Characterization of Zonal Flows and Their Dynamics in Experiment and Simulation

by
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with
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Overview of Results

- **Zero mean frequency (ZMF) zonal flow now observed in core of DIII-D**
  - First observation of ZMF in a high-temperature tokamak
  - Transition from ZMF dominated core to Geodesic Acoustic Mode (GAM) dominated edge region documented

- **GAM-Driven Cascade of Internal Energy Has Been Measured in Edge of DIII-D**
  - First direct measurement of zonal flow driven nonlinear energy transfer in a high-temperature tokamak
  - Simulations of core turbulence indicate that ZMF zonal flows drive a similar cascade

- **Generation of a zonal flow via Reynolds stress has been demonstrated in the CSDX experiment at UCSD**

- **Taken together, results represent experimental validation of key linear and nonlinear aspects of the 'drift-wave - zonal flow' paradigm**

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Motivation

- **Zonal flows now recognized as essential component for understanding drift-wave turbulence**
- **They have received extensive analytic and numerical investigation, but experimental results have lagged until recently**
  - Experimental observations of the ‘zero mean frequency’ zonal flow branch as well as nonlinear interactions between turbulence and zonal flows have been extremely limited
- **Upgraded Beam Emission Spectroscopy (BES) system on DIII-D now allows for measurement of turbulence and zonal flows over wide region of plasma**
- **CSDX experiment at UCSD supports complimentary studies of drift-wave turbulence in a basic laboratory experiment**
- **Goal:** use BES and CSDX to provide necessary experimental support for theory and simulation of drift-wave - zonal flow turbulence

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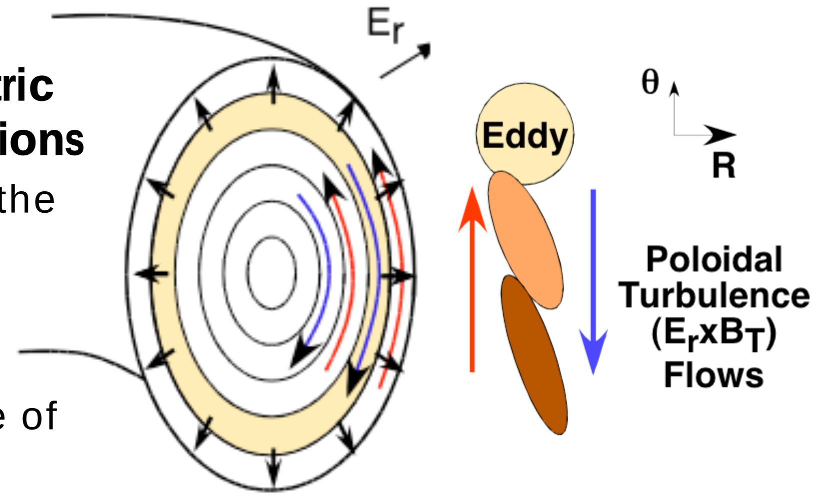
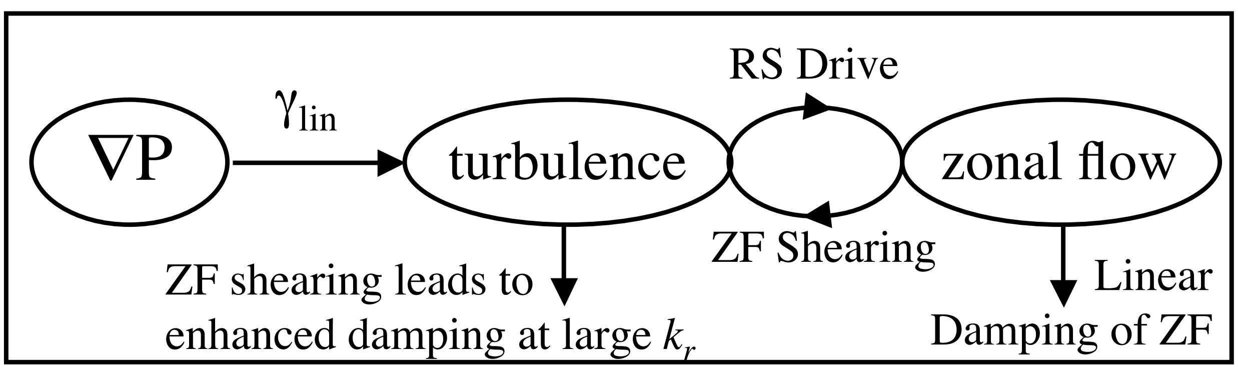
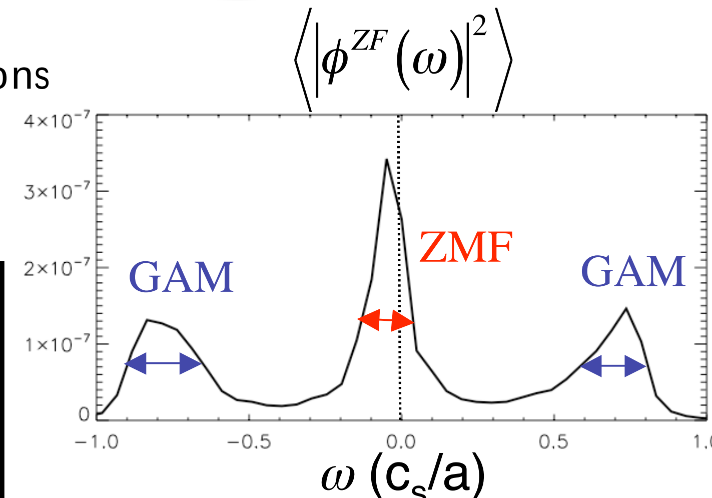
Zonal Flows Believed to Provide Dominant Saturation Mechanism for Drift-Wave Turbulence

- **Zonal flows consist of (at minimum) axisymmetric radial electric fields which shear apart fluctuations**
  - Nonlinearly generated by the Reynolds stress of the turbulence (Diamond & Kim, PoF B 1991)
- **Two branches:**
  a) finite-frequency, rapidly decaying Geodesic Acoustic Mode (GAM); widely observed in edge of many machines
  b) weakly damped zero mean frequency (ZMF) (Rosenbluth & Hinton, PRL 1998); limited observations (CHS stellerator). Timescale: $\tau_{turb} < \tau_{ZMF} < \tau_{equil}$



Drift-Wave - Zonal Flow “Energetics”





Zonal flow spectrum from GYRO simulation w/ $q = 3$

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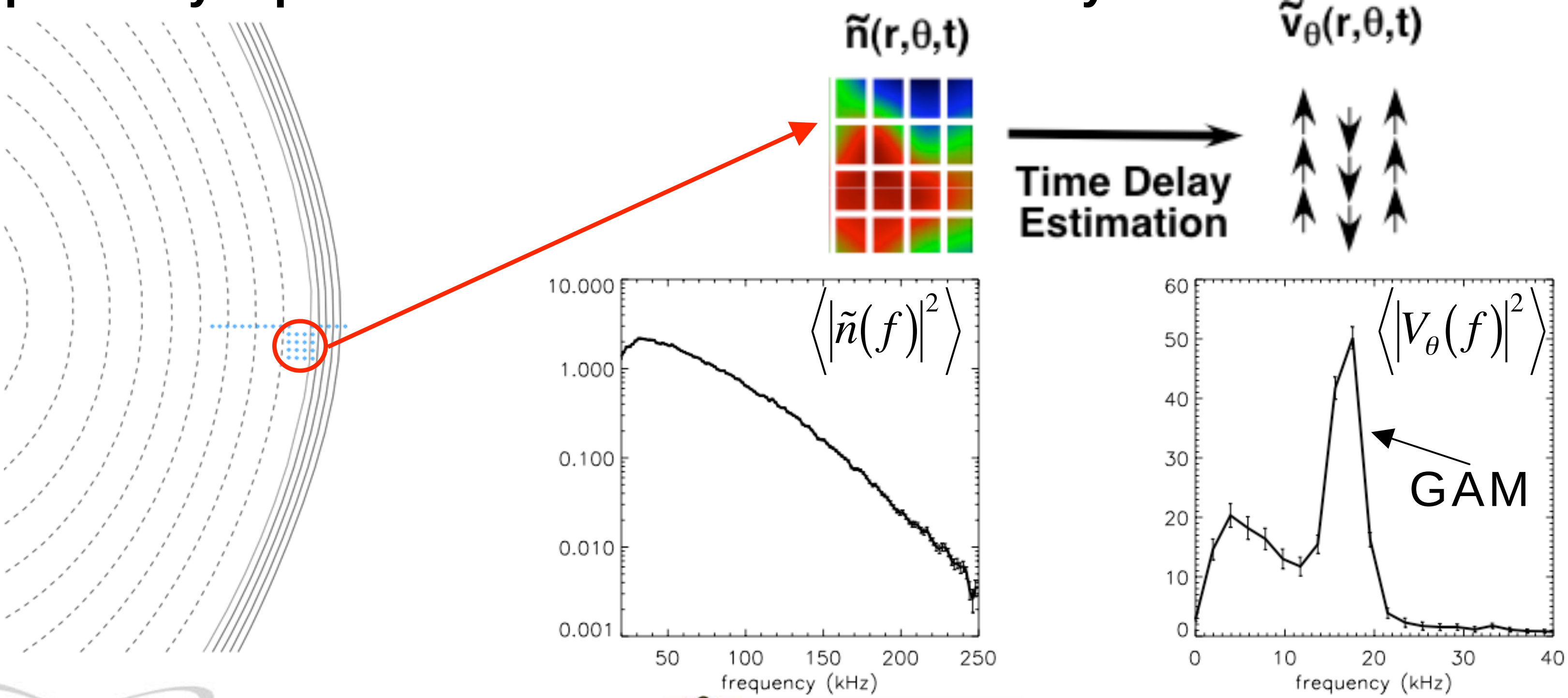
BES System Configured to Provide Zonal Flow Measurements Over Large Fraction of Plasma

- **BES measures localized, long-wavelength ($k_{\perp}\rho_i < 1$) density fluctuations**
  - Can be radially scanned shot to shot to measure turbulence profiles
  - Recent upgrades allow for BES to measure core fluctuations (Gupta *et al*, Rev. Sci. Inst **75** 3493 2004)

- **Time-delay estimation (TDE) technique uses cross-correlations between two poloidally separated measurements to infer velocity**



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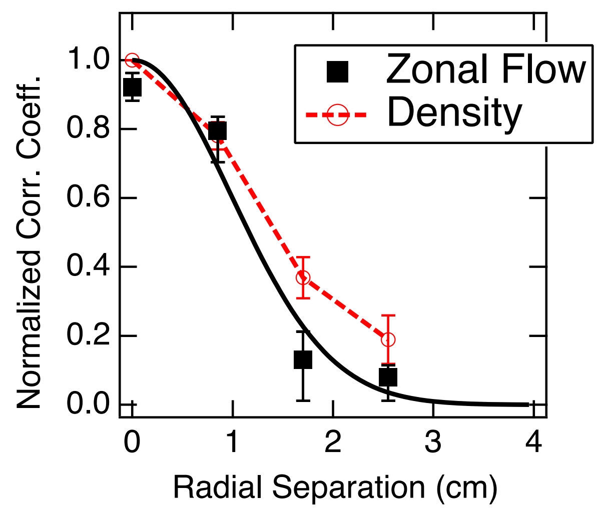
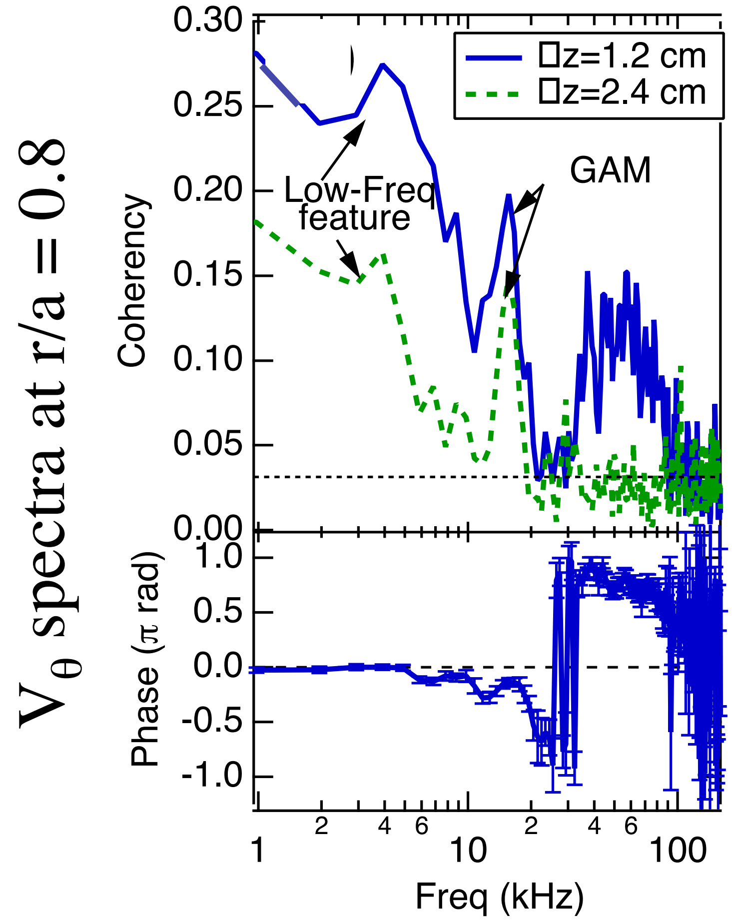
Measured V_θ Spectra Exhibit Signatures of Both ZMF Zonal Flows and GAMs

- **Spectra indicate broad, low-frequency structure with zero measurable poloidal phase shift**
  - Consistent with low-m (m=0?)
  - Peaks at/near zero frequency
- **GAM also clearly observed near 15 kHz**
- **ZMF zonal flow has radial correlation length comparable to underlying density fluctuations**
  - Necessary for effective shearing of turbulence





Gupta *et al.*, PRL **97** 125002 (2006)

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Observe Transition from ZMF-Dominated Core to GAM-Dominated Edge

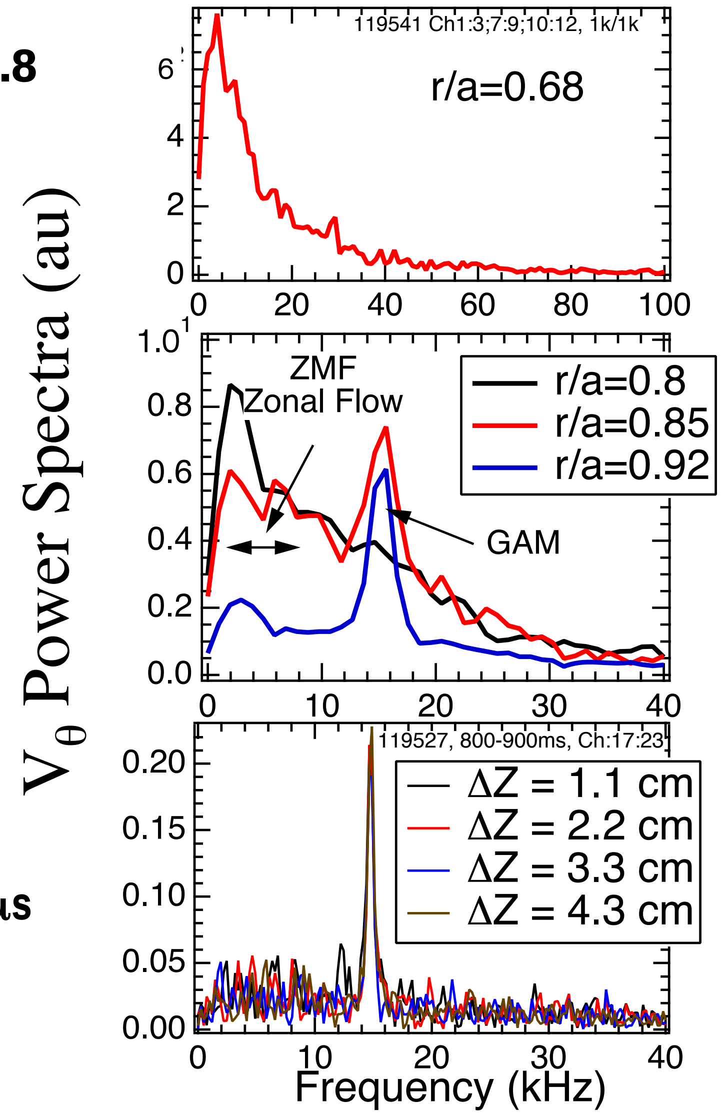
- **Velocity spectra show broad ZF spectrum for r/a < 0.8 → ZMF flow**

- **Superposition of broad spectrum and GAM peak near r/a = 0.85**

- **GAM dominates for r/a > 0.9**

- **Consistent with theory/simulation expectations that GAM strength increases with *q***
  - Increase in GAM strength with q_{95} also observed (McKee *et al.*, PPCF 2006)

- **GAM is highly coherent, with correlation time τ_{GAM} > 1 ms and oscillation period $1/f_{GAM} \approx 55\ \mu s$, both larger than turbulence decorrelation time $\tau_{turb} \sim 10\ \mu s$**
  - Indicates GAM is "slow" relative to edge turbulence timescales, and so can effectively interact with turbulence (Hahm *et al.*, PoP '99)



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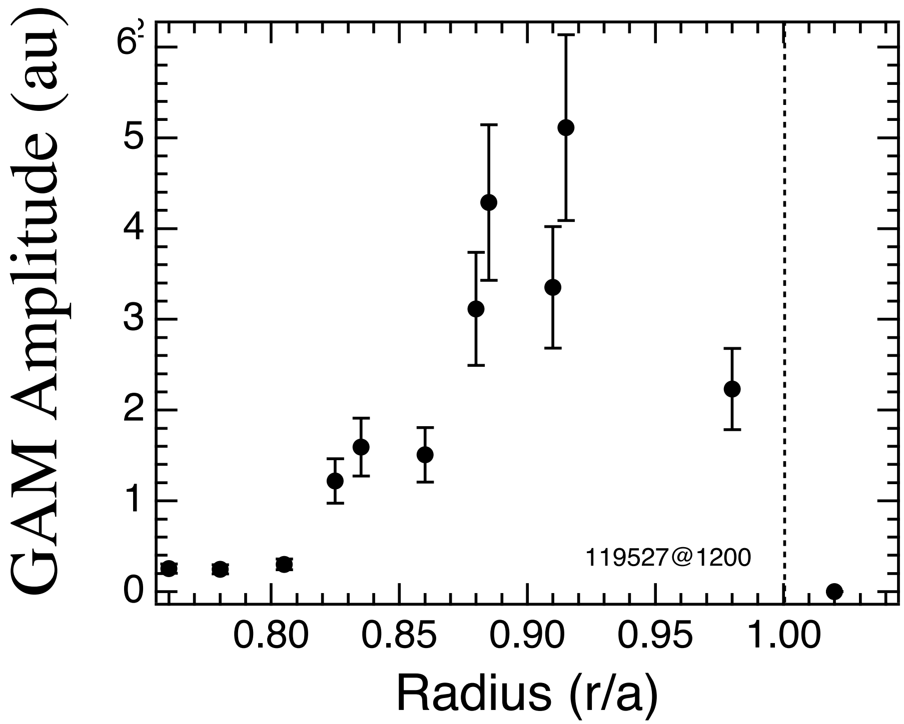
GAMs Observed to Peak in Plasma Edge

- **GAM velocity oscillation amplitude peaks near r/a ~0.9–0.95**
  - Decays near separatrix
  - Decays inboard, still detectable to r/a ~ 0.75
  - Consistent with HIBP measurements on JFT-2M (Ido *et al.*, PPCF 2006)

- **ZMF zonal flows not observed for r/a > ~0.9, but do increase towards core**
  - Harder to quantify radial dependence because of broad spectral characteristics

GAM Amplitude vs. Minor Radius



McKee *et al.*, PPCF 2006

Measuring Nonlinear Interactions Between Zonal Flows and Turbulence

- **Analytic theory and simulation clearly indicate the importance of specific nonlinear interactions between the zonal flows and underlying drift-wave turbulence**
  - Zonal flows should shear apart the turbulence, transferring energy to smaller (radial) scales
  - Turbulence in turn generates zonal flows via the Reynolds stress

- **Experimental validation of the ‘drift-wave - zonal flow’ paradigm requires measuring these nonlinear interactions, in addition to characterizing the spatio-temporal characteristics of the zonal flows**

- **Present two measurements that address this issue**
  1. GAM-driven nonlinear energy transfer in edge of DIII-D
  2. Generation of a zonal flow by the Reynolds stress in CSDX

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Measuring Nonlinear Energy Transfer in Experiment

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

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

$$x = r - r_0$$
$$y = r_0 \theta$$

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Measuring Nonlinear Energy Transfer in Experiment

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

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$$y = r_0\theta$$

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

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

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Measuring Nonlinear Energy Transfer in Experiment

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

$$x = r\text{-}r_0$$
$$y = r_0\theta$$

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

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

Coupling of flux to background density gradient (source)

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

Collisional dissipation of fluctuation energy (sink)

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

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

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Measuring Nonlinear Energy Transfer in Experiment

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

- **$T_n^Y(f',f)$ measures the transfer of energy between density fluctuations at f and poloidal density gradient fluctuations at f' at a specific spatial location due to poloidal convection**
  - A positive value of T_n^Y indicates that $n(f)$ is gaining energy from $\partial n/\partial y(f')$
  - A negative value indicates that $n(f)$ is losing energy to $\partial n/\partial y(f')$

- **Have all the quantities needed to *experimentally* calculate the portion of $T_n^Y(f',f)$ associated with GAM convection (with $\delta I \approx n$)**
  1. $n(r,t) = (n_1 + n_2)/2$
  2. $\partial n/\partial y(r,t) = (n_1 - n_2)/\Delta y$
  3. $V_y(r,t)$ from TDE algorithm

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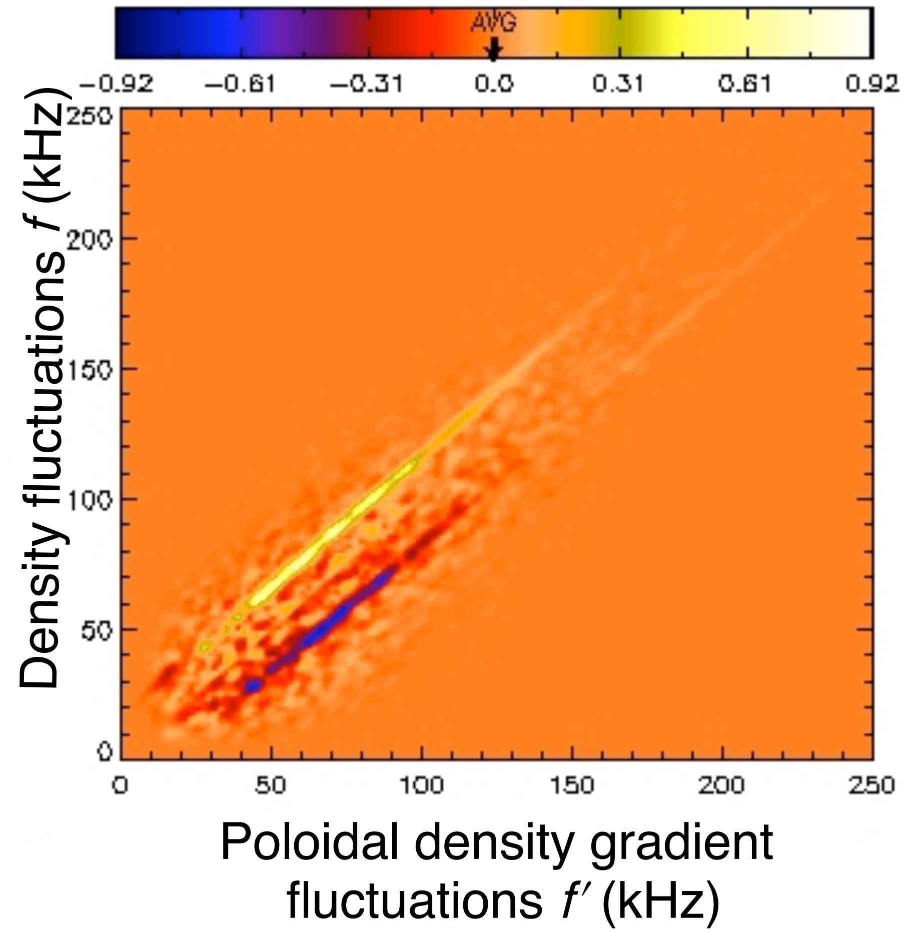
GAMs Drive Clear Forward Cascade of Internal Energy in Frequency Space

- $T_n^Y(f',f)$ clearly shows that fluctuations at $f = f' + f_{GAM}$ gain energy, while those at $f = f' - f_{GAM}$ lose energy

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



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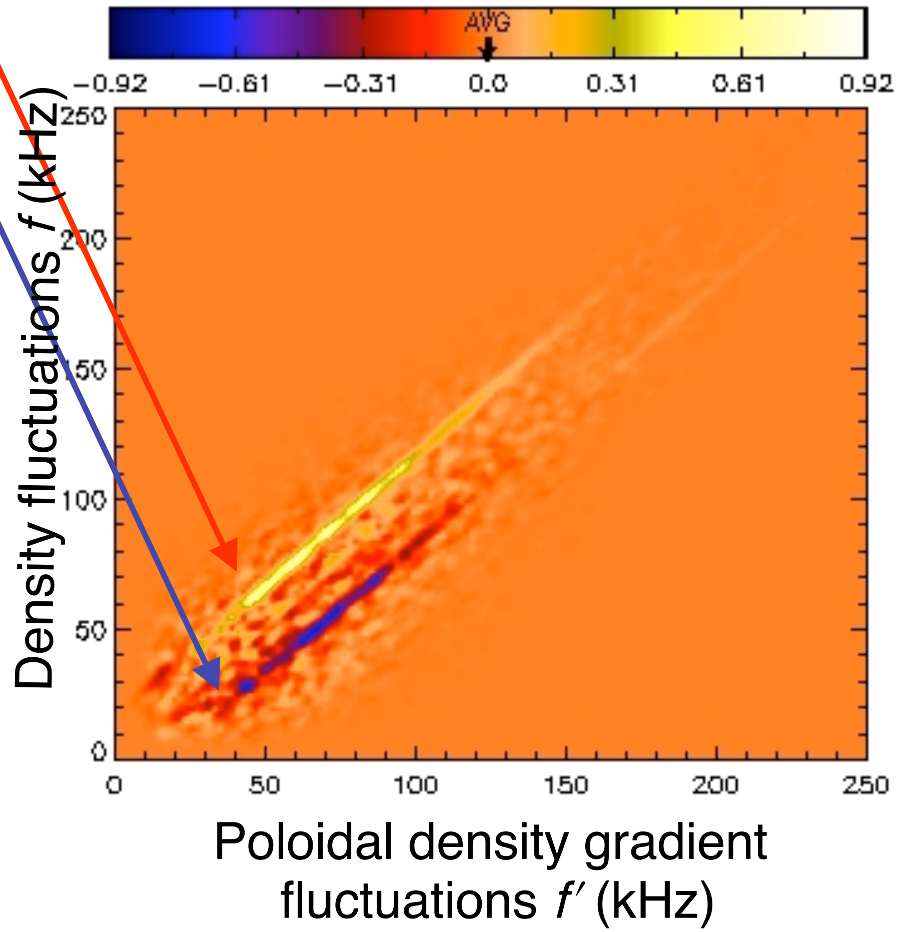

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- Density fluctuations gain energy from lower frequency gradient fluctuations, and lose energy to higher frequency gradient fluctuations

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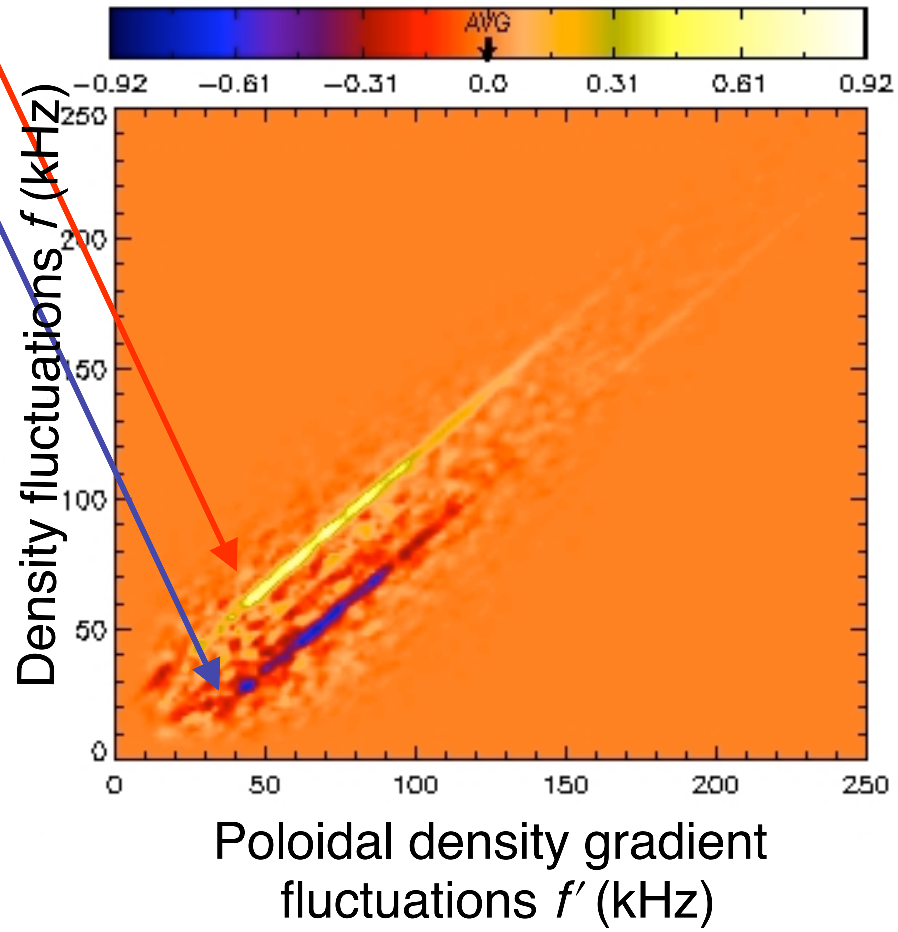

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- Density fluctuations gain energy from lower frequency gradient fluctuations, and lose energy to higher frequency gradient fluctuations
- Simple picture: energy moves between n, $\partial n/\partial y$ to high f in "steps" of f_{GAM}

→ net transfer of energy to high f!

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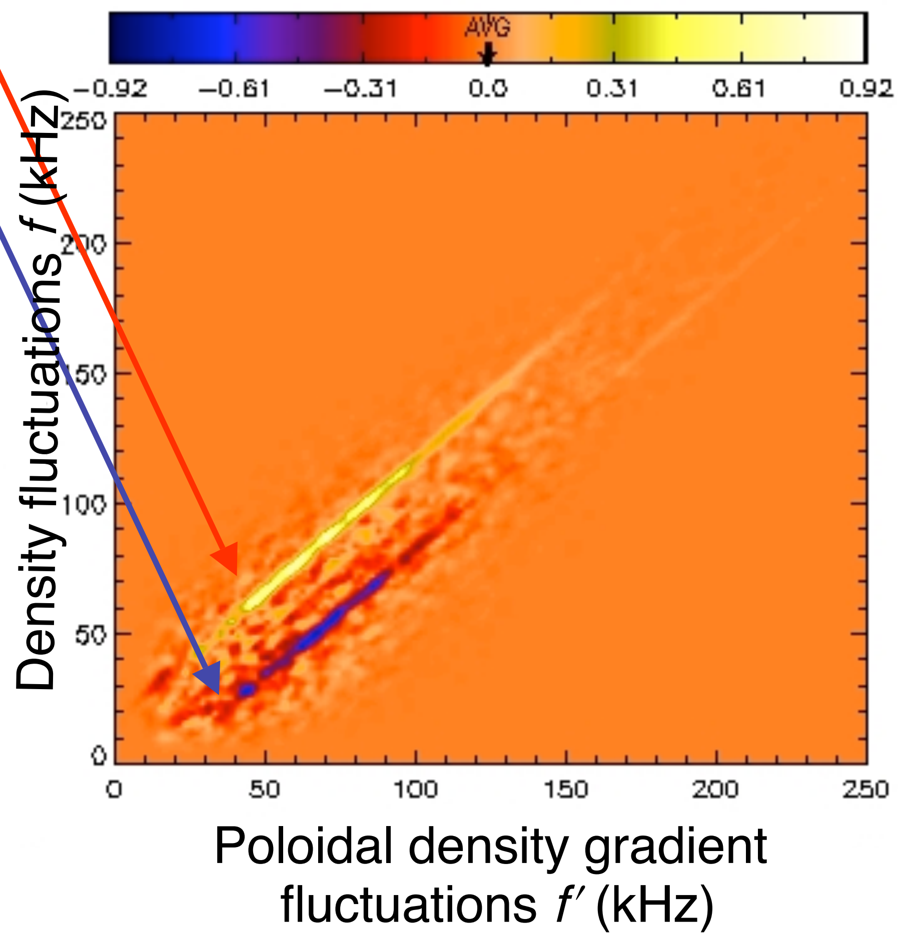

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GAMs Drive Clear Forward Cascade of Internal Energy in Frequency Space

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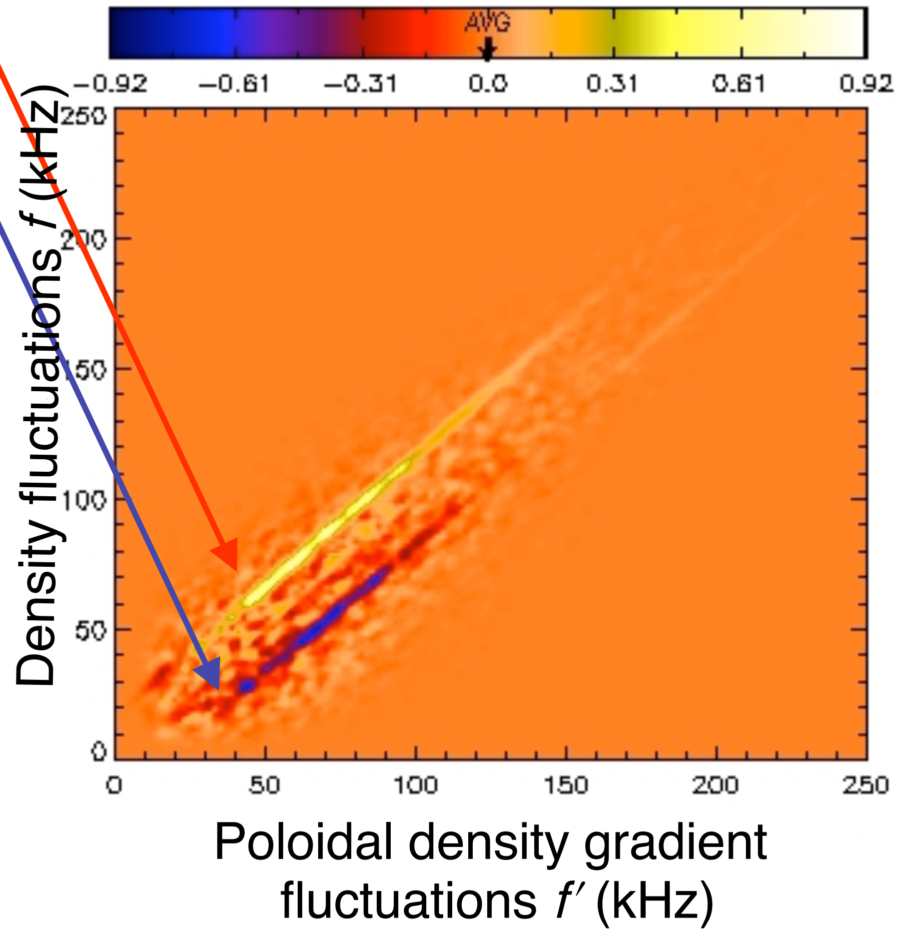
- Simple picture: energy moves between n, $\partial n/\partial y$ to high f in "steps" of f_{GAM}

→ net transfer of energy to high *f*!

- Demonstrates that the convection of density fluctuations by the GAM leads to a cascade of internal energy to high *f*

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

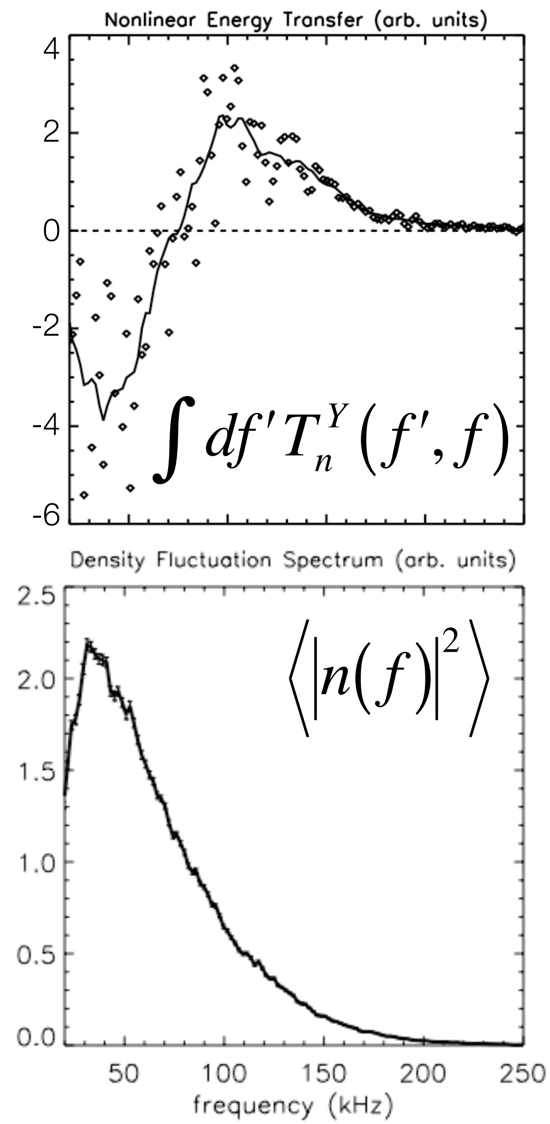


GAM Convection Leads to Net Energy Transfer From Low to High Frequencies

- **Integrating $T_n^Y(f',f)$ over f' quantifies net rate at which poloidal convection nonlinear transfers energy into / out of fluctuations with frequency f**

- **Balances linear growth / damping *and* nonlinear transfer due to radial convection to determine turbulent spectrum**

- **Key question:** how to clearly connect to shearing mechanism?
  - **First step:** investigate frequency and wavenumber space transfer in simulation



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Studying Energy Transfer in Simulation

- **To gain more insight into zonal flows driven energy transfer, use the GYRO code to look at the interactions in more detail**

- **Use CYCLONE base case parameters (q = 1.4, r d(ln q)/dr = 0.786, R/L_n = 2.22, R/L_T = 6.92, T_e/T_i = 1)**
  - Assumes adiabatic electrons: $\tilde{n}/n_0 = e\left(\phi - \langle\phi\rangle\right)/T_e$
  - All analysis is done at outboard midplane
  - Long run time (T = 3000 a/C_s) needed for converged statistics
  - Corresponds to core rather than edge turbulence parameters

- **Goal is to examine energy transfer in a simple, well-studied model of the turbulence rather than quantitative reproduction of the experimental results**
  - CYCLONE parameters represent logical point for this study

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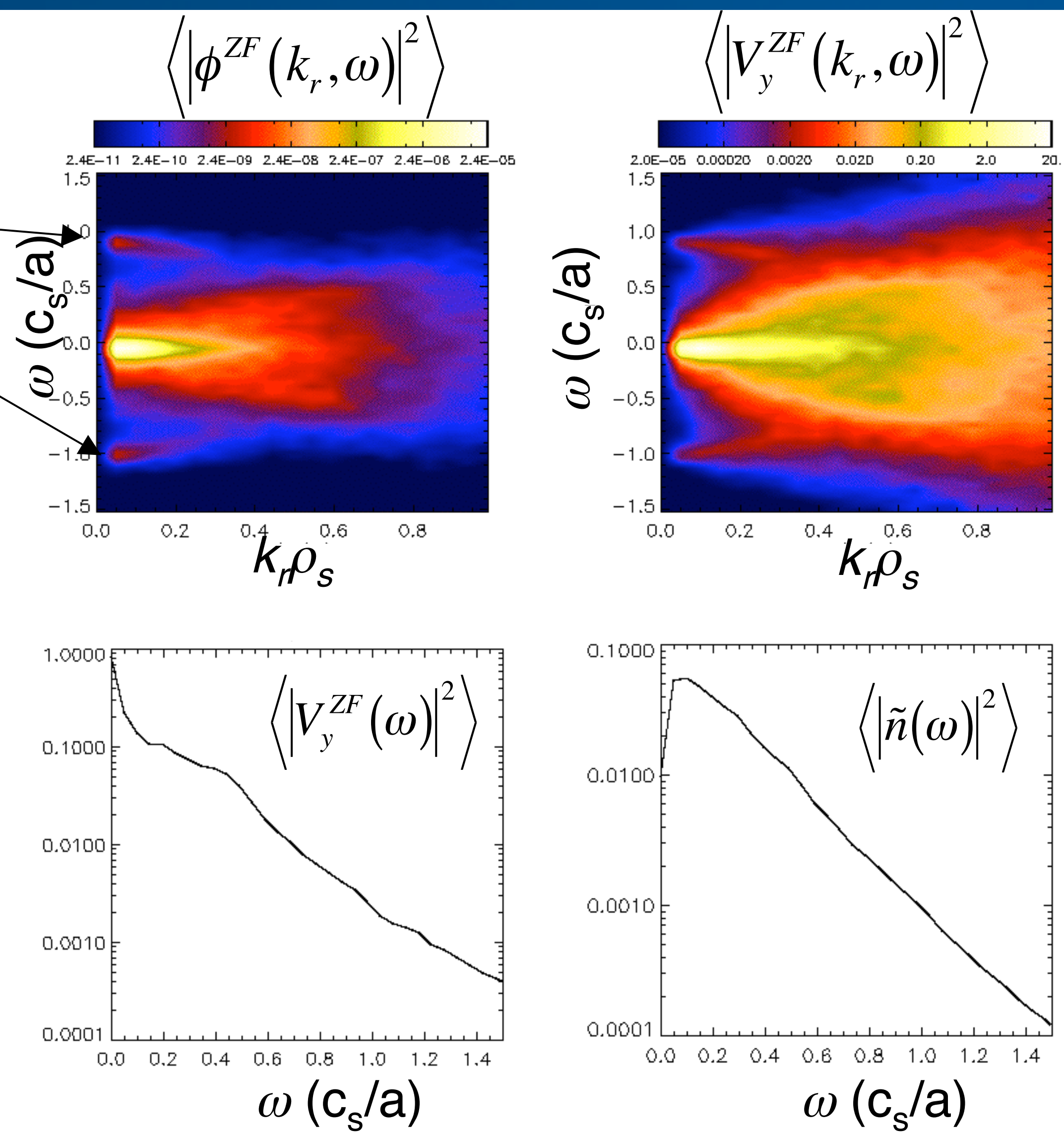
Simulation Exhibits Broad Density Spectrum and ZMF Dominated Zonal Flows

- **For q = 1.4 (and adiabatic electrons), GAMs are weak feature at $\omega \sim \pm\, c_s/a$ and low k_r**

- **Zonal flow ExB velocity $cE_r/B \propto k_r\phi$, such that GAM contribution to velocity is overwhelmed by higher k_r components**

- **Density spectrum broad and featureless**



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Connecting to Wavenumber-Space Energy Transfer

- **Experimental results showed a forward cascade in frequency space at a particular spatial location, but would like to make more direct contact with theory which describes transfer between different wavenumbers**

- **To quantify effects of zonal flow convection on internal energy transfer in GYRO, look at *k*-space resolved energy transfer term $T_n^{ZF}(k_\theta,k_r,k_r')$**

$$T_n^{ZF}\left(k_\theta,k_r,k_r'\right) = -\mathrm{Re}\left\langle \tilde{n}^* \vec{V}_{ZF} \cdot \vec{\nabla}\tilde{n} \right\rangle$$

$$\rightarrow T_n^{ZF}\left(k_\theta,k_r,k_r'\right) = k_\theta\left(k_r - k_r'\right)\mathrm{Re}\left\langle \tilde{n}^*\left(k_r,k_\theta\right)\phi\left(k_r - k_r', k_\theta = 0\right)\tilde{n}\left(k_r',k_\theta\right) \right\rangle$$

- **Note that because zonal flows have $k_\theta = 0$, they couple density fluctuations with different values of k_r, but the same k_θ**
  - Can either sum over k_θ, or select specific values of k_θ to gain insight into how zonal flows affect turbulence on different spatial scales

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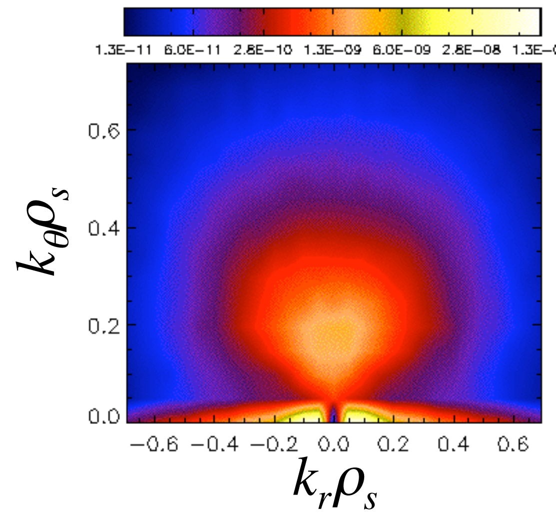
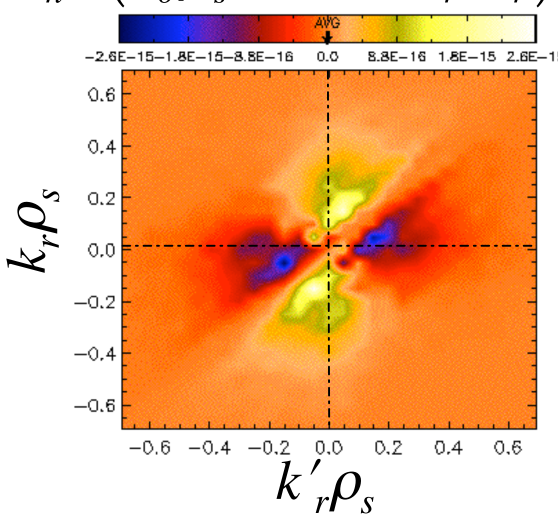
k-space Energy Transfer Shows Forward Cascade In $|k_r|$, In Agreement with Expectations From Theory

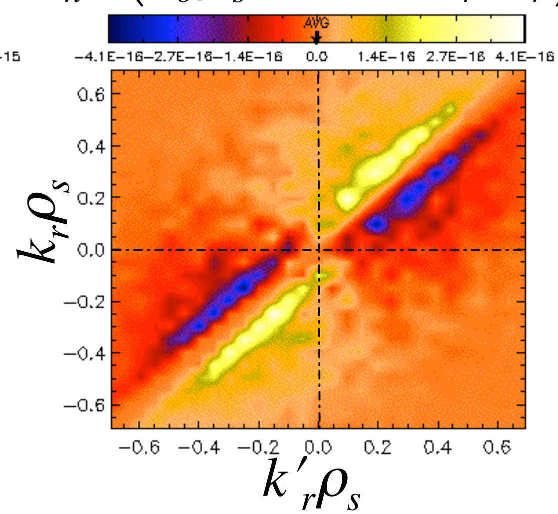
- **Fluctuations with $|k_r| > |k_r'|$ gaining energy, while those with $|k_r| < |k_r'|$ losing energy**
- **Corresponds to expectation that radial decorrelation by ZFs leads to transfer of energy to smaller radial scales (higher k_r)**
- **So what does frequency-space transfer look like?**



$\left\langle \left| \phi(k_r, k_\theta) \right|^2 \right\rangle$

$T_n^{ZF}(k_\theta \rho_s = 0.19, k_r', k_r)$ $T_n^{ZF}(k_\theta \rho_s = 0.39, k_r', k_r)$





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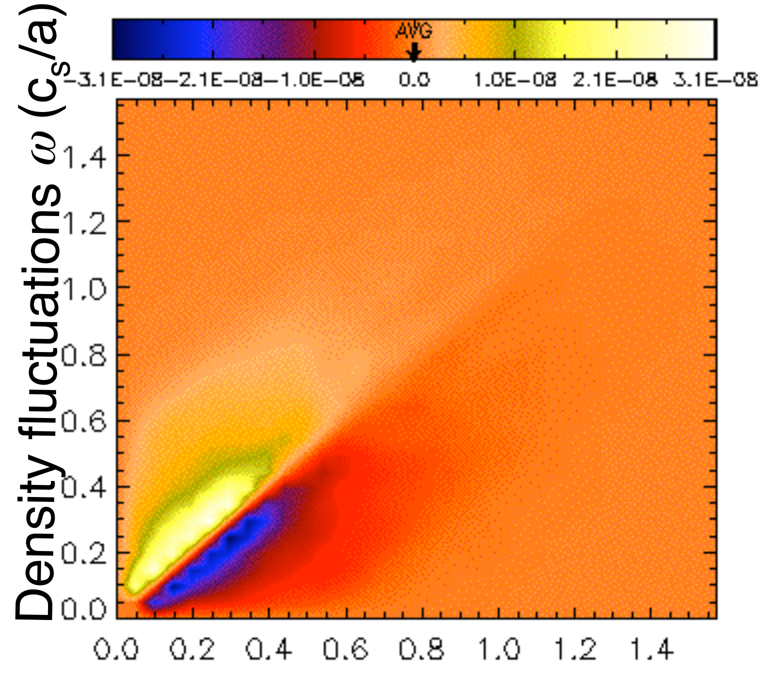
ZMF Zonal Flows Also Drive Forward Cascade in Frequency Space

- **Calculation of $T_n^Y(\omega', \omega)$ in GYRO indicates the ZMF zonal flows transfer internal energy to higher frequencies**

- **Key difference from experiment: transfer now occurs in bands along $\omega = \omega'$ with width set by ZF spectral width, rather than along narrow curves $f = f' +/- f_{GAM}$**

- **Again, underlying physics picture similar in simulation and experiment, when spectral differences between ZMF modes and GAMs are accounted for**

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



Poloidal density gradient fluctuations ω' (c_s/a)

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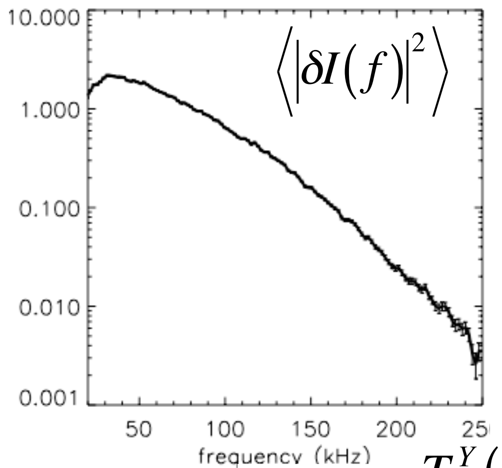
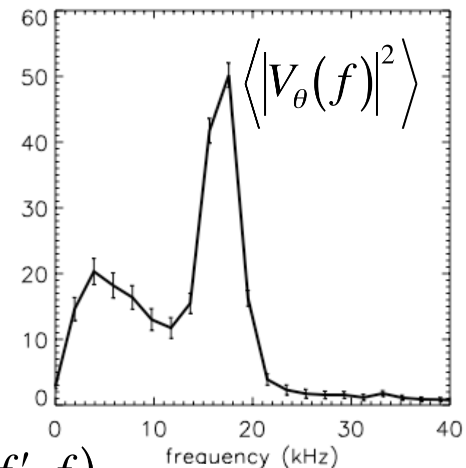
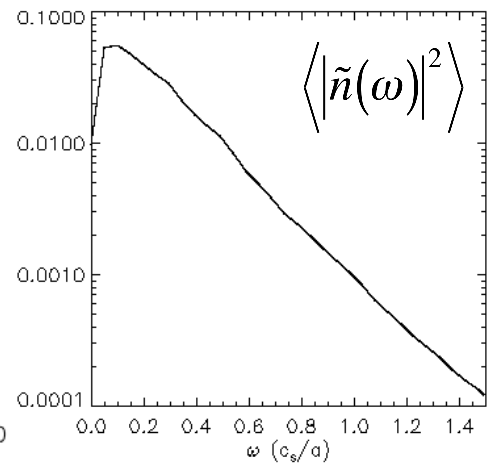
Comparison of Experimental and Simulation Energy Transfer Results Illustrates Similarities

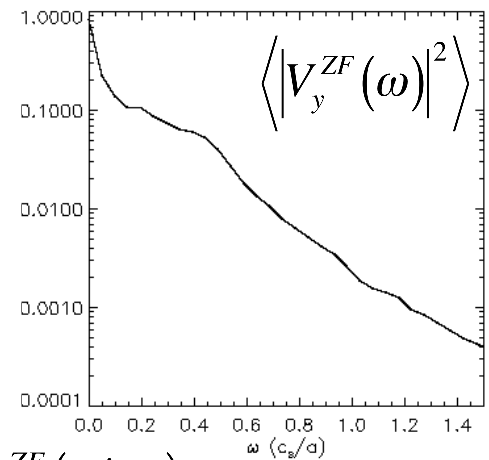
DIII-D edge



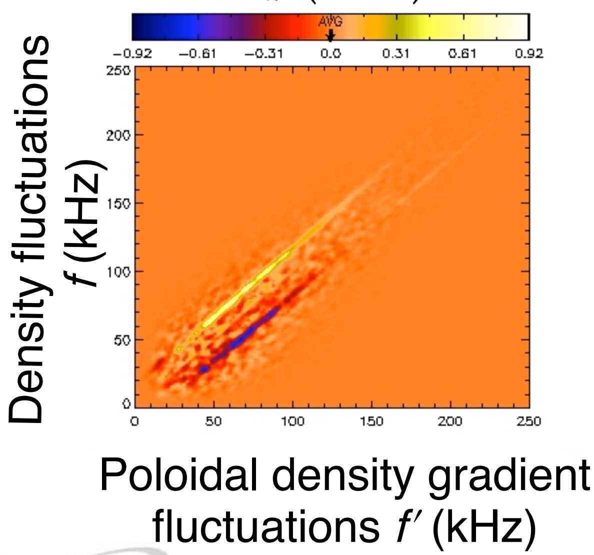


GYRO

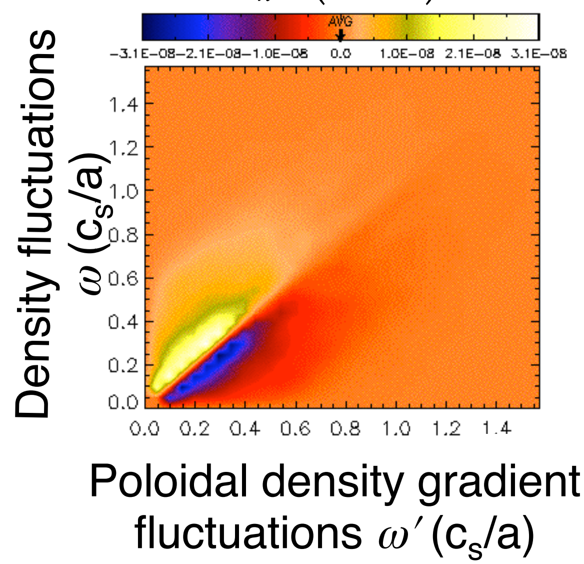




$T_n^Y(f',f)$



$T_n^{ZF}(\omega',\omega)$



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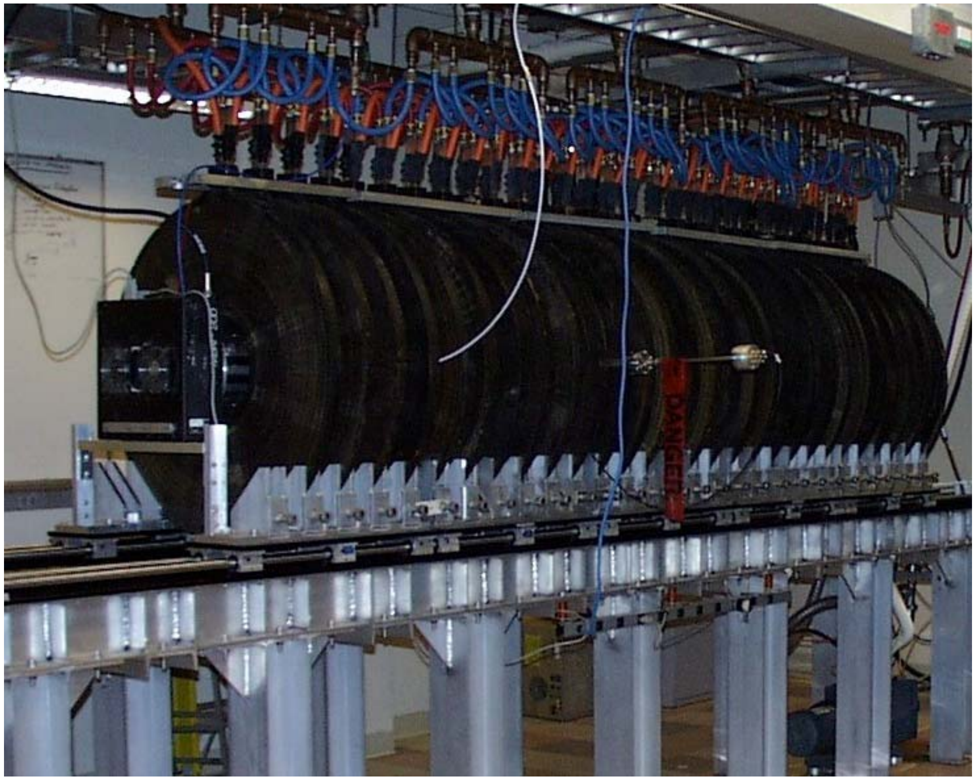
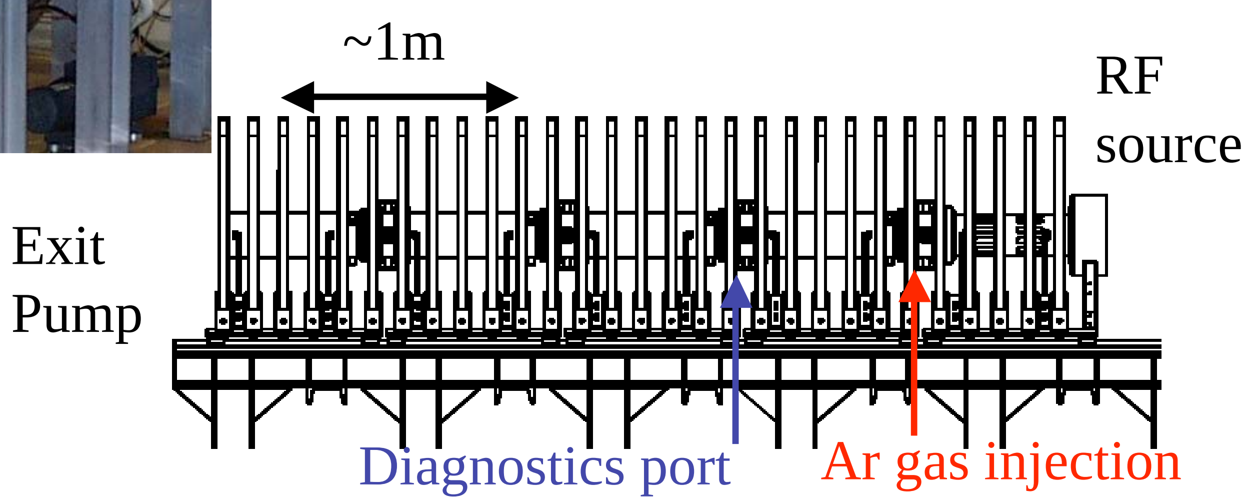
Controlled Shear Decorrelation Experiment (CSDX) at the University of California, San Diego



CSDX Parameters

- **Helicon source (m = 0, 1.5 kW, 13.5 MHz)**
- $n_e = 10^{13}\ cm^{-3}$
- $T_e = 3$ eV, $T_i \sim 1$ eV
- **B = 980 G**



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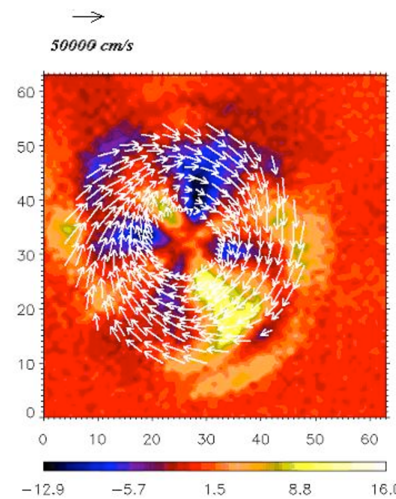
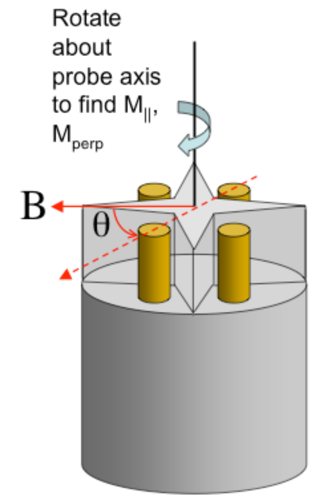
Measuring Zonal Flow Generation in CSDX

- **Work at DIII-D focused characterizing zonal flows and how they impact the turbulence**
- **Complimentary work on CSDX at UCSD on measuring how drift-wave turbulence generates zonal flows via the Reynolds stress**
- **Multiple diagnostics on CSDX allow us to measure zonal flow velocity and Reynolds stress across machine radius**
  - Turbulence clearly identified as collisional drift-waves
- **Plan:** Demonstrate that experimentally measured flow profile consistent with flow expected from azimuthal momentum balance, given the measured Reynolds stress and reasonable damping profiles

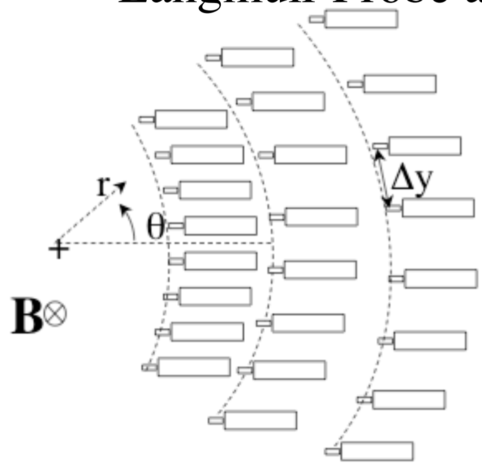


Fast-Framing Camera

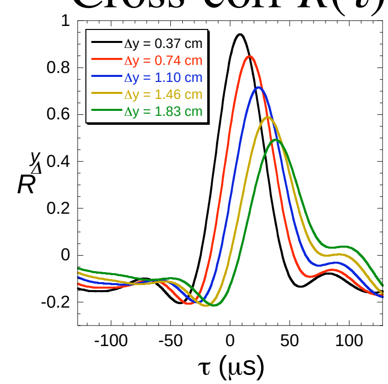


Mach Probe

Langmuir Probe array



Cross-corr $R(\tau)$



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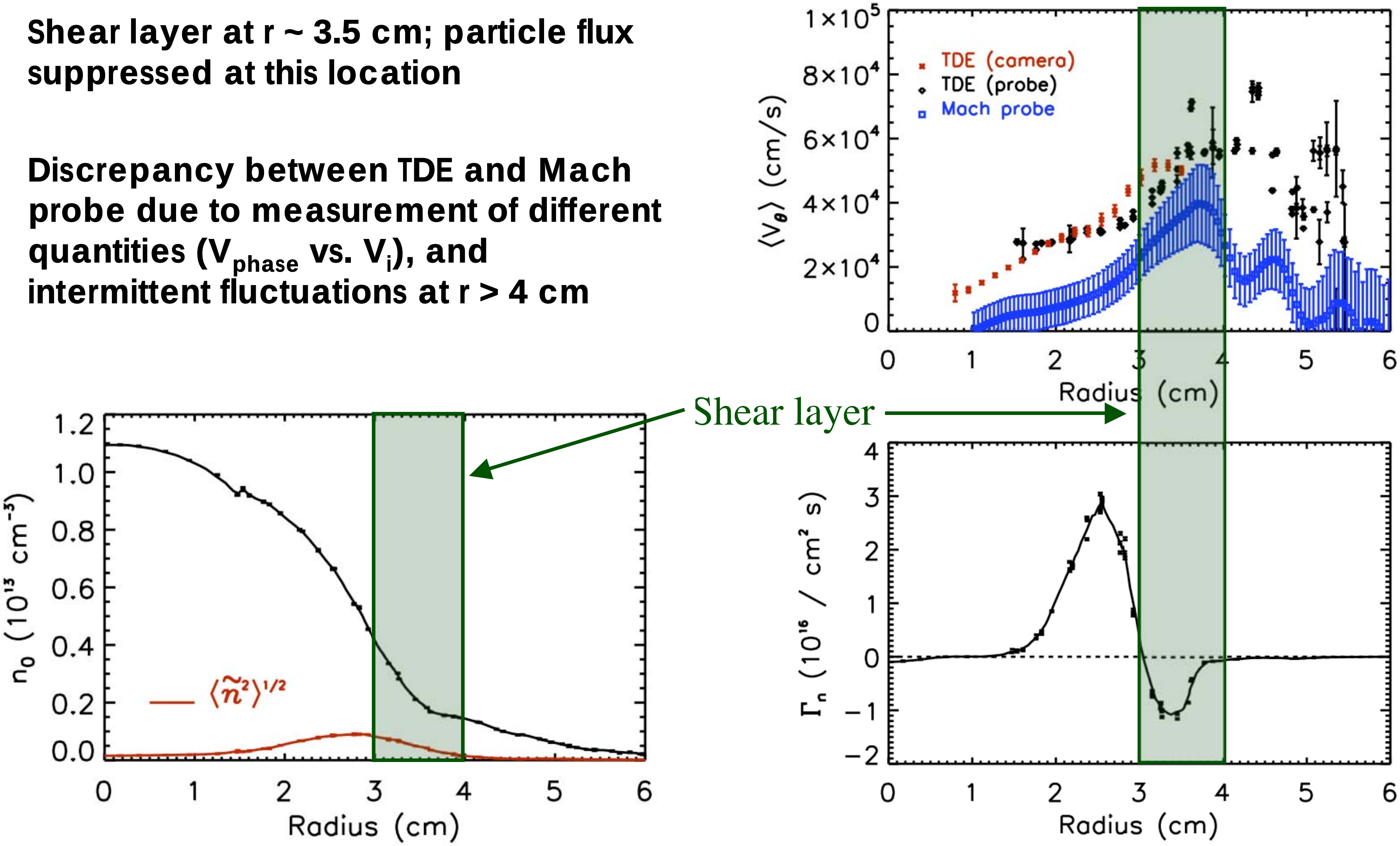
Shear Flow and Associated Flux Suppression Observed in CSDX

- **Shear layer at r ~ 3.5 cm; particle flux suppressed at this location**
- **Discrepancy between TDE and Mach probe due to measurement of different quantities (V_{phase} vs. V_i), and intermittent fluctuations at r > 4 cm**



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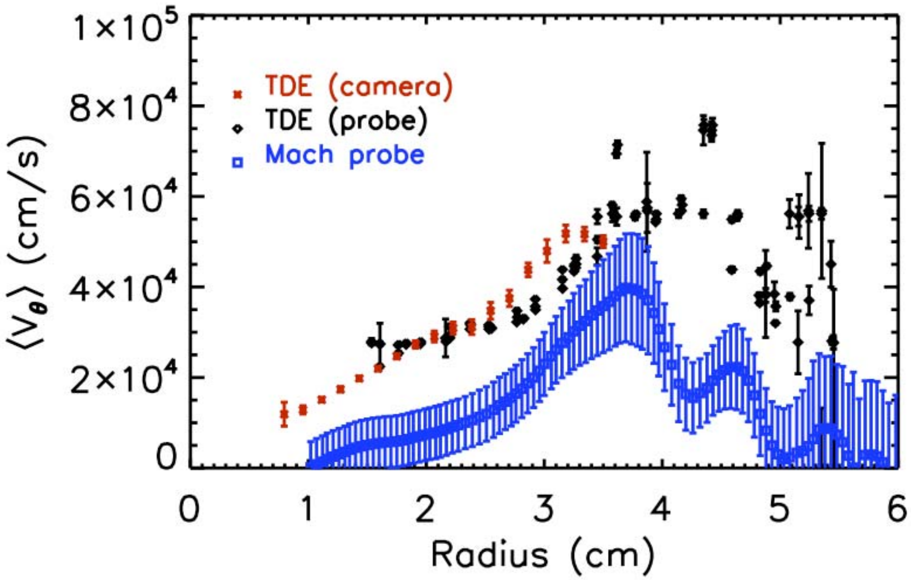
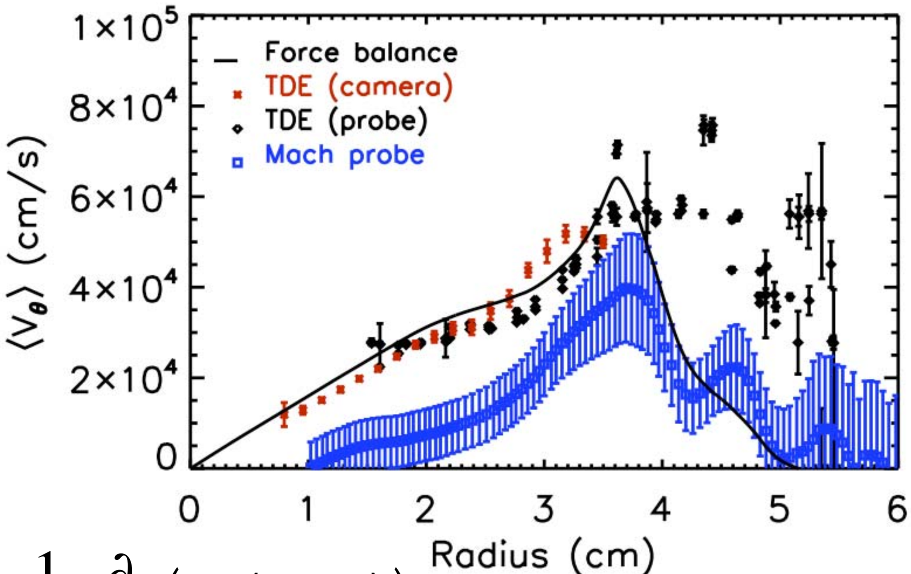
Flow Profile Predicted by Force Balance Consistent With Measured Profile

- **Observe sheared mean azimuthal flow profile in CSDX with all diagnostics**
  - Shear layer at r ~ 3.5 cm; particle flux suppressed at this location

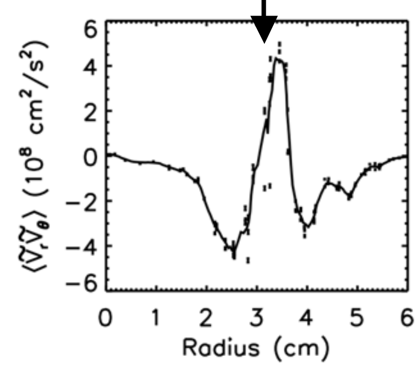


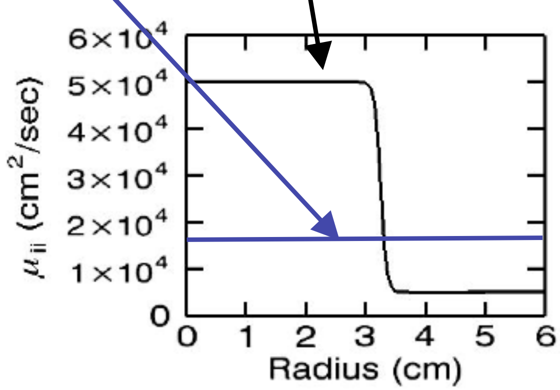
Flow Profile Predicted by Force Balance Consistent With Measured Profile

- **Observe sheared mean azimuthal flow profile in CSDX with all diagnostics**
  - Shear layer at r ~ 3.5 cm; particle flux suppressed at this location
- **Measure Reynolds stress using 4-pt Langmuir probe, and integrate force balance equation**
  - Prediction in good agreement with measurements
  - Use reasonable guesses for ν_{i-n} and μ_{ii} since radially resolved neutral and ion temperature measurements not available



$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\left\langle \tilde{V}_r \tilde{V}_\theta \right\rangle\right) = -\nu_{i-n}\left\langle V_\theta \right\rangle + \mu_{ii}\nabla^2\left\langle V_\theta \right\rangle$$





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Flow Profile Predicted by Force Balance Consistent With Measured Profile

- **Observe sheared mean azimuthal flow profile in CSDX with all diagnostics**
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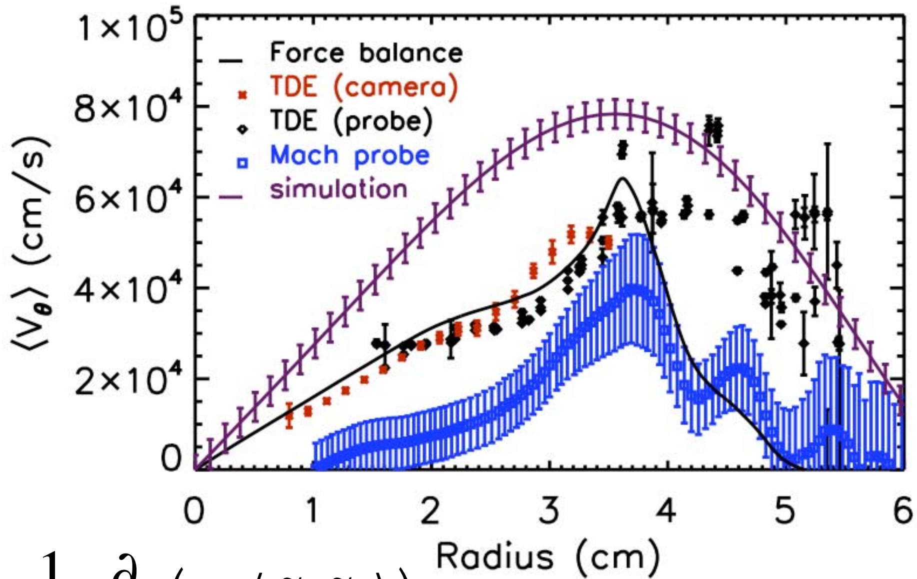
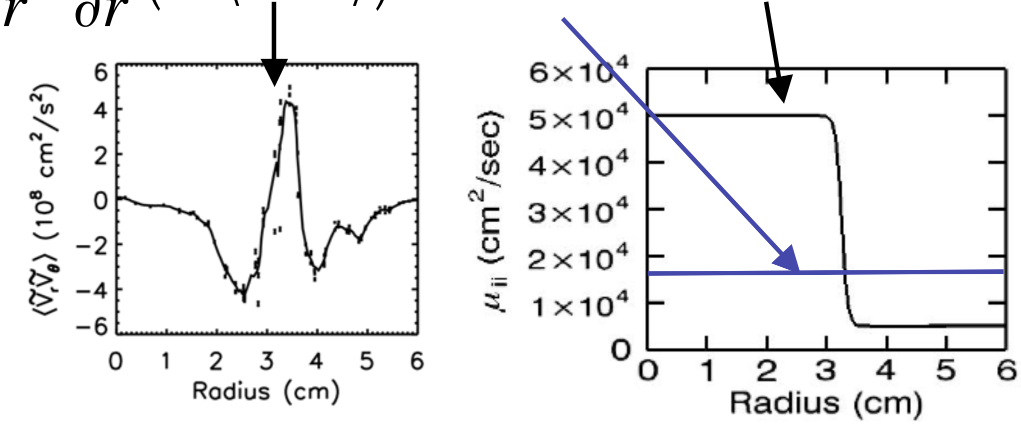
- **Measure Reynolds stress using 4-pt Langmuir probe, and integrate force balance equation**
  - Prediction in good agreement with measurements
  - Use reasonable guesses for ν_{i-n} and μ_{ii} since radially resolved neutral and ion temperature measurements not available
- **Simple simulation of collisional drift-waves in CSDX geometry in qualitative agreement**
  - Used Hasegawa-Wakatani model



$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\left\langle \tilde{V}_r\tilde{V}_\theta\right\rangle\right) = -\nu_{i-n}\left\langle V_\theta\right\rangle + \mu_{ii}\nabla^2\left\langle V_\theta\right\rangle$$



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Summary of Results

- **Zero mean frequency (ZMF) zonal flow now observed in core of DIII-D**
  - First observation of ZMF in a high-temperature tokamak
  - Transition from ZMF dominated core ($r/a < 0.8$) to Geodesic Acoustic Mode (GAM) dominated edge ($r/a > 0.8$) region documented

- **GAM-Driven Cascade of Internal Energy Has Been Measured in Edge of DIII-D**
  - First direct measurement of zonal flow driven nonlinear energy transfer in a high-temperature tokamak
  - Simulations of core turbulence indicate that ZMF zonal flows drive a similar cascade

- **Generation of a zonal flow via Reynolds stress has been demonstrated in the CSDX experiment at UCSD**

- **Taken together, results represent experimental validation of key linear and nonlinear aspects of the 'drift-wave - zonal flow' paradigm**

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Backup slides

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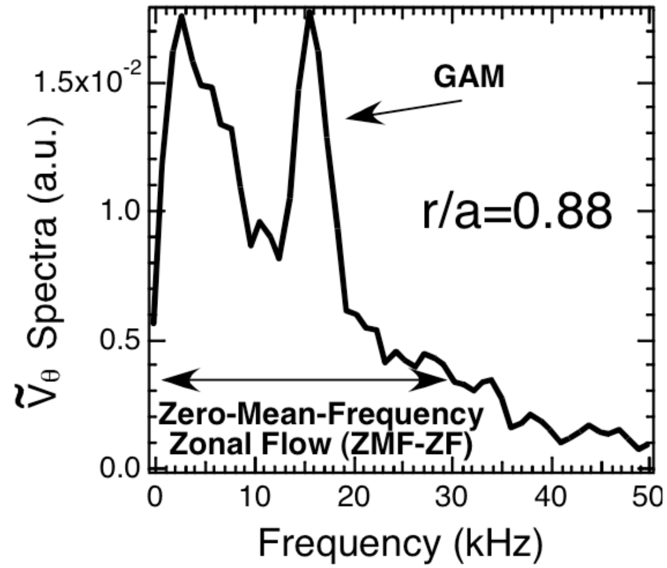
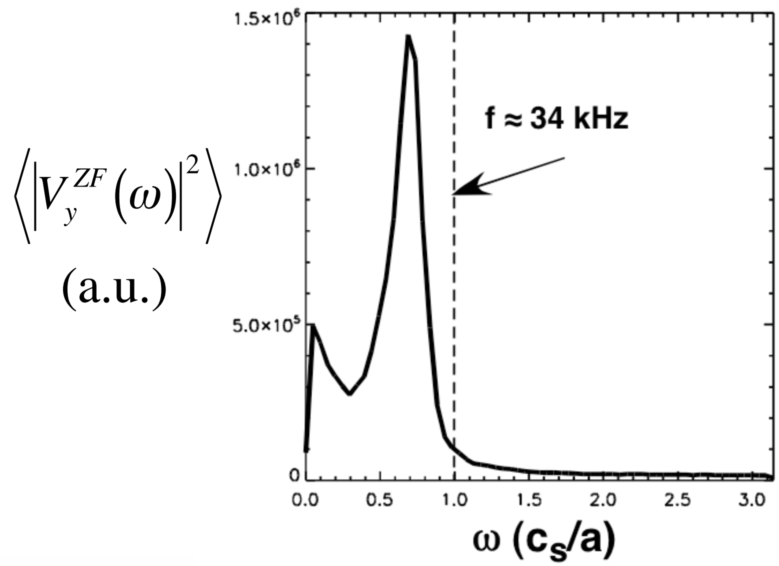
Experimentally Measured Spectra Qualitatively Consistent with Gyrokinetic Simulation

- **Measured velocity spectra at r/a = 0.88 (top), zonal flow velocity spectrum from GYRO (bottom)**

- **Simulation used CYCLONE parameters, except *q* = 3 and kinetic electrons**
  - $R/L_n = 2.22$, $R/L_T = 6.92$, $T_e/T_i = 1$





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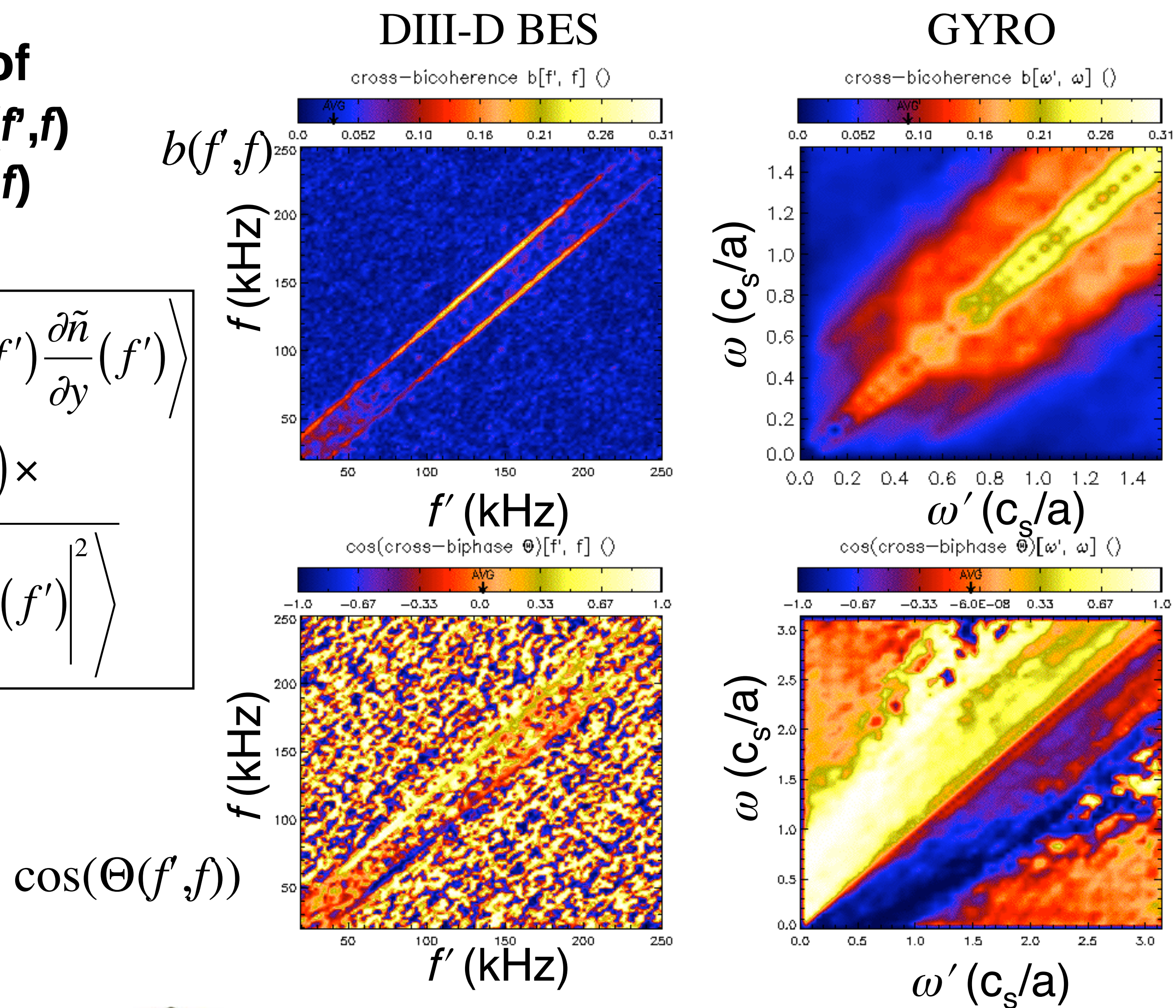
Good Agreement Between Experiment and Simulation Bicoherence and Biphase as Well

Express $T_n^Y(f',f)$ in terms of a cross-bicoherence $b(f',f)$ and cross-biphase Θ (f',f)

$$T_n^Y(f',f) = -\mathrm{Re}\left\langle \tilde{n}^*(f) V_y(f-f') \frac{\partial \tilde{n}}{\partial y}(f') \right\rangle$$
$$= b(f',f)\cos\big(\Theta(f',f)\big) \times$$
$$\sqrt{\left\langle \left|\tilde{n}(f)\right|^2 \right\rangle} \sqrt{\left\langle \left| V_y(f-f') \frac{\partial \tilde{n}}{\partial y}(f') \right|^2 \right\rangle}$$



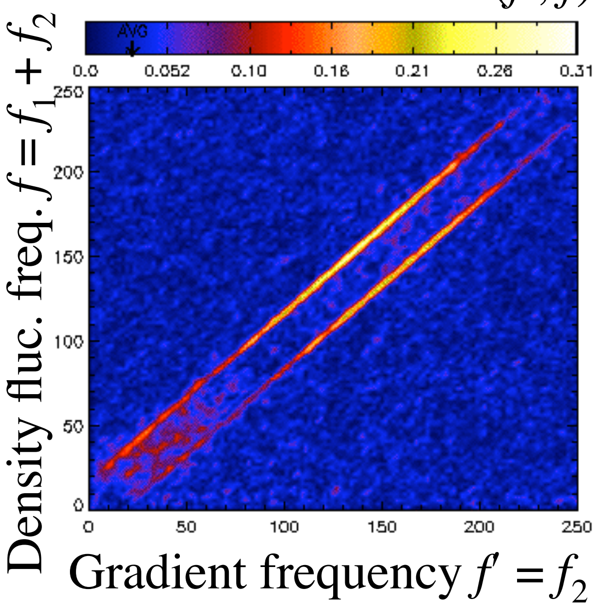
Bicoherence in (f′,f) vs. (f_1,f_2) Planes; Cross vs. Auto-Bicoherences

- **Formulation in (f',f) and (f_1,f_2) planes <u>equivalent</u> ($f = f_3 = f_1 + f_2$, $f' = f_2$)**

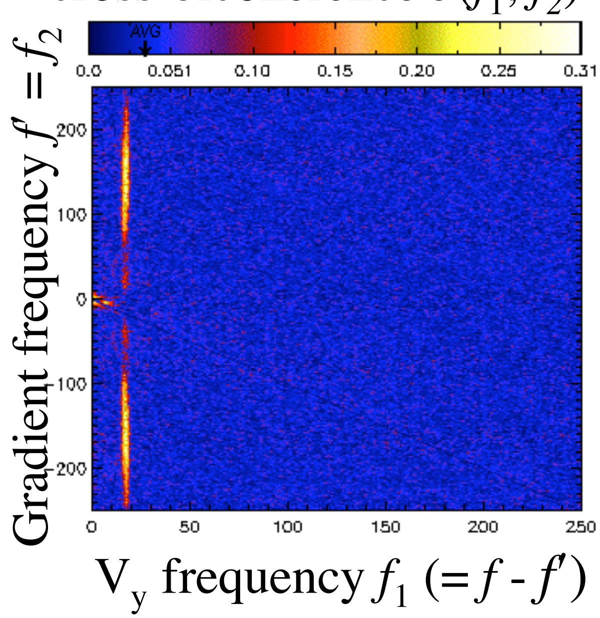
$$\frac{\left\langle \tilde{n}^*(f) V_y(f-f')\partial_y \tilde{n}(f')\right\rangle}{\sqrt{\left\langle\left|\tilde{n}(f)\right|^2\right\rangle}\sqrt{\left\langle\left|V_y(f-f')\partial_y\tilde{n}(f')\right|^2\right\rangle}} = b(f',f) \equiv b(f_1,f_2) = \frac{\left\langle \tilde{n}^*(f_1+f_2) V_y(f_1)\partial_y \tilde{n}(f_2)\right\rangle}{\sqrt{\left\langle\left|\tilde{n}(f_1+f_2)\right|^2\right\rangle}\sqrt{\left\langle\left|V_y(f_1)\partial_y\tilde{n}(f_2)\right|^2\right\rangle}}$$

- **Auto-bicoherence of BES signals (on right) both qualitatively and quantitatively different -> Illustrates danger in using "proxy" bispectra**

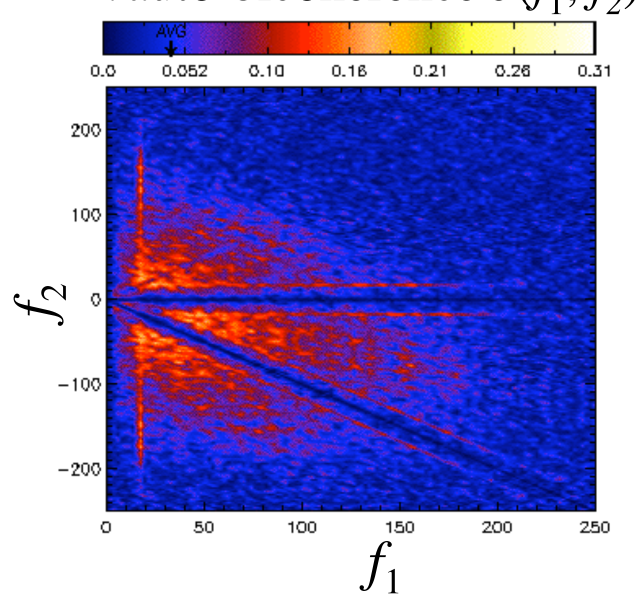
cross-bicoherence $b(f',f)$



cross-bicoherence $b(f_1,f_2)$



$\tilde{n}$ auto-bicoherence $b(f_1,f_2)$



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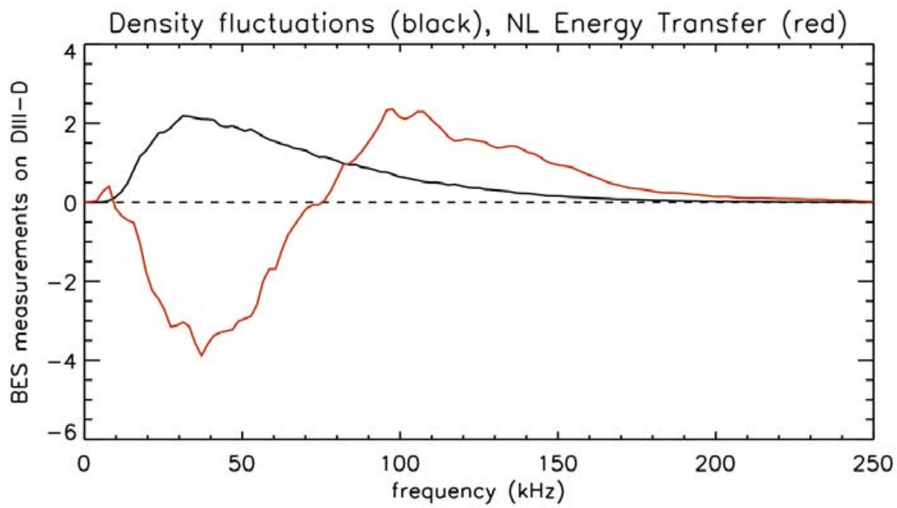
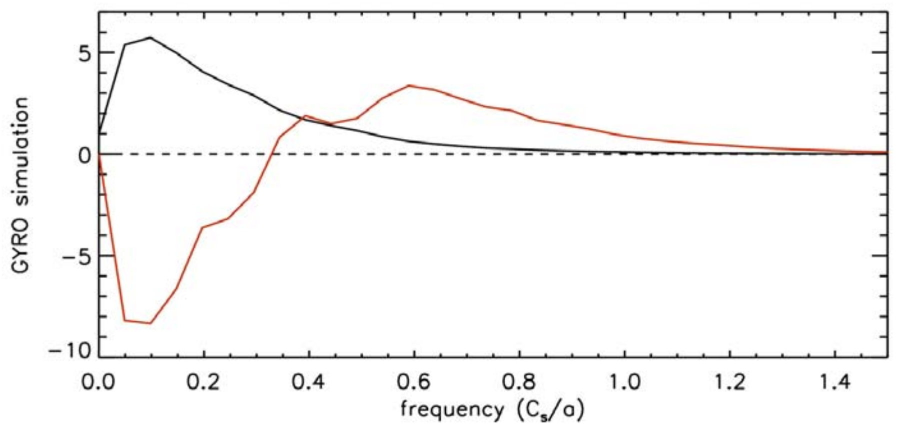
Integrated Transfer Functions Show Clear Similarities Between Experiment & Simulation, *f* and *k*-space

Frequency Space

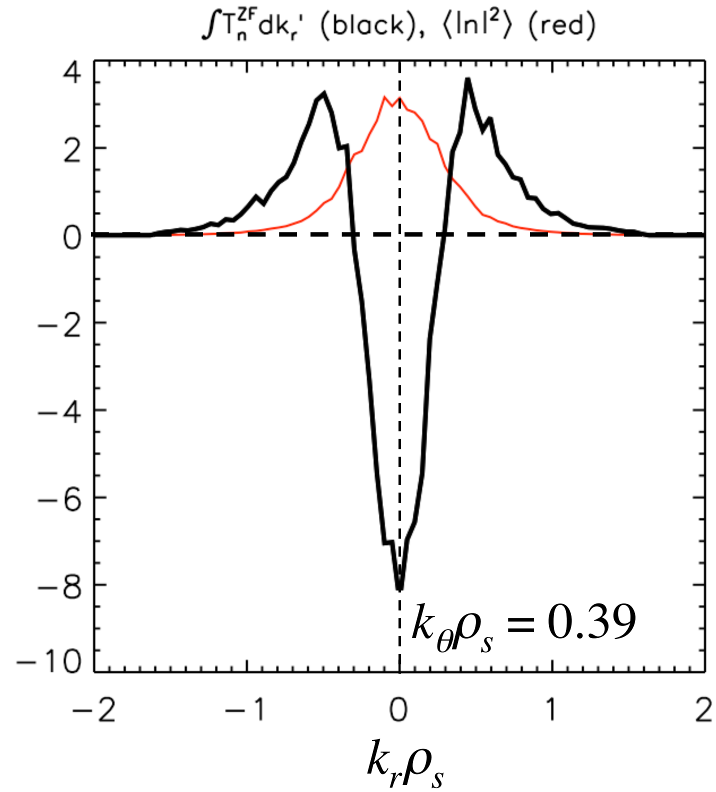
DIII-D



GYRO



GYRO Wavenumber Space



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