Poster # 1778

Power scaling of the density limit and particle transport events

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Importance of power scaling of density limit

- Greenwald density limit scaling $\bar{n}_g = I_p/\pi a^2$ is power (Q) independent !(?) . [Greenwald PPCF 2002]

- But, Q dependence has been observed in many experiments! Some recent examples are:

  - Huber et al JNM 2013 $n_{crit} \sim Q^{0.4}$ [JET database]

  - Zanca et al NF 2019. $n_{crit} \sim Q^{4/9}$ [Multi-machine database]

  - P Manz et al NF 2023. $n_{crit} \sim Q^{0.38 \pm 0.08}$ [Multi-machine database]

- Why care? Fusion power $\sim n^2$!

Preview of results

- Density limit (DL) phenomenology is linked with *shear layer collapse*. Radiative effects are *secondary* to transport bifurcation.

- We show that *power scaling of L mode density emerges from zonal shear layer collapse dynamics*. Shear layer strength increases with power (Q) → improved particle confinement → n_{crit} ↑. Latest experimental analysis[P Manz et al NF 2023] is in close agreement with our prediction of $n_{crit} \sim Q^{1/3}$.

- A critical dimensionless parameter associated with L→DL transition has been identified. This again is supported by latest experimental analysis of a large dataset[P Manz et al NF 2023].

- At L→DL, shear layer collapse triggers enhanced particle transport events consisting of strong turbulence spreading and emission of density blobs.

- Predictions beyond scalings: Zonal shear layer collapse is hysteretic. Hysteresis is due to *dynamical delay in bifurcation* due to critical slowing down. *Fundamentally different* from L→H , H→L hysteresis due to bi-stable states.

- In the primacy hierarchy, scalings are at the 'surface'. *Fluctuations and dynamics are more fundamental.* Hysteresis is a manifestation of the underlying transport bifurcation process. Experimental observation of shear layer and fluctuation hysteresis would *validate* the linkage of density limit to transport bifurcation.

Conventional Wisdom associates Density Limit to radiative events

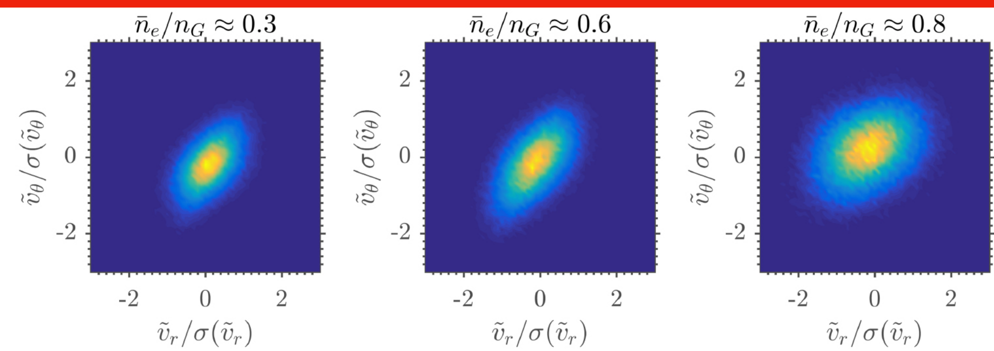
Density limit is often associated with macroscopic events

- Global thermal collapse, Radiative condensation / MARFEs. Poloidal detachment, Divertor detachment, MHD activity -radiation driven islands.

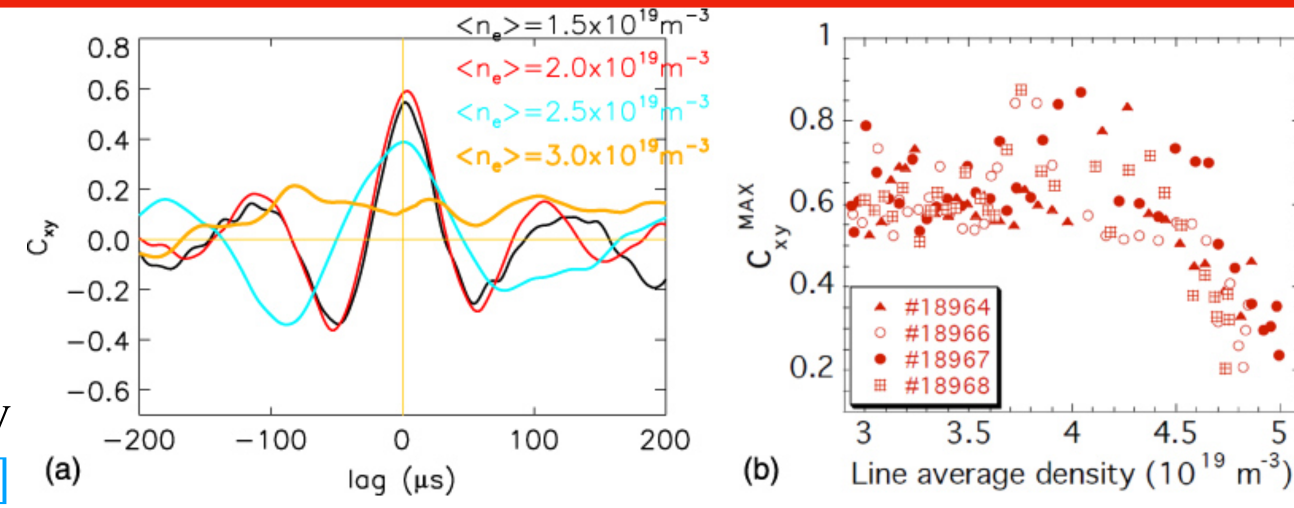
- High density→Edge cooling→MARFEs→Current profile shrinkage → Tearing→Islands …→Disruption!

What's the role of microscopic transport physics?

Towards Microscopics:
Recent experiments suggest Shear Layer decay→Density Limit

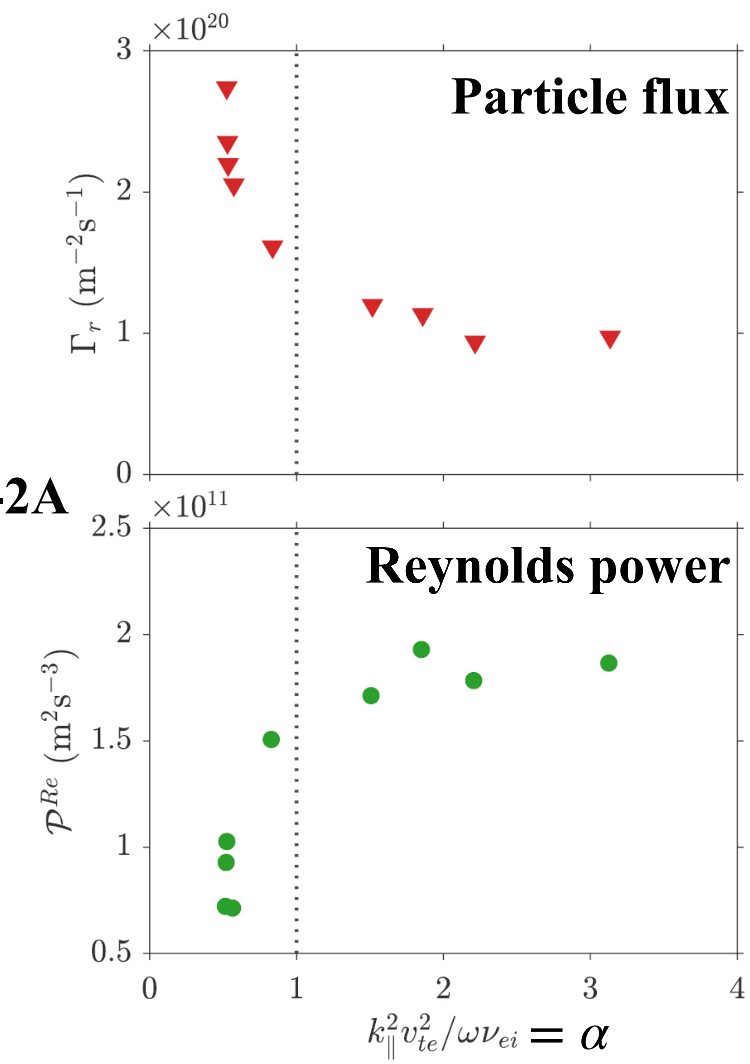


Correlations of radial and poloidal velocity fluctuations drops as $n \rightarrow n_G$ [Hong *et al* NF 2018]

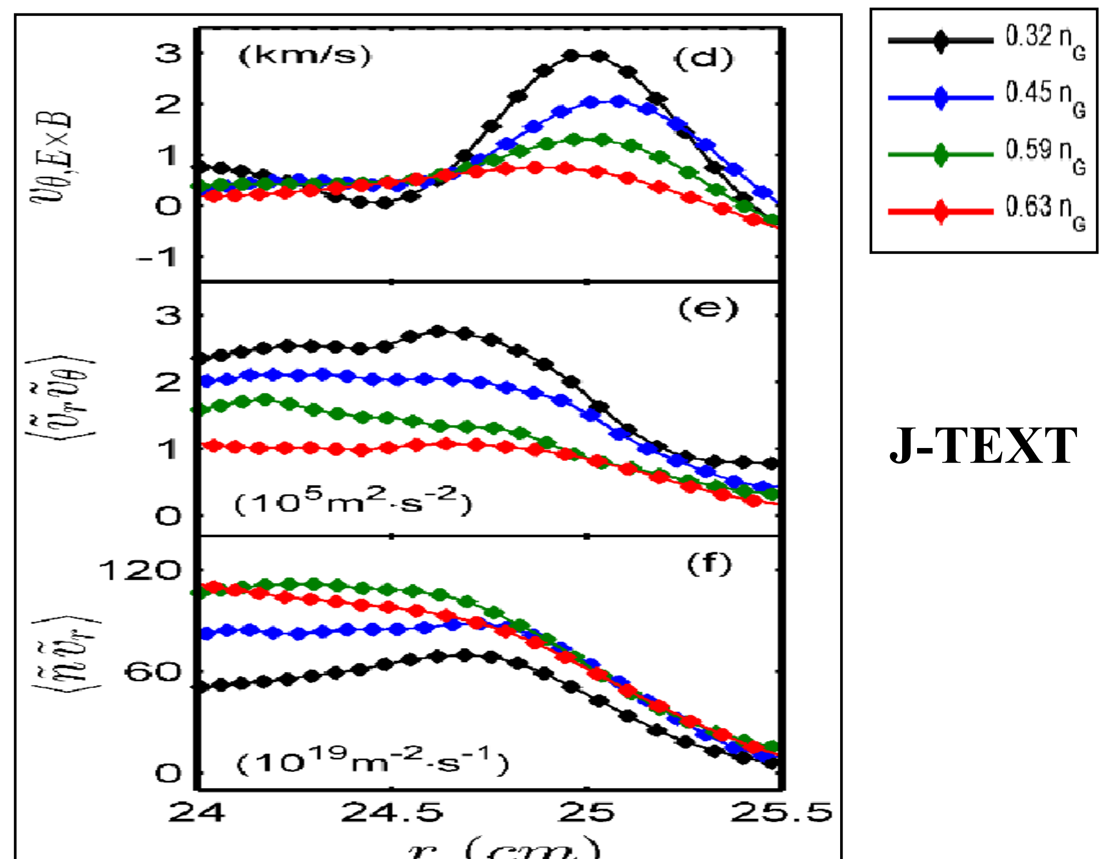


Long range correlations (LRC) decrease as the line averaged density increases in both TEXTOR and TJ-II. LRC ↔ZF strength [Y. Xu *et al* NF 2011]

HL-2A

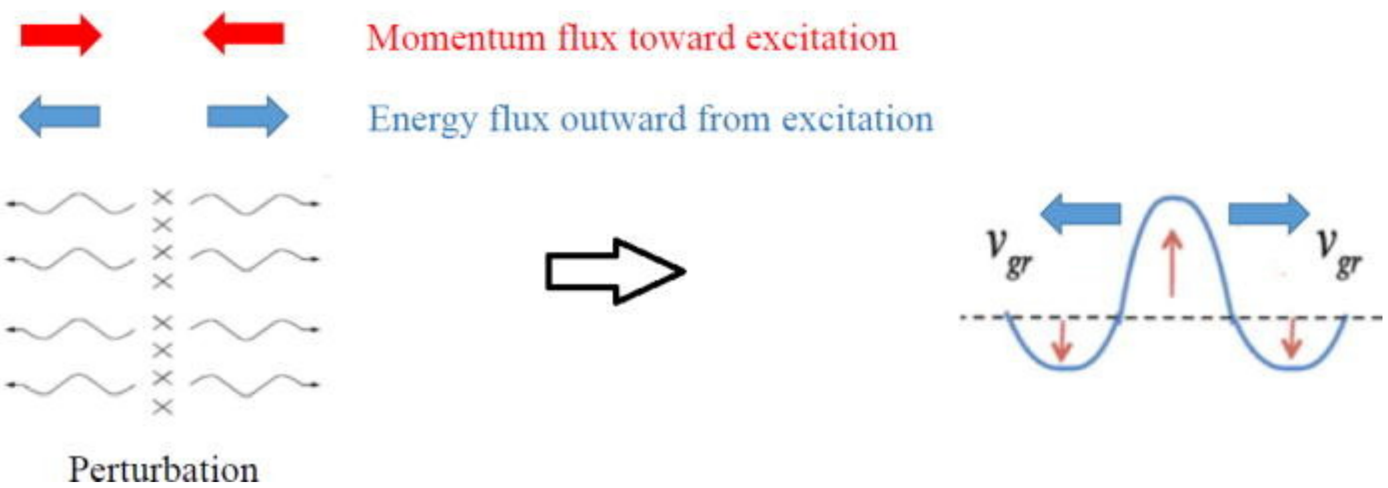


Reynolds power $P_{Re} = -\langle v_\theta \rangle \partial_r \langle \tilde{v}_r \tilde{v}_\theta \rangle$ ↓ and particle flux ↑ as α drops below 1



Particle flux ↑ and Reynolds stress, ExB flow and flow shear ↓ as $n \rightarrow n_g$. [T Long *et al* NF 2021]

Shear layer collapse in hydro- regime and origin of current scaling



In hydro-regime the link of wave energy flux to Reynolds stress is broken !

- Plasma response for Hasegawa - Wakatani :- HDM Theory[Hajjar, Diamond, Malkov 2018]
- $\Gamma_n, \chi \uparrow$ and Π^{res}, $\nabla_\perp^3 \overline{\phi} \downarrow$ as the electron response passes from adiabatic to hydrodynamic regime.
- Weak zonal flow production for $\alpha \ll 1$ $\rightarrow$ weak regulation of turbulence and enhancement of particle transport and turbulence.

- **<u>Origin of current scaling:</u>** zonal flow drive is "screened" by neoclassical dielectric [Rosenbluth - Hinton 1998]. ;
- Poloidal gyro-radius ρ_θ emerges as screening length ρ_{sc}! Effective ZF inertia $\downarrow$ as $I_p \uparrow$ $\rightarrow$ZF strength increases with I_p, for fixed drive.
- Favorable I_p scaling persist in plateau regime (edge of interest). NO I_p scaling in P-S regime. [Singh & Diamond NF 2021]

$$\frac{\partial}{\partial t}\left\langle \left|\phi_k\right|^2 \right\rangle = \frac{2\tau_c \left\langle \left|S_k\right|^2 \right\rangle}{\left|\varepsilon(q)\right|^2};$$

Emission from polarization interaction

Neoclassical response

$$\varepsilon = \varepsilon_{cl} + \varepsilon_{neo} = \frac{\omega_{pi}^2}{\omega_{ci}^2}\left\{1 + \frac{q^2}{\epsilon^2}\right\} k_r^2 \rho_i^2$$

Zonal wave #

Shear layer collapse in adiabatic regime

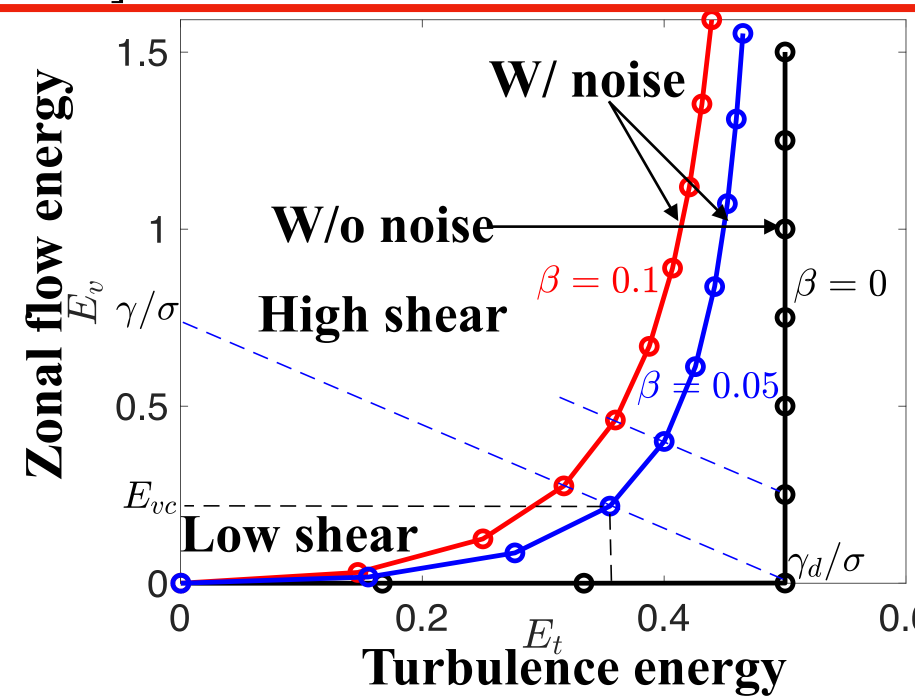
[Singh and Diamond NF 2021]

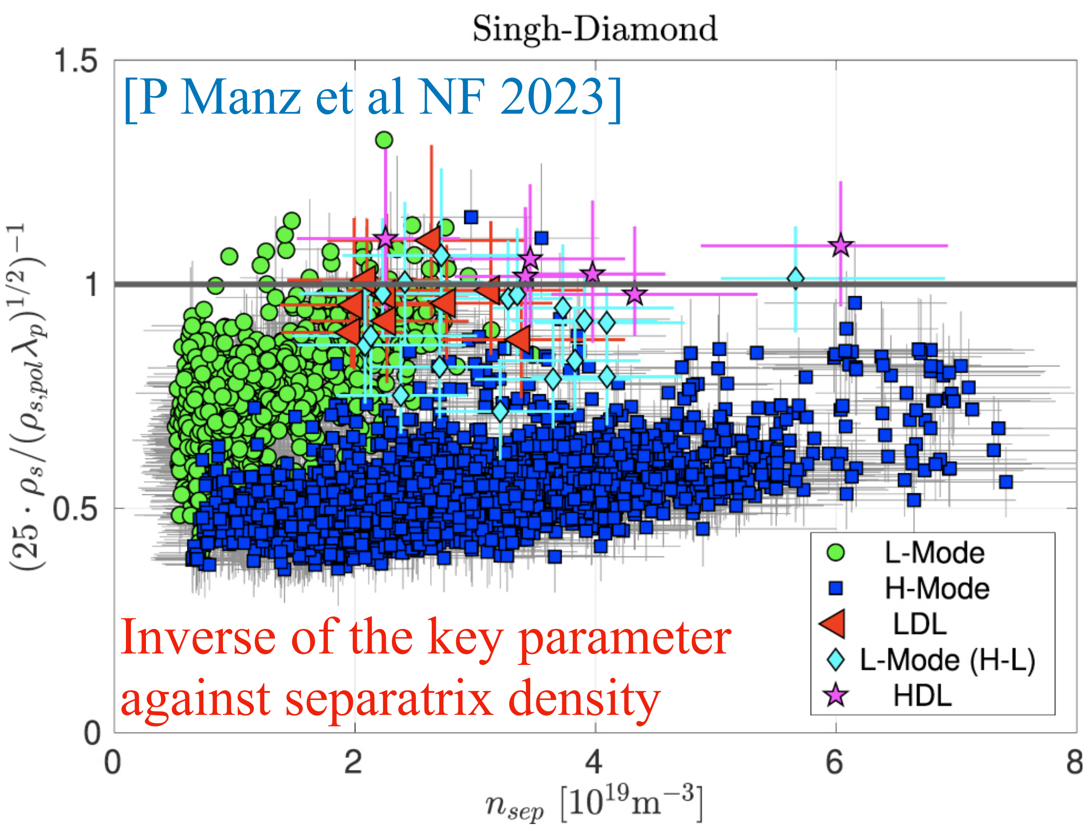
Neoclassical screening + drift wave - zonal flow dynamics → a novel predator - prey model.

$\partial_t E_t = \gamma E_t - \sigma E_v E_t - \eta E_t^2; \partial_t E_v = \sigma E_t E_v - \gamma_d E_v + \beta E_t^2$

Notice, $\sigma \sim \varepsilon^{-1} \sim B_\theta^2 \sim I_p^2$ and $\beta \sim \varepsilon^{-2} \sim B_\theta^4 \sim I_p^4$

- I_p **jacks up modulational growth and zonal noise** → stronger feedback on turbulence. Noise eliminates threshold for zonal flow production.





- Criterion for zonal flow collapse:

$$\gamma < \eta \frac{\gamma_d}{\sigma} \implies \boxed{\frac{\rho_s}{\sqrt{\rho_{sc} L_n}}} < \left[\frac{\eta}{\Omega_i} \frac{\gamma_d}{2k_x^2 \rho_s^2 \Theta \Omega_i^2} \frac{\hat{\alpha}}{q_\perp^2 \rho_s^2} \frac{\left(1 + q_\perp^2 \rho_s^2\right)^3}{q_y^2 \rho_s^2} \right]^{1/4}$$

Key Dimensionless parameter

- Large B_θ enhances the persistence of zonal flows.
- This prediction of key dimensionless parameter has been recently verified in tokamak disruption database study.

Particle source S

$\rho_s / \sqrt{\rho_{sc} L_n} < crit \rightarrow S < S_c \sim B_\theta^{-3} \sim I_p^{-3}$

Local edge density n	**Zonal flow damping**
$n > n_c \sim I_p S^{1/3}$	**Viscosity dominated**
$n > n_c \sim I_p^2 S^{2/3}$	**Charge exchange friction**

Extended model for power scaling of density limit from shear layer collapse scenario

- A variant of KD03 model - used for L-H studies, Power (Q) limited to the **L mode**
- Coefficients derived for ITG mode, Includes **neoclassical zonal flow screening** response
- In Gyro-Bohm normalization

Normalized Turbulence energy $\mathscr{E}$:

$$\frac{\partial \mathscr{E}}{\partial t} = \frac{a_1 \gamma(\mathscr{N}, \mathscr{T})\mathscr{E}}{\left(1 + a_3 \mathscr{V}^2\right)} - a_2 \mathscr{E}^2 - \frac{a_4 \mathscr{E}_z \mathscr{E}}{\left(1 + b_2 \mathscr{V}^2\right)}$$

↑ Nonlinear Damping

Normalized Zonal flow energy $\mathscr{E}_z$:

$$\frac{\partial \mathscr{E}_z}{\partial t} = \frac{b_1 \mathscr{E} \mathscr{E}_z}{\left(1 + b_2 \mathscr{V}^2\right)} - b_3 \hat{n} \mathscr{E}_z + b_4 \mathscr{E}^2$$

↑ Mod. Growth ↑ Coll. Damping ↑ Zonal noise

Normalized Temperature gradient $\mathscr{T}$:

$$\frac{\partial \mathscr{T}}{\partial t} = -c_1 \frac{\mathscr{E} \mathscr{T}}{\left(1 + c_2 \mathscr{V}^2\right)} - c_3 \mathscr{T} + Q$$

↑ Turb. Flux ↑ Neo. Flux ↑ Input power

Normalized Density $\hat{n}$:

$$\frac{\partial \hat{n}}{\partial t} = -d_1 \frac{\mathscr{E} \hat{n}}{\left(1 + d_2 \mathscr{V}^2\right)} - d_3 \hat{n} + S$$

↑ Turb. Flux ↑ Neo. Flux ↑ Source

Control knobs (Q, S)

Normalized Mean ExB shear $\mathscr{V}$ (from radial force balance):

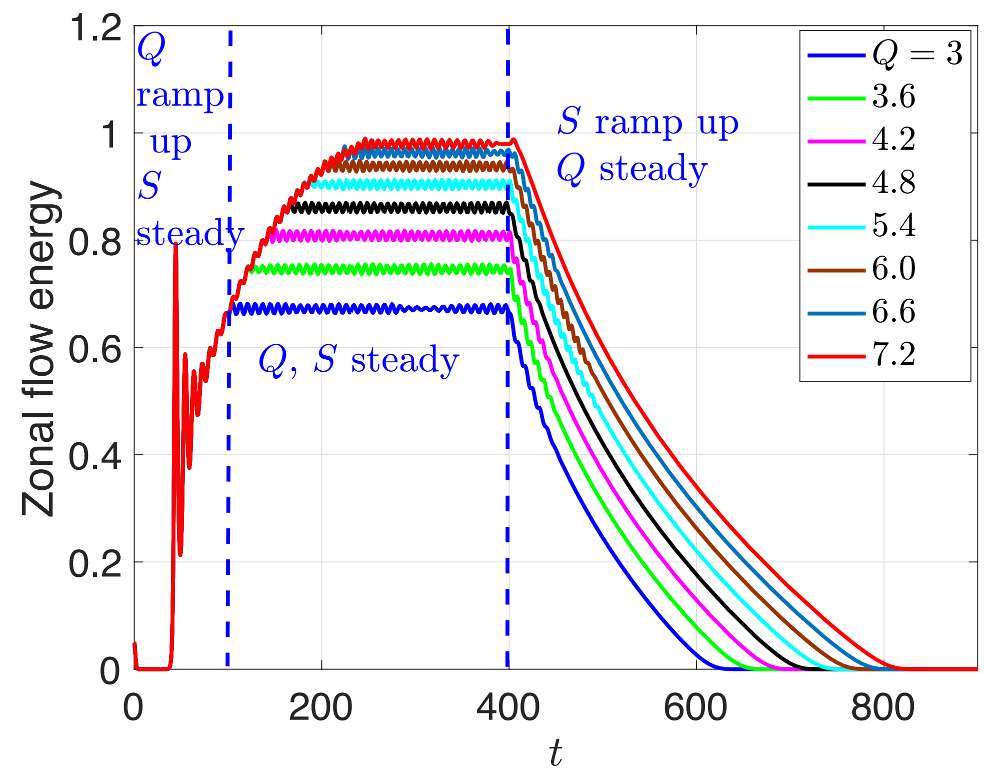
$$\mathscr{V} \equiv \frac{V_E' a}{\rho^\star v_{thi}} = -\frac{1}{\hat{n}} \mathscr{N} \left(\frac{1}{\hat{n}} \mathscr{N} + \frac{1}{\hat{T}} \mathscr{T} \right).$$

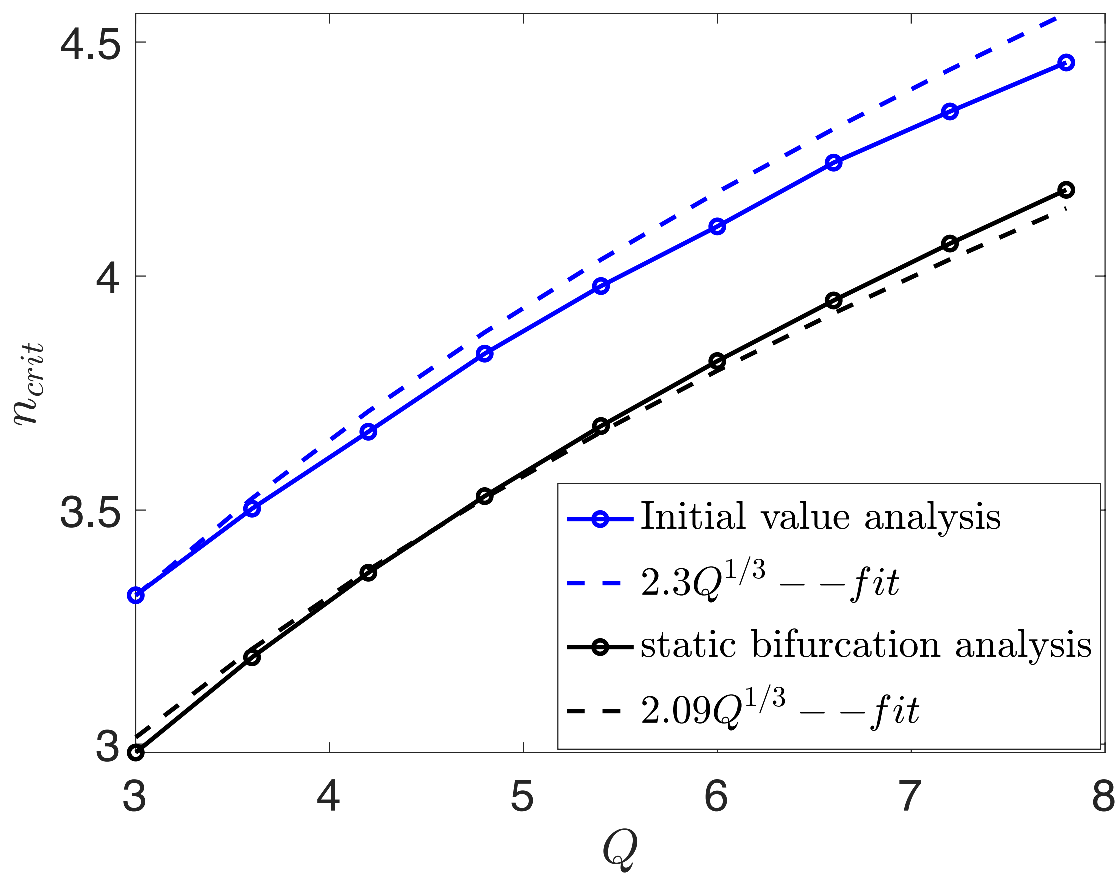
Density gradient $\mathscr{N}$ remains frozen.

Notice, Modulational growth $b_1 \sim \varepsilon^{-1} \sim B_\theta^2 \sim I_p^2$ and zonal noise $b_4 \sim \varepsilon^{-2} \sim B_\theta^4 \sim I_p^4$

L →DL transition studies: Power Scaling

- Look for shear layer collapse in Power (Q) ramp up followed by particle source (S) ramp-up.
- Zonal flow increases with power (Q).
- Oscillations→Predator - prey.
- Higher power (Q) → longer ZF damping time →n_{crit} ↑.

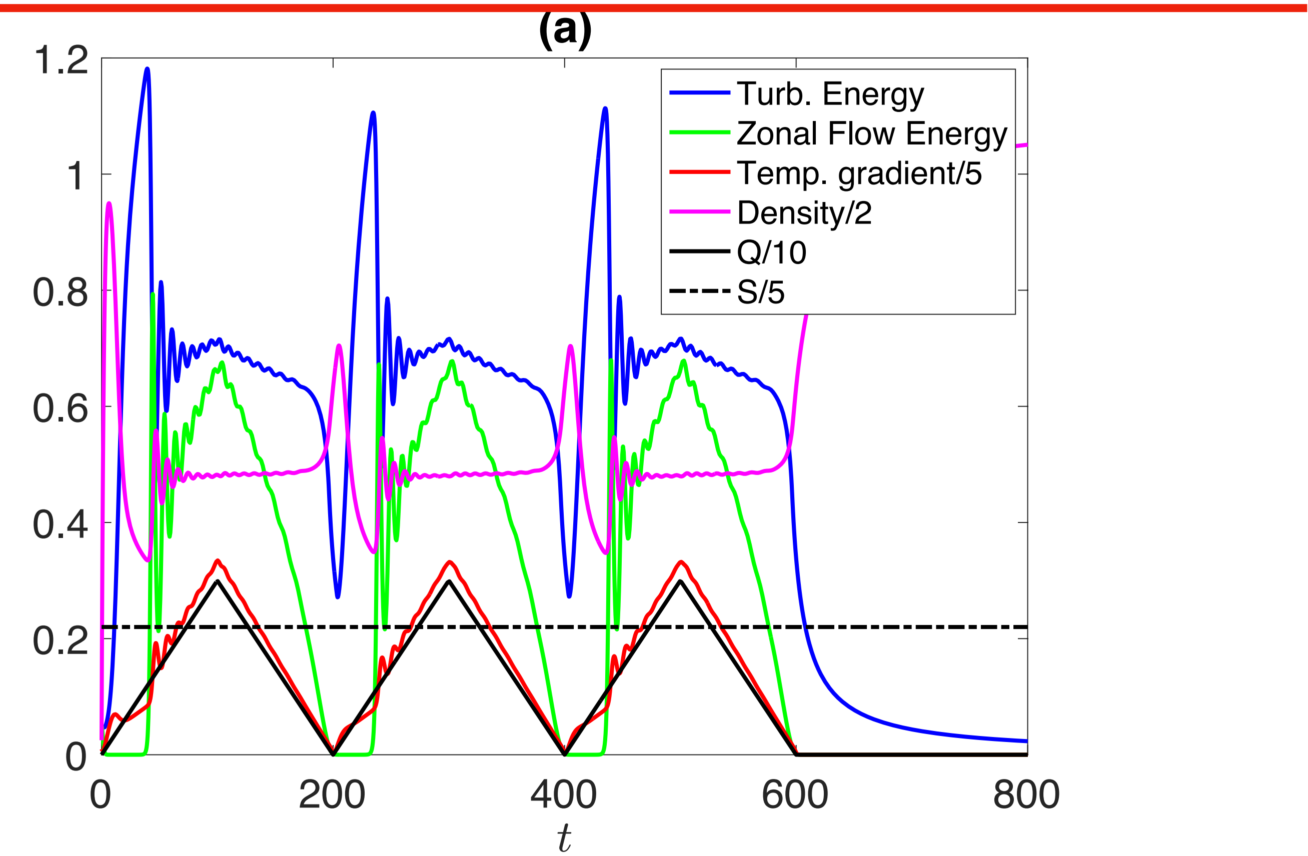


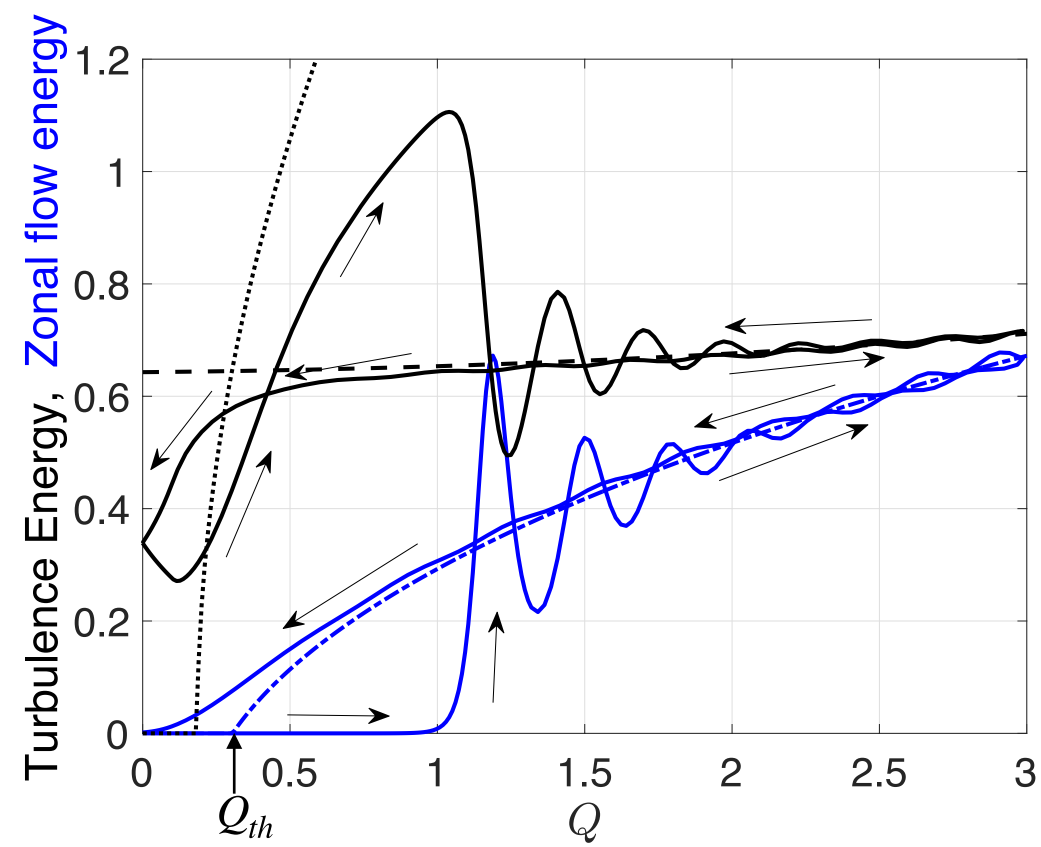


- <u>Favorable</u> power scaling $n_{crit} \sim Q^{1/3}$
- Our prediction is in close agreement with $n_{crit} \sim Q^{0.38 \pm 0.08}$, recently obtained from L-mode disruption database [P Manz et al NF 2023].
- <u>Physics</u>: $\gamma(\nabla T)$ vs ZF damping + saturation by ZF
  - Shear layer strength increases with Q ↑ → improved particle confinement → n_{crit} ↑
- n_{crit} from initial value > n_{crit} from static bifurcation → bifurcation delay due to critical slowing down→ indicates dynamical hysteresis

Hysteresis with cyclic power ramp

- All fields exhibit hysteresis in cyclic Q ramp!
- Physics prediction - - - beyond scalings !
- Physics:
  - Two states L(w/ ZF), DL(w/o ZF)
  - But only one stable state at any moment —then why hysteresis?
  - Delay in (transcritical) bifurcation due to critical slowing down at the static bifurcation point Q_{th}.
- Significance: Links scaling to microscopic dynamics, a clear testable prediction of dynamics!

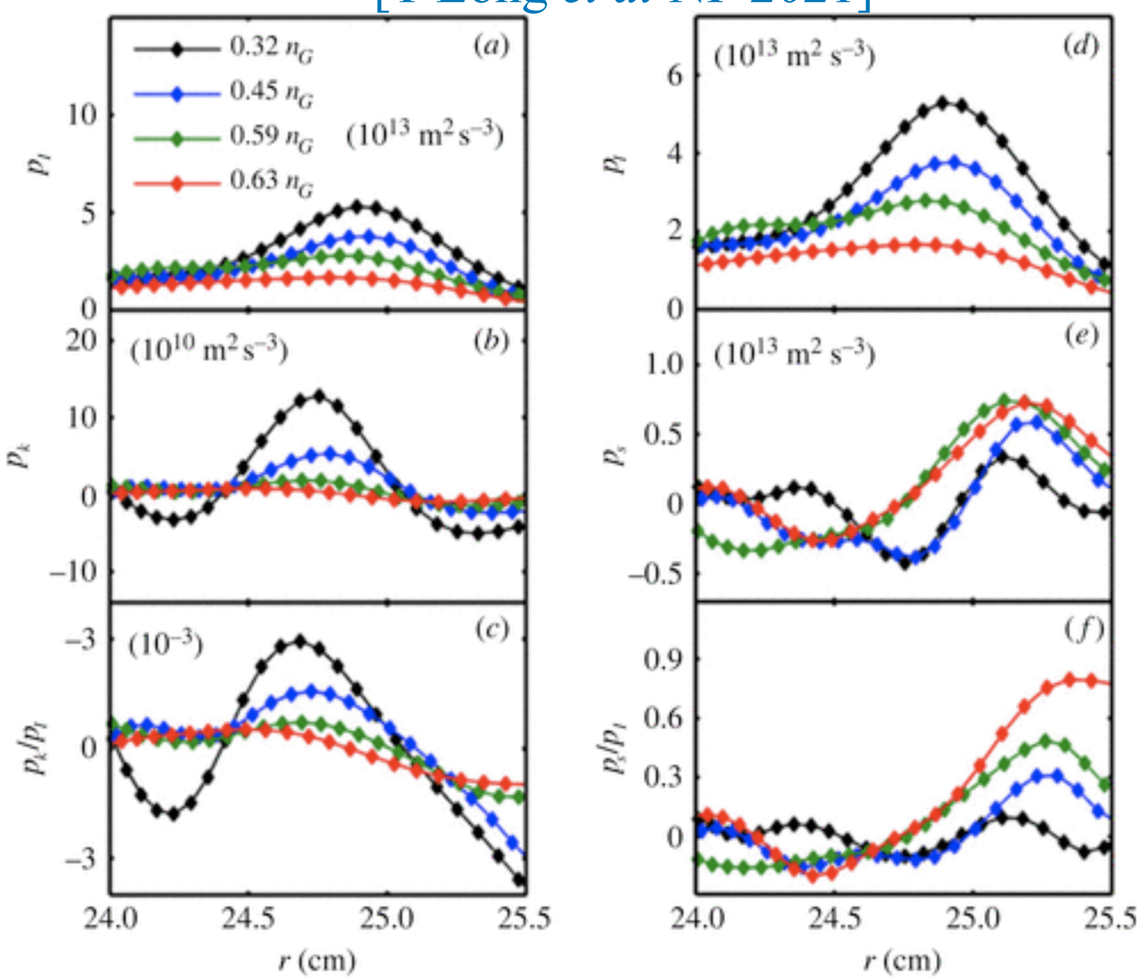


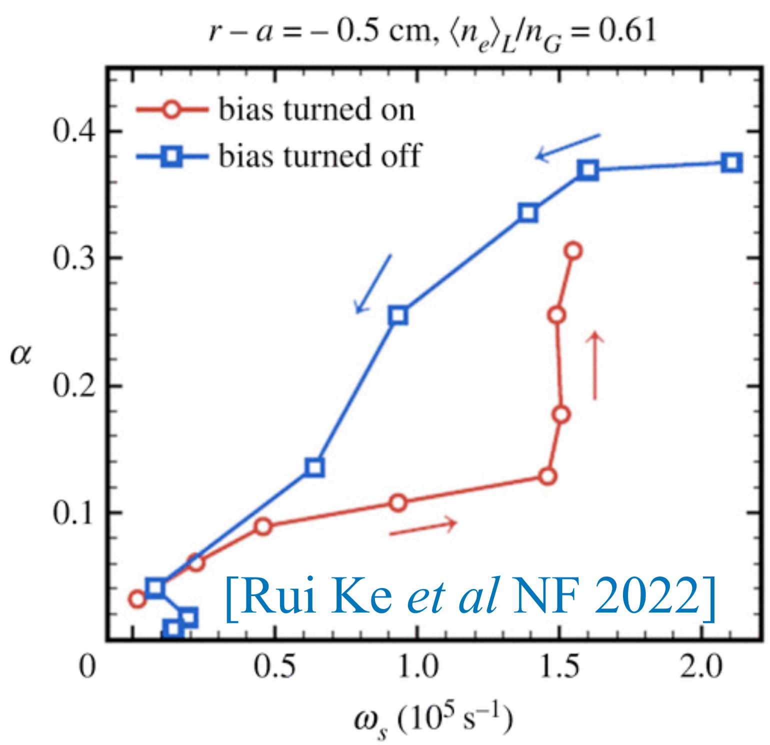


Particle transport events at the density limit

- In a collisionless drift wave turbulence model: (a) turbulence production power from ∇n is $P_I = -c_s^2 \langle \tilde{v}_r \tilde{n} \rangle \frac{1}{\langle n \rangle} \frac{d\langle n \rangle}{dr}$, (b) Reynolds power is $P_{Re} = P_k = \langle \tilde{v}_r \tilde{v}_\theta \rangle \langle v_E \rangle'$.
- Obviously both P_I and P_k/P_I drop (c) as n_e/n_G rises. Meanwhile, the turbulence spreading ratio P_s/P_I enhances as n_e/n_G rises(d-f).
- At L→DL, the shear layer collapsed and the edge density fractalizes into a 'soup' of spreading, patchy turbulence.

[T Long *et al* NF 2021]

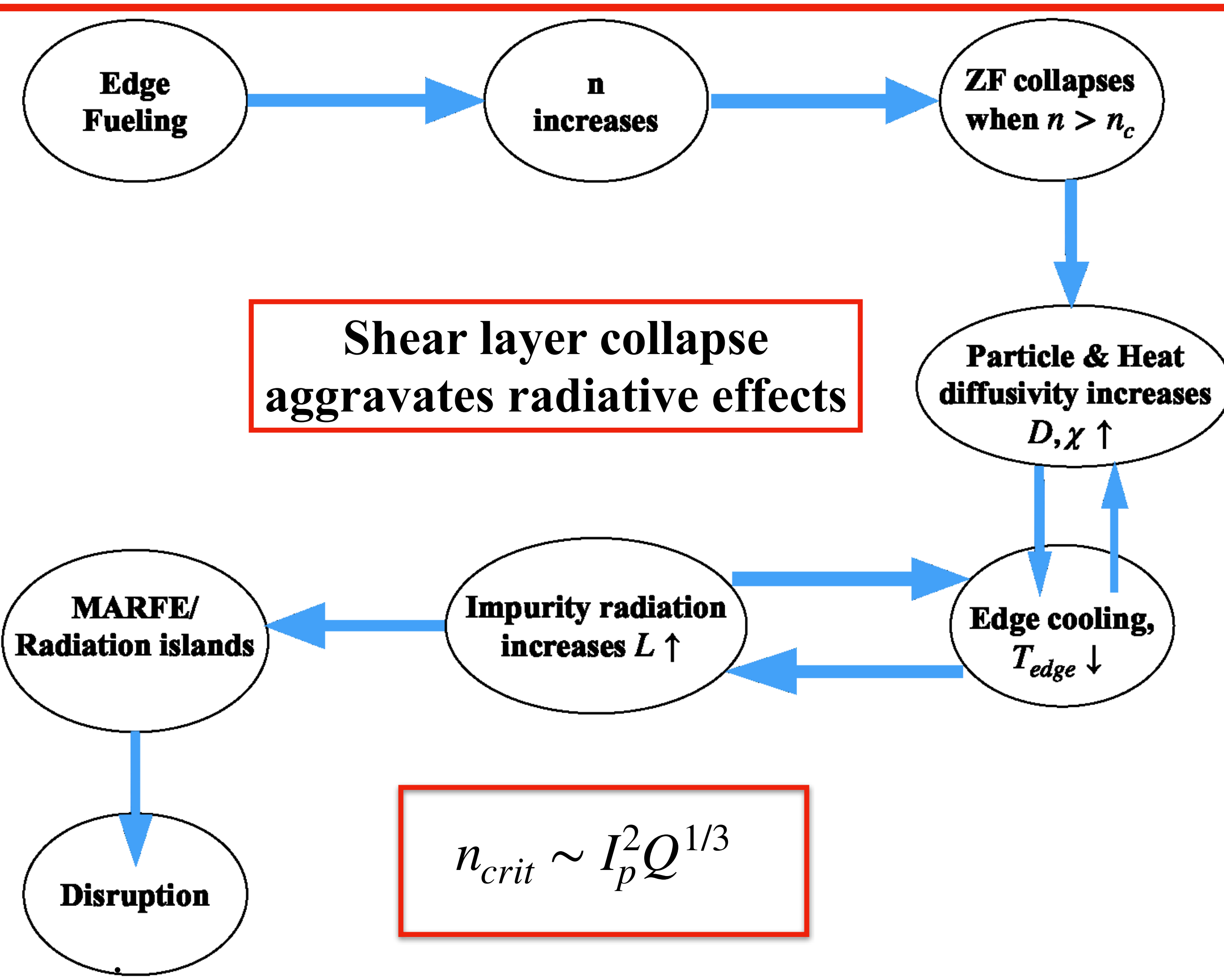




[Rui Ke *et al* NF 2022]

- Obviously edge shear layer collapse linked to DL. Effect of external bias on DL?
- Edge shear ω_s increases, turbulence spreading drops, line averaged density and n_{edge} increases with external bias!
- Hysteresis between adiabaticity parameter α and edge shear ω_s. Notice counter clock rotation → ω_s "leads" α!

Conclusions



- Radiative cooling is secondary (i.e., a consequence of) to the transport bifurcation.
- Density limit is a back transition L→DL phenomena
- L→DL associated with shear layer collapse
- <u>Scalings</u> emerge from shear layer dynamics
    - I_p scaling from neoclassical zonal flow screening
    - Favorable Q scaling due to strengthening of shear layer for increasing Q, thus preventing shear layer collapse
    - A critical dimensionless parameter has been identified, consistent with analysis of a large dataset.
- <u>L→DL hysteresis</u> due to dynamical delay in bifurcation (resulting from critical slowing down) is a testable prediction of the model beyond scalings! It is fundamentally different from L→H , H→L hysteresis due to bistability.

Current issues

- H-mode density limit: H→L back transition by mean ExB shear collapse followed by progression to Greenwald. Mechanism of mean shear collapse at high density? Ballooning modes at the separatrix vs turbulence spreading from the SOL? Electromagnetic pedestal turbulence ?

- Core fueling: Future plasmas may likely be fueled through core by pellet injection etc. Interplay of power deposition and fueling?

- Collisionless regimes: Fluid models are dubious in collisionless regimes. $\alpha < 1$ regimes, and resistive ballooning turbulence etc. are not relevant to a collisionless edge.

- Shaping effects: How flux surface shaping effects the shear layer collapse criterion? Triangularity scaling of n_{crit} ?

- Theoretical matters: (1) 1D model of DL power scaling to predict the density scale length. (2) The question of triple point 'phase-coexistence' of L-mode, H mode and a strongly turbulent DL regime remains unresolved and is of fundamental interest.