磁場閉じ込めトロイダルプラズマにおける輸送の非局所応答

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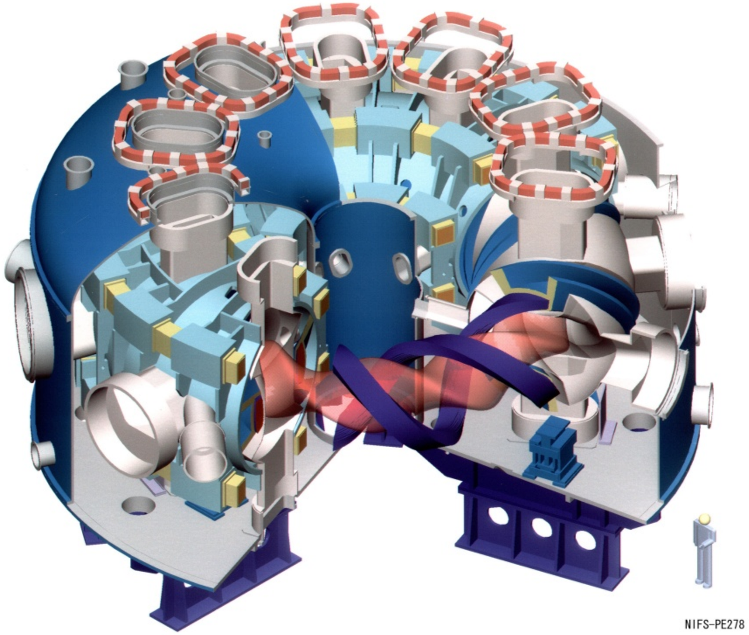
第16回若手科学者によるプラズマ研究会
“プラズマ輸送・閉じ込め物理の総合的理解に向けた予測・検証手法の進展”

日本原子力研究開発機構　那珂核融合研究所

5 March 2013



講演概要

✓ はじめに

- 磁場閉じ込めトロイダルプラズマにおける熱輸送
- 輸送の非局所応答（非局所性）とは？
- 輸送の非局所応答の好例：
  「非局所輸送現象」

✓ 非局所輸送現象に対して最近得られた知見

- 熱流束と温度勾配の複雑な関係
- 長距離相関を持つ電子温度揺動
- 電子熱輸送における潜在的空間構造

✓ 核融合研究における輸送の非局所応答の研究意義

✓ まとめ

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磁場閉じ込めトロイダルプラズマにおける熱輸送

磁場閉じ込め方式の核融合研究における重要課題

✓ **熱輸送の完全なる理解**

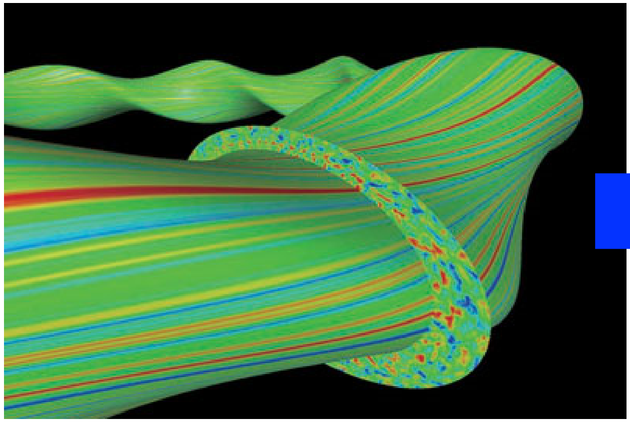
- アルファ粒子加熱を念頭に置くと、**特に電子について重要**
- 炉性能の予測精度向上に不可欠

磁場閉じ込め高温プラズマにおける輸送は、**クーロン衝突（新古典輸送）**ではなく、**微視的乱流（異常輸送）**によって決まっている

✓ **乱流輸送の理解が鍵！**

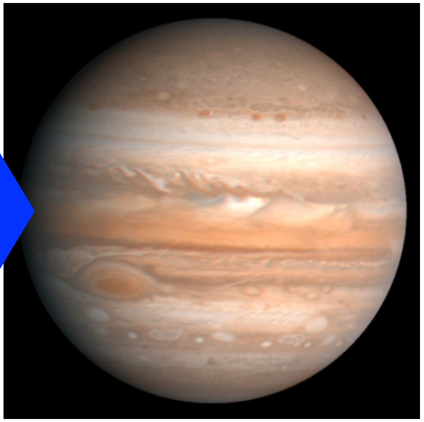
乱流輸送の理解は諸分野にまたがる共通課題

✓ 自然界において、共通性の高い現象が多く観測



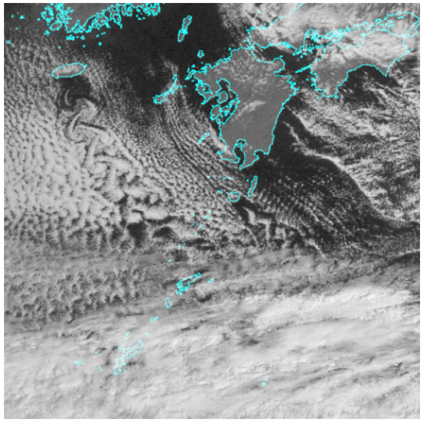
http://www.dss.nifs.ac.jp

シミュレーションによる大型ヘリカル装置プラズマ中の「ゆらぎ」分布



http://photojournal.jpl.nasa.gov

木星大気に見られる帯状構造



http://weather.is.kochi-u.ac.jp/

済州島南の雲渦に見られるカルマン渦列

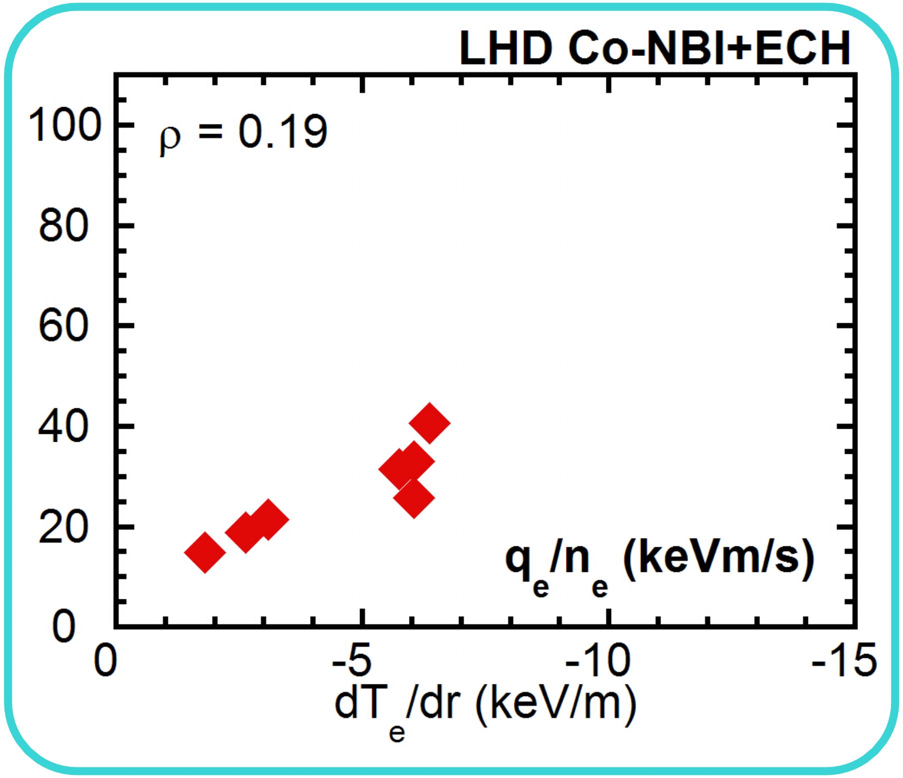
http://chandra.harvard.edu

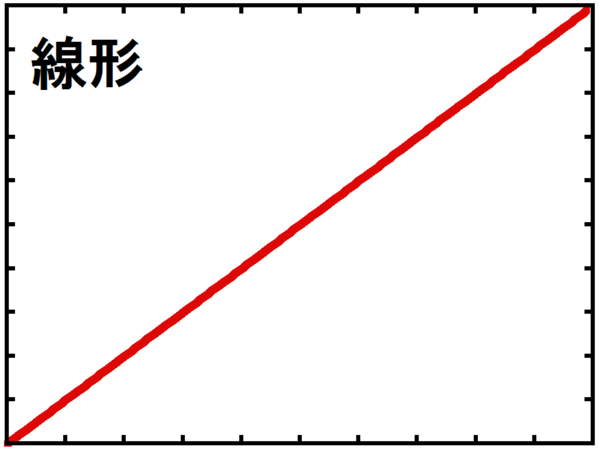
降着円盤と宇宙ジェット形成

磁場閉じ込めトロイダルプラズマにおける流束と勾配の関係

熱流束の表式（フーリエの法則によると仮定）

✓ $q = -n\chi\nabla T$ （χ：熱拡散係数）





熱流束が低い状態に対しては，線形近似が成り立ちそう

磁場閉じ込めトロイダルプラズマにおける流束と勾配の関係

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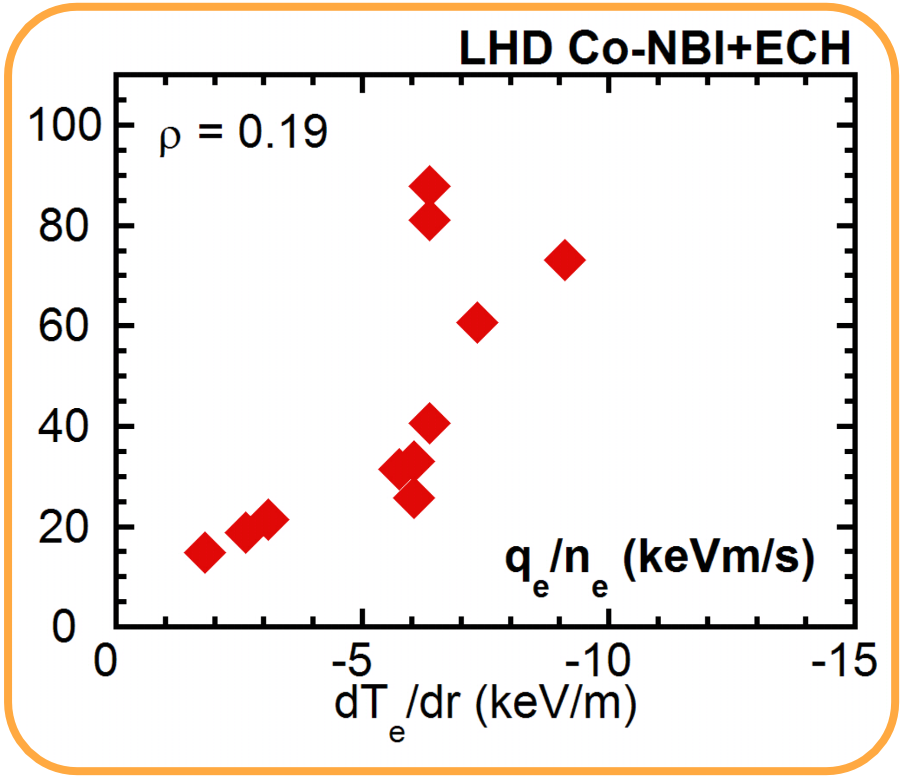

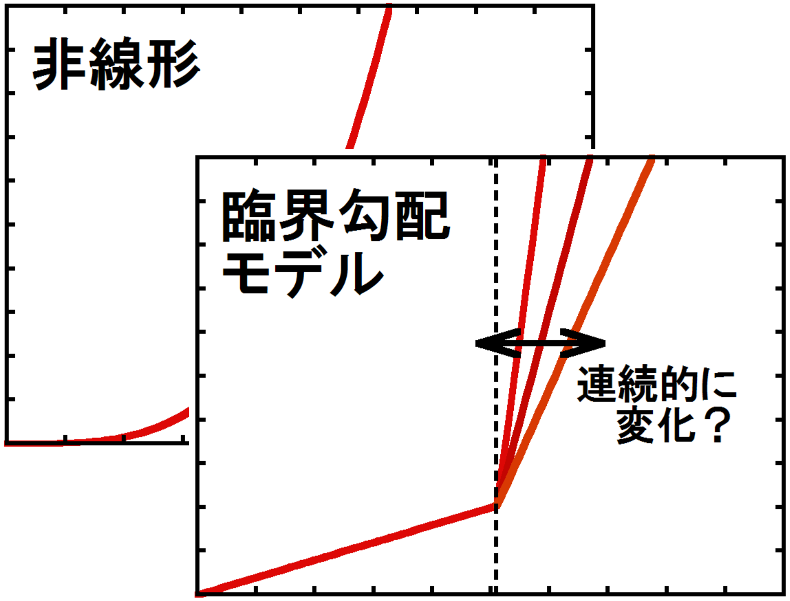

熱流束が増加しても，勾配がほとんど増加しない状態に移行

- ✓ 非線形性（熱拡散係数の温度勾配依存性，$\chi \propto \nabla T_e^{\alpha}$）が必要そう
- ✓ もしくは，別の物理モデル（例えば，臨界勾配モデル？）が必要？

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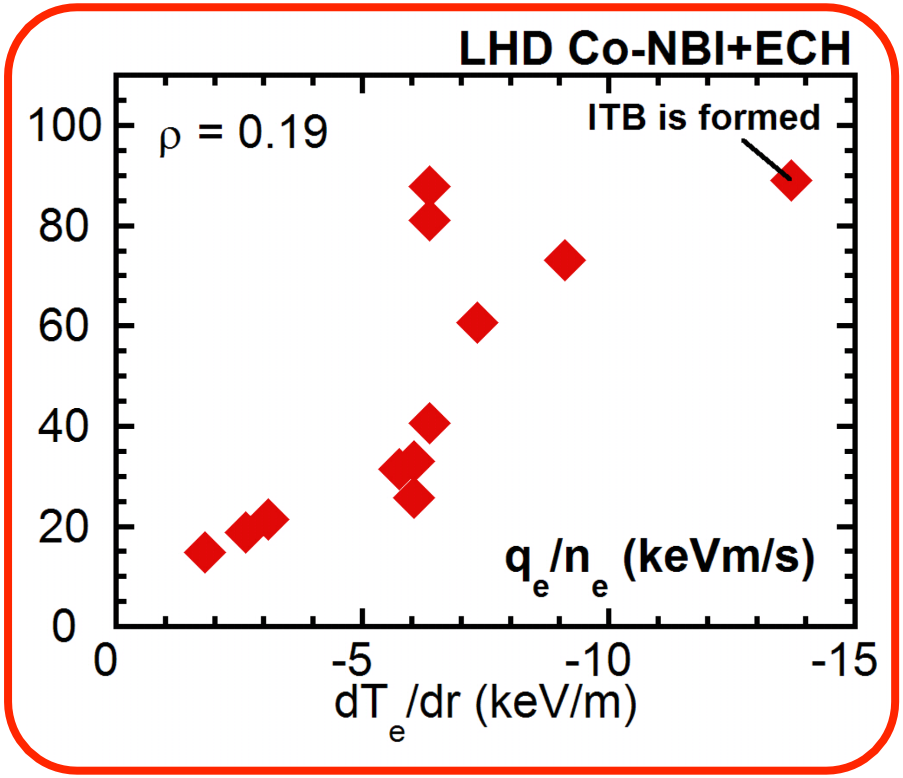
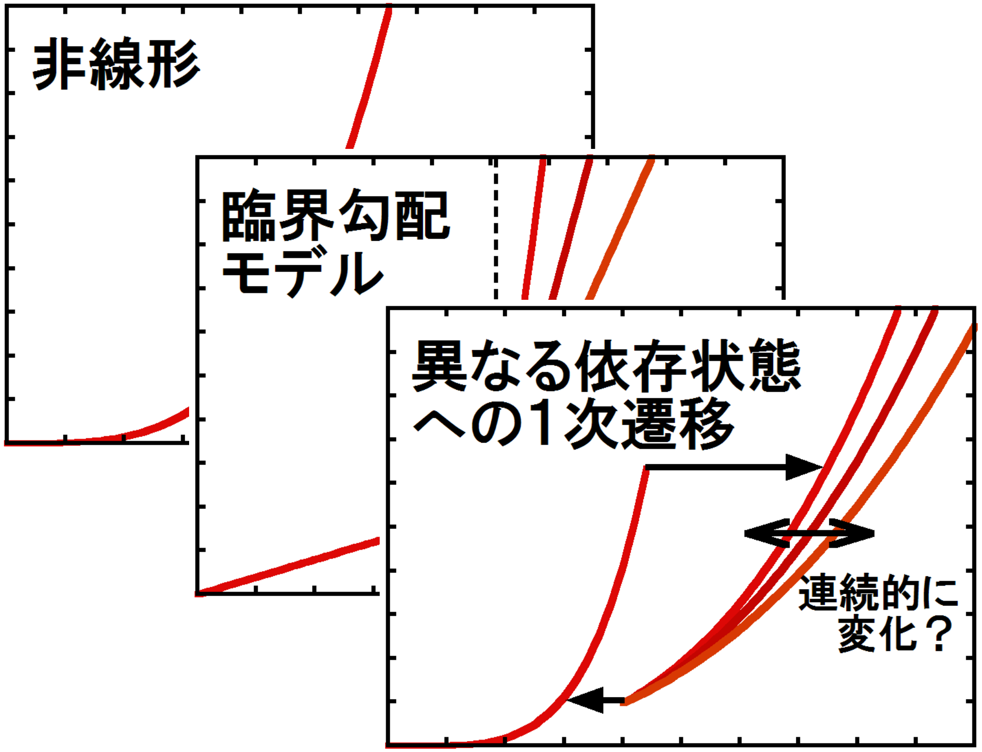




さらに，高閉じ込め状態への遷移も発生しうる

✓このように，実験では多様な流束と勾配の関係が観測されている

磁場閉じ込めトロイダルプラズマにおける流束と勾配の関係（一般化）

- ✓ Transport matrix

$$\begin{array}{lcccc}
 & \text{Flux} & & \text{coefficient} & \text{gradient} \\
\begin{matrix}\text{Particle}\\ \text{Momentum}\\ \text{Heat}\end{matrix} & \begin{pmatrix}\Gamma\\ \Pi_{\phi,\theta}\\ Q_{e,i}\end{pmatrix} & = & \begin{pmatrix} -D & M_{12} & M_{13}\\ M_{21} & -\mu_{\phi,\theta} m_i n_i & M_{23}\\ M_{31} & M_{32} & -n_{e,i}\chi_{e,i}\end{pmatrix} & \begin{pmatrix}\nabla n_e\\ \nabla V_{\phi,\theta}\\ \nabla T_{e,i}\end{pmatrix}
\end{array}$$

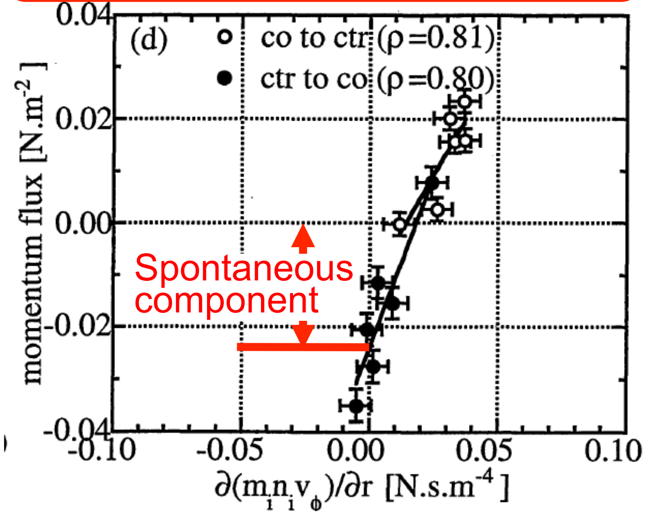
Contribution form diagonal term (M_{nn})
→ **Diffusive transport**

Contribution from off-diagonal terms (M_{nl})
→ **Non-Diffusive transport**

- ✓ Examples for Non-Diffusive transport
  - ● Particle: Inward pinch(Ware pinch, …)
  - ● Momentum: Spontaneous rotation

These rest on the validity of
the Fourier-Fick's LOCAL prescription

Spontaneous toroidal rotation in JFT-2M tokamak



K. Ida et al., J. Phys. Soc. Jpn. **67**, (1998) 4089

磁場閉じ込めトロイダルプラズマにおける流束と勾配の関係(一般化)

✓ Transport matrix

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\end{array}$$

However, many of the experiments demonstrate the violation of Fourier-Fick’s prescription

In fact, contribution from **values at a distant location**

→ **Non-Local transport**

Mathematical structure of
nonlocal models
for heat transport

$$q_{nl}(\rho,t) = -\int\int K\left(\rho'-\rho, t'-t\right)\nabla T(\rho',t')\,dt'\,d\rho'$$

Paradigm shift has begun!

Most Famous Example of Nonlocal Response in Electron Heat Transport

Abrupt rise of core T_e in response to the edge cooling

= **"Nonlocal Transport Phenomenon (NTP)"**

Other examples

- ✓ Ultrafast/ballistic heat/cold pulse propagation
- ✓ Core T_e drop due to the edge heating

  = **"Large Scale Transport Event (LSTE)"**

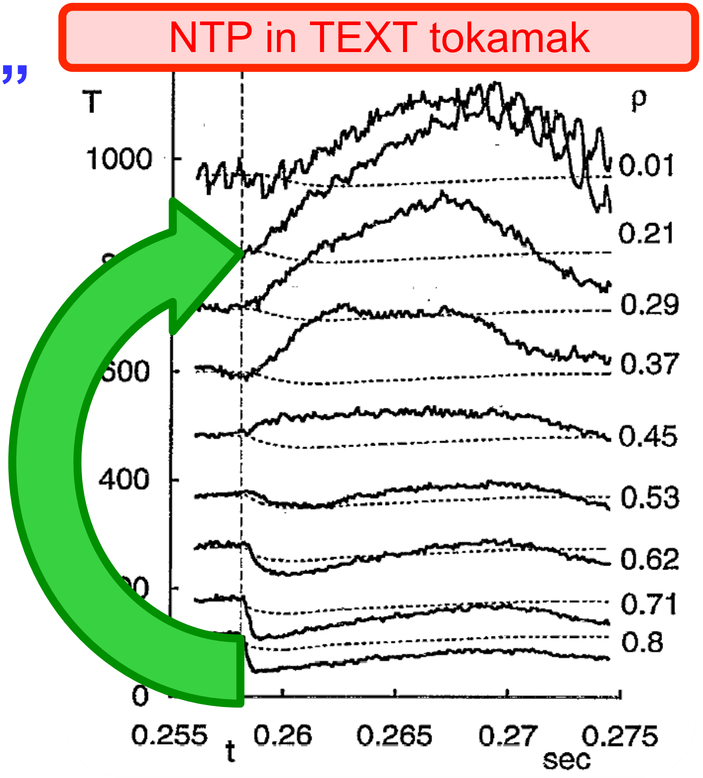
  in general

Main feature of the LSTE

- ✓ Characteristic time of change

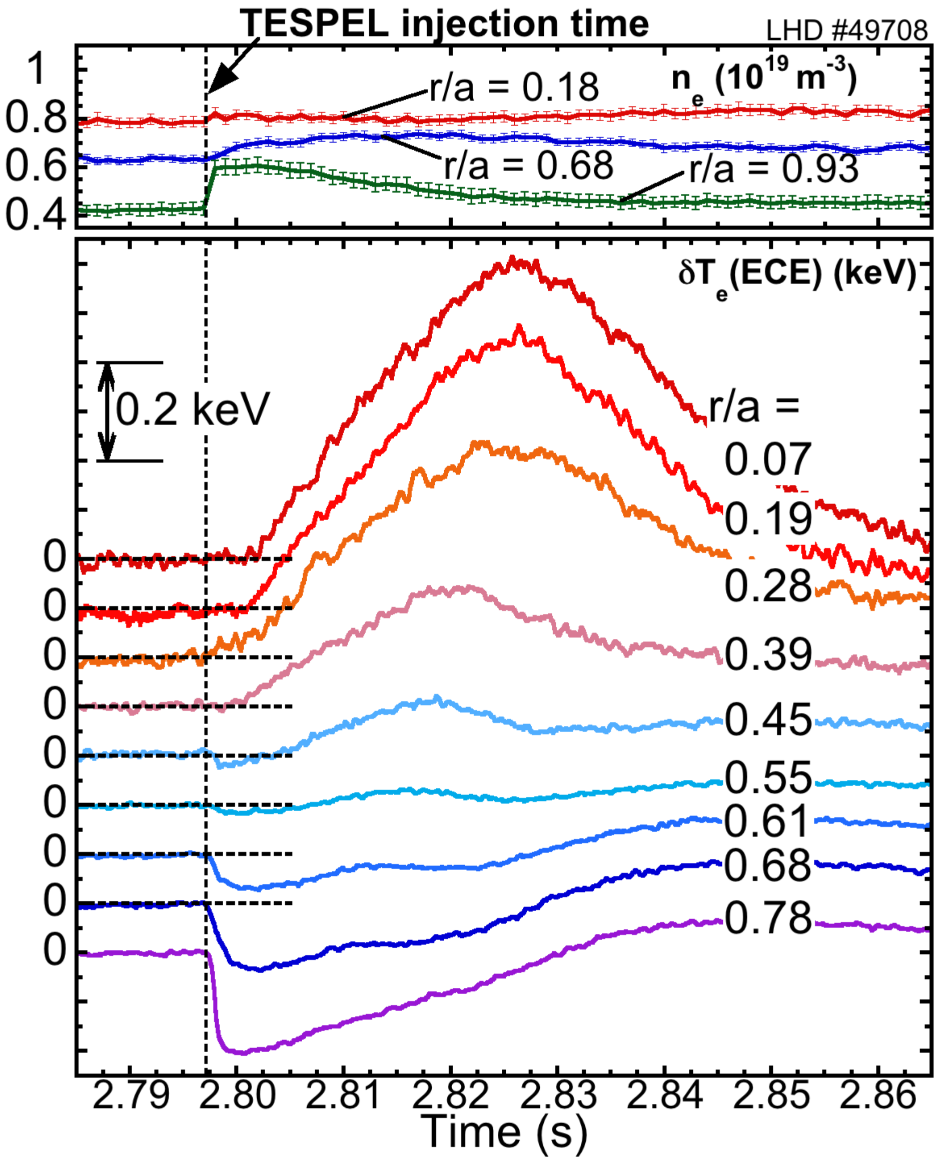
  $\ll$ *a*(plasma size)$^2/\chi$
- ✓ Characteristic length of change

  $\gg$ characteristic length of n_e, T_e gradients


NTP in TEXT tokamak

K. W. Gentle et al., PoP **2** (1995) 2292

Nonlocal Transport Phenomenon in Large Helical Device (LHD)



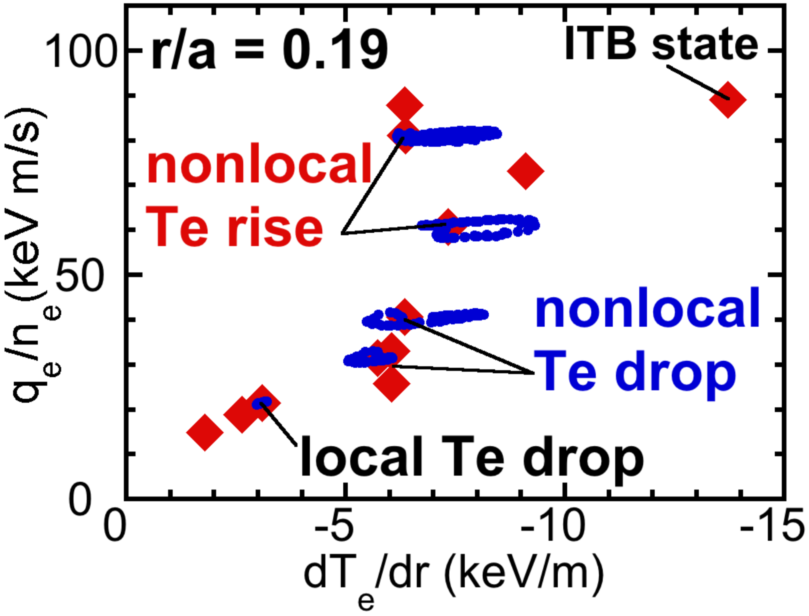
N. Tamura et al., PoP **12** (2005) 110705

Core T_e is abruptly increased just after a tracer impurity pellet (TESPEL) injection

- ✓ No change in low-m MHD modes
- ✓ No density peaking
- ✓ Electron heating dominates ($T_e/T_i>1$)

Key elements

- ✓ Low collisionality & High heat flux



S. Inagaki and N. Tamura et al., PPCF **52** (2010) 075002

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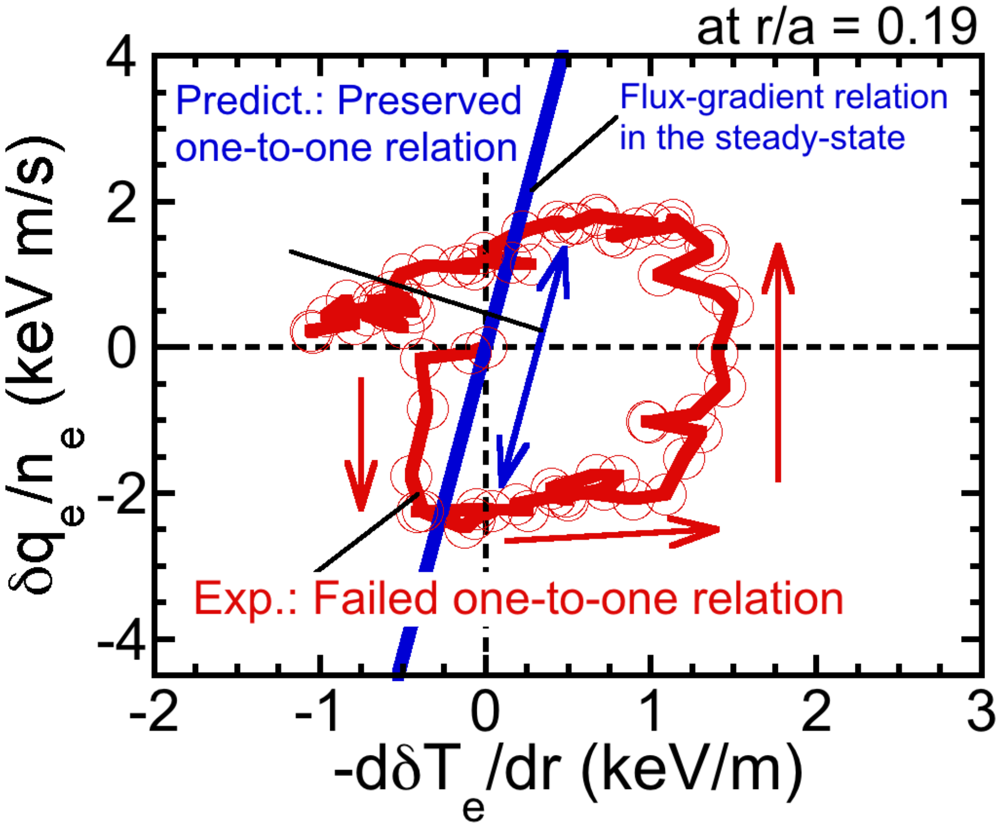
Complex Relationship Between Heat Flux and ∇T_e was Revealed in Nonlocal Transport Phenomenon of LHD

Completely-failed one-to-one relation between heat flux and ∇T_e is observed

- ✓ Reduction of $\delta q_e/n_e$ without changes in local ∇T_e
  = Clear evidence against "local diffusive paradigm"

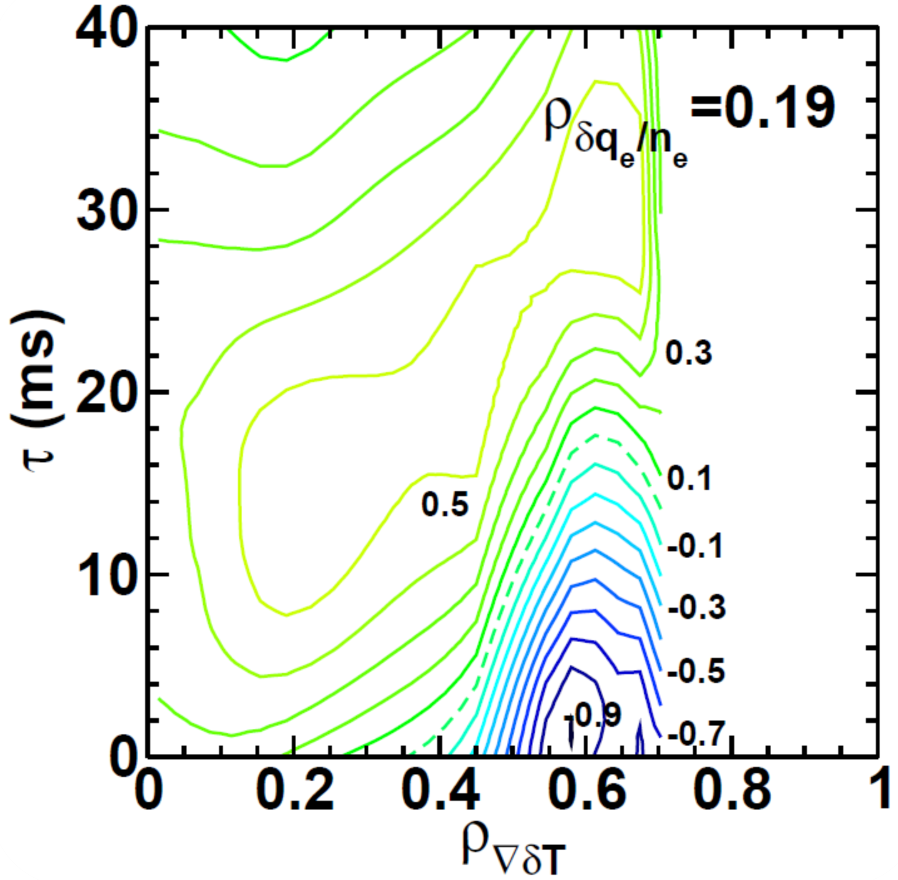


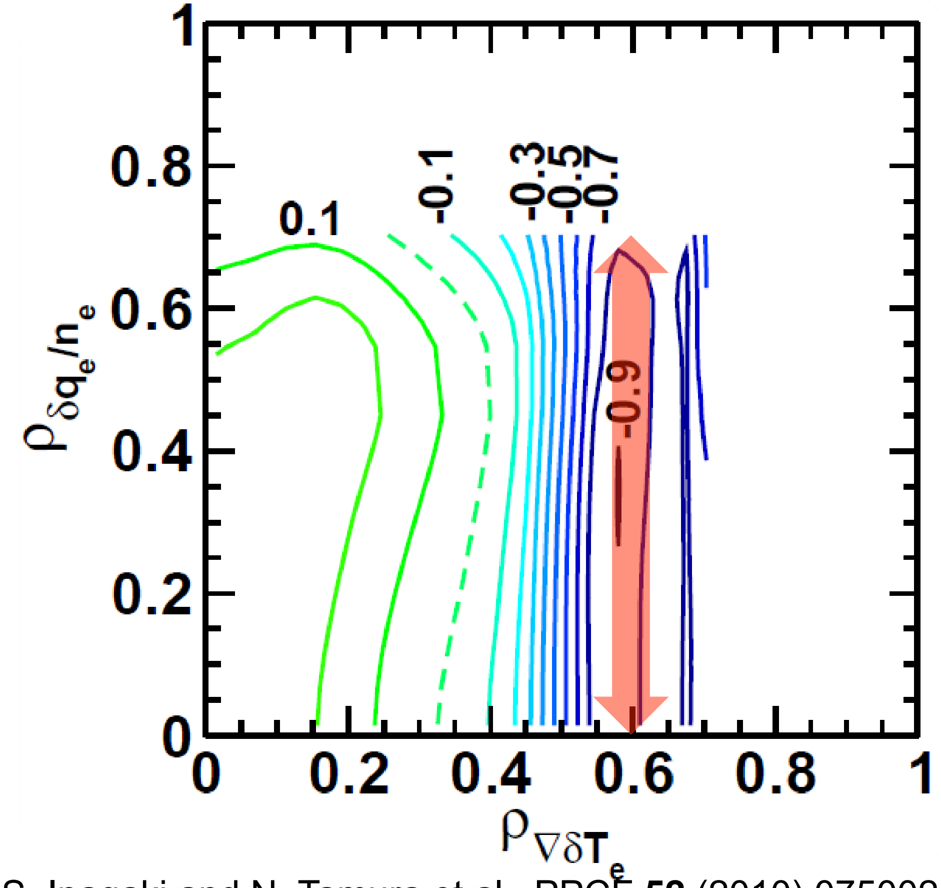
Cross-Correlation Analysis between Heat Flux And T_e Gradient Suggests a Long Distance Correlation

A strong negative correlation between core q_e/n_e and edge ∇T_e

✓$(-\partial(q_e/n_e)/\partial\nabla T_e) < 0$ is often observed in the transition phase

✓Correlation length ~ 0.7a = close to a macro-scale





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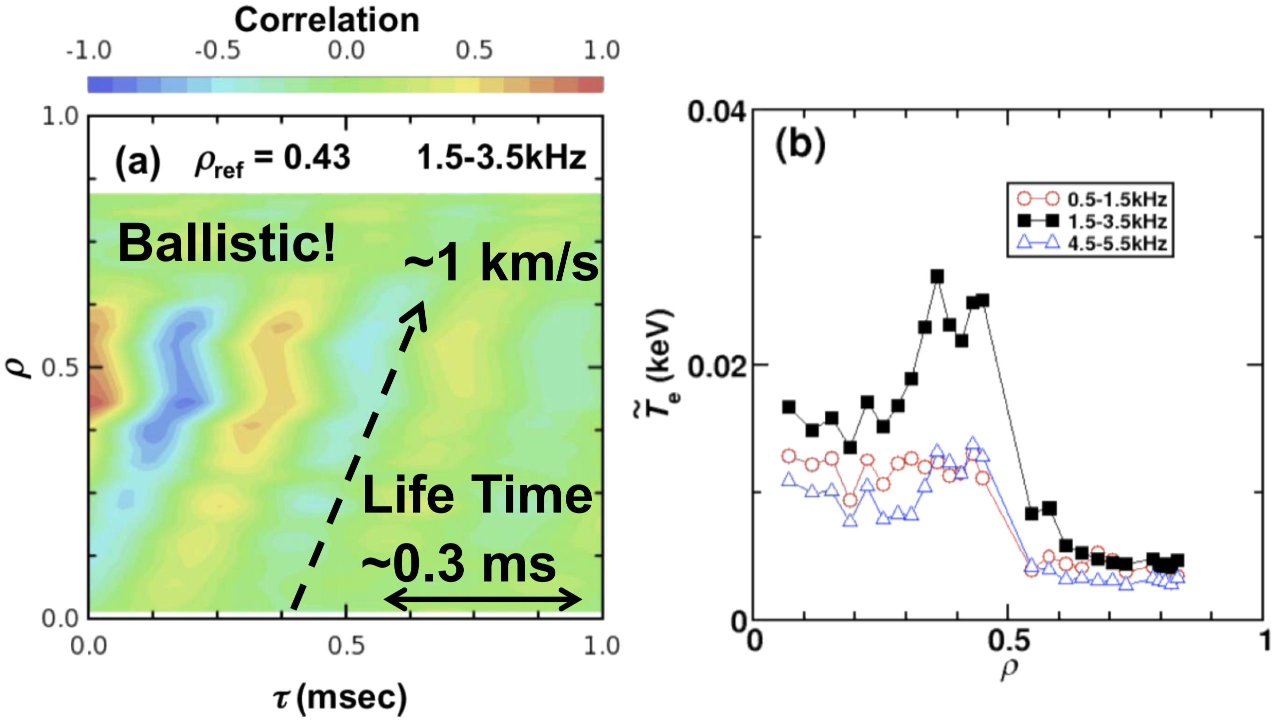
Long-Range Fluctuations was Discovered in the Plasma Showing the Nonlocal Response in Transport

Turbulences between distant locations should be connected

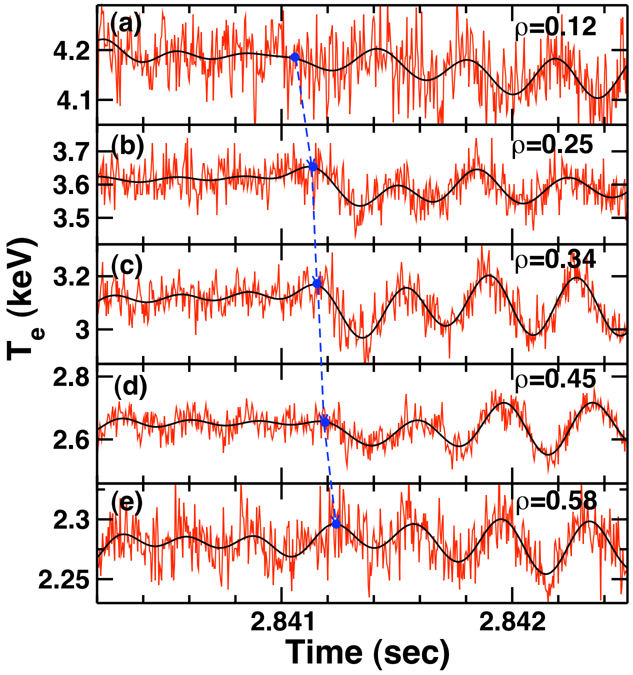
✓ Possible mediators: Turbulence spreading, Meso-scale structures, **Long-range fluctuations**



Ballistic!

~1 km/s

Life Time ~0.3 ms

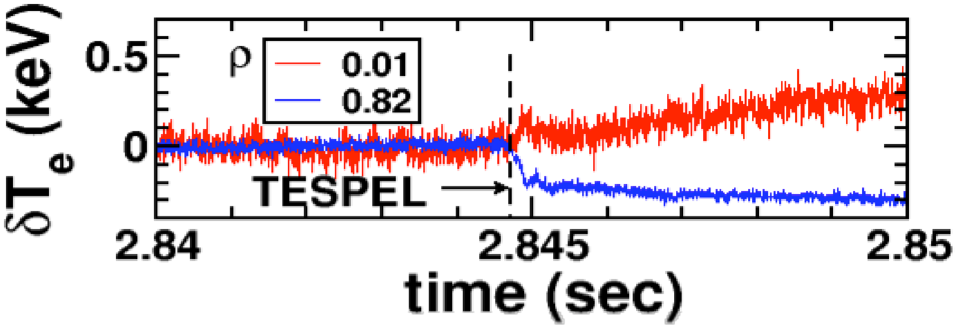


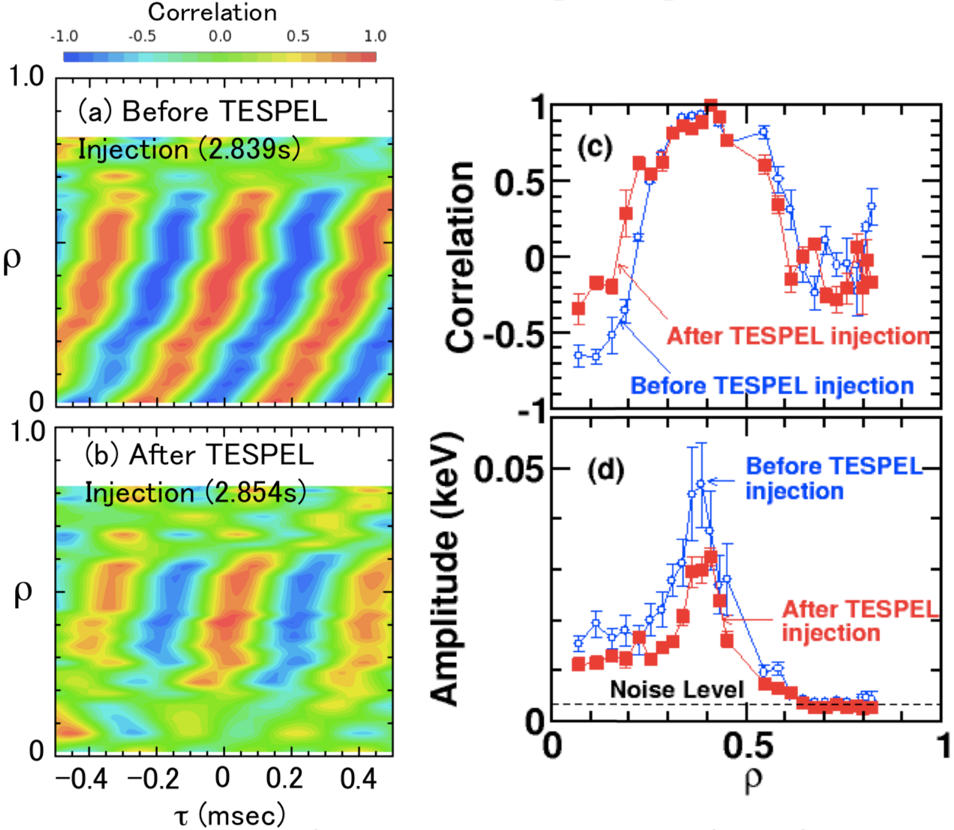
Change propagates in 100 μs order
≒ Response time of non-local T_e rise

Further *quantitative* studies are required to understand the role of the long-range T_e fluctuations

S. Inagaki et al., PRL **107** (2011) 115001

Structure of Long-range Low-freq. Fluctuation is Modified after the Edge Perturbation





S. Inagaki et al., NF **52** (2012) 023022

Structural change in the long-range low-freq. fluctuation is observed before and after the edge perturbation

After the edge perturb.,

- ✓ **Amplitude is reduced**
- ✓ **Radial correlation length becomes shorter**

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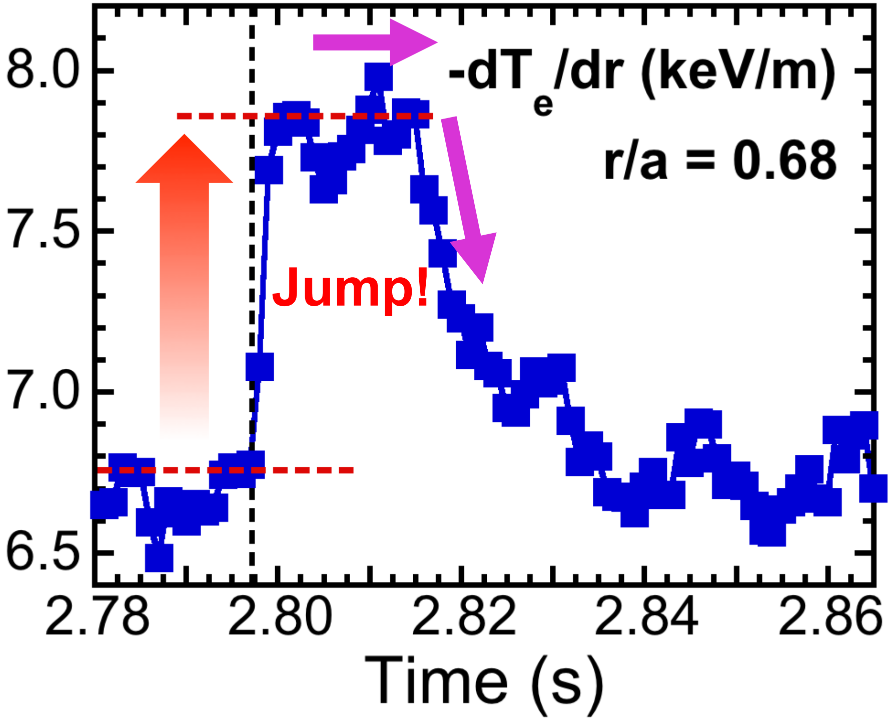
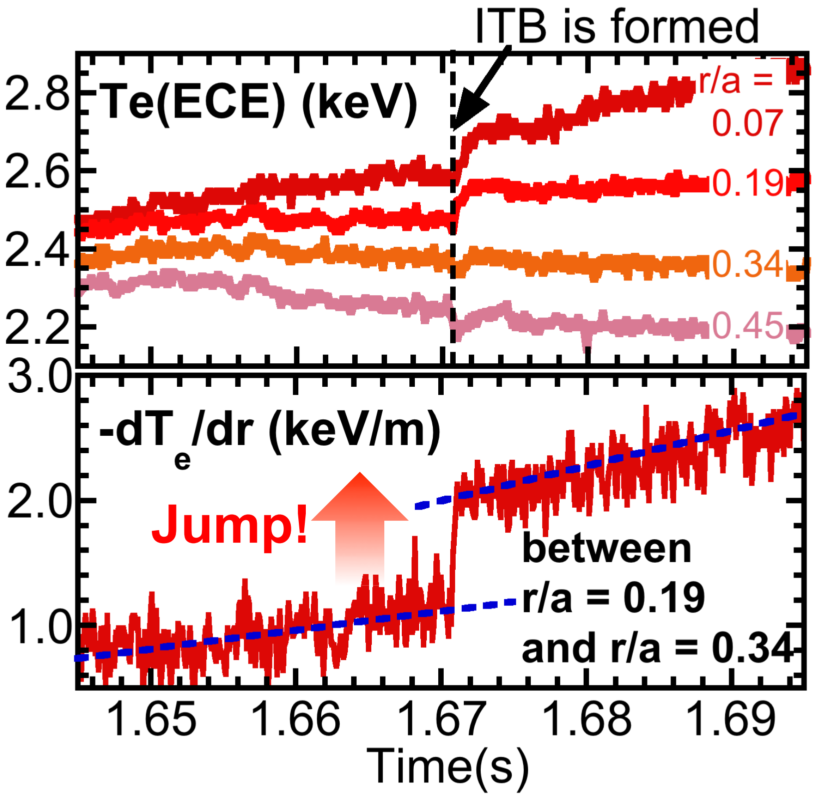
Temporal Behavior of ∇T_e Represents Dynamics of Local Heat Transport States

✓ **First-order transition takes place** in the region extending from ρ ~ 0.6 to at least ρ ~ 0.7 (at least **6 cm wide**)

✓ **First-order transition:**
Discontinuity in ∇T_e

- Can be seen in ITB formation, L-H transition, etc.



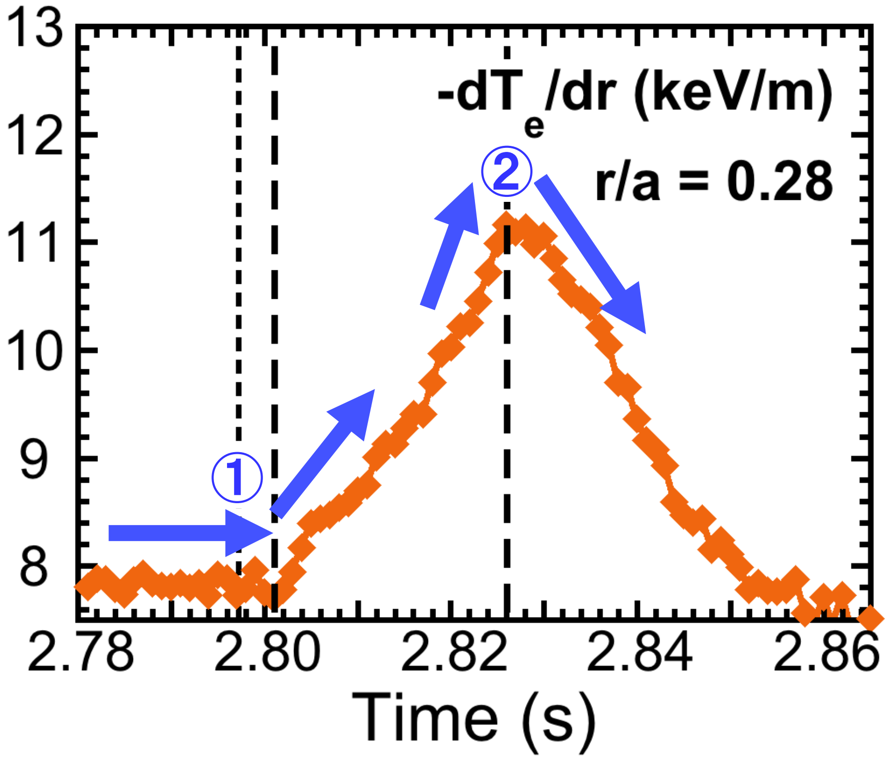


✓ **Backward second-order* transition takes place afterward**
***Discussed in the next page**

Temporal Behavior of ∇T_e Represents Dynamics of Local Heat Transport States (Cont'd)

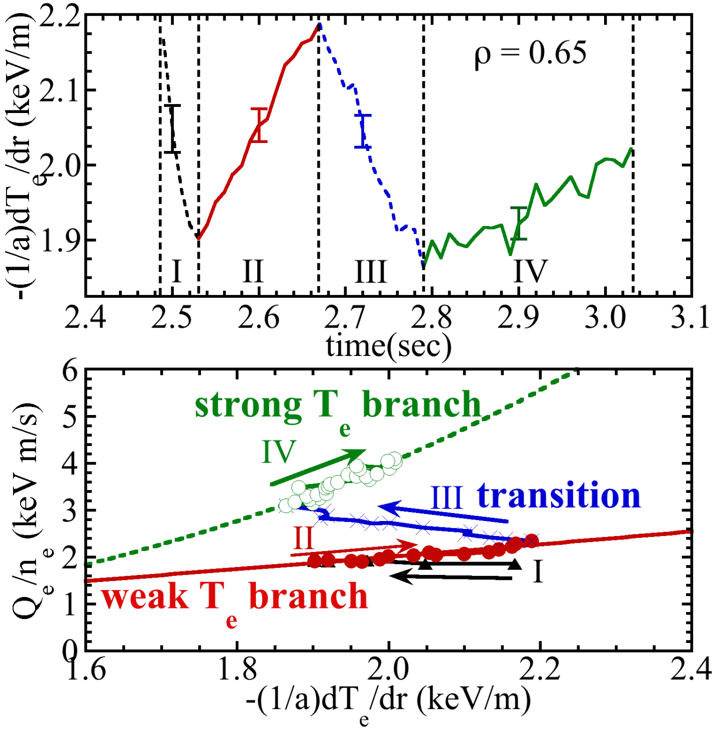
✓ **Second-order transitions take place** over wide regions

- e.g. at the initial phase, 0.28 < ρ ≤ 0.45 (**about 10 cm wide**)



✓ **Second-order transition**:
Discontinuity in $d(\nabla T_e)/dt$

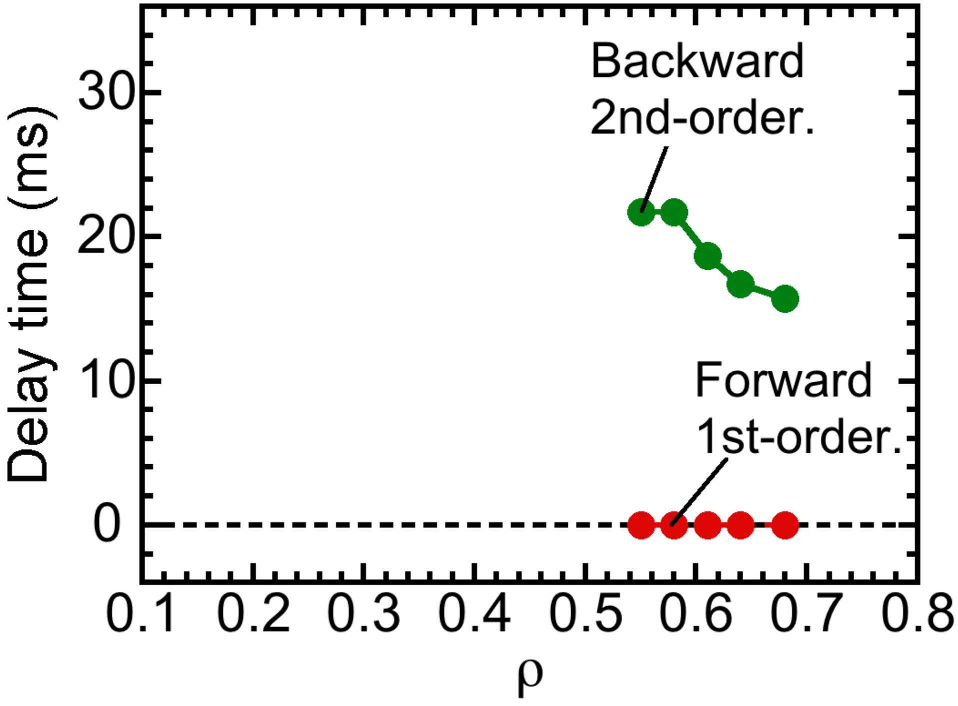
- Can be seen in "**slow change**" of transport



K. Ida et al., PRL **96** 125006 (2006)

✓ Transitions over a wide region suggest the existence of **"Large Scale Structures"**, because a typical μ-turb. eddy size is **a few mm**

Delay Time of Transitions Indicates the Dynamics of Large Scale Structures



Note: Here, a delay time of the 2nd-order transition is estimated from the folding points in the temporal evolution of ∇T_e

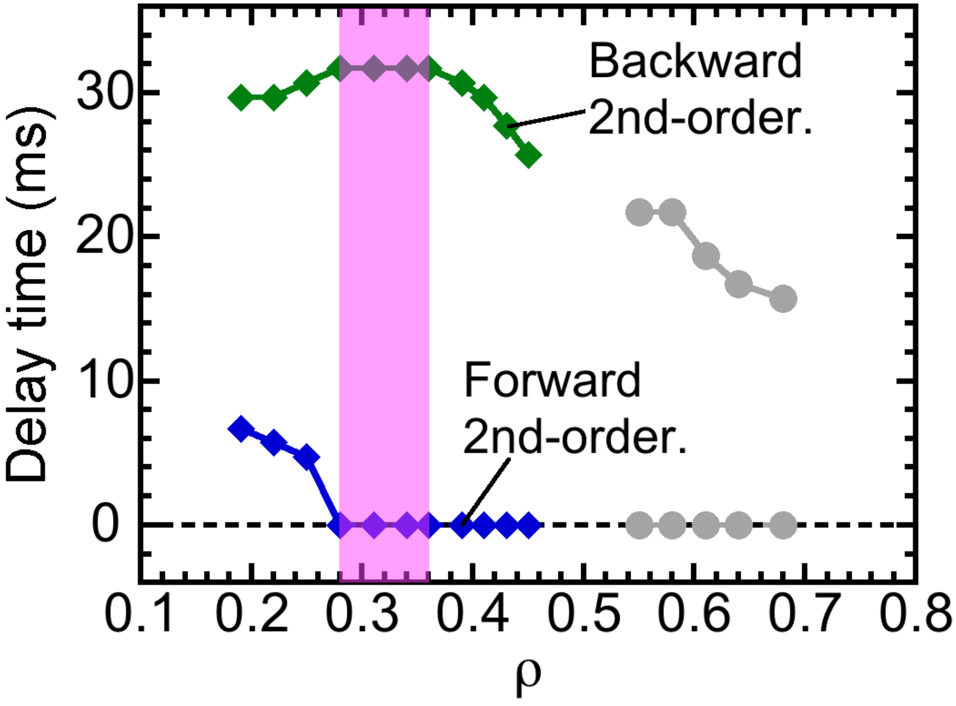
In the edge region,

- ✓ **Forward 1st-order transition: nearly simultaneously (≲ 1 ms)**
- ✓ **Backward 2nd-order transition: transition front propagates towards the core**

⬇

Edge large scale "coherent" structure becomes incoherent after the 1st-order transition

Delay Time of Transitions Indicates the Dynamics of Large Scale Structures (Cont'd)



Note: Here, a delay time of the 2nd-order transition is estimated from the folding points in the temporal evolution of ∇T_e

In the intermediate region,

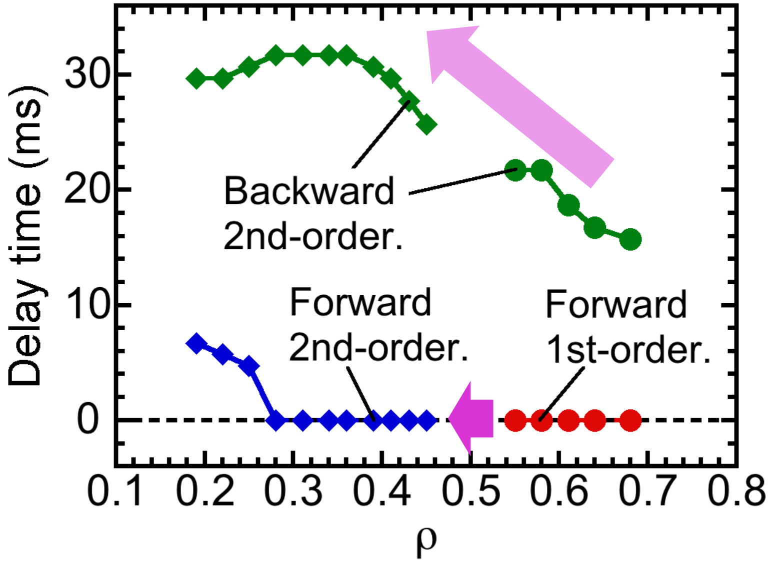
- ✓ **Forward 2nd-order transition: nearly simultaneously (≤ 1 ms)**
- ✓ **Backward 2nd-order transition: nearly simultaneously (≤ 1 ms), even the region having such a simultaneity is shrank**

Large scale "coherent" structure in the intermediate region continues to exist

Summarizing the points so far

Abrupt core T_e rise in response to the edge perturb. in LHD can be evoked

- ✓ **by interaction of the region with 1st-order transition and that with 2nd-order transition**
- ✓ **NOT by an ultrafast propagation from the edge to the core**



These results prompt following questions:

- ✓ Is the 2nd-order transition in the core region a movement between two transport branches?
- ✓ Why does the edge region with the 1st-order transition go back to the original state soon?

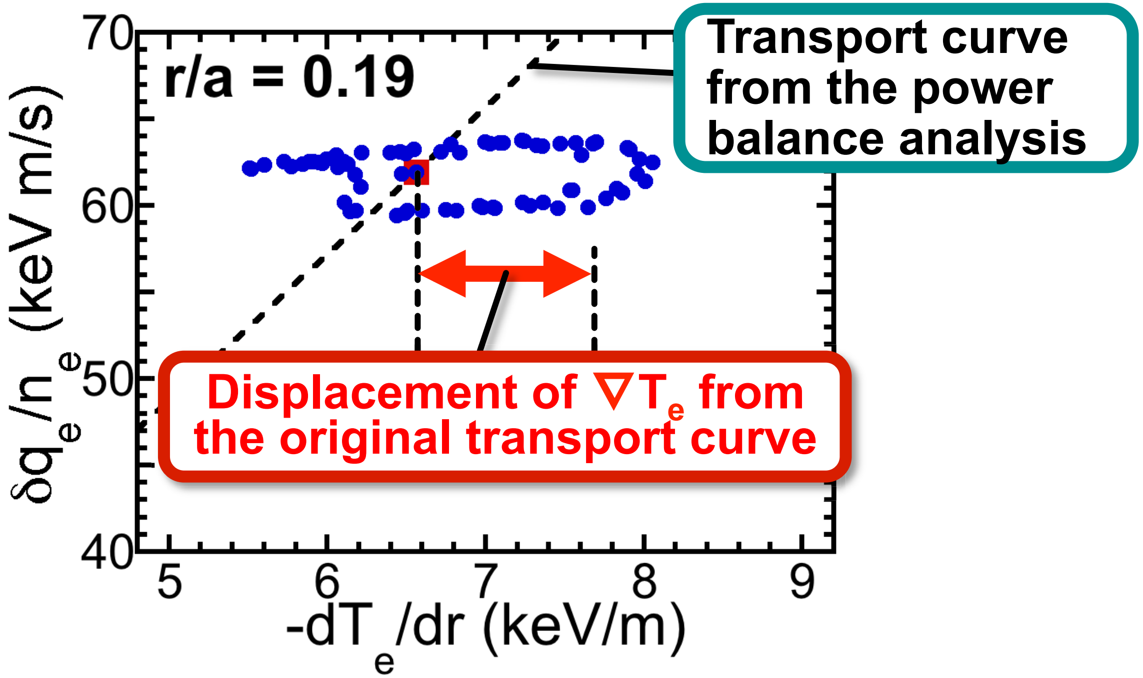
Need to quantify "stability of transport state"

Transit Time Distribution (TTD) is Applied to Evaluate How the Local Heat Transport States Change

- ✓ "Dynamics of transport state" can be evaluated by a "displacement from the original transport curve"

K. Ida et al., J. Phys. Soc. Jpn. **77** (2008) 124501

- ✓ A "**T**ransit **T**ime **D**istribution **(TTD)**" for a certain window of "$d\delta T_e/dr$" can be interpreted as **an index of the extent to which plasma can be attracted by a certain transport state**
  - ● Here, the variation of the normalized heat flux is very small (see fig. below)
  - ● Working hypothesis: a "**transit time** of $d\delta T_e/dr$" **equals** a "**lifetime** of transport state determined by a certain turbulence condition"

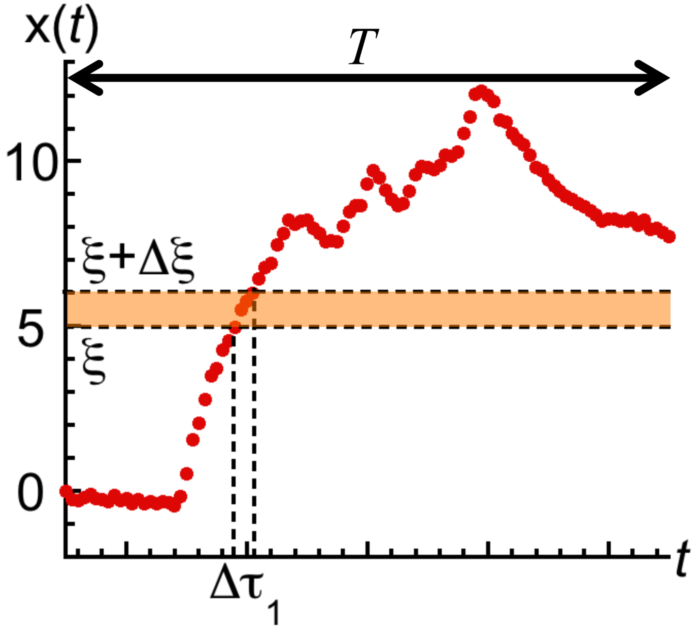


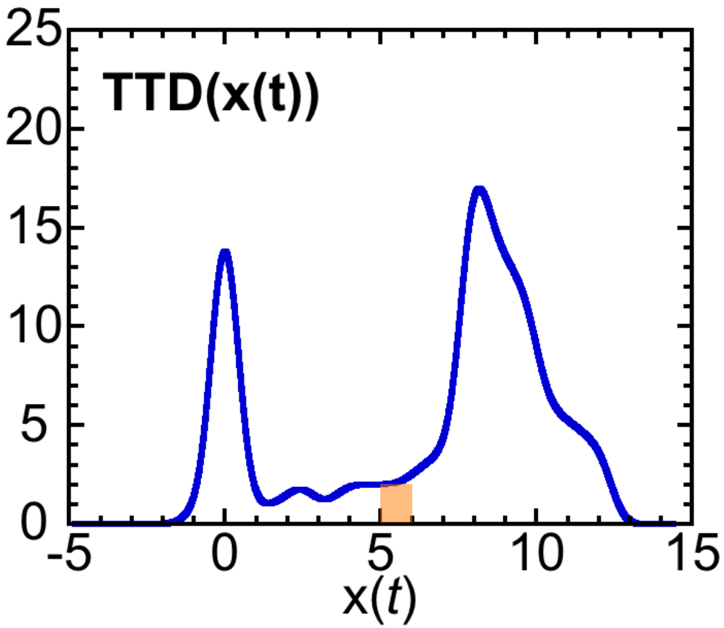
Transport curve from the power balance analysis

Displacement of ∇T_e from the original transport curve

How to Measure the “Transit Time Distribution”

TTD can be obtained in almost the same manner as the PDF (probability density function)





TTD of x(t): $\mathrm{TTD}(x) = \lim_{\Delta\xi \to 0} n_j$

PDF of x(t): $p(x) = \lim_{\Delta\xi \to 0} \lim_{N \to +\infty} n_j / N$

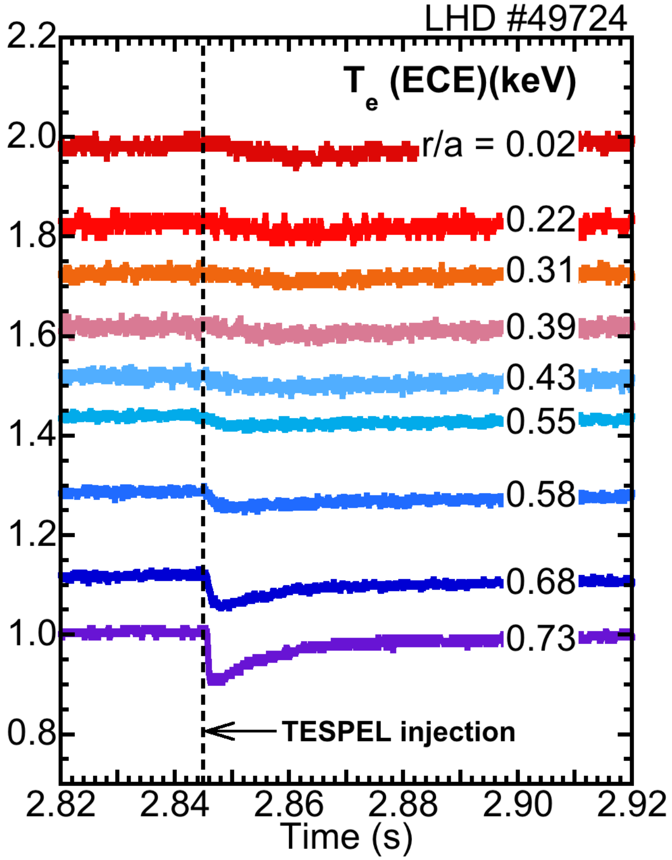
Δξ: bin size, n_j: number of data points between ξ and ξ+Δξ , N: total number of data points within T, T: measuring time

In practice, the number of data points between ξ and ξ+Δξ is just counting, because Δξ is finite number

Availability of Transit Time Distribution

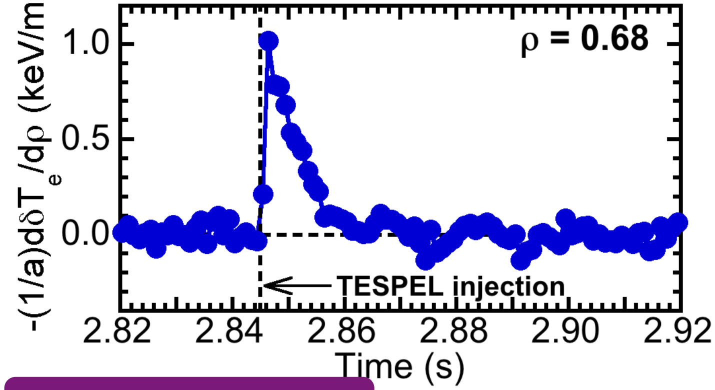
TTD Analysis Example:

Plasma with a higher density (line avg. $n_e = 2.20 \times 10^{19}\ \mathrm{m^{-3}}$), where a diffusive nature dominates

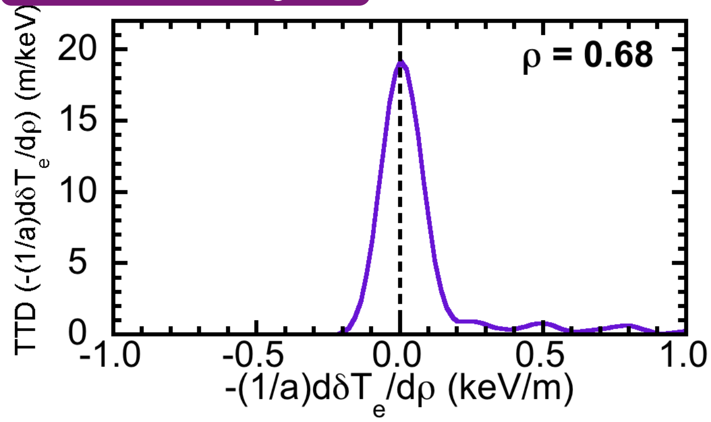


Cold pulse propagates

Temporal evolution of $d\delta T_e/dr$

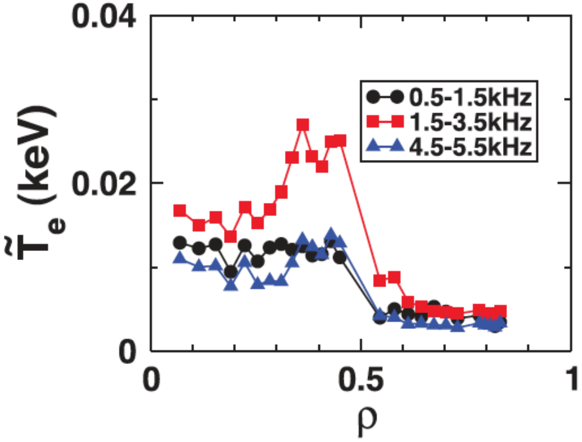


TTD of $d\delta T_e/dr$



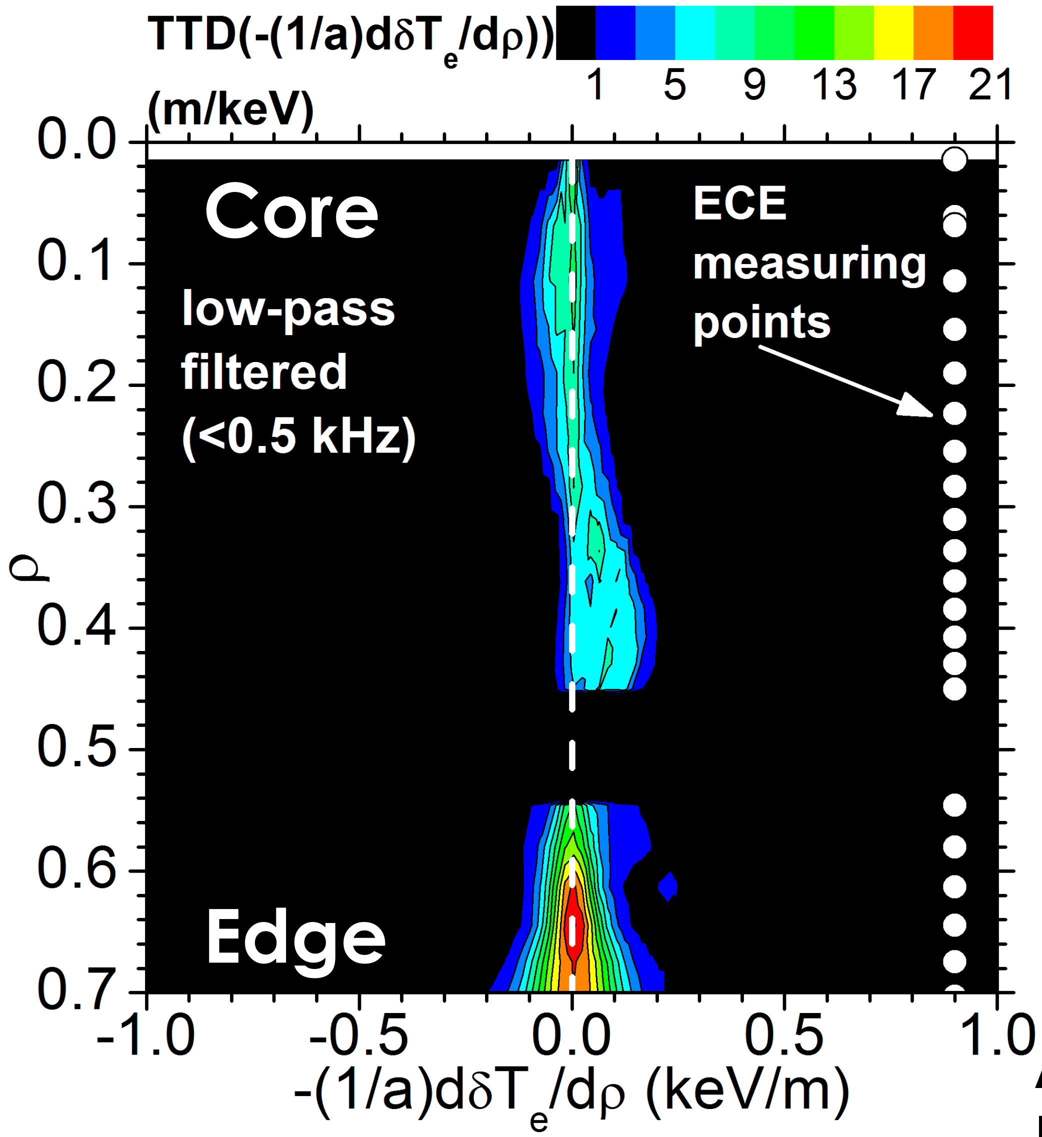
Low-pass filtered (<0.5 kHz) ECE data is used for eliminating the contribution of

- ✓ High-freq. noise
- ✓ Low-freq. (1~3kHz) T_e fluctuation



S. Inagaki et al., PRL **107** (2011) 115001

Availability of Transit Time Distribution (Cont'd)



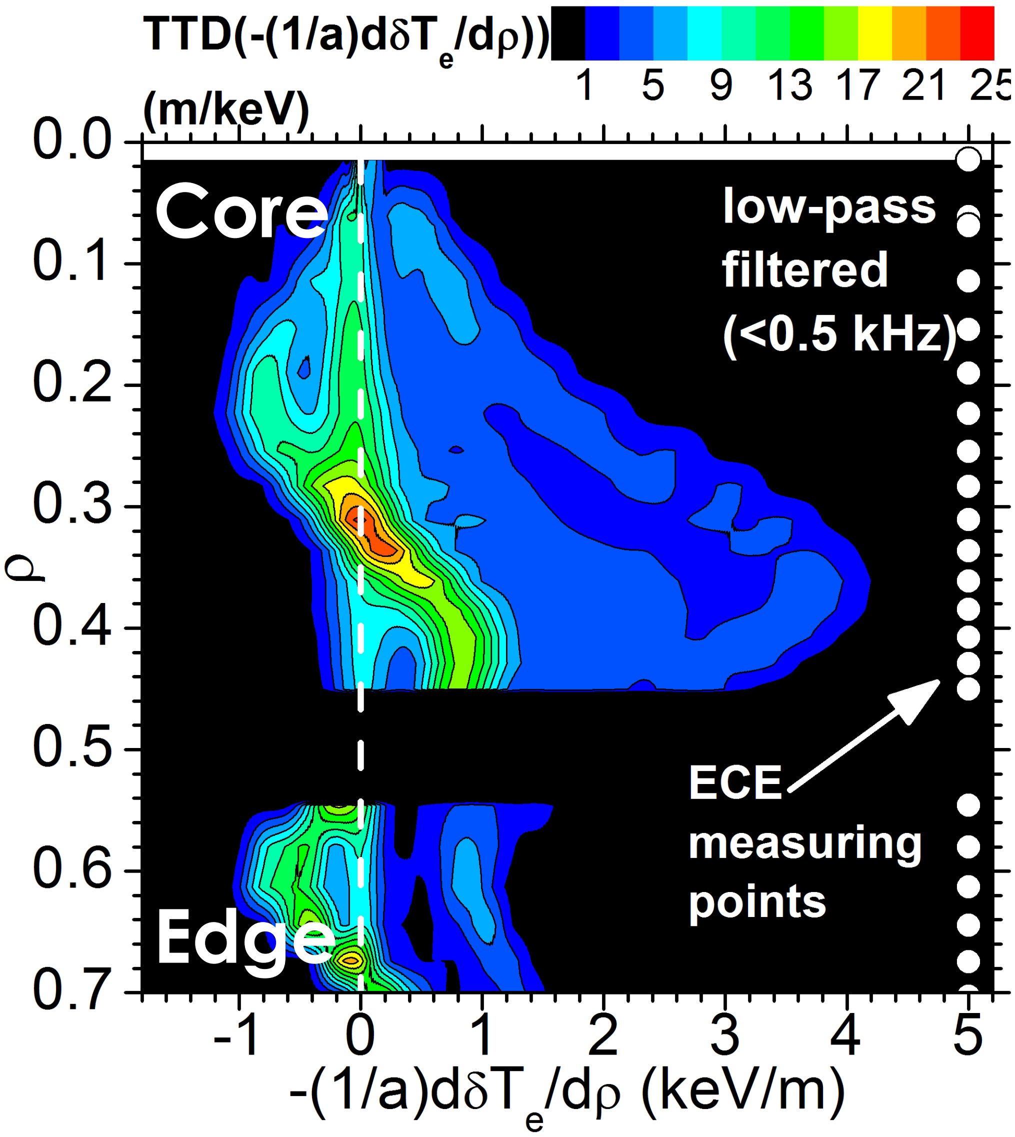
Crests appear near the original ∇T_e in the TTD map

- ✓ **Original transport state in this plasma is robust** against the perturbation
- ✓ Agrees with the fact that the plasma restored to the original state

Analysis condition:

For t=2.82s~2.92s at 1ms interval

TTD for the Plasma with Non-local T_e Rise Shows Characteristic Patterns Both in Core and Edge Region



Core (with 2nd-order transition): "WEAK" resilience is found

- ✓ Due to that, in some regions, **"landing point" of the transport state is not the same** as the previous one
- ✓ **No another transport branch in this map**

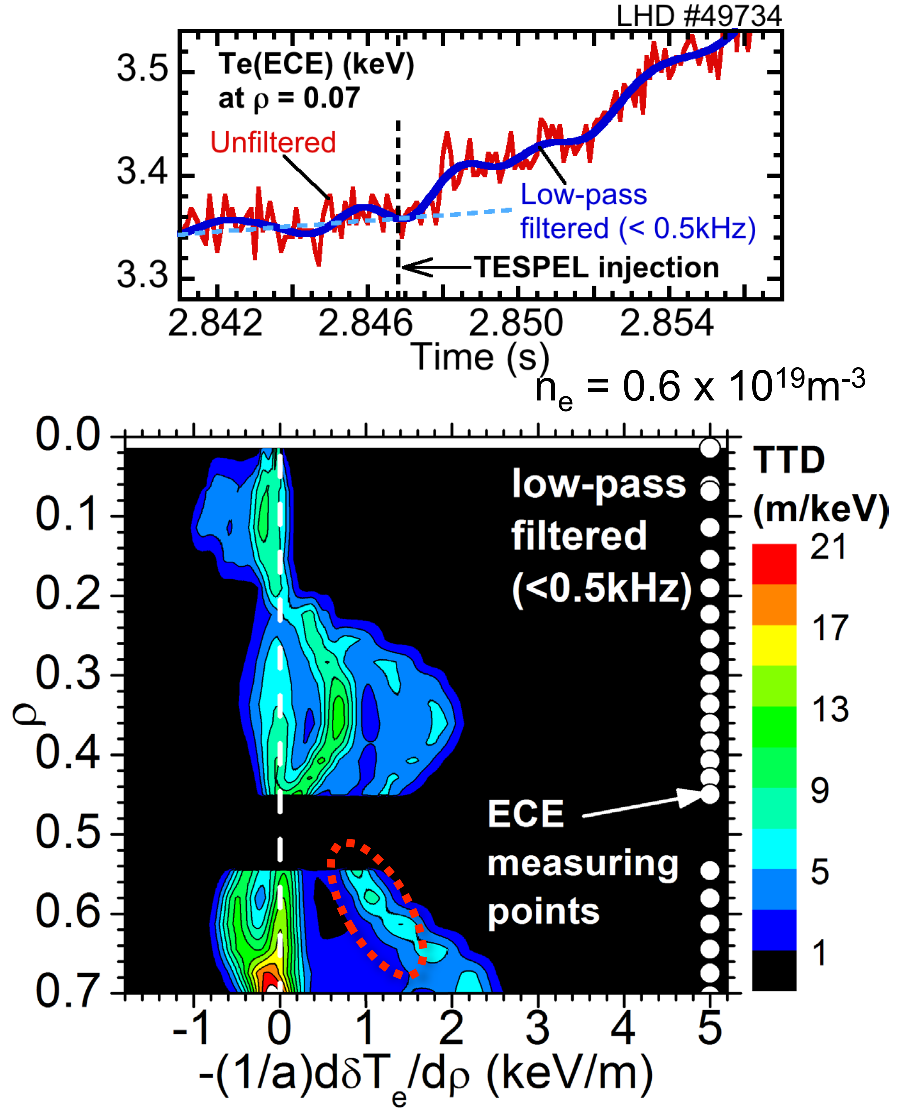
Edge (with 1st-order transition): Another transport branch is found

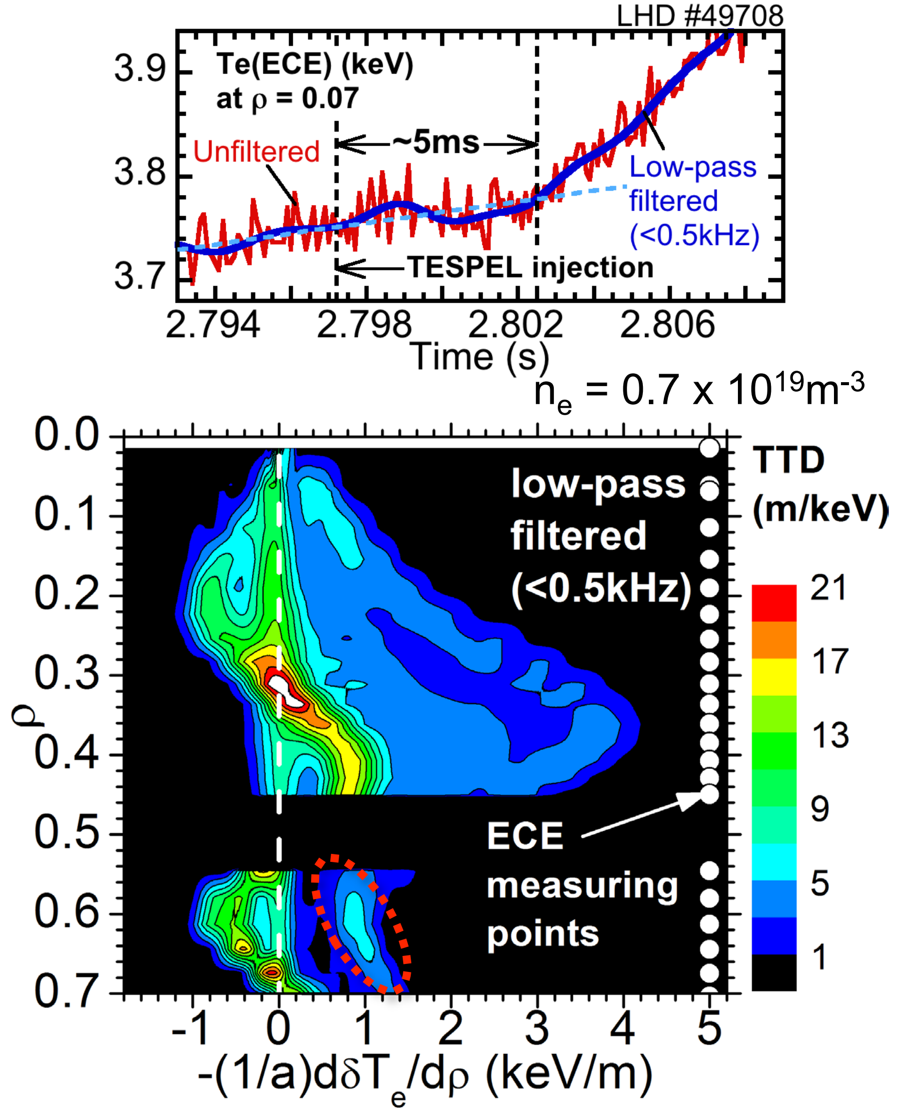
- ✓ **Weaker attracting force**, compared with the original branch
- ✓ This can be why the backward 2nd-order transition of the edge e-heat transport takes place

Analysis condition:

For t=2.78s~2.89s at 1ms interval

When the 1st-Order Transition Region Moves Outside, the Response Time of the Core T_e rise is Delayed



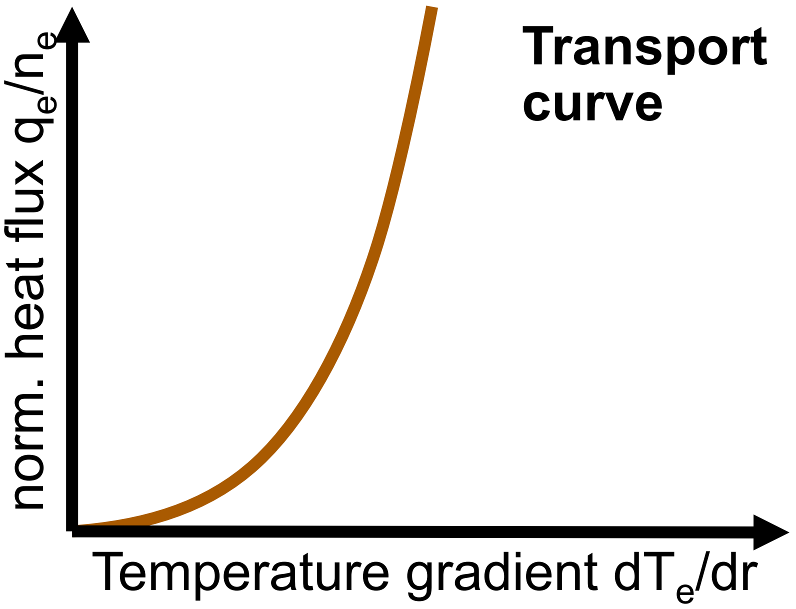


Width of the $d\delta T_e/dr$ jump in the edge region also decreased

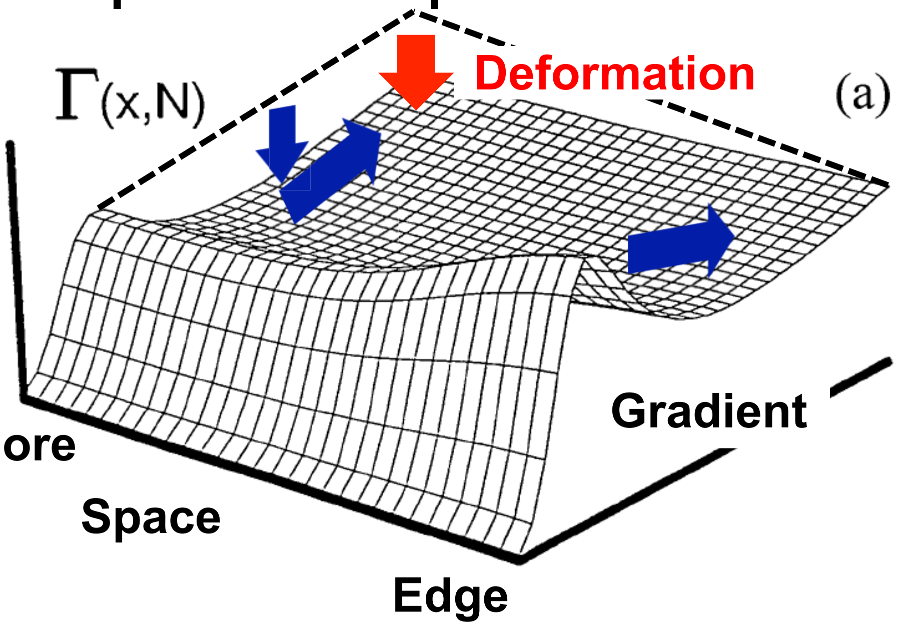
Characteristic TTD Map Can be Understood by the Instant Deformation of Flux-Gradient Landscape

Flux-gradient curve can be extended to flux-gradient surface (landscape)

- ✓ Coupling by the meso-scale (ZF, …), macro-scale (LRC, …) structures



Transport landscape



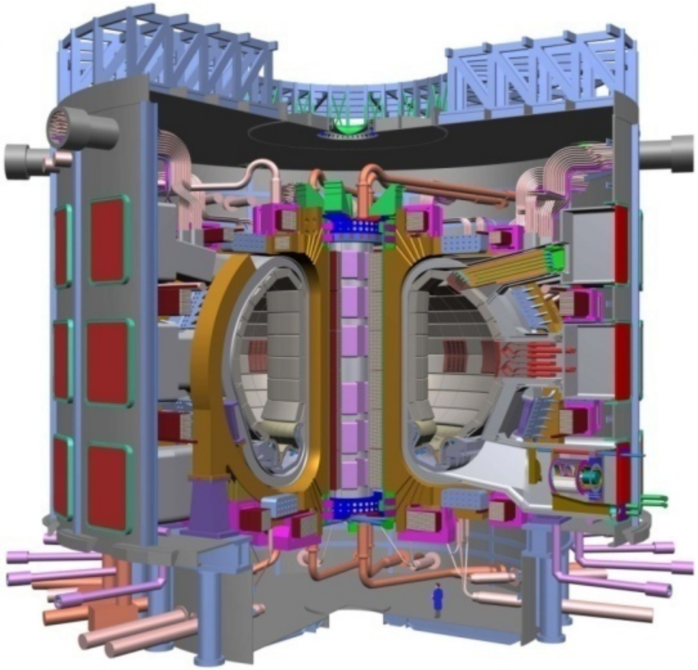
P.H. Diamond et al., PRL **78** (1997) 1472.

This model can reproduce the complex changes in the flux-gradient relationship observed experimentally

講演概要

- ✓ はじめに
  - ● 磁場閉じ込めトロイダルプラズマにおける熱輸送
  - ● 輸送の非局所応答（非局所性）とは？
  - ● 輸送の非局所応答の好例：「非局所輸送現象」
- ✓ 非局所輸送現象に対して最近得られた知見
  - ● 熱流束と温度勾配の複雑な関係
  - ● 長距離相関を持つ電子温度揺動
  - ● 電子熱輸送における潜在的空間構造
- ✓ **核融合研究における輸送の非局所応答の研究意義**
- ✓ まとめ

核融合研究における輸送の非局所応答の研究意義



ITERで実現する核燃焼プラズマ
＝ 制御ノブが限定された高自律系プラズマ

- ✓ それを制御しつつ長時間安定保持するためには、輸送の時空間応答時に顕著になる「非局所性」の理解が必要
- ✓「非局所性」を積極的に利用することで、新たな制御ノブとして「非局所性」を積極的に活用できるかもしれない

まとめ

- ✓ 磁場閉じ込めトロイダルプラズマの熱輸送は、特にその動的応答において「局所輸送」の考え方では到底理解できない性質を示す場合がある
- ✓ その好例である非局所輸送現象に対して、大型ヘリカル装置による実験により、以下のことが明らかとなっている
  - ● プラズマコア部において熱流束と温度勾配の一意的関係が破れている、すなわち非局所輸送が存在している
  - ● プラズマコア部の熱流束とプラズマ周辺部の温度勾配との間に強い非局所相関関係、すなわち輸送のエッジ—コア結合が存在している
  - ● プラズマコア部及びプラズマ周辺部それぞれの電子熱輸送において大規模かつコヒーレントな構造が形成されており、それらが相互作用していることで非局所輸送現象が発現していると考えられる
- ✓ 核燃焼プラズマの熱輸送の動的制御を安全に行うためには、熱輸送の動的応答、特に熱輸送の非局所応答は理解しておくべき課題である