Edge turbulence and blob transport

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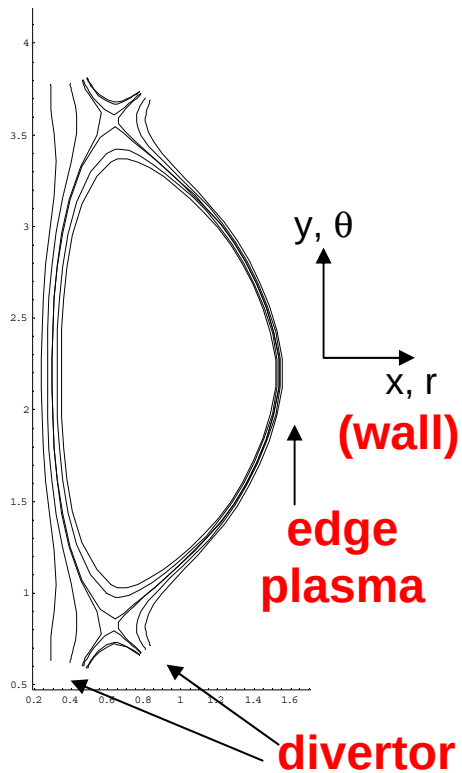
Lodestar

Edge plasma physics is important for fusion research

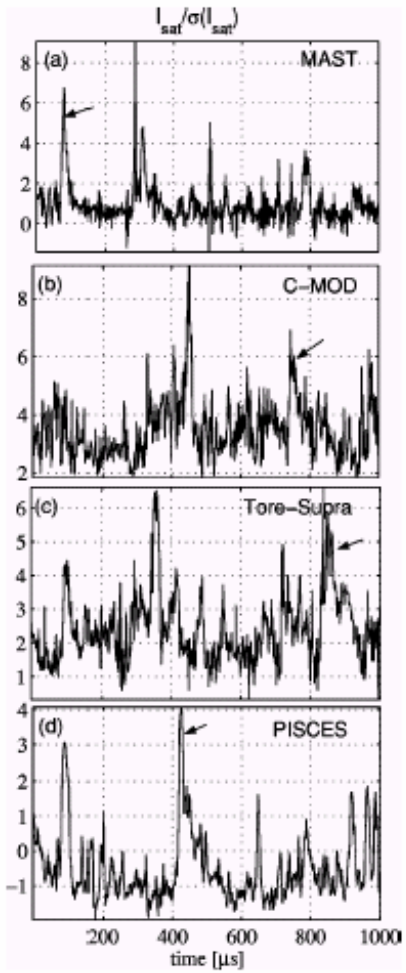
- What is the "edge"?
  - from just inside the separatrix (~ a few cm's) to the wall
  - physics is **highly nonlinear and turbulent**
  - physics is **"generic" to all confined plasmas**

- Why is it important for ITER ?
  - **Pedestal** parameters ⇒ confinement and Q
  - **Cross-field transport** ⇒
    - PFC ("wall") damage
    - short-circuit divertor?
    - wall content (tritium inventory)
    - impurity transport to core



Edge = “extreme physics”

- Couples plasma, atomic and solid state physics
- Fully-developed turbulence regime
  - **no space scale separation** of background and fluctuations
  - **convective** (vs. diffusive) **transport**
  - **strong nonlinearity** **[**O(1) fluctuations**]**
- Turbulence ⇒ mesoscale **coherent structures** ⇒ intermittent transport
  - non-Gaussian statistics
  - universal for confined plasmas



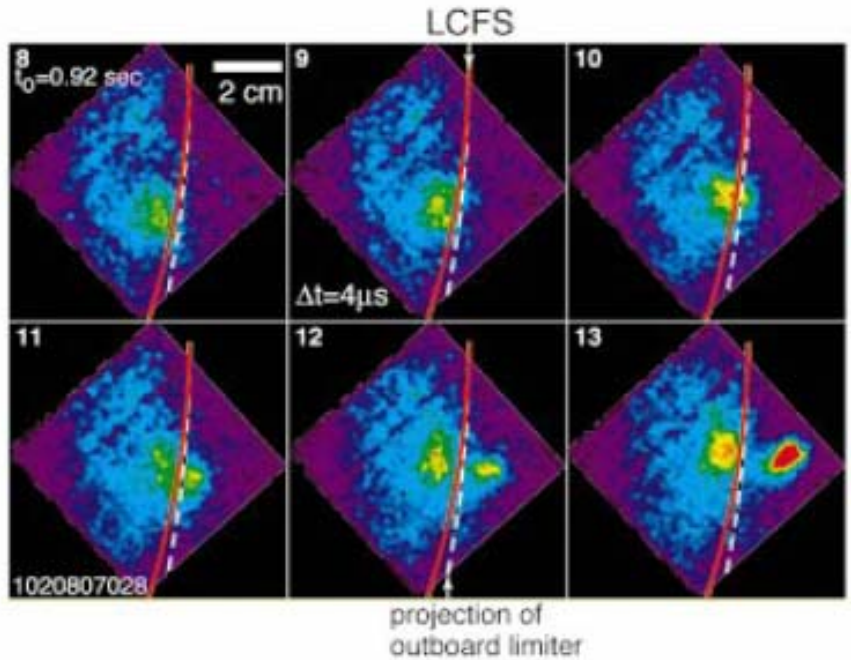
Antar et al., Phys. Plasmas **10**, 419 (2003)

2D imaging techniques show coherent structures in the edge and scrape-off-layer

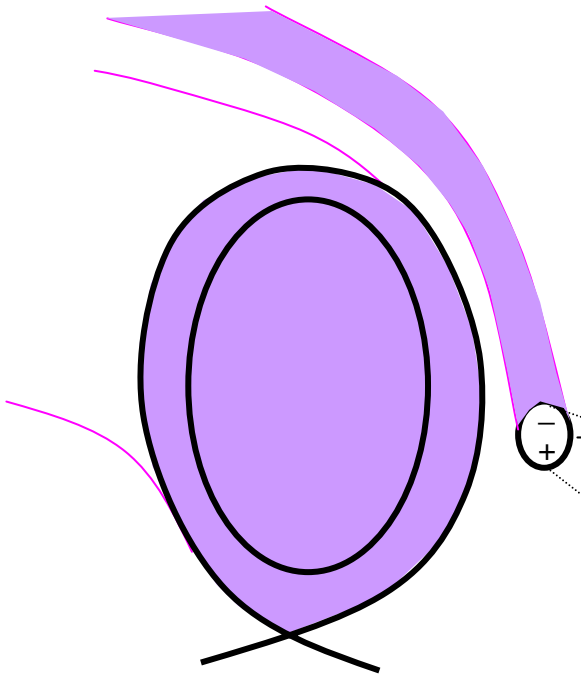
- Gas Puff Imaging on C-Mod, NSTX and other experiments
  - Zweben, Terry
- Beam Emission Spectroscopy (BES) on DIII-D
  - McKee
- large (cm) scale objects emerge from near the separatrix and propagate radially outwards ("blobs")

J.L. Terry, S. Zweben et al.,

Phys. Plasmas 2003 [C-Mod]

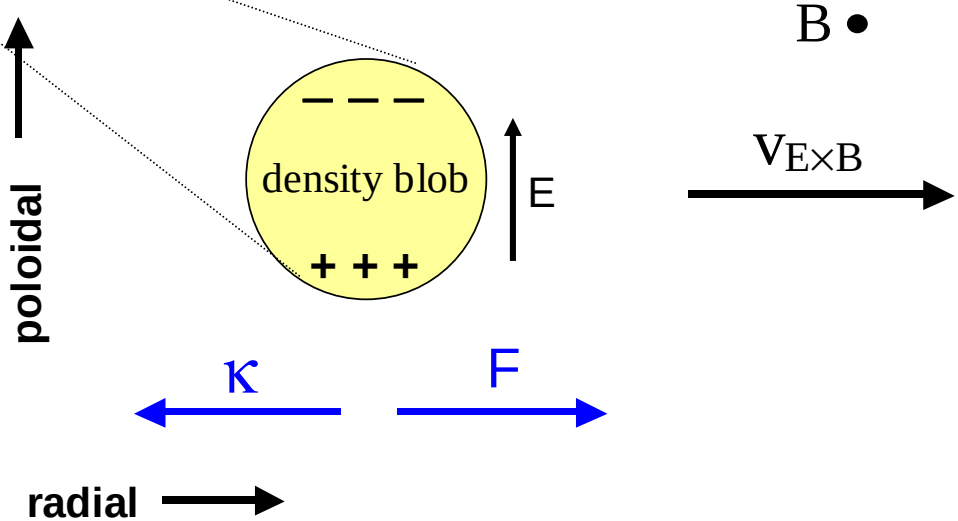


The “blob model” explains the outwards convection



- blob = flux tube containing (much) more plasma than its surroundings
- filamentary along B
- cm-scale across B

blob convection mechanism

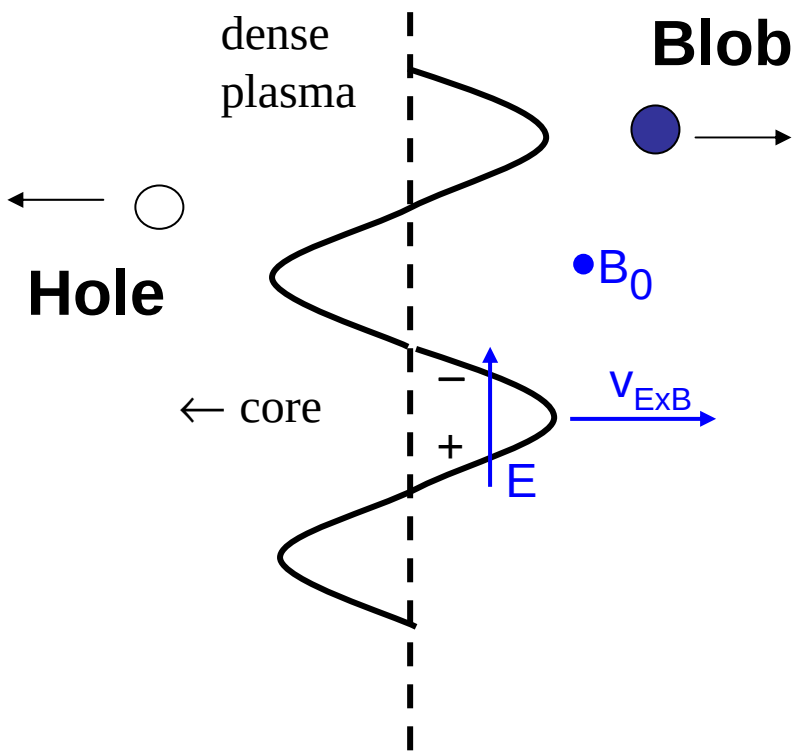


- <u>curvature</u>

  Krasheninnikov 2001
  D'Ippolito 2002
- ∇ neutral friction

  Krasheninnikov 2003
- centrifugal

Nonlinear saturation of linear instability
⇒ coherent objects (blobs, holes)



Rosenbluth Longmire 1957

- **experiments and simulations show that nonlinear saturation of linear instability at location of max γ ⇒ blobs**
- **blobs move by the same R-L mechanism (Krasheninnikov, 2001)**
- **"blob correspondence principle" (Myra, D'Ippolito, 2005)**

$$\gamma \to \frac{v_x}{\delta_b},\ k_\perp \to \frac{1}{\delta_b},\ L_n \to \delta_b,\ k_\parallel \to \frac{1}{L_\parallel}$$

where δ_b = blob radius

Model for theory & simulations

- The minimal model for studying turbulent transport is the coupled vorticity and continuity equations (conservation of charge and particles)

- Dimensionless analysis on these equations gives the scalings of the blob velocity in various parameter (stability) regimes

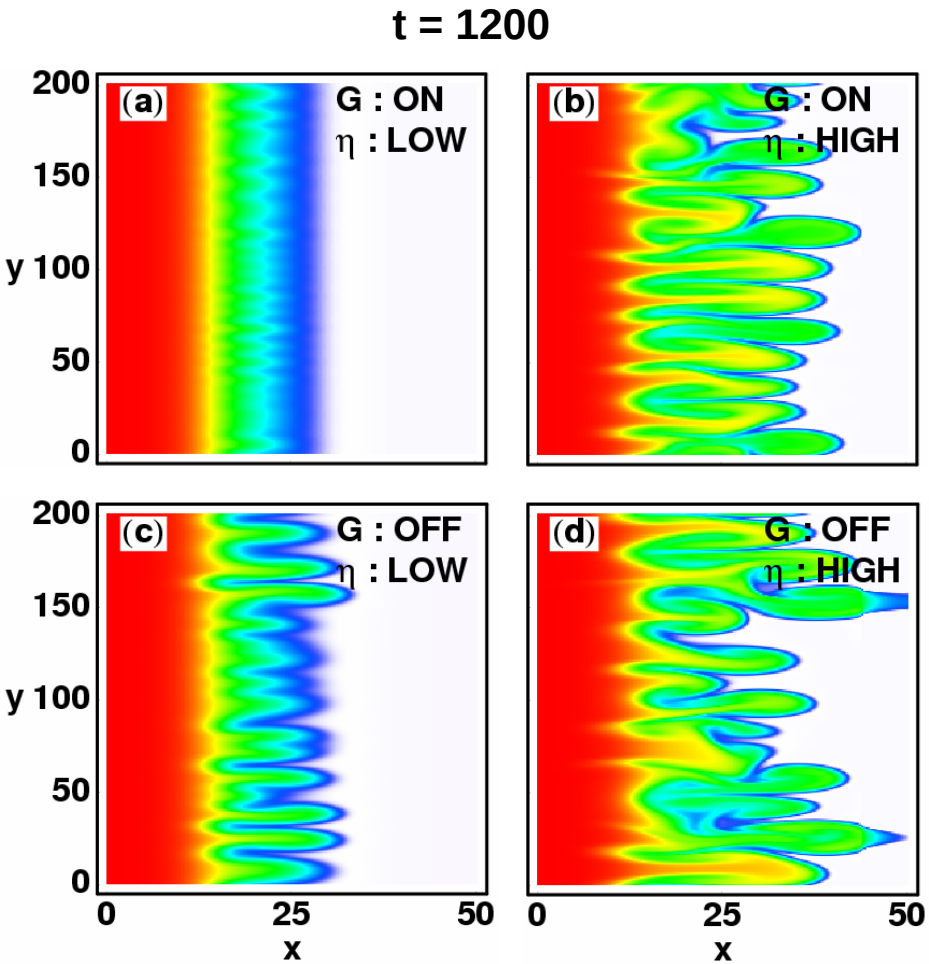
  $v_x = v_x$(blob size, collisionality, magnetic shear, X-point fanning,…)

- This analysis cannot give the blob creation rate (or particle flux)

- Simulations have been carried out to study various questions:
  - radial location and rate of blob generation
  - turbulent particle flux (and fraction due to large events, i.e. blobs)
  - turbulent statistics
  - test the blob correspondence principle, identify dominant regimes

Simulations: density n(x,y) at outer midplane

(4 cases: vary magnetic geometry and parallel resistivity)



X-pt geometry
ON or OFF

LOW or HIGH η

- **blobs (streamers) are generated by turbulence**

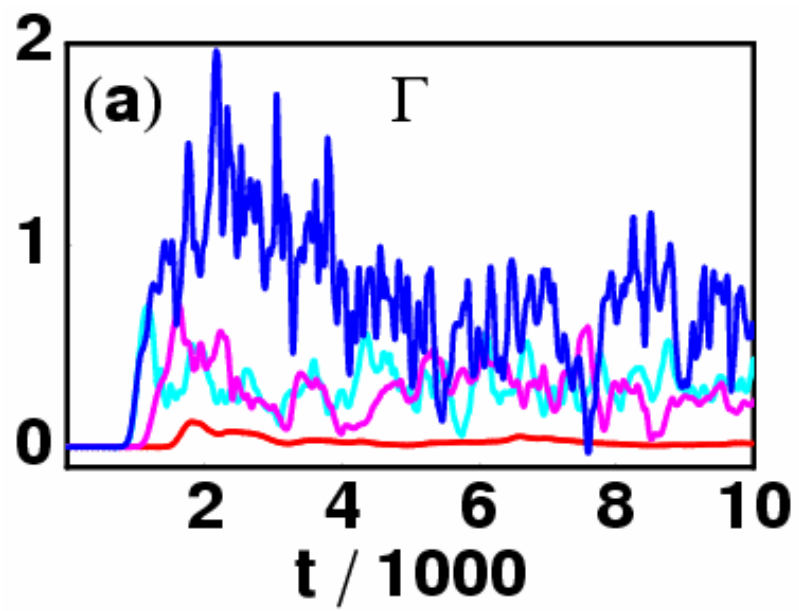
- **|| disconnection for high η $\Rightarrow$ larger growth rate and faster transport**

Russell et al., 2007
(submitted to Phys. Plasmas)

Time history of turbulent particle flux (intermittent)

- G: OFF, low η
- G: ON, low η
- G: OFF, high η
- G: ON, high η

$\Gamma(t)$ at x = 30 at outer midplane



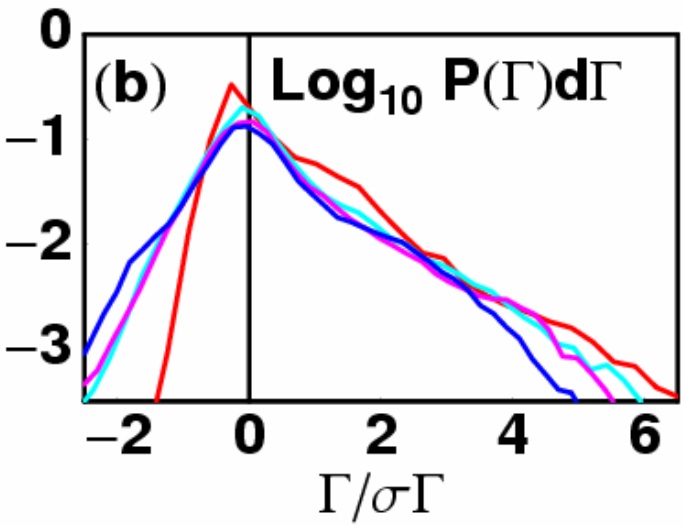
Note: temporally intermittent

$$\Gamma \equiv \langle \Gamma \rangle_y \uparrow \quad \text{as} \quad \eta \uparrow$$

$$\Gamma \downarrow \quad \text{for} \quad G:\text{ON}$$

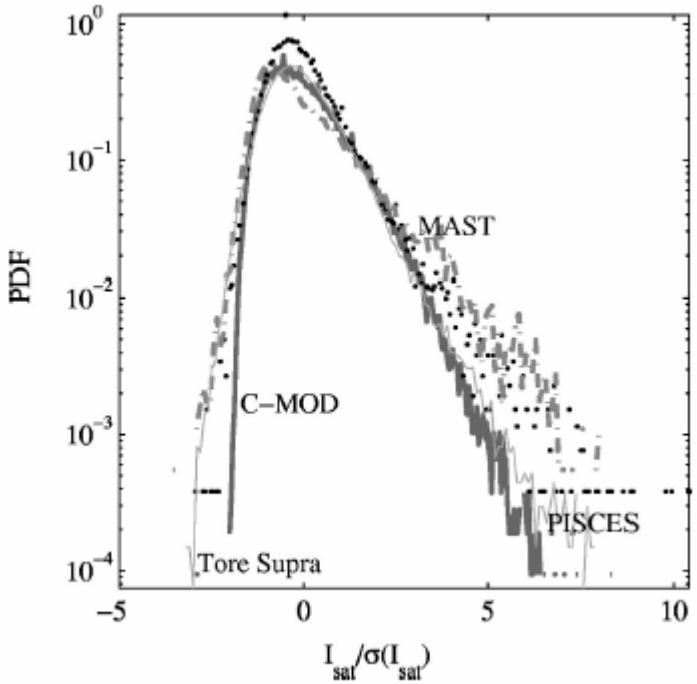
Fluctuation PDFs show skewed, non-Gaussian tails ⇒ blob transport; PDFs have a universal character

Simulated "probe data" for turbulent particle flux Γ (Russell et al.)



PDF of flux at x = 30: non-Gaussian, insensitive to case , similar to experimental data

Experimental data (I_{sat})



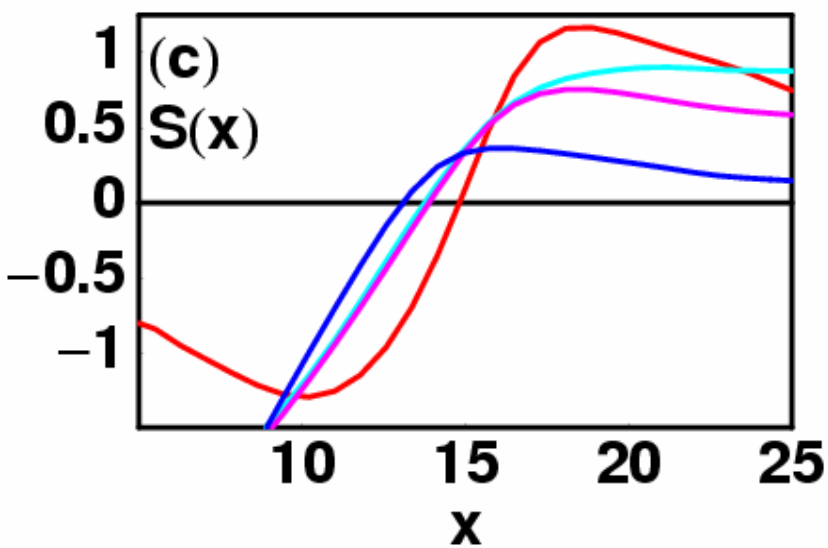
Antar, Phys. Plasmas 2003

Skewness profiles S(x) in simulations resemble experiment

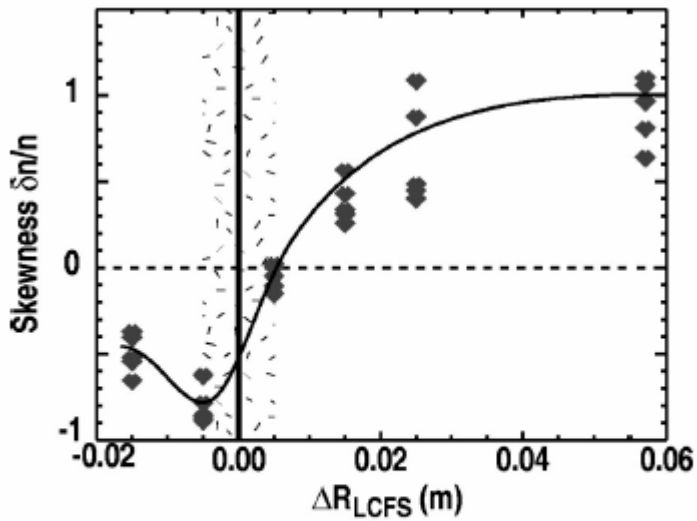
- Skewness **S(x) = <S>$_{y,t}$** measures intermittency of turbulence

$$S = \frac{1}{\tau}\int_0^{\tau} dt\,[n(t) - \bar{n}]^3 / \sigma^3$$

SOLT-TRM code (Russell et al.)



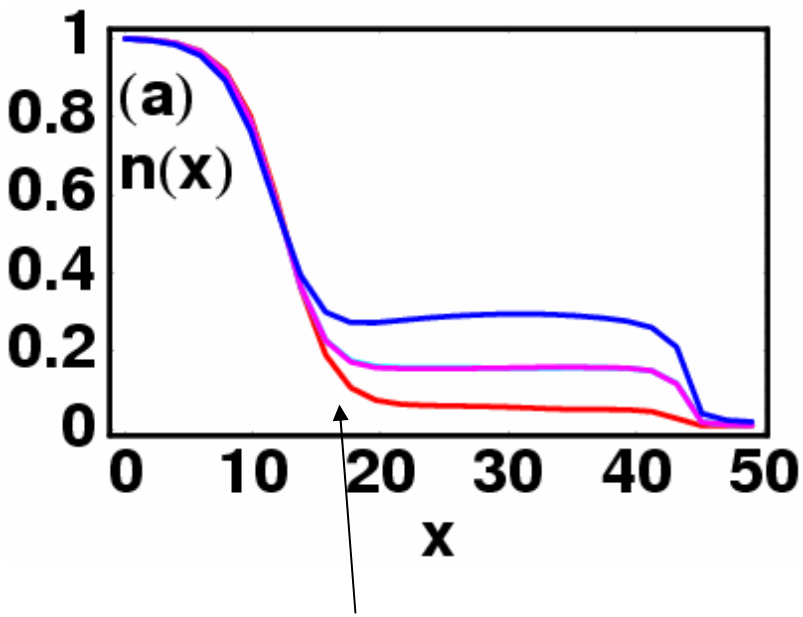
DIII-D BES data



Boedo, PoP (2003)

Turbulent (blob) transport flattens n(x) in far SOL

- G: OFF, low η
- G: OFF, high η
- G: ON, low η
- G: ON, high η

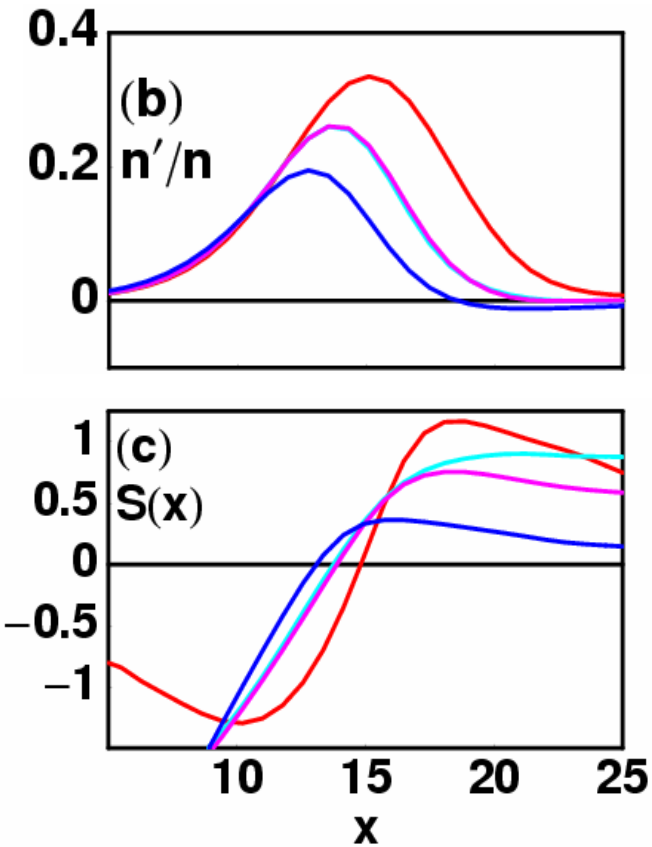


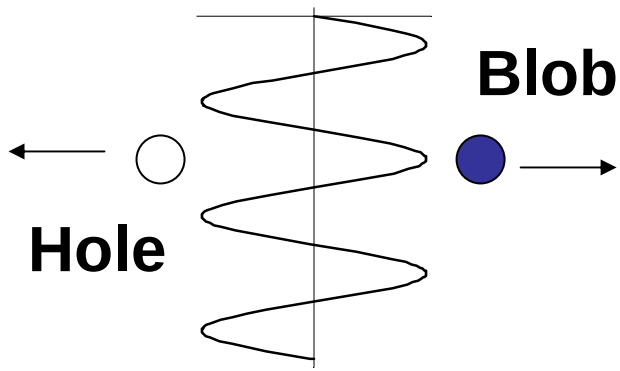
Blob generation zone

Simulations show two-scale SOL density profile observed in experiments

(Russell et al., 2007)

Blob creation zone is at the location of the maximum linear growth rate





S = 0

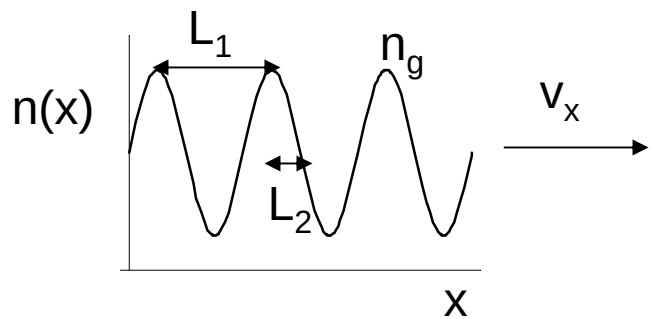
Similar behavior for all 4 cases:

- **blobs created near point where S = 0**
- **coincides with maximum linear mode growth, $\gamma \propto | n^{-1}\, dn/dx |$**

Blob creation rate and "packing fraction"

Particle flux ∝ blob creation rate, which can be related to a "packing fraction" $0 \le f_p \le 1$

$f_p = 2L_2/L_1$



Note: f_p can be estimated from the turbulent profiles $\Gamma(x)$ and $n(x)$.

$$\boxed{\Gamma(x) = f_p\, n_g\, v_x(x)} \Rightarrow \quad f_p(x) = \frac{n(x)}{n(x_g)}\ , \quad S(x_g) \equiv 0$$

$$v_x(x) \equiv \Gamma(x)/n(x) \quad \text{(convective velocity)}$$

Results for packing fraction

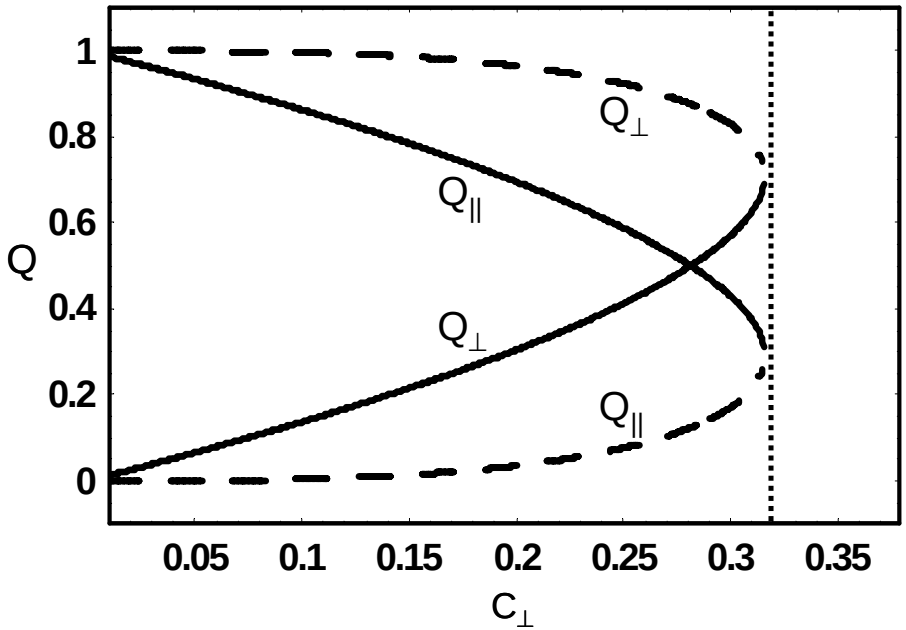
Results for our 4 reference cases at x = 30 show that

- the packing fraction f_p is order unity
- f_p increases with resistivity and drops due to X-pt geometry
- 30 - 50% of scaling of the particle flux Γ is due to changes in the blob creation rate (f_p)

- **G: OFF, low η:** $f_p = 0.43$
- **G: ON, low η:** $f_p = 0.21$
- **G: OFF, high η:** $f_p = 0.65$
- **G: ON, high η:** $f_p = 0.41$

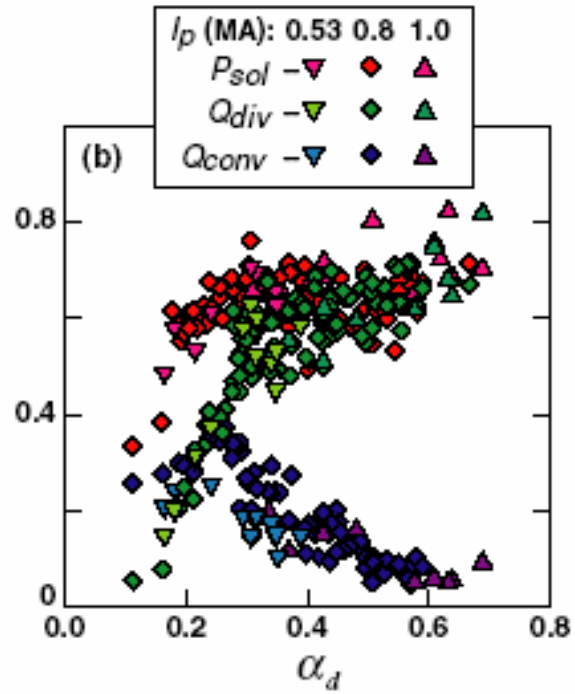
Analytic model: Blob heat convection ⇒ density limit

Model (D'Ippolito & Myra, PoP 2006)



collisionality →

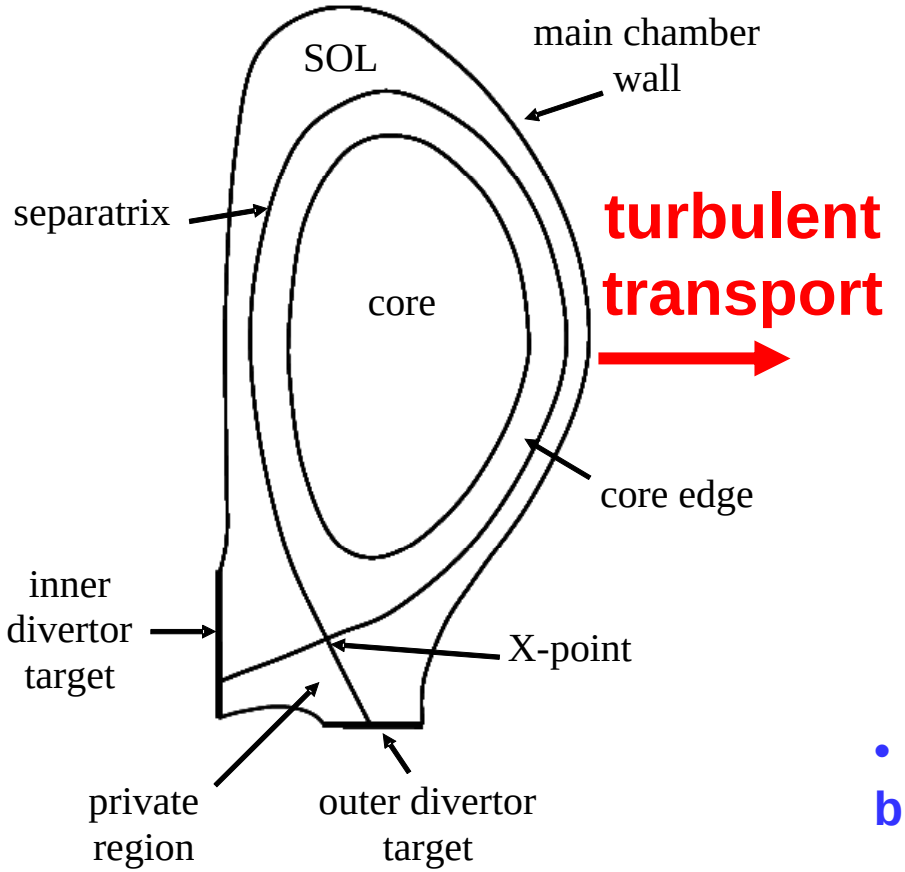
C-Mod data



← collisionality

LaBombard et al, NF 2005

Conclusions



- **For ITER, we need to predict fluxes to wall of particles, heat, momentum and currents**
- **Edge theory, simulations, and experiments $\Rightarrow$ forces that drive instabilities also drive SOL transport**
- **Transport is intermittent with large fluctuations (blobs / ELMs with $\delta n / n \sim 1$)**
- **Impact on ITER is not yet understood but a worldwide effort is underway**