Blob transport at high collisionality and the SOL density limit

D. A. D'Ippolito, J. R. Myra, and D. A. Russell
Lodestar Research Corporation

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Summary and Conclusions

- **Coherent structures ("blobs")** created by edge turbulence $\Rightarrow$ convective transport of particles and heat across the SOL

- Experiments, simulations and theory show that the **transport rate increases with collisionality**.
  - increased collisionality Λ (and resistivity $\eta_{||}$) $\Rightarrow$ strong ballooning (disconnection from sheaths) $\Rightarrow$ faster ExB drift
  - **new 2-region 2D code** encapsulates the essential physics

    $\Rightarrow$ reduced connection to sheaths, larger turbulent flux at high Λ

- A **correspondence rule** ($\gamma \rightarrow v_x/a_b$) has been exploited to understand **new regimes of blob transport**
  - includes collisionality and geometry dependence
  - valid in near SOL and edge region (blob birth zone)
  - **blob transport ~ mixing length transport** in edge plasma at high Λ

- **2-region thermal equilibrium model** gives good agreement with C-Mod experiments
  - **convective density limit (CDL)** due to thermal instability
  - CDL corresponds to $q_\perp > q_{||}$ in edge plasma
  - occurs at high collisionality
- The **general picture** from all of this work is that:
  - the distinction between edge and SOL disappears at high collisionality because of shorter $L_{||} \sim \lambda_{ei}$
  - edge transport increases dramatically and can be estimated using collisional blob models with "packing fraction" ~ 1

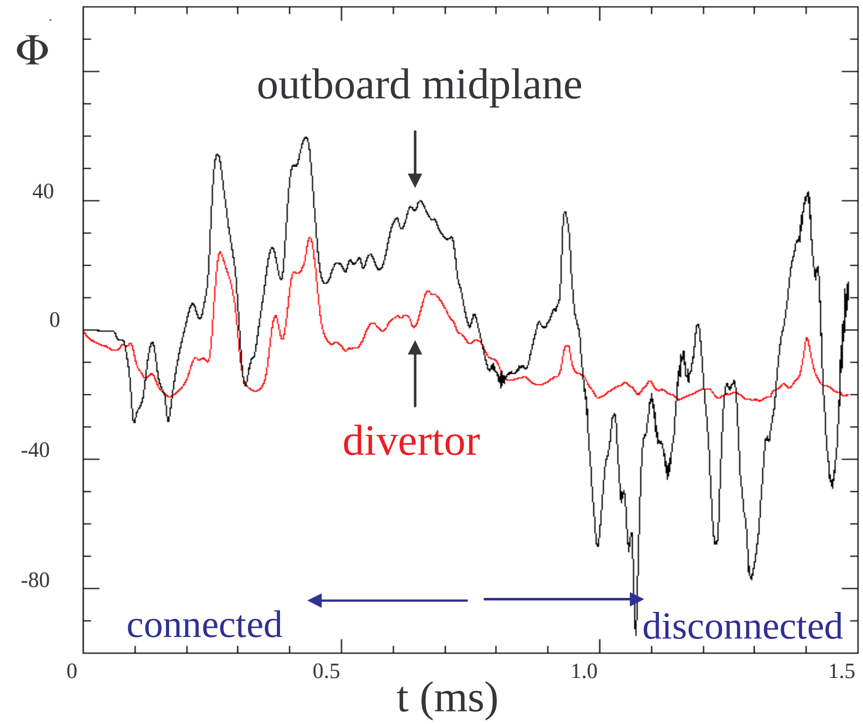
3D BOUT turbulence simulations show faster blobs at higher collisionality

BOUT simulation with $\delta n/n \sim 1$ by X. Xu (2003);

Blob analysis by D. Russell (2004)

$\Rightarrow$ 3D structure is important!

- **density and collisionality Λ increase with time (gas puffing)**
- **blobs disconnect from divertor region and move faster as $\eta_{||}$ and Λ increase**



Russell et al, Phys. Rev. Lett 2004

Physical picture: linear growth rate, blob velocity and turbulent transport increase with $\eta_{||} \propto \nu_e \propto \Lambda$

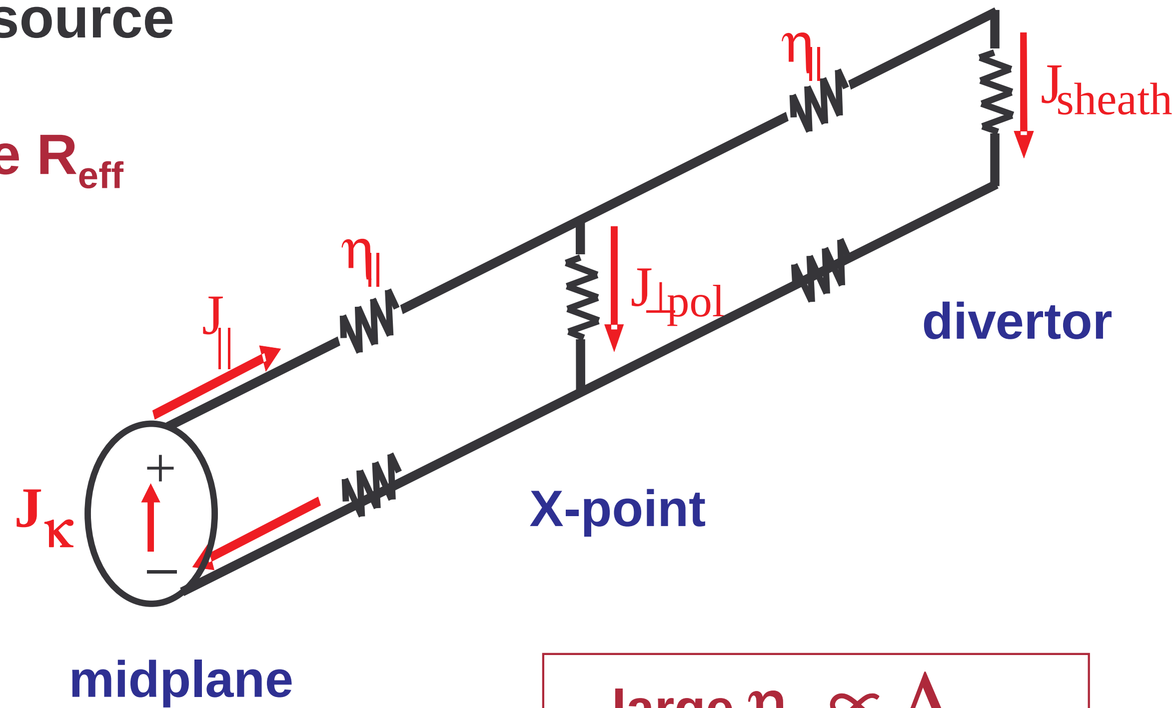
Curvature drift $\Rightarrow$ current source

Effective circuit resistance R_{eff}

$\Rightarrow$ **potential** $\Phi \sim R_{eff} J_\kappa L_{||}$

$\Rightarrow$ **growth rate** γ (linear)

$\Rightarrow$ **E $\times$ B speed** v_x (blob)



large $\eta_{||} \propto \Lambda$

$\Rightarrow$ **disconnection**

Blob transport and mixing length estimate

In the edge plasma, the blob and mixing length transport estimates agree in order of magnitude provided that the blob "packing fraction" ~ 1 (skewness ~ 1) and we use the "**blob correspondence rule**" (see next page).

Mixing length estimate:

$$\tilde{v}_x \sim i k_\perp \tilde{\Phi} \;, \quad \tilde{n}/n_0 \sim k_\perp \tilde{\Phi}/(\omega L_n) \;,$$

Use saturation condition: $\omega \sim k_\perp \tilde{v}_\perp \;\Rightarrow\; \tilde{\Phi} \sim \omega / k_\perp^2$

$$\Rightarrow \;\Gamma \sim \mathrm{Re}[\tilde{n}\,\tilde{v}_x^*] \sim n_0 \gamma/(k_\perp^2 L_n)$$

Blob estimate:

$$\Gamma \sim n_b v_x \quad \text{where} \;\; n_b \sim n_0 \;\; \text{and} \;\; v_x \sim \gamma a_b \quad \text{(correspondence rule)}$$

Using the correspondence rule, both estimates agree.

Correspondence rule between linear instability and nonlinear blob physics

- As noted by *Endler et al. (NF 1995)* for sheath-interchange modes, there is a correspondence between the linear instability and the resulting turbulence.
- For all instabilities that saturate by wave breaking ($\omega \sim k \cdot \tilde{v}$) we postulate the following **correspondence rule** between the instability and the blob velocity:

$$\gamma \rightarrow \frac{v_x}{a_b}, \quad k_\perp \rightarrow \frac{1}{a_b}, \quad L_n \rightarrow a_b$$

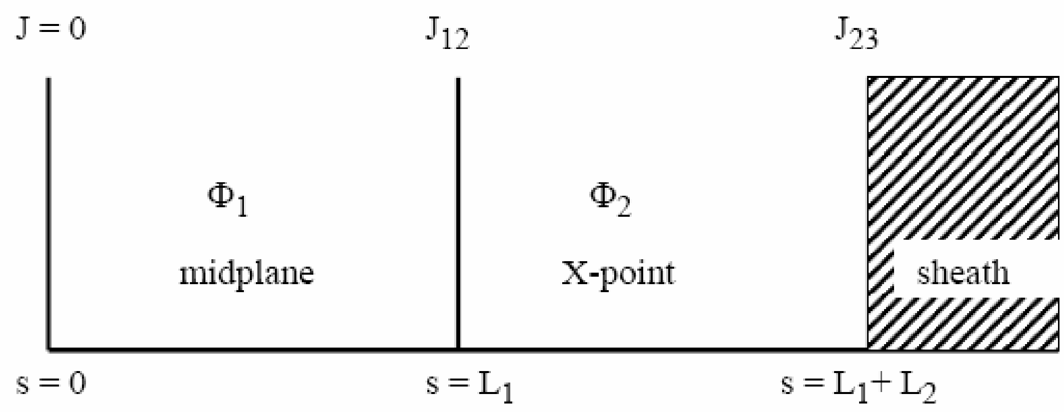
growth rate

wavenumber

density
scale length

blob radius

Two-region 2D model for studying transition to collisional, disconnected regimes



Notes:
- **similar eqs. for T_j, but T = const. here**
- **Bohm units (dimensionless)**

charge

$$n_1 \frac{d}{dt} \nabla^2_{\perp 1} \Phi_1 = J_{12} / L_1 - \beta \frac{\partial n_1}{\partial y} \qquad n_2 \frac{d}{dt} \nabla^2_{\perp 2} \Phi_2 = (J_{23} - J_{12}) / L_2$$

$$J_{\perp pol} \;:\; J_{\|} \;:\; \text{curvature} \qquad J_{\perp pol} \;:\; J_{\|sh} \;:\; J_{\|}$$

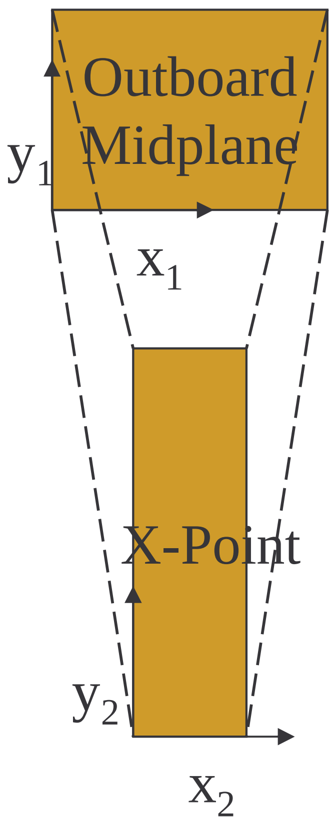
density

$$\frac{dn_1}{dt} + \Gamma_{12} / L_1 = 0 \,, \quad \Gamma_{12} = n_1 c_{s1} \,, \qquad \frac{dn_2}{dt} = (\Gamma_{12} - \Gamma_{23}) / L_2 \,, \quad \Gamma_{23} = n_2 c_{s2} \,,$$

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \qquad J_{12} = \frac{-\sigma_{12}}{L_{12}} (\Phi_2 - \Phi_1) \,, \quad J_{23} = n_2 \alpha \Phi_2$$

Cross-field conductivity is enhanced in region 2 (X-pt) by field line fanning f

- Field lines from midplane region $(x, y)_1$ are mapped to stretched / squeezed coordinates in X-point region $(x, y)_2$ by “fanning factor” f << 1. At present the model neglects magnetic shear.



$$\frac{\partial}{\partial x_2} = f\,\frac{\partial}{\partial x_1}\ , \qquad \frac{\partial}{\partial y_2} = \frac{1}{f}\,\frac{\partial}{\partial y_1}\ .$$

- charge is conserved between regions 1 and 2
- sheath boundary conditions are applied at the end of region 2

$$J_{||} = n e c_s \left(1 - e^{-e(\Phi - \Phi_0)/T_e}\right)$$

$\approx 3T_e$

The model equations are invariant under a scale transformation

$$\phi \to \lambda\phi, \quad t \to \lambda^{2\mu-3} t, \quad x \to \lambda^{\mu-1} x$$

$$\sigma \to \lambda^{5-4\mu}\sigma, \qquad \text{for arbitrary } \lambda, \mu$$

$$(\rho_s / R, L_{||} / R) \to \lambda^{5-3\mu}(\rho_s / R, L_{||} / R)$$

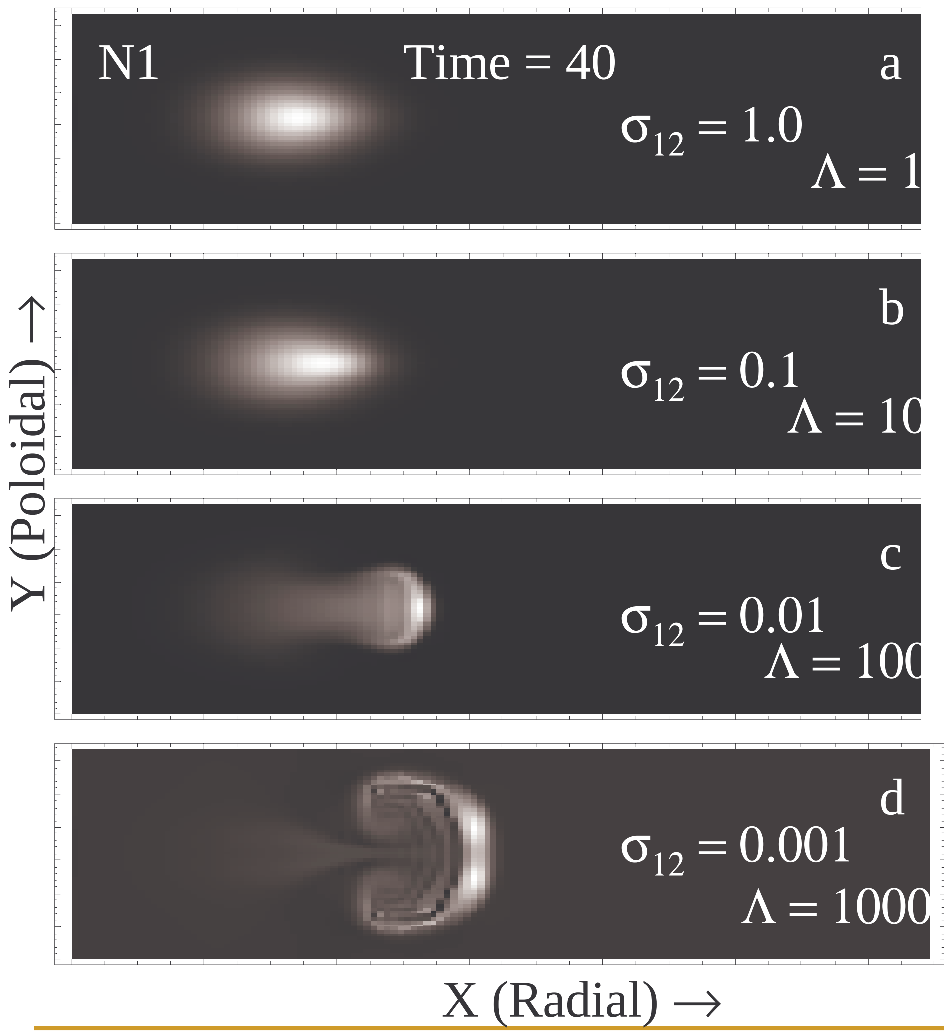
invariant scaling method:
Connor & Taylor, Phys. Fluids 1984

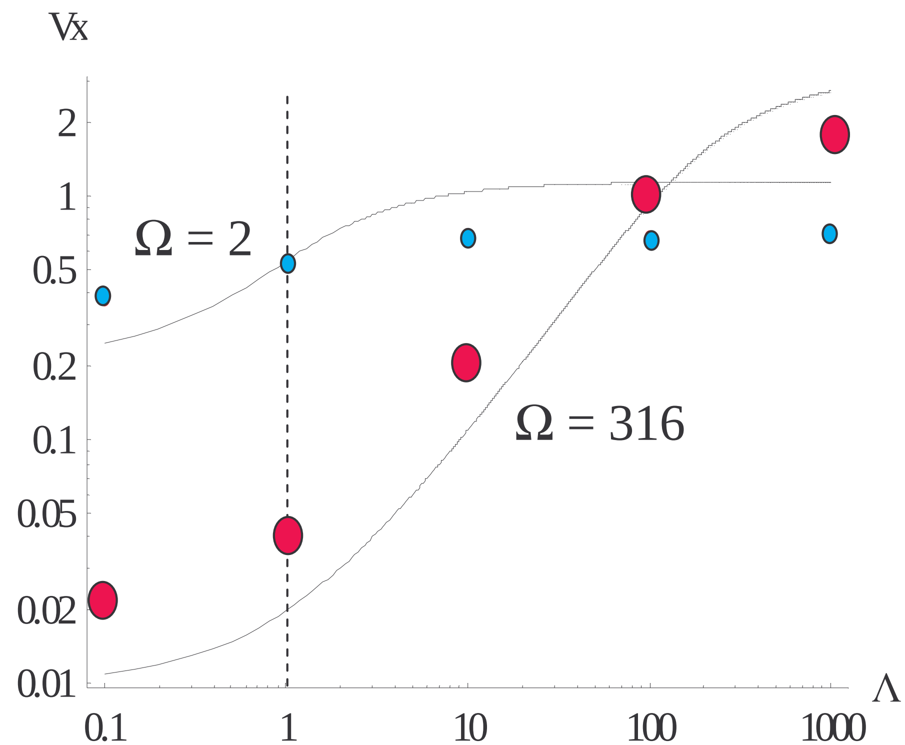
- the following ***invariant* combinations** characterize the dimensionless parameter space (Λ = collisionality, Ω = scale size)

$$\Lambda = \frac{\omega_{\eta 1}\omega_{s1}}{\omega_{a1}^2} = \frac{\nu_e}{\Omega_e}\frac{L_{||}}{\rho_s}, \qquad \Omega = \frac{\omega_{s1}}{\gamma_{mhd}} = \left(\frac{L_n R}{L_{||}^2}\right)^{1/2} \frac{1}{k_{\perp 1}^2 \rho_s^2},$$

- dispersion relation can be written as $\hat{\omega} \equiv \dfrac{\omega}{\gamma_{mhd}} = \hat{\omega}[\Lambda, \Omega(k), \varepsilon]$
- **same dispersion relation applies to blobs using the correspondence rule: $\omega \to v_x/a_b$ and L_n, $1/k_\perp \to a_b$**

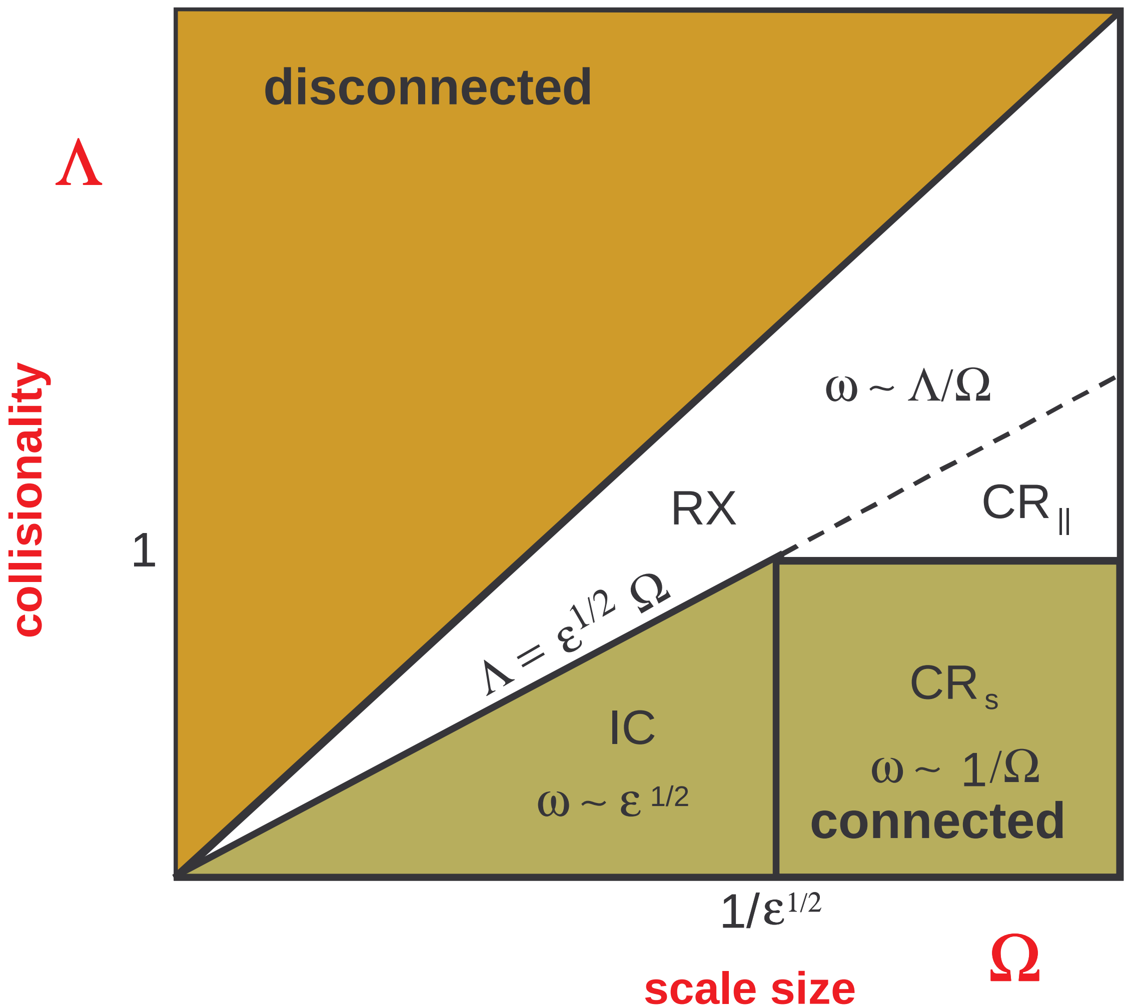
2-region code (with initialized blobs) shows good agreement with blob "dispersion relation" scaling





- **blobs speed up with increasing collisionality Λ ($\propto$ resistivity)**
- **for low Λ, small blobs move fastest** (nb: $\Omega = (a_b/a_*)^{5/2}$ **~ blob size**)

Linear instability / blob regimes



- **electrostatic 2-region model**
- $\Omega = (a_b/a_*)^{5/2}$
- $\mathbf{a^* = \rho_s^{4/5} L_{||}^{2/5} / R^{1/5}}$
- $\varepsilon \equiv \varepsilon_x^2 = f^2 =$

  X-pt fanning factor

Turbulence simulations: particle transport in two-region code

The two-region fluid turbulence code predicts an **increase in turbulent particle flux with collisionality**, as seen in experiments.

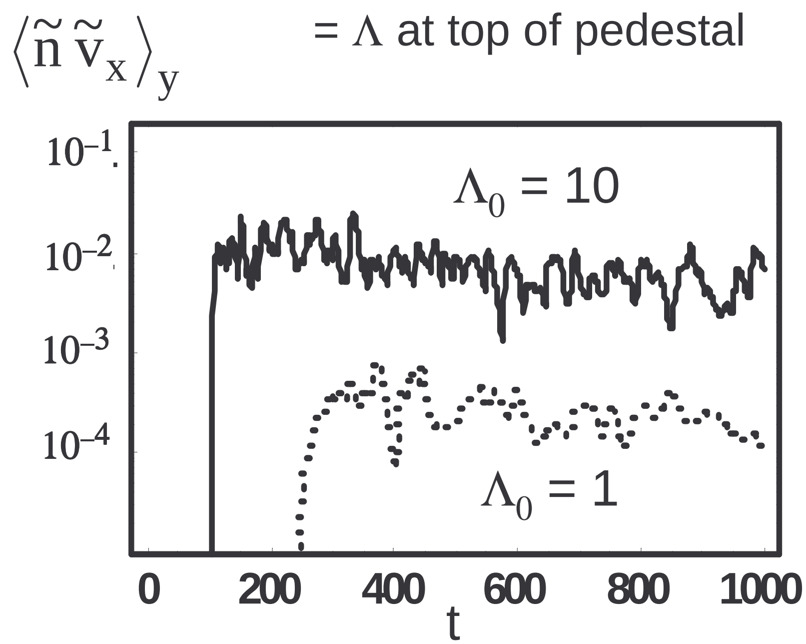
Figure: Time history of the turbulent (blob) particle flux Γ for two values of the collisionality parameter Λ_0 with f = 1/4.

Γ is averaged over poloidal direction y for a fixed radial point in the SOL.

Note the earlier onset of the nonlinear turbulent phase and the much larger particle flux for large Λ_0.

collisionality parameter Λ_0

= Λ at top of pedestal



D. Russell (2006)

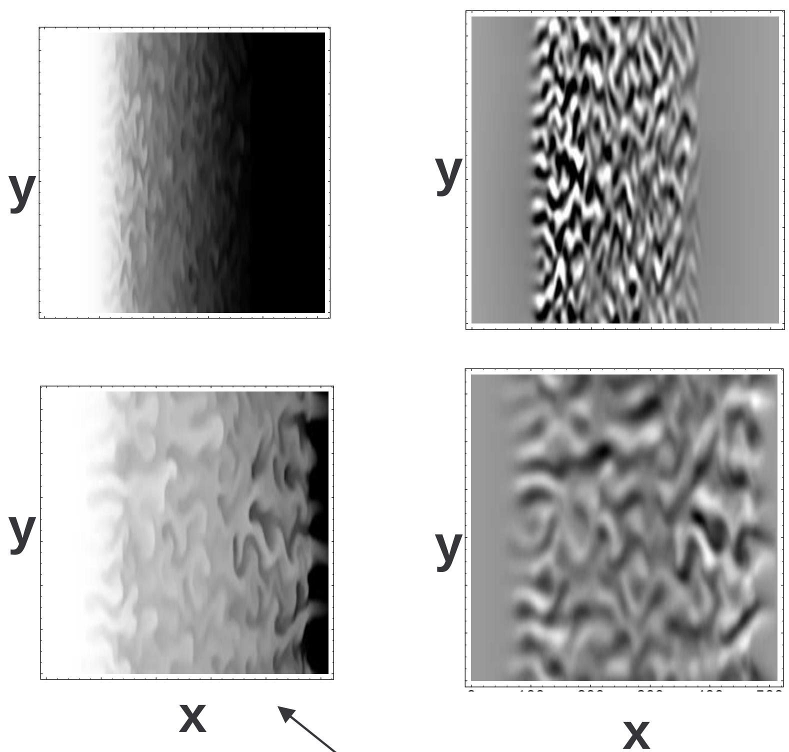
Turbulence simulations: edge / SOL turbulence & blob structure depend on collisionality

$n_1(x,y)$ $\phi_1(x,y)$

$f = 1/4,\ \beta = 1,\ \sigma_{23} = 1,\ \ t = 1000$

$\Lambda_0 = 1$

$\Lambda_0 = 10$



blobs

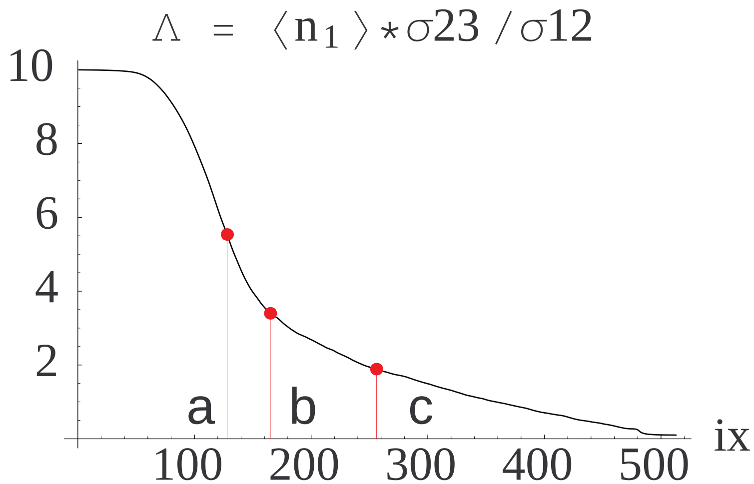
D. Russell (2006)

Note: more blobs and faster v_x as Λ_0 increases

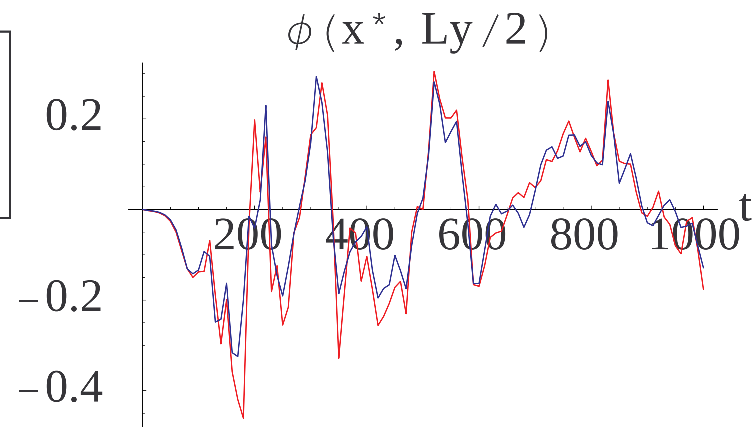
Disconnection caused by high local collisionality Λ

Red: midplane
Blue: X-point

$\phi_1(t)$, $\phi_2(t)\,|_{x,y}$ **at x = b**

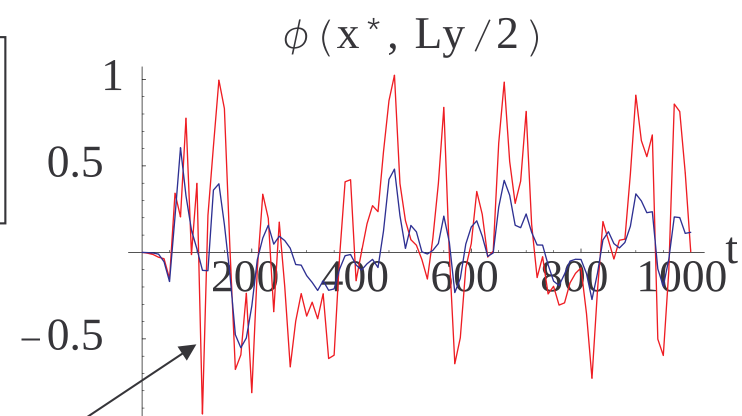


$\Lambda_0 = 1$
$\Lambda \approx 0.3$



max ∇(ln n) at x = b

$\Lambda_0 = 10$
$\Lambda \approx 3$



$f = 1/4$, $\beta = 1$, $\sigma_{23} = 1$

partially disconnected: $\phi_1(t) > \phi_2(t)$

D. Russell (2006)

SOL density limit due to blob heat transport

In this work, we include heat transport in an analytic 2-region model for (Φ, T_e) with n_1, n_2 = const.

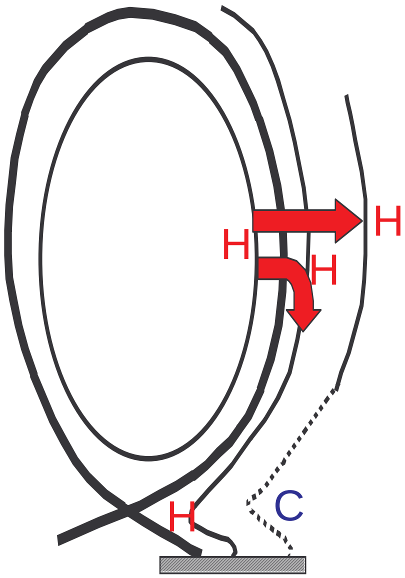
$\Rightarrow$ **SOL thermal equilibrium limit $\Rightarrow$ density limit**

higher density $\Rightarrow$ higher collisionality $\Rightarrow$ faster radial heat transport $\Rightarrow$ lower T $\Rightarrow$ thermal instability $\Rightarrow$ thermal collapse of SOL

- C-Mod observes **convective density limit (CDL)** with $q_\perp > q_\parallel$
- our model $\Rightarrow$ **CDL when $q_\perp$ increases as X-point cools**

(thermal instability analogous to MARFE with radiative cooling $\rightarrow$ radial convection) *(D'Ippolito and Myra, Phys. Plasmas, June, 2006)*

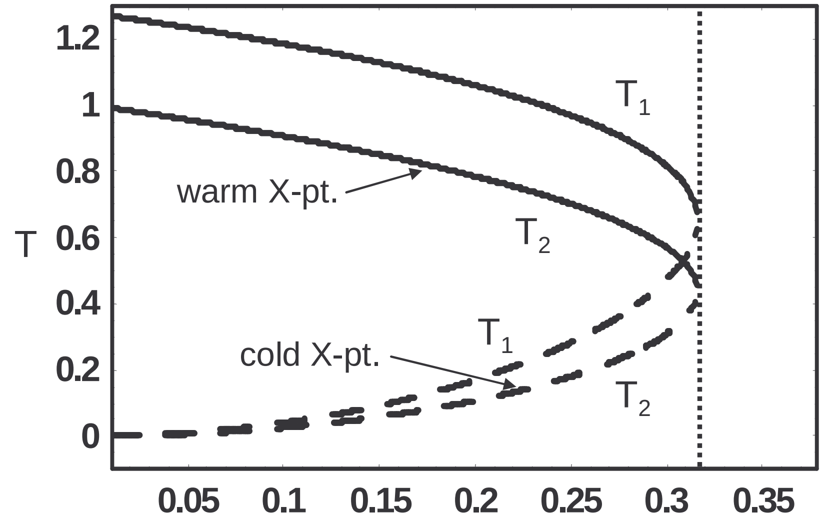
Physical picture is supported by calculation



warm X-pt root (solid) is thermally stable

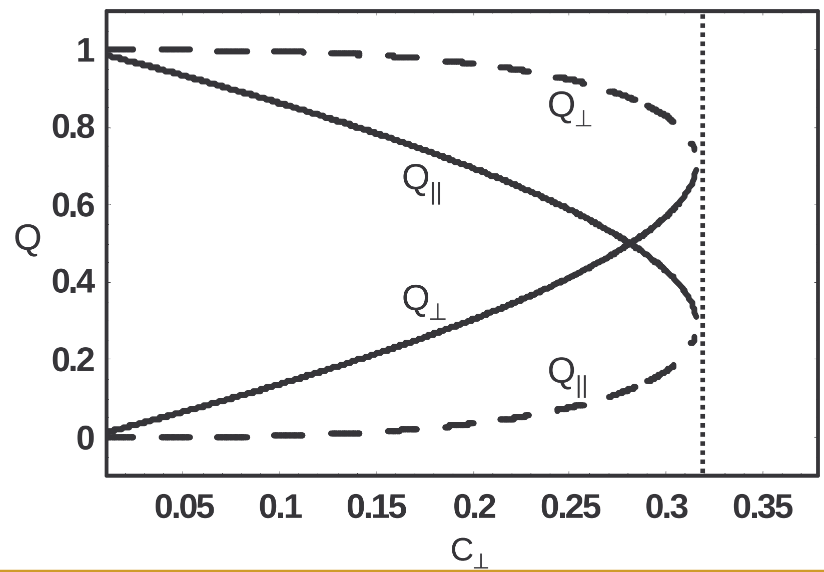
cold X-pt root (dashed) is unstable $\Rightarrow$ thermal instability of SOL

root coalescence = CDL



T_1 = midplane, T_2 = X-pt

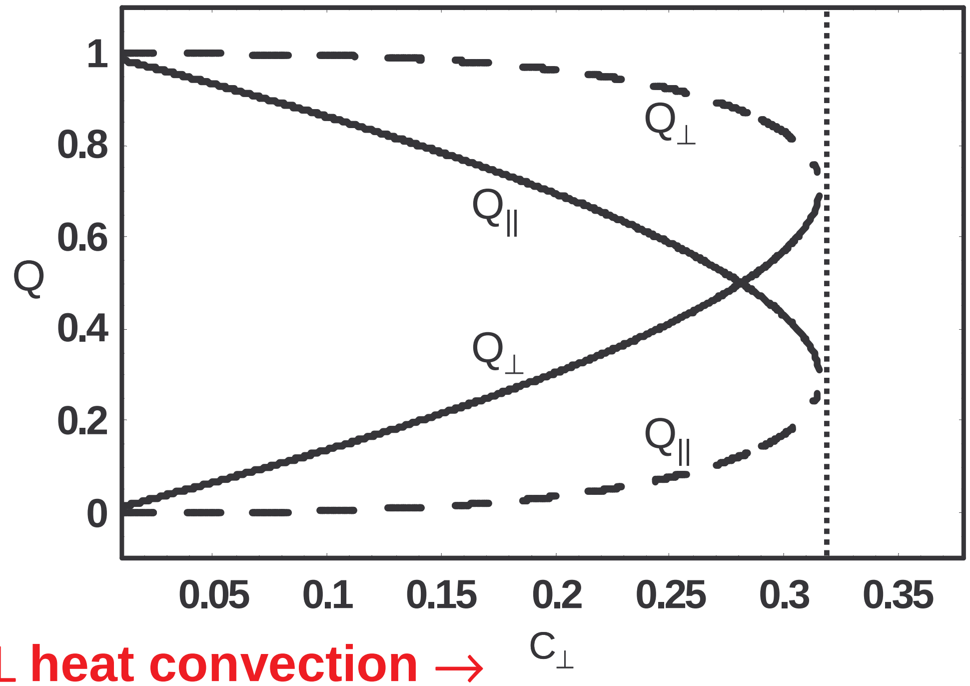
$C_\perp$ **$\perp$ heat convection $\rightarrow$**



$C_{||}$ fixed

2-region thermal equilibrium model qualitatively agrees with C-Mod density limit experiments

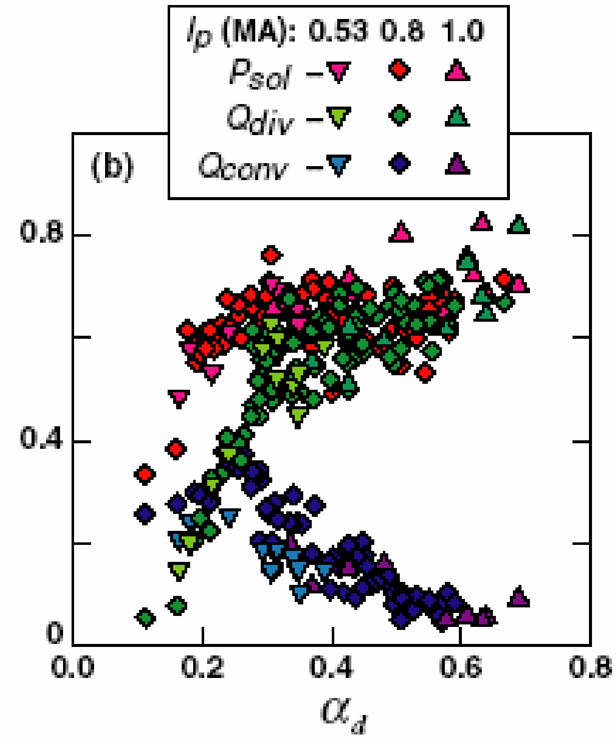
Model



⊥ heat convection →

$$\alpha_d \propto \left(\frac{1}{\Lambda}\right)^{1/2} \propto \left(\frac{1}{C_\perp}\right)^{1/2}$$

C-Mod data



LaBombard et al, NF 2005