On the Transport Physics of the Density Limit

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Collaborations:

- Theory
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  - Zhibin Guo (UCSD→PKU)
- Experiment
  - Rongjie Hong, G. Tynan, HL-2A Team (UCSD and SWIP)

Discussion: Martin Greenwald

Outline

- <u>Basics of Density Limit → Mostly L-mode</u>
  - General Trends
  - Some Indications of Transport as Fundamental
  - Modelling – The Conventional Wisdom
- <u>Recent Studies → HL-2A (L-mode)</u>
  - Edge Shear Layer Evolution as $\bar{n} \rightarrow \bar{n}_g$
  - Shear Layer ←→ Electron Adiabaticity Connection
  - Synthesis
  - Confronting the Conventional Wisdom

A Theory of Shear Layer Collapse

- Thesis: For hydrodynamic electrons, drift wave turbulence cannot regulate itself via self-generated shear flows. Turbulence levels rise.
- A Simple Argument
- Collisional drift wave-zonal flow turbulence for $k_H^2 v_{T_e}^2/\omega\gamma_e \gtrless 1$
- Scaling Comparison
- What of PV Mixing?
- Scenario for edge cooling

Implications and Directions

Some Thoughts on Density Limit in H-mode

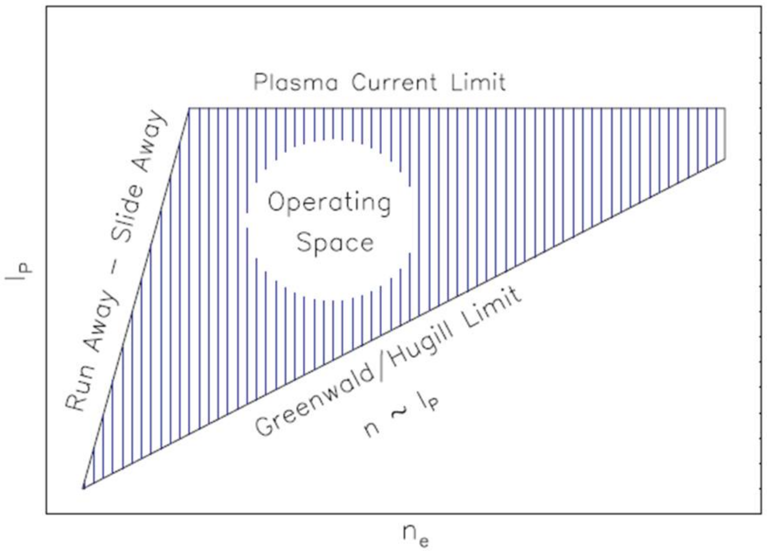
Conclusion

Basics of Density Limits

Density Limits

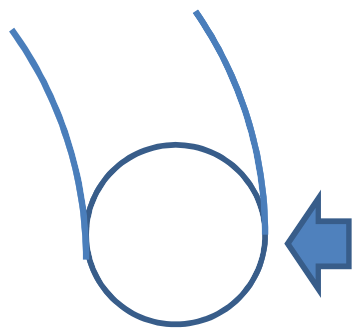
- Not a review! Incomplete!
- Greenwald density limit:

$$\bar{n} = \bar{n}_g \sim \frac{I_p}{\pi a^2}$$



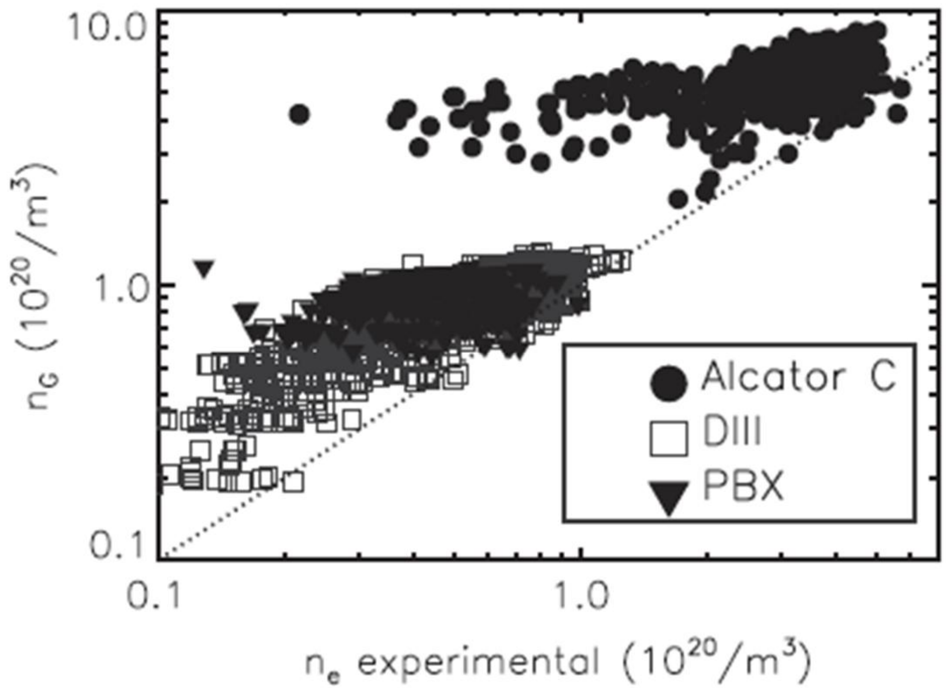
Tokamak Operating Space

- Global limit
- Simple dependence
- Begs origin of I_p scaling?!
- Most fueling via edge → edge transport critical to $\bar{n}$ limits



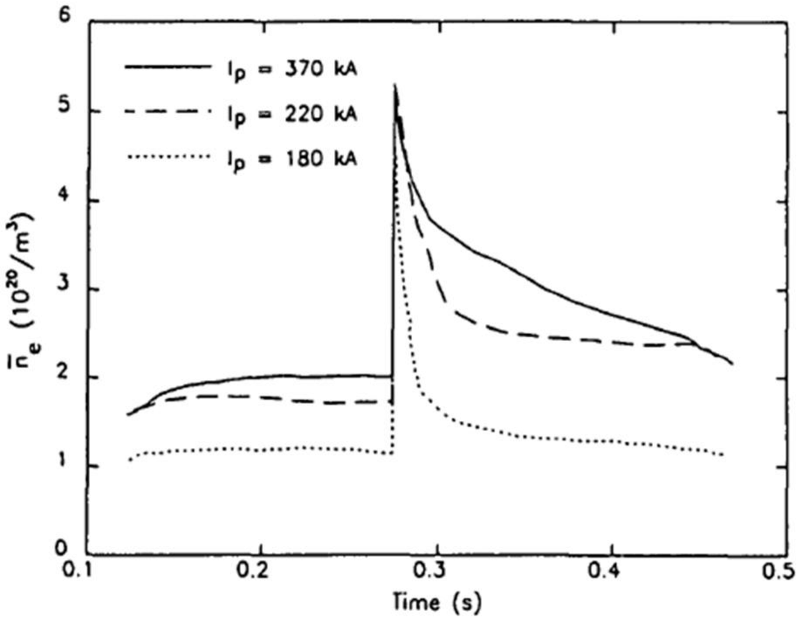
- Manifested on other devices (more later)
  - See especially RFP

- Trends well established



- Often (but not always!) linked to:
  - MARFE (radiative condensation instability) ←→ Impurity influx
  - MHD disruption
  - Divertor detachment
  - H→L Back-transition

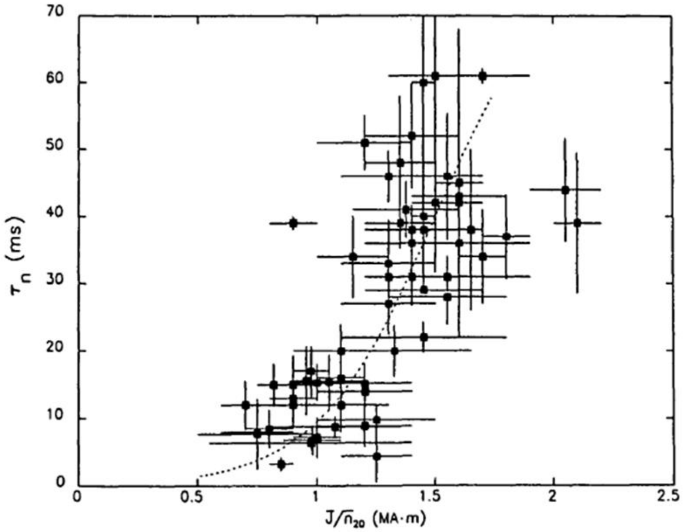
- Argue:
  - ‘Disruptive’ scenarios secondary outcome, largely consequence of edge cooling, due fueling
  - $\bar{n}_g$ reflects fundamental limit imposed by particle transport
- Some Evidence

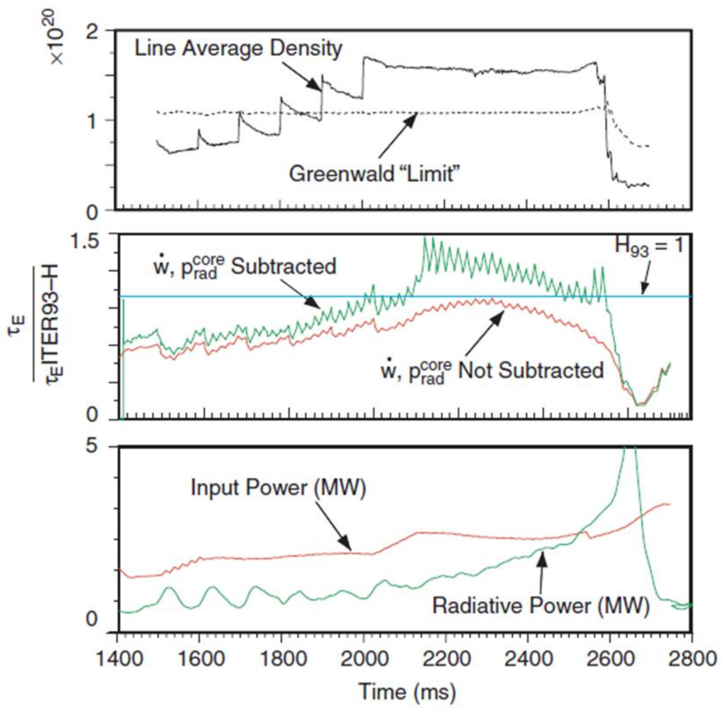


(Alcator C)

- Density decays non-disruptively after pellet injection
- $\bar{n} \sim I_p$ asymptote
- Density limit enforced non-disruptively!

- More Evidence:

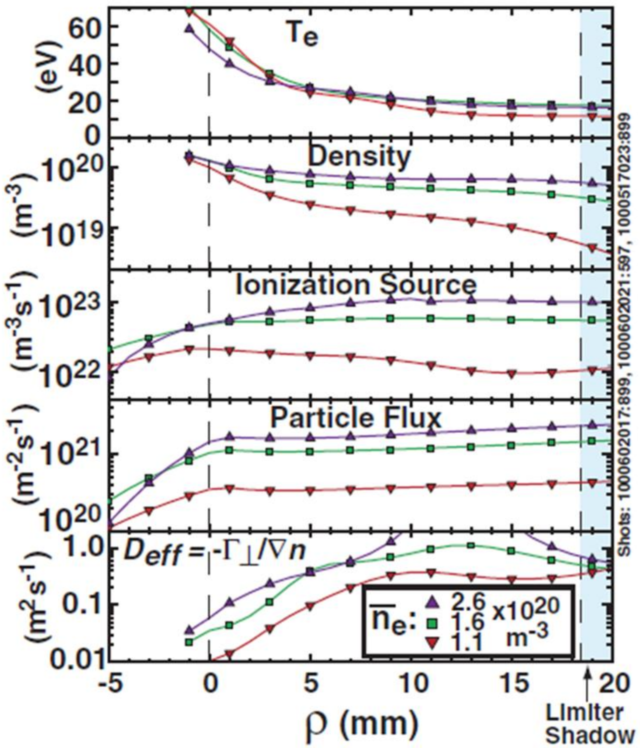


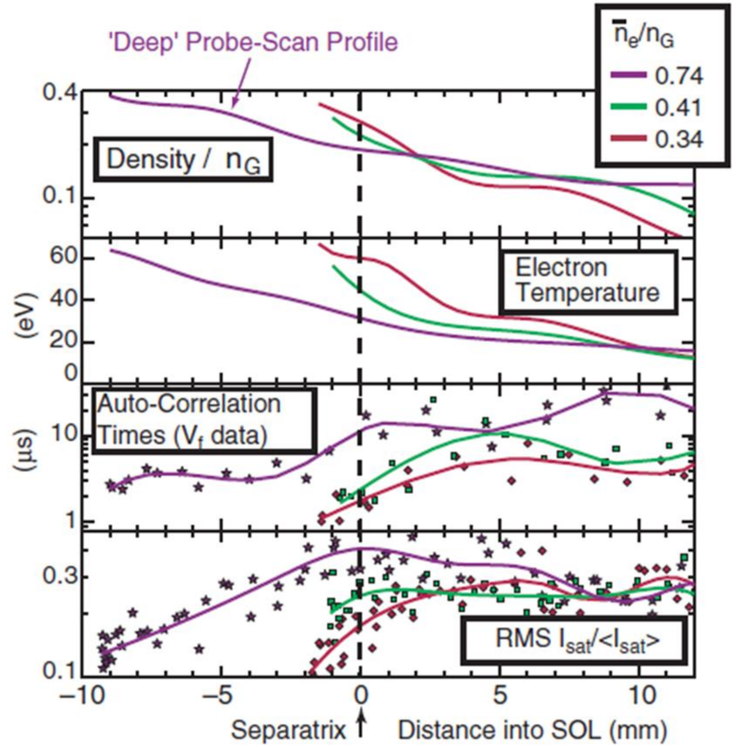


  - Post pellet density decay rises with $\bar{J}/\bar{n}$
  - Limit at: $\bar{J}/\ \bar{n}\ \sim 1$
  - Pellet in DIII-D beat $\bar{n}_g$
  - Peaked profiles ←→ enhanced core particle confinement ~ ITG turbulence
  - Reduced particle transport ➔ impurity accumulation

Looking at the Edge

- <u>Edge Fueling</u> ←→ edge <u>transport</u> crucial to density limit





- C-Mod SOL profiles
- As $n\uparrow$, high $\perp$ transport region extends <u>inward</u>

- Scan of edge/SOL profiles, $\bar{n} \to \bar{n}_G$
- Large fluctuation activity develops in main plasma, inward from SOL, for $\bar{n} \to \bar{n}_G$

Tentative Conclusions

- Turbulence intensities
- $\perp$ particle transport increases

} At edge, as $\bar{n} \to \bar{n}_g$

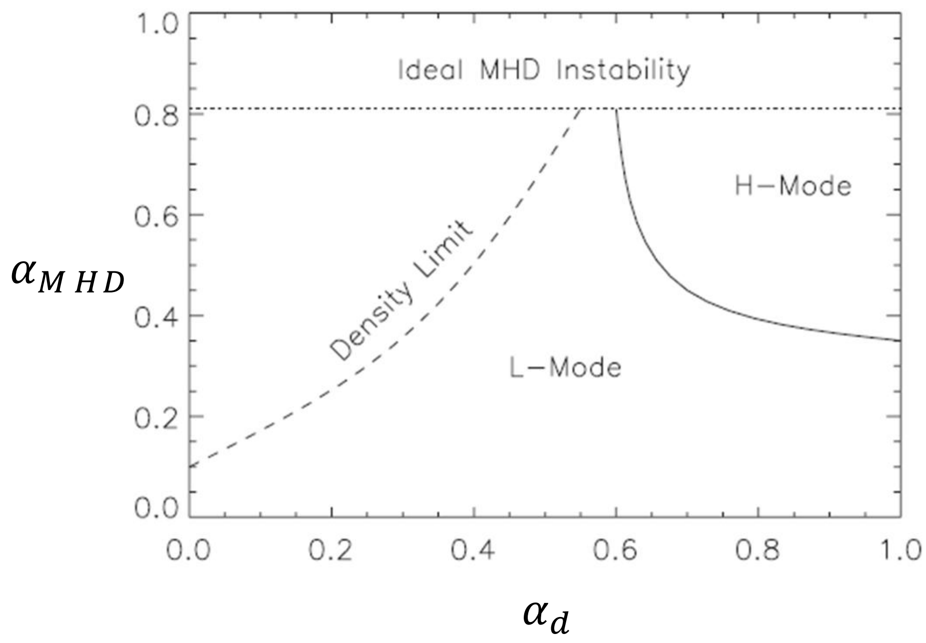
- Pellet injection admits $\bar{n} > \bar{n}_g$, with non-disruptive relaxation, as edge cooling avoided

Key Question:

→ What physics is under-pinning of rise in turbulence, transport as $\bar{n} \to \bar{n}_g$?

Conventional Wisdom (Rogers + Drake '98)

Reduced Fluid Simulation (no heat source)



- D+R on n-limit physics:
  - DWT → resistive ballooning turbulence
  - State of high $\nabla P, \beta$, cool electrons
  - Check: $\gamma > \omega_S, \omega_*$?

    shear

$$\alpha_{MHD} = -Rq^2 d\beta / dr$$

←→ ∇P ➔ ballooning drive

$$\alpha_d = \rho_S C_s t_0 / L_n L_0$$

$$t_0 = \frac{(RL_n 2)^{\frac{1}{2}}}{c_S}$$

$$L_0 = 2\pi q \left(\frac{\gamma_e R \rho_s}{2\Omega_e}\right)^{1/2}$$

→ Hybrid of drift frequency and adiabaticity

So, Conventional Wisdom ➔

- In density limit conditions, another linear instability - resistive ballooning – emerges and dominates
- Transition mechanism/physics not addressed
- Is there more to this than convention?

Recent Studies on HL-2A

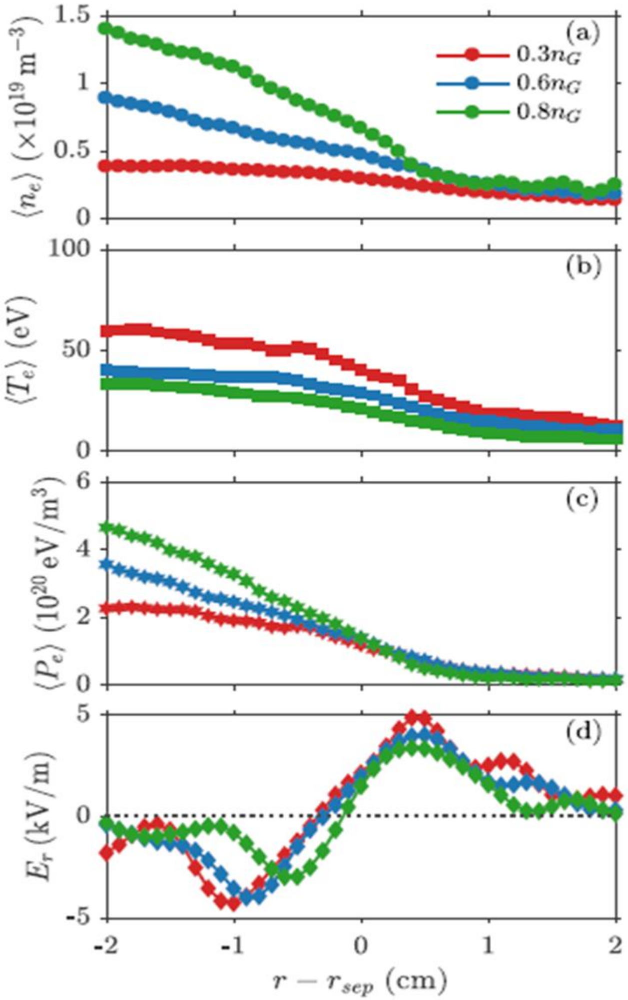
(Ronjie Hong, Tynan, P.D., HL-2A Team/NF2018)

➔ New twist: Edge Fluctuation Studies! (L-mode)

- Edge Langmuir probe array
- Curiously absent from $\bar{n}$ limit literature

Basic Results

- OH, $I_p \sim 150kA$, $B_T = 1.3T$, $q = 3.5 \rightarrow 4$
- $\bar{n} = 0.25 \rightarrow 0.9\, \bar{n}_g$
- Profiles



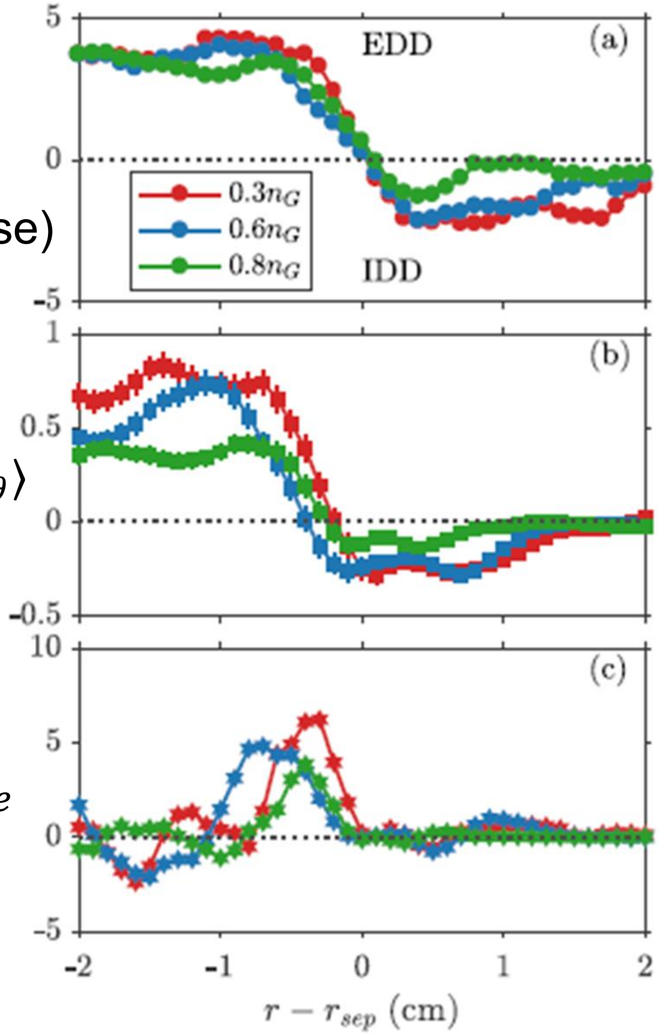
- Fluctuation Properties

$\langle V_\theta \rangle$

(phase)

$\langle \tilde{V}_r \tilde{V}_\theta \rangle$

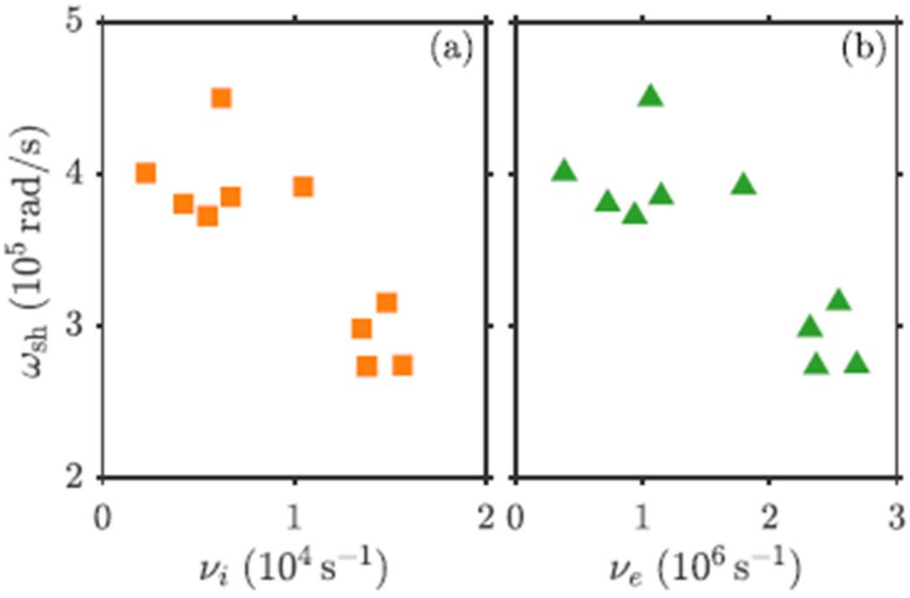
P_{Re}



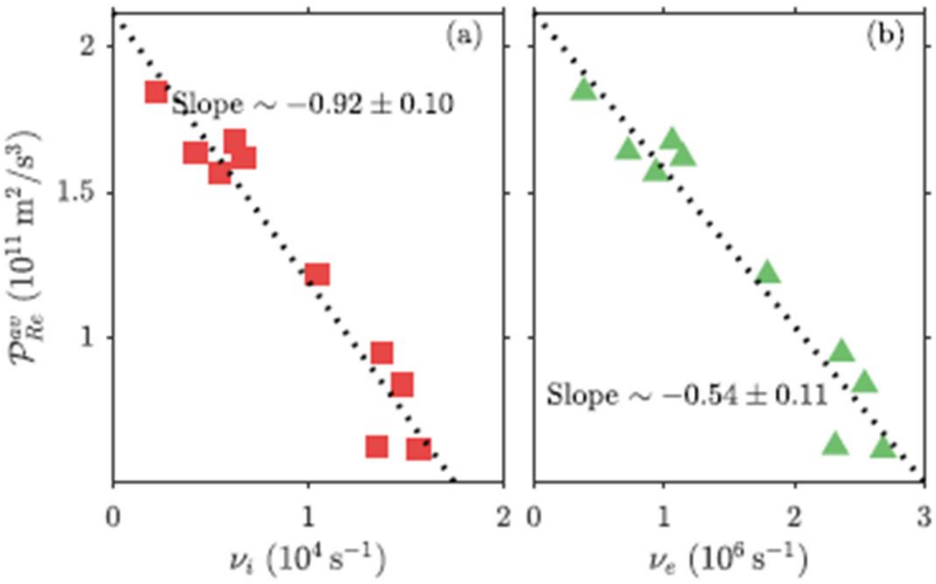
$P_{Re} = -\langle V_\theta \rangle \partial_r \langle \tilde{V}_r \tilde{V}_\theta \rangle$ → energy gained by low-f flow

DROPS as $\bar{n} \rightarrow \bar{n}_g$

Further Studies of Stress and Flows



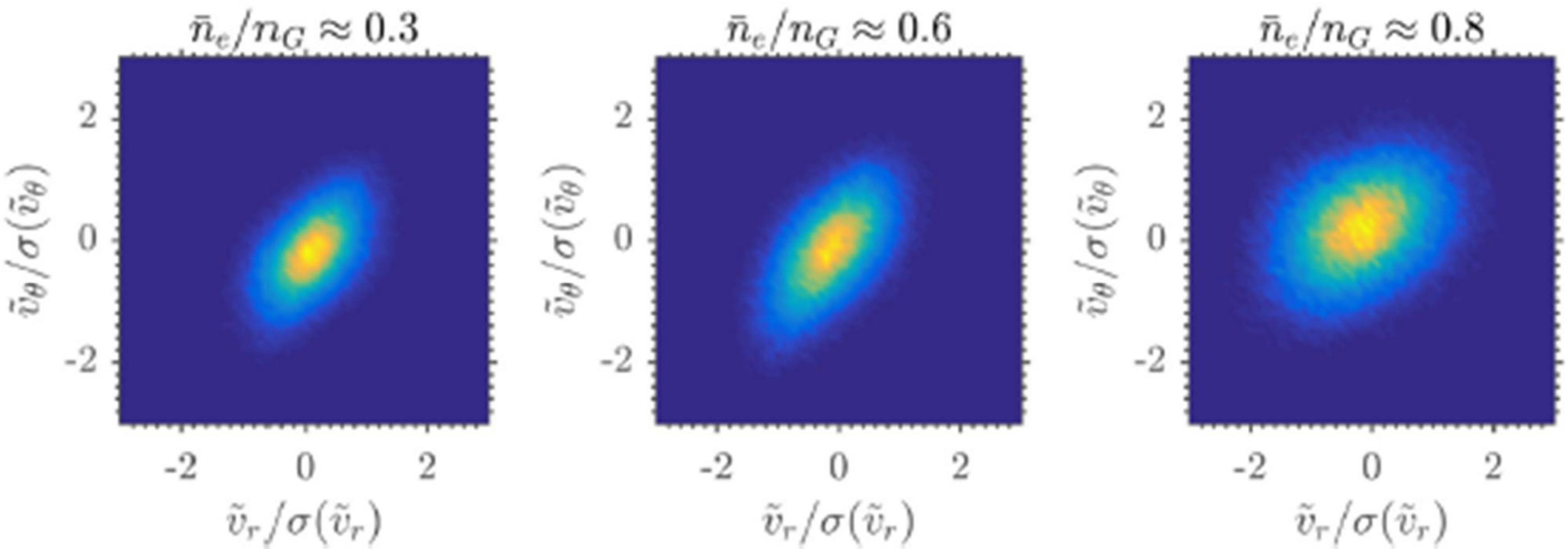
- Flow shearing rate drops as collisionality increases



- Reynolds power (to flow) drops as collisionality increases

cf: Schmid, et. al. 2017

Further Studies



- Joint pdf of $\tilde{V}_r, \tilde{V}_\theta$ for 3 densities
- $r - r_{sep} = -1cm$
- Note:
  - Tilt lost, symmetry restored as $\bar{n} \rightarrow \bar{n}_g$
  - Consistent with drop in P_{Re}

➔Weakened production by Reynolds stress

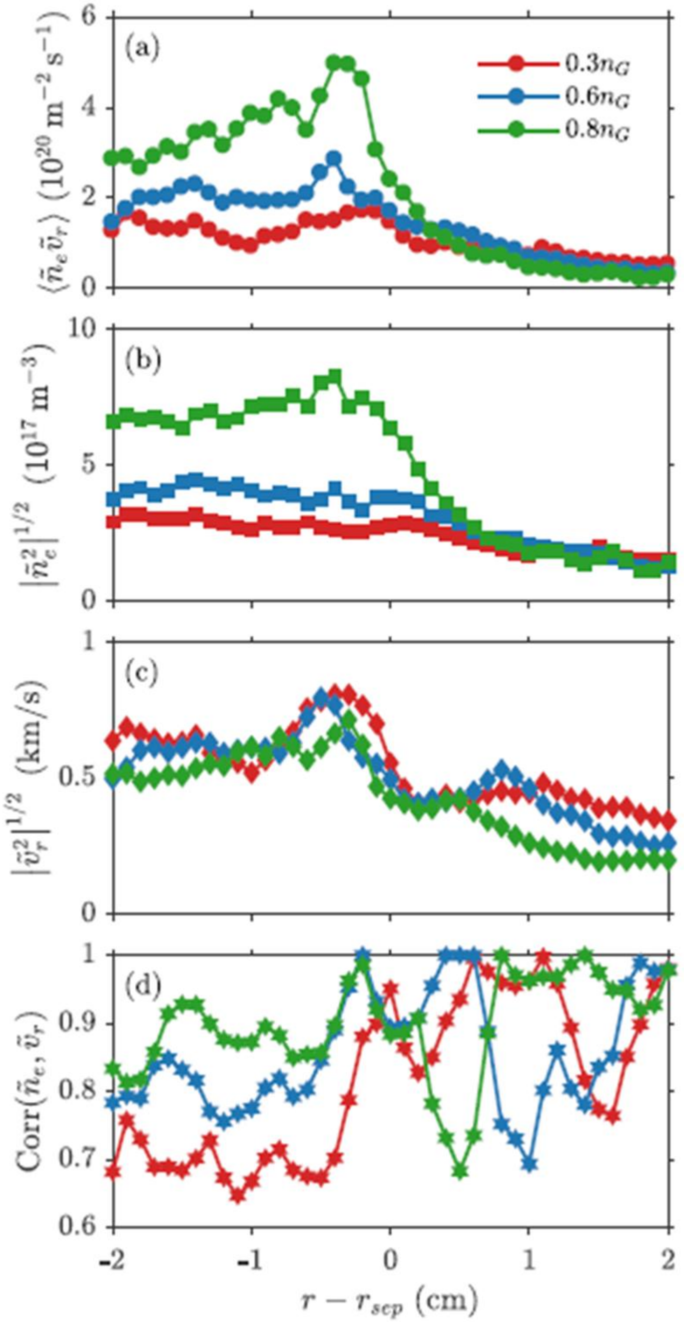
Transport

$\langle \tilde{V}_r \tilde{n} \rangle$

$\langle \tilde{n}^2 \rangle^{1/2}$

$\langle \tilde{V}_r^2 \rangle^{1/2}$

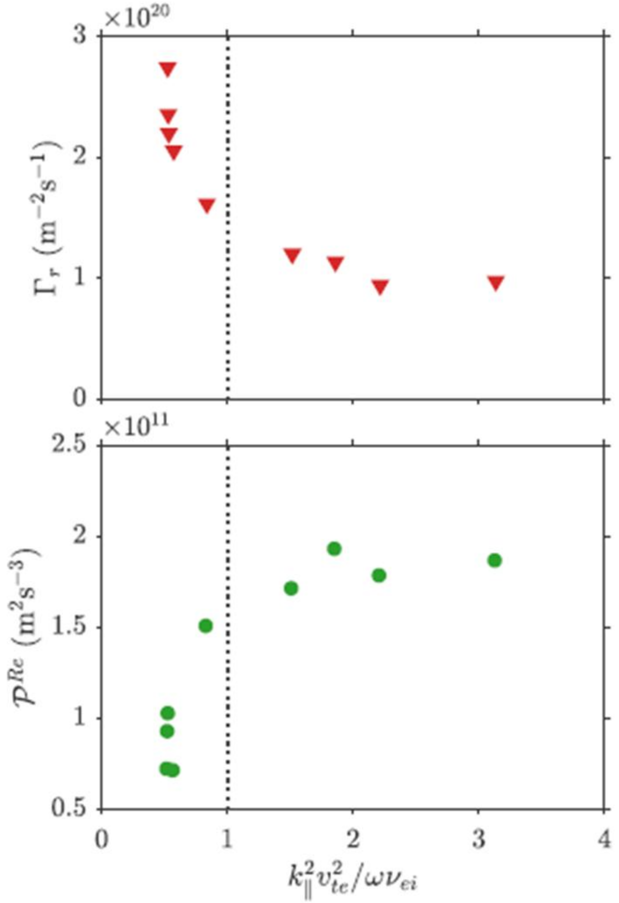
Corr



- Γ_n rises as $\bar{n} \rightarrow \bar{n}_g$
- Density fluctuations rise dramatically.

The Key Parameter

- Electron adiabaticity emerges as the telling local parameter ➔ $k_{\parallel}^{2}V_{the}^{2}\,/\omega\gamma$
- Drops from ~ 3 → 0.5 during $\bar{n}$ scan

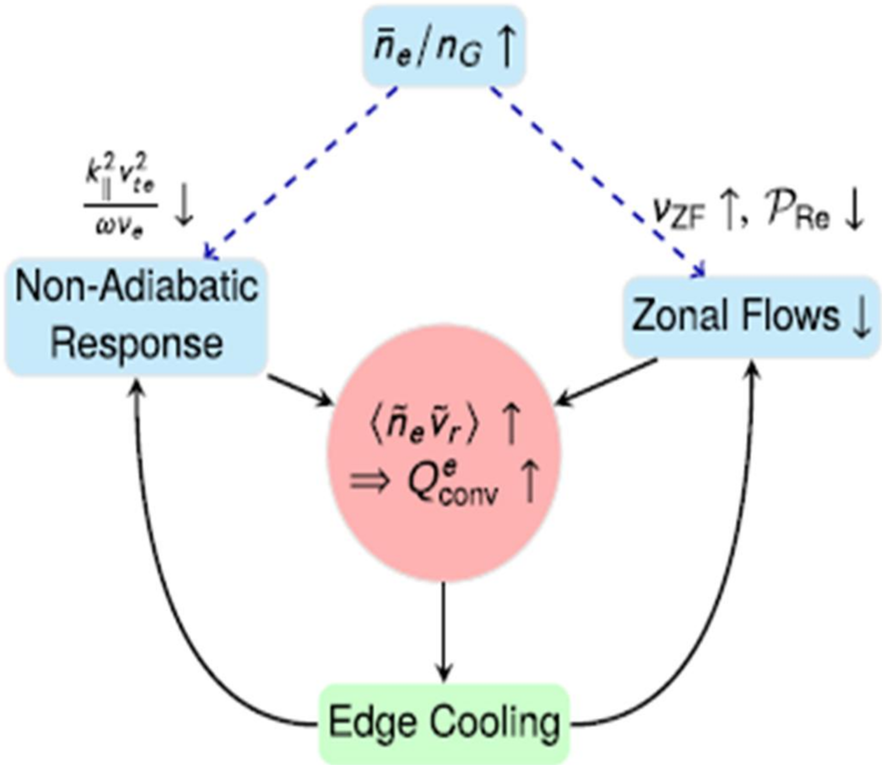


- Reynolds work plummets as

  $k_{\parallel}^{2}V_{the}^{2}\,/\omega\gamma \ll 1$

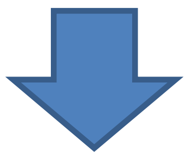
- $P_{Re}\downarrow$ as shear layer weakens
- Turbulent particle flux rises as $P_{Re}\downarrow$

The Feedback Loop (per experimentalists)



- $k_\parallel^2 V_{the}^2 / \omega\gamma > 1$ to < 1
  - Weakens ZF (how?)

    N.B. beyond damping?
  - Enhances turbulence
- Increased turbulent transport cools edge



Unpleasantries

The Key Question

- What is fate of ZF for hydrodynamic electrons ($k_{\parallel}^2 V_{the}^2 / \omega\gamma < 1$)? Underlying Physics?
- How reconcile with our understanding of drift wave-zonal flow physics?

A Theory of Shear Layer Collapse

(R. Hajjar, P.D., Malkov)

Thesis:

- For hydrodynamic electrons, ZF production by drift wave turbulence drops
- DWT cannot regulate itself by zonal flow shears
- Turbulence, transport rise

N.B.

- Many simulation studies note weakening or outright disappearance of ZF in hydro. Regime
  - Numata, et. al. ‘07
  - Gamargo, et. al. ‘95
  - Ghantous & Gurcan, ‘15

  …

  - However, mechanism left un-addressed, as adiabatic electron regime of primary interest

Model: Collisional Drift Wave / Hasegawa-Wakatani → Simplest viable for edge

$$\frac{dn}{dt} = -\frac{v_{th}^2}{\nu_{ei}}\nabla_{\parallel}^2(\phi - n) + D_0\nabla^2 n$$

$$\frac{d\nabla^2\phi}{dt} = -\frac{v_{th}^2}{\nu_{ei}}\nabla_{\parallel}^2(\phi - n) + \mu_0\nabla^2(\nabla^2\phi)$$

$\alpha = \frac{k_{\parallel}^2 V_{th}^2}{\omega\gamma}$ → coupling parameter

→ Adiabaticity parameter

- Fluctuations

$$\partial_t\tilde{n} + \tilde{v}_x.\nabla\bar{n} = -\frac{v_{th}^2}{\nu_{ei}}\nabla_{\parallel}^2(\tilde{\phi} - \tilde{n}) - \{\tilde{\phi}, \tilde{n}\} + D_0\nabla^2\tilde{n}$$

$$\partial_t\nabla^2\tilde{\phi} + \tilde{v}_x.\nabla\overline{\nabla^2\phi} = -\frac{v_{th}^2}{\nu_{ei}}\nabla_{\parallel}^2(\tilde{\phi} - \tilde{n}) - \{\tilde{\phi}, \nabla^2\tilde{\phi}\} + \mu_0\nabla^2(\nabla^2\tilde{\phi})$$

- Mean Fields:

$$\partial_t\bar{n} = -\partial_x\langle\tilde{V}_x\tilde{n}\rangle + D_0\bar{\nabla}_x^2\bar{n}$$

$$\partial_t\overline{\nabla_x^2\phi} = -\partial_x\langle\tilde{V}_x\nabla^2\tilde{\phi}\rangle + \mu_0\nabla_x^2\overline{\nabla_x^2\phi}$$

A Simple Argument: Wave Propagation (Quasilinear)

- Fundamental dispersion character charges between $\alpha > 1$ and $\alpha < 1$, i.e.

- $\alpha > 1$ → traditional 'drift wave' scaling

$$\omega = \frac{\omega_*}{1+k_\perp^2\rho_s^2} + i\,\frac{\omega_{*e}k_\perp^2\rho_s^2}{\alpha}\,, \qquad \alpha > 1$$

↑ wave + inverse dissipation

- $\alpha < 1$ → hydrodynamic 'convective cell' scaling

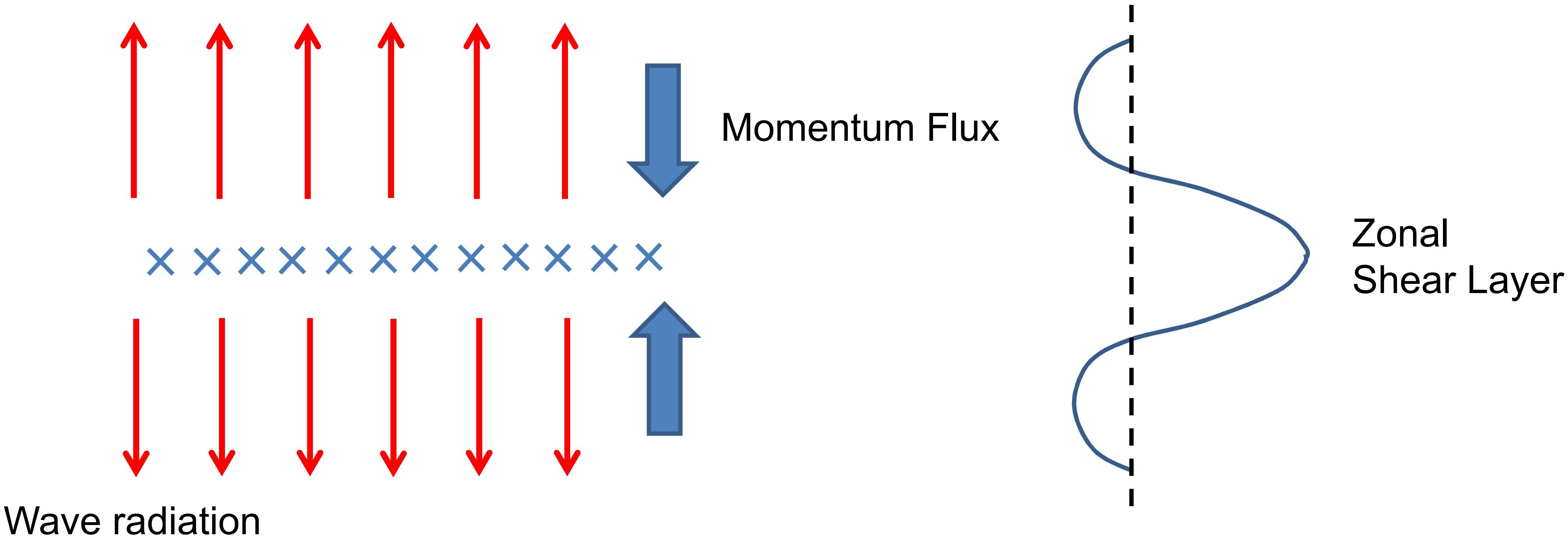
- $$\omega = \left(\frac{|\omega_*|\hat{\alpha}}{2k_\perp^2\rho_s^2}\right)^{1/2}(1+i), \qquad \hat{\alpha} = \frac{k_\parallel^2 V_{th}^2}{\gamma}$$

↖ Cell

Ubiquity of Zonal Flow?

- 'Standard argument': ZF → made of minimal { Inertia, Damping, transport } (DI^2H)
- My favorite: (GFD)

"… the central result that a rapidly rotating flow, when stirred in a localized region, will converge angular momentum into the region" (Isaac Held, '01)



Why?

- Direct proportionality of wave group velocity to Reynolds stress ←→ spectral correlation $\langle k_x k_y \rangle$

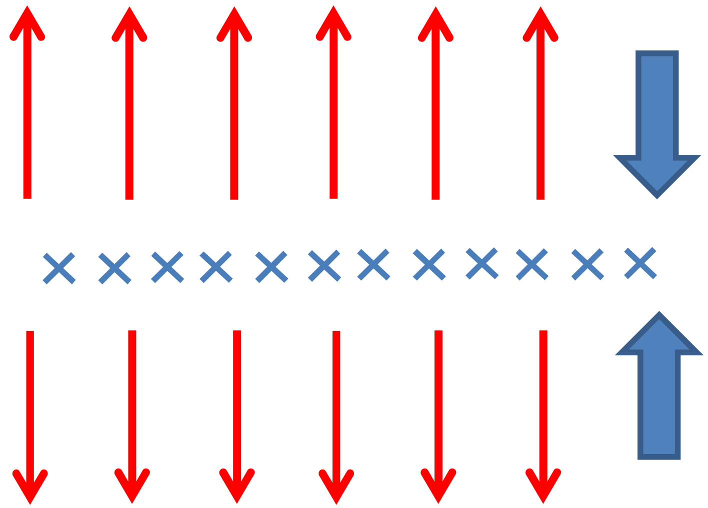
i.e.

$\omega_k = -\beta\, k_x / k_\perp^2$: (Rossby)

$V_{g,y} = 2\beta\, k_x k_y / (k_\perp^2)^2$

$\langle \tilde{V}_y \tilde{V}_x \rangle = -\sum_k k_x k_y |\phi_k|^2$

So: $V_g > 0\ (\beta > 0)$ ⬅➔ $k_x k_y > 0$ ➔ $\langle \tilde{V}_y \tilde{V}_x \rangle < 0$



- Outgoing waves generate a flow convergence! ➔ Shear layer spin-up

But for hydro limit:

- $\omega_r = \left[\frac{|\omega_{*e}|\hat{\alpha}}{2k_\perp^2\rho_s^2}\right]^{1/2}$

- $V_{gr} = -\frac{2k_r\rho_s^2}{k_\perp^2\rho_s^2}\,\omega_r \quad \overset{?}{\leftarrow\rightarrow} \quad \langle\tilde{V}_r\tilde{V}_\theta\rangle = -\langle k_r k_\theta\rangle$

→ Link between energy, momentum flux link <u>weakened</u>

↓

→ Eddy tilting ($\langle k_r k_\theta\rangle$) does not arise as consequence of causality

➔ ZF generation <u>not</u> 'natural' outcome in hydro regime!

N.B. Issue is somewhat non-trivial in that:

- Symmetry breaking ←→ ∇n
- Mode coupling
- PV mixing

→ All persist in hydrodynamic regime

➔ Need look in depth

Reduced Model

- Utilize models for real space structure to address shear layer

  e.g. { Balmforth, et. al. / Ashourvan, P.D. } ➔ Outgrowth of staircase studies

  See also: J. Li, P.D. '2018 (PoP)

- Exploit PV conservation:
  - $q = \ln n - \nabla^2 \phi$ → conserved PV
  - $\tilde{q} = \tilde{n} - \nabla^2 \tilde{\phi}$

So

- Natural description: $\langle n \rangle, \langle \nabla^2 \phi \rangle, \langle \tilde{q}^2 \rangle = \varepsilon$ ε = fluctuation P.E.

Reduced Model, cont'd

$$\partial_t n = -\partial_x \Gamma_n + D_0 \nabla_x^2 n$$

$$l_{mix} = \frac{l_0}{\left(1 + \frac{(l_0 \nabla u)^2}{\varepsilon}\right)^{\delta}} \rightarrow l_0$$

$$\partial_t u = -\partial_x \Pi + \mu_0 \nabla_x^2 u$$

$$\partial_t \varepsilon + \partial_x \Gamma_\varepsilon = -(\Gamma_n - \Pi)(\partial_x n - \partial_x u) - \varepsilon^{\frac{3}{2}} + P$$

- Fluxes:

Γ_n → Partial flux $\langle \tilde{V}_x \tilde{n} \rangle$

Π → Vorticity flux $\langle \tilde{V}_x \nabla^2 \tilde{\phi} \rangle = -\partial_x \langle \tilde{V}_x \tilde{V}_y \rangle$ (Taylor)

↕

Reynolds Force

Γ_ε → spreading, $\langle \tilde{V}_x \tilde{\varepsilon} \rangle$ → triad interactions

The Fluxes – Physics Content

- Proceed by QLT

- $\Pi = -\chi_y \, \partial_x u + \Pi_{resid}$

Diagonal,
Shear relaxation

Residual ←→ ∇n, via $\hat{\alpha}$
Production → key measure
(K-H ignored)

- $\Gamma_n = -D_n \nabla n$

- Primary focus on scalings with $\underline{\alpha}$

- i.e. what changes as $\alpha > 1 \;\rightarrow \alpha < 1$

Basic Results

- Adiabatic ($\hat{\alpha} \gg |\omega|$)

$$n_0\Gamma_n = -\frac{\langle \delta v_x^2 \rangle}{\hat{\alpha}} \frac{d\bar{n}}{dx} \simeq -\frac{\varepsilon l_{mix}^2}{\hat{\alpha}} \frac{d\bar{n}}{dx}$$

$$\Pi = -\frac{|\gamma_m| \langle \delta v_x^2 \rangle}{|\omega|^2} \frac{d^2 \bar{v}_y}{dx^2} - \frac{\omega_{ci} \langle \delta v_x^2 \rangle}{\hat{\alpha}} \frac{d\bar{n}}{dx} \left(\frac{k_\perp^2 \rho_s^2}{1 + k_\perp^2 \rho_s^2} \right)$$

$$\simeq -\frac{\varepsilon l_{mix}^2}{\hat{\alpha}} \frac{d^2 \bar{v}_y}{dx^2} - \frac{\omega_{ci} \varepsilon l_{mix}^2}{\hat{\alpha}} \frac{d\bar{n}}{dx}$$

- Reduction:

$$\Gamma_n \simeq -(\varepsilon l_{mix}^2 / \hat{\alpha}) \nabla \bar{n}$$

$$\chi_y \simeq \varepsilon l_{mix}^2 / \hat{\alpha}$$

$$\Pi^{res} \simeq -(\omega_{ci} \varepsilon l_{mix}^2 / \hat{\alpha}) \nabla \bar{n}$$

Results, cont'd

- Hydrodynamic ($\hat{\alpha} \ll |\omega|$)

$$n_0\Gamma_n \simeq -\sqrt{\frac{k_\perp^2\rho_s^2}{2k_\theta\rho_s c_s}}\sqrt{\frac{|d\bar{n}/dx|}{\hat{\alpha}}}\langle\delta v_x^2\rangle \simeq -\frac{\varepsilon l_{mix}^2}{\sqrt{\hat{\alpha}|\omega^\star|}}\frac{d\bar{n}}{dx}$$

$$\Pi = -\frac{|\gamma_m|\langle\delta v_x^2\rangle}{|\omega|^2}\frac{d^2\bar{v}_y}{dx^2} - \frac{\omega_{ci}\langle\delta v_x^2\rangle}{k_\theta\rho_s c_s}.\sqrt{\frac{k_\perp^2\rho_s^2}{2}}\sqrt{\frac{\hat{\alpha}}{|\omega^\star|}}$$

$$\simeq -\frac{\varepsilon l_{mix}^2}{\sqrt{\hat{\alpha}|\omega^\star|}}\frac{d^2\bar{v}_y}{dx^2} - \frac{\omega_{ci}\varepsilon\sqrt{\hat{\alpha}}l_{mix}^2}{|\omega^\star|^{3/2}}\frac{d\bar{n}}{dx}$$

- Reduction:

$$\Gamma_n \simeq -(\varepsilon l_{mix}^2/\sqrt{\hat{\alpha}|\omega^\star|})\nabla\bar{n}$$

$$\chi_y \simeq \varepsilon l_{mix}^2/\sqrt{\hat{\alpha}|\nabla\bar{n}|}$$

$$\Pi^{res} \simeq -(\omega_{ci}\varepsilon\sqrt{\hat{\alpha}}l_{mix}^2/|\omega^\star|^{3/2})\nabla\bar{n}$$

Shear Strength!?

- Vorticity gradient emerges as natural measure

  of production vs. turbulent mixing

  i.e. Π_{resid} vs. χ_y

- Stationary vorticity flux:

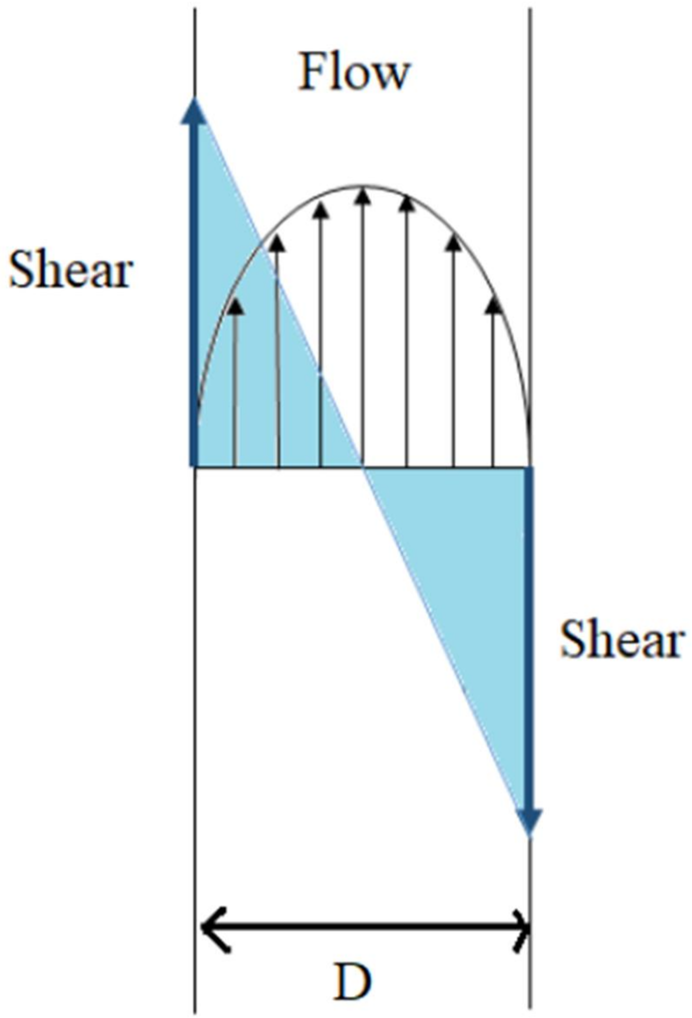
$$\nabla u = \Pi_{resid} \ / \ \chi_y$$

n.b.: $u' = \left(V_y'\right)'$

∇u as FOM

- How characterize layer?

Shear Strength, cont'd



- Jump in flow shear over scale D equivalent to vorticity gradient on that scale
- Vorticity gradient characteristic of flow shear layer strength
- N.B. ∇u central measure of Rossby wave elasticity!

$$l_{Rh} \sim \left(\tilde{V}/\nabla u\right)^{1/2}$$

Tabulation: α scaling - answer

Plasma Response	Adiabatic $\alpha \gg 1$	Hydrodynamic $\alpha \ll 1$
Turbulent enstrophy $\sqrt{\varepsilon}$	$\sqrt{\varepsilon} \propto 1/\alpha$	$\sqrt{\varepsilon} \propto 1/\sqrt{\alpha}$
Particle Flux Γ	eq.(20a) $\Gamma \propto 1/\alpha$	eq.(24a) $\Gamma \propto 1/\sqrt{\alpha}$
Turbulent Viscosity χ_y	eq.(20b) $\chi_y \propto 1/\alpha$	eq.(24b) $\chi_y \propto 1/\sqrt{\alpha}$
Residual Stress Π^{res}	eq.(20c) $\Pi^{res} \propto -1/\alpha$	eq.(24c) $\Pi^{res} \propto -\sqrt{\alpha}$
$\frac{\Pi^{res}}{\chi_y} = (\omega_{ci}\nabla\bar{n})\times$	$\left(\frac{\alpha}{\lvert\omega^\star\rvert}\right)^0$	$\left(\frac{\alpha}{\lvert\omega^\star\rvert}\right)$

- Note:

$\alpha > 1, \nabla u \sim \alpha(0)$

$\alpha < 1, \nabla u \sim \alpha$

i.e. χ_y rises; Π_{resid} drops with α

- Fluctuation Intensity rises
- Particle flux rises

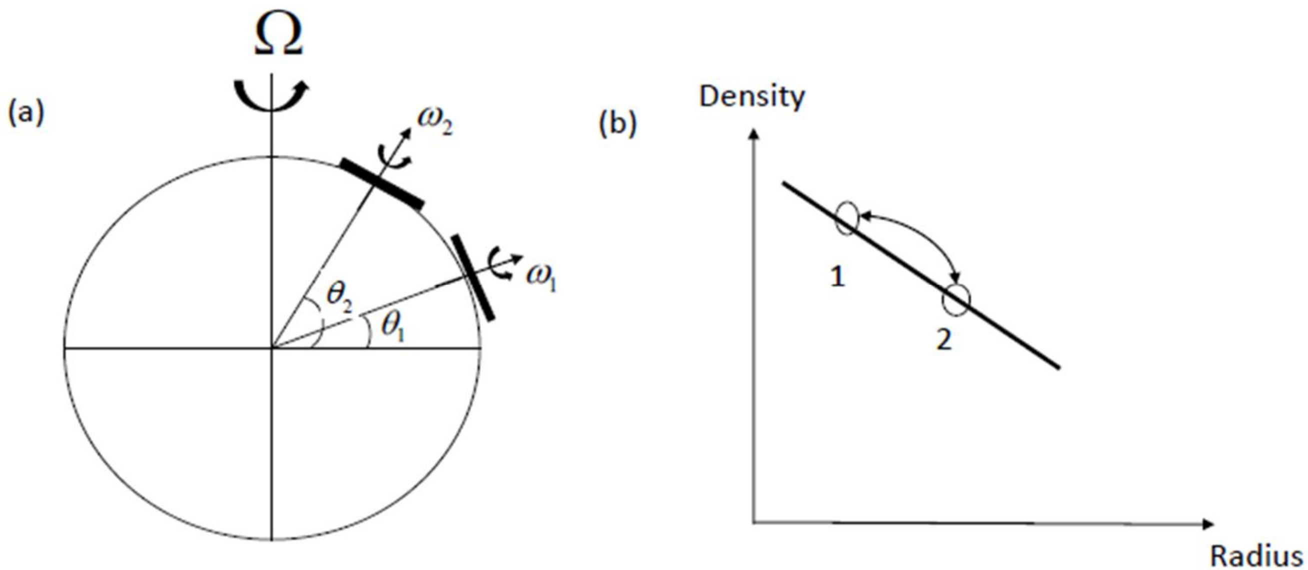
Bottom Line

- Shear Layer, via production, collapses as $\alpha \downarrow < 1$
- Transport and fluctuations rise, as $\alpha \downarrow < 1$
- Edge $\alpha = k_{\parallel}^2 V_{the}^2 / \omega\gamma$ is key local parameter

What of 'PV Mixing' ?

- PV mixing persists in hydro regime
- Key: Unlike GFD/Adiabatic Regime,

  PV mixed via several channels
- The Cartoons:



$$\left\{ \begin{array}{l} \omega + 2\Omega\hat{z} \text{ frozen in} \\ q = \nabla^2\phi + \beta y \end{array} \right.$$

PV, cont'd

- H-W:

$$q = \ln n - \nabla^2 \phi$$

$$= \ln(n_0(x)) + \frac{|e|\hat{\phi}}{T} + \tilde{h} - \rho_s^2 \nabla^2 \left(\frac{|e|\hat{\phi}}{T}\right)$$

N.B. Boltzmann response does not contribute to net PV mixing

PV mixing

$$\Gamma_q = \langle \tilde{V}_x \tilde{h} \rangle - \rho_s^2 \langle \tilde{V}_x \nabla_x^2 \left(\frac{|e|\hat{\phi}}{T}\right) \rangle$$

Branching ratio?!

PV flux

Particle flux

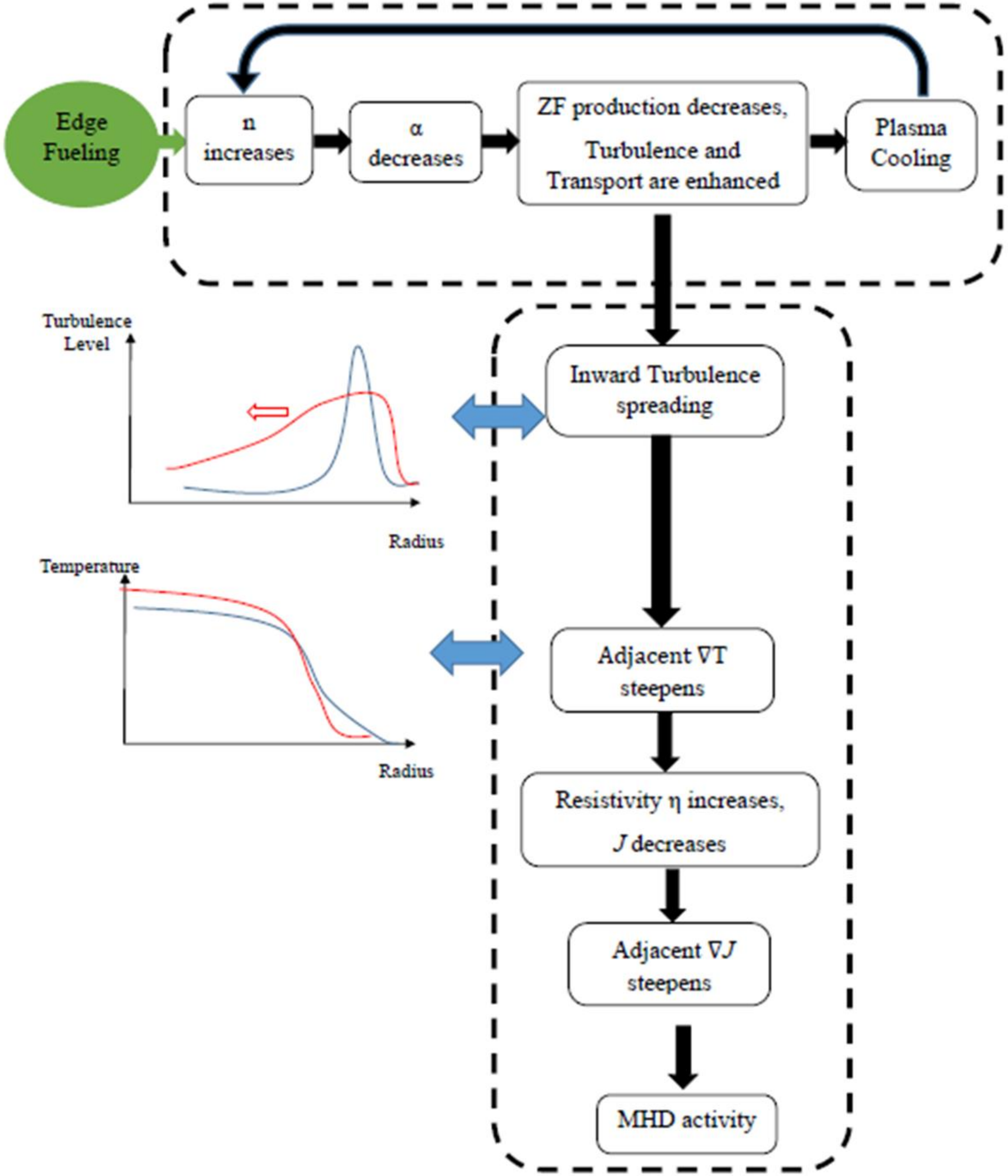
Vorticity flux, Reynolds force

PV, cont'd

$$\Gamma_q = \langle \tilde{V}_x \tilde{h} \rangle - \rho_s^2 \langle \tilde{V}_x \nabla_x^2 \left(\frac{|e|\hat{\phi}}{T} \right) \rangle$$

- $\alpha > 1$
  - Fields tightly coupled, $\sim \alpha$
  - $\Gamma_n, \ \Pi_{resid} \quad \sim \quad 1/\alpha$
  - Both channels transport PV
  - ZF robust
- $\alpha < 1$
  - Fields weakly coupled
  - $\Gamma_n \sim 1/\sqrt{\alpha}$, $\Pi_{Resid} \quad \sim \sqrt{\alpha}$
  - PV transported via particle flux
  - ZF dies

Edge Cooling Scenario



- Inward turbulent spreading can increase resistivity and steepen ∇J, resulting in MHD

N.B. For CDW, $Q \sim \Gamma_n$

Implications and Directions

Implications

- Density limit a 'back-transition' phenomenon

  i.e. drift-ZF state → convective cell, strong fluctuation turbulence

  ➔ scaling of collapse? (spatio-temporal)

  ➔ bifurcation? Trigger?, hysteresis?!

  ➔ control parameter ←→ α

- Cooling front as secondary

  ➔ Extent penetration of turbulence spreading?

  ➔ Strength, depth penetration ➔ operating regime

Directions

Experiment

- Test α criticality → $\alpha \sim T_e^{\frac{5}{2}}/n$. Achieve $\bar{n}/\bar{n}_g > 1$ with $\alpha > 1$?
- T vs n trade-off at $\bar{n}_g$? Sustain $\bar{n} > \bar{n}_g$?!
- Hysteresis in n manifested? Space-time evolution of turbulence
- Localized edge shear layer response to SMBI, small pellets? Relaxation rate, persistence
- Established α vs $\bar{n}/\bar{n}_g$ connection
- Explore changes in bi-spectra <ZF|DW,DW> vs $\bar{n}/\bar{n}_g$ (after Schmid, et. al.)
- Core-edge coupling?

Directions, cont'd

Theory / Model

- As usual, more 'stuff' in model…

⇩

- N.B. In HL-2A, $\alpha_{MHD} \uparrow$ 0.1 → 0.3

  $\alpha \downarrow$ 3 → 0.5

  Onset of RBM dubious

- In particular:
  - Neutral penetration – i.e. fueling source

    → CX damping of flows
  - Impurity → build-up
  - $Q_{e,core}$ explicit

L→H model of Miki et.al.

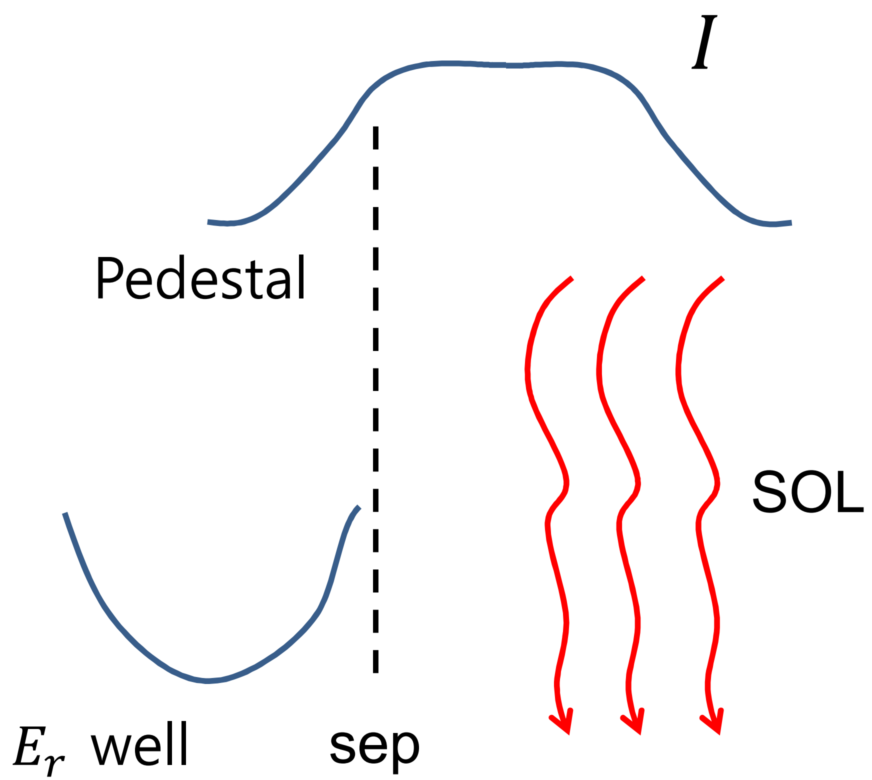
may be useful

Dynamical Modelling

- Feedback loop
- Macroscopics vs α
- Layer scale, expansion
- Heating vs fueling trade-off
- $\bar{n} / \bar{n}_g \leftrightarrow \alpha$?

Density Limit in H-mode

- SOL strongly turbulent; pedestal quiescent
- Shear layer at separatrix
- Turbulence penetration of pedestal (H→L BACK Transition) ➔ needed for $\bar{n}$ limit phenomena
- SOL turbulence set by:
  - Q
  - Fueling
  - Divertor conditions

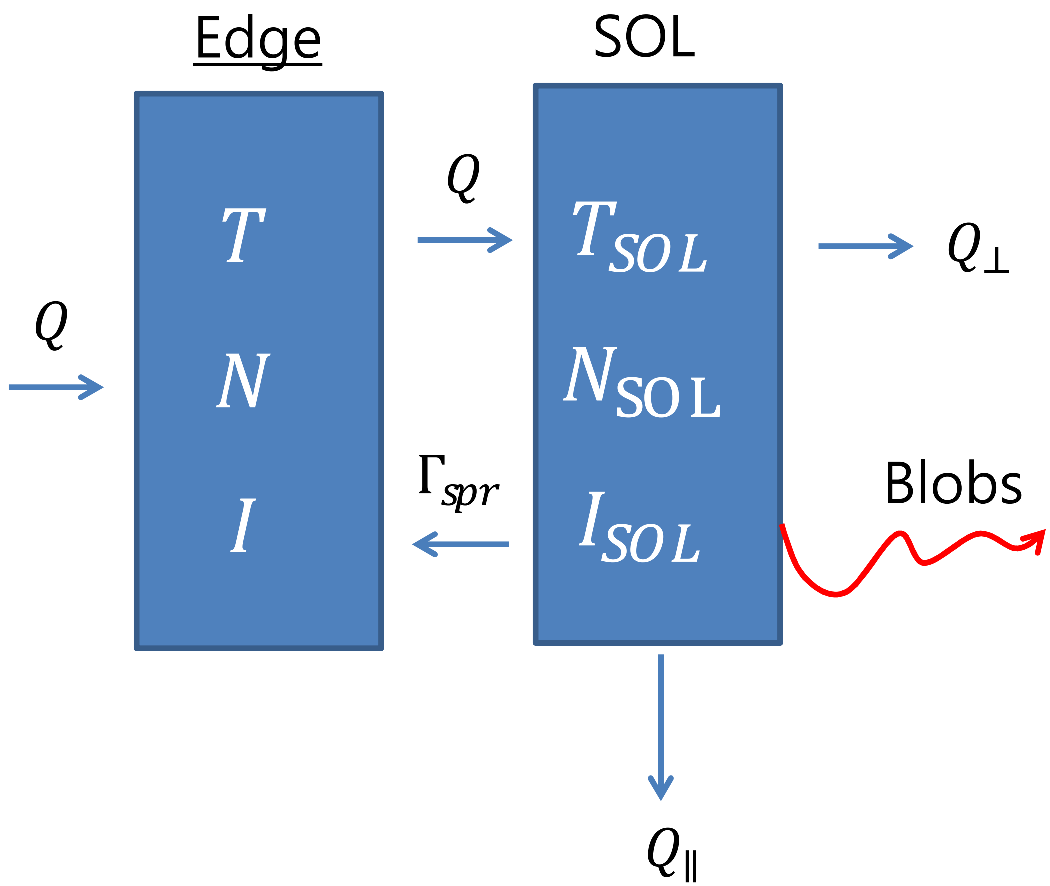


n.b. SOL curvature unfavorable

Treat via Box Model

(ZBG, PD 2018)

- $Q_{\perp}$, $Q_{\parallel}$ regulate I_{SOL}
- Sufficient I_{SOL} → ETB penetration
- What are fueling, n_{SOL}, Q to trigger turbulence in flux and pedestal collapse. Barrier penetration is critical?
- Recent: H-mode density limit set by SOL ballooning?! (SOL P limit) (Goldston, Sun)



Conclusions

- Density limit is consequence of particle transport processes
- L-mode density limit experiments:
  - Edge, turbulence-driven shear layer collapse
  - Local parameter $\alpha = k_{\parallel}^2 V_{th}^2 / \omega\gamma$
- Theory indicates:
  - Zonal flow production drops with α, $\alpha < 1$
  - Edge transport, turbulence $\uparrow$

➔ Self-regulation fails

- $\bar{n}$-limit in L-mode as transition from drift-zonal turb. ➔ strong drift turbulence