zonal flow staircase effects on electron heat transport avalanching in KSTAR L-mode plasmas and *elongated* plasmas

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Outlines

I. Introduction

II. KSTAR L-mode plasmas: **experiments** and nonlinear gyrokinetic **simulations**

III. Shaped (elongated) plasmas: “cyclone” based parameters

IV. Conclusion and future work, open question discussion

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I. Introduction

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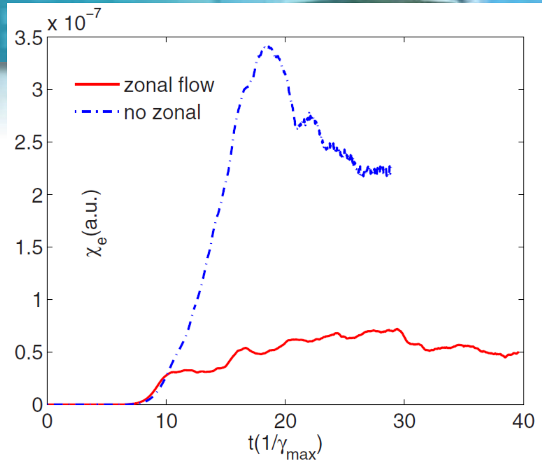
III. Shaped (elongated) plasmas: “cyclone” based parameters

IV. Conclusion

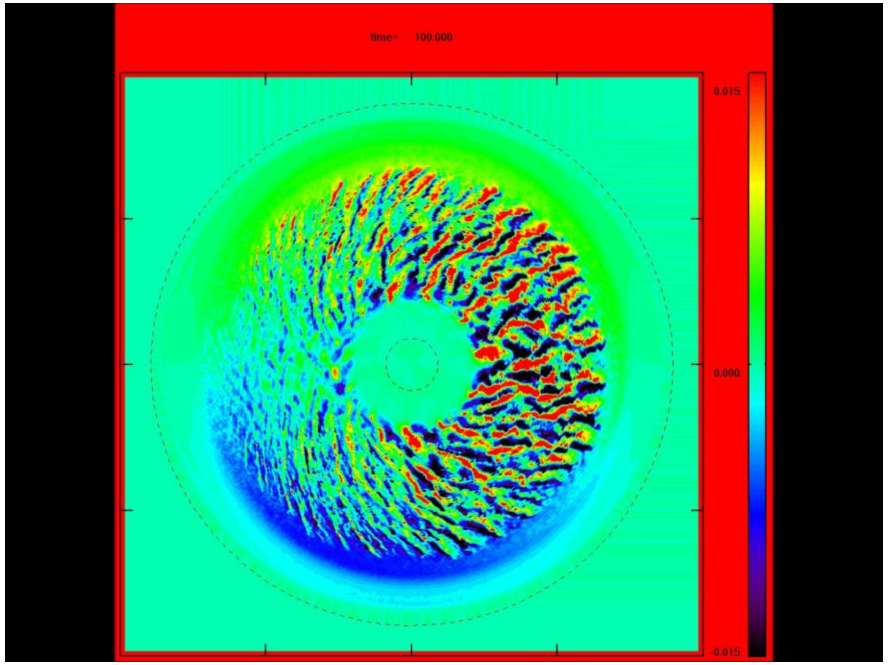
I. Introduction

Zonal flow is important in TEM turbulence

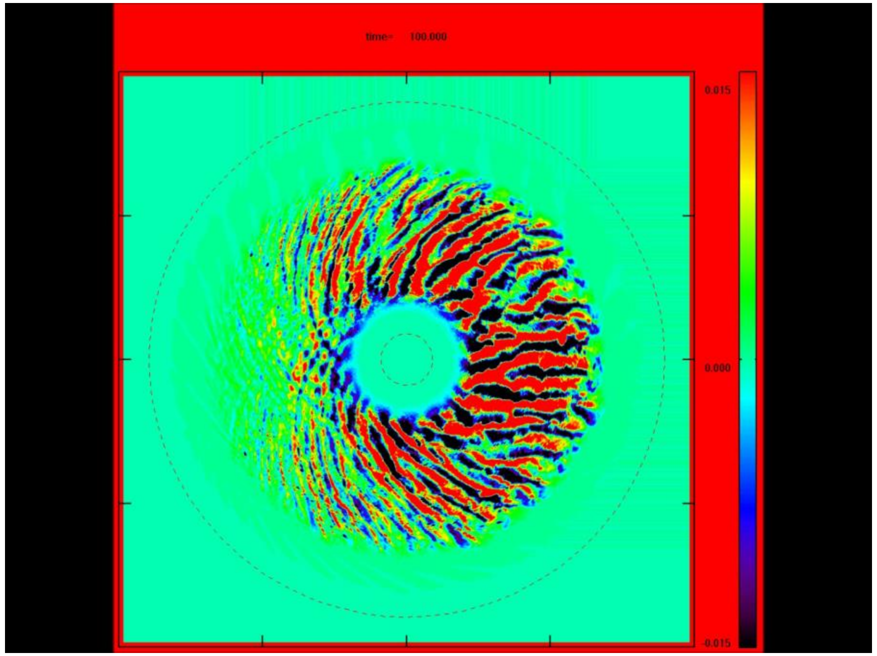
- ✓ As a **saturation mechanism**
- ✓ Reduce TEM driven transport by shearing (*Hahm, PoP 1995, PPCF 2000*).



With zonal flow



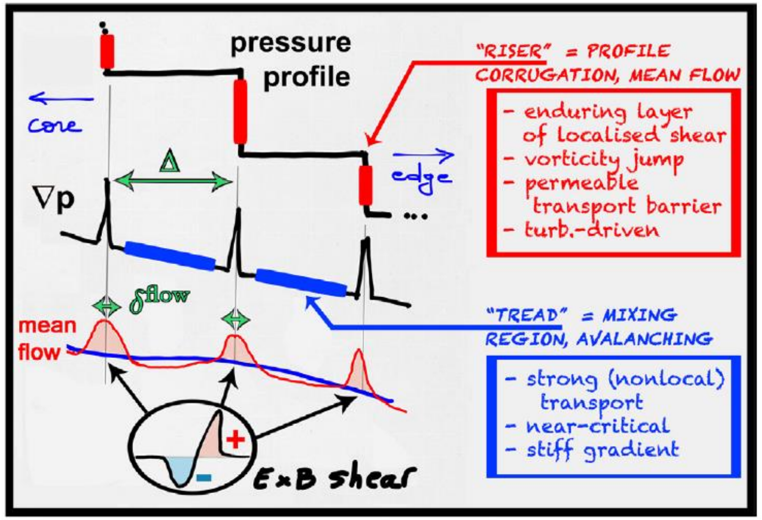
Without zonal flow



I. Introduction

Zonal flow is important in TEM turbulence

- ✓ Zonal flow radial profile is important. The long-live structure, such as staircase, is found to play significant roles in **regulating large scale transport avalanching**. (*Dif-Pradalier, et al., PRE 2010, PRL 2015*)



From G. Dif-Pradalier et al., NF, 2017

Mechanism in generation of zonal flow radial profiles is still a mystery!

I. Introduction

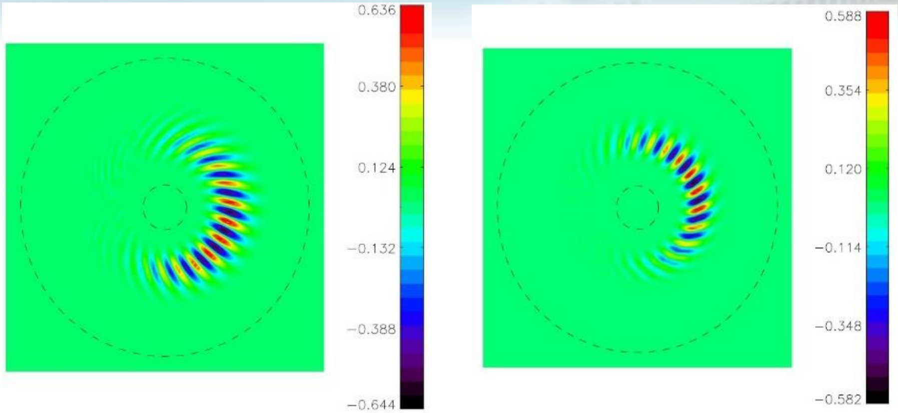
I. Present status on zonal flow staircase study

- ✓ **Nearly all studies** are from full-f gyrokinetic simulation of ITG (*Dif-Pradalier, et al., NF 2017; W. Wang et al., NF 2018*). Full-f GK study of TEM is too expensive due to computational requirement from kinetic trapped electron.
- ✓ On the other hand, **TEM is more interesting** for fusion plasmas such as ITER, since fusion product α particles can significantly heat electrons (*Taylor et al., PRL 1996; Thomas P.R. et al., PRL1998*).
- ✓ How about zonal flow staircase and its effects in TEM driven turbulence transport?

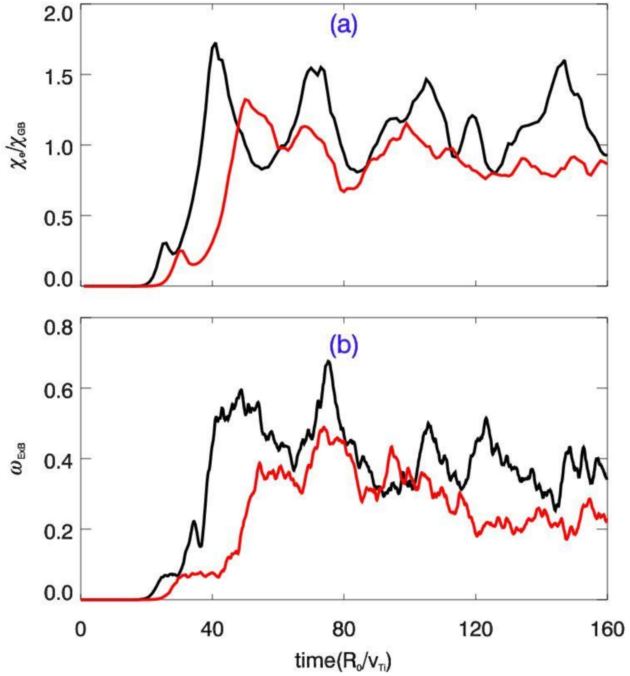
II. Recently, thanks to the development of δf gyrokinetic modeling with **bounce-averaged**(*Fong-Hahm, PoP 1999*) kinetic trapped electrons in gKPSP (*L. Qi et al., PoP 2016, J-M. Kwon et al., CPC 2017*). The investigation of long-lived zonal structure in TEM turbulence can be easily achieved.

I. Introduction

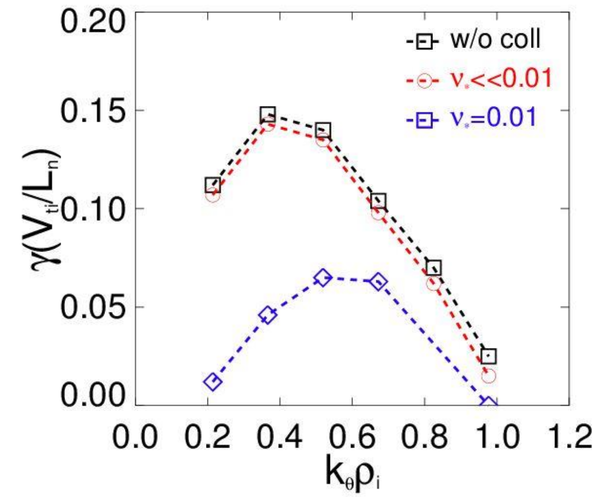
Both **linear** (*L. Qi, et al., PoP 2016*) and **nonlinear** (*Jae-Min Kwon et al., CPC 2017*) simulations of ITG/TEM in either **circular, shaped** or **general experimental tokamak geometry** can be done.



ITG TEM



Nonlinear results w/o (black) and with low collision (red):
(a) electron heat diffusivity; (b) zonal flow shearing rate



Linear TEM growth rates as collision increases (*J.M. Kwon, et al., CPC 2017*)

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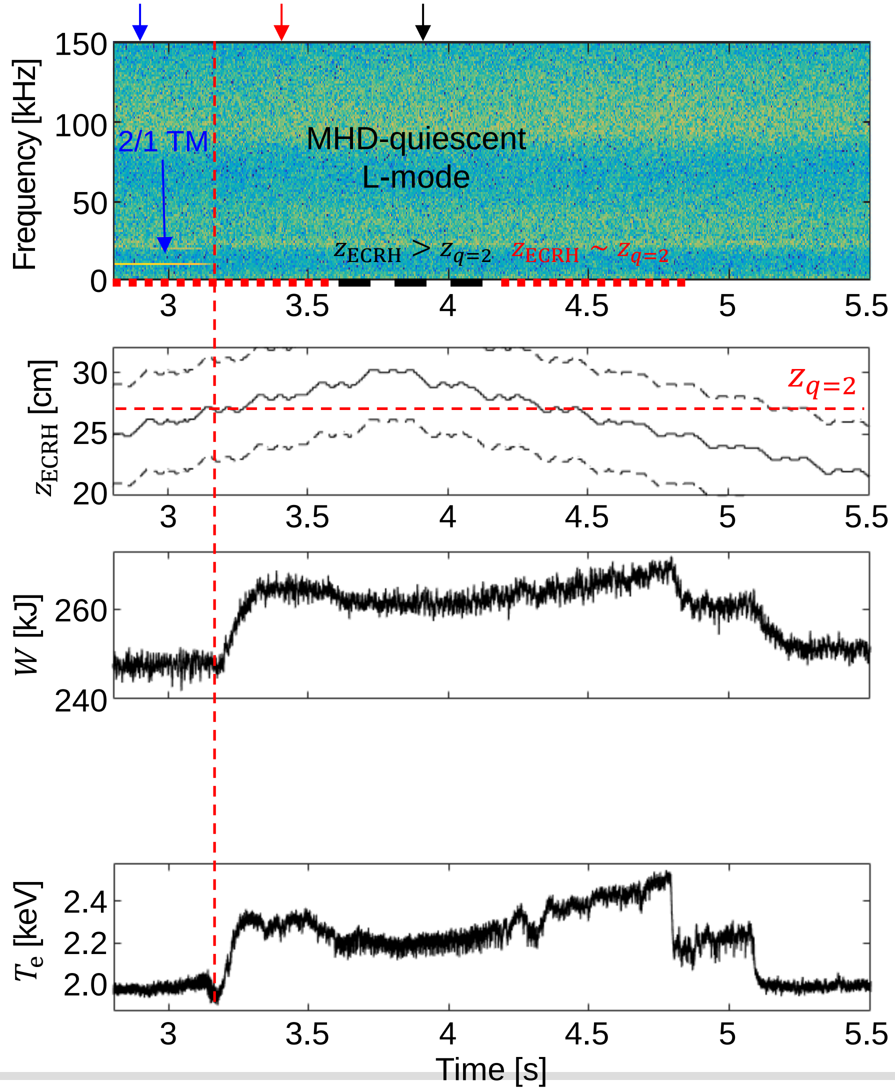
III. Shaped (elongated) plasmas: “cyclone” based parameters

IV. Conclusion

II. KSTAR L-mode: experiment

- Electron heat transport events in the MHD-quiescent L-mode plasmas, which is achieved in the limited configuration.
  - No H-mode transition
    - ✓ No edge localized mode
  - $q_0 > 1 \rightarrow$ no sawtooth
  - The 2/1 TM was unstable
    - ✓ Suppressed by the ECRH



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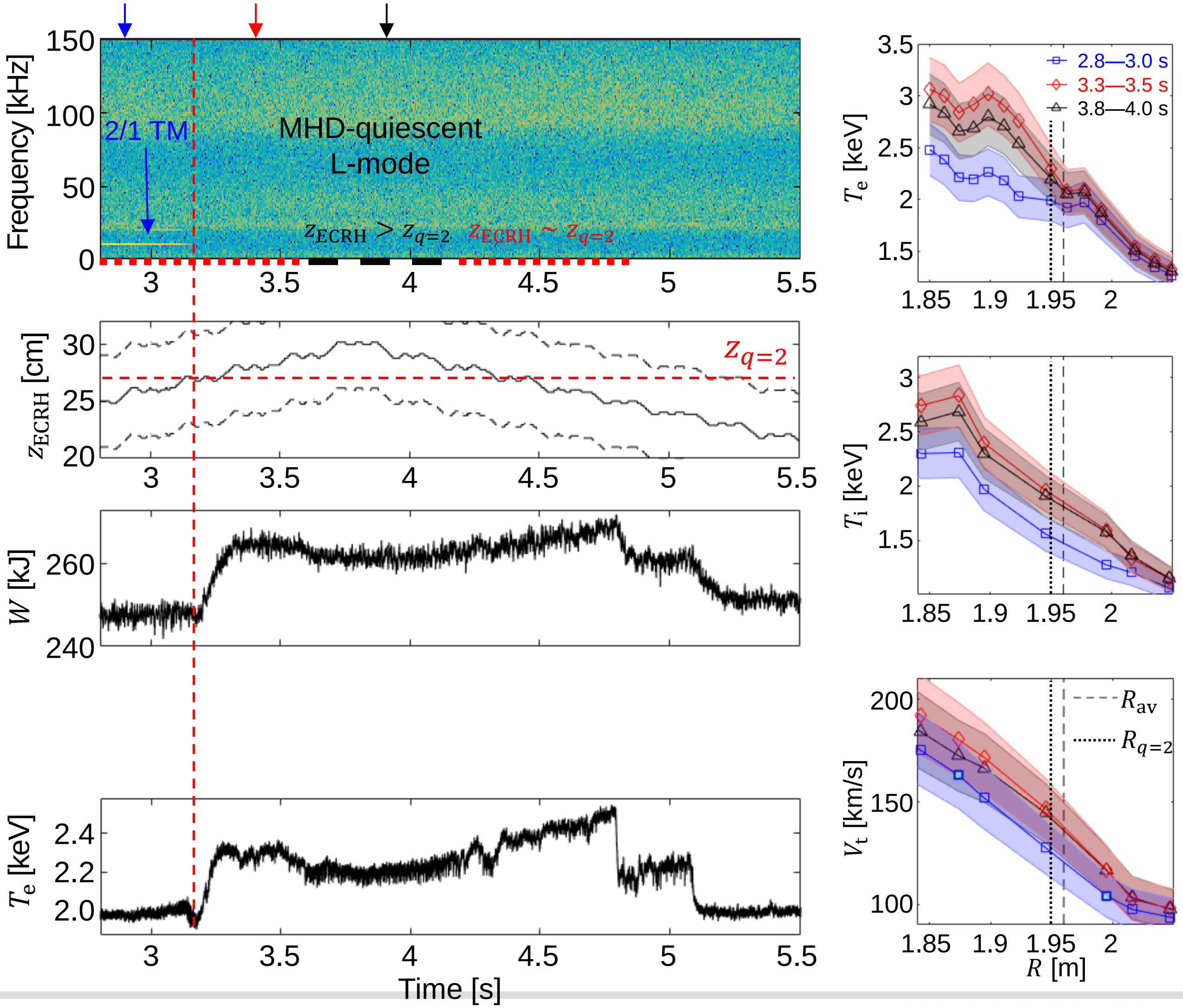
- ❖ Profiles are recovered after the TM suppression



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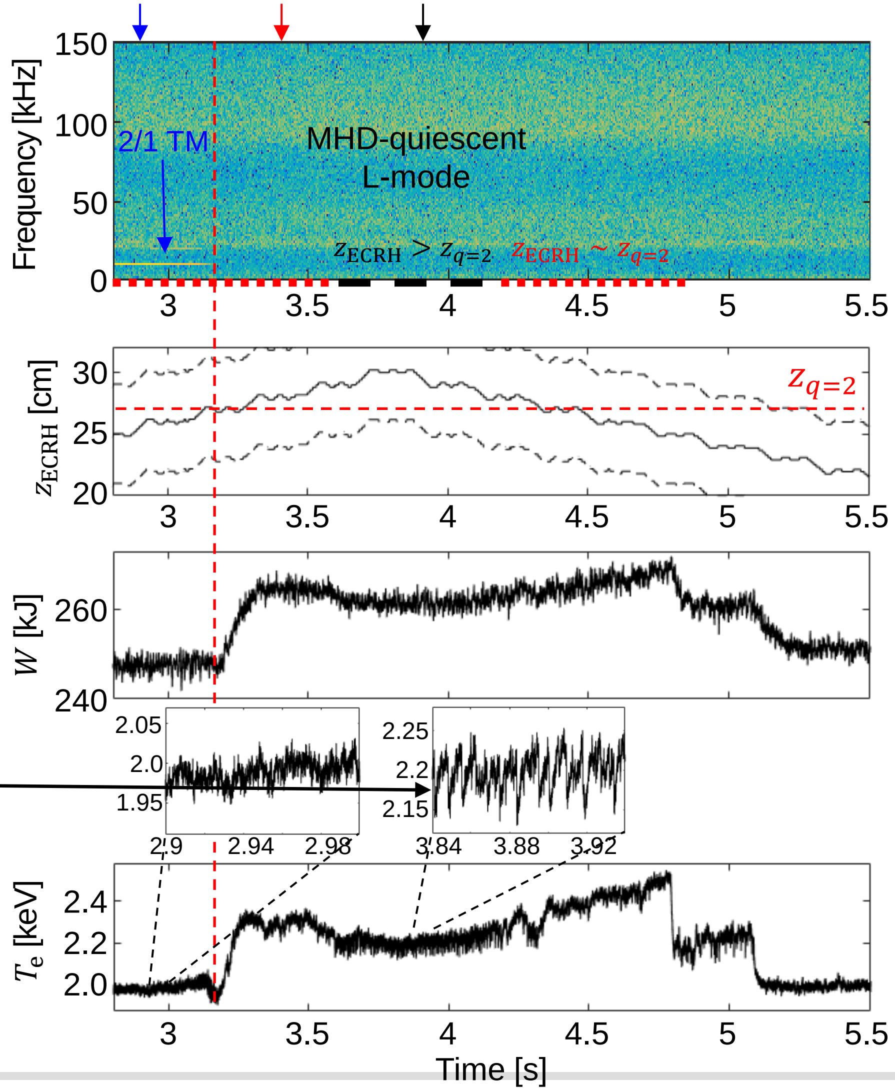
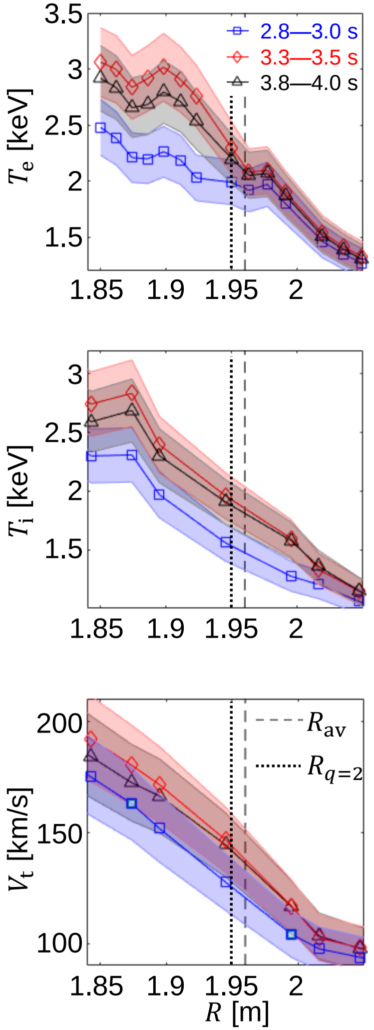
❖ Transport events are observed during the MHD-quiescent period

➢ $R_{\mathrm{av}} \sim R_{q=2}$





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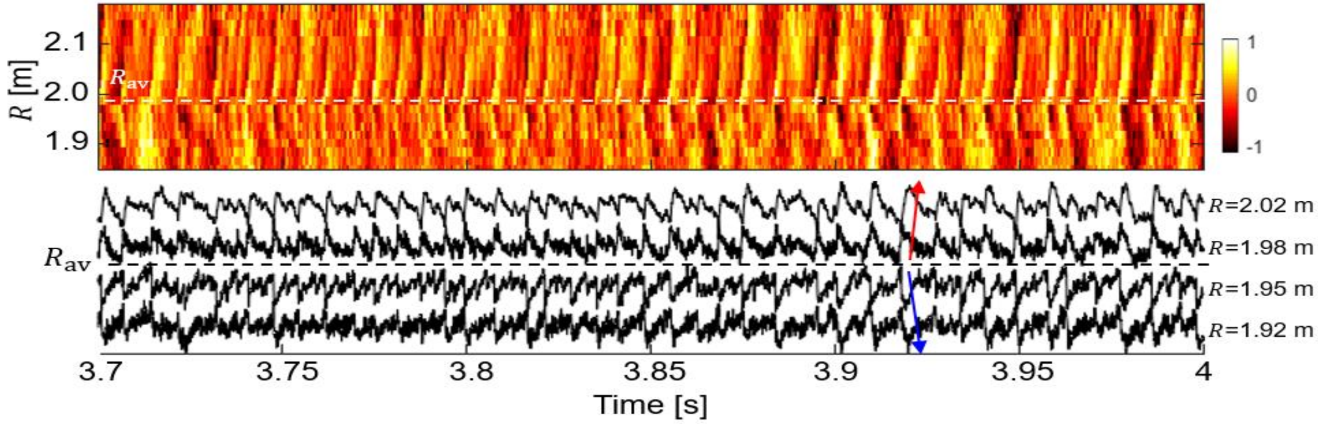
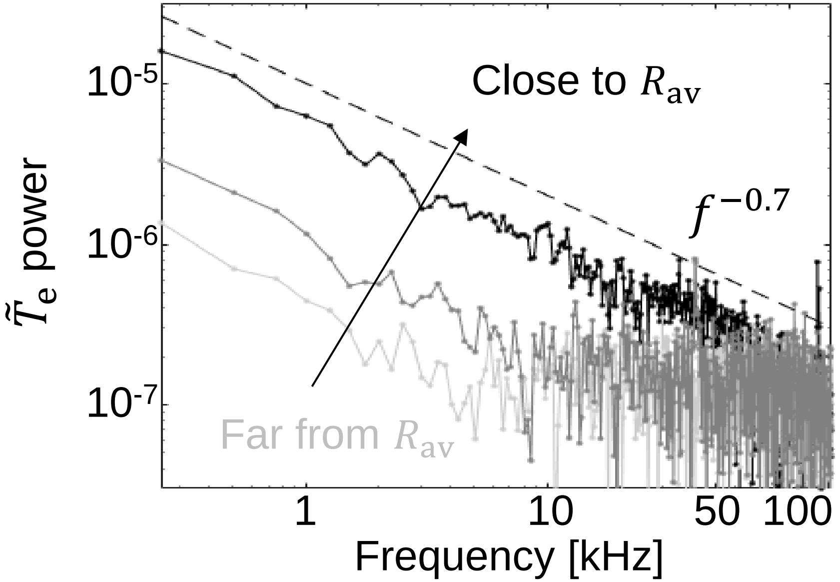
II. KSTAR L-mode: experiment

Non-diffusive and avalanche-like characteristics of the transport events

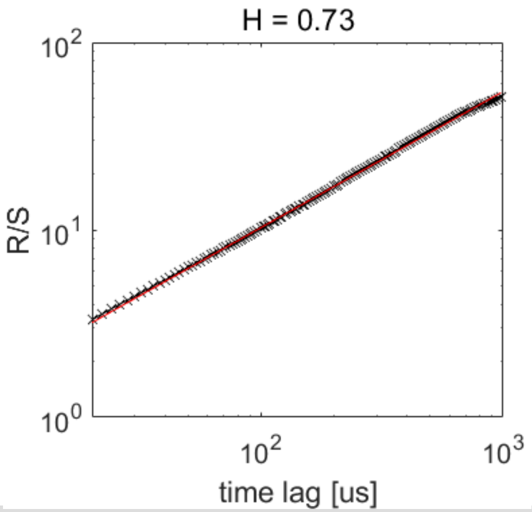
Spatio-temporal pattern of the normalized T_e measurements (rescaled) 2D ECEI





The power-law spectra ($S(f) \propto f^{-0.7}$) of the event size (δT_e) prevails, showing overlapping of avalanching events

The Hurst exponent $H \sim 0.73 > 0.5$ of T_e fluctuation is found using the R/S method

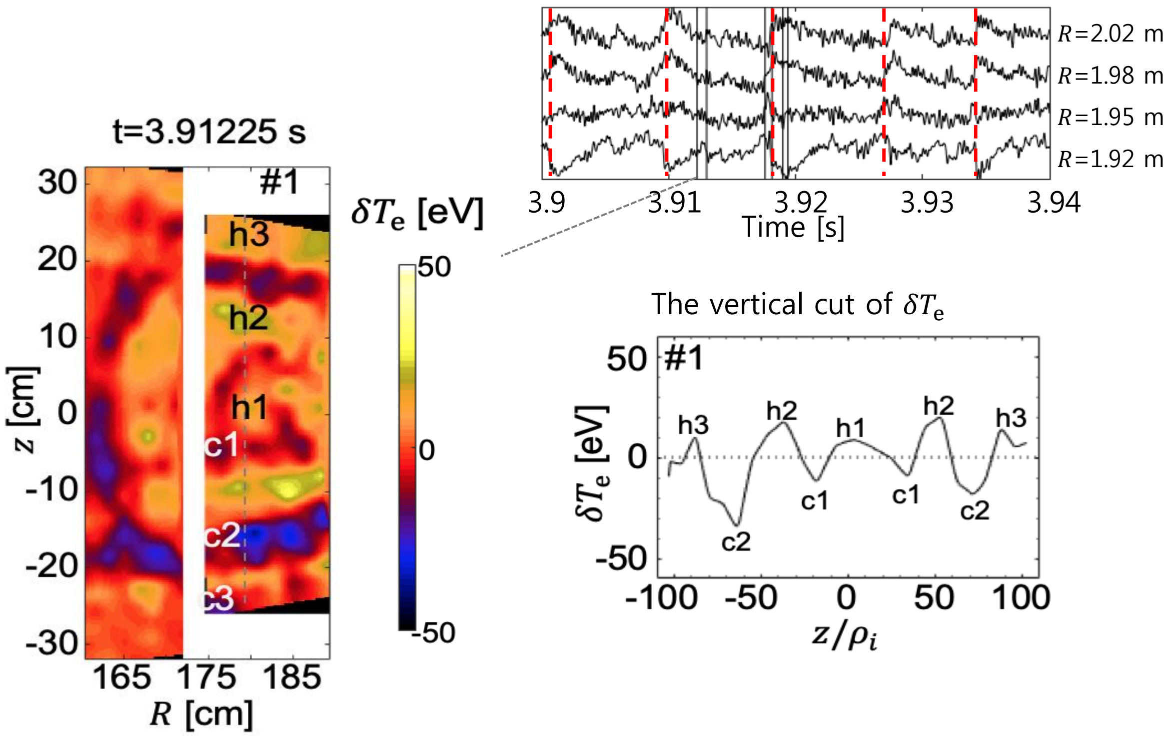


II. KSTAR L-mode: experiment

Observation of the temperature profile corrugation: The T_e profile corrugation is clearly identified in the 2D $\delta T_e = T_e - \langle T_e \rangle$ image

- ➢ Estimated width ~ 45 ρ_i, a mesoscale structure

Dashed line : large amplitude long range avalanche-like events



For more details, Ref:
Minjun Choi, et al., NF, 2019

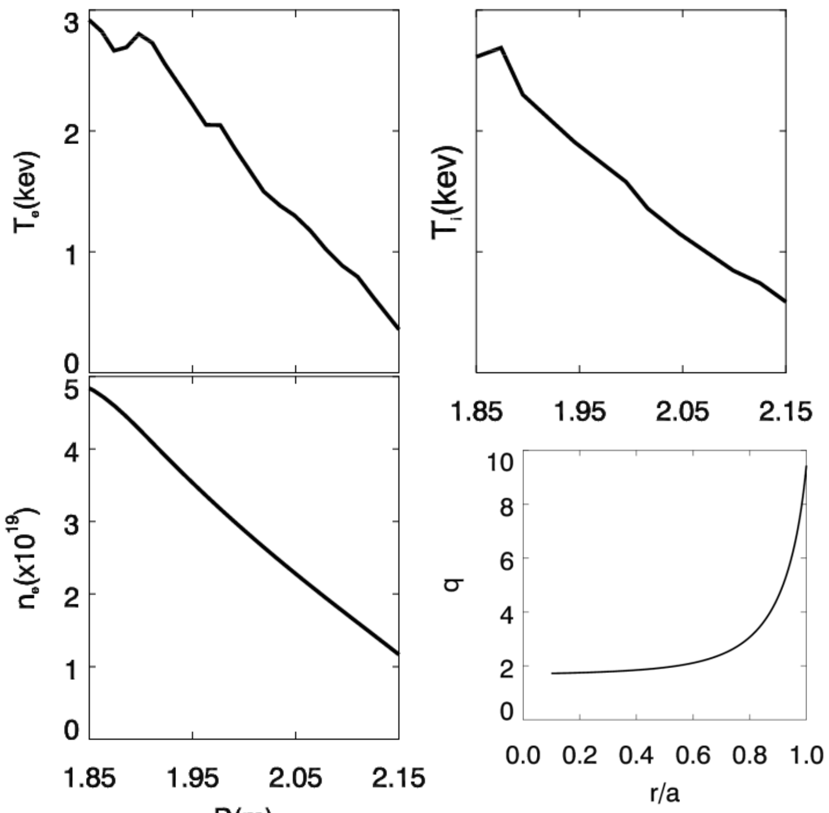
It is therefore interesting to investigate KSTAR L-mode plasmas directly from nonlinear gyrokinetic simulations with global gKPSP code.

II. KSTAR L-mode: simulation

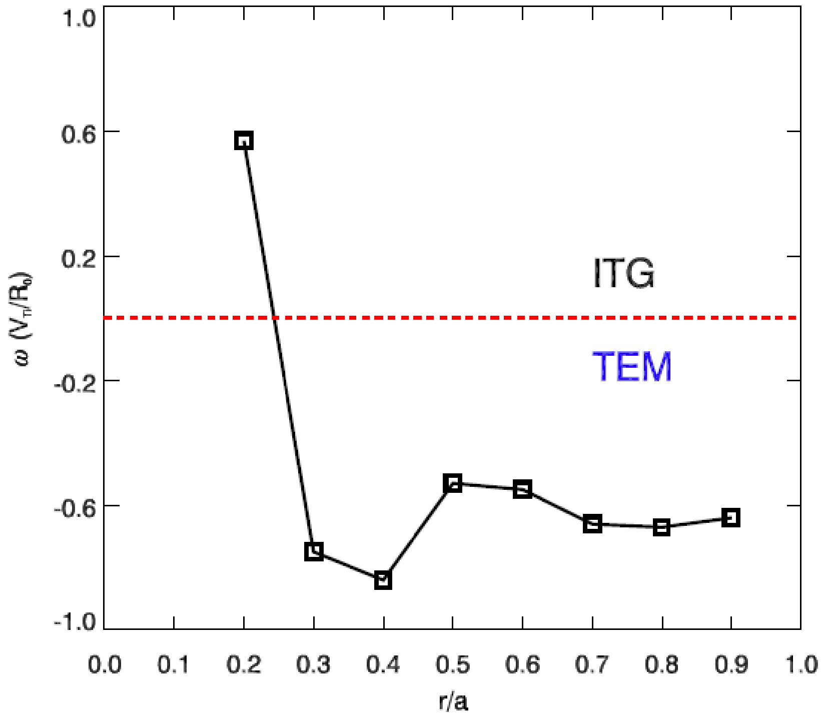
Nonlinear gKPSP gyrokinetic simulation of the above KSTAR L-mode plasmas:

- Realistic experimental profiles, T_e, T_i, n_e, etc..
- Realistic experimental configuration from EFIT, q-profile, plasma shape, etc..

Profiles from experimental data



Linear simulation shows TEM dominance in most region



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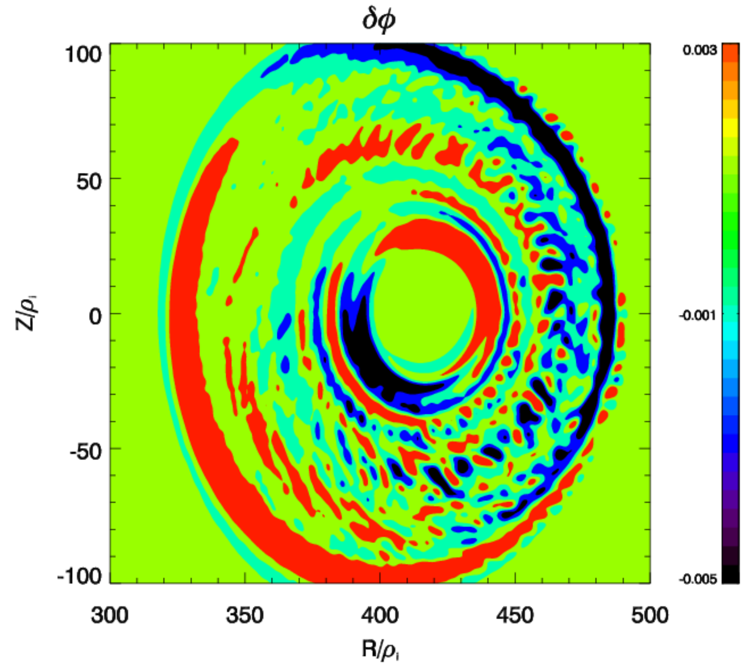
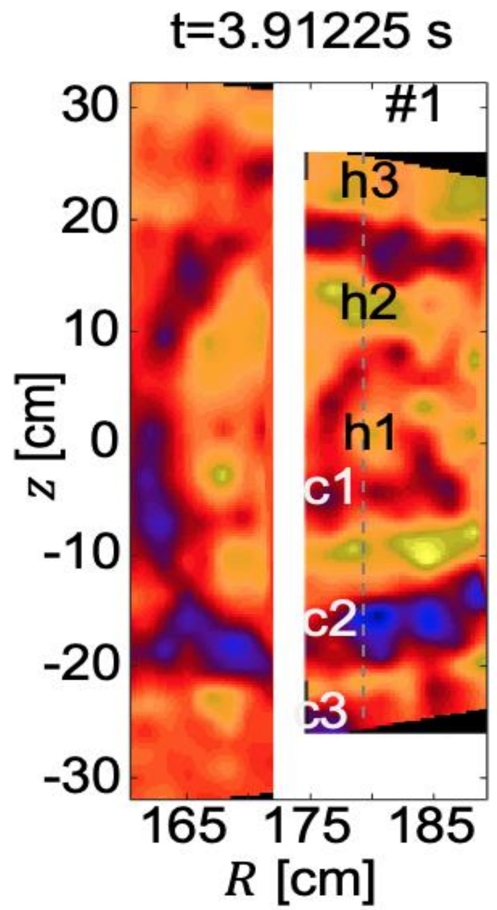
II. KSTAR L-mode: simulation

Observation of the avalanching activities from simulations





Contour plot of mean electrostatic potential fluctuation $\delta\phi$ in poloidal cross section R-Z plane.

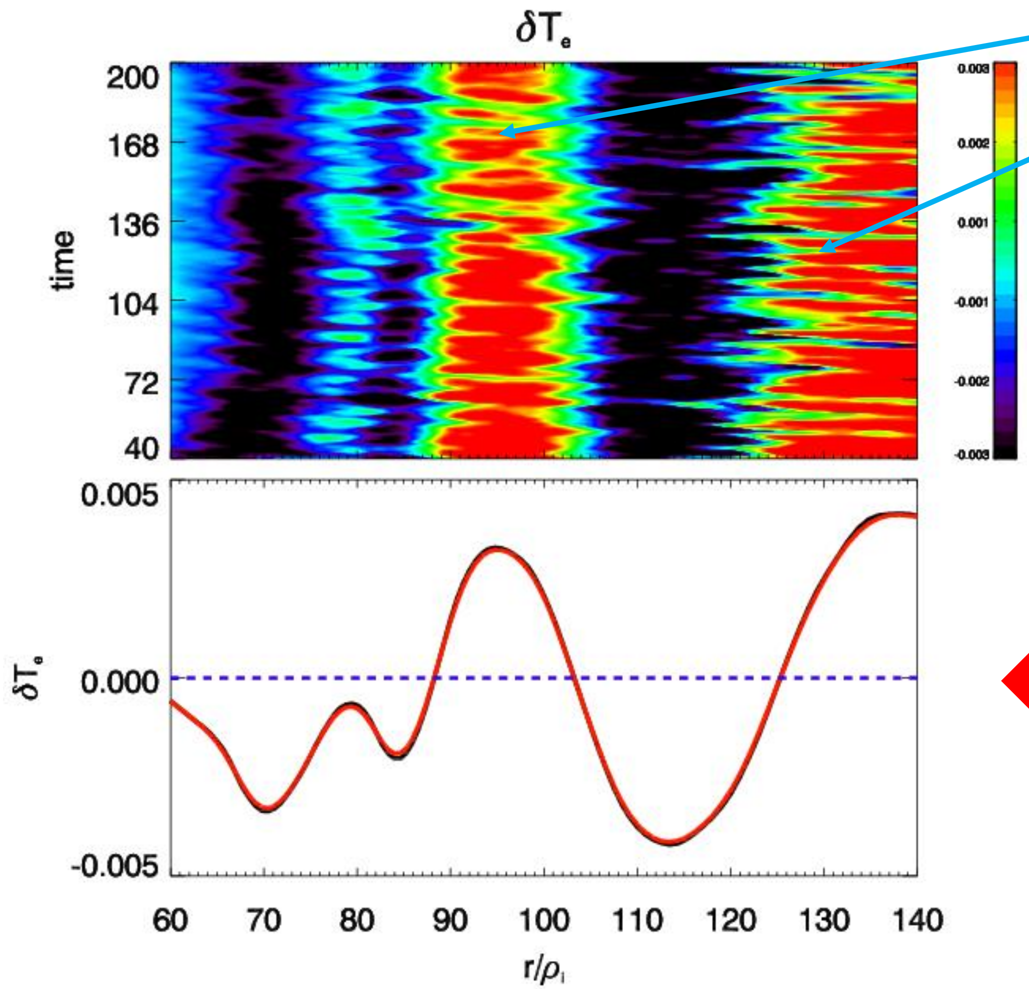
Electron temperature fluctuation δT_e in this format is on the way.

Electron temperature fluctuation δT_e in R-Z plane from experimental data

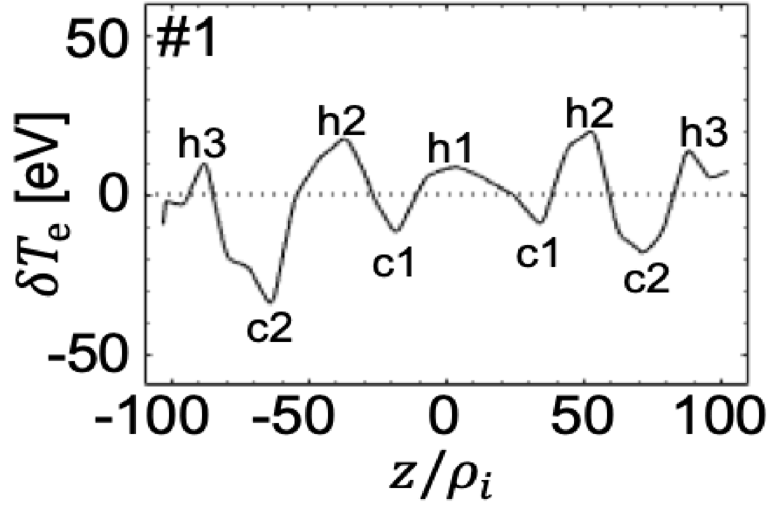
II. KSTAR L-mode: simulation

Flux-surface averaged electron temperature fluctuation δT_e, top contour plot in radial-time domain. Time-averaged mean fluctuation at bottom plot.

Avalanching like burst

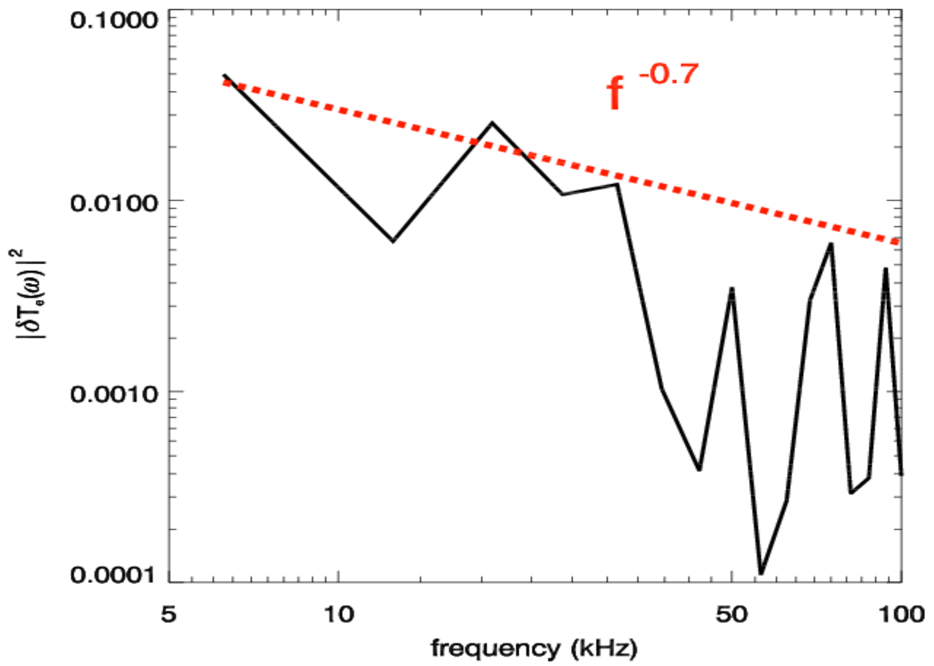


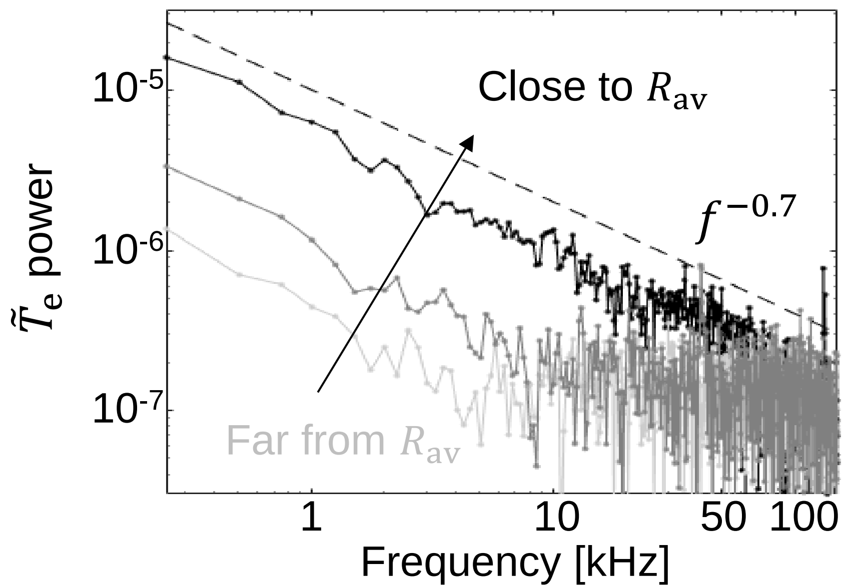
Corrugations in electron temperature fluctuation profile are observed. Corrugation scale (width) is $\sim \mathbf{45}\boldsymbol{\rho_i}$, consistent with experimental observations.



II. KSTAR L-mode: simulation

Spectrum scaling for $|\delta T_e(\omega)|^2$



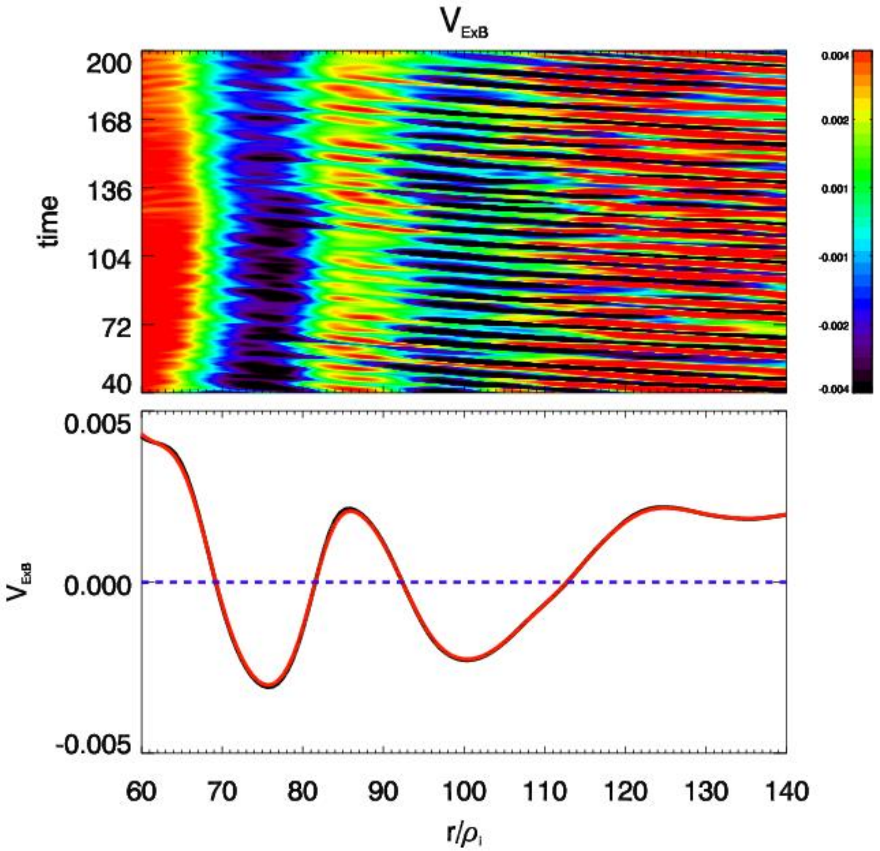


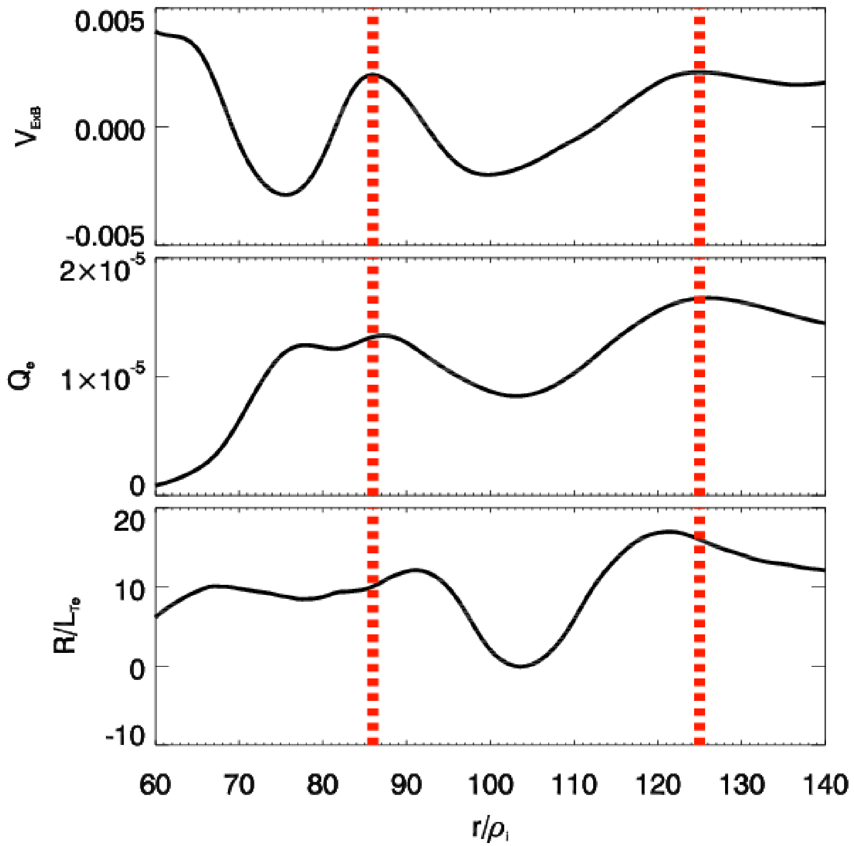
The spectrum scaling from our simulations $\boldsymbol{f^{-0.7}}$ is also consistent with experimental one, indicating strong overlapping of avalanches.

Simulation with longer time to obtain better frequency spectrum resolution is ongoing.

II. KSTAR L-mode: simulation

Zonal flow staircase from our nonlinear gyrokinetic simulation is found **responsible** to regulate the avalanches, leading to the <u>electron temperature fluctuation radial corrugations</u>. Zonal flow staircases are highly correlated with corrugations in electron temperature radial profile, **leaving footprints on electron heat avalanches**.





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IV. Conclusions (Part 1)

1. **Nonlinear gyrokinetic simulation of KSTAR L-mode plasmas**
   - ✓ Successfully reproduces the experimental observations
     - Large scale avalanches in electron heat transport. (spectrum scaling $\boldsymbol{f^{-0.7}}$)
     - Radial corrugations in electron temperature fluctuations. (width $\sim\boldsymbol{45\rho_i}$)
   - ✓ Shows direct evidence of zonal flow staircase and its footprints in regulating electron heat avalanches.
2. **Nonlinear gyrokinetic simulation of TEM turbulence in elongated plasmas finds**
   - ✓ Zonal flow staircases shear the turbulence, leading to corrugations in turbulence potential fluctuations and corrugations in radial profiles of transport avalanching.
   - ✓ Zonal flow corrugations are highly correlated with temperature and density profile corrugations
   - ✓ Elongation enhances zonal flow staircase in TEM driven turbulence.
     - Reduces the staircase step size
     - strengthens zonal flow staircase shearing
   - ✓ Transport levels are therefore reduced.

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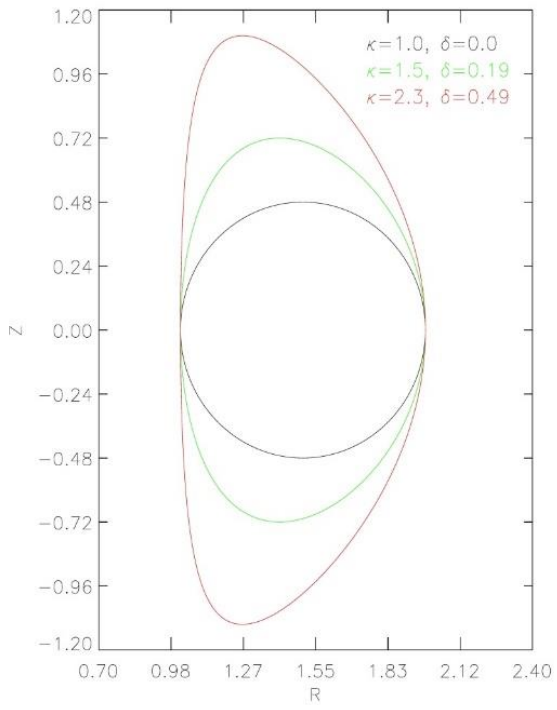
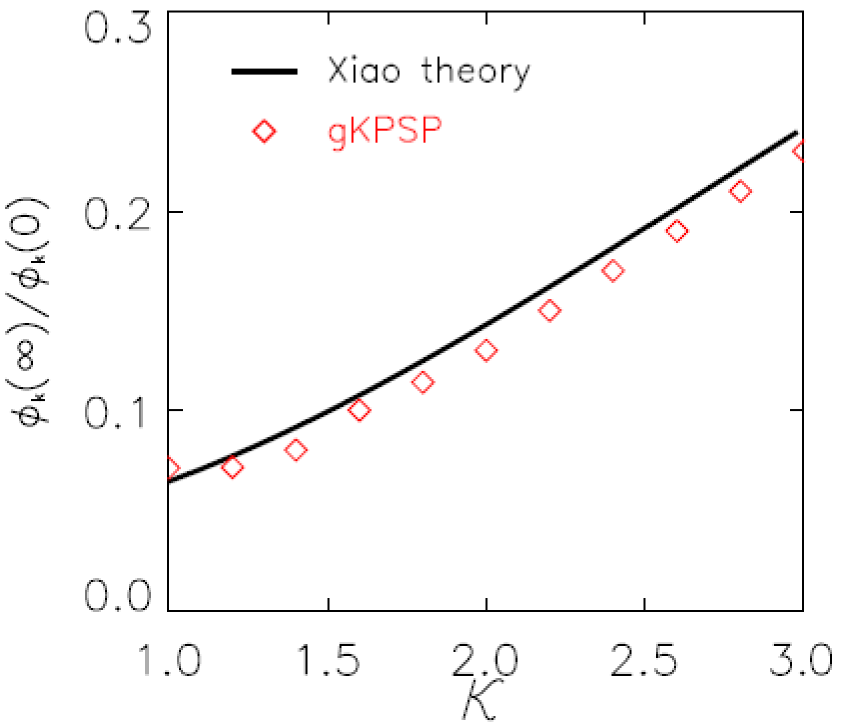
III. Elongated plasmas: simulations

Plasma elongation is interesting to study

- ✓ ITER IPB98(y,2) H-mode confinement empirical scaling law shows $\tau_E \propto \kappa^{0.78}$ (κ is elongation).
- ✓ Elongation enhances Rosenbluth-Hinton **residual zonal flow** (*Xiao and Catto, PoP 2006, L. Qi et al., PoP 2016*)





How about elongation effect on zonal flow staircase? And the consequent effects on TEM turbulence and transport.

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III. Elongated plasmas: simulations

For this theoretical study, we use the “Cyclone” based parameters

Normalized profile gradients are:

$$\frac{R_0}{L_{Te}} = 6.9$$

$$\frac{R_0}{L_n} = 2.2$$

$$\frac{R_0}{L_{Ti}} = 2.2$$

A pure TEM case, ITG suppressed.

Elongation $\kappa = 1 \; and \; 2$ are used.

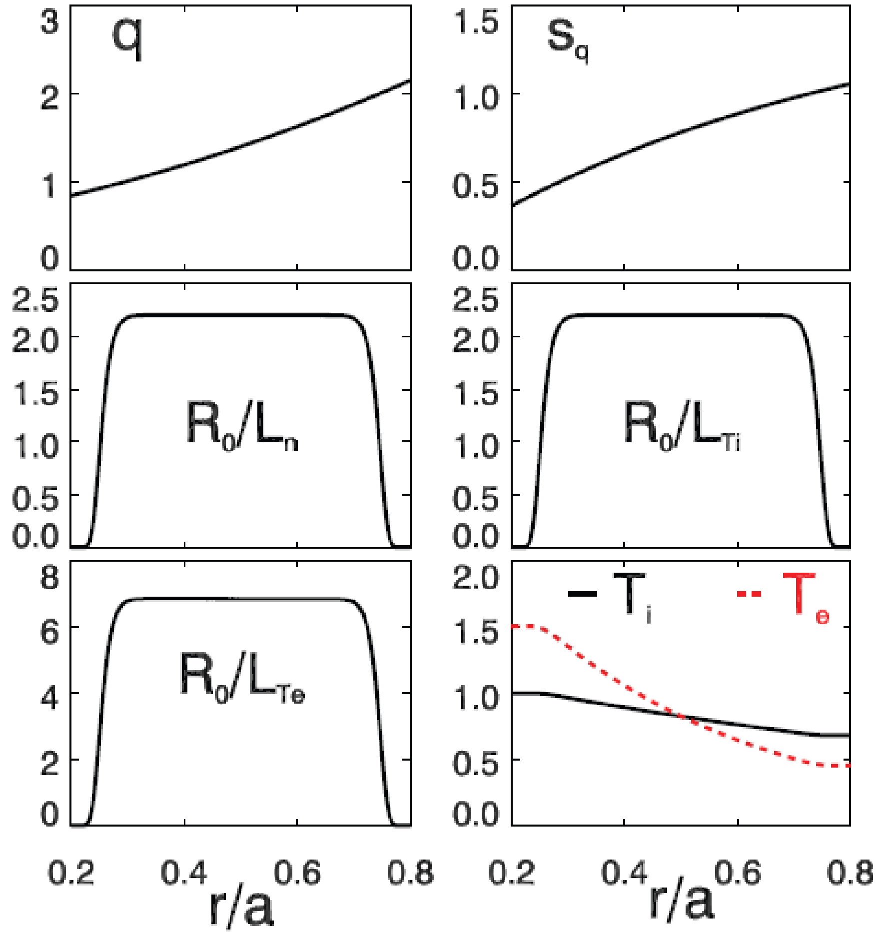
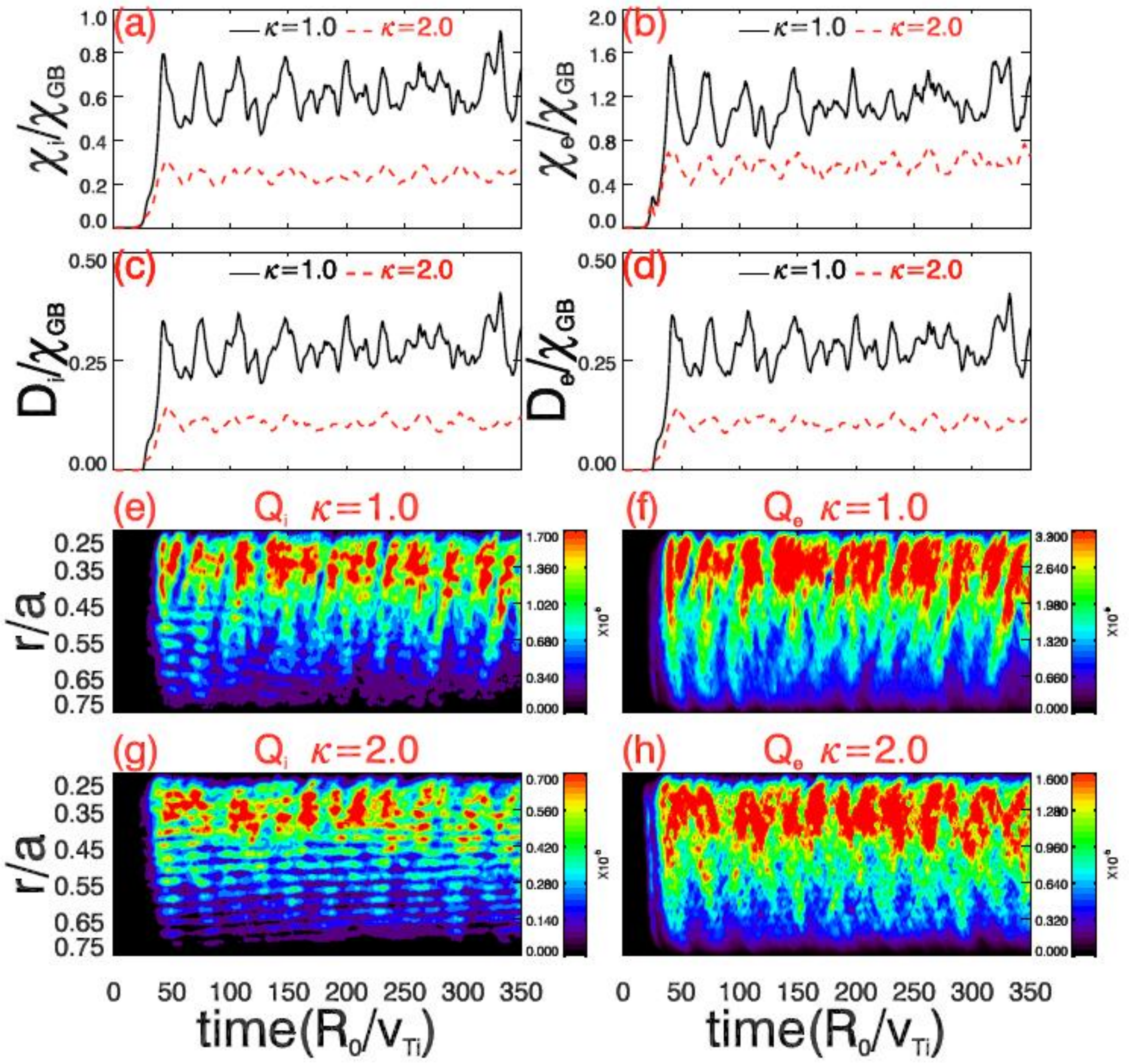


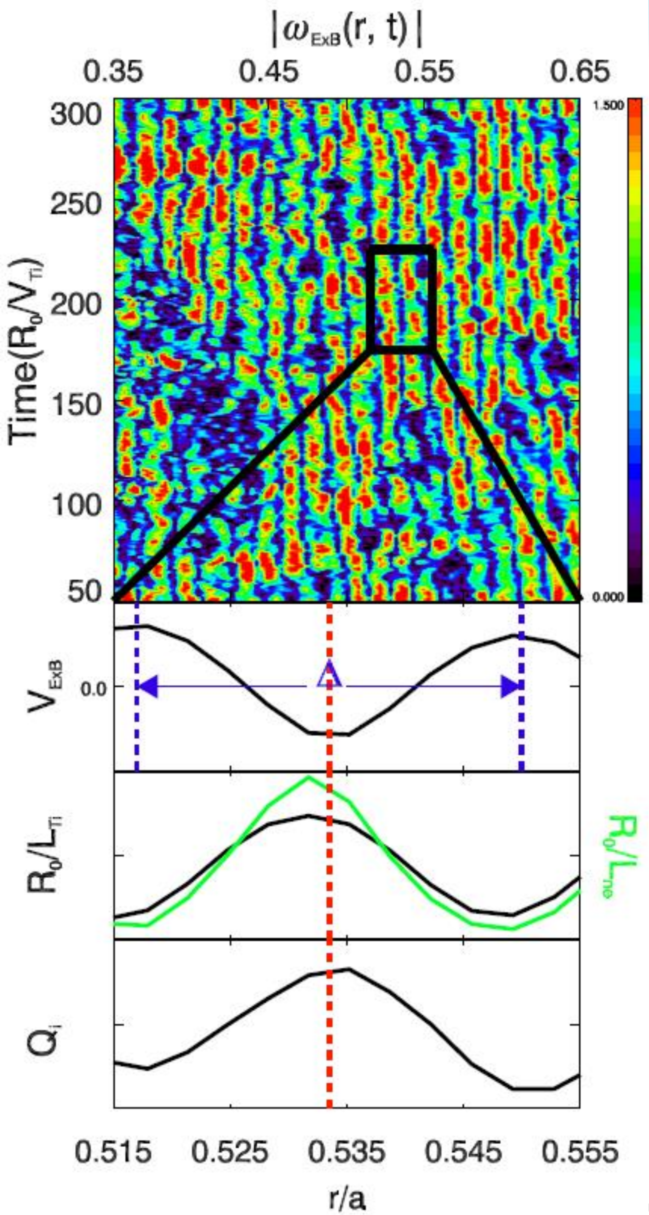
Figure 1. Initial setup of radial profiles for safety factor q, magnetic shear $\hat{s}_q$, density gradient R_0/L_n, ion temperature gradient R_0/L_{Ti}, electron temperature gradient R_0/L_{Te} and ion (electron) temperature $T_{\mathrm{i(e)}}$.

III. Elongated plasmas: simulations



1. Elongation stabilizes TEM driven transport in all channels.
2. Transport shows avalanching bursts and also radial corrugations. Transport are more regulated in a higher elongation (*Lei Qi et al., NF 2017 (Lett.), NF 2019*). Why? Is it sheared by zonal flow staircase? We will answer.
3. In electron heat flux channel, regulations by zonal flow staircase is weak. Why? Not clear yet.

III. Elongated plasmas: simulations



Zonal flow features obtained from simulations:

1. Contour of zonal flow shearing rate $\omega_{E\times B} = \frac{(RB_\theta)^2}{B}\left|\frac{\partial}{\partial\psi}\frac{E_r}{RB_\theta}\right|$ (*Hahm and Burrell, PoP 1995*) in radial-time domain shows **long-lived peaks and valleys**.

2. **Step-like (staircase) patterns:** Corrugations in profile gradients are highly correlated with zonal flow staircase generation, which shears turbulence and leads to corrugations in transport fluxes.

3. Δ indicates the **staircase scale length ~$\boldsymbol{10\rho_i}$** in this case.

Ref: Lei Qi et al., NF 2019

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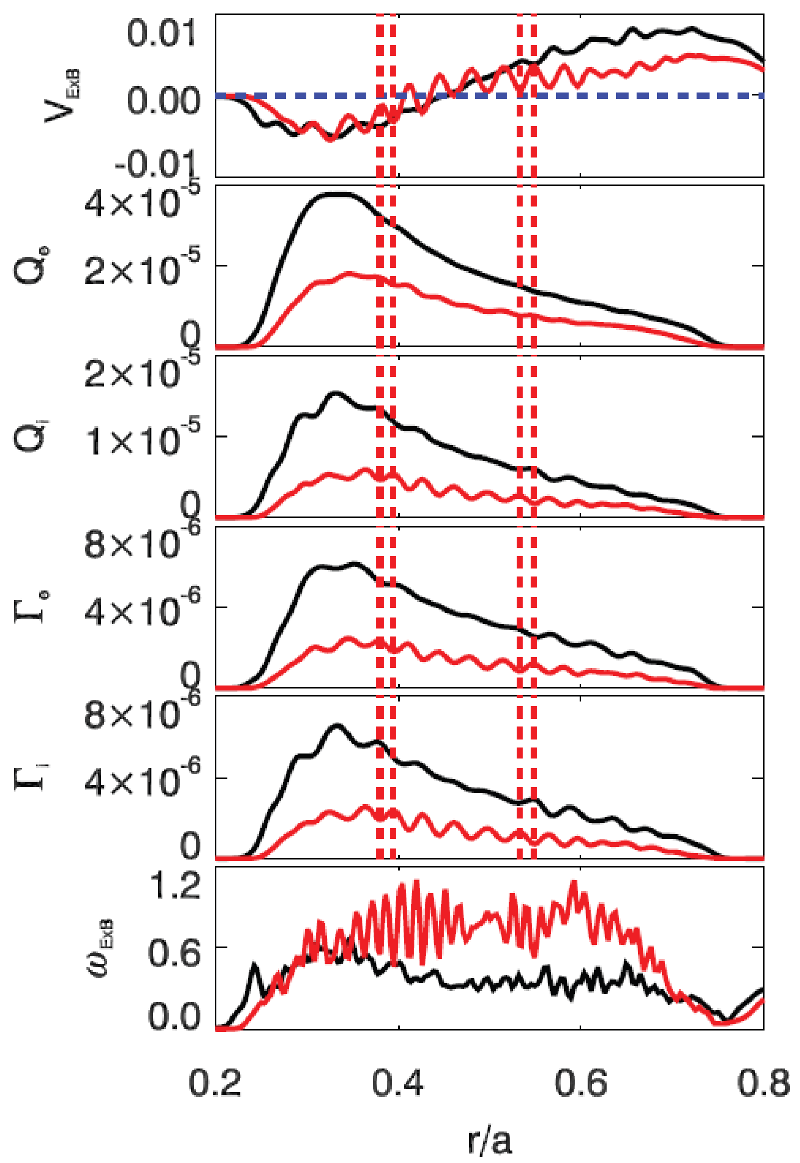
III. Elongated plasmas: simulations



- ✓ Radial profiles of $V_{E\times B}, Q_e, Q_i, \Gamma_e, \Gamma_i, \omega_{E\times B}$, averaged over the whole saturation time. Black: $\kappa = 1$, Red: $\kappa = 2$.

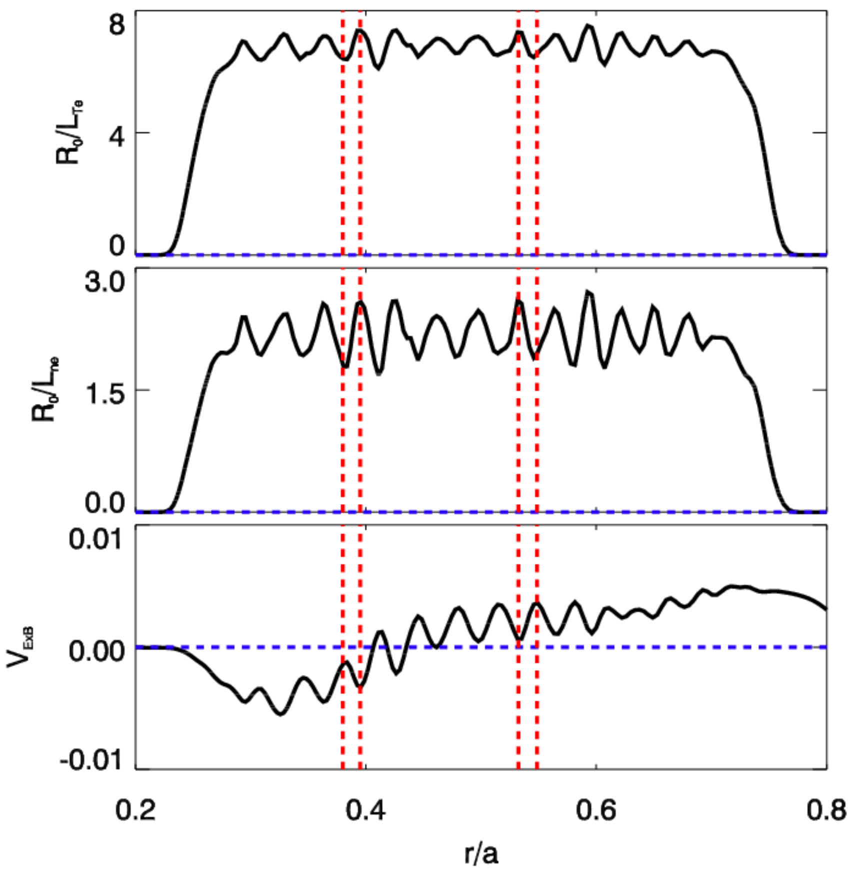
- ✓ Elongation reduces the transport level in all flux channels and the whole radial domain.

- ✓ It seems zonal flow shears and regulates the transport.

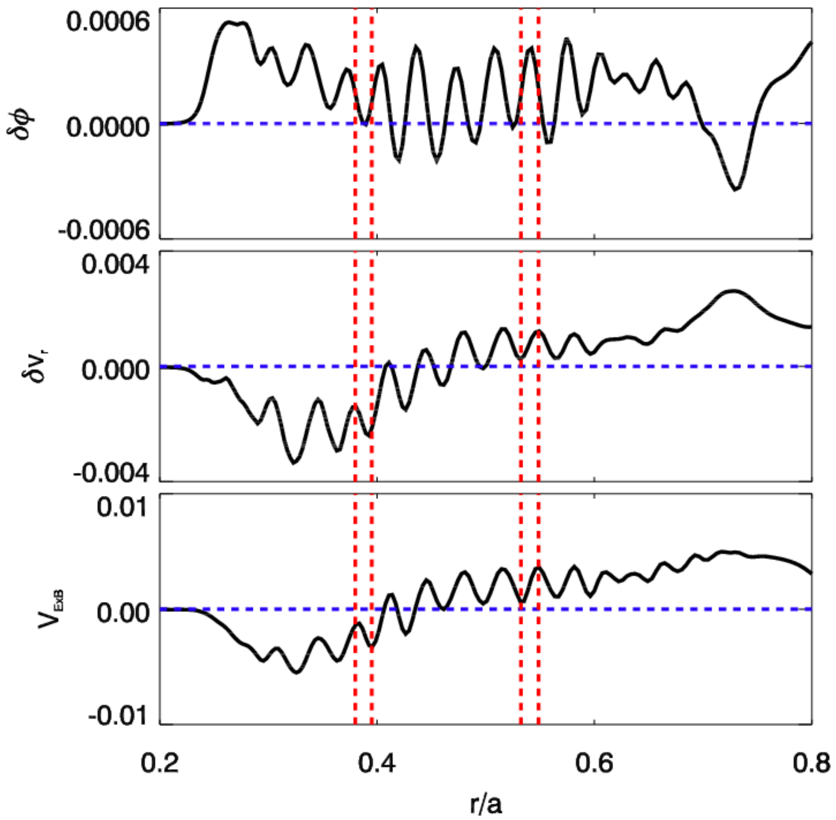
- ✓ By qualitatively observation, elongation enhances the zonal flow staircase and its shearing rate.

III. Elongated plasmas: simulations

Taking κ =2 case as an example. Quasistationary corrugations in background density and temperature profiles, flux-surface averaged turbulent potential fluctuation $\delta\phi$, turbulence driven radial $E \times B$ velocity δv_r and mean zonal flow.



Time-averaged electron density and temperature gradients compared with zonal flow in radius



Particle flux: $\Gamma = \int f(v)\delta v_r dv$

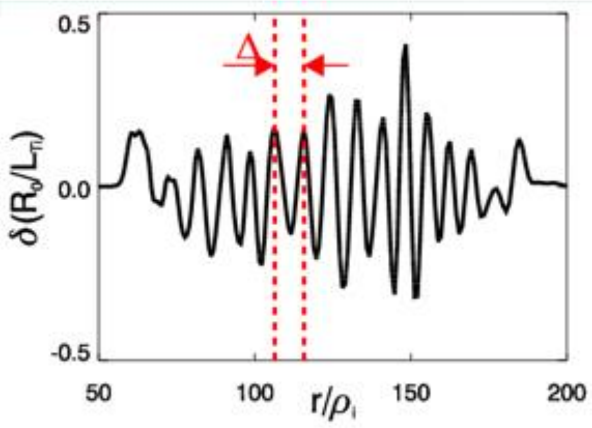
Heat flux: $Q = \int f(v)v^2\delta v_r dv$

Corrugations in transport radial profiles?

III. Elongated plasmas: simulations

To quantify the effects of elongation on zonal flow staircase, we measure the following two physical quantities. The staircase step size Δ is measure between the bounding corrugations to characterize the staircase scale. The long-live staircase shearing is calculated as $|\omega_{ss}| \equiv \left|\frac{\partial <V_{E\times B}>_t}{\partial r}\right|$ to indicate the strength of staircase. Here $< \cdots >_t$ means time average.

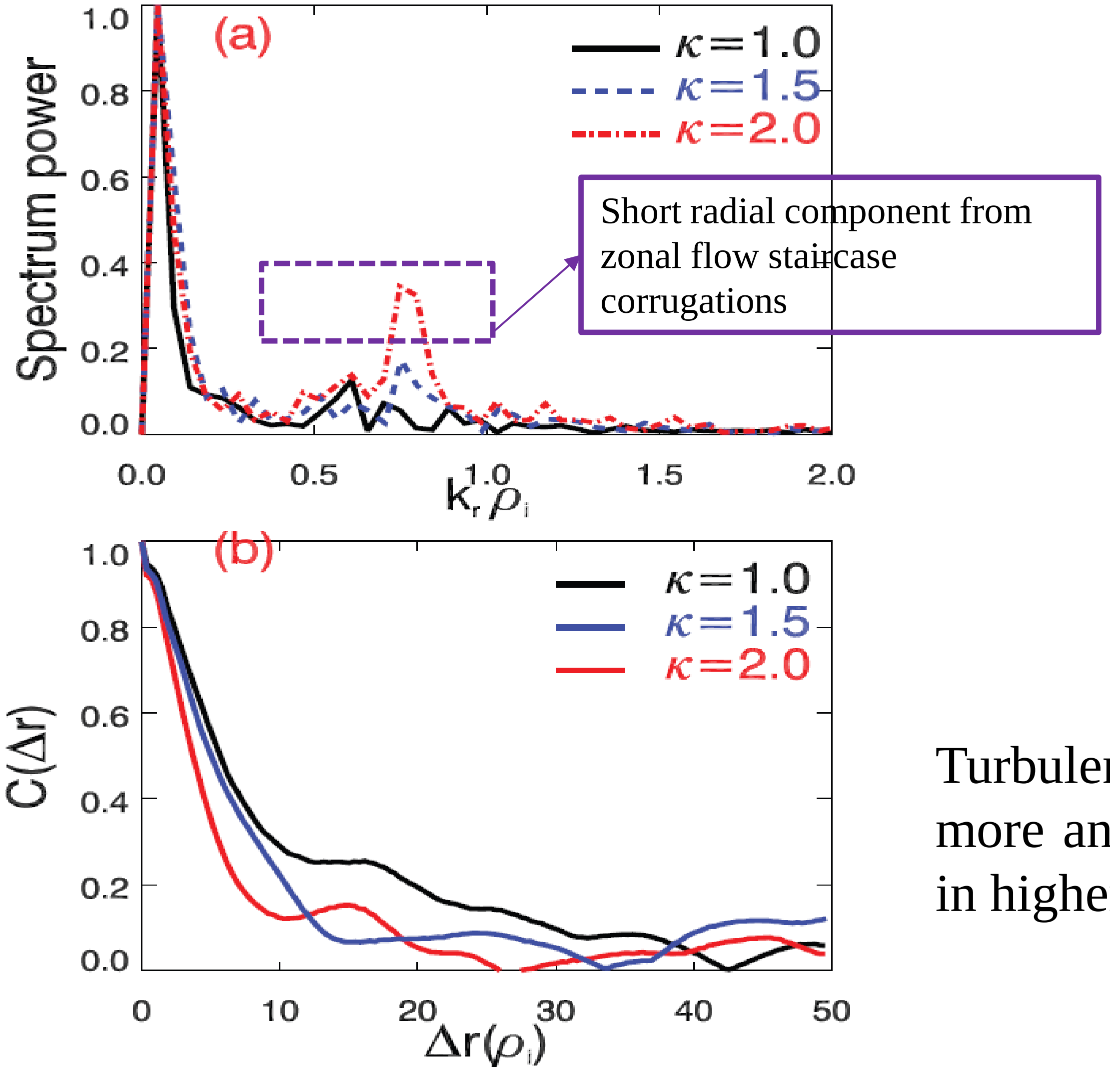
	$\kappa = 1.0$	$\kappa = 1.5$	$\kappa = 2.0$
$\omega_{E\times B}/\sigma$	0.36/0.14	0.65/0.26	0.79/0.27
l_c	8.5	6.0	4.5
$\bar{\Delta}$	11.4	9.5	8.0
$\bar{k}_r$	0.55	0.66	0.78
$\langle\omega_{ss}\rangle_r/\sigma(\times 10^{-3})$	1.96/1.6	3.06/2.7	3.89/3.4

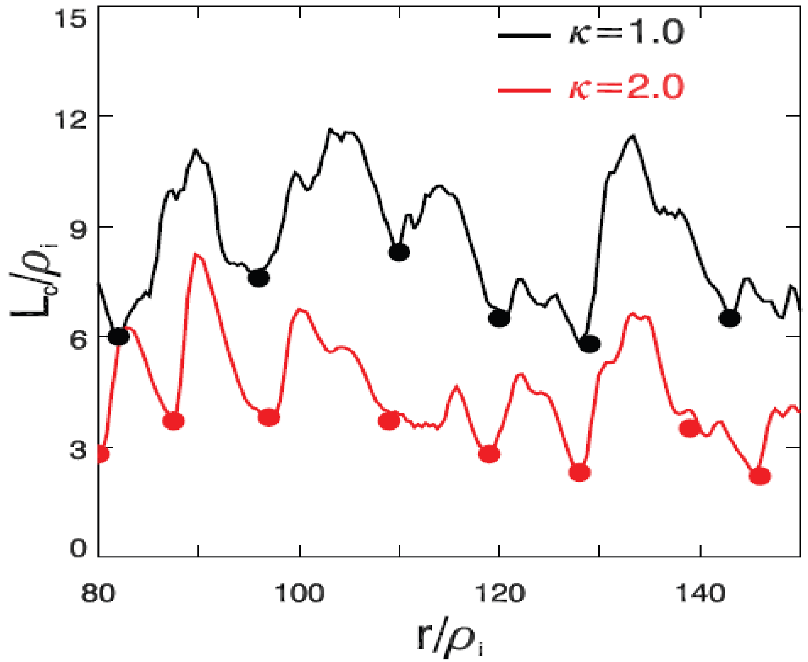


1. Elongation reduces staircase scale
2. Elongation enhances staircase shearing.

III. Elongated plasmas: simulations

Elongation enhances zonal flow staircase and its shearing in reducing turbulence radial correlation, and consequently leads to reduced transport.

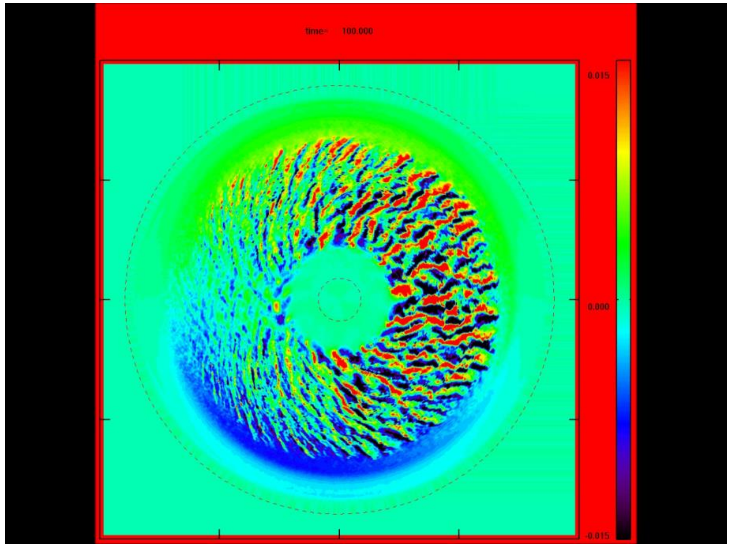


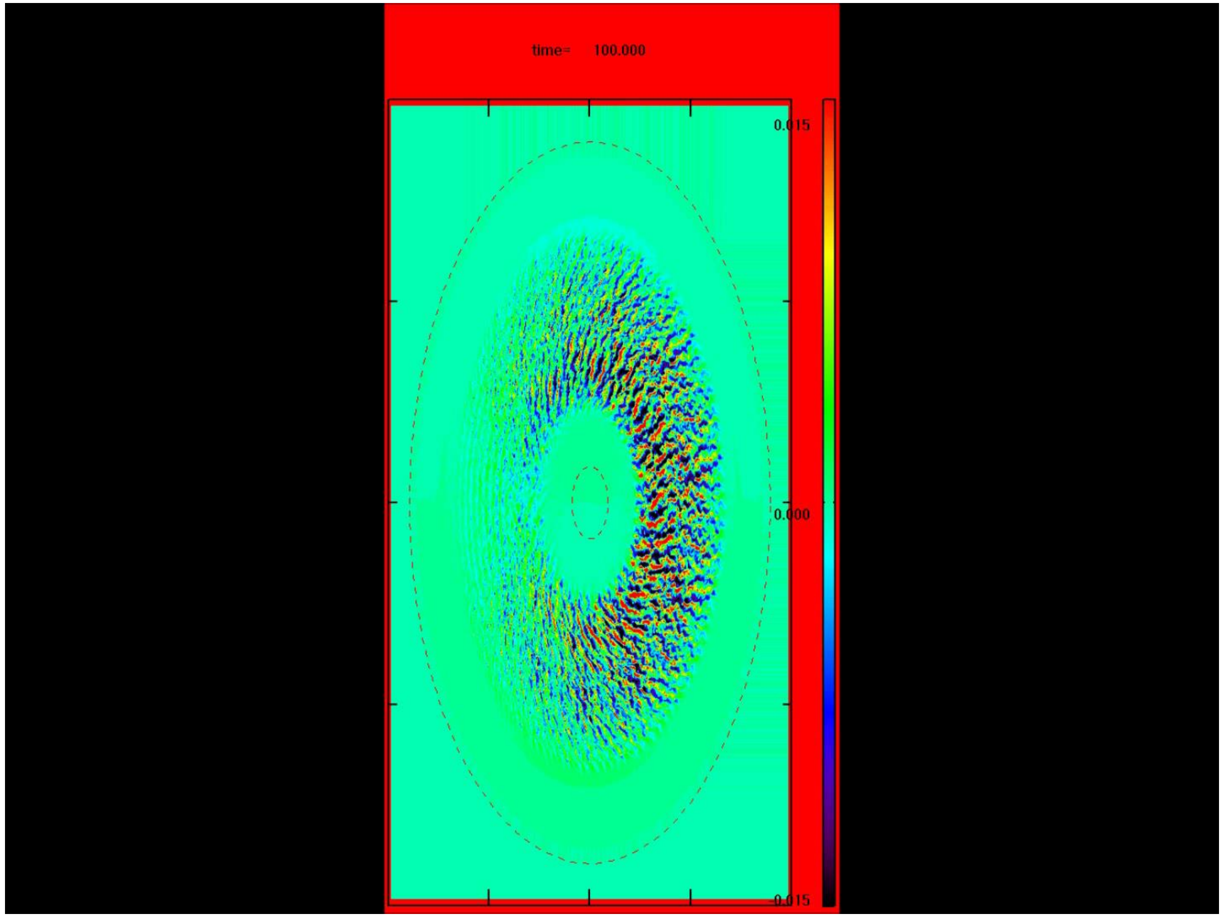


Turbulence is less correlated and eddies are broken into more and smaller pieces by zonal flow staircase shearing in higher elongation plasmas.

III. Elongated plasmas: simulations

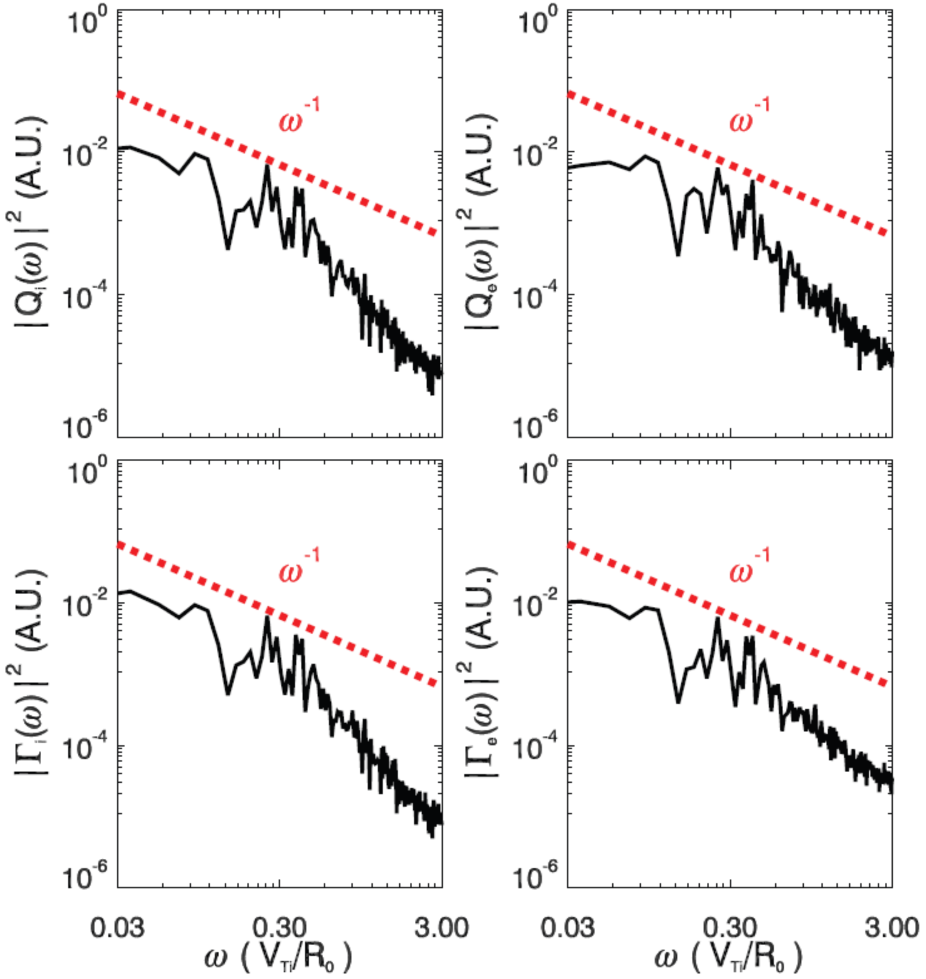
Contour plots of turbulence potential shows turbulence eddies are more sheared by zonal flow in higher elongation.





III. Elongated plasmas: simulations

Spectra evidence of avalanching events from δf gyrokinetic simulations in all transport channels.



$1/f$ type spectra at low frequency indicates the **overlapping of avalanches**. (*Kadanoff L. P. et al., PRA 1989*)

Strong decay at high frequency corresponds to frequent small scale.

This kind of spectrum is a typical characteristic of self-organized criticality (SOC) (*Sanchez R. et al., NF 2001, Hahm and Diamond, JKPS 2018*) and also **consistent with *full-f* gyrokinetic simulations** (*Idomura et al., NF 2009*).

IV. Conclusions (Part 2)

1. **Nonlinear gyrokinetic simulation of KSTAR L-mode plasmas**
   - ✓ Successfully reproduces the experimental observations
     - Large scale avalanches in electron heat transport. (spectrum scaling $f^{-0.7}$)
     - Radial corrugations in electron temperature fluctuations. (width $\sim 45\rho_i$)
   - ✓ Shows direct evidence of zonal flow staircase and its footprints in regulating electron heat avalanches.
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   - ✓ Zonal flow corrugations are highly correlated with temperature and density profile corrugations
   - ✓ Elongation enhances zonal flow staircase in TEM driven turbulence.
     - Reduces the staircase step size
     - strengthens zonal flow staircase shearing
   - ✓ Transport levels are therefore reduced by higher elongations.

IV. Future work and open discussion

- Longer simulations of the KSTAR L-mode plasmas are on going to acquire better resolution in the frequency space and better electron temperature fluctuation diagnostic.

- Proposal to KSTAR experiments for the study of elongation effects on zonal flow staircase (electron temperature fluctuation corrugations) has be submitted in collaboration with Drs. Minjun Choi and Jaemin Kwon.

OPEN QUESTION: We found different zonal flow scales in KSTAR L-mode experiment plasmas and “cyclone” based elongated plasmas. ***What is the generation mechanism of zonal flow staircase and what determines the staircase scale?***