A Journey Through Mesotopia

P.H. Diamond

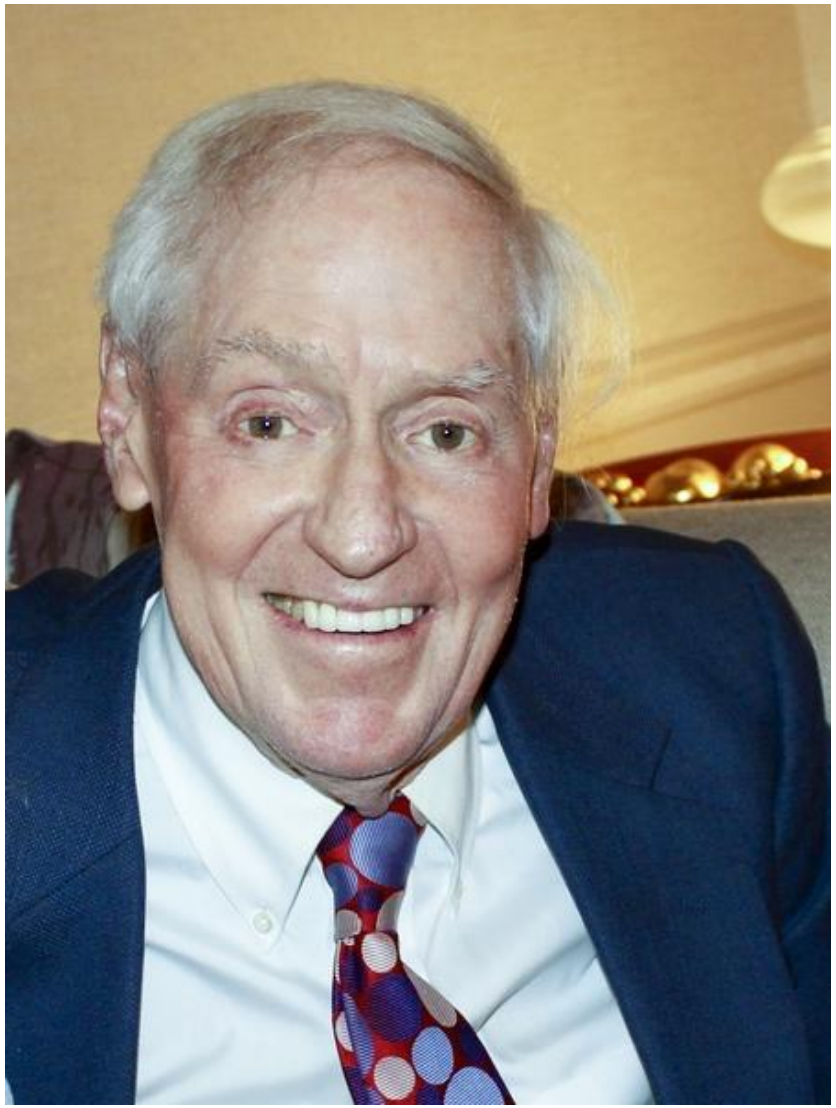
Depts. Astronomy & Astrophysics and Physics

U.C. San Diego

Maxwell Prize Lecture

APS-DPP Nov. 4. 2026

Dedication: Thomas H. Dupree



- For fundamental and far-reaching contributions to our understanding of plasma turbulence, which still guide us today
- For teaching and communicating his superb physical insight

Dedication: Marshall N. Rosenbluth



- For fundamental contributions to these topics, and countless others
- For dedication indispensable to the world fusion program
- For steadfast promotion of international collaboration in fusion, and arms control

Thank You !

- **Long term collaborators:**
  - **T.S. Hahm, Ozgur Gurcan, George Tynan, Guilhem Dif-Pradalier, Kimitaka Itoh, Sanae Itoh, Zhibin Guo, Ting Long, Xavier Garbet, Ben Carreras, Rongjie Hong, John Rice, Weixin Guo, Lothar Schmitz, Y. Kosuga, M. Malkov, X.-Q. Xu**
- Contributions to this talk:
  - Zeyu Li, Zheng Yan, George Mckee, Ting Long, G. Tynan, G. Dif-P, Y. Sarazin, J.-M. Kwon, Peter Manz, M.J. Choi, Mingyun Cao, Rameswar Singh, Rui Ke, Lothar Schmitz, Nami Li, Lei Qi
- Collaborators:
  - Steve Tobias, Ting Wu, Lu Wang, Min Xu, Qinghao Yan, Xu Chu, Xiang Fan, Fredy Ramirez, F. Kin, Arash Ashourvan, Keith Burrell, F. Khabanov, G.-J. Choi, Xiaodi Du, Chris McDevitt, Chris Holland, D.W. Hughes, Andrea Garofalo, E. Kim, Y. Andrew, F. Wagner
- Discussions:

  Festival de Theorie 2001 - 2025
  - Grisha Falkovich, Annick Pouquet, R.Z. Sagdeev, Uriel Frisch, Rick Salmon, Mike McIntyre, R. Pandit, Anna Frishman, T. Hwa, M. Vergassola, N. Goldenfeld, S. Cappello, M. Greenwald

A Journey Through Mesotopia

or

The ‘Zootopia’ of Mesoscopic Turbulence Phenomena



https://movies.disney.com/zootopia

Outline

- Primer on Turbulence in MCF

Mesotopia

- Zonal Shear Flows
- Avalanches
- Staircases
- Looking Ahead…

Approach

- This talk is about MODELS

"The sciences do not try to explain, they hardly even try to interpret, they mainly make models … i.e. *the model* has to be more or less simple compared to the described phenomena"

- John von Neumann

"All models are wrong. Some models are useful"

- George Box

"Without simple models, you don't get anything out of numerical simulation"

- M.J. Feigenbaum, APS Centennial 1999

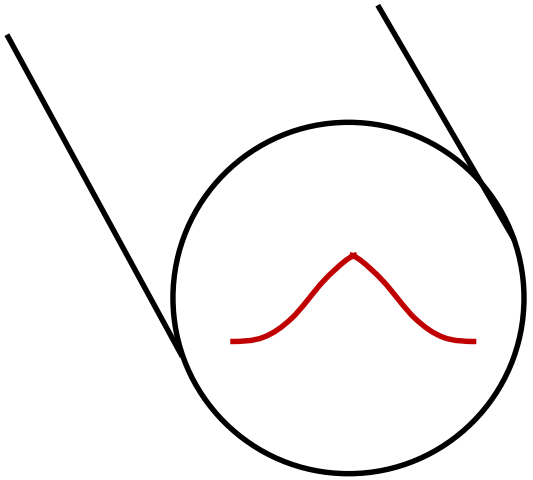
- Emphasis on key physics and recent progress, not historical development
- For History:
  - A. Hasegawa, EPJH (2018)
  - F. Wagner, EPJH (2018)
  - P.D., A. Hasegawa, K. Mima, PPCF (2011)

Primer: Turbulence in MCF Plasmas

- **Why turbulence? – sets τ_E in Lawson # ~ $nT\tau_E$**
- **Focus: Contrast with Kolmogorov/Prandtl models you study in school…**

Primer I - Basics

- Strongly magnetized, $\omega < \Omega_i$ of interest
  - Anisotropic cells, 2D-like ←→ 'inverse cascade'
  - Constrained by magnetic configuration
- $\nabla T, \nabla n$ etc. driven
- $\vec{V}_\perp = \frac{c}{B}\vec{E} \times \vec{B}$, magnetic flutter

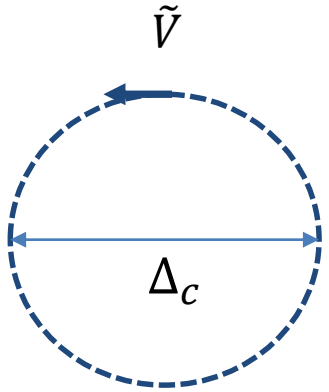


- Akin to R-B convection/thermal Rossby wave with g → magnetic curvature
- Resembles "wave turbulence", not high Re Navier-Stokes turbulence → "*Drift Wave Turbulence*"
- Kubo number $Ku \sim \tilde{V}\tau_c/\Delta_c \sim 1$ *usually*, exceptions notable. Mean Field Theory?

Indicates MEMORY

Kubo Number

- $Ku \sim \tau_{ac} \,/\, \tau_{circ} \sim \tau_{ac}\, \tilde{V} \,/\, \Delta_c$



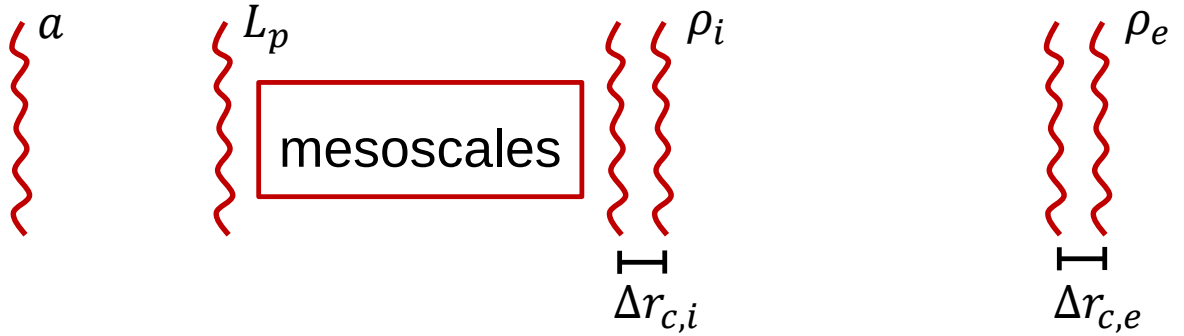
"eddy"

- Compares auto-coherence with circulation
- Ku # characterizes the mixing/transport process
  - $Ku < 1$ → many kicks in circulation
    → Fokker-Planck, etc easy limit
  - $Ku > 1$ → coherence over many circulations
    → avalanches, percolation difficult, the future
  - $Ku \sim 1$ → ?? "mixing length limit"

Primer II - Scales

- Contrast:
  - K41: Cascades $l_0 \rightarrow l_1 \rightarrow \cdots \rightarrow l_d, \quad l_0/l_d \sim Re^{3/4}$ Dynamic range tied to Re
  - "Drift Wave Turbulence": intrinsically multi-scale

$$a > L_p > \Delta r_{ci} > \rho_i > \Delta r_{ce} > \rho_e$$

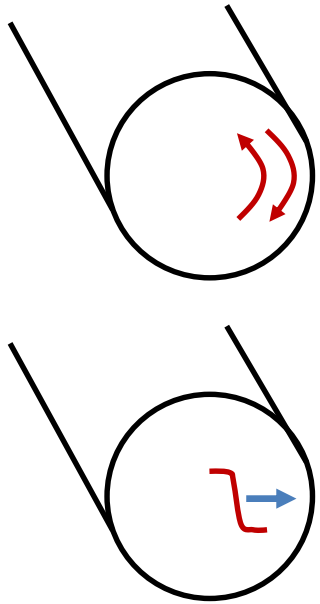


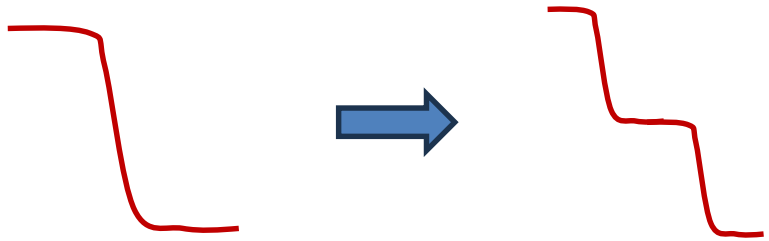
$$\rho_* \sim \frac{\rho_i}{a}$$

  - $\Delta r_{ci}/L_p \sim \rho_* \ll 1$ → key ordering – ensures mesotopia is large
  - Broad dynamic range w/o strong excitation $l_0/l_{min} \sim \sqrt{m_i/m_e}\ /\ \rho_*$

Primer III – Mesoscopic Structures

- Primary drift waves set at Δr_{ci} scale (c.f. Kadomtsev and Pogutse, RPP 1970)
- Secondary: (*not* linear instabilities!)
  - Shear / Zonal flows → system regulation and transitions (L → H + …)
  - Mesoscopic Transport Events (i.e. Avalanches, Entrainment/Spreading fronts) → fast propagating turbulence excitation, related "nonlocality"
- N.B.: Pattern formation competition!
  - ExB staircase and Layering → *resolution: spontaneous emergence of order*





Primer IV – Why Care? → Secondary Modes Regulate Confinement

- How? – Scale Selection
- Mixing length model (Kadomtsev, after Prandtl)

$D \sim V\, l \sim V_*\, l_{mix}$ $\qquad$ $V_* \sim (\rho_c/L_\perp)\, v_{thi} \sim \rho_*\, v_{thi}$ → Diamagnetic velocity

What is l_{mix} ?

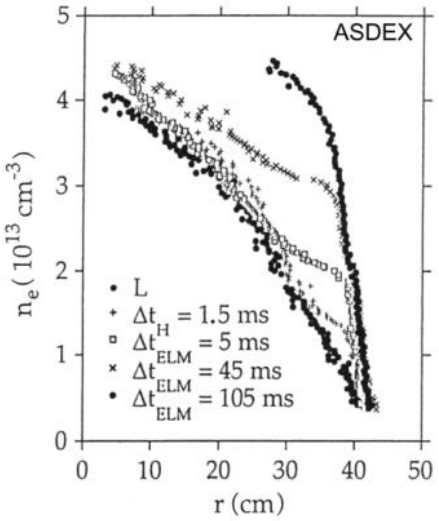
- $\rho_* \ll 1$ → $\rho_i \leq l_{mix} \leq a$ possible
- $l_{mix} \sim a$ → $D \sim T/B \sim D_{Bohm}$

  $l_{mix} \sim \rho_i$ → $D \sim \rho_* D_B$ (GyroBohm)

  "Broken GB" → $D \sim \rho_*^{\alpha}\, D_B, \quad \alpha < 1$ (McKee +, IAEA 2000)
- Pattern competition – determines l_{mix}

Primer V – The Challenge of Transitions

- States of turbulence and confinement manifest bifurcation transitions, with features akin to *phase transitions*
- These are a major challenge…
- Classic: L(low) → H(high) confinement transition (F. Wagner, 1982)



L→H transition:

Edge transport barrier
and pedestal form

Hydro analogy:
(polymer) drag reduction

- Also ITBs…
- Provoke question: Is strong suppression of turbulence a good thing?

  c.f. NT studies

I) Sheared Zonal Flows and Transitions

Reviews:

cf: P.D., S. Itoh, K. Itoh, Hahm; PPCF 2005 (Wave Kinetics)

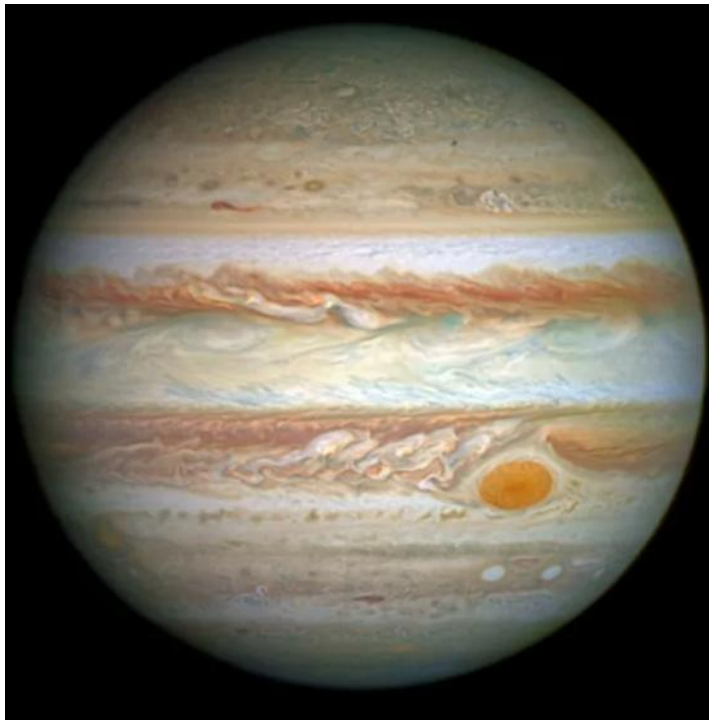
Gurcan, P.D.; J. Phys A 2014 (Envelope)

G.R. Tynan, A. Fujisawa; PPCF 2009 (Experiment)

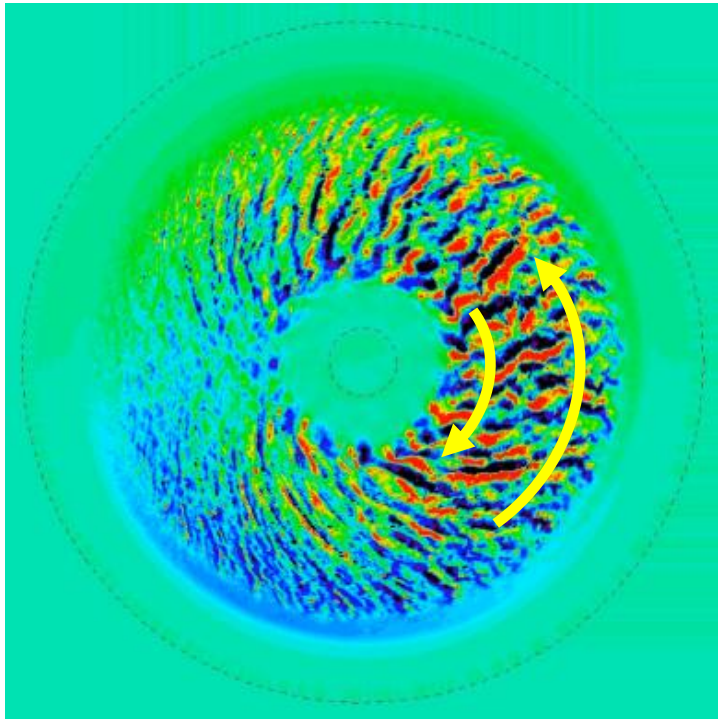
T.S. Hahm, G.J. Choi; RMPP 2024 (Shearing)

MFE relevance: Transitions, Core Confinement

Zonal Flows



Jupiter, with belts



Tokamak Zonal Flow
(GKPSP Simulation)

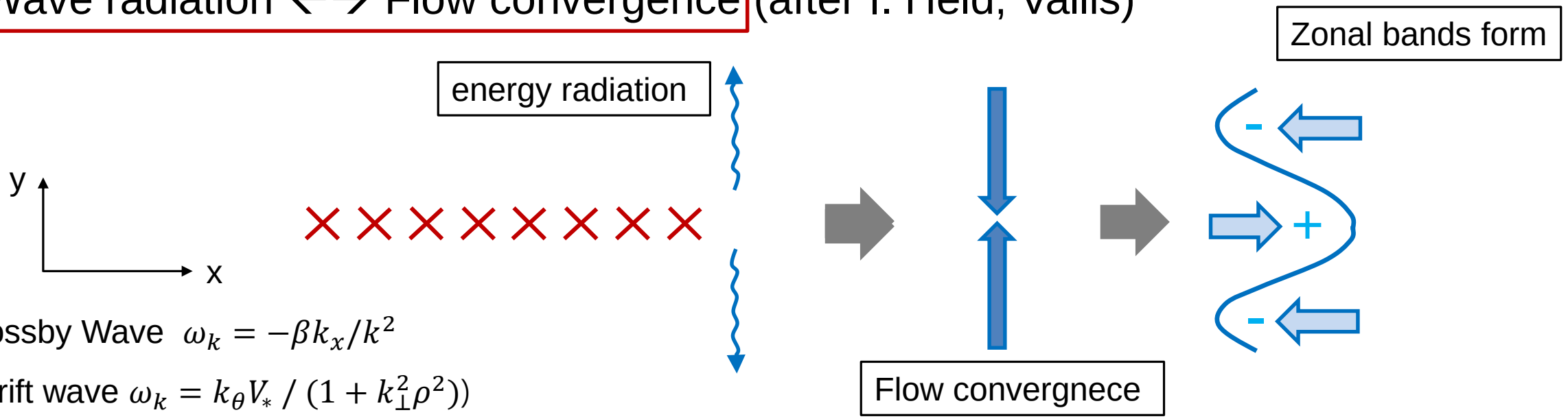
- PV / Polarization charge density transport + 1-direction of symmetry (azimuthal, toroidal) → Zonal Flows (McIntyre, Wood)
- Lorentz ←→ Coriolis (Hasegawa, Mima 1978)

Zonal Flows: What and Why ?

- What is a zonal flow?
  - n = 0 potential mode, m = 0, with possible sideband (GAM)
  - Toroidally, poloidally symmetric ExB shear flow
- Why are ZF's important ?
  - Zonal flows are nonlinearly driven secondary
    - Modes of minimal inertia (Hasegawa; Sagdeev + '78)
    - Modes of minimal damping (Rosenbluth, Hinton '98)
    - Drive zero transport (n = 0)
  - Natural "predators" to regulate "prey" of gradient driven microturbulence
  - Benign energy repository

ZF Formation – Heuristics

- Wave radiation ←→ Flow convergence (after I. Held, Vallis)



Rossby Wave $\omega_k = -\beta k_x / k^2$

(Drift wave $\omega_k = k_\theta V_* / (1 + k_\perp^2 \rho^2)$)

$$V_{gy} = 2\beta k_x k_y / k_\perp^2 \ , \quad \langle V_y V_x \rangle = -\sum_k k_y k_x \, |\phi_k|^2$$

- NB: $V_{gy}\, V_{phy} < 0$ Drift-Rossby: backward wave

Flow convergence at stirring location

ZF Formation, cont'd

- Alternative Perspective: Adiabatic Theory
- $\omega_{ZF} \ll \omega_{DW}$ ←→ time scale separation → exploit adiabatic theory (P.D.+ '98)

  (after Zakharov, Sagdeev)

$$N = \varepsilon/\omega$$

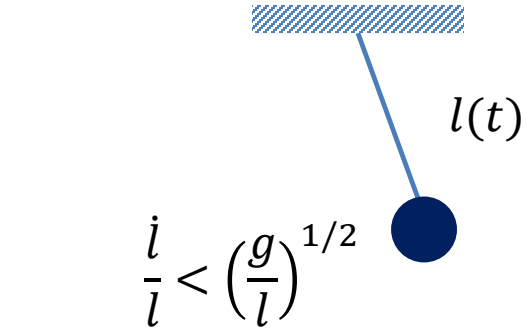
Wave Action Density (Whitham)

$$\omega = k_\theta V_* / 1 + k_\perp^2 \rho^2$$

$$\frac{dk_r}{dt} = -k_\theta V_E'$$

Shearing - Refraction

Ala'



Shearing → k_r^2 ↑ → ω_{DW} ↓ but N conserved so ➔ ε ↓ so flow shear amplified

- Reynolds stress → momentum *transport* ➔ *flow shear amplification*

On Shearing

- Zonal Shears: Wave kinetics (Zakharov et. al.; P.D. et. al. '98, et. seq.)

- $dk_r / dt = -\partial(\omega + k_\theta V_E)/\partial r$

Mean shearing $: k_r = k_r^{(0)} - k_\theta V_E' \tau \quad V_E = \langle V_E \rangle + \tilde{V}_E$

Zonal Random shearing $: \langle \delta k_r^2 \rangle = D_k \tau$

$$D_k = \sum_q k_\theta^2 \left| \tilde{V}_{E,q}' \right|^2 \tau_{k,q}$$

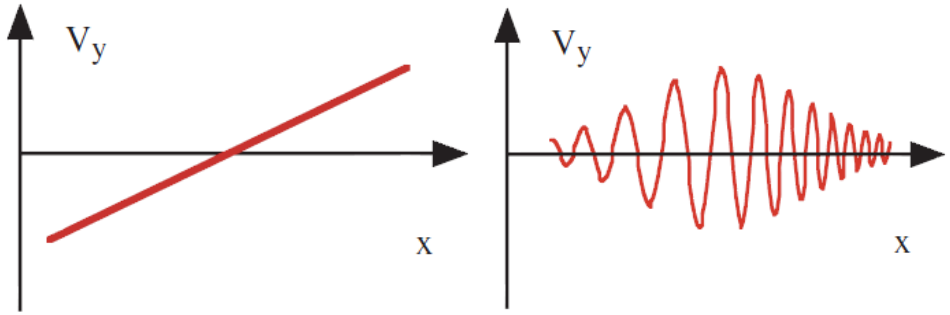
- Mean Field Wave Kinetics

$$\frac{\partial N}{\partial t} + (\vec{V}_{gr} + \vec{V}) \cdot \nabla N - \frac{\partial}{\partial r}(\omega + k_\theta V_E) \cdot \frac{\partial N}{\partial \vec{k}} = \gamma_{\vec{k}} N + C\{N\}$$

$$\Rightarrow \boxed{\frac{\partial}{\partial t}\langle N \rangle - \frac{\partial}{\partial k_r} D_k \frac{\partial}{\partial k_r} \langle N \rangle = \gamma_{\vec{k}} \langle N \rangle + \langle C\{N\} \rangle}$$

Zonal shearing

Intermediate Regimes: P.D., Malkov '01



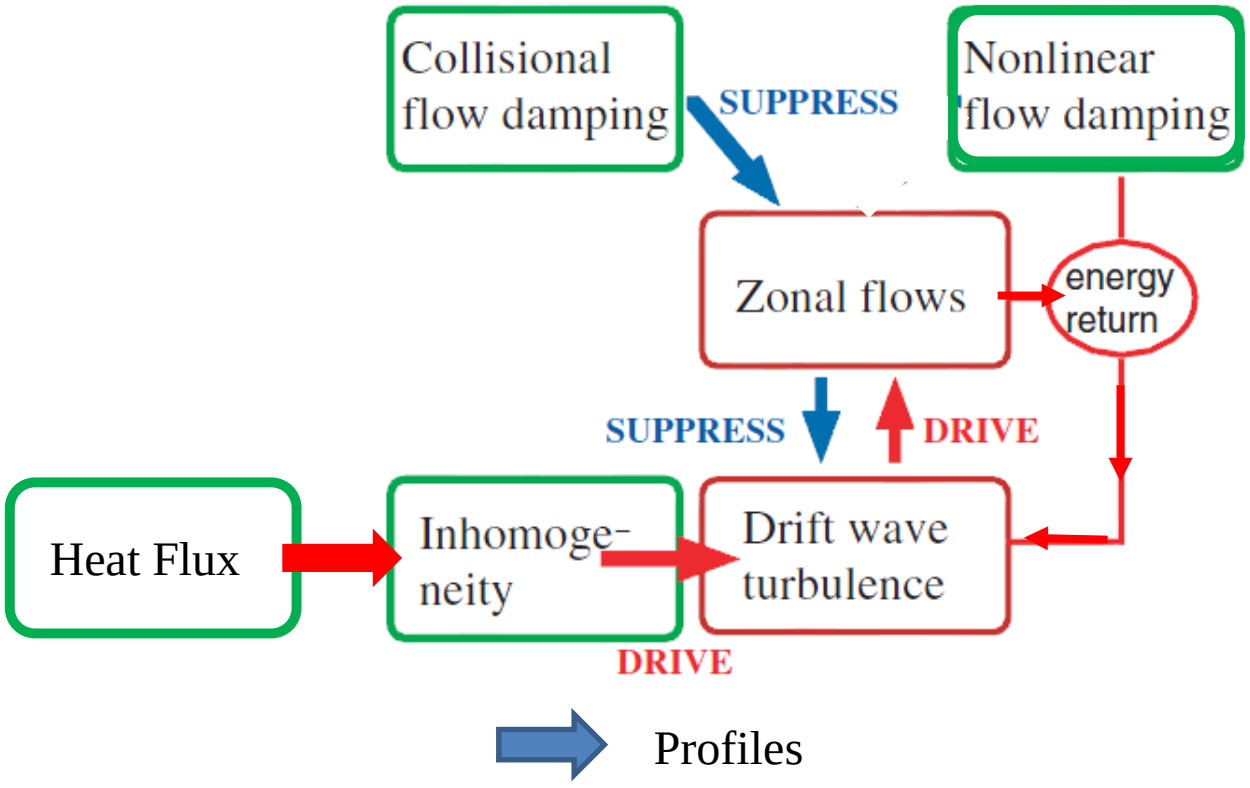
- Wave ray chaos (not shear RPA) underlies $D_k \rightarrow$ induced diffusion
- Induces wave packet dispersion
- Applicable to ZFs and GAMs
- For foundation of C(N), see Y. Deng+ Fields Medal 2026

Predator-Prey Models



Feedback I - Schematics

- Key: Close the loop of shearing and Reynolds power → spectral 'Predator-Prey' Model



Prey → Drift waves, <*N*>

$$\frac{\partial}{\partial t}\langle N\rangle - \frac{\partial}{\partial k_r} D_k \frac{\partial}{\partial k_r}\langle N\rangle = \gamma_k \langle N\rangle + \langle C\{N\}\rangle$$

Predator → Zonal flow, $|\phi_q|^2$

$$\frac{\partial}{\partial t}|\phi_q|^2 = \Gamma_q \left[\frac{\partial \langle N\rangle}{\partial k_r}\right]|\phi_q|^2 - \gamma_d |\phi_q|^2$$

Feedback II

- Recovering the 'dual cascade':
  - Prey → <N> ~ <Ω> ⇒ induced diffusion to high k_r { ⇒ Analogous → forward potential enstrophy cascade; PV transport
  - Predator → $|\phi_q|^2 \sim \langle V_{E,\theta}^2 \rangle$ { ⇒ growth of *n=0, m=0* Z.F. by turbulent Reynolds work ⇒ Analogous → inverse energy cascade

- Mean Field Predator-Prey Model

  (P.D. et. al. '94, DI^{2}H '05)

$$\frac{\partial}{\partial t} N = \gamma N - \alpha V^2 N - \Delta\omega N^2$$

$$\frac{\partial}{\partial t} V^2 = \alpha N V^2 - \gamma_d V^2$$

⇒ Can reduce to TDGL with shear as order parameter

System States

State	No flow	Flow ($\alpha_2 = 0$)	Flow ($\alpha_2 \neq 0$)
N (drift wave turbulence level)	$\frac{\gamma}{\Delta\omega}$	$\frac{\gamma_d}{\alpha}$	$\frac{\gamma_d + \alpha_2 \gamma \alpha^{-1}}{\alpha + \Delta\omega\alpha_2\alpha^{-1}}$
V^2 (mean square flow)	0	$\frac{\gamma}{\alpha} - \frac{\Delta\omega\gamma_d}{\alpha^2}$	$\frac{\gamma - \Delta\omega\gamma_d\alpha^{-1}}{\alpha + \Delta\omega\alpha_2\alpha^{-1}}$
Drive/excitation mechanism	Linear growth	Linear growth	Linear growth Nonlinear damping of flow
Regulation/inhibition mechanism	Self-interaction of turbulence	Random shearing, self-interaction	Random shearing, self-interaction
Branching ratio $\frac{V^2}{N}$	0	$\frac{\gamma - \Delta\omega\gamma_d\alpha^{-1}}{\gamma_d}$	$\frac{\gamma - \Delta\omega\gamma_d\alpha^{-1}}{\gamma_d + \alpha_2\gamma\alpha^{-1}}$
Threshold (without noise)	$\gamma > 0$	$\gamma > \Delta\omega\gamma_d\alpha^{-1}$	$\gamma > \Delta\omega\gamma_d\alpha^{-1}$

Feedback III

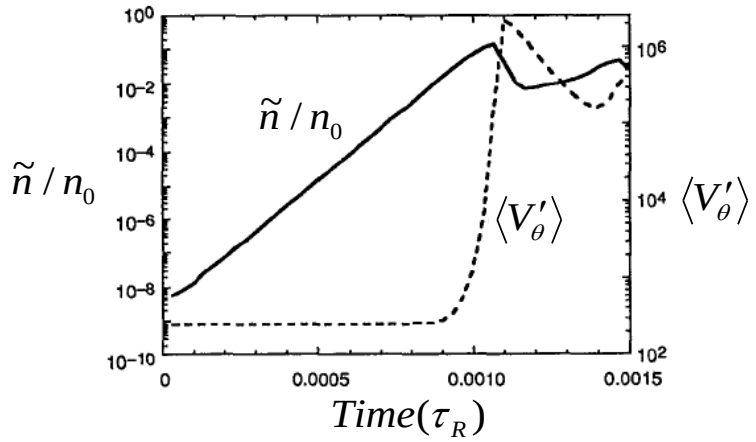
	Parallel flow gradient driven instability	Resistive interchange instability	Drift thermal instability
α_1	$\dfrac{\gamma_0 \rho_s^4 c_s^2}{W_0^6 \lvert V_\parallel' \rvert^2}$	$\dfrac{k_\theta^2 \rho_s^2 c_s^2}{\gamma_0 W_0^2 \Lambda^{5/3}}$	0
α_2	$\dfrac{k_\theta^2 W_0^2}{2\gamma_0} \dfrac{W_0^2}{\rho_s^2}$	$\dfrac{k_\theta^2 W_0^2}{\gamma_0}$	$\dfrac{k_\theta^2 W_0^2}{\omega_a}$
α_3	$\dfrac{k_\theta^2 c_s^2}{2\gamma_0}$	$\dfrac{k_\theta^2 \rho_s^2 c_s^2}{\gamma_0 W_0^2 \Lambda^{2/3}}$	$\dfrac{k_\theta^2 \rho_s^2 c_s^2}{\omega_a W_0^2}$
W_0	$\left(\dfrac{\gamma_0 \rho_s L_s}{k_\theta c_s}\right)^{1/2}$	$\left(\dfrac{\gamma_0^2 r_c L_n}{k_\theta^2 c_s^2}\right)^{1/2}$	$\left(\dfrac{\chi_\perp L_s^2}{\chi_\parallel k_\theta^2}\right)^{1/4}$
$\dfrac{b}{a}$	$\left(\dfrac{L_g}{L_s}\right)^2 \dfrac{2\mu L_s}{k_\theta \rho_s c_s}$	$\left(\dfrac{k_\theta^2}{\langle k_\theta^2 \rangle}\right)^{1/2}$	0

Table of Coefficients

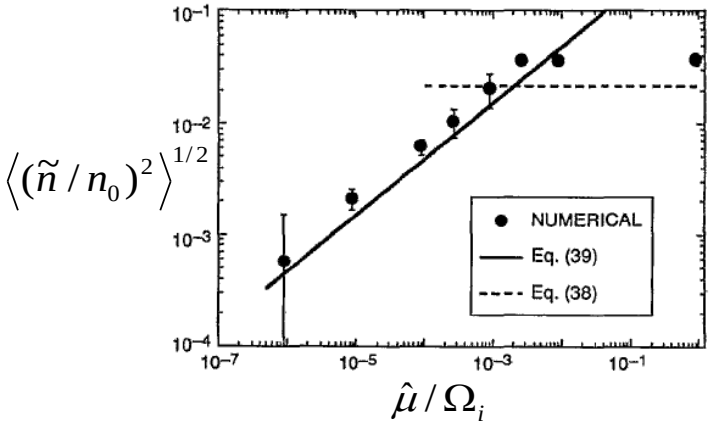
Feedback IV, cont'd

- Early simple simulations confirmed several aspects of mean field predator-prey dynamics

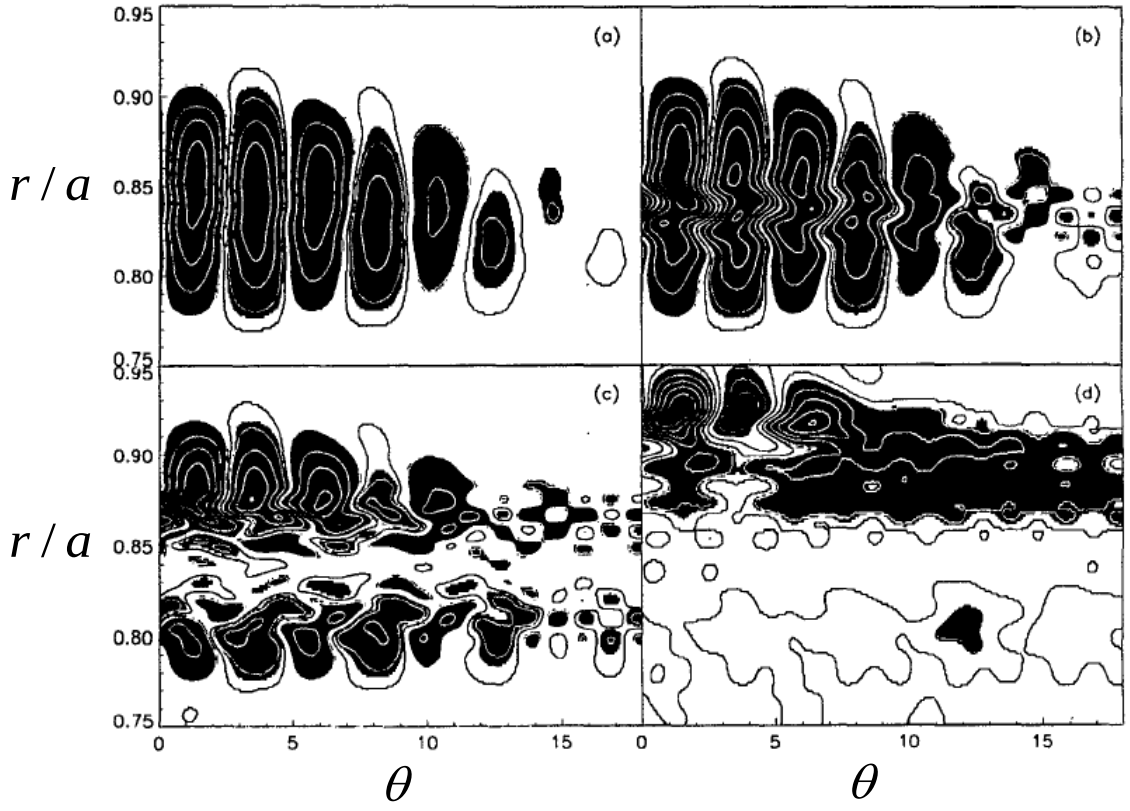
(L. Charlton et. al. '94)



Shear flow grows above critical point



'With Flow' and 'No Flow'.
Scalings of $\langle (\tilde{n}/n_0)^2 \rangle$ appear. Role of damping evident



Generic picture of fluctuation scale reduction with flow shear

Feedback V

- ∇P coupling
  - γ_L drive $\langle V_E \rangle'$

$$\partial_t \varepsilon = \varepsilon N - a_1 \varepsilon^2 - a_2 V^2 \varepsilon - a_3 V_{ZF}^2 \varepsilon$$

$$\partial_t V_{ZF} = a_2 \varepsilon V_{ZF} - b_3 V_{ZF}$$

$$\partial_t N = -c_1 \varepsilon N - c_2 N + Q$$

$\varepsilon \equiv$ *DW energy*

$V_{ZF} \equiv$ *ZF shear*

$N \equiv \nabla\langle P \rangle \equiv$ *pressure gradient*

$V = dN^2$ *(radial force balance)*

- Simplest example of 2 predator + 1 prey problem (E. Kim, P.D., 2003)

  i.e. prey sustains predators
  predators limit prey
  } usual feedback

  now: 2 predators (*ZF*, $\nabla\langle P \rangle$) compete
  $\nabla\langle P \rangle$ as both drive and predator

- Relevance: LH transition, ITB
  - Builds on insights from Itoh's, Hinton
  - ZF ⇒ triggers
  - $\nabla\langle P \rangle$ ⇒ 'locking in'

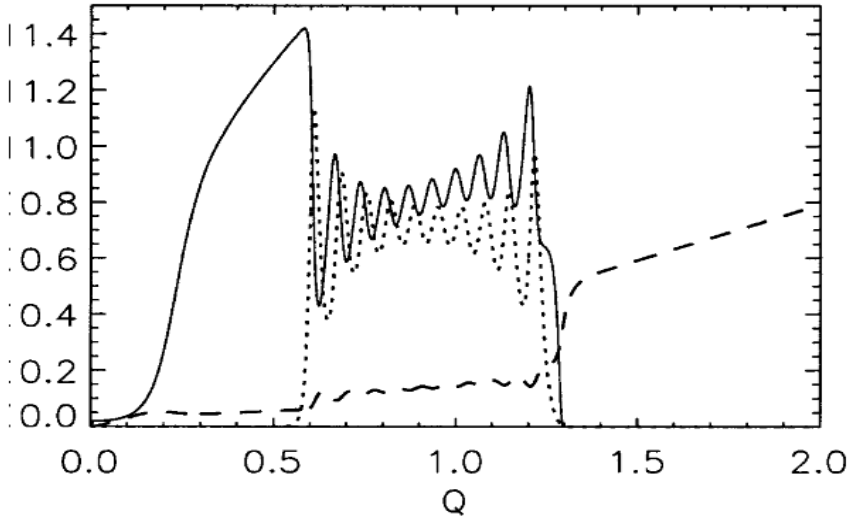
Multiple predators





Feedback VI, cont'd

Kim, P.D. '03

- 

Solid - ε

Dotted - V_{ZF}

Dashed - $\nabla\langle P\rangle$

See also:

- K. Miki + PoP '12 et. seq., especially space-time
- R. Singh, P.D. PPCF 22 – incoherent mode coupling

- Observations: I-Phase
  - ZF's trigger transition, $\nabla\langle P\rangle$ and $\langle V\rangle$ lock it in
  - Period of dithering, pulsations …. during ZF, $\nabla\langle P\rangle$ oscillation as $Q\uparrow$
  - Phase between ε , V_{ZF}, $\nabla\langle P\rangle$ varies as Q increases
  - $\nabla\langle P\rangle \Leftrightarrow$ ZF interaction $\Rightarrow$ effect on wave form

What does the data say?

Contributions From: Zheng Yan, Lothar Schmitz, George Tynan



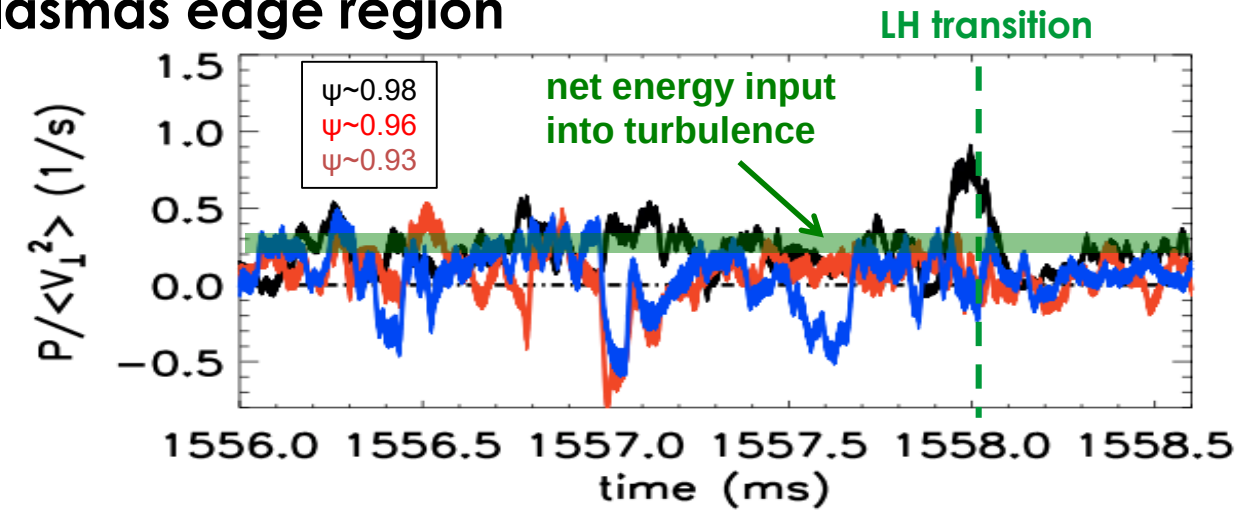
Experimentalist – Theorist Dialogue

2D measurements of the spatiotemporal dynamics of density fluctuations demonstrate the increased flow shear triggering the L-H transition

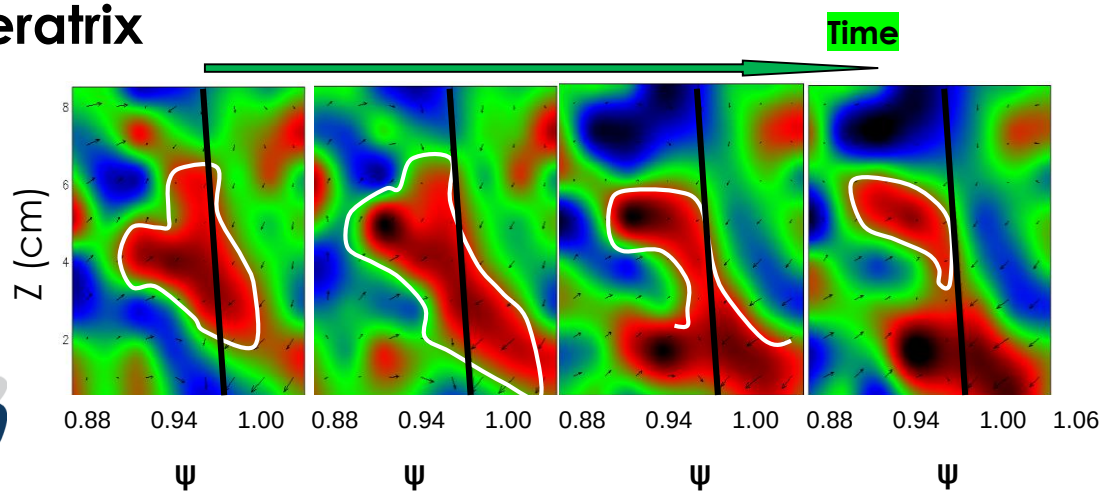
Zheng Yan



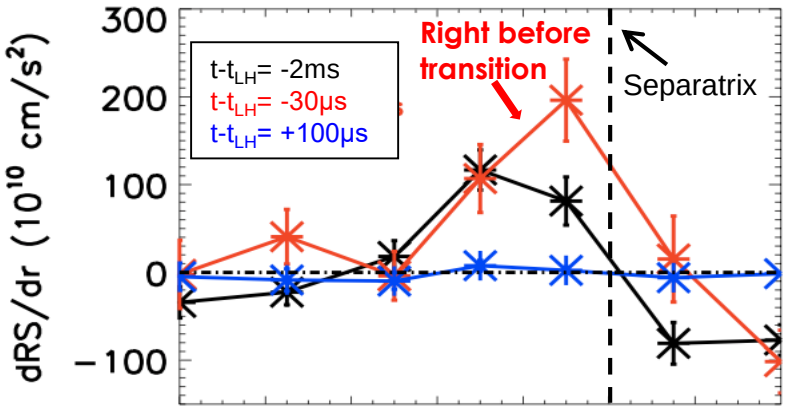
- **Rapid change in energy transfer is localized to the plasmas edge region**

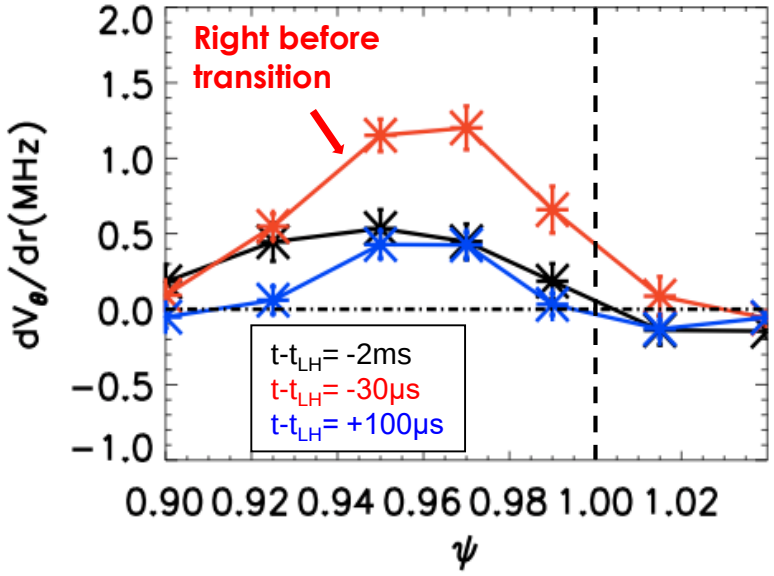


- **Turbulence is sheared and suppressed just inside the seperatrix**



- **Increased Reynolds stress gradient driving increased flow and flow shear**





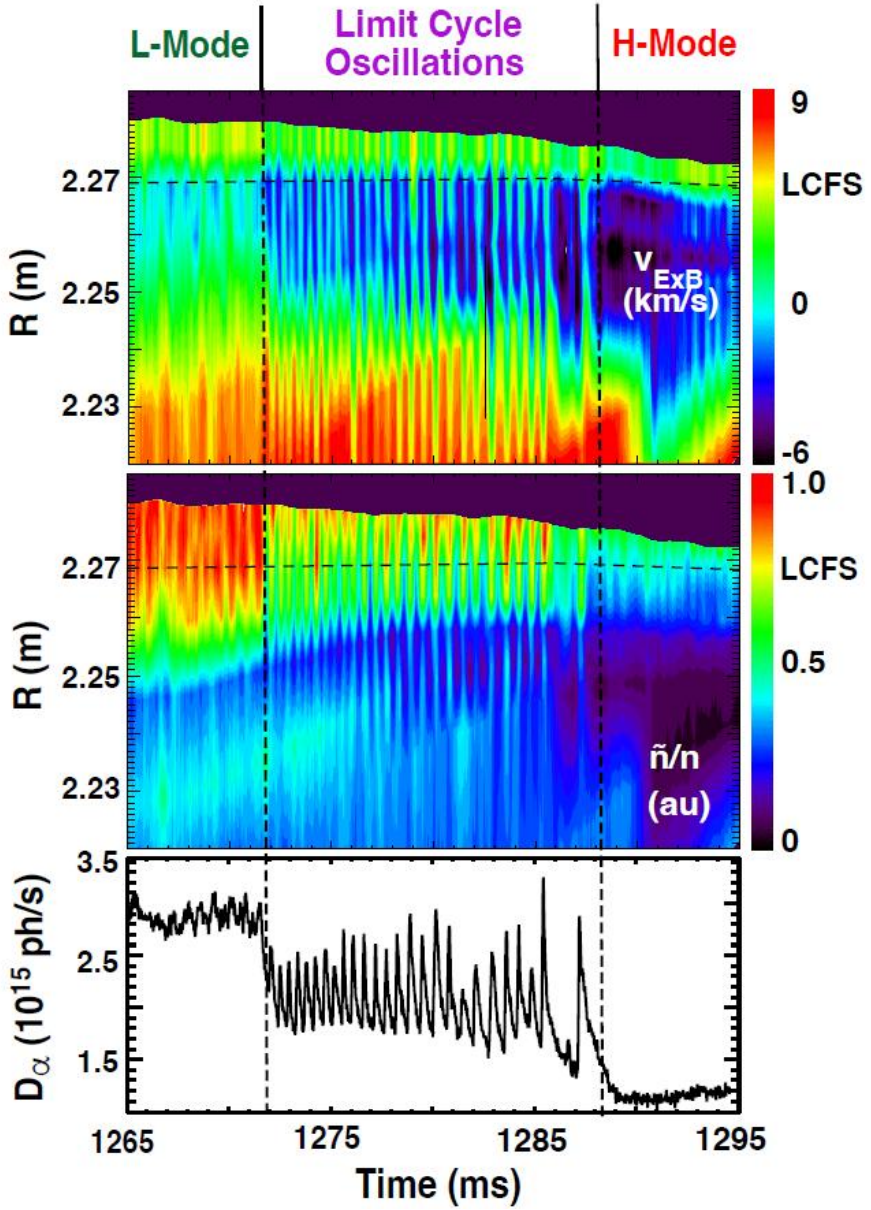
DIII-D NATIONAL FUSION FACILITY

Limit Cycles (LCO) initiate L-H Transition: Modulated density fluctuation level, E×B Flow (Zonal Flow), and plasma outflow (D_α)



Lothar Schmitz

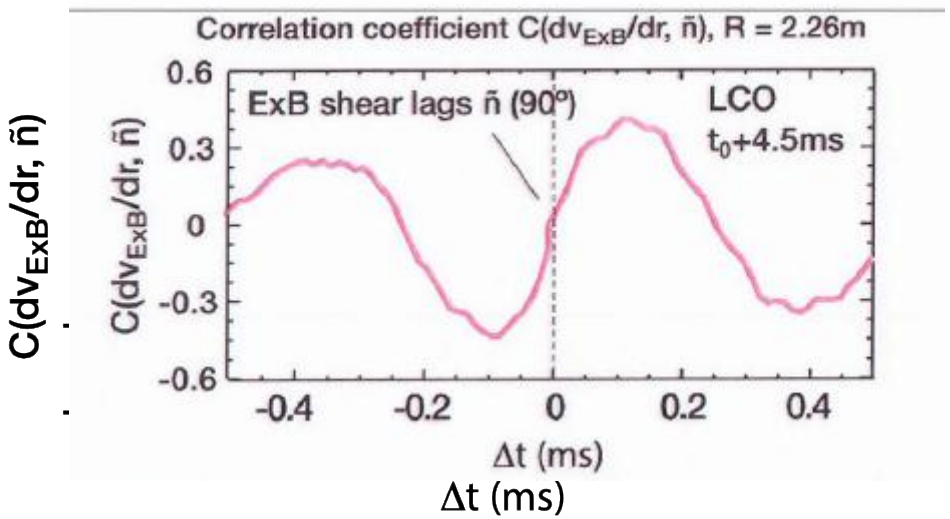
- Oscillating shear flows are triggered and increase periodically (LCO) before the H-mode transition
- The density fluctuation level ñ/n decreases periodically at high shear towards the final H-mode transition
- Local transport is reduced throughout the oscillatory (LCO) phase (n, T_e, T_i increase)
- The LCO frequency is reduced by increasing diamagnetic (mean) shear



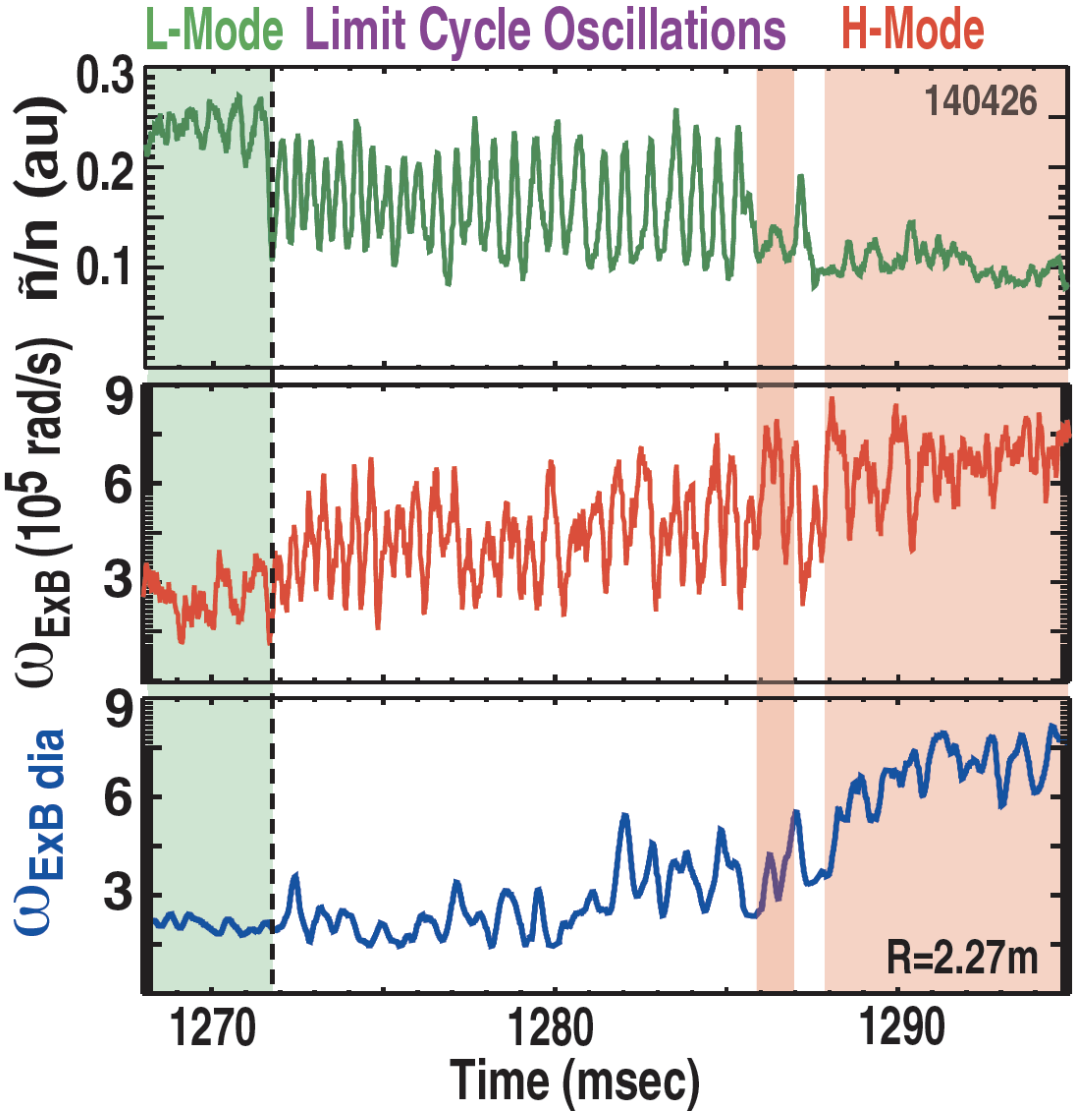
L. Schmitz, PRL 66 155002 (2012)

ZF shear dominates LCO initially; equilibrium (diamagnetic) shear increases more slowly

- ñ fluctuations are initially clearly reduced by oscillating Zonal Flow shear
- Predator-prey dynamics during LCO: E×B shear lags ñ by 90°

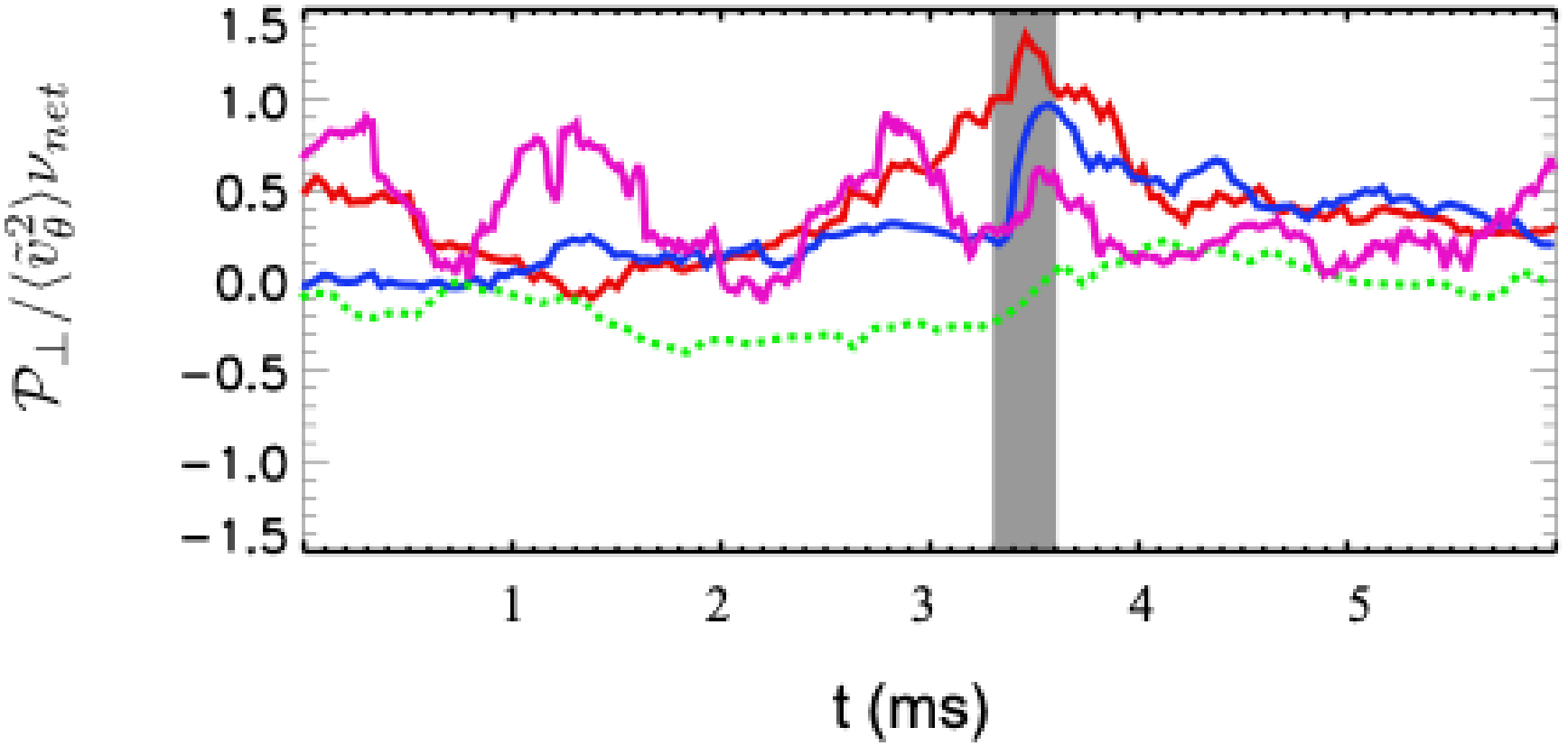


- Diamagnetic shear increases more slowly due to pressure profile evolution; eventually slows down LCO (dominating ZF shear)



L. Schmitz, PRL 66 155002 (2012)

Normalized Shear Flow Production Rate





P. Manz



G. Tynan

Reynolds power density fraction peaks at transition
(c.f. Manz, Tynan ’12)

Manz et al PoP’12

Ongoing Research in Zonal Flows

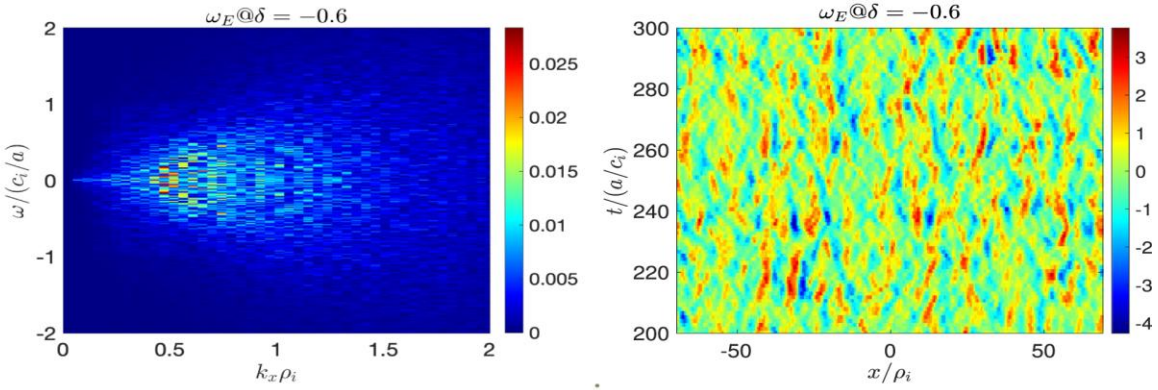
Contributions: Rameswar Singh, Ting Long

Is Shearing Field Coherent? – Clearly Not !



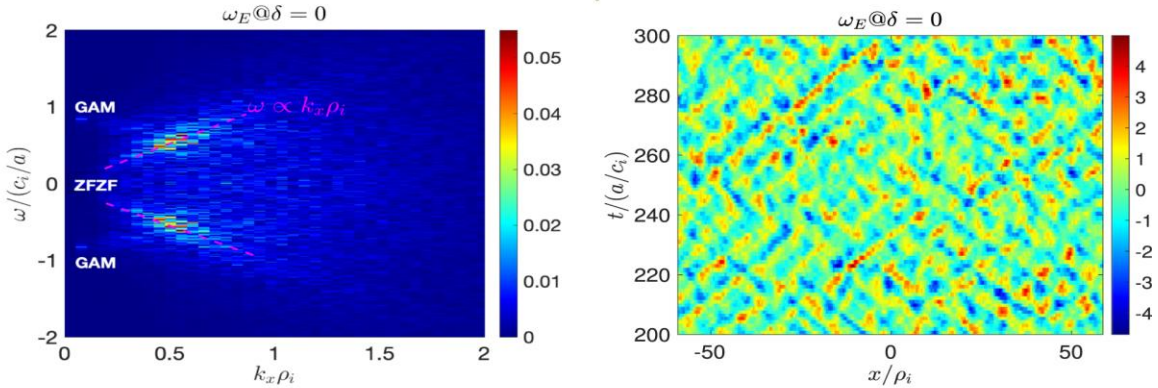
Rameswar Singh

NT



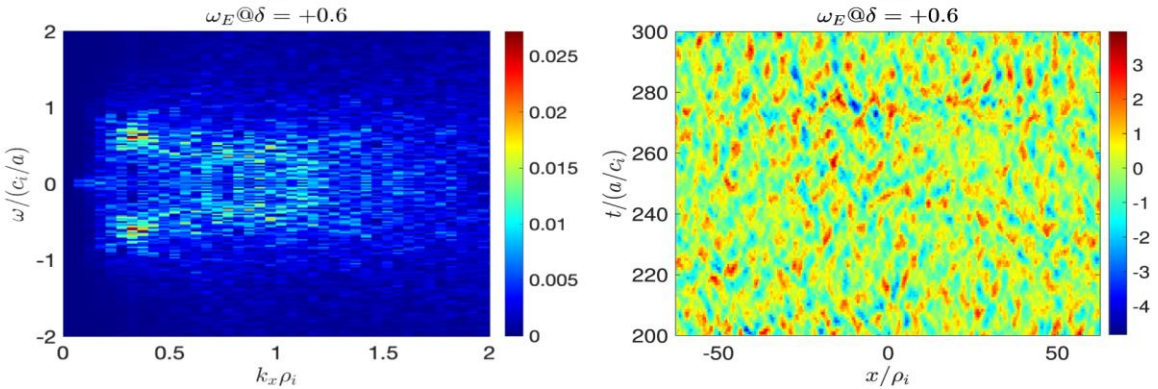
$\delta < 0$

0



$\delta = 0$

PT



$\delta > 0$

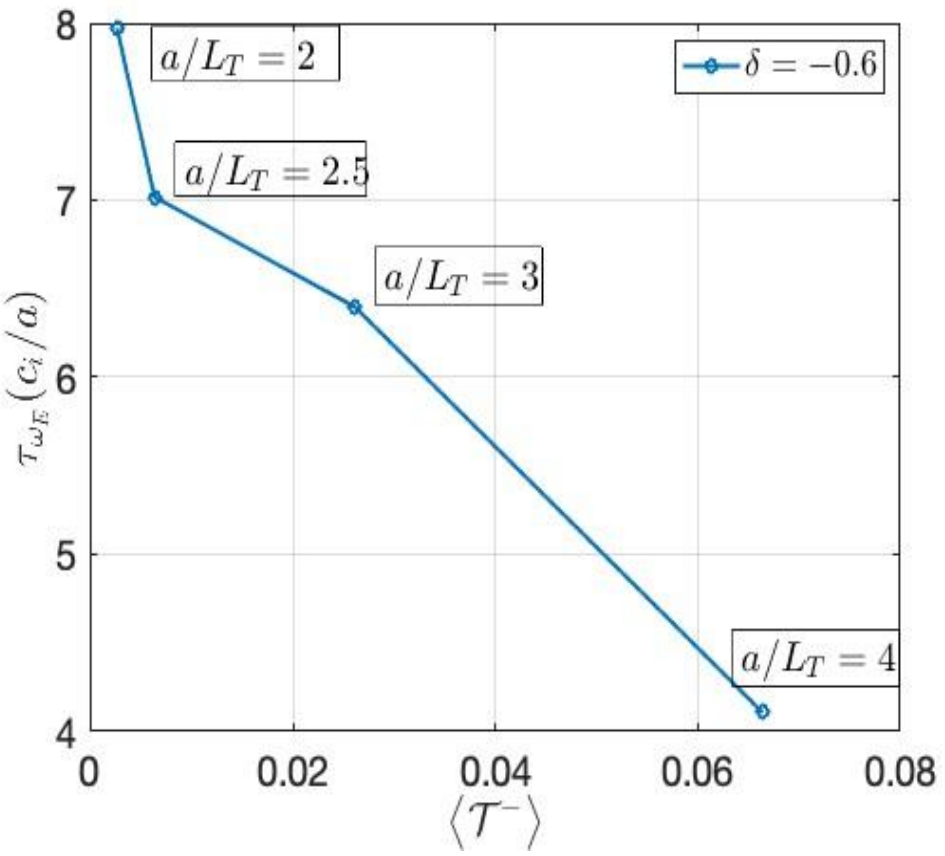
Degraded zonal coherency

←→ Energy scattered from ZF

→ DW (R. Singh, P.D. ‘26)

Zonal $Ku_Z \sim V_E'\tau_Z$ Significant !

Zonal Shear Lifetime vs Zonal Back-Transfer



Increased back-transfer ZF → DW

Reduced zonal shear auto-correlation time

→ZF auto-correlation is indicator of nonlinear transfer out of ZF

→Similar result for corrugations

➔ Role in ZF scale selection !?

See also: B. Vanovac, Invited talk Thurs. 11am

Zonal flow determines confinement evolution in density limit



Rongjie Hong



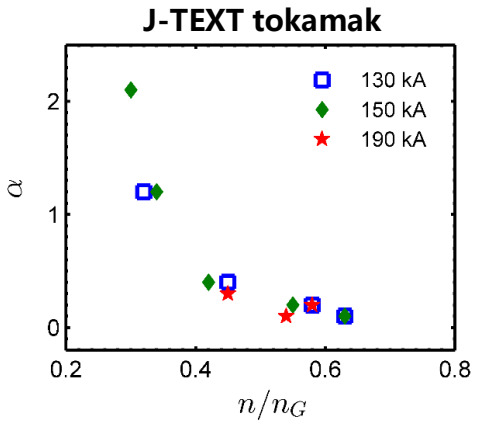
Ting Long

- **Theoretical prediction:** density limit related to breakdown of turbulence self-regulation
- Based on **zonal flow-turbulence diagram**:

Scenario	Plasma response	Zonal flow shear	Turbulence
L-mode with high density /density limit	Hydrodynamic ($\alpha < 1$)	Weak	Strong
L-mode with common density	Adiabatic ($\alpha > 1$)	Moderate	Moderate
H-mode	Irrelevant	Strong	low

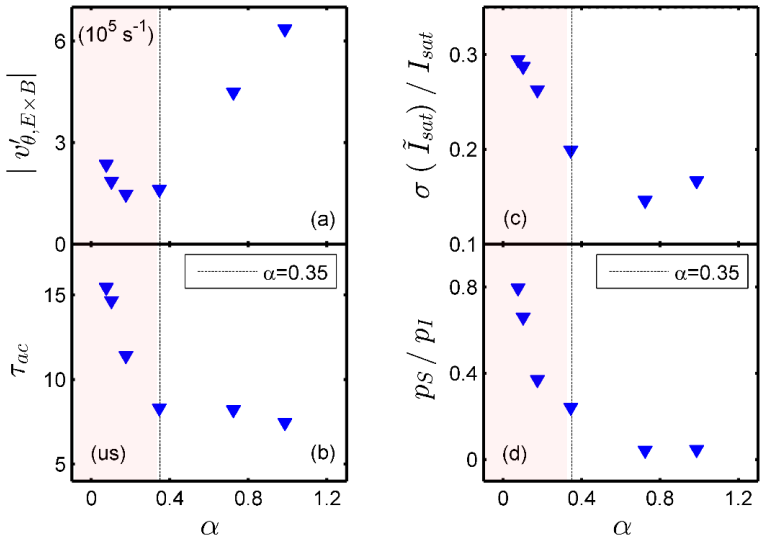
- **Experiments:** adiabaticity decreases **from $\alpha \sim 1$ to $\alpha \ll 1$ approaching density limit**

→ **Zonal flow collapses** & **turbulence enhances**



$$n_G = \frac{I_p}{\pi a^2}$$

$$\alpha = \frac{k_\parallel^2 v_{th,e}^2}{\nu_{ei}|\omega|}$$

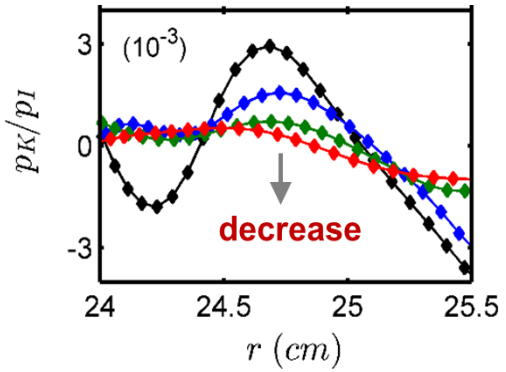


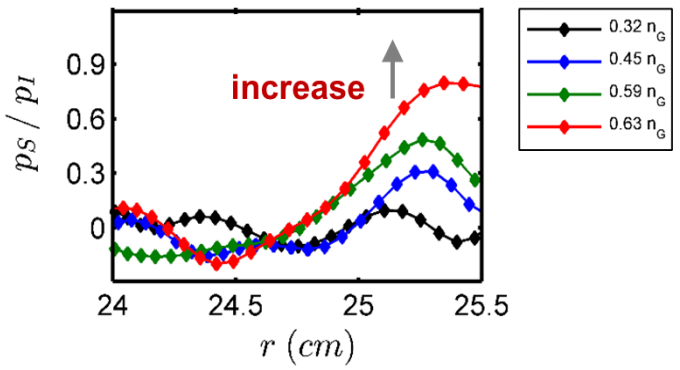
- ✓ *B. N. Rogers, et al. Phys. Rev. Lett. 81 4396 (1998)*
- ✓ *R. J. Hajjar, P. H. Diamond, et al. Phys. Plasma 25 062306 (2018)*
- ✓ *R. Singh, P. H. Diamond, et al. Nuclear Fusion 61 076009 (2021)*
- ✓ *Long T, Diamond P H, et al. Nuclear Fusion 61 126066 (2021)*
- ✓ *P. H. Diamond, et al. Phil. Trans. R. Soc. A 381 20210227 (2023)*

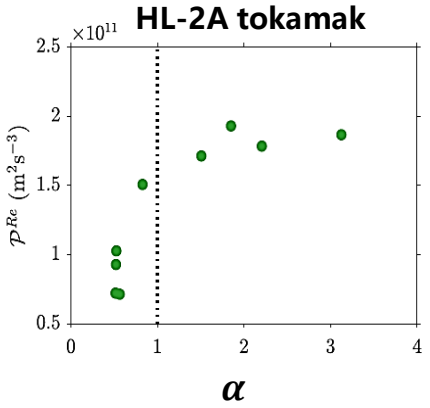
Zonal flow determines confinement evolution in density limit

- **Physics** (turbulence energy evolution of kinetic VS internal): **diverted from zonal flow drive** (Reynolds power) to **outward spreading** → enhanced particle & heat transport

$(\mathcal{P}_K/\mathcal{P}_I)_{peak} * (\mathcal{P}_S/\mathcal{P}_I)_{peak} \sim \mathbf{const}$

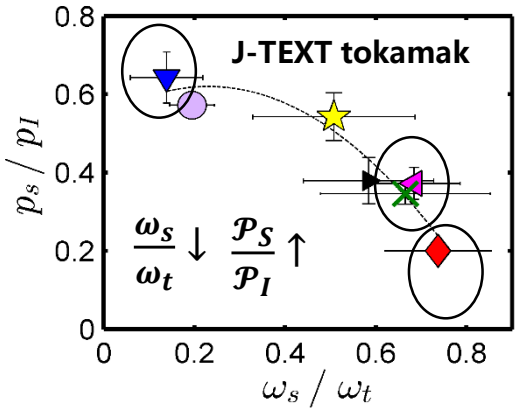






- **Flow shear-turbulence interaction**: reconcile the I_p **dependence** of density limit

I_p	187kA	152kA	126kA
$\bar{n}$	$4.0 \times 10^{19}\ m^{-3}$	$4.0 \times 10^{19}\ m^{-3}$	$4.0 \times 10^{19}\ m^{-3}$
$\bar{n}/n_G$	0.45	0.55	0.63
ω_s	$1.04 \times 10^5\ s^{-1}$	$1.73 \times 10^5\ s^{-1}$	$0.68 \times 10^5\ s^{-1}$
ω_t	$1.4 \times 10^5\ s^{-1}$	$2.6 \times 10^5\ s^{-1}$	$4.9 \times 10^5\ s^{-1}$



$$\frac{\mathcal{P}_S}{\mathcal{P}_I} = \frac{-\partial_r \langle \tilde{v}_r \tilde{n}^2 \rangle / 2}{-\langle \tilde{v}_r \tilde{n} \rangle \partial_r \langle n \rangle}$$

$$\frac{\omega_s}{\omega_t} = \frac{k_\theta\, l_{cr} \left| \partial_r v_{\theta,E\times B} \right|}{4 \langle \tilde{v}_r^2 \rangle\, \tau_{ac} / l_{cr}^2}$$

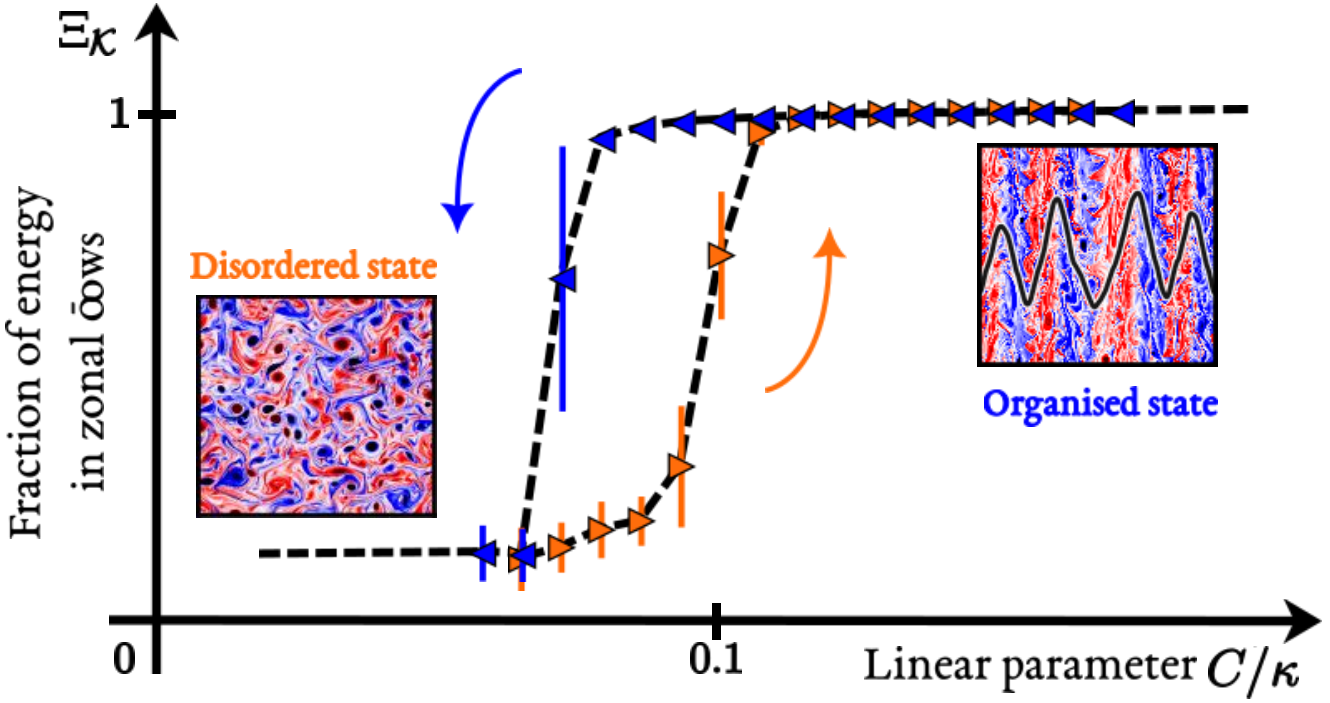
✓ *Long T, Diamond P H, et al. Nuclear Fusion 61 126066 (2021)*
✓ *Hong R, Tynan G R, Diamond P H, et al. Nuclear Fusion 58 016041 (2018)*
✓ *Long T, Diamond P H, et al. Nuclear Fusion 64 066011 (2024)*

Zonal Flow Evolution during Adiabaticity Scan



Pierre Guillon

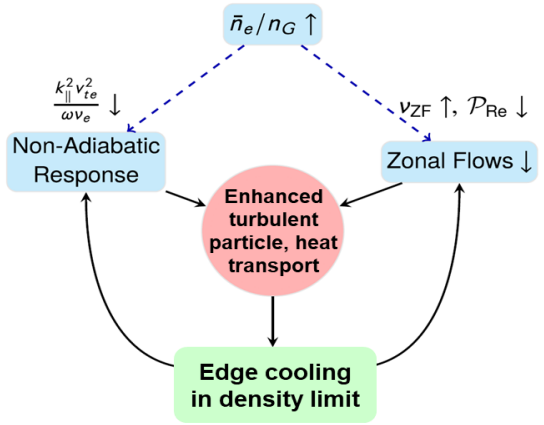
- Pierre Guillon, O.D. Gurcan PoP 2025
- H-W system manifests hysteresis in adiabaticity scan → phase transition in turbulence



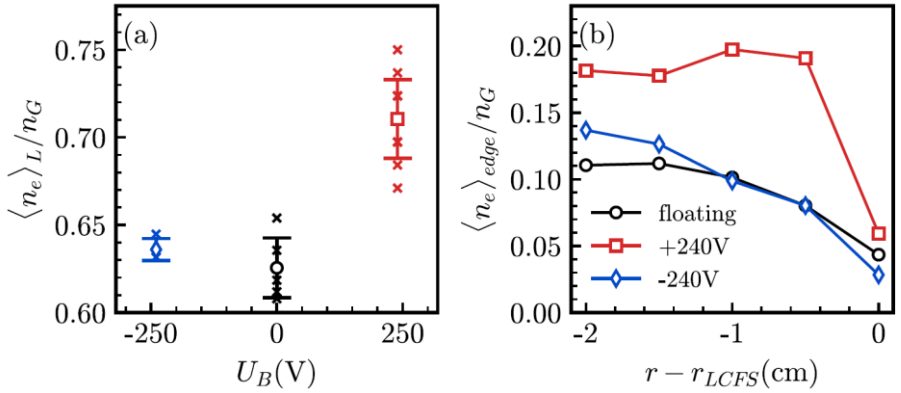
- Zonal flows collapse for low adiabaticity

Zonal flow determines confinement evolution in density limit

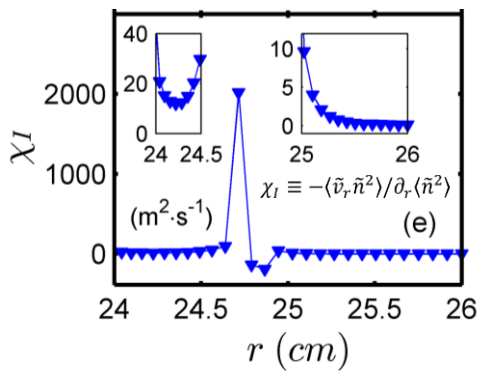
- **Feedback mechanism** in high density plasmas

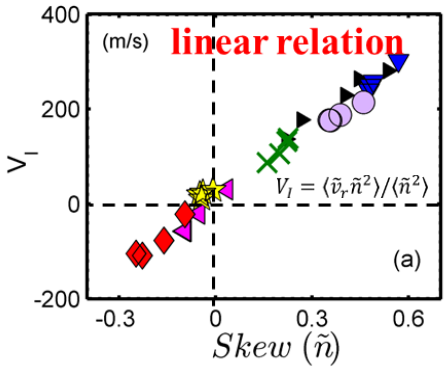


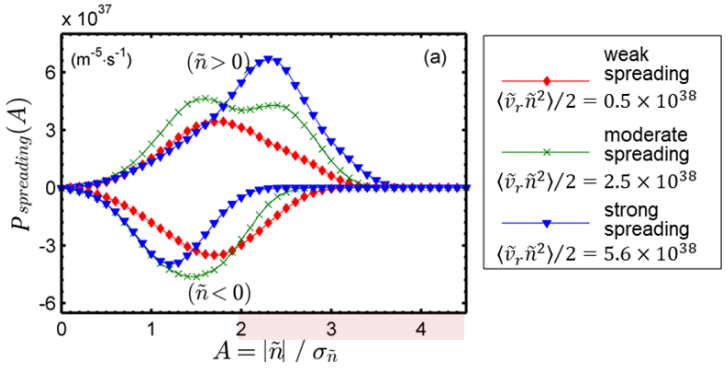
- **Externally driven shear flow** (via bias electrode): reduce turbulence spreading → **higher density limit**



- **Easter egg:** convective structures convey **non-diffusive turbulence spreading** as zonal flow collapses → breakdown of Fick's law







✓ *Ke R, Diamond P H, et al. Nuclear Fusion, 62(7): 076014 (2022)*

✓ *Long T, Diamond P H, et al. Nuclear Fusion 64 064002 (2024)*

Mesoscopic Transport and Mixing Events

MFE application:

Transport, especially near marginal stability,

Turbulence spreading, heat load broadening,

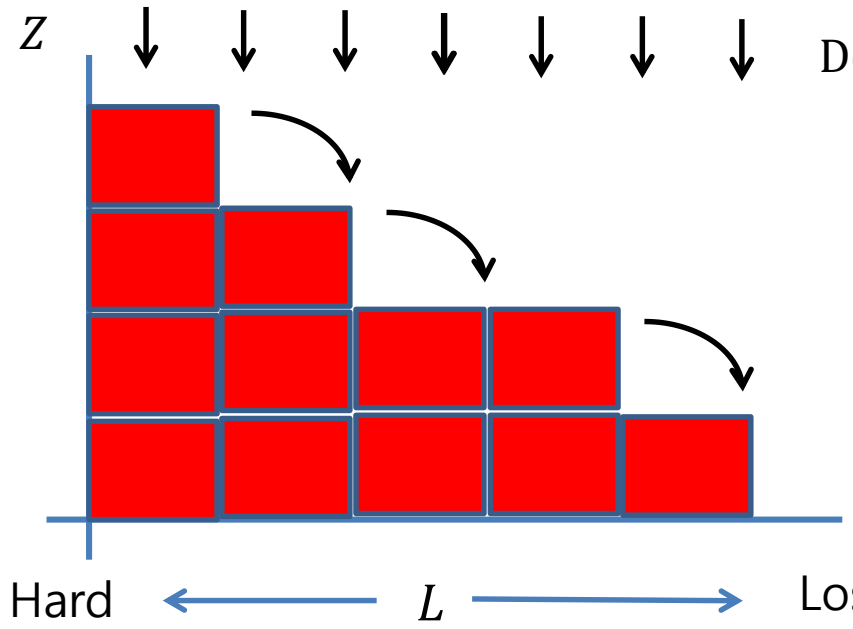
Core-Edge Integration

II) Mesoscopic Transport and Mixing Events

- Propagating mixing front
  - Transport flux → "*Avalanche*"
  - Intensity flux → "*Spreading*"

- Intrinsically coupled phenomena; distinction arbitrary
- Reviews:
  - K. Ida +, NF 2016 – Nonlocal Transport
  - Hahm, P.D., J. Kor. Phys. Soc. 2018
  - Long, Choi, P.D.; Phil Trans 2026
  - P.D., Kosuga+, Phil Trans 2026

- Avalanching: Classic Model – 1D driven lossy pile (Kadanoff '89)



Deposition → can profile

Toppling Threshold ←→ Mixing

If
$Z_i - Z_{i+1} > \Delta Z_{crit}$
$Z_{i+1} \rightarrow Z_{i+1} + N$
$Z_i \rightarrow Z_i - N$
Etc.

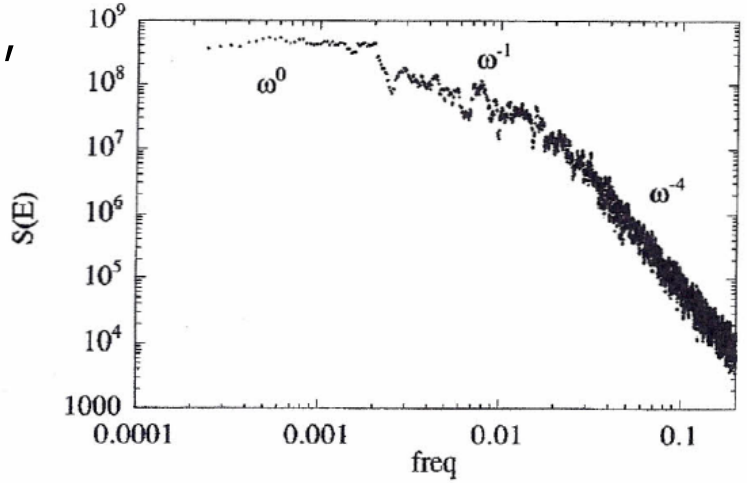
Grains ejected at boundary

- Interesting dynamics only if $L/\Delta \sim N \gg 1$ ←→ equivalent to $\rho_* \ll 1$ condition
- Interaction driven, i.e. $Ku \geq 1$

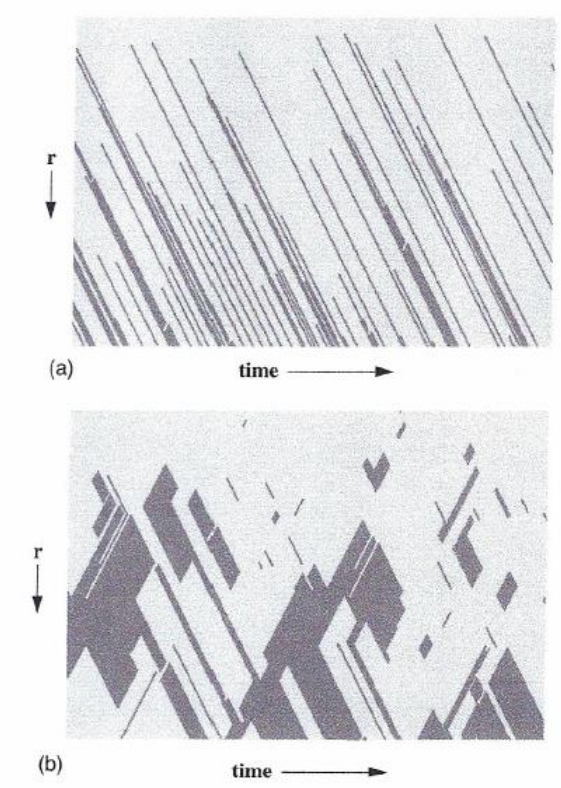
TABLE I. Analogies between the sandpile transport model and a turbulent transport model.

Turbulent transport in toroidal plasmas	Sandpile model
Localized fluctuation (eddy)	Grid site (cell)
Local turbulence mechanism:	*Automata rules*:
Critical gradient for local instability	Critical sandpile slope (Z_{crit})
Local eddy-induced transport	Number of grains moved if unstable (N_f)
Total energy/particle content	Total number of grains (total mass)
Heating noise/background fluctuations	Random rain of grains
Energy/particle flux	Sand flux
Mean temperature/density profiles	Average slope of sandpile
Transport event	Avalanche
Sheared electric field	Sheared flow (sheared wind)

- Avalanching, cont'd



Power spectrum of over-turnings $\langle(\Delta Z)^2\rangle_\omega$



Avalanching

{ dark → over-turning
  light → stable

- Some generic results
  - 1/f range manifest
  - Large power in slowest, lowest frequencies
  - Loosely, 3 ranges:
    - ω^0 → Large discharges
    - 1/f → avalanching, interaction dominated
    - $1/f^4$ → self correlation dominated

→ Outward, inward avalanching …

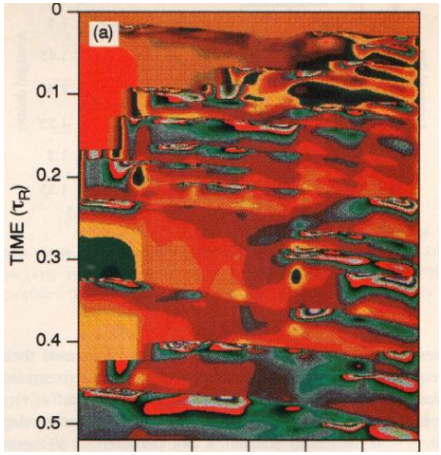
- Do Avalanches Really Happen in MFE Plasmas?
  - An early example, outside sandbox
- Continuum Simulation
  - (Carreras+ '96) *Flux driven* resistive interchange turbulence;

    "weak drive"

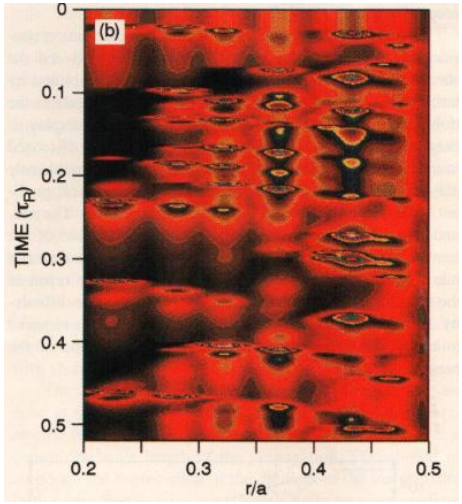
    noise

    - Noisy source: $S_0 = S(r) + \tilde{S}$
    - Reynolds stress driven flows, viscosity
    - Threshold: ala' Reyleigh, ∇P vs ν, D_c
  - Flux drive, fast gradient evolution essential, as $V_{aval} \sim V_*$

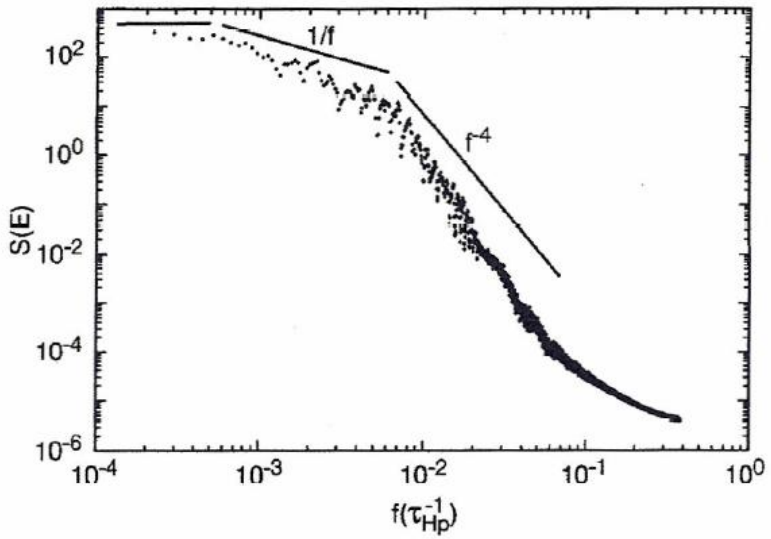
Avalanches indeed happen!



P



$e\phi/T$



– Clear difference in left pressure contours

vs right $(e\phi/T)_{rms}$ contour

– Avalanches evident in δP

But

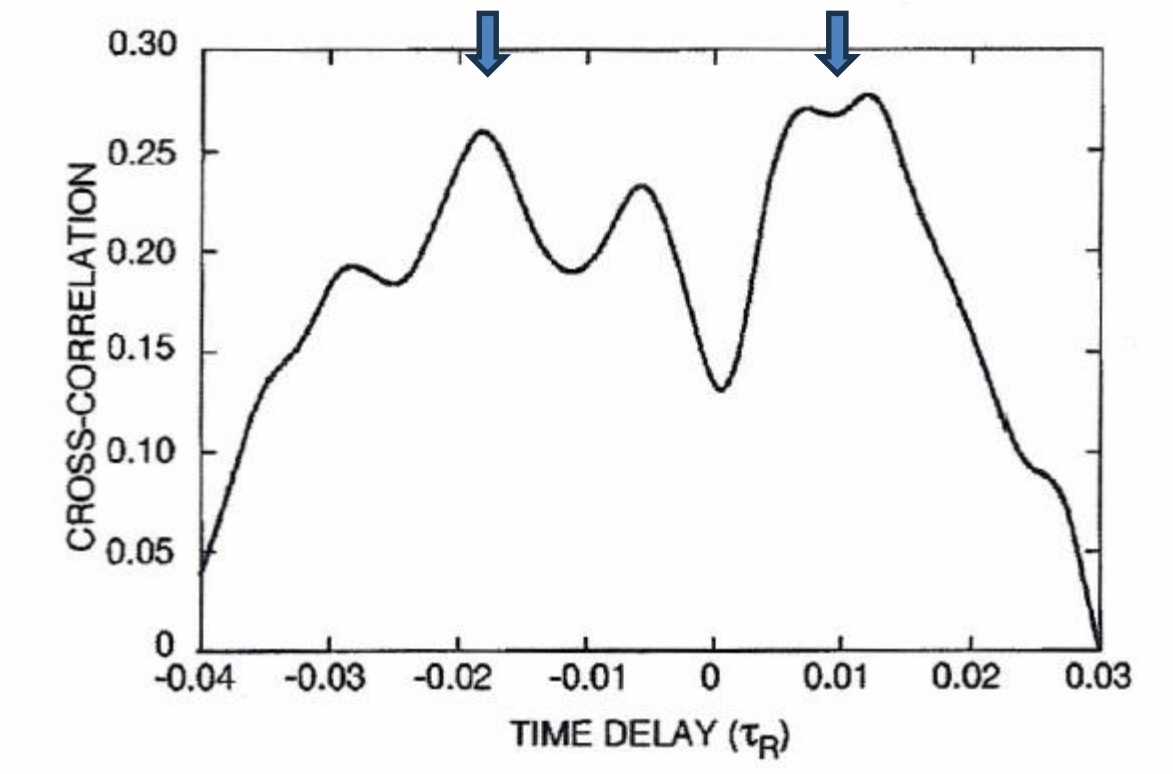
– Modes, resonant surfaces visible in $e\phi/T$

➔ illustrates collective character of avalanches

– 1/f recovered in $\langle\left(\frac{e\tilde{\phi}}{T}\right)^2\rangle_\omega$

– Very similar to pile spectrum

- 2 peaks in cross correlation of low frequency modulation

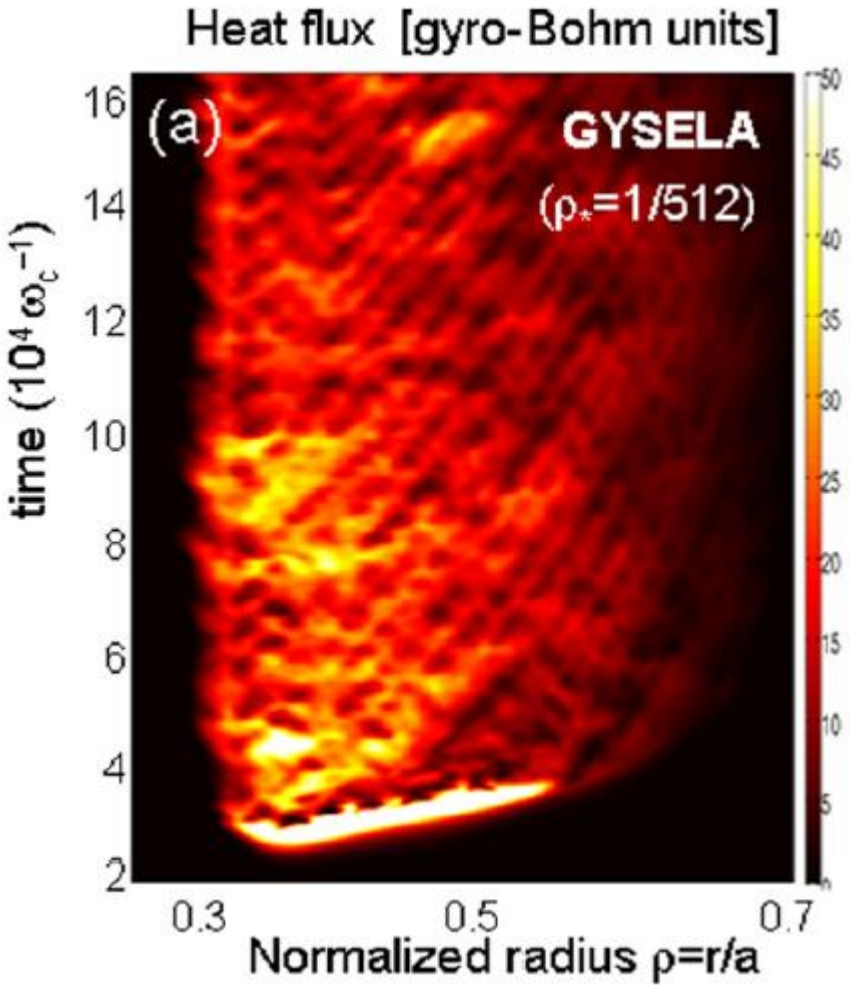


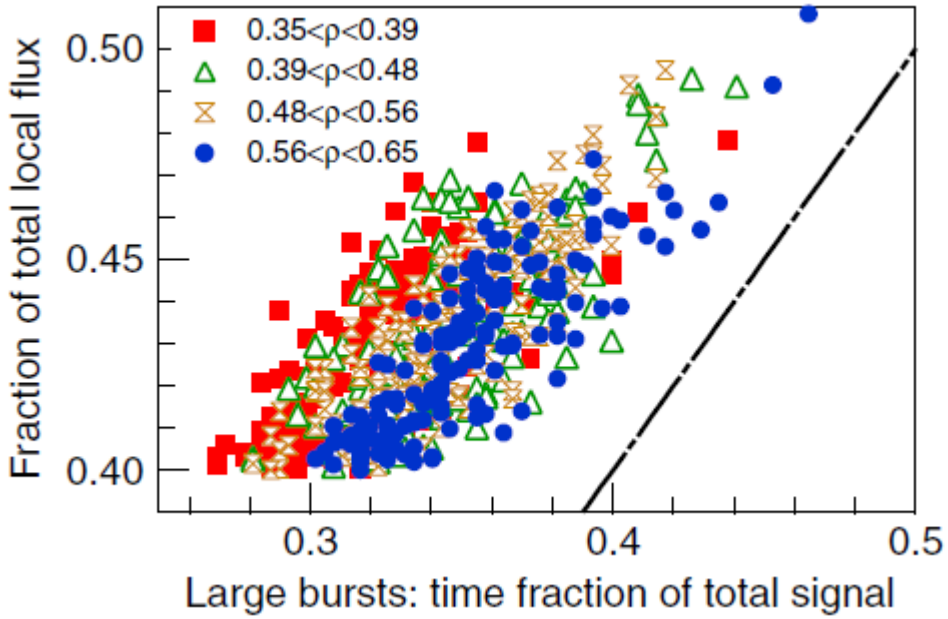
2 peaks → ingoing, outgoing avalanches

- Shear flow can truncate avalanches

- **Do Avalanches "Matter" ? – Yes ! - GYSELA**

GYSELA, rhostar=1/512 [Sarazin et al., NF 51 (2011)]





Large bursts carry ≥ 40% of total heat flux

Avalanches indeed matters, cont'd

- Distribution of Flux Excursion and Shear Variation

  GYSELA, rhostar=1/64 [Sarazin et al., NF 50 (2010) 054004]

Asymmetry!

Q_{turb}

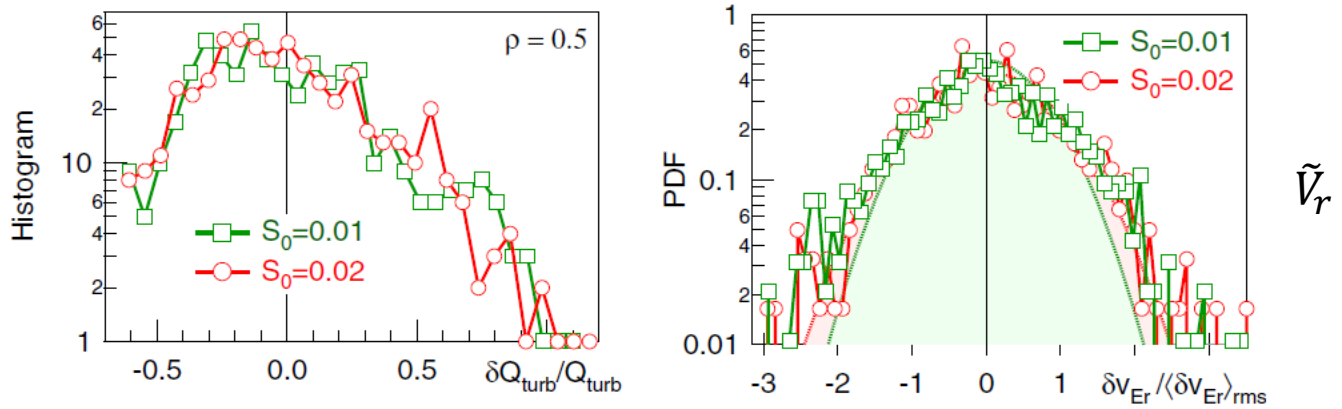


Figure 7. (Left) histogram of the turbulent heat flux Q_{turb} at $\rho = 0.5$ for two magnitudes of the source ($\rho_* = 1/64$). δQ_{turb} stands for the difference between Q_{turb} and its time average, taken over the entire non-linear saturation phase. (Right) corresponding PDF of the fluctuations of the radial component of the electric drift. (Colour online.)

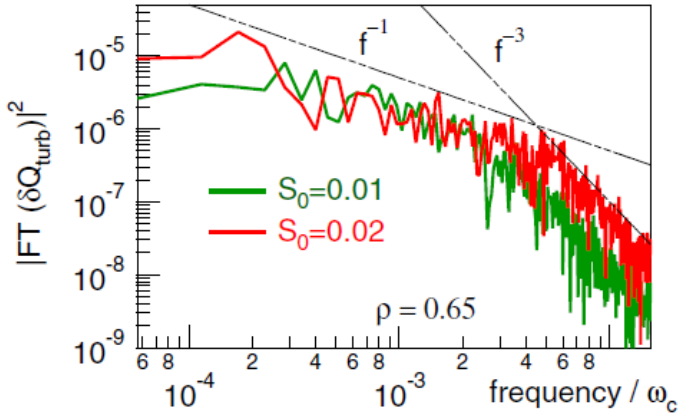
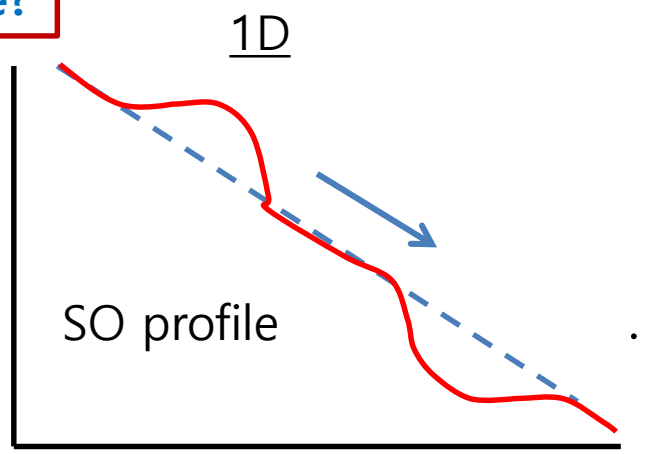


Figure 8. Frequency Fourier spectrum of the turbulent heat flux at $\rho = 0.65$ for two magnitudes of the source ($\rho_* = 1/64$). (Colour

Towards a Model: Hwa, Kardar '92; P.D., Hahm et seq. '95 → mesoscopic perturbation dynamics

→ How think about avalanche?



$\delta P \equiv P - P_{SO}$ → order parameter

→ Local excess, deficits

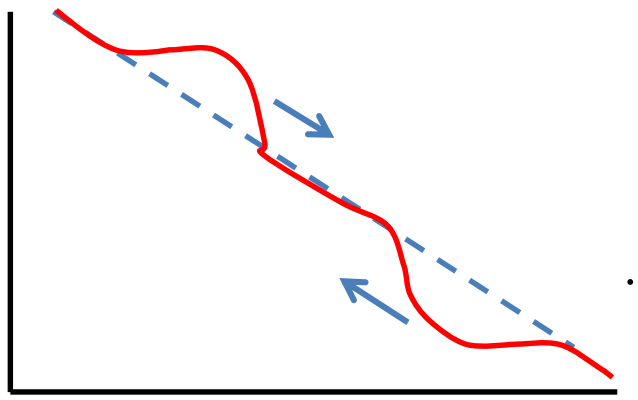
P_{SO} = self-organized profile

How do profiles evolve?

If dynamics <u>conservative;</u>

- $\partial_t \delta P + \partial_x \Gamma(\delta P) - D_0 \partial_x^2 \delta P = \tilde{S}$
- Simple hydro equation
- δP conserved to $\tilde{S}$ boundary
- How constrain $\Gamma(\delta P)$? → symmetry!, as in Ginzburg-Landau theory
- Higher dimension, $\partial_x \to \partial_\parallel$, and $D_{\perp,0}, \nabla_\perp^2$ enter

Model, cont'd



Excitations: Local excess, deficit

$\delta P > 0$ → bump, excess

→ Tends move down gradient, to right

$\delta P < 0$ → void, deficit

→ Tends move up gradient, to left

- Joint reflection symmetry principle

$x \to -x$

$\delta P \to -\delta P$

→ $\Gamma(\delta P)$ unchanged

i.e. flip pile, blob

→ void structure → rt.

- Allows significant simplification of general form of flux:

$$\Gamma(\delta P) = \sum_{m,n,q,r,\alpha} \{A_n(\delta P)^n + B_m(\partial_x \delta P)^m + D_\alpha(\partial_x^2 \delta P)^\alpha + C_{q,r}(\delta P)^q(\partial_x P)^r + \cdots\}$$

So $\Gamma(\delta P) \approx \alpha\, \delta P^2 - D\, \partial_x \delta P$; α, D set by micro-model

Model, cont'd

- So, lowest order, "smoothest" model:

$\Gamma(\delta P) \approx \alpha\, \delta P^2 - D\partial_x \delta P$; α, D coeffs, as in Ginzburg-Landau

N.B.: Heuristic correspondence

$$\alpha \delta P^2 \leftrightarrow -\chi \left(\frac{1}{P} \nabla P - \frac{1}{L_{P_{crit}}} \right) \nabla P$$

transport threshold

And have:

$$\partial_t \delta P + \partial_x (\alpha \delta P^2 - D \partial_x \delta P) = \tilde{s}$$

- Noisy Burgers equation
- Solution absent noise → shock → realizes avalanche
- Spectrum of avalanches → shock turbulence

Model, cont'd

- Avalanche Turbulence
  - Statistical understanding of nonlinear dynamics → renormalization
  - Conserved order parameter

$$\partial_x (\alpha \delta P^2) \rightarrow \nu_T k^2 \, \delta P_k$$

$$\nu_T \approx \left(\alpha^2 S_0^2 \int_{k_{min}}^{0} dk/k^4\right)^{1/3} \rightarrow (\alpha^2 S_0^2)^{1/3} k_{min}^{-1}$$

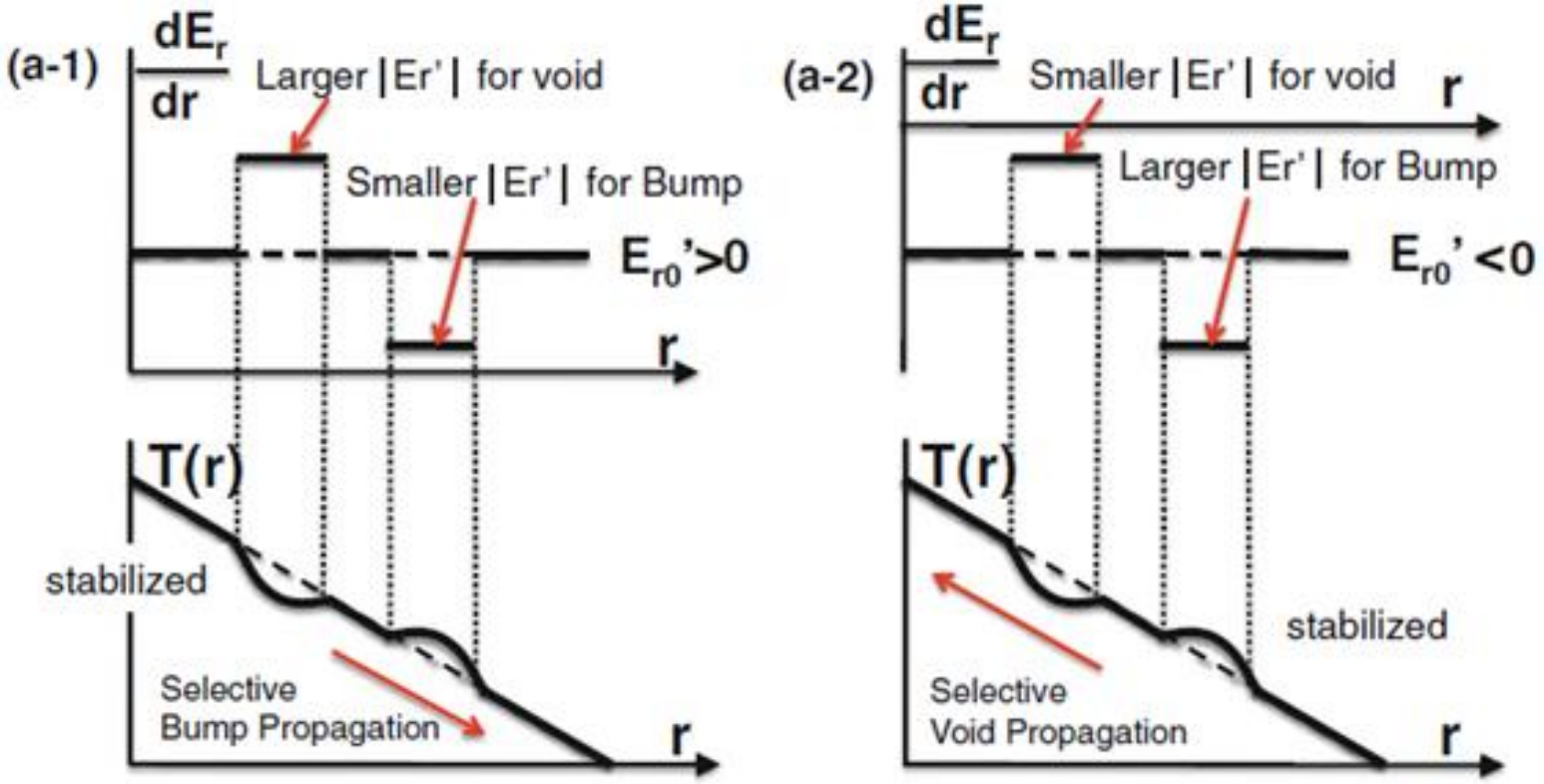
$$\sim (\alpha^2 S_0^2)(\delta l)$$

Infrared divergence due slow relaxation

  - $(\delta l)^2 \sim \nu_T \delta t$ ➔ $\boxed{\delta l \sim \delta t}$
    - H → 1 (Hurst Exponent) → memory indicator
    - 'Ballistic' scaling

- If SOC profile ≈ Marginal profile

  can link E_r' to bump/void imbalance (Idomura)



➔ Blobs dominate, $E_r' > 0$

Voids dominate, $E_r' < 0$

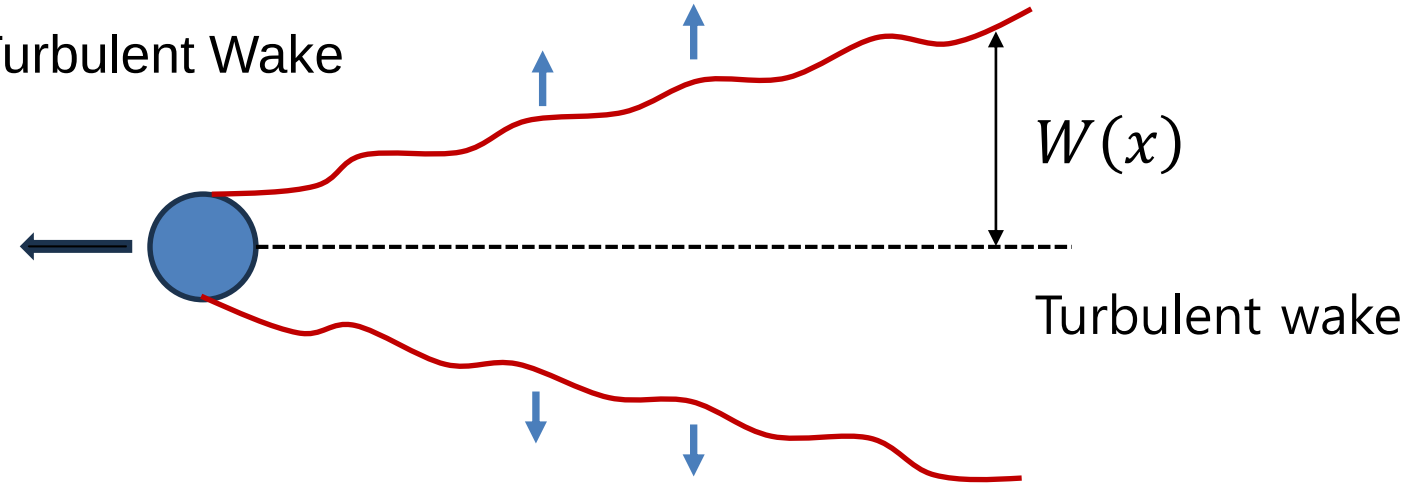
via radial force balance

Entrainment / Turbulence Spreading

- Propagating mixing front
  - Transport flux → "Avalanche"
  - Intensity flux → "Spreading"

Spreading can be beneficial !

- Classic example: Turbulent Wake



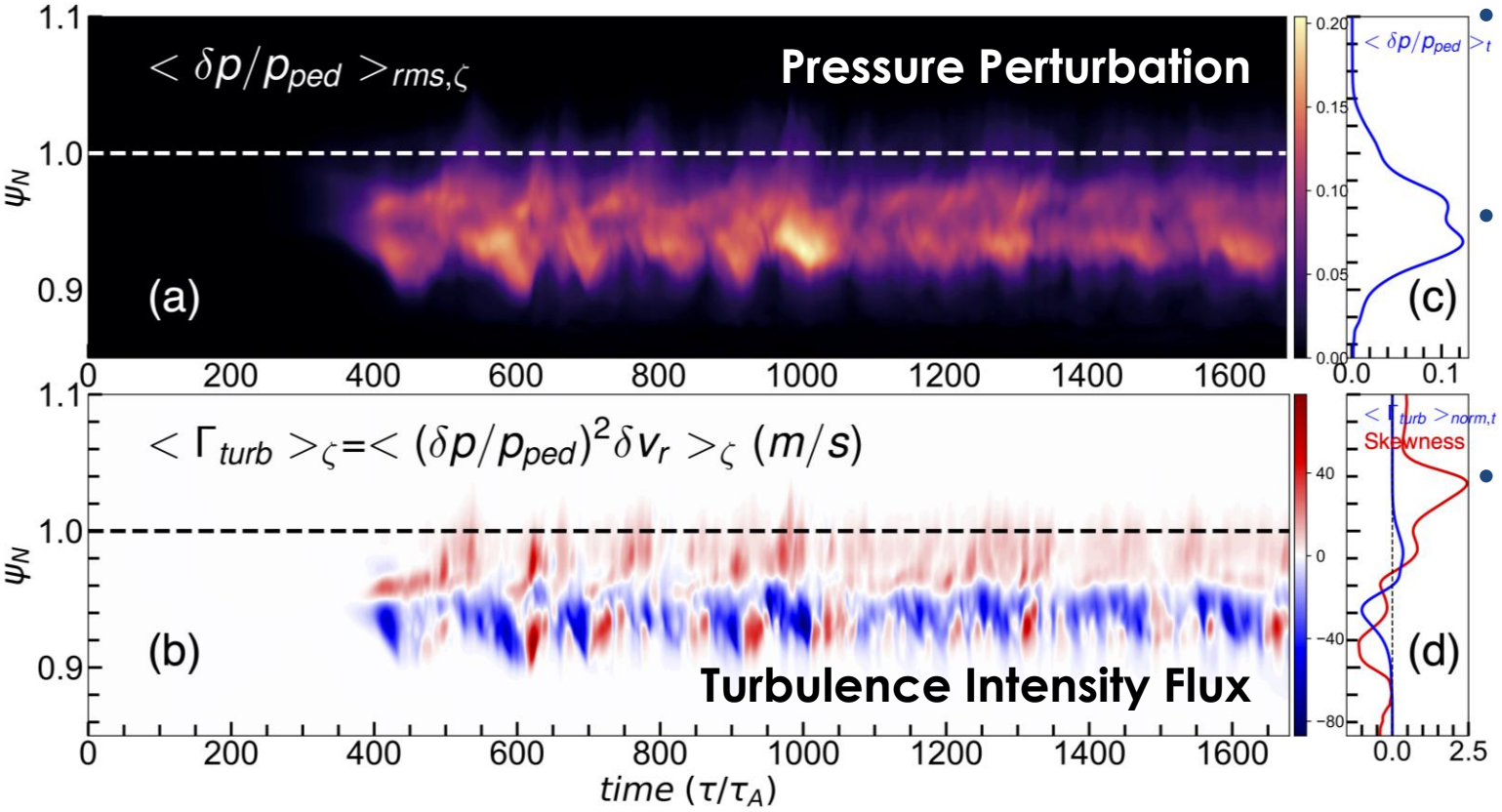
- FOM
  - Intensity flux, $\langle \tilde{V}_r \tilde{n} \tilde{n} \rangle$
  - Production Ratio, $\langle \tilde{V}_r \tilde{n} \tilde{n} \rangle \,/\, \int dr \frac{\partial \langle n \rangle}{\partial r} \langle \tilde{V}_r \tilde{n} \rangle$
  - P.R. ≥ 1 → interaction dominated dynamics

Turbulence Spreading into the SOL is Observed for the BOUT++ Modeling



Zeyu Li

BOUT++ modeling of the experimental QH profiles
Turbulence Spreading at Outboard-Midplane

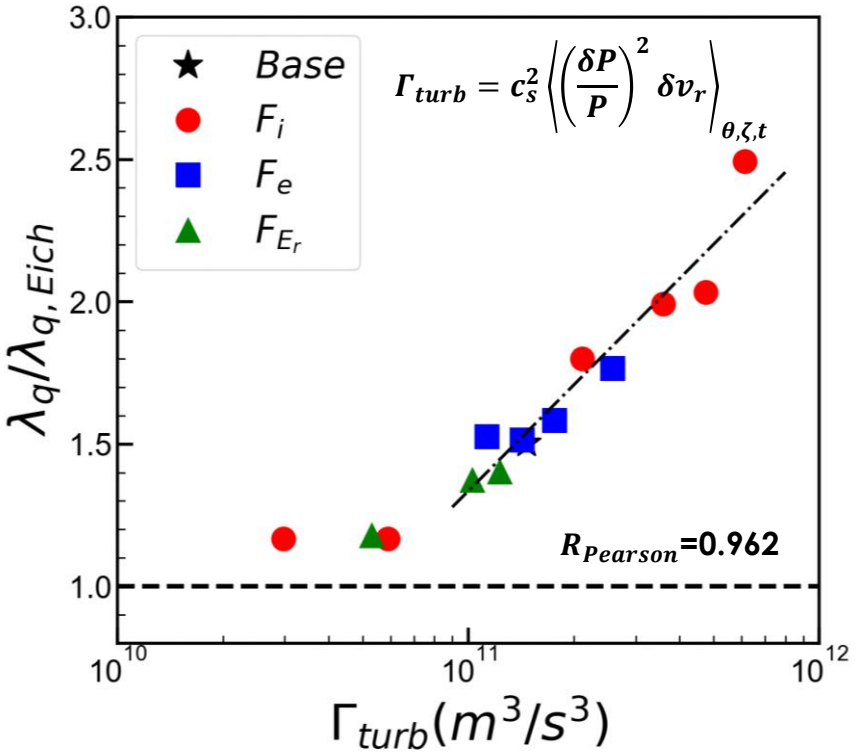


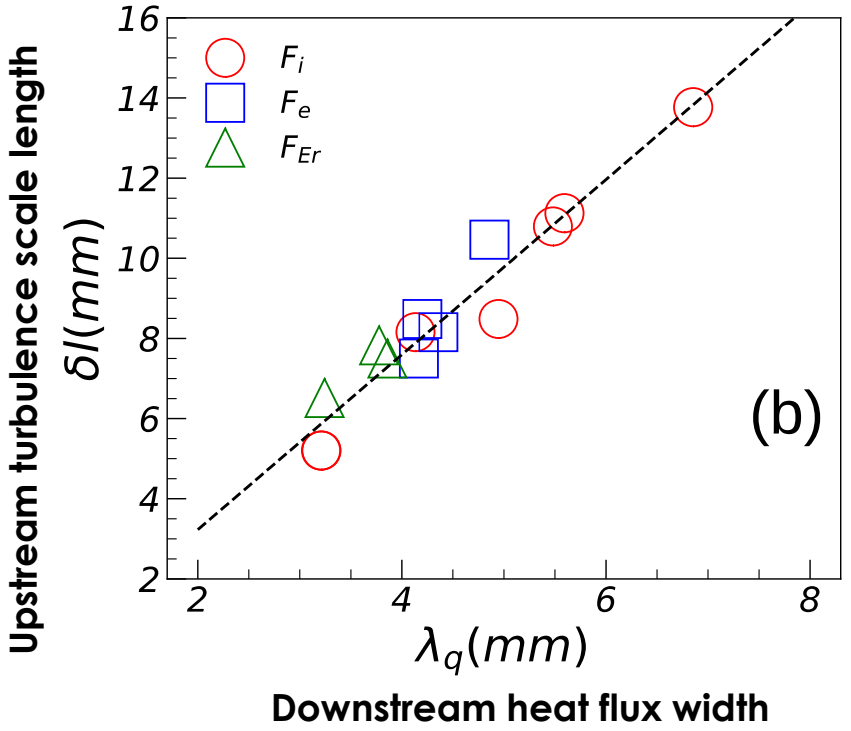
- **Turbulence is generated inside of the pedestal ~ψ_N=0.95**
- **Turbulence is spread radially and across the separatrix**
  - *Pressure perturbation in the SOL*
- **Turbulence intensity flux show the dual direction of spreading**
  - *Negative skewness inside pedestal and positive skewness into SOL*
  - *Both inward and outward spreading*
  - *Good quantity to quantify the turbulence spreading*

From Zeyu Li

Z. Li, X. Chen, P. H. Diamond et al., Commun. Phys 7, 96 (2024)

Divertor Heat Flux Width Increases with the Turbulence Intensity Flux





- **Different scans performed by BOUT++:**
  - *Ion temperature, Electron temperature, Local separatrix Er shear*
- **Turbulence intensity flux shows a threshold behavior on λ_q**
- **Turbulence scale length Shows good proportionality with divertor heat flux width**

DIII-D NATIONAL FUSION FACILITY

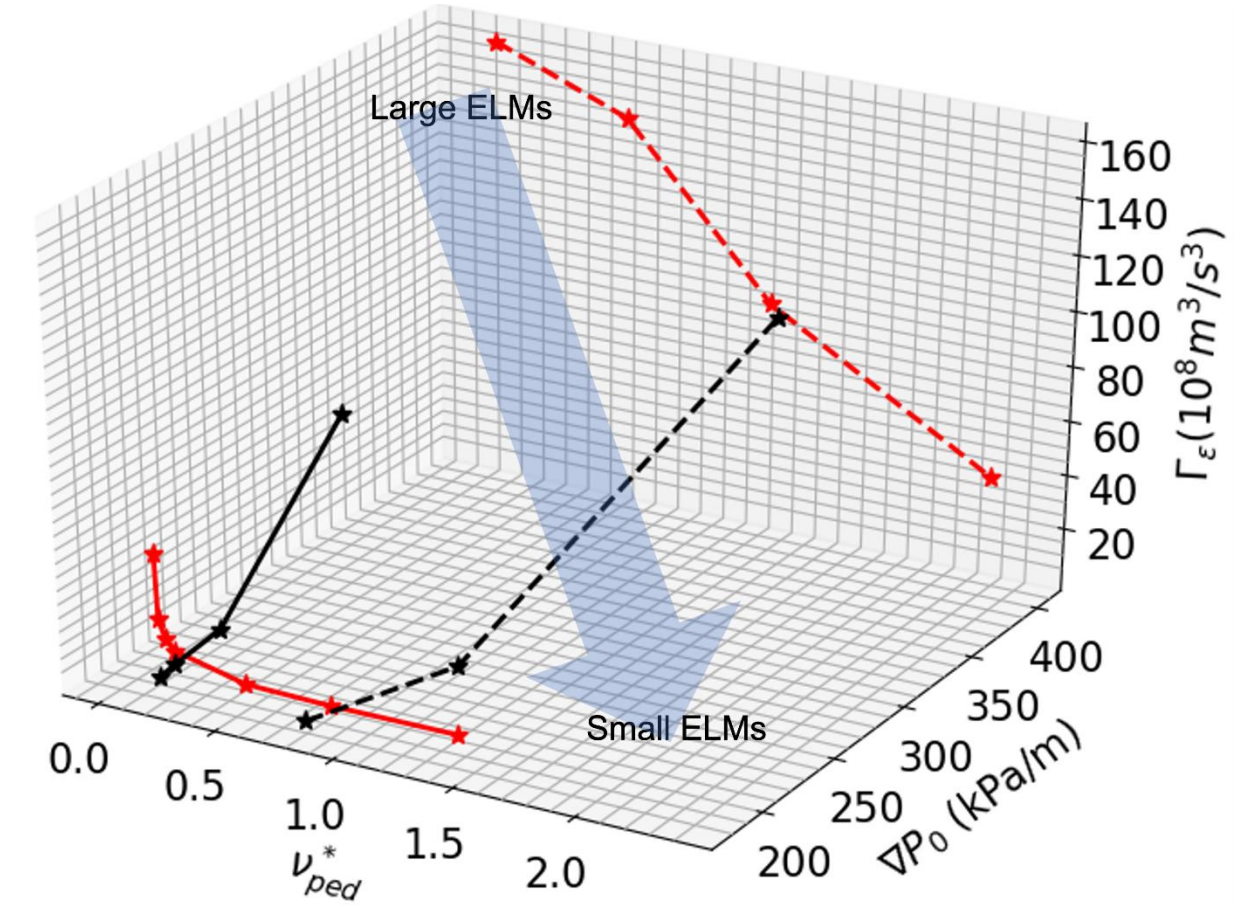
Z. Li, X. Chen, P. H. Diamond et al., Commun. Phys 7, 96 (2024)

Pedestal parameters control outward spreading (ABOUND Project)

BOUT++ six-field two-fluid turbulence simulations



Nami Li



Spreading strengthens with

Higher pedestal pressure gradient
Lower pedestal collisionality

Low-n peeling modes have a wider radial structure and larger mixing length.

Weak peeling turbulence offers broadening with small ELMs.
Strong peeling can drive large ELM heat loads.

From Nami Li, LLNL

N. Li et al., "How fluctuation intensity flux drives SOL expansion," Nucl. Fusion 63, 124005 (2023)

Recent Developments in Mesoscopic Transport and Mixing

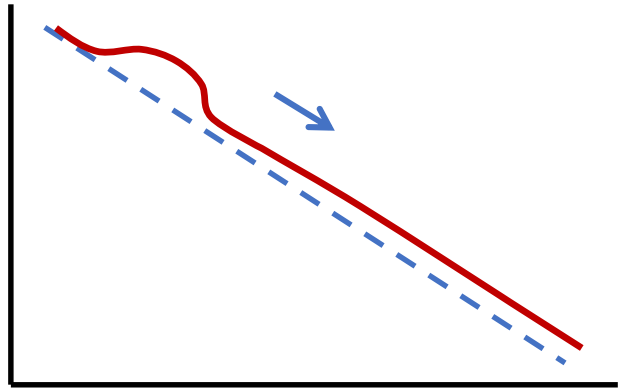
Recent Developments in Mesoscopic Transport and Mixing

- Increased awareness of “Near Marginality”
- Experimental results on MTE’s – especially KSTAR
- Flux Jamming
- Edge → Core Coupling

Ackn: G. Dif-Pradalier, Minjun Choi, Yusuke Kosuga,
Mingyun Cao, F. Kin

When will MTE's be significant?

- "Near" Marginality ?



Near marginal profiles will naturally propagate pulses over many Δr_c

➔ MTE activity

N.B.:
- Simulation indicate Ku > 1 (Gillot +)
- SPARC→ ITG dominated (N. Howard+, 2026)

- FOM for external control ←→ deviation from marginality

P/P_{ITER} Power Density

ITER $(\frac{100MW}{830m^3})$	JET $(\frac{33MW}{100m^3})$	DIII-D $(\frac{23MW}{11m^3})$
1	3.3	18

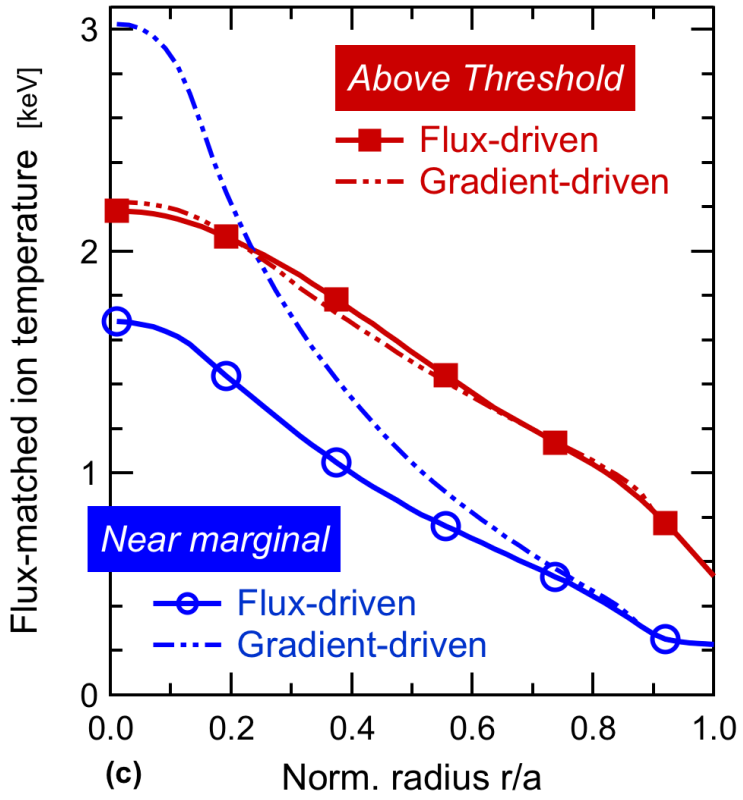
Future → near marginal …

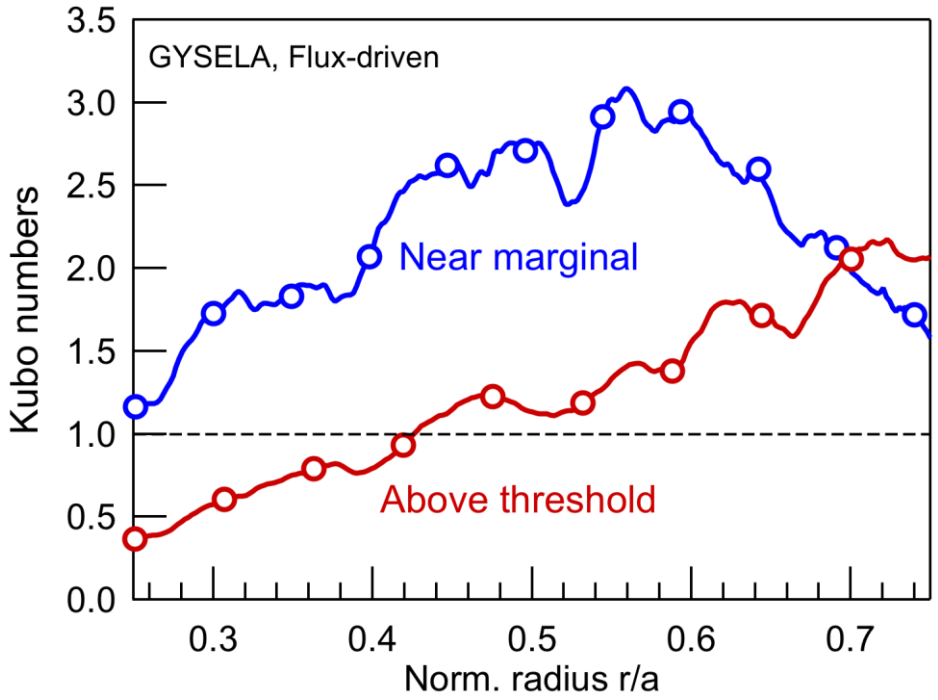
SPARC

(c.f. Dif-Pradalier)

Near marginality, flux- and gradient-driven forcing part ways

Adiabatic electrons, GYSELA: ion temperature profiles matched on heat flux, and Kubo numbers [Gillot, PPCF (2023)]





Near marginal

Matched flux:

→ different FD ≠ GD profiles

Matched profiles:

→ different FD ≠ GD fluxes

Kubo > 1 almost everywhere
→ nonlinear

Above threshold

FD ≈ GD profiles

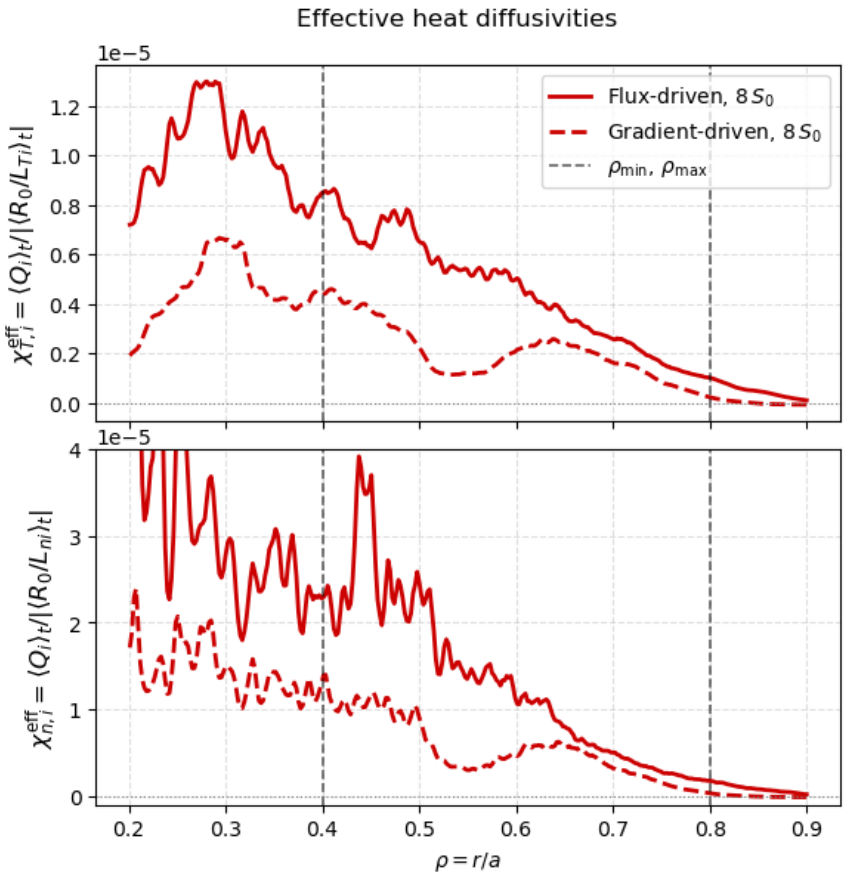
Kubo ~ 1

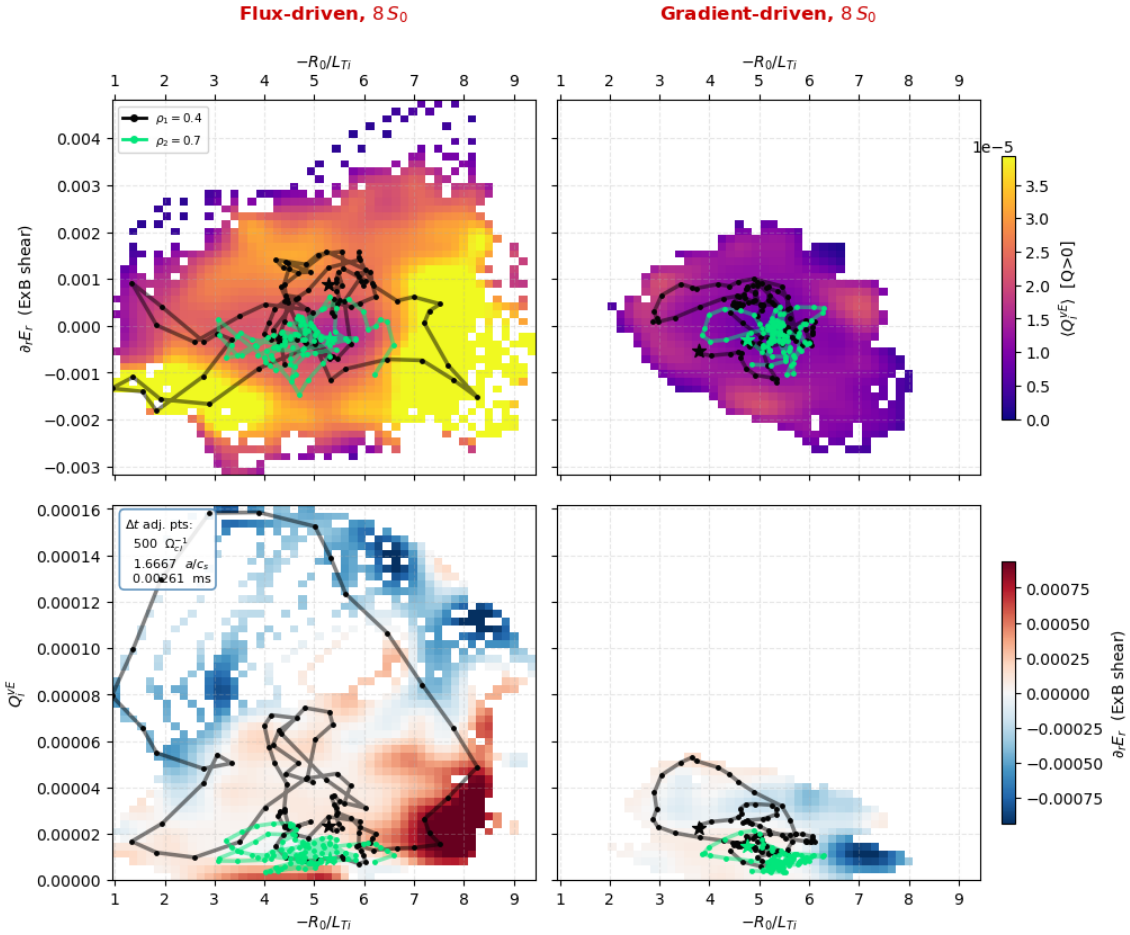
→ Near marginality, **how turbulence is forced matters**:

- matching the heat fluxes matches neither the profiles nor the turbulence regime
- matching the profiles → same issue

Kinetic electrons: same mean gradients, different dynamics

Trapped kinetic electrons, GYSELA, same statistical gradients → **≠ flows, ≠ transport, ≠ dynamics**





400 %
variation of R/L_{Ti} within 30 µs

< 10 %
of time where most transport events occur

× 3
zonal-flow production rate, in flux-driven

→ Factor **× 2** discrepancy in heat & particule diffusivities, with same gradients
→ Flux-driven turbulence explores a much **wider state space**
- transport is carried by rare excursions ; shear also generated in sporadic bursts

[Dif-Pradalier, EPS 2026 & in preparation]

Flux- vs gradient-driven: opposite energy partitioning

Energy shares in zonal flows, turbulence and profiles vs. ion drive R_0/L_{Ti}

Flux-driven

- more structures: zonal flows and fields
- longer lasting

low R/L_T → zonal flows dominate

larger R/L_T → zonal fields dominate

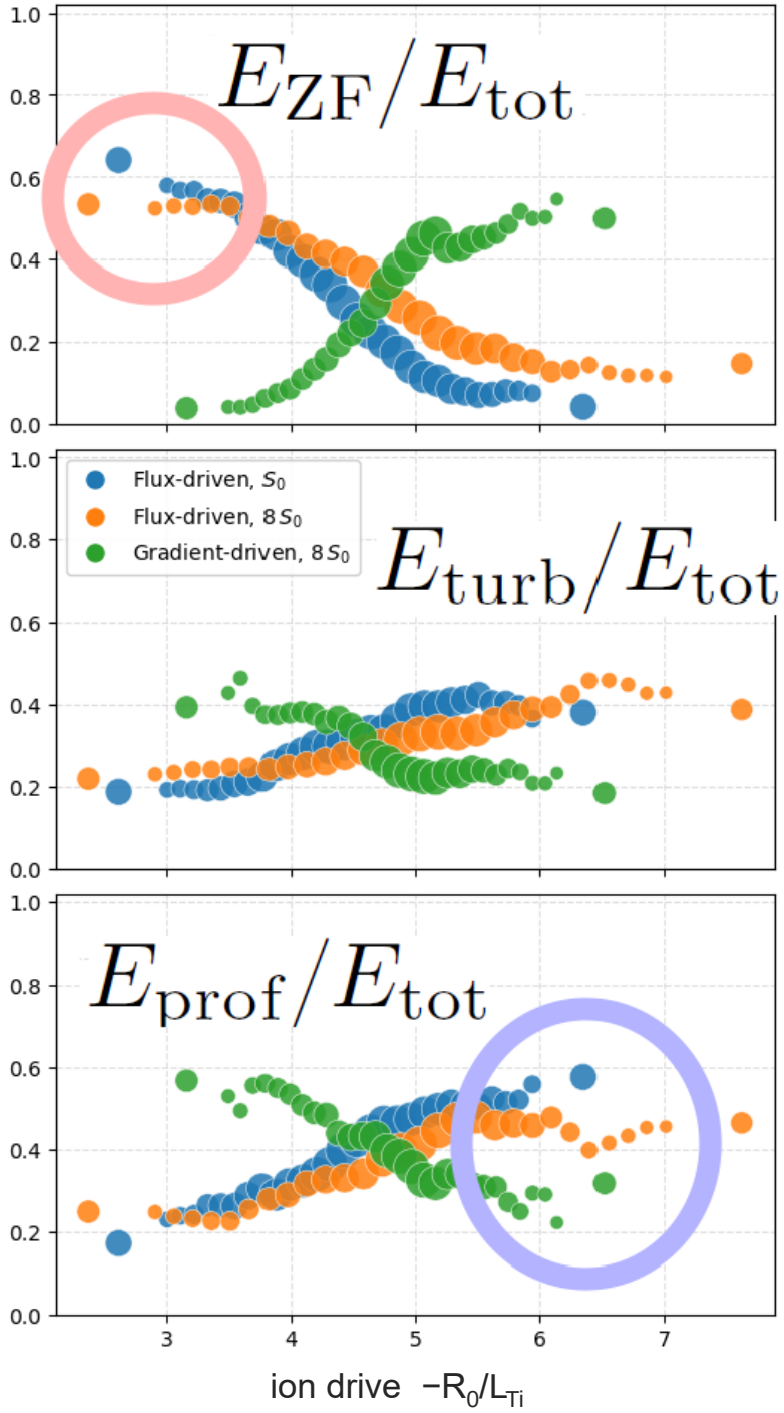
[Dif-Pradalier, EPS 2026 & in preparation]

Gradient-driven: opposite behaviour (!)

ZF share grows with drive, profile share drops

Trapped kinetic electrons, GYSELA, same statistical gradients

→ The forcing scheme **reverses where energy goes**: gradient-driven is not a proxy for flux-driven

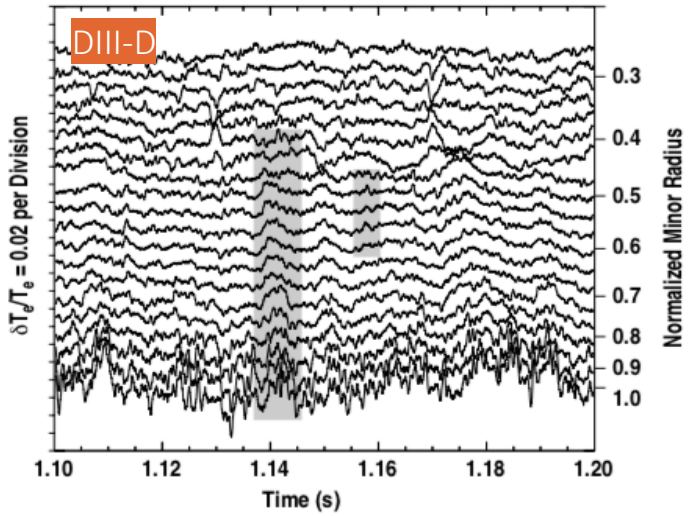


Previous studies on mesoscopic transport events (avalanches)

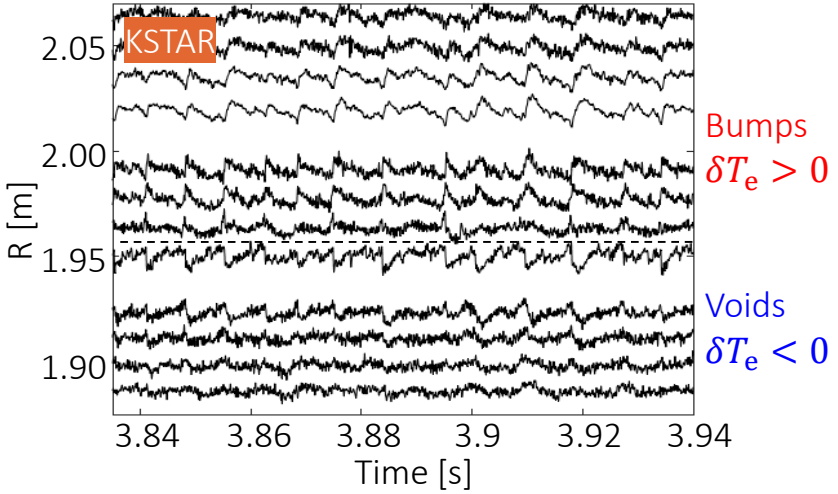


Minjun Choi

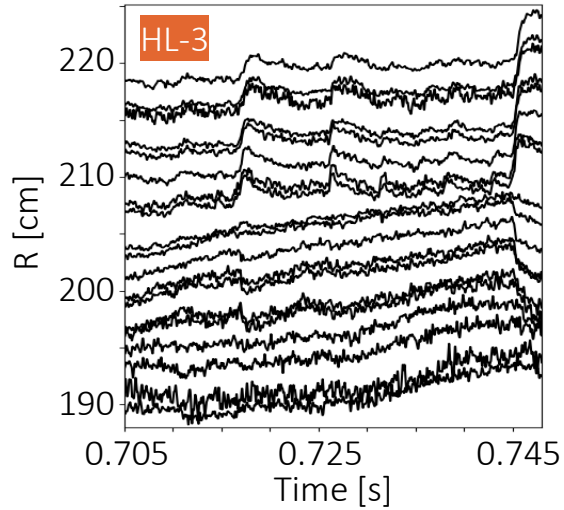
- Near ballistic propagation of heat flux



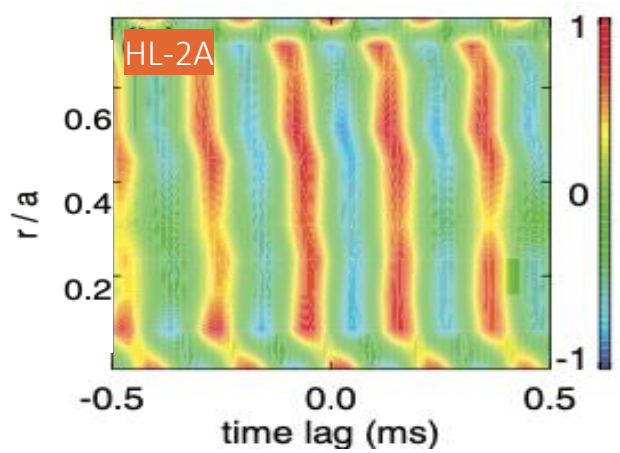
P. A. Politzer, Phys. Rev. Lett. 84 (2000) 1192



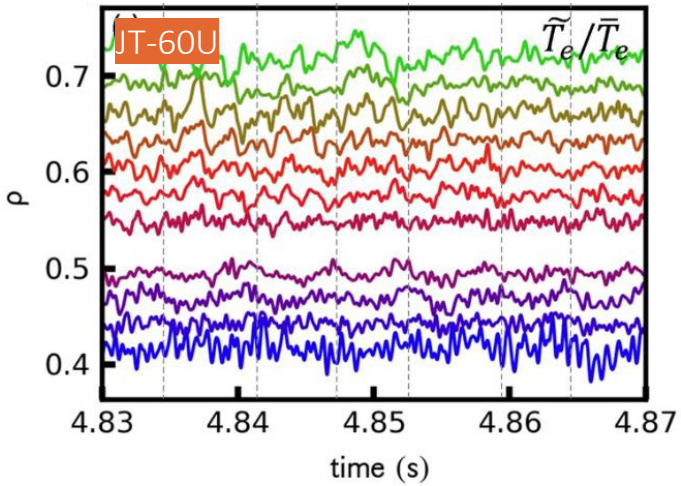
M. J. Choi+, Nucl. Fusion 59 (2019) 086027



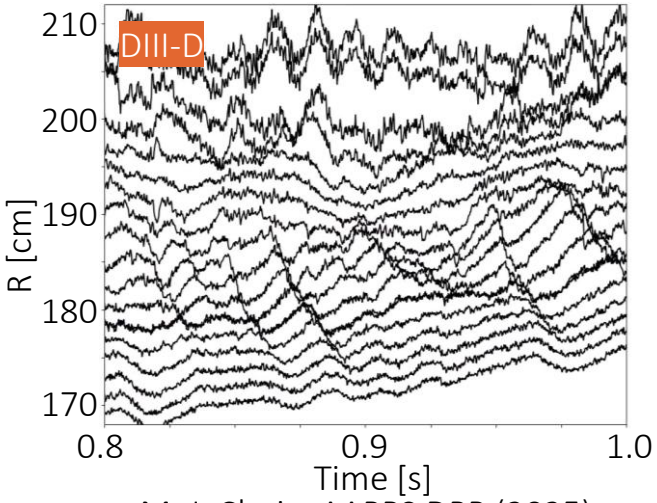
M. J. Choi+, AAPPS DPP (2025)



O. Pan+, Nucl. Fusion 55 (2015) 113010



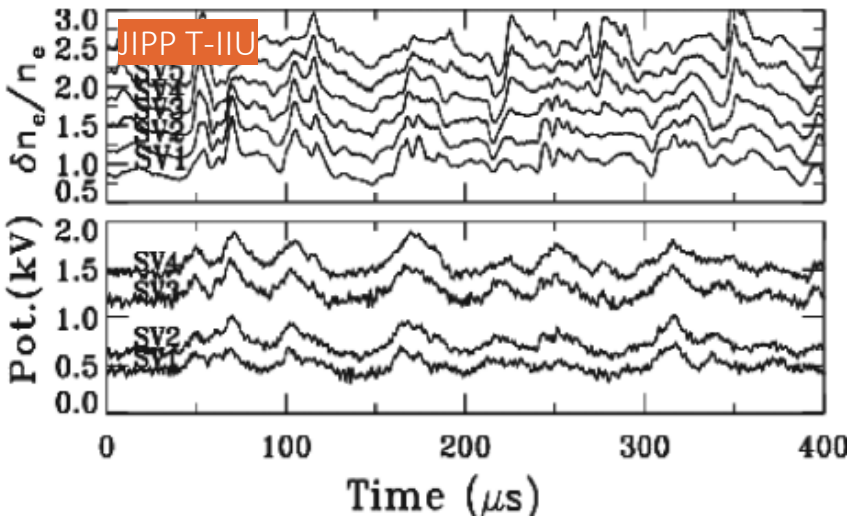
F. Kin+, Sci Rep 13 (2023) 19748



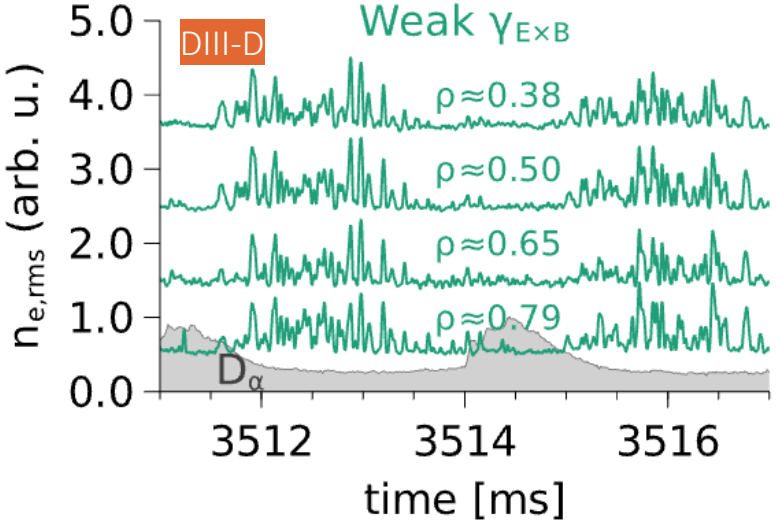
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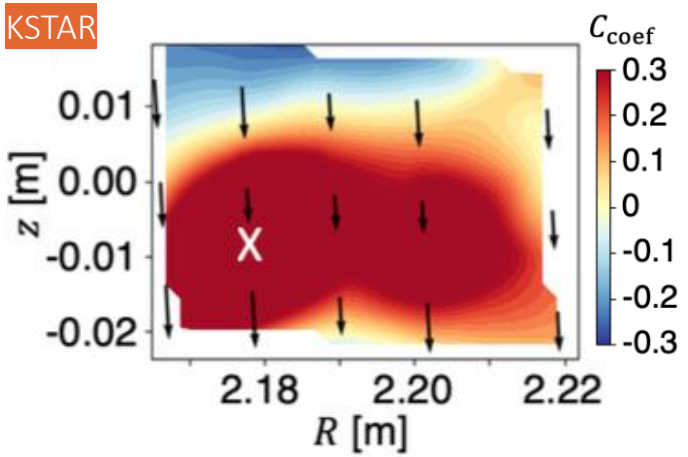
- Long range spatial correlation in potential/density fluctuations



Y. Hamada+, Phys. Rev. Lett. 96 (2006) 115003



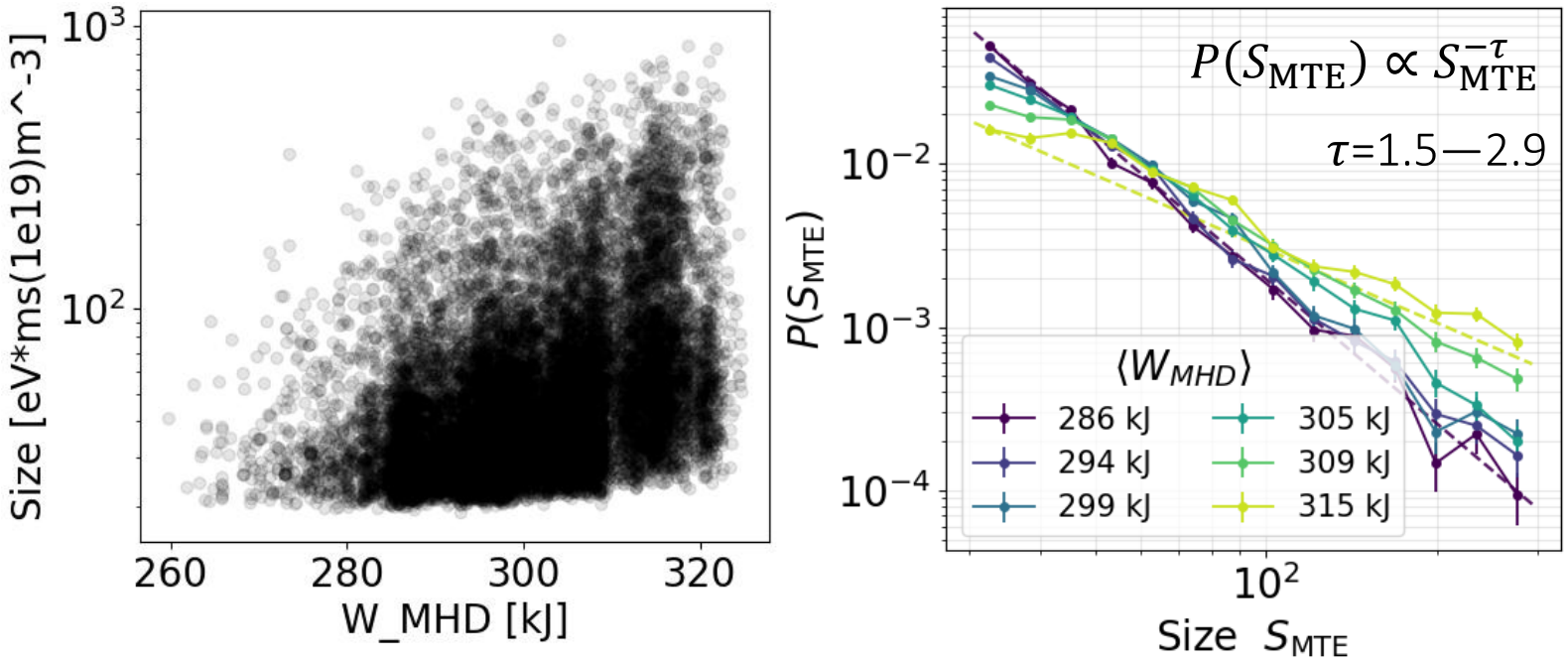
R. Hong+, Phys. Plasmas 30 (2023) 072512



M. J. Choi+, Plasma Phys. Control. Fusion 66 (2024) 065013

Distributions of mesoscopic transport event (MTE) characteristics

- Size distributions for different stored energy groups
  - The "size ($S_{MTE} \approx \Delta E$)" distribution is affected by "the plasma stored energy (W_{MHD})"
  - Event sizes are widely scattered (power-law) despite nearly identical macroscopic state variable
    - $\delta S_{\mathrm{MTE}}/\langle S_{\mathrm{MTE}}\rangle \sim 0.7$ *for all* W_{MHD} *groups*



MTE is too variable to be adequately captured by the transport frameworks relying on the scale separation

Primer on Jams

Y. Kosuga



- Kinematic waves (Lighthill & Whitham) – Ideal

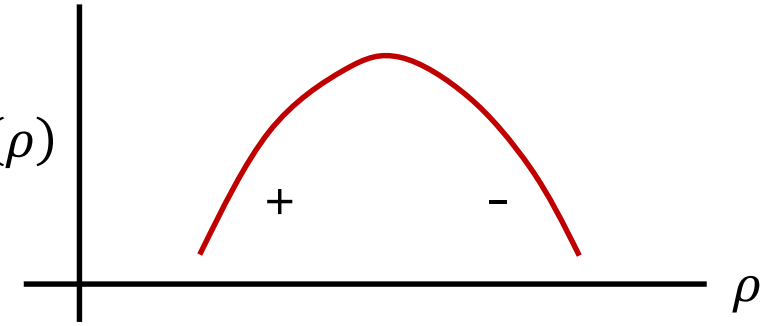
Mean field Driver anticipation

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}\left(\rho V(\rho)\right) - D\frac{\partial^2 \rho}{\partial x^2} = 0$$

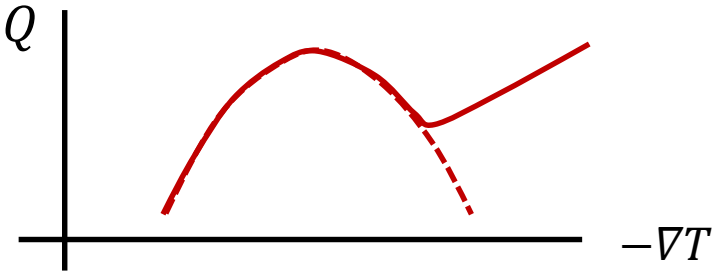
$Q(\rho)$

$\rho =$ density, conserved O.P.

- Key: Flux $Q(\rho)$
- $V > 0$: $c(\rho)$ perturbation speed
  - $\frac{dQ}{d\rho} > 0$ → $c(\rho) > 0$ → shock
  - $\frac{dQ}{d\rho} < 0$ → $c(\rho) < 0$ → jam (backward shock)



- Analogue: S-curve



V → $C(\rho) > 0$ → shock

V → $C(\rho) < 0$ → jam

Primer on Jams, cont'd

- Beyond mean field theory (dissipation) Derive from CA rules

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho V) = 0$$

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} = -\frac{1}{\tau_R}\left(V - V(\rho) + \frac{D}{\rho}\partial_x \rho\right)$$

Driver reaction time

Mean field flow

- V relaxes to $V(\rho)$ on τ_R
- BUT: $V \neq V(\rho)$
- System supports <u>clustering instabililties</u>

i.e. for $D_{eff} = [D - \tau_R(V_0 - c_0)^2] < 0$

Negative diffusion (n.b. Q′ irrelevant)

N.B. Anticipation vs Reaction – ala' swarms

How near is “near” ?

For Jam:

$$\frac{c_0^2}{\chi_{neo}} > \frac{1}{\tau_0}\left(R/L_T - R/L_{T_c}\right)^{\mu} \qquad c_0 \sim \alpha\delta T$$

i.e. Avalanche speed must exceed speed of diffusion in a relaxation time

- Weak residual / neoclassical diffusion +

  Larger avalanche speed favors larger τ_R and jamming

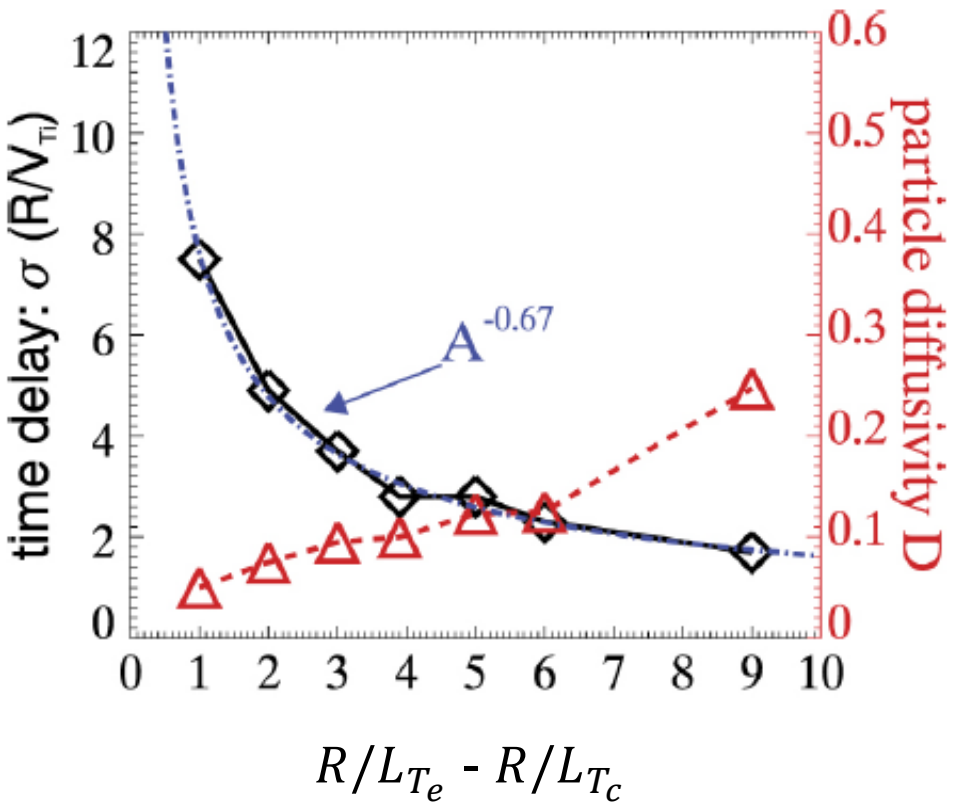
  ←→ Power and neoclassical scaling trends testable

  i.e. $\alpha\delta T$ – modulation amplitude

  χ_{neo} - predictable scalings, especially I_p

- Form suggests general utility…

How near is “near” ?



GKPSP (δf) simulation by Lei Qi +

For Experimentalists

- Determine μ – critical exponents

  $\frac{\tau_0}{\tau_c} \sim \left[R/L_T - R/L_{T_{crit}}\right]^{\mu}$

  Power, Torque scan?



- Probe c_0^2 vs $(\chi_{neo}/\tau_0)\left[R/L_T - R/L_{T_{crit}}\right]^{\mu}$

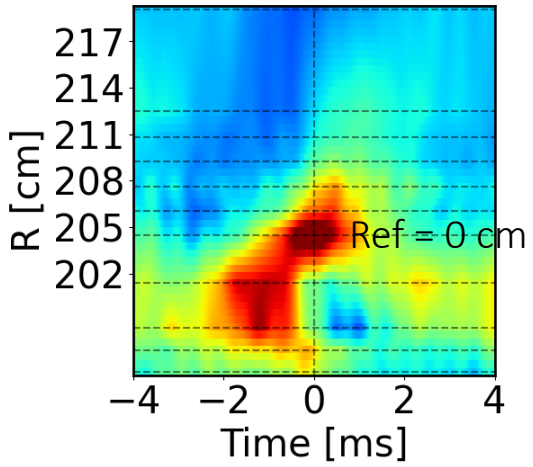
  Condition for corrugation

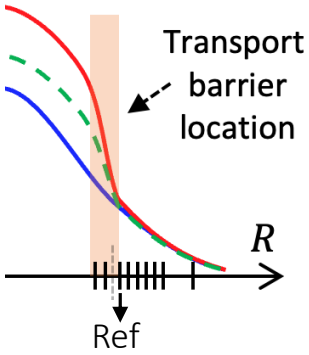
- Q vs $Q(\delta T)$, Q_{QL} via transients

- (Computation) Flux driven simulation + AI → Fit form $Q_T(\delta T)$

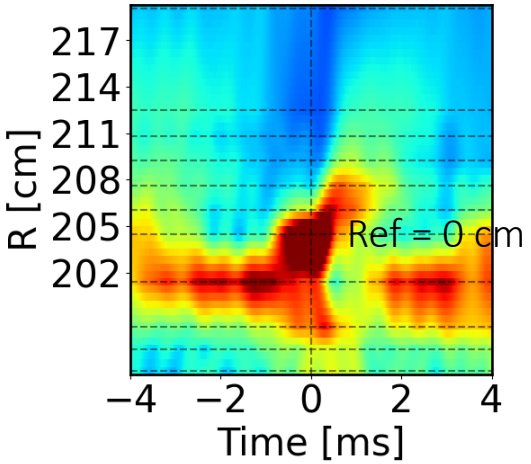
Flux jamming observed for large amplitude events

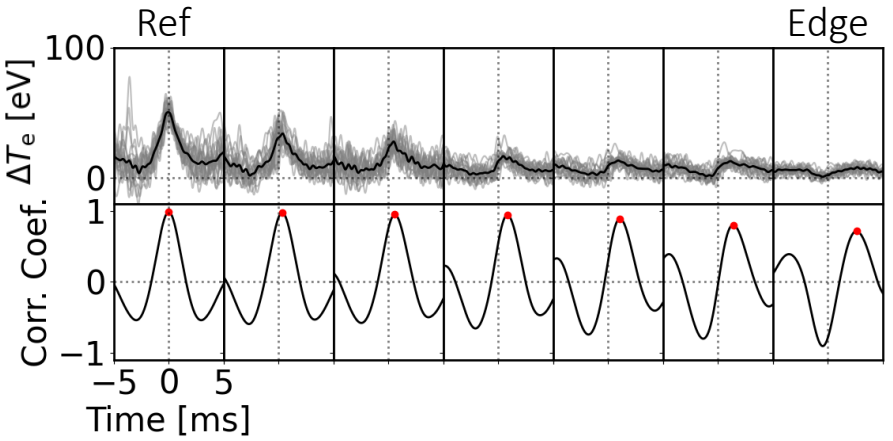
Smaller amplitude event

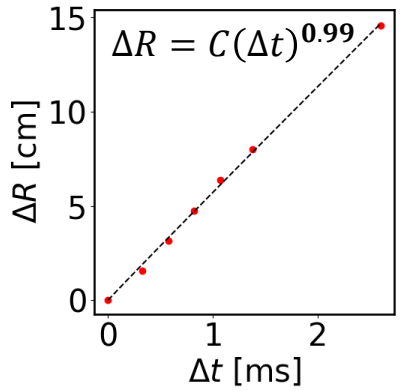


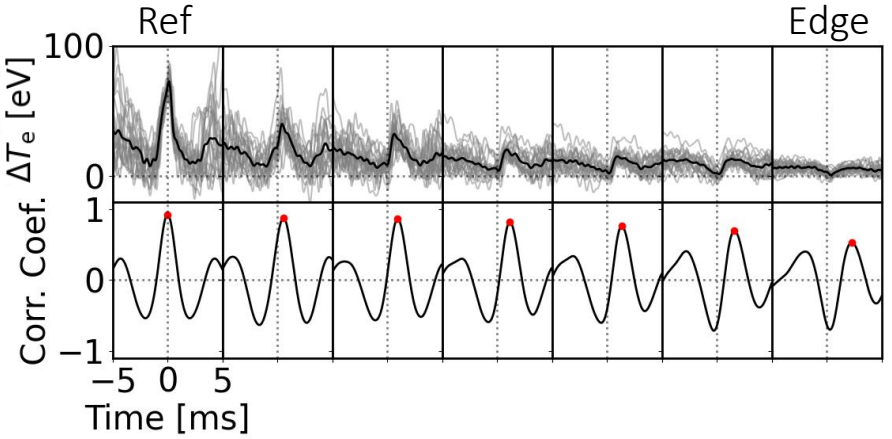


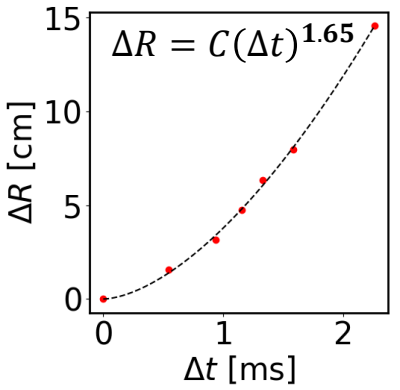
Larger amplitude event











Temporary flux jamming[1,2]? Jamming induced by an amplitude threshold, or amplification through jamming, or both?

[1] Y. Kosuga+, Phys. Rev. Lett. 110 (2013) 105002; [2] L. Qi+, Nucl. Fusion 62 (2022) 126025; [3] M. J. Choi+, Plasma Phys. Control. Fusion 66 (2024) 065013

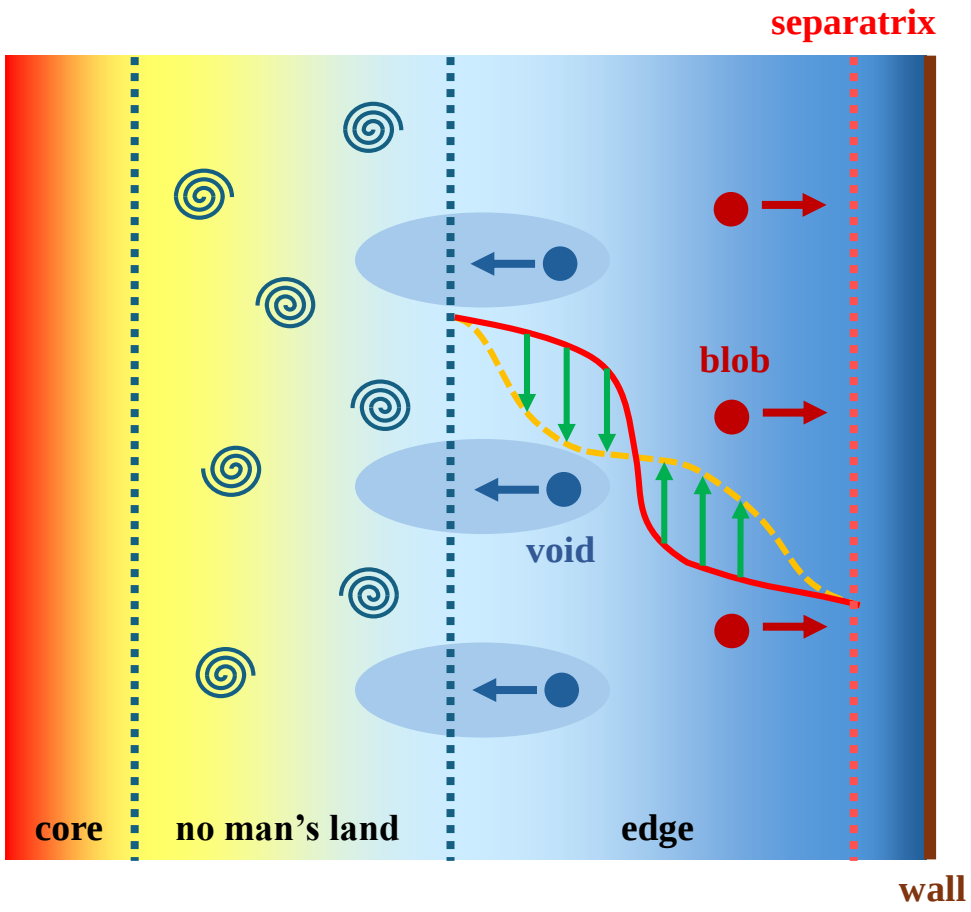
Physics of Edge-Core Coupling by Inward Turbulence Propagation

Mingyun Cao* and P.H. Diamond†

Physical Review Letters 134.23 (2025): 235101. DOI: https://doi.org/10.1103/PhysRevLett.134.235101

Mingyun Cao





- **Results:**
  - **Physical picture:** inward-moving voids generated from edge gradient relaxation events (GREs) excite drift wave turbulence and self-regulated flow in the edge-core coupling region (no man's land).
  - **Quantitative predictions:**
    1. Scaling of the no man's land width.
    2. Shearing rate of void-driven zonal flow.
    3. Scaling of void lifetime.

    } Consistent with experiments
- **Significance:**
  - First serious theoretical model of the inward turbulence spreading that addresses the shortfall in GK simulations.
  - First calculation of turbulence intensity driven by coherent structures.
- **Implications:**
  - Simulation practice: Need for flux-driven simulations, since no GRE in profile-driven simulations.
  - Experimental test: Correlation between GRE characteristics and turbulence intensity in no man's land.

How in blazes can zonal shear and MTE's coexist in the same plasma?

ExB Staircase

Staircases, Layering and Inhomogeneous Mixing

Reviews:

- “Anti-diffusive transport and layering”

  Phil. Trans Roy Soc. A 384, 2026 (just out!)

- Newton Inst. ADI 2024

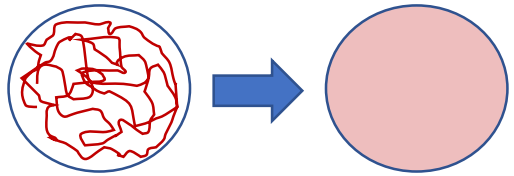
  newton.ac.uk/event/adi/

- KITP staircase 21, 2021

  kitp.ucsb.edu/activities/staircase21

Dynamics in Real Space – What of the Configuration?

- Conventional Wisdom → Homogenization ?!
  - Prandtl, Batchelor, Rhines: (2D fluid)
  - PV homogenized: Shear + Diffusion



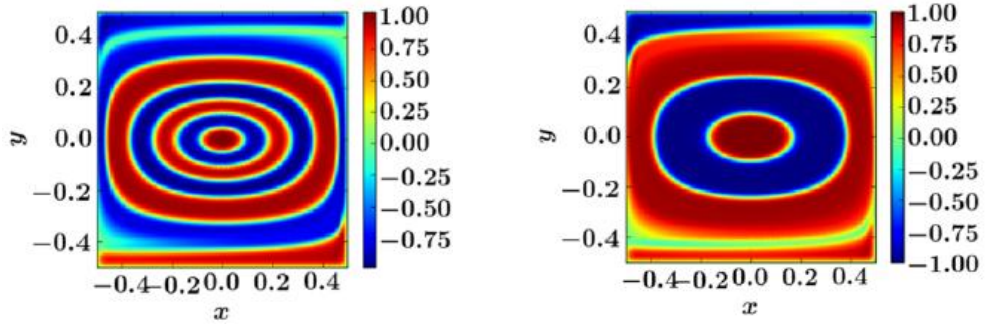
$\nabla q \to 0$

2 scales: $a,\ a/Re^{1/3}$
BL → "emergent"

  - Mechanism: - Shear dispersion $\tau \sim \tau_{rot}\,(Re)^{1/3}$ → $\tau_{rot}\,Re$

    - '<u>PV Mixing</u>'

  - Introduce Bi-stable Mixing → Layers



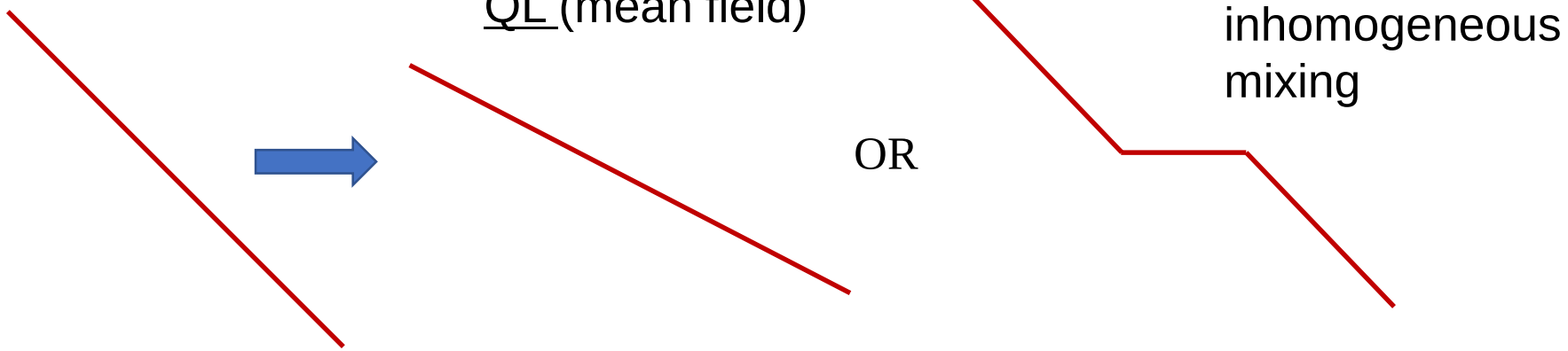
coarsens

  - Cahn-Hilliard + Eddy Flow ←→ bistability

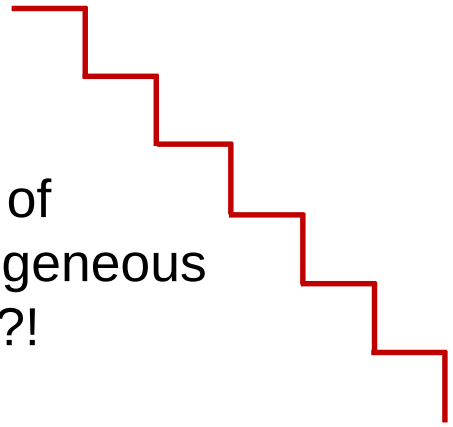
(spinodal decomposition) → target pattern

(Fan, P.D., Chacon, PRE Rap. Com. '17)

Fate of Gradient?

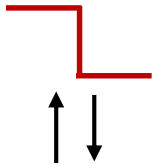


OR - ‘staircase’



pattern of
inhomogeneous
mixing ?!

- layers, steps, corrugations
- shear layers ←→ relation to corrugations?



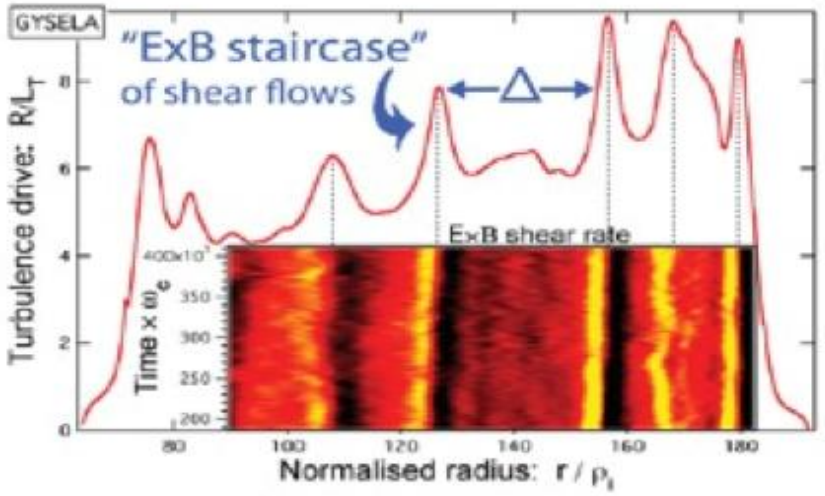
?

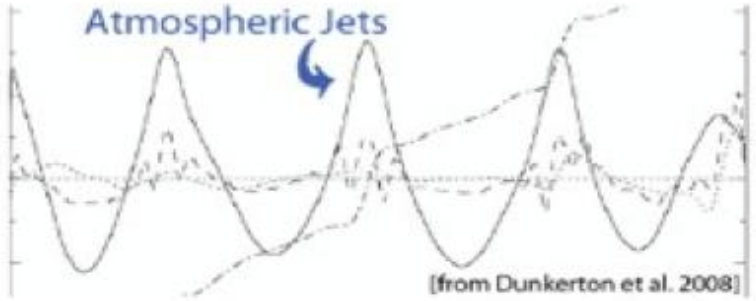
Zonal shears at corrugations ?

Spatial Structure: ExB staircase formation (after PV staircase Dritschel + McIntyre)

- ExB flows often observed to self-organize structured pattern in magnetized plasmas
- `ExB staircase' is observed to form

(G. Dif-Pradalier, P.D. et al. Phys. Rev. E. '10)





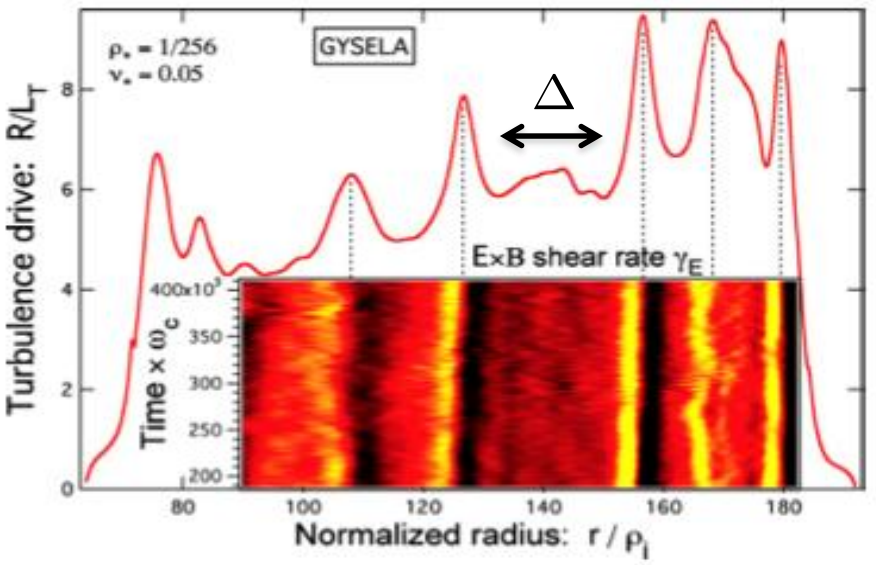
also: GK5D, Kyoto-Dalian-SWIP group, gKPSP, ... several GF codes

- flux driven, full f simulation
- Quasi-regular pattern of shear layers and profile corrugations (steps)
- Region of the extent $\Delta \gg \Delta_c$ interspersed by temp. corrugation/ExB jets

  → ExB staircases
- so-named after the analogy to PV staircases and atmospheric jets
- Step spacing → avalanche distribution outer-scale
- scale selection problem

ExB Staircase, cont'd

- Important feature: co-existence of shear flows and zones strong mixing



- Seem mutually exclusive ?

  → strong ExB shear prohibits transport

  → mesoscale scattering smooths out corrugations

- Can co-exist by separating regions into:

  1. mixing zones of the size $\Delta \gg \Delta_c$

  2. localized strong corrugations + jets

- How understand the formation of ExB staircase??

  - What is process of self-organization linking avalanche scale to ExB step scale?

  i.e. how explain the emergence of the step scale ?

- Some similarity to phase ordering in fluids – spinodal decomposition
  → bistability as key

How do Staircase Form?

←→ What can be learned from reduced models?

‘Bistable’ Mixing – A Simple Mechanism

- Mean field model with 2 mixing scales (Ashourvan, P.D. 2018)
- So, for H-W: PE, $\langle n \rangle$, $\langle \nabla^2 \phi \rangle$
- Density: $\frac{\partial}{\partial t}\langle n \rangle = \frac{\partial}{\partial x}\left(D_n \frac{\partial \langle n \rangle}{\partial x} \right) + D_c \frac{\partial^2 \langle n \rangle}{\partial x^2}$

simple mixing + 2 length scale
→ staircase

- Vorticity: $\frac{\partial}{\partial t}\langle u \rangle = \frac{\partial}{\partial x}\left[(D_n - \chi)\frac{\partial \langle n \rangle}{\partial x} \right] + \chi \frac{\partial^2 \langle u \rangle}{\partial x^2} + \mu_c \frac{\partial^2 \langle u \rangle}{\partial x^2},$
- Potential Enstrophy(intensity): $\frac{\partial}{\partial t}\varepsilon = \frac{\partial}{\partial x}\left(D_\varepsilon \frac{\partial \varepsilon}{\partial x} \right) + \chi \left[\frac{\partial \langle n - u \rangle}{\partial x} \right]^2 - \varepsilon_c^{-1/2}\varepsilon^{3/2} + \gamma_\varepsilon \varepsilon.$

→ includes crude turbulence spreading model

- $D, \chi \sim \tilde{V} l_{mix}$

$$l_{\mathrm{mix}} = \frac{l_0}{(1 + l_0^2 [\partial_x (n - u)]^2 / \varepsilon)^{\kappa/2}},$$

l_0 → excitation scale (drive)
l_R → Rhines scale (emergent)
ω_{MM} vs $\Delta\omega$ - can be generalized

- Scale cross-over → ‘transport bifurcation’

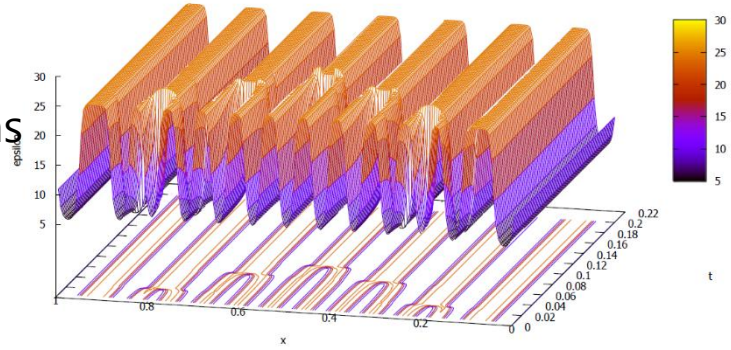
two scales!

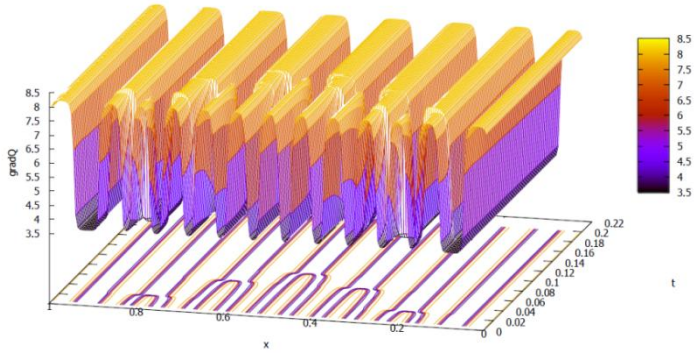
- $l_0/l_R < 1$ → strong mixing (eddys)
- $l_0/l_R > 1$ → weak mixing (waves) → gradient sharpening feedback
- Is this ~ equivalent to ‘two-fluid’ mixing length model ala’ Ed Spiegel ?

Simplest Model – Formation and Merger (QG-HM)

Energy

fluctuations



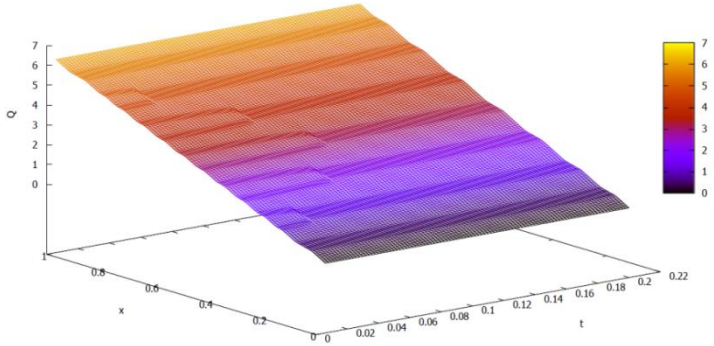


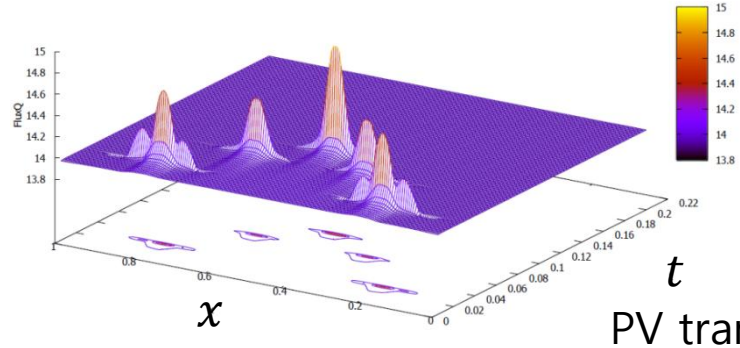
∇q

q

→

mergers





x t

PV transport

- ϵ
- $\partial q/\partial y$

} top

- q
- Γ_q

} bottom

- PV mixing events

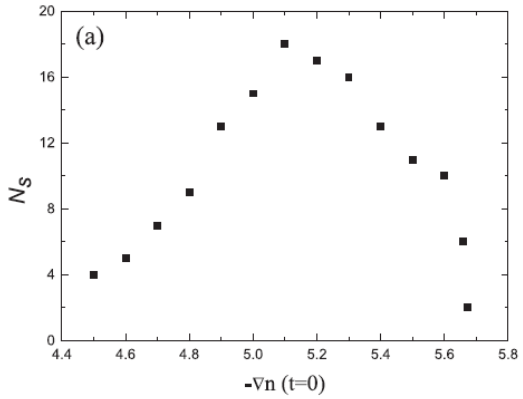
Note later staircase mergers induce strong PV flux bursts!

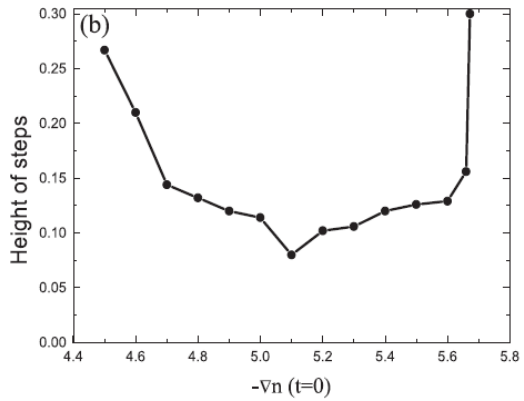
(Malkov, P.D.; PR Fluids 2018)

Staircase Structure?

- Number of steps? - domain L → Scale Selection ?!
- Scan # steps vs ∇n at t=0 (n.b. mean gradient)
  - a maximum # steps (and minimal step size) vs ∇n
  - rise: increase in free energy as $\nabla n \uparrow$
  - drop: diffusive dissipation limits N_s
- Height of steps?
  - minimal height at maximal #

➔ system has a ∇n 'sweet spot' for many, small steps and zonal layers

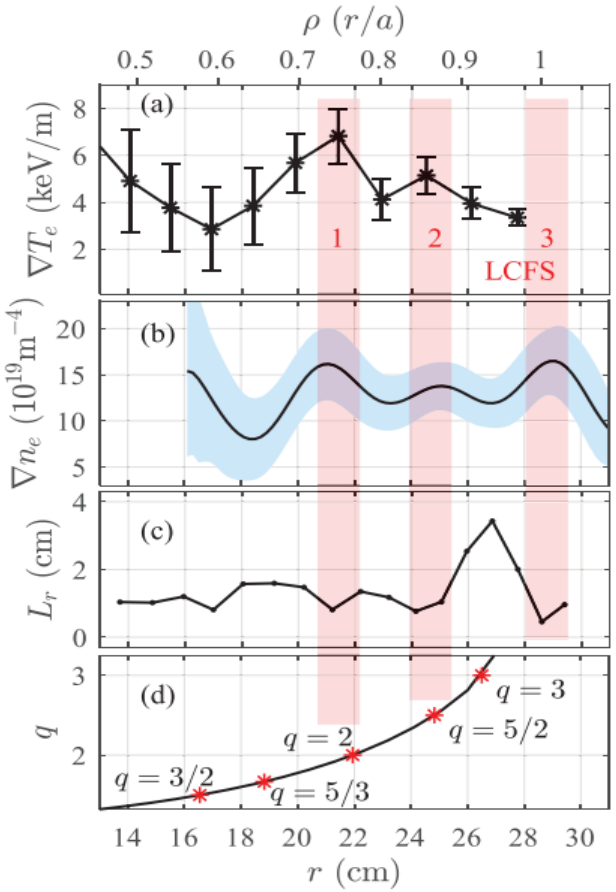




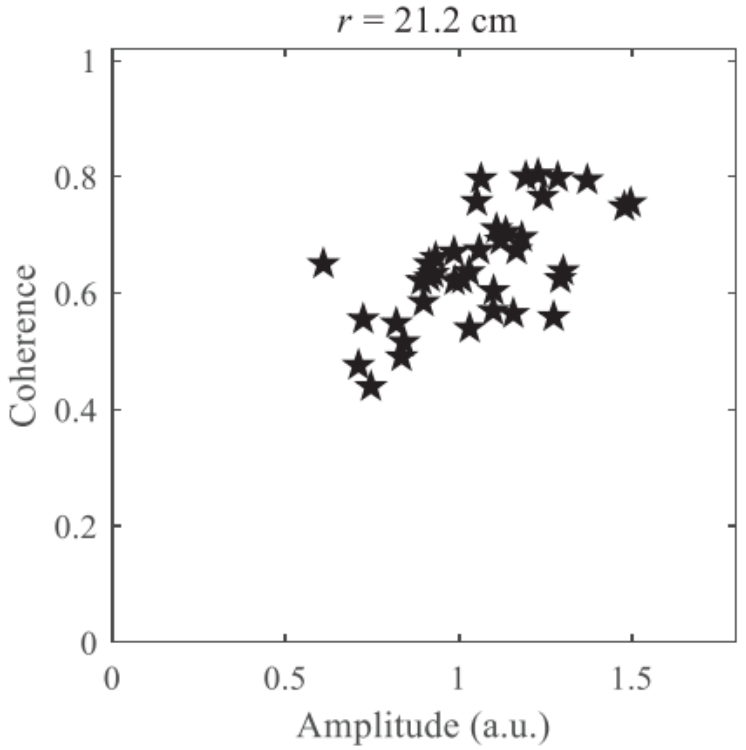
W.X. Guo + (2019)

Staircases in Experiment

- Wenbin Liu, Rui Ke, George McKee, Zheng Yan, Kairui Fang, Zengchen Yang, Zhe Gao, Yi Tan, G. Tynan, PoP 2021
- BES studies on HL-2A

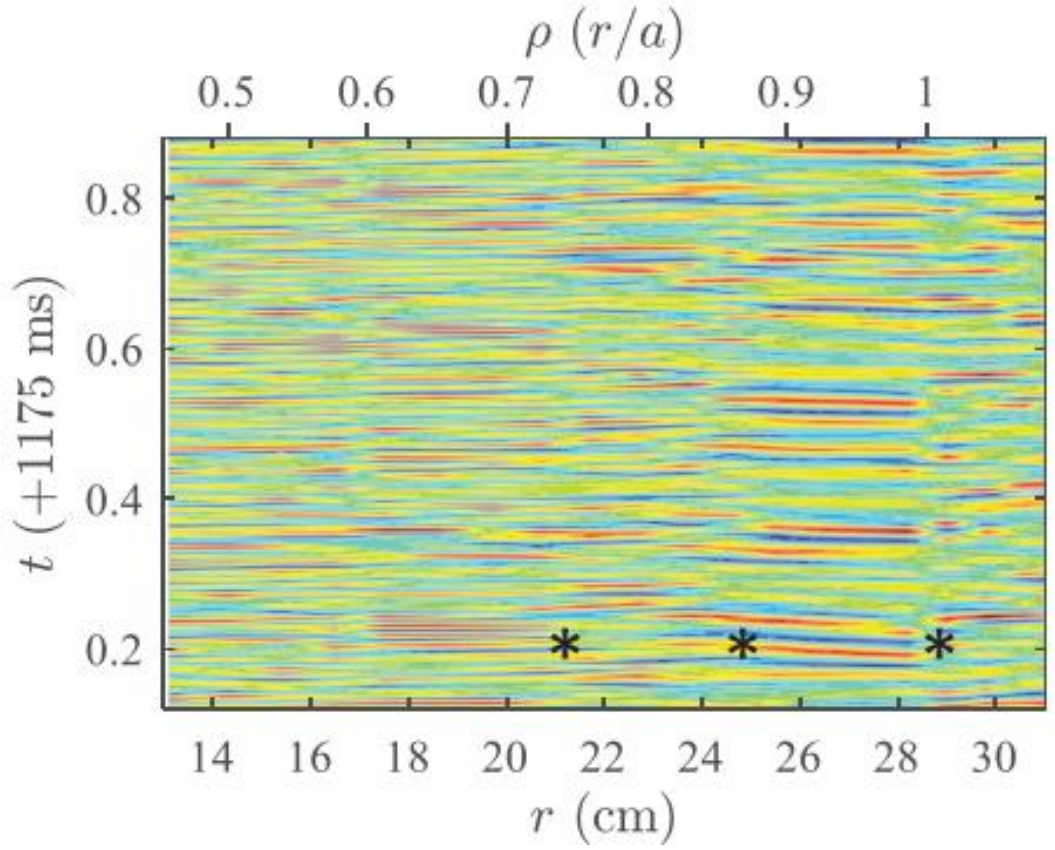


Profile Structure



Semi-Permeable Barrier

Staircases in Experiment, cont'd



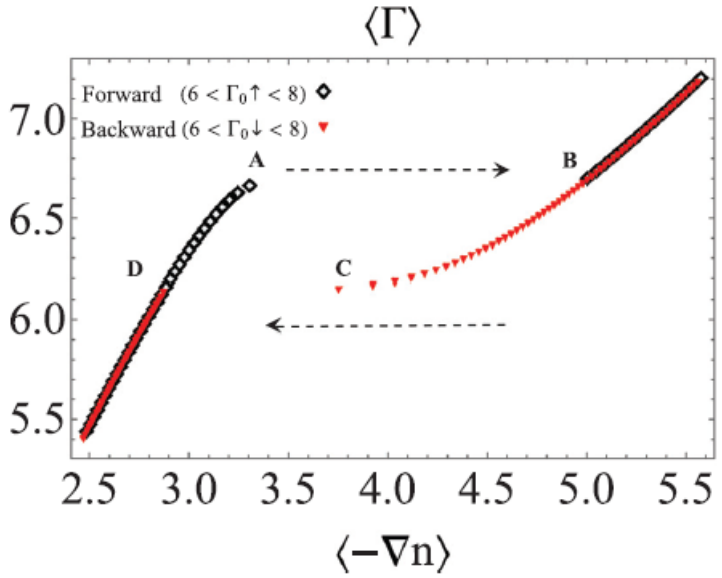
Layered Structure Evident

Space-Time History of $\tilde{n}/n$

- For comparative summary of recent staircase experiment, see Ting Long+ Phil. Trans 2026 on Inhomogeneous Mixing

Global Bifurcation in Staircase

- Average $\langle \Gamma \rangle$ vs $\langle \nabla n \rangle$ plot shows GLOBAL transport bifurcation and hysteresis



S-curve once more,
with feeling !

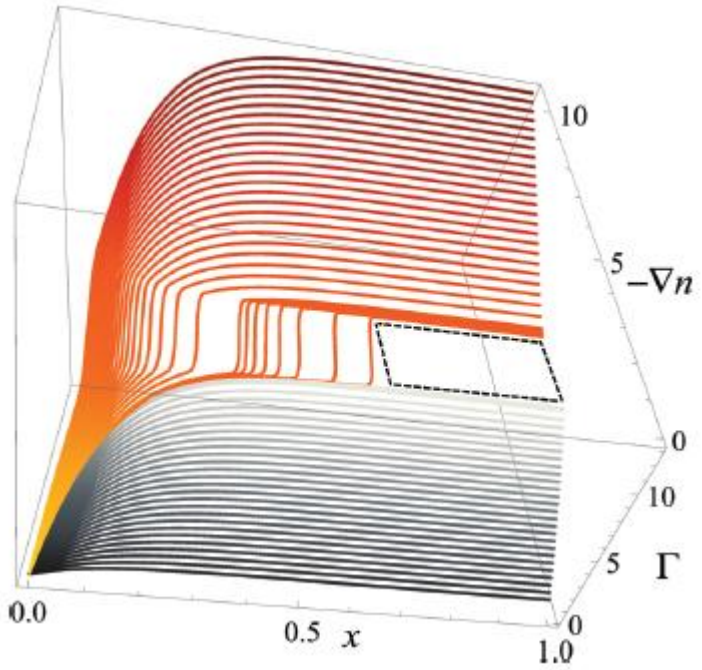
- Global confinement bifurcation, in staircase state
- Regional weightings l_0 , l_{Rh}. Good confinement, l_{Rh} dominates
- Merits of staircase state ?! Compare to single barrier ?!

Global and Local ↔ Flux Landscape

Flux Landscape ↔ family of S-curve

Red → enhanced confinement

Grey → normal confinement



- See also
  - P.D., V.B. Lebedev, el. al., PRL ’97
  - Lebedev, P.D., Phys. Plasmas ’98 (barrier propagation)

Looking Ahead...

Thoughts – Future Work

- Next generation devices (e.g. SPARC) will operate “near marginal stability” ➔ MTE phenomena likely significant
  - Flux PDF footprint of confinement trends? Speculate: population of large events?
  - Quantify how near is “near”? Models should address domain validity. (c.f. Fredy Ramirez+ 2026)
- Can the staircase be ‘tuned’ to achieve optimal confinement?

Staircase state as attractive alternative to ITB ?!

Is there an optimal turbulent core-edge integration which reconciles confinement and power handling?

Thoughts – Future Work, cont'd

- EP → AE + micro-turbulence + zonal flows

  Aka: '3 Animal Problem' - a feedback loop wonderland! see: Xiaodi Du, W. Heidbrink+

  Will require constructive interaction of EP and Transport communities

- Experiments → limitless possibilities…
  - Recent Frontiers DIII-D experiment correlating heat avalanche + turbulence pulse (F. Kin, Zeyu Li)
  - Basic experiments can contribute (c.f. B. Van Compernolle + 2015)
- Fundamentals:

  Heat/turbulence pulse dynamics as directed percolation process (N. Goldenfeld)

Stay Tuned

