Complex Dynamics of Edge Plasma Transport

presented by

Rick Moyer

Fusion Energy Research Program
University of California, San Diego

in collaboration with

T.L. Rhodes, C.L. Rettig, T.E. Evans, R.J. Groebner, E.J. Doyle, W.A. Peebles, D. Rudakov, and D. Turney

UC San Diego

UCLA Electrical Engineering

GENERAL ATOMICS

COLORADO COLLEGE 1874

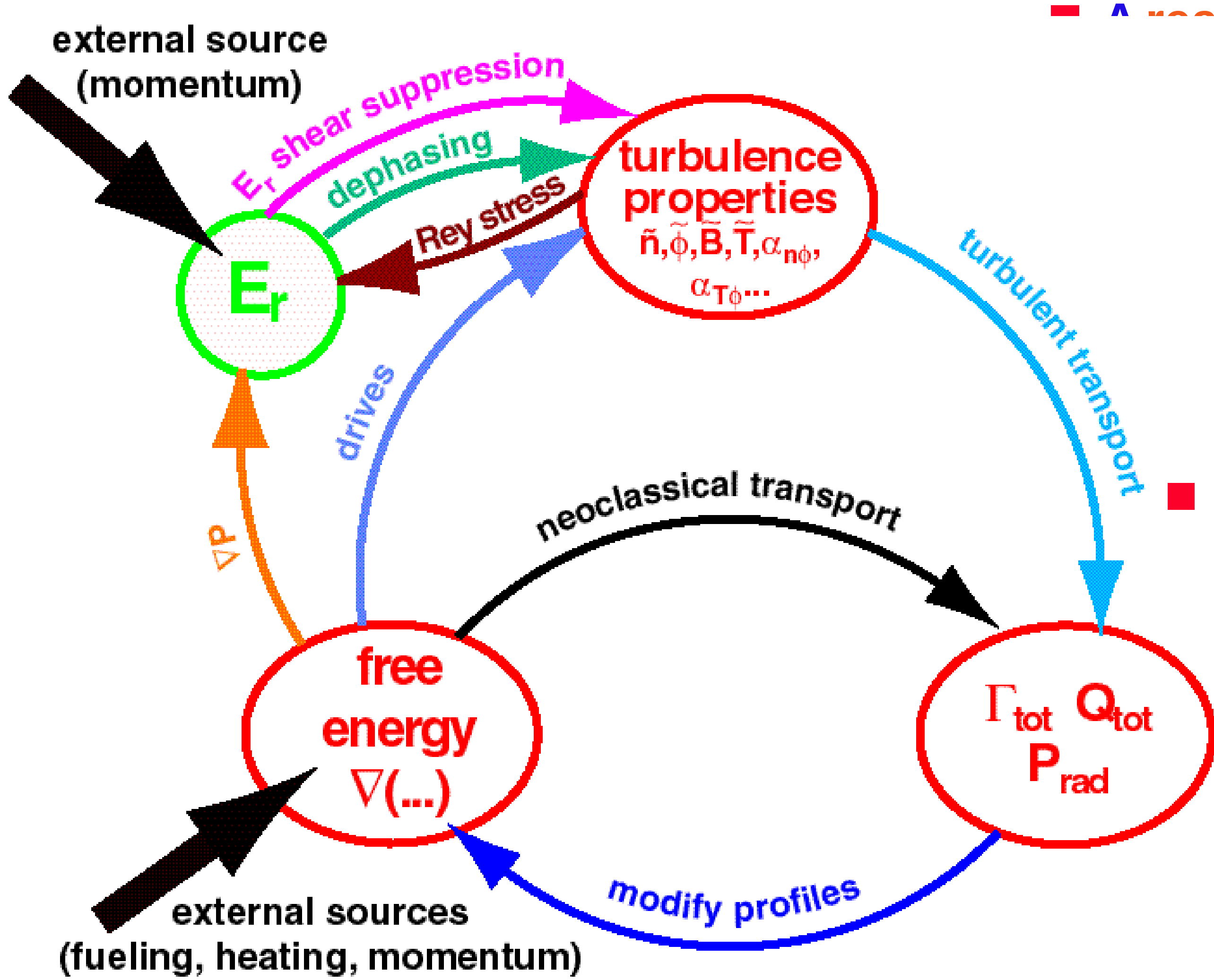
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Abstract

It is becoming increasingly clear that in order to make progress on understanding plasma turbulence and transport that the plasma-turbulence-transport must be treated as an interacting system. That is, the turbulent transport affects the turbulence drives which then affect the turbulence and the transport. This is the essence of a complex dynamical system. Progress in this regard (theory and experiment) is demonstrated by recent work on self-organized systems, long time/spatial correlations, etc. Data from the DIII-D edge plasma indicate that the plasma is a complex system of turbulence drives, $E \times B$ shear suppression and phase decorrelation, and avalanche-like transport events. We find that $\tilde{n}$ scales more closely with ∇P_e than with either ∇T_e or ∇n_e; that $E \times B$ shear reduces turbulent transport by altering both fluctuation amplitudes and cross-phases; and that avalanche-like transport events are an important part of the total edge transport. The edge profile, fluctuation, and transport diagnostics on DIII-D have been used to investigate these effects in various conditions in the DIII-D boundary. The data will be discussed from an interacting system or complex dynamics point of view with the goal of obtaining a deeper understanding of the tokamak as a complex, driven-dissipative system.

This work supported by U.S. DOE Grants DE-FG03-95ER54294 and DE-FG03-86ER-53266; Contracts DE-AC03-99ER54463 and DE-AC04-95AL85000; and by the U.S.1999 National Undergraduate Fellowship Program in Fusion Science.

Edge turbulent transport is a complicated problem involving coupled dynamical processes...



- A r…sonable model of …ynamical system …rbulent edge …port might look like
- …nportant point: this …odel is intrinsically …ocal.
- Can a local model capture all the physics?
  - is there any evidence for “emergence”– unexpectedly complex behavior?
  - if we “push” hard enough, will it “break”?

...but is it a Complex Dynamical System?

- "complex system" can be defined as a system with large variability over a wide range of scales ("Chinese box" phenomenon)
  - [P. Bak, How Nature Works: the science of self-organized criticality]
- systems with few degrees of freedom, and equilibrium systems cannot display complex behavior without fine tuning.
  - perturbations of a stable equilibrium system don't produce much change
- system has to be "open", driven externally. System is poised in a "critical state" which is far out of balance, and in which minor disturbances may lead to events of all sizes (avalanches). Most of the changes take place through large scale (catastrophic events) rather than by following a smooth, gradual path
  - concept of "punctuated equilibrium" [S. Gould, *Wonderful Life*]
  - dynamics are inherently global, not local.
- Key question: can we understand the edge turbulence and transport in a local model?

Experimental tests of transport models are complicated by the need to evaluate effects self-consistently.

- **The drives for edge turbulence haven't been identified experimentally due to difficulty in isolating effects.**
- **The underlying nonlinear dynamics of E × B shear suppression haven't been verified experimentally.**
  - **turbulent transport response to E × B shear in experiments may differ from that in gyrofluid and gyrokinetic code simulations (nonlinear saturation and cross-phase changes versus mode stabilization)**
  - **agreement with measured statistical properties of the turbulence (ensemble-averages of power weighted integrals over spectrum) may not be unique to a particular model**
- **The dynamical processes underlying anomalous transport are not yet well understood:**
  - **universality of fluctuation power spectra**
  - **origin of turbulence and anomalous transport in plasma regions below marginal stability to the modes causing turbulent transport**
  - **need to understand rapid radial propagation (non-locality) of perturbations (cold and heat pulses) in experiments**
  - **need to understand Bohm (device size) scaling of anomalous transport that is due to small spatial scale turbulence.**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Summary

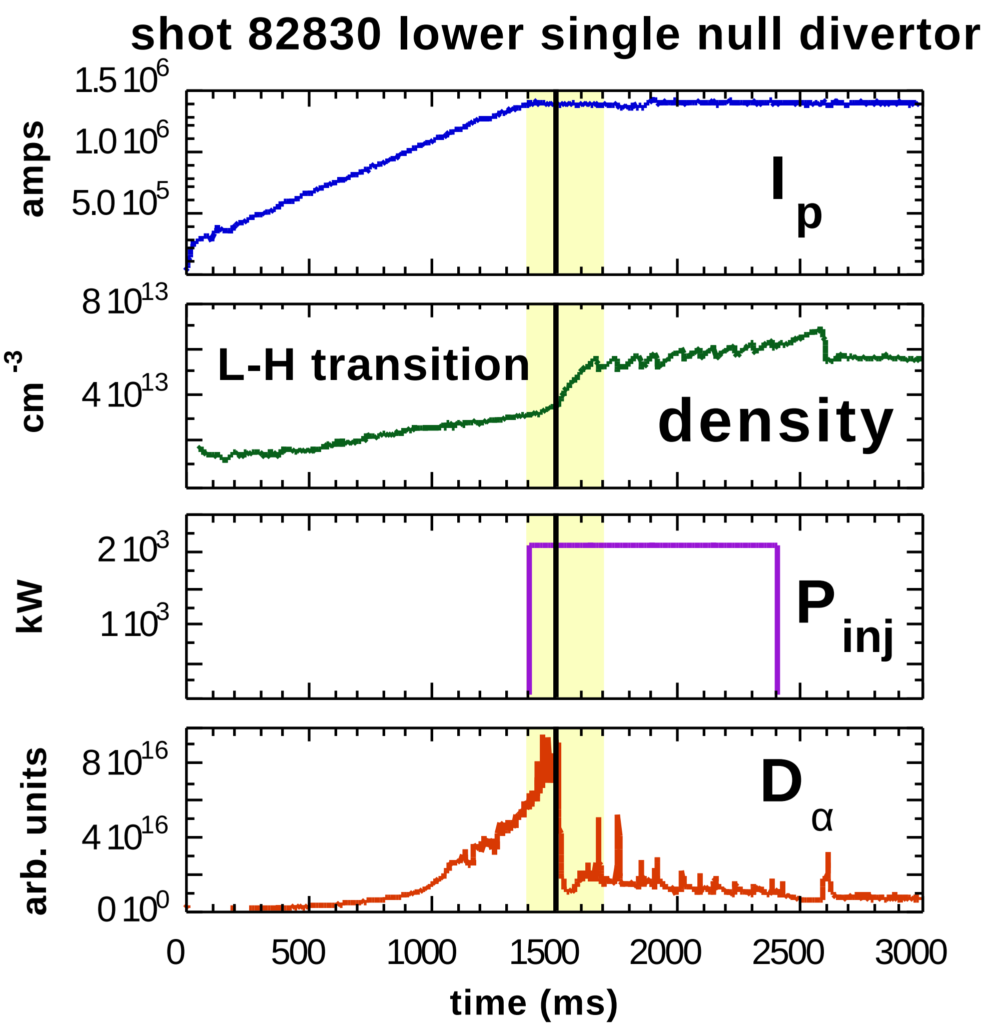
- **In L-mode, the fluctuation level scales with edge gradients (takey your pick), but...**
- **In H-mode, no clear scaling is seen due to competing (E × B shear effects):**
  - **E × B shear alters fluctuation amplitudes, correlation lengths, wavenumbers, and transport-relevant cross-phases.**
  - **cross-phase change means that fluctuation amplitudes can increase substantially without corresponding increases in transport**
- **Turbulent transport in the edge occurs in a “bursty” fashion that is very similar in L and H mode:**
  - **bursts are coincident with strong coherent 3-wave coupling indicating “structure” in either time or space (avalanches?)**
  - **probability distribution of transport events displays an extended 1/ event size scaling range consistent with criticality.**
  - **interacting avalanche range of particle flux power spectrum is responsible for more than 50% of the total transport.**
- **Do we need a more global picture? If so, what do we do about it?**

Summary

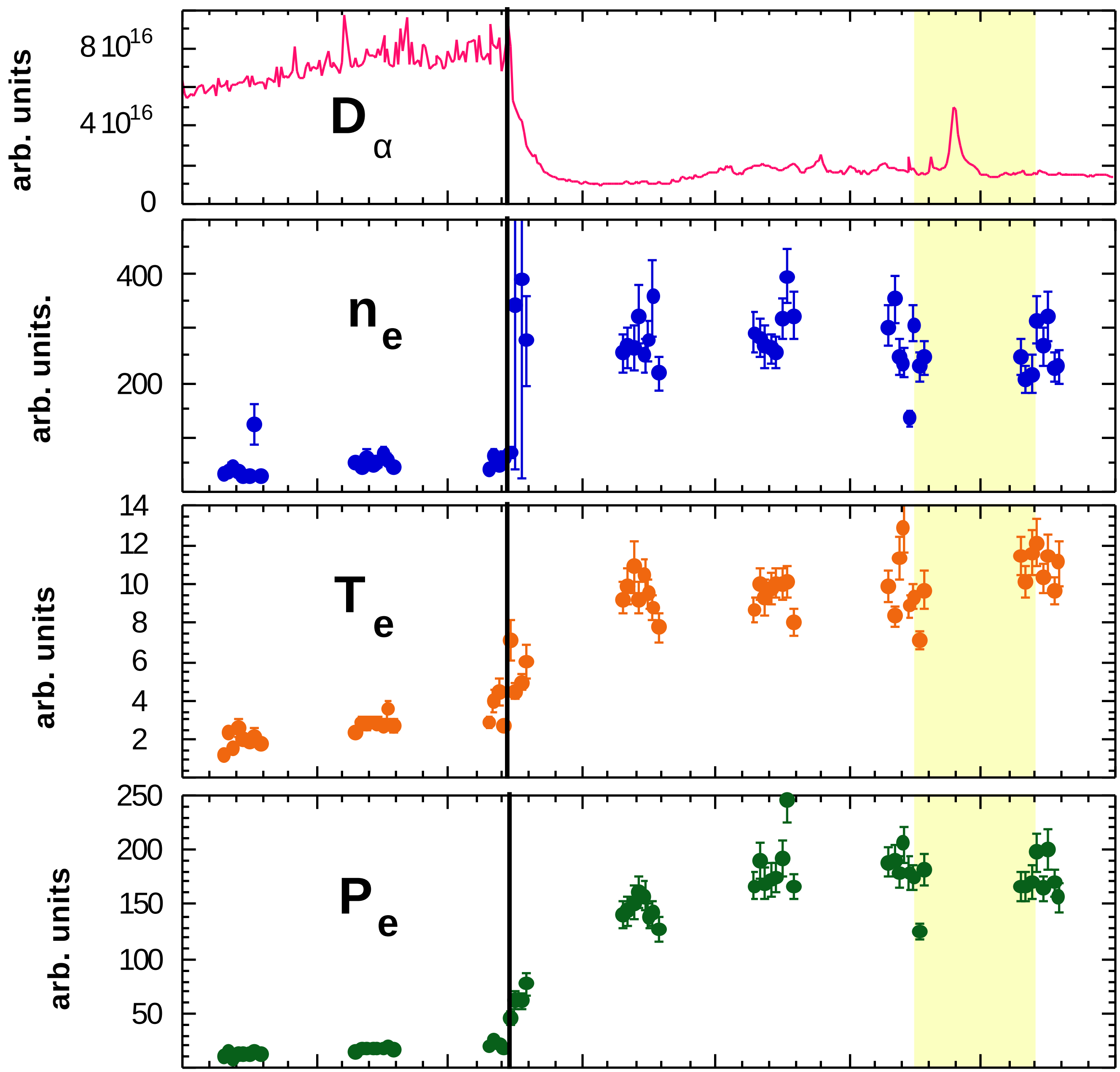
- **In L-mode, the fluctuation level scales with edge gradients (takey your pick), but...**
- **In H-mode, no clear scaling is seen due to competing ($E \times B$ shear effects):**
  - **$E \times B$ shear alters fluctuation amplitudes, correlation lengths, wavenumbers, and transport-relevant cross-phases.**
  - **cross-phase change means that fluctuation amplitudes can increase substantially without corresponding increases in transport**
- **Turbulent transport in the edge occurs in a "bursty" fashion that is very similar in L and H mode:**
  - **bursts are coincident with strong coherent 3-wave coupling indicating "structure" in either time or space (avalanches?)**
  - **probability distribution of transport events displays an extended 1/ event size scaling range consistent with criticality.**
  - **interacting avalanche range of particle flux power spectrum is responsible for more than 50% of the total transport.**
- **Do we need a more global picture? If so, what do we do about it?**

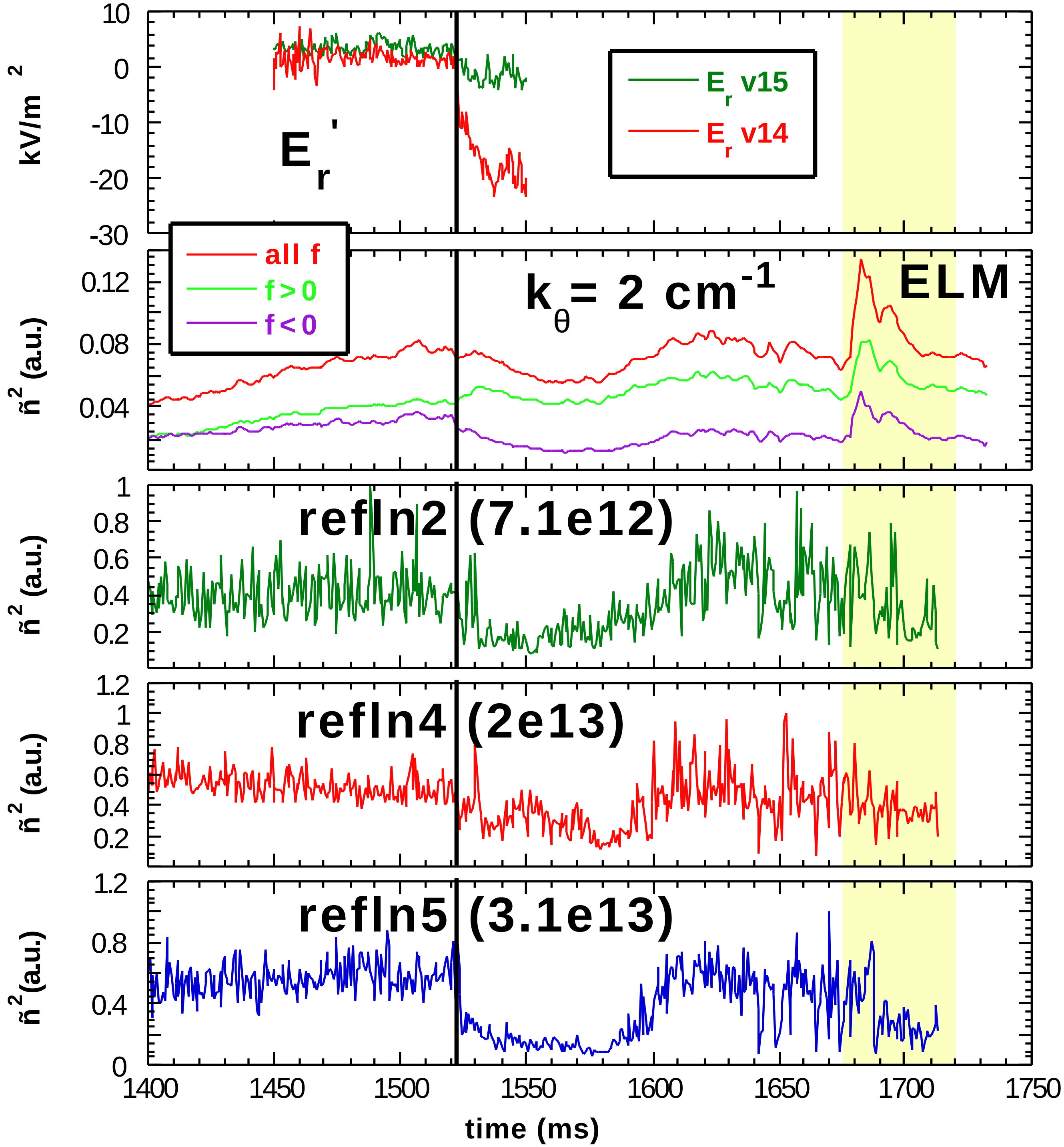
In ELM-free H-mode, fluctuations return to near L-mode levels as the density, stored energy, and edge gradients, saturate.

- **Is this an opportunity to learn about the coupling between turbulence drive and damping mechanisms?**



shot 82830 L-H transition expanded

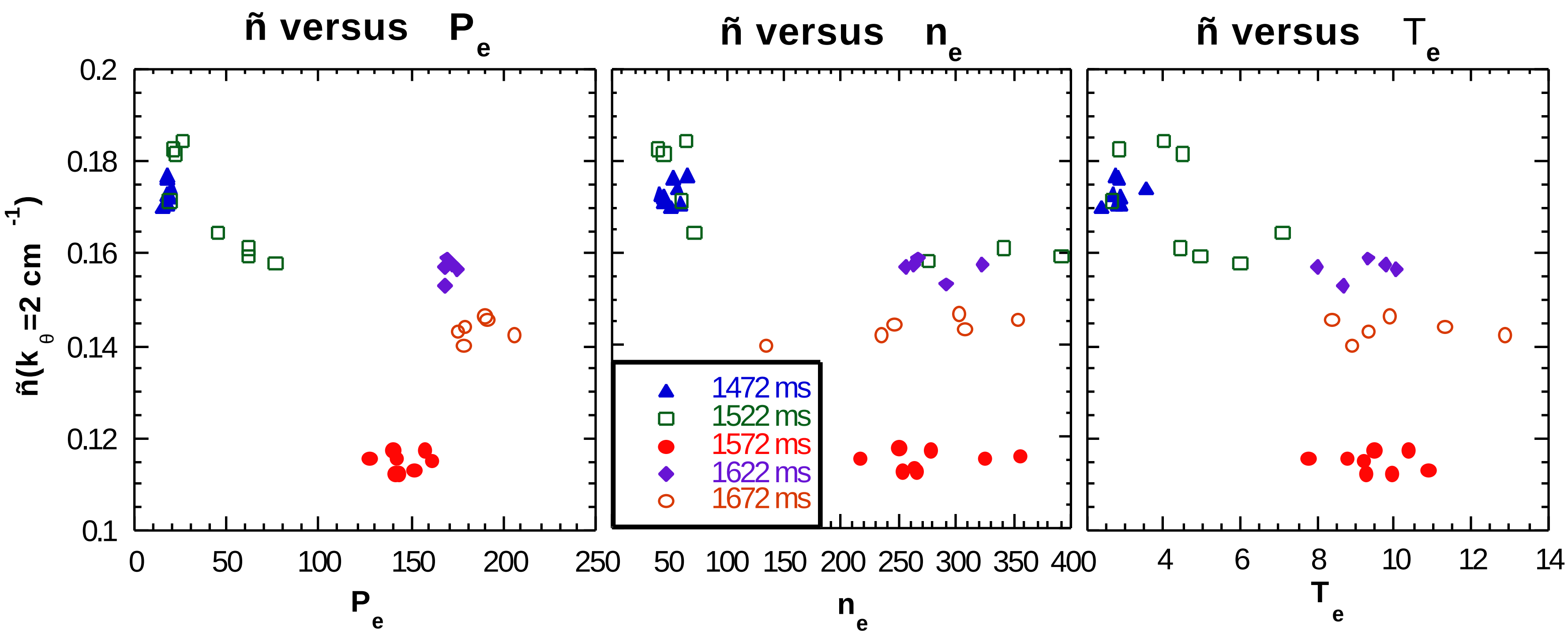




kV/m 2
E r '
E r v15
E r v14
all f
f>0
f<0
k θ = 2 cm -1
ELM
ñ 2 (a.u.)
refln2 (7.1e12)
refln4 (2e13)
refln5 (3.1e13)
time (ms)
1400
1450
1500
1550
1600
1650
1700
1750

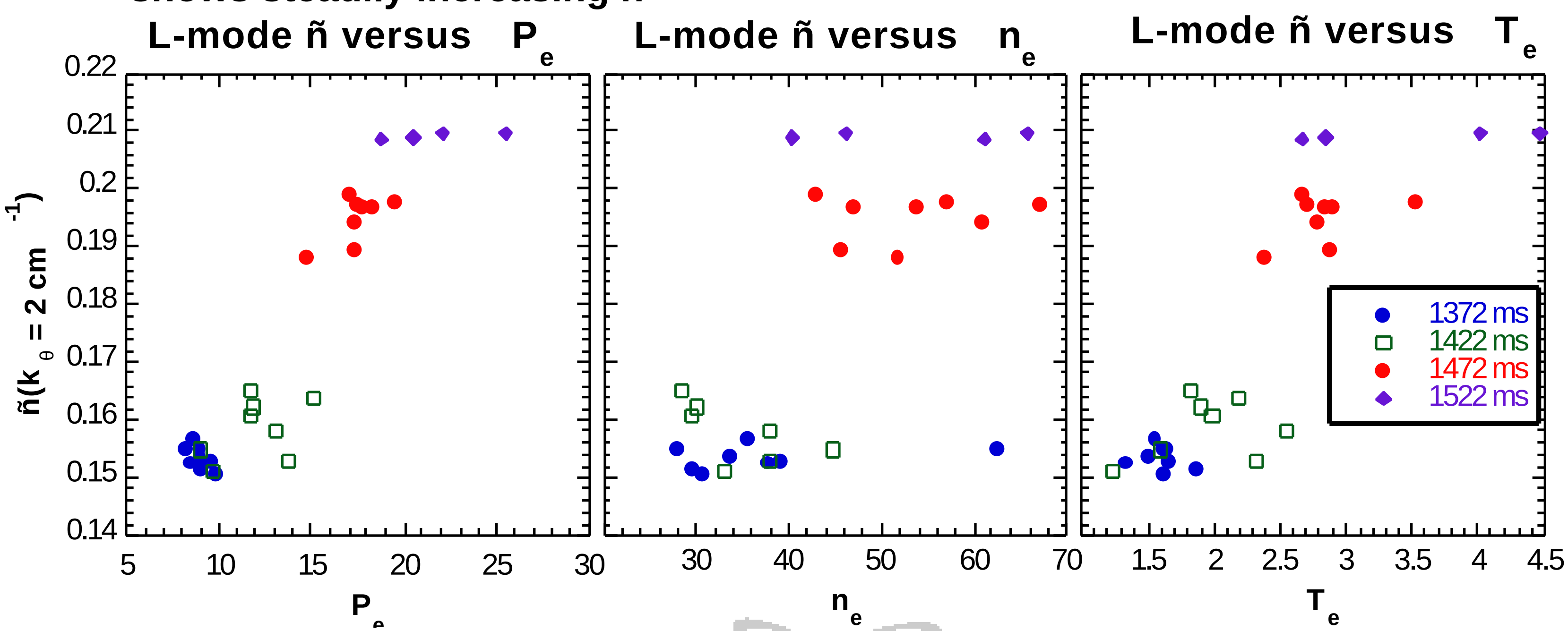
Fluctuation evolution in ELM-free H-mode is complicated by competition between increasing gradients and increasing E × B shear

- **ñ (k_θ = 2 cm^{-1} FIR) follows P_e more closely than either n_e or T_e after E_r shear has stopped evolvin, but more convincing evidence is needed.**
  - **similar result obtained using reflectometry (REFLN2, 4, and 5)**



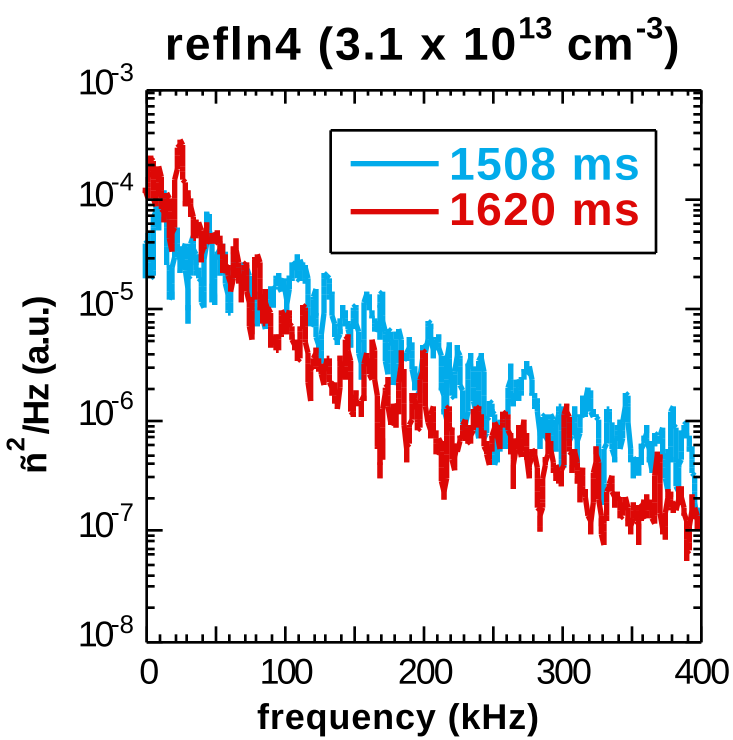
Similar analysis of LFS edge ñ (f > 0) in L mode could be consistent with n_e, T_e, or P_e gradient drive.

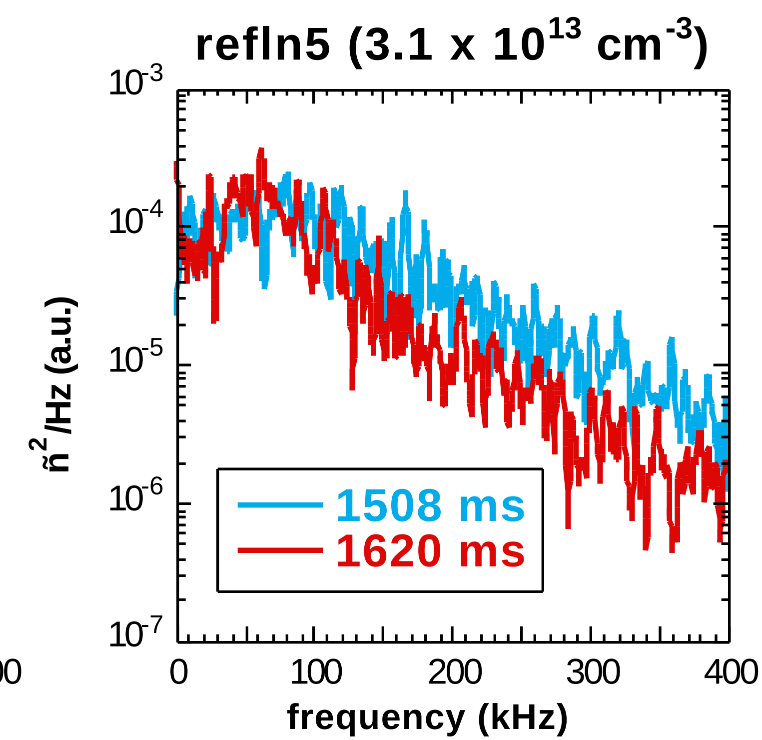
- Although the FIR response is weighted to the LFS edge, in L-mode there is no E_r well to localize the measurement to the LFS edge as in H-mode.
- Evolution of the edge density profile complicates interpretating the reflectometry measurements:
  - refln measures ñ at constant n which is more like ñ/n than ñ
  - reflectometer channels show relatively constant ñ/n during the time that FIR shows steadily increasing ñ



Broadband spectrum of the fluctuations after increase in H-mode suggests that the origin is still microturbulence.

- Indicates that the rise in fluctuation levels near the end of the ELM-free H-mode is not due to the onset of MHD or other coherent activity.

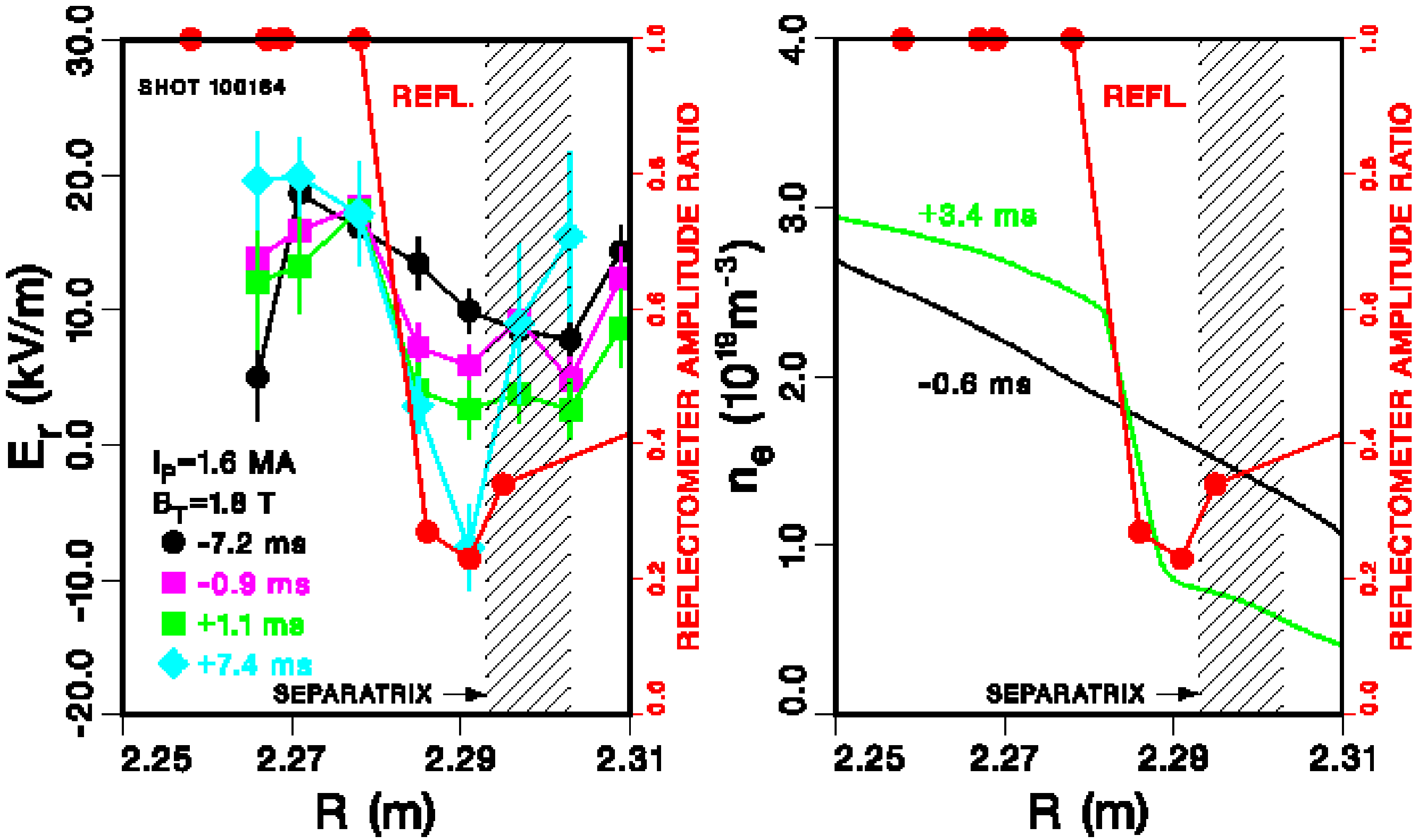




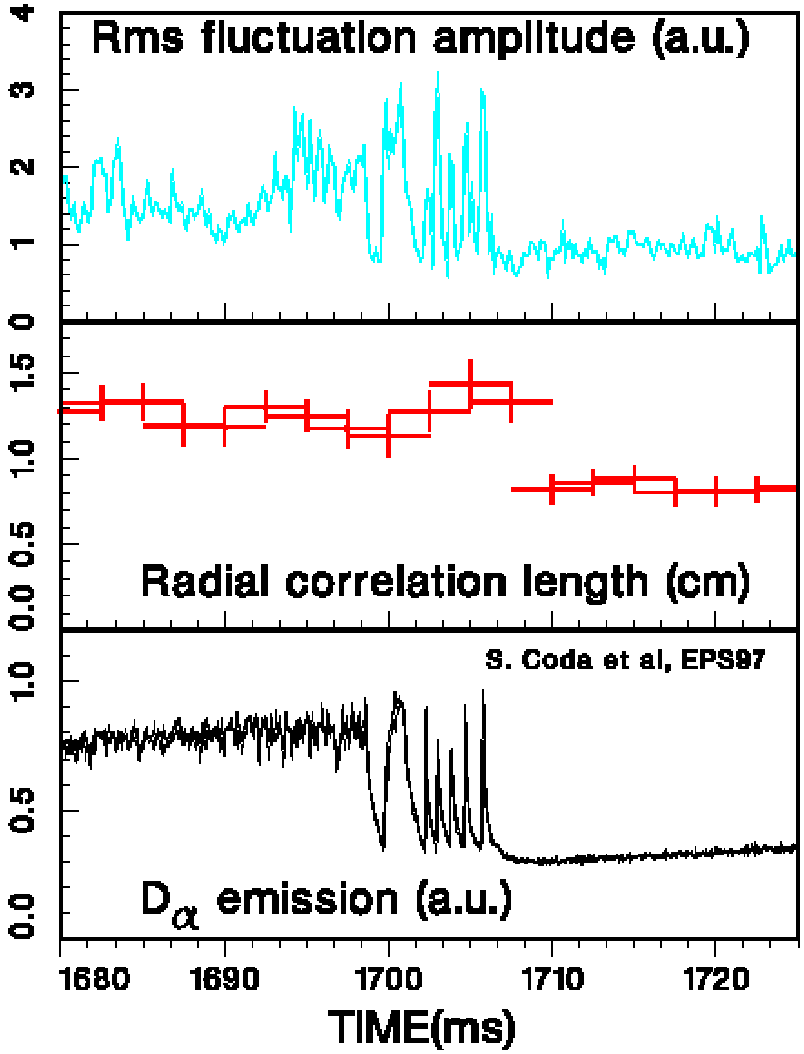
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

At the L to H transition, the increasing E_r shear leads to a large reduction in density fluctuations.

- **Large ñ reduction coincident in space and time with increases in edge E_r shear and edge profile gradients.**

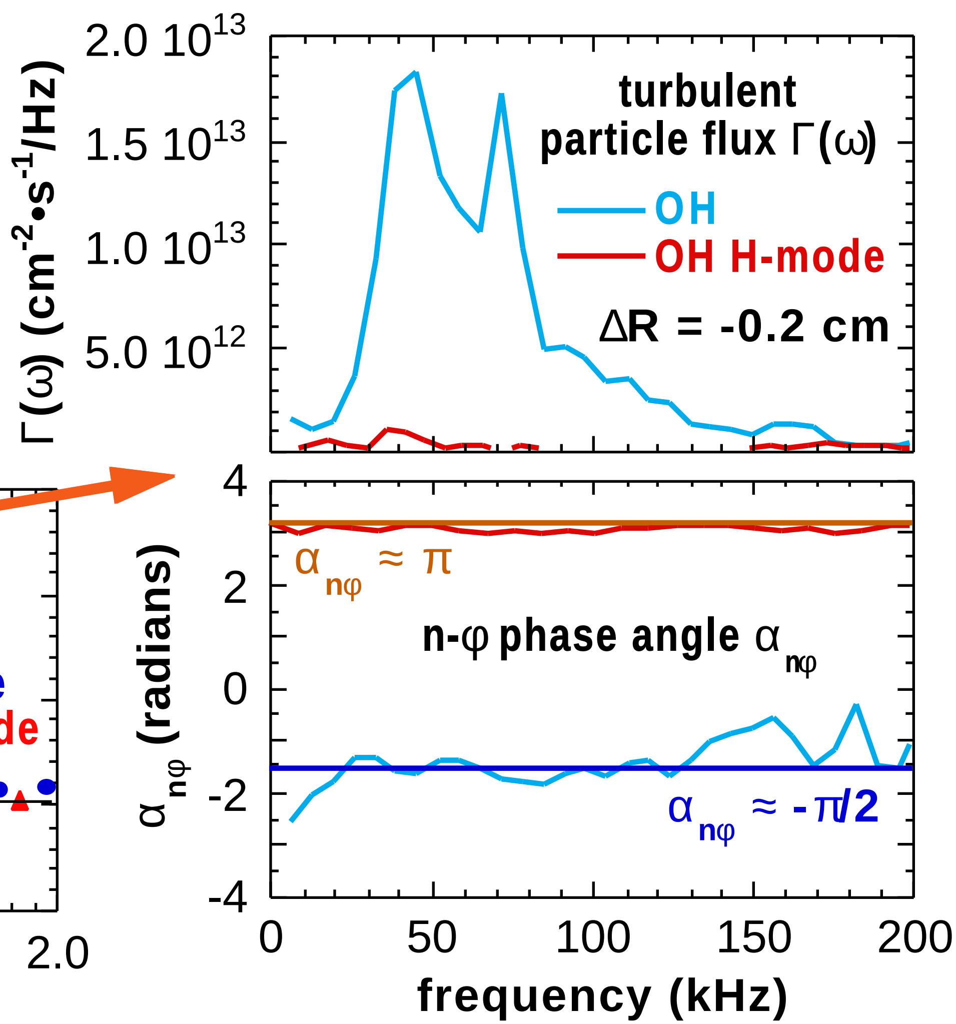


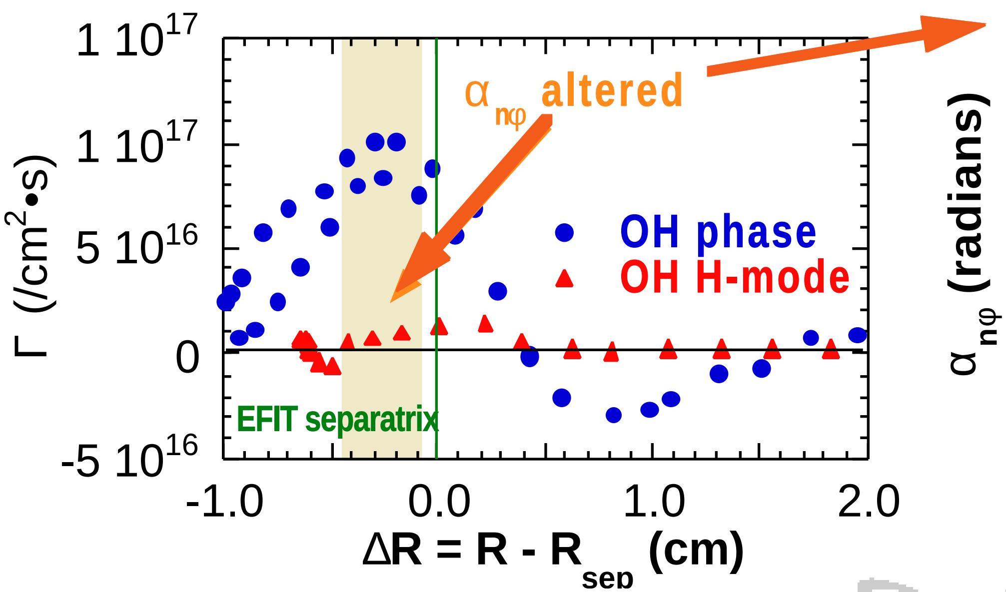
Increasing E_r shear reduces the radial correlation length as well as the amplitude of the density fluctuations.



E × B shear flow induced changes to the (ñ,φ) cross-phase are also well established experimentally.

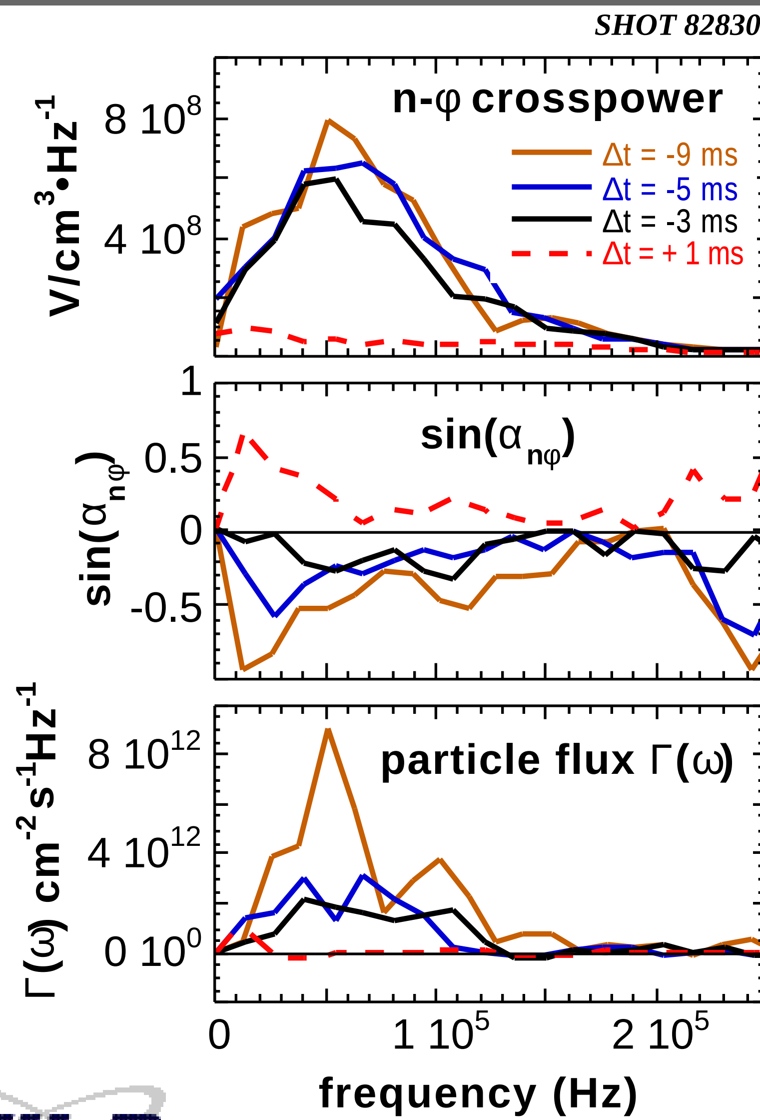
- **Example: ohmic L and H modes in DIII:**
  - Moyer et al, Phys. Plasmas 2 ('95) 2397.
  - others (Tynan, Boedo...)
- **Cross-phase changes only inside the E_r well.**





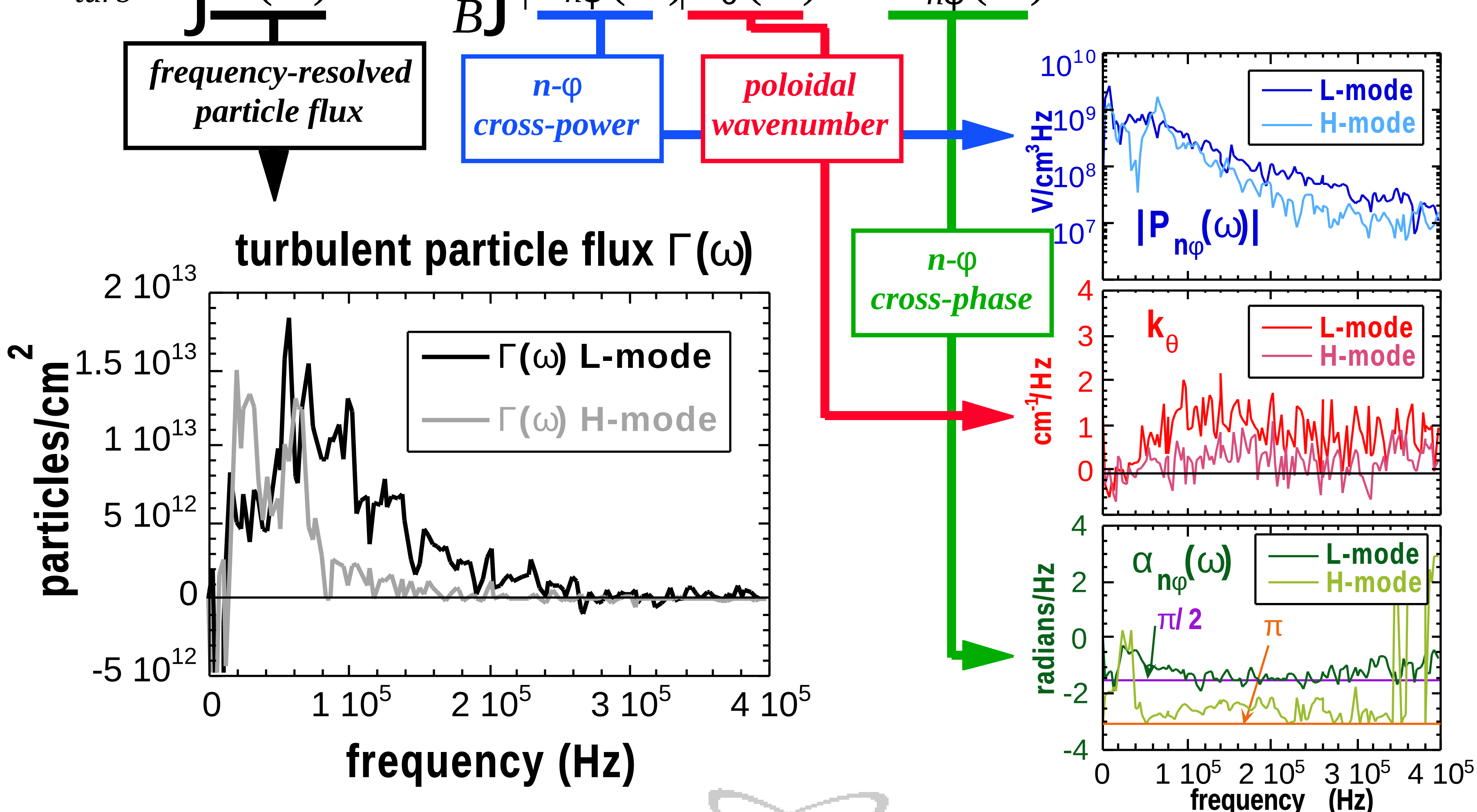
n-φ cross-phase changes before the fluctuation amplitudes are suppressed, reducing transport 2.5×.

- **n-φ cross-phase evolves during the last 10 ms of L mode (as E_r well develops prior to D_α drop?)**
- **Cross-phase change reduces turbulent particle flux with only a small change in fluctuation amplitudes.**
- **Γ $\sin(\alpha_{n\varphi})$ the spectral power weighted n-φ cross-phase:**
  Δt = -9 ms: $\sin(\alpha_{n\varphi})$ = -0.53
  Δt = - 5 ms: $\sin(\alpha_{n\varphi})$ = -0 .27
  Δt = -3 ms: $\sin(\alpha_{n\varphi})$ = -0.19
  Δt = +1 ms: $\sin(\alpha_{n\varphi})$ = +0.35
- **At the transition, however, there is a strong amplitude suppression that quenches all remaining transport.**



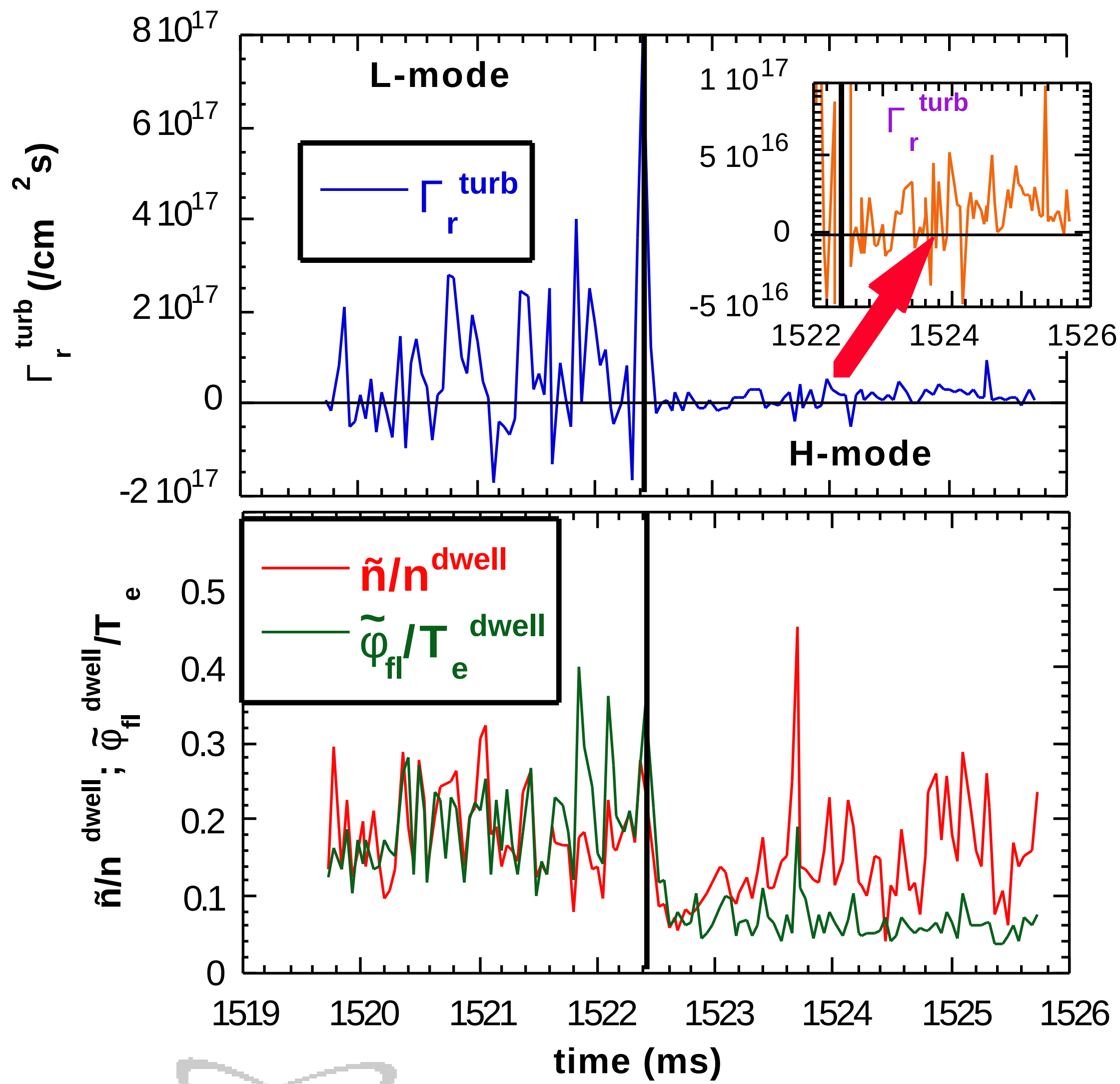
Late in ELM-free H-mode, rms levels return to near L mode values, and E ×B shear suppression, $(\tilde{n},\varphi)$ dephasing, and k_θ reduction (increased L_θ) all contribute to maintaining the transport barrier.

$$\Gamma_{turb} = \int \Gamma(\omega)d\omega = \frac{2}{B}\int \left|P_{n\varphi}(\omega)\right| k_\theta(\omega) \sin\alpha_{n\varphi}(\omega)d\omega$$



L mode and ELM-free H mode are both characterized by bursts of high transport and intervals of low transport.

- **L mode differs from ELM-free H mode in two ways:**
  - **intervals of large transport have higher flux than "large" transport intervals in ELM-free H-mode**
  - **higher % of L-mode intervals have high transport than H-mode intervals.**
- **picture is suggestive of the "punctuated equilibrium" model of complexity**



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

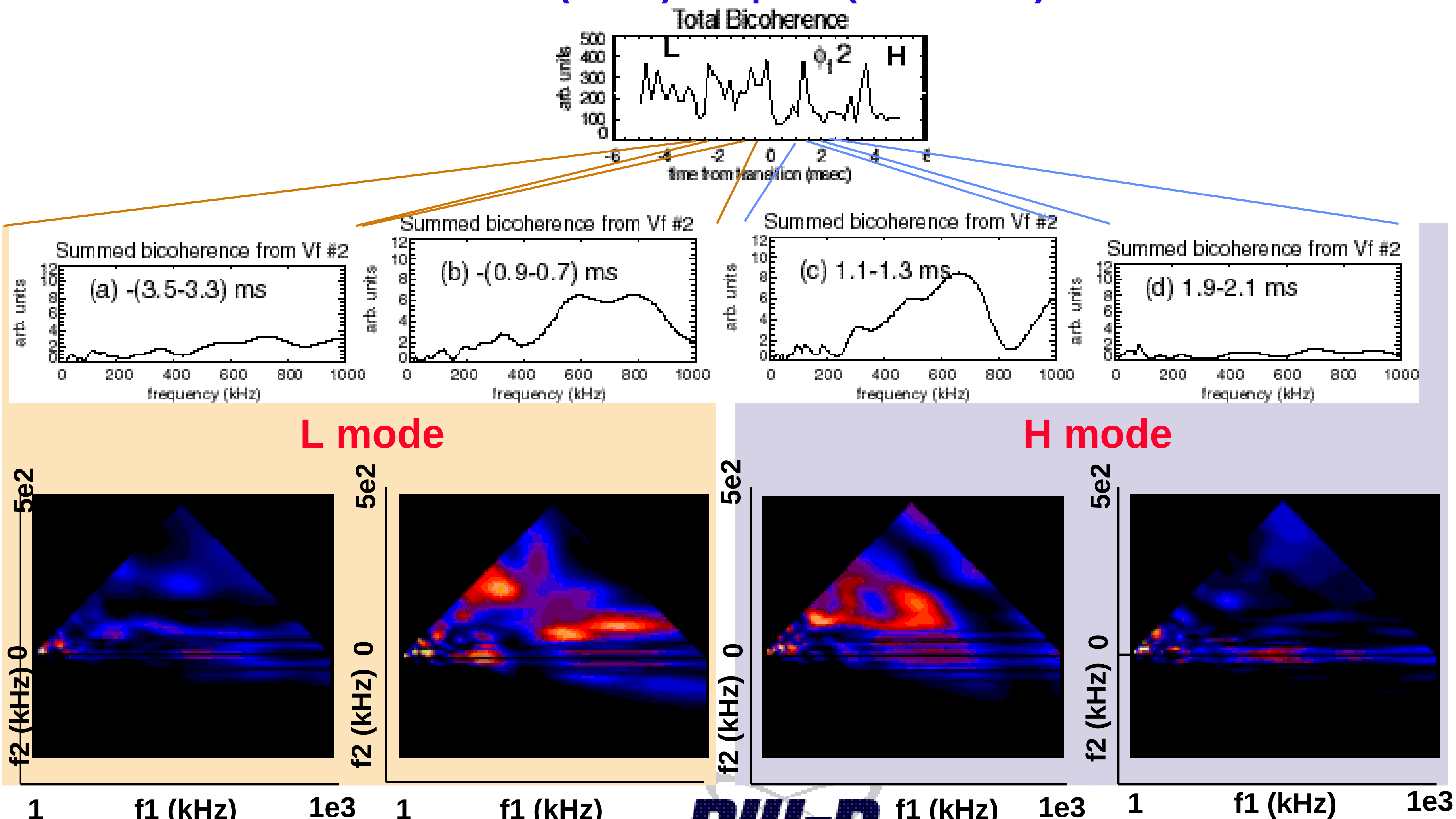
Wavelets can be used to look at such bursting behavior.

- **Wavelet bicoherence combines two types of analysis: wavelets (instead of Fourier modes) and bispectral analysis.**
  - **technique used here first described by van Milligan et al. Phys. Rev. Lett. 74 ('95) 395; see also: Phys. Plasmas 2 ('95) 3017; Rev. Sci. Instrum. 68 ('97) 967.**
- **Wavelet analysis allows temporal variation in the signals to be resolved by trading frequency resolution for temporal resolution.**
  - **use Gaussian modulated sine waves as the analyzing wavelets**
- **Wavelet bispectral analysis measures the amount of phase coupling that occurs in an interval T between wavelet components of scale lengths a_1 and a_2 of the signal f(t) and scale a of g(t) such that the sum rule is satisfied: $1/a = 1/a_1 + 1/a_2$**
  - **Data sampled at 5 MHz with 12 bit resolution; records segmented into 200μs intervals of 1000 points. Computations truncated at $f = 0.4 f_{Nyquist} = 1$ MHz to speed computations and reduce memory requirements. Bispectra are computed on a grid of 100 frequency binds of 10 kHz each, with $f_{max} = 1$ MHz, $0 < f_1 < f_{max}$, and $-f_{max} < f_2 < f_{max}$.**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

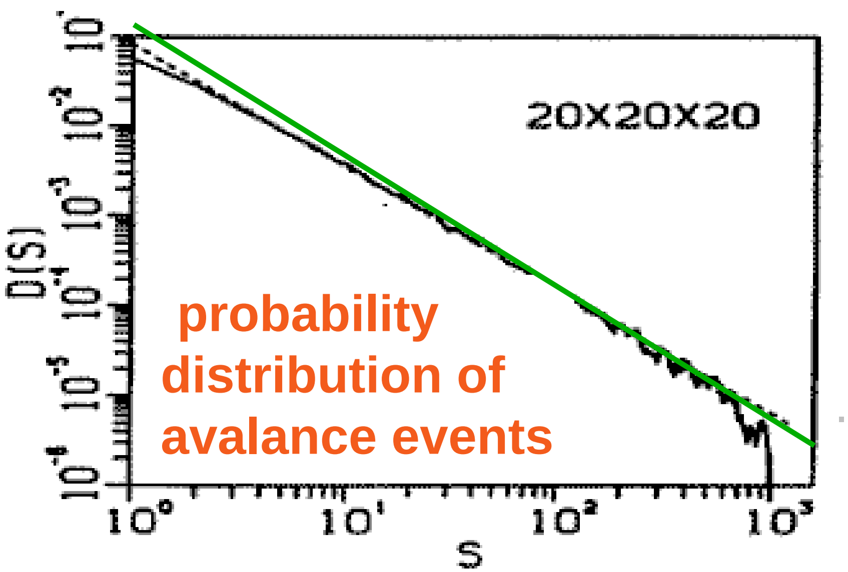
High transport bursts have strong 3-wave coupling, and intervals of low transport have weak 3-wave coupling.

- **Large bicoherence indicates strong, coherent 3-wave coupling -> "structure" in either time (burst) or space (avalanche)**

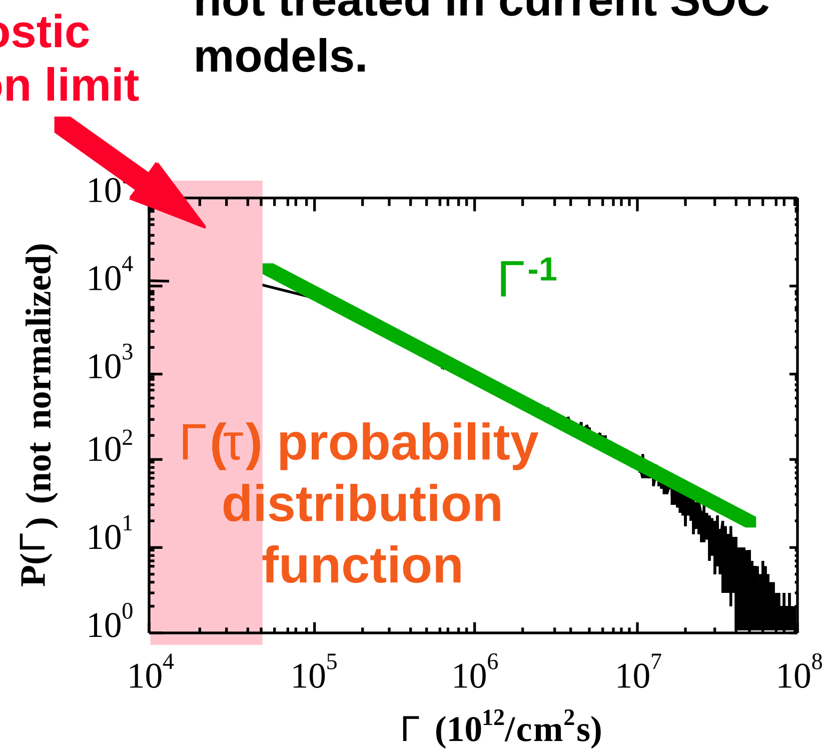


In L mode, the probability distribution function of the particle flux Γ “bursts” scales as Γ^{-1} indicating criticality.

- probability distribution of avalanche or flux events, from P. Bak running sandpile SOC model:

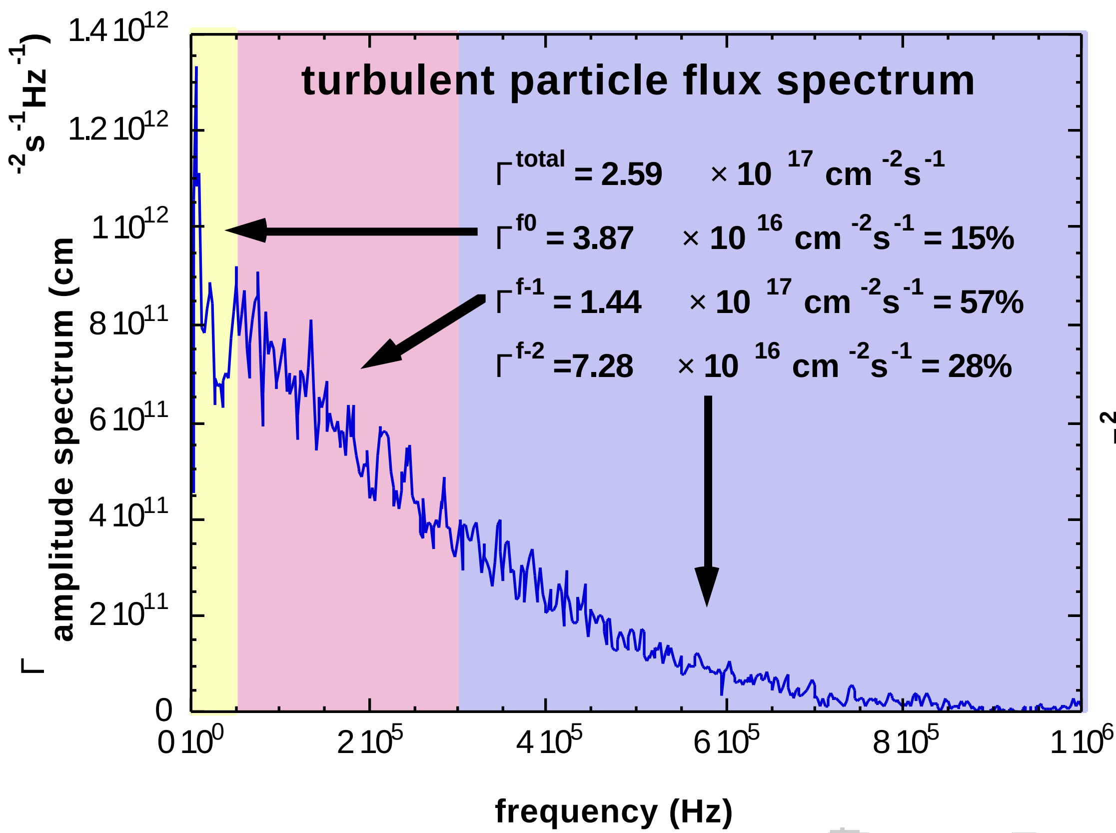


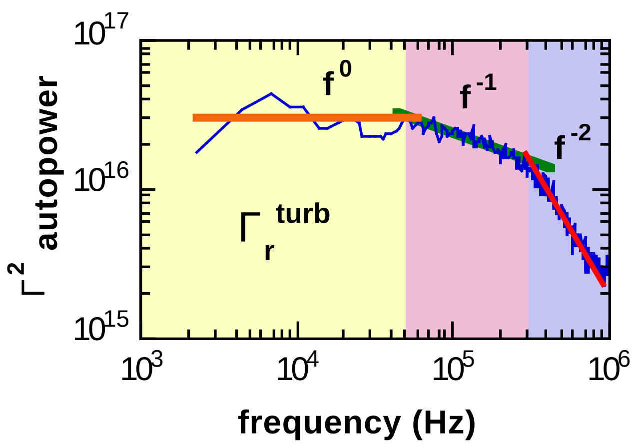
- P(Γ≥0) from Langmuir probe
  - P(Γ<0) corresponding to radially inward transport is not treated in current SOC models.



The avalanches are important because they account for more than half of the total flux.

- **Yes, the 1/f range of interacting avalanches contributes 57% of the total transport!**





To date, the fusion community has made considerable progress with a fundamentally reductionist approach:

- **we have investigated (or at least tried to!) one or two factors at a time with considerable success**
- **but our understanding and progress toward a quantitative understanding difficult**
  - **inherent difficulties in dealing with the inter-connectedness of the local model in real experiments**
  - **is the model incomplete? often we exclude phenomena (e.g. sawteeth, ELMs, disruptions) from our model because we believe that they are "something else"; is this approach valid?**
- **our system is difficult in part because it manifests some features of emergence in a complex system**
  - **examples: avalanche phenomena such as Politzer's T_e structures and Ken Gentle's heat and cold pulses**
  - **our reductionist approach based on local models, is not in the spirit of complex dynamical systems analysis!**
- **Is there a way to approach the system in a more global way that still allows us to get "numbers" out of the model?**