Blobs, Edge Turbulence and Interaction with Sheared Flows

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Outline

- **motivation and background**
- **physical mechanisms of blob dynamics**
- **modeling of NSTX/GPI**
- **turbulence saturation mechanisms and flows**

review

recent work

review:

S. I. Krasheninnikov, D. A. D'Ippolito, and J. R. Myra, J. Plasma Physics **74**, 679 (2008).

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- **motivation and background**
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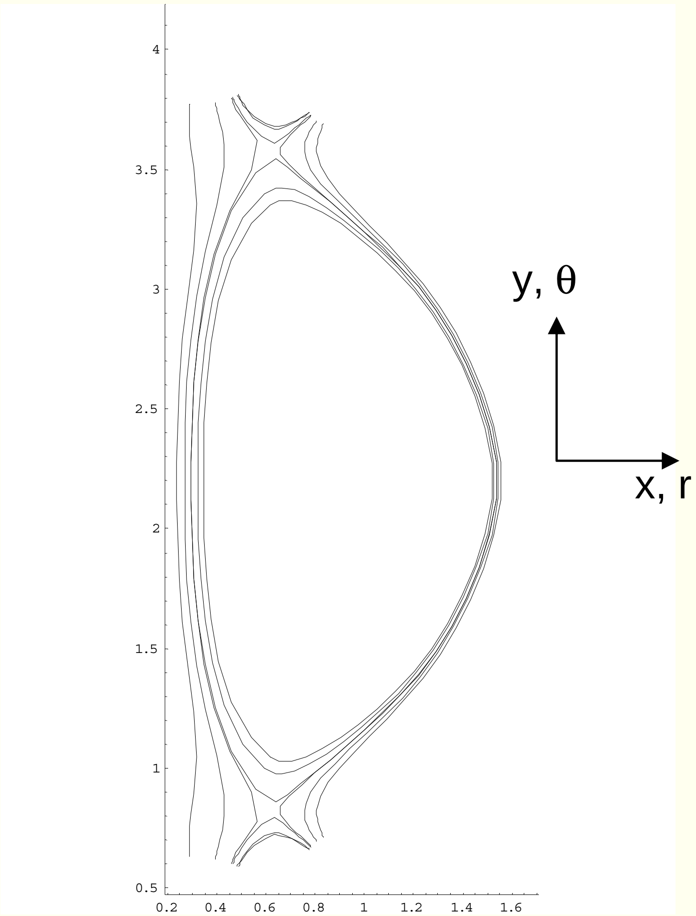
- motivation
- history
- experimental observations

Edge plasma physics is important for fusion research

- What is the "edge"?
  – just inside the separatrix (~ cm's) to the wall
  – some tokamak specific, much generic to magnetically confined plasmas

- Programmatic: [Loarte, ITER Physics Basis 1999]
  – **edge parameters** critical for performance,
  – **power handling**: "wall" damage by impact from plasma; **SOL width**
  – **wall content** (tritium inventory)
  – **scrape-off-layer (SOL) environment** for RF antennnas



Classical picture of the edge: plasma flows to divertor

classical picture

- turbulence diffuses plasma flux across separatrix (anomalous)
- plasma flows <u>along field lines</u> to divertor

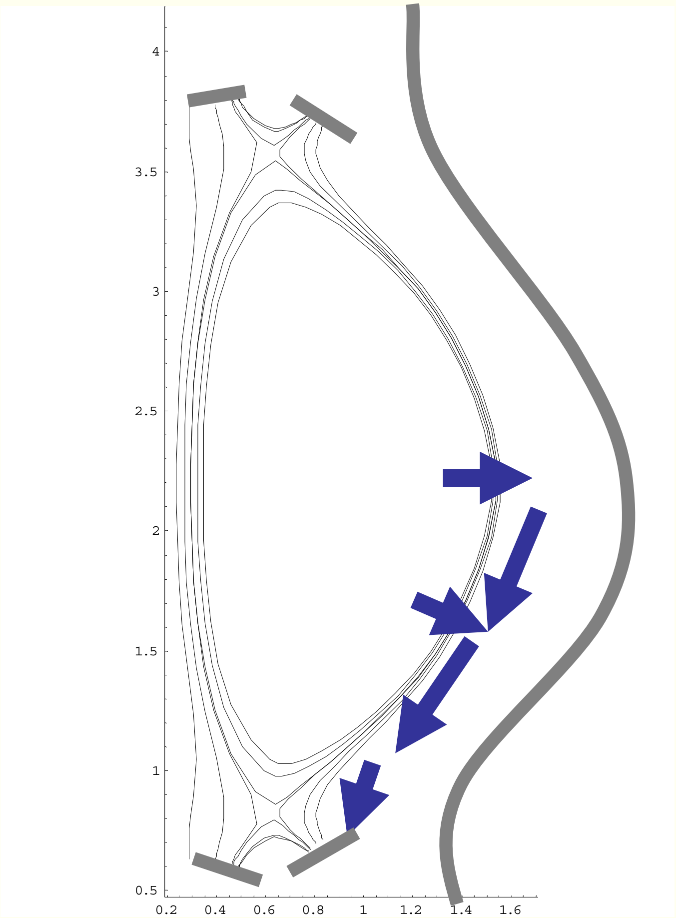
classical assumptions

- parallel losses ($\tau_{||} = c_s/L_{||}$) dominate in the scrape-off-layer (SOL)
- weak diffusive process set SOL width, λ

$$\lambda = (D\tau_{||})^{1/2}$$

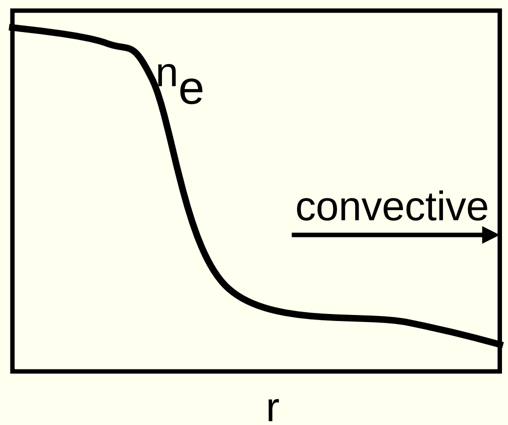
<u>but</u> early observations in edge revealed

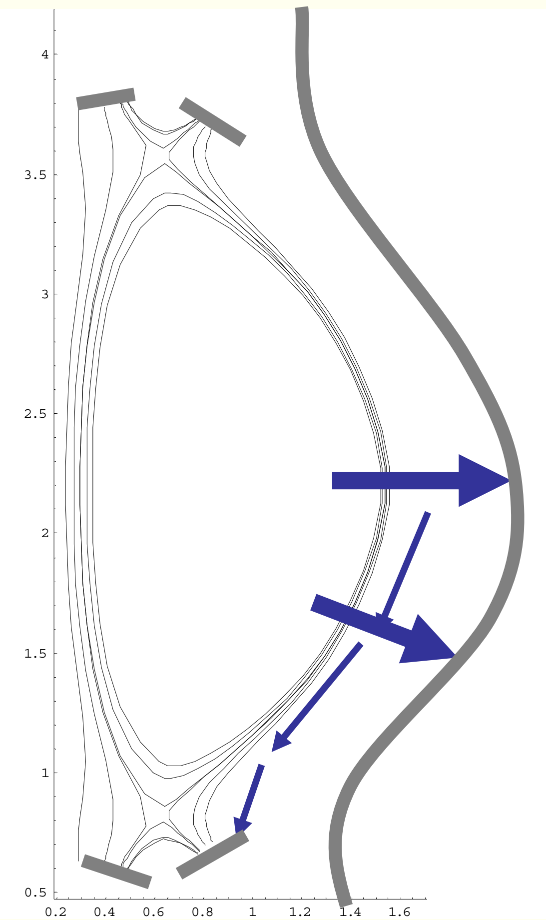
- very large amplitude, intermittent fluctuations
- coherent structures
  - Goodall 1982
  - Zweben 1985



Fall of the classical picture: main chamber recycling and blobs

- Alcator C-Mod experiments: large fraction of plasma flows to walls instead of divertor [Umansky 1998]
- SOL transport not diffusive ($\propto D\nabla n$) but convective ($\propto n v_{conv}$)
  - far SOL profiles can be flat
  - v_{conv} vs. c_s

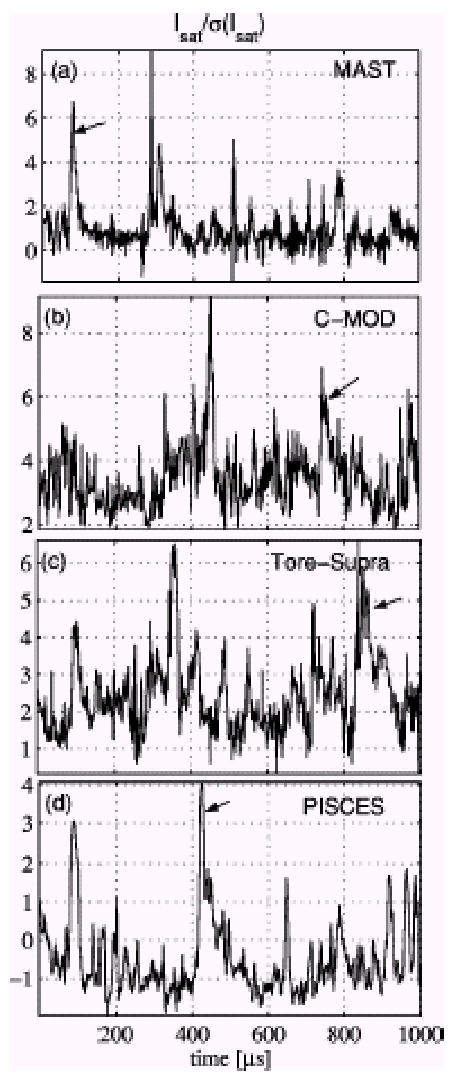




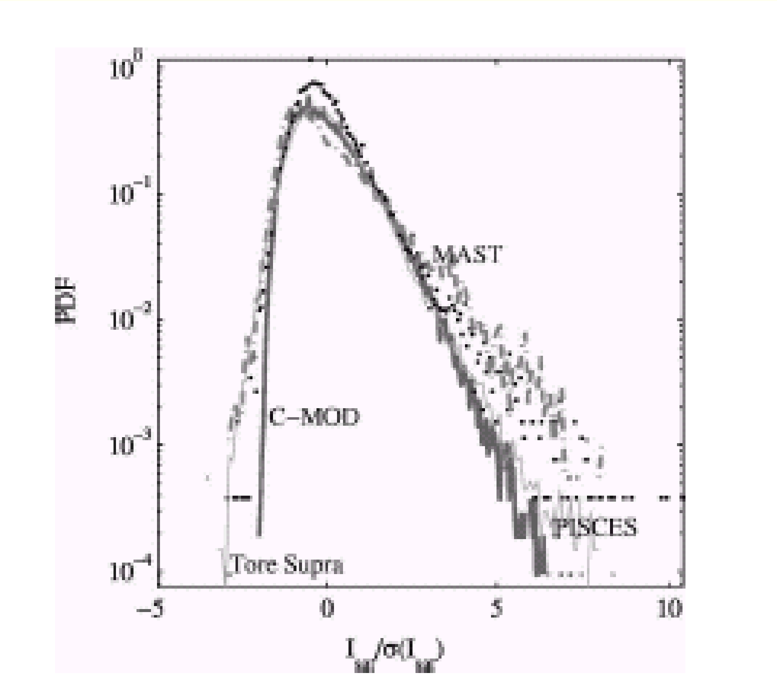
- plasmas convects across SOL in thin field-aligned blob-filaments

  [Krasheninnikov 2001; D'Ippolito et al. 2002]
  - main ingredients of blob physics known previously
  - blob now emerges as fundamental, individual, coherent object

Fluctuation PDFs show skewed non-Gaussian tails, and have a universal character



Antar, Counsell, Yu, LaBombard, Devynck
Phys. Plasmas **10**, 419 (2003)

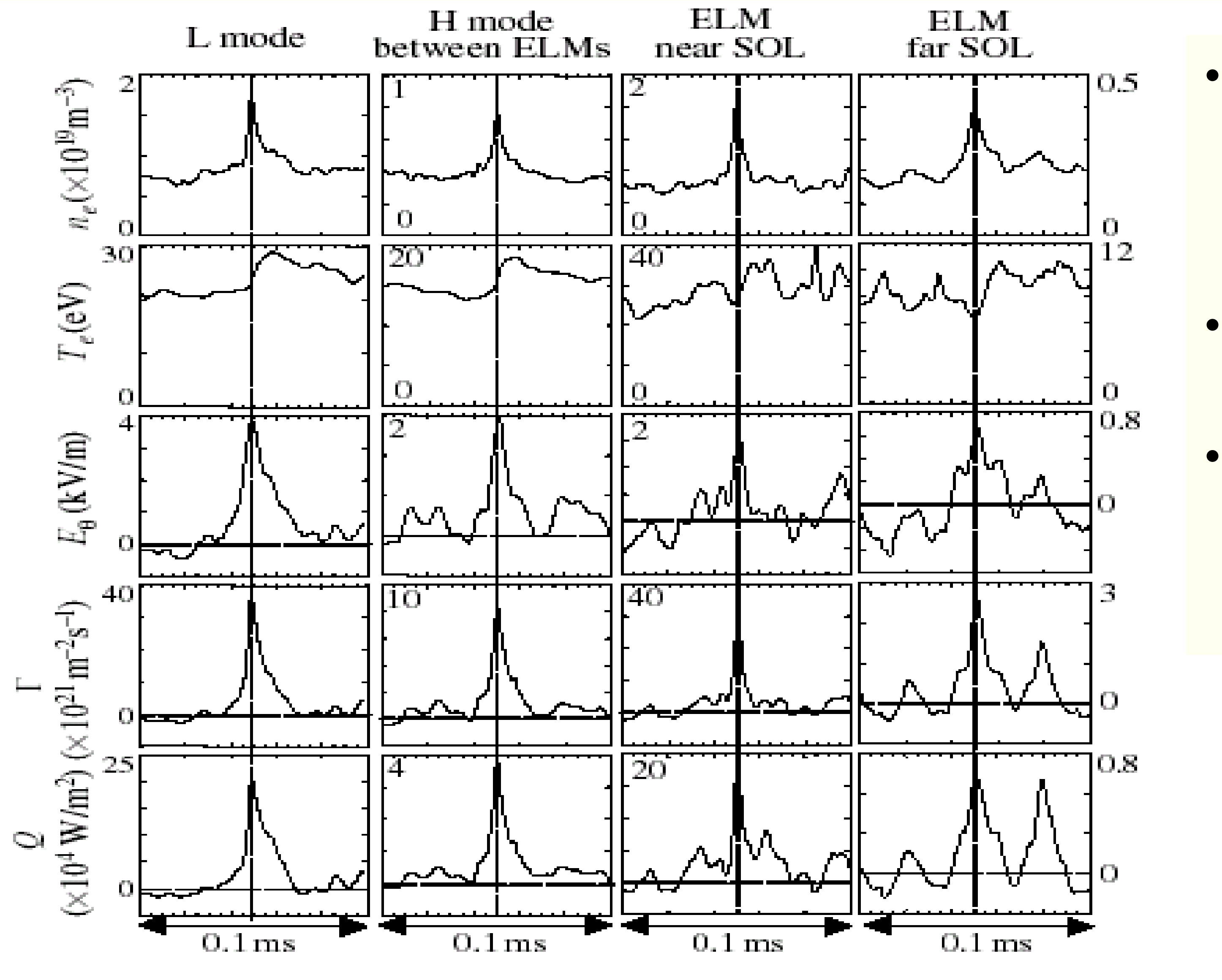


- PDF = probability distribution function (for fluctuating quantities)

- PDF of I_{sat} is skewed towards rare positive events (non-Gaussian)
- large events propagate radially outwards …

Probe signals show intermittent transport

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



time

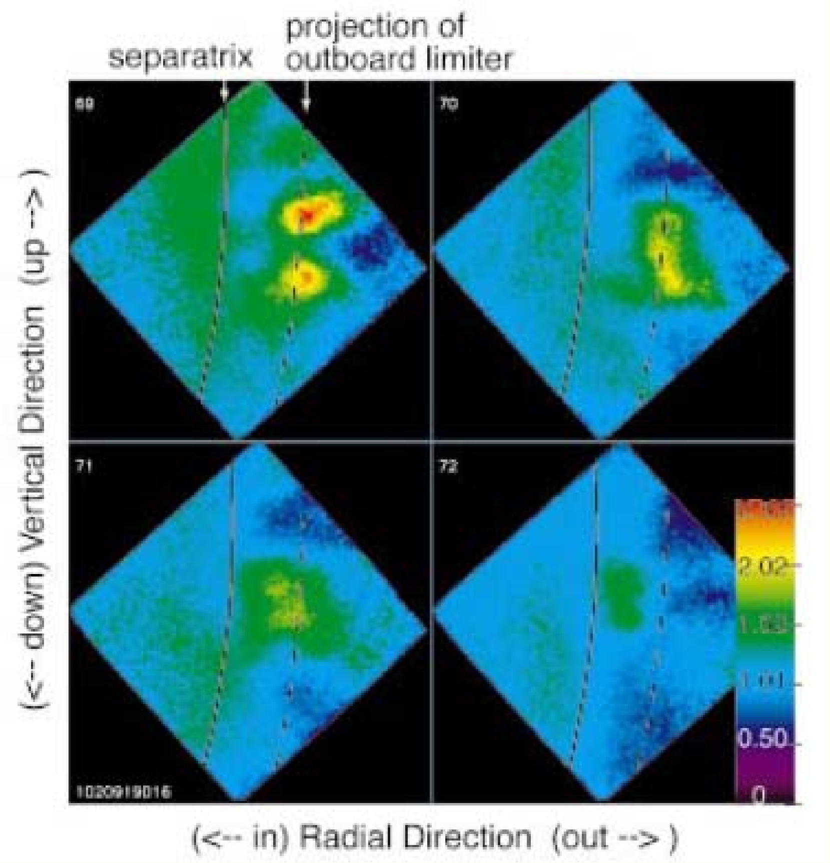
- conditionally-averaged signals: intermittency, strong nonlinearity
- fast rise, slow decay
- E_θ correlated with density and flux (convection)

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

J.L. Terry et al., 2003 [C-Mod]



Characteristic time and space scales

- spatial correlation length $\perp$ B (“blob” radius): $a_b = 0.5 – 3$ cm
- radial size of edge region: 5 - 20 cm
- correlation time: τ_c = 10’s of μs
- structure (“blob”) velocity: $v_x \sim a_b / \tau_c \sim 10^5$ cm/s = 1 km/s
- parallel correlation (connection) length: $L_{||}$ = 100’s of cm
- parallel loss (flow) time $\tau_{||}$ ~ 100’s of μs

- tokamak edge/SOL plasma characteristics
  - $n_e = 10^{12} – 10^{14}\ \mathrm{cm}^{-3}$
  - T_e = 5 -50 eV
  - $\rho_j < L_\perp, a_b$
  - $\lambda_{ei} < L_{||} \Rightarrow$ collisional $\Rightarrow$ try resistive, fluid modeling
  - $\Omega_{cj}\, \tau_c >> 1 \Rightarrow$ gyro-averaged (low frequency) theory

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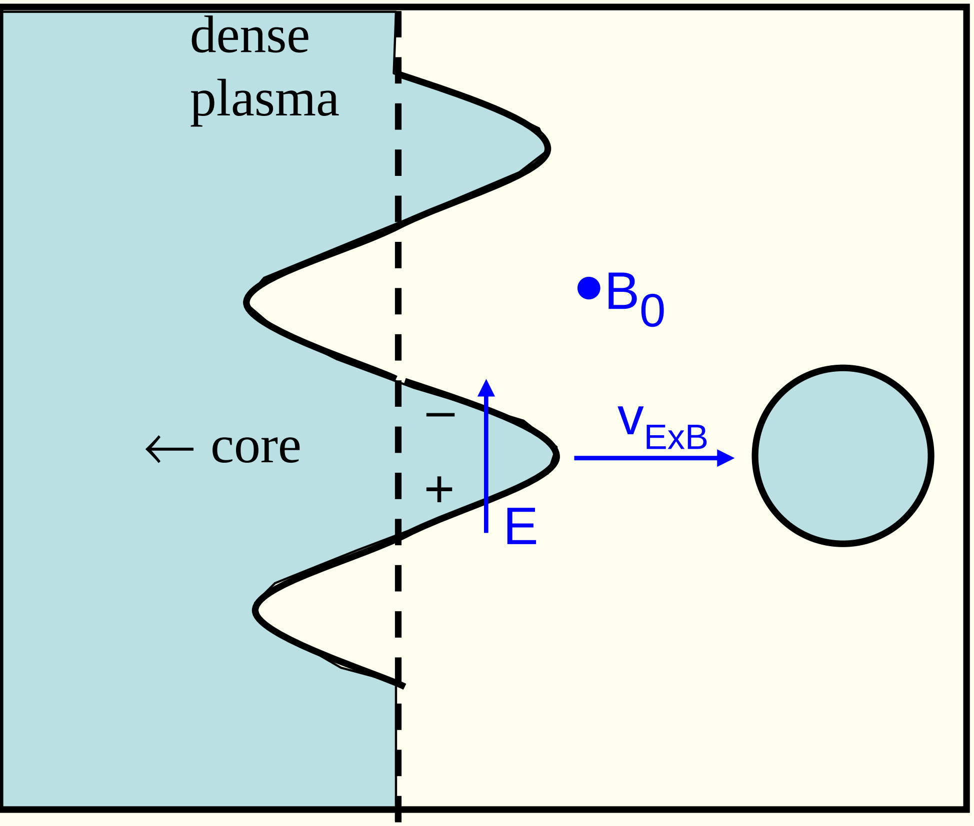
- drive terms
- current closures
- electrostatic blob regimes
- EM effects, ELMs

Curvature drifts & charge separation drives interchange modes



Rosenbluth Longmire 1957

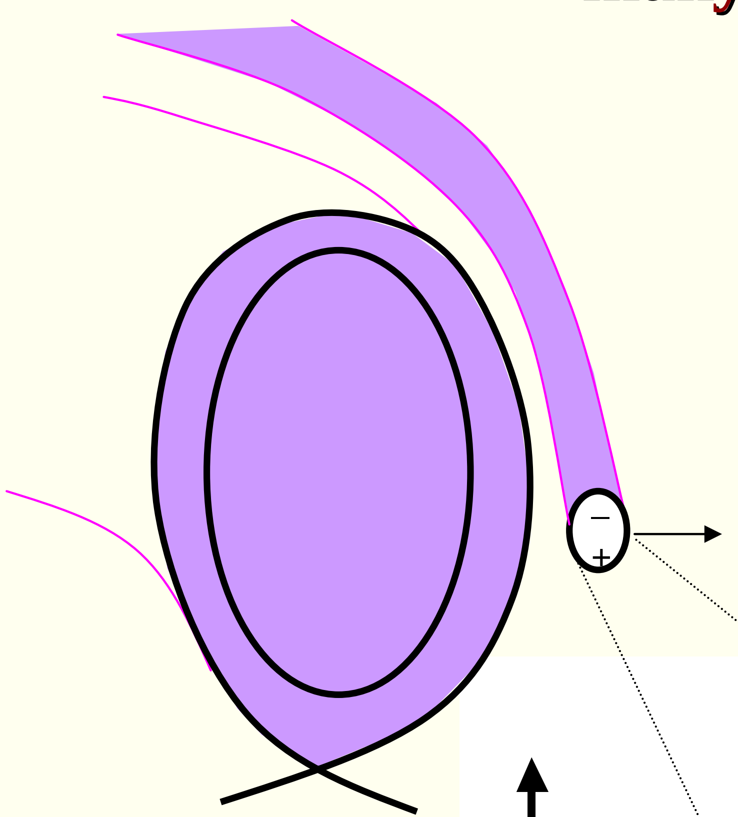
- unstable interchange mode
- crests break off ⇒ blobs
- troughs penetrate in ⇒ holes

$$\nabla \cdot \mathbf{J}_\perp + \nabla_\| J_\| = 0$$

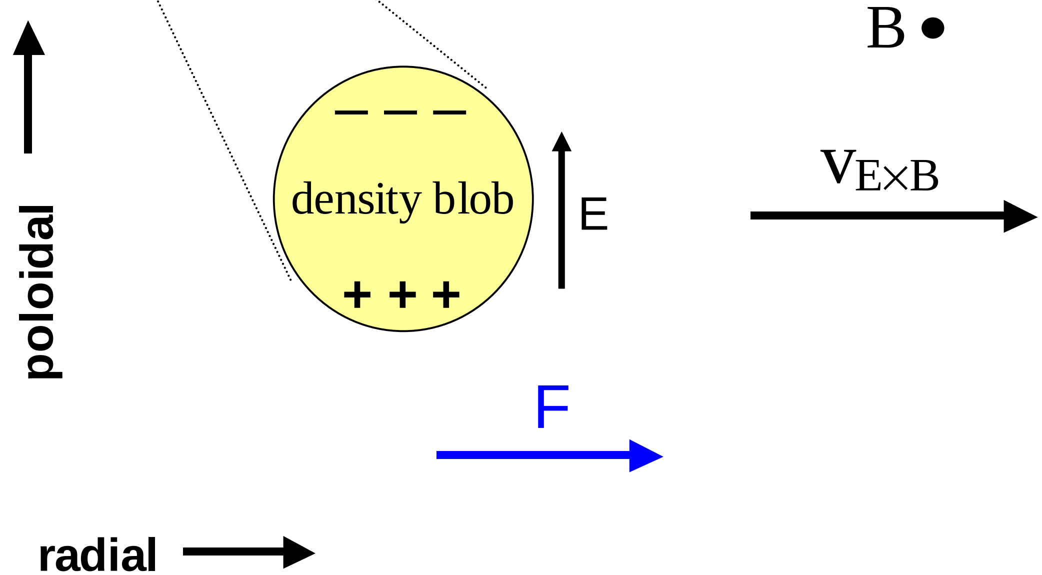
$$\nabla \cdot \frac{d}{dt}\left(\frac{n m_i c^2}{B^2}\nabla_\perp \mathbf{\Phi}\right) = \cancel{\nabla_\| J_\|} + \frac{c}{B}\mathbf{b}\cdot\nabla\times\mathbf{F}$$

$$= -\frac{m_i c}{B} g_{sp} \frac{\partial n}{\partial y}$$

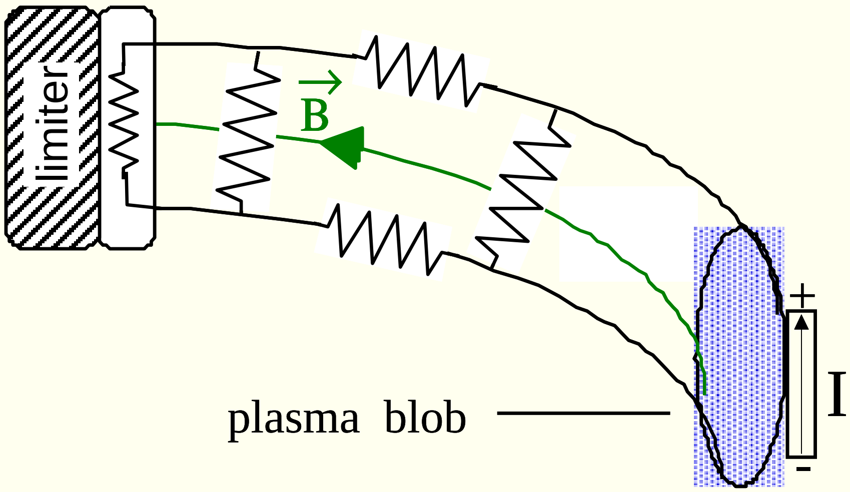
Blob structures result from the saturation of edge turbulence; many drive mechanisms



- <u>curvature</u> $g_\kappa = 2c_s^2/R$
  Krasheninnikov 2001
  D'Ippolito 2002
- <u>neutral wind</u> $g_{nw} = v_n \nu_{in}$
  Krasheninnikov 2003
- <u>centrifugal</u> $g_{cent} = V_\theta^2/a$
- <u>plate tilt</u> $g_{tp} = 2c_s^2 \cot\theta / L_{||}$
  Cohen, Ryutov 2006



Charge separation drives currents which must close



- parallel plasma resistivity
- cross-field resistivity
- sheath resistivity
- EM effects

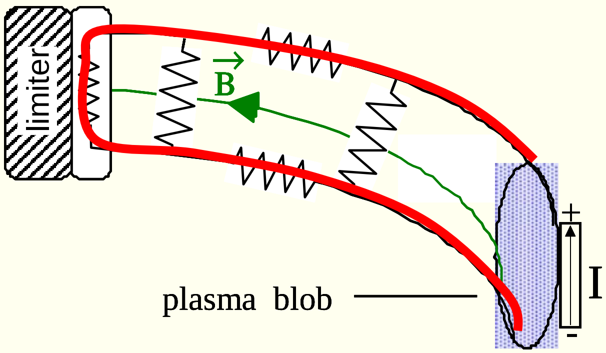
The size of the various effective resistances controls the distribution of currents, as well as the total potential and therefore the blob speed $v_{E\times B} \sim \Phi/a_b$.

Speed ratio $v_\perp/c_s$ controls “SOL width”, divertor footprint, midplane wall

2D physics and closure relations

Sheath limited blobs (Nedospasov instability)

- parallel resistance is small; perpendicular resistance large $\Rightarrow$ current loop closes in the sheath



$$\nabla_{\|} J_{\|} \to \frac{2}{L_{\|}} n e c_s \left(1 - e^{-e(\Phi - \Phi_f)/T}\right) \approx \frac{2 n e^2 c_s (\Phi - \Phi_f)}{L_{\|} T}$$

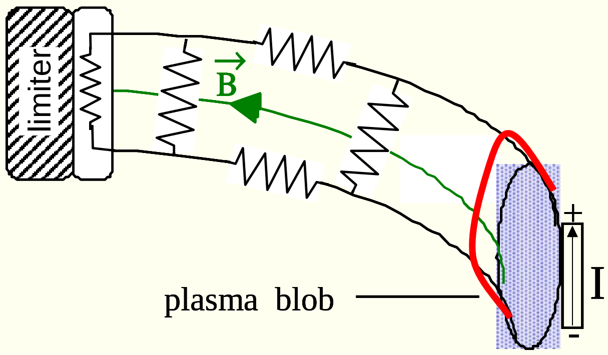
$$v_b = 2 c_s \left(\frac{\rho_s}{a_b}\right)^2 \frac{L_{\|}}{R}$$

Inertia limited blobs (resistive ballooning mode)

- parallel resistance is large; current flows *locally* across field lines

$$\nabla_{\|} J_{\|} \to 0$$

$$v_b = \frac{a_b^{1/2} c_s}{R^{1/2}}$$

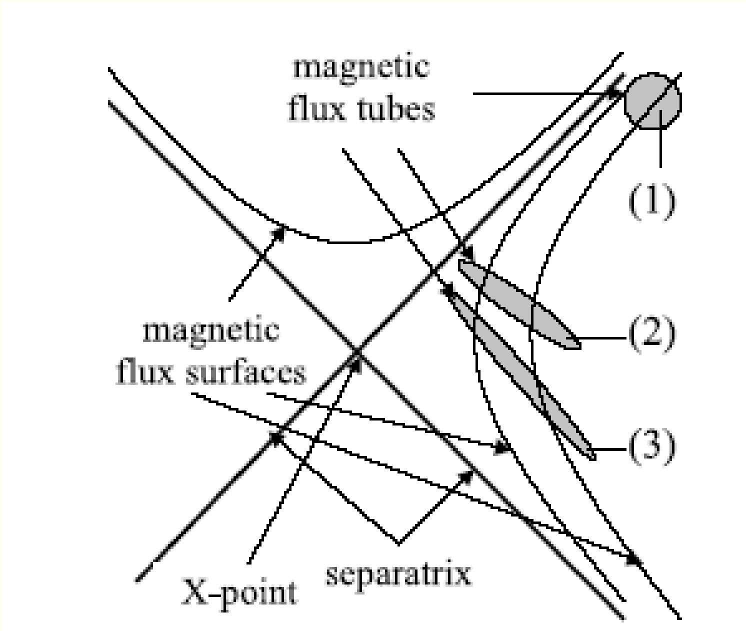


- sheath and inertial limits introduce some characteristic scales

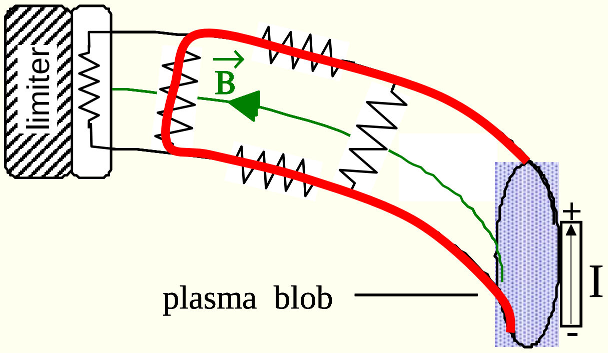
$$\underbrace{a_* = \rho_s \left(\frac{L_{\|}^2}{\rho_s R} \right)^{1/5}}_{\text{scale where sheath resistance, curvature drive, and inertial term balance}} \qquad v_* = c_s \left(\frac{a_*}{R} \right)^{1/2} = c_s \left(\frac{\rho_s^2 L_{\|}}{R^3} \right)^{1/5}$$

X-point limited blobs (resistive X-pt mode)

- parallel current flows to X-pt where shear (flux tube squeezing) enhances perpendicular conduction and enables closure of the current path



Krasheninnikov, Ryutov and Yu, 2004



$$\nabla_{\parallel} J_{\parallel} \rightarrow \frac{(\sigma_{\parallel}\sigma_{\perp})^{1/2}}{L_{\parallel}\delta_b}\Phi$$

$$v_b \propto \begin{cases} g_{sp}^{2/3} / a_b^{1/3} & \text{ion polarization} \\ g_{sp} / a_b & \text{electron } \sigma_{\perp} \end{cases}$$

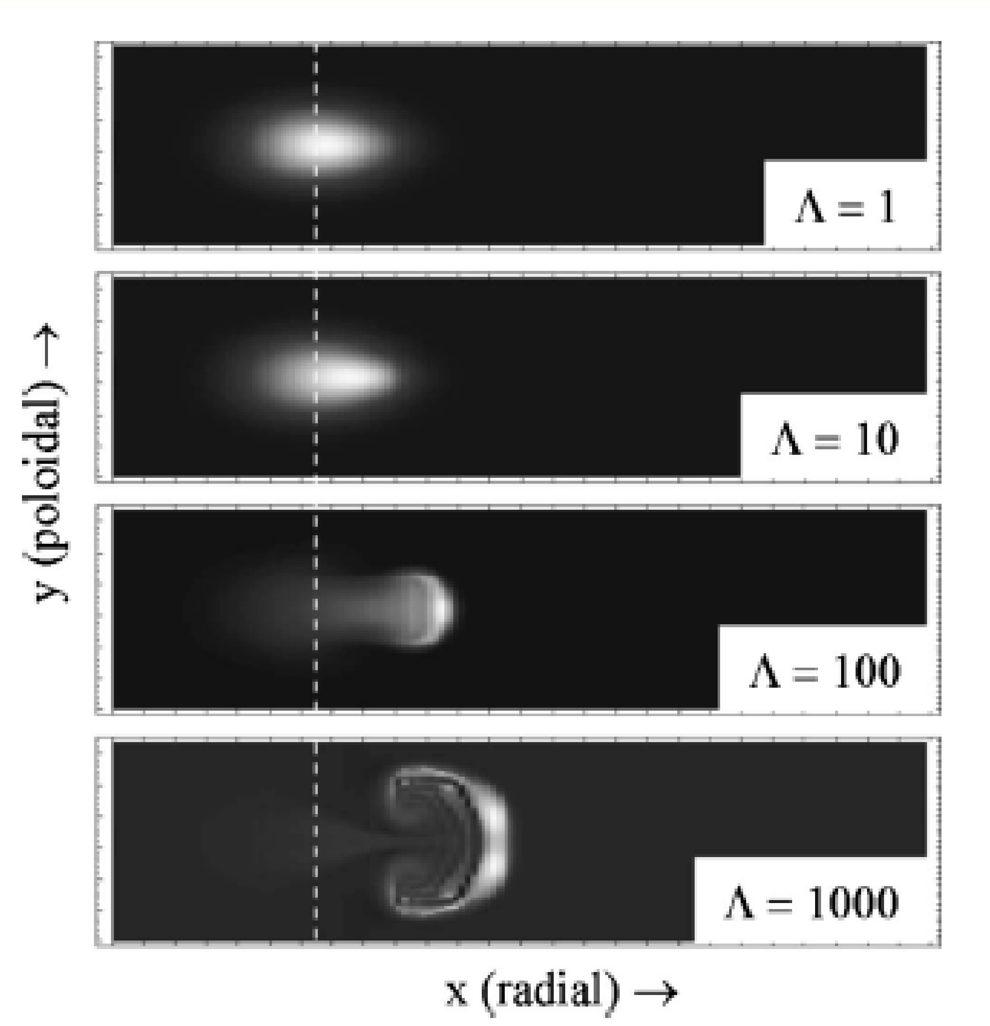
ion polarization: Myra & D'Ippolito 2005

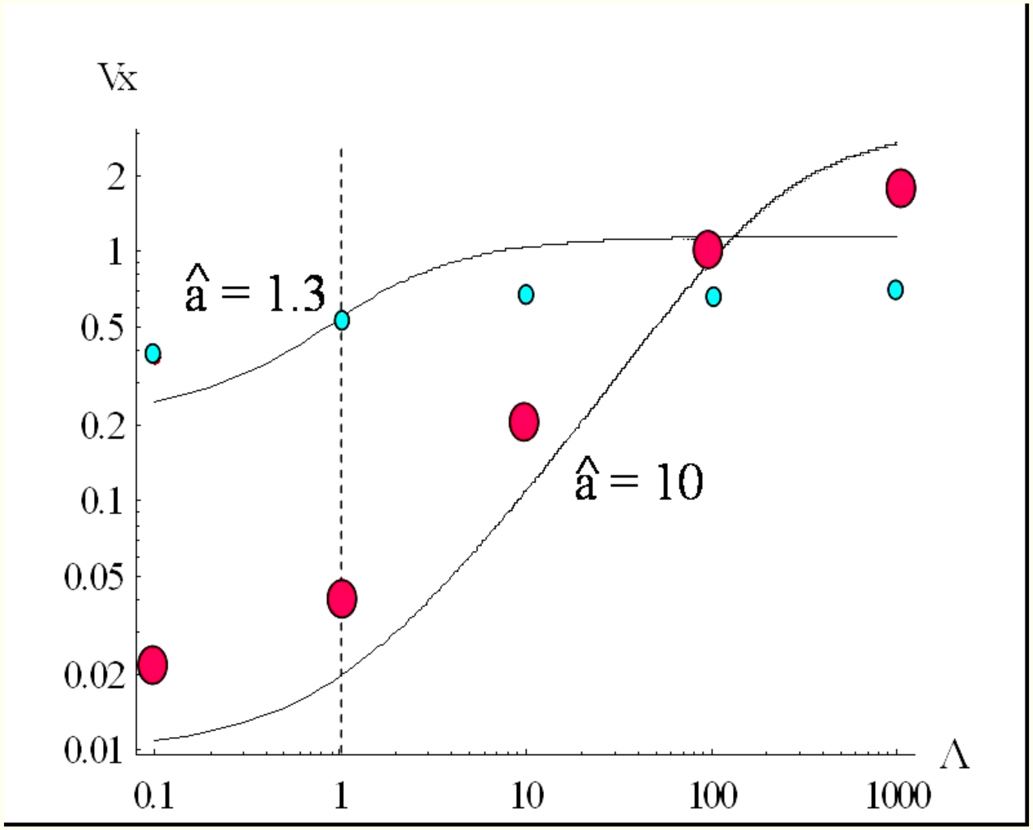
electron $\sigma_{\perp}$: Krasheninnikov, Ryutov and Yu, 2004

Theory and simulations show the scaling of blob velocity vs. size (a) and collisionality regime (Λ)

- linear theory with *correspondence rules* give a rather good description of blob speed $\gamma \to \frac{v_x}{a_b},\ k_\perp \to \frac{1}{a_b},\ L_n \to a_b,\ k_\| \to \frac{1}{L_\|}$

CT invariant scaling





- **blobs speed up with collisionality Λ**
- **for low Λ, small blobs move fastest**
- **for large Λ, large blobs move fastest**

Myra, Russell, D'Ippolito 2006

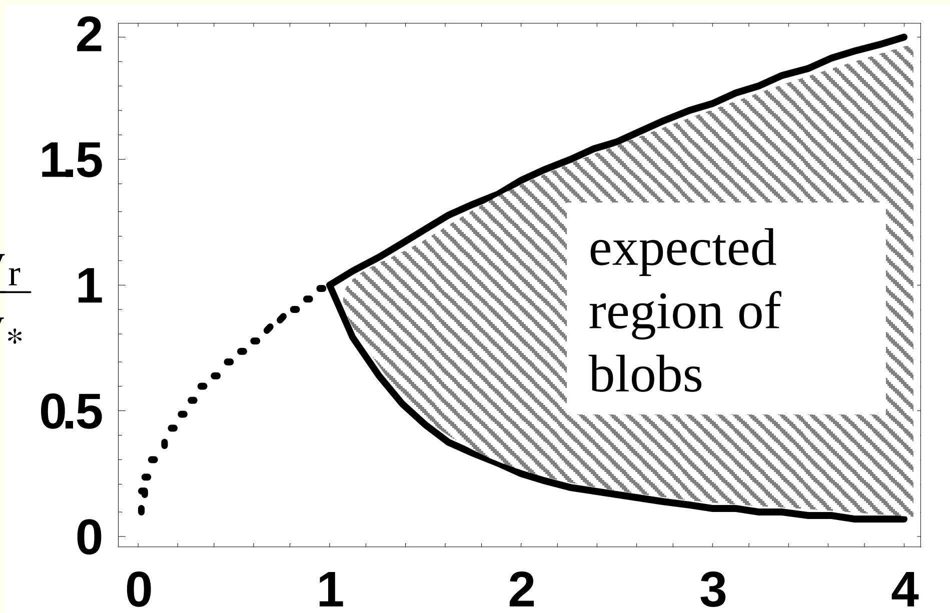
Electrostatic regime diagram characterizes blob speeds

- specific scaling predicted in each regime

$$\Lambda = \frac{\nu_{ei} L_{\|}}{\Omega_e \rho_s} \qquad \hat{a} = \frac{a_b}{a_*} \qquad \hat{v} = v / v_*$$

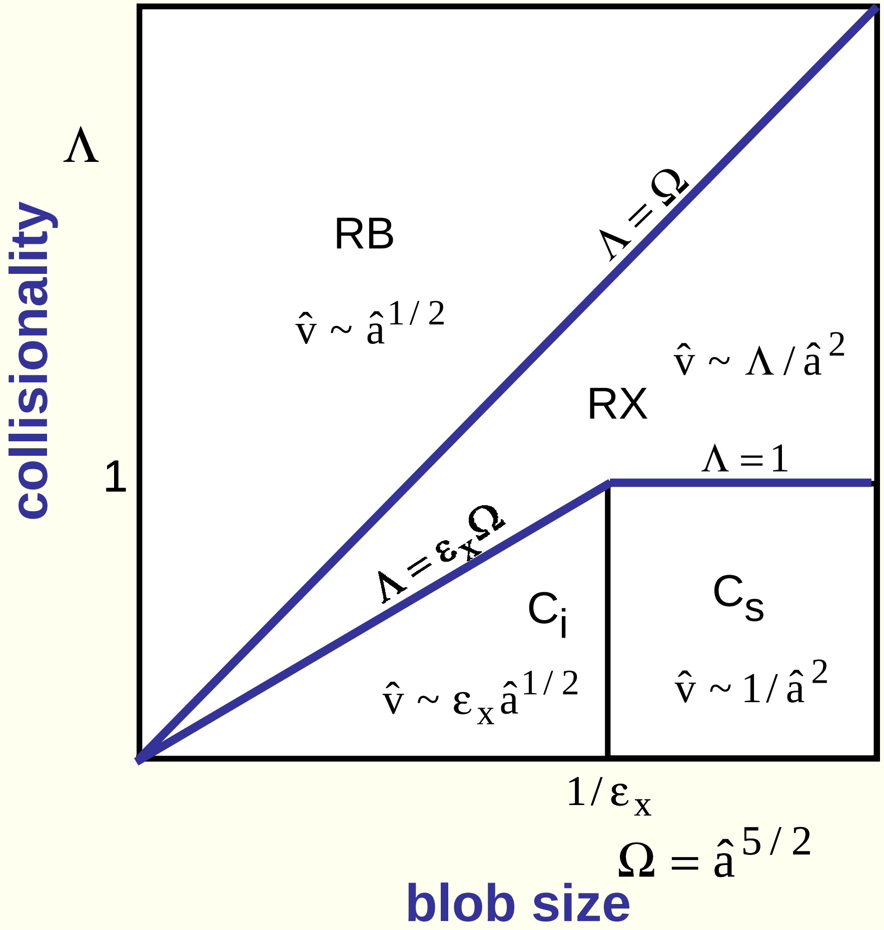
- expected range of blob velocities is bounded

$$\frac{1}{\hat{a}^2} < \frac{v_r}{v_*} < \hat{a}^{1/2}$$

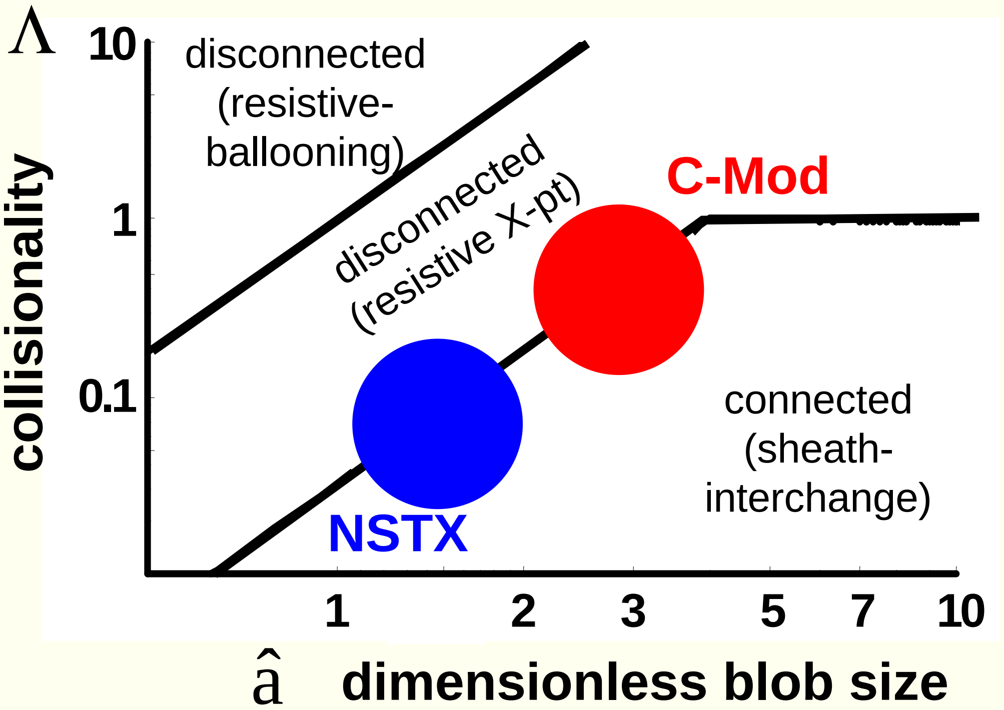


$\hat{v} = \frac{v_r}{v_*}$

$\hat{a} = \frac{a_b}{a_*}$



NSTX and C-Mod explore different regions of edge/SOL parameter space



- B ratio 20, n_e ratio 30 …
- Observed v_{blob} similar
- Characteristic v_* is similar
  $v_* \sim 2$ km/s

$$\Lambda = \frac{\nu_{ei} L_\parallel}{\Omega_e \rho_s} = 1.7\times10^{14}\frac{n_e L_\parallel}{T_e^2} \qquad \hat{a} \equiv \frac{a_b}{a_*} = \frac{a_b R^{1/5}}{L_\parallel^{2/5}\rho_s^{4/5}} = 0.018\frac{a_b B^{4/5} R^{1/5}}{L_\parallel^{2/5} T_e^{2/5}}$$

$$v_* = c_s\left(\frac{a_*}{R}\right)^{1/2} = 5.1\times10^6\frac{L_\parallel^{1/5} T_e^{7/10}}{B^{2/5} R^{3/5}}$$

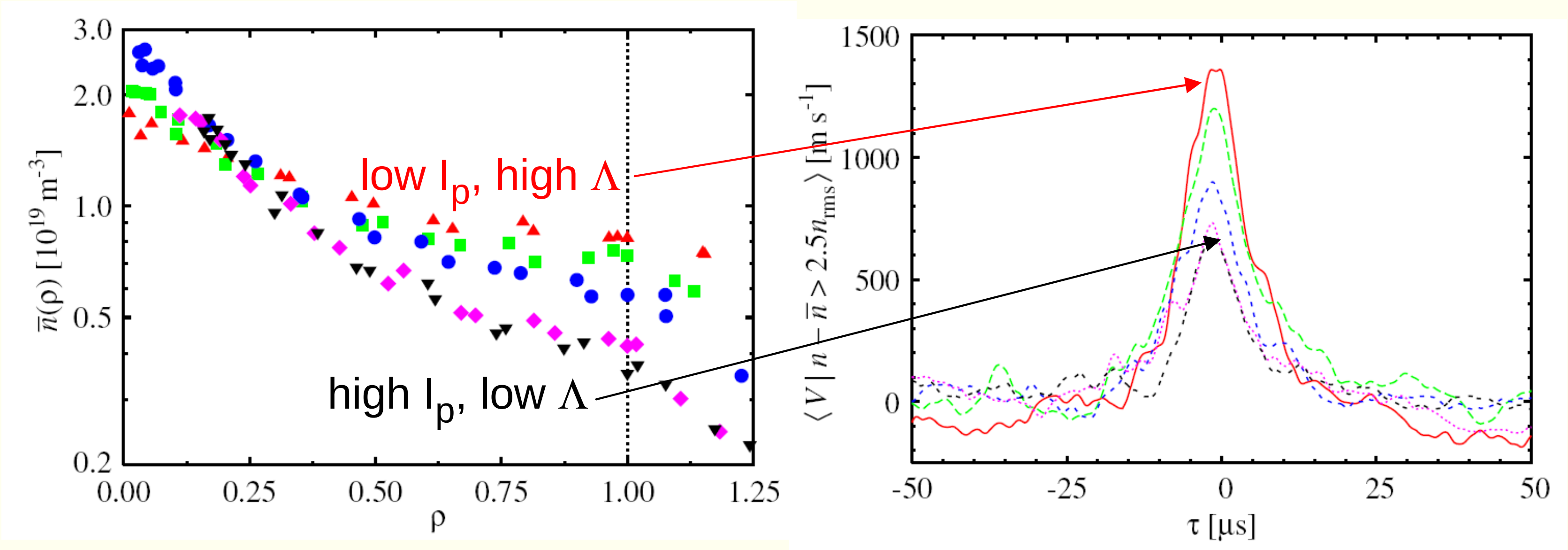
Theoretical bounds on blob radial velocity

$$\frac{1}{\hat{a}^2} < \frac{v_x}{v_*} < \hat{a}^{1/2}$$

sheath　　resistive bal.

Experiments on TCV showed collisionality scaling

Garcia et al. PPCF 2007



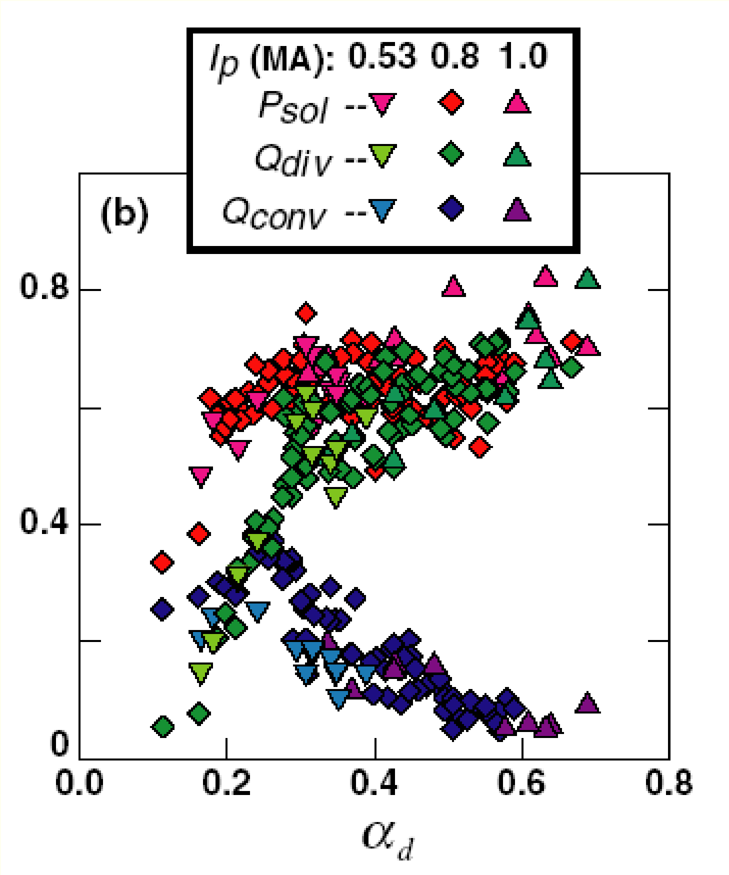
SOL n_e profile broadens at low $I_p \Rightarrow$ high collisionality ($\sim L_{||}/\lambda_{ei} \propto \Lambda$)

radial blob velocity (cross-correlated with n_e fluctuations)

also seen on C-Mod [e.g. LaBombard PoP 2008]

- blobs speed up and SOL broadens with collisionality Λ

Heat transport and density limit implications of blob theory



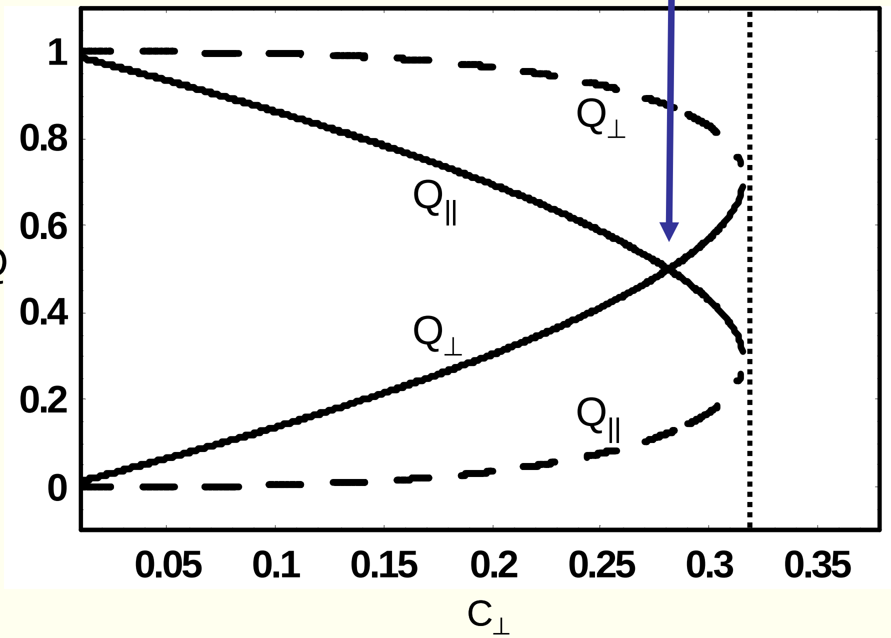
← **collisionality**

LaBombard NF 2005

Greenwald PPCF 2002

collisionality dependence of blob model:
v_b in increases with ν_{ei}

For the physically-observable high-T root (solid), $Q_\perp$ exceeds $Q_{||}$ just before the equilibrium limit is reached.



collisionality →

D'Ippolito & Myra, PoP 2006

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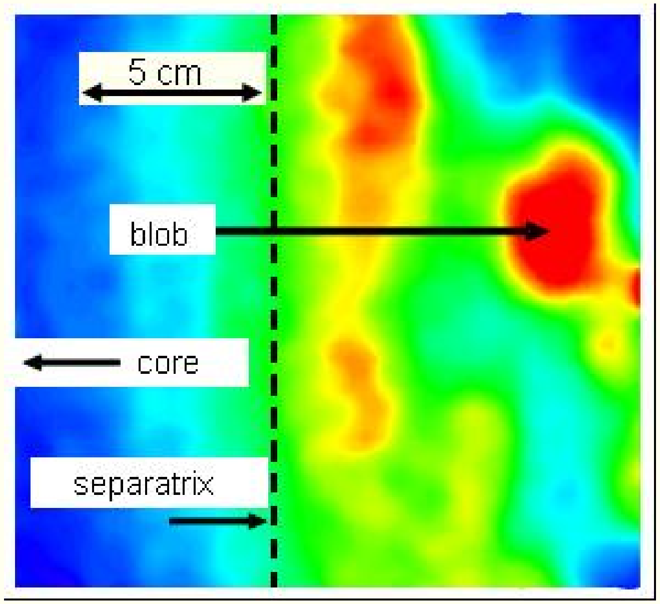
- **turbulence saturation mechanisms and flows**

- background
- comparison with analytic estimates
- comparison with turbulence code

Background – GPI

- Gas Puff Imaging (GPI)
  - Zweben 2004; Maqueda 2003; Terry 2003
  - look for visual emission pattern from puffed gas in presence of plasma
  - 2D movies of edge turbulence blob motion
- GPI measures light intensity, not n_e, T_e
  HeI 5876 line intensity is $I = n_0 F(n_e, T_e)$
  n_0 = neutral He density
  $F(n_e, T_e)$ = atomic physics
- test theory of blob v_x
- difficult to do with probe data alone
  - 1D time-slice through blob
  - unknown impact parameter (no y info)
- NSTX and C-Mod GPI diagnostic well matched to blob dynamics
  - spatially and temporally



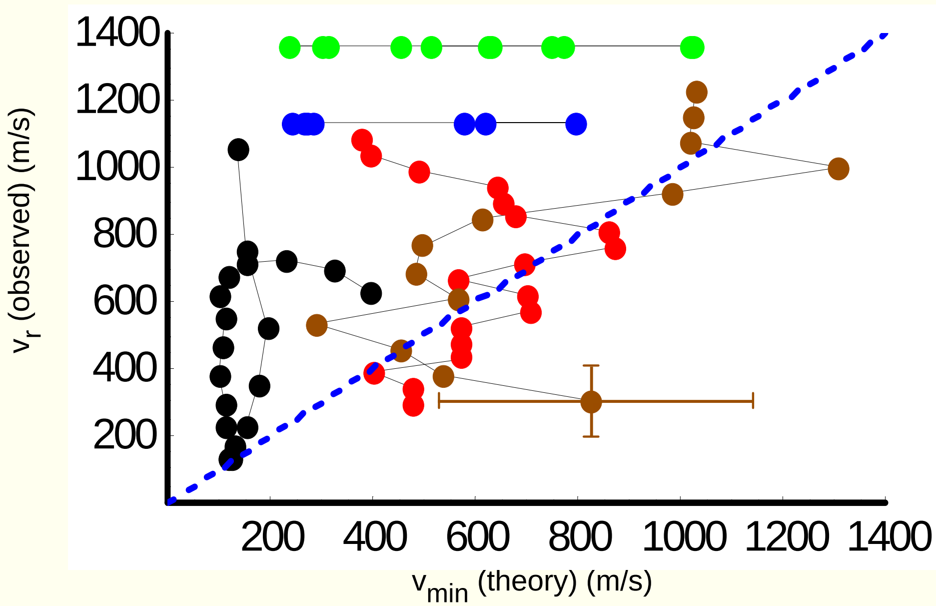
sample GPI frame

NSTX shot 112825
L mode 4.5 kG, 800 kA
0.8 MW NBI
He puff (HeI filter)

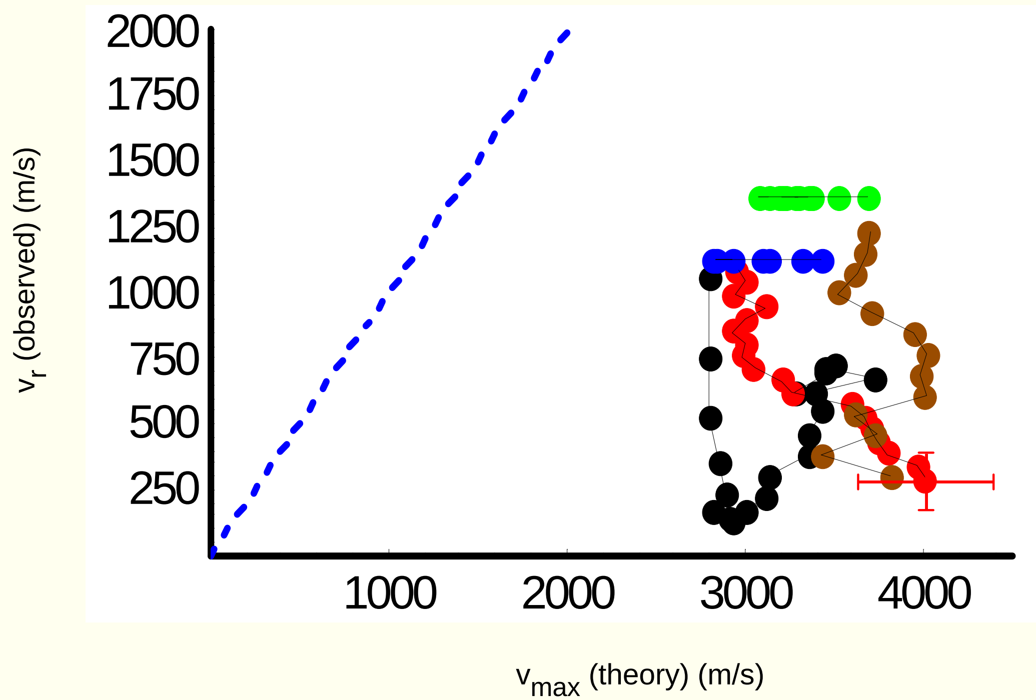
NSTX: Observed blob velocity is bounded by theoretical minimum and maximum

- database of blobs with size, speed, intensity …
- bounds, but no scaling $\frac{1}{\hat{a}^2} < \frac{v_r}{v_*} < \hat{a}^{1/2}$

v_r (GPI) vs. v_{min}

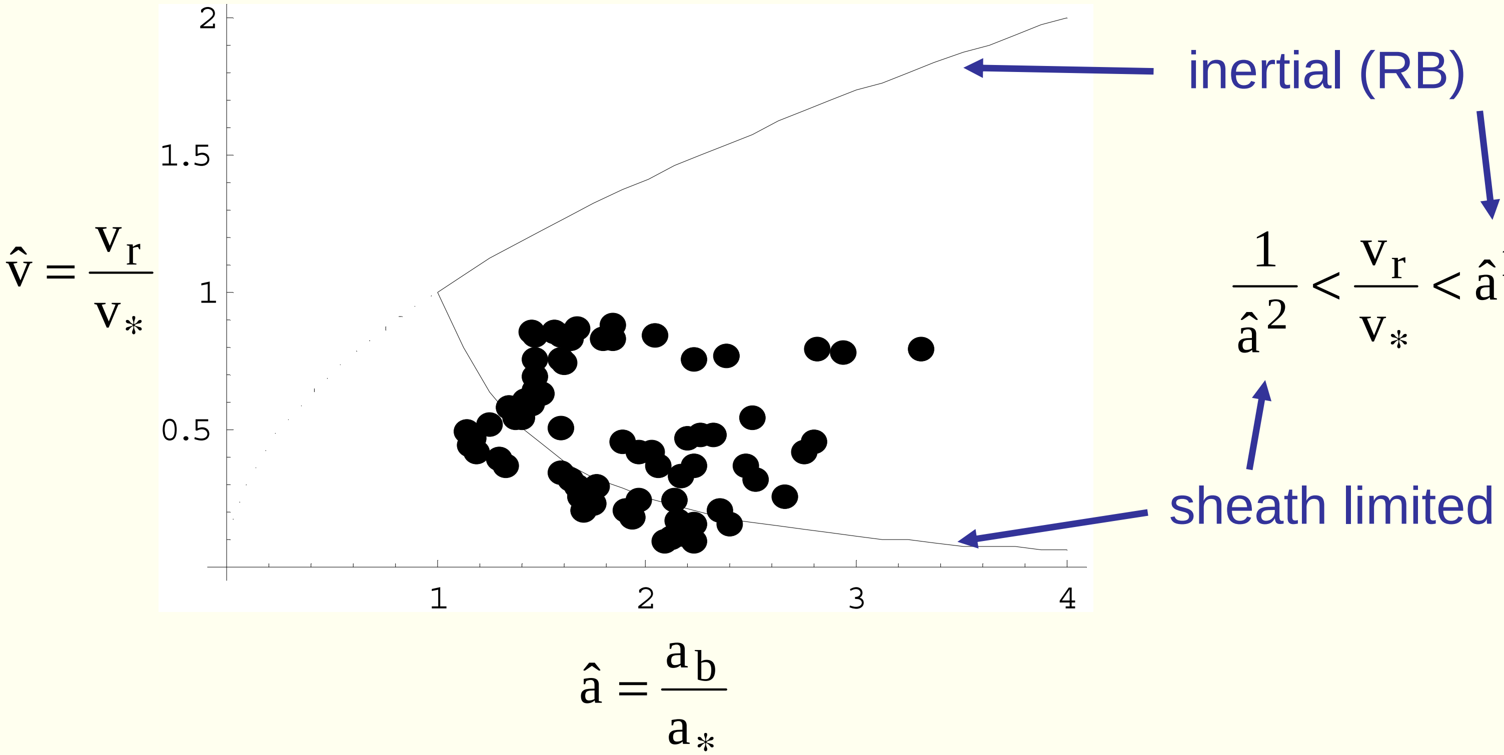


v_r (GPI) vs. v_{max}



Myra, D'Ippolito, Stotler, Zweben et al. PoP 2006

Blobs lie in expected regime of parameter space



$$\frac{1}{\hat{a}^2} < \frac{v_r}{v_*} < \hat{a}^{1/2}$$

- another way of looking at the same data
- possible evidence for $\hat{a}$ independent upper limit, consistent (large error bars) with Alfvén-wave high-β closure
- hidden parameter is Λ ⇒ try controlled collisionality experiment

Generally, more satisfactory theory/experiment comparisons require: analytic scalings $\rightarrow$ turbulence code

statistical variation of v_{blob} is large:

- initial conditions for blob (vorticity)
- parallel properties
- blobs not isolated, round …

- **Can we understand the dynamics of an individual blob with known properties?**
  - given n_e, T_e, a_b compare observed v_x

well in hand

- **What properties are blobs created with and why?**
  - rate & statistics of blob generation, scale size a_b, n_e, T_e
    - flux $\Gamma \sim v_b\, n_b\, f_p$
  - v_y shear, nonlinear coupling effects on blob generation

in progress

The SOLT [Scrape-off-Layer Turbulence] code

- 2D fluid, strong turbulence, $\delta n/n \sim 1$
- simulated GPI diagnostic

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Lodestar

vorticity

$$\partial_t \nabla^2 \tilde{\phi} = \left\{ -\mathbf{v}_E \cdot \nabla\nabla^2 \phi + \alpha_{DW} \frac{\overline{T}^{3/2}}{\overline{n}} \{\phi - T\ln(n)\} + \alpha_{sh}\sqrt{T}\left[1 - e^{\Lambda_B - \phi/T}\right] - \frac{\beta}{n}\partial_y(nT) + \hat{\mu}\nabla^4\phi \right\}$$

advection — parallel response — sheath current — curvature

density

$$(\partial_t + \mathbf{v}_E \cdot \nabla)n = \alpha_{DW}\overline{T}^{3/2}\{\phi - T\ln(n)\} - \alpha_{sh} n\sqrt{T}\, e^{\Lambda_B - \phi/T} + S_n + D\nabla^2 n$$

sources and dissipation

temperature

$$(\partial_t + \mathbf{v}_E \cdot \nabla)T = -\alpha_{sh} S_E T^{3/2} e^{\Lambda_B - \phi/T} + S_T + D\nabla^2 T$$

zonal momentum

$$\partial_t \langle n v_y \rangle + \partial_x \langle n v_x v_y \rangle = \int dx \left\langle \alpha_{sh} n\sqrt{T}\left[1 - e^{\Lambda_B - \phi/T}\right]\right\rangle + \overline{\mu}\partial_x^2 \langle v_y \rangle - \nu_{py}\langle n v_y \rangle + S_\phi$$

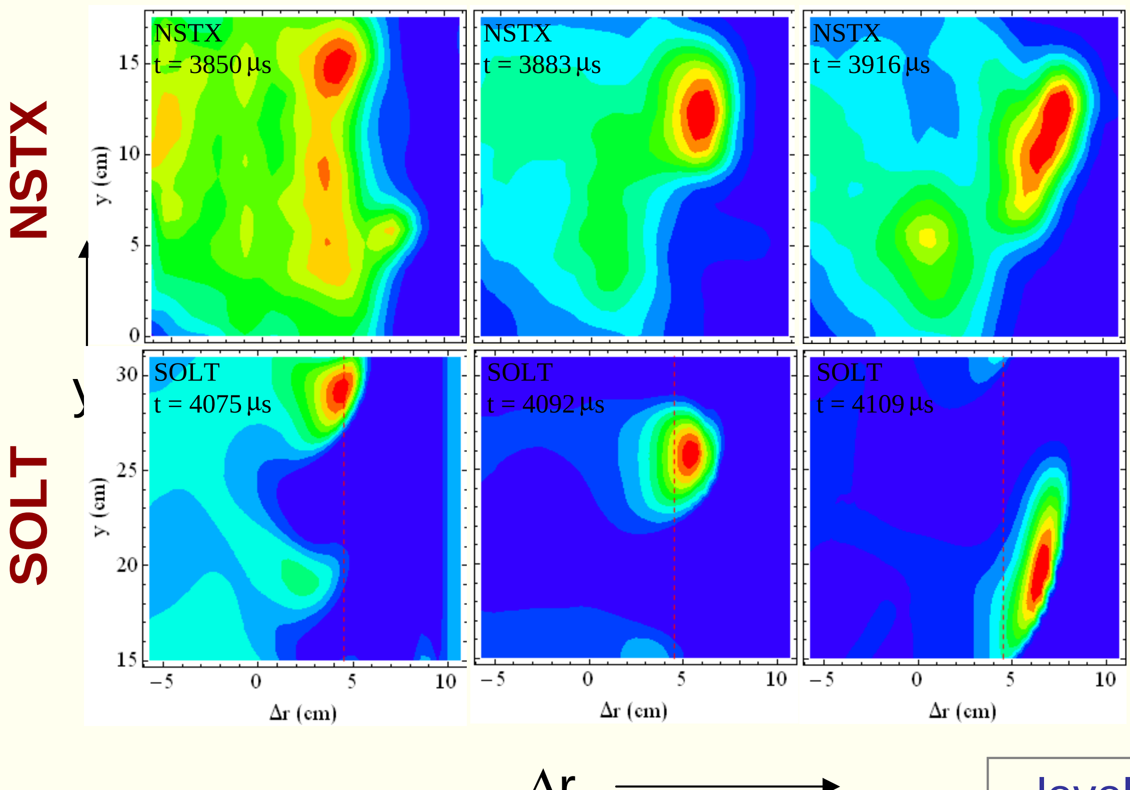
passive convection + Reynolds stress — momentum loss to sheaths

Qualitative blob behavior in GPI movies is similar in simulation and experiment

$\delta I / < \bar{I} >$ in $\Delta r - y$ plane

overbar $\Rightarrow$ y-avg <…> $\Rightarrow$ t-avg

$\delta I = I - < \bar{I} >$



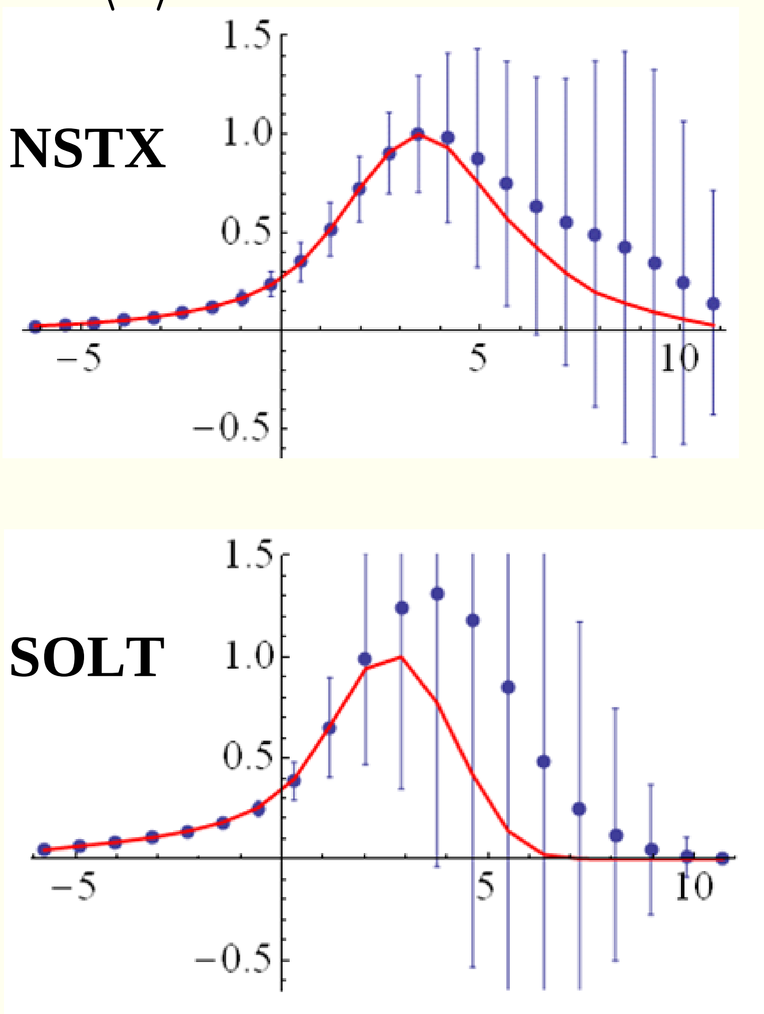
- turbulence is **intermittent**, and blobs are emitted in random bursts
- blobs have **similar shape**, propagate in both x and y, and elongate in y

D'Ippolito, IAEA 2008

level of agreement between experiment and simulated turbulence is sensitive to parameters that control how close the system is to marginal stability, e.g. **dissipation**.

Simulations provide a reasonable match to I(r) profiles and fluctuations levels

$\langle \bar{I} \rangle$ & $Median\ I\ (red)$

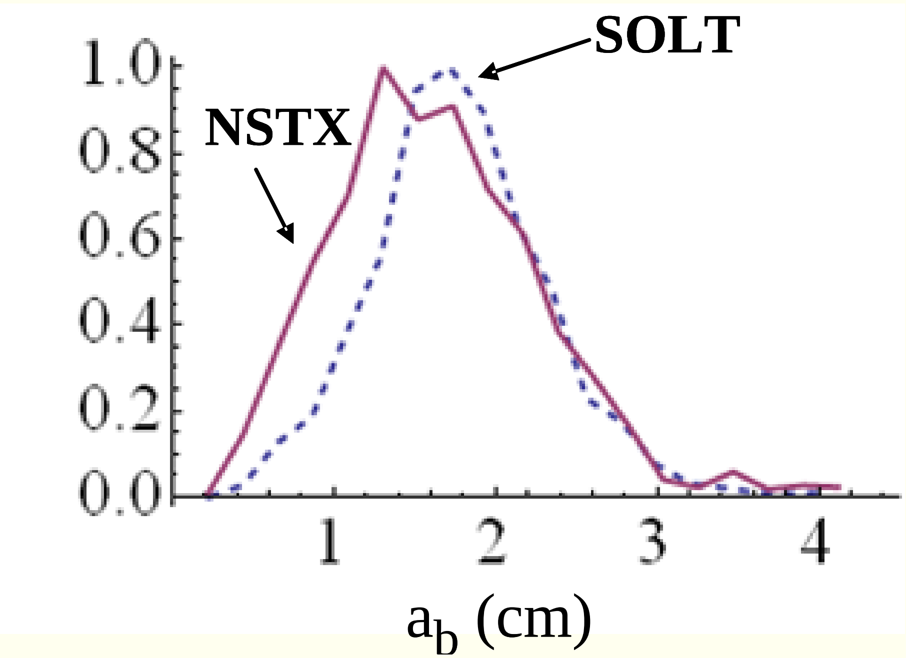


Δr $\longrightarrow$

- Simulated and exp. data processed in same way and normalized to 1.
- location of peak intensity agrees
- simulated intensity too small for Δr > 5 cm (radial region where field lines connect to sheath)
- $\Rightarrow$ sheath losses too large in the simulation for Δr > 5 cm

PDFs of blob size are in reasonable agreement

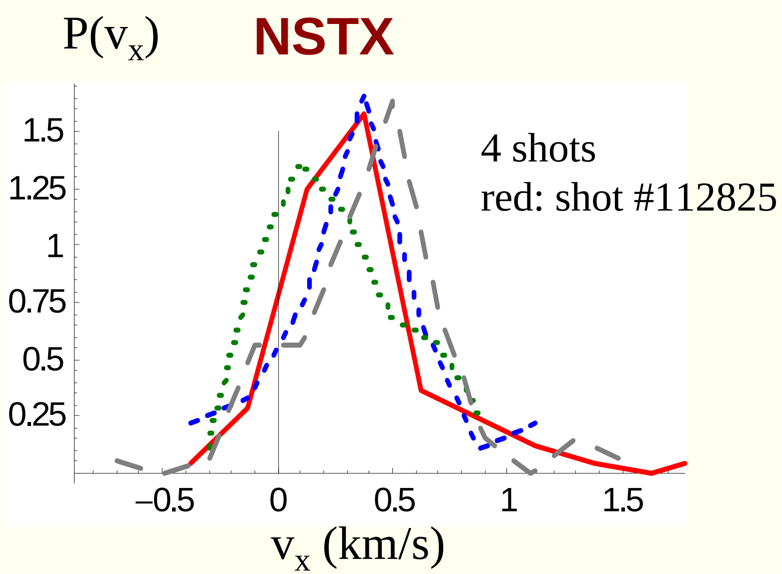
probability distribution

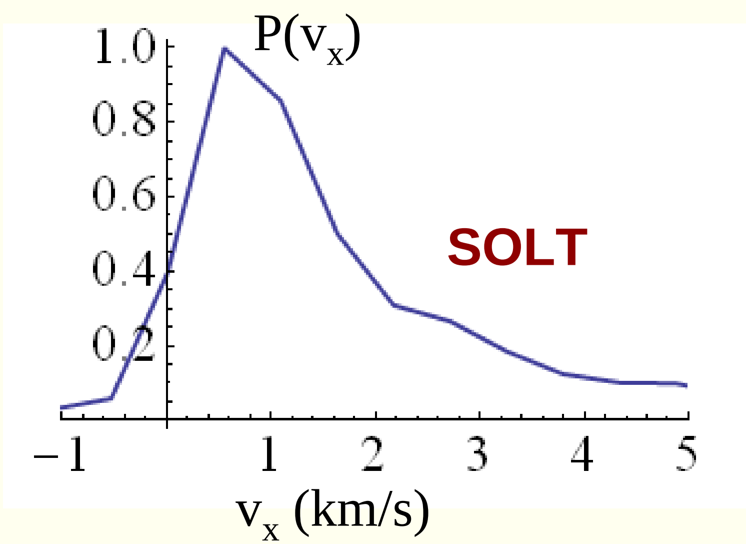


blob poloidal half-width

- apply blob selection criteria (filtering, smoothing) to create a blob database
- analysis covers a spatial range $0 < \Delta r < 10$ cm and a time slice of 1200 ms
- same procedure used for both simulation and experimental data
- most probable $a_b \sim 1.5 - 2.0$ cm in both cases
- width of PDF also agrees

PDFs of blob velocity show discrepancy





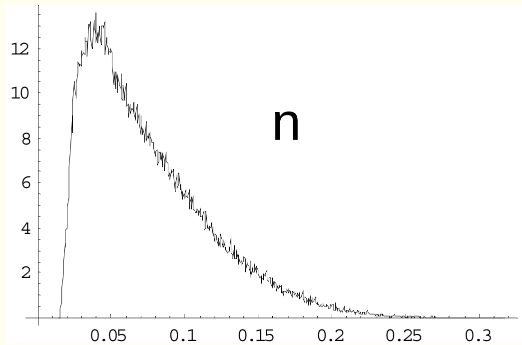
- here, exp. and simulation are NOT processed in same way:
  - v_x (NSTX) is the **kinematic** velocity of the intensity blob;
  - v_x (SOLT) is the $E \times B$ velocity
- qualitative agreement in shape, but SOLT v_X sacle is larger by factor of ~ 2
- possible explanation: turbulence too strong in simulation (too far from marginal stability)
- work in progress: kinematic v_x (data & SOLT) using Tobin Munsat's optical tracking algorithm

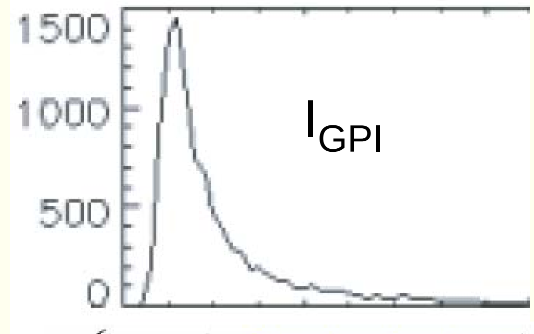
SOLT code reproduces generic features of boundary turbulence observed in many experiments

SOLT code | **NSTX + others**

PDF of fluctuations

non Gaussian

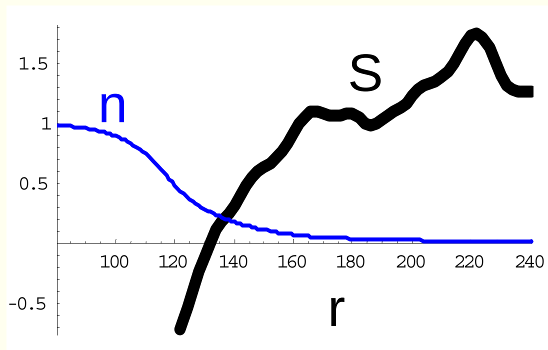


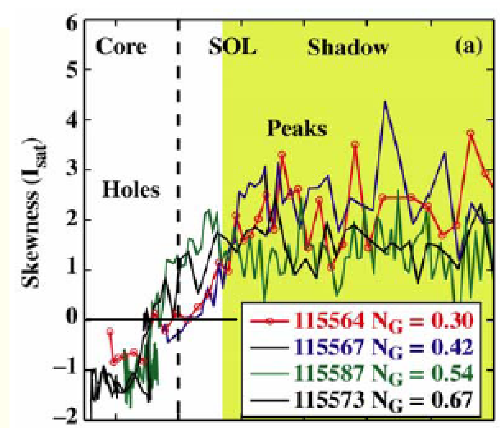


Zweben, 2004

Skewness vs. radius

+ events in SOL

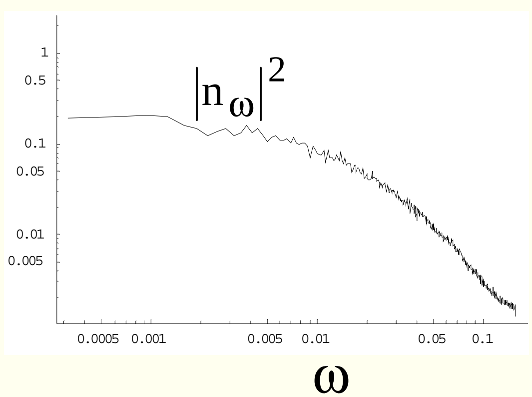


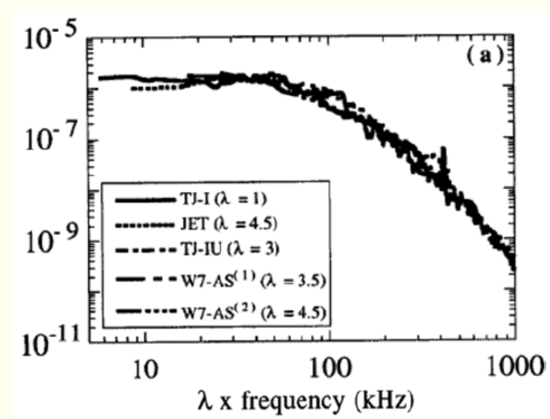


Boedo, 2006

Freq. spectrum

power law





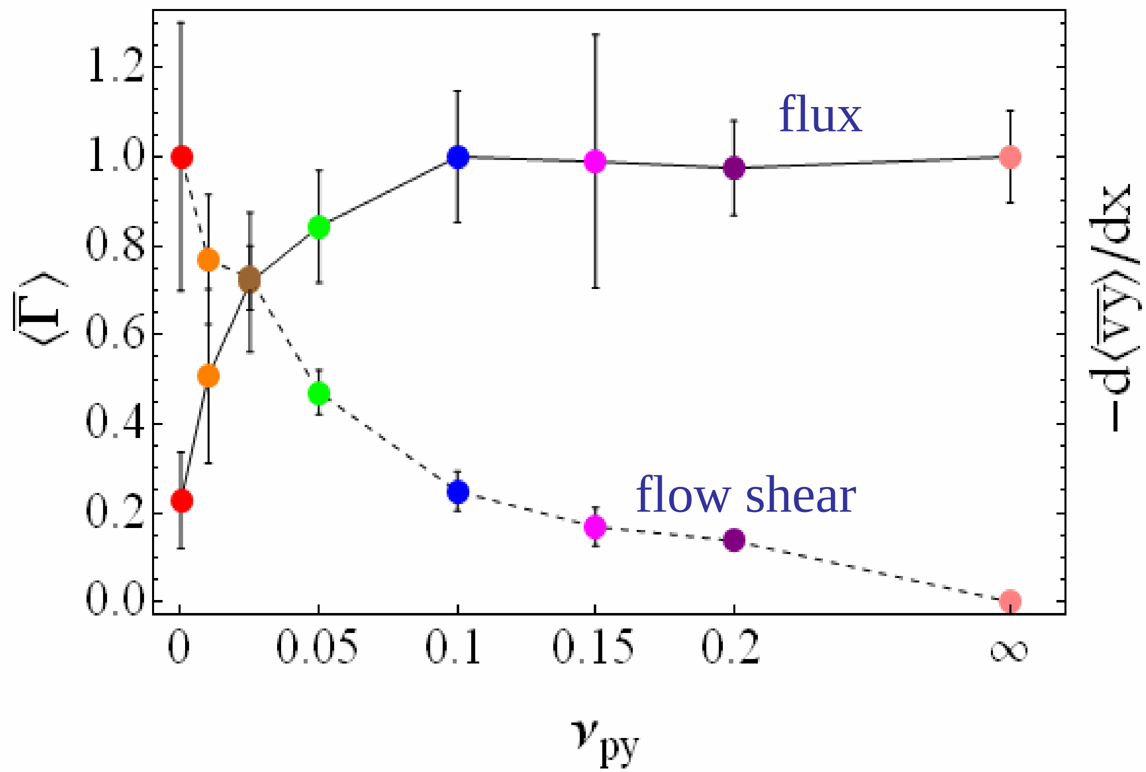
Zweben, 2007

Outline

- **motivation and background**
- **physical mechanisms of blob dynamics**
- **modeling of NSTX/GPI**
- **turbulence saturation mechanisms and flows**

- role of ZF damping
- profile modification
- sheared flow saturation
- momentum transport and spin-up

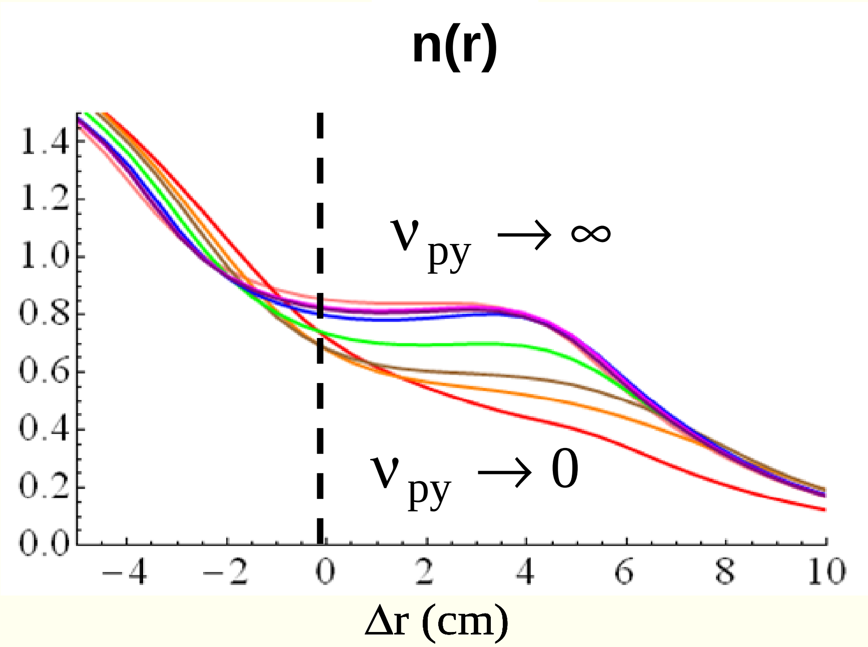
Strong zonal flow damping enhances turbulence and blob transport



SOLT turbulence code simulations
[Russell et al. 2008; D'Ippolito IAEA 2008]

- ν_{py} = zonal flow damping rate
- large damping $\Rightarrow$
  - no zonal flows
  - saturation by wave-breaking and plateau formation
  - radial streamers & quasi-periodic oscillations
- small damping $\Rightarrow$
  - saturation by zonal flows
  - convecting objects are blob-like
  - intermittent bursts (in turb. flux)

Density profile modification saturation occurs when flows are damped

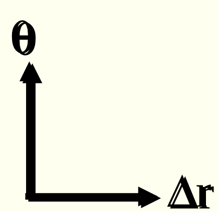


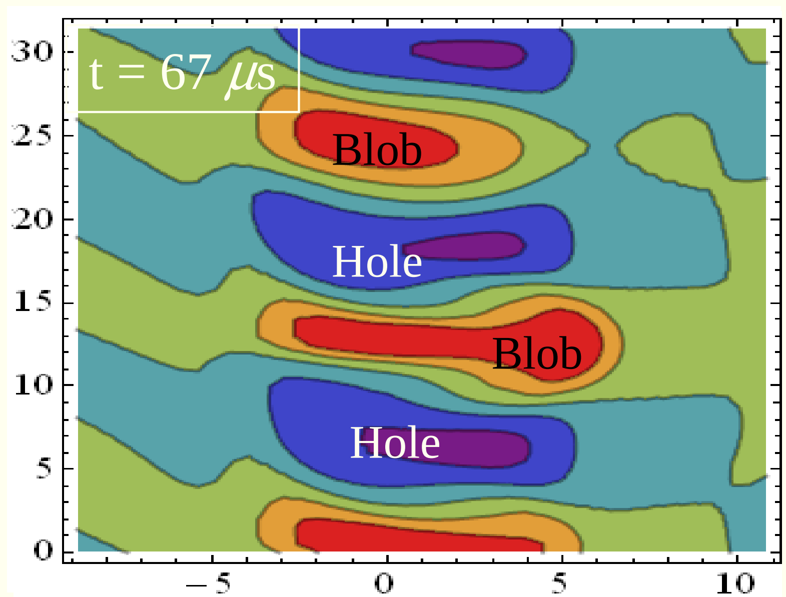
- for $\nu_{py} \rightarrow \infty$

$$\Gamma \sim D\nabla_x \bar{n}$$

$$D \sim \gamma / k_y{}^2$$

- Kadomtsev estimate works to within a factor of 2
- gives Γ independent of ν_{py}



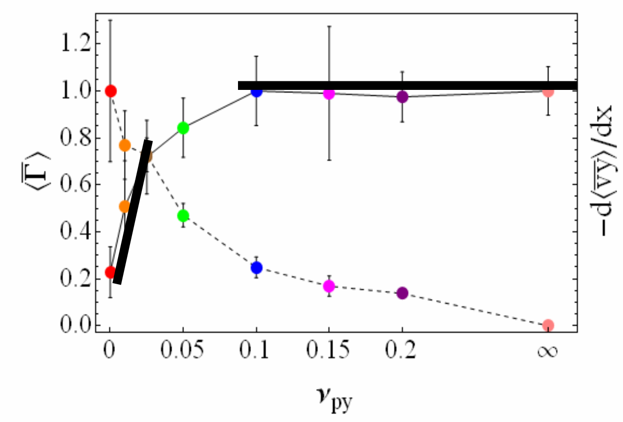


$\boldsymbol{\nu_{py} \rightarrow \infty}$

Nonlinear Regime
Blobs Move Out
Holes Move In
<n> is Flattened

The small ν_{py} regime saturates by sheared flows

$$\gamma \sim \bar{v}'_y \sim \bar{v}_y / L_v$$



- balance Reynolds stress with flow dissipation

$$\bar{v}_y = (k_x / k_y)^2 (k_y^3 \,|\tilde{\phi}|^2) / \nu_{py}$$

- to get

$$\Gamma = <\tilde{n}\tilde{v}_x> \sim (k_y / k_x)^2 (\bar{n}\,\nu_{py} L_v)/(k_y L_n) \propto \nu_{py}$$

- agrees qualitatively up to the knee of the curve

- for very small ν_{py}, passive loss dominates $\partial_t \langle n v_y \rangle = -\nu_{py} \langle n v_y \rangle - \partial_x \left(\langle v_y \rangle \langle n v_x \rangle \right) + \ldots$

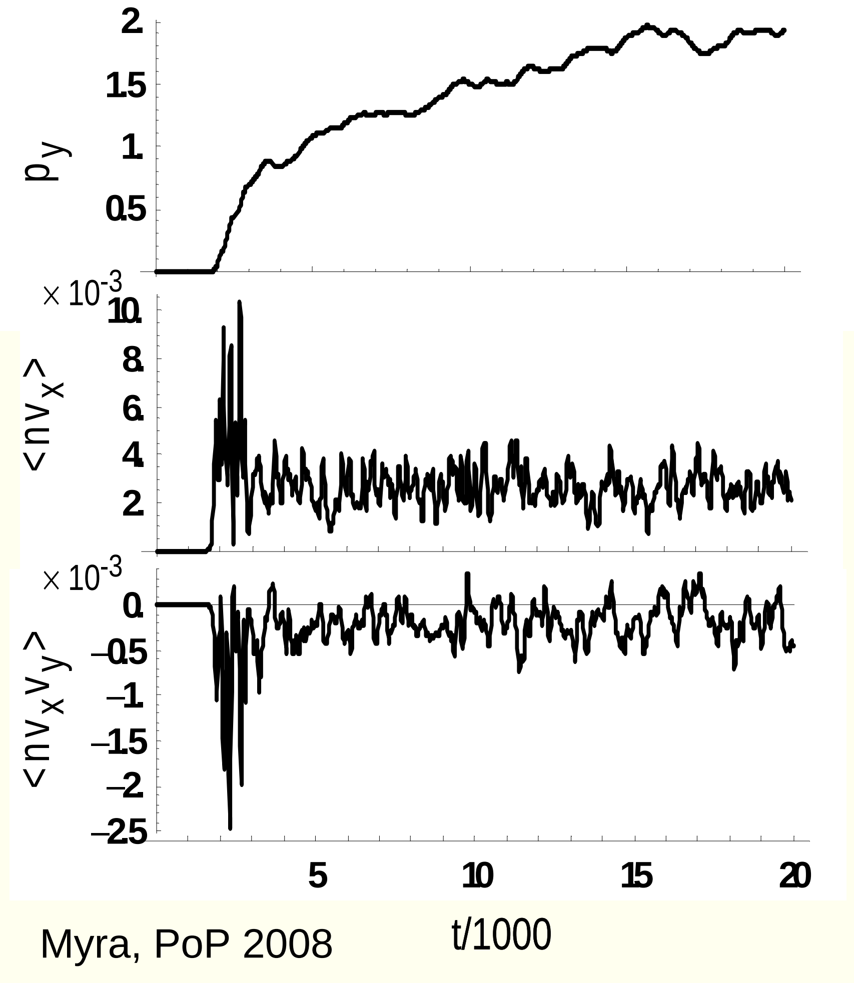
$$\nu_{py} << \frac{\langle n v_x \rangle}{\bar{n} L_x}$$

  - very bursty transport

need better understanding of SOL dissipation: neutrals?, measurements

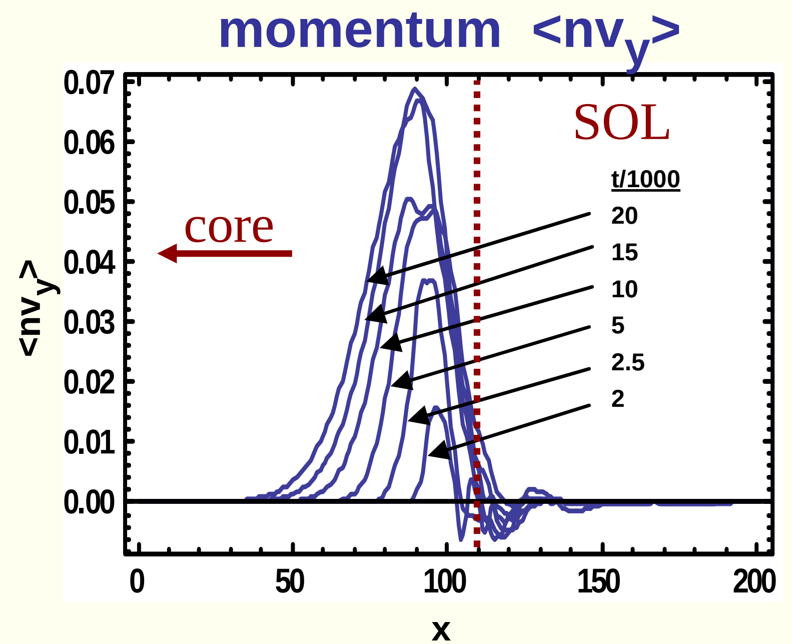
Edge turbulence carries momentum across the separatrix

- back reaction spins up plasma
  - Coppi [EPS 2006 paper P4.017 & NF 2002] spontaneous toroidal rotation
- here examine transport of $v_\perp$ only (2D problem)



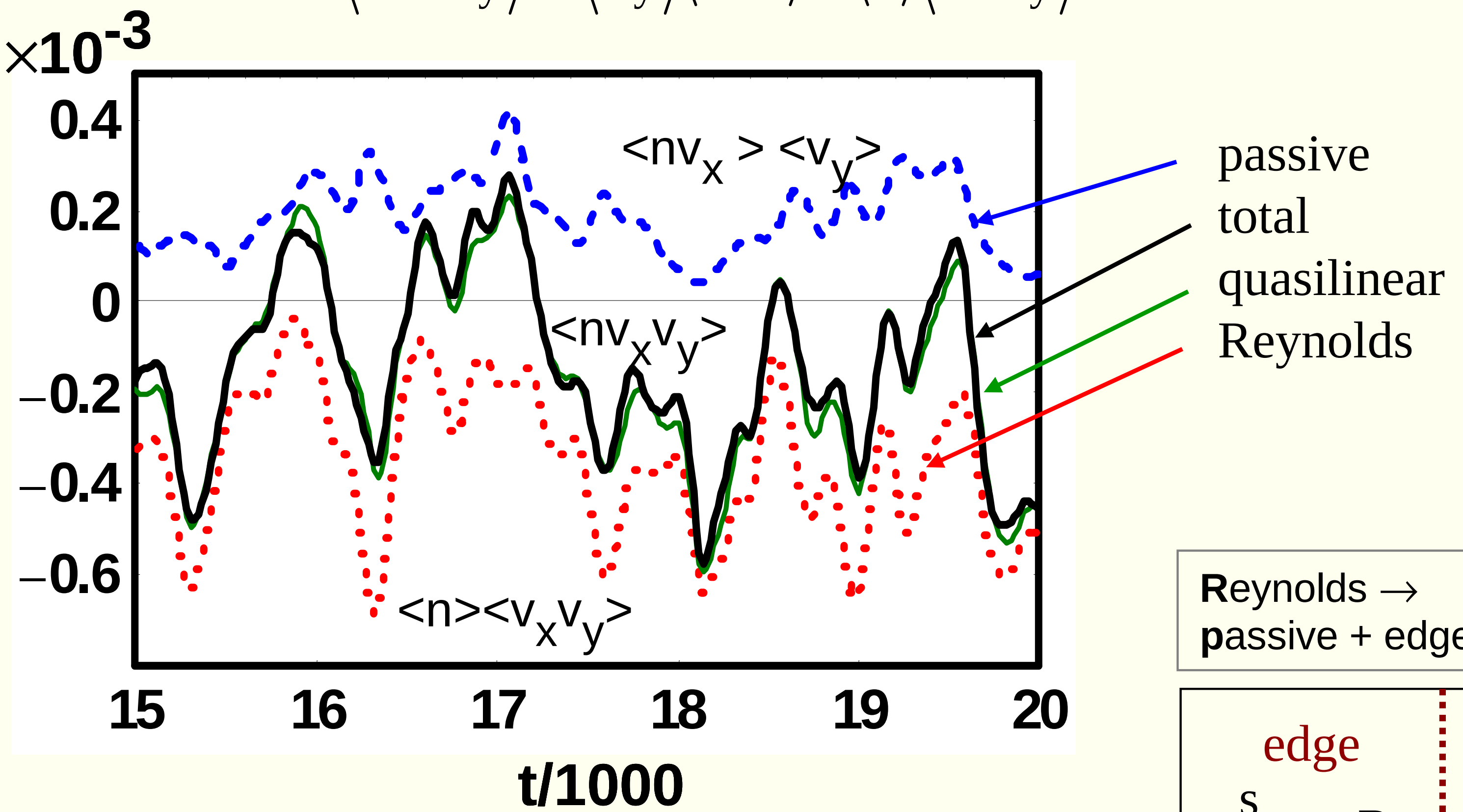
Myra, PoP 2008

- net plasma momentum buildup (balanced by sheath momentum loss)
- initial transient blob "kick"
- intermittency
- inward momentum diffusion

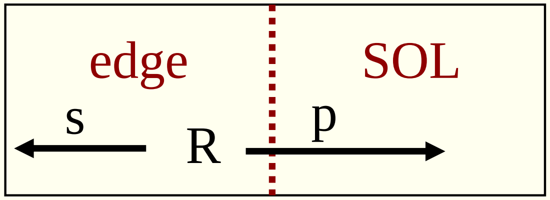


Residual from Reynolds and passive momentum flux provides edge source

$$\langle nv_x v_y \rangle \approx \langle v_y \rangle \langle nv_x \rangle + \langle n \rangle \langle v_x v_y \rangle$$



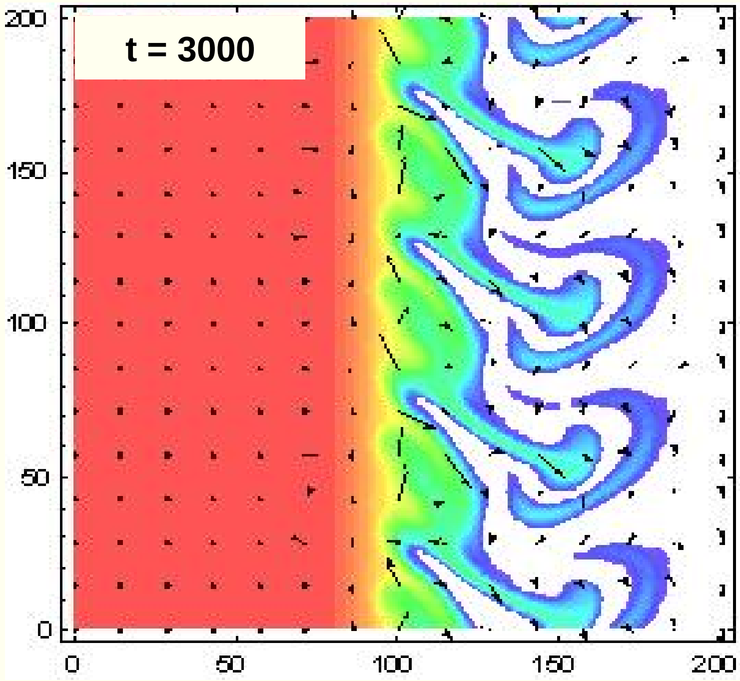
Reynolds → passive + edge source

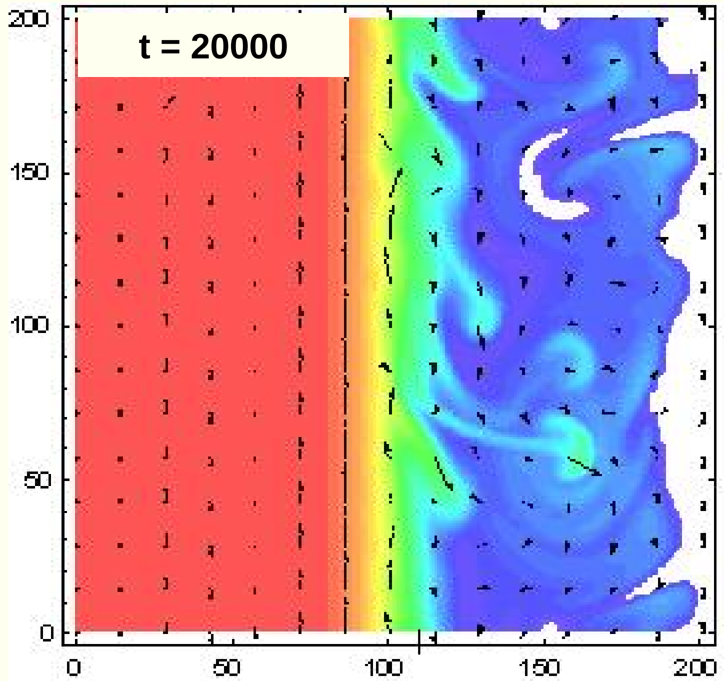


- Reynolds term generates flows
- passive momentum losses carry flows to SOL (blobs)
- residual ⇒ edge source

Dynamics of blob formation and momentum transport

snapshots: density palette, momentum arrows





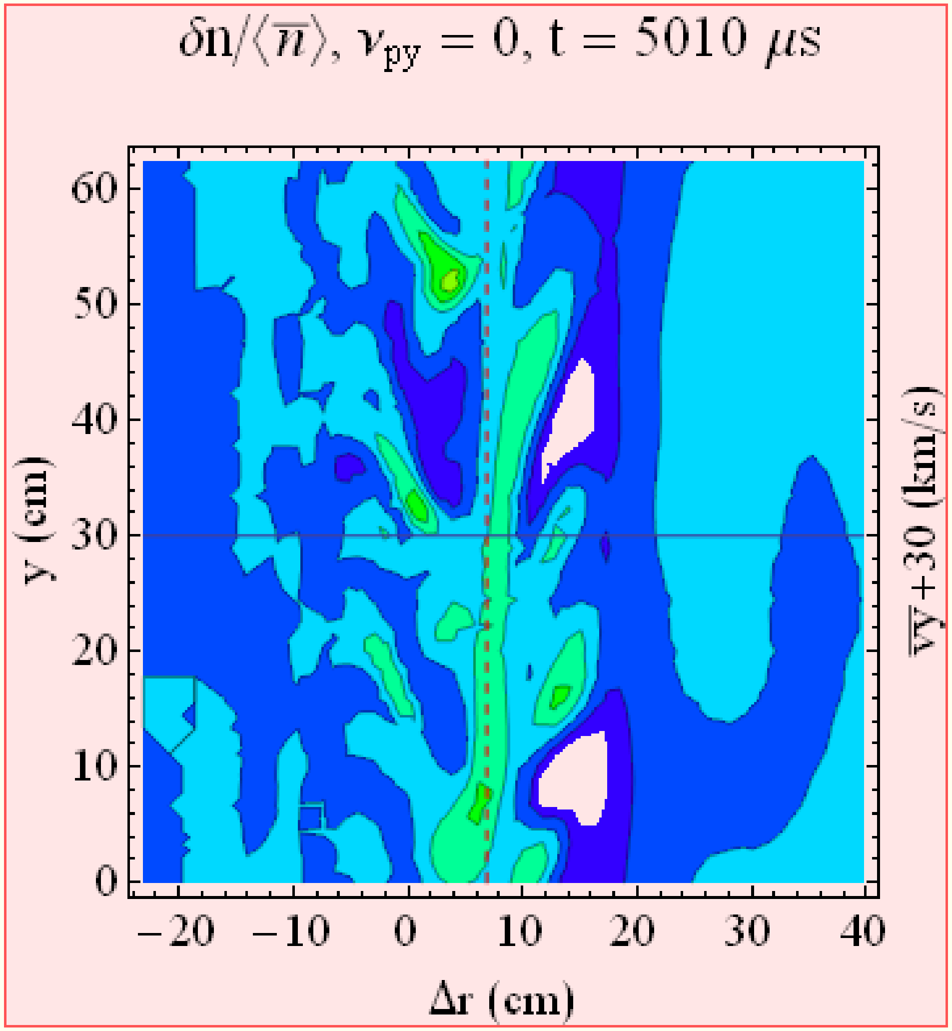
- early nonlinear development of seeded m = 4 mode
  - downward ejection of blobs (streamers); upward momentum “kick”
  - upward moving wave crests twisted around and down in ejection process
- later quasi-steady intermittency
  - sheared flows pinch off streamers ⇒ blobs

note flow reversal across separatrix

similar to C-Mod observations by Cziegler & Terry

SOLT simulation movie of strongly driven case

Russell 2008



core SOL

- rainbow palette
  - red large > 0
  - blue large < 0
  - white clipped
- counter-streaming flows
- intermittent blob ejection correlated with flows

Conclusions

- dynamics of individual blobs well in hand theoretically
  - velocity scalings known and regimes established
  - some, but not much, experimental confirmation
- predictive modeling of blob formation and the resulting SOL width is in progress
  - some encouraging agreement of NSTX GPI with 2D fluid turbulence simulations
  - discrepancies remain to be resolved
  - edge dissipation mechanisms need to be better understood
- turbulence saturation by profile modification and by sheared flows is being studied
  - may play a role in bulk plasma rotation as well as sheared bipolar flows

Coherent structure formation and convective transport in edge plasmas is a very rich and challenging area of research.

Supplemental

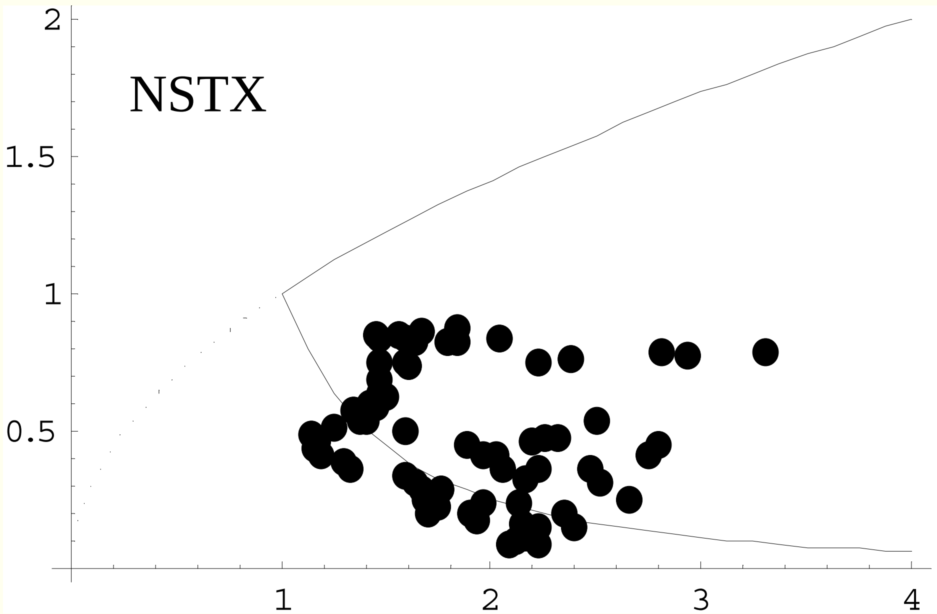
Alfvén wave closure and high-beta blobs/ELMs

- parallel current is limited by EM effects: magnetic field is perturbed causing excitation of Alfvén waves [Parks 2000 ; Krasheninnikov 2004]

$$\nabla_{\|} J_{\|} \rightarrow -\frac{2}{L_{\|}} \frac{c^2}{4\pi V_{A0}} \nabla_{\perp}^2 \Phi$$

$$v_b \propto g_{sp} \qquad \text{independent of } a_b$$

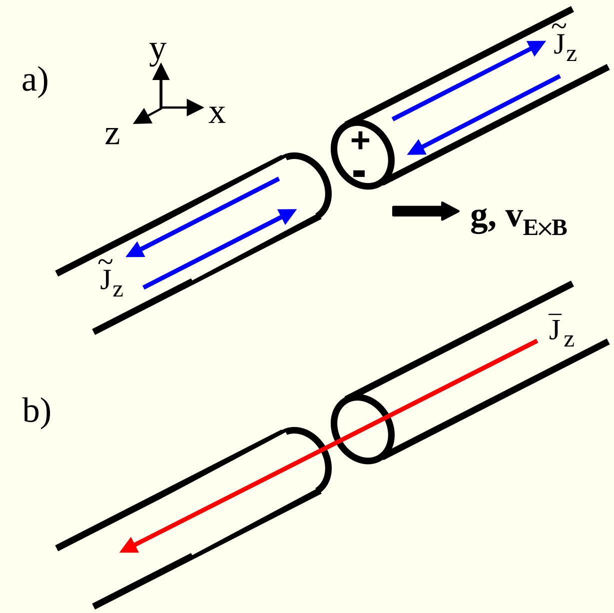
$$\hat{v} = \frac{v_r}{v_*}$$



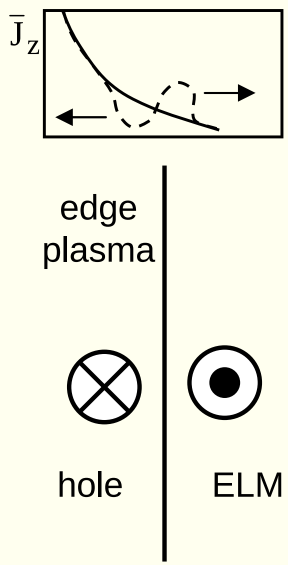
$$\hat{a} = \frac{a_b}{a_*}$$

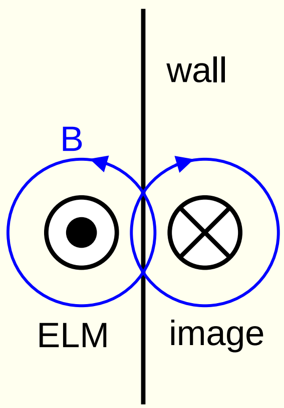
ELM filaments can also carry net current

- introduces additional magneto-static forces
  - enhance coherency of filaments in 2D plane (current pinch)
  - also introduces kink and rippling instabilities
- filament is accelerated away from the plasma near the edge (hole repulsion)
- decelerated close to the wall (image current repulsion)



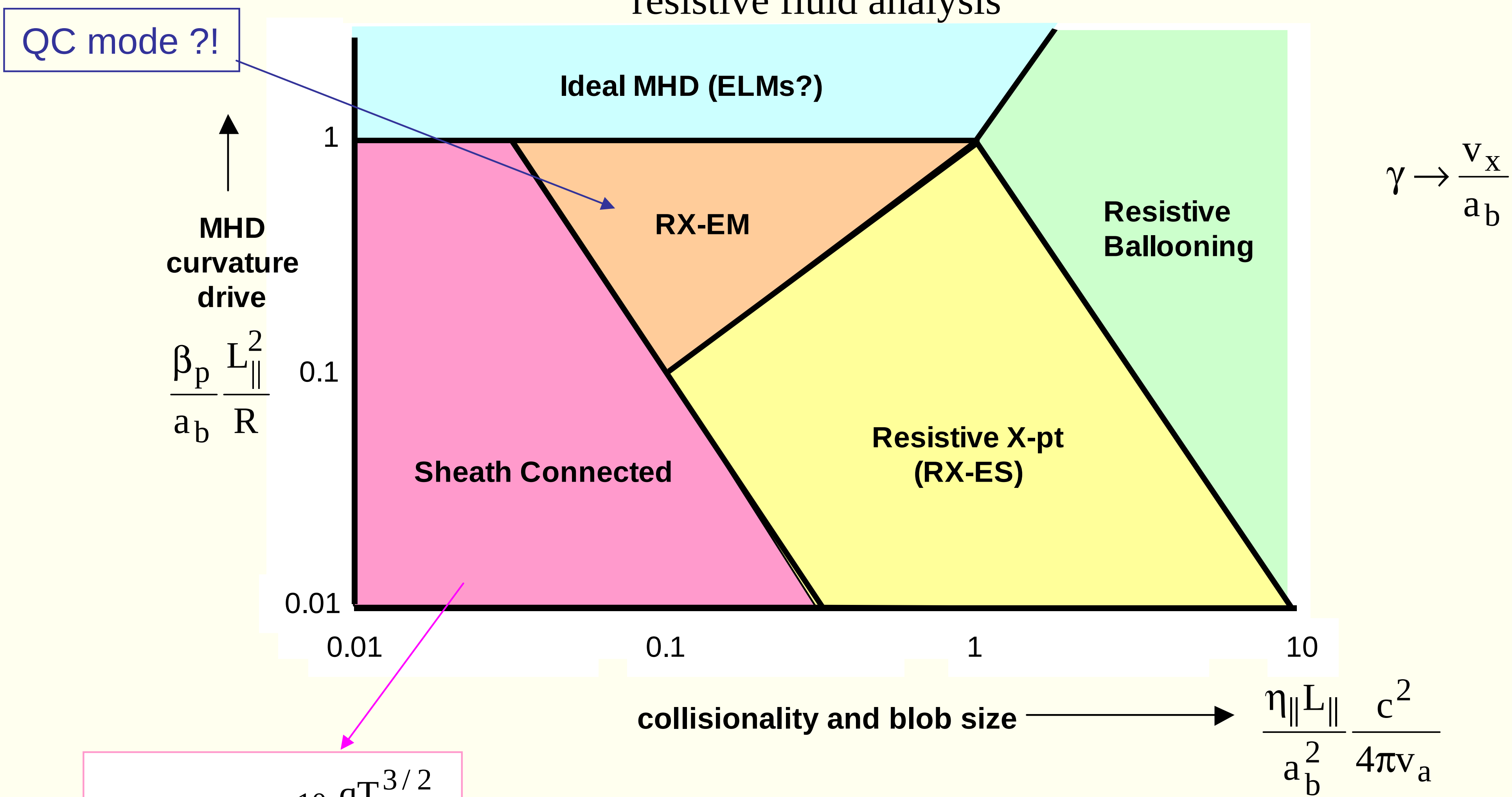
Myra, PoP 2007





Electromagnetic instability and blob regimes

resistive fluid analysis



$$v_x \sim 2.9\times10^{10}\,\frac{qT_e^{3/2}}{a_b^2 B^2}$$

each regime has a characteristic magnitude and scaling of blob radial velocity

$v_x(n_e, T_e, a_b; B, q, R)$

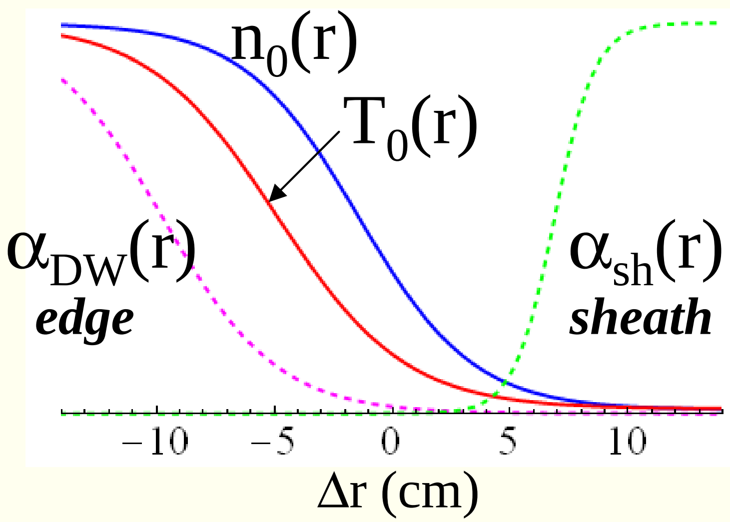
The SOLT Model

α_{sh} $\Rightarrow$ losses of particles and charge to sheath

α_{dw} $\Rightarrow$ electron adiabaticity (i.e. drift wave physics)

- momentum conserving zonal flows (non-Boussinesq)

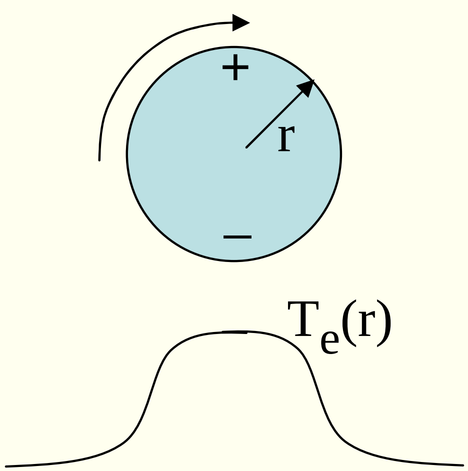
target profiles



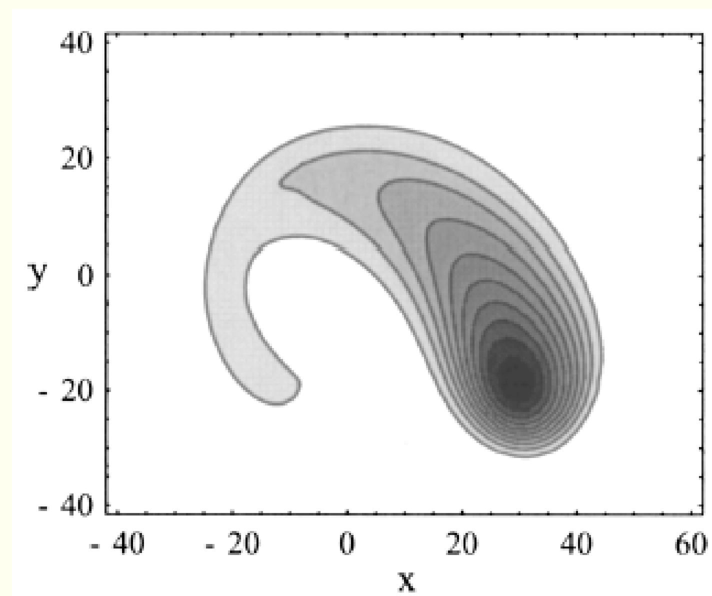
- **Three radial regions:**
  - *edge (inside LCS)*
    - Sources of particles and heat
    - electron drift waves
    - curvature-driven modes (blob birth zone)
    - closed field lines
  - *near SOL (just outside LCS)*
    - field lines open but disconnected ($\Rightarrow$ large $L_{\|}$), e.g. by X-point effects
  - *far SOL*
    - field lines connect to sheaths
    - sheath absorption of charge, particles, momentum
    - curvature-driven modes in both SOLs

Blobs transport energy and can spin

- in the SOL, $\perp$ and $\|$ transport compete
- particles flow out at $c_s \Rightarrow \tau_{\|p} = L_{\|}/c_s$ (ambipolarity)
- energy is conducted by $\chi_{e\|}$ or flows out faster than $c_s \Rightarrow \tau_{\|E} << \tau_{\|p}$
- on short time scales, $\tau < \tau_{\|E}$, blobs can carry excess T_e
- such sheath-connected blobs will spin
- charge mixing of +/- dipole $\Rightarrow$ spinning blobs slow down radially and move poloidally



$$\Phi(r) \sim 3T_e$$
$$\Downarrow$$
$$E_r \times B$$



Myra, D'Ippolito, Krasheninnikov & Yu, Phys. Plasmas 2004