Search for Edge Zonal Flows in NSTX and Alcator C-Mod

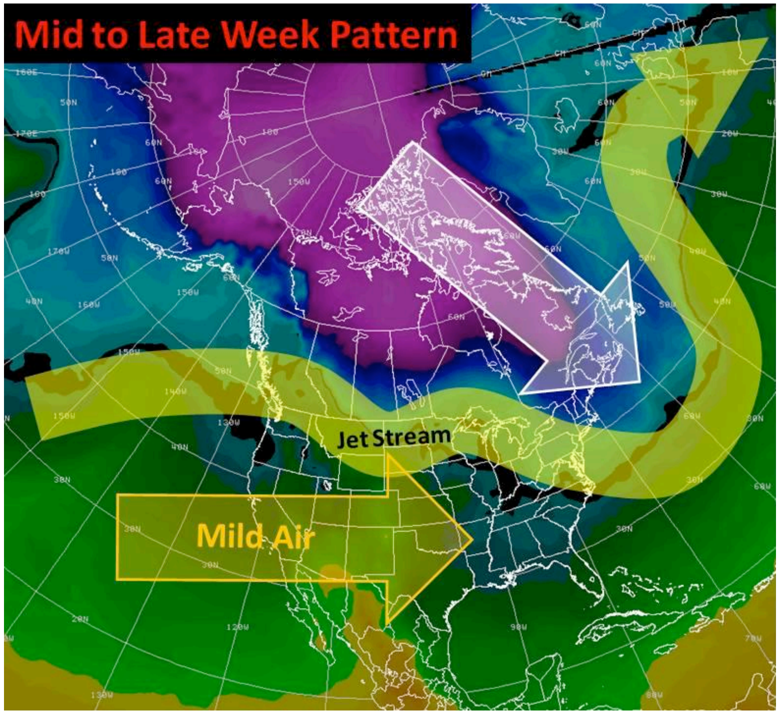
S.J. Zweben with collaborators:

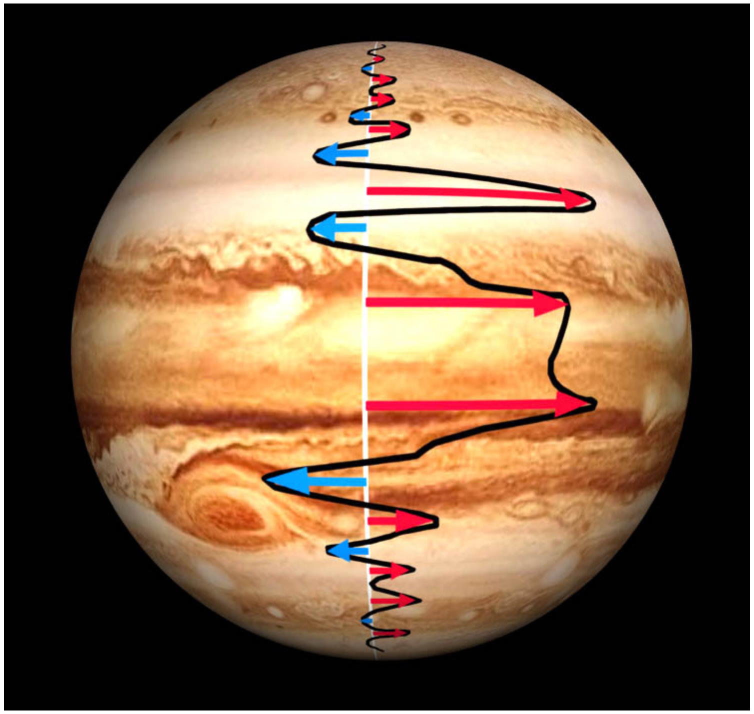
R.J. Maqueda, S. Kaye, L. Roquemore, D. Stotler et al - *PPPL*
J. Terry, B. LaBombard, M. Agostini, O. Grulke -- *MIT*
T. Munsat and Y. Sechrest -- *University of Colorado*
D. A. D'Ippolito, J. R. Myra, D.A. Russell -- *Lodestar*
R. Hager and K. Hallacheck - *IPP Garching*

- Introduction to zonal flows (20 min)
- Results from NSTX (20 min)
- Results from Alcator C-Mod (15 min)

PPPL Graduate Student Seminar March 7, 2011

Zonal Flows in Planetary Atmospheres



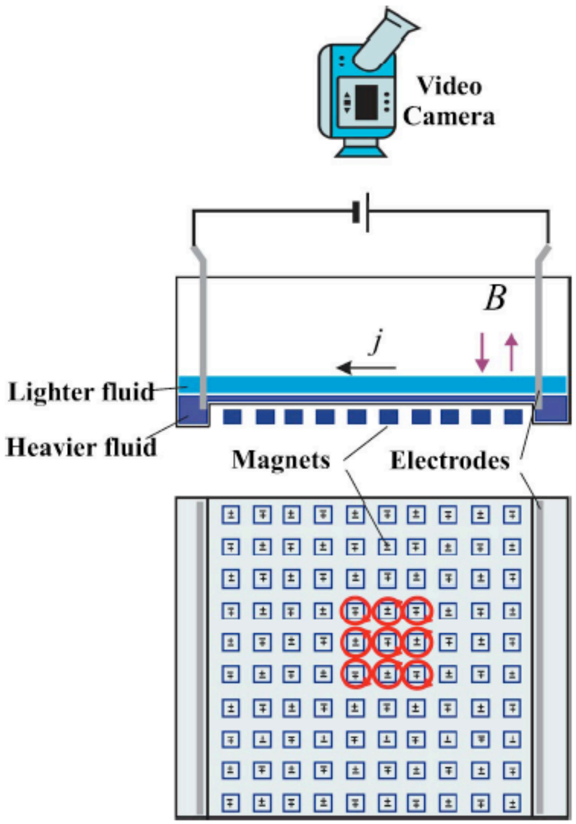


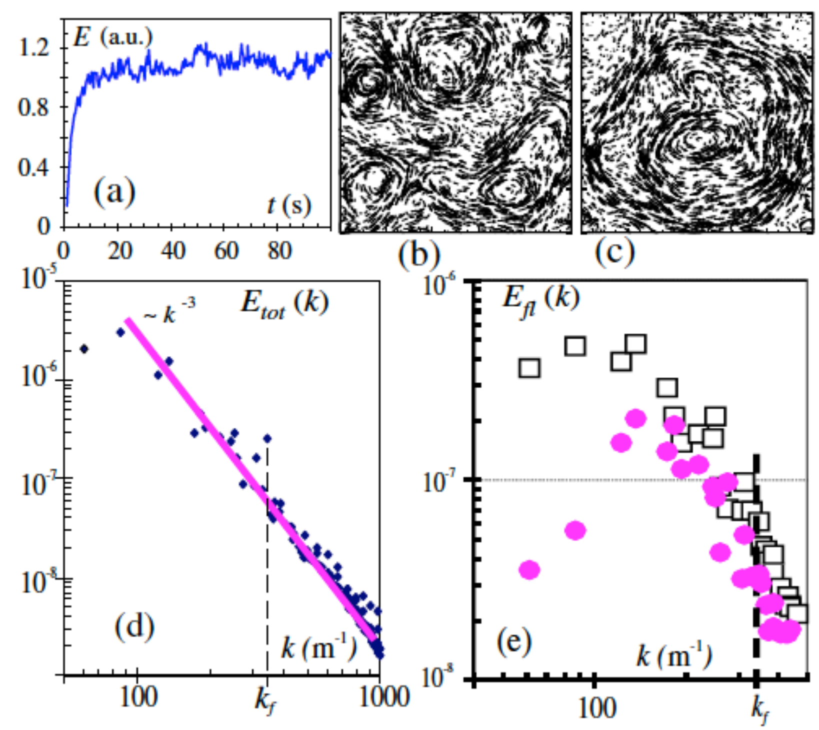
- These flows seem to be interesting and important
- Explanation of these flows is apparently not simple

Zonal Flows in Fluid Experiments

Probably 2-D turbulence needed to simulate planetary flows

Related fluid experiments created a single coherent vortex

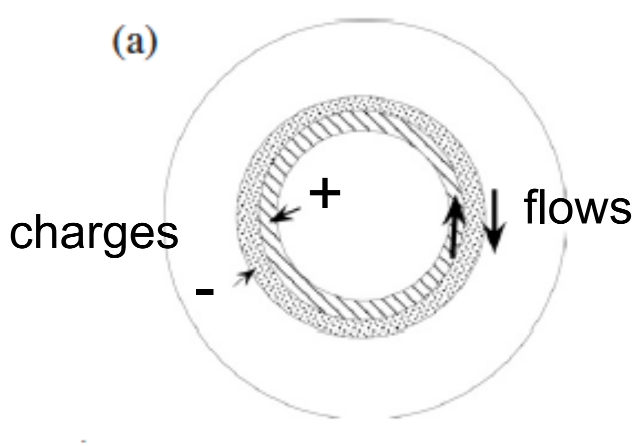


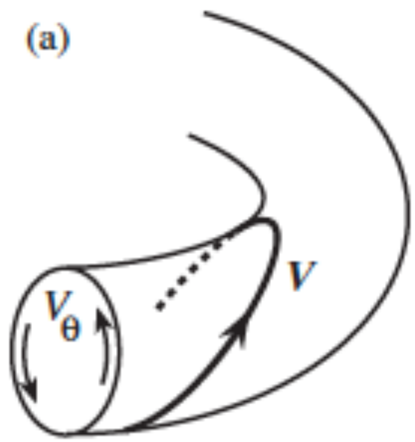


Shats et al, PRE 2007; PRL 2007

Theory of Zonal Flows in Tokamaks

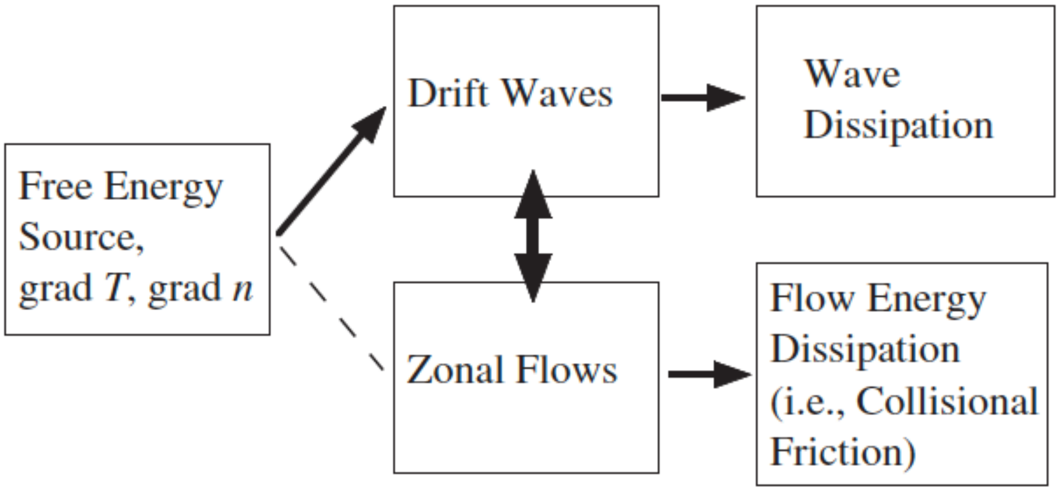
- Zonal flow is mainly in the poloidal direction, with m=n=0
- Zonal flow is associated with radial zones of varying E_r
- Zonal flows can be near-zero frequency or oscillating



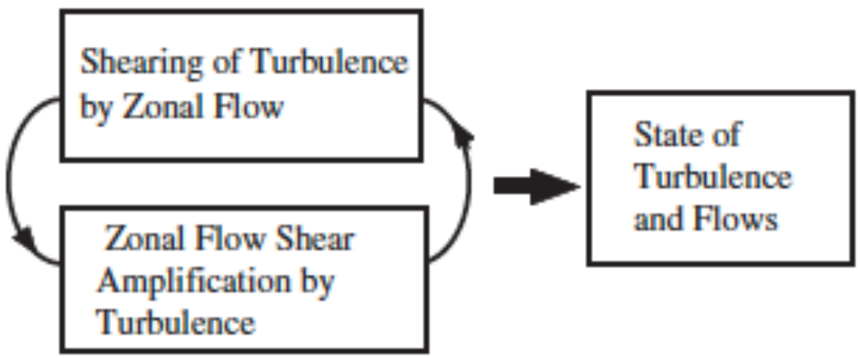


from "Zonal flows in plasma—a review" Diamond, Itoh, Itoh, Hahm, PPCF '05
(first simulation of zonal flows in tokamaks in Hasegawa et al, PRL 1987)

The “Drift-wave-Zonal-Flow” Paradigm



Energy flow

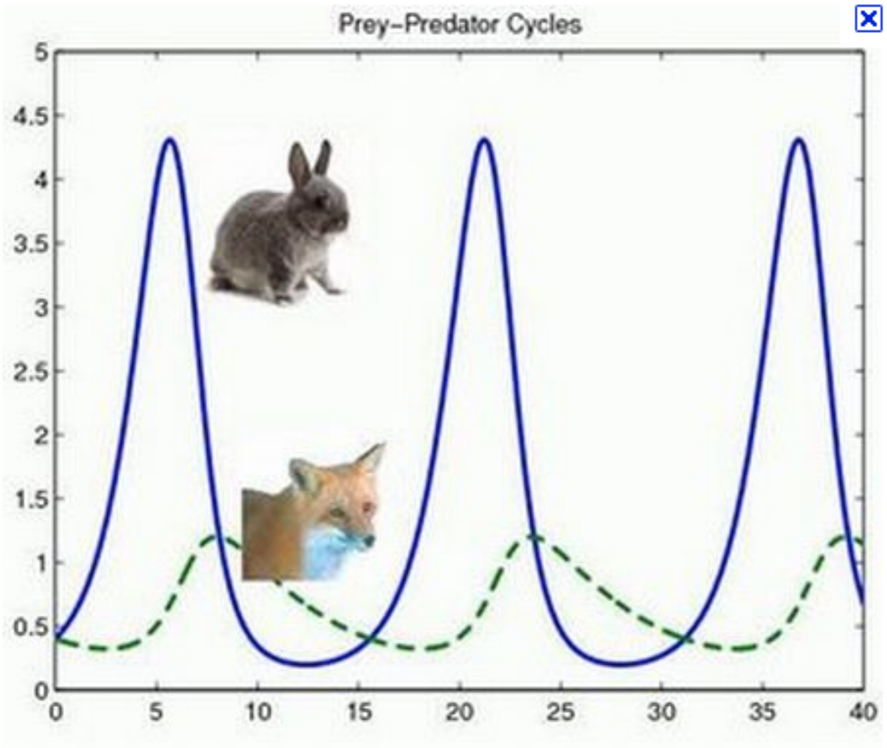


Mechanisms

Diamond et al, PPCF ’05
Tynan et al, PPCF ‘09

The Predator-Prey Model

- The zonal flow is like the predator (eats the turbulence)
- The turbulence is like the prey (eats the drift waves)
- Turbulence and transport is ***reduced*** by zonal flows



Measurements of Zonal Flow in Plasmas

- Turbulence in plasmas has been measured since the 1940's
- Mean shear flows have been measured since the 1980's
- Fluctuating zonal flows were not measured until ~2000's
  - experimentalists didn't think they were very important
  - zonal flows don't change the turbulence very much
  - transport effects of zonal flows were not evident

zonal flow measurement have mainly been done in small fusion devices, laboratory plasmas, or in the edge region of large tokamaks, due to diagnostic limitations

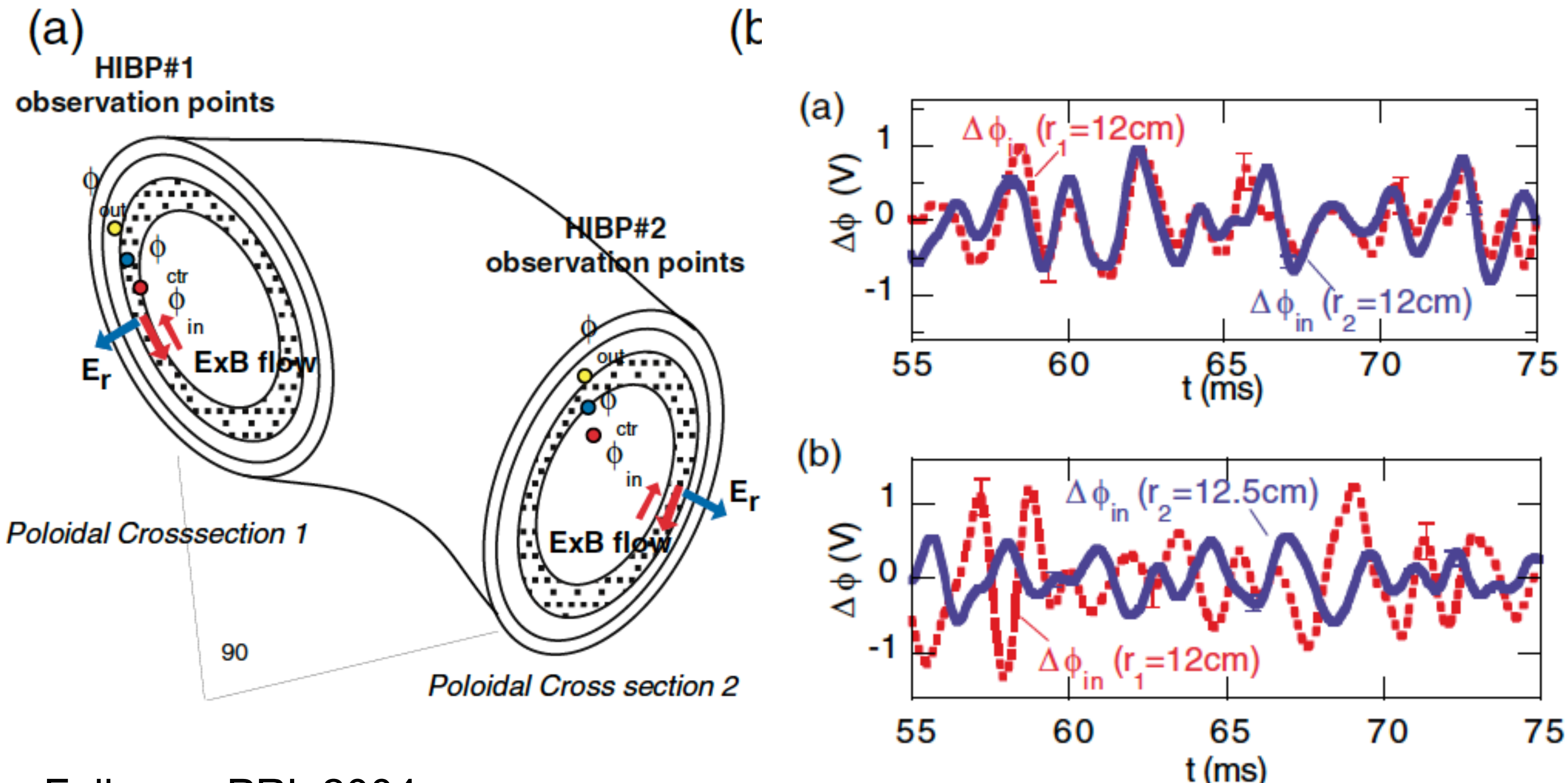
Zonal Flow Diagnostics in Tokamaks

Diagnostic	Flow measurement	Measurable quantities	Advantages
HIBP	Space potential	Density	Direct electric field measurement
Doppler reflectometry	Doppler shift of turbulence spectrum	Density	Accessibility for future large plasmas
BES	Movement of fluctuation pattern	Density	Two-dimensional measurements
Langmuir probe	Floating potential	Density, Temperature	Easy extension to multi-channel detection
GPI	Movement of fluctuation pattern	Density, Temperature	Two-dimensional measurements

adapted from “A review of zonal flow experiments”, A. Fujisawa NF ‘09

Data from Heavy Ion Beam Probe

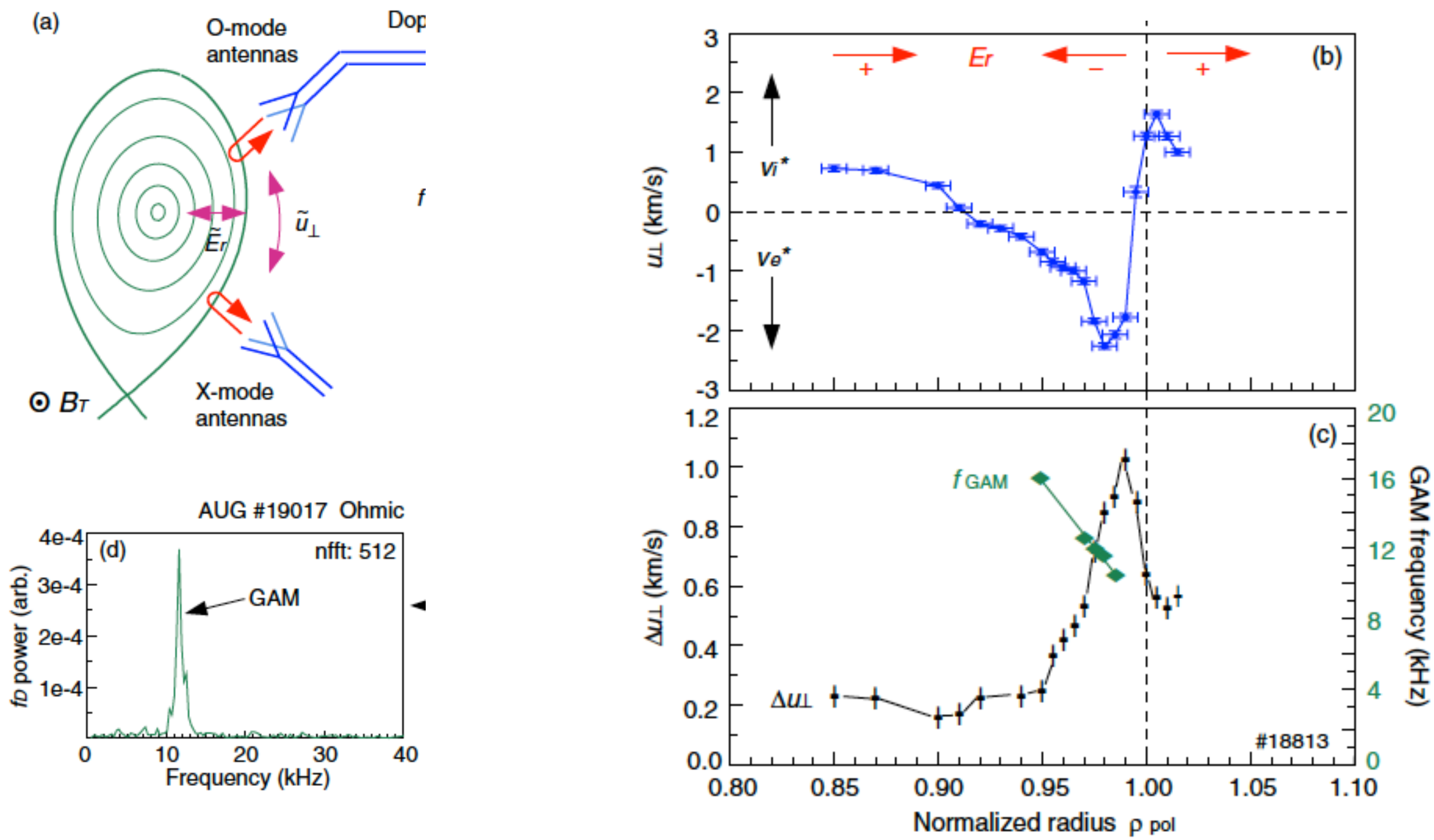
Radial electric field fluctuates the same at different toroidal locations on the same magnetic flux surface in CHS



Fujisawa PRL 2004

Data from Doppler Reflectometry

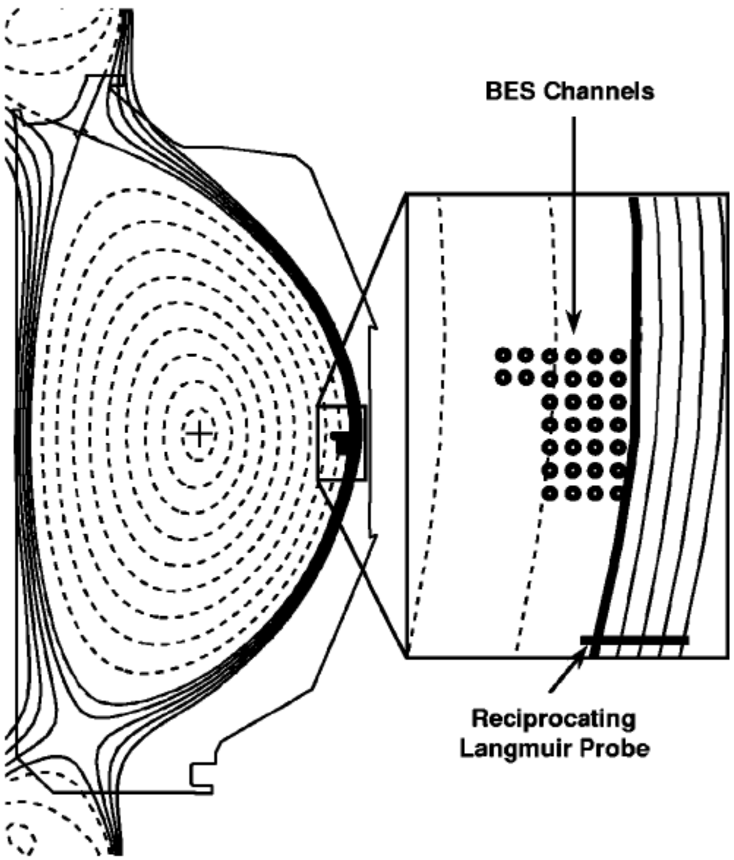
Coherent modulation of turbulence frequency near edge identified as geodesic acoustic mode (GAM)



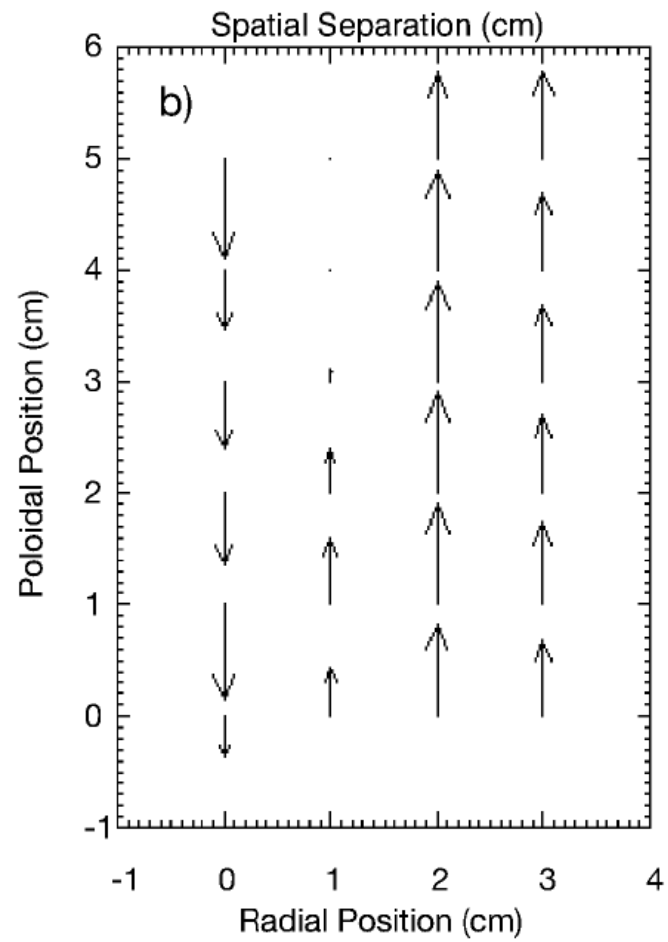
Conway PPCF '05

Data from Beam Emission Spectroscopy

~ 15 Hz poloidal flow in edge as identified as GAM

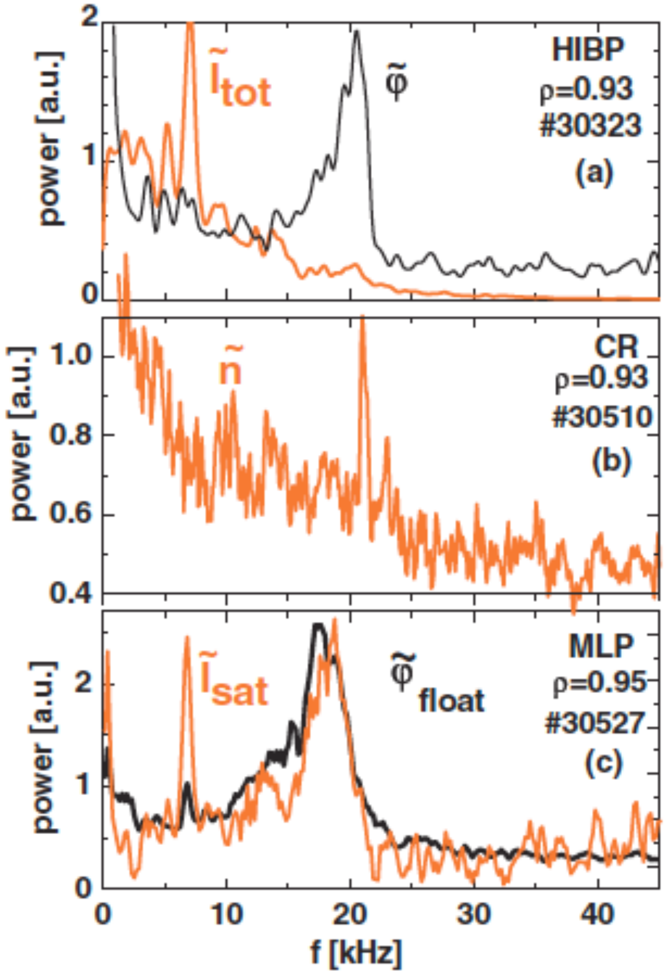


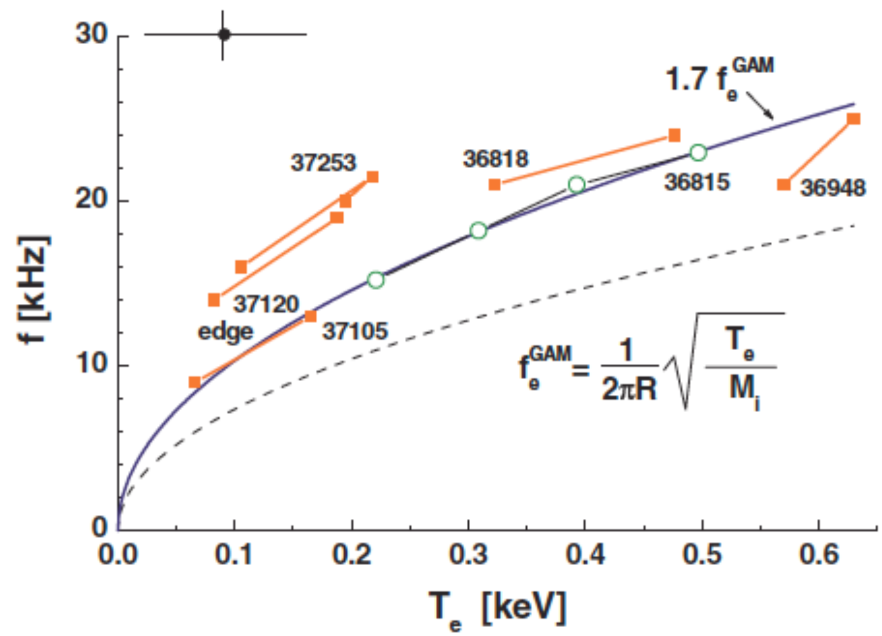
McKee et al PoP 2003



Data from HIBP, Reflectometry, and Probes

GAM seen in T-10 simultaneously with HIBP, correlation reflectometry, and Langmuir probe in the edge

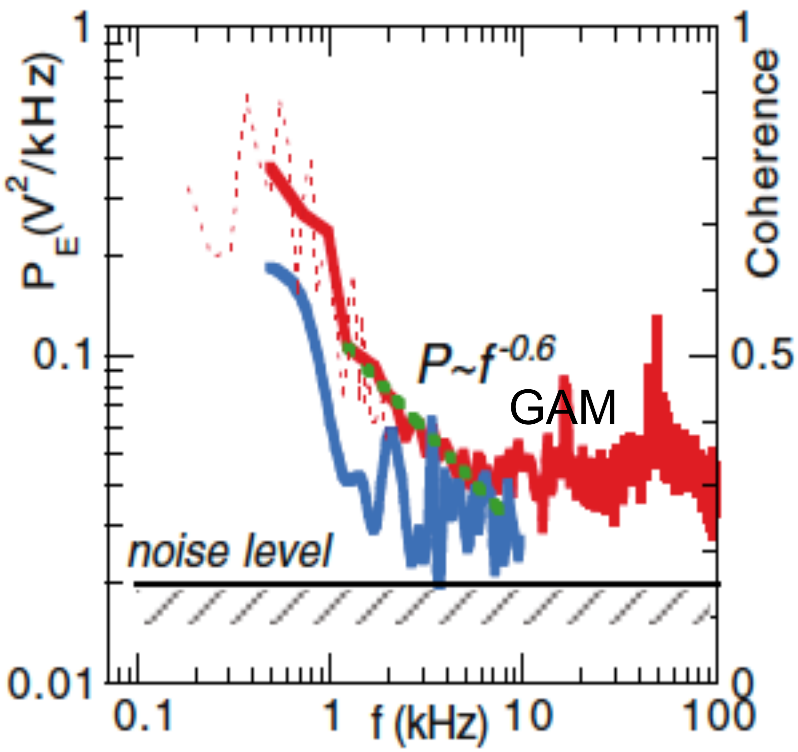




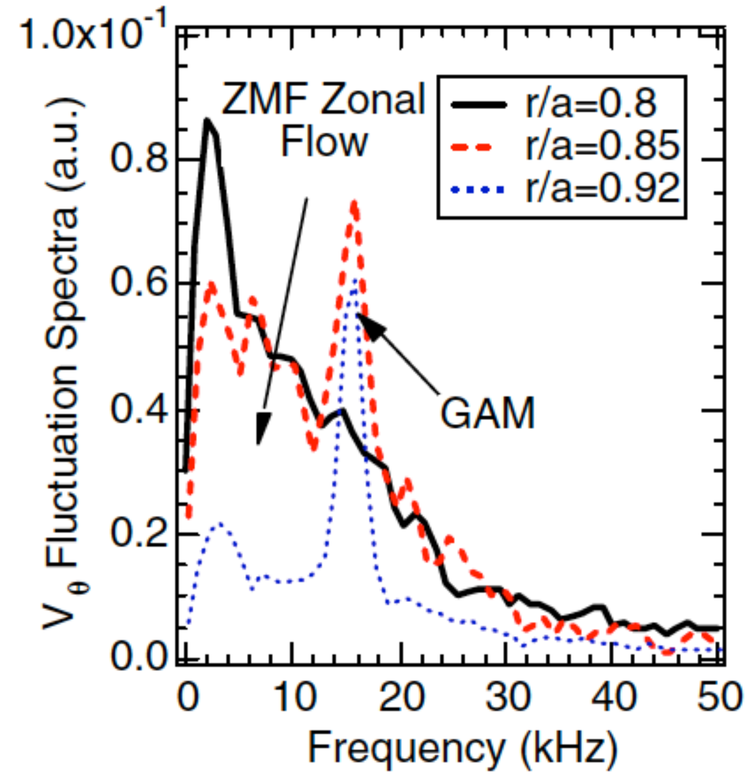
Melnikov et al, PPCF 2006

Low Frequency Zonal Flows

Some experiments have seen broadband low frequency poloidal flows, often at smaller minor radii than GAM



Fujisawa PRL 2004

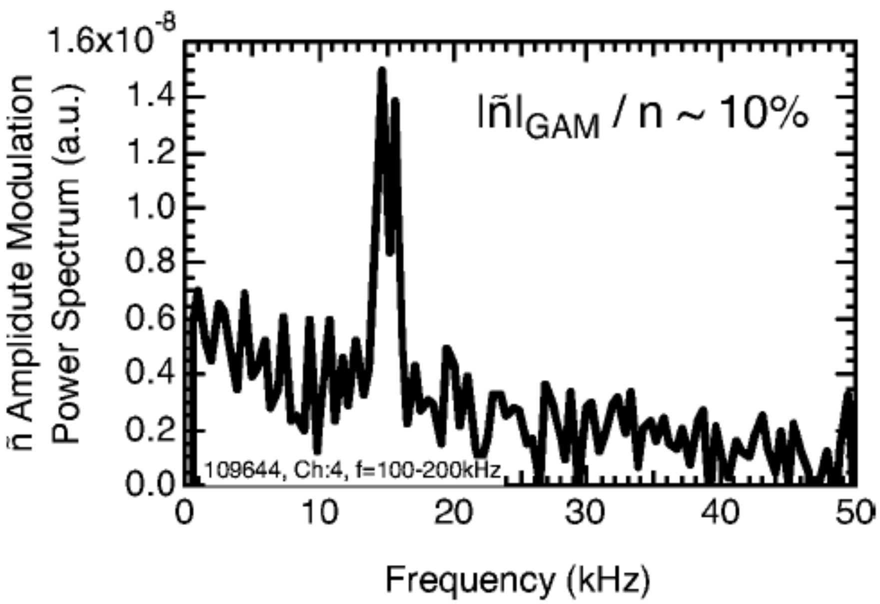


Gupta et al PRL '06

Turbulence Modulation by Zonal Flows

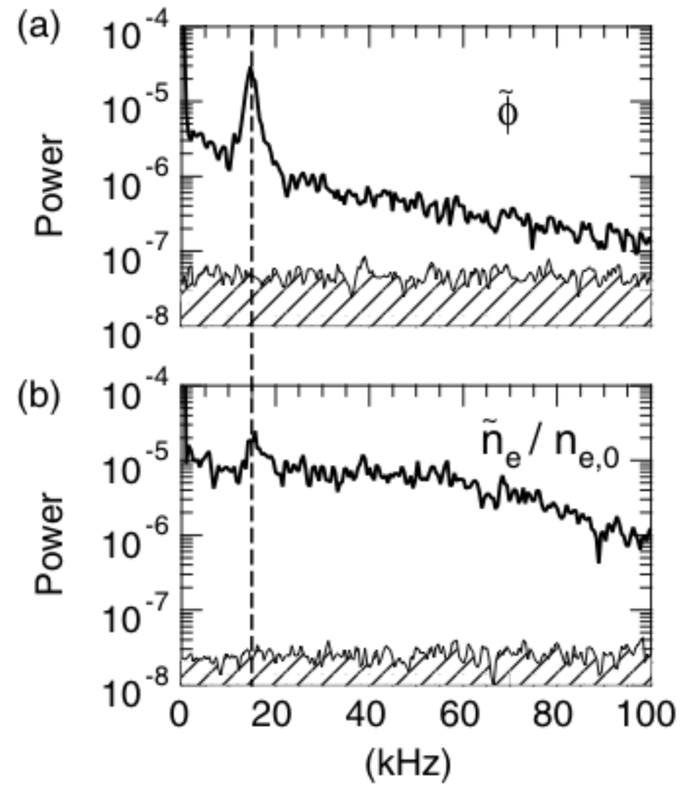
only slightly modulation of turbulence correlated with GAM

spectrum of envelope of density fluctuations 100-200 kHz in DIII-D (broadband background removed)



McKee et al PoP 2003

JFT-2M HIBP



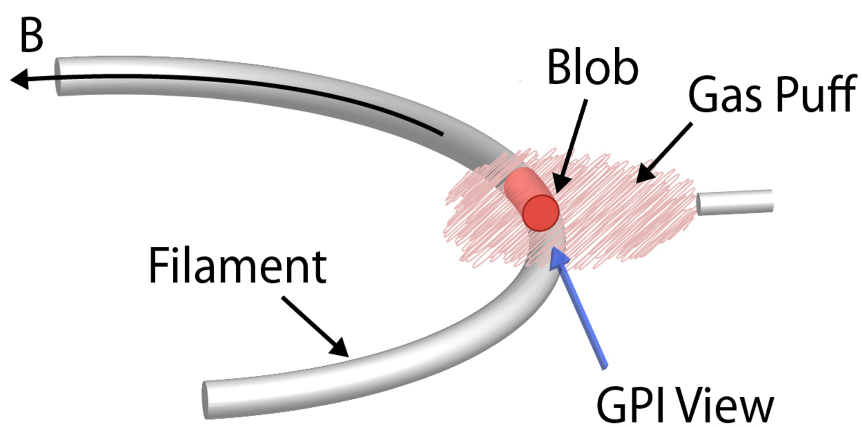
Ido et al PPCF 2006

Summary of Zonal Flows in Tokamaks

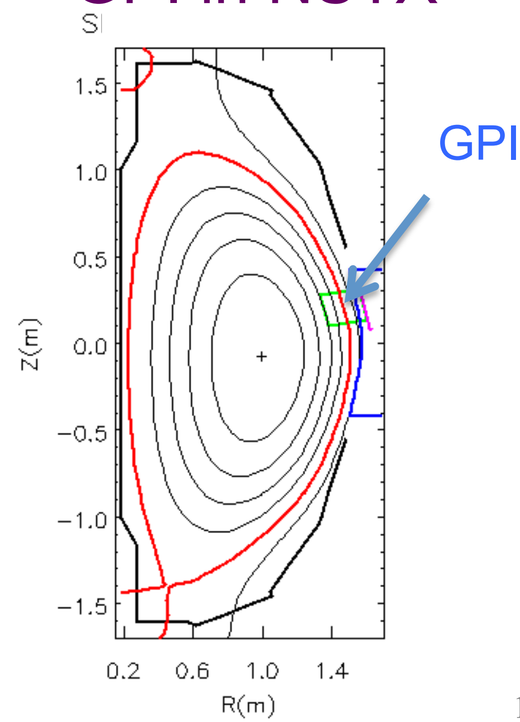
- Theory and simulation of zonal flows is highly developed and used to explain core ITG transport (e.g. Dimits shift)
- Coherent zonal flows (GAMs) clearly observed mainly in edge of several devices using 4 different diagnostics
- Lower frequency incoherent zonal flows sometimes seen but frequency spectrum not understood quantitatively
- Drive and damping mechanisms and transport effects of zonal flows seen in experiments not yet understood

Gas Puff Imaging (GPI) Diagnostic

- Optics view along B toward D_α emission from D_2 gas puff
- Oriented to view 2-D radial vs. poloidal plane at gas cloud

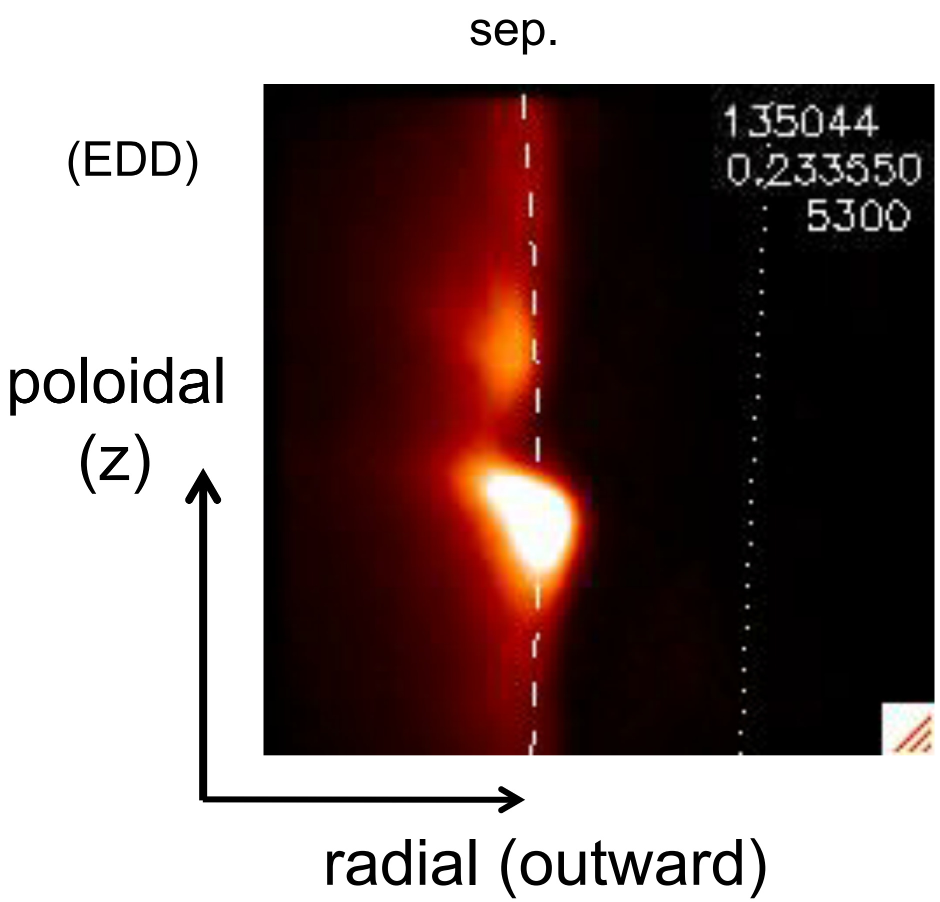


GPI in NSTX



Movie of Edge Turbulence in NSTX

- This movie 285,000 frames/sec for ~ 1.4 msec
- Viewing area ~ 25 cm radially x 25 cm poloidally



playback @
35 μsec/sec

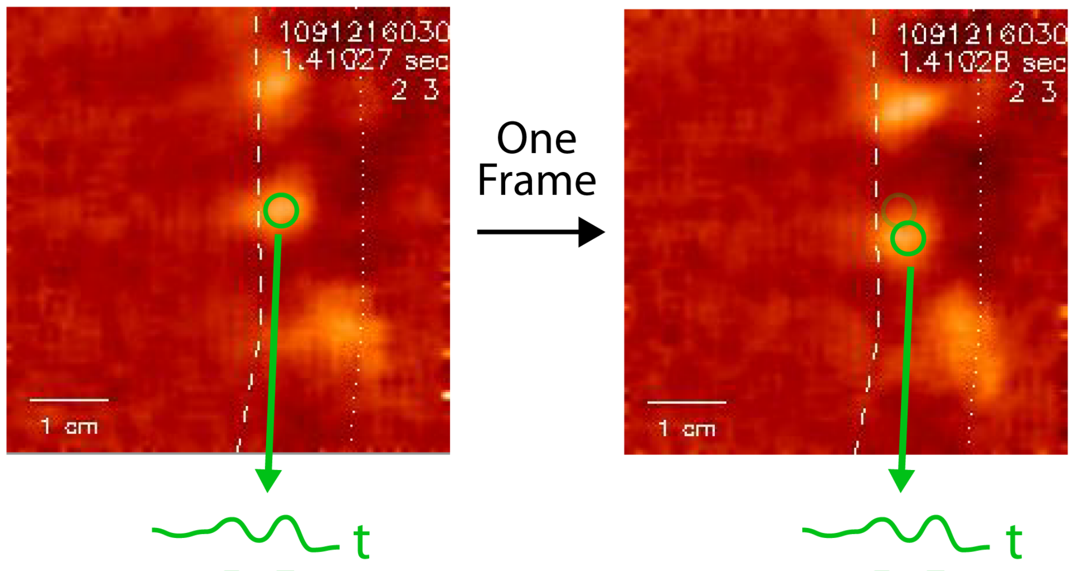
What Are We Seeing in GPI ?

- Seeing local emission of $D_\alpha \sim n_o\, f(n_e,T_e)$ within window where D_α is emitted in plasma edge, where $T_e \sim 10$ -100 eV
- Can measure 2-D ***turbulence structure and motion*** even if response of D_α is nonlinear (like contrast knob on a TV)
- Can ***not directly measure fluid (ion) flow*** or ExB flow, but measures turbulence flow velocity, as done previously*

* McKee et al, PoP ’03 using BES on DIII-D
Conway et al, PPCF ’05 using Doppler reflectometry on AUG

Method to Evaluate Turbulence Velocity

- choose a pixel and a time, and make a short time series around it (~20 μs)
- look at nearby pixels one frame later and find best match to original series
- find V_{rad} and V_{pol} from relative displacement, then average these poloidally



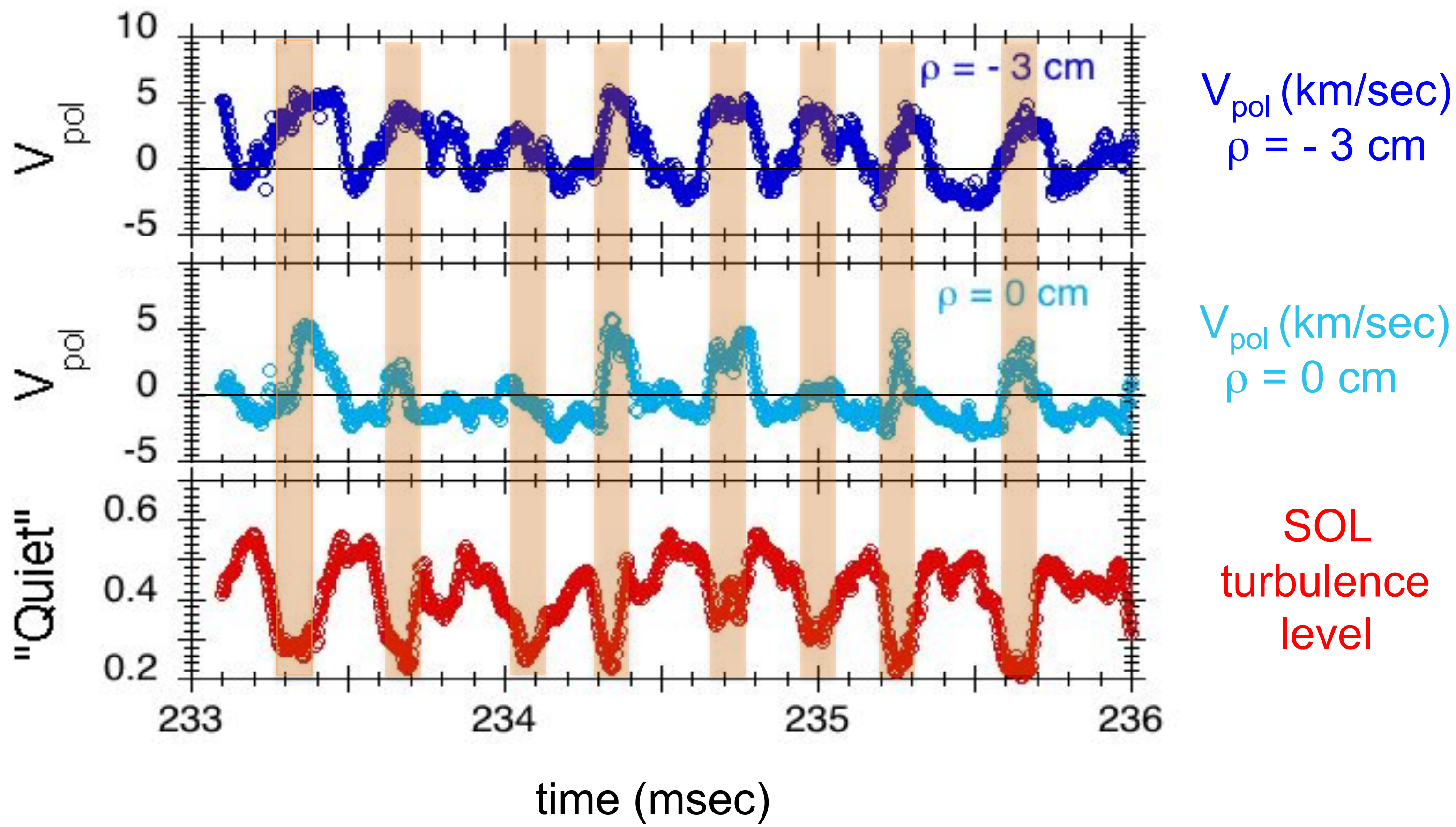
Some Limitations of this Analysis

- Poloidal average is only over δz ~ 20 cm in NSTX (δz ~ 5 cm in C-Mod), so not measuring m~0 structure (like BES)
- Can not easily distinguish flow (“group”) velocity from the possible phase velocity of waves in a stationary plasma
- Significant statistical uncertainty in evaluation of these velocities for real GPI data

this turbulence velocity is only an approximate estimate of the plasma flow (i.e. ExB) velocity

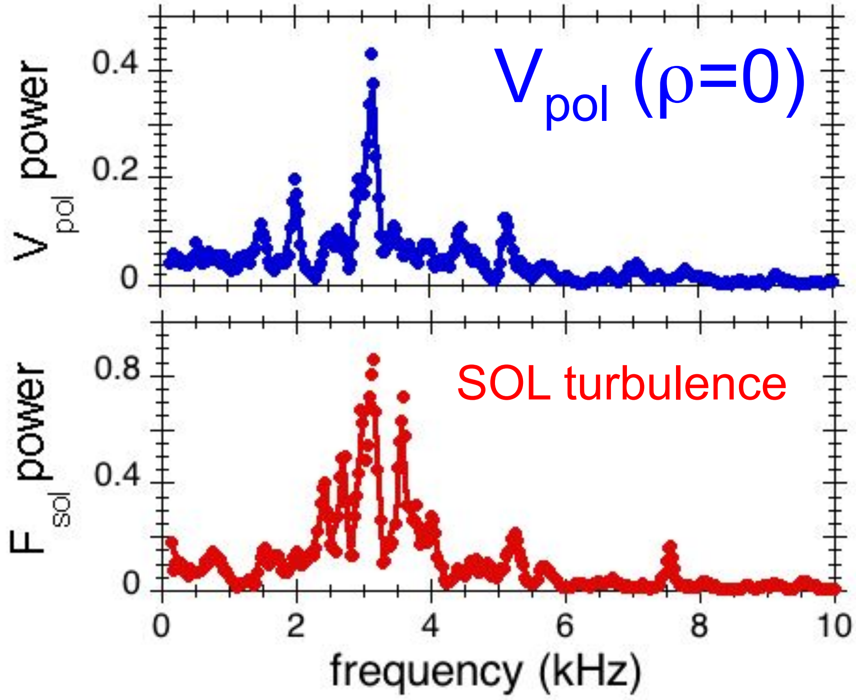
Fluctuating Poloidal Flow and Turbulence

- Poloidal flow direction oscillates at ~ 3 kHz in phase with "quiet periods" in local turbulence level as seen in GPI



Frequency Spectrum of Zonal Flow

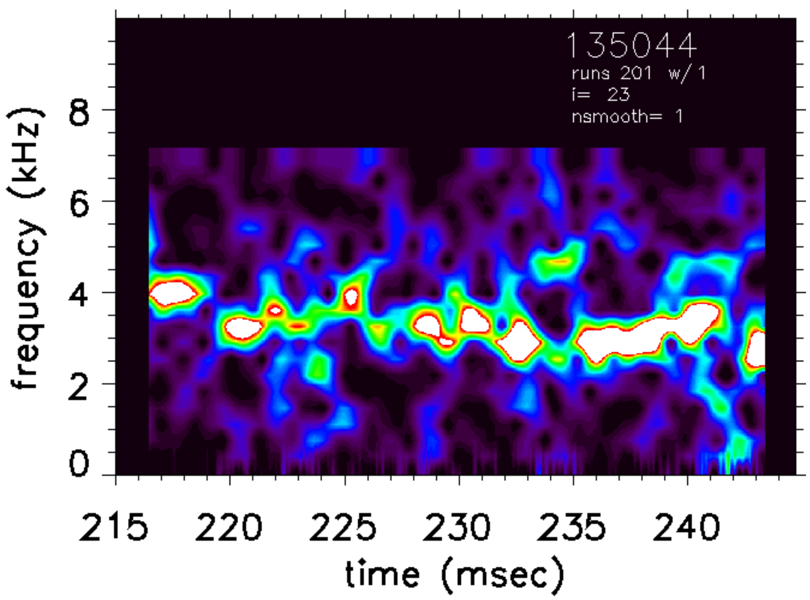
- Poloidal flow and SOL turbulence have peak near 3 kHz
- Cross-correlation of V_{pol} and F_{sol} ~ 50% over $\rho = \pm 3$ cm



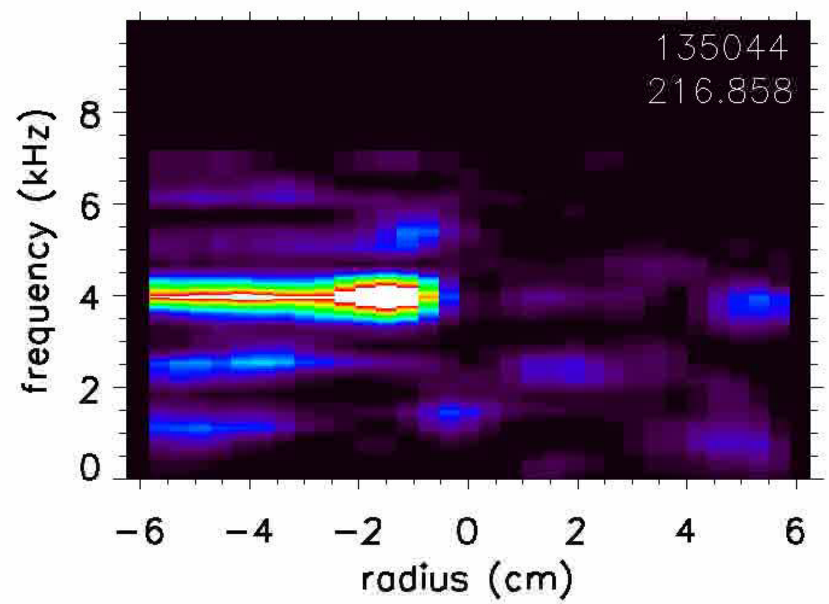
Time and Radial Dependence of Zonal Flow

- Zonal flow spectrum intermittent in frequency and amplitude
- Zonal flow amplitude largest ρ ~ 0 to -5 cm inside separatrix

V_{pol} spectrum at ρ = -2 cm



V_{pol} spectrum vs. ρ vs. time



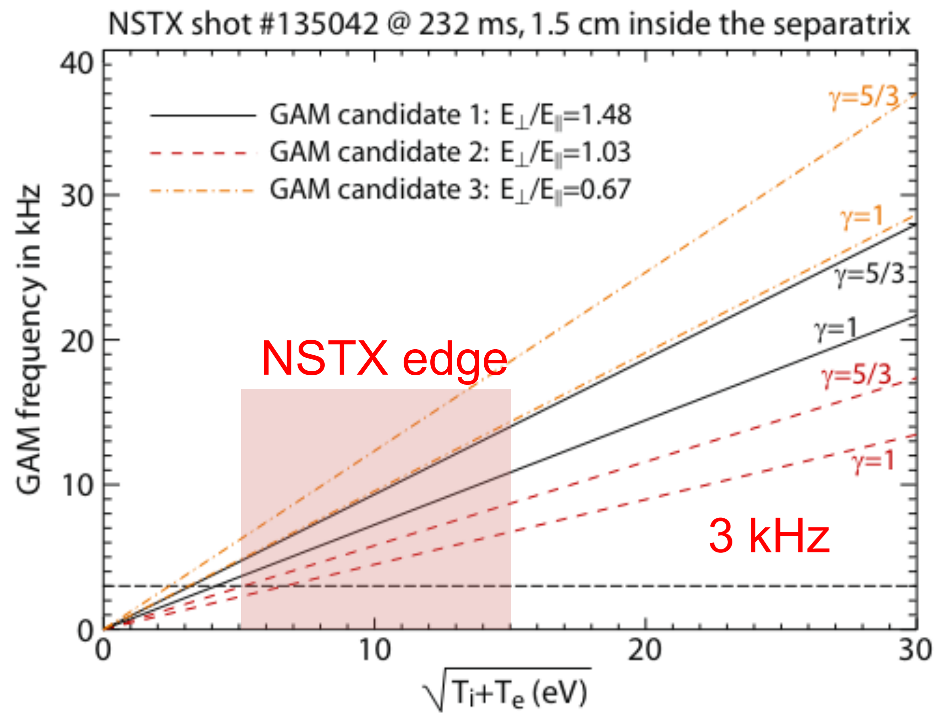
Geodesic Acoustic Mode (GAM) in NSTX

R. Hager, K. Hallatschek, IPP Garching

- GAM expected roughly at $f = G\,(1/\pi R)\,[\gamma(T_i+T_e)/m_i]^{1/2}$
- For NSTX case G (geometry factor) = 0.31, 0.49, 0.65

- linear simulations show GAMs at f ~ 4.6-12.3 kHz for $T_e \sim T_i \sim 50$ eV

- nonlinear simulations show low frequency GAM at f ~ 6.3 kHz

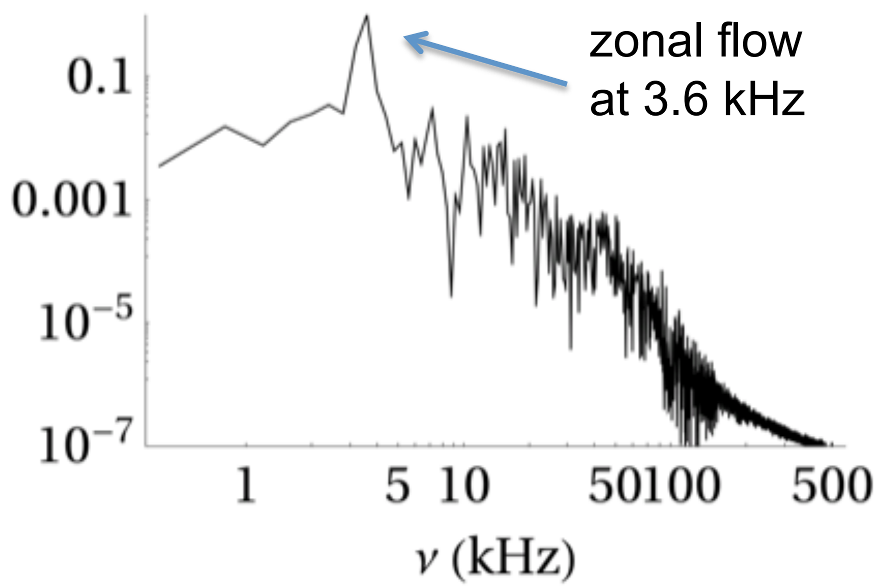


Hager and Hallatschek, PoP 2010

2-D Simulation of Edge Zonal Flow in NSTX

D.A. Russell, J.R. Myra, D. A. D'Ippolito - Lodestar

- SOLT code shows ~ 3-4 kHz edge zonal flows (*not GAMs*)
- Zonal flow frequency ~ profile relaxation ~ c_s/R ~ GAMs

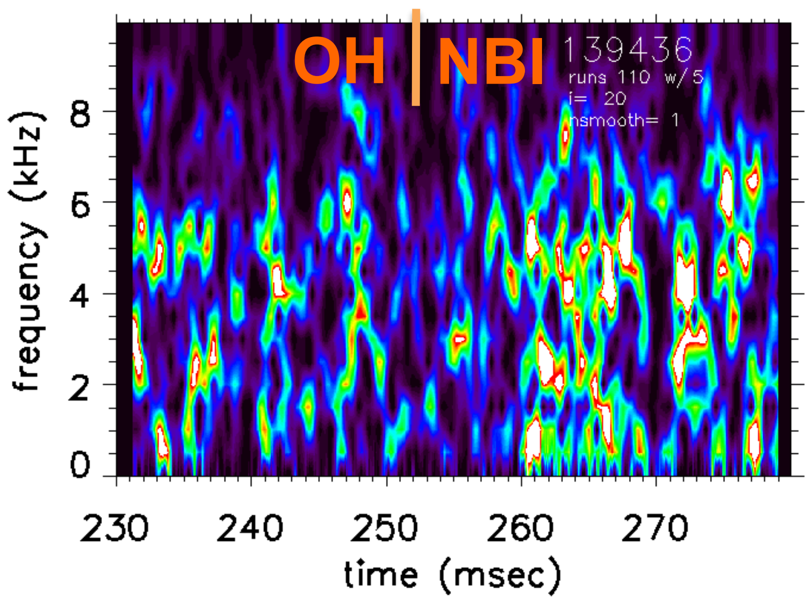


Russell, PoP 2009

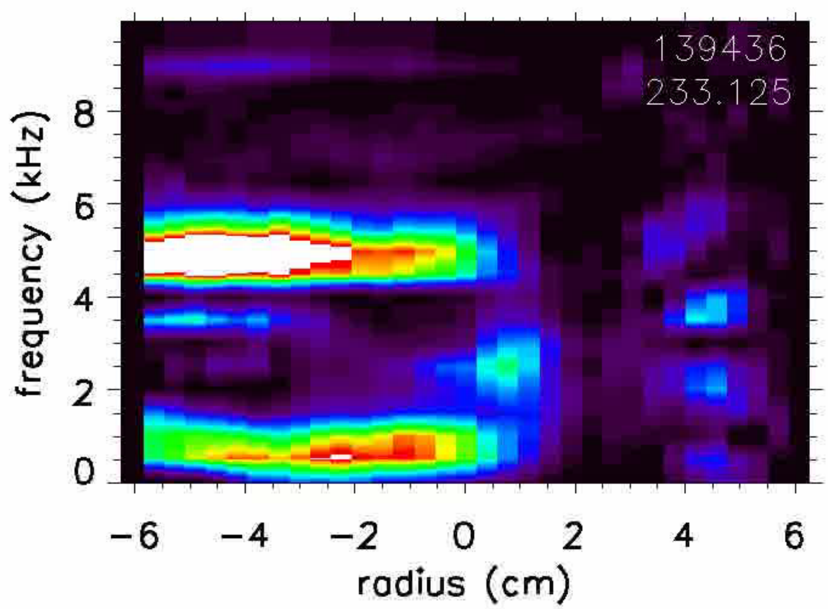
Complex Zonal Flow Spectrum

- Sometimes see broadband zonal flow with f ~ 1-6 kHz with ***intermittent zonal flow bursts*** of ~ 1-2 msec

V_{pol} spectrum at ρ = -3 cm

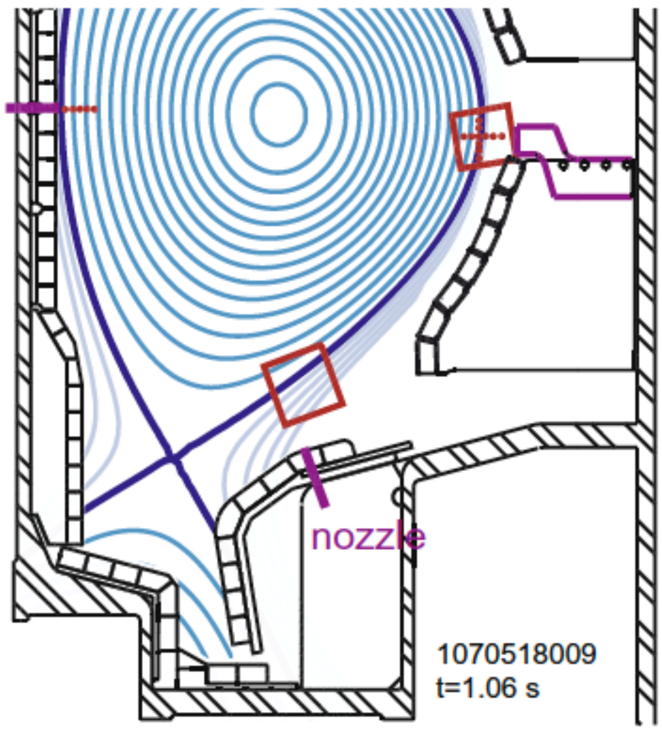


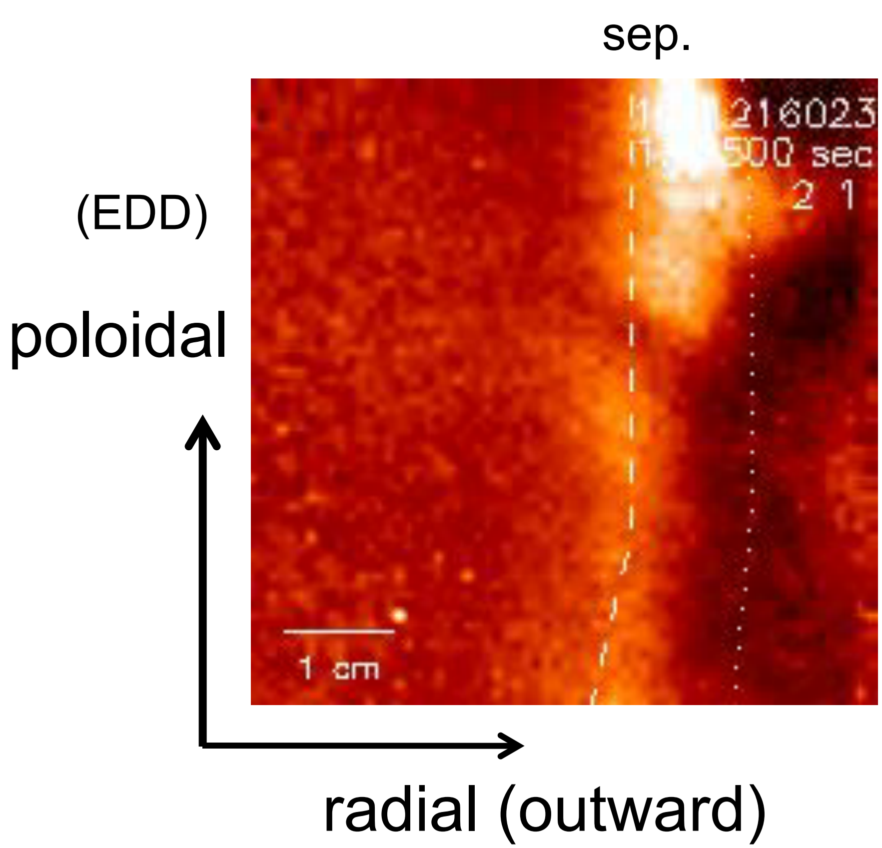
V_{pol} spectrum vs. ρ vs. time



Alcator C-Mod GPI Movie

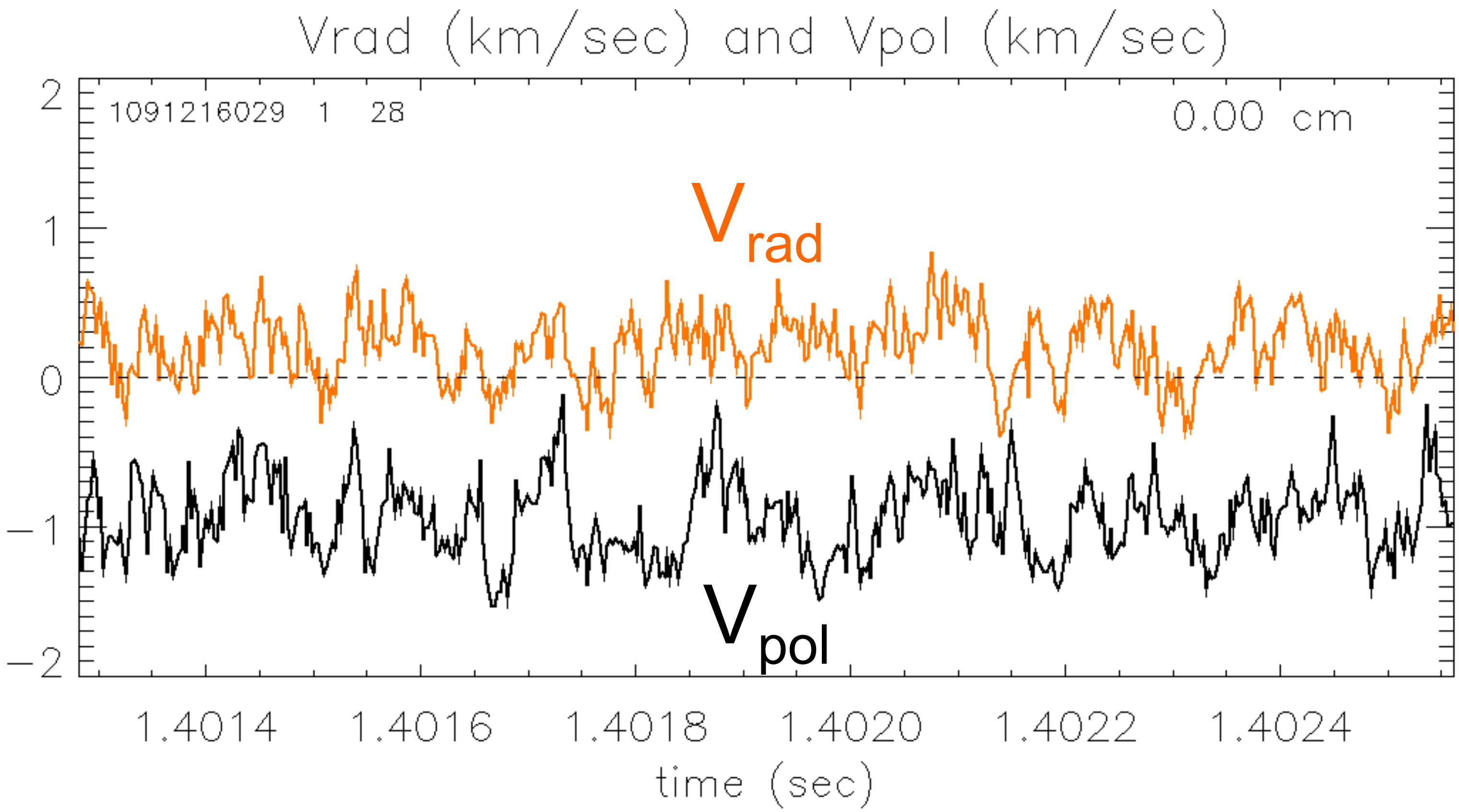
- This movie 400,000 frames/sec (normalized to average)
- Viewing area ~ 6 cm radially x 6 cm poloidally





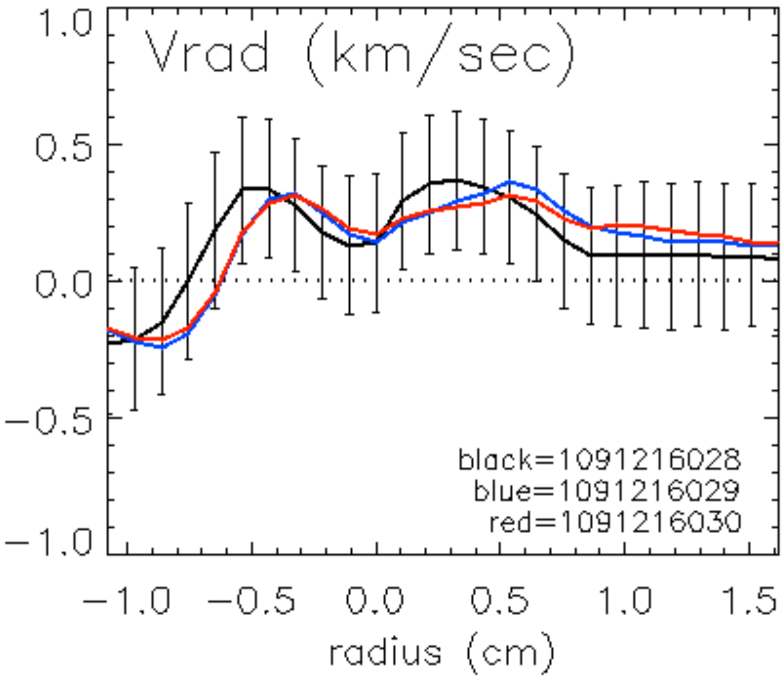
Typical Turbulence Velocities vs. Time

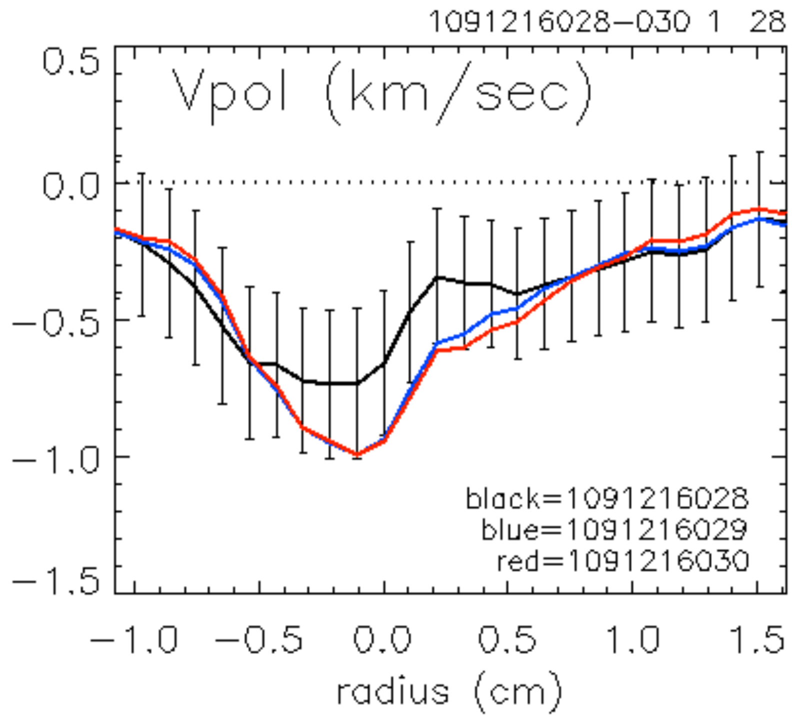
- V_{rad} (orange) and V_{pol} (black) @ ρ ~ 0 cm (poloidal average)



Radial Profiles of Velocities

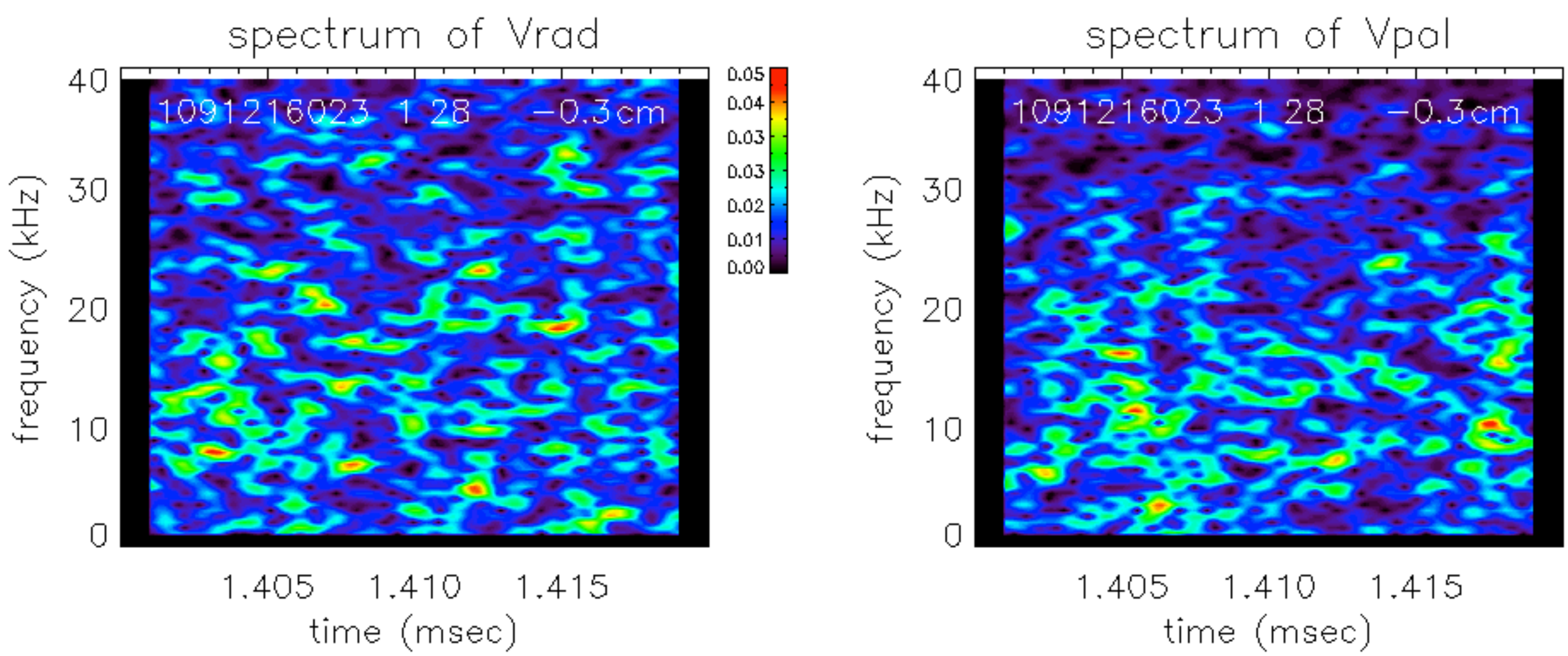
- Poloidal and radial velocity fluctuations ~ mean velocities





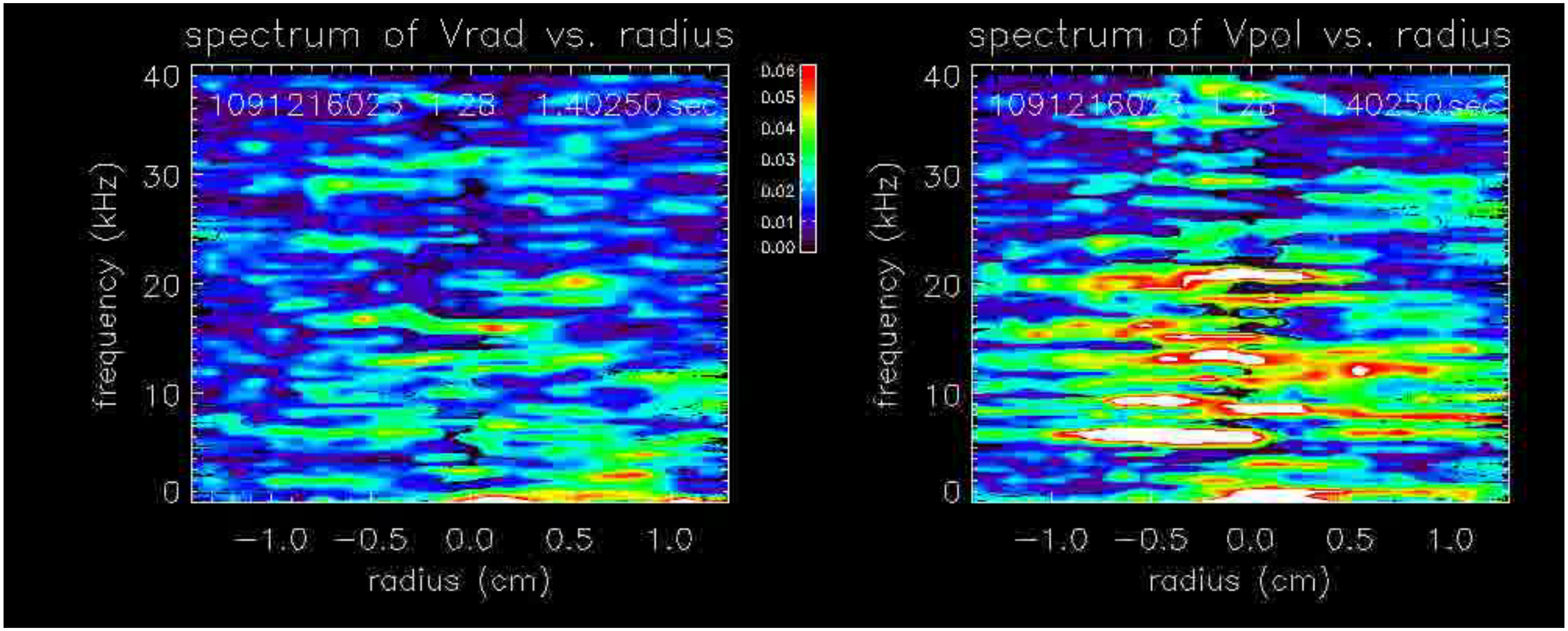
Time Dependence of Velocity Spectra

- No clear spectral features lasting more than ~ 1 msec
- Looks similar at other radii and for other similar shots



Radial Profile of Velocity Spectra

- Spectra of V_{pol} seems to have intermittent harmonic structure
- This structure seems localized within ± 1 cm of separatrix



Theoretical GAM Frequency for C-Mod

- GAM frequency $f = G\, c_s/(\pi R)$ with G=geometric factor,

  $R = R_o + r$, and $c_s = [\gamma(T_i + T_e)/m_i]^{1/2}$

where $G \sim (2^{-1/2})\, (2/(1+\kappa)\, (1+1/(2A^{2/3})\, (1+1/(4q^2))$

for C-Mod with $A=3$, $\kappa=1.6$, $q=3$, $T_e=T_i=50$ eV, $\gamma=4/3$ and $m_i=2$

→ $f_{GAM} \sim 20$ kHz

- These analytic values (from R. Hager) can still deviate a factor-of-two from experiment (Hallatschek PPCF 2007)

Summary of NSTX and C-Mod Results

- Coherent zonal flows detected with GPI in NSTX at ~ 3 kHz, which look similar to the GAMs seen in the edge plasma of other tokamaks
- Intermittent broadband flows apparently detected in Alcator C-Mod, and in other cases in NSTX, which have not yet been understood or identified

Still very much to learn !

Revised Predator – Prey Model