EX2-1



# Dynamic method to study turbulence and turbulence transport

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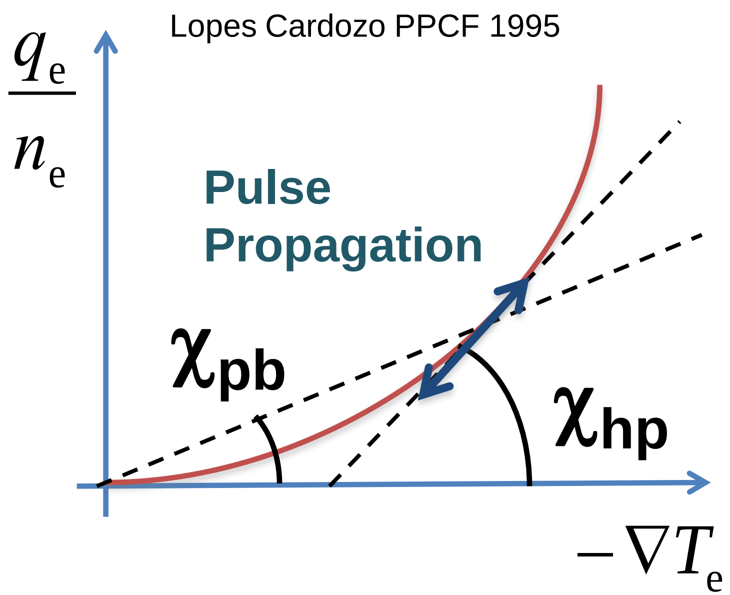
# Revisiting heat pulse propagation analysis

## Discovery of the New Transport Relation on LHD

### Conventional Approach

$$\chi_{hp} = \frac{-\partial q_e}{n_e \partial \nabla T_e} \neq \frac{-q_e}{n_e \nabla T_e} = \chi_{pb}$$

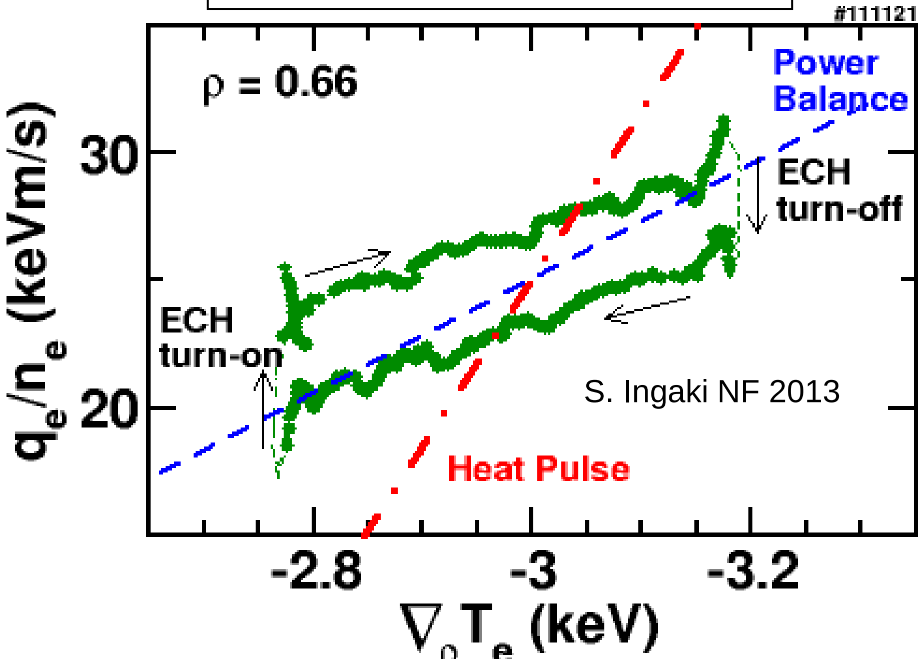



Single-Valued Function

One time-scale

### Conventional method has serious difficulty

Periodic power modulation




Multiple-Valued Function (→hysteresis)

Two time-scales

# Contents



## Method to study turbulence transport

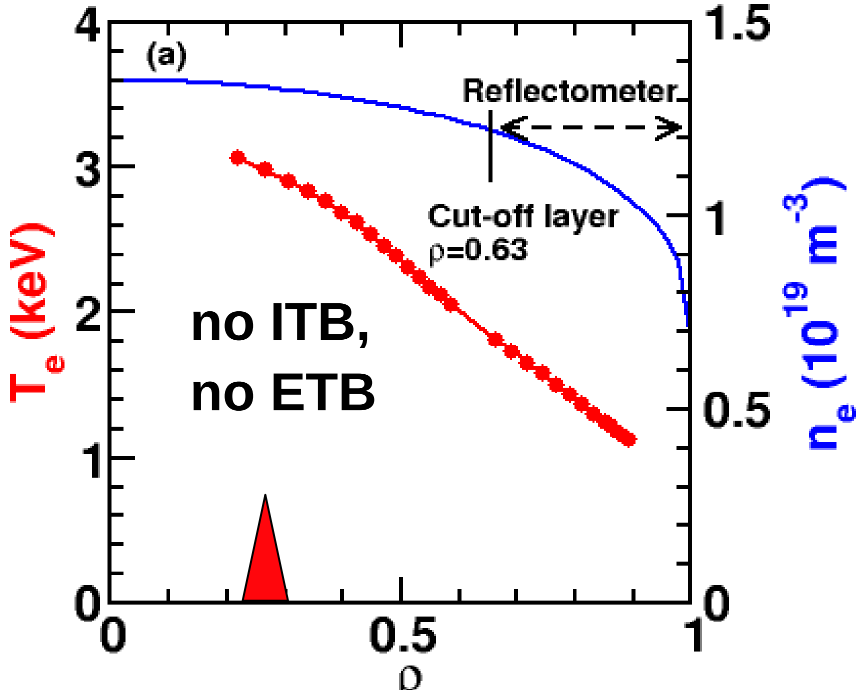
- Assessment of conventional method (What is $\chi_{hp}$?).
- A simplified new approach to understand the transport with multiple-valued flux (hysteresis, barrier formation)

## Method to observe multi-scale couplings of turbulence

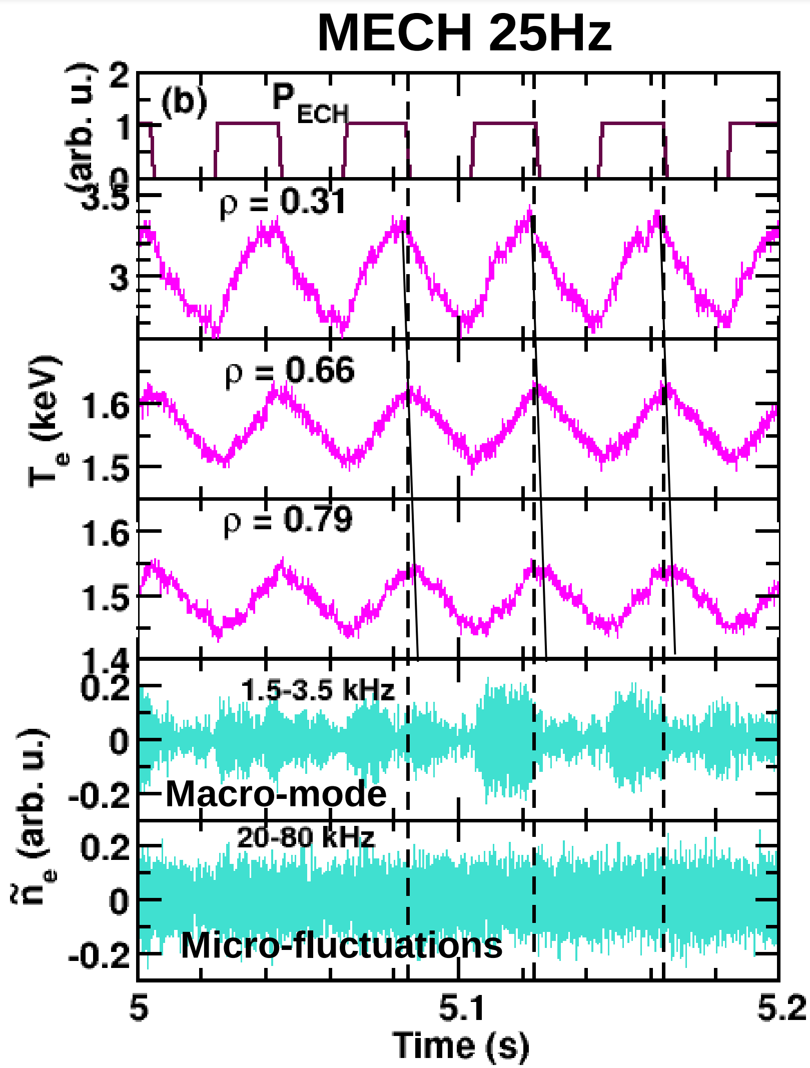
- Observation of coupling of micro-fluctuations at distant locations

# Exp. Set-up and Conditional Averaging

- Target plasma (NBI+MECH)
- Modulations of $T_e$, $\nabla T_e$ and fluctuation are observed simultaneously




**no evidence of high-energy tail**

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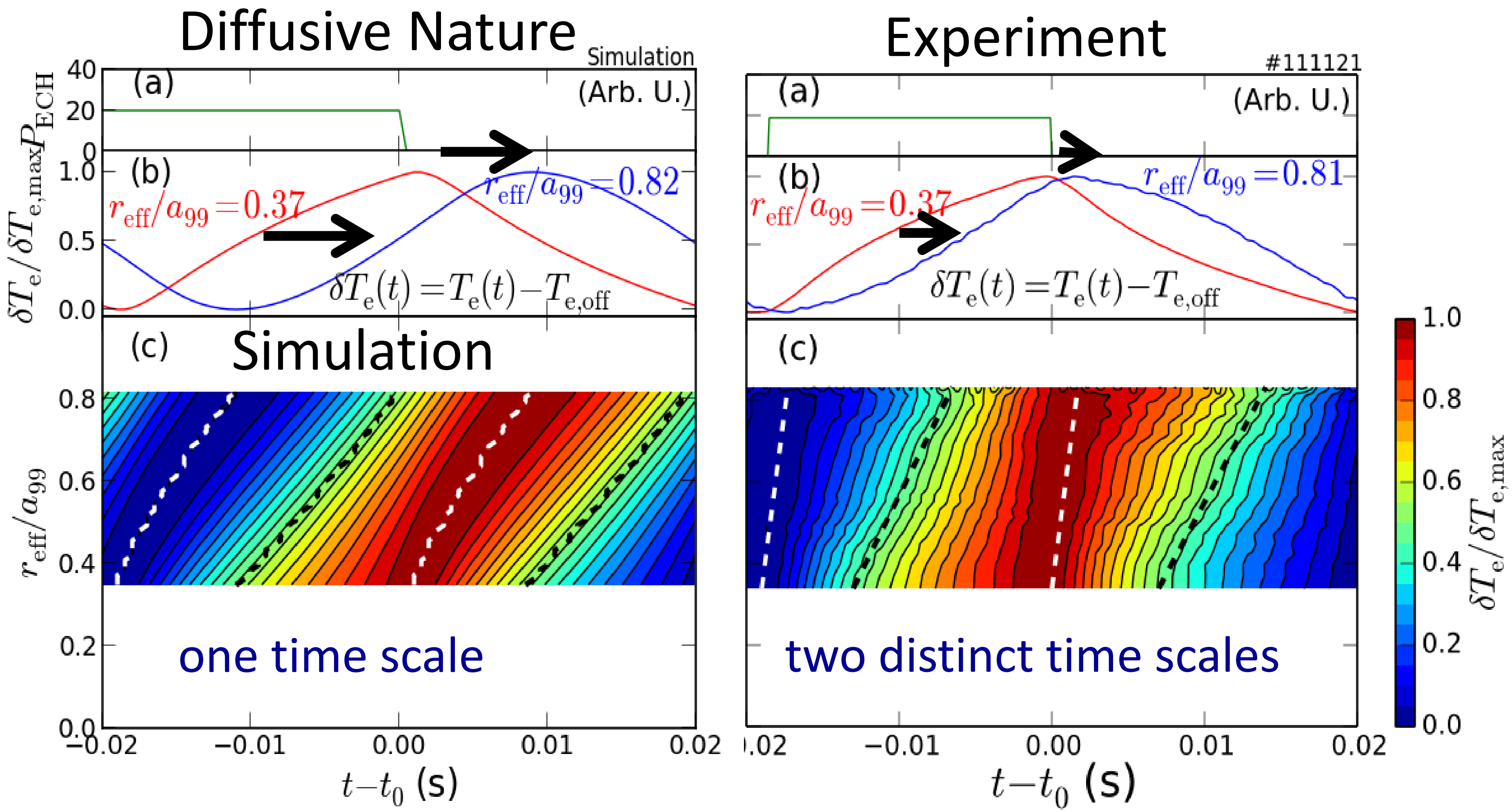
Periodic temporal evolution of signals are precisely extracted.

# Precise spatiotemporal structure of heat pulse



## Conditional averaging technique is very powerful tool



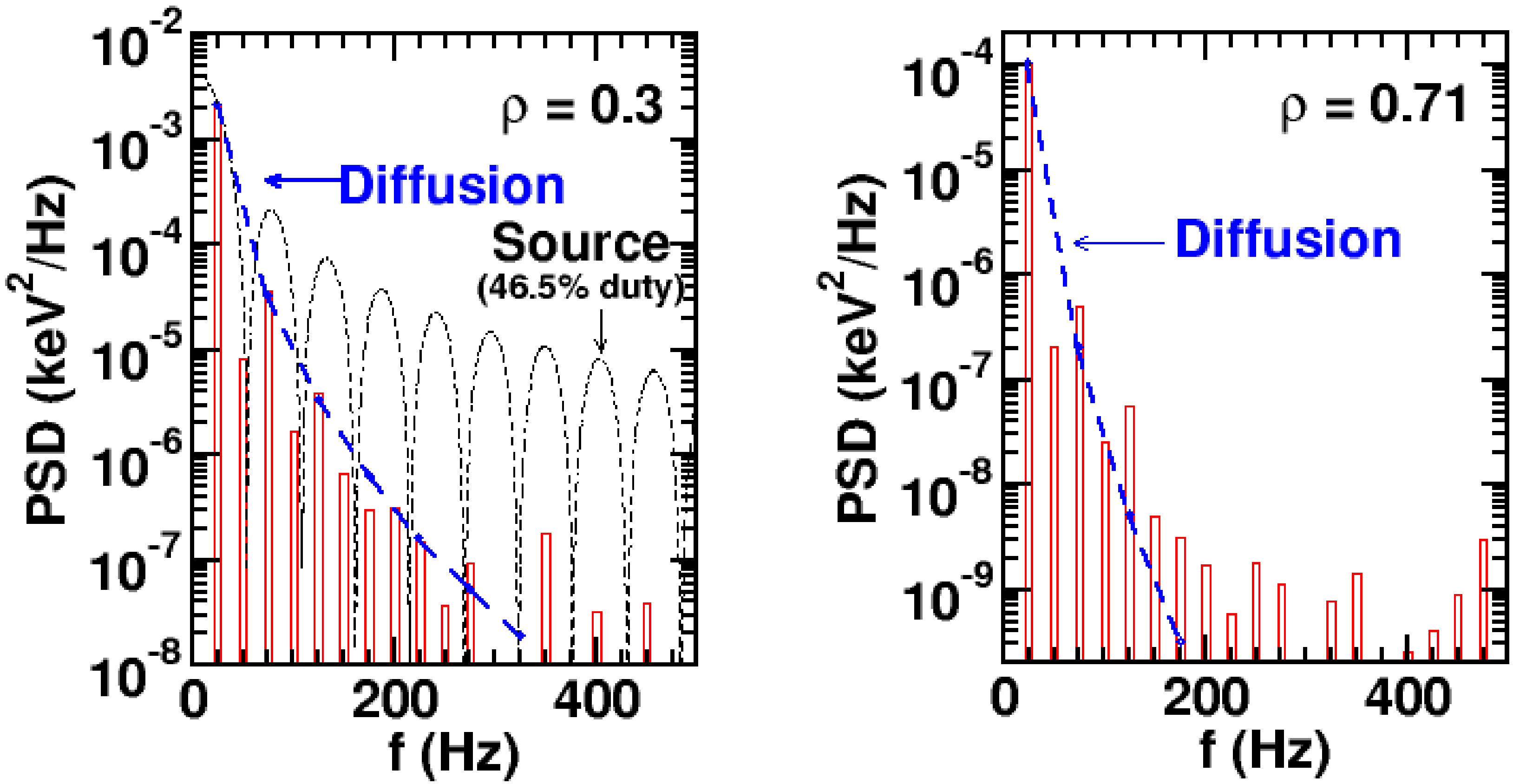

The conventional $\chi_{hp}$ is flawed since it neglects two time scales in transient response.

# Higher harmonics in the heat pulse propagation



The two-time scale feature should appear in the response of extremely-higher harmonics

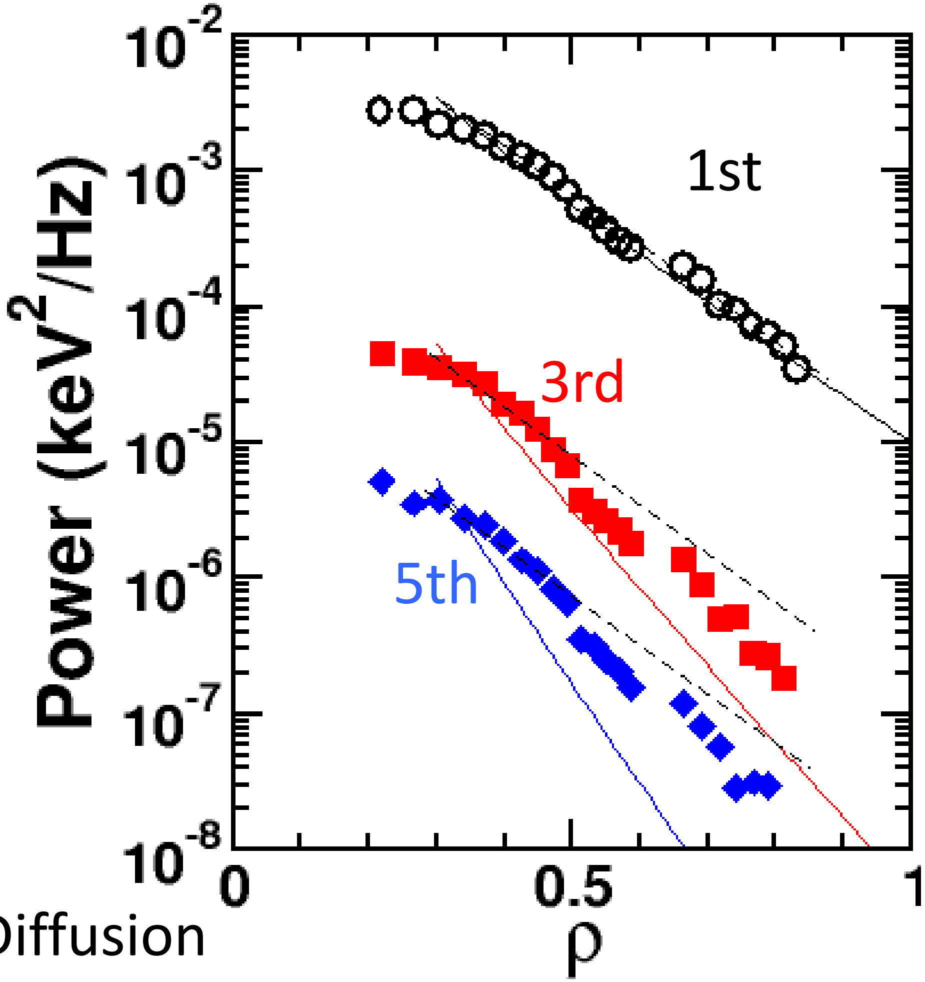
(Conditional Averaged)



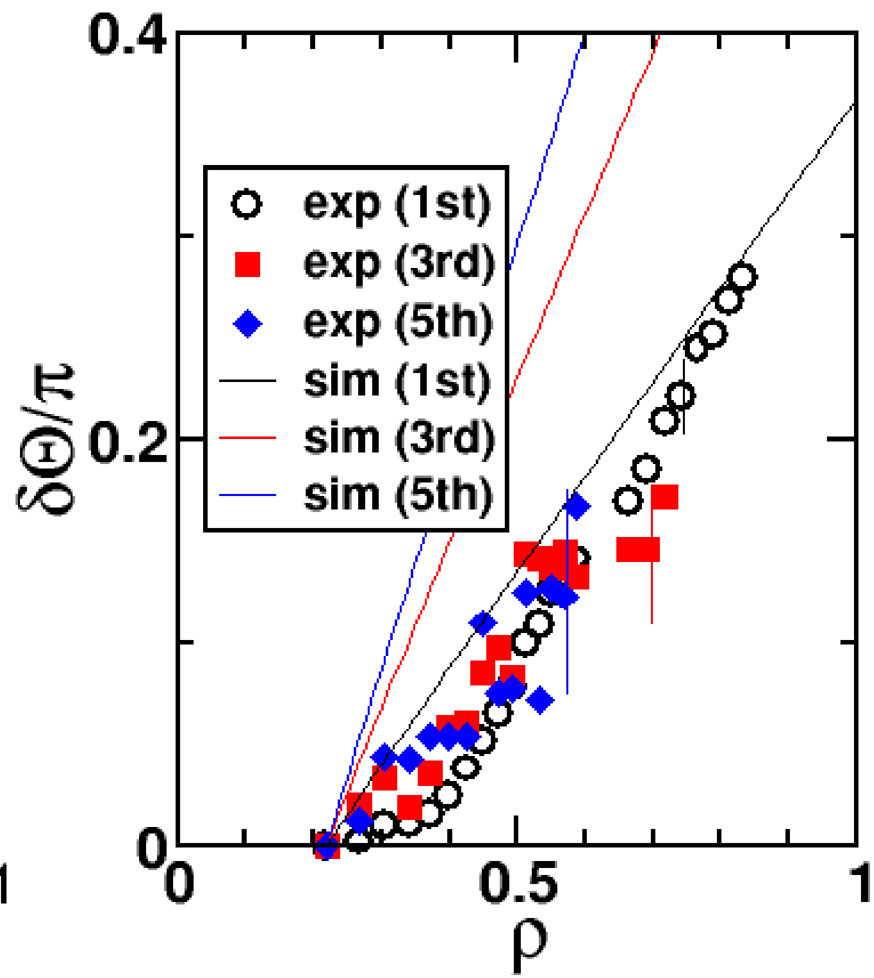

More-than 10th harmonics are observed even far away from source

# Features of Higher harmonics

## Weaker decay in amplitude




## Faster propagation

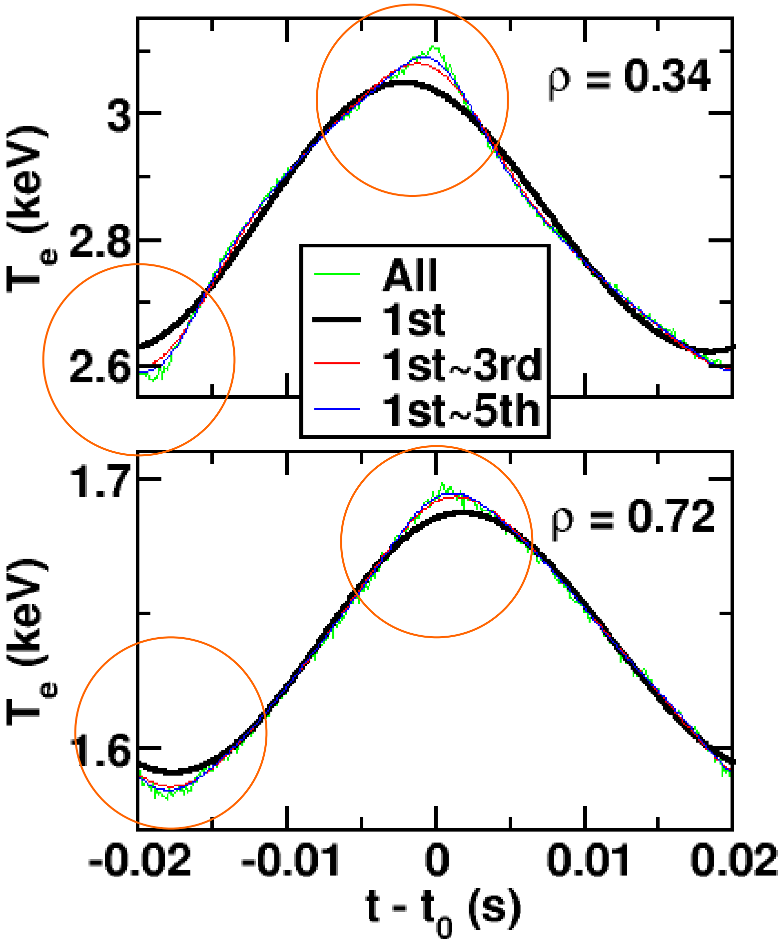



Diffusion

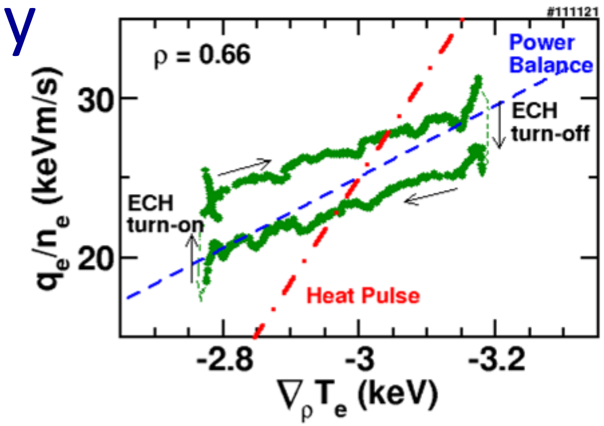
$$\frac{1}{A}\frac{\partial A}{\partial r} \sim \frac{\partial \Theta}{\partial r} \propto \sqrt{m}$$

Observations far from diffusive nature

# Higher harmonics in the heat pulse propagation




Fundamental mode can not catch the response around turn-on/off of ECH power where $q_e$ changes discontinuously

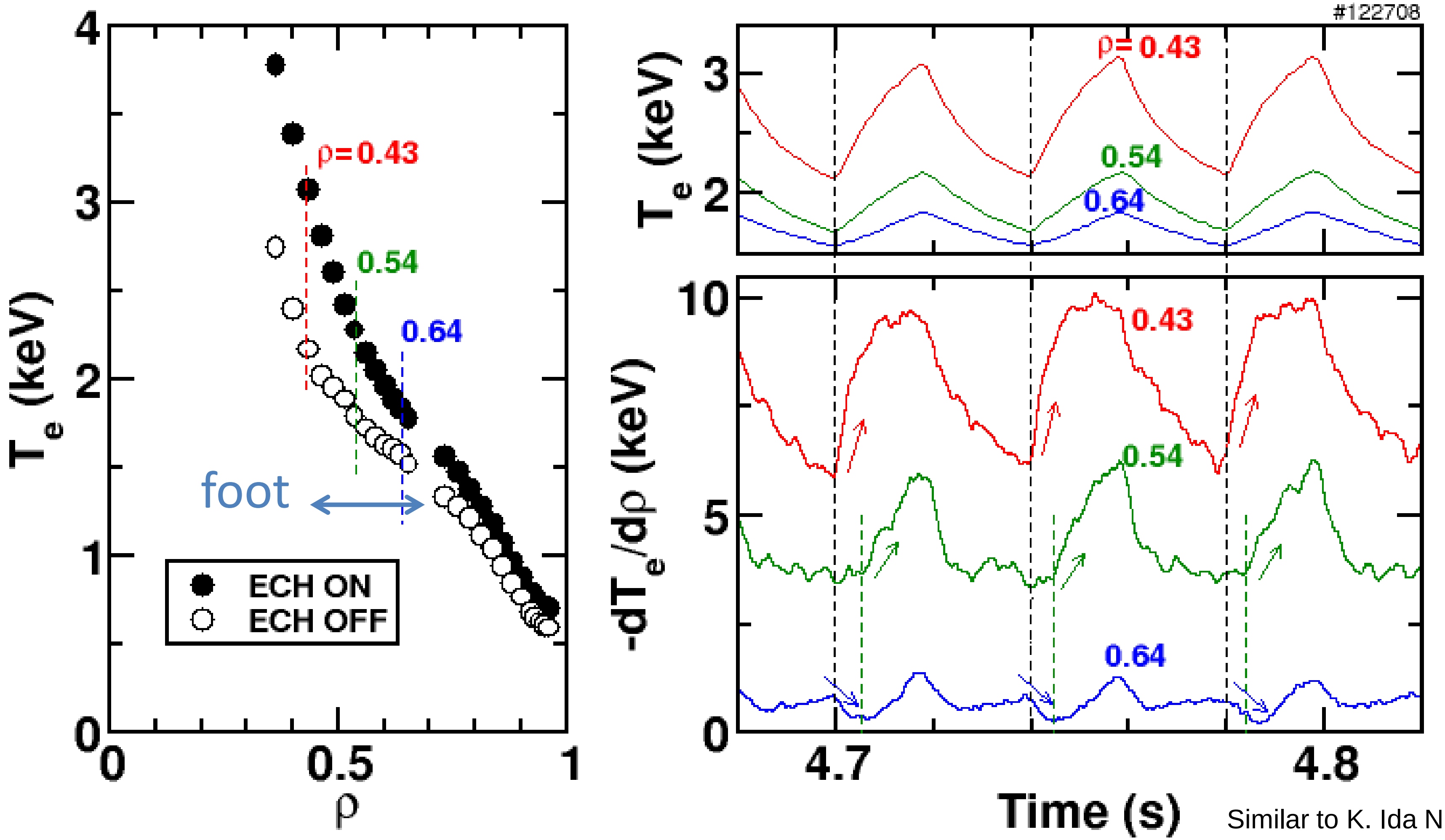



To describe a discontinuous function, higher harmonics is essential

Higher harmonics should be more routinely checked to clarify the transport with multiple-valued flux

# Heat pulse propagation during ITB transition

- ECH modulation experiment near the ITB transition
- The ITB foot shifts back and forth during ECH modulation




Similar to K. Ida NF 2009

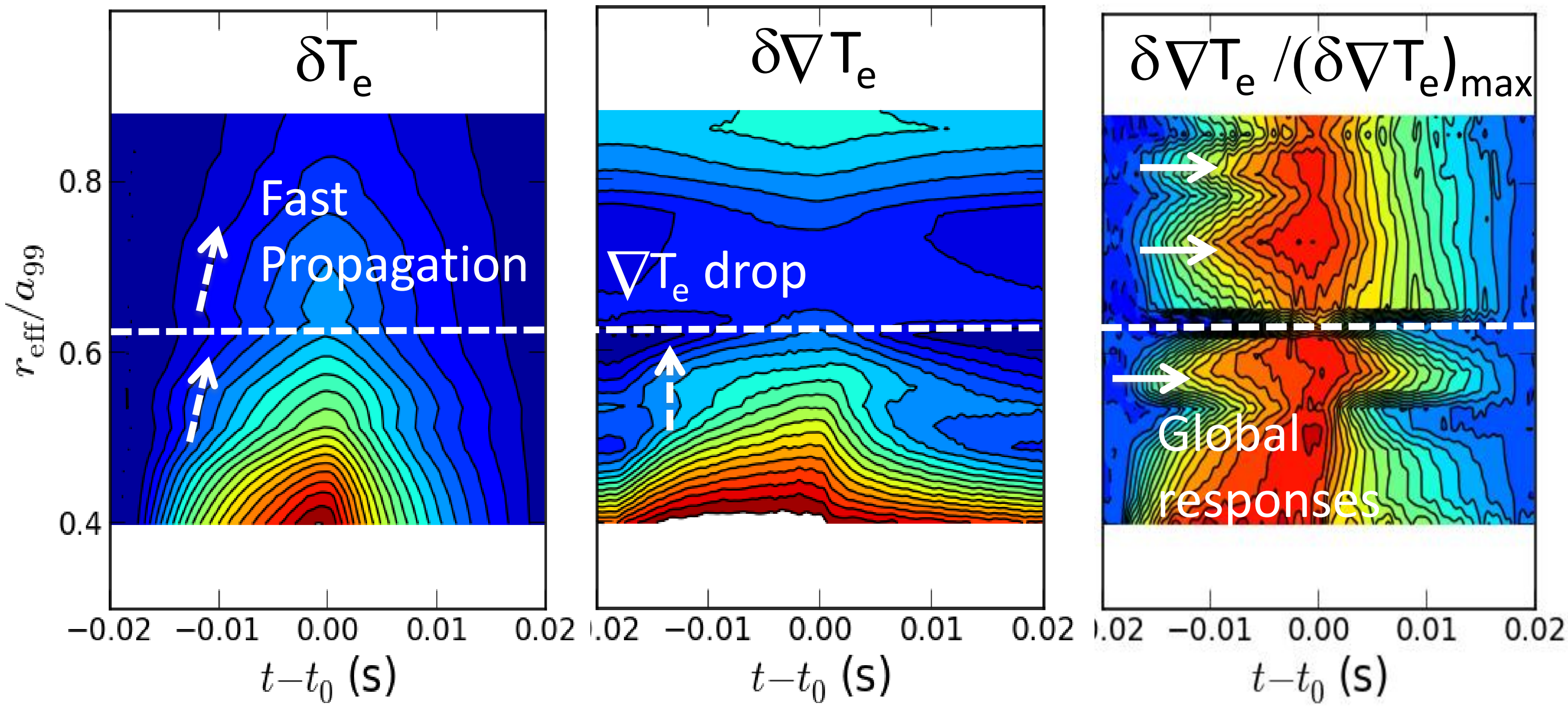
**Delayed rises and simultaneous drops are observed**

# Mixed time-scale phenomena



- Three or four dynamics combined
- Fast propagation, Displacement of ITB front, Global (non-local) response in $\nabla T_e$

(Conditional Averaged)

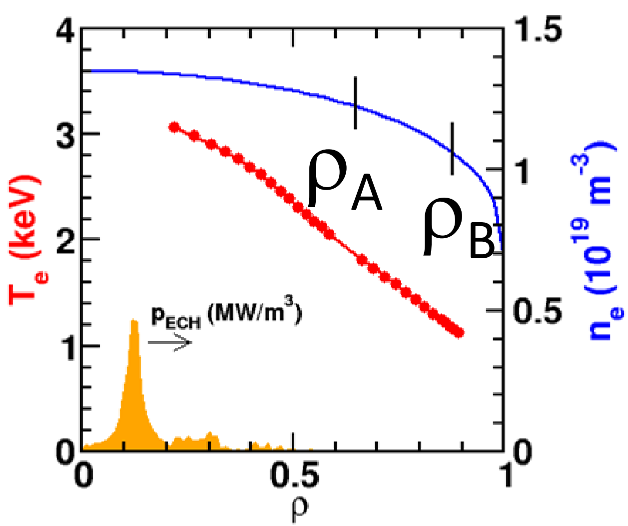


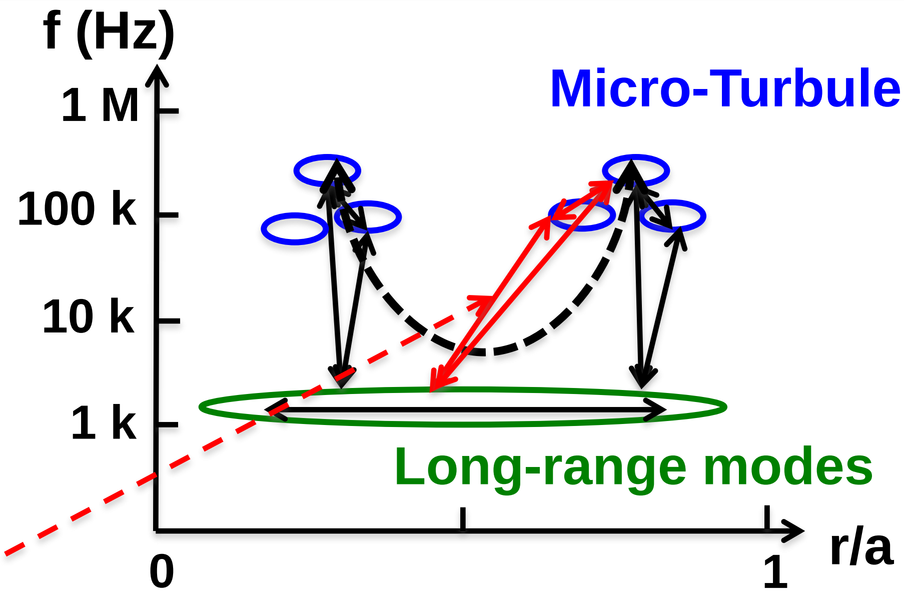

ITB transition is involved with multi-mechanisms

# Method to observe multi-scale couplings of turbulence

Non-locality of turbulence is one of the important keys to understand the multiple-valued flux (hysteresis and two time-scale response)

# Cross Bi-Coherence of Fluctuations at Distant Locations




Non-Local Bi-Coherence

$$b_{\mathrm{nl}}^2(f_1, f_2) = \frac{\left|\left\langle F^*(f_3, r_A)\, f(f_1, r_B)\, f(f_2, r_B)\right\rangle\right|^2}{\left\langle \left|F(f_3, r_A)\right|^2 \right\rangle \left\langle \left|f(f_1, r_B)\, f(f_2, r_B)\right|^2 \right\rangle}$$

$\phi(f_1, \rho_B)$, $\phi(f_2, \rho_B)$: Fluctuations at $\rho_B$

$\Phi(f_3, \rho_A)$: Fluctuations at $\rho_A$

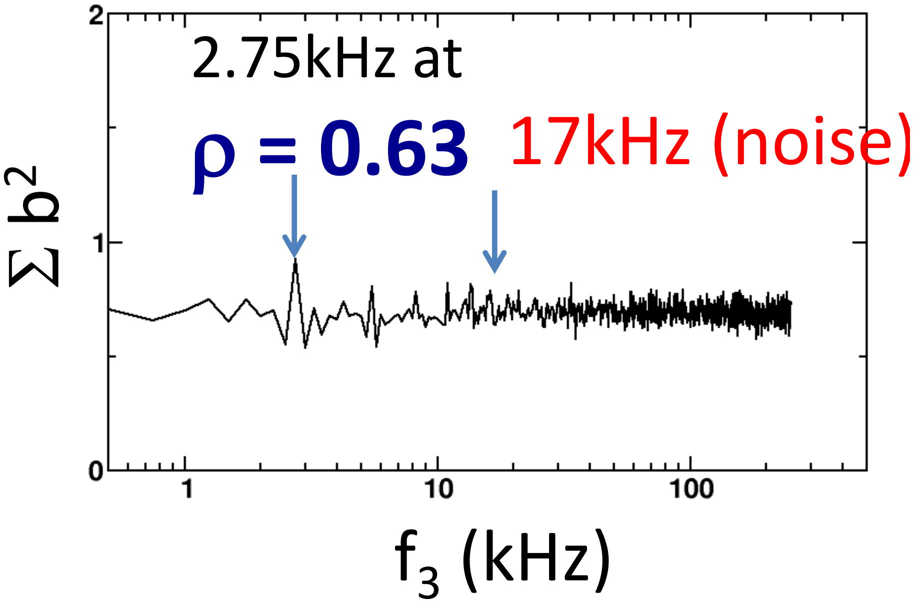
$\rho_B - \rho_A \gg$ correlation length of micro-modes

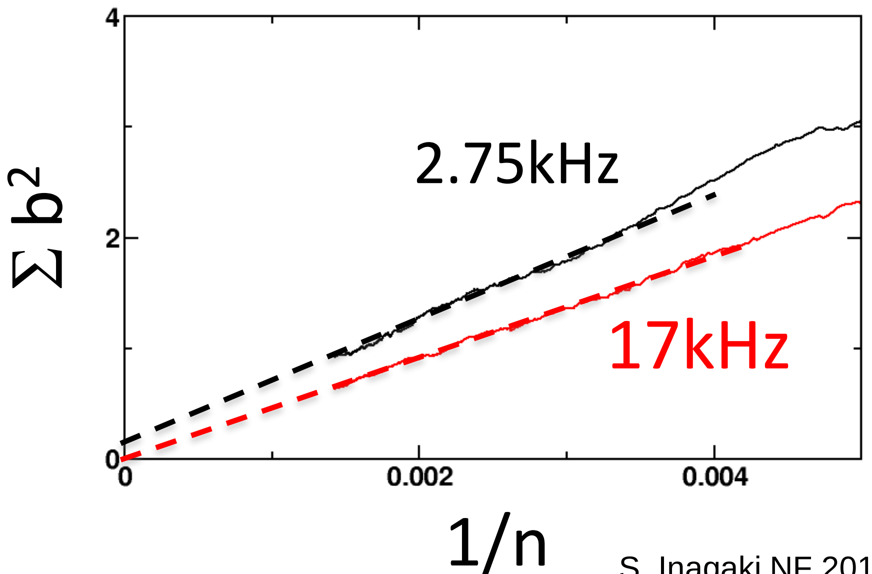
# Non-Local Micro-Global Coupling



- Summed bi-coherence shows a peak at 2.75 kHz
- The summed bi-coherence converges to 0.2 (~1/10 of the local summed bi-coherence)

150 kHz < $f_1$ < 250 kHz at **ρ = 0.88**

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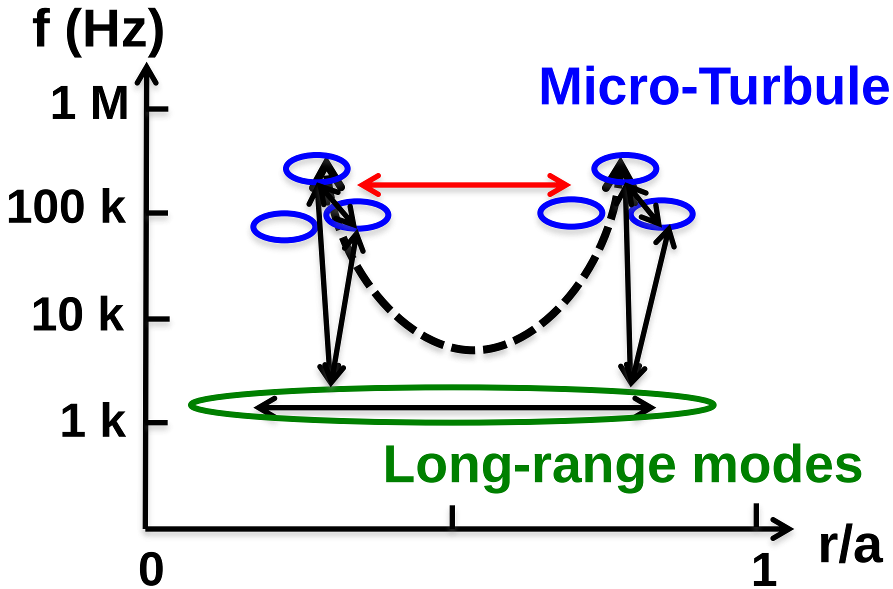
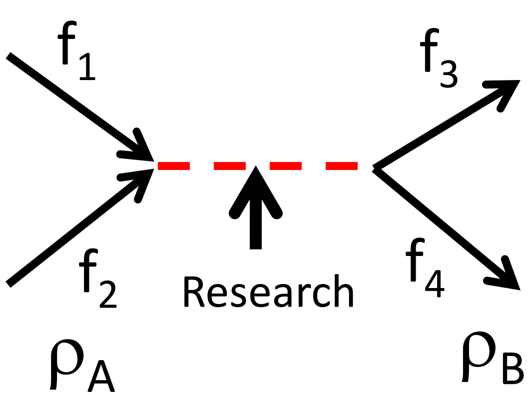
Global fluctuation(2.75 kHz) at $\rho_A$ = 0.63 non-locally couples with micro-fluctuations (150-250 kHz) at $\rho_B$ = 0.88

# Tri-Coherence analysis is just started

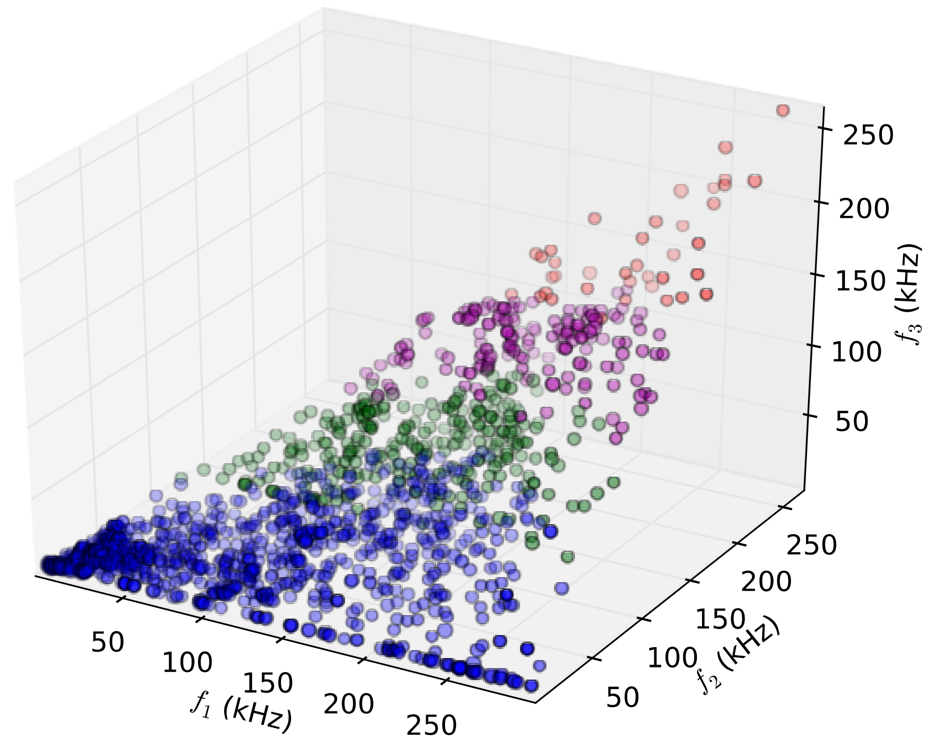



4-Wave coupling between distant locations

$$f_1 + f_2 = f_3 + f_4$$




$\gamma_{tri}^2 > 0.1$




Tri-coherence at two distant locations is calculated

# Summary



This study established methods for analyzing (i) heat transport dynamics beyond Fick's law and (ii) 'non-local' coupling of micro-fluctuations.

- Conditional averaging technique is very useful to understand the transport with multiple-valued flux

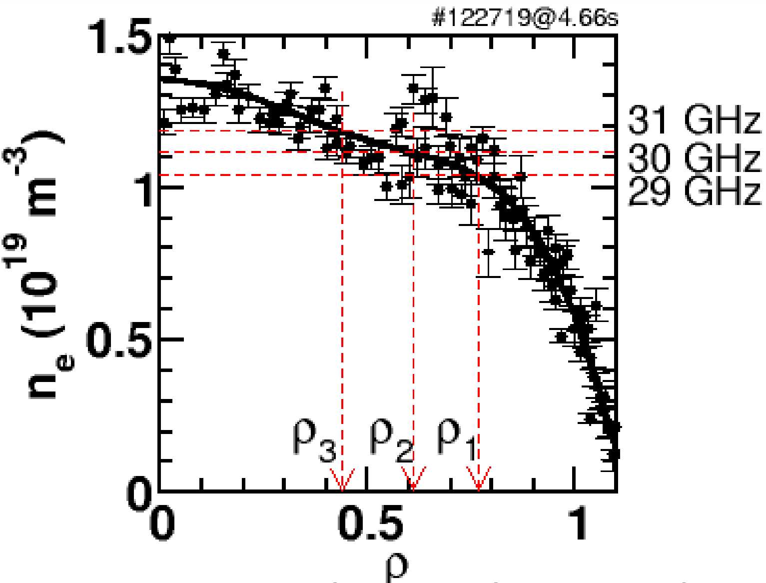
  Hysteresis in transport = two-time scale response
  =Slow decay and fast propagation of the higher harmonics

  Identification of three or four time-scale responses in the ITB plasma

- Non-local bi-/tri-spectrum analysis allows us to study the non-local coupling between micro-fluctuations

These results are beneficial for understanding of the plasma dynamics in future fusion reactors.

# Non-Local Micro-Micro Coupling




Tri-coherence suggests

- Micro-fluctuations (>50 kHz) at two different locations are coupled
- Global-fluctuations (<10 kHz) are involved

< 10 kHz     < 10 kHz

Like-scale couplings e.g 102kHz+101kHz →99kHz+103kHz