Experiments on Fully Developed Turbulence

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AST 559
Oct. 2011

- Why study fully developed turbulence ?
- Historical overview with examples
- Turbulence in tokamak plasmas
- Zonal flows in tokamak plasmas
- Magnetic turbulence experiments

Why Study Fully Developed Turbulence ?

a fluid or plasma has 'fully developed' turbulence when the (ω,k) spectra are broad, with few or no coherent modes

- This is the normal state of fluid motion for much around us (car at 60 mph => R ~ 10^7)

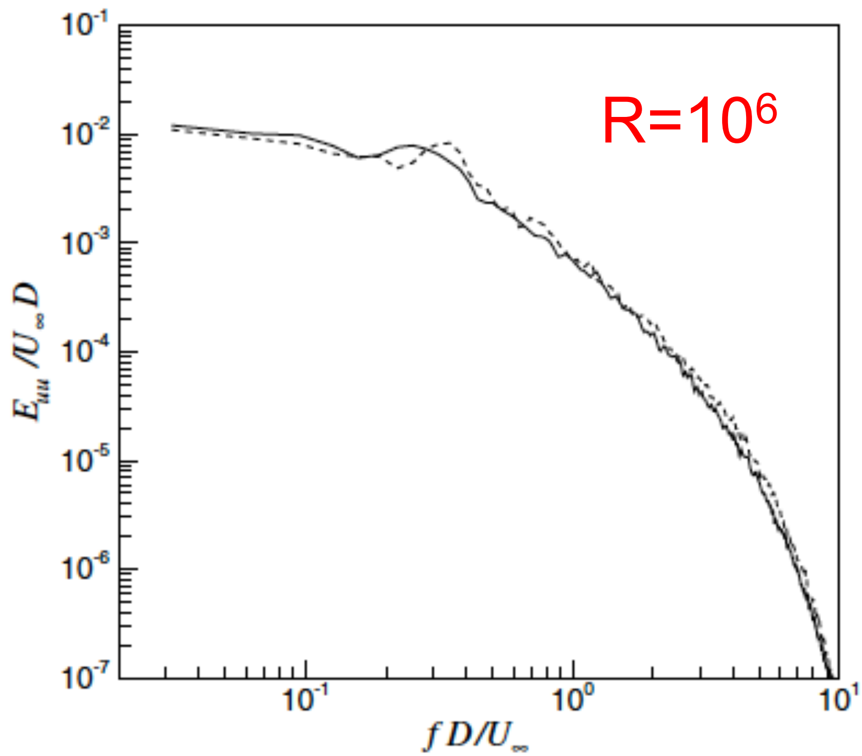
- This is the normal state of plasma in magnetic fusion devices and the probable cause of their heat and particle transport

- Plasma turbulence is common in other situations:
  - plasma torches, thrusters, arcs
  - solar atmosphere and solar wind
  - magnetosphere and ionosphere
  - interstellar fields and supernova

Simulation of Turbulent Flow Past a Cylinder

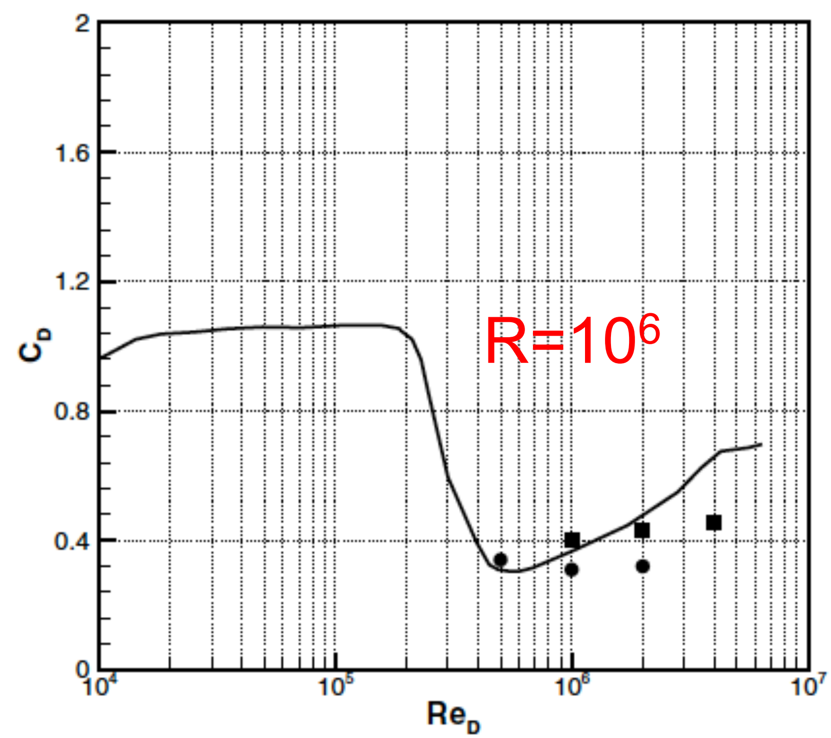
- Numerical simulation of with model boundary conditions do a pretty good job of predicting turbulent fluid flow

velocity vs. frequency



frequency

drag vs. Reynolds #



Catalano et al, Int'l J. Heat and Fluid Flow (2003) 463

Example of Fully Developed Fluid Turbulence

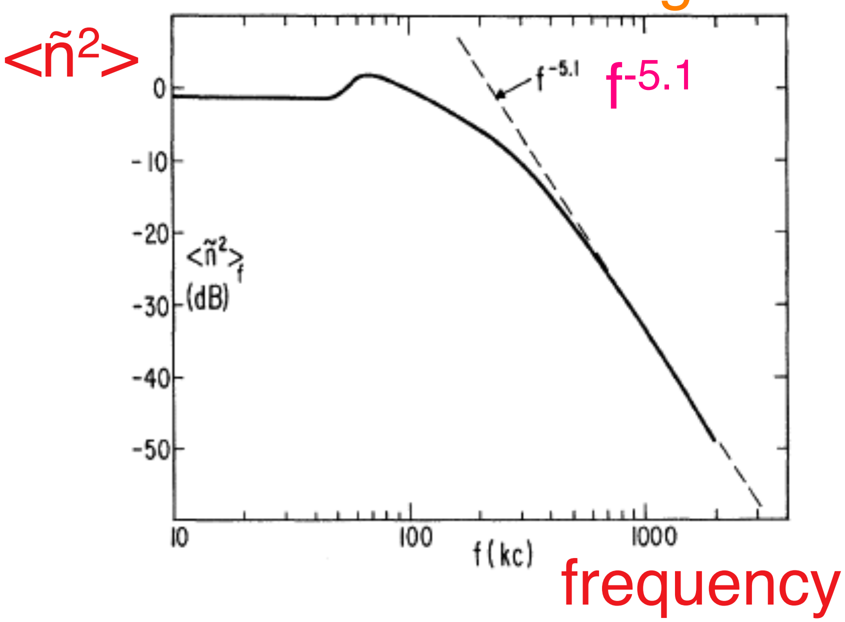
History of Fusion Plasma Turbulence

- Bohm and others saw “hash” in arc plasmas (1940’s)
- Early fusion experiments reported turbulence (1950’s)
- First nonlinear theories of plasma turbulence (1960’s)
- Initial comparisons of experiment and theory (1970’s)
- Many measurements of turbulence in tokamaks (1980’s)
- Development of simulations, e.g. gyrokinetics (1980’s)
- “Verification and Validation” of simulations (1990’s -)

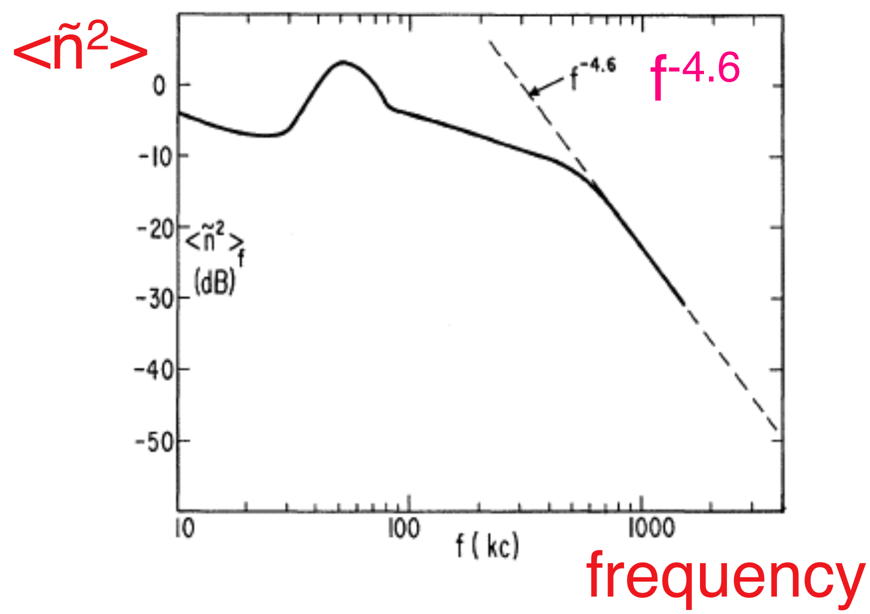
Spectrum of Low β Plasma Turbulence (1965)

- Similar broadband fluctuations in linear and toroidal plasmas
- Tried to explain apparent “universal” power law in spectrum by dimensional analysis (~ analogous to Kolmogorov)

Linear discharge



Etude stellarator

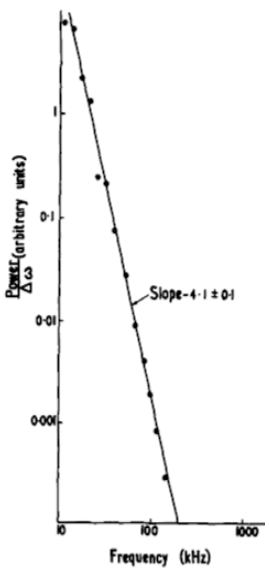


F.F. Chen, PRL 15 (1965) 381

Magnetic Turbulence in the Zeta RPF (1971)

- Broadband frequency spectrum of magnetic fluctuations ~ similar to that seen for density fluctuations by Chen
- Short spatial correlation lengths across B, long spatial correlation lengths along B => strongly anisotropic !

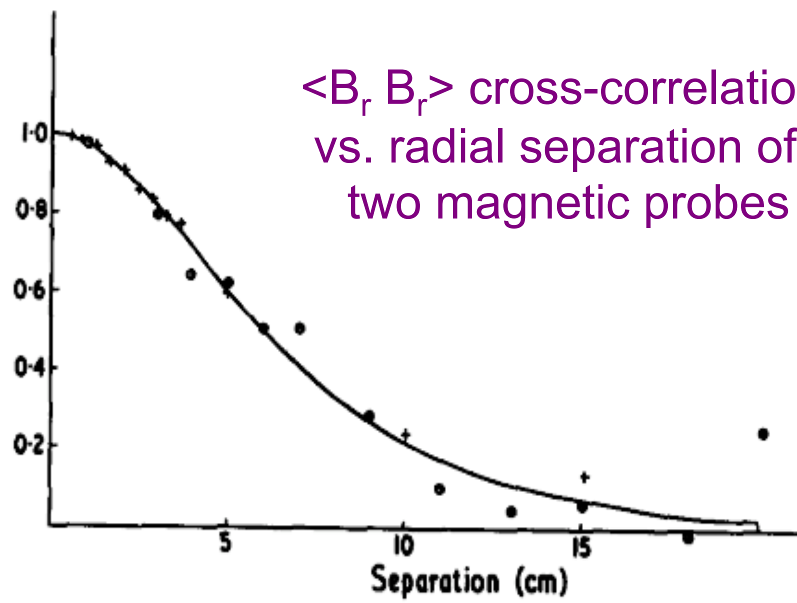
power



frequency

magnetic field spectrum

(slope ~ 4)



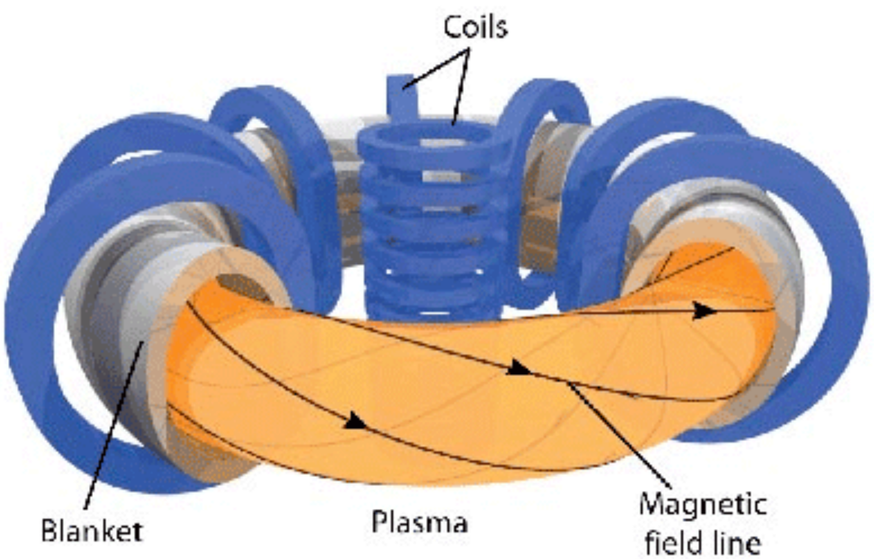
$\langle B_r B_r \rangle$ cross-correlation vs. radial separation of two magnetic probes

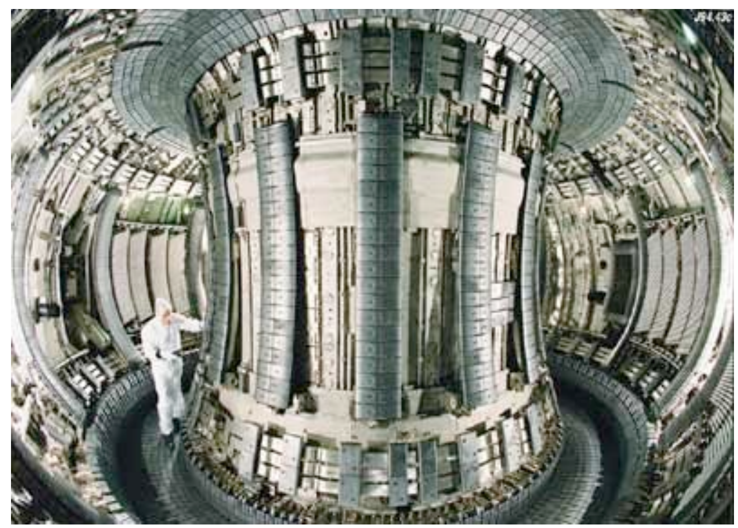
Robinson and Rusbridge Phys. Fluids 14 (1971) 2499

Tokamaks

- Russian acronym for “toroidal magnetic chamber”
- Plasma confined by 3-D helical magnetic field
- Plasmas now close to fusion reactor conditions

  (T ~ 10 keV, n ~ 10^{14} cm^{-3}, τ = 1 sec)

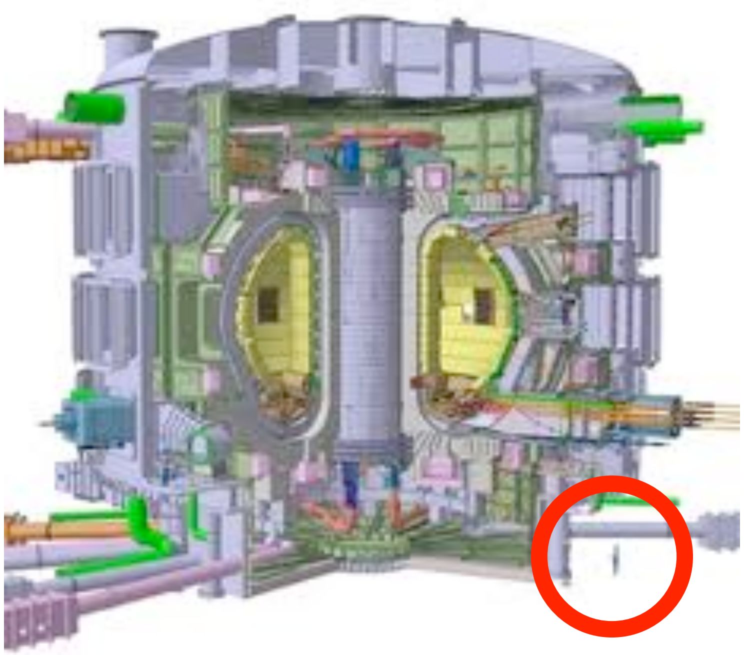


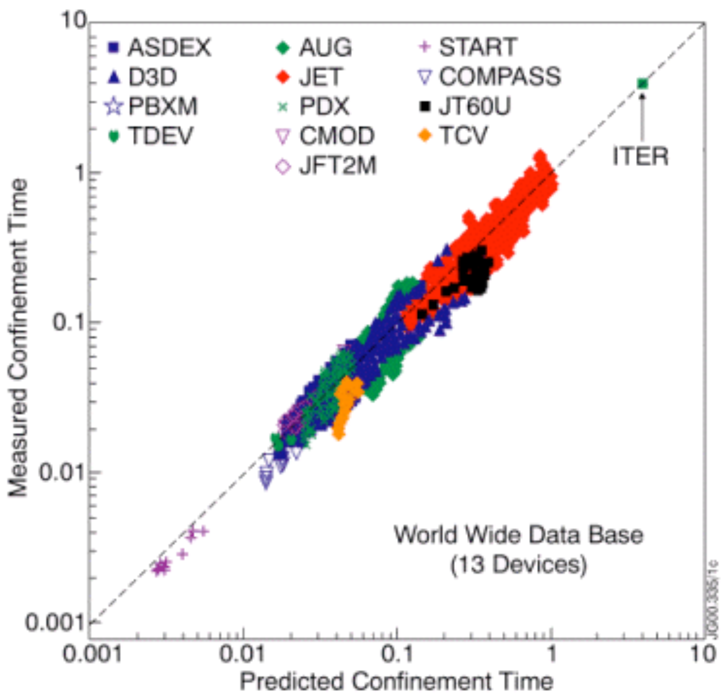


Turbulence in Tokamak Plasmas

- Main motivation is to understand turbulent transport, which dominates energy loss in present tokamaks

- Prediction of energy loss in ITER was done with empirical scaling using global engineering parameters (B, I, P...)





Relation Between Turbulence and Transport

- Cross-B-field transport results from the *correlations* of plasma parameter fluctuations with the radial velocity fluctuations

- Flux driven by electrostatic instabilities with $\delta v_r = \delta E_{pol} \times B/B^2$

  particle flux: $\Gamma = \langle \delta n \, \delta v_r \rangle$

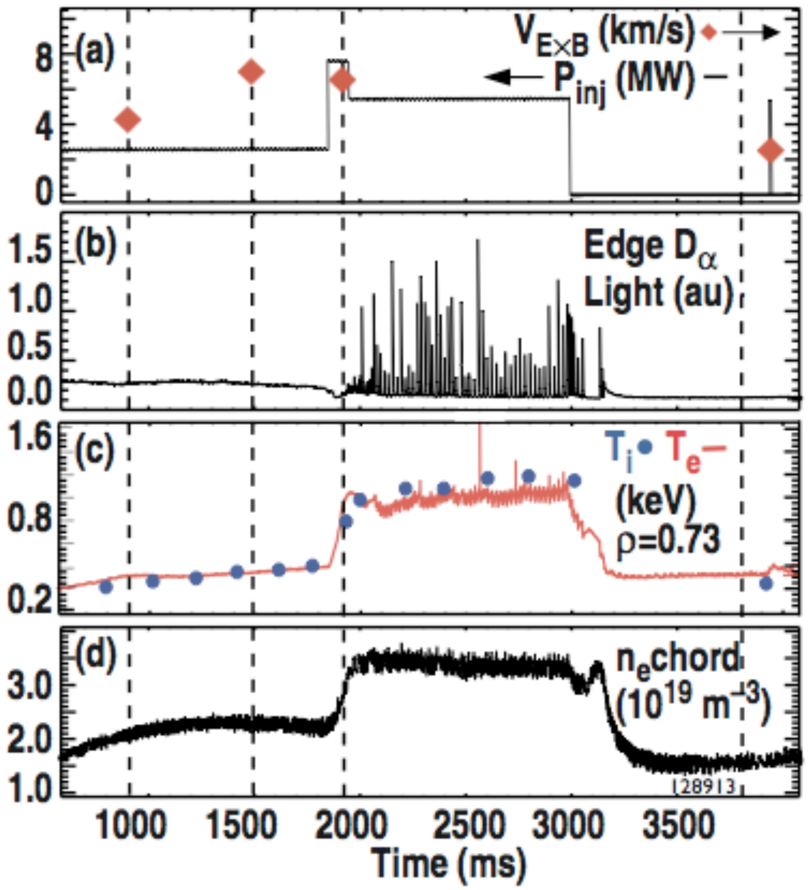
  heat flux: $Q = 3/2 \, nT_e \, [\langle \delta v_r \, \delta T_e/T_e \rangle + \langle \delta v_r \, \delta n/n \rangle]$

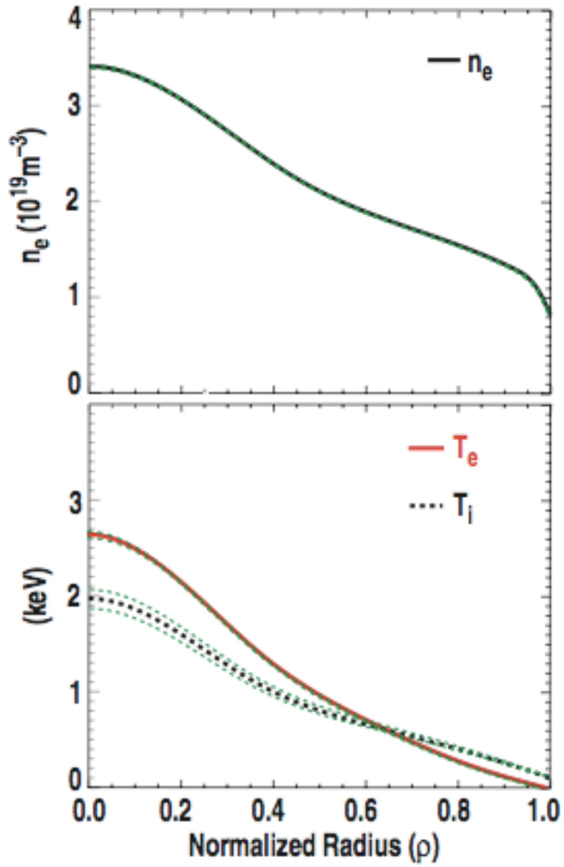
- Additional heat transport can be due to magnetic fluctuations, especially at high temperature due to $\delta v_r = v_{||}(\delta B_r/B)$

  => Should measure δn, δE_{pol}, δT_e, δB_r and all the phases between them at all frequencies and locations !?

Turbulence Experiments on the DIII-D Tokamak

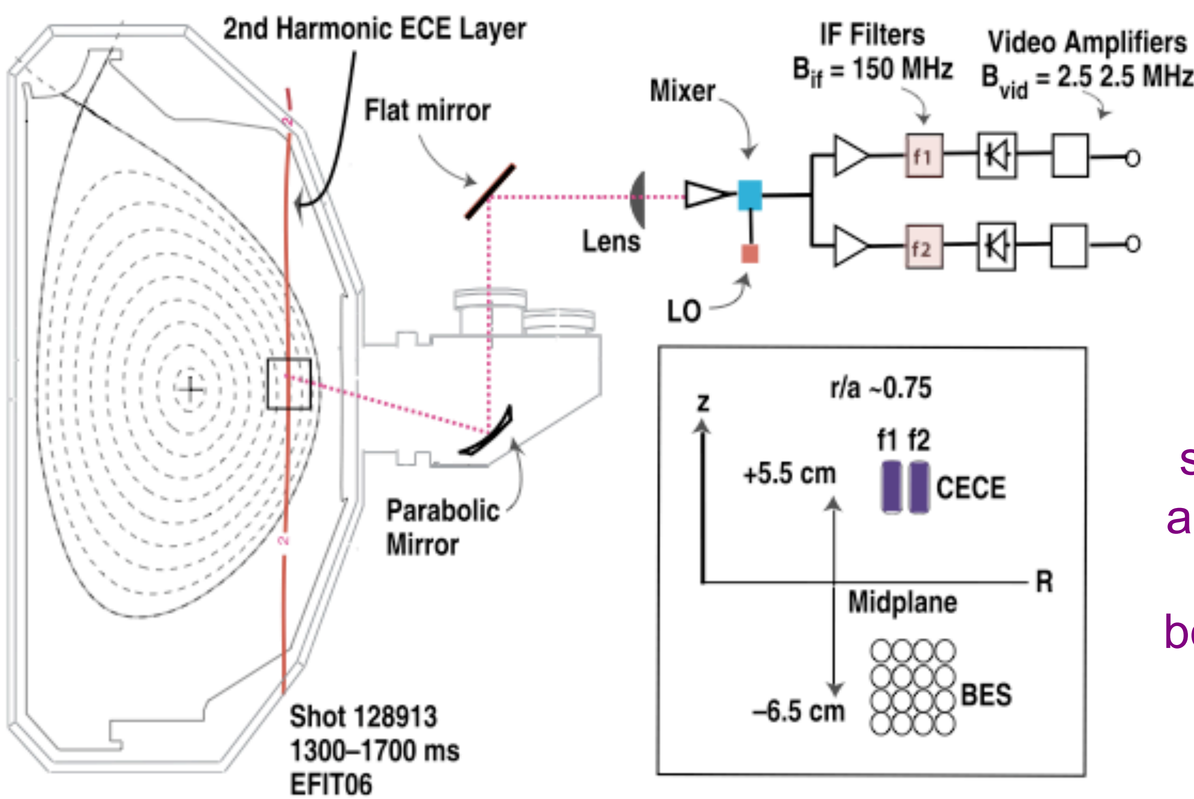
- Plasma parameters $n(0) \sim 3\text{x}10^{13}$ cm^{-3}, $T_e(0) \sim T_i(0) \sim 2$ keV
- Core plasmas way too hot to use Langmuir probes





Core Fluctuation Diagnostics in DIII-D

- Measure δn using Beam Emission Spectroscopy (BES)
- Measure δT_e using electron cyclotron emission (CECE)

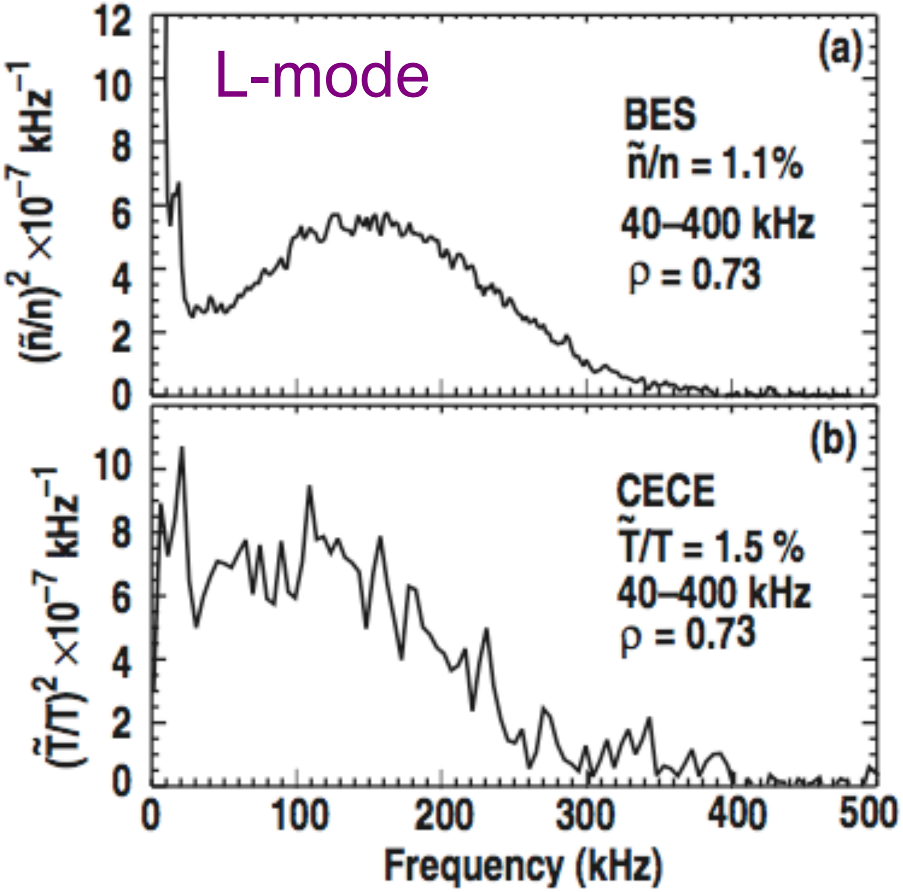


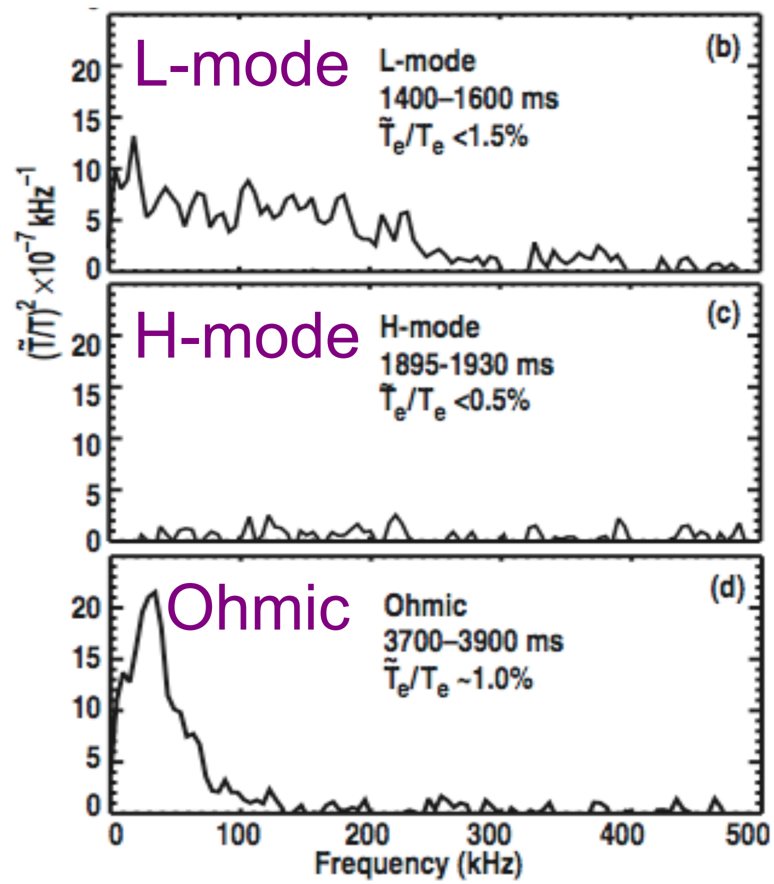
spatial location and k-resolution are similar for both diagnostics

White et al, Phys. Plasmas 15 (2008) 056116

Temperature and Density Fluctuation Spectra

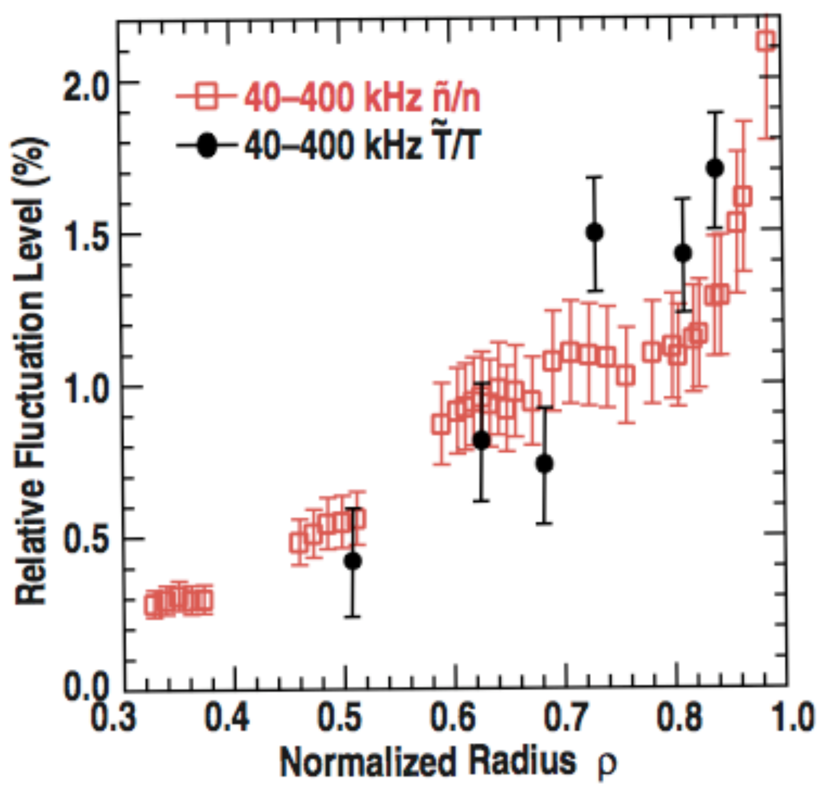
- Similar δT_e and δn spectral shape at same place and time
- But spectral width can change with toroidal rotation speed





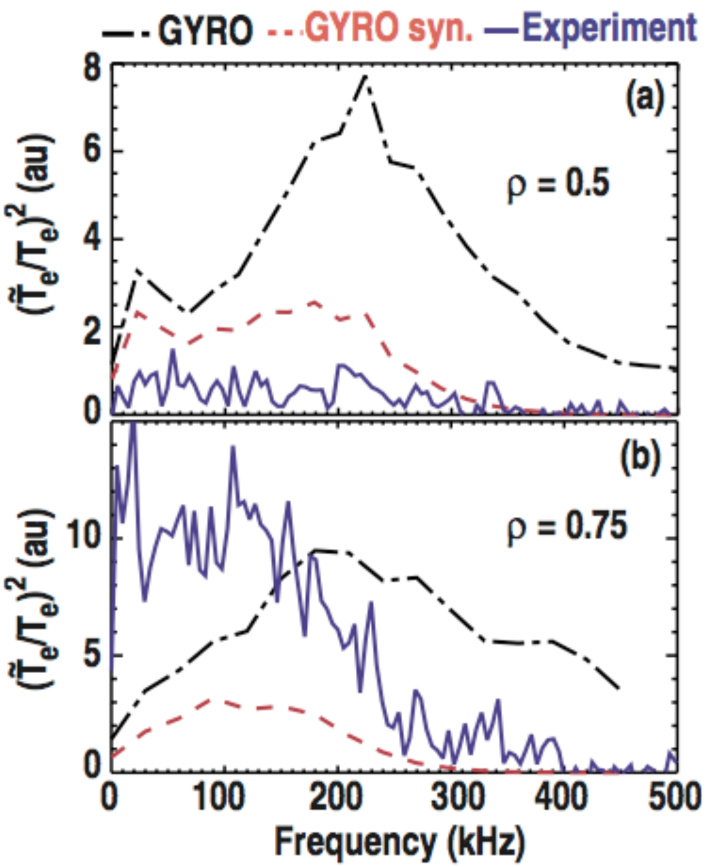
Turbulence Levels Vary Strongly with Radius

- Fluctuation levels of δT_e and δn both ~ 1% in core plasma
- Fluctuation levels go down toward center (smaller ∇p ?)



Comparison of Turbulence with Simulations

- Gyrokinetic turbulence code GYRO run for this experiment
- Instrumental resolutions included with "synthetic diagnostic"



"reasonable agreement with the experimental spectral shapes"

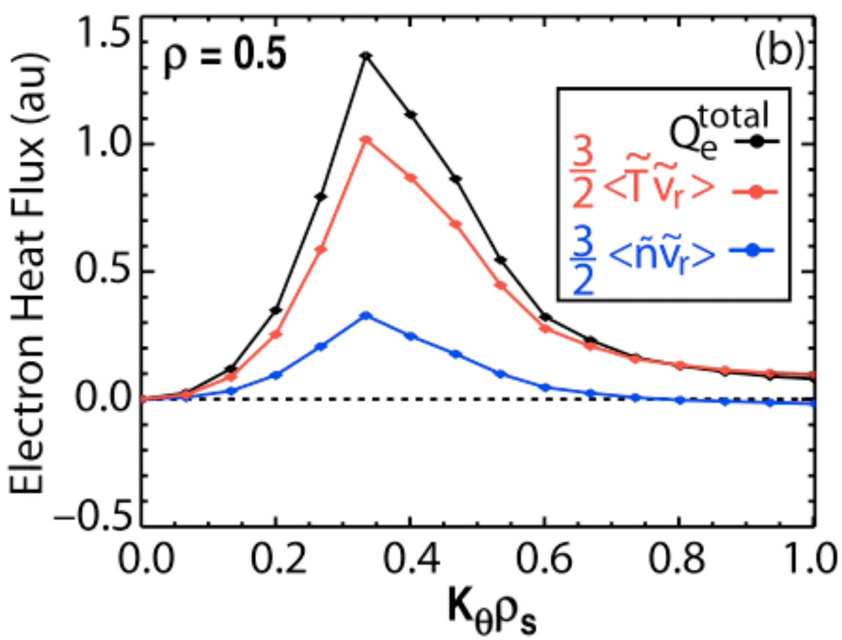
code: $\delta n/n$ = 0.50% @ r/a =0.5
data: $\delta n/n$ = 0.55% @ r/a =0.5

code: $\delta T_e/T_e$ = 0.7%@ r/a =0.5
data: $\delta T_e/T_e$ = 0.4% @ r/a =0.5

=> *at least partial consistency*

Turbulence Calculation of Electron Heat Flux

- Electron heat flux can not be directly measured since the radial velocities and phases were not measured here
- Code can calculate heat electron heat flux, and finds it to be in "fairly good" (~x2) agreement with measured flux



largest heat flux from δT_e at $k_\theta\rho_s$ ~ 0.3

even ~ 1% fluctuations can cause transport close to that observed

Summary of DIII-D Turbulence Results

- Turbulence in tokamak core plasmas is broadband in frequency but relatively small in magnitude (~1%)

- State-of-the-art computational simulations can explain the core electron heat flux to within ~ factor of 2

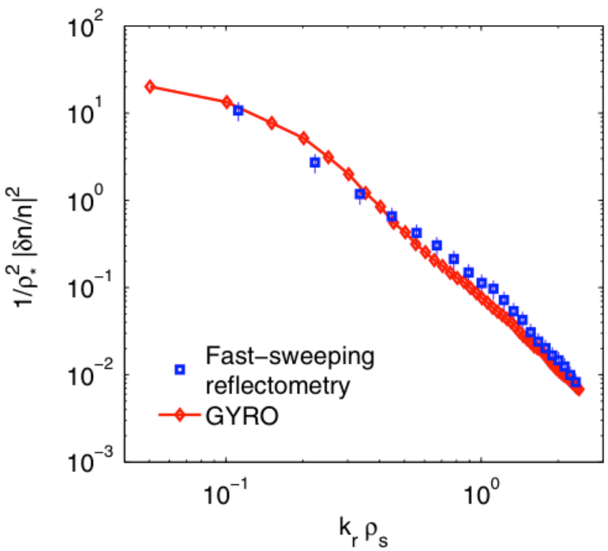
note:

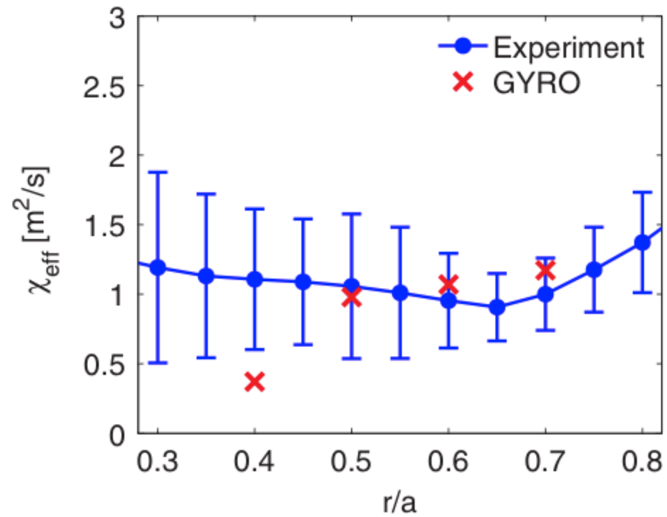
- only a few discharges analyzed (very expensive)
- measurements only along outboard midplane
- velocity fluctuations not directly measured
- no scaling with dimensionless parameters
- no predictions for future devices like ITER

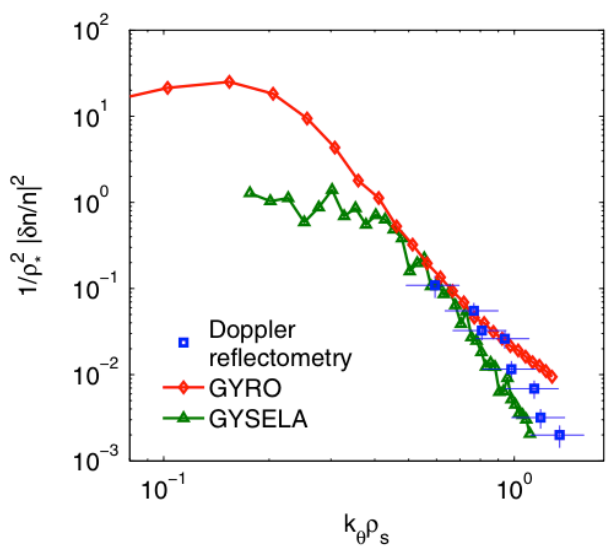
=> *partial success in understanding turbulent transport*

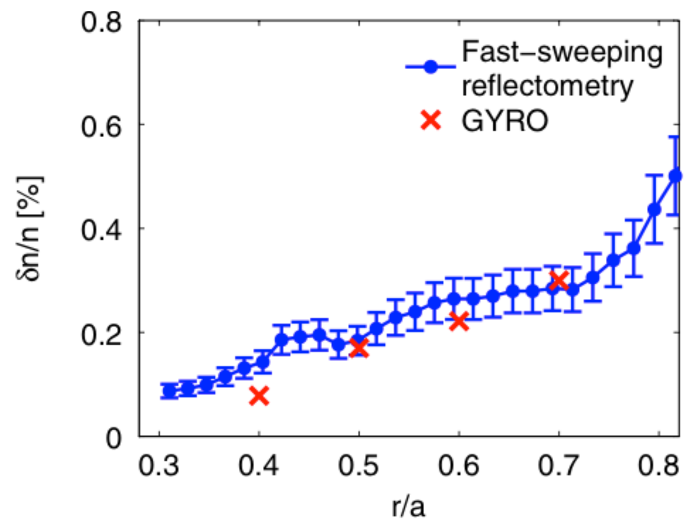
Confirmation of DIII-D Results in Tore-Supra

- measurements of δn made using microwave reflectometry





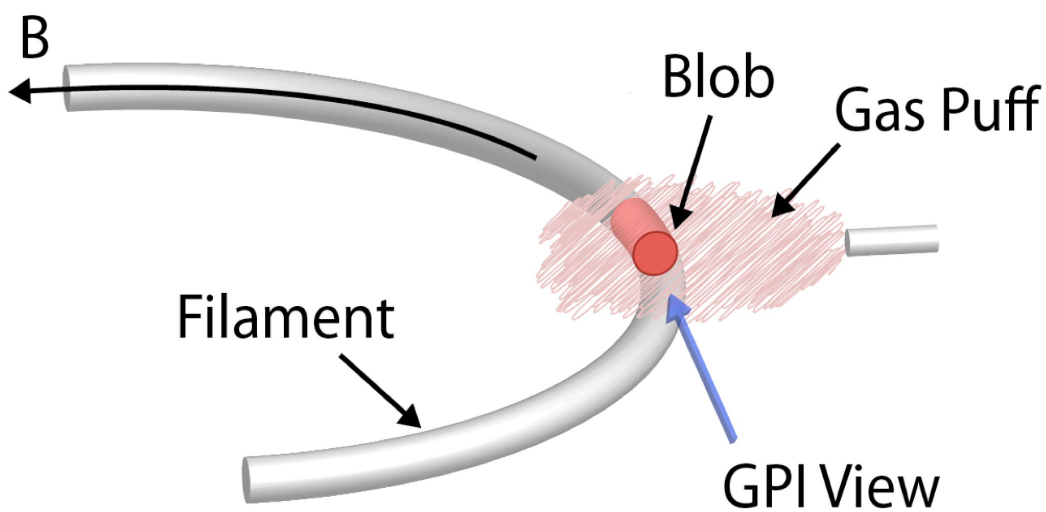


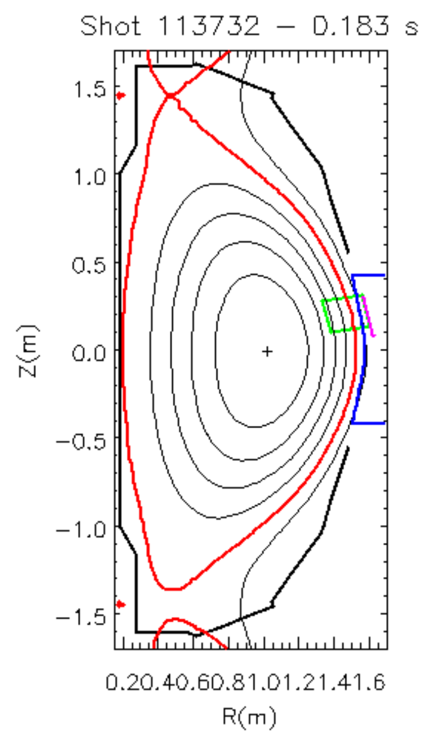


A. Casati et al, PRL 102 (2009) 165005

Edge Turbulence Measurements in NSTX

- High speed cameras make images of edge turbulence
- 3-D 'filaments' localized to 2-D by gas puff imaging (GPI)



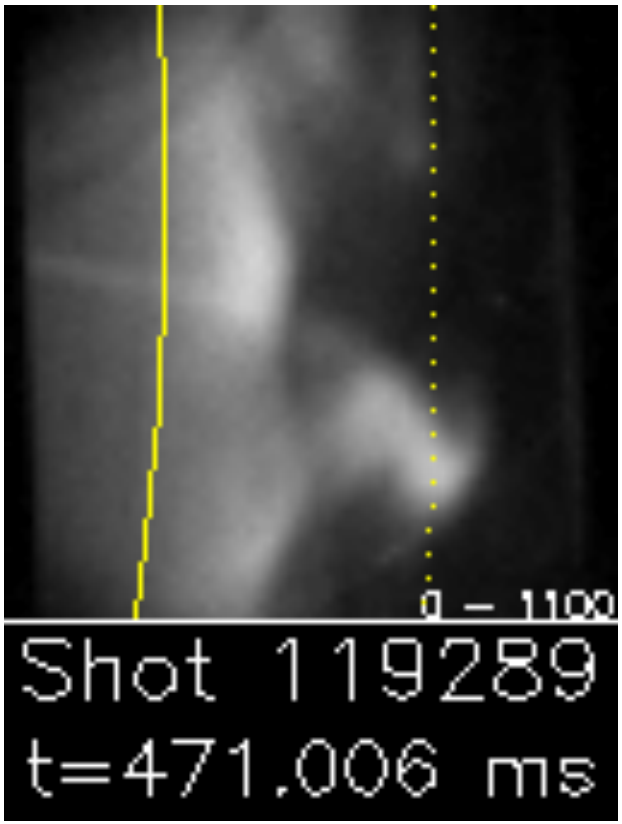


Zweben et al, Nuclear Fusion 44 (2004), R. Maqueda et al, Nucl. Fusion 50 (2010)

Movies of Edge Turbulence in NSTX

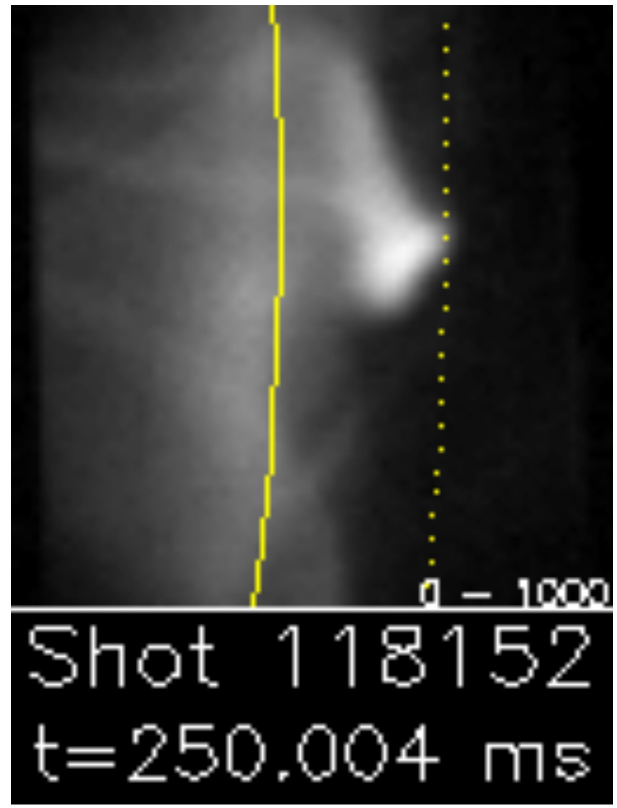
L-mode (~ 2 MW)

separatrix limiter



H-mode (~ 7 MW)

separatrix limiter

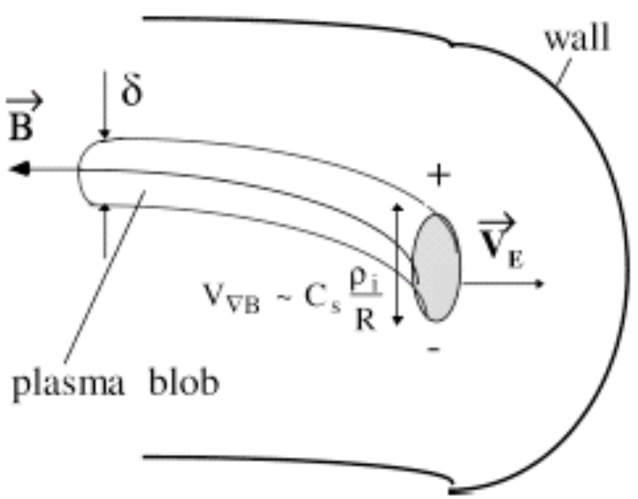


R. Maqueda, PPPL

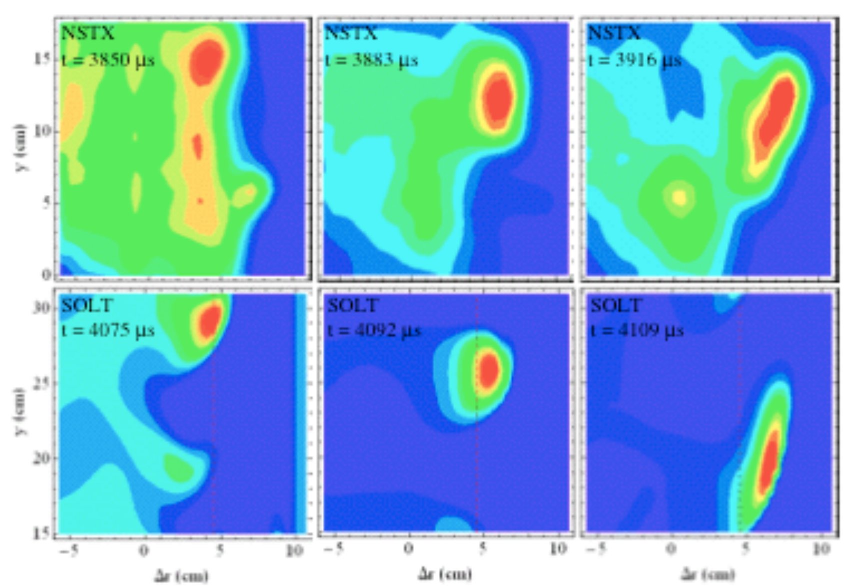
Coherent Structures a.k.a. "Blobs"

- Small 'blobs' of plasma seem to break off and fly out
- Some understanding can come from simplified models

simple 'blob' model (Krash. 2001)

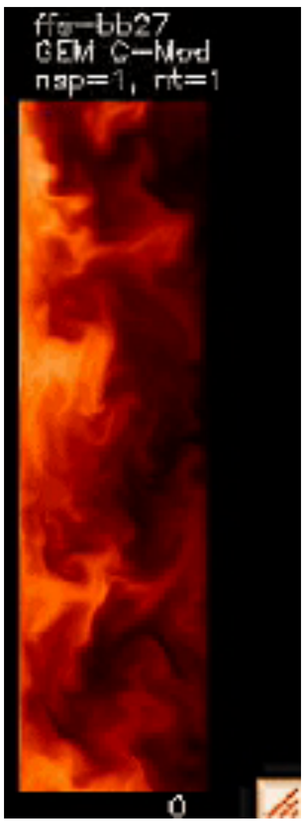


2D turbulence model (D'Ippolito 2008)

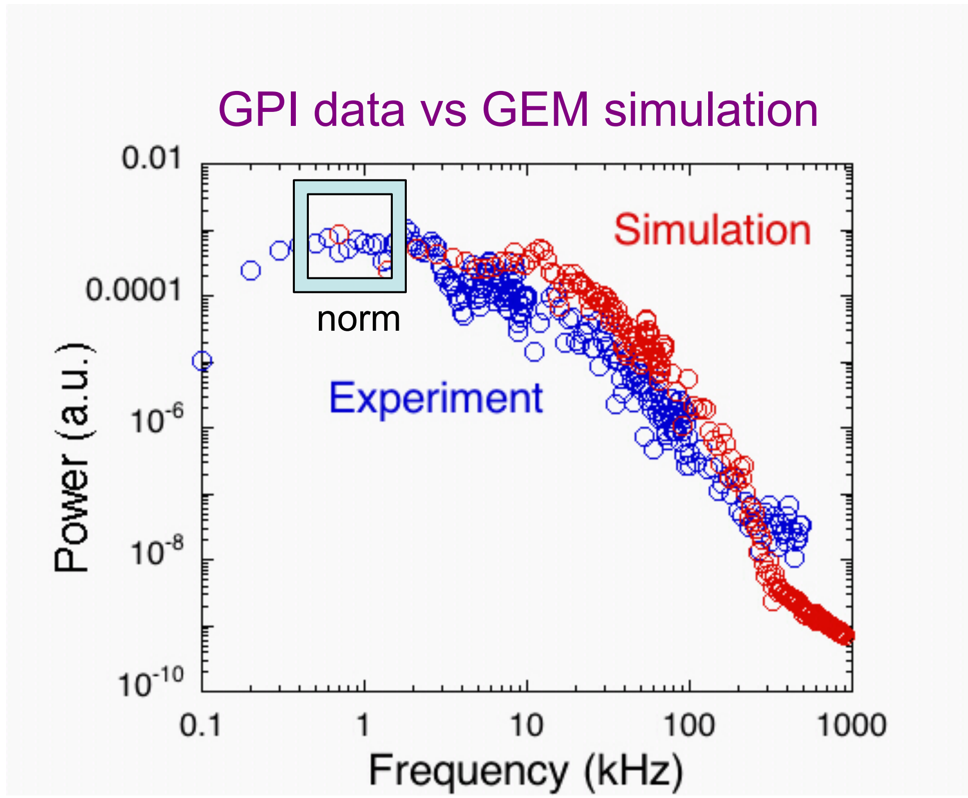


Edge Turbulence vs. Edge Simulation

- Complex 3-D plasma codes can compute edge turbulence
- Efforts underway to compare them with experimental data



GEM simulation of C-Mod tokamak edge turbulence (Scott)

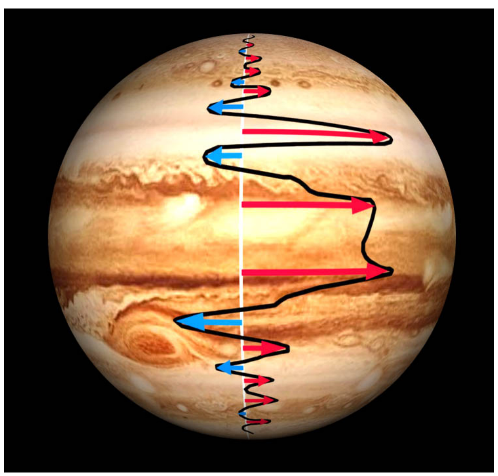


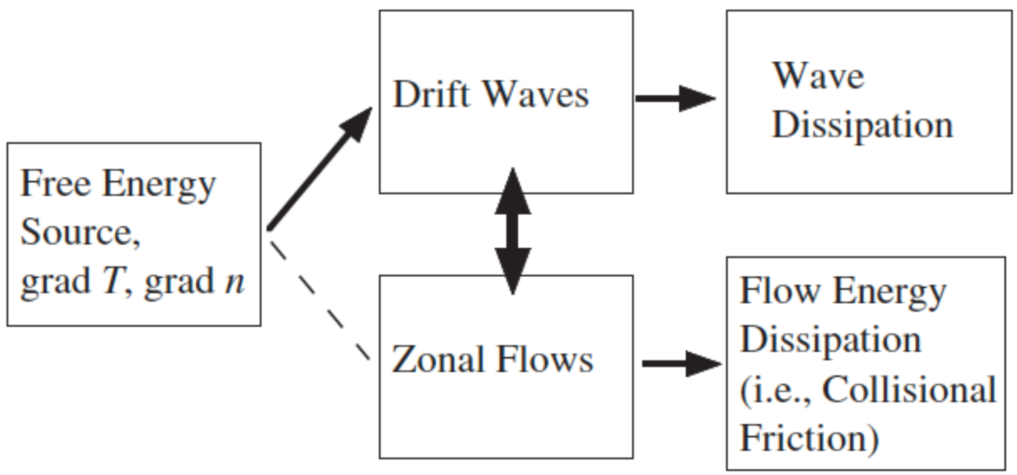
S. Zweben, B.D. Scott et al, POP 2009

Zonal Flows in Magnetized Plasmas

- Zonal flows in magnetized plasmas are fluid flows perp. to B and ∇n, supposedly like Jupiter's atmospheric bands

- Zonal flows can reduce energy in drift wave turbulence, and so reduce turbulent radial transport (in theory)

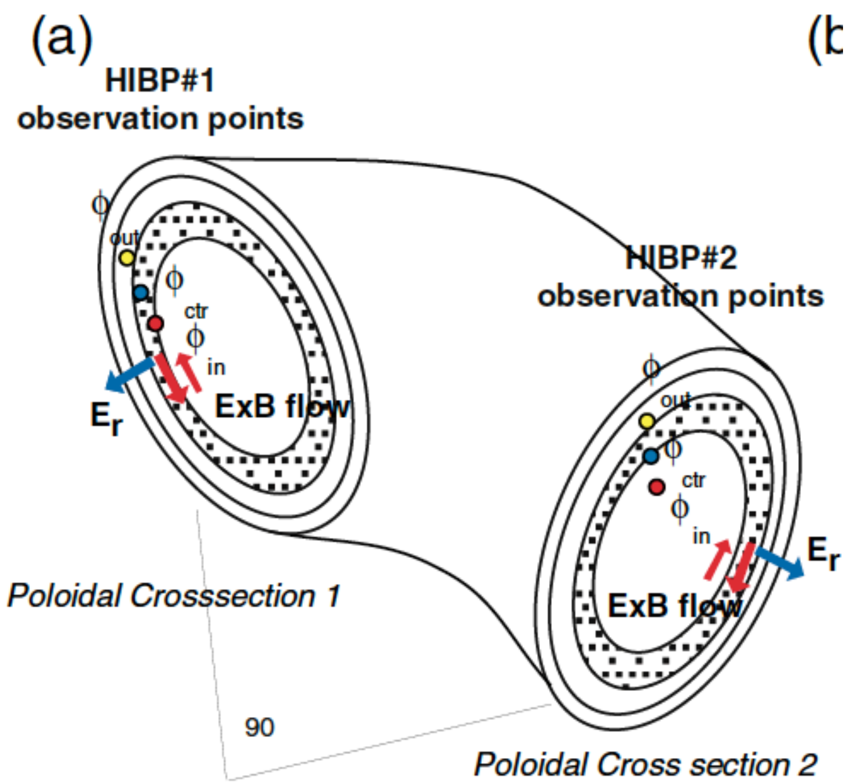


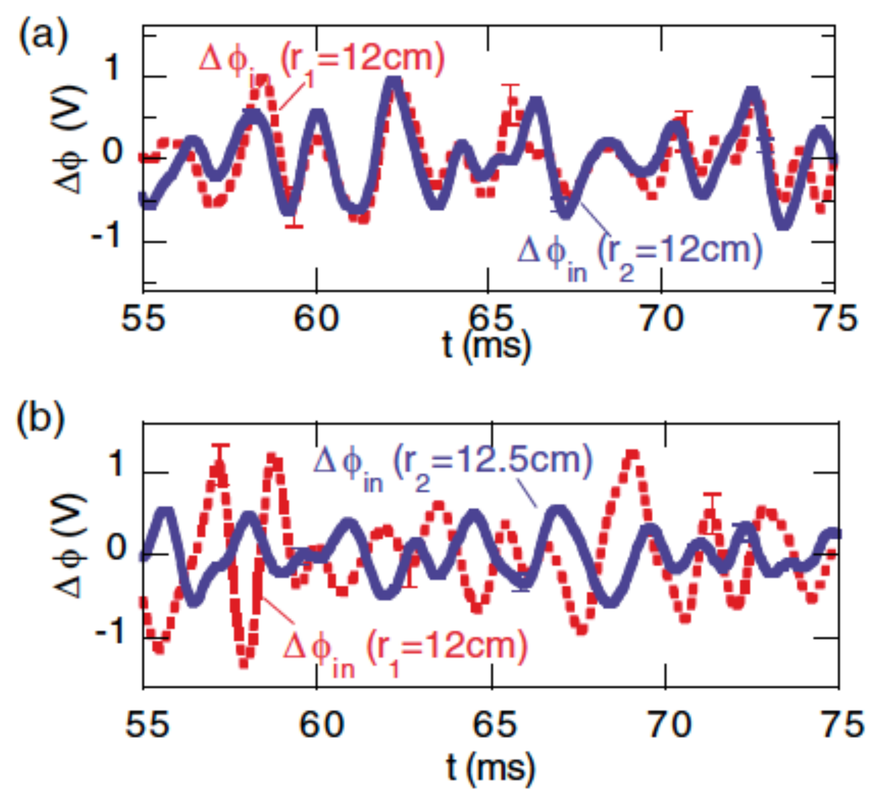


Diamond et al, PPCF '05 Fujisawa NF '09

Zonal Flows Data from Heavy Ion Beam Probe

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

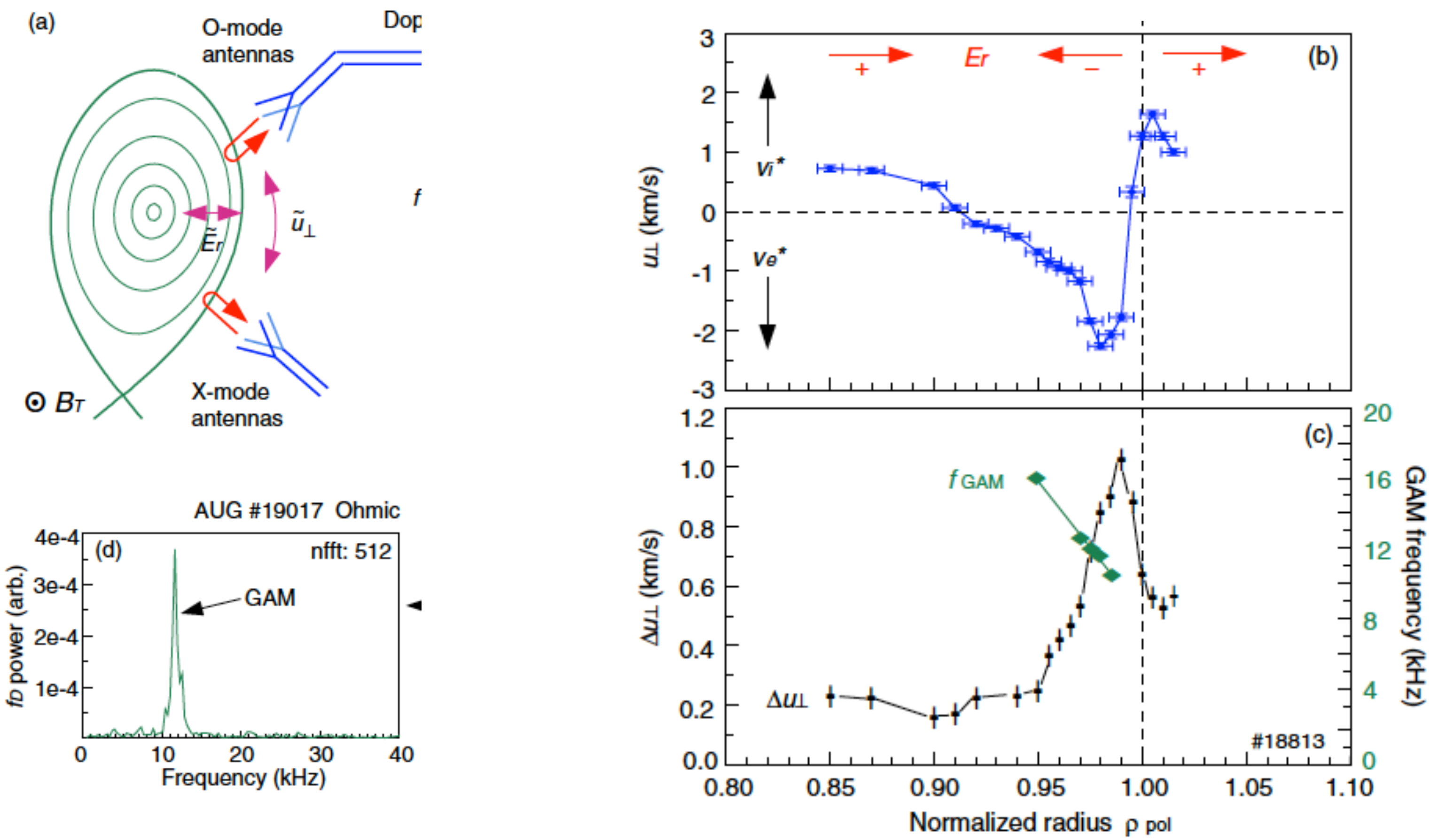




Fujisawa PRL 2004

Zonal Flow Data from Doppler Reflectometry

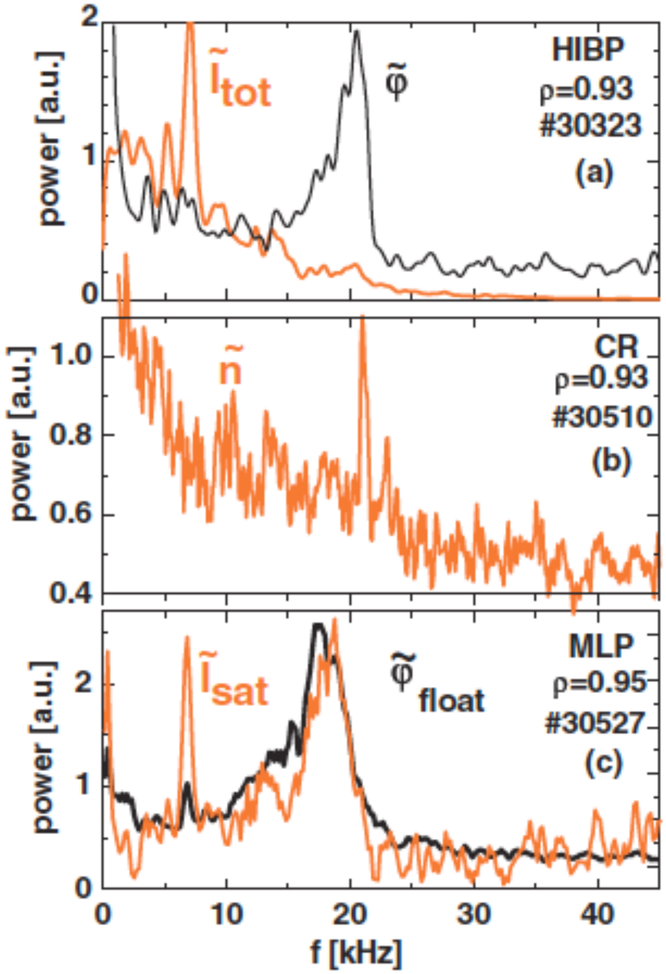
Coherent modulation of turbulence frequency near edge identified as geodesic acoustic mode (GAM)



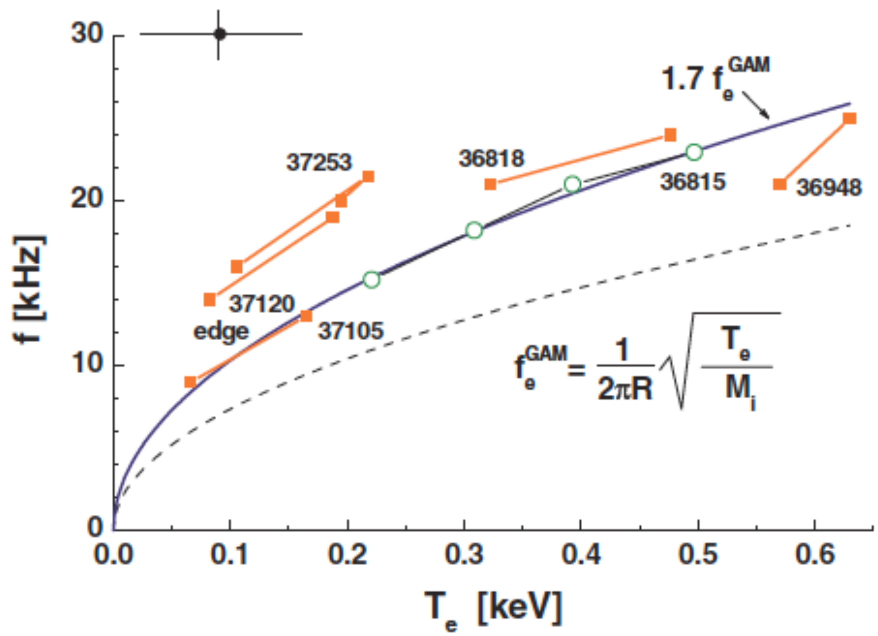
Conway PPCF '05

Zonal Flows Data from Three Diagnostics

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



comparison with simple GAM theory



$$f_e^{GAM} = \frac{1}{2\pi R}\sqrt{\frac{T_e}{M_i}}$$

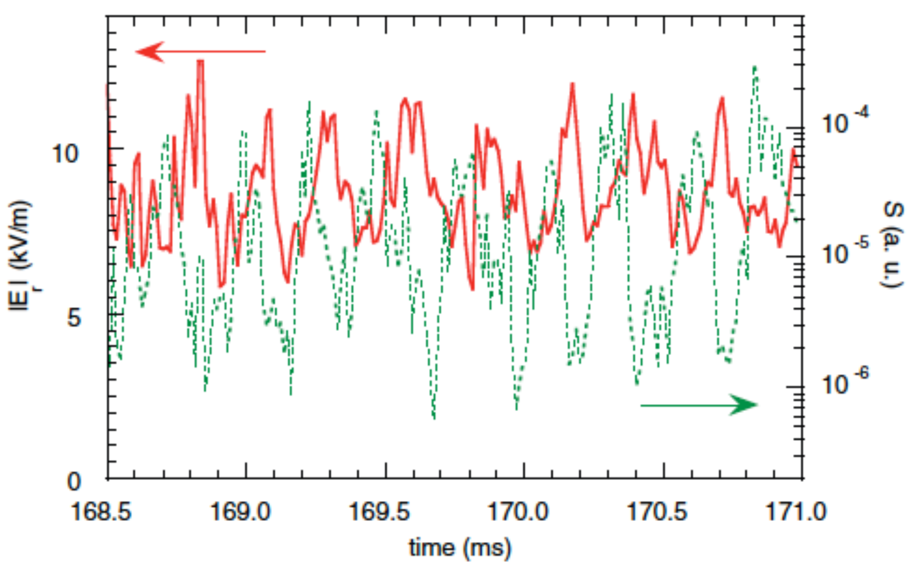
Melnikov et al, PPCF 2006

Zonal Flows and L-H Transition in Tokamaks

- Cyclic modulation of turbulence and edge zonal flows observed before L-H transition with reflectometry

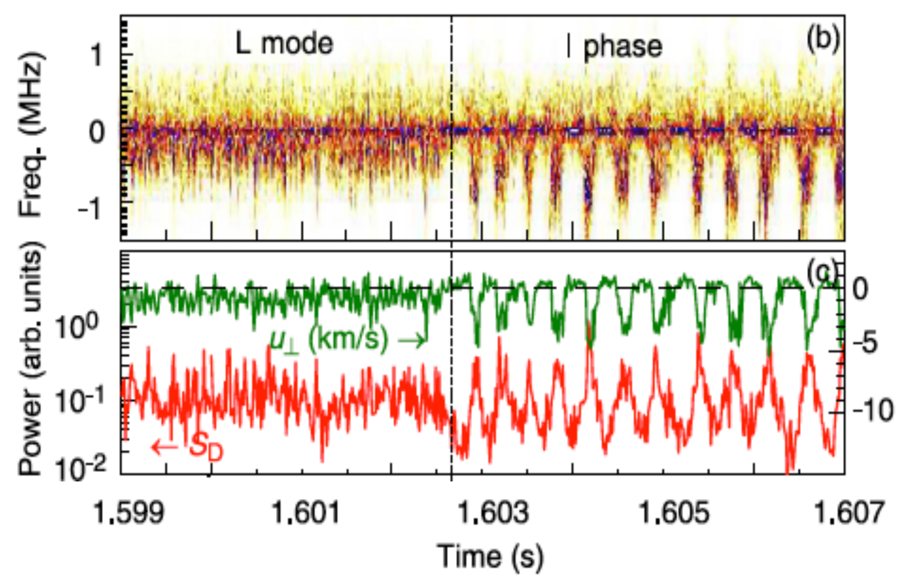
- Perhaps can be understood as "predator-prey' system, with mean and zonal flows as predators of turbulence

TJ-II



Estrada et al, EPL 2010

AUG



Conway et al, PRL 2011

Magnetic Turbulence Experiments

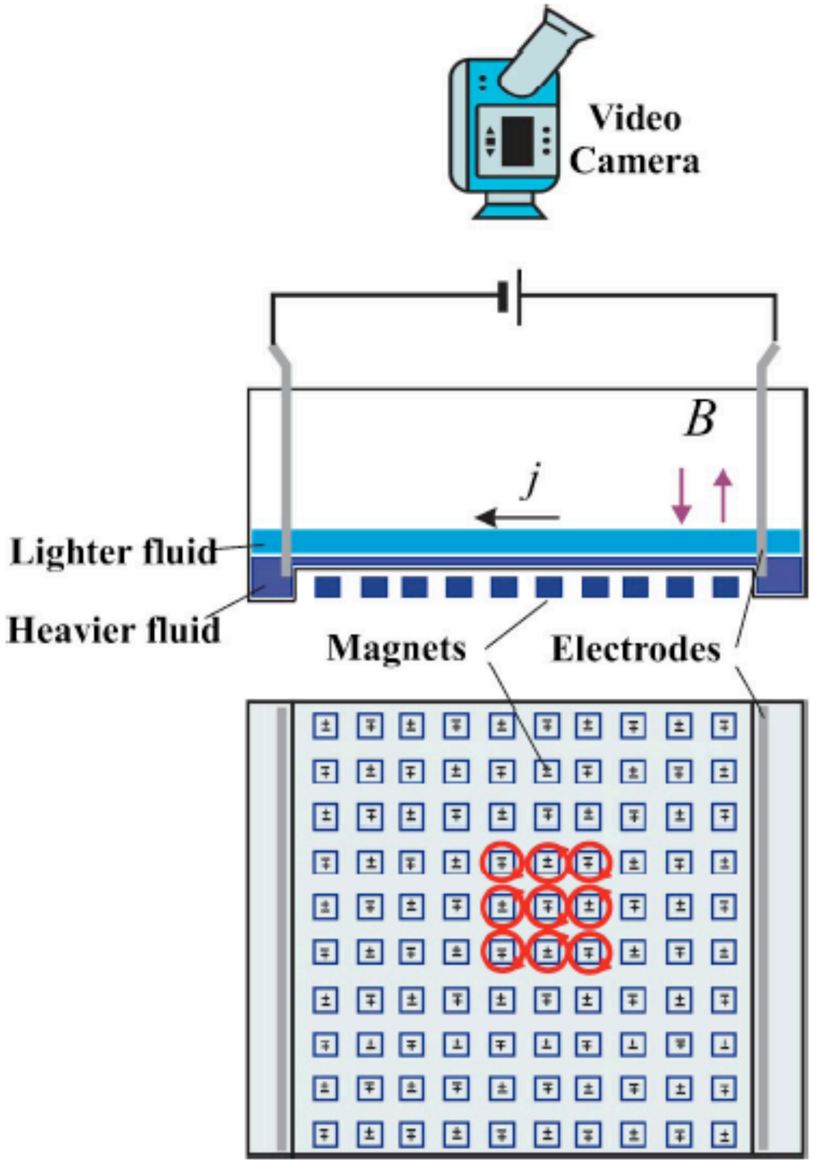
- Previously discussed plasma turbulence experiments involved "electrostatic" turbulence and measured plasma density, potential and temperature fluctuations

- Other interesting experiments involve fluctuations mainly in magnetic field, current and pressure ($\nabla p = j x B$), i.e. in the MHD (magnetohydrodynamic) fluid limit

- Experiments on MHD most easily done using conducting fluids and have applications to technology

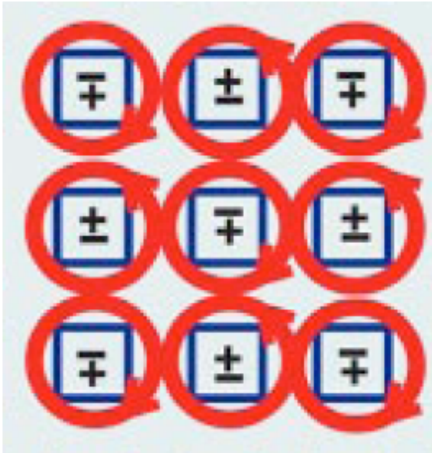
- Magnetic field fluctuations in plasmas can also be important at high β when fluctuations in the pressure can bend the magnetic field lines (e.g. space physics)

Simple Experiment on 2-D MHD Turbulence



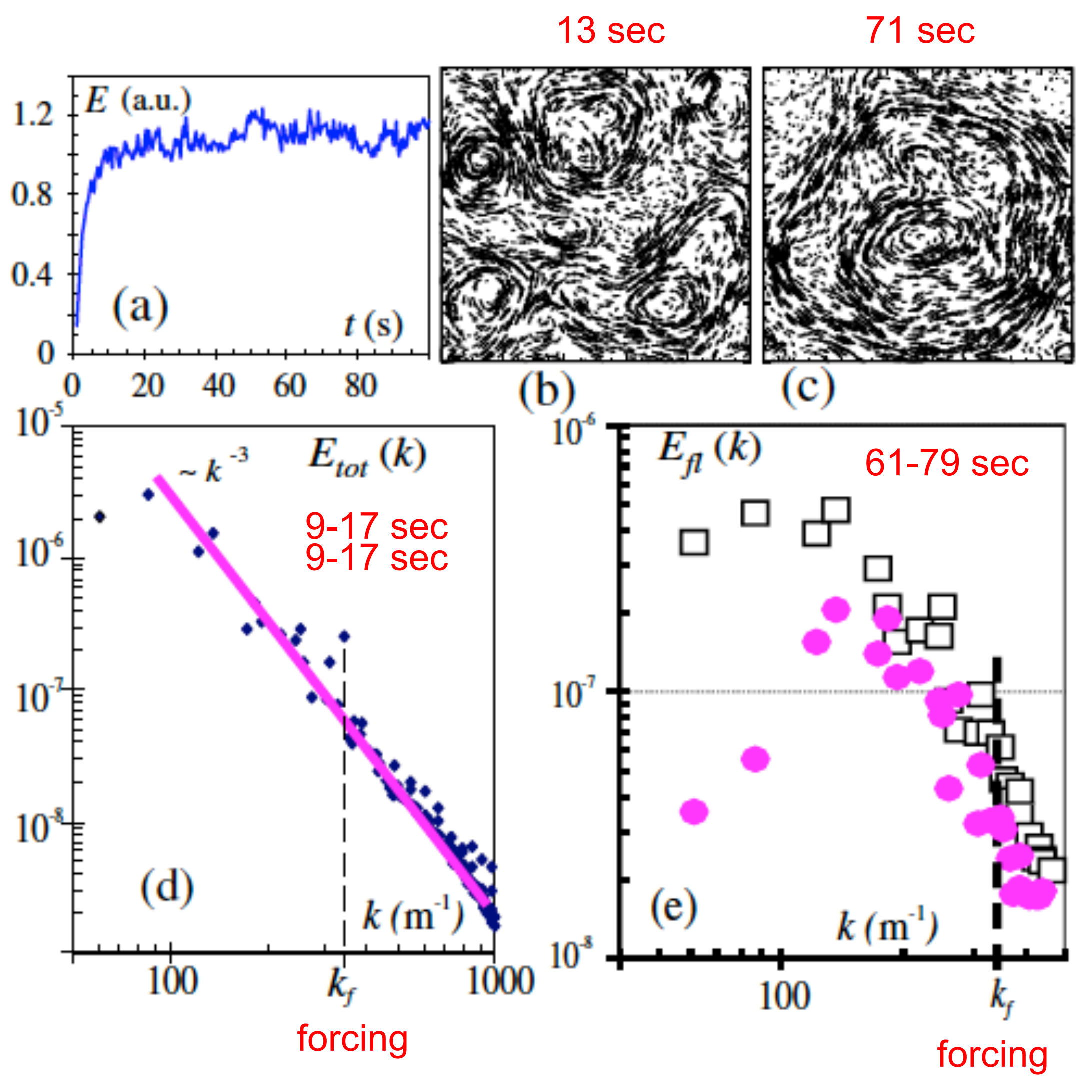
- 2-D layer of conducting fluid
- DC current applied right-to-left
- 10 x 10 array of magnets below
- initially array of small vorticies

what happens at later times ?



Shats et al, PRE 2007; PRL 2007

Inverse Cascade and Zonal Flow Formation



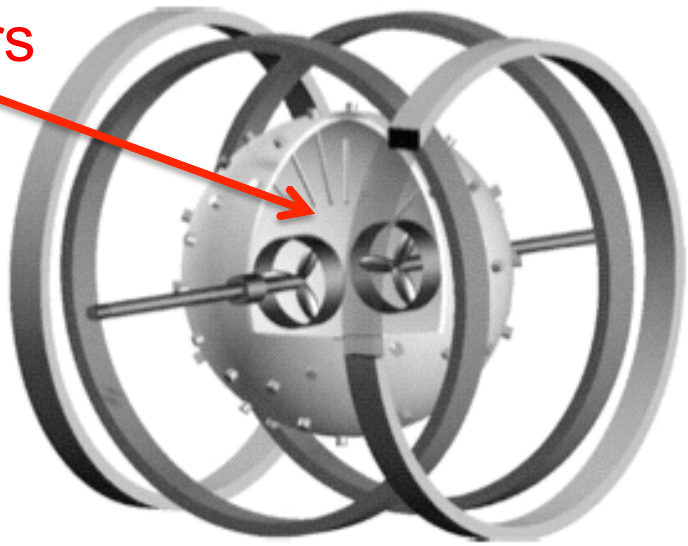
- inverse cascade forms moderate-size vorticies at 9-17 sec
- vortices merge into a single large vortex at 61-79 sec
- shearing due to this 'zonal flow' reduces turbulence at small scales

works like a tokamak ?

Turbulence in the Madison Dynamo Experiment

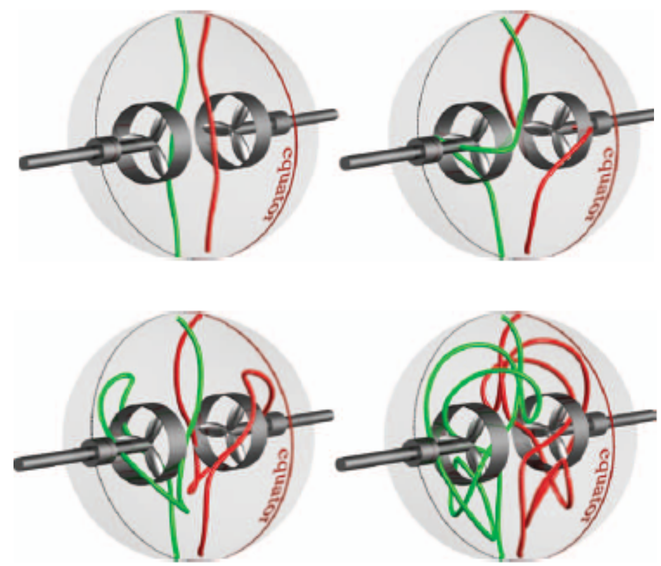
- Try to simulate Earth's dynamo effect by a 1 meter sphere of rapidly-flowing liquid sodium at 100 ºC (≤ 5 m/s)
- First measure how conducting fluid flow distorts applied B

counter-rotating impellers



applied B-field coils

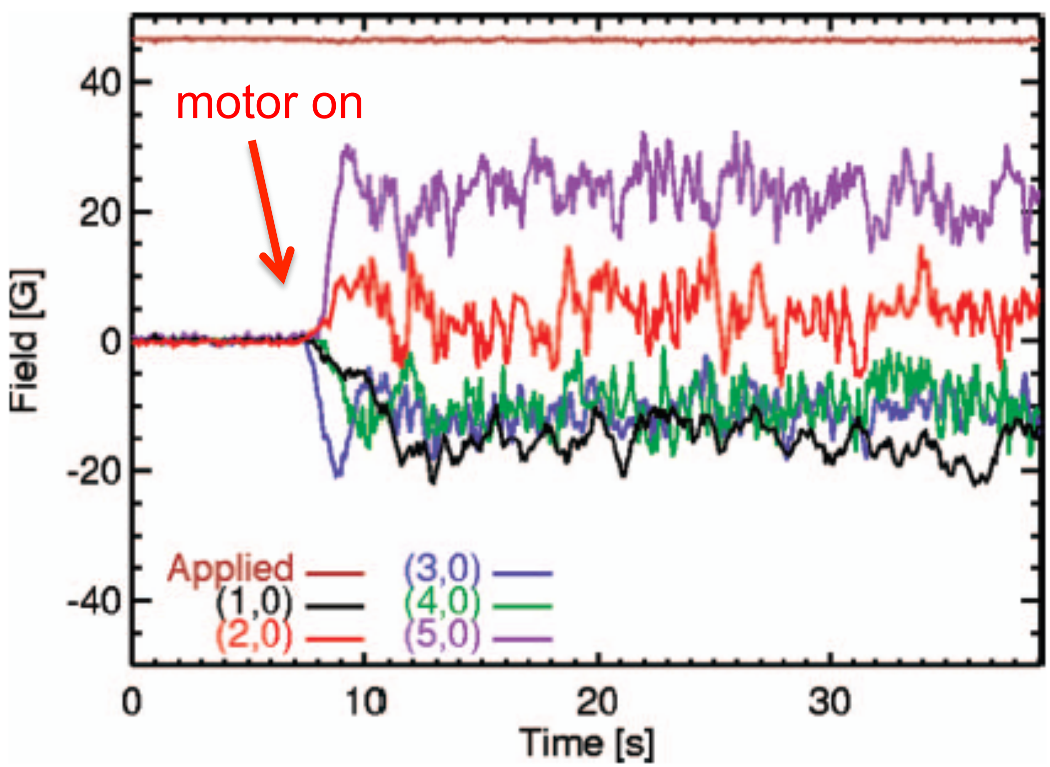
evolution of an applied B (simulation)



Nornberg et al Phys. Plasmas 2006

Magnetic Field Measurements Outside MDE

- B field measured by probes at outside surface of sphere
- No net amplification of applied field at these flows, so no spontaneous dynamo effect seen yet (as in Earth)

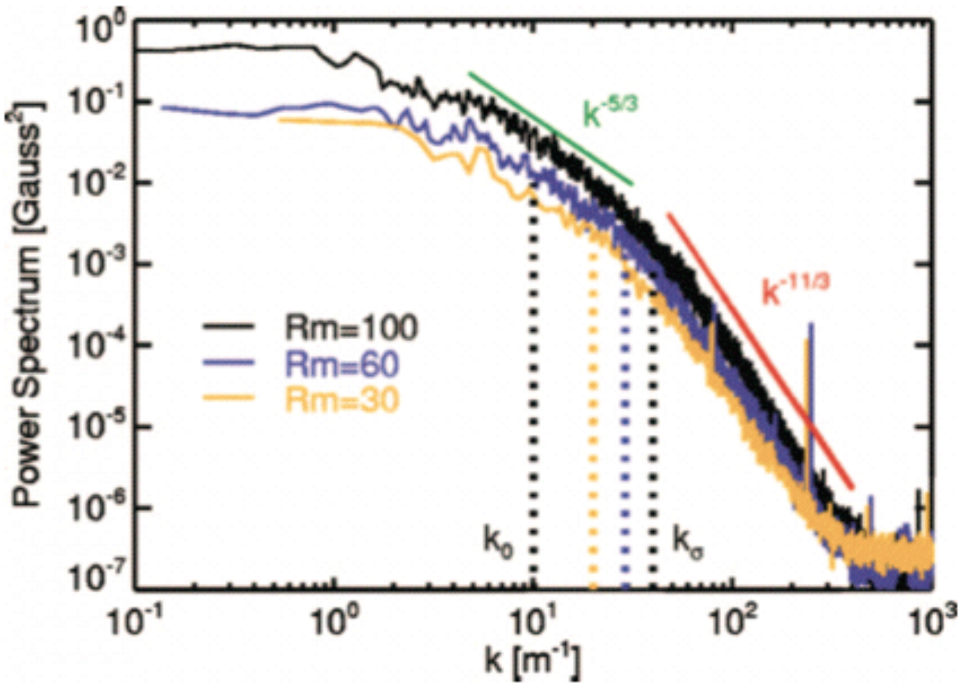


applied B field

various spherical harmonics of B at surface of sphere

Spectrum of MHD Turbulence Inside MDE

- Fluid flow is turbulent, R ~ 10^5 and drags magnetic field, so low-k part of spectrum follows $k^{-5/3}$ fluid scaling
- High-k part of spectrum damped by resistive dissipation, and so should follows $k^{-11/3}$ spectrum



assumes $k=\omega/v_{water}$

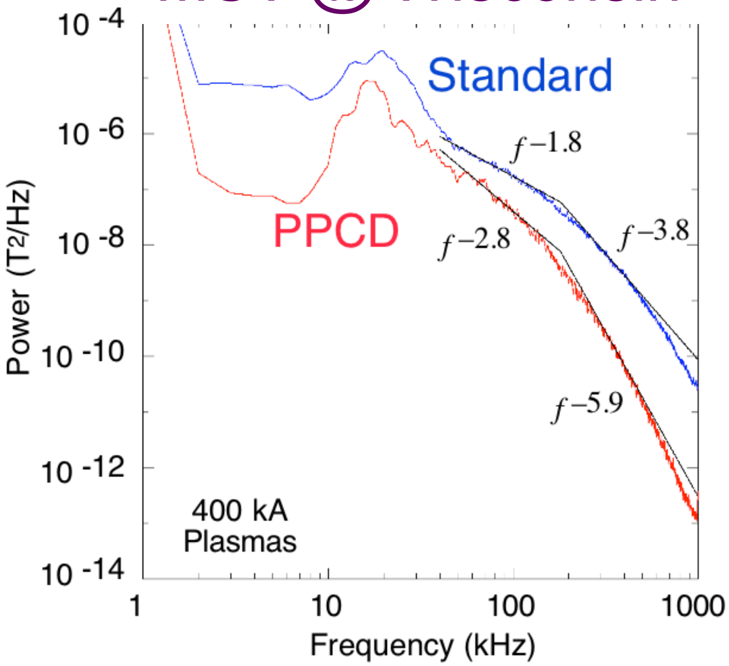
k_o = sphere size scale

k_σ = resistive dissipation scale ~ $R_m=av/\rho$

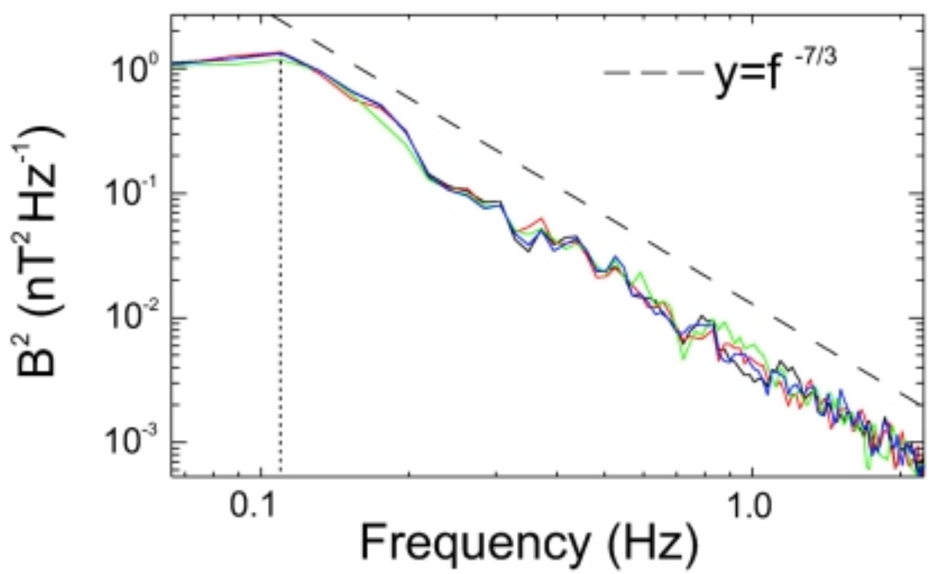
Spectra of Magnetic Turbulence in Plasmas

- Measurements of δB using probes typically show broad spectra similar to electrostatic fluctuation spectra

MST @ Wisconsin



Cluster @ magnetopause



Prager et al, Nucl. Fusion 45 S276 (2005)

Sahraoui et al, PRL 075002 (2006)

Summary of Plasma Turbulence Experiments

- Turbulence seen in a very wide variety of plasmas and in a number of different "fields", e.g. n, T, E, B

- Fundamental 'drive' and 'damping' physics not usually clear from the experimental measurements, i.e. no simple dimensionless parameters in most cases

- Most common feature is a broadband frequency and size-scale spectrum, but range of (ω,k) variable

- So far not limited "predictive" capability based on analytic or computational simulation of plasma turbulence