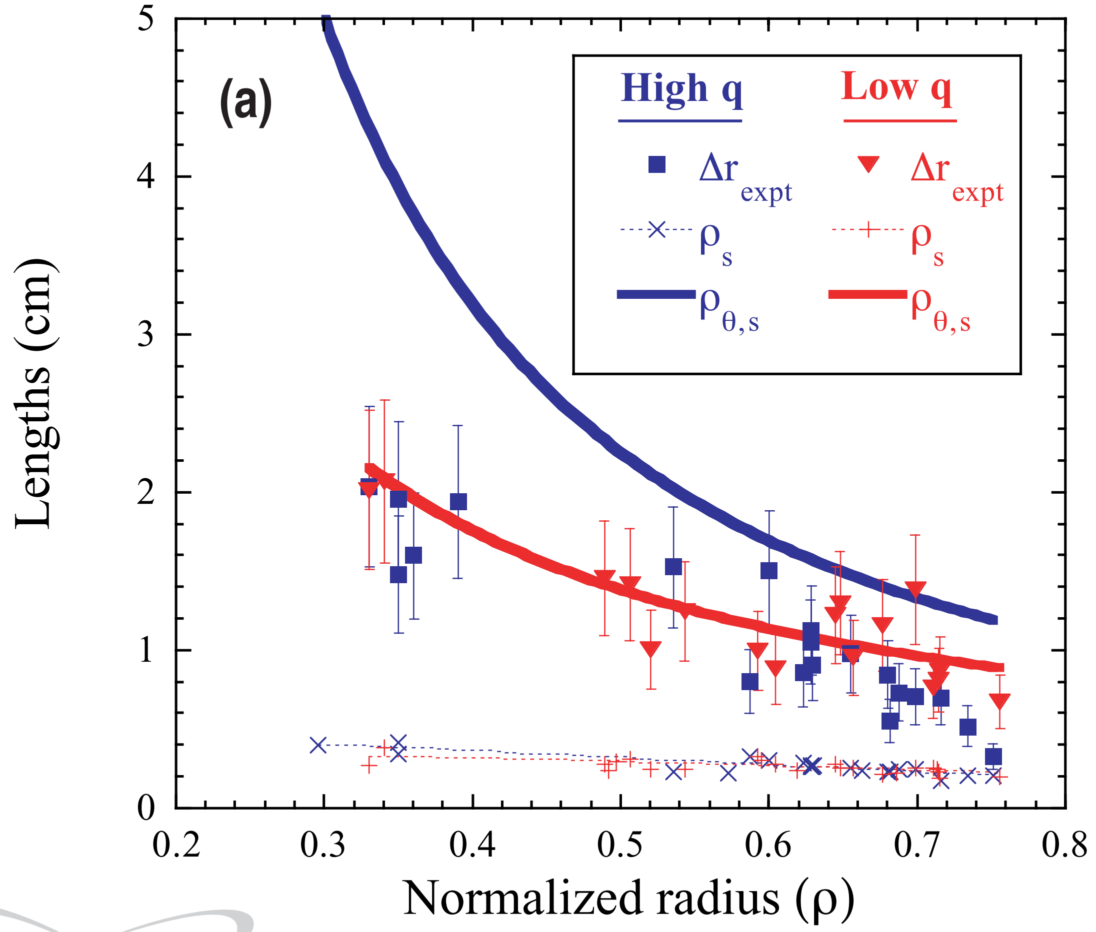
*G. McKee, Nuclear Fusion **41**, 1235 (2001)*

*P. Hennequin, Plasma Phys. Control. Fus. **46**, B121 (2004)*

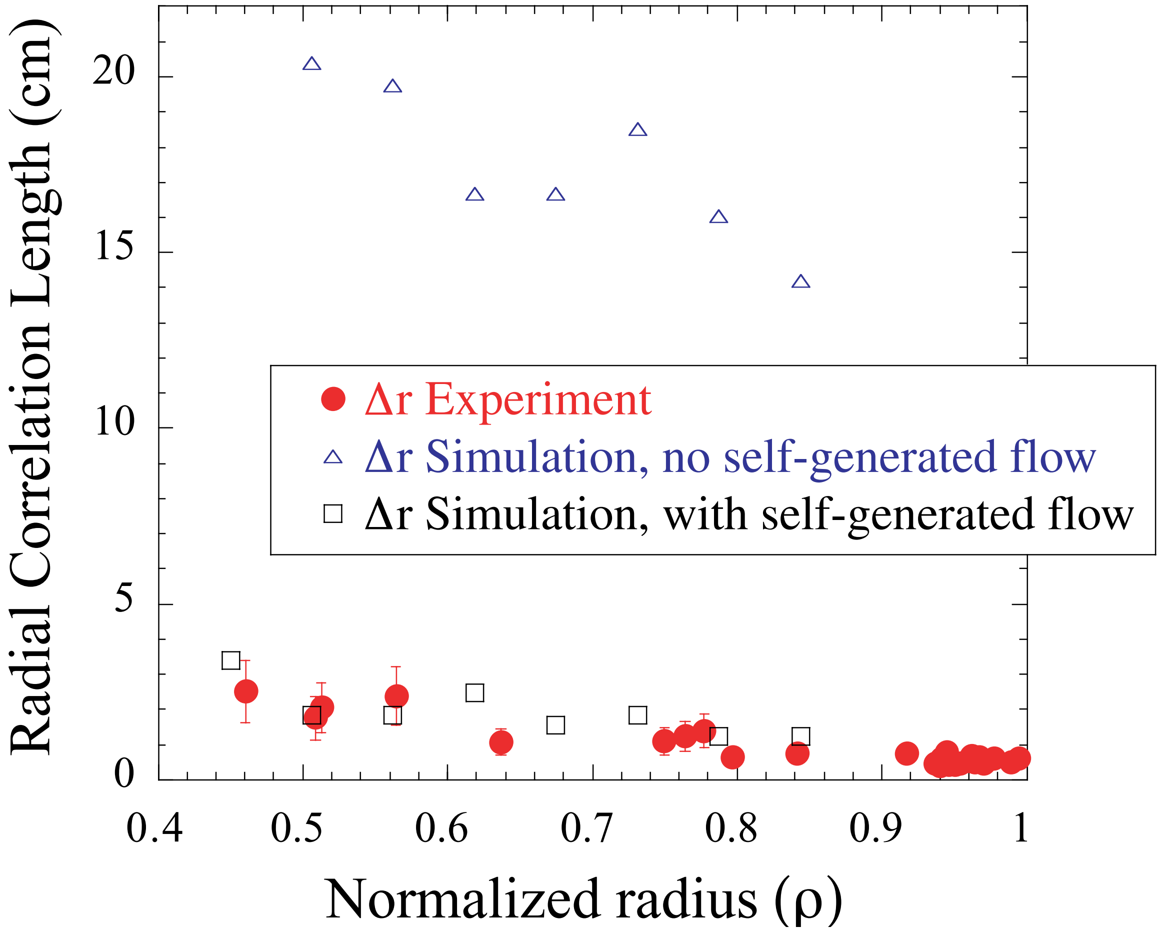
# Turbulence Correlation Lengths Scale with the Toroidal Ion Gyroradius, consistent with Simulations

- **Scaling with Toroidal vs Poloidal ion gyroradius determined via current variation**
  - Demonstrates clear $\rho_I$ (and *not* $\rho_\theta$) scaling
  - Important for distinguishing between various models
- **Simulations must include zonal flow shearing to obtain proper scale lengths**

**$L_{c,r}$ scaling**



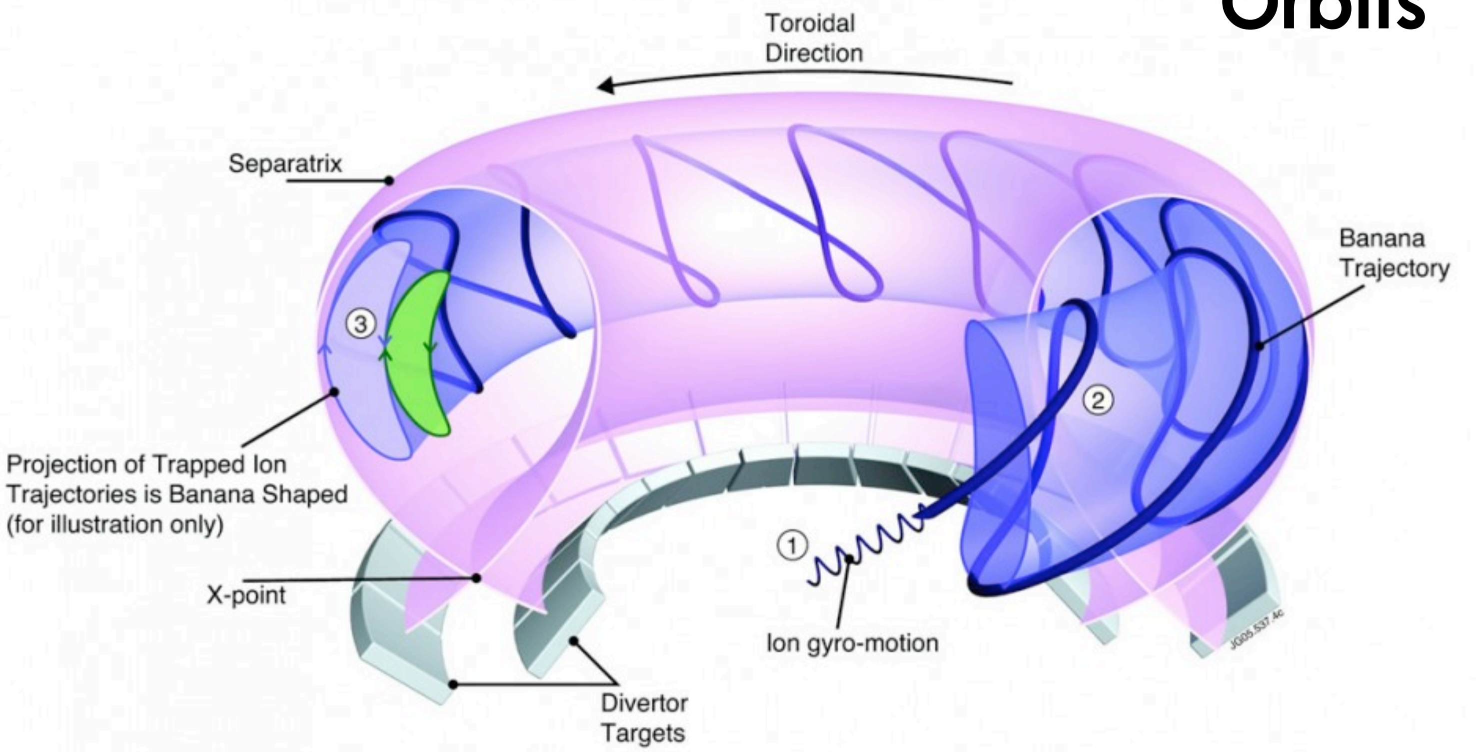
**Zonal Flow Effects**



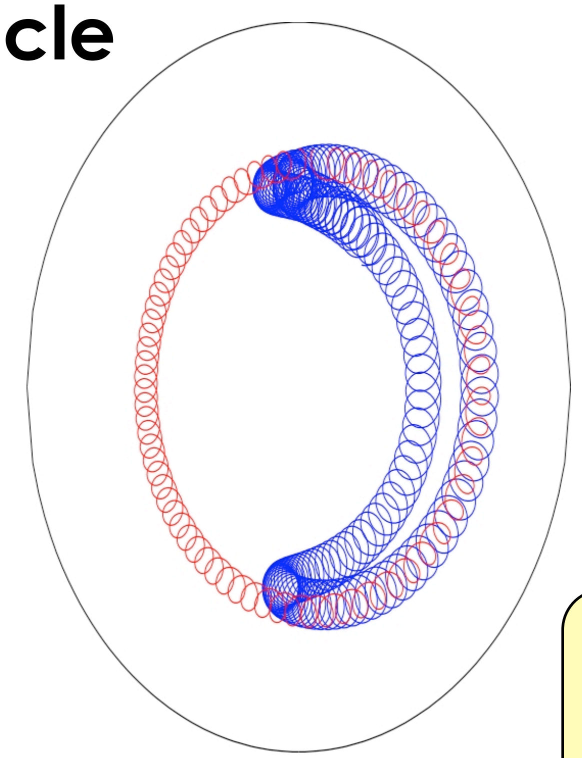
*T. Rhodes, Phys. Plasmas* ***9****, 2141 (2002)*

# Density and Collisionality Dependence of Turbulence Characteristics

## - Identification of Underlying Instability Modes Driving Turbulence



**Trapped Particle Orbits**

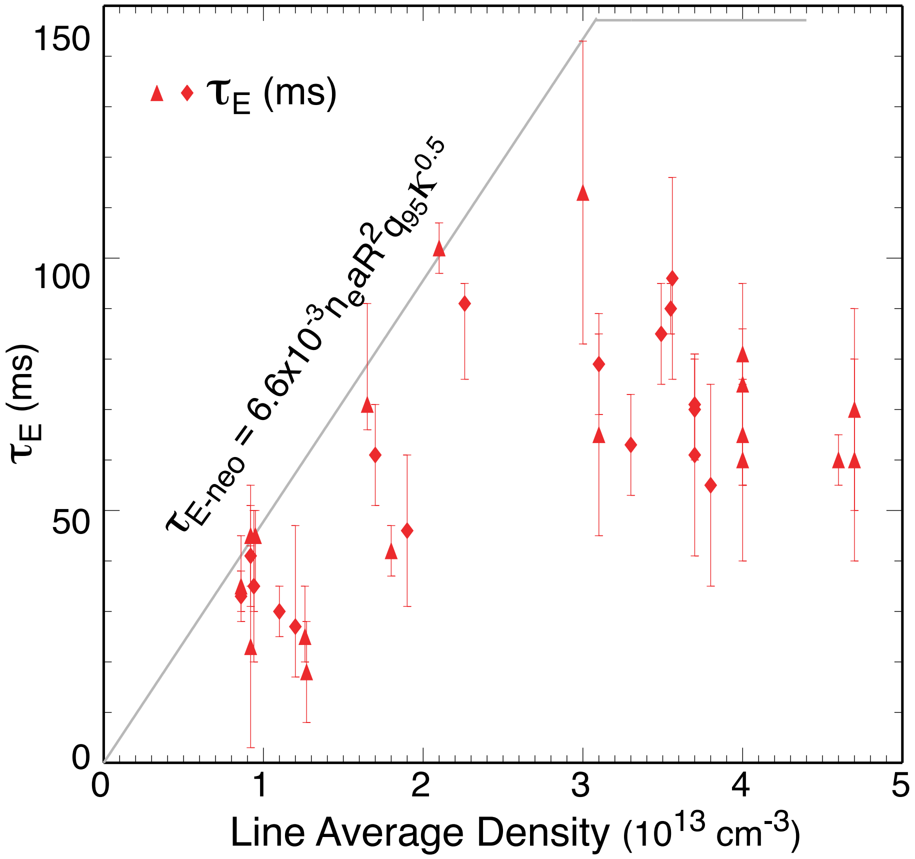


$$\nu_* \equiv \frac{\nu_{ii}}{\omega_b} \sim \frac{na}{T^2}$$

# Long-Wavelength Fluctuations Increases at Higher Density: Transition to “Saturated Ohmic Confinement” Region

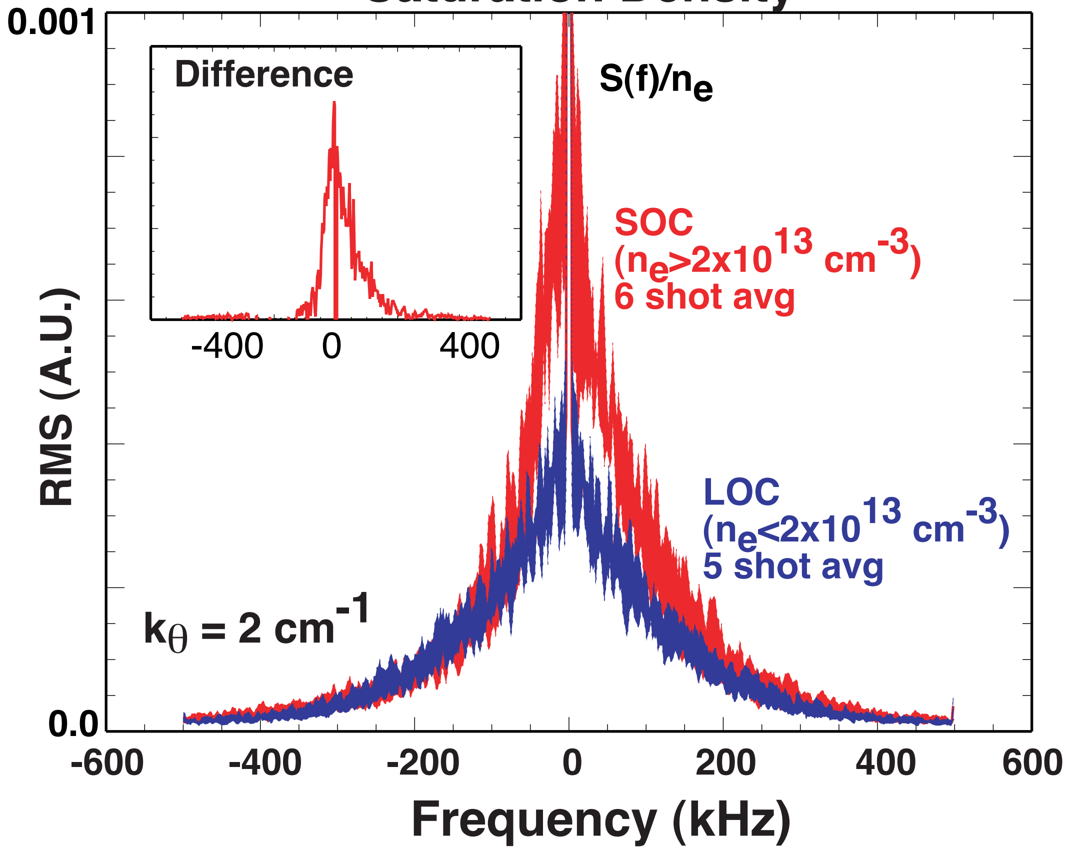
- **Confinement increases linear with density at low density (Alcator-A)**
  - Linear ohmic confinement (LOC)
- **Confinement ~constant with density above threshold**
  - Saturated ohmic confinement (SOC)

**Energy Confinement Time vs Line Average Density**



## Far-Infrared Scattering Spectra

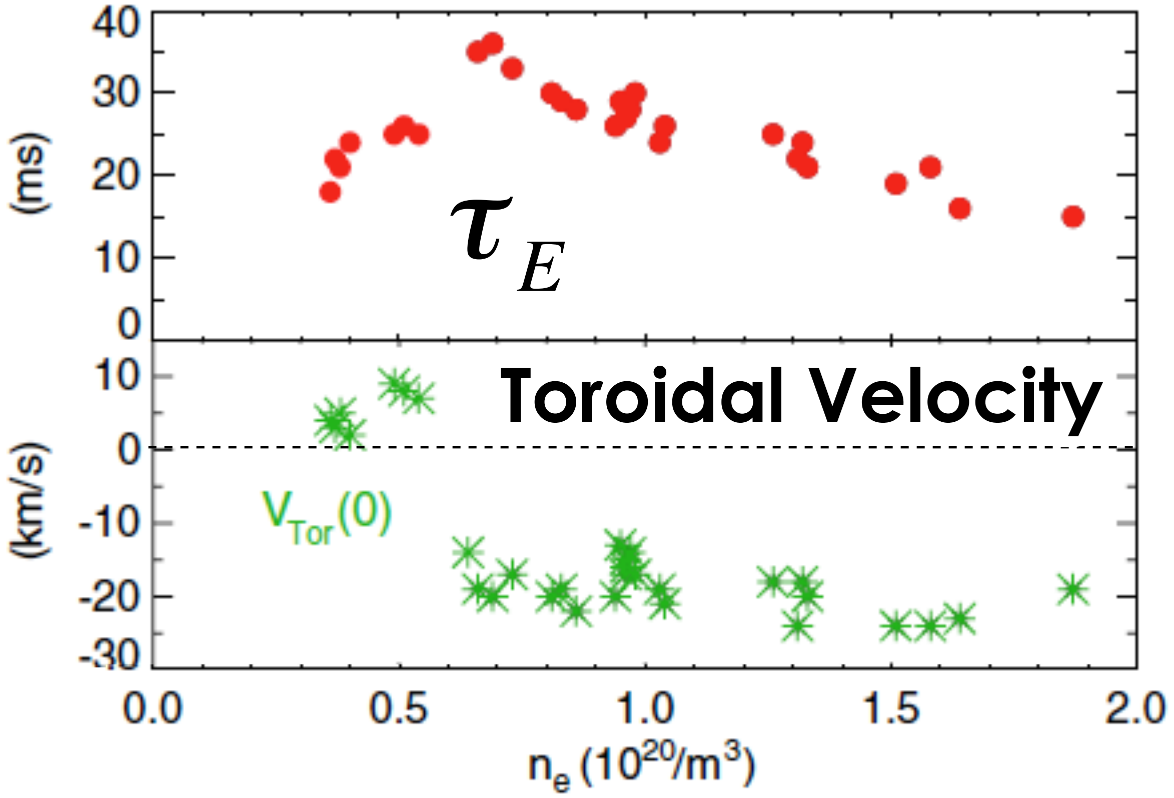
**Average of Multiple Discharges: Spectra are Well Separated by Saturation Density**



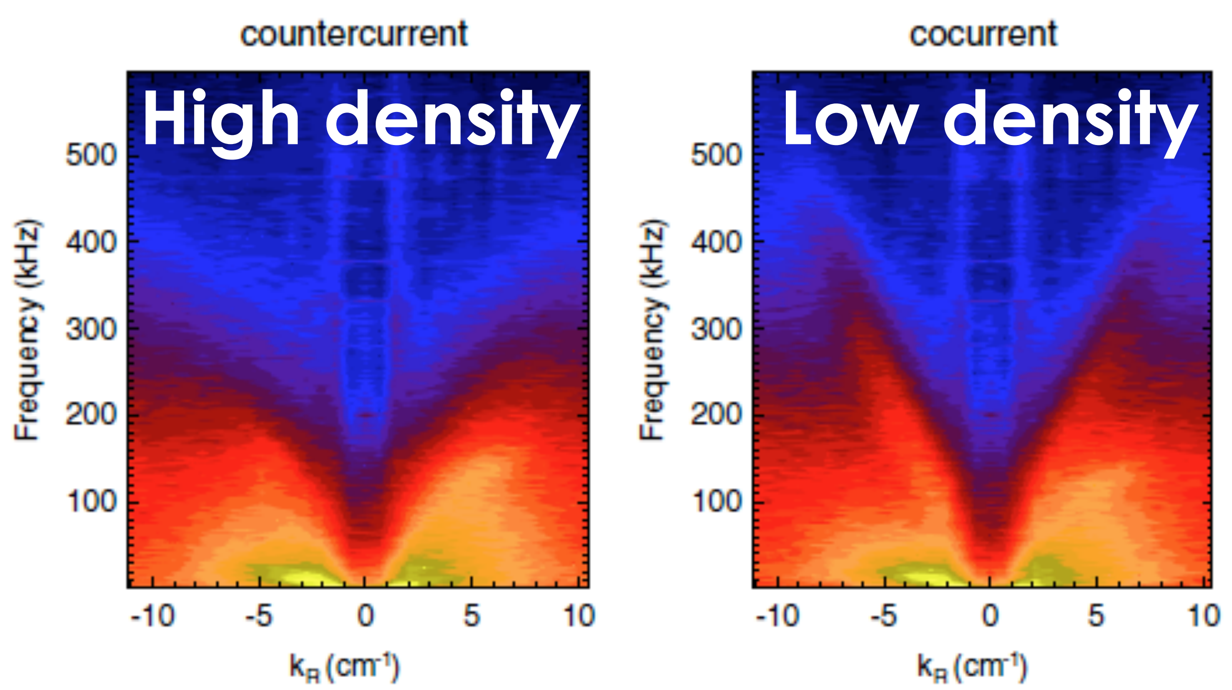
- **Long-wavelength mode consistent with expectations for ITG mode**

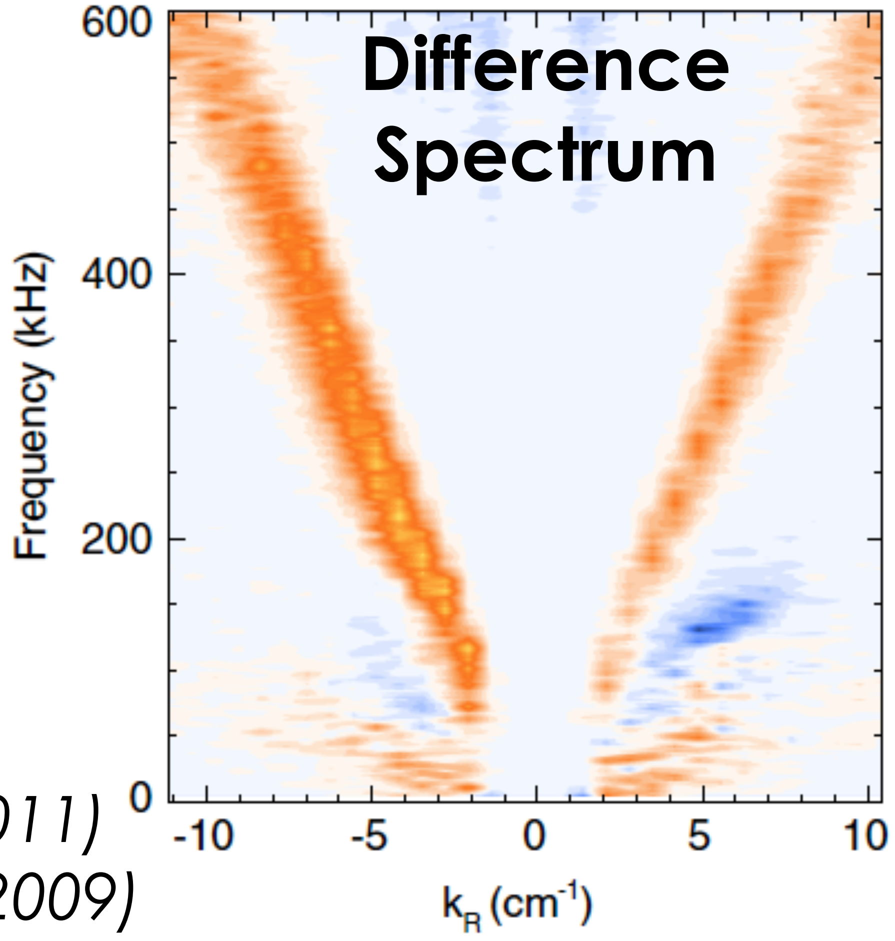
*C. Rettig, Phys. Plasmas* ***8****, 2232 (2001)*

# Core Turbulence Mode Structure Correlates with Changing Transport Properties



**S($k,\omega$) spectra**





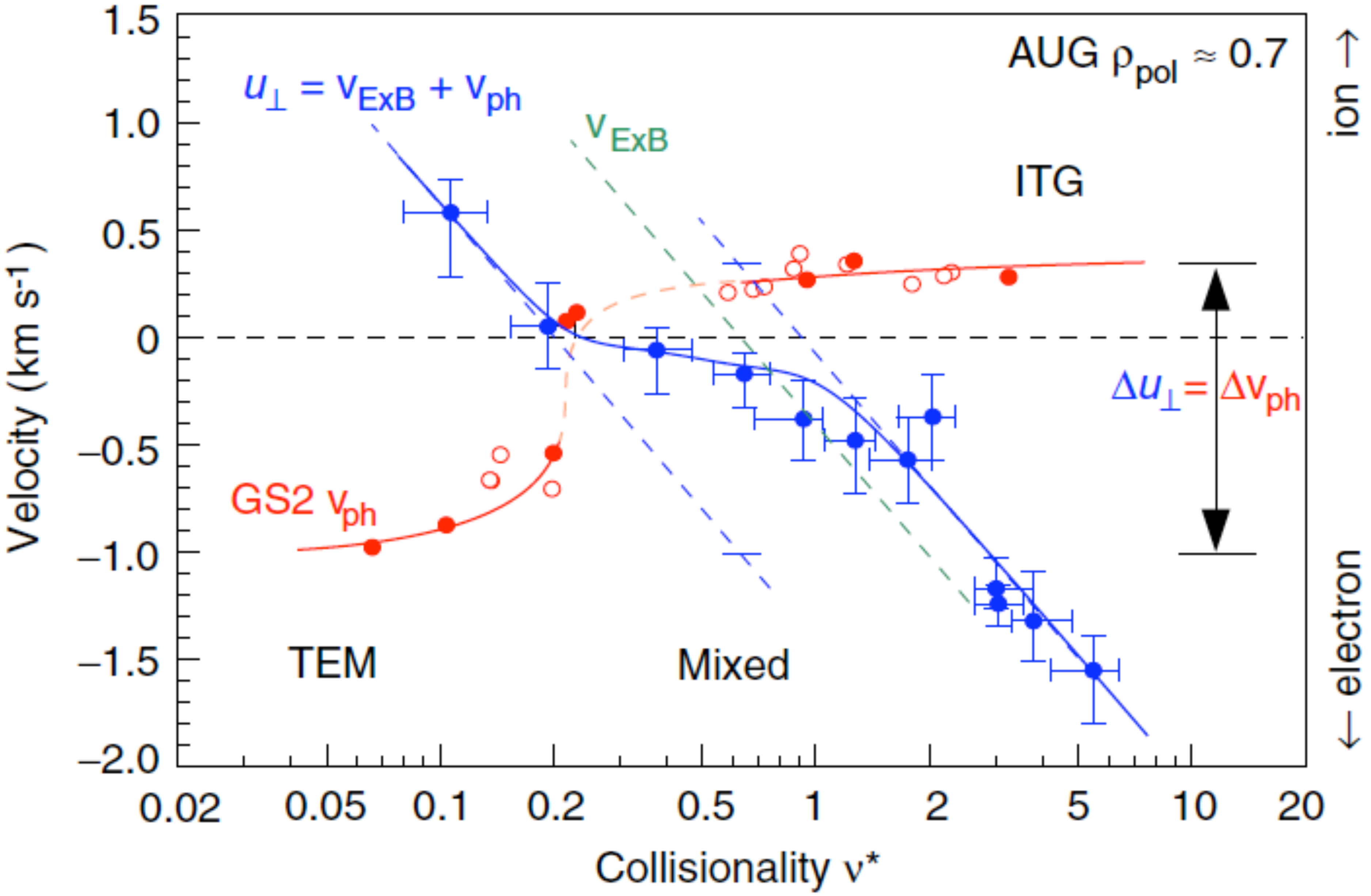
- **As density increases:**
  - Core intrinsic toroidal rotation reverses direction from co-$I_p$ to counter-$I_p$
- **Consistent with a change in dominant instability from TEM to ITG**
  - Turbulent Reynolds Stress => rotation reversal

*J. Rice, Phys. Rev. Lett.* ***107****, 265001 (2011)*
*P. Diamond, Nucl. Fusion* ***49****, 045002 (2009)*

Alcator C-Mod

# Drift Velocity Changes with Collisionality, Consistent with Change in Dominant Instability from TEM to ITG

**Laboratory Turbulence Mode Velocity**



**Doppler Backscattering**

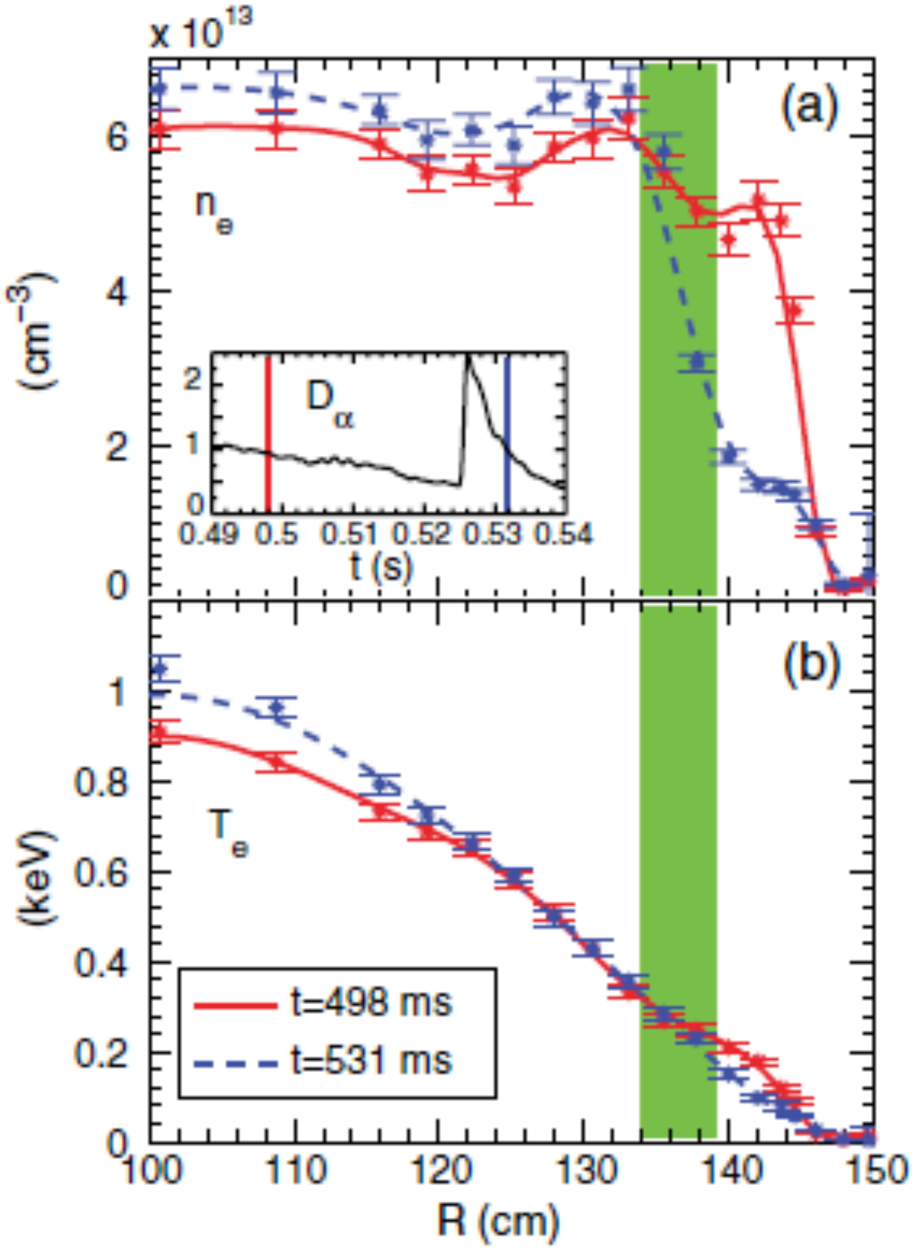
- **Theory predicts that higher collisionality will damp TEM and enhance ITG, consistent with changes in turbulence flow direction**

Max-Planck-Institut
für Plasmaphysik

*G. Conway, Plasma Phys. Control. Fusion* ***50****, 124026 (2008)*

# Increasing Density Gradient Reduces Small-Scale (Electron-Temperature-Gradient?) Turbulence

**Density gradient changes rapidly after "ELM" event**

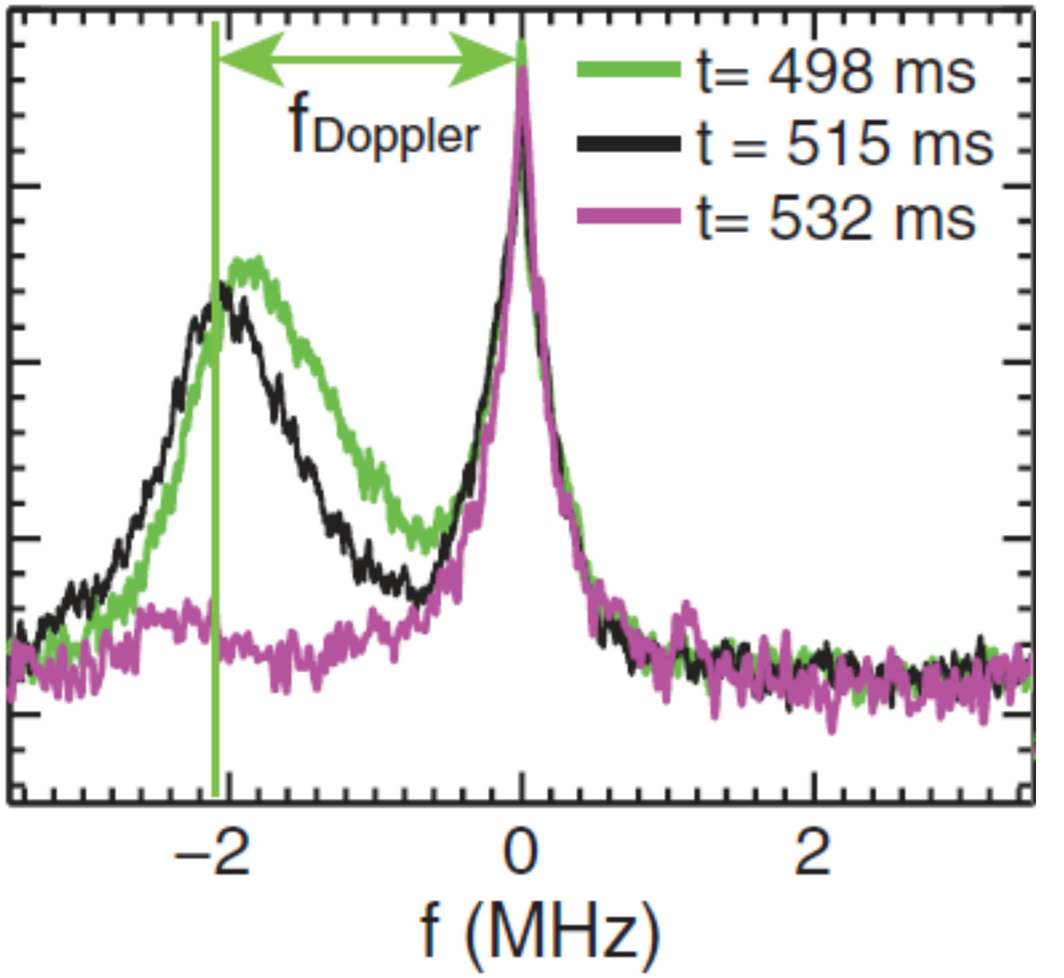


**Drive term for ETG:**

$$\eta_E = \frac{\nabla T_e / T_e}{\nabla n_e / n_e}$$

**Fluctuation Spectrum shows disappearance of higher-f feature at higher $\nabla n_e$**

**High-k Collective $\mu$-wave Scattering**



- **Electron scale ($\rho_e$) fluctuations respond as predicted for electron temperature-gradient-driven modes**

*Y. Ren, Phys. Rev. Lett.* ***106****, 165006 (2011)*

# Outline and Major Themes

- Introduction, Motivation and Measurement of Turbulence
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  - Spatial structure exhibit strong radial-poloidal asymmetry
  - Relation to radial transport
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  - Consistent with predicted linear instabilities
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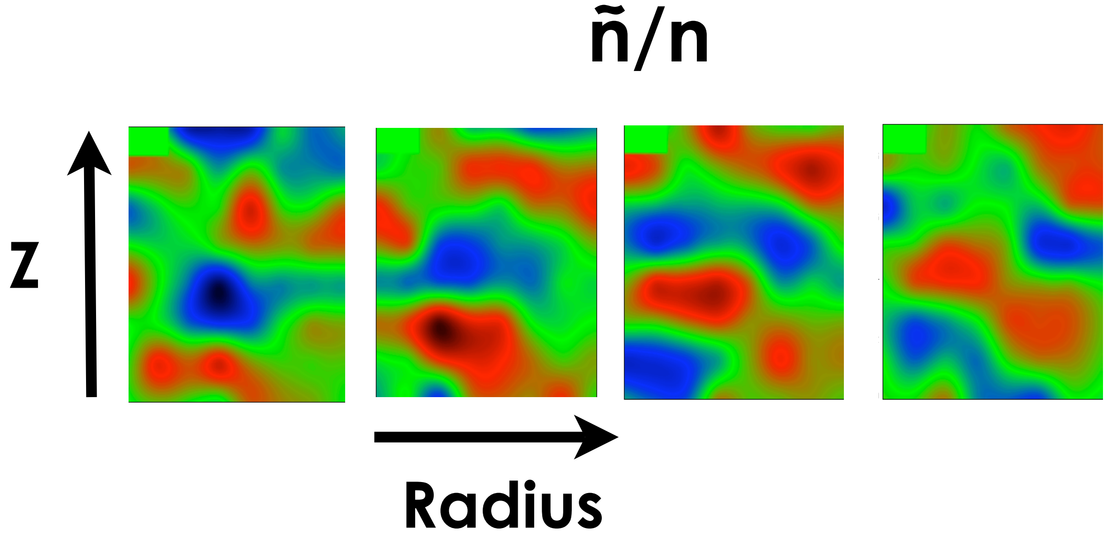
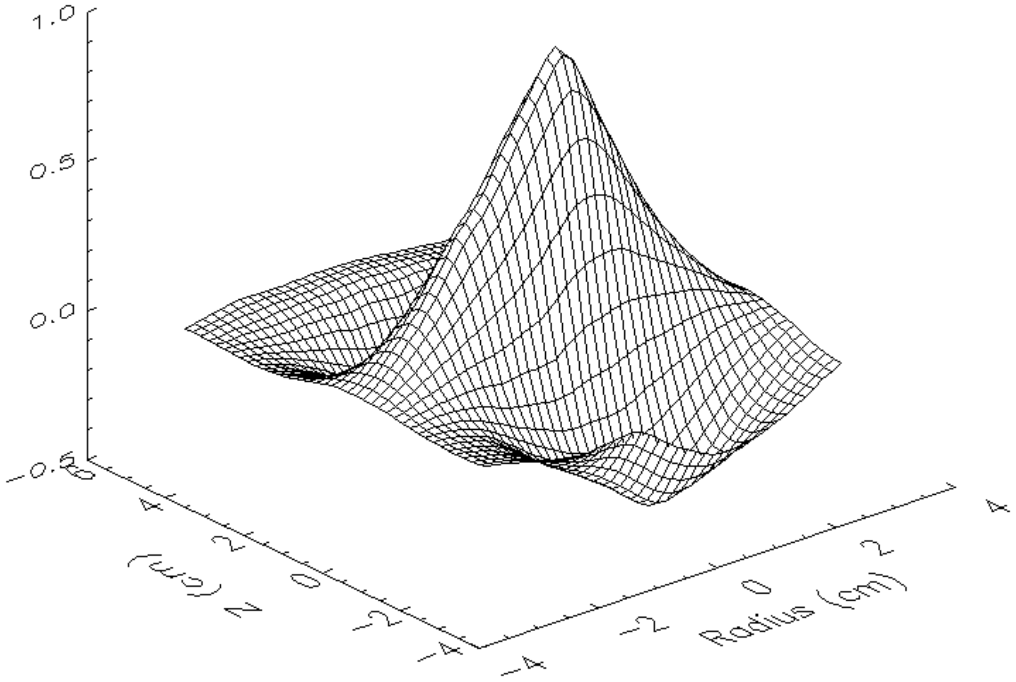
  - Quantitative comparisons show generally good agreement
  - Cases of disagreement leading to refinement of physics models
- Controlling turbulence offers potential to improve performance

# Nonlinear Simulations and Advanced Fluctuation Diagnostics Allow for *Quantitative* Comparisons of Turbulence Properties

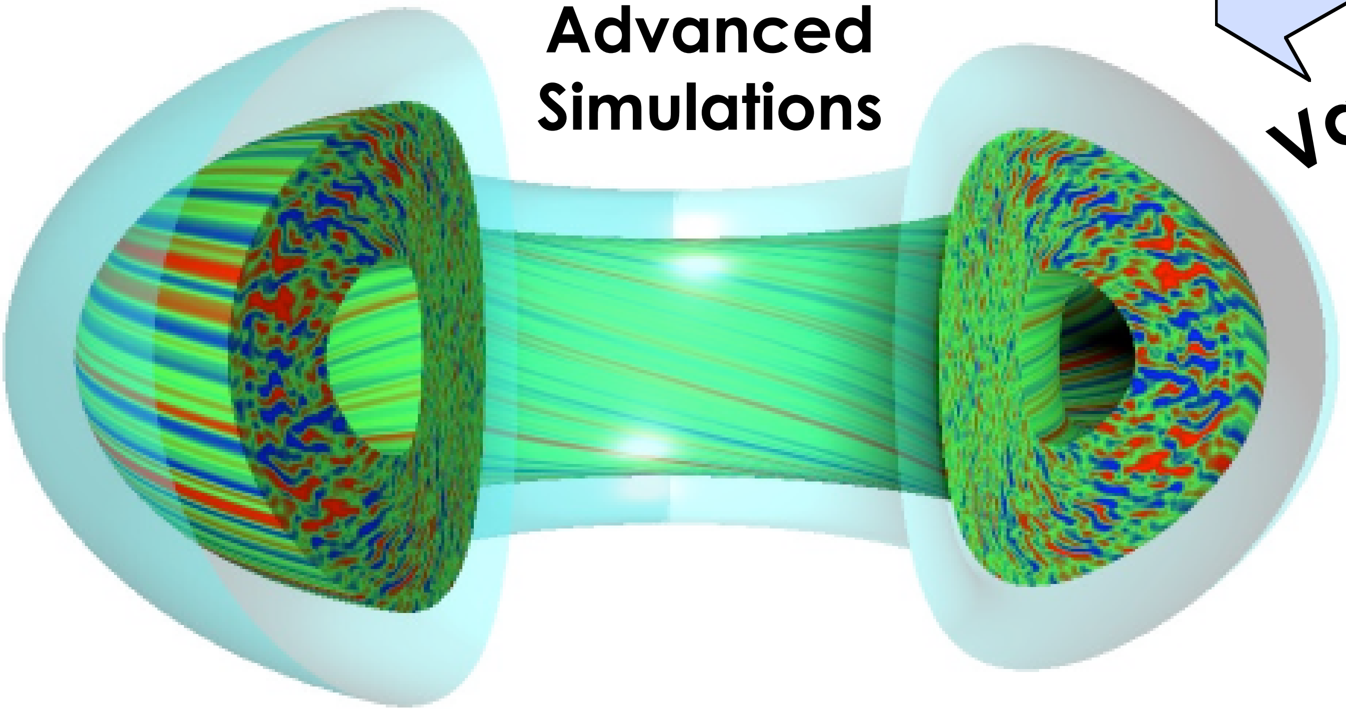




**Comparison**

**Validation**

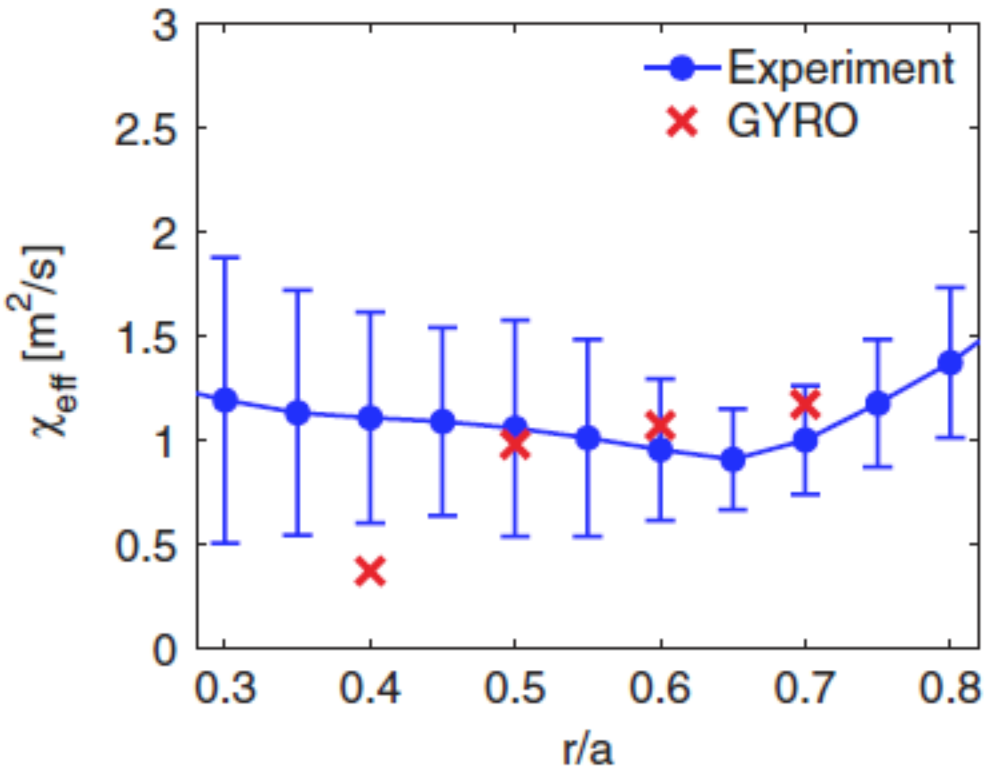
**Advanced Simulations**

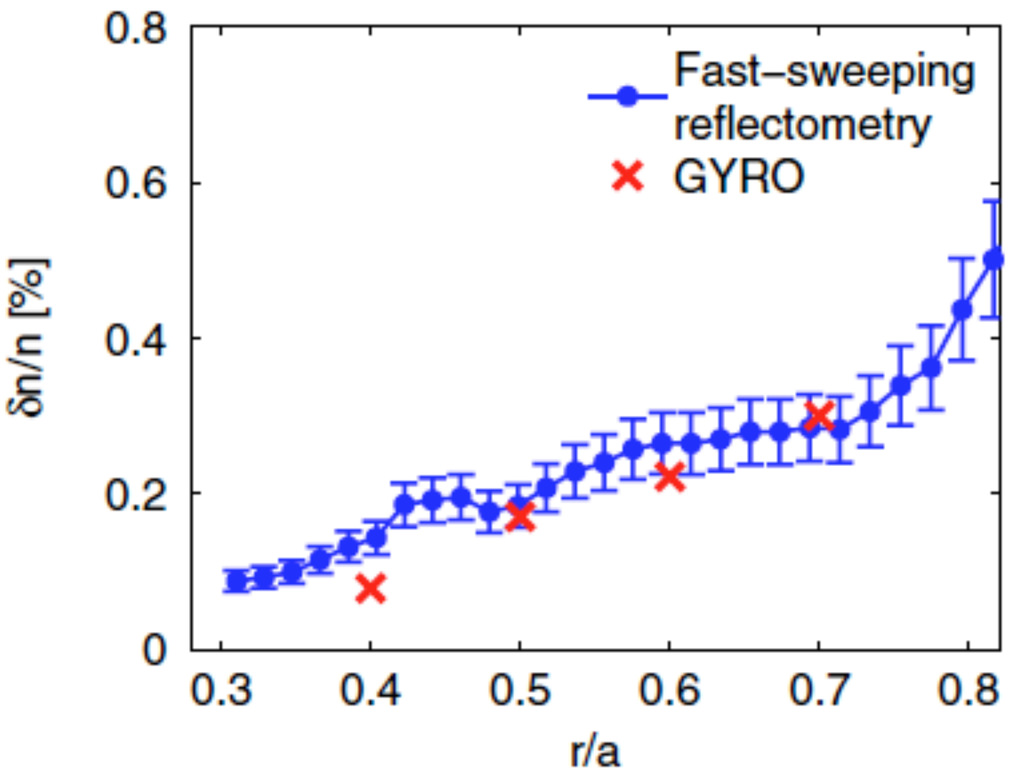


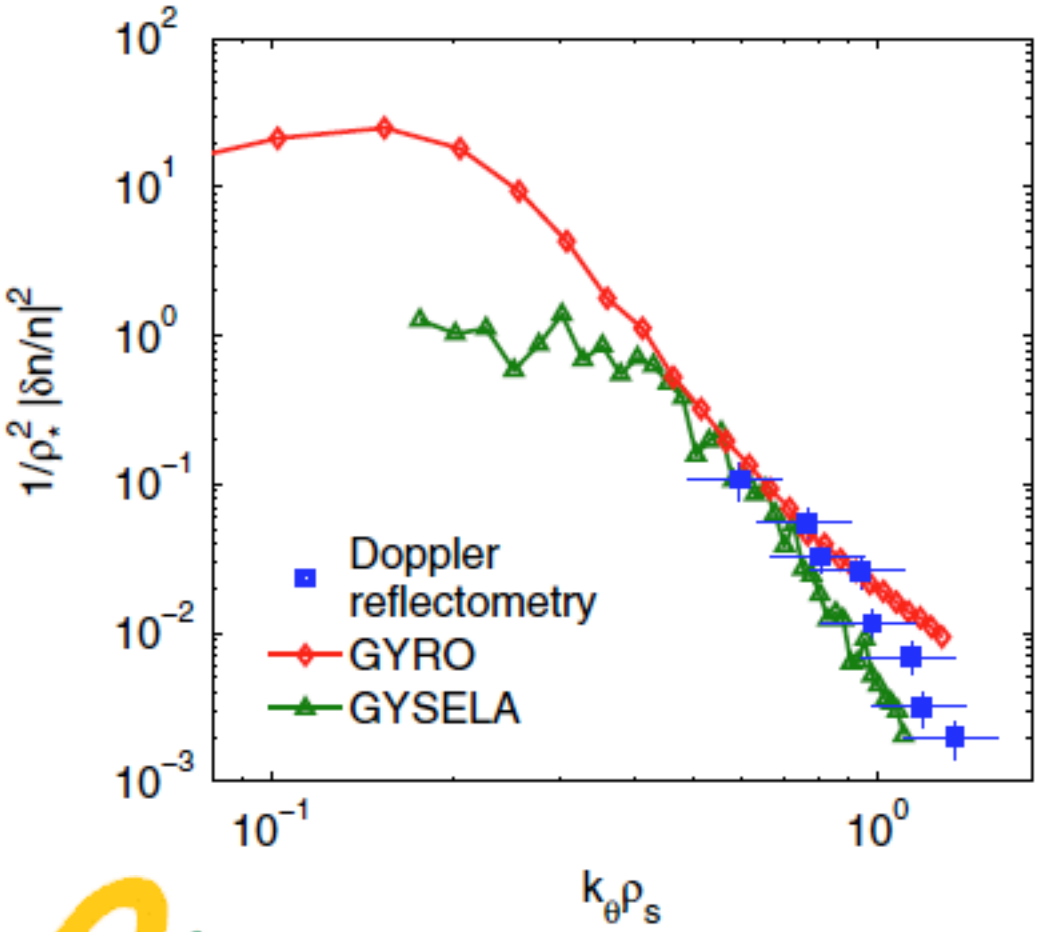
**GYRO, J. Candy, GA**

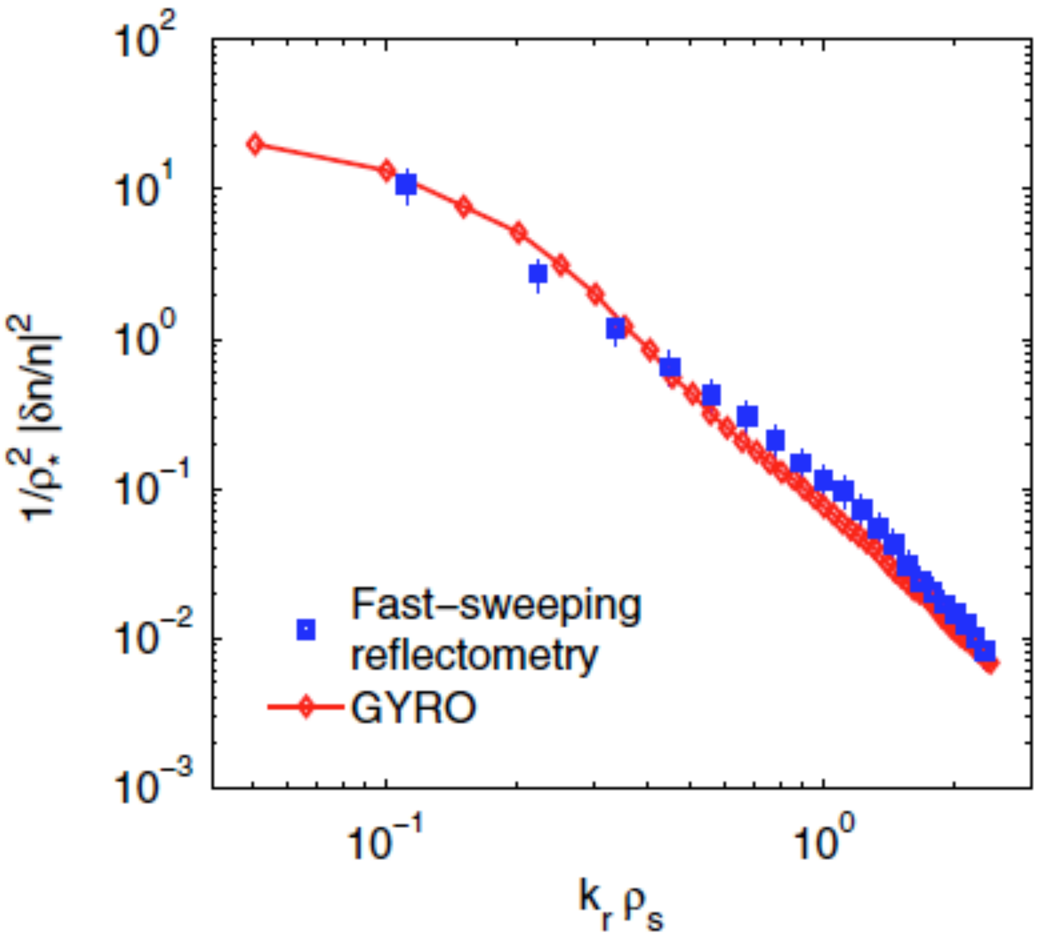
**R- $\theta$ Cross-Correlation Function**

# Good Quantitative Comparison of Doppler Reflectometer to GYRO Simulations on Tore Supra







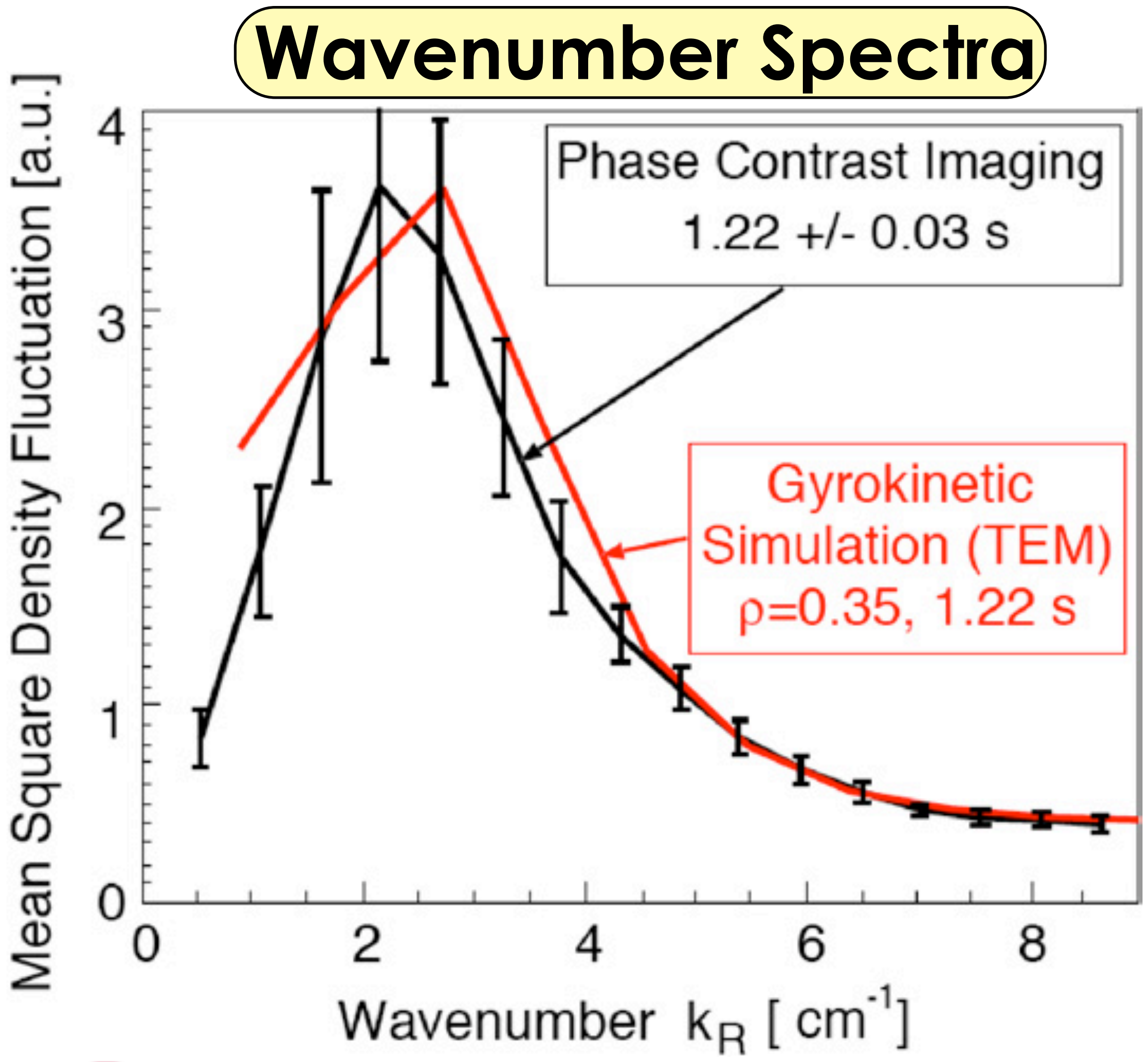


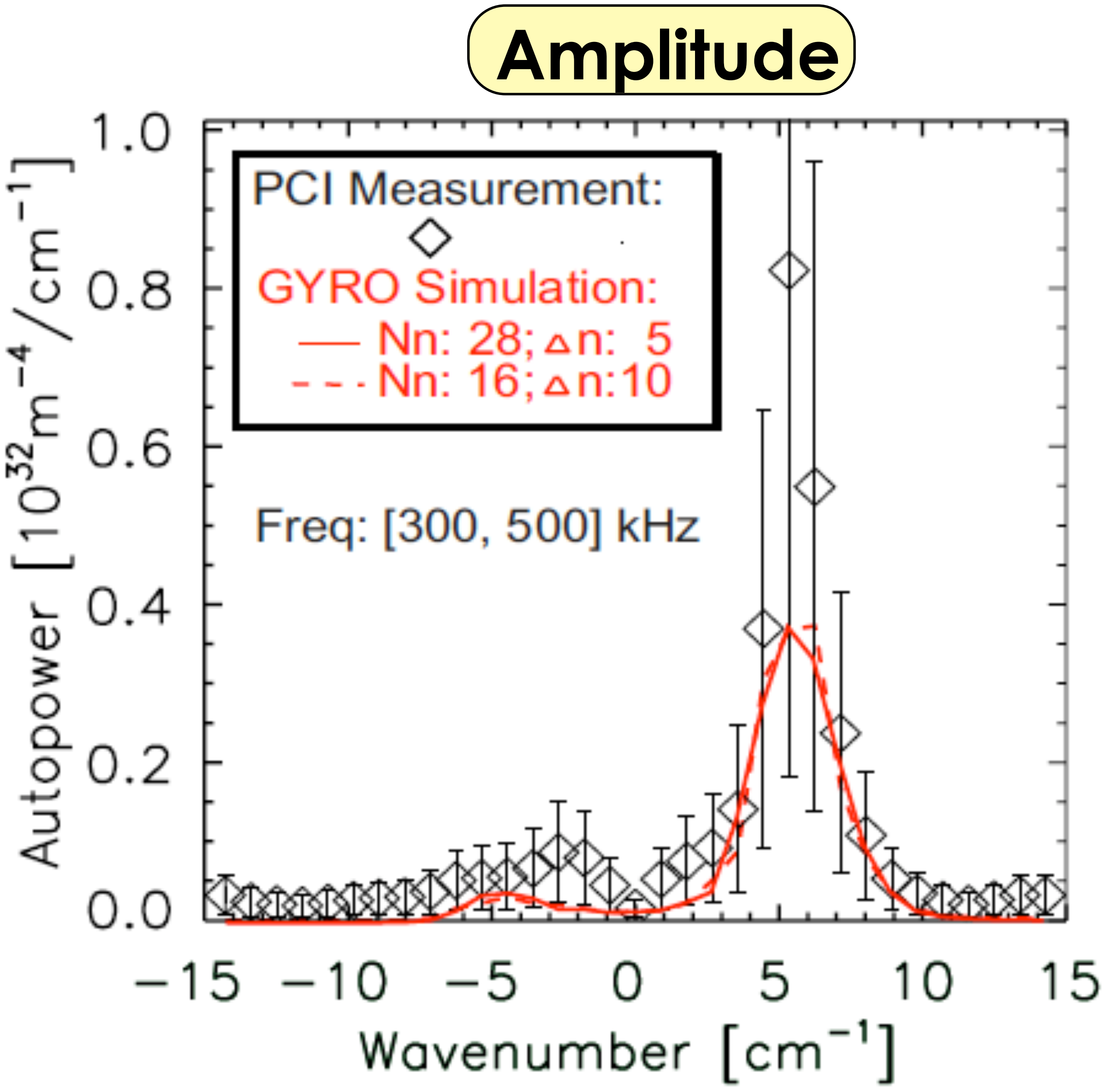
*A. Casati, Phys. Rev. Lett.* ***102****, 165005 (2009)*

TORE SUPRA
EURATOM-CEA

# Fluctuation Wavenumber Spectra and Amplitude Compare Well with Simulations

- **“Synthetic Diagnostics” applied to simulation output to allow for direct, quantitative comparison between measurement and simulation**



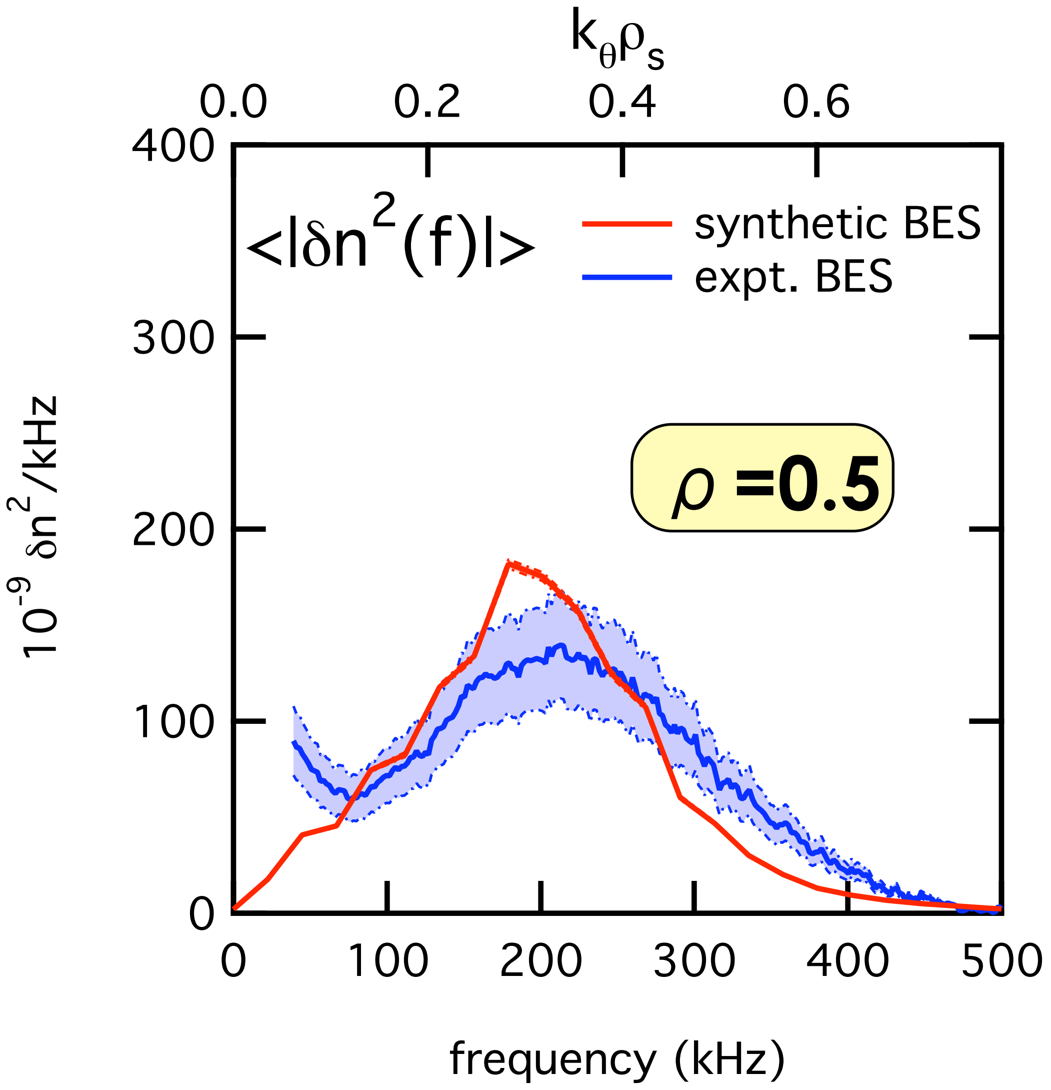


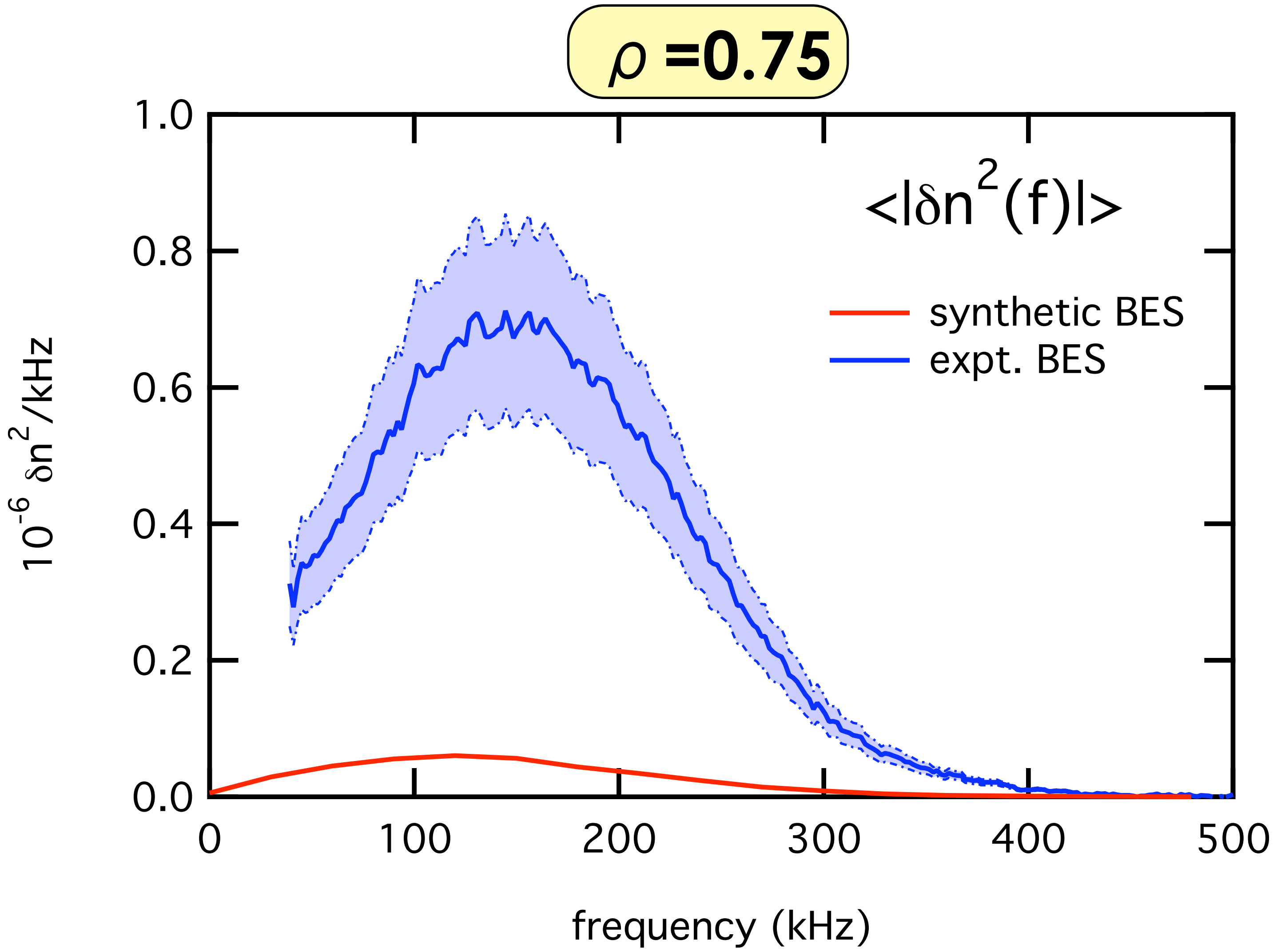
Alcator C-Mod

*D. Ernst, IAEA-CN-149/TH/1-3 (2006)*
*L. Lin, Phys. Plasmas **16**, 012502 (2009)*

# Comparison of Turbulence Power Spectra: GYRO-BES Demonstrate Agreement in core, Underestimate at Edge

- **Synthetic BES diagnostic applied to GYRO fluctuation output:**
  - Allows equivalent quantities to be compared
  - Profile uncertainty does not explain shortfall in calculated turbulence and transport
- **Excellent agreement at mid-radius; “shortfall” at outer radius**

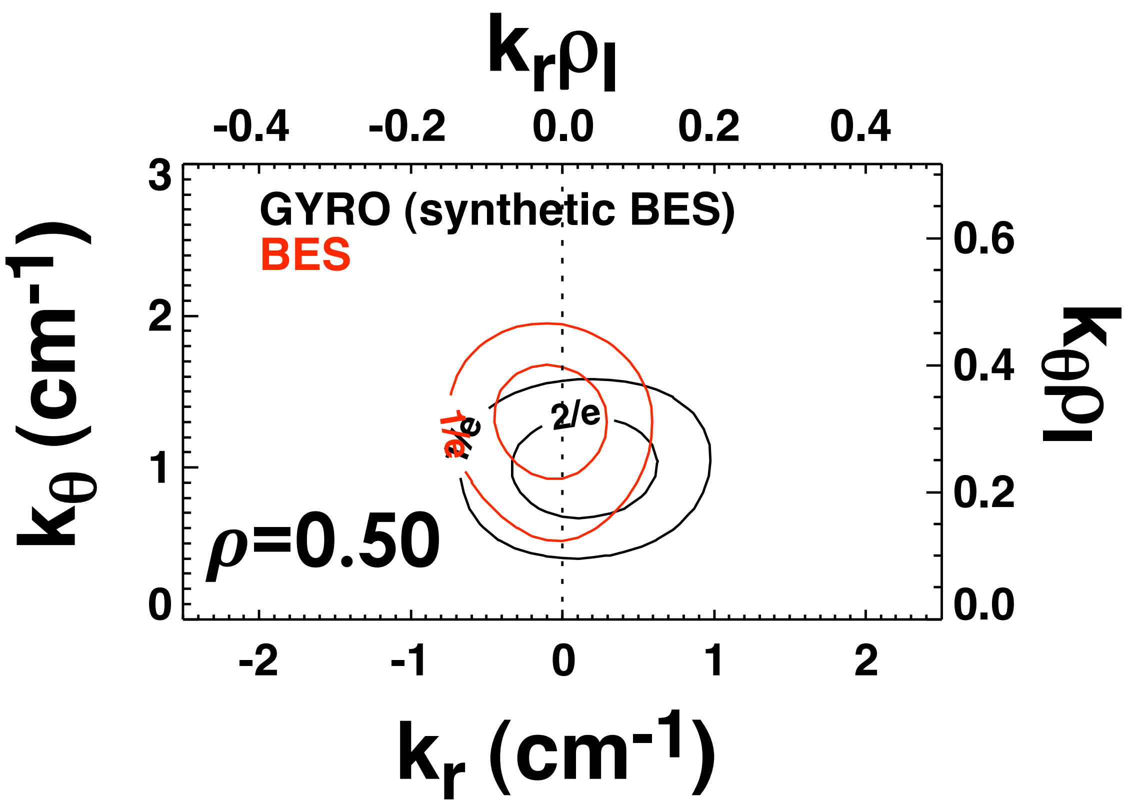


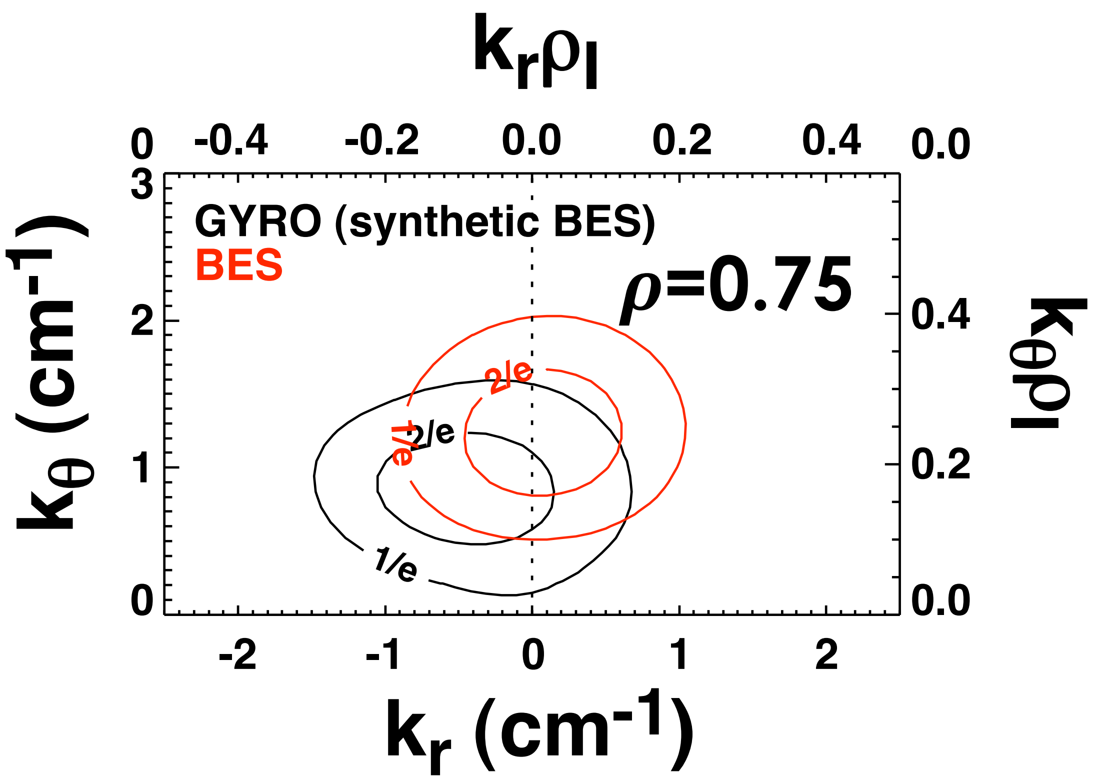


*C. Holland, Phys. Plasmas* ***16****, 052301 (2009)*
*R. Waltz, Invited Talk (this conference)*

# 2D Wavenumber Spectra Suggest Data-Simulation Differences that May Explain Edge Shortfall Mystery

- **Core location ($\rho$=0.5) exhibits good quantitive agreement**
  - Fluctuation amplitudes and thermal fluxes also agree well
- **Outer location ($\rho$=0.7) shows finite but significant difference**
  - GYRO exhibits finite $k_r$, not seen in BES data
  - May indicate an overestimate of shear effects on turbulence
  - Consistent with under prediction of fluctuation amplitude and transport

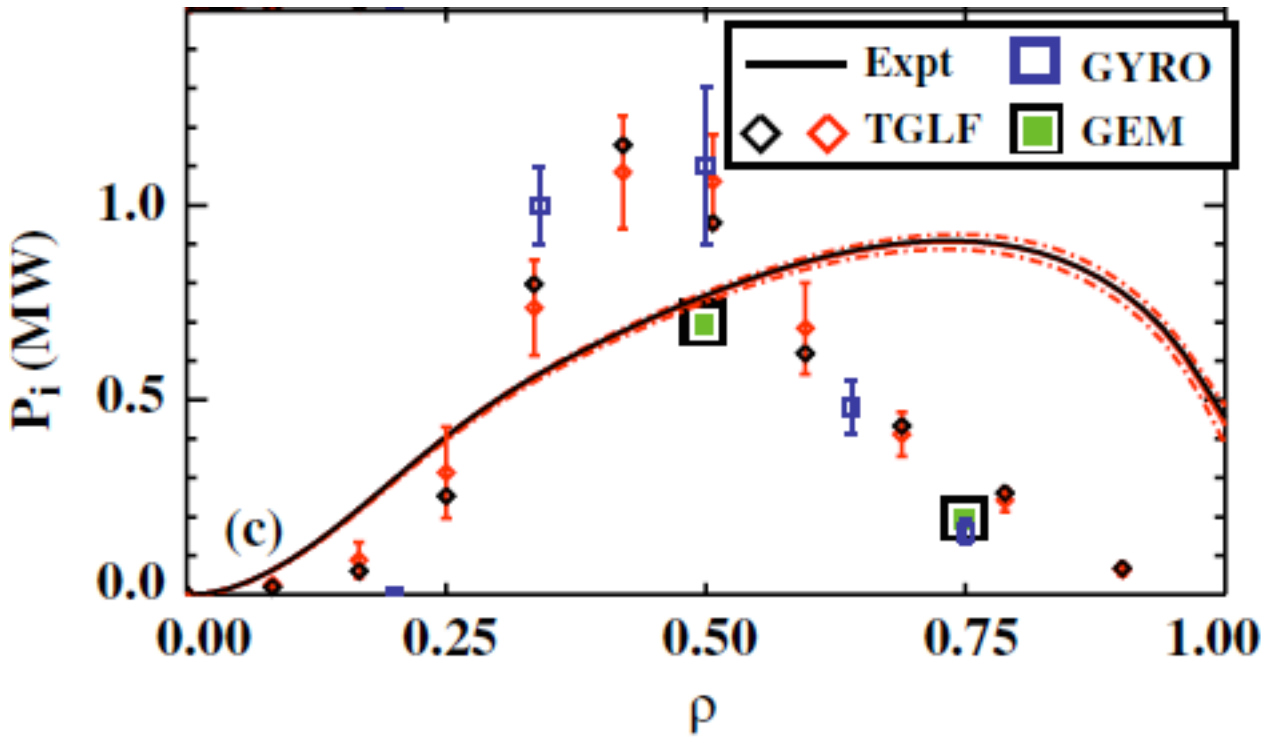




*M. Shafer, Phys. Plasmas* ***19****, 032504 (2012)*

# Multifield Comparisons of Turbulence and Transport Allow for a More Complete Comparison with Simulation

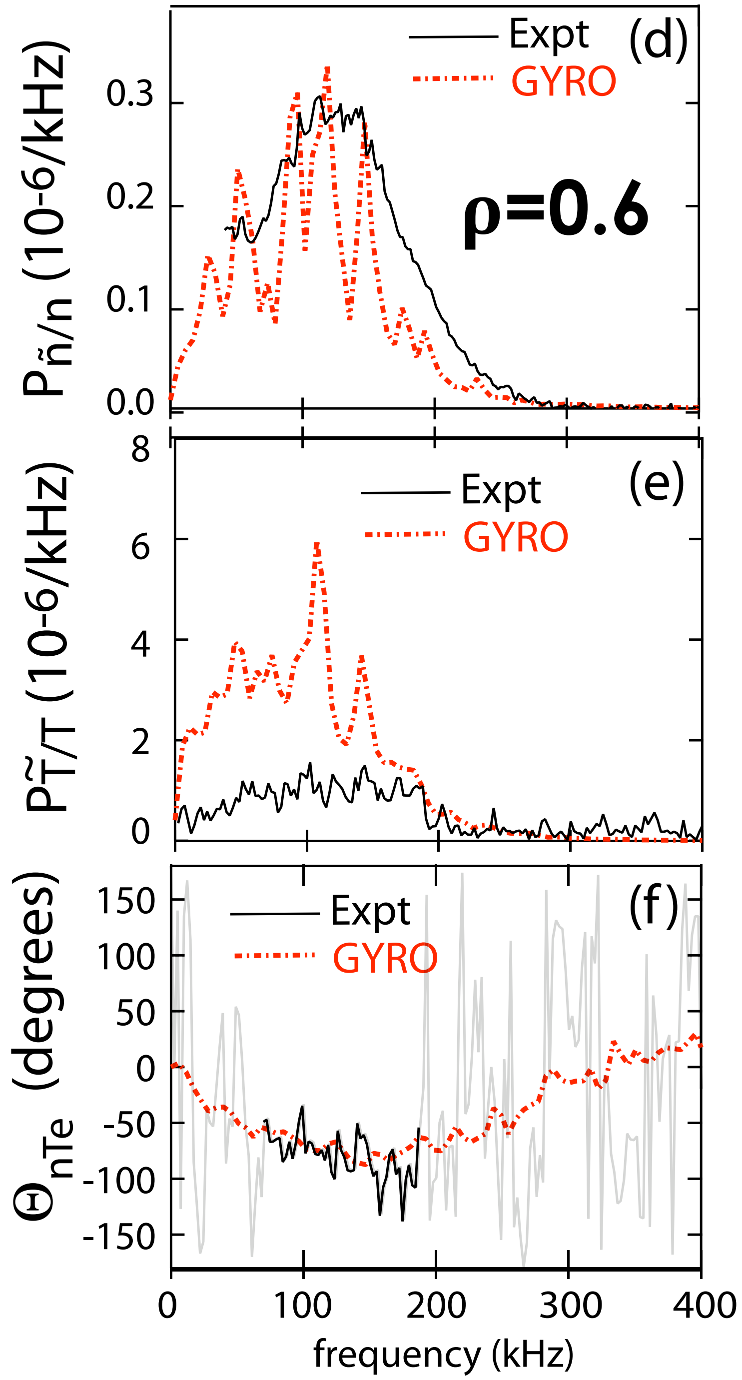
**Measured and Simulated Power fluxes**



$\tilde{n}/n$

$\tilde{T}_e/T_e$

$\Theta_{nT}$



- **Transport simulations approximately correct at mid-radii, but underestimate transport and turbulence at outer radii**

*T. Rhodes, Nucl. Fusion* ***51****, 063022 (2011)*

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  - Relation to radial transport
  - Saturation via self-driven Zonal Flows and dissipation
- **Behavior and Dependence on Plasma Transport Parameters**
  - Amplitudes and spatiotemporal characteristics scale with gyrokinetic parameters (ion gyroradius, gyrokinetic time scale, $a/c_s$)
  - Dominant instabilities depend on plasma collisions
  - Consistent with predicted linear instabilities
- **Testing, Challenging and Validating Nonlinear Simulations**
  - Quantitative comparisons show generally good agreement
  - Cases of disagreement leading to refinement of physics models
- **Controlling turbulence offers potential to improve performance**

# Suppression of Turbulence and Transport via $E_r x B_T$ Flow Shear

Competition between shearing rates and turbulence decorrelation rate

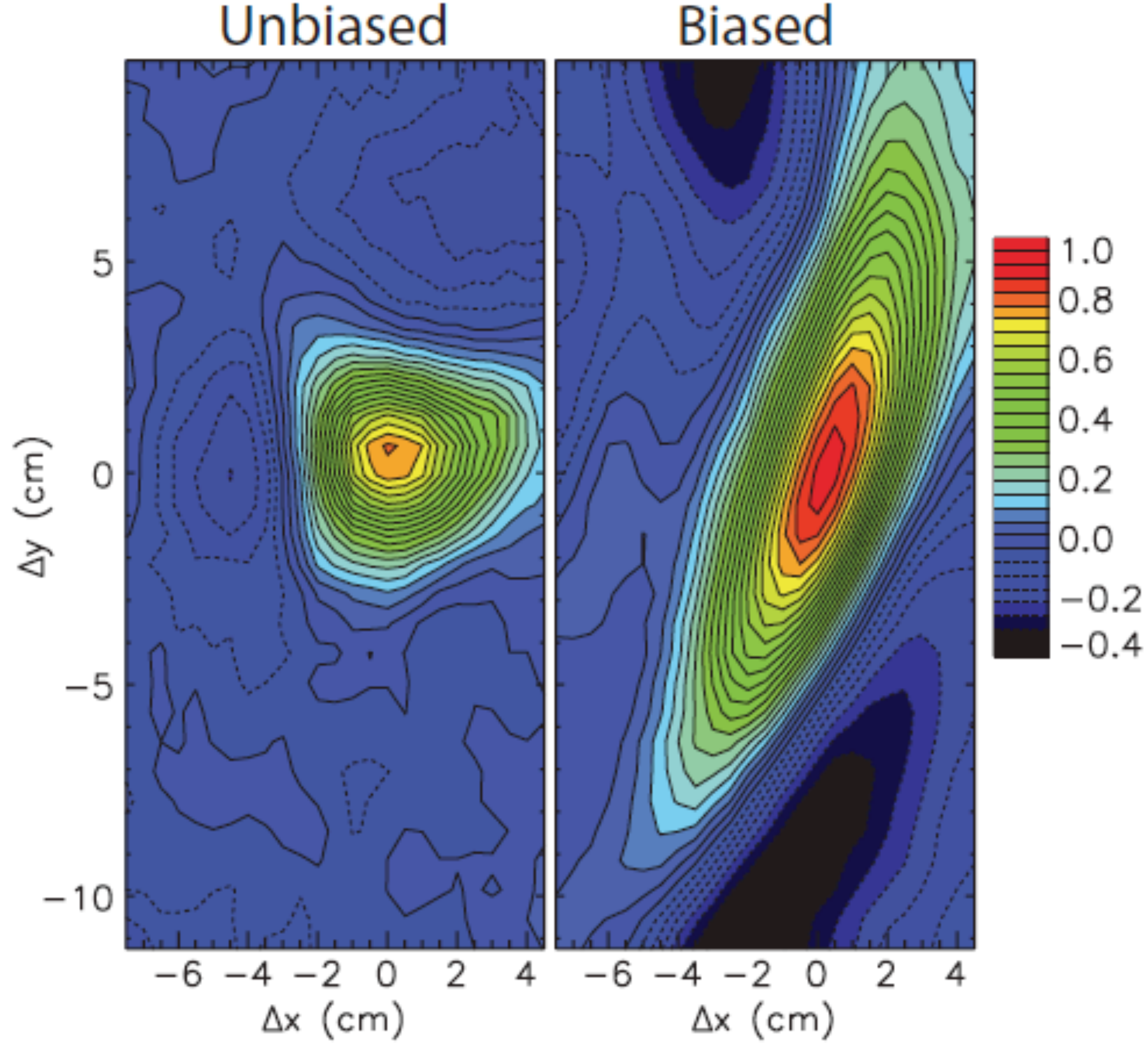
**ExB Shearing Rate** $\omega_{E\times B} = \frac{(RB_\theta)^2}{B}\frac{\partial}{\partial\psi}\frac{E_r}{RB_\theta} \approx \frac{d}{dr}V_\theta$

**Decorrelation Rate** $(\tau_c)^{-1}$

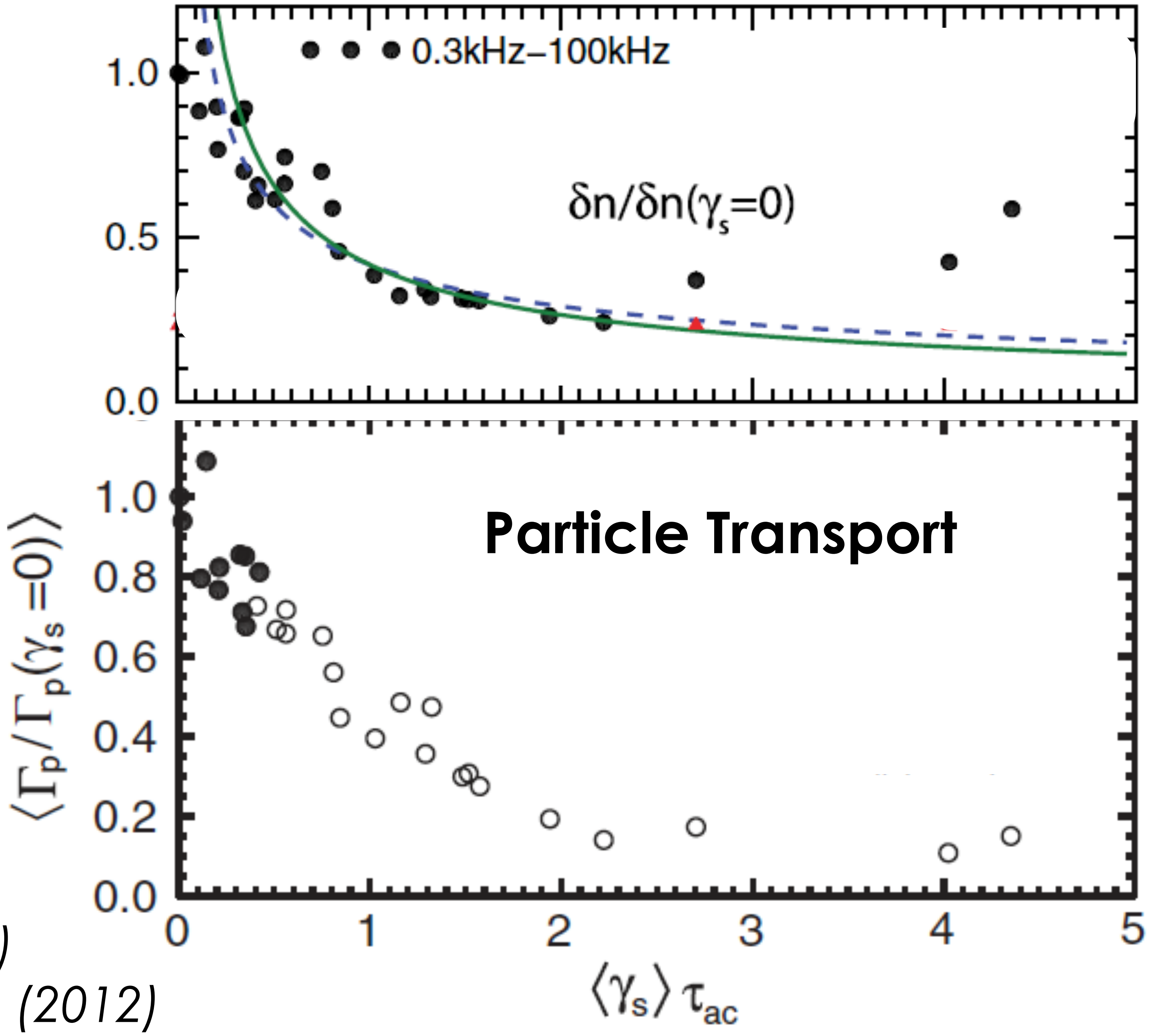
# Imposed Flow Shear Stretches Eddy Structure and Reduces Turbulence and Radial Transport

- **Biased limiter applied to magnetized cylindrical plasma to generate shear flow and test turbulence response**

**Eddy Spatial Correlation**



**Turbulence and Turbulent Transport Decrease as Shearing Rate Increases**



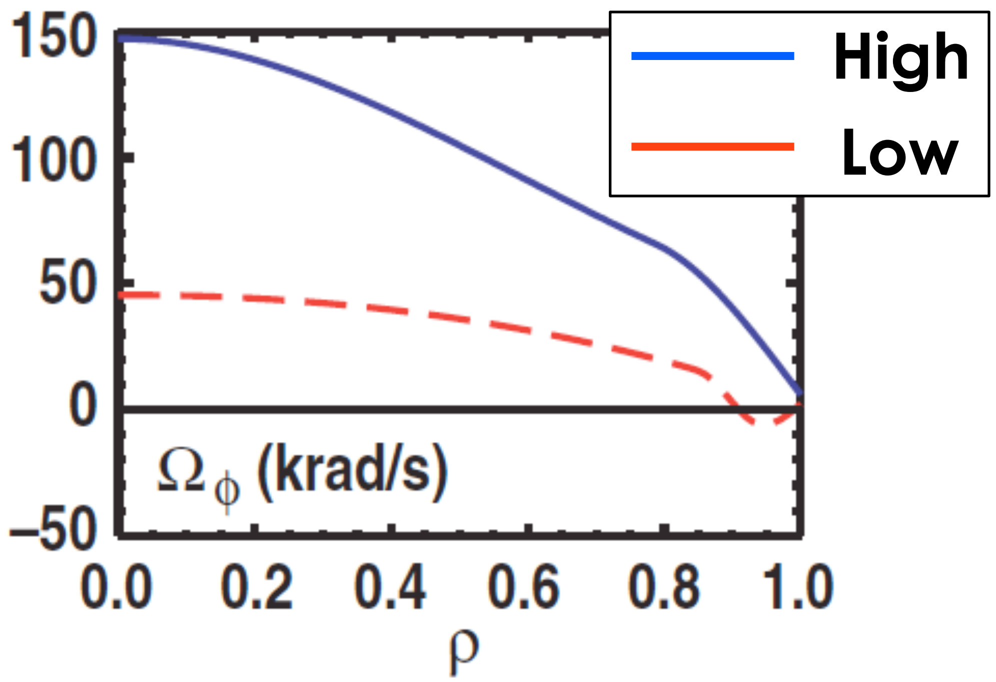
**Normalized Shearing Rate**

*T. Carter, Phys. Plasmas **16**, 012304 (2009)*
*D. Schaffner, Phys. Rev. Lett. **109**, 135002 (2012)*

**LAPD** **UCLA**

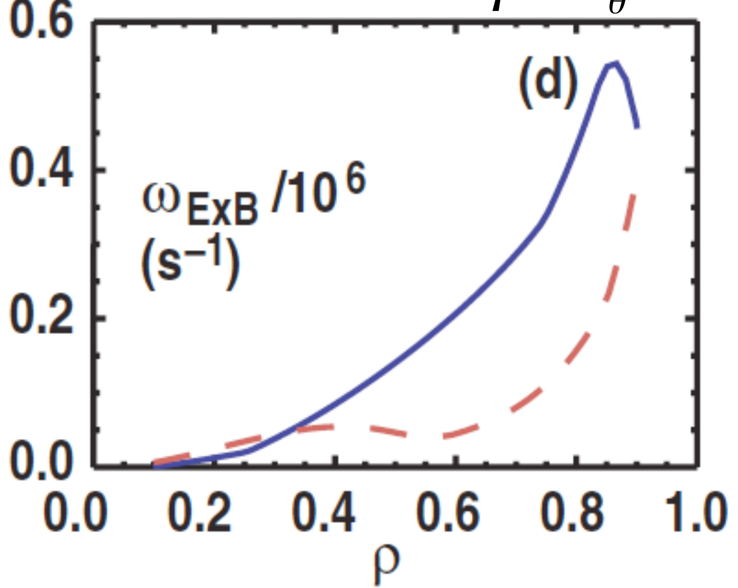
# Increasing Toroidal Rotation Increases $E_r x B_T$ Shearing Rate, Improves Confinement and Tilts Turbulent Eddy Structure

**Toroidal Rotation**

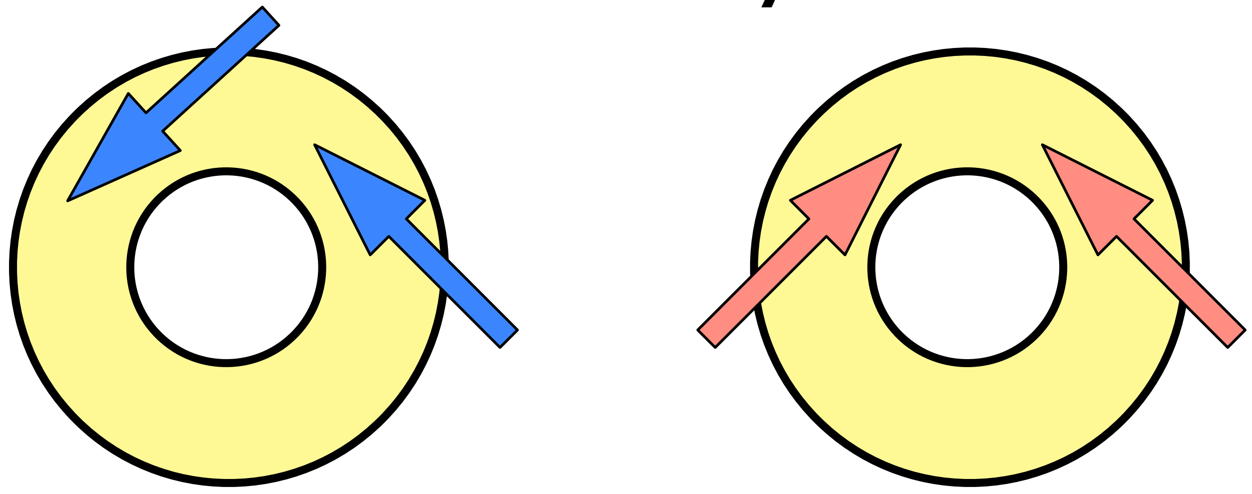


**ExB Shearing Rate**

$$\omega_{E\times B} = \frac{(RB_\theta)^2}{B}\frac{\partial}{\partial\psi}\frac{E_r}{RB_\theta}$$

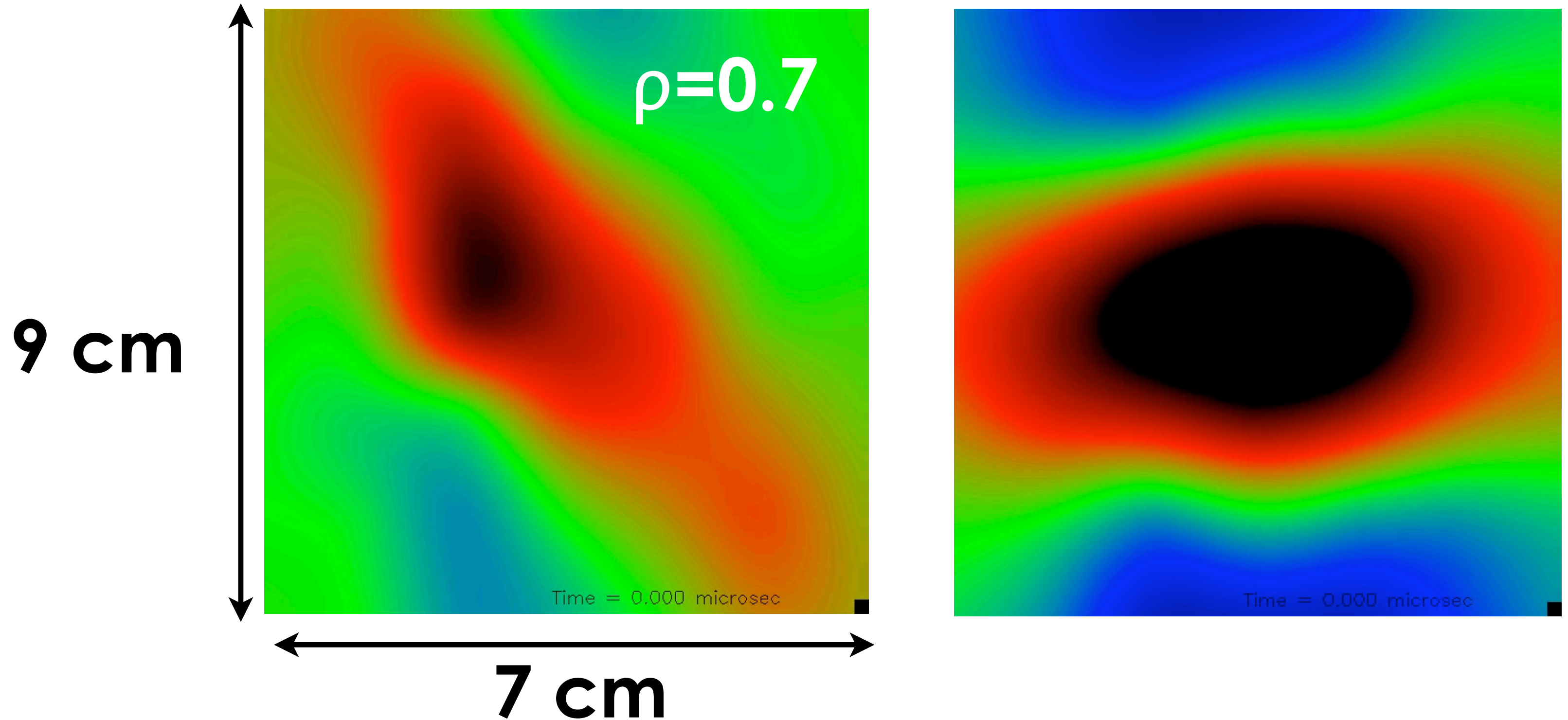


**Neutral Beams vary Rotation**



**High Rotation** **Low Rotation**

**Eddy Cross-Correlation in High-Rotation Plasma** **Eddy Cross-Correlation in Low-Rotation Plasma**



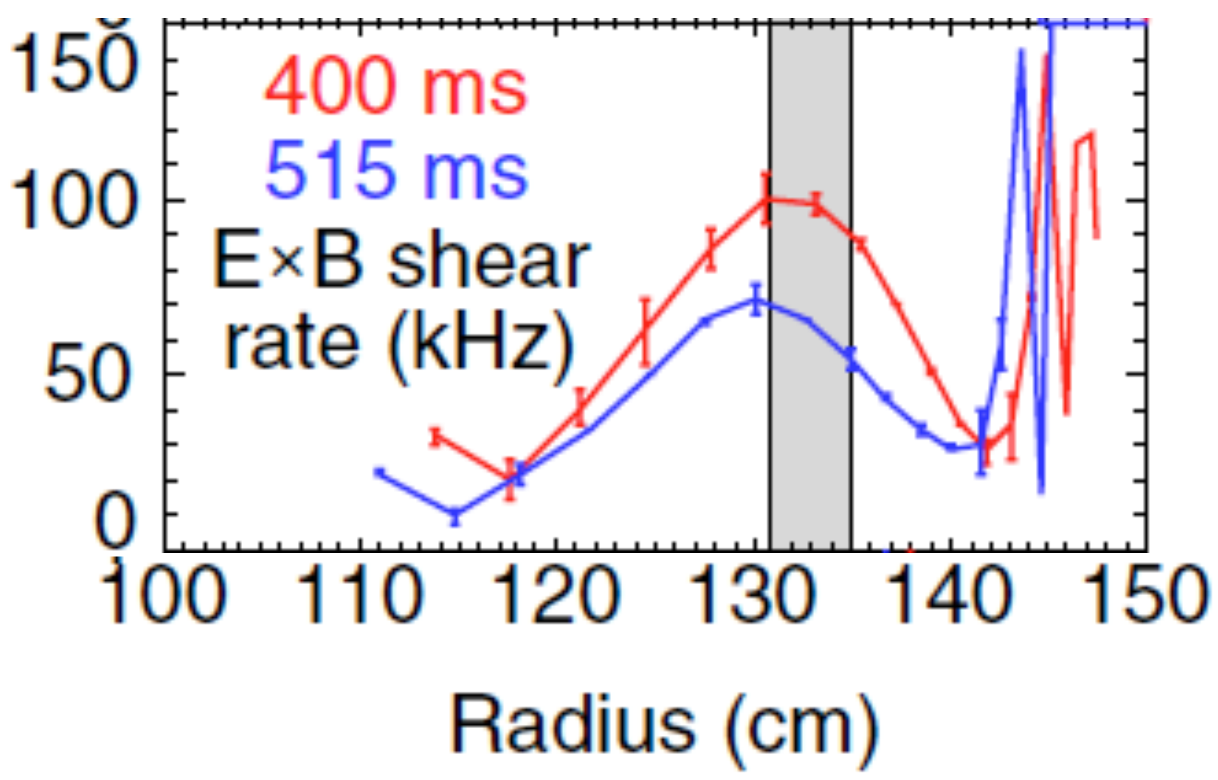
- **Global energy confinement 25% higher in High-Rotation Plasma**

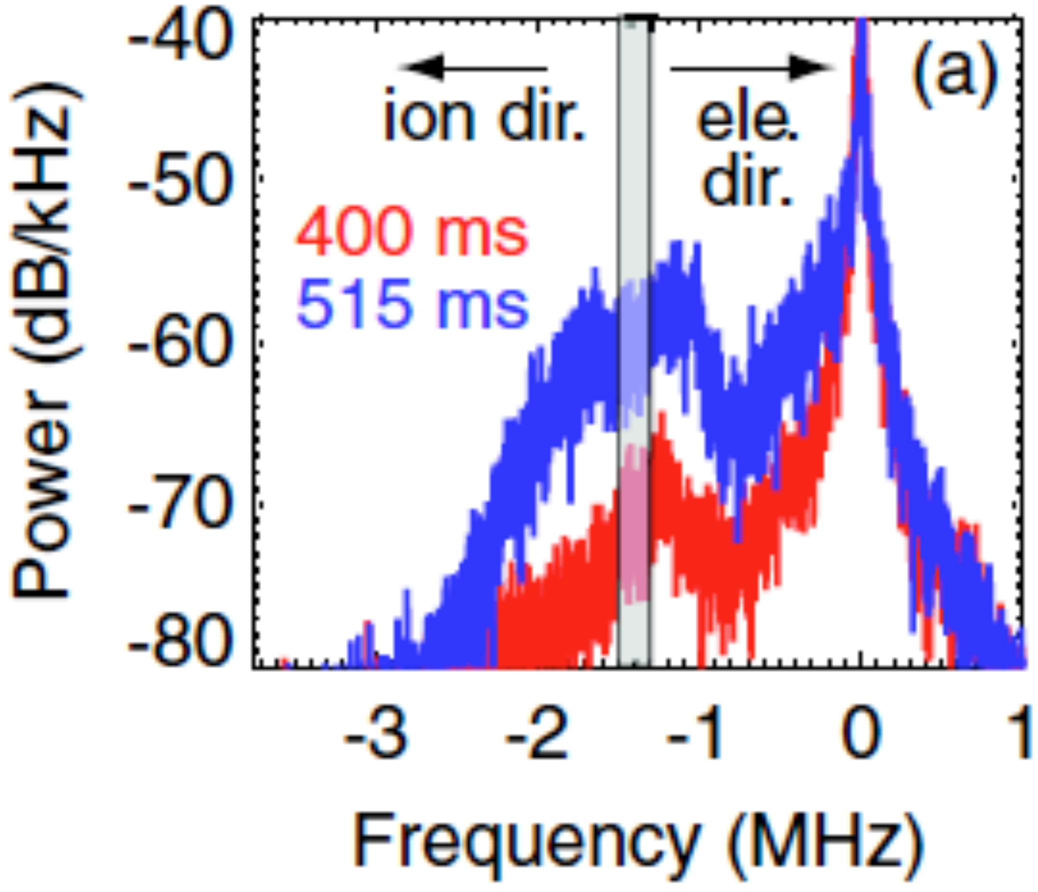
*P. Politzer, Nucl. Fusion* ***48****, 075001 (2008)*

*K. Burrell, Phys. Plasmas Phys.* ***4****, 1499 (1997)*

# ExB Flow Shear Suppresses Small Scale Fluctuations

- **Fluctuations with characteristics of Electron Temperature Gradient (ETG) Modes observed**
  - $k_{\perp}\rho_e$~0.15-0.2
  - Propagate in the electron diamagnetic direction
  - Calculated critical gradient for ETG near measured $T_e$ gradients
- **Fluctuations decrease at higher local shearing rates**





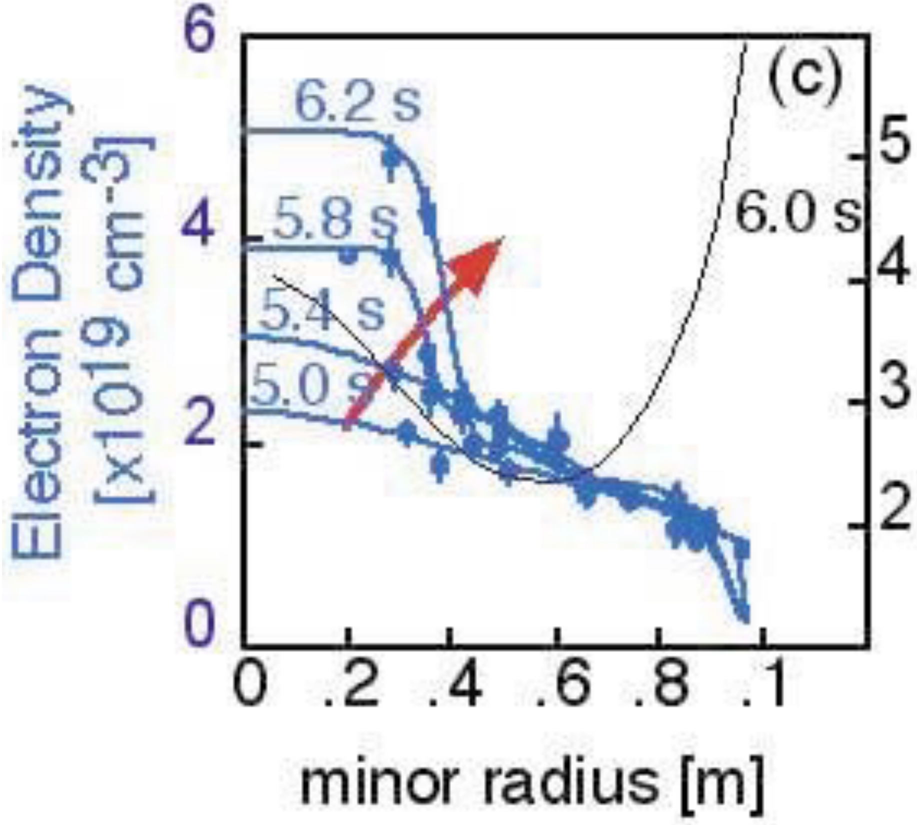
*D. Smith, Phys. Rev. Lett.* ***102****, 225005 (2009)*

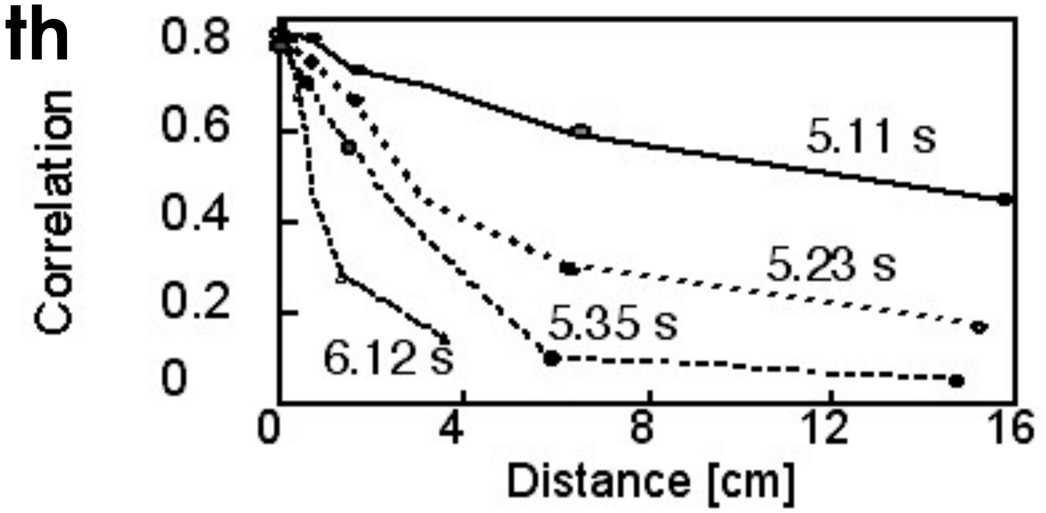
# Internal Transport Barrier Formation Correlates with Reduction in Turbulence Scale Length

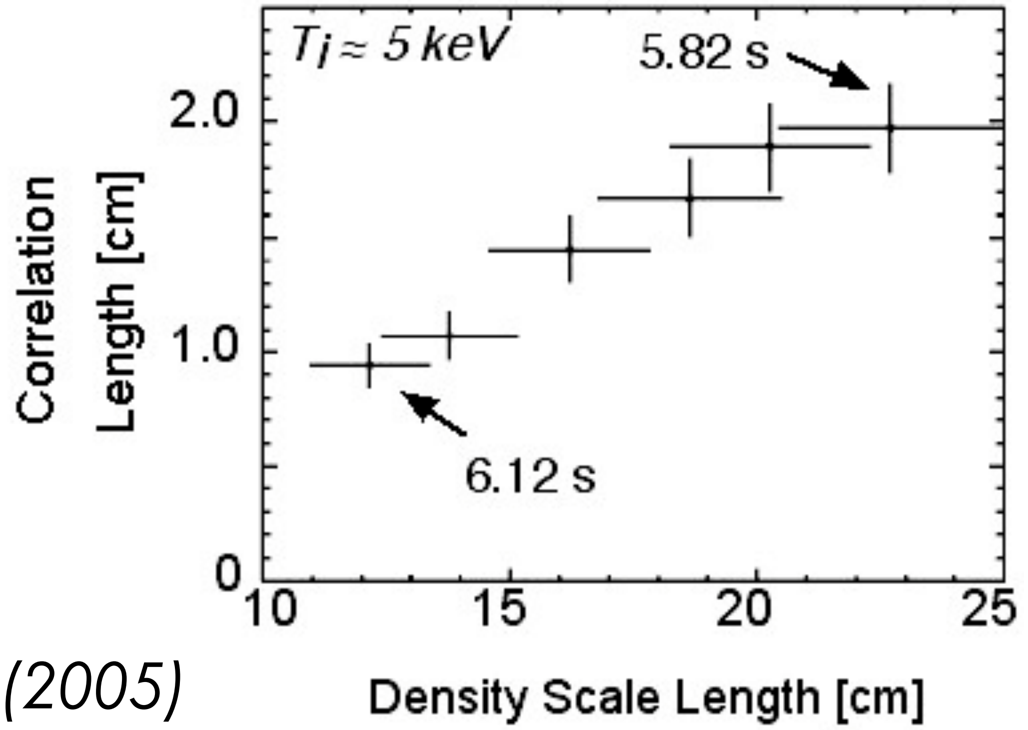
- **Barrier evident in strongly steepening density profile**
  - $T_i$ also increases sharply during this phase
  - Increased ExB shear from rotation facilitates turbulence suppression
  - Negative central shear ($q_{min}$) facilitates barrier formation
- **Turbulence radial correlation length linearly correlated with density gradient scale length**

**Microwave Reflectometer**

**ITB Formation**



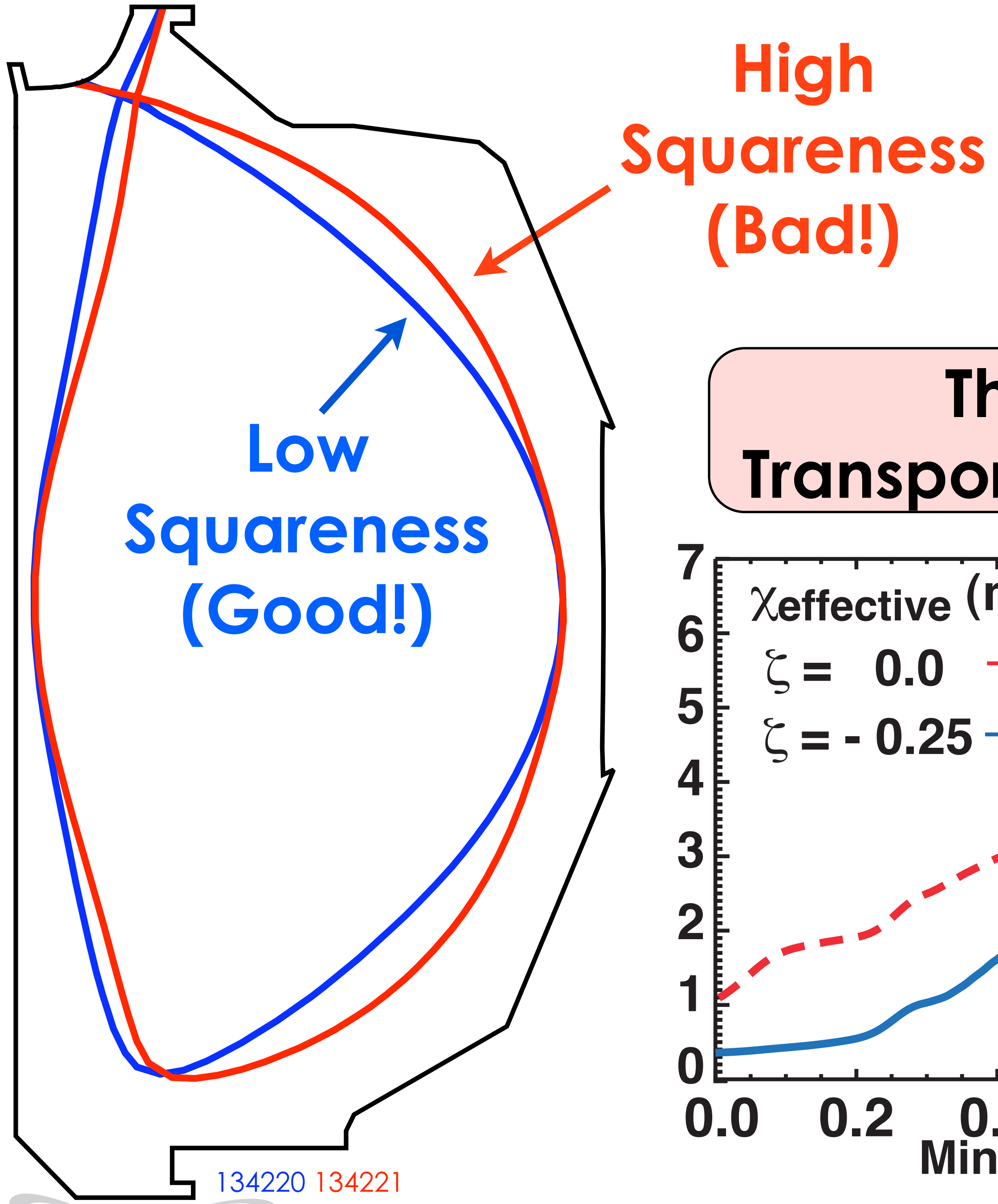




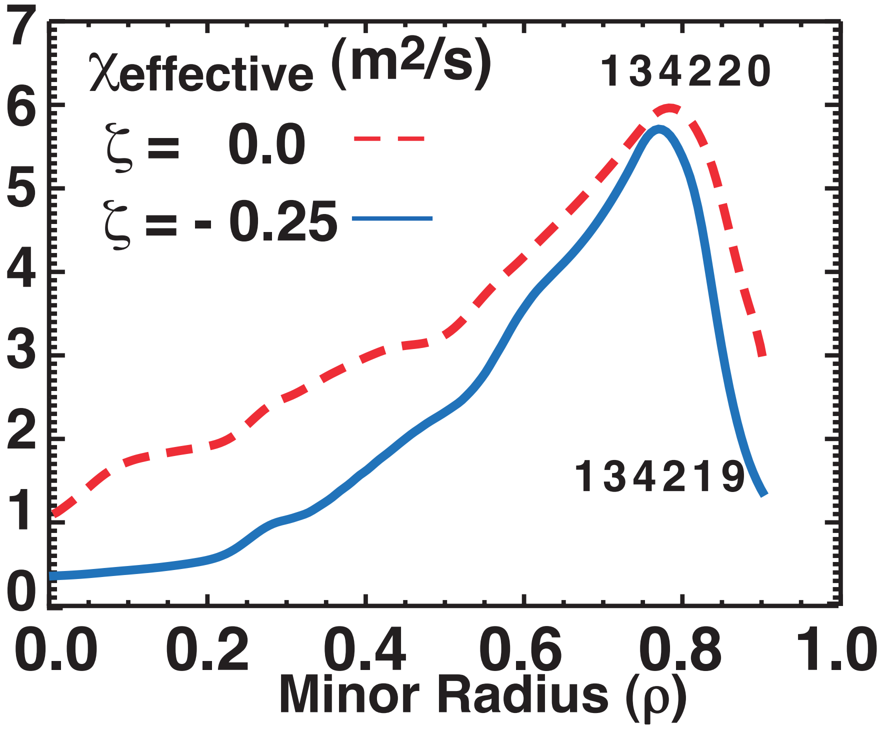
*R. Nazikian, Phys. Rev. Lett.* ***94****, 135002 (2005)*

# Macroscopic Plasma Shape Strongly Impacts Turbulence and Transport

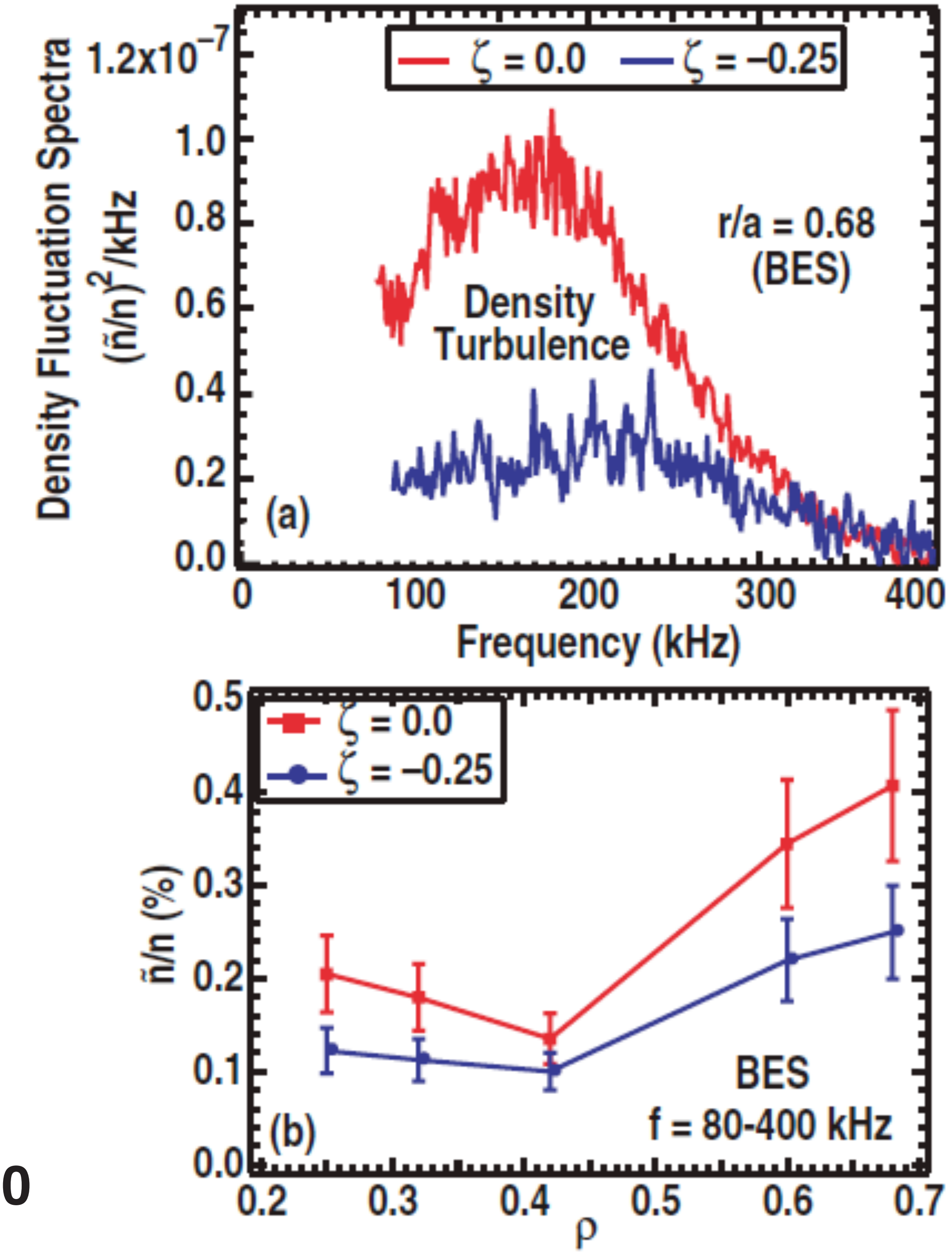
**"Squareness" is a shaping parameter referring to outer upper/lower boundary**



**Thermal Transport Coefficient**



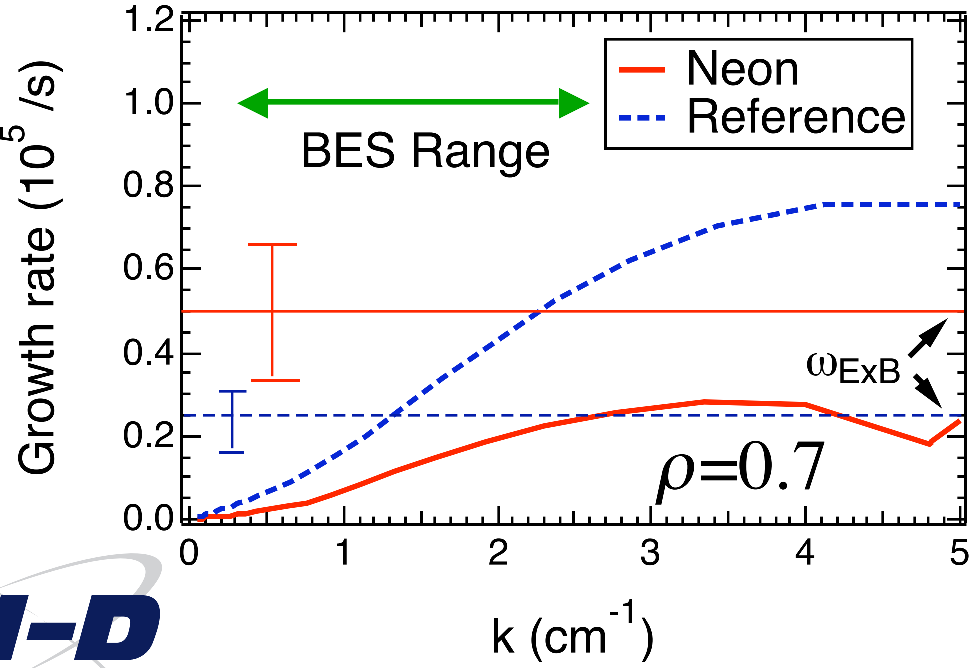
**Turbulence and Transport Increase with Squareness**



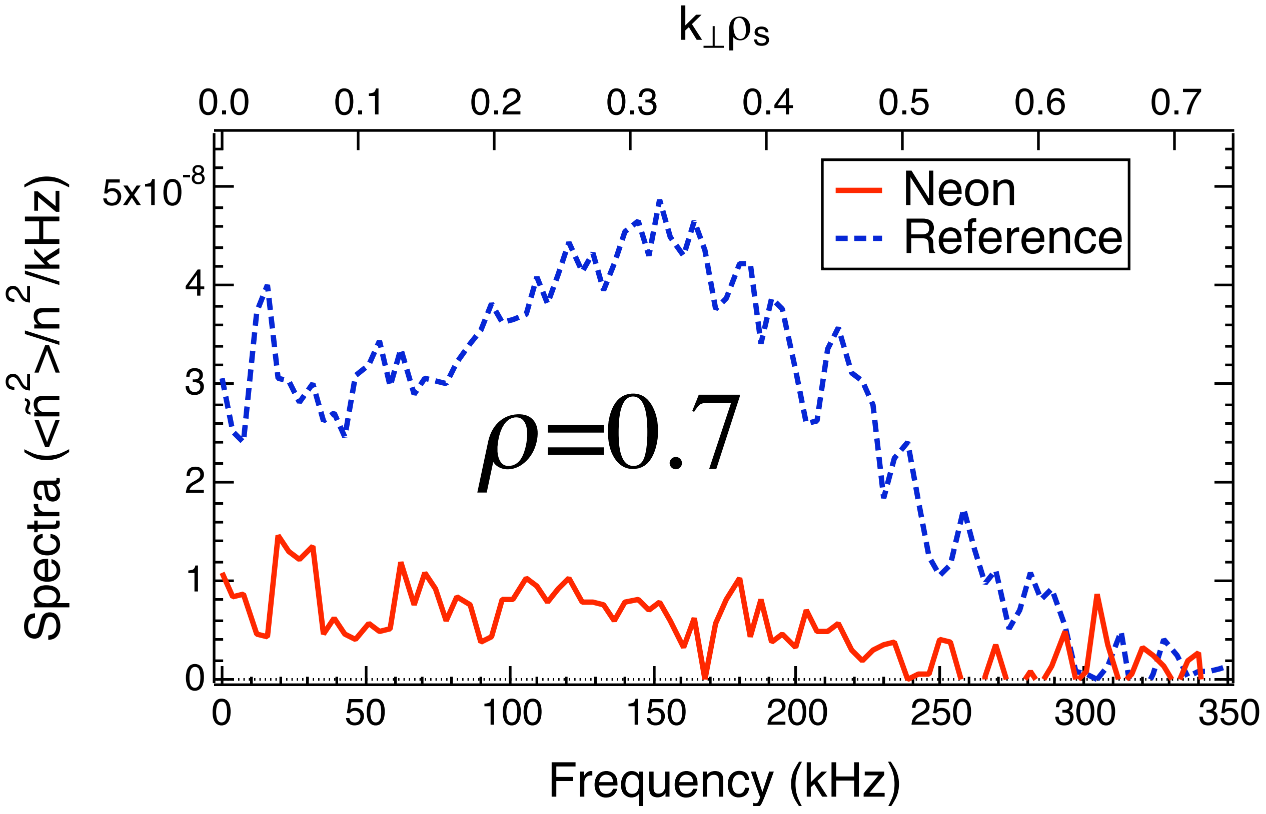
C. Holcomb, *Phys. Plasmas* ***16***, *056116 (2009)*

# Adding Impurity Species Reduces Turbulence and Transport

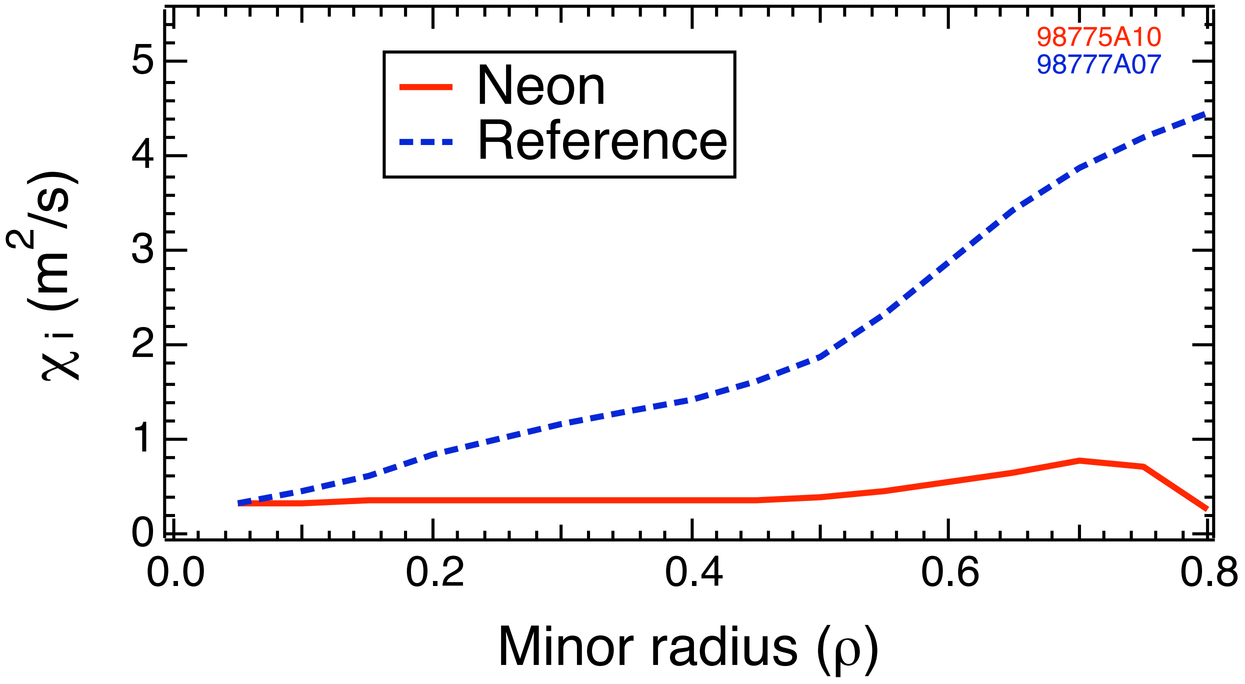
- **“Radiative-Improved” Mode:**
  - Increases energy confinement; reduced transport
  - Radiative losses dramatically increased
  - Observed at multiple experiments
- **Reduced turbulence and improved confinement**
- **Simulations: reduced growth rates**
  - Fuel ion dilution
  - Stabilization of ITG



**Growth Rates**



**Turbulence**



**Ion Thermal Transport**

# Summary: In Hot Plasmas, Turbulence Happens!

- **Dynamic process active in magnetically-confined plasmas**
- **Drives radial transport of particles, energy, momentum**
- **Critical role in establishing equilibrium profiles and global energy confinement and performance**
- **Exhibits behavior consistent with drift-wave instabilities:**
  - Evidence for role of:
    - *Ion Temperature Gradient modes*
    - *Trapped Electron Modes*
    - *Electron Temperature Gradient modes*
- **Varies with plasma transport parameters ($\rho^*$, $\nu^*$, $Z_{eff}$)**
  - Correlation lengths, decorrelation times, amplitude consistent with gyrokinetics
- **Turbulence suppression crucial to Internal Transport Barrier formation**
  - Depends on magnetic shear; low-order rational q-surfaces
- **Quantitative consistency (sometimes!) with gyrokinetic simulations**
  - Establishing a validated predictive capability for transport in burning plasmas

# Thank you!

- K. Burrell, R. Buttery, A. Garofalo, T. Luce, C. Petty, R. Waltz..*General Atomics*
- R. Fonck, D. Smith, I. Uzun-Kaymak, Z. Yan.........*University of Wisconsin*
- M. Shafer.................................................*Oak Ridge National Laboratory*
- P. Diamond, C. Holland, G. Tynan.....*University of California-San Diego*
- T. Rhodes, T. Carter, L. Schmitz........*University of California-Los Angeles*
- J. Rice, J. Terry, A. White............*Massachusetts Institute of Technology*
- S. Zweben,Y. Ren...........................*Princeton Plasma Physics Laboratory*
- K. Ida, K. Tanaka..................*National Institute of Fusion Science, Japan*
- S. Inagaki...............................................................Kyushu University
- C. Hidalgo..........................................................*CIEMAT, Madrid, Spain*
- G. Conway................*Max Planck Institute for PlasmaPhysiks, Germany*
- C. Bourdelle, P. Hennequin, L. Vermare, .......*CEA, Cadarache, France*