The $\mathbf{E} \times \mathbf{B}$ staircase as the self-organization in non-equilibrium complex systems

Minjun J. Choi[1] *, Jae-Min Kwon[1], Lei Qi[1], P. H. Diamond[2], T. S. Hahm[3], Hogun Jhang[1], Juhyung Kim[1], M. Leconte[1], Hyun-Soek Kim[1], Jisung Kang[1], Byoung-Ho Park[1], Jinil Chung[1], Jaehyun Lee[1], Minho Kim[1], Gunsu S. Yun[4], Won-Ha Ko[1], K. D. Lee[1], June-Woo Juhn[1]

[1] Korea Institute of Fusion Energy

[2] University of California, San Diego

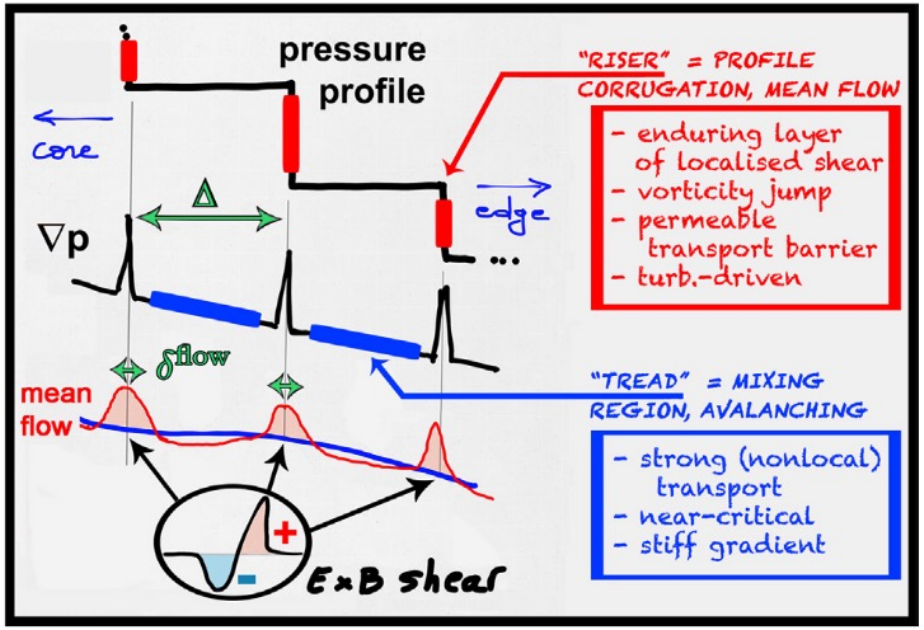
[3] Seoul National University

[4] Pohang University of Science and Technology

mjchoi@kfe.re.kr

Intro: the $\mathrm{E} \times \mathrm{B}$ staircase

- The $\mathrm{E} \times \mathrm{B}$ staircase: globally self-organized mini transport barriers (shear flow layers)



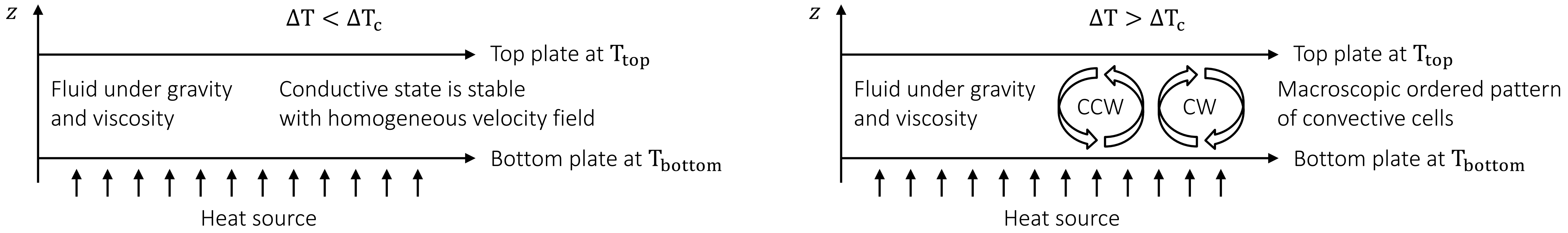
[G. Dif-Pradalier et al., Nucl. Fusion 57, 066026 (2017)]

- How does a "macroscopically ordered" pattern arise?

Intro: the self-organization in non-equilibrium complex systems

- The self-organization: emergence of macroscopically ordered structure (of various size and duration) in non-equilibrium complex systems (open, driven, strongly nonlinear) [Goldenfeld, Science (1999)] [Nicolis & Prigogine, *Exploring complexity* (1989)] [Sánchez & Newman, *A Primer on Complex System* (2018)]
  - Distributions of structure characteristics are rarely normal
  - Structures are sensitive to the initial random microscopic condition
  - They are a way of efficiently extracting the excess energy in the system

- Rayleigh-Bénard convection cells [Nicolis & Prigogine, *Exploring complexity* (1989)] [Livi & Politi, *Nonequilibrium statistical physics* (2017)]



Physical meaning of $\Delta T > \Delta T_c$: efficiency (1/time scale) of convection is sufficiently larger than that of conduction

Rayleigh number $Ra(\Delta T) = \frac{\tau_{cond}}{\tau_{conv}} > Ra_c(\Delta T_c)$

Intro: revisiting the $\mathrm{E} \times \mathrm{B}$ staircase

- The $\mathrm{E} \times \mathrm{B}$ staircase is observed in the near-marginal regime where avalanche transport is dominant

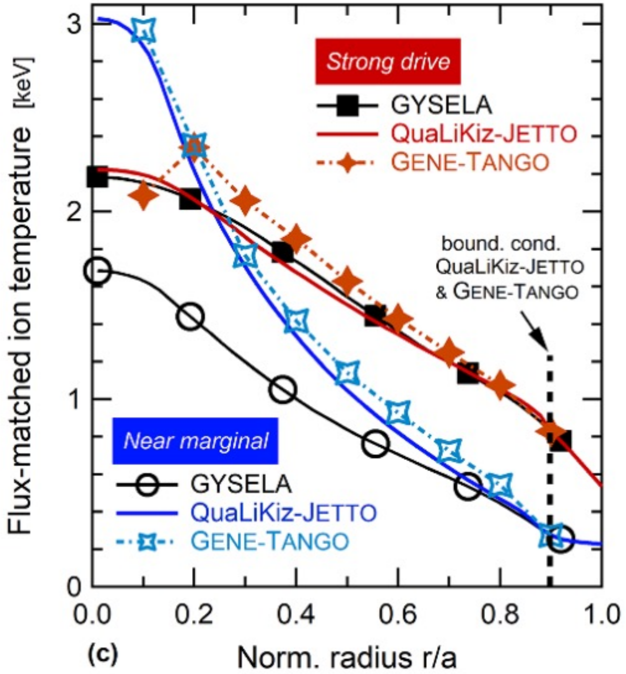
GYSELA simulation [Dif-Pradalier, NF (2017)]
KSTAR experiment [M.J. Choi, NF (2019)]

- The near-marginal regime: $\mathrm{Q}_{\mathrm{total}} - \mathrm{Q}_{\mathrm{neo}} \sim \mathrm{Q}_{\mathrm{neo}}$
  - It is characterized by Kubo number $\mathrm{K} \equiv \frac{\tau_{\mathrm{det}}}{\tau_{\mathrm{exc}}} > 1$ [Gillot, PPCF (2023)]

    τ_{det} is particles' detrapping time across eddies
    τ_{exc} is particles' excursion time along an turbulence eddy
    - Ballistic transport events (avalanche) are dominant
    - Wave-particle interaction is important

$\mathrm{K} < 1$: diffusion by many kicks or detrappings
$\mathrm{K} > 1$: excursion on a turbulence eddy

Inconsistency in the near-marginal regime
between flux-driven GK vs gradient-driven GK or quasi-linear model



[Gillot & Dif-Pradalier, PPCF (2023)]

- How is the $\mathrm{E} \times \mathrm{B}$ staircase related with the dominant (efficient) transport process in the near-marginal regime?
  - The avalanche transport
  - Phase space structures?

Outline

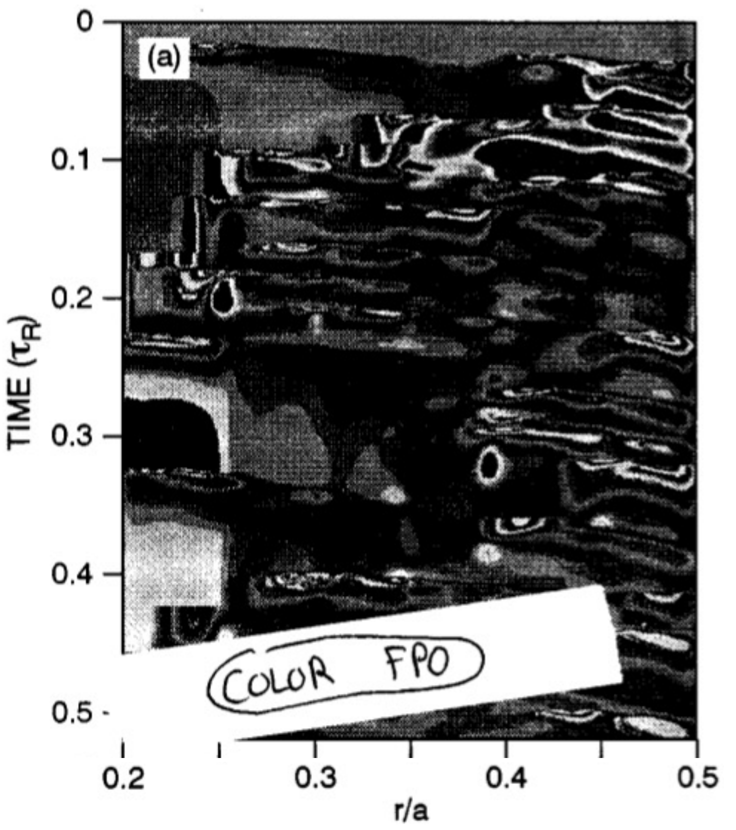
[M.J. Choi et al., arXiv:2207.06610, submitted to Nucl. Fusion]

- Near-marginal transport in tokamak plasmas*
  - The avalanche transport
  - The $\mathrm{E} \times \mathrm{B}$ staircase
- The KSTAR avalanche/staircase plasma
- Experimental analyses of the avalanche transport
  - Ballisitic behavior, η_i dependency, radially elongated eddy, the power-law distribution
- Experimental analyses of the $\mathrm{E} \times \mathrm{B}$ staircase
  - Fast propagation of initial perturbation, collisionality dependency, zonal three-wave coupling, the Fréchet distribution
- Discussions
  - Role of the avalanche on the $\mathrm{E} \times \mathrm{B}$ staircase formation and its width distribution
  - The $\mathrm{E} \times \mathrm{B}$ staircase as the self-organization near an non-equilibrium critical state
  - The avalanche and $\mathrm{E} \times \mathrm{B}$ staircase: two faces of the one thing

*A recent review available on this topic
[T.S. Hahm & P.H. Diamond, J. Korean Phys. Soc. 73, 747 (2018)]

The avalanche transport: ballistic propagation event

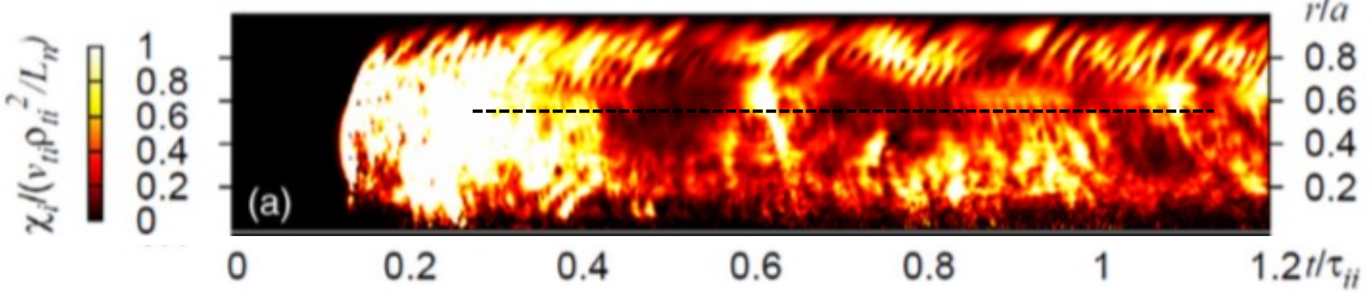
- Near ballistic flux propagation events are observed in various simulations



[B.A. Carreras et al., Phys. Plasmas 3, 2903 (1996)]

GT5D [Y. Idomura et al., Nucl. Fusion 49, 065029 (2009)]

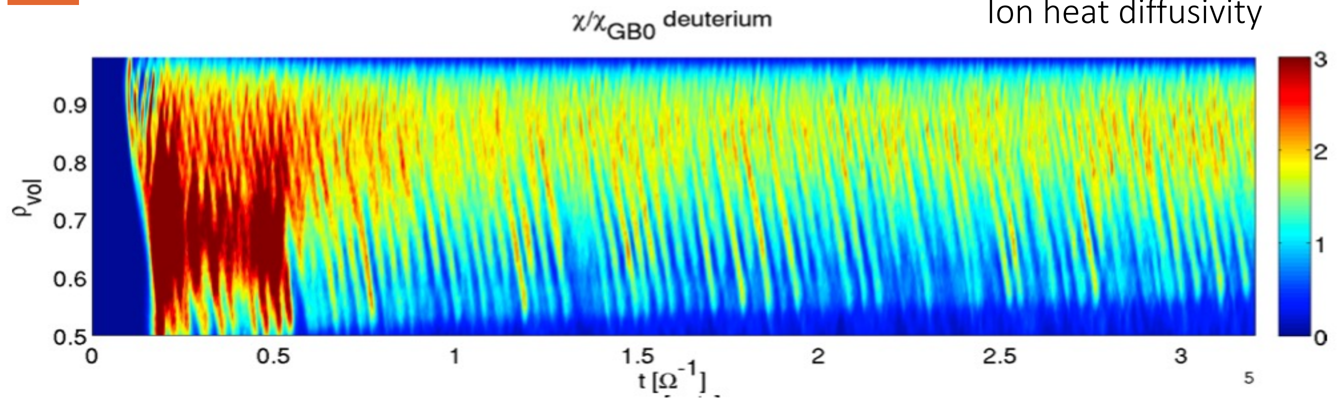
Ion heat diffusivity



Time

ORB5 [L. Villard et al., J. Phys.: Conf. Ser. 561, 012022 (2014)]

Ion heat diffusivity



Time

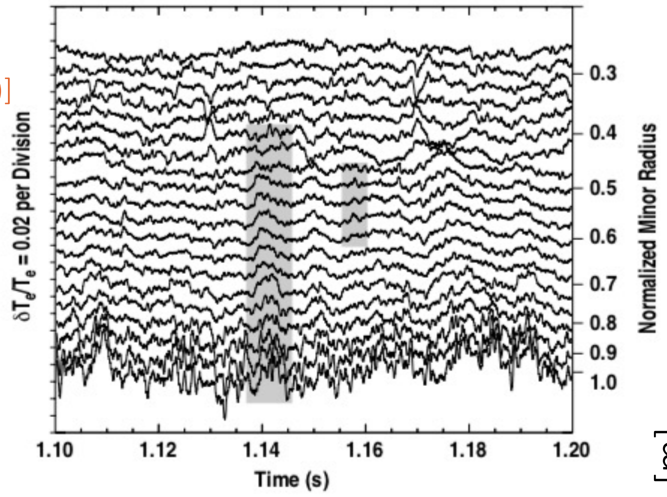
More simulation studies: Garbet PoP 1998, Beyer PRL 2000, Mier PoP 2006 & 2008, Tokunaga PoP 2012
Ku NF 2009 & 2012, Sarazin NF 2010 & 2011, Dif-Pradalier PRE 2010 & NF 2017, Jolliet NF 2012, Wang NF 2019 & 2020, Qi NF 2019, 2020, & 2022

The avalanche transport: ballistic propagation event

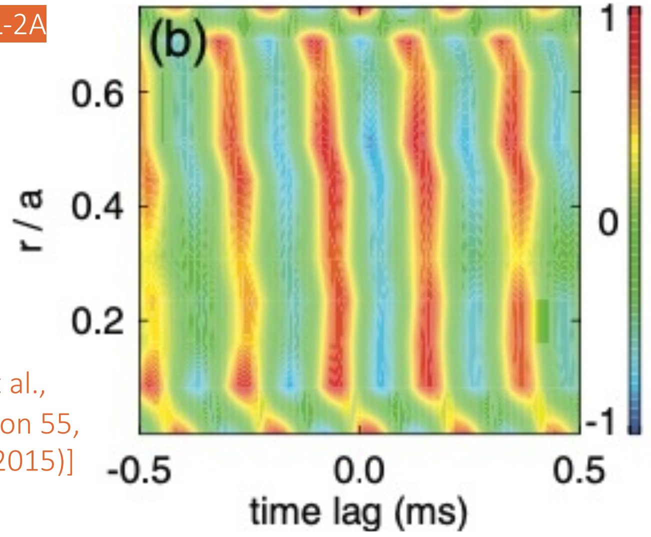
- Near ballistic flux propagation events are observed in DIII-D, HL-2A, KSTAR, etc

[P.A. Politzer, Phys. Rev. Lett. 84, 1192 (2000)]

DIII-D

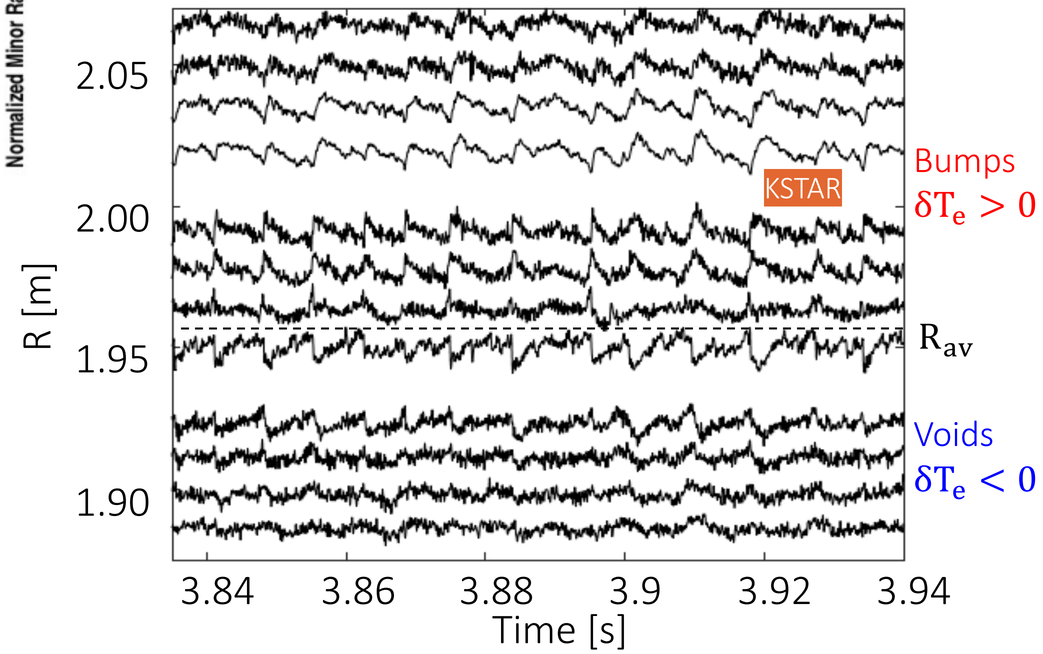


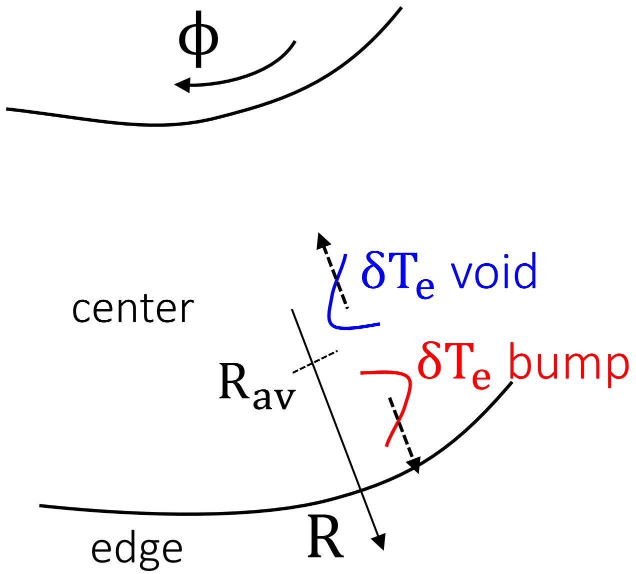
HL-2A



[O. Pan et al., Nucl. Fusion 55, 113010 (2015)]

[M.J. Choi et al., Nucl. Fusion 59, 086027 (2019)]





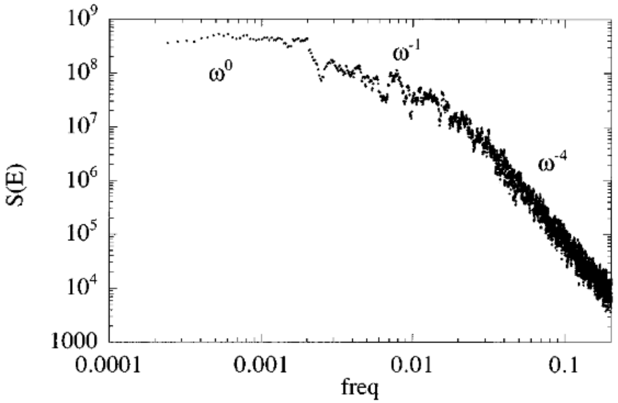
Joint reflection symmetry

[P.H. Diamond and T.S. Hahm, Phys. Plasmas 2, 3640 (1995)]

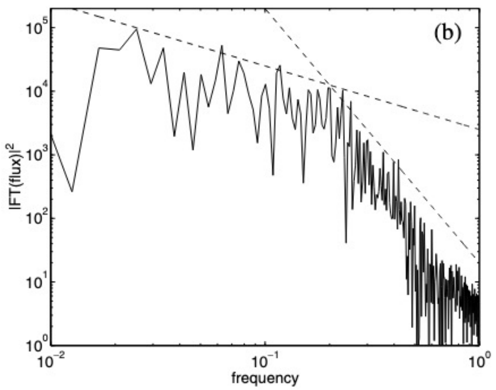
More experimental studies: Van Compernolle PoP 2017, Zhang PPCF 2019, Chen NF 2020, Kin PoP 2019, Hong PoP 2023, NF 2023

The avalanche transport as scale-free process

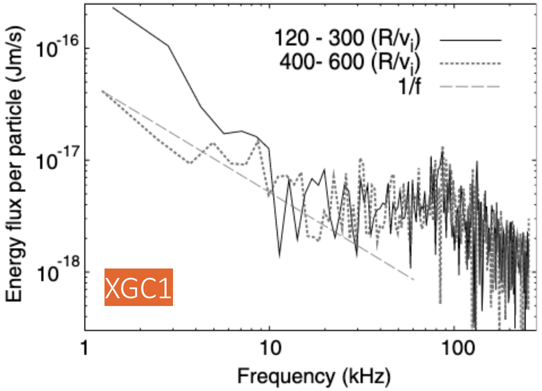
- Scale-free characteristics of the avalanche transport in both simulations and experiments
  - Avalanches of various spatial scales up to ~ the machine size (a) (finite system size) were observed
  - The frequency spectrum of avalanche (psuedo-) size is observed to follow the power-law f^{-a}



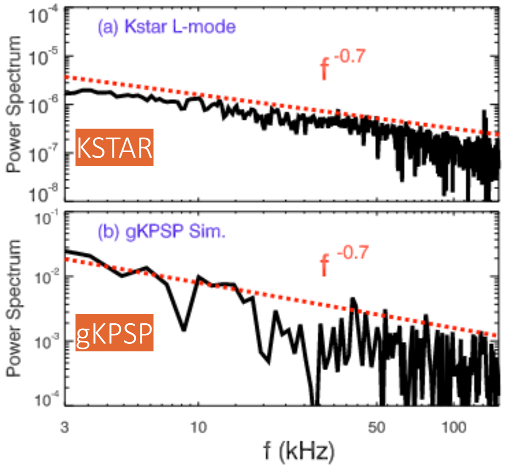
[Newman, PoP 1996]



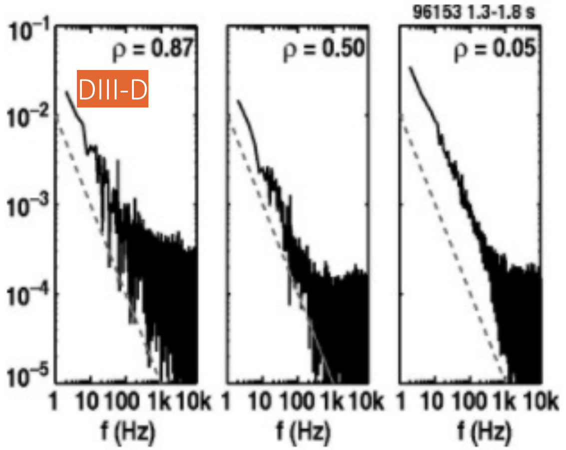
[Beyer, PRL, 2000]



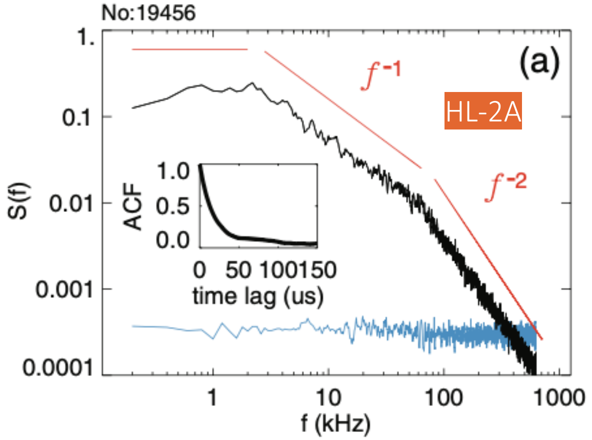
[Ku, NF, 2009]



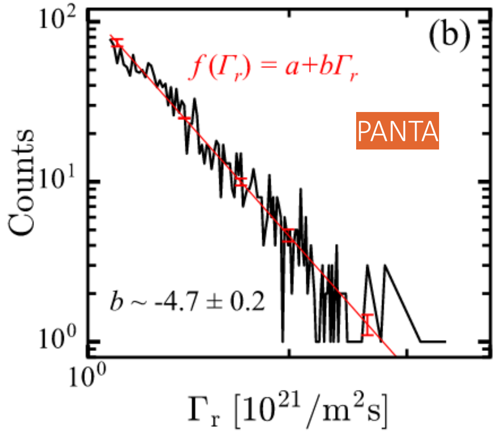
[Choi, NF, 2019][Qi, NF, 2021]



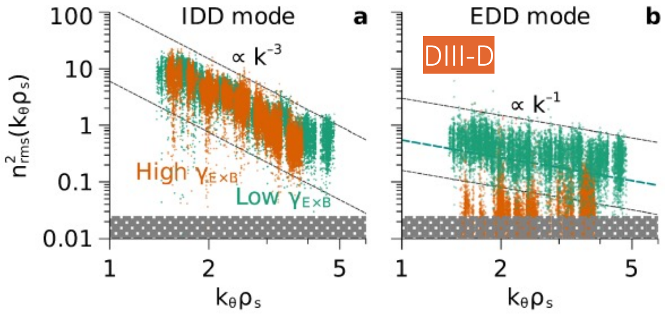
[Politzer, PoP 2002]



[Pan, NF, 2015]



[Kin, PoP, 2019]



[Hong, PoP, 2023]

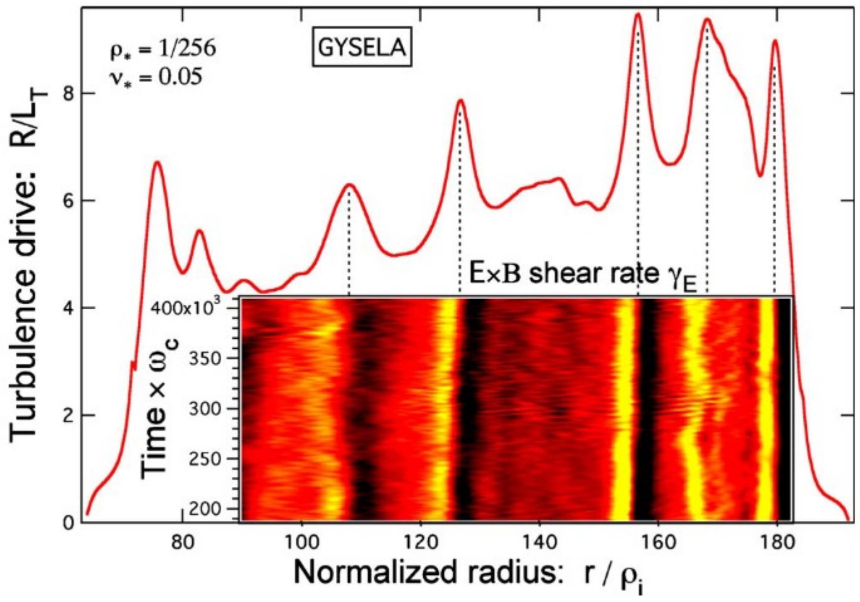
Understanding the avalanche transport in tokamak plasmas

- Characteristics of the avalanche transport
  - Nondiffusive behavior: ballistic flux propagation
  - Scale-free behavior: power-law distribution of characteristics

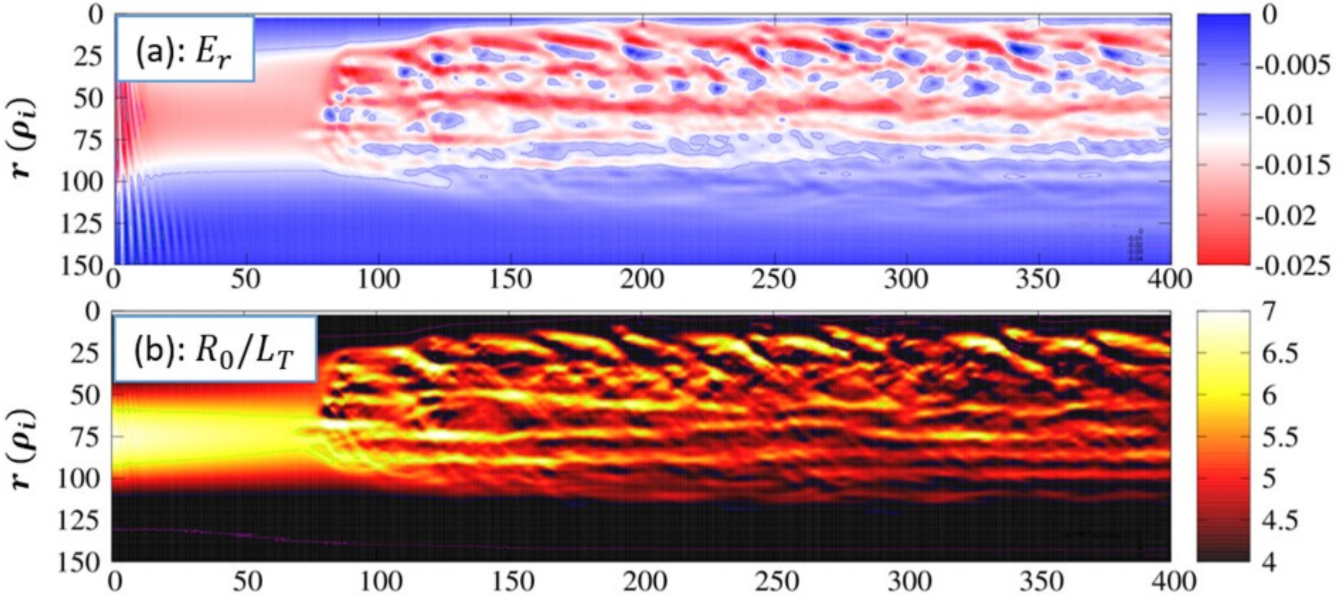
- Various physical models relevant to the avalanche transport
  - Domino effect as in the self-organized criticality system [Diamond & Hahm, PoP, 1995]
  - Linear toroidal mode coupling [Garbet et al., NF, 1994]
  - Turbulence energy spreading by plasma inhomogeneity [Hahm et al., PPCF, 2004][Gürcan et al., PoP, 2005]
  - Streamer formation (requiring sufficient zonal flow damping) [Champeaux & Diamond, PLA, 2001]
  - Wave trapping and propagation with GAM [Sasaki, PoP, 2018]
  - Tertiary instability propagation [Zhu, PRL, 2020]

$E \times B$ staircase: globally self-organized transport barriers

- $E \times B$ staircase is observed in various simulations



GYSELA [G. Dif-Pradalier, Phys. Rev. E. 82, 025401(R) (2010)]



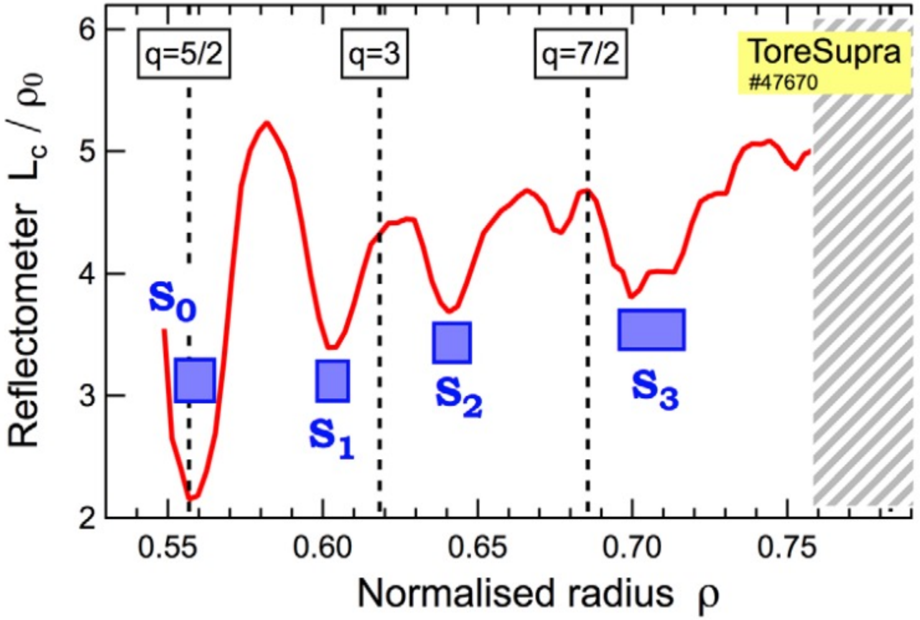
GKNET [W. Wang, Nucl. Fusion 58, 056005 (2018)]

More simulation studies: Wang NF 2020, Villard JPCS 2014, Qi NF 2019, 2020 & 2022, Dominski PoP 2015, Rath PoP 2021

E × B staircase: globally self-organized transport barriers

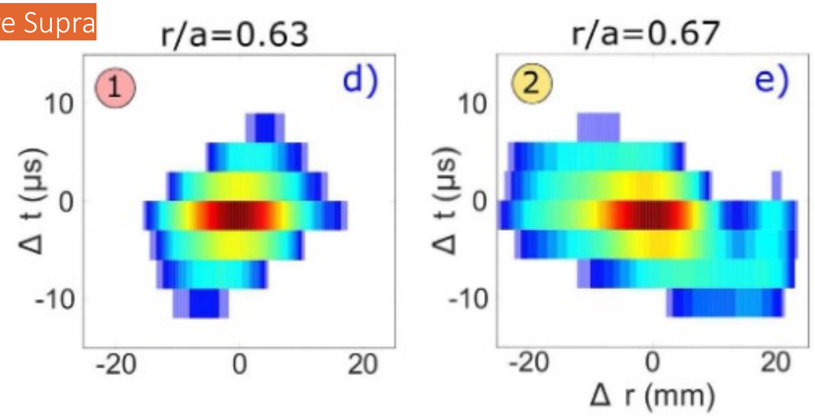
- E × B staircase is observed (indirectly) in ToreSupra, KSTAR, DIII-D, and HL-2A
  - Tore Supra and HL-2A observed the radial variation of the turbulence correlation length and the turbulence eddy tilting as evidences of shear flow layers

[G. Dif-Pradalier et al., Phys. Rev. Lett. 114, 085004 (2015)]



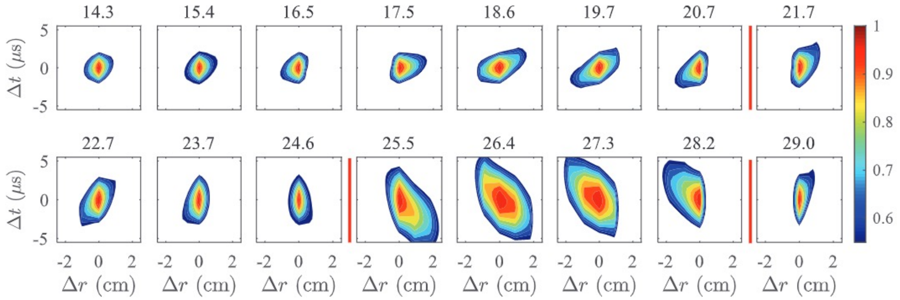
[G. Hornung et al., Nucl. Fusion 57, 014006 (2017)]

Tore Supra

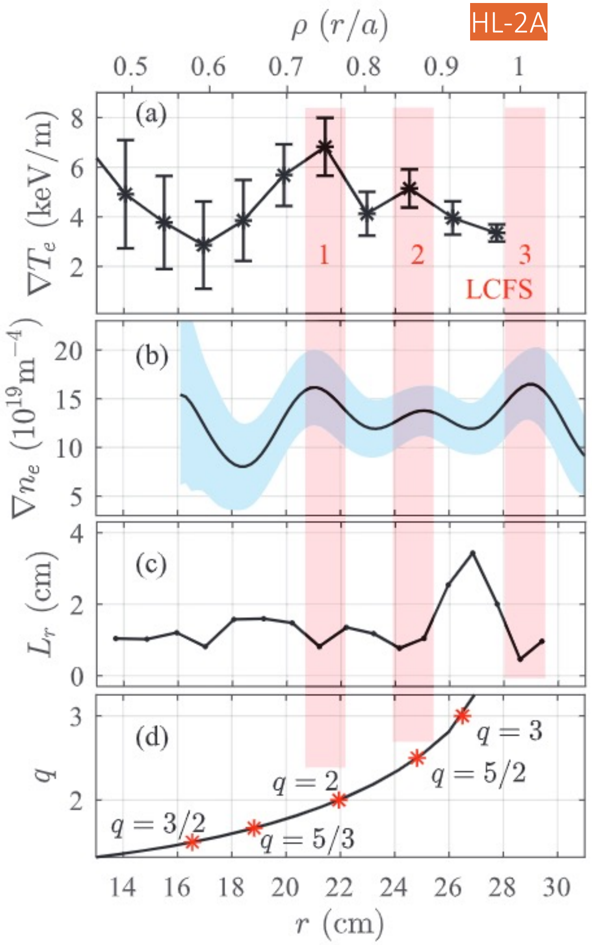


[W. Liu et al., Phys. Plasmas 28, 012512 (2021)]

HL-2A



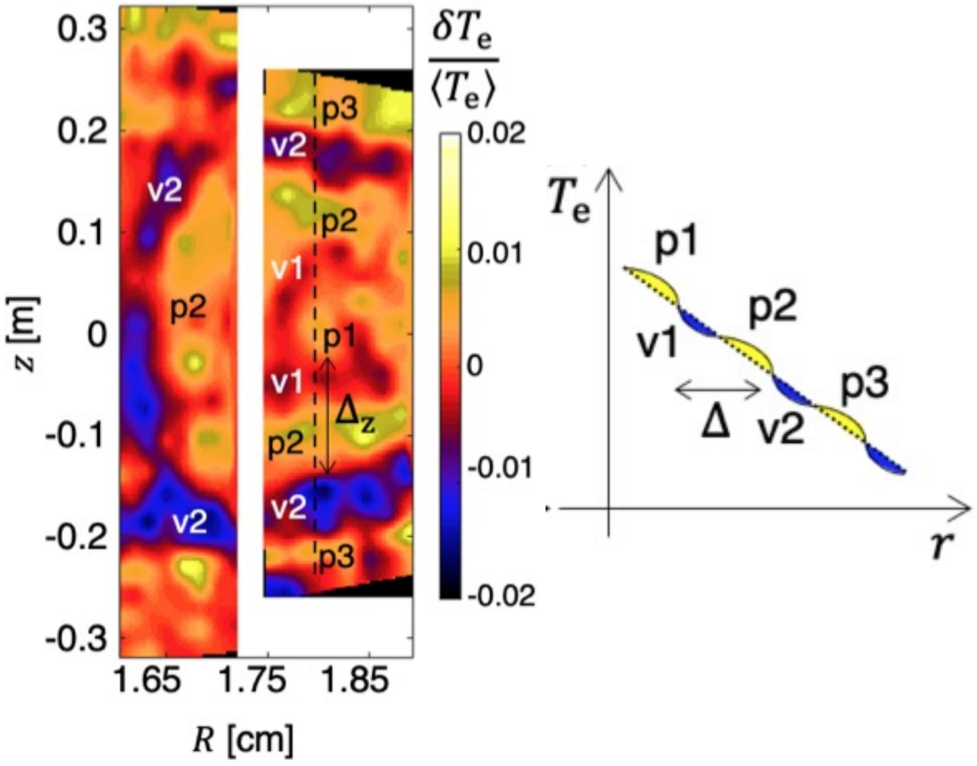
HL-2A



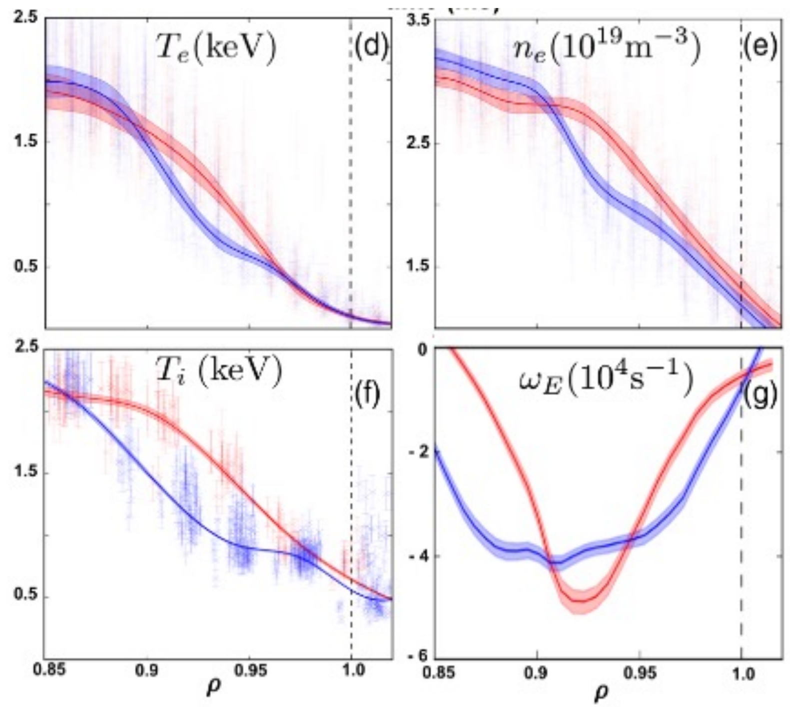
$\mathrm{E} \times \mathrm{B}$ staircase: globally self-organized transport barriers

- $\mathrm{E} \times \mathrm{B}$ staircase is observed (indirectly) in ToreSupra, KSTAR, DIII-D, and HL-2A
  - KSTAR, DIII-D, and HL-2A observed the corrugation in 2D/1D electron/density temperature profiles

KSTAR [M.J. Choi et al., Nucl. Fusion 59, 086027 (2019)]



DIII-D [A. Ashourvan et al., Phys. Rev. Lett. 123, 115001 (2019)]



- Other possibly relevant observations (long range correlated multiple transport barriers) were reported in CHS, TJ-II, W7-X, and JET [Fujisawa PRL 2004][Hillesheim PRL 2016][van Milligen Entropy 2019]

Understanding the $\mathrm{E} \times \mathrm{B}$ staircase in tokamak plasmas

- Characteristics of the $\mathrm{E} \times \mathrm{B}$ staircase (in progress)
  - Meso-scale inter-barrier widths, not very stationary but persistent behavior, the collisional damping, etc

Outline

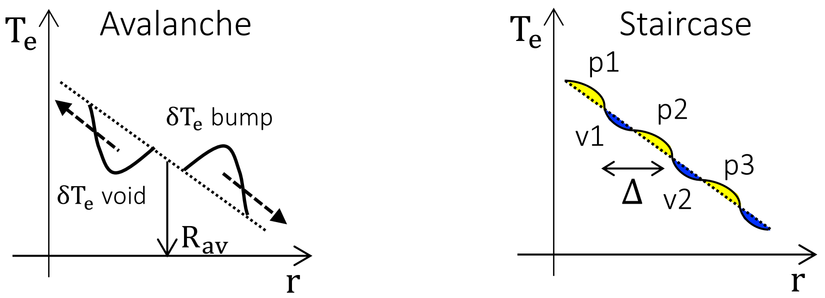
[M.J. Choi et al., arXiv:2207.06610, submitted to Nucl. Fusion]

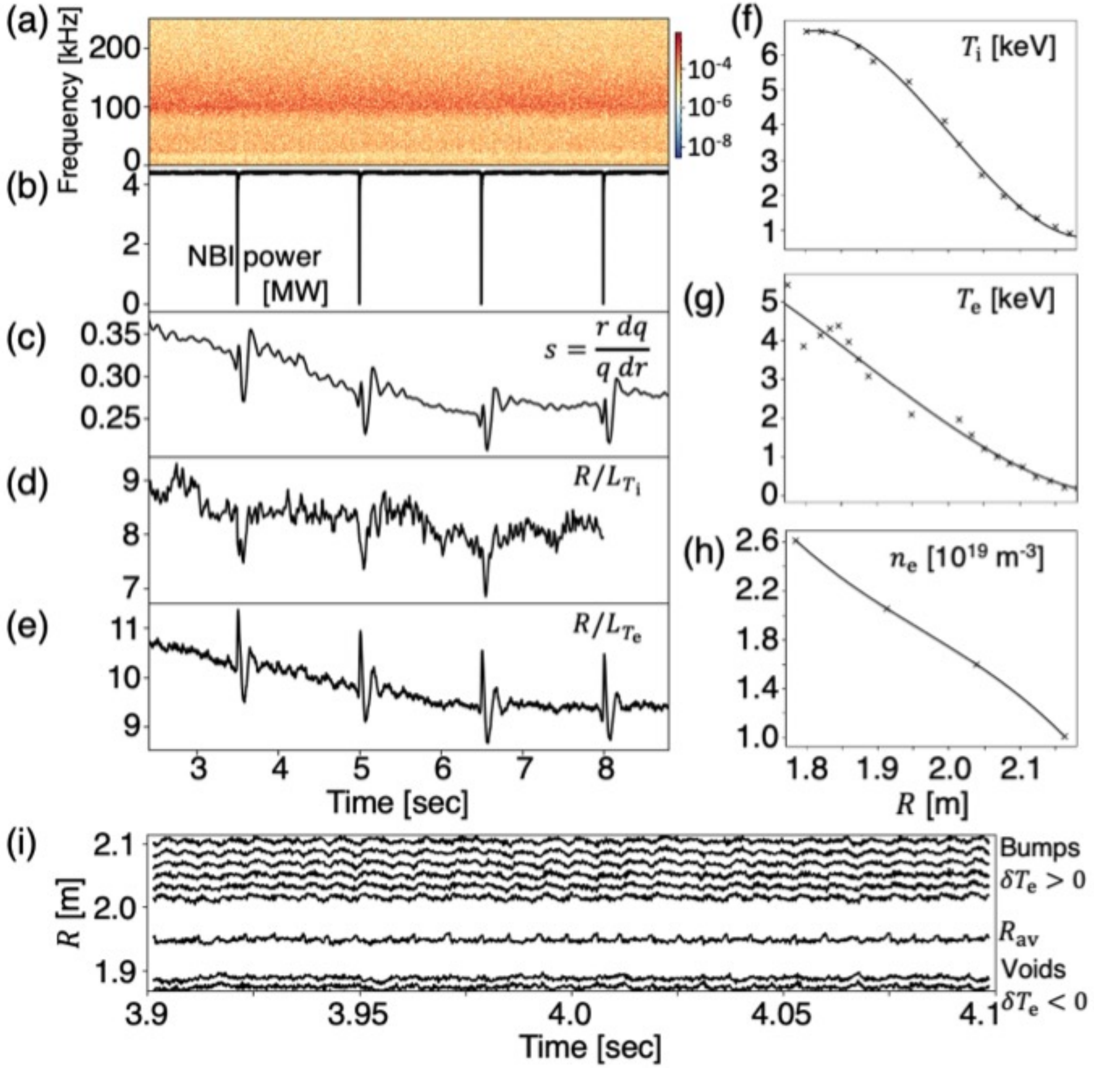
- Near-marginal transport in tokamak plasmas*
  - The avalanche transport
  - The $\mathrm{E} \times \mathrm{B}$ staircase
- The KSTAR avalanche/staircase plasma
- Experimental analyses of the avalanche transport
  - Ballisitic behavior, η_i dependency, radially elongated eddy, the power-law distribution
- Experimental analyses of the $\mathrm{E} \times \mathrm{B}$ staircase
  - Fast propagation of initial perturbation, collisionality dependency, zonal three-wave coupling, the Fréchet distribution
- Discussions
  - Role of the avalanche on the $\mathrm{E} \times \mathrm{B}$ staircase formation and its width distribution
  - The $\mathrm{E} \times \mathrm{B}$ staircase as the self-organization near an non-equilibrium critical state
  - The avalanche and $\mathrm{E} \times \mathrm{B}$ staircase: two faces of the one thing

*A recent review available on this topic
[T.S. Hahm & P.H. Diamond, J. Korean Phys. Soc. 73, 747 (2018)]

KSTAR avalanche/staircase regime

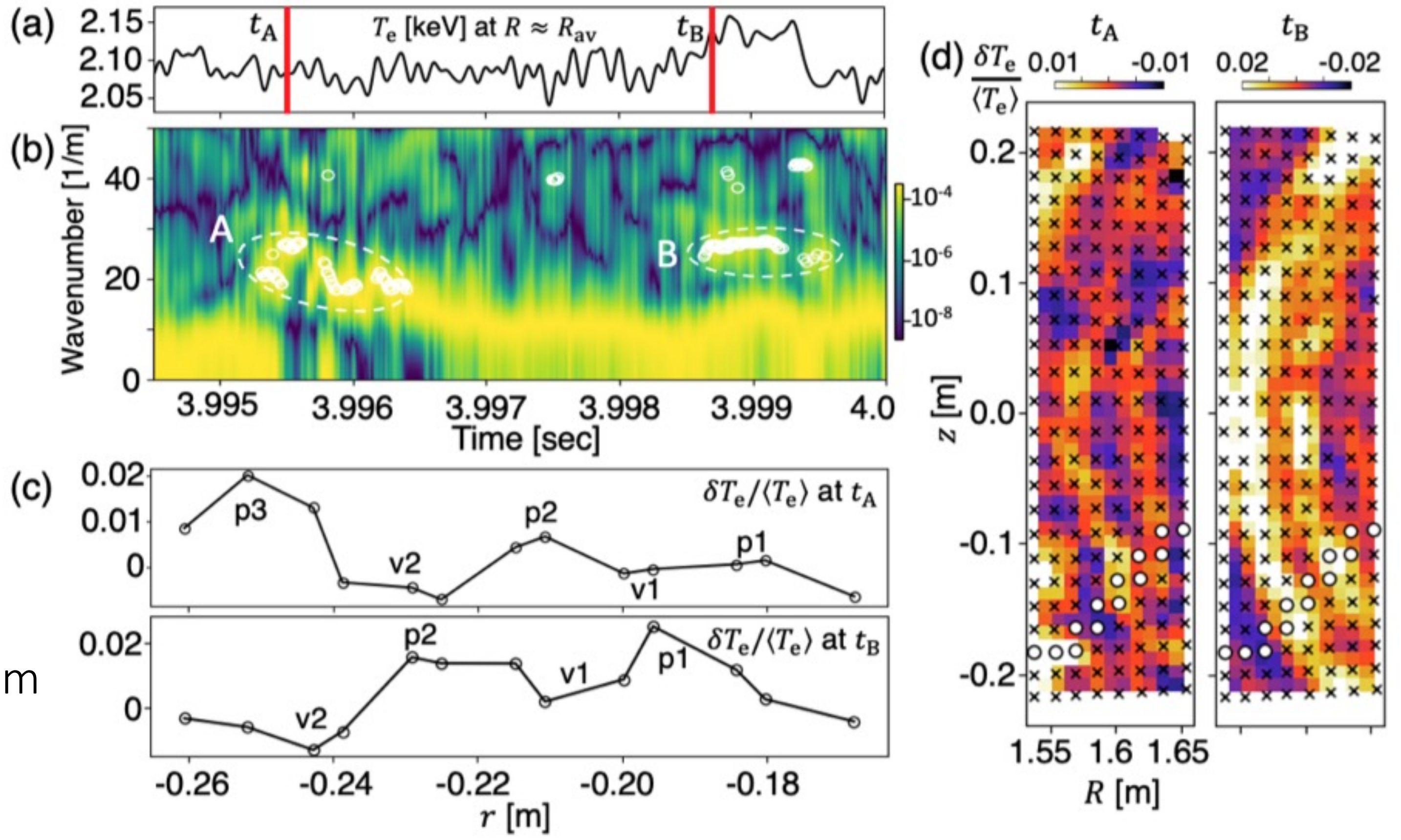
- KSTAR avalanche/staircase regime
  - B_t = 2.7—3.3 T, I_p = 500 kA, 3 NBIs = (90, 90 75) keV
    - Large scale MHD instabilities are avoided (limiter plasma)
  - Avalanches are identified as ballistic propagation of the electron temperature perturbations
  - The $E \times B$ staircase is identified as the electron temperature corrugation





Systematic procedure to identify the $E \times B$ staircase

1) Select good signal-to-noise ratio channels of the 2D T_e diagnostics on (R,z)
2) Obtain the radial (non-uniform) profile of temperature corrugation: $\delta T_e/\langle T_e\rangle(r)$
3) Calculate the the power spectrogram using the Lomb-Scargle periodogram: $S(k,t)$
4) Identify transport barriers with corrugations (white circles) above thresholds
   - Power > $(\delta T_e/\langle T_e\rangle)^2|_{th}$ to neglect the noise
   - Wavenumber > k_{th} to neglect avalanche pulse
5) Group measurements using the cluster algorithm (OPTICS)
6) Measure the lifetime, the power $(\delta T_e/\langle T_e\rangle)^2$, and the radial tread width $\Delta = 1/k$ of each transport barriers for statistics



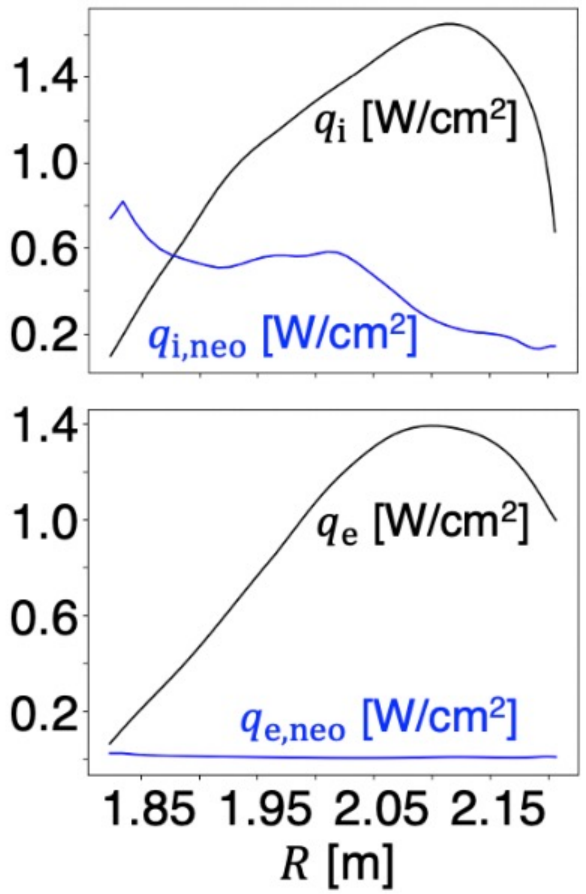
Barriers are classified as classes A and B

Class A: away from the large avalanche event
Class B: close to the large avalanche event

Diagnostics: [G.S. Yun et al., Rev. Sci. Instrum. 85, 11D820 (2014)]
Lomb-Scargle periodogram: [J.T. VanderPlas, ApJS 236, 16 (2018)]
OPTICS: [F. Pedregosa et al., J. Machine Learning Research 12, 2825 (2011)]

Transport and linear stability analyses

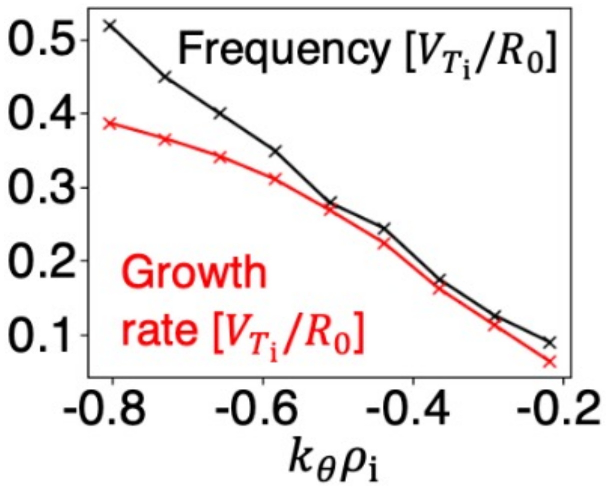
- The power balance analysis was performed using TRANSP and NUBEAM codes
  - Neoclassical ion heat flux ~ turbulent ion heat flux near the avalanche initiation region



- The linear gyrokinetic simulation was performed using the global delta-f electrostatic gKPSP code with the bounce-averaged kinetic electron and collisions

[L. Qi et al., PoP, 2016]
[J.M. Kwon et al., CPC, 2017]

  - The ion temperature gradient (ITG) mode may be a dominant micro-instability in this palsma



Outline

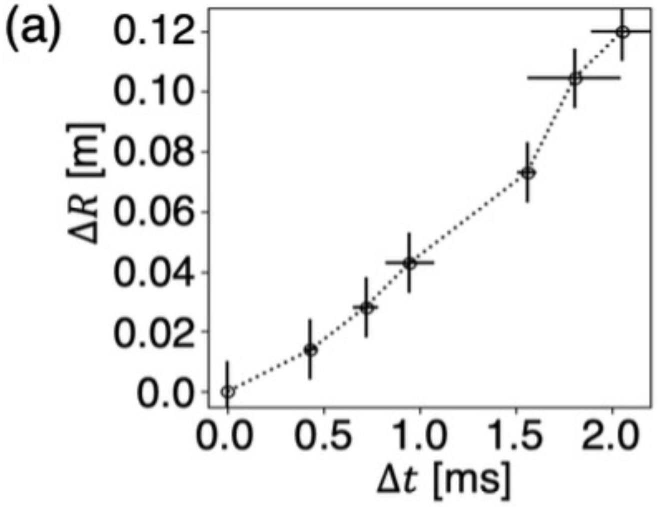
[M.J. Choi et al., arXiv:2207.06610, submitted to Nucl. Fusion]

- Near-marginal transport in tokamak plasmas*
  - The avalanche transport
  - The $\mathrm{E} \times \mathrm{B}$ staircase
- The KSTAR avalanche/staircase plasma
- Experimental analyses of the avalanche transport
  - Ballisitic behavior, η_i dependency, radially elongated eddy, the power-law distribution
- Experimental analyses of the $\mathrm{E} \times \mathrm{B}$ staircase
  - Fast propagation of initial perturbation, collisionality dependency, zonal three-wave coupling, the Fréchet distribution
- Discussions
  - Role of the avalanche on the $\mathrm{E} \times \mathrm{B}$ staircase formation and its width distribution
  - The $\mathrm{E} \times \mathrm{B}$ staircase as the self-organization near an non-equilibrium critical state
  - The avalanche and $\mathrm{E} \times \mathrm{B}$ staircase: two faces of the one thing

*A recent review available on this topic
[T.S. Hahm & P.H. Diamond, J. Korean Phys. Soc. 73, 747 (2018)]

Dynamics of the avalanche transport

- Ballistic propagation of large avalanches
  - Propagation speed ranges 20—80 m/s about one order slower than the approximated mean diamagnetic velocity ($\overline{\rho_s C_s / a}$ = 720 m/s)



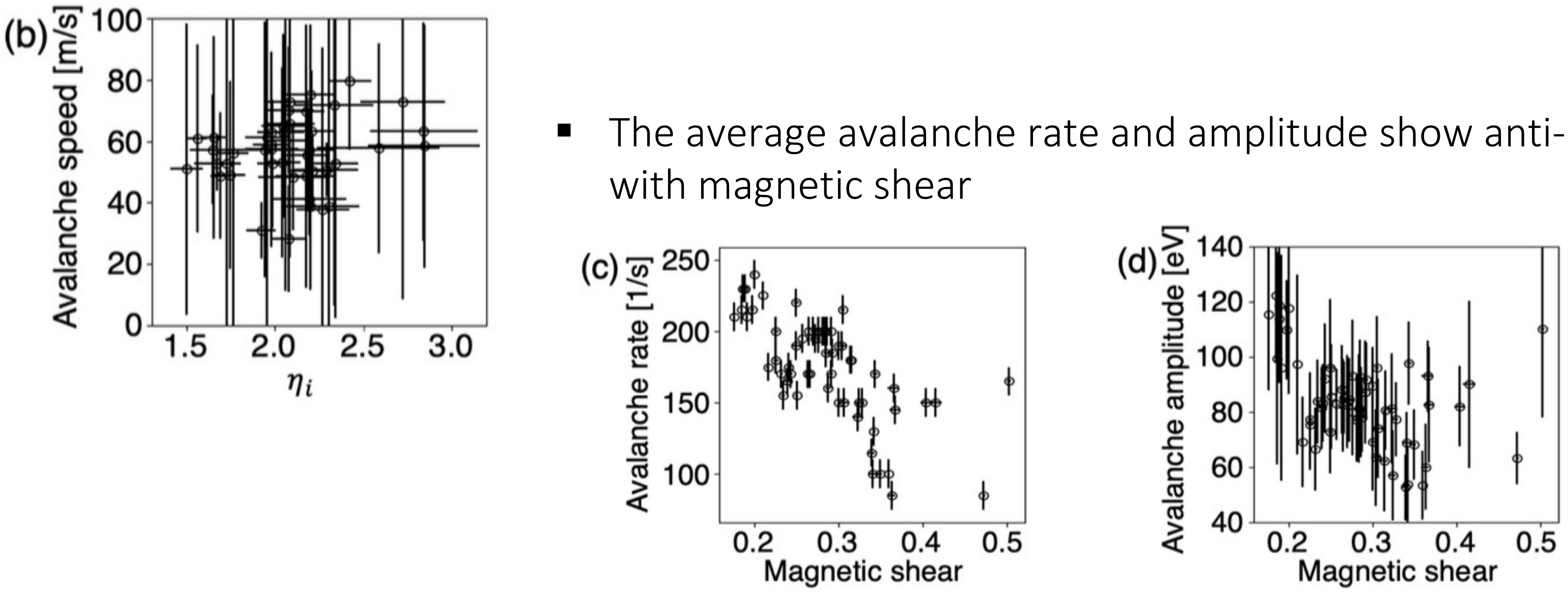
- Propagation behavior changes when ~ 1 MW continuous ECRH was applied

Parameter dependency of the avalanche transport

- The avalanche propagation speed shows a scattered correlation with $\eta_i \equiv L_n/L_{T_i}$
  - The plasma is ITG-dominant, and so it may be consistent with the model of turbulence spreading where turbulence energy propagation speed depends on the linear growth rate of underyling fluctuation

[Ö.D. Gürcan et al., Phys. Plasmas 12, 032303 (2005)]

- The average avalanche rate and amplitude show anti-correlations with magnetic shear

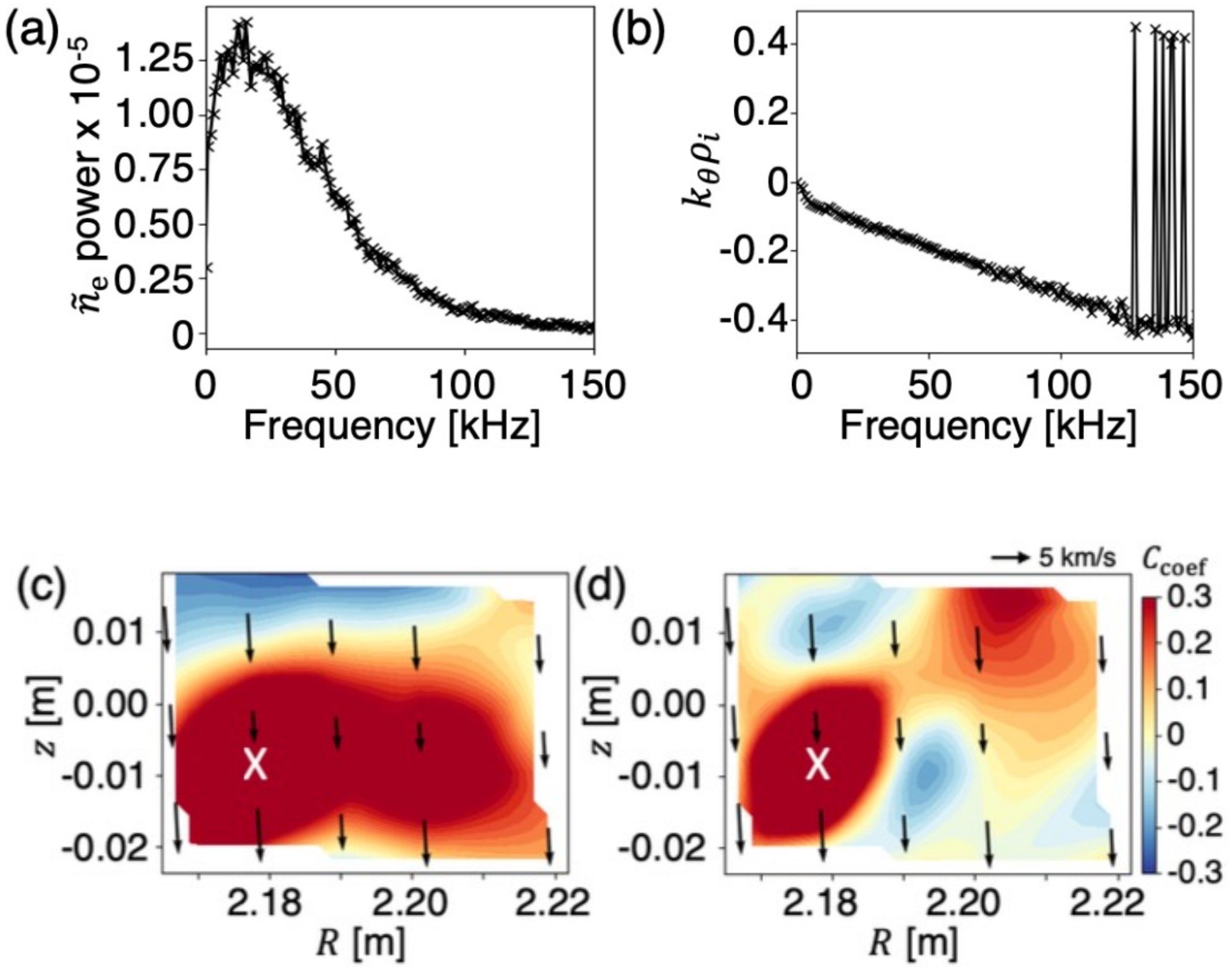


Structure of the avalanche transport

- Edge density fluctuation can be measured using the KSTAR BES diagnostics
  [Y. U. Nam et al., RSI (2014)]

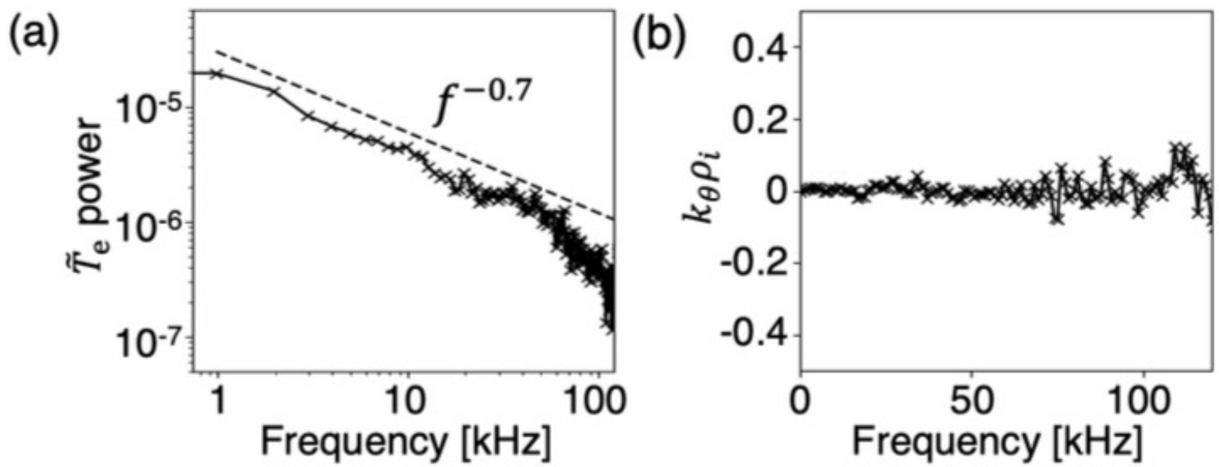
- Broadband density fluctuation, rotating in the ion diamagnetic direction, is observed

- A radially extended poloidally localized coherent structure appears during the large avalanche propagation phase (c)
  - Colors represent the cross correlation coefficient against the reference channel (X)
  - Laboratory frame phase velocities are indicated by the arrows



Statistics of the avalanche transport

- The avalanche pseudo-size distribution follows the power-law
  - Pseudo-size is defined as the volume of the temperature perturbation by one avalanche ~ height x width x length = $\delta T_e \times \delta R \times 2\pi R \approx \delta T_e^2$
    - Assume $\delta T_e \sim \delta R$ (the amplitude of avalanche ~ its radial perturbation width)



$m = 0$ means that measured fluctuations are the temperature variation by transport events rather than turbulence eddies

Outline

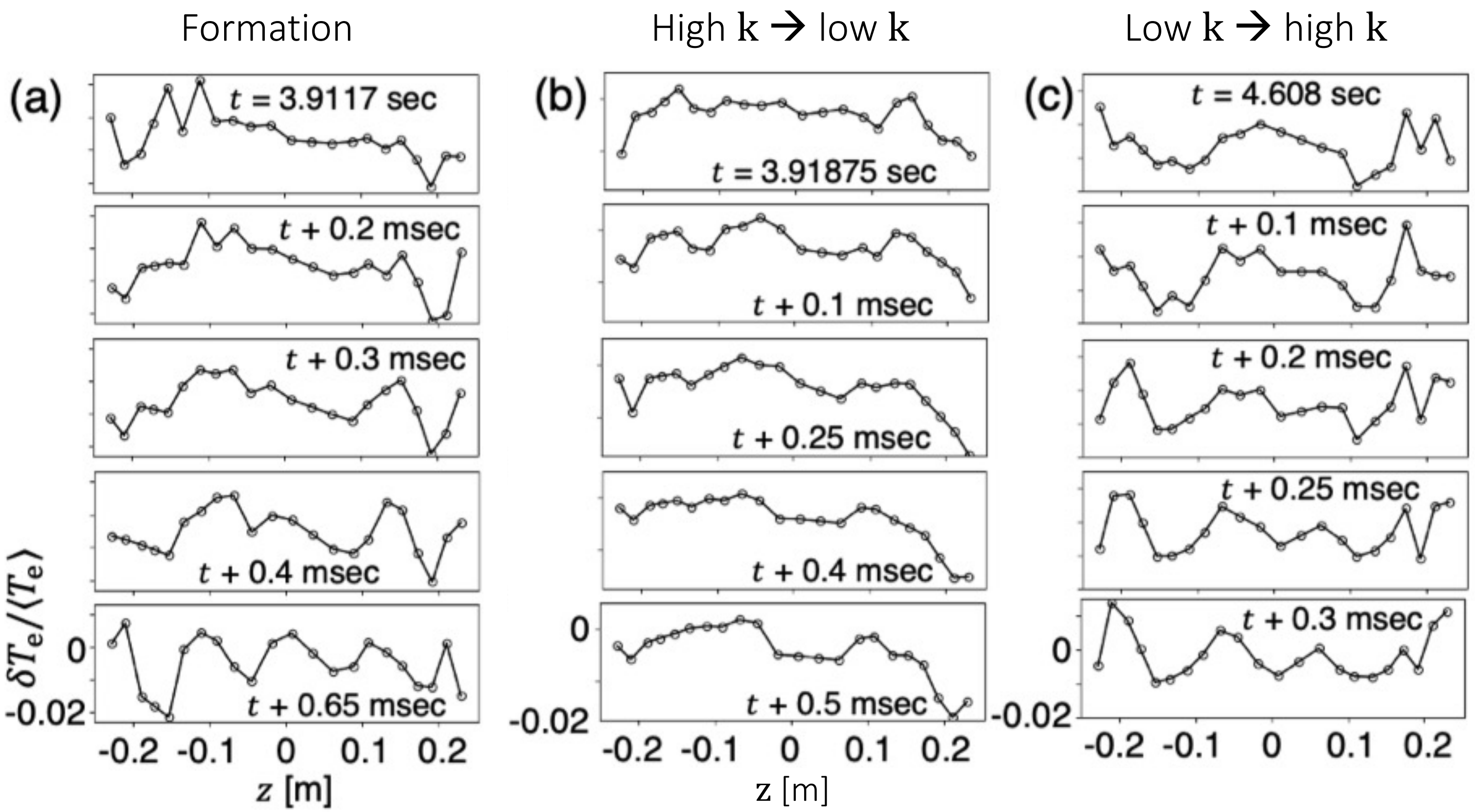
[M.J. Choi et al., arXiv:2207.06610, submitted to Nucl. Fusion]

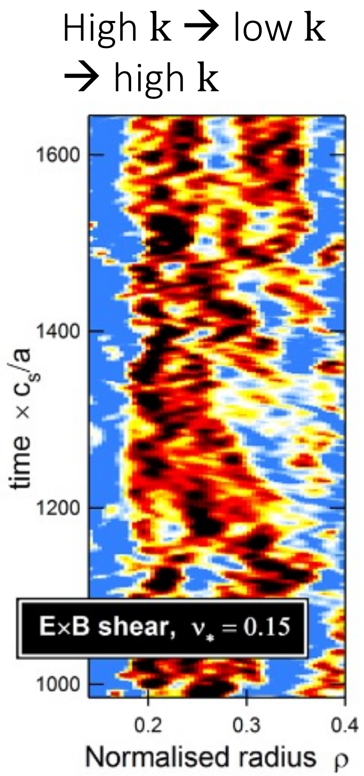
- Near-marginal transport in tokamak plasmas*
  - The avalanche transport
  - The $\mathrm{E} \times \mathrm{B}$ staircase
- The KSTAR avalanche/staircase plasma
- Experimental analyses of the avalanche transport
  - Ballisitic behavior, η_i dependency, radially elongated eddy, the power-law distribution
- Experimental analyses of the $\mathrm{E} \times \mathrm{B}$ staircase
  - Fast propagation of initial perturbation, collisionality dependency, zonal three-wave coupling, the Fréchet distribution
- Discussions
  - Role of the avalanche on the $\mathrm{E} \times \mathrm{B}$ staircase formation and its width distribution
  - The $\mathrm{E} \times \mathrm{B}$ staircase as the self-organization near an non-equilibrium critical state
  - The avalanche and $\mathrm{E} \times \mathrm{B}$ staircase: two faces of the one thing

*A recent review available on this topic
[T.S. Hahm & P.H. Diamond, J. Korean Phys. Soc. 73, 747 (2018)]

Dynamics of the E × B staircase

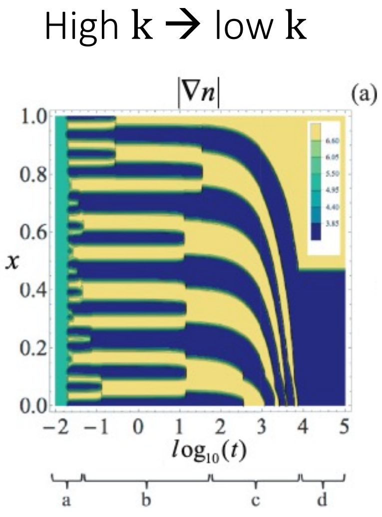
- Long term behavior: persistent but not very stationary [M.J. Choi et al., Nucl. Fusion 59, 086027 (2019)]
  - Repeated formation and destruction
- Initial formation and transformation processes





GYSELA

[G. Dif-Pradalier et al., Nucl. Fusion 57, 066026 (2017)]



Reduced model

[A. Ashourvan et al., Phys. Rev. E. 94, 051202(R) (2016)]

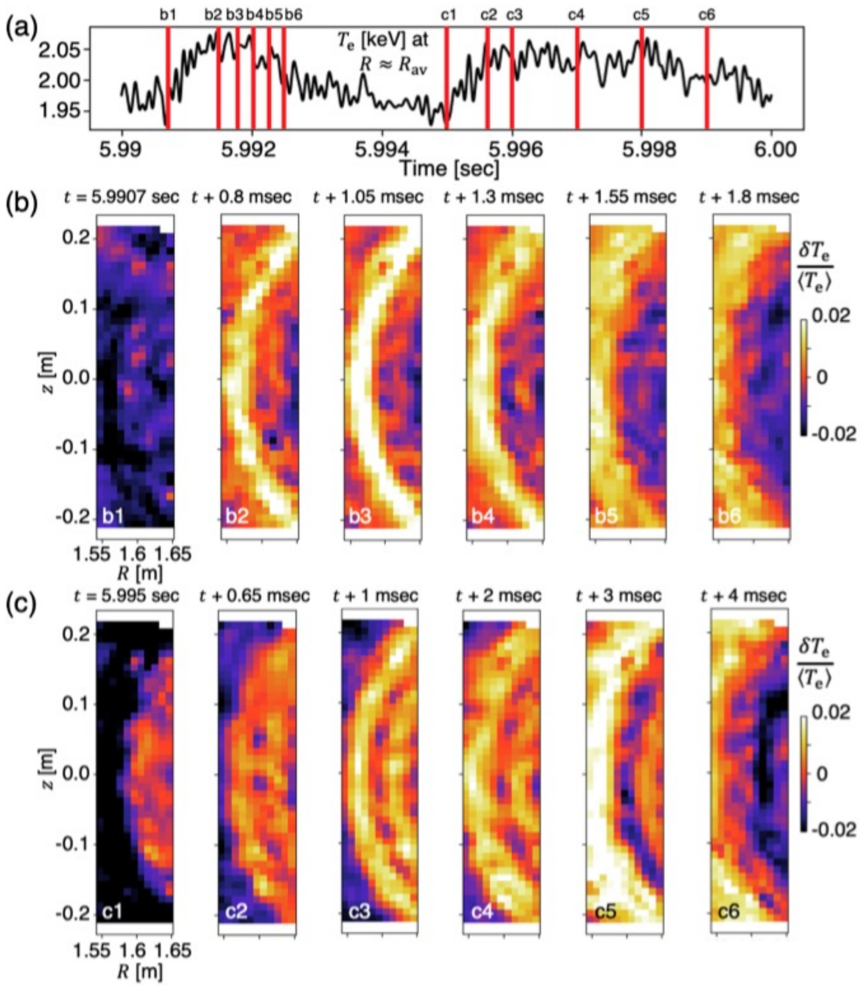
The E × B staircase confines the avalanche transport

- Avalanche propagation is retarded by the staircase: stopping capability

[P. Ghendrih et al., European Phys J D 68, 303 (2014)]

Avalanche $\delta T_e/\langle T_e\rangle$ propagation w/o the barriers

Avalanche $\delta T_e/\langle T_e\rangle$ propagation with the barriers



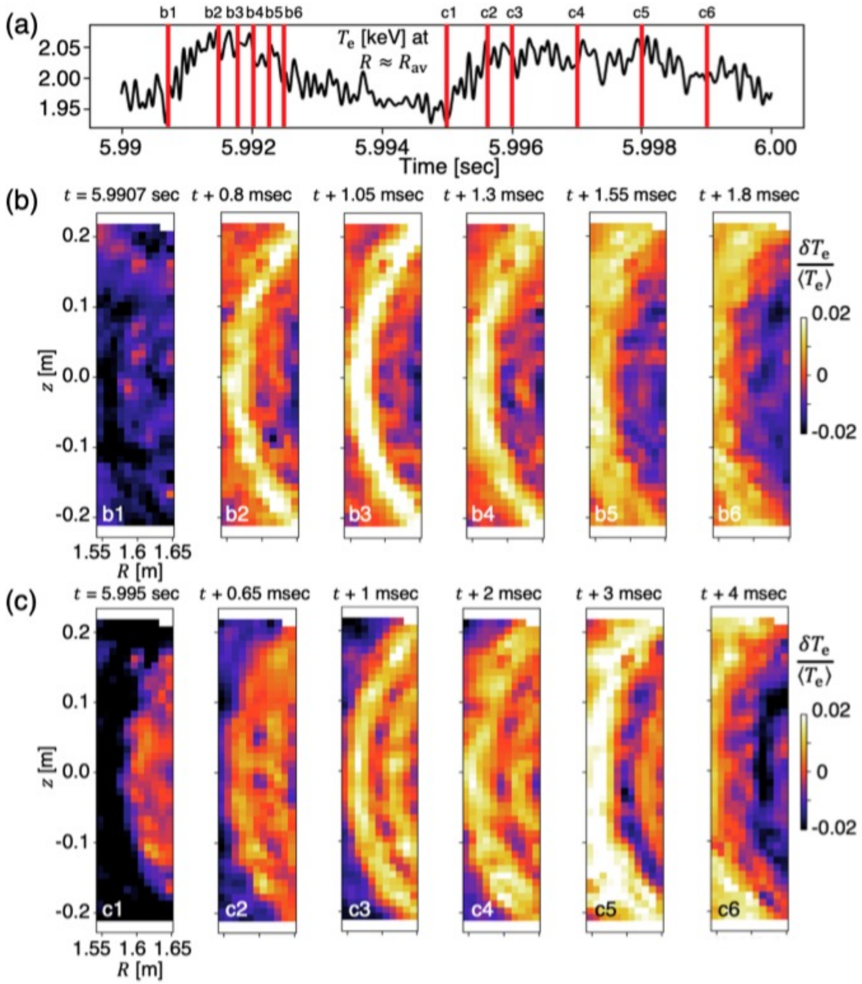
The large avalanche triggers the E × B staircase

- Avalanche propagation is retarded by the staircase: stopping capability

[P. Ghendrih et al., European Phys J D 68, 303 (2014)]

Avalanche $\delta T_e/\langle T_e \rangle$ propagation w/o the barriers

Avalanche $\delta T_e/\langle T_e \rangle$ propagation with the barriers



- Avalanche & staircase relation

The heat pulse jam model: the avalanche heat pulse is jammed when it is so fast to overtake the heat flux wave carried by the system

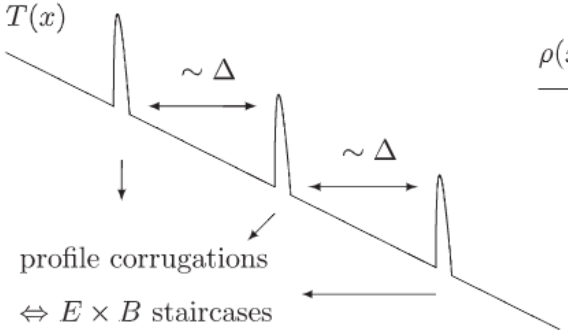


FIG. 1. $E \times B$ staircases and profile corrugations.

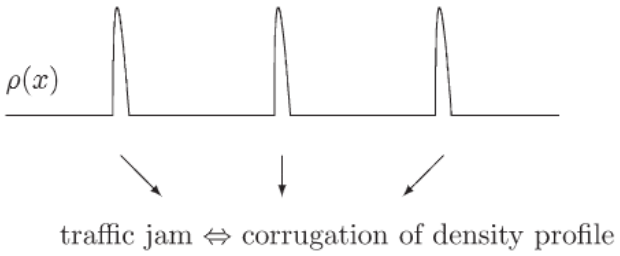


FIG. 2. Traffic jam and density corrugation.

Model: [Y. Kosuga et al., Phys. Rev. Lett. 110, 105002 (2013)]
Fluid simulation: [Y. Kosuga et al., Phys. Plasmas 28, 082302 (2021)]

gKPSP simulation: [L. Qi et al., Nucl. Fusion (2022)]

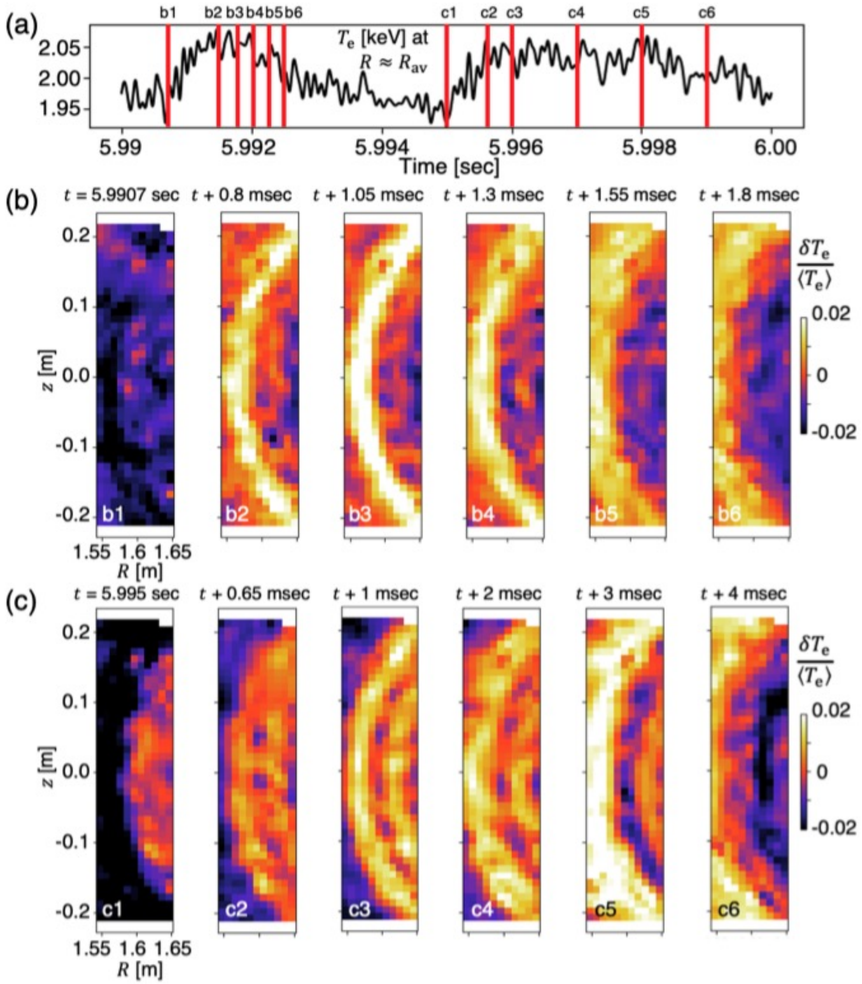
The large avalanche triggers the E × B staircase

- Avalanche propagation is retarded by the staircase: stopping capability

[P. Ghendrih et al., European Phys J D 68, 303 (2014)]

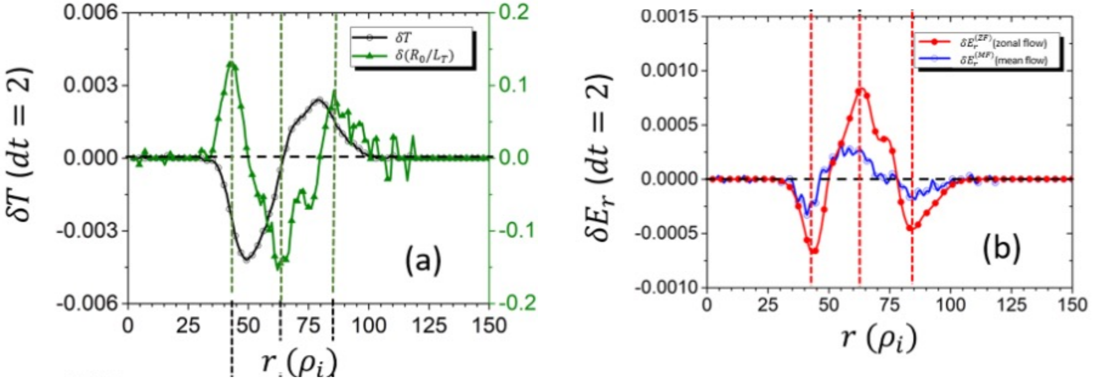
Avalanche $\delta T_e/\langle T_e \rangle$ propagation w/o the barriers

Avalanche $\delta T_e/\langle T_e \rangle$ propagation with the barriers



- Avalanche & staircase relation

Turb. driven zonal flow + mean flow variation by T_i variation of avalanche (radial force balance)



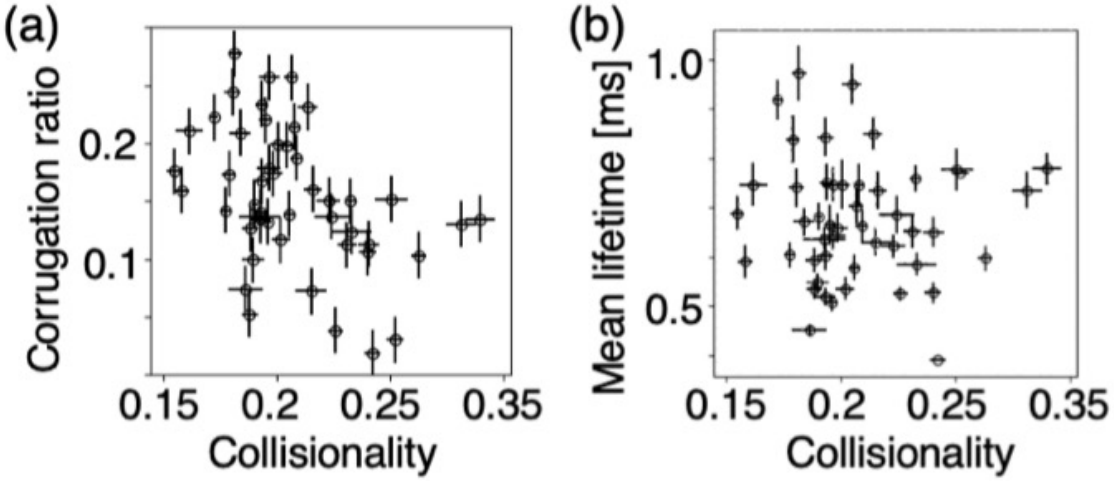
GKNET [W. Wang et al., Nucl. Fusion 58, 056005 (2018)]

Reinforcement of the neighboring zonal flow by the avalanche-like propagation of the turbulence energy by tertiary instability

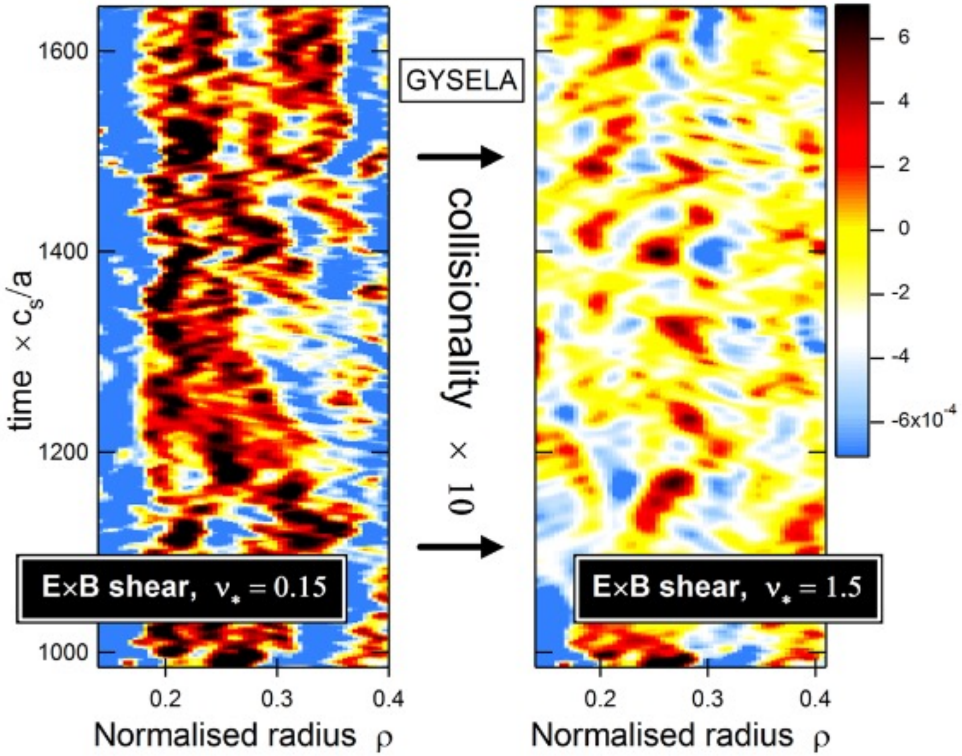
[H. Zhu et al., Phys. Rev. Lett. 124, 055002 (2020)]

Parameter dependency of the $\mathrm{E} \times \mathrm{B}$ staircase

- Collisional dissipation might be the cause of the staircase destruction
  - The transport barriers appear for the smaller fraction of the analysis period when the collisionality increases



Corrugation ratio : $\frac{\text{period with a significant } T_e \text{ corrugation (staircase)}}{\text{whole anlaysis period}}$



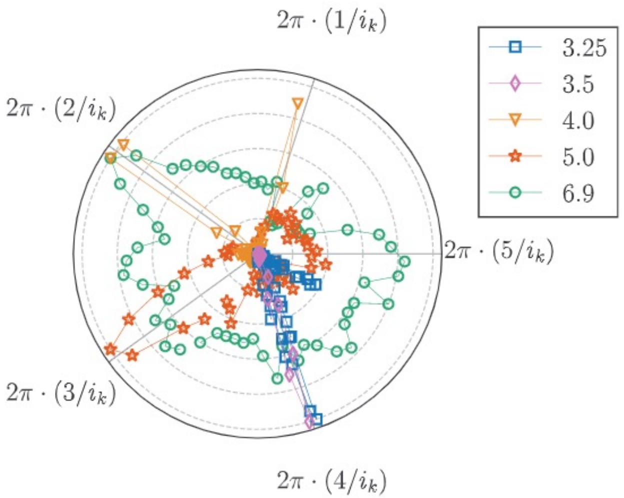
GYSELA [G. Dif-Pradalier et al., Nucl. Fusion 57, 066026 (2017)]

Parameter dependency of the $\mathrm{E} \times \mathrm{B}$ staircase

- Rational surface can be important
  - $\mathrm{R_{av}} \sim \mathrm{R_{q=2}}$ [M.J. Choi et al., Nucl. Fusion 59, 086027 (2019)]
  - Rational surface ~ the barrier riser location

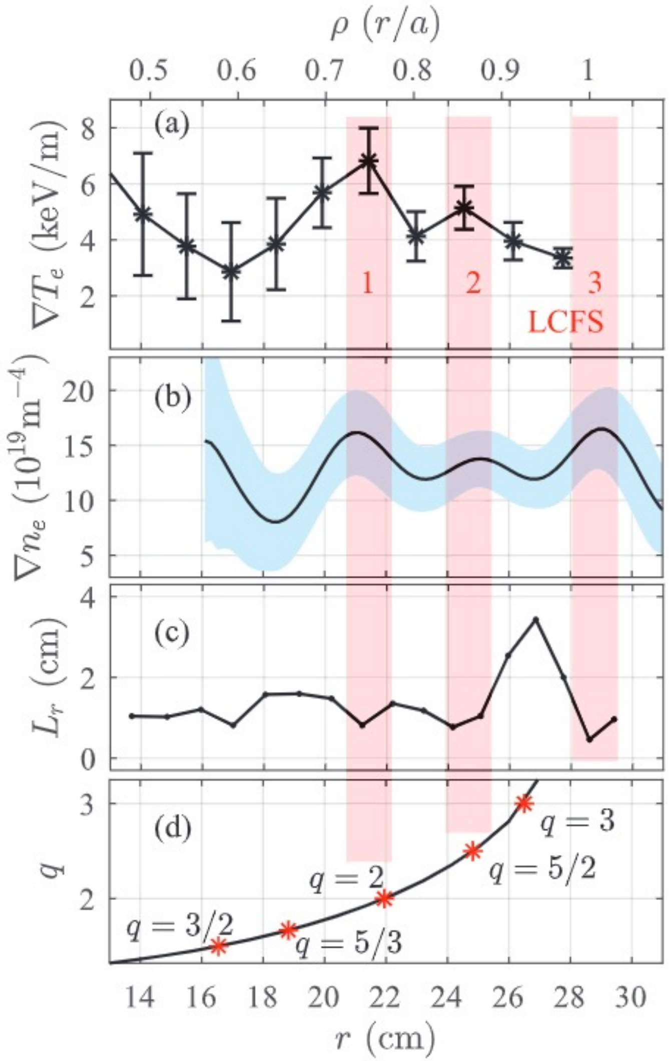
→ Kinetic electron effect?

Lock-in of staircase (zonal mode) at the rational surface
[F. Rath, A.G. Peeters, & A. Weikl, Phys. Plasmas 28, 072305 (2021)]
GKW



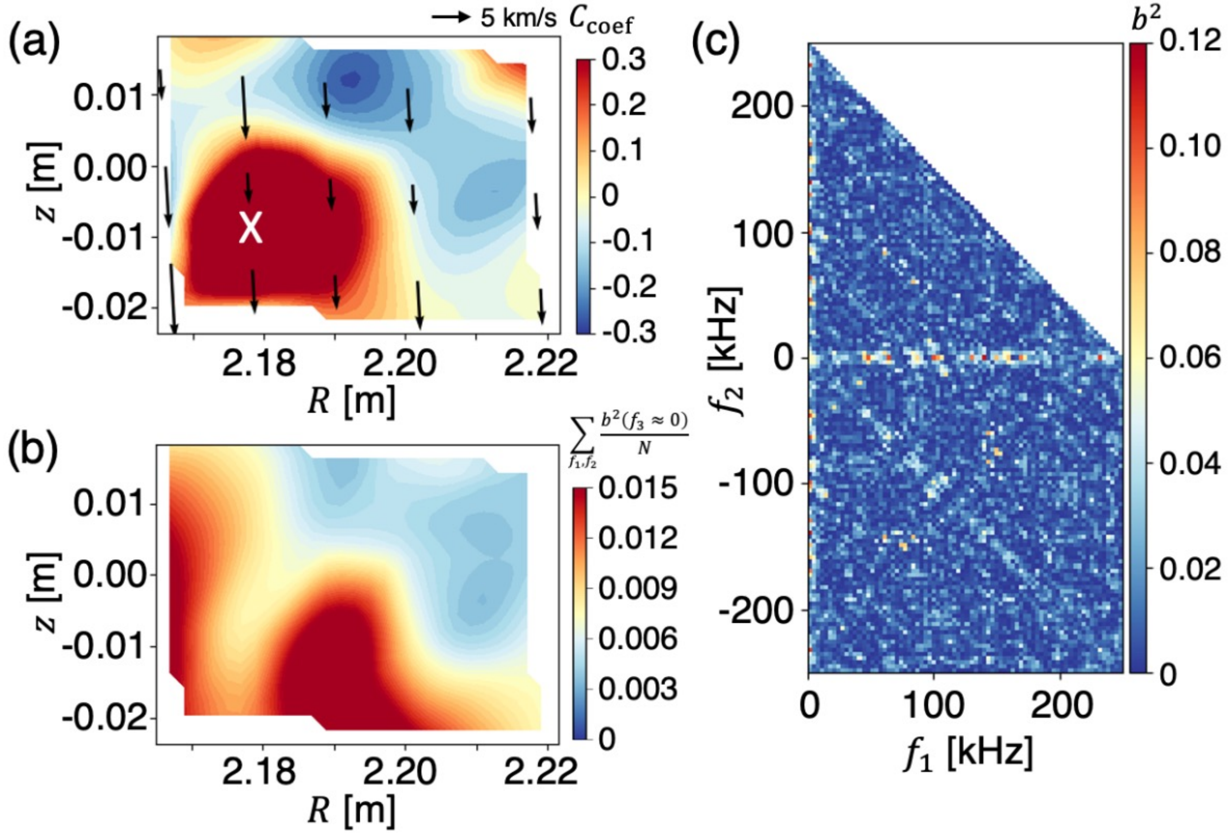
Passing electron destabilization at the rational surface
GENE [J. Dominski et al., Phys. Plasmas 22, 062303 (2015)]

HL-2A [W. Liu et al., Phys. Plasmas 28, 012512 (2021)]

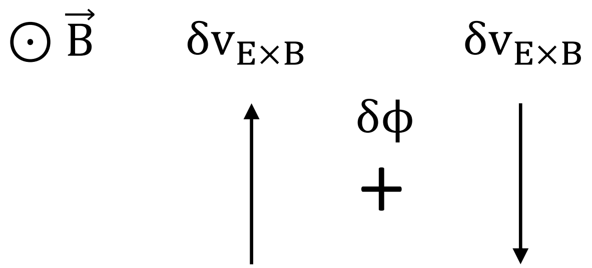


Structure of the $\mathrm{E} \times \mathrm{B}$ staircase

- A radially limited structure is observed (a) compared to the long range coherent structure during the large avalanche propagation phase



- The zonal density mode arises near both ends of the structure through three-wave coupling?
  - Might correspond to the positive zonal potential considering the variation of the laboratory frame phase velocity

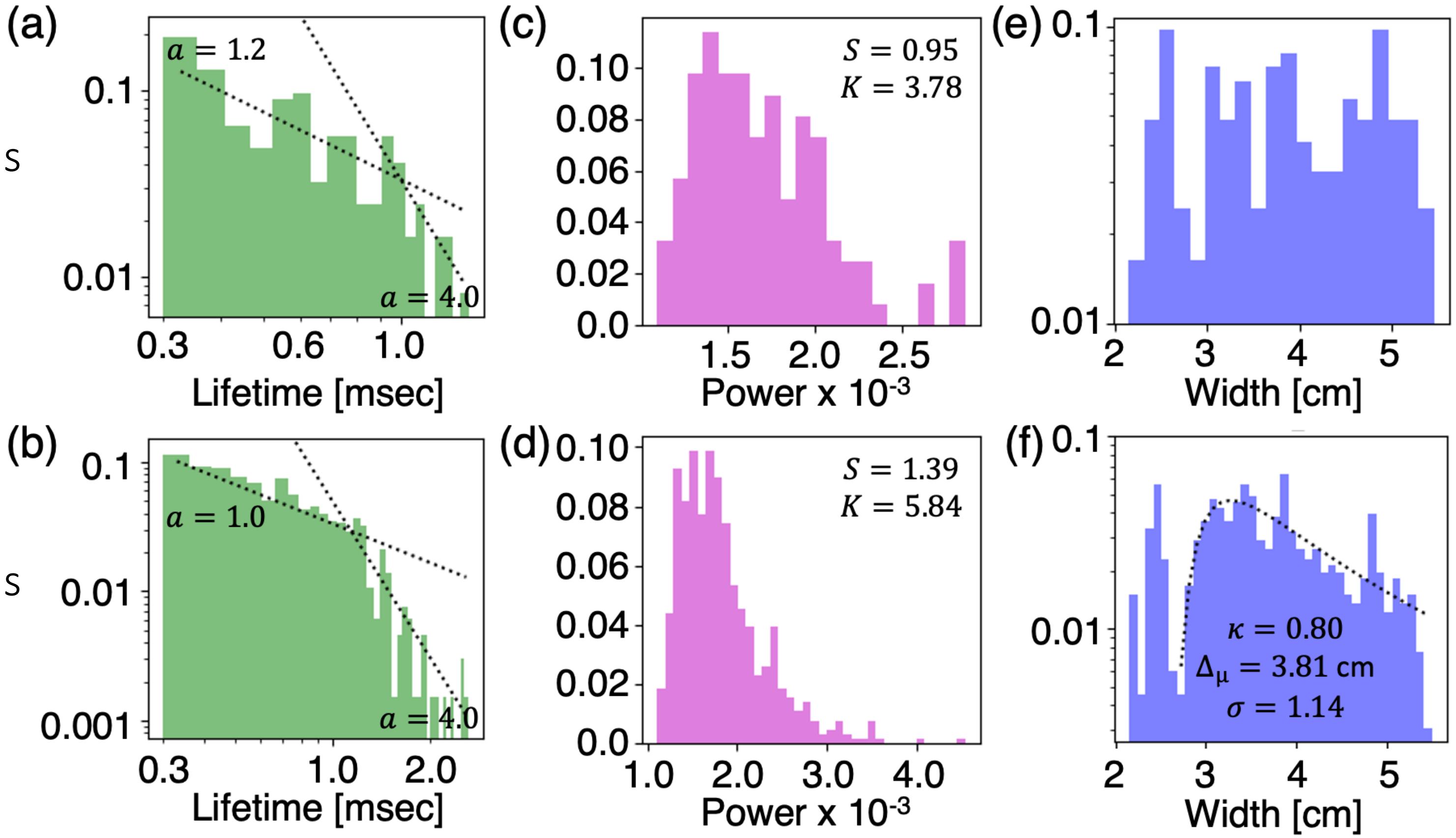


Statistics of the $\mathrm{E} \times \mathrm{B}$ staircase

- Lifetime, power $(\delta T_e/\langle T_e\rangle)^2$, and the radial tread width (Δ) probability distributions
  - Data are collected in the similar quasi-stationary periods: magnetic shear = 0.23—0.35, R/L_{T_i} = 7.5—9.0, R/L_{T_e} = 9.0—10.5, Collisionality = 0.18—0.215, plasma stored energy = 300—320 MJ

Class A:
123
corrugations

Class B:
659
corrugations

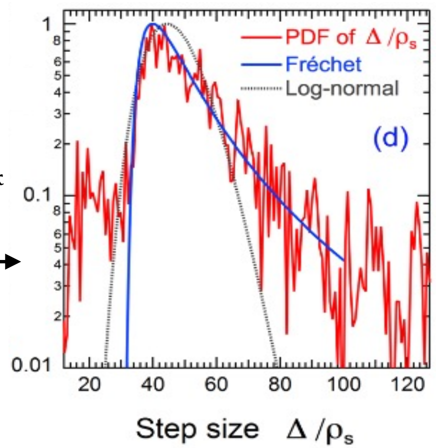


Effect of avalanche transport on the barrier size distribution?
Fréchet-like distribution for class B as in the GYSELA simulation

$$F(\Delta) = \frac{\tau^{1+\kappa}}{\sigma} e^{-\tau}$$

where $\tau = \left(1 + \kappa \frac{\Delta - \Delta_\mu}{\sigma}\right)^{-1/\kappa}$

GYSELA



[G. Dif-Pradalier et al., Nucl. Fusion 57, 066026 (2017)]

Outline

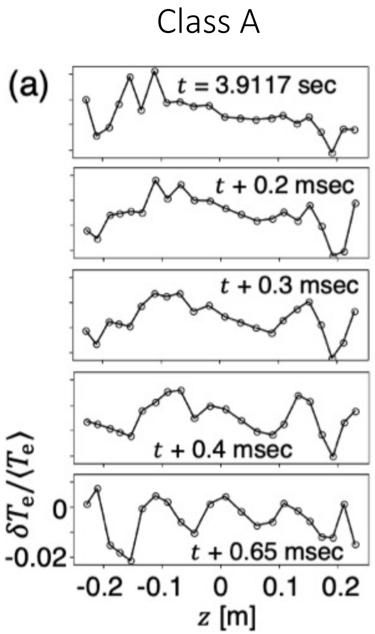
[M.J. Choi et al., arXiv:2207.06610, submitted to Nucl. Fusion]

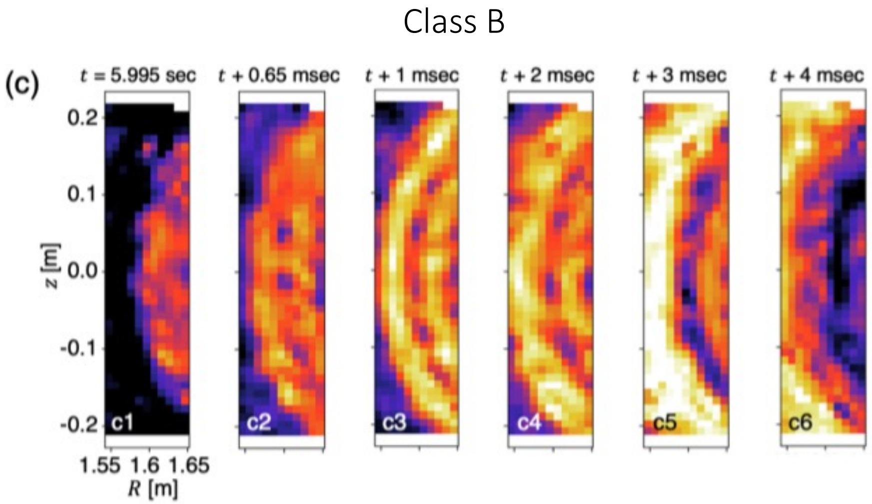
- Near-marginal transport in tokamak plasmas*
  - The avalanche transport
  - The $\mathrm{E} \times \mathrm{B}$ staircase
- The KSTAR avalanche/staircase plasma
- Experimental analyses of the avalanche transport
  - Ballisitic behavior, η_i dependency, radially elongated eddy, the power-law distribution
- Experimental analyses of the $\mathrm{E} \times \mathrm{B}$ staircase
  - Fast propagation of initial perturbation, collisionality dependency, zonal three-wave coupling, the Fréchet distribution
- Discussions
  - Role of the avalanche on the $\mathrm{E} \times \mathrm{B}$ staircase formation and its width distribution
  - The $\mathrm{E} \times \mathrm{B}$ staircase as the self-organization near an non-equilibrium critical state
  - The avalanche and $\mathrm{E} \times \mathrm{B}$ staircase: two faces of the one thing

*A recent review available on this topic
[T.S. Hahm & P.H. Diamond, J. Korean Phys. Soc. 73, 747 (2018)]

The avalanche effect on the $\mathrm{E} \times \mathrm{B}$ staircase

- The staircase may require an initial seed perturbation to grow





- Among various noises, the large avalanche can provide a sufficient perturbation for the staircase
  - This can explain why the number of class B (659) > the number of class A (123)

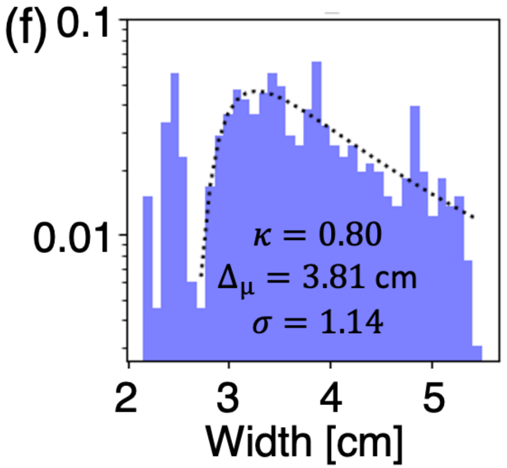
The avalanche effect on the $\mathrm{E} \times \mathrm{B}$ staircase

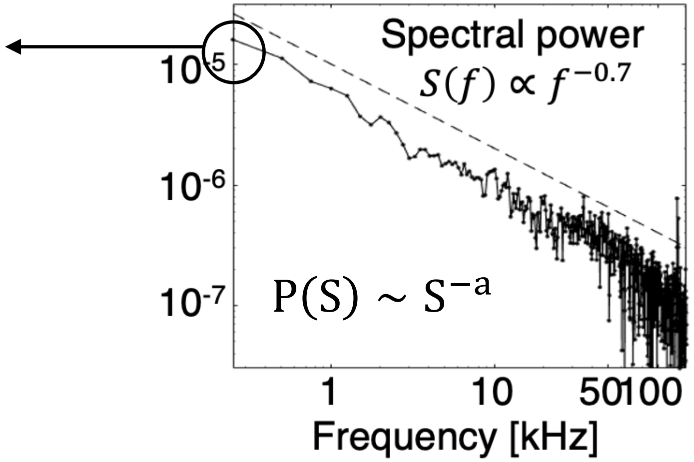
- The Fréchet distribution of the staircase width for class B
  - It is one of extreme value distributions, a distribution of maxima of samples when samples follow the long tail distribution such as the power-law

the staircase width $\Delta \sim$ pseudo-size $\mathrm{S}(\delta\mathrm{R})$ of triggering large and rare avalanche

$$\mathrm{P}(\Delta) = \frac{\tau^{1+\kappa}}{\sigma} e^{-\tau}$$

where $\tau = \left(1 + \kappa \frac{\Delta - \Delta_\mu}{\sigma}\right)^{-1/\kappa}$



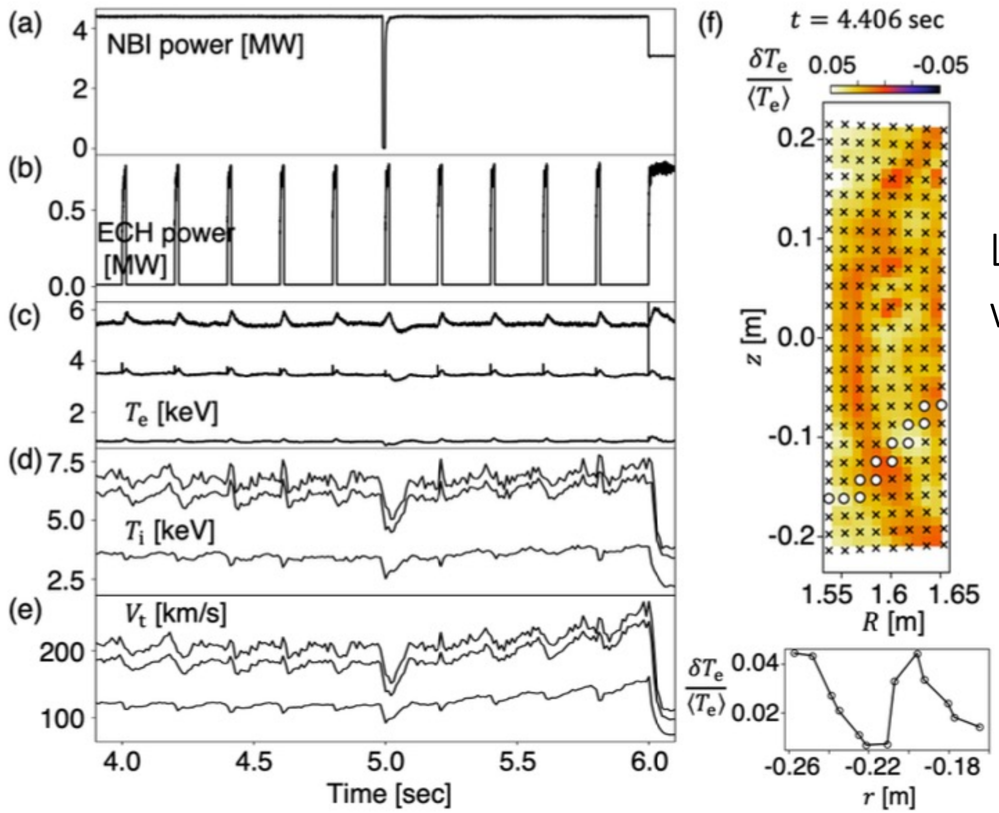


- But, class A and also large avalanches w/o staircase formation imply “more than size” for threshold

Threshold condition and positive feedback

- The threshold can be studied using the external heat pulse scan in different conditions
  - $F(S, \nu^*, \Delta\phi_{diamag-Reynolds}, \ldots) > F_c$ [Y. Kosuga et al., Phys. Rev. Lett. 110, 105002 (2013)] [W. Wang et al., Nucl. Fusion 58, 056005 (2018)]

The fixed ECRH pulses are injected



Larger Δ with stronger S

- Feedback process may occur through the radial force balance as other transport barriers in tokamak plasmas
  - Further investigation of the ion channel is necessary [F. Kin, Sci. Rep. 13, 19748 (2023)]

Understanding the $E \times B$ staircase with analogy

	Rayleigh-Bénard cells	The $E \times B$ staircase	Physics model?
Dominant transport	Convection	Avalanche (ITG; both in heat and momentum?)	
Threshold condition	$Ra = \frac{\tau_{cond}}{\tau_{conv}} > Ra_c$	$F(S, \nu^*, \Delta\phi, \dots) > F_c$ related with avalanche transport condition $K \equiv \frac{\tau_{det}}{\tau_{exc}} = \frac{l_{exc}}{l_{det}} > K_c$?	
Origin of threshold	Viscosity	Collisional dissipation ~ Detrapping process	
Positive feedback	Rayleigh-Bénard instability	$E_r \sim \nabla P$?	

Physics models for the $\mathrm{E} \times \mathrm{B}$ staircase

- Inhomogeneous potential vorticity mixing with negative diffusivity [Ashourvan, Diamond, Guo+]
  - Mechanism: diffusive transport based on a Rhines scale involved mixing length [A. Ashourvan et al., Phys. Rev. E. 94, 051202(R) (2016)] [W. Guo et al., PPCF 61, 105002 (2019)]

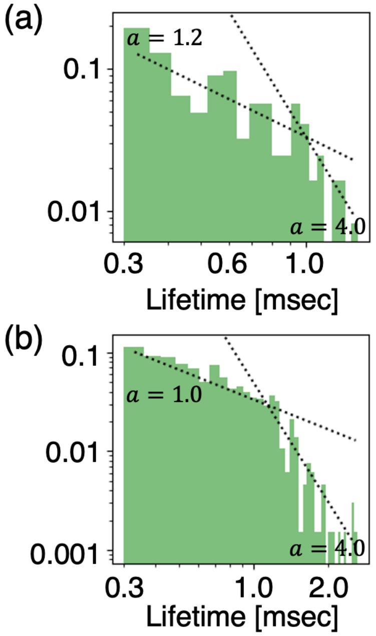
- Traffic jam instability + radial force balance [Kosuga, Diamond] [Y. Kosuga et al., Phys. Rev. Lett. 110, 105002 (2013)]
  - Mechanism: jamming of ballistic flux propagation (~avalanche) by finite time delay btw flux and field

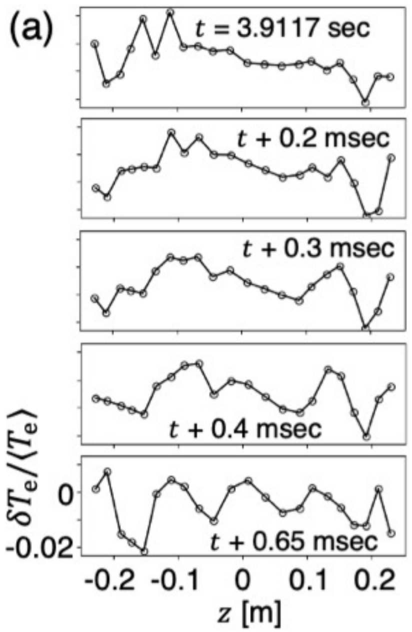
- Synergy between diamagnetic flow variation by avalanche and Reynolds flow [Wang]
  [W. Wang et al., Nucl. Fusion 58, 056005 (2018)]

- Neighboring zonal flow reinforcement by tertiary avalanche [Zhu] [H. Zhu et al., Phys. Rev. Lett. 124, 055002 (2020)]
  - Tertiary avalanche (arising from an initial state with (secondary) zonal flows)

The E × B staircase as the non-equilibrium critical phenomena

- Long tail distributions & ballistic and macroscopic propagation of localized perturbation
  - Can we understand their dynamics as non-equilibrium critical phenomena?

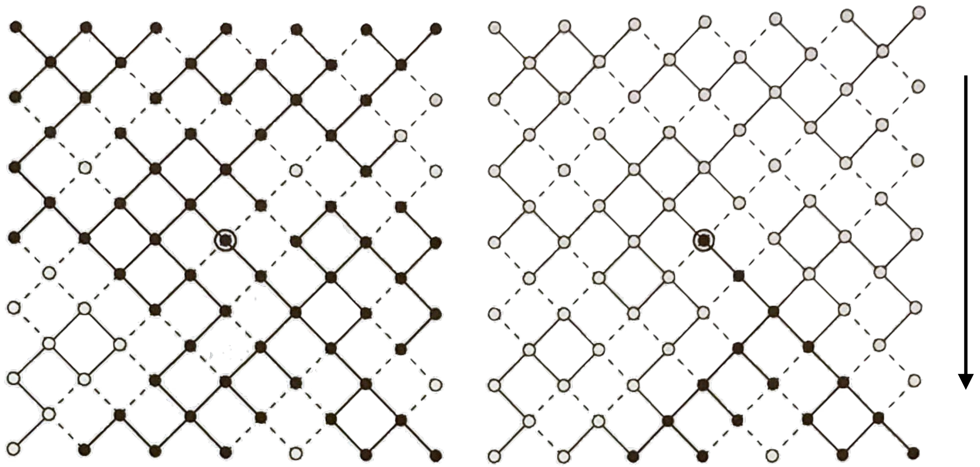




- Several models/classes of non-equilibrium critical phenomena [Livi & Politi, *Nonequilibrium statistical physics* (2017)]
  - Self-organzined criticality
  - Directed percolation

Directed (bond) percolation

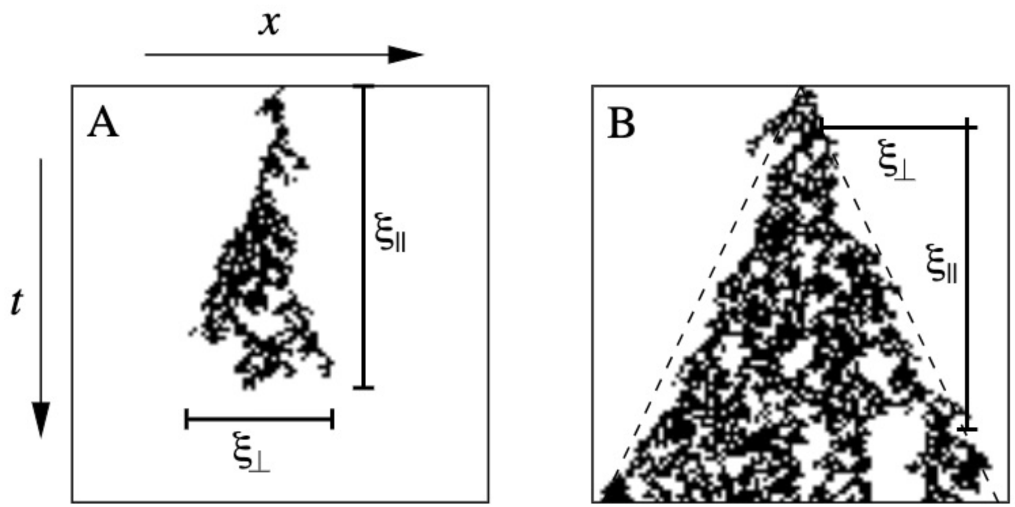
- Configuration, dynamic rule, and phase transition in DP
  - Configuration: wet site (filled), dry site (empty), active bond (bold), inactive bond (dotted)
  - Dynamic rule: Each bond can be active with the probability p, and the wet site can only propagate through the active bond
  - Phase transition: If $\mathrm{p} < \mathrm{p_c}$, the system ends up with an absorbing phase (finite correlation lengths). If $\mathrm{p} \geq \mathrm{p_c}$, the system falls into an active phase (an infinite length of correlation)



2D isotropic percolation

Directed percolation in 1 (time) + 1 (space) dimension

[Livi & Politi, *Nonequilibrium statistical physics* (2017)]



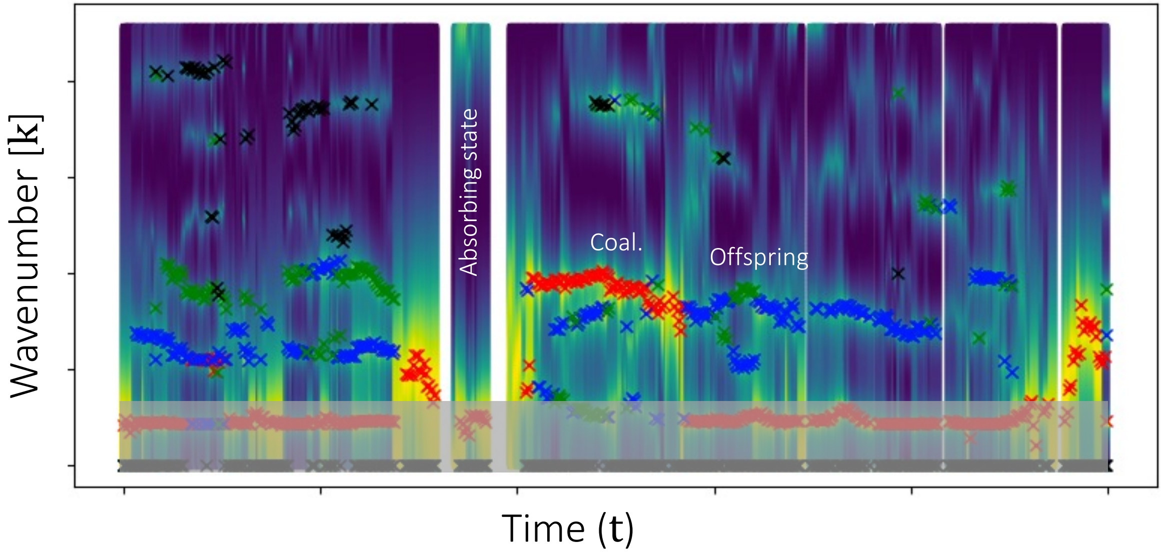
$p<p_c$ $p>p_c$

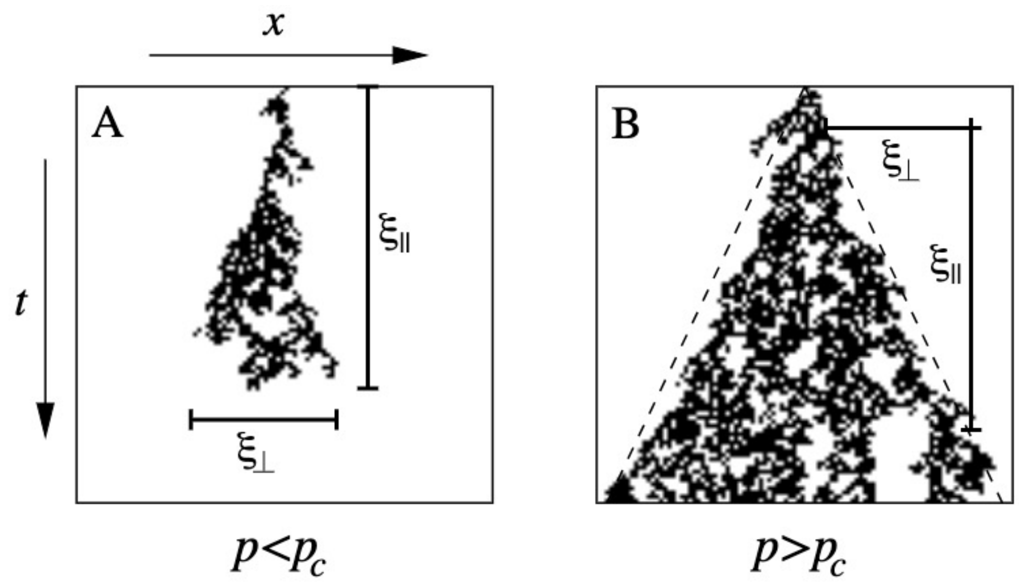
Near $\mathrm{p} = \mathrm{p_c}$, correlation lengths diverge $\xi \sim |\mathrm{p} - \mathrm{p_c}|^{-\nu}$

[H. Hinrichsen, Adv. Phys. 49, 815 (2000)]

The E × B dynamics as a DP process

- The staircase dynamics in wavenumber space (periodogram) ~ DP with slow drive and many absorbing states?





[H. Hinrichsen, Adv. Phys. 49, 815 (2000)]

DP in x+t	Wet site	Dry site	Death	Offspring	Coalescence	Diffuse left	Diffuse right	$p < p_c$	$p > p_c$
	●	○						Fully dry sites ○ ○ ○ ○ ○ ○	Active phase with infinite $\xi_{\perp,\parallel}$
Barriers dynamics in k+t	Mode	Damped mode						Fully damped modes	Infinite $\xi_{\parallel}$: lifetime^{-a} Infinite $\xi_{\perp}$: infinite ks → $\delta(x)$ (one large barrier)

Two faces of the one thing

- Both the avalanche transport and the staircase formation exhibit critical features
  - The avalanche transport is named after the avalanche phenomena in the self-organized criticality (SOC) system (SOC can be thought as one kind of DP process (slow drive & fast relaxation) in real space) [Livi & Politi, *Nonequilibrium statistical physics* (2017)]
  - The critical feature of the staircase might be explained by the momentum avalanche

    [S. Ku et al., Nucl. Fusion 52, 063013 (2012)]
    [H. Zhu et al., Phys. Rev. Lett. 124, 055002 (2020)]

- Both are initiated by some initial perturbations (noises)
  - Depending on initial conditions, some perturbation might result in avalanche, the other might result in the staircase, or both

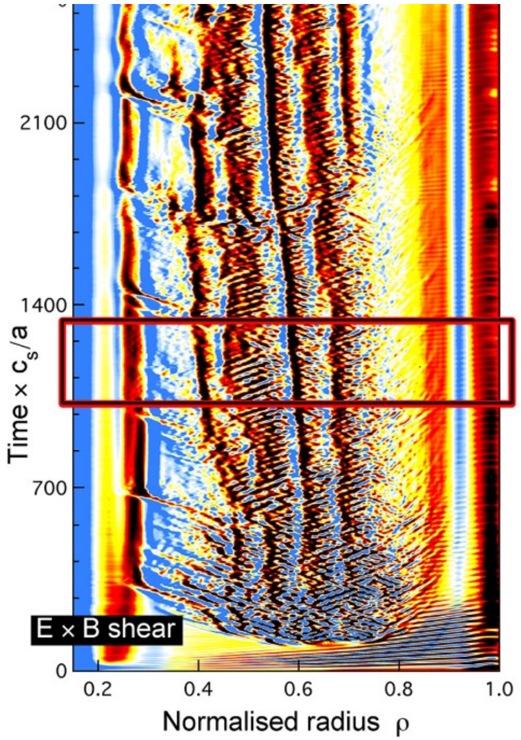
- Both are a way of efficiently releasing (avalanche) or reserving/dissipating (staircase) the excess energy for the system to reach a stationary state

Summary

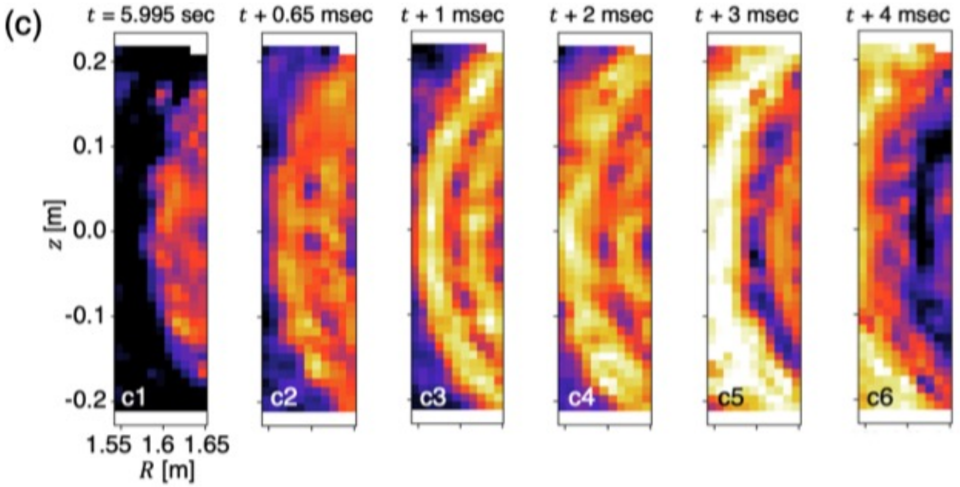
- A picture of the meso-scopic transport has emerged from both gyrokinetic simulations and experiments in the near-marginal regime [T.S. Hahm & P.H. Diamond, J. Korean Phys. Soc. 73, 747 (2018)]
  - Ballistic avalanche and persistent $\mathrm{E} \times \mathrm{B}$ staircase

GYSELA

[G. Dif-Pradalier et al., Nucl. Fusion 57, 066026 (2017)]



KSTAR [M.J. Choi et al., arXiv:2207.06610]



Summary

[M.J. Choi et al., arXiv:2207.06610, submitted to Nucl. Fusion]

- Characteristics of the avalanche and the staircase and their relation are understood based on perspective to consider the staircase as the self-organization in the non-equilibrium complex system
  - Distributions of structure characteristics are rarely normal
  - Structures are sensitive to the initial random microscopic condition
  - They are a way of efficiently extracting the excess energy in the system

	The avalanche transport	The $\mathbf{E} \times \mathbf{B}$ staircase
Dynamics	- Initial (large) perturbation propagates rapidly over the long range - Propagation speed ~ η_i	- Initial perturbation propagates rapidly over the long range - High-k → low-k or low-k → high-k - Radially drifts slowly
Structure	- Radially extended poloidally localized, streamer-like structure	- Radially limited structure by the zonal component arising nonlinearly (three-wave)
Parametric dependency	- More frequently observed with lower $\hat{s}$ - Stronger amplitude with lower $\hat{s}$	- Observed for longer time with lower collisionality
Statistics	- The power-law distribution of the pseudo-size	- Non-Gaussian distribution of τ_{life} and δT_e^2 - Fréchet-like distribution of the radial width
Relation	- The avalanche can trigger the staircase → Fréchet-like width distribution - The staircase can confine the avalanche within its meso-scopic width	

Acknowledgements

- The authors would appreciate supports from the KSTAR team
- One of the authors (M.J.C.) acknowledges helpful discussion with K. Razumova, Y. Kishimoto, Y. Kosuga, W. Wang, K. Ida, T. Kobayashi, F. Kin and M. Sasaki during the UNIST-Kyoto University workshop, the Asia-Pacific Transport Working Group meeting, the Asia-Pacific Conference on Plasma Physics and elsewhere.
- This work was supported by R&D Programs of “KSTAR Experimental Collaboration and Fusion Plasma Research (EN2301-14)” and “High Performance Fusion Simulation R&D (EN2341-9)” through Korea Institute of Fusion Energy (KFE) funded by the Government funds