# Long-Wavelength Turbulence Characteristics, Dynamics, and Flows in Tokamak Plasmas


George R. McKee [1]

J. Candy[2], R. Fonck[1], C. Holland[3], C. Petty[2], M. Shafer[4], A. White[5], Z. Yan[1] and the DIII-D Research Program

[1] *University of Wisconsin*

[2] *General Atomics*

[3] *University of California-San Diego*

[4] *Oak Ridge National Laboratory*

[5] *Massachusetts Institute of Technology*



Gyrokinetics In Laboratory and Astrophysical Plasmas

Isaac Newton Institute for Mathematical Sciences

Cambridge, United Kingdom

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DIII-D

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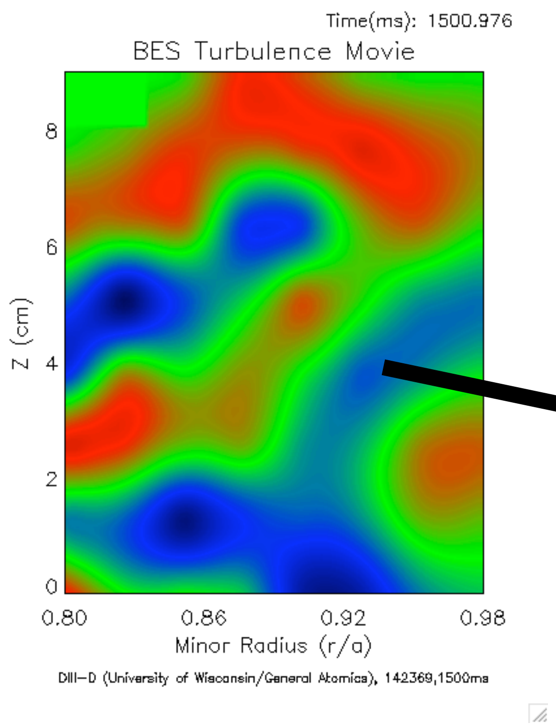
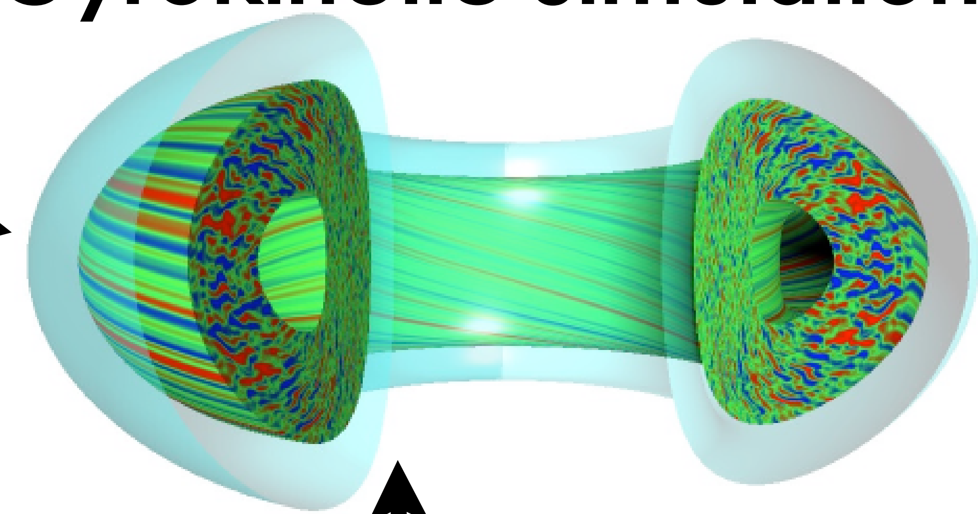
# Turbulence plays a Central Role in Behavior and Performance of Magnetically-Confined Plasmas

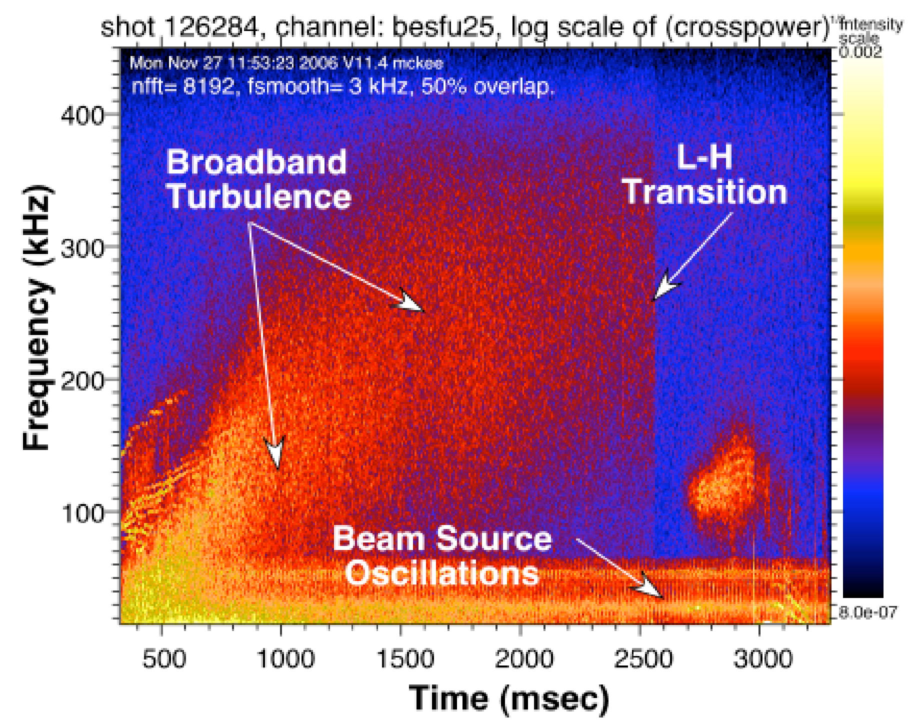
## Turbulence Measurement

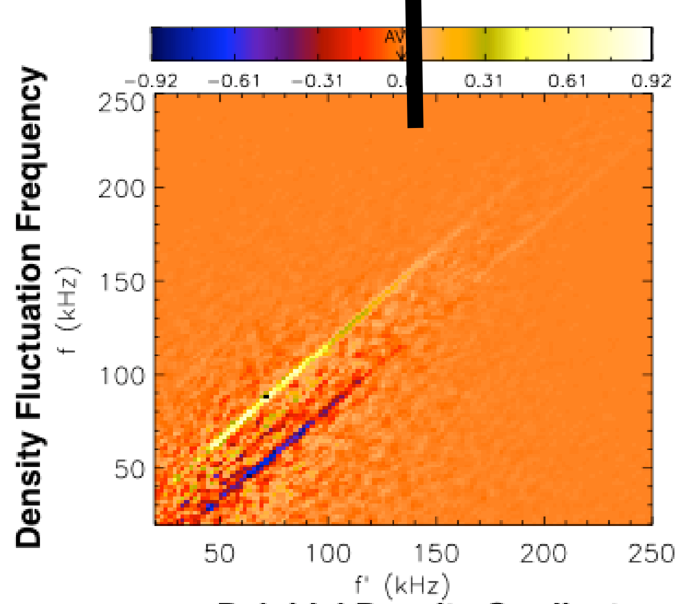



## Validation of Gyrokinetic Simulations



## Confinement Bifurcations




## Nonlinear Dynamics

**Measurements helping to validate models and understand transport behavior**

# Outline

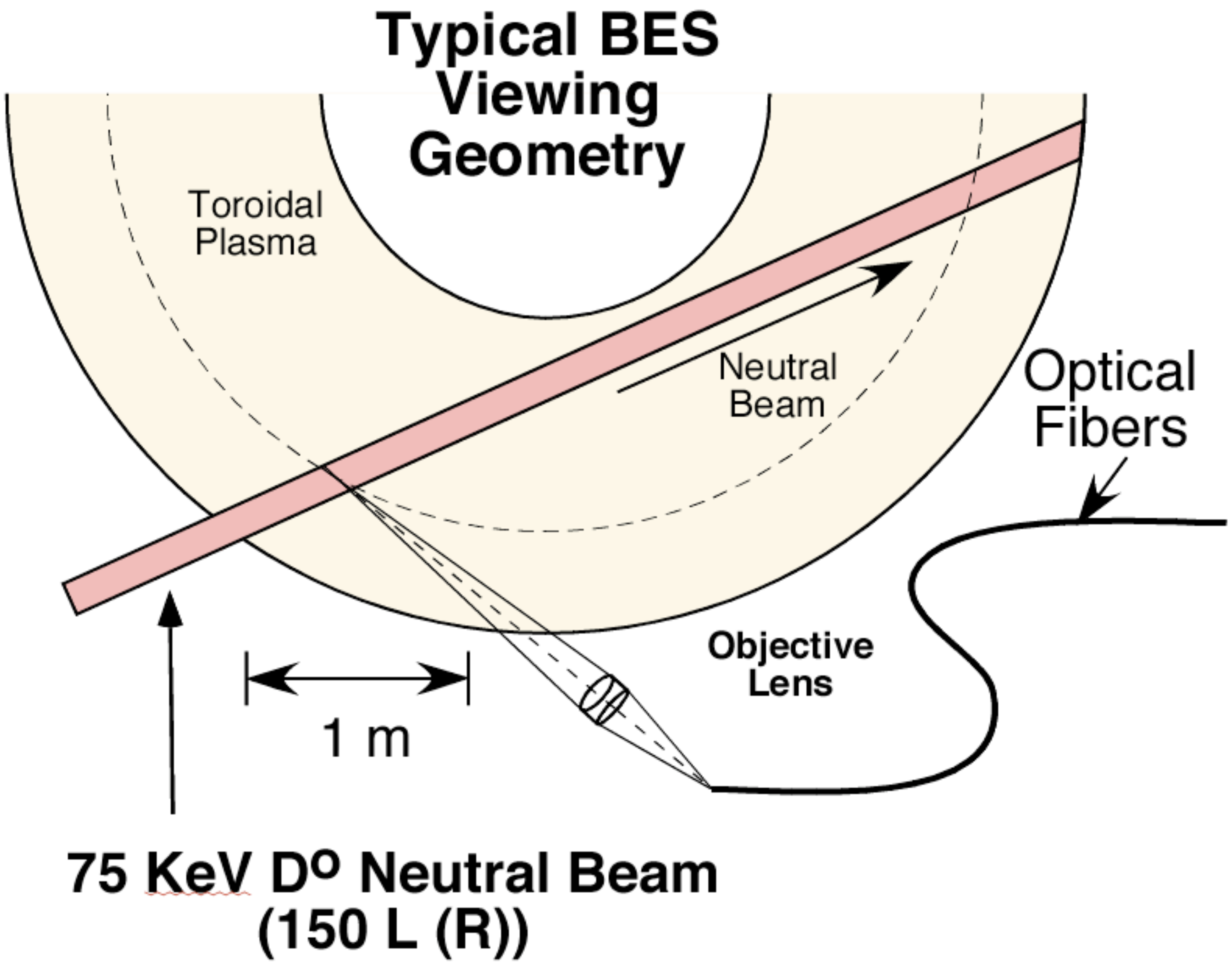
- **Diagnostic capability for measuring 2D long-wavelength density turbulence with Beam Emission Spectroscopy (BES)**
- **Turbulence imaging and visualization**
- **Turbulence characteristics and parameters**
- **Spatiotemporal correlation and spectral characteristics**
- **Time-dependent zonal flows**
  - Zonal Flow/Geodesic Acoustic Modes
  - Nonlinear energy transfer mediated by zonal flows
- **Comparisons with nonlinear 3D gyrokinetic simulations**

# Beam Emission Spectroscopy Measures Fluorescence of Heating Neutral Beam to Detect Local Density Fluctuations

**Collisionally-excited, Doppler-shifted neutral beam fluorescence**

$$D^o + e,i \Rightarrow \left(D^o\right)^* \Rightarrow D^o + \gamma(n = 3 \rightarrow 2, \lambda_o = 656.1 \text{ nm})$$

**Exploits Neutral Beam Heating Systems**



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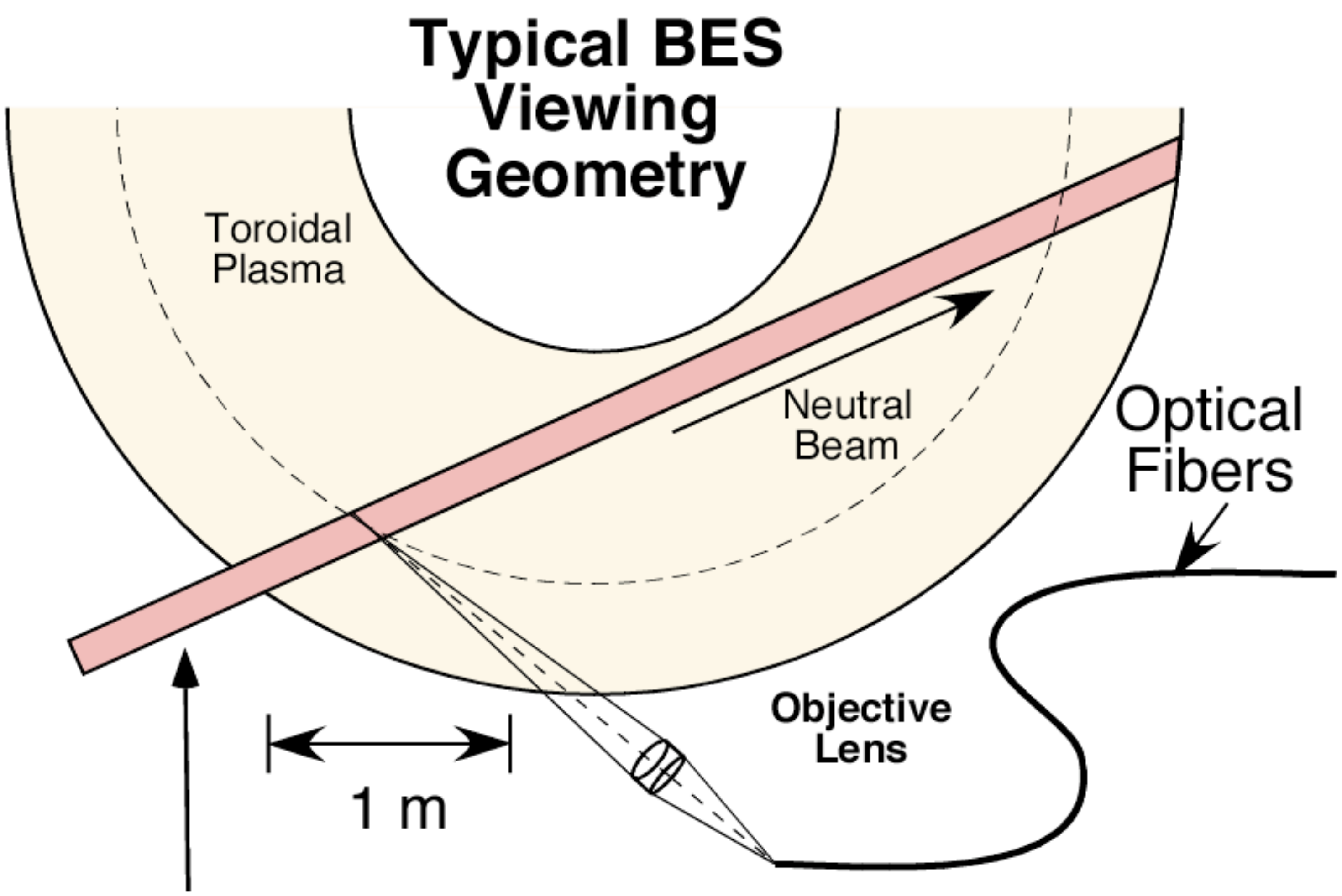
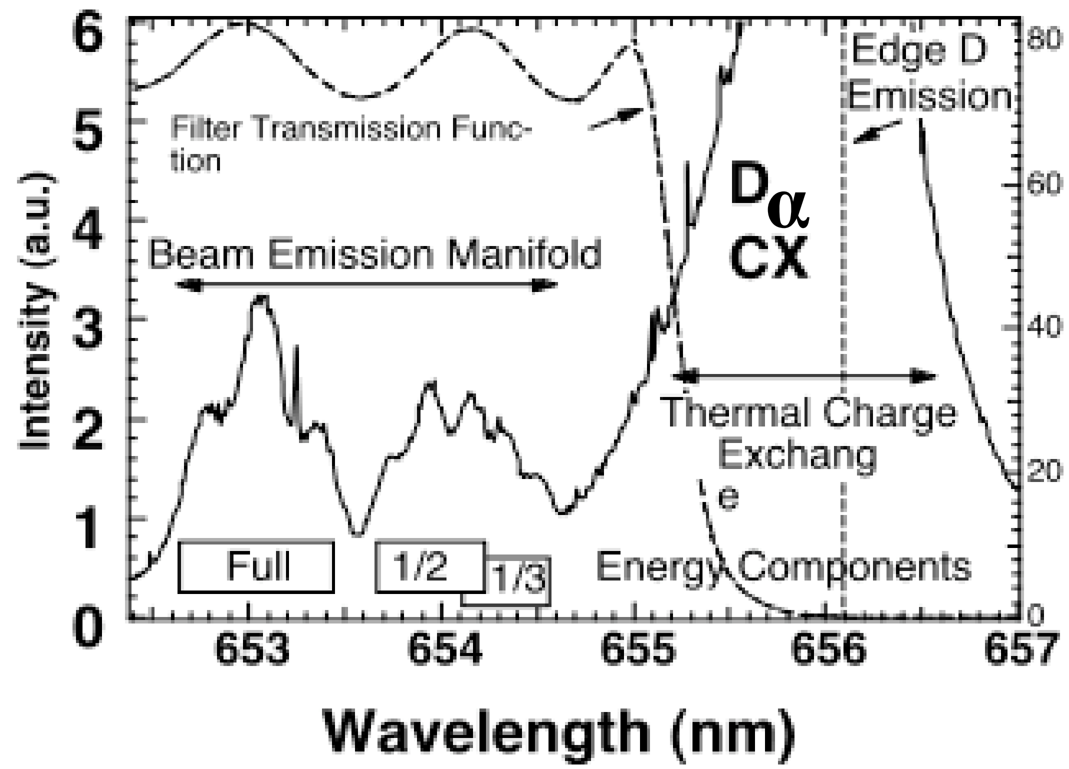



**75 KeV D$^{O}$ Neutral Beam (150 L (R))**



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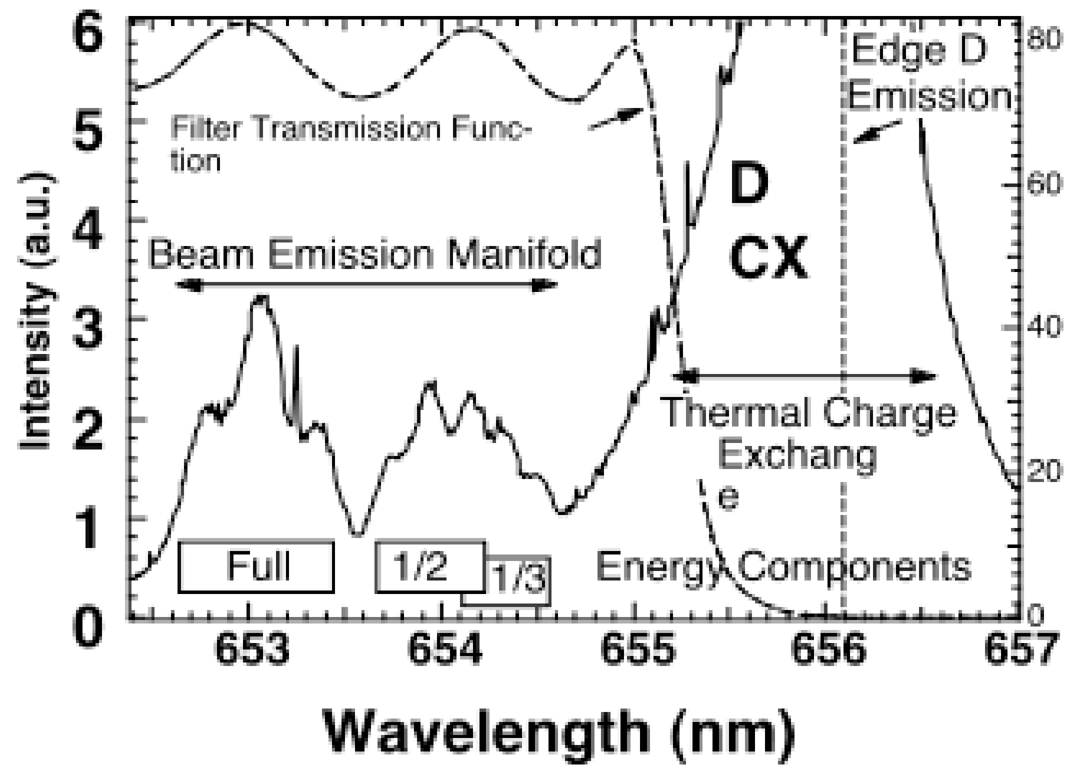


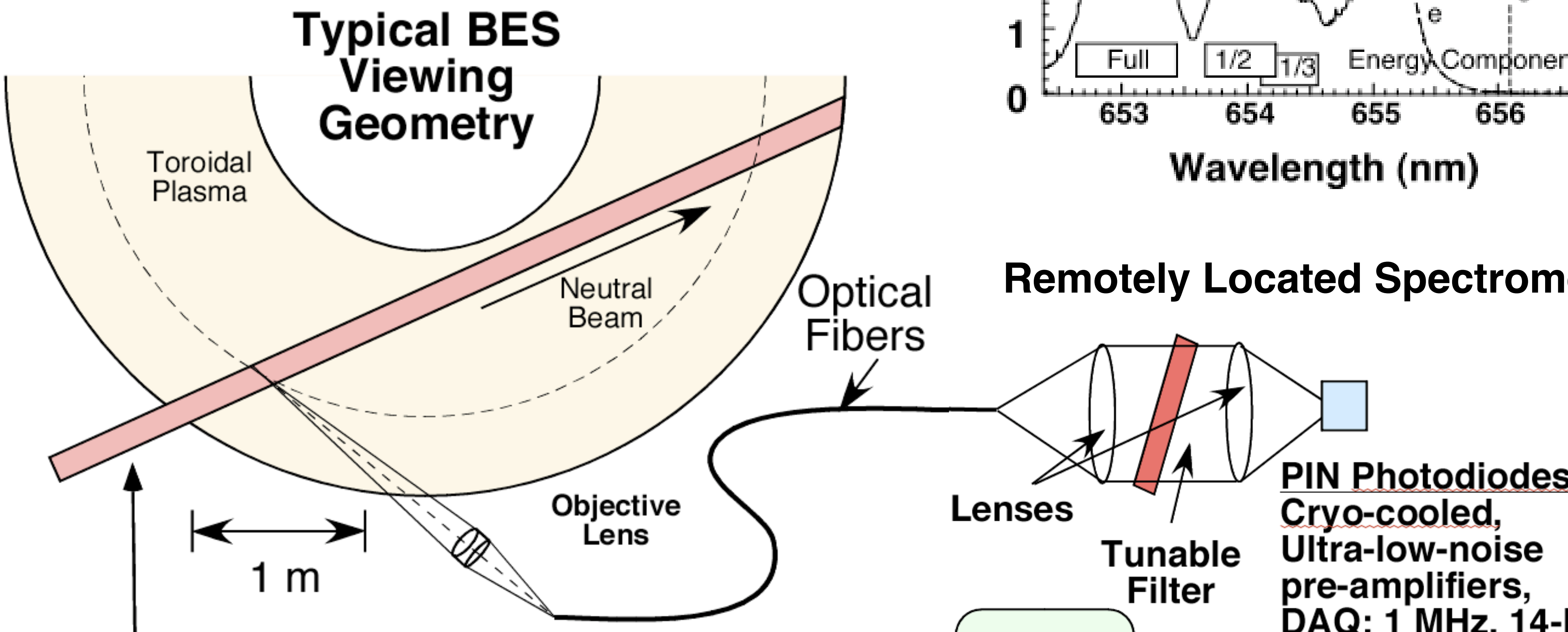


**75 KeV $D^o$ Neutral Beam (150 L (R))**

$$\frac{\tilde{I}}{I} \propto \frac{\tilde{n}}{n}$$ (via Atomic Physics)

$k_\perp < 3$ cm$^{-1}$

# Beam Emission Spectroscopy Measures Fluorescence of Heating Neutral Beam to Detect Local Density Fluctuations

**Collisionally-excited, Doppler-shifted neutral beam fluorescence**

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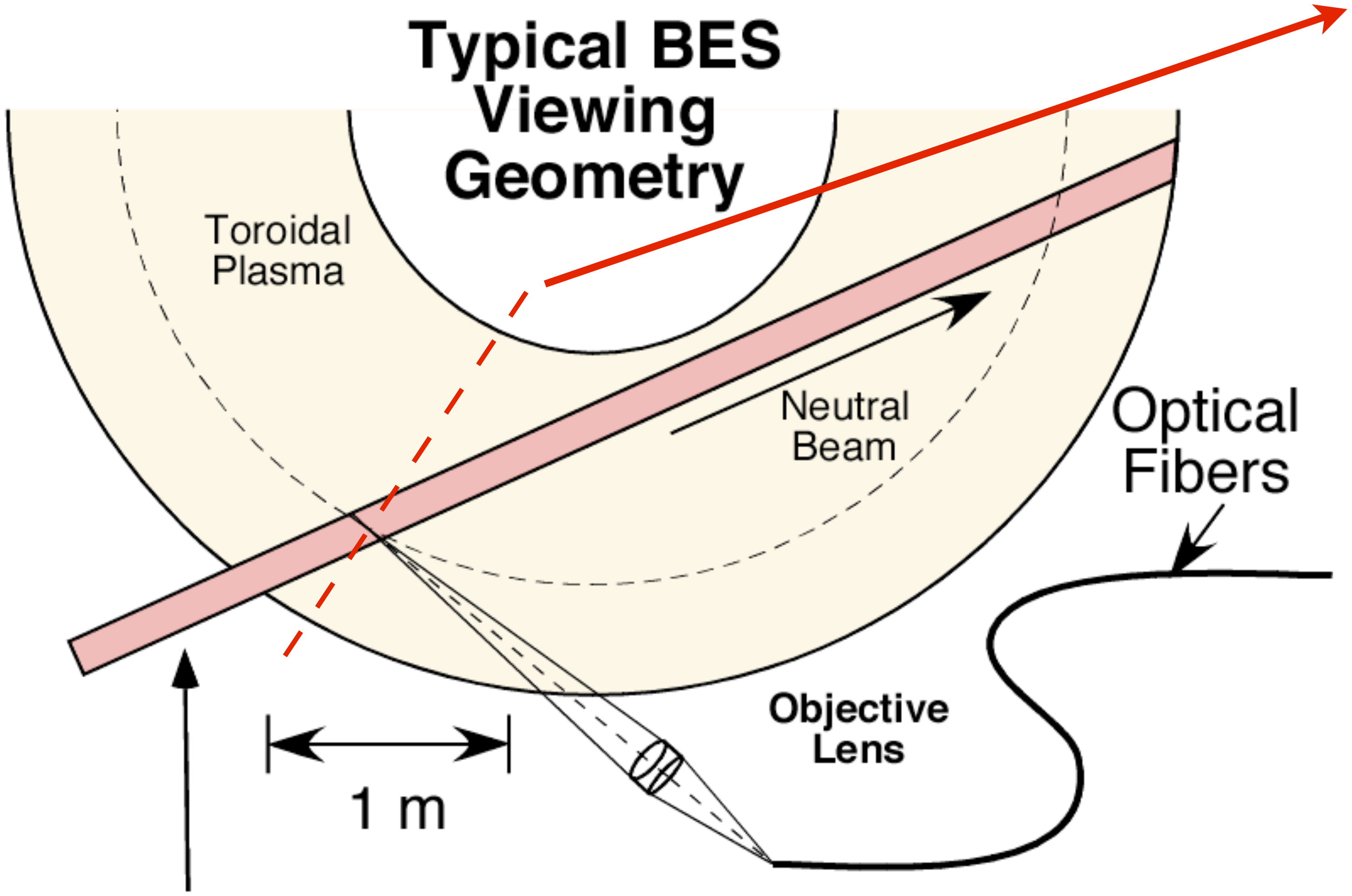


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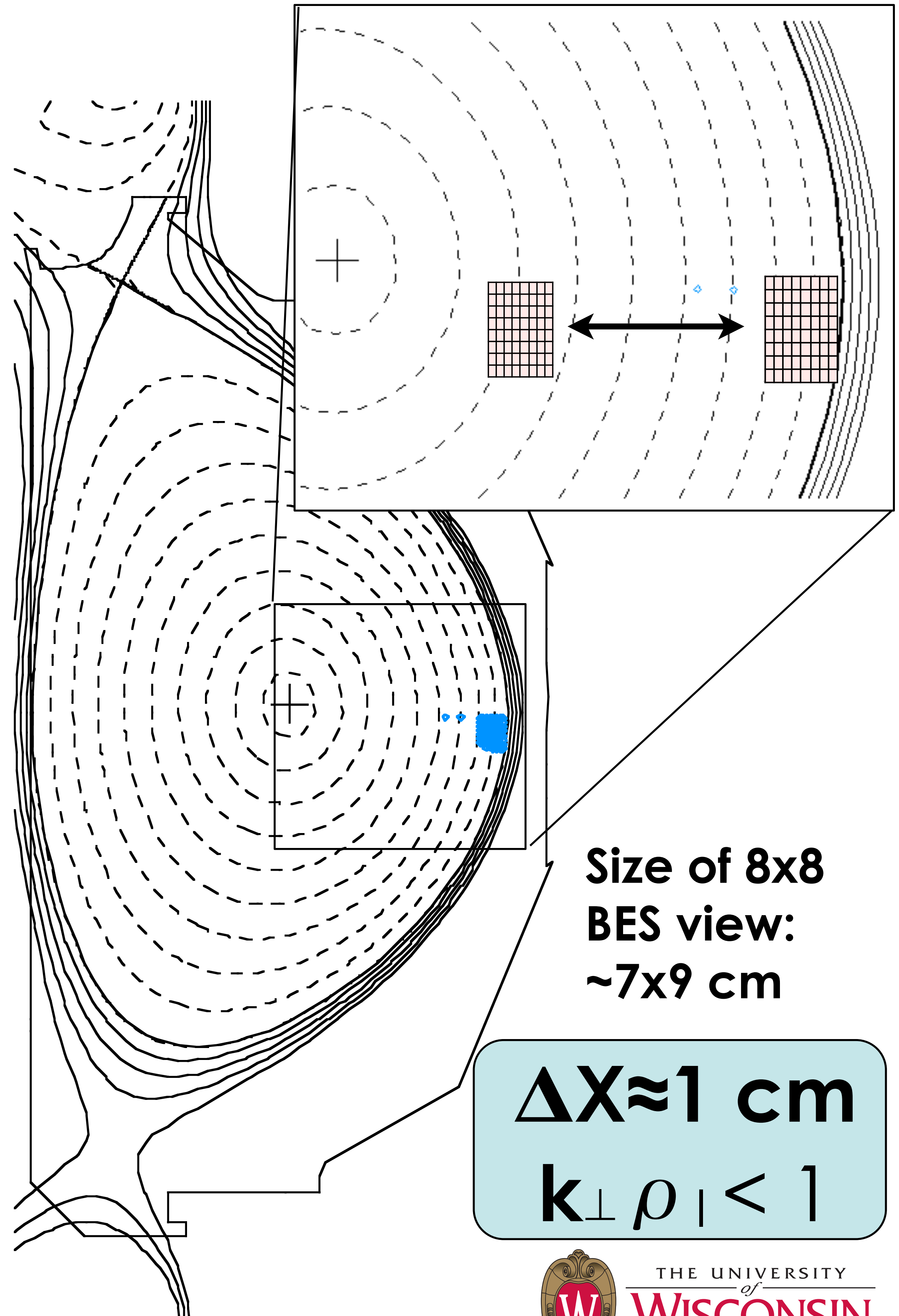


**Size of 8x8 BES view: ~7x9 cm**

**$\Delta X \approx 1$ cm**

**$k_{\perp} \rho_{I} < 1$**

# Turbulence Spectrum Evolves Dynamically During Discharge

- **Measurements obtained in Low Confinement-mode Discharges:**
  *Ip=1 MA, BT = -2.0 T*
  *Pinj = 5 MW,*
  $n_{e,o}$*=3x10*$^{19}$ *m*$^{-3}$*,*
  $T_{e,o}$*=2.2 keV,* $T_{i,o}$*=2.7 keV*

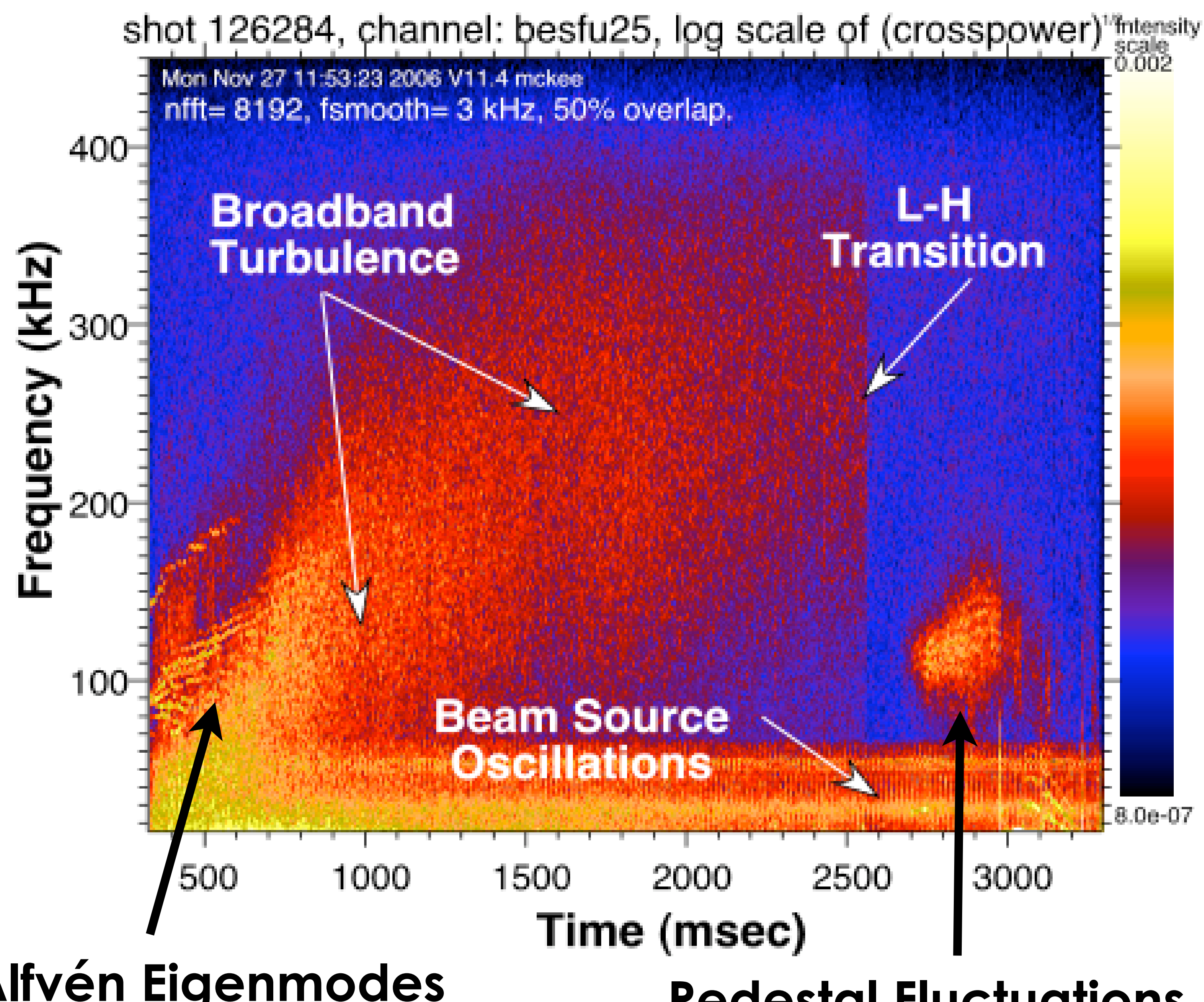
- **Coherent energetic particle driven-modes observed early in plasma**

- **Broadband turbulence evolves to quasi-steady phase**

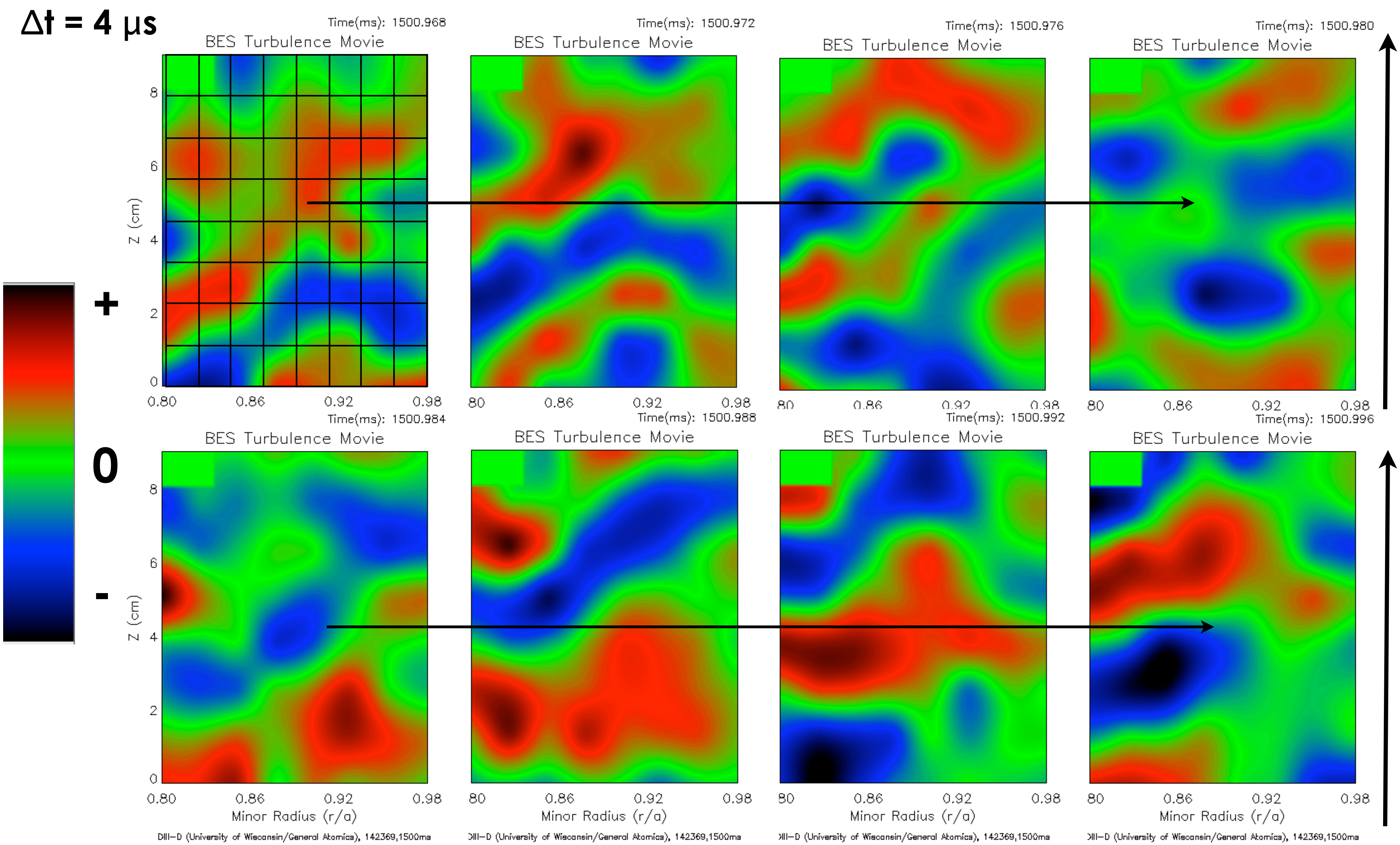
- **Fluctuations markedly reduced in core region at LH transition**

- **Beam source oscillations can be isolated and subtracted**

**Cross Power Spectrum at r/a=0.64 (ΔZ=1.2 cm)**



# Example Turbulence Images from 8x8 BES Array



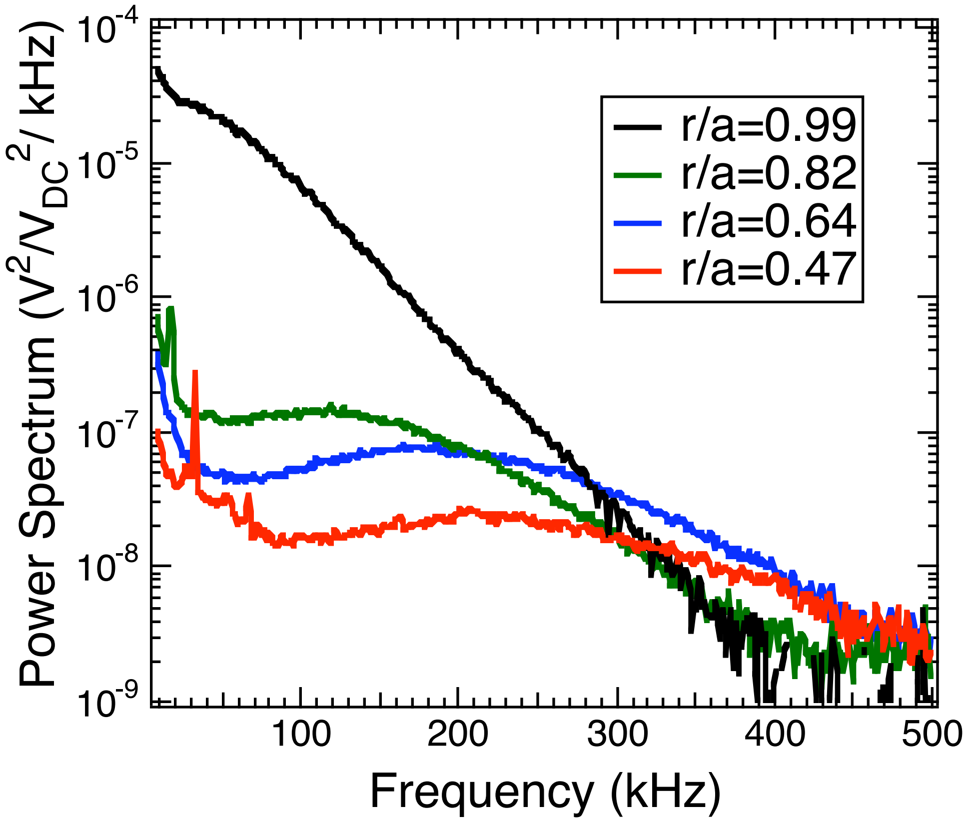

See visualization ⟶

# Features Observed on Visualization

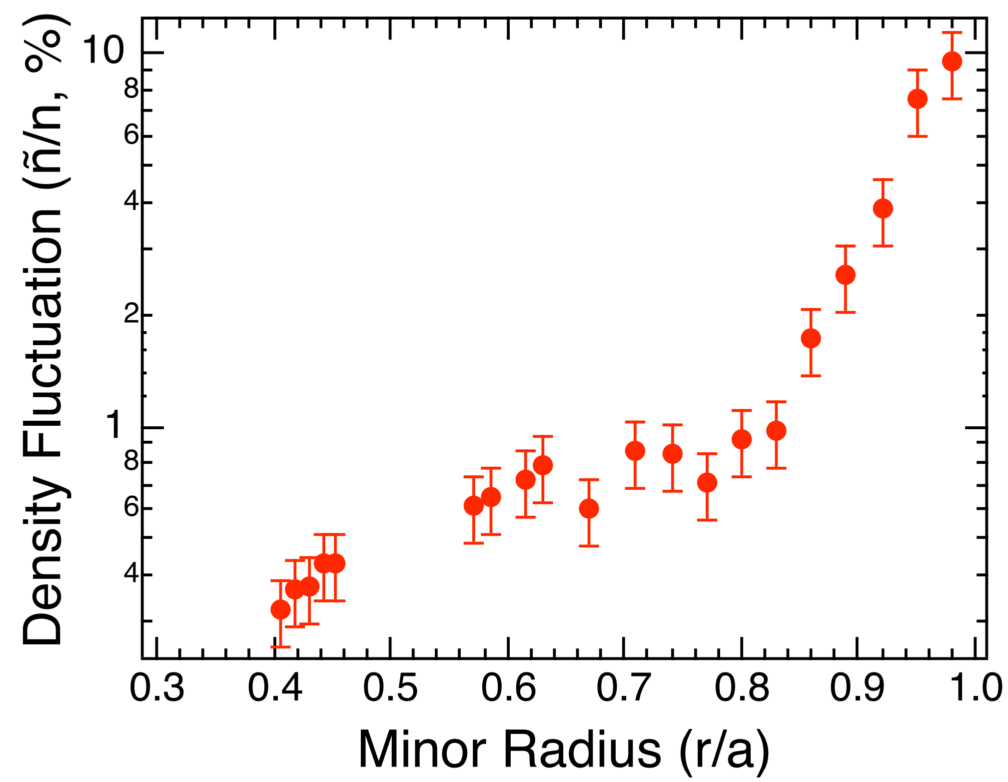
- **Eddy structures exhibit ~1-2 cm correlation lengths (~10$\rho_I$)**
  - consistent with ensemble-averaged correlation functions
  - Periodically, significantly larger structures appear
- **Poloidal drift ("upwards" in visualization)**
  - Consistent with ExB drift in ion diamagnetic direction (co-current plasma rotation from neutral beams)
  - Fluctuating radial and poloidal motion
- **Turbulent eddy lifetimes ~10-20 $\mu$s**
- **Significant interaction of smaller and larger eddy structures**
  - Evidence of nonlinear interactions; internal energy transfer
- **Shearing of eddies from background sheared flow**
- **Features are not observed in time (ensemble) averaged correlations**

# Fluctuation Spectra and Amplitude Vary Strongly with Radius

## Fluctuation Spectra at Several Radii



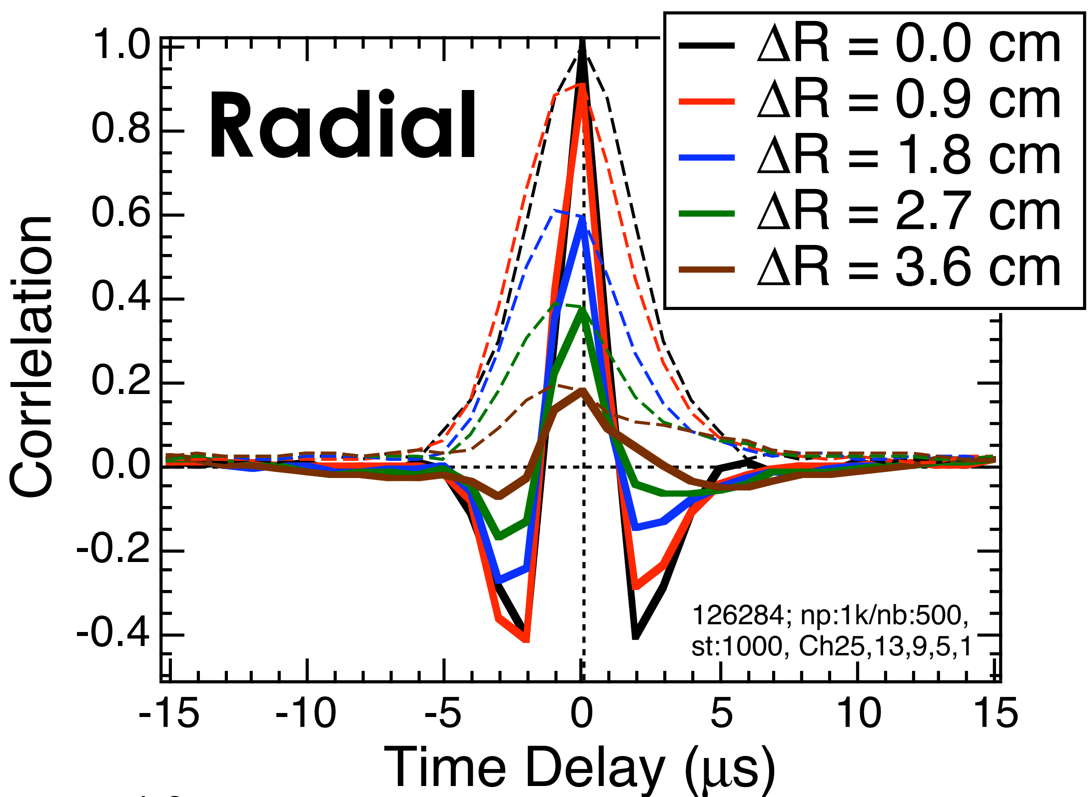

## Density Fluctuation Amplitude Profile

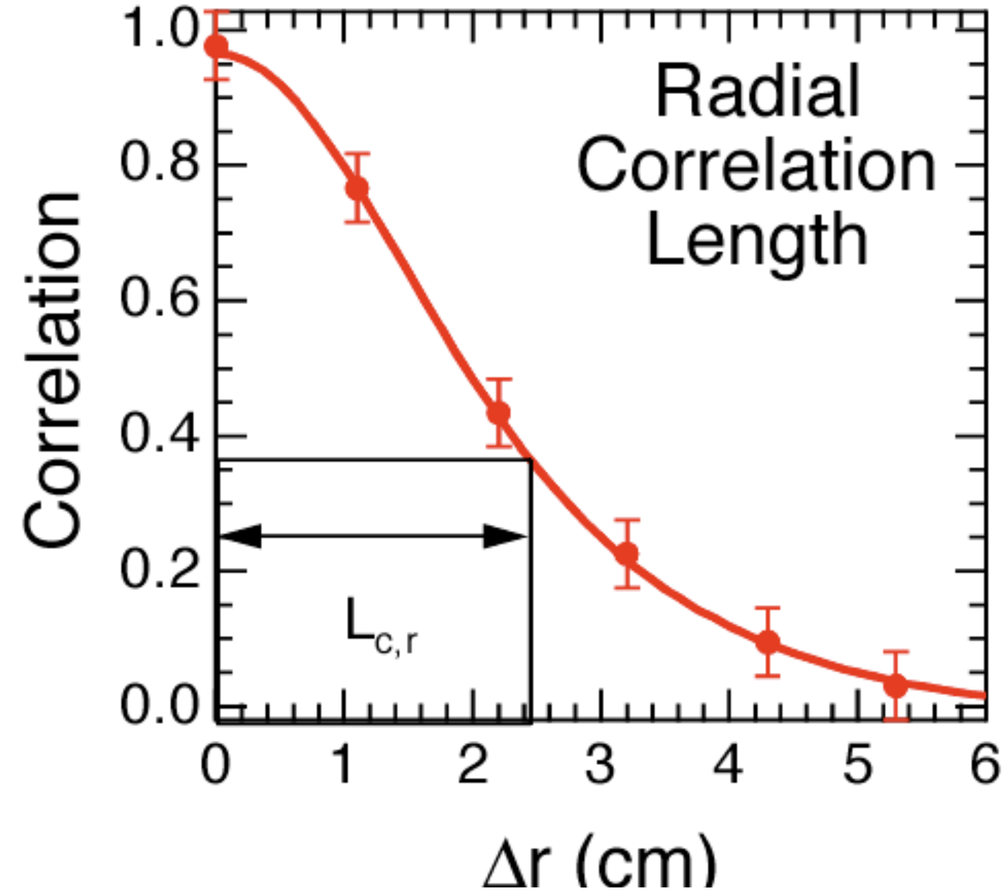


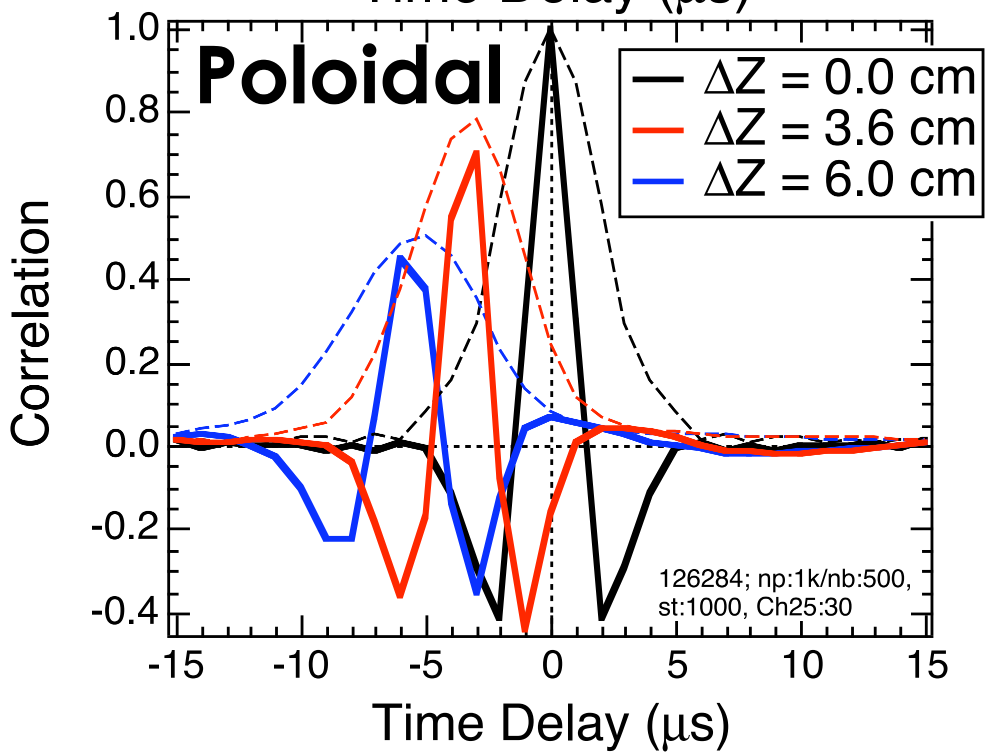

- **Density fluctuation amplitude in L-mode discharges shows wide dynamic range across plasma radius**
  - *Intense edge fluctuations routinely observed in L-mode plasmas*

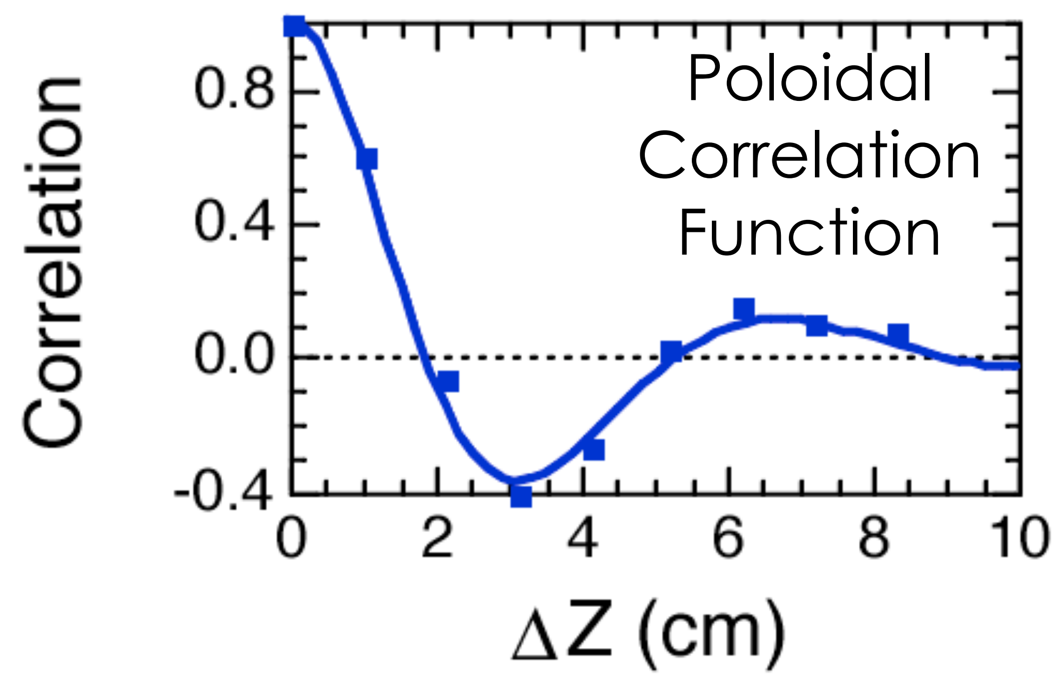
- **Spectra Doppler-shifted to higher frequency towards core**

# Turbulence Correlation Lengths ~ 10 Ion Gyroradii, consistent with gyrokinetic predictions



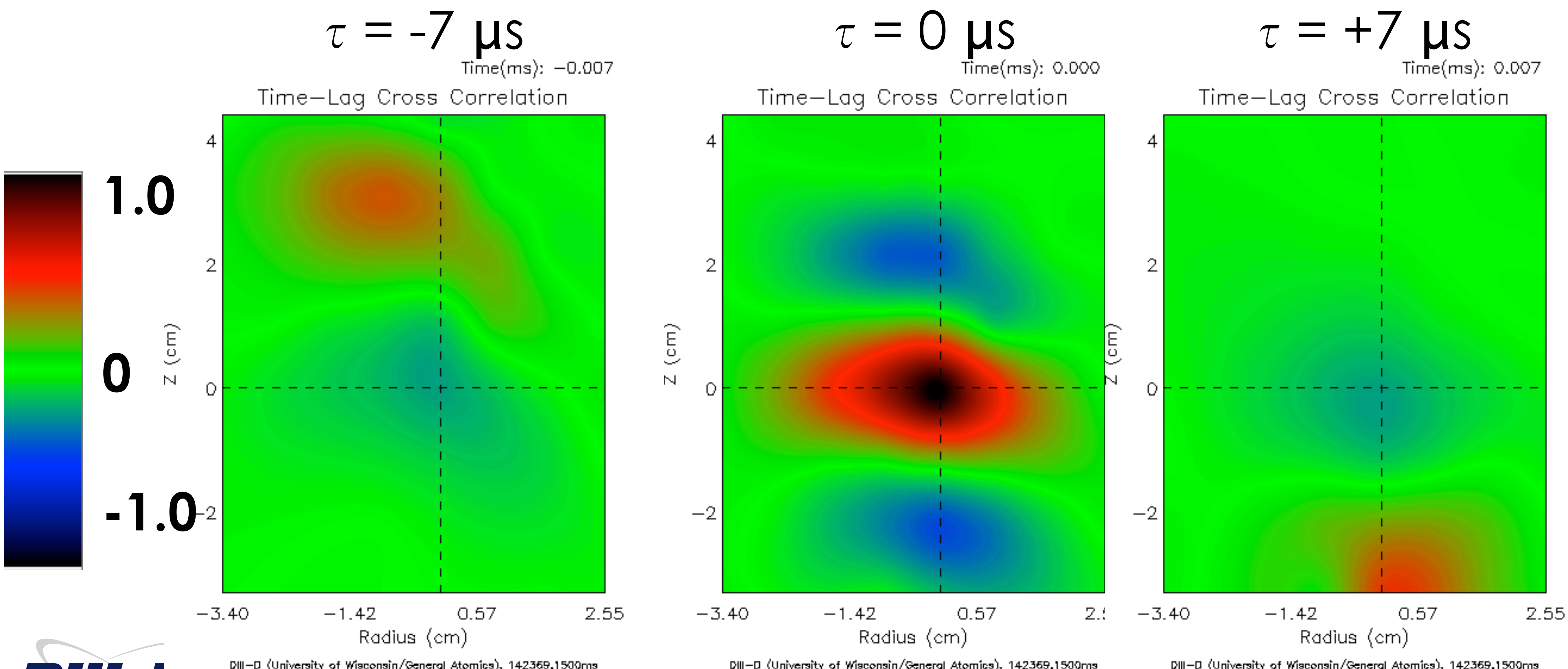




**$L_{c,r}$~2.4 cm, $L_{c,\theta}$~4 cm, ~10 $\rho_I$**

# 2D Array Observes Full $\tau$ = 0 Spatial Cross Correlation Function

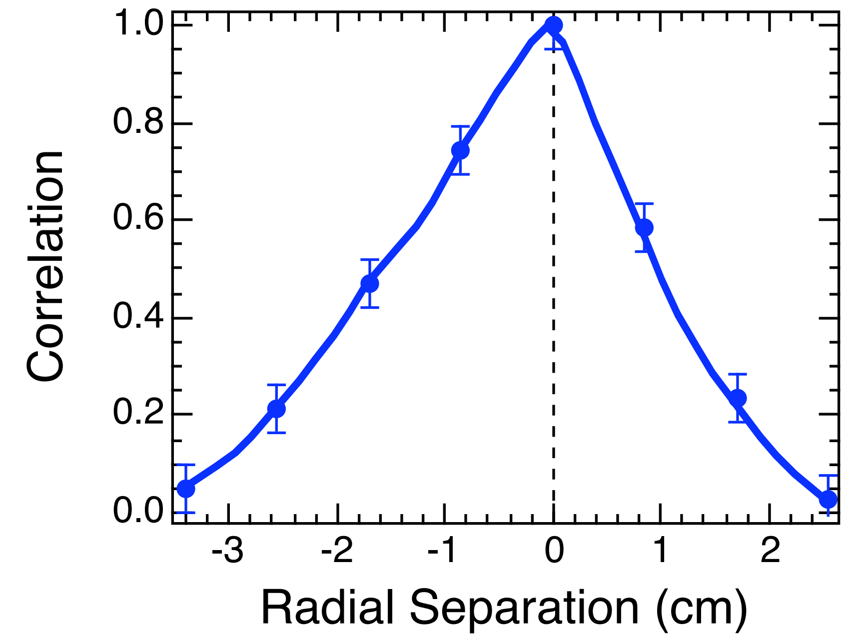
- **Ensemble-averaged, time-resolved 2D cross correlation function assembled from individual 2-point cross-correlations**
- **Illustrates poloidal advection, and alignment of 2D grid to flux surfaces**
- **Point-Spread-Function ( $\Delta$X~1 cm) NOT deconvolved from data**

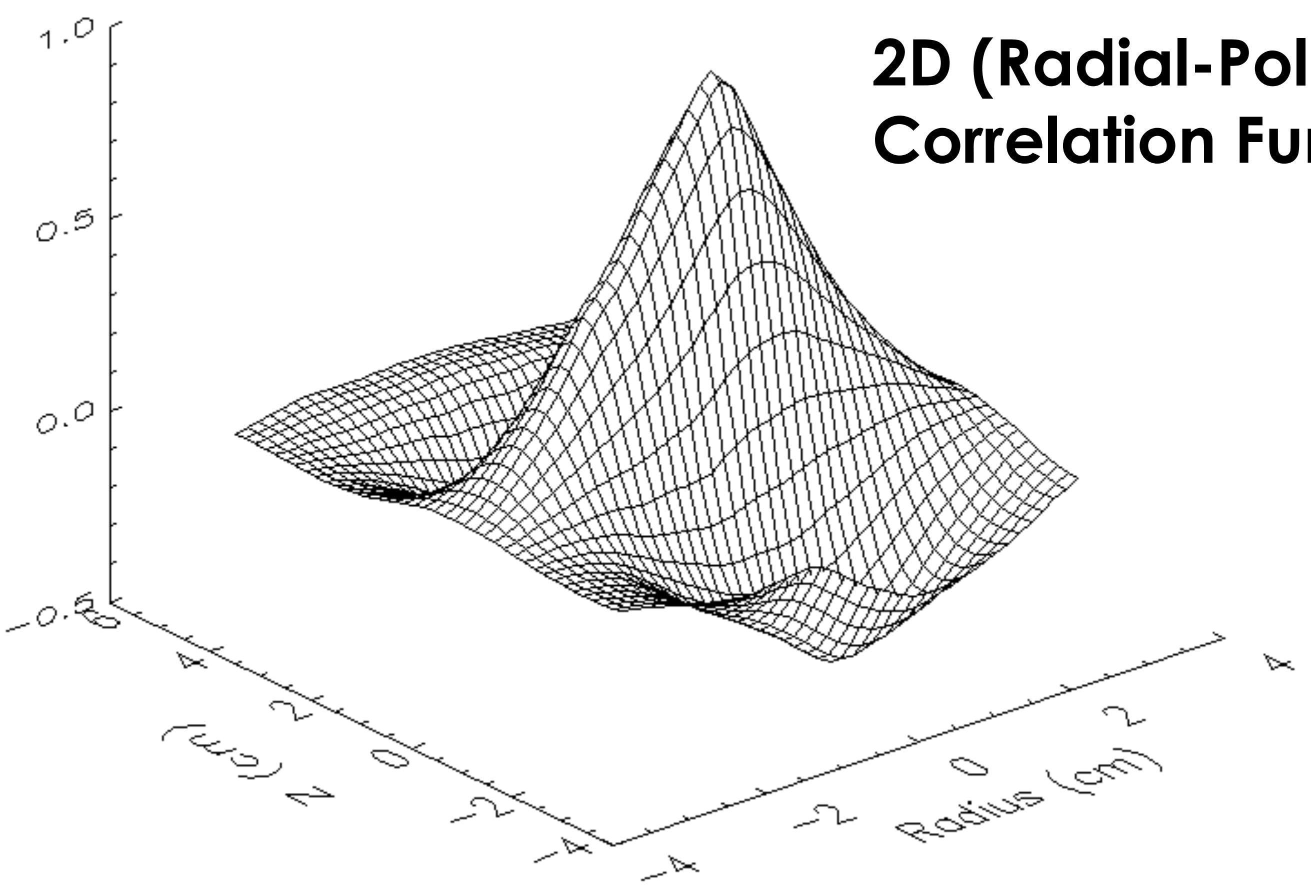


# Full $\tau$ = 0 Spatial Cross Correlation Function, $S(k_r, k_\theta)$ spectra measured with 2D 8x8 Array

- **2D correlation function exhibits wave-like poloidal structure and decaying radial structure**
  - Point Spread Function not yet applied
  - Radially asymmetric function

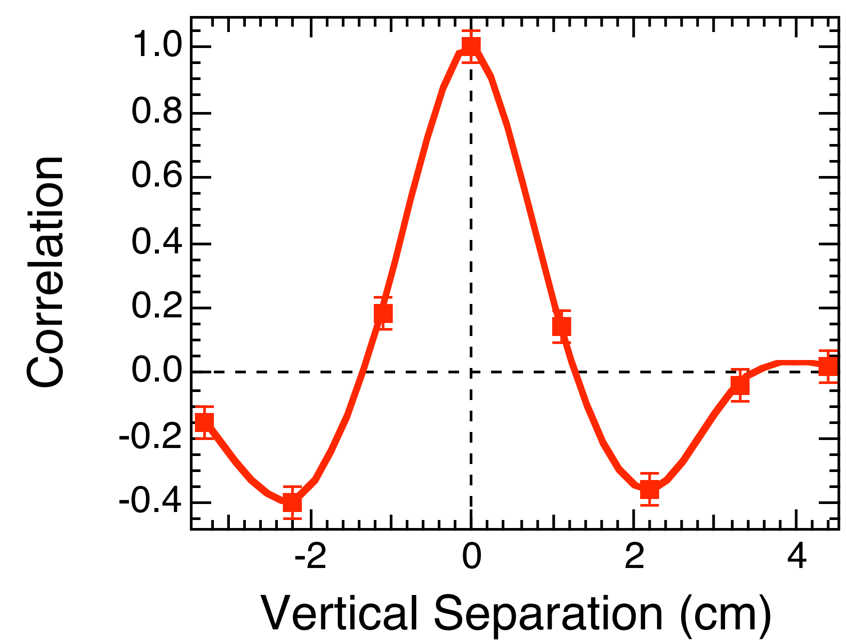
**Radial Correlation**




**2D (Radial-Poloidal) Correlation Function**

**Poloidal Correlation**



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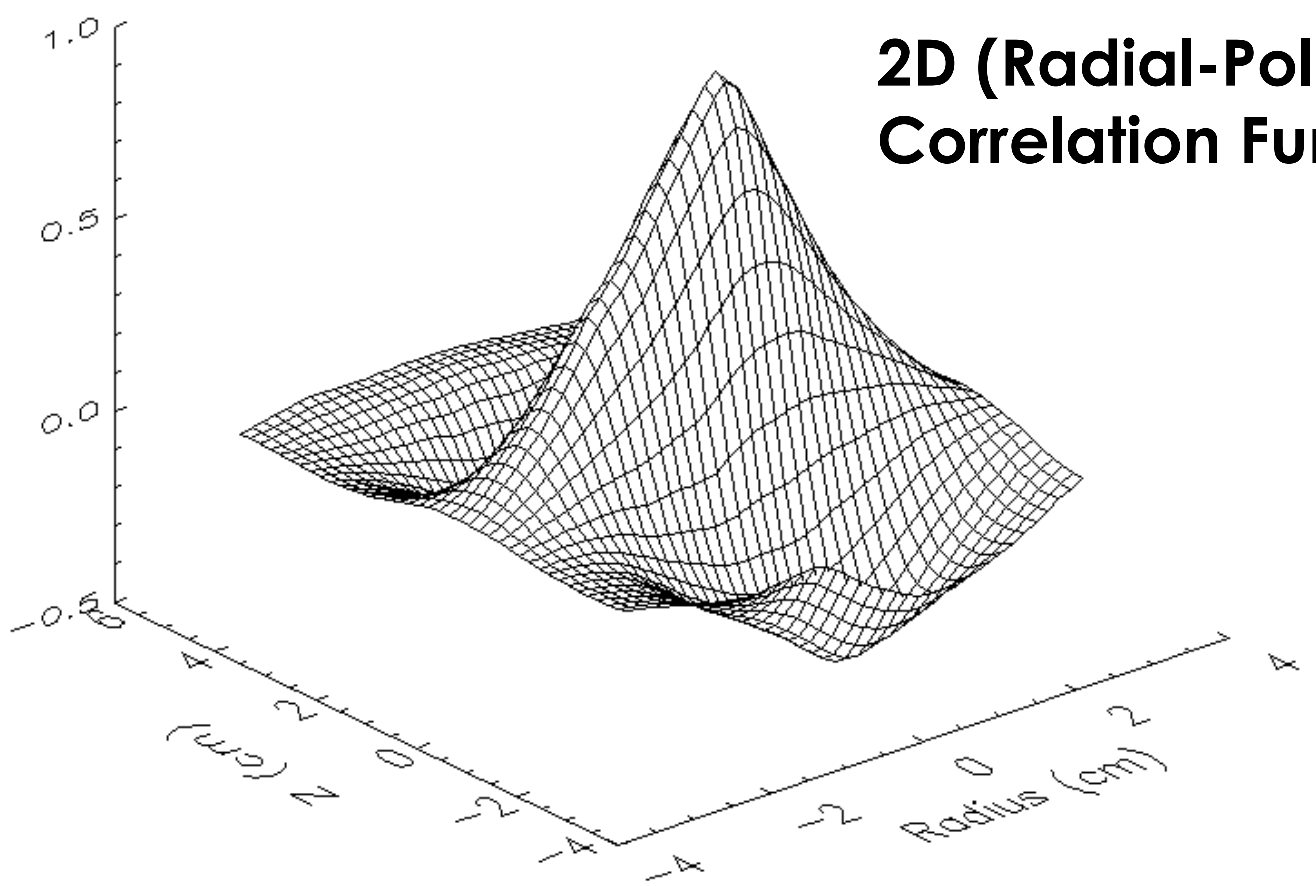
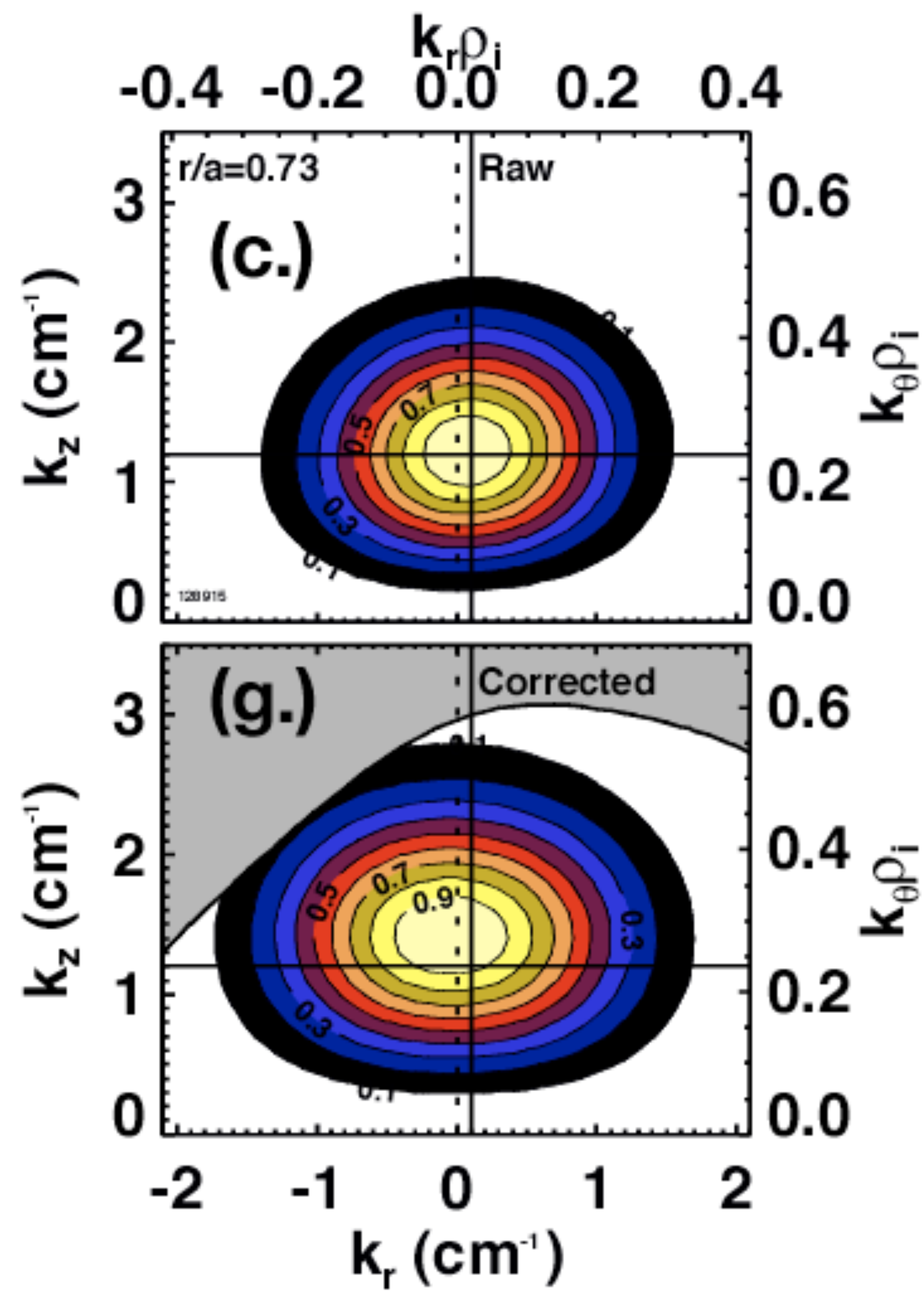
- **2D correlation function exhibits wave-like poloidal structure and decaying radial structure**
  - Point Spread Function Deconvolved
  - Radially asymmetric function




**2D (Radial-Poloidal) Correlation Function**

**$S(k_r,k_\theta)$**





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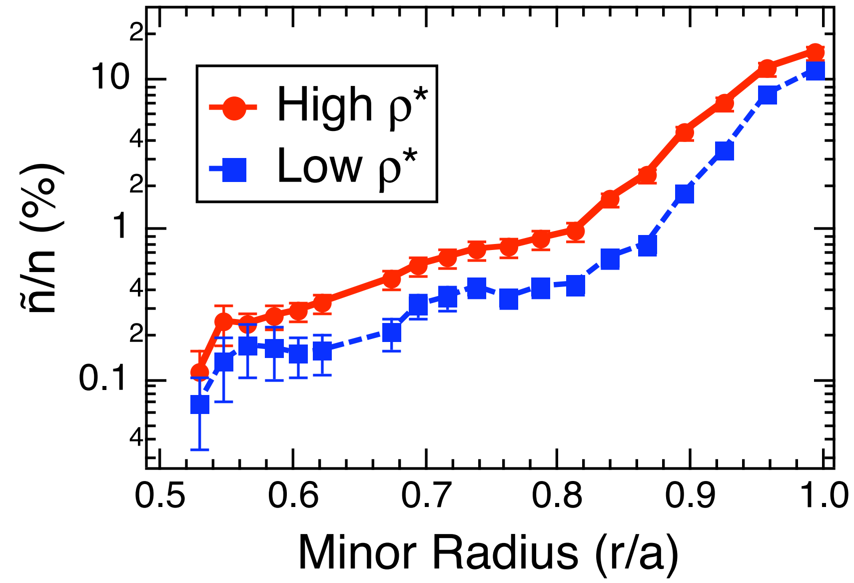
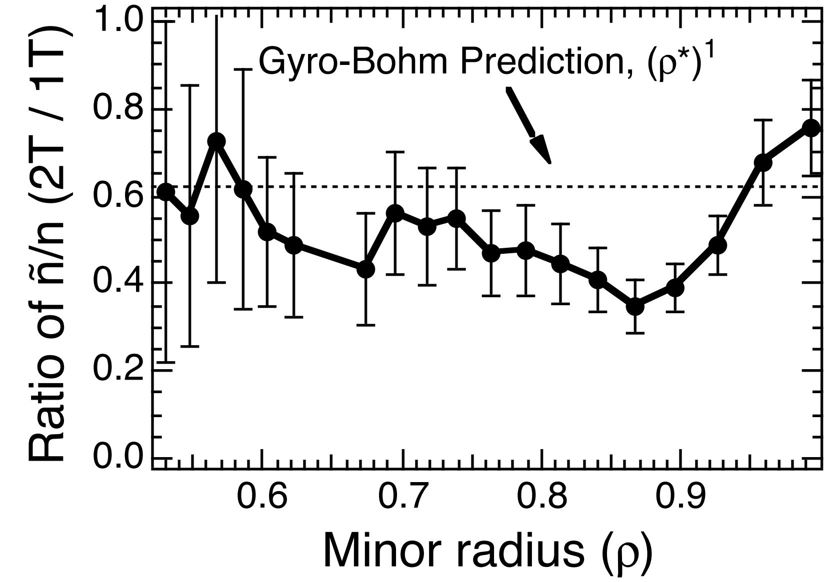
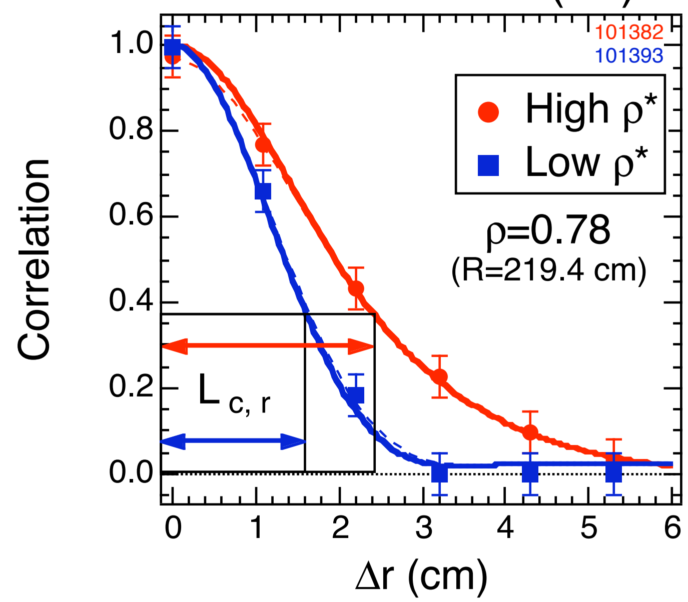
# Spatiotemporal Features of Turbulence Scale with $\rho_I^*$, as Expected from Gyrokinetic Equations

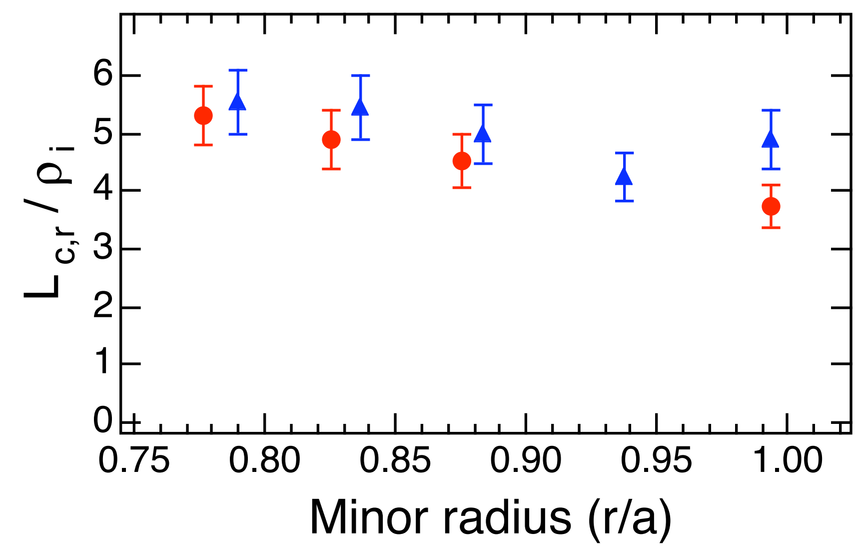
- **Fluctuation amplitude**
  - Scales as $\tilde{n}/n \sim \rho_I^*$



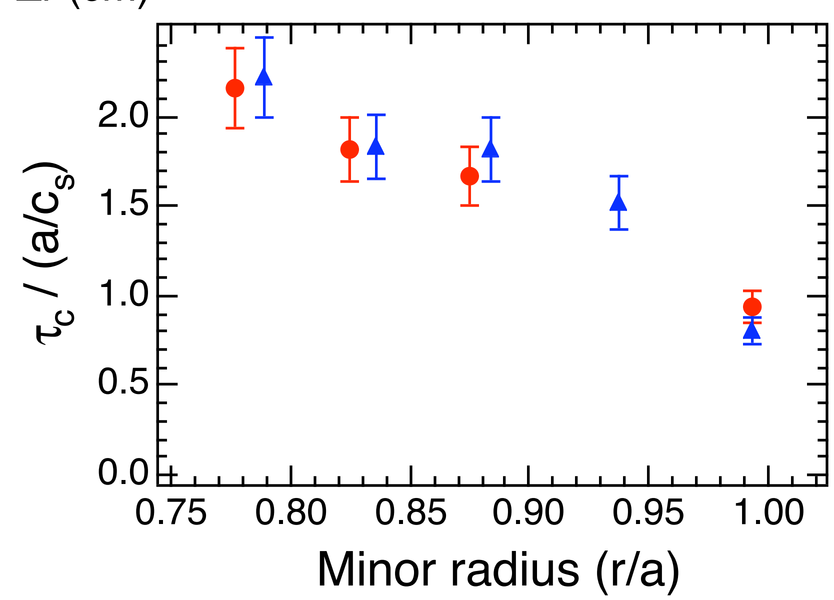




- **Radial Correlation Length**
  - Scales with ion gyroradius, $\rho_I$



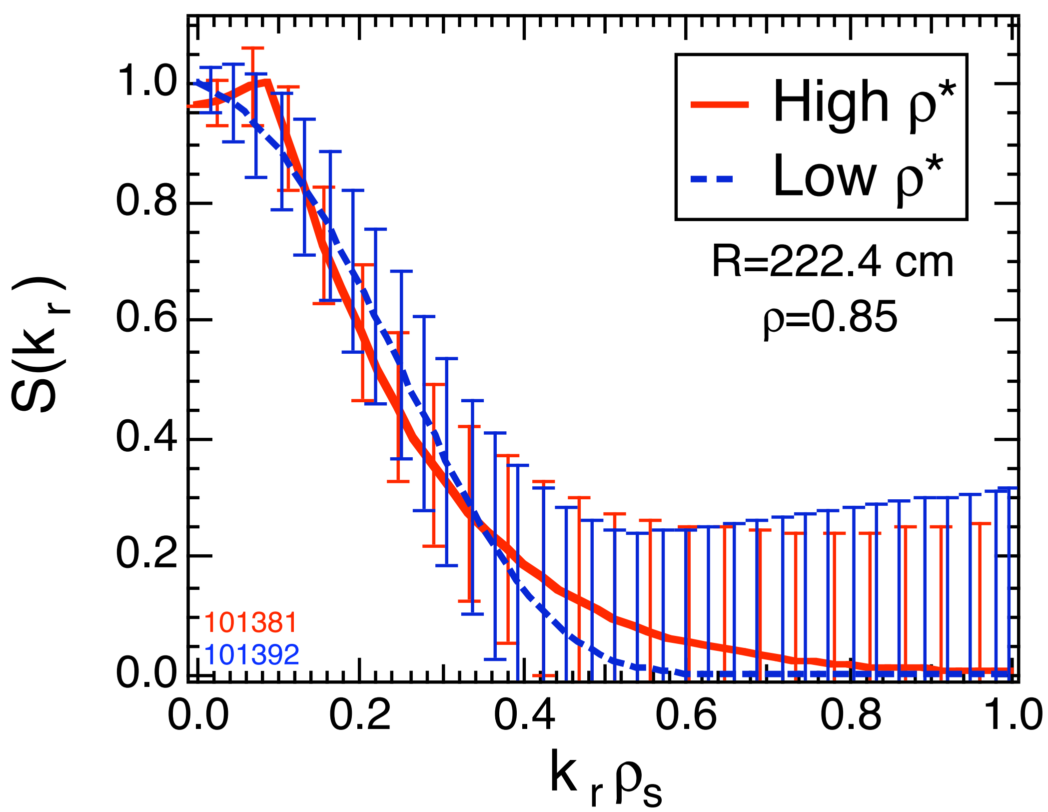




- **Decorrelation time**
  - $\tau_c \sim a/c_s$

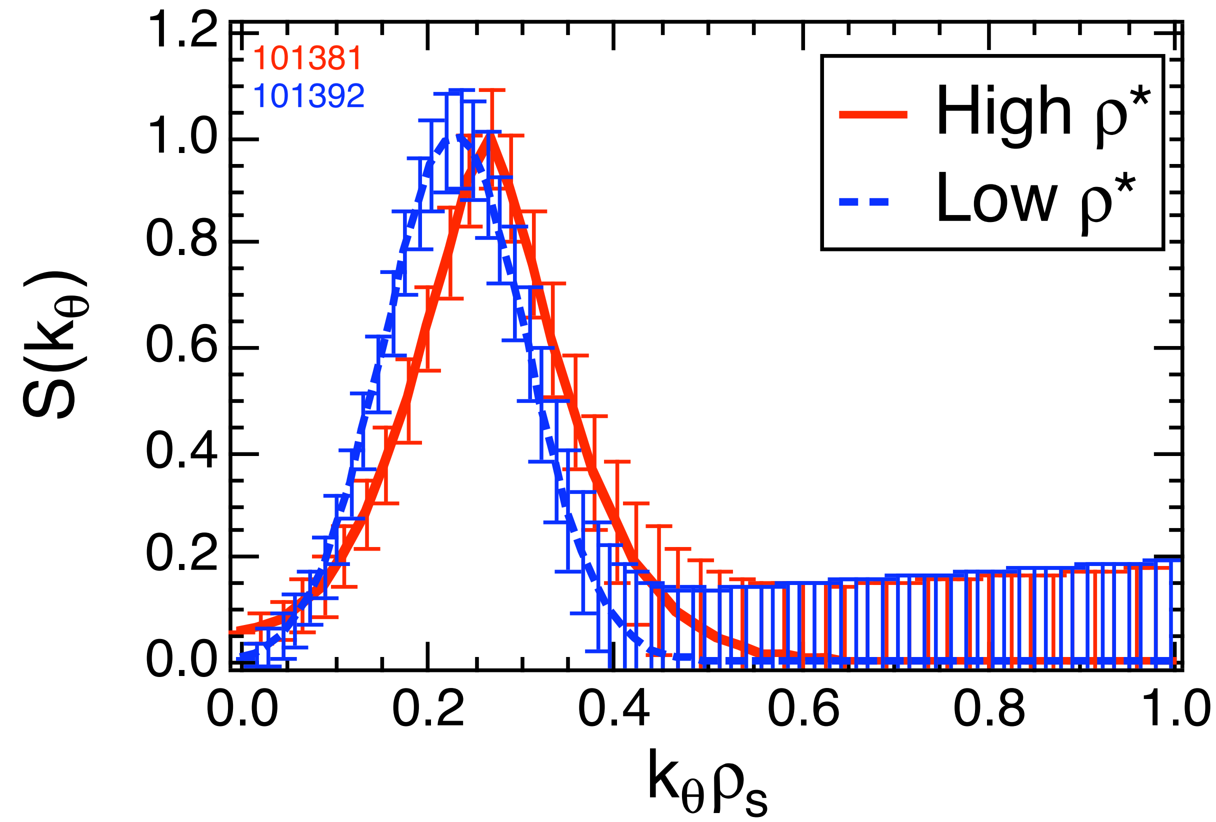


# Measured Wavenumber Spectra are Matched as $\rho_I^*$ Varied

## $S(k_r)$ Spectrum




## $S(k_\theta)$ Spectrum



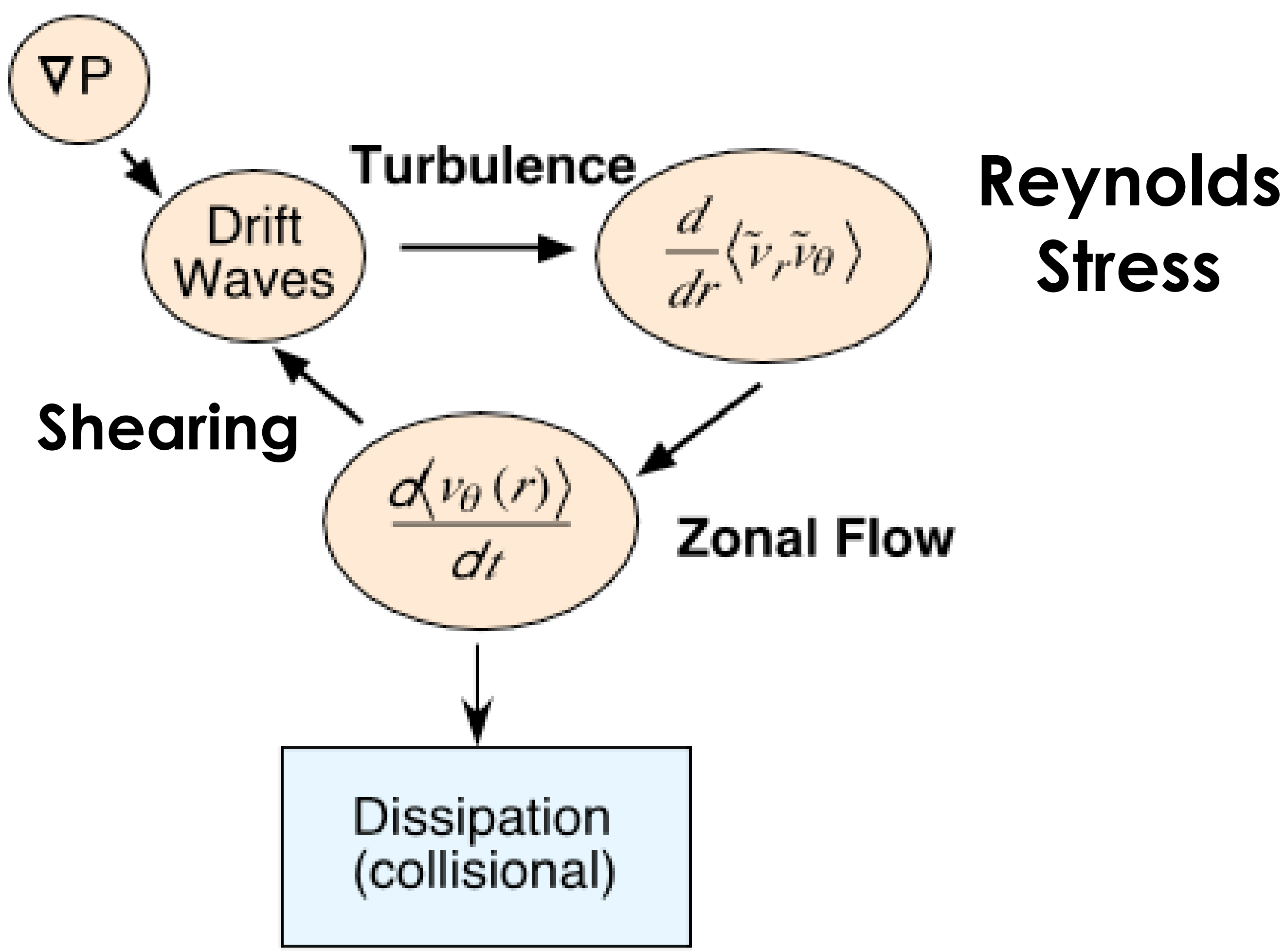

- **Normalized spectra are nearly self-similar**

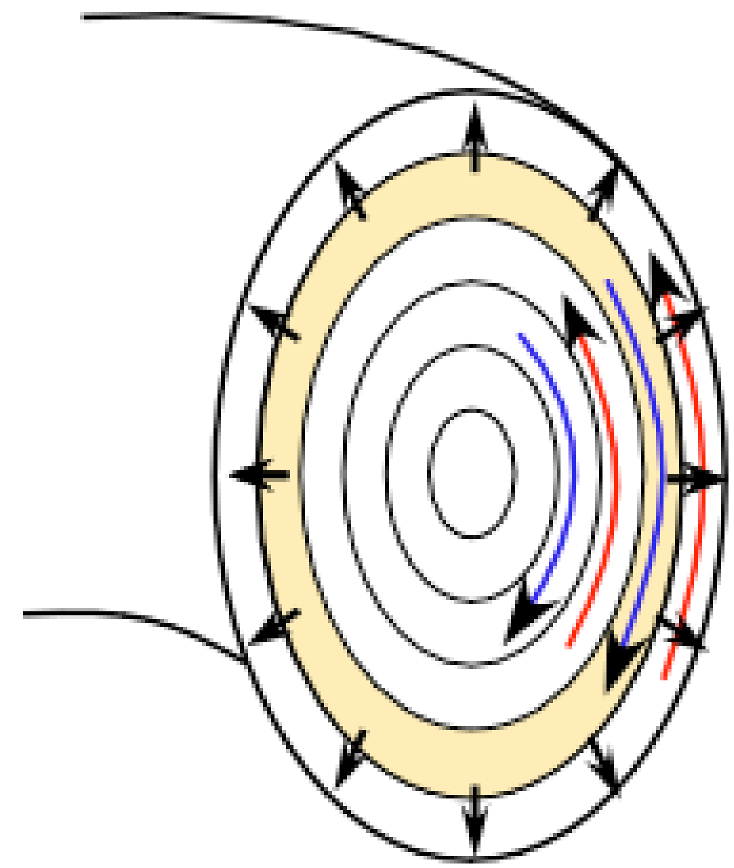
# Theoretically-predicted Zonal Flows Thought Crucial to Mediating Fully Saturated Turbulence in Plasmas

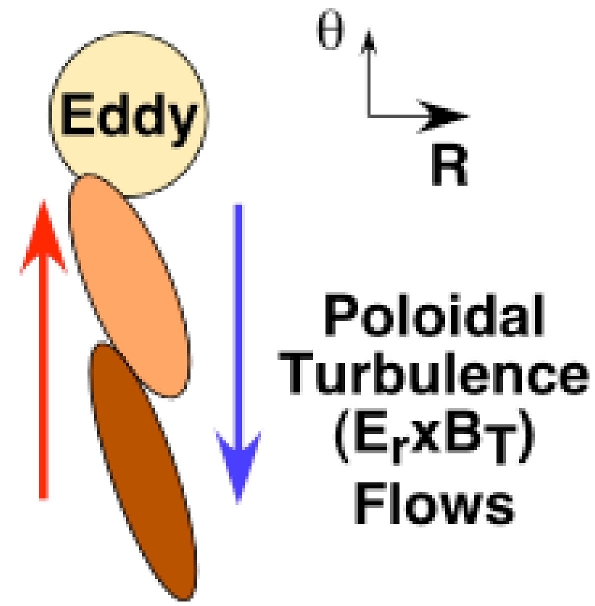
- **Regulate turbulence via fluctuating $E_r x B_T$ ($v_\theta$) flows**
  - *Observed in turbulence simulations*
- **Radially-localized, n=0, m=0, electrostatic potential**

  *1) Zero-Mean-Frequency zonal flow(ZMF-ZF, $\Delta f \sim \nu_{ii} < 10$ kHz)*

  *2) Geodesic Acoustic Mode (GAM, coherent, 10-20 kHz)*



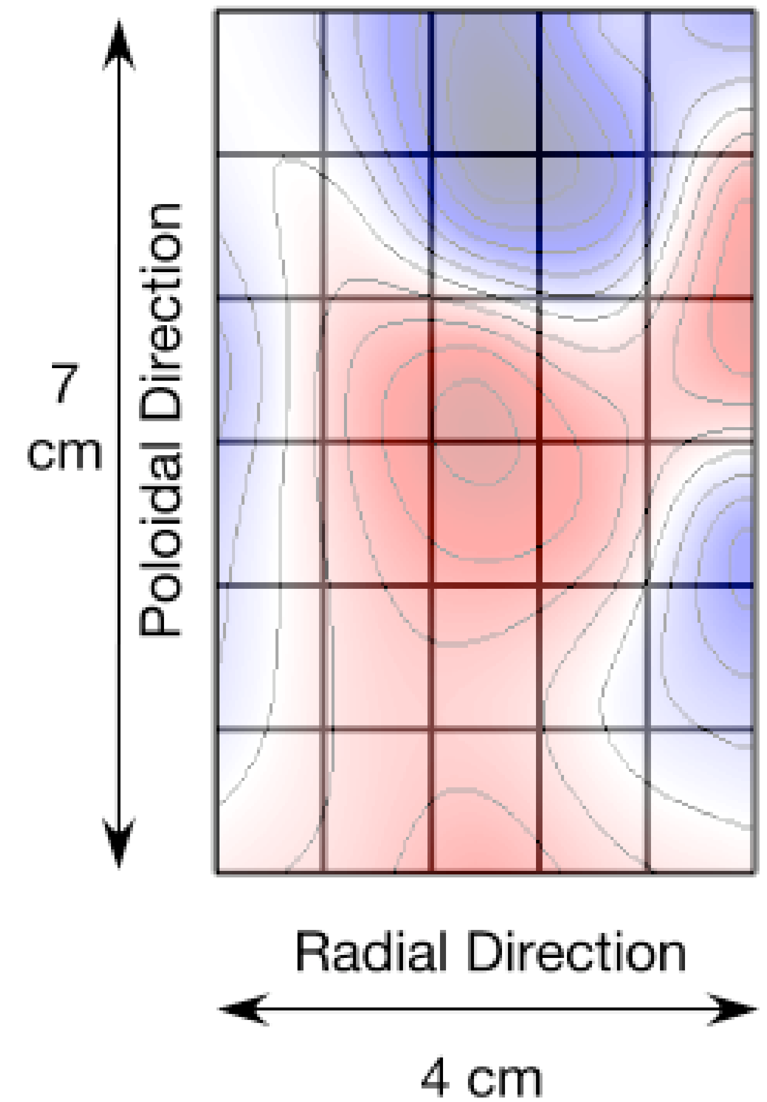






*P. Diamond, S. Itoh, K. Itoh, T.S. Hahm, PPCF 47, R35 (2005).*

# Time-Varying Turbulence Flows Measured Via 2D ñ with BES to Discern Zonal Flow Characteristics

Turbulence imaged with discrete channels deployed on 2D grid




**Time Delay Estimation between poloidally-adjacent channels:**

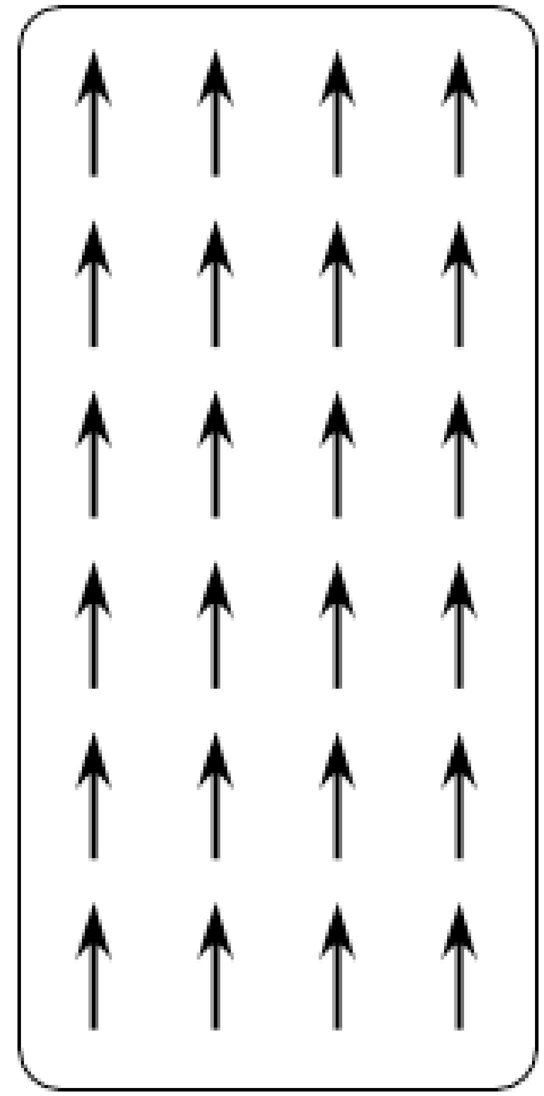
**1) Wavelet-based cross-phase ($\Delta\theta(t)$)**

**2) Time-resolved cross-correlation ($\tau_{\rho,max}(t)$)**

**3) Dynamic Programming (vector matching method)**

***$V_\theta(R,Z,t)$***

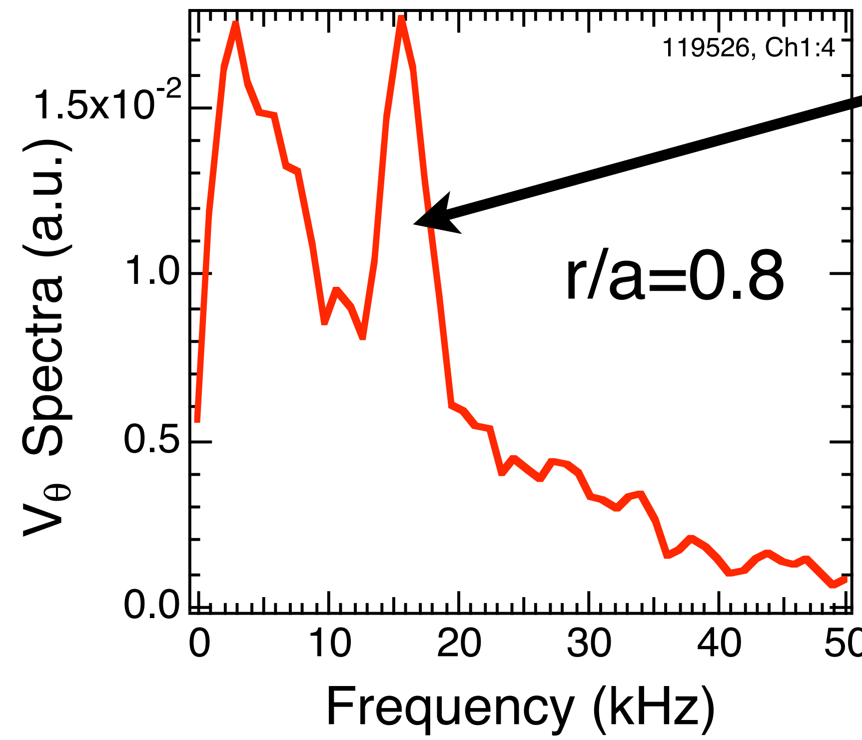
on relevant time scale ($0 < f < 200$ kHz)



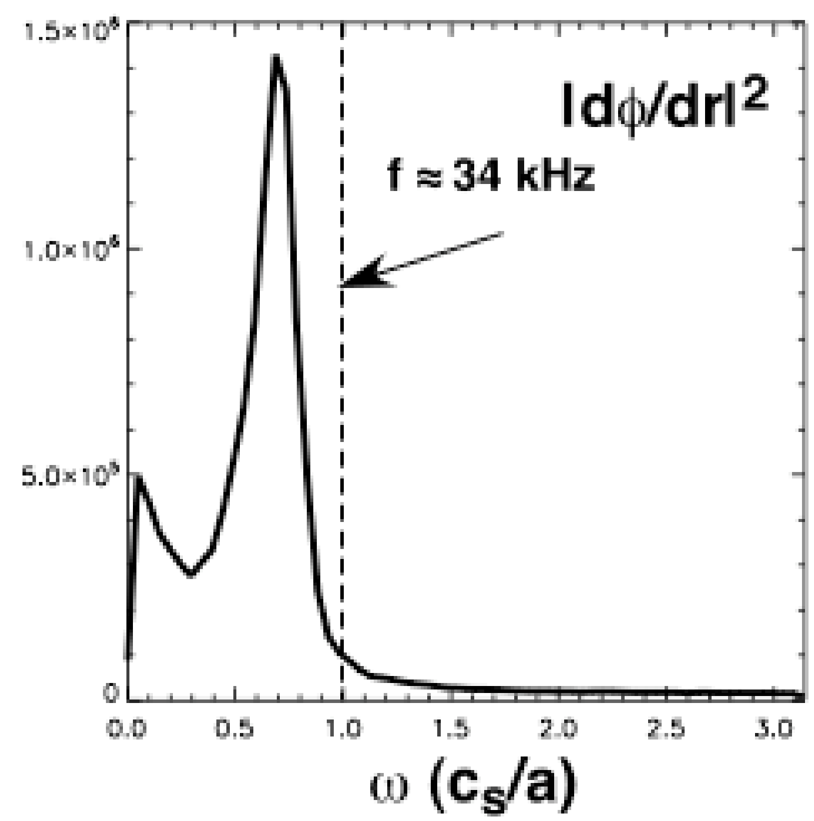
Spectral and spatial analysis of $v_\theta(R, Z, t)$ to search for flow features

# Zonal Flow Features Observed in the $V_\theta$ Spectrum

- **Spectrum shows broad, low-frequency structure:**
  - *Peaks near zero frequency*
  - *Width, Δf~20 kHz*
- **GAM also clearly observed near f = 15 kHz**
  - *Observed on DIII-D and other experiments (JFT-2M, ASDEX, HL-2A, JIPP-TIIU, CHS)*
- **GYRO simulation of zonal flow spectrum exhibits qualitative similarity to measured spectrum**




**Poloidal velocity spectrum measured with BES**

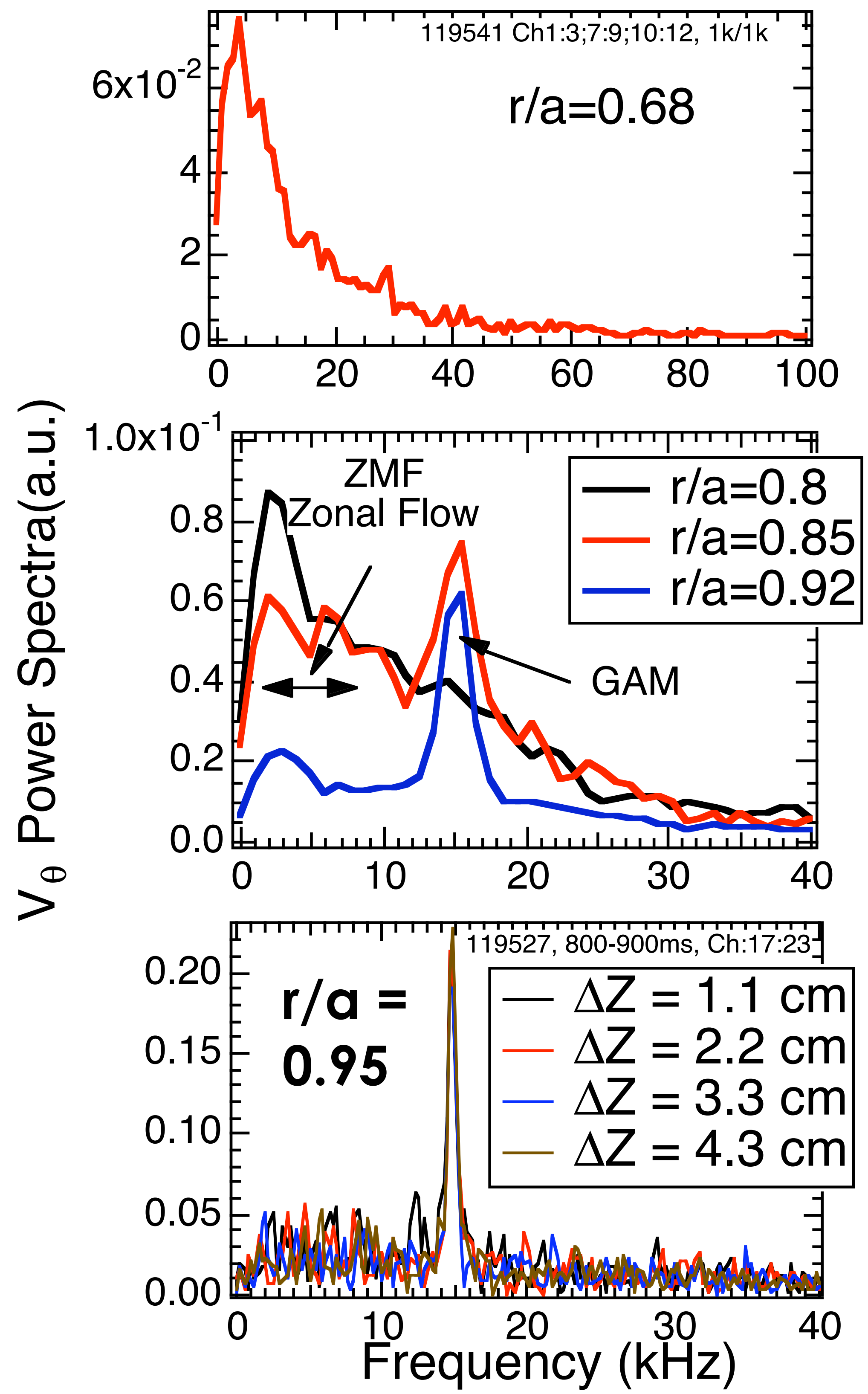



**GYRO** (q=3, flux tube, kinetic electrons)

# Transition from a low-frequency Zonal Flow in core to a GAM-dominated flow in edge region

- **Velocity spectra exhibit broad Zero-Mean-Frequency Zonal Flow spectrum for r/a < ~0.8**
- **Broad ZMF-ZF spectrum and GAM superimposed near r/a=0.85**
- **Geodesic Acoustic Mode dominates spectrum for r/a > 0.9**
  - $f_{GAM} = c_s/2\pi R$
- **Theory and simulation predict ZMF-ZF to dominate at lower q (core) while GAM dominates at higher q (edge)**
- **High coherence, f/Δf > 20, indicates GAM lifetime ($\tau_{GAM}$ > 1 ms), two orders of magnitude longer than turbulence decorrelation time:**

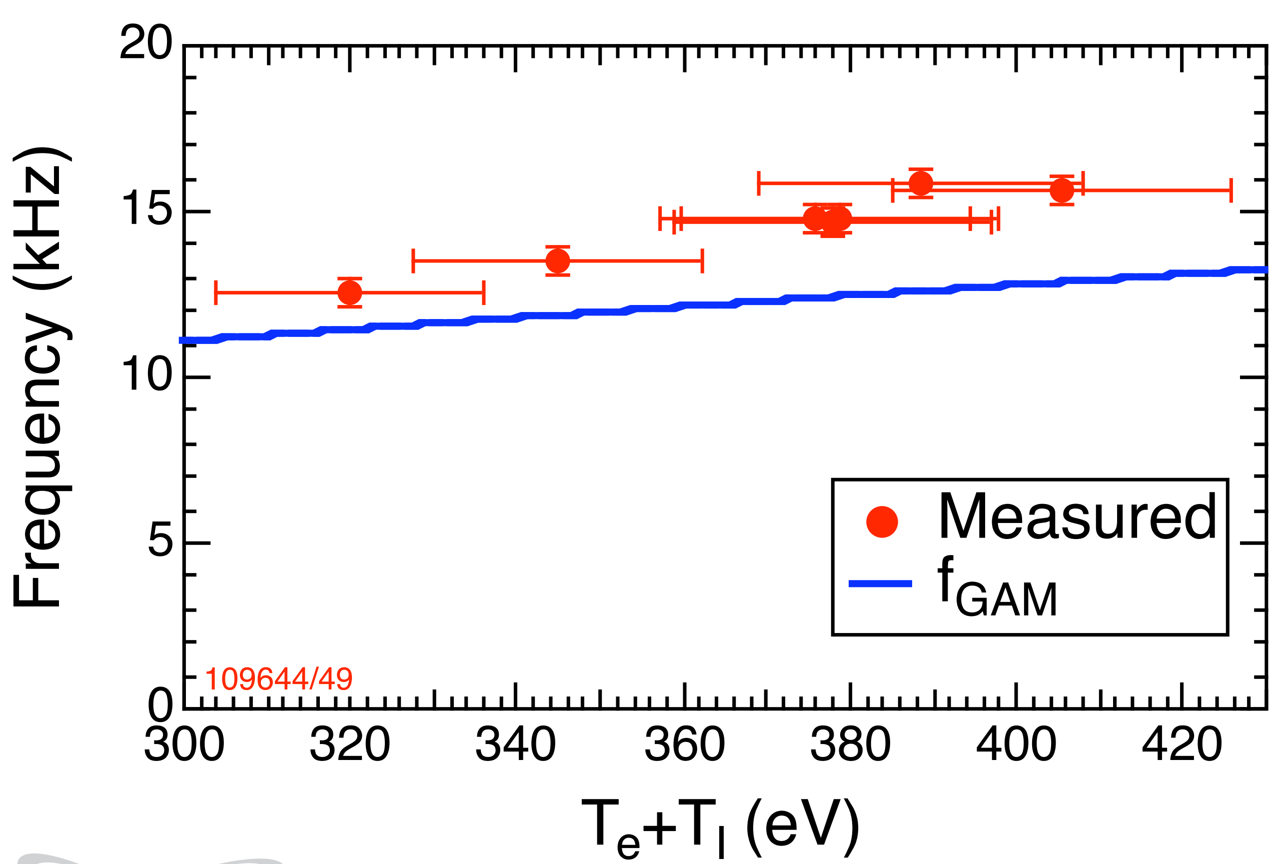
  $\tau_{GAM} >> \tau_{Turbulence}$ (~10 μs)

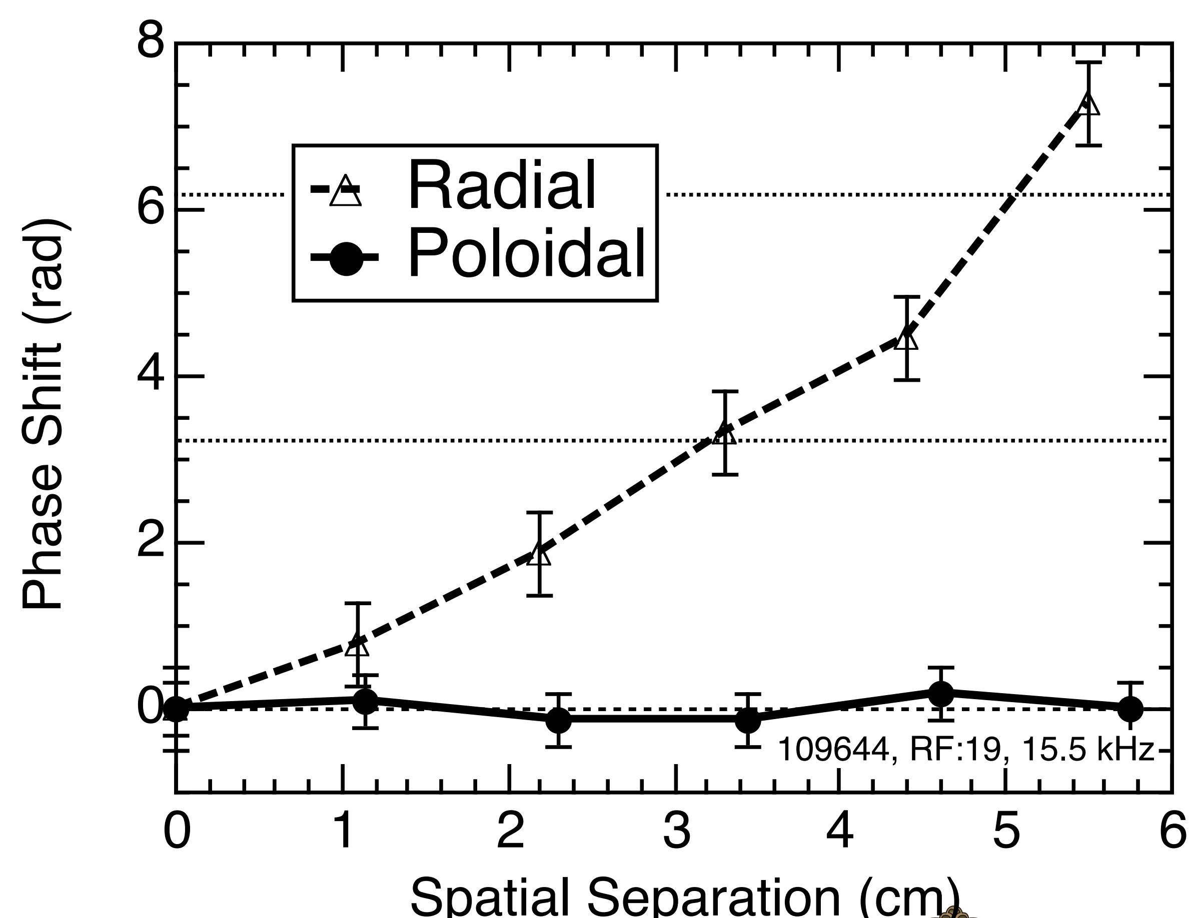


# GAM Exhibits Theoretically-Expected Temperature and Spatial Dependence

- **Frequency scales closely with sound speed**
- **Velocity oscillation exhibits little or not poloidal phase shift**
  - |m|<3 , consistent with expected m=0
- **Radial phase shift, finite radial wavenumber: $k_r \sim 1\ cm^{-1}$**
  - Finite shearing rate sufficient to affect turbulence, $\omega_{s,GAM} \approx 0.3\tau_c^{-1}$

$$f_{GAM} \cong c_s / 2\pi R = \sqrt{(T_e + T_I)/M_I} / 2\pi R$$



# Nonlinear Transfer of Energy Can be Measured Experimentally

- **Consider a model of density evolution:**

$$x \rightarrow r$$
$$y \rightarrow r\theta$$

$$\frac{\partial \tilde{n}}{\partial t} \approx -V_x \frac{dn_0}{dx} - V_x \frac{\partial \tilde{n}}{\partial x} - V_y \frac{\partial \tilde{n}}{\partial y} + D\nabla_\perp^2 \tilde{n}$$

$$\rightarrow \frac{1}{2}\frac{\partial \langle |\tilde{n}|^2 \rangle}{\partial t} = -\langle \Gamma_x \rangle \frac{dn_0}{dx} - \mathrm{Re}\left\langle \tilde{n}^* V_x \frac{\partial \tilde{n}}{\partial x} \right\rangle - \mathrm{Re}\left\langle \tilde{n}^* V_y \frac{\partial \tilde{n}}{\partial y} \right\rangle + D\left\langle |\nabla_\perp \tilde{n}|^2 \right\rangle$$

$$= -\langle \Gamma_x(f) \rangle \frac{dn_0}{dx} + \sum_{f'} T_n^X(f,f') + \sum_{f'} T_n^Y(f,f') + D\left\langle |\nabla_\perp \tilde{n}(f)|^2 \right\rangle$$

**Coupling of flux to background density gradient (source)**

**Collisional dissipation of fluctuation energy (sink)**

**Nonlinear "three-wave" interactions which exchange energy between different space/timescales**

$$T_n^X(f,f') = -\mathrm{Re}\left\langle \tilde{n}^*(f) V_x(f-f') \frac{\partial \tilde{n}}{\partial x}(f') \right\rangle$$

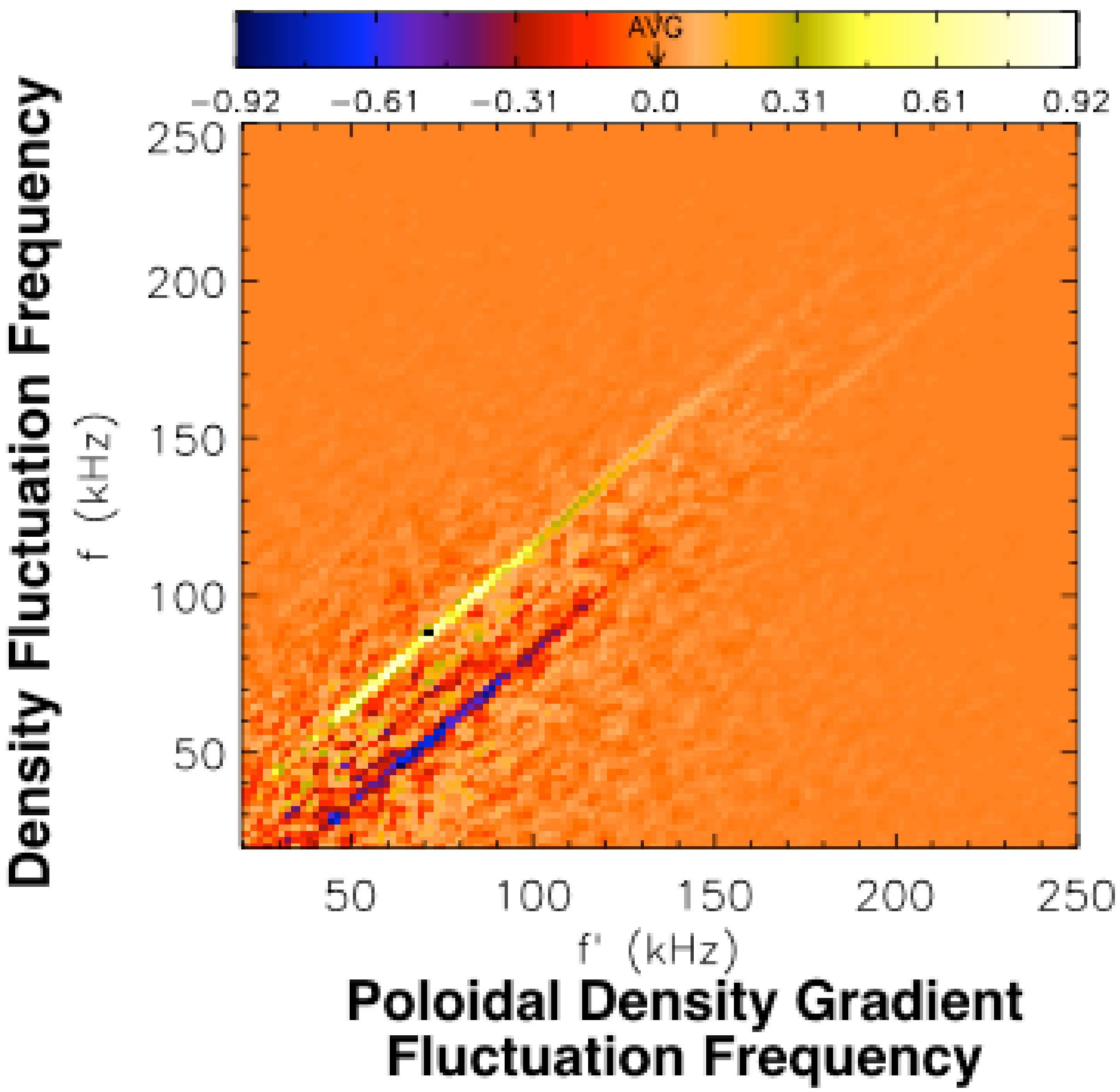
$$T_n^Y(f,f') = -\mathrm{Re}\left\langle \tilde{n}^*(f) V_y(f-f') \frac{\partial \tilde{n}}{\partial y}(f') \right\rangle$$

***C. Holland, UCSD***

# GAM Interacts Nonlinearly with Ambient Turbulence: Drives Forward Cascade of Energy to Higher Frequency

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

<u>**Bispectrum measures 3-wave interactions**</u>

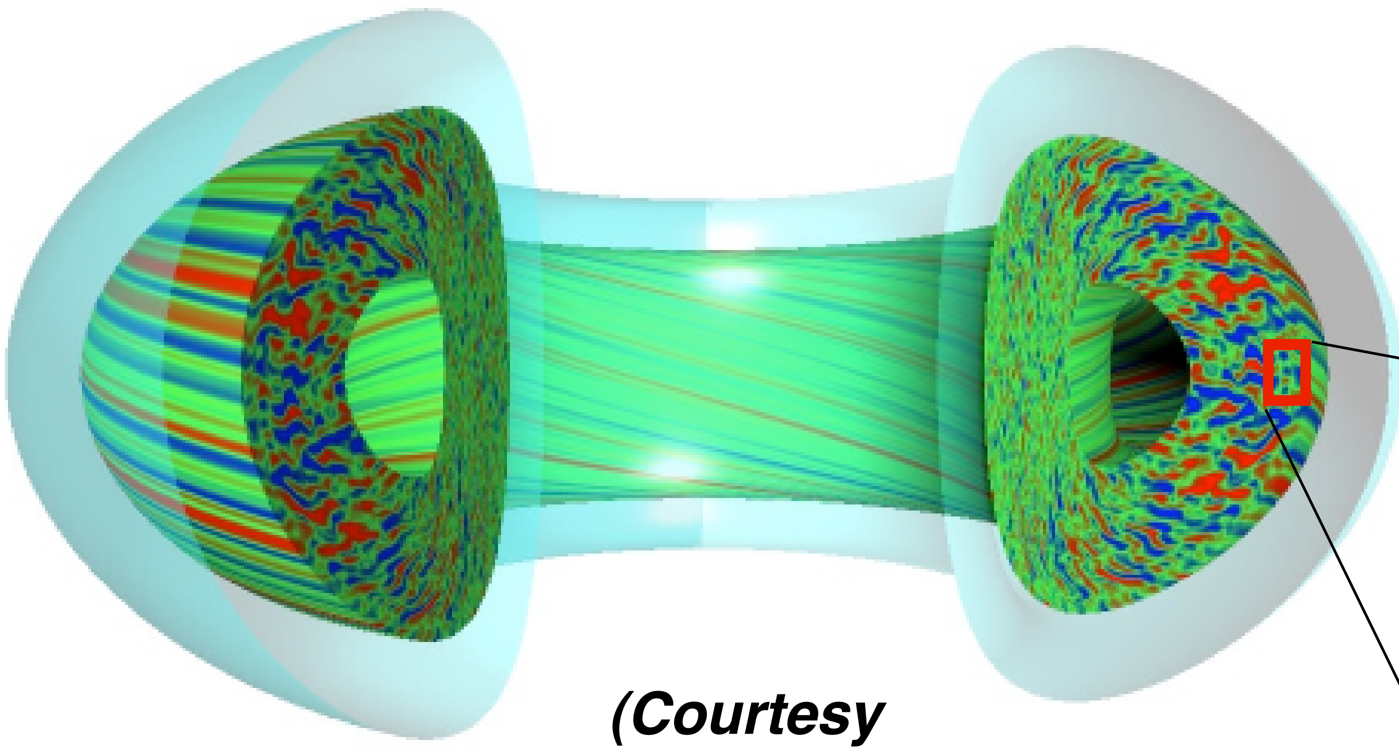



- **All quantities are experimentally measured with 2D BES ñ data**
- **Strong interaction at |f - f'| = $f_{GAM}$**
- **Density fluctuations at f gain energy from poloidal density gradient fluctuations at f' = f - $f_{GAM}$, and lose energy to those at f' = f + $f_{GAM}$**
- **Energy moves between n, dn/dy to higher f in steps of $f_{GAM}$**
- **Convection of density fluctuations by the GAM leads to a cascade of energy to higher f**

- ***GAM plays an active role in mediating turbulence spectrum***

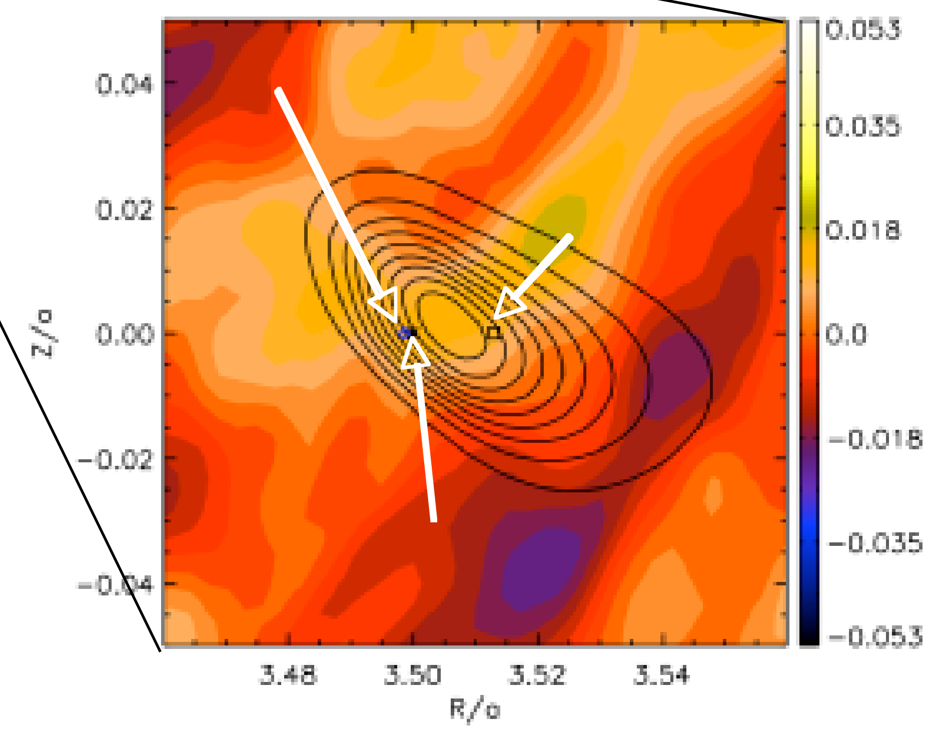
***C. Holland, Phys. Plasmas 14, 2007***

# Experimental Fluctuation Measurements are Quantitatively Compared with Nonlinear Simulations



*(Courtesy J. Candy, R. Waltz, GA)*

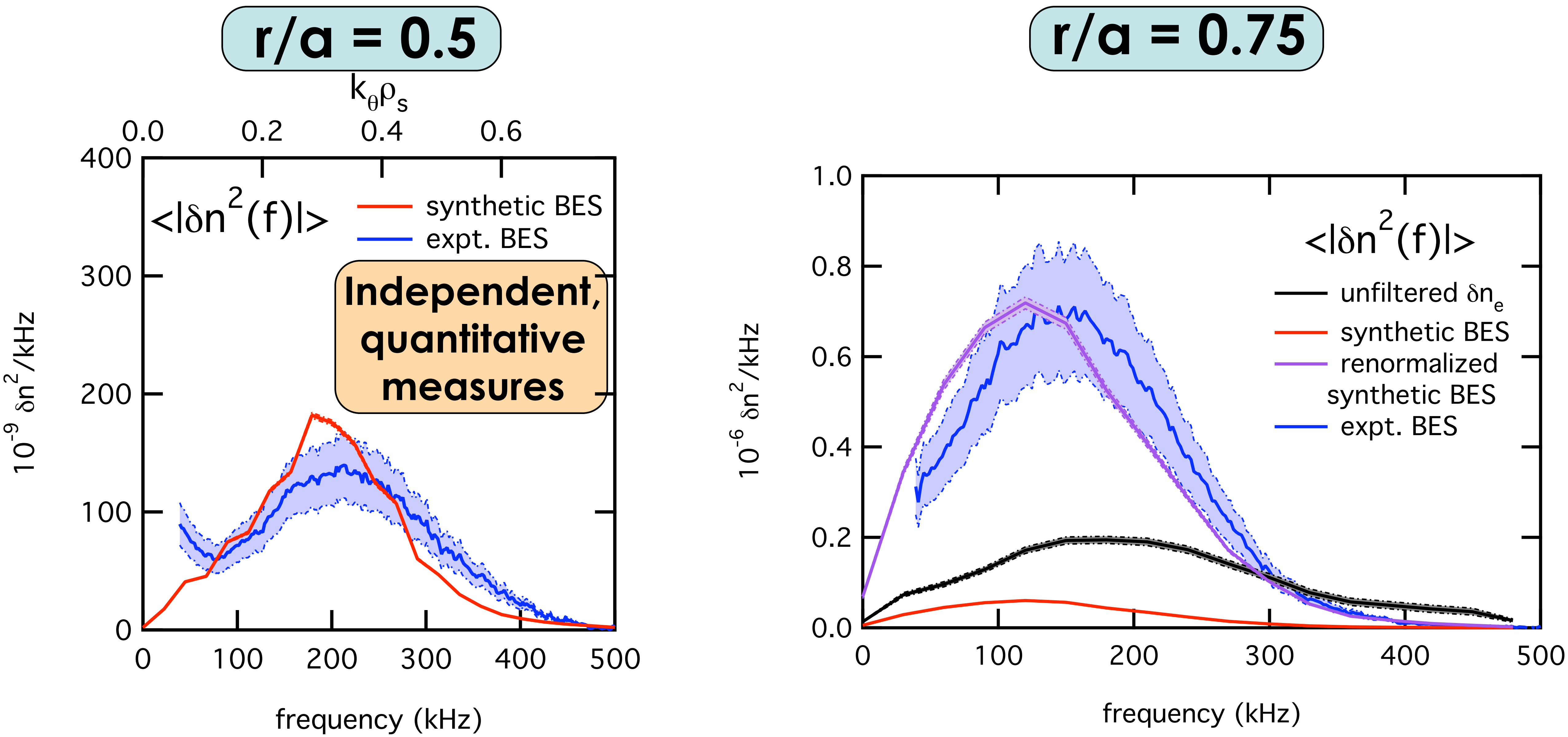
**GYRO, a Eulerian continuum code, simulates plasma turbulence and transport with full physics and geometry, experimental profiles**




**"Synthetic Diagnostics" model measurement physics and diagnostic parameters to allow quantitative comparisons between simulation and measurements**

$$\delta n_{synthetic}(x,y,t) = \frac{\int d^2x' \psi_{PSF}(x-x', y-y')\,\delta n_e^{GYRO}(x',y',t)}{\int d^2x' \psi_{PSF}(x-x', y-y')}$$

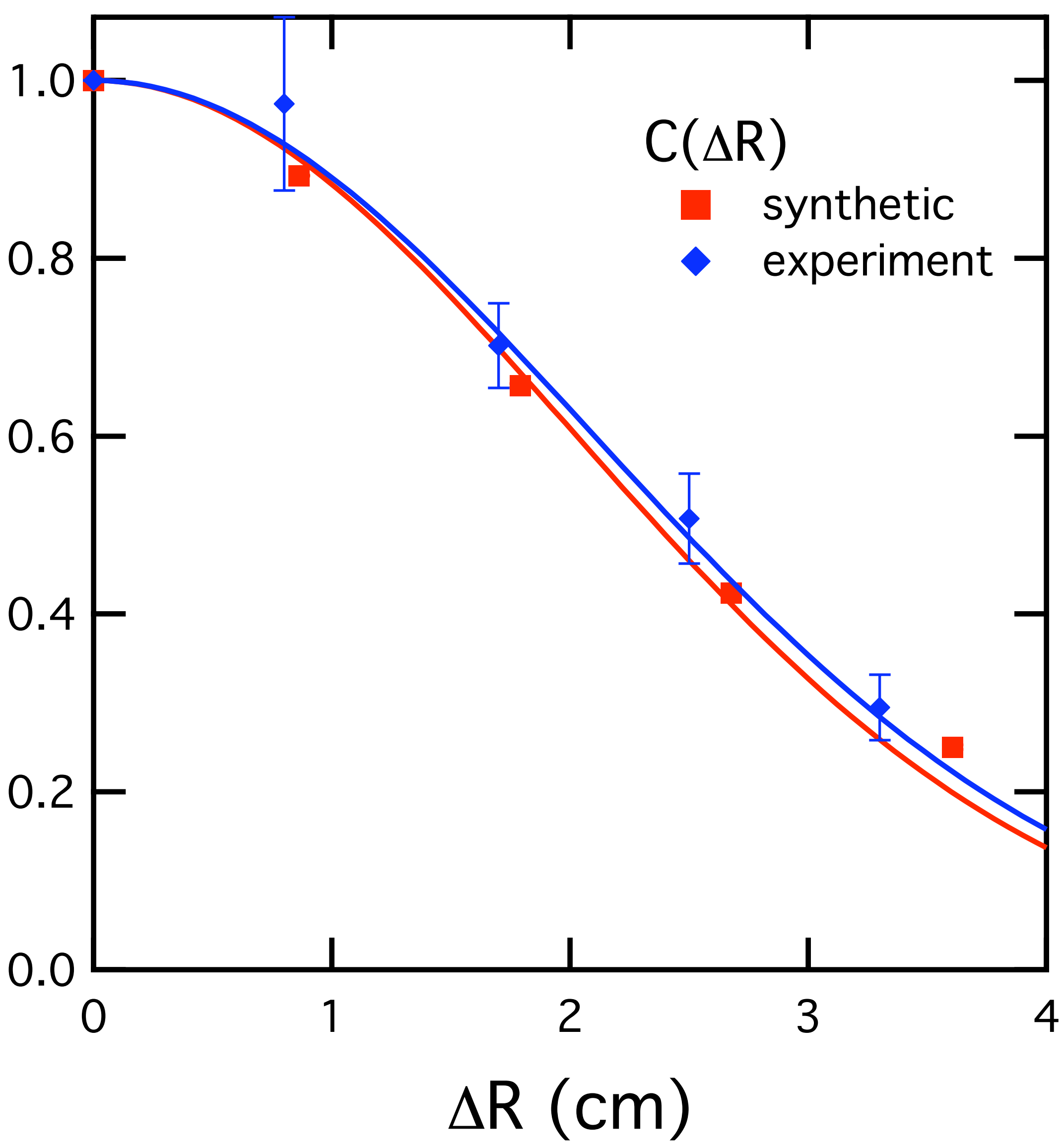
# Density Fluctuation Spectra from BES and GYRO are Compared at 2 Radii



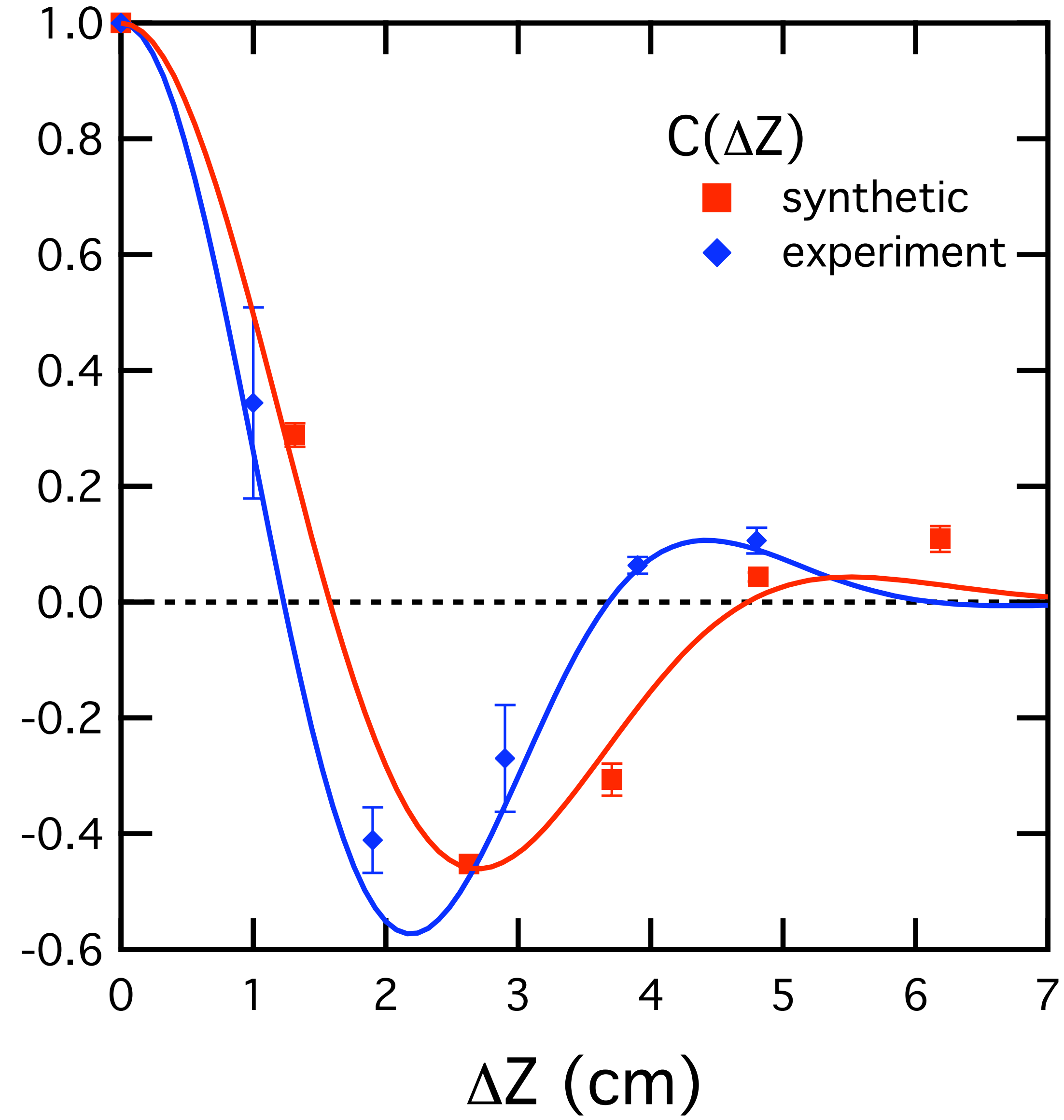

- **At mid-radial location (0.5), excellent agreement is found between measurement and simulation**
- **At outer location (0.75), GYRO underestimates measured fluctuation spectrum**
  - Turbulent diffusivities also underestimated by similar factor

# Spatial Correlations Exhibit Good Quantitative Comparison

## Radial Correlation



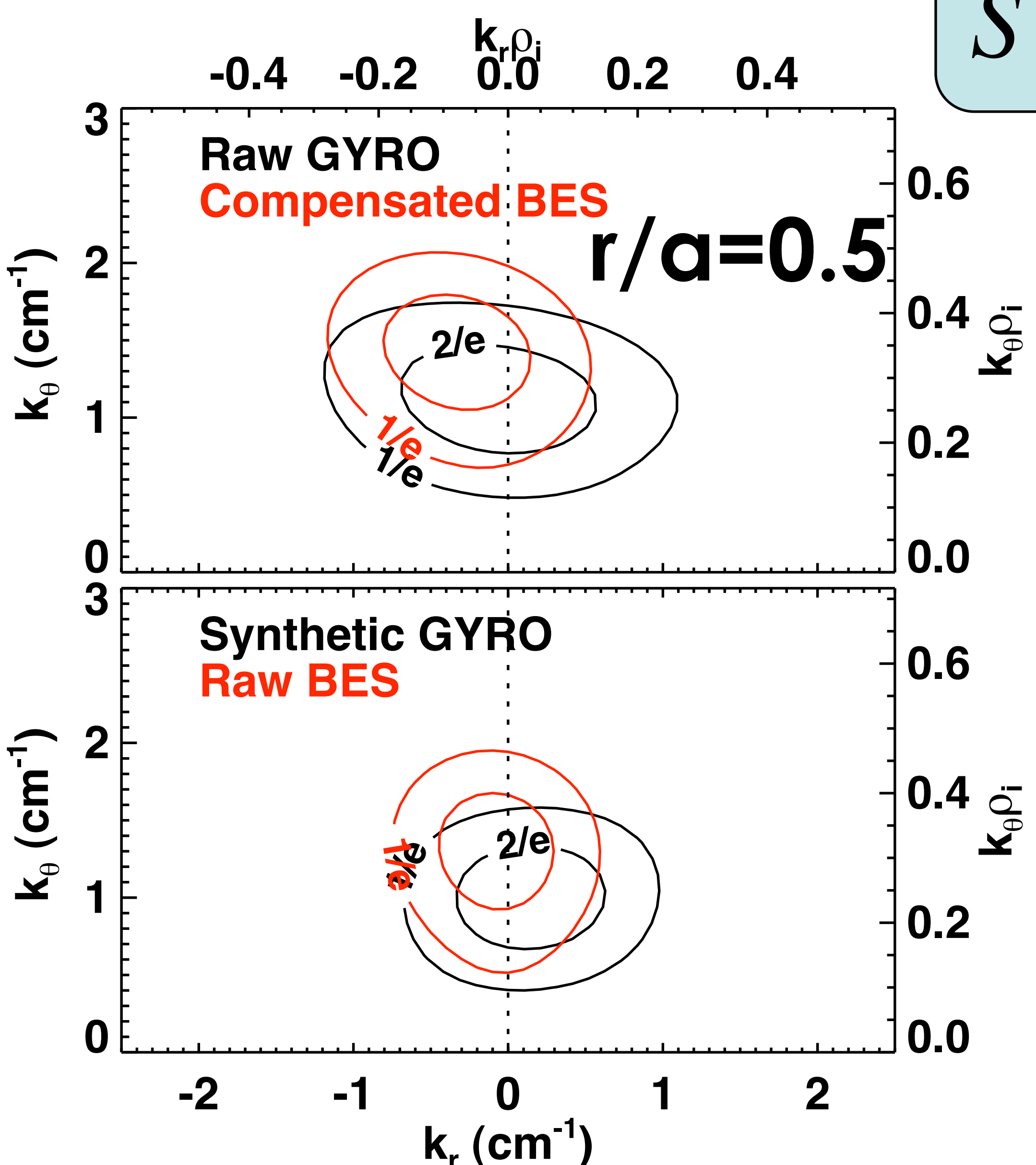

## Poloidal Correlation

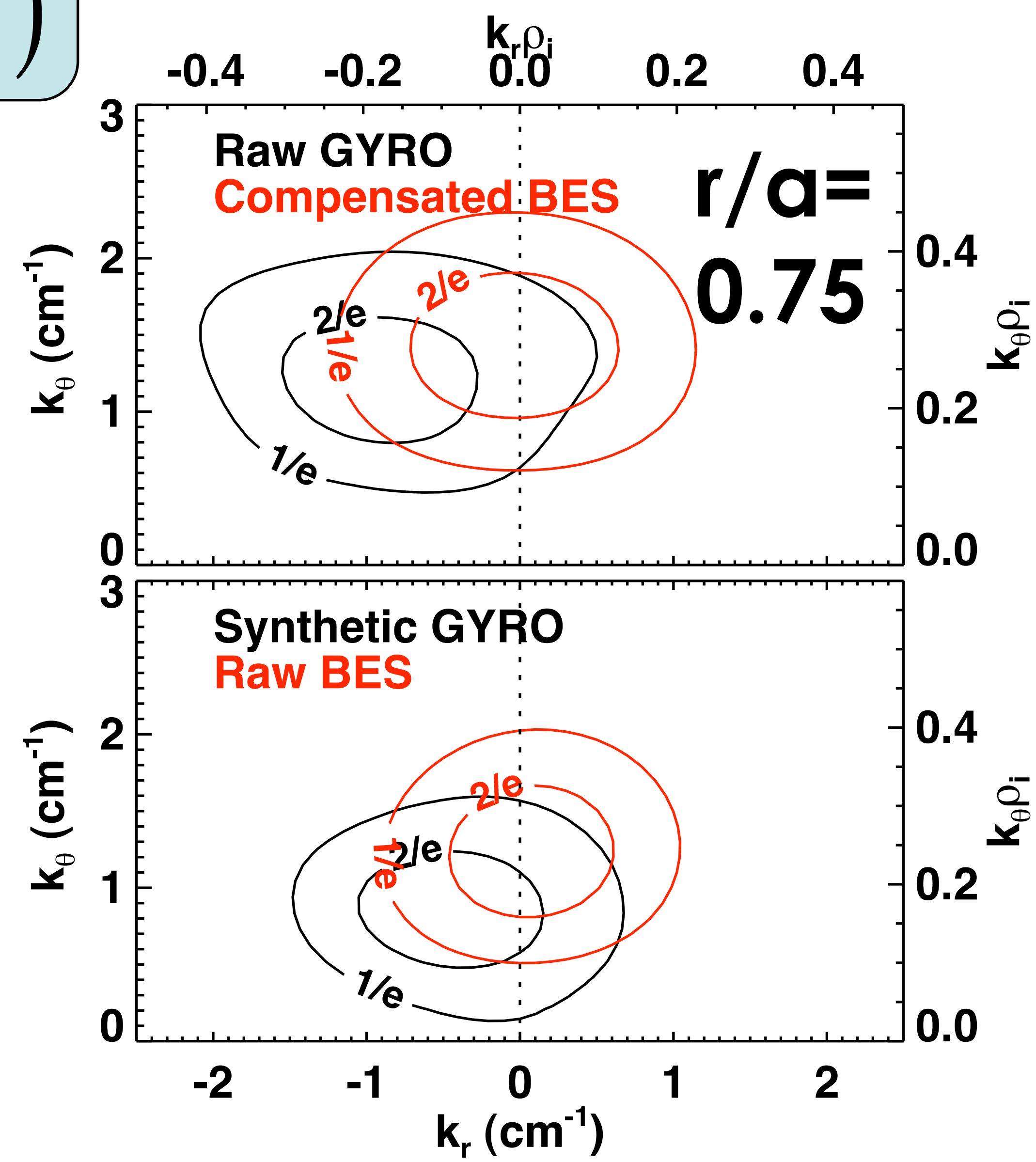



- **Radial and poloidal correlation functions in good overall agreement**
  - Poloidal correlations differ modestly
- **Demonstrates the GYRO is reasonably correctly predicting scales**

# Comparison of BES-GYRO 2D $S(k_r,k_\theta)$ Wavenumber Spectra Reveal Notable Differences

$$S(k_r,k_\theta)$$




- **2D wavenumber spectra show that GYRO predicts a finite $k_r$ that is not observed experimentally**
  - Might reflect an exaggeration of ExB shear effect on turbulent structure, which is also consistent with underprediction of turbulent-driven energy fluxes

# Conclusion

- **2D Measurements providing key insights into the characteristics and dynamics of long-wavelength density turbulence**
- **Visualizations of turbulence demonstrate:**
  - Turbulence flow patterns
  - Eddy interactions
  - Shear effects
- **Spectra typically peak near $k_r \approx 0$, $k_\theta \approx 1\ cm^{-1}$, $k_\theta \rho_I \approx 0.3$**
  - Largely consistent with expectations from gyrokinetics
  - Correlation lengths scale with $\rho_I$
- **Advanced analysis methods applied to 2D measurements reveal:**
  - Zonal flow/GAM features in the turbulence flow-field
  - Nonlinear transfer of internal energy
- **Quantitative comparisons with fully nonlinear simulations are providing critical information towards validating models of turbulent transport**
  - Find cases of good agreement, and those where improvements are required