# Blob Transport in the Tokamak Scrape-off-Layer

D. A. D'Ippolito, J. R. Myra, and D. A. Russell

*Lodestar Research Corporation, Boulder, Colorado*

S. I. Krasheninnikov, G. Q. Yu, and A.Yu. Pigarov

*University of California, San Diego, California*

***Acknowledgements***

G. Antar, J. Boedo, R. Macqueda, G. McKee,

W. Nevins, D. Stotler, D. Rudakov

J. Terry, X. Xu, S. Zweben

*Presented at the 9th International Workshop on Plasma Edge Theory in Fusion Devices, San Diego, California, September 3-5, 2003*

# Motivation and Introduction

● growing experimental evidence that intermittent radial transport in the SOL can be explained by coherent, propagating structures (“blobs”).

- **two-scale structure** of SOL density profiles; non-diffusive in the far SOL (C-MOD, DIII-D, AUG)
- **wall recycling** dominates particle fueling in C-MOD

  ⇒ **importance of convective transport in far SOL**
- diagnostic imaging & probe data on C-MOD, DIII-D, NSTX, Tore Supra, MAST, and PISCES

  (Zweben, J. Terry, Maqueda, Antar, Boedo, Rudakov, McKee, Labombard, Endler… )

  - **turbulence ⇒ propagating coherent structures**
  - **responsible for large fraction of SOL transport**
  - **non-Gaussian statistics similar on all machines (Antar, Boedo)**
  - **correlated with ELMs (Boedo, Endler)**

● simple theoretical models of blob propagation and decay exhibit some of the qualitative features seen in the experiments.

Krasheninnikov, Phys. Lett. A**, 283**, 368 (2001)
D’Ippolito, Myra, Krasheninnikov, Phys. Plasmas **9**, 222 (2002)

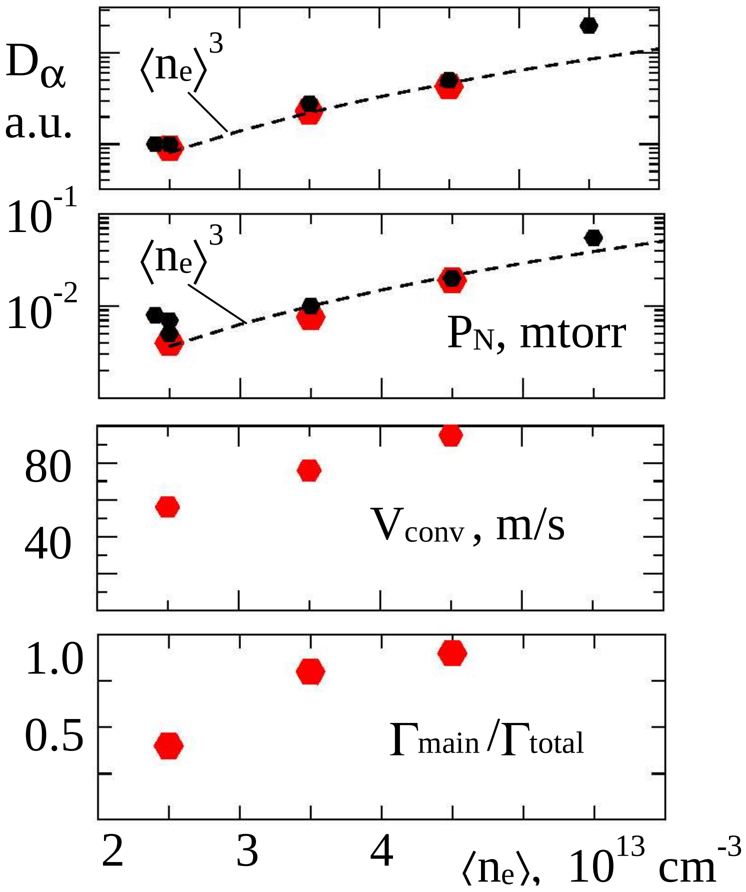
● recent simulations extend these models to include blob dynamics and interaction with the background plasma.

## UEDGE simulations of DIII-D provide evidence of convective transport

● include time-independent cross-field convective velocity $V_{conv}$ in 2D edge transport code UEDGE

● analyze a series of DIII-D L-mode discharges having the same NBI input power but different average densities

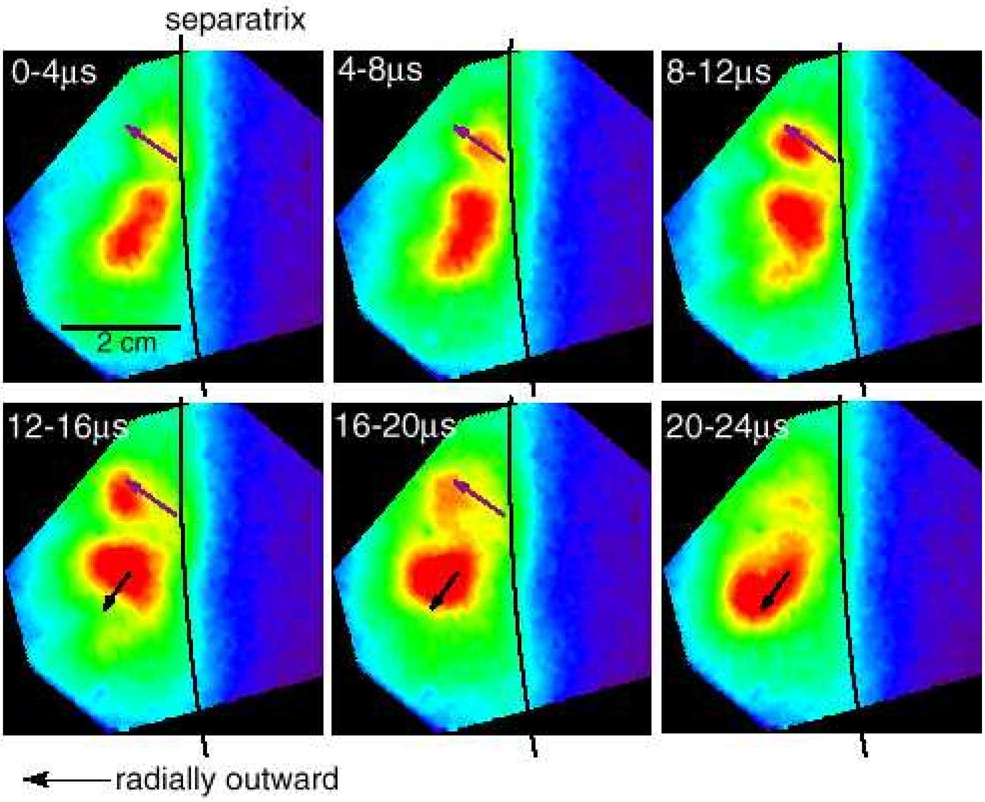
- ➢ need outwards $V_{conv}$ to match experimental profiles
- ➢ $V_{conv}$ increases with density




$V_{conv} << v_{x,blob}$

A. Pigarov et al., J. Nucl. Mater. **313-316**, 1076 (2003)
S. Krasheninnikov et al., IAEA Conf. 2002, paper TH/4-1.

# Gas Puff & BES imaging shows blobs

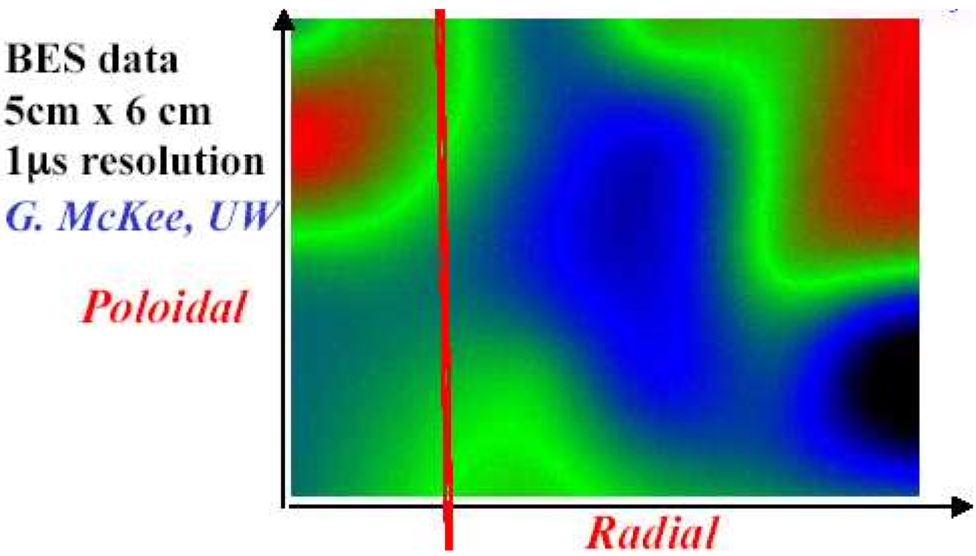



GPI data on C-MOD

(S. Zweben, J. Terry, et al., APS 2001)

BES data on DIII-D

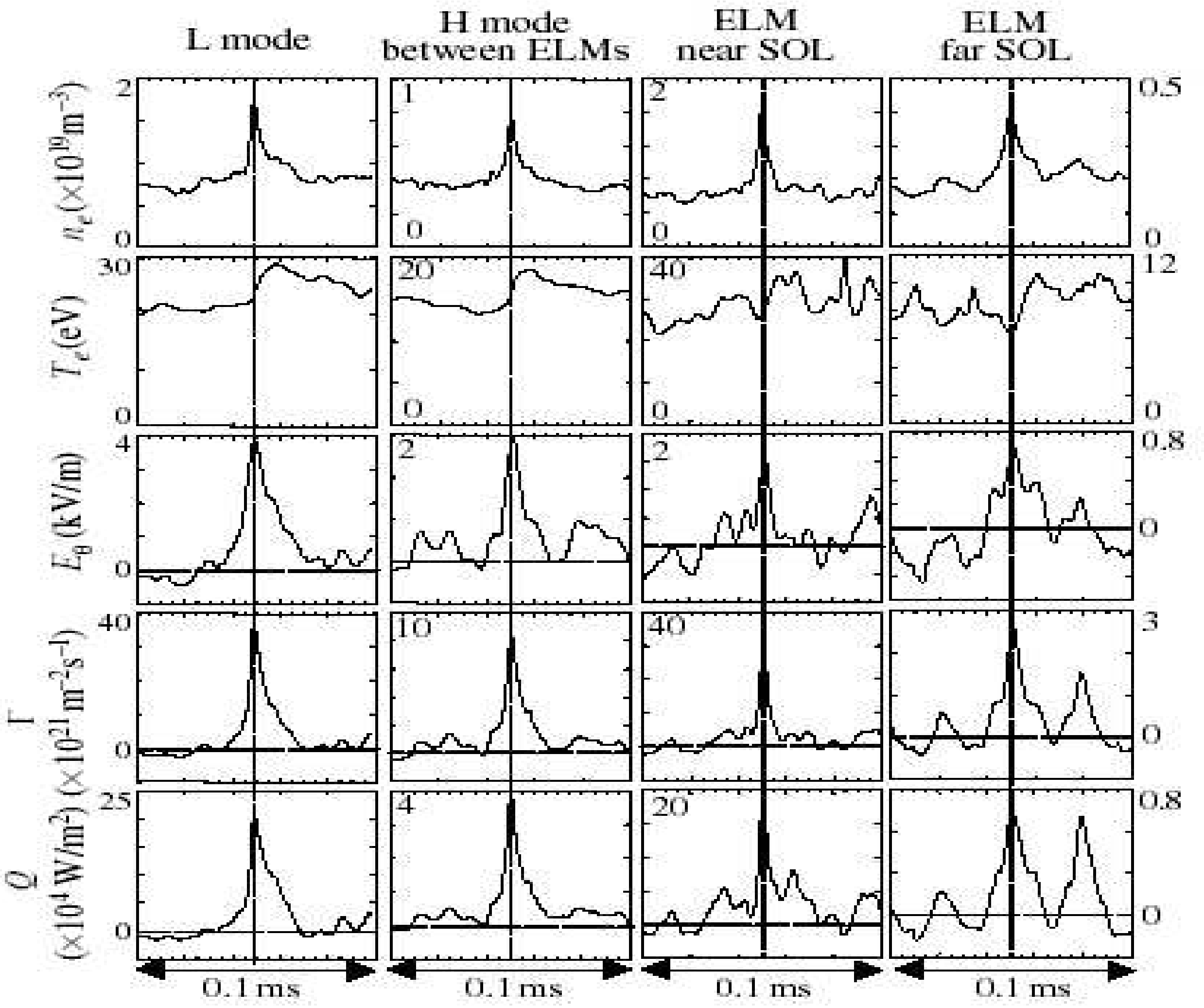
(Boedo, APS 2002)




Blobs are localized ⊥ **B**, but extended along **B** field lines.

## Probe signals on DIII-D show intermittent transport in L- and H-modes due to blobs

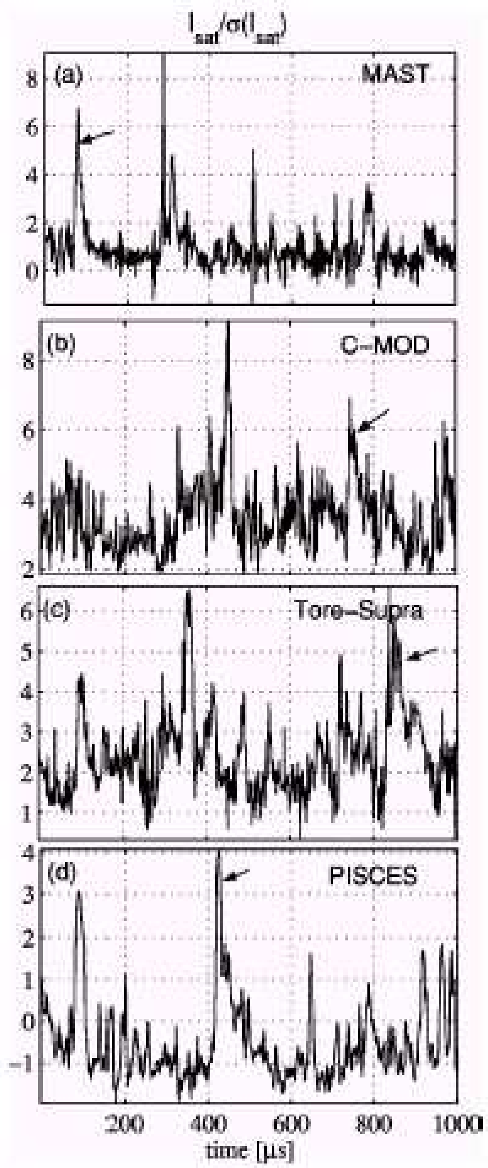
- conditionally-averaged signal shows *intermittent* events with *fast-rise and slow decay* in density and fluxes
- $E_\theta$ correlated with density and flux pulses
- blobs produced in all regimes (*also by ELMs*)



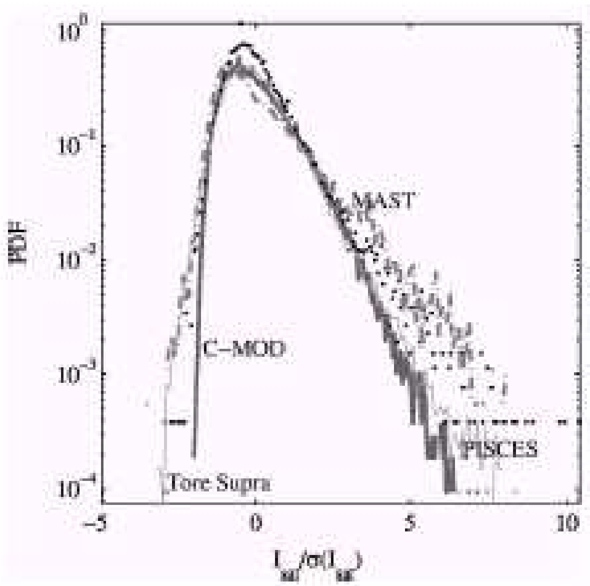

D. Rudakov, J. Boedo, R. Moyer et al., PPCF **44**, 717 (2002)

# Blob transport similar on different machines; statistics are non-Gaussian

Ion saturation current shows similar intermittency on several machines (toroidal and linear)




- large events are blobs propagating outwards
- PDF of $I_{sat}$ is skewed towards positive events (non-Gaussian)
- PDF is similar on different machines




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

# Characteristic Time Scales

- Estimate blob time scales for typical tokamak parameters

  blob radius: $a = 2$ cm
  distance to wall: $w = 10$ cm
  blob velocity: $u_x = 10^5$ cm/s = 1 km/s
  connection length: $L_{||} = 600$ cm

  $$\Rightarrow \tau_{||} = L_{||}/c_s = 200\ \mu s$$
  $$\tau_w = w/u_x = 100\ \mu s$$
  $$\tau_c = a/u_x = 20\ \mu s$$

- Notes:
  - $\tau_w/\tau_{||} \sim \frac{1}{2}$ $\Rightarrow$ flattened profiles with plasma at wall
  - $\tau_c$ is comparable to the experimentally-measured autocorrelation times (~ 10 - 30 $\mu$s)

## Motivation and Introduction

● growing experimental evidence that intermittent radial transport in the SOL can be explained by coherent, propagating structures (“blobs”).

- two-scale structure of SOL density profiles; non-diffusive in the far SOL (C-MOD, DIII-D, AUG)
- wall recycling dominates particle fueling in C-MOD

  ⇒ importance of convective transport in far SOL
- diagnostic imaging & probe data on C-MOD, DIII-D, NSTX, Tore Supra, MAST, and PISCES

  (Zweben, J. Terry, Maqueda, Antar, Boedo, Rudakov, McKee, Labombard, Endler… )

  - o turbulence ⇒ propagating coherent structures
  - o responsible for large fraction of SOL transport
  - o non-Gaussian statistics similar on all machines (Antar, Boedo)
  - o correlated with ELMs (Boedo, Endler)

● simple theoretical models of blob propagation and decay exhibit some of the qualitative features seen in the experiments.

Krasheninnikov, Phys. Lett. A, **283**, 368 (2001)
D’Ippolito, Myra, Krasheninnikov, Phys. Plasmas **9**, 222 (2002)

● recent simulations extend these models to include blob dynamics and interaction with the background plasma.

# Outline of Talk

- Analytic blob model
- Secondary instabilities and effect of background profiles
  - "essential stability"
  - 2D simulation results for curvature and velocity-shear instabilities
  - rotational instabilities & ELMs
- Other topics
  - Blob statistics
  - Diagnostics for blobs in 3D codes
  - Analysis of NSTX GPI blob data
- Assessment of blob model
- Summary and conclusions

---

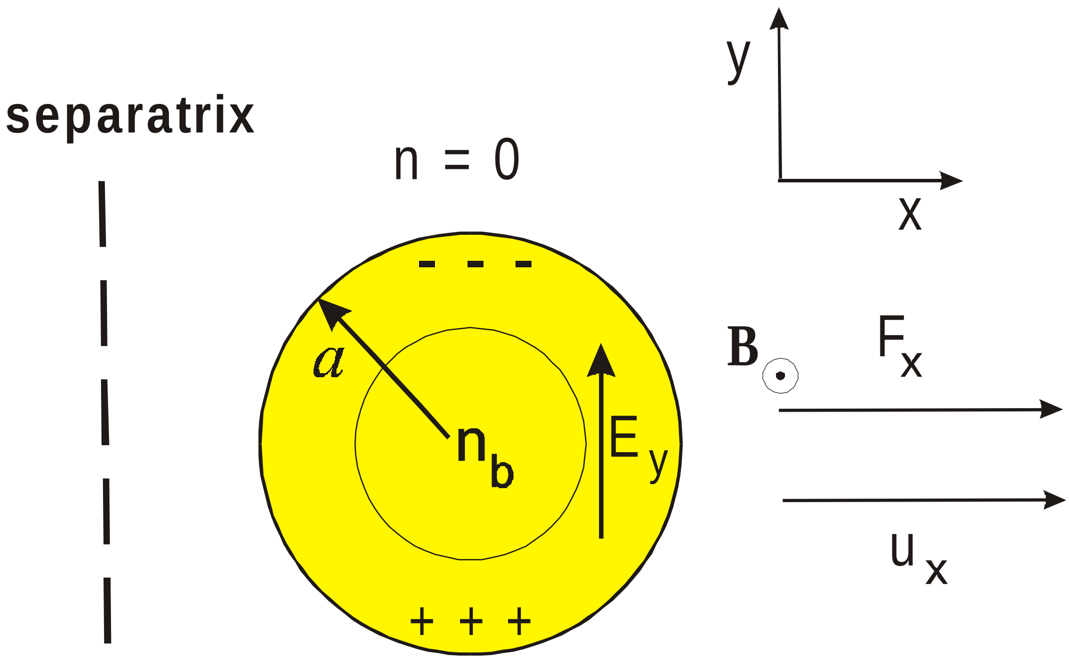
Scope:

(1) focus on theory

(2) blob stability and transport
(not turbulent origin of blobs)

## Blobs move due to radial force

- net species-summed radial force $F_x$ ($\mathbf{b} \cdot \nabla \times \mathbf{F} \neq 0$) (curvature, centrifugal, neutral wind…)
- axial B field $\Rightarrow$ species-dependent $\mathbf{F} \times \mathbf{B}$ drift
- sheath or plasma resistivity $\Rightarrow$ charge polarization




- velocity $u_x$ of blob depends on blob radius a

$$n(r) = n_b \exp\left[-\left(r^2 / 2a^2\right)\right] + n_f$$

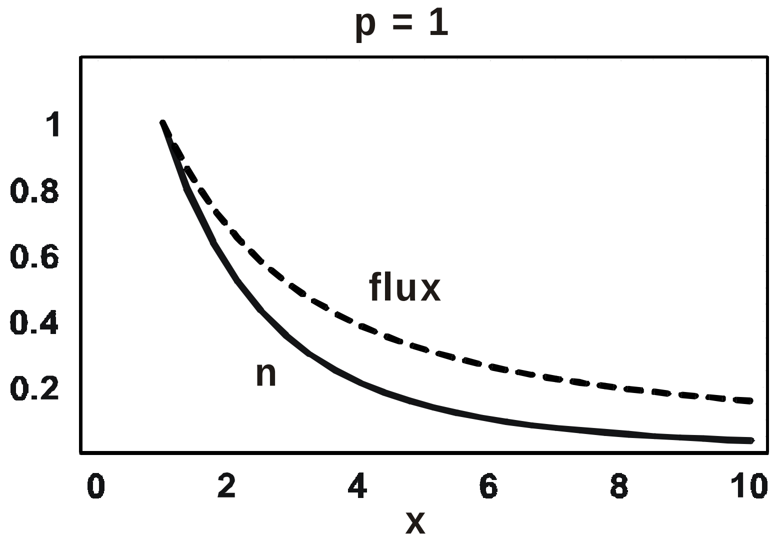
$$n_f = 0 \quad \Rightarrow \quad u_x = q / a^2 \text{ where } q = L_{\|} / R$$

- density *blobs* move out to wall ($n_b > 0$ ),
- density *holes* move in towards core ($n_f \neq 0$, $n_b < 0$ )

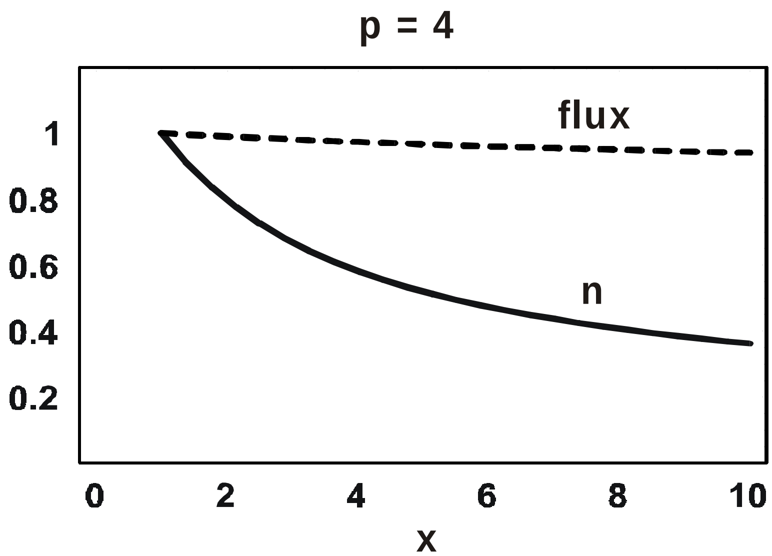
## Profiles depend on the blob size distribution

Ensemble average over power law distribution

$$f(a) = a^{-p}, \quad a = \text{blob radius}$$




**large blobs dominate transport for p = 1, small blobs for p = 4**




D'Ippolito, Myra, Krasheninnikov, Phys. Plasmas **9**, 222 (2002)

Small blobs travel faster and penetrate farther than large blobs

# Outline

- Analytic blob model
- Secondary instabilities and effect of background profiles
    - "essential stability"
    - 2D simulation results for curvature and velocity-shear instabilities
    - rotational instabilities & ELMs*
- Other topics
    - Blob statistics*
    - Diagnostics for blobs in 3D codes*
    - Analysis of NSTX GPI blob data*
- Assessment of blob model
- Summary and conclusions

---

*work in progress

## Study "secondary instabilities" of blobs

- Use far SOL model (T = const) described by the following equations

$$\frac{d}{dt}\nabla_\perp^2\varphi + \nu\nabla_\perp^2\varphi = \alpha\varphi - \frac{\beta}{n}\nabla_y n$$

$$\frac{dn}{dt} = D\,\nabla_\perp^2 n - \alpha n$$

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla = \frac{\partial}{\partial t} + \mathbf{b}\times\nabla\varphi\cdot\nabla$$

$\alpha = (2\rho_s/L_{||})$ = sheath parameter
$\beta = (2\rho_s/R)$ = curvature parameter
$\nu$ = viscosity, D = diffusion

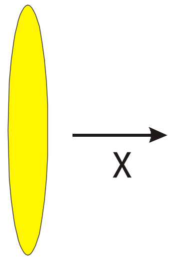
dimensionless: $\Omega_i\,dt \rightarrow dt$, $\rho_s\nabla \rightarrow \nabla$,
$e\Phi/T_{es} \rightarrow \Phi$, $v/c_s \rightarrow v$, etc.

- Secondary "sheath-interchange" (SI) instability driven by internal blob pressure profile affects the radial velocity:
  - same force drives motion and instability ($\nabla$B)
  - SI instability $[\gamma \propto k_y^2\ (\beta/\alpha L_{nx})]$ breaks up blobs
  - smaller fragments move faster, increasing transport

(The global SOL version of this instability was studied by Nedospasov 1989, Garbet et al. 1991, Endler et al. 1995.)

## Competition between stability and transport determines maximum blob size

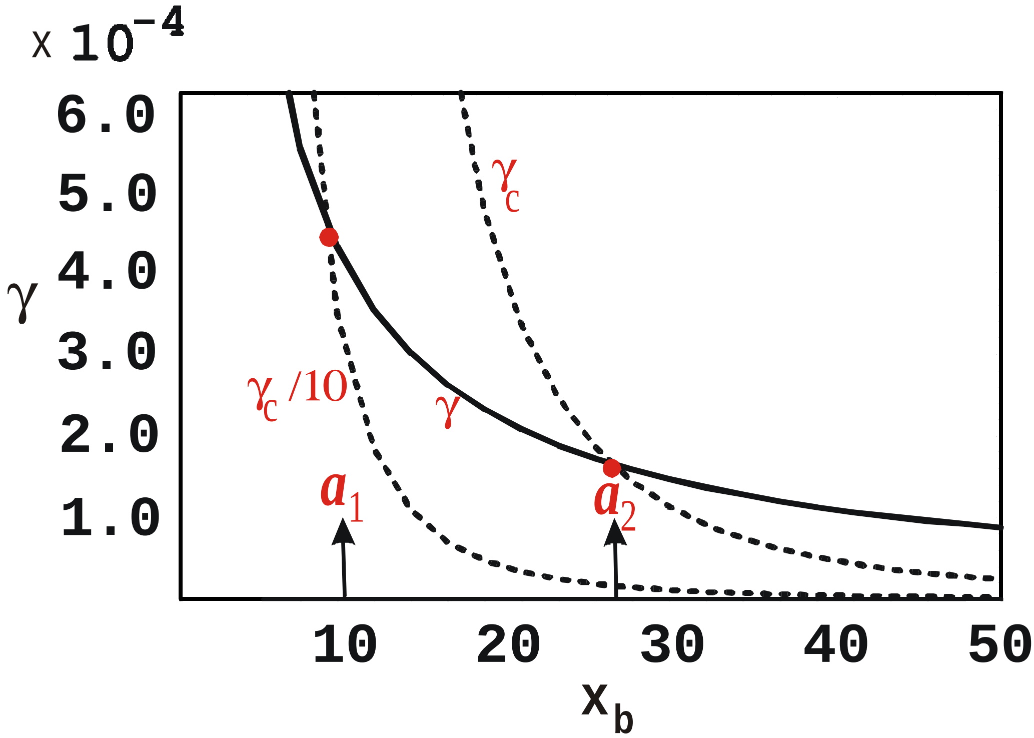
- linear growth rate $\gamma$ for 1D "poloidally-elongated blob" ($y_b >> x_b$)
- transport rates for blob of radius $a = x_b$




diffusion rate $\gamma_d = D/a^2$ << other rates

convection rate $\gamma_c = u_x / a = q/a^3$

transport rate to wall $\gamma_w = u_x / \Delta x$, let $\Delta x \approx 10a$

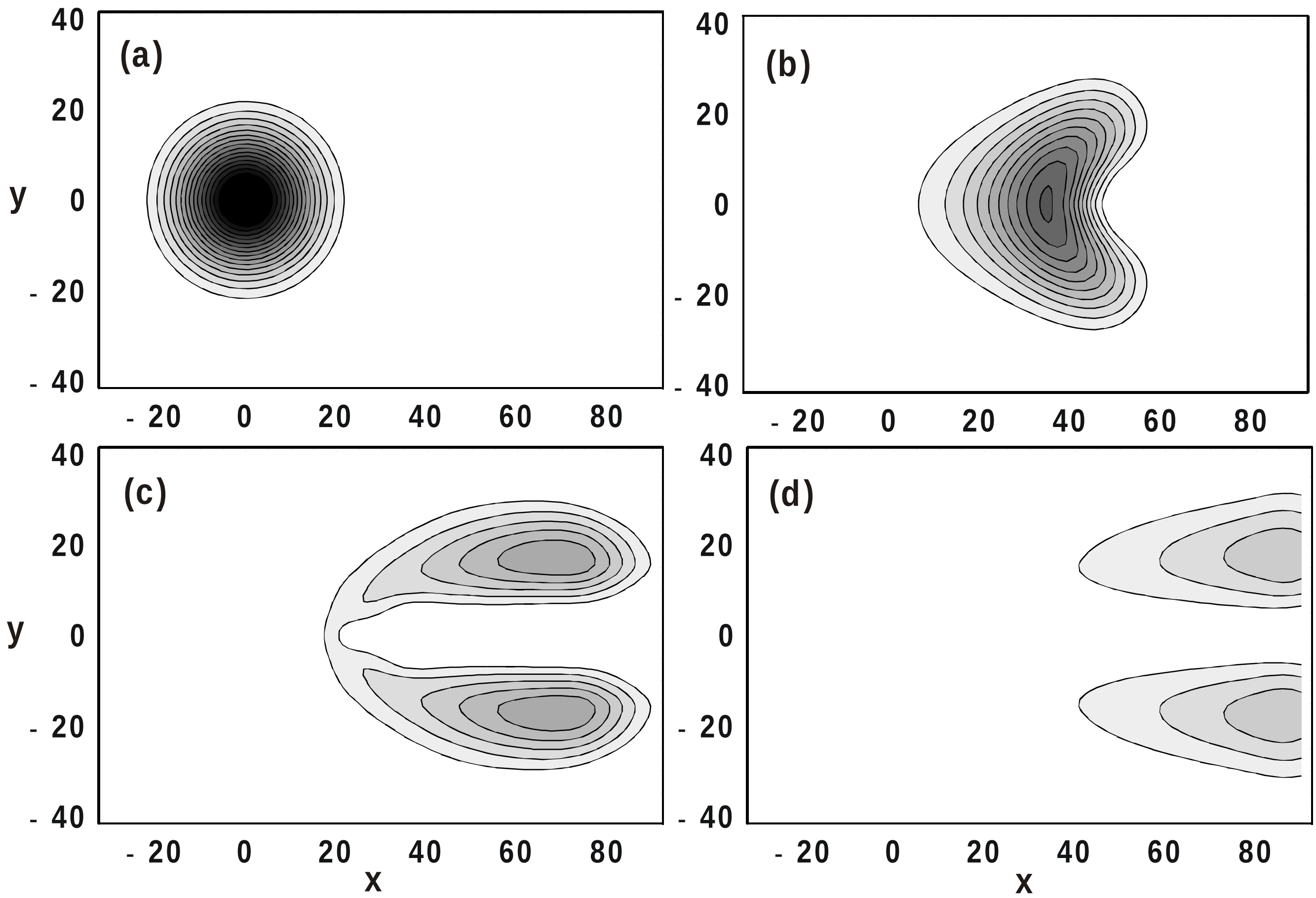



**D'Ippolito and Myra, Phys. Plasmas (2003)**

- "essential stability" for $\gamma < \gamma_w \Rightarrow a < a_1$
- lower bound on $u_x$: $u_x > q/a_1^2$
- $a_2/u_x \Rightarrow$ maximum expected autocorrelation time

# Nonlinear instability breaks up blobs

- 2D simulations ⇒ nonlinear evolution of instability can cause blob to bifurcate

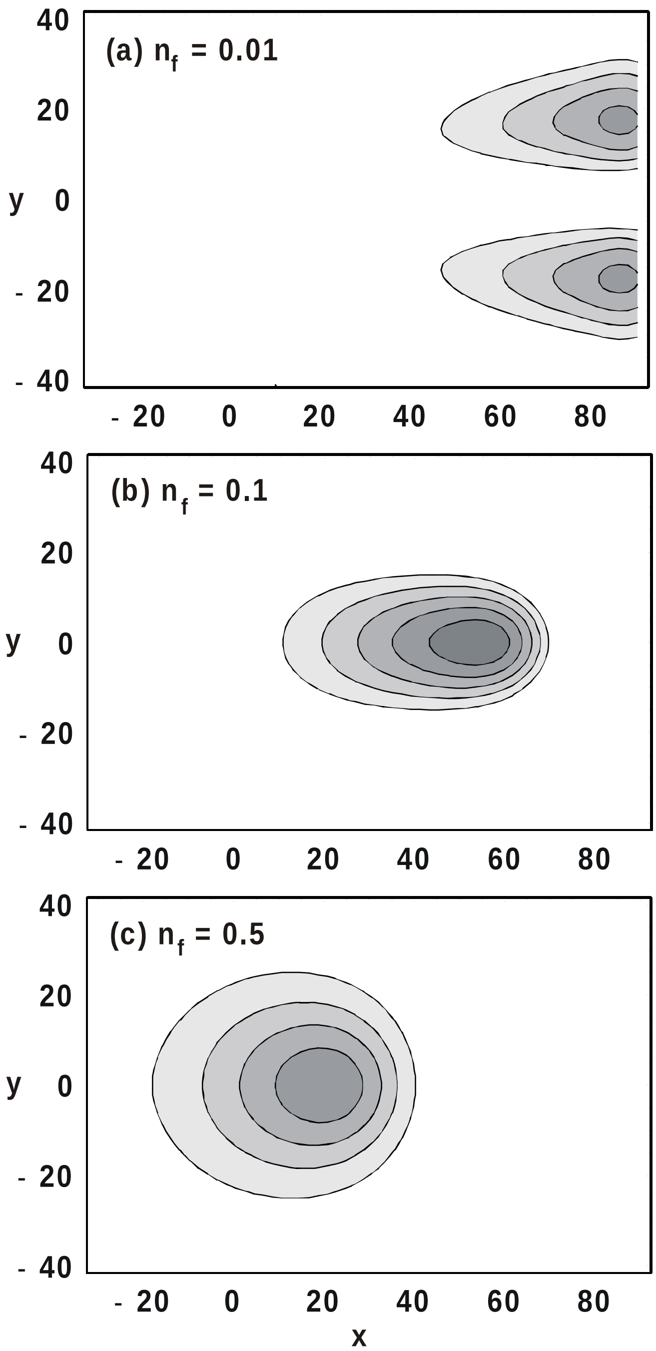



**D'Ippolito and Myra, Phys. Plasmas (2003)**

$t/\tau_C$: (a) 0, (b) 6, (c) 9, and (d) 12; $n_f = 0.01$, $D = 0.005$, and $a_s = 7$.
neglect inertia in vorticity eq.

- characteristic blob deformation before bifurcating
- also observed by G. Q. Yu *et al.* Phys. Plasmas (2003)

# Effect of background density on blobs (1)




With small background:

- blobs move faster
- blobs are unstable

Background density:

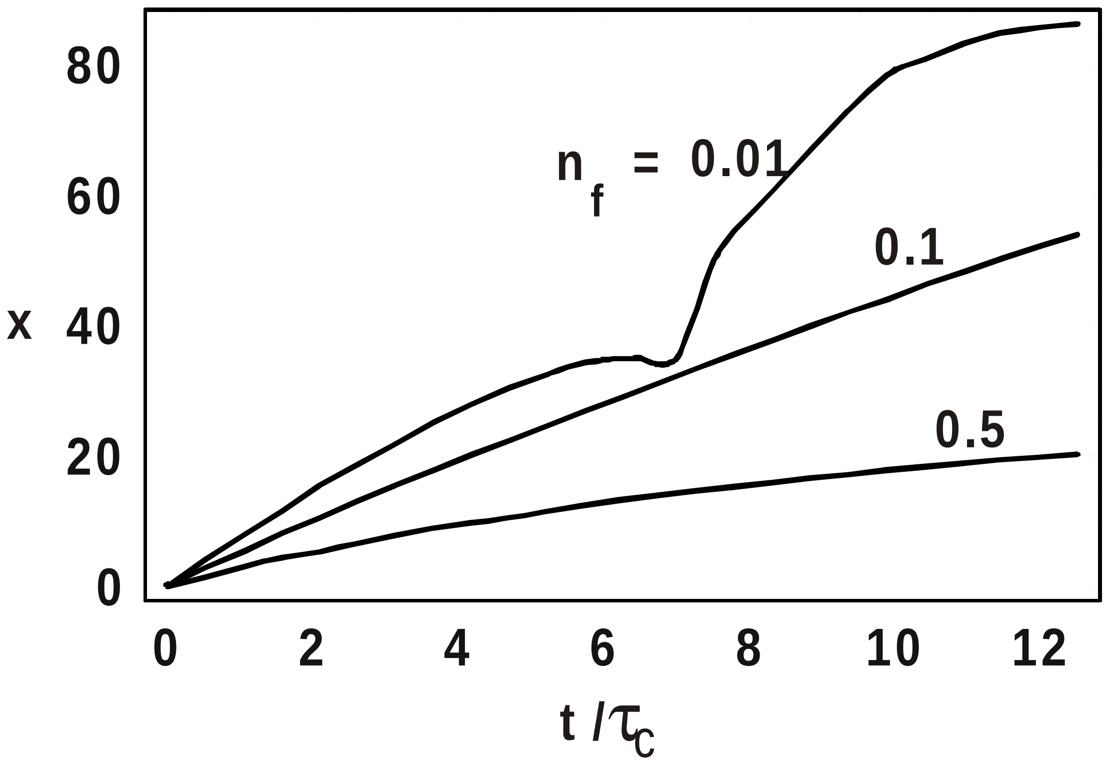
- slows and stabilizes
- changes blob shape
  + steep leading edge
  + trailing wake

**D'Ippolito and Myra, Phys. Plasmas (2003)**

The blob equilibrium, stability and transport depends on the blob height above the background.

Effect of background density on blobs (2)

- Simulations show
  - strong effect of background on radial velocity $u_x$
  - dependence of $u_x$ on blob size:



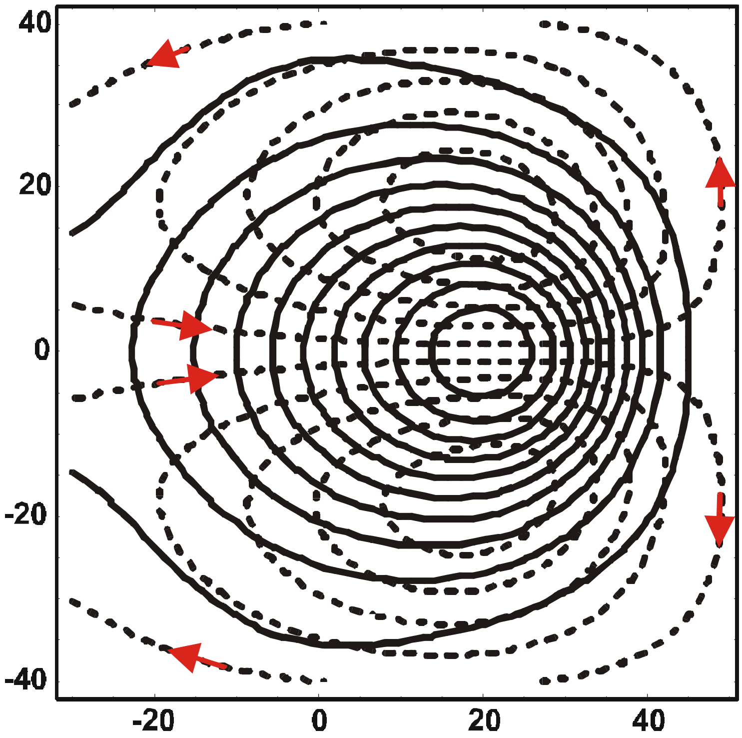

**D'Ippolito and Myra, Phys. Plasmas 2003**

- blob slows down before bifurcation and speeds up afterwards (consistent with analytic model)
- blob accelerates down the SOL density profile

# Effect of background density on blobs (3)

- blob in vacuum $\Rightarrow$ uniform $u_x$

  blob on background $\Rightarrow$ vortex flow pattern

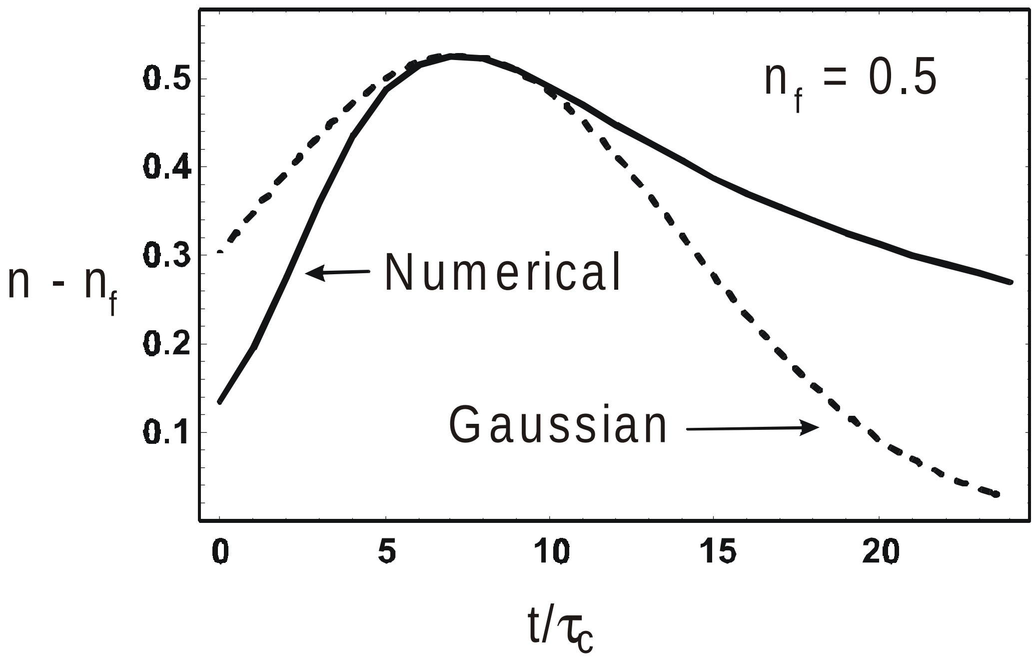



contours of density (solid) & flow (dashed) in lab frame

- sheared flow drives KH instability,

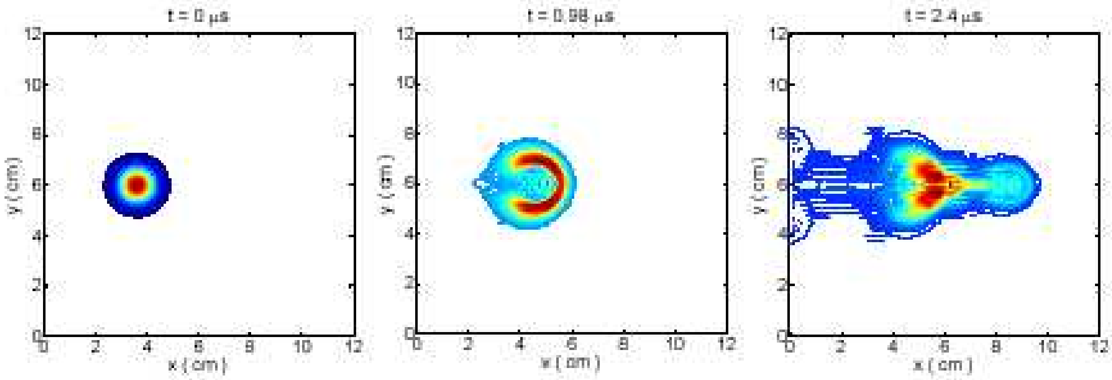
  $$\gamma \propto v_x / L_y$$

- gives steep leading edge and trailing wake
- shape $\Rightarrow$ qualitative agreement with probe data

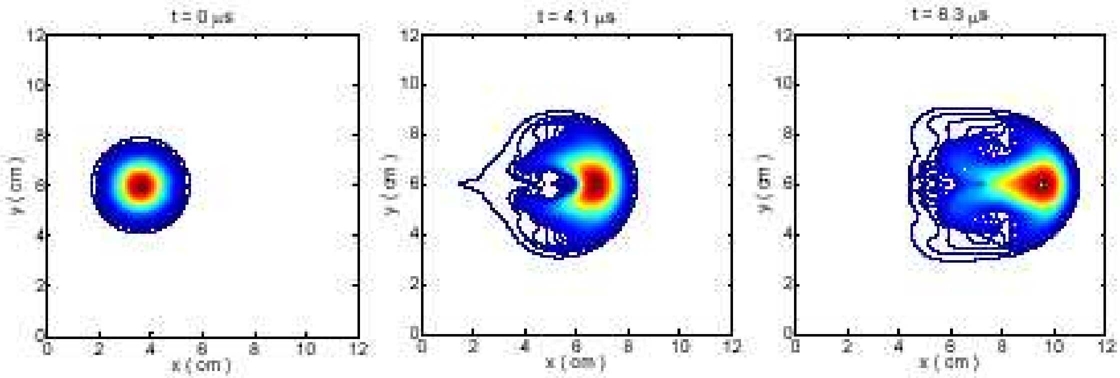


# Small blobs are unstable to Kelvin-Helmholtz instability

*a* = 0.6 cm (smaller blobs are more unstable to K-H)




*a* = 0.9 cm

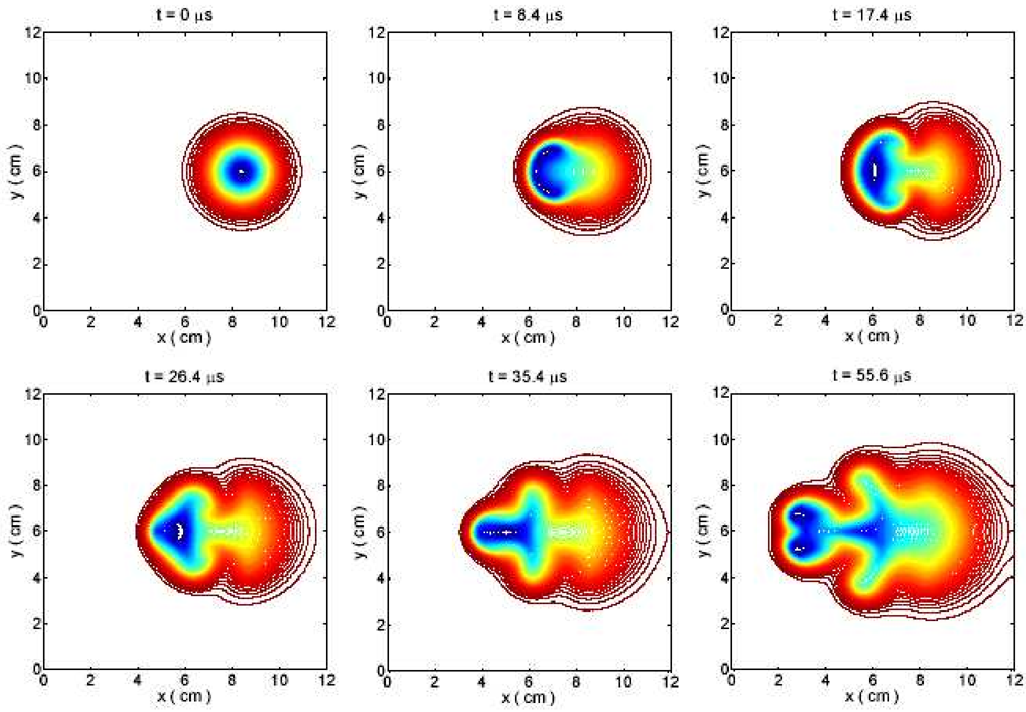



**Yu and Krasheninnikov, Phys. Plasmas (2003)**

**[Blob steepening and K-H also studied by Bian *et al.*, (2003), and in ionospheric context by Guzdar et al., (1998 )]**

# Density dips and impurity transport

Evolution of density dip with $a$ = 1.2 cm,   small D = 0.01

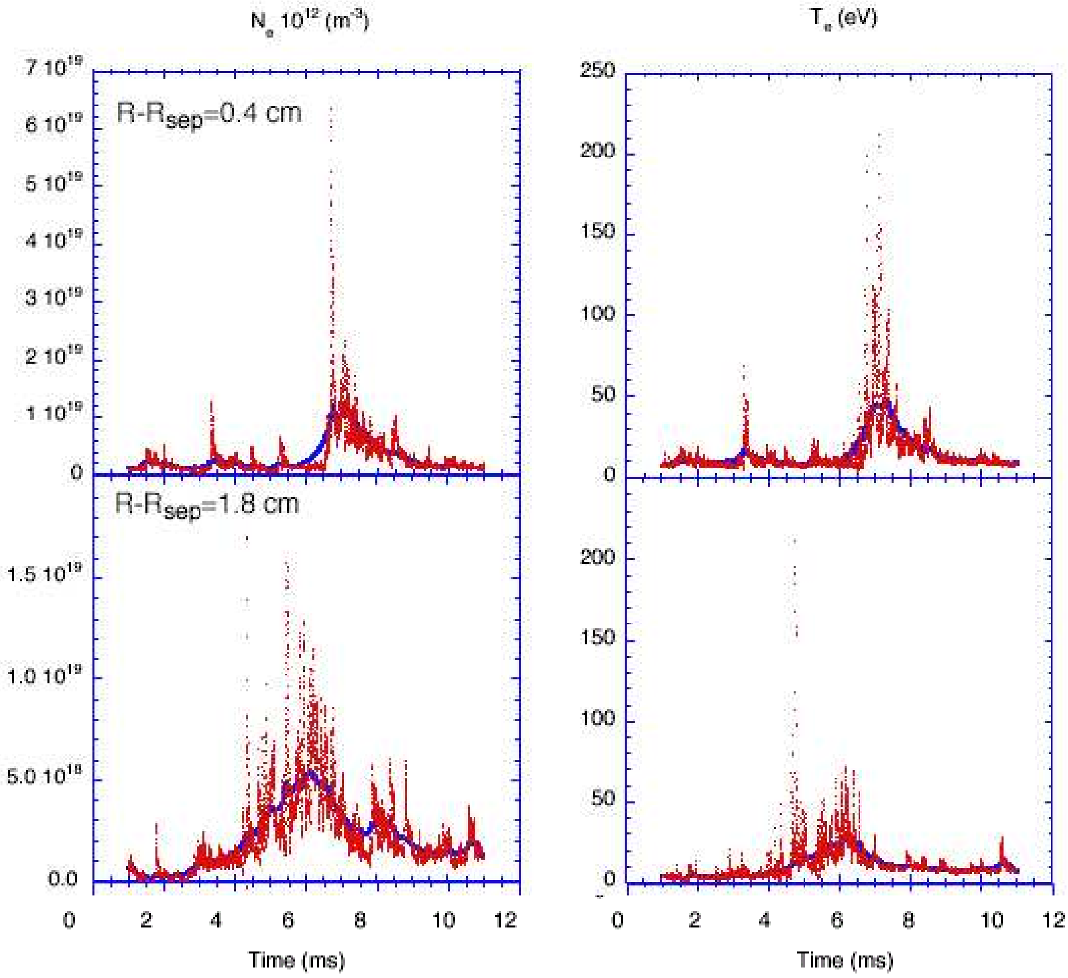



**Yu and Krasheninnikov, Phys. Plasmas (2003)**

- density dips /holes propagate *inwards* from wall to core
- provides mechanism for enhanced impurity transport
- dips are unstable to secondary K-H instability

# ELMs, Blobs and Rotational Instabilities

- ELMs $\Rightarrow$ density and temperature pulses propagating to the wall (JET, AUG and DIII-D)
- Pulses have blob-like behavior (outwards convection, steep leading edge, etc.) but have more *fine structure.*
- Is fine structure due to rotational instabilities?




J. Boedo et al., submitted to Phys. Plasmas (2003)

# Blob rotation

Blob theory needs to be generalized to include temperature and Bohm sheath potential ($\Phi \approx 3T_e$) effects on blob dynamics

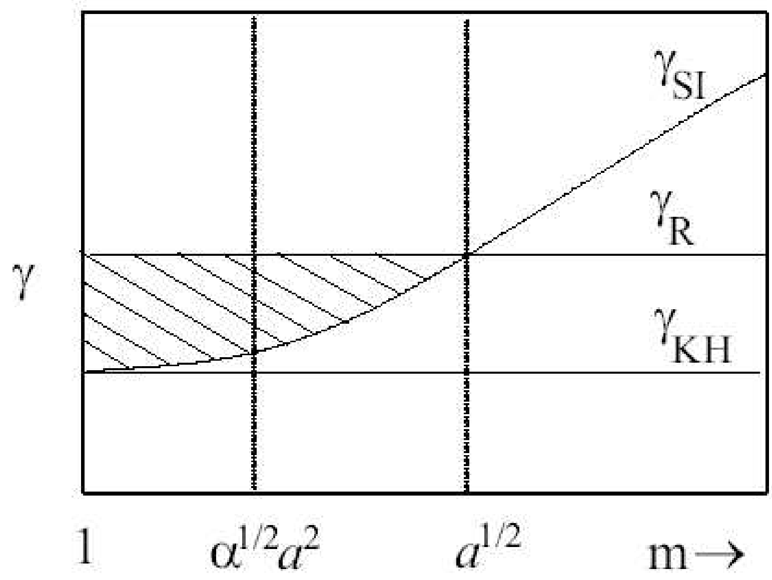
- background T(x) $\Rightarrow$ poloidal drift
- internal T(r) $\Rightarrow$ blob rotation

Blob rotation can drive rotational instabilities
[*see D'Ippolito et al., APS-DPP (2003)*]

- centrally-peaked T(r) $\Rightarrow E_r > 0$
  $\Rightarrow$ centrifugal and Coriolis terms are destabilizing

  (Freidberg and Pearlstein, Phys. Fluids 1978)

- rotational growth rate $\gamma_R \sim 1/a^2$ exceeds $\gamma_{K\text{-}H} \sim 1/a^3$ for $a >> 1$ and $\gamma_{SI} \sim m^2/a^2$ for mode number $m < m_{crit} \sim a^{1/2}$ [*shaded region* below] :



# Outline

- Analytic blob model
- Secondary instabilities and effect of background profiles
    - "essential stability"
    - 2D simulation results for curvature and velocity-shear instabilities
    - rotational instabilities & ELMs*
- Other topics
    - Blob statistics*
    - Diagnostics for blobs in 3D codes*
    - Analysis of NSTX GPI blob data*
- Assessment of blob model
- Summary and conclusions

---

*work in progress

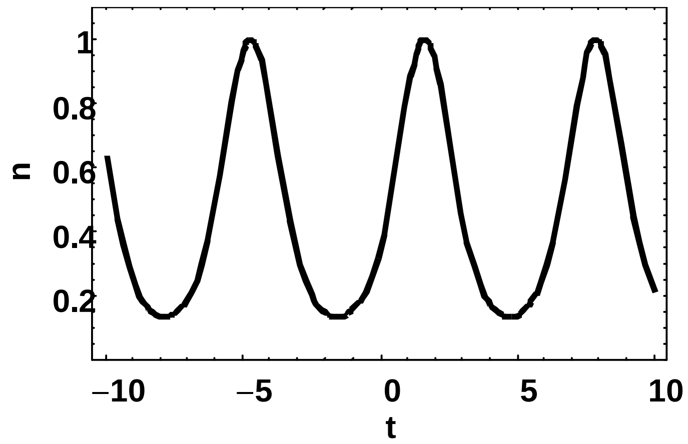
# Blob transport leads to non-Gaussian statistics

[*see Myra et al., APS-DPP( 2003)*]

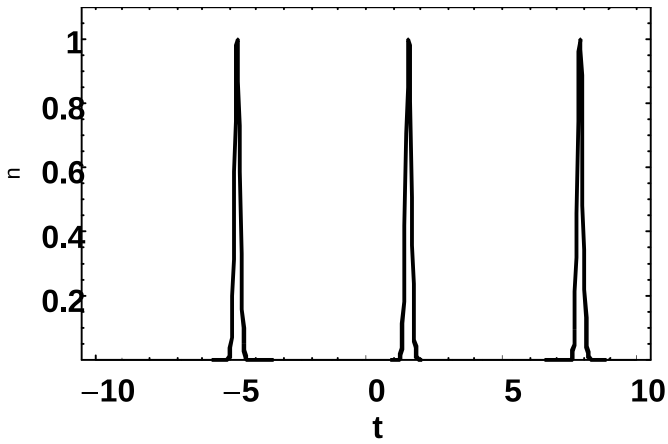
- analytic model of periodic blob train passing a probe:

$$n(t) = n_0 \exp\left[\xi\left(\sin\frac{2\pi t}{\tau} - 1\right)\right]$$

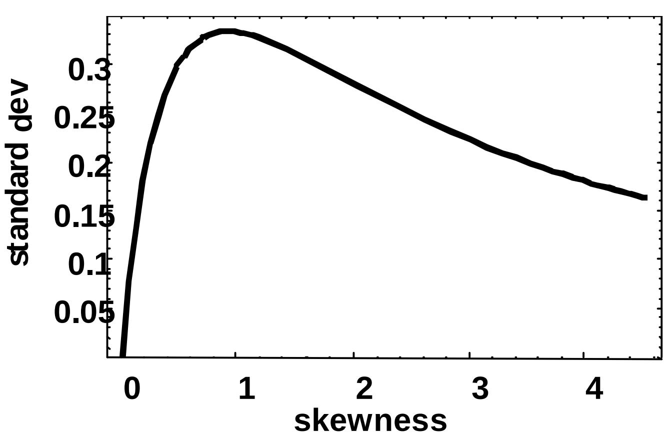
$n(t)/n_0$ for $\xi = 1$



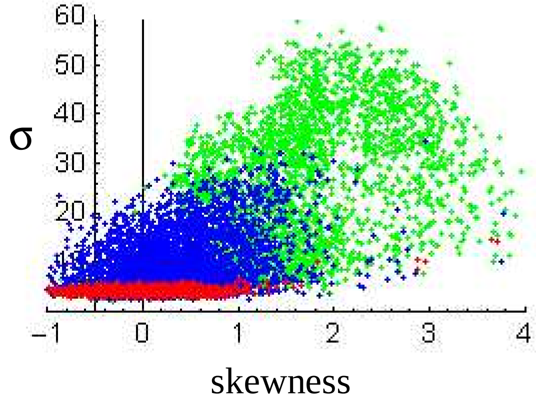

$n(t)/n_0$ for $\xi = 100$




- specific predictions about density statistics as $\xi\uparrow$: (mean$\downarrow$, skewness$\uparrow$ but standard deviation $\sigma$ is not monotonic in $\xi$). NSTX GPI data shows similar behavior:




red→blue→green ⇒ increasing x

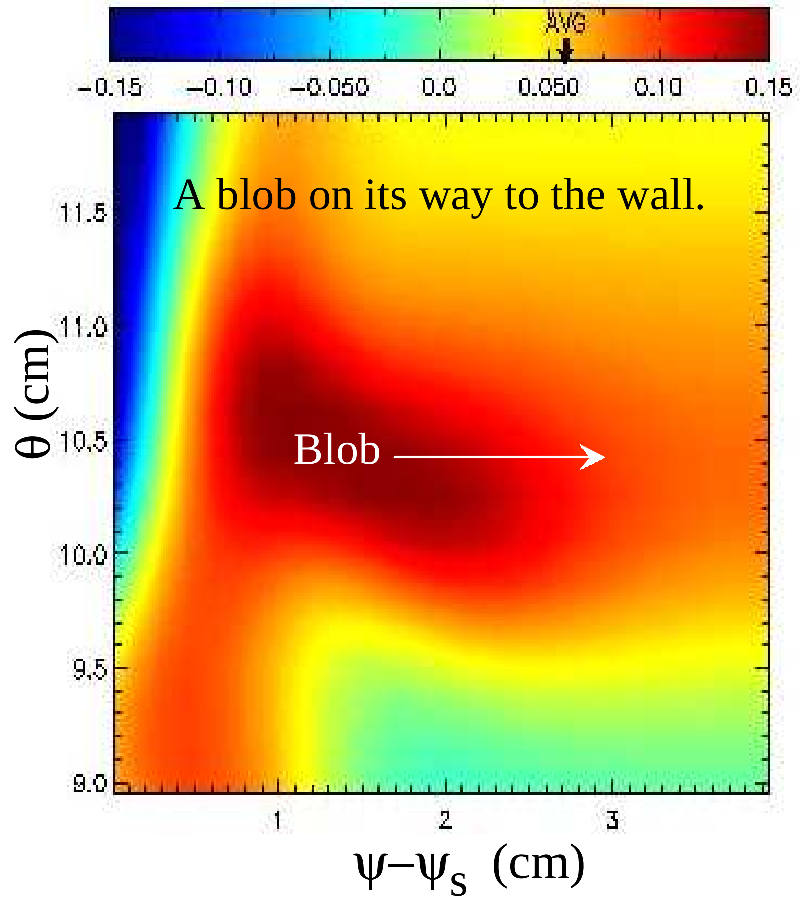


# Using GKV to diagnose blobs in BOUT simulations

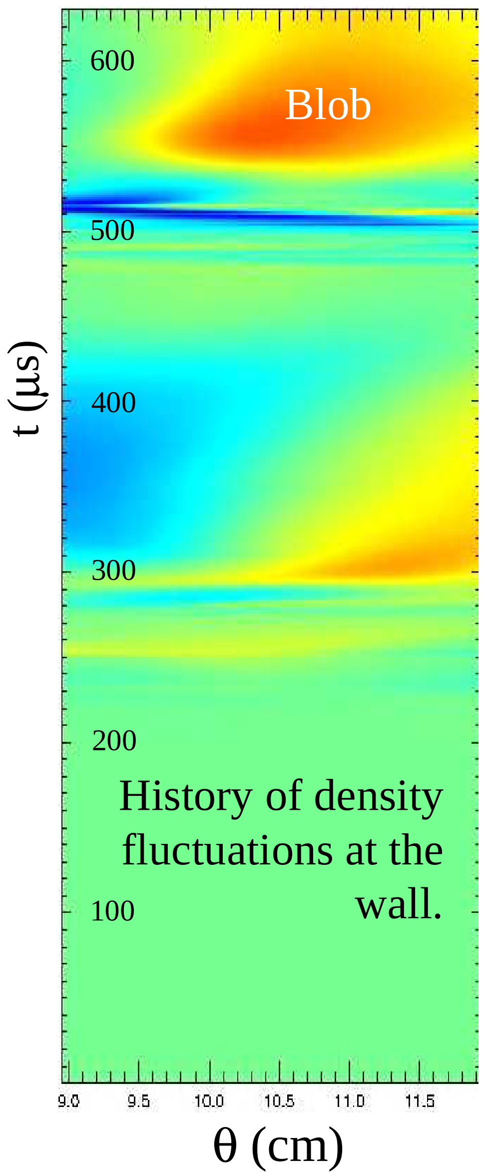
D.A. Russell, J.R. Myra and D.A. D' Ippolito (Lodestar)
W.M. Nevins and X. Xu (LLNL)

[*see Russell et al., APS-DPP (2003)*]

$\delta n(\psi,\theta, t = 550\ \mu s)$




$\delta n(\theta,t, \psi-\psi_s = 4\ \mathrm{cm})$



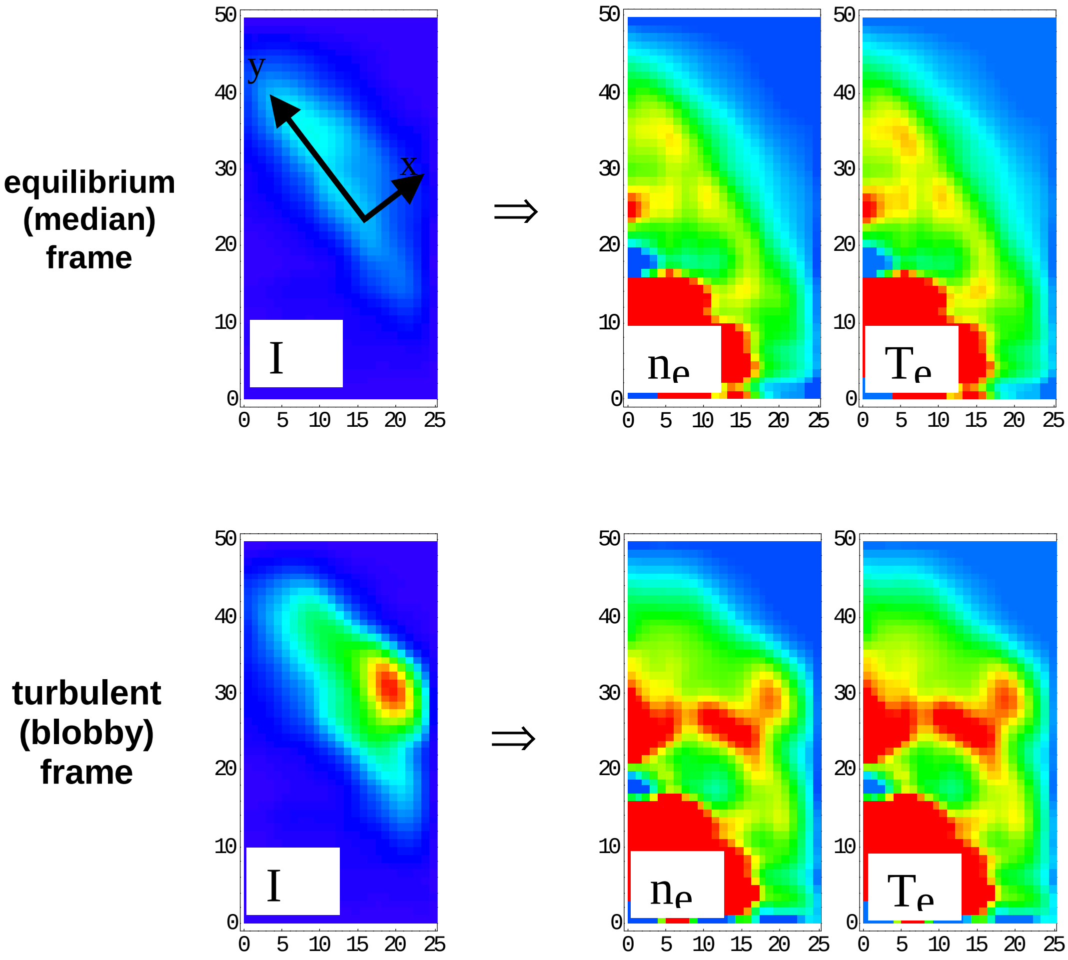

X.Q. Xu, BOUT: DIII-D Shot # 107404@4500ms
W. M. Nevins, GKV Analysis & Visualization Tools

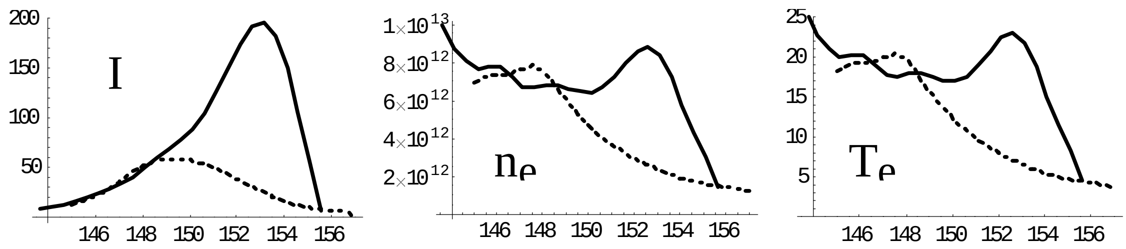
# Comparison of NSTX turbulence data with blob theory: extracting $n_e$,$T_e$ from GPI intensity

*see  Stotler et al. (this meeting)*
*Myra et al. (APS/DPP 2003, Albuquerque)*

$$I = n_0\, F(n_e, T_e)$$

**Gas Puff Imaging data from S. Zweben and R. Maqueda**




cuts across the frames: equilibrium dashed, blobby solid

## Assessment of the Blob Model

Some *qualitative* features of the experiments emerge naturally from the analytic blob model and the corresponding numerical simulations:

- *robust* mechanism for convective plasma transport
- two scale density and flux profiles
- faster decay of T(x) than n(x)
- critical particle flux for ionization-sustained equilibria
- mechanism for inward transport of impurities
- shape of propagating pulses
- intermittency and non-Gaussian statistics
- possible mechanisms for the density limit and for fine structure in ELMs?

A more *quantitative* comparison with experiment requires further development of both the theory and the measurements:

- include T(x,y), sheared $v_x$ and $v_y$, and rotation in 2D simulation codes
- include blob variation along B (at high density)
- use 3D turbulence codes (e.g. BOUT) to study blob formation; develop new code diagnostics for blobs
- *dedicated experiments in SOL transport:* coordinate complementary diagnostics to simultaneously measure all parameters needed for theory

# Summary

- Blob transport provides a robust mechanism for explaining the observed intermittency and radial transport in the far SOL.

- Blob motion is driven by a net radial force giving species-dependent drifts:

    - grad-B due to toroidal curvature (tokamaks)
    - centrifugal force (linear machines like PISCES)
    - neutral forces, e.g. "neutral wind" in LAPD [S. Krasheninnikov, PoP 2003]

- Radial convective flux of plasma depends on

    - blob size distribution
    - blob height above background density
    - ionization of neutrals (not discussed here)

- SOL convective transport has important implications for tokamaks

    - "main chamber recycling regime" ⇒ reduced divertor efficiency (Umansky et al., 1999; Pigarov et al., 2002)
    - may be related to the density limit on C-MOD (Greenwald, 2001; Xu, 2002; Myra et al., 2002)

Supplementary slides
(background material)

# Effect of plasma resistivity on blob motion

● Sheath conductivity term ($\propto \alpha$) + curvature drift term ($\propto \beta$) balance in the vorticity equation to give the blob potential induced by charge polarization

$$\varphi = \frac{\beta}{\alpha n} \nabla_y n = \frac{L_\|}{R\,n} \nabla_y n$$

● Plasma resistivity $\eta = m_e \nu_{ei}/ne^2$ enhances the blob potential and increases its radial velocity

$$\varphi \to \left(1 + \frac{m_e L_\| \nu_{ei}}{m_i c_s}\right) \frac{L_\|}{R\,n} \nabla_y n$$

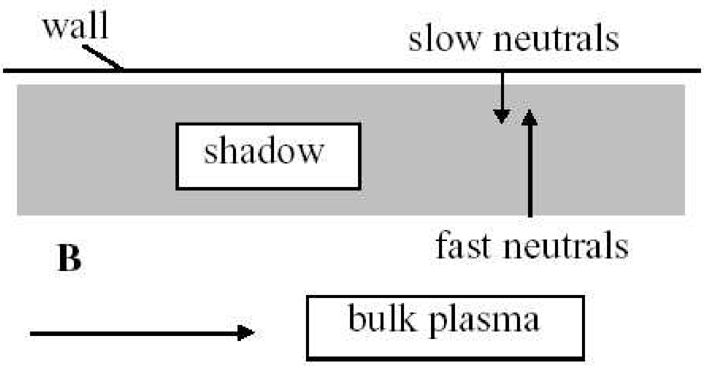
● Thus, plasma resistivity allows blob motion *inside* the separatrix and adds to sheath resistivity in SOL.

● Is plasma resistivity in SOL related to the density limit? (Xu, 2002)

## Blob propagation due to "neutral wind"

S. Krasheninnikov and S. Smolyakov,
to be published in Phys. Plasmas, 2003

Outwards radial force due to imbalance between the friction of the *fast neutrals* from the core and the *slow neutrals* from the wall ⇒ radial blob motion.




Force:

$$F_{Ni} = \mu_{Ni} n \left\{ (NV)_{fast} K_{fast} + (NV)_{slow} K_{slow} \right\}$$

(K = neutral-ion collision rate)

Resulting outwards velocity:

$$v_x \propto NV_{fast} \left( \frac{K_{fast} - K_{slow}}{\Omega_i} \right) \frac{L_{\|}}{{y_b}^2}$$

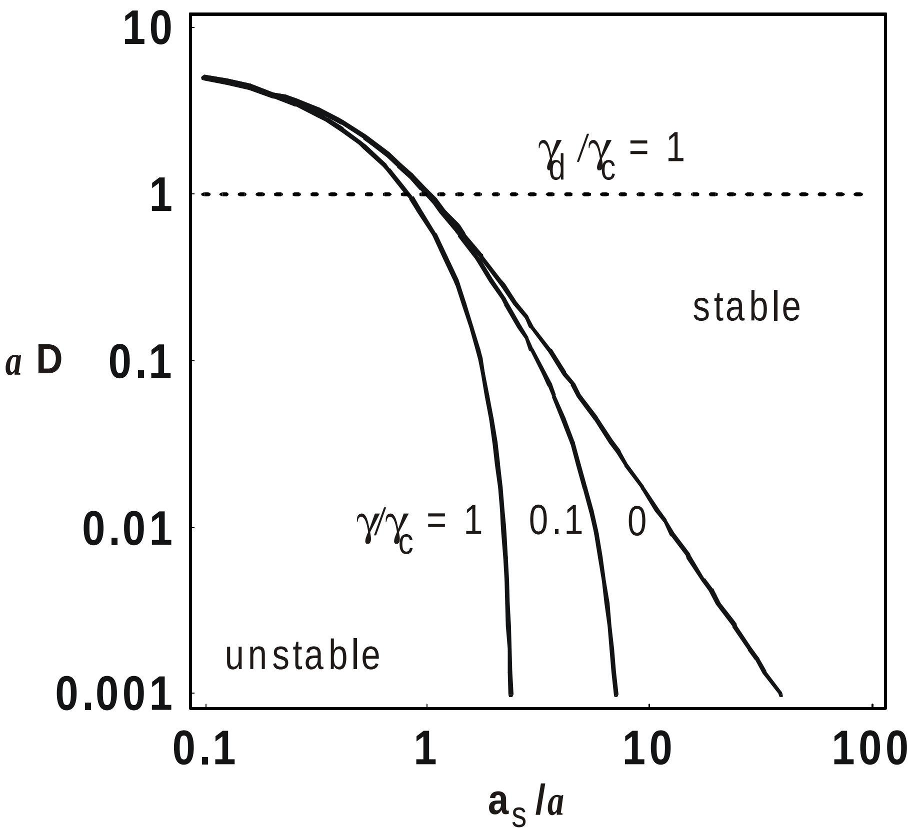
Estimate $v_x \approx 10^5$ cm/s for LAPD parameters in agreement with experiment.

## Stability and transport boundaries vs normalized D and $\nu$

If the inertial term in the vorticity equation is negligible, the blob radius $a$ can be scaled out of the equations; the equations are invariant under the transformation:

$$D \to a\,D\,, \quad a_s \to a_s/a\,, \quad \gamma \to \gamma\, a^3\,,$$

$$\varphi \to a\,\varphi\,, \quad n \to n$$



# Physics and scaling of K-H instability

- Kelvin-Helmholtz instability is driven by velocity shear in vorticity inertial term

$$\frac{d}{dt}\nabla^2\varphi = 0 \;\Rightarrow\; \gamma_{KH} \sim k_x v_x \leq \frac{v_x}{L_y}$$

- Blob flow pattern with velocity shear requires substantial background density.

- Compare scaling of K-H growth rate with that of sheath-interchange mode

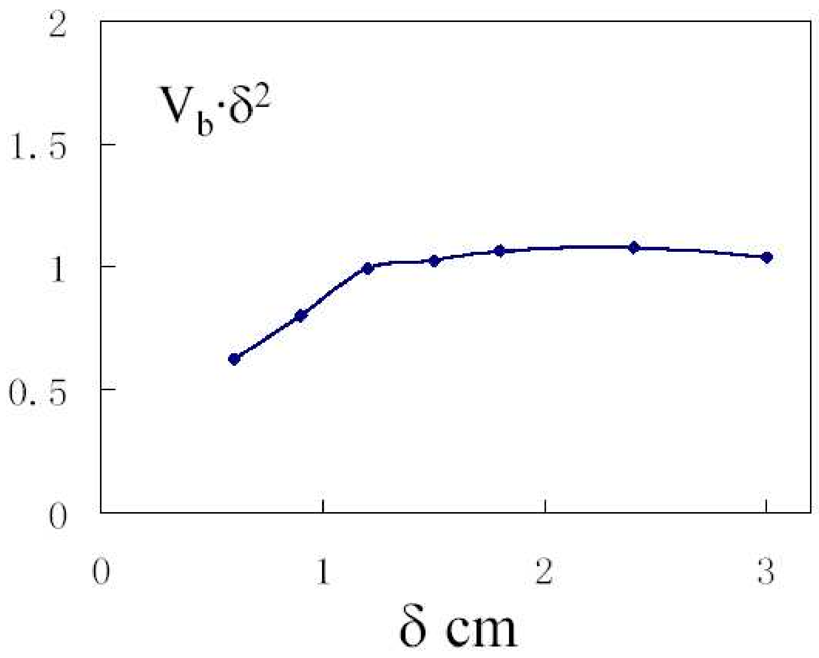
$$\gamma_{KH} \sim \frac{v_x}{L_y} \sim \frac{1}{{y_b}^3} \;, \quad \gamma_{SI} \sim \frac{{k_y}^2}{L_x} \sim \frac{1}{{x_b}^3}$$

- Note that $\gamma_{KH}$ and $\gamma_{SI}$ have opposite dependences on blob shape

  - $\gamma_{KH}$ larger when $x_b >> y_b$
  - $\gamma_{SI}$ larger when $y_b >> x_b$

# Reduction in blob velocity by K-H instability

2D Simulations by Yu *et al.* (2002) show that the radial blob velocity $V_b$ *decreases* for small blobs due to the Kelvin-Helmholtz instability:




Normalized $V_b \cdot \delta^2$ of blobs with $\delta_x = \delta_y = 0.6 \sim 3$cm

(Notation: $V_b = u_x$, $\delta = a$)