Blob Transport Models, Experiments, and the Accretion Theory of Spontaneous Rotation*

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presented at the 21st IAEA Fusion Energy Conference
October 16-21, 2006, Chengdu, China
paper TH/P6-21

**work supported by USDOE (DE-FG03-02ER54678, DE-FG02-97ER54392) and by CNR of Italy*

Introduction to Part I: Blobs, velocity scaling, GPI analysis

- blob = intermittent filamentary convecting plasma structure
- radial convection competes with parallel transport ⇒
  - radial penetration of plasma into SOL
  - wall interaction (recycling, damage)
- goal: understand scaling of radial blob velocity v_r
- blob theory considered here:
  - electrostatic (mostly)
  - sheath connected and resistive ballooning (inertial) regimes provide v_r bounds
  - role of collisionality and B-field geometry
- gas-puff-imaging (GPI) provides high speed & high resolution data
- GPI modeling important to extract plasma info
- GPI data from NSTX compared successfully with theoretical bounds

Introduction to Part II: Accretion theory of spontaneous rotation

- tokamaks rotate spontaneously without explicit momentum sources such as NBI
  - rotation & sheared flows important for improved confinement and stability
- Accretion theory [B. Coppi, Nucl. Fusion **42**, 1 (2002).] has many connections to experiments
- momentum diffusion and inflow from ITG, VTG modes establishes core profiles [Coppi, Lontano, Varischetti]
- edge momentum source:
  - blobs carry away momentum to “walls” (sheath losses)
  - unstable edge modes drive momentum loss
- nonlinear simulations give detailed dynamics of edge momentum processes

Current loop closure determines blob regime

- blobs driven by curvature, ∇B charge separation
- parallel current closes locally (disconnected limit) or at sheaths (connected limit)

parameters:

collisionality

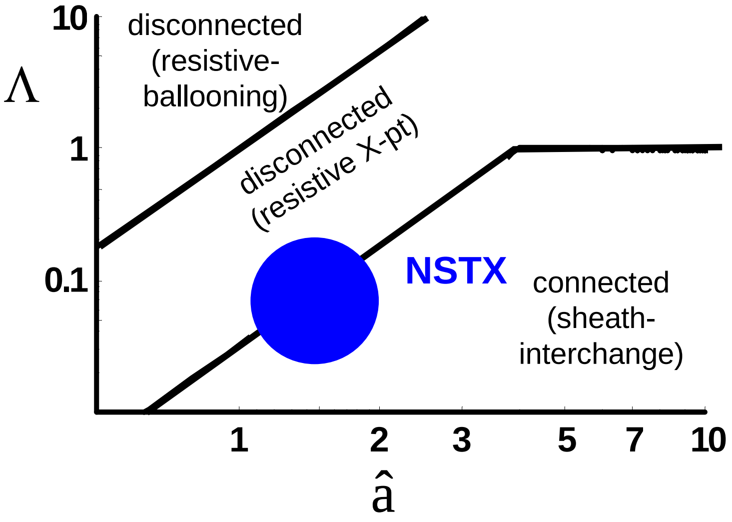
$$\Lambda = \frac{\nu_{ei} L_{\|}}{\Omega_e \rho_s}$$

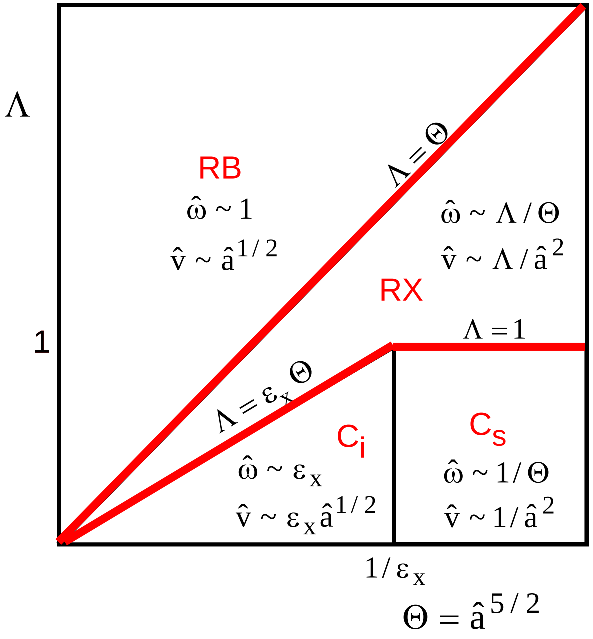
size

$$\hat{a} = \frac{a_b}{a_*} = \frac{a_b R^{1/5}}{L_{\|}^{2/5} \rho_s^{4/5}}$$

velocity

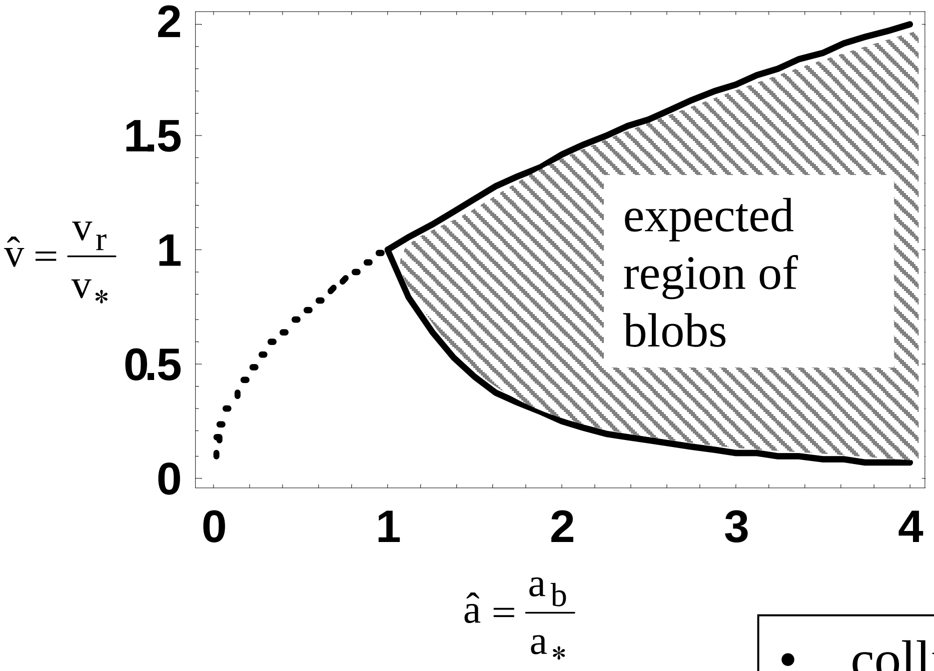
$$\hat{v} = \frac{v_r}{v_*} = \frac{v_r}{c_s}\left(\frac{R}{a_*}\right)^{1/2}$$





Blob velocity is bounded in electrostatic theory

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



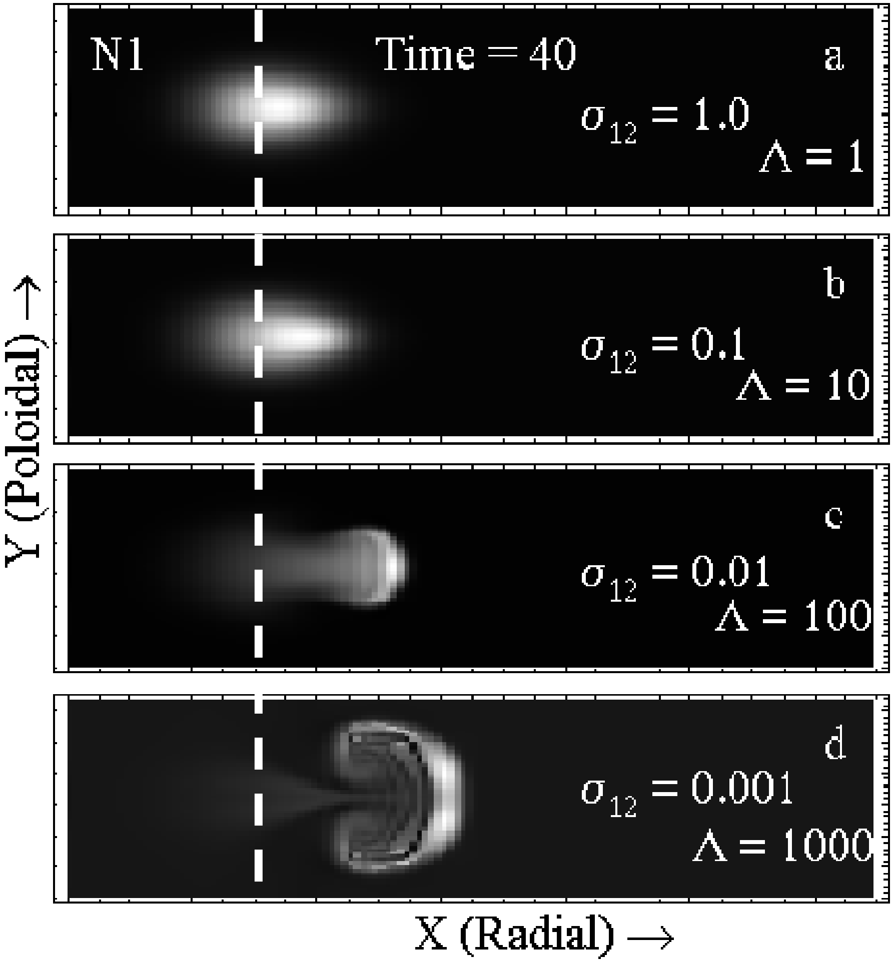
- hidden parameter is collisionality, Λ ⇒ parallel structure
  - sheath connected (small Λ) slow
  - disconnected (large Λ) fast

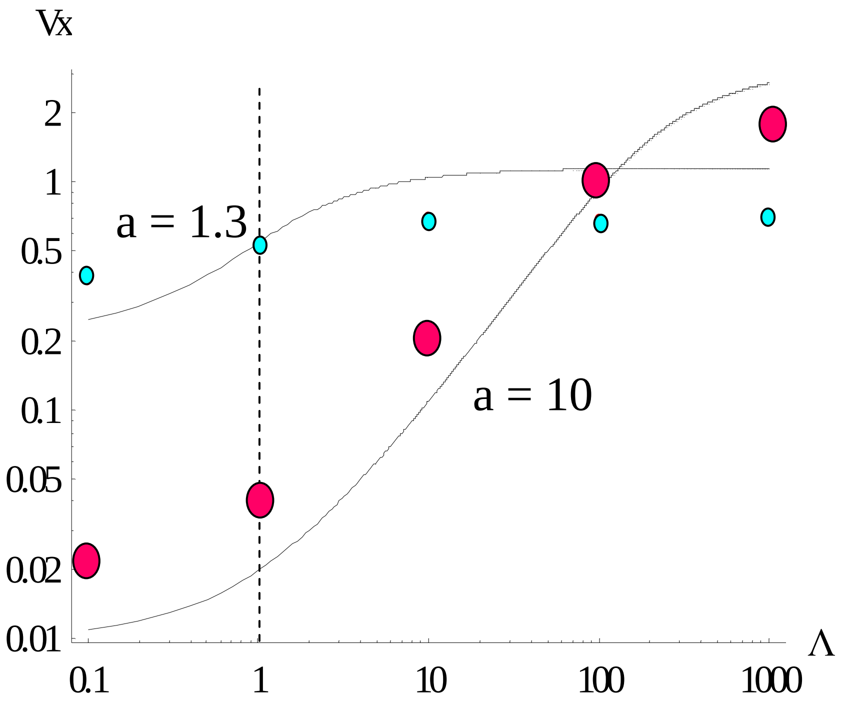
This diagram unifies various theoretical papers

- collisionality controls speed:
  - large circuit resistance ⇒ large Φ
  - larger E×B radial drift

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

Myra, Russell, D'Ippolito, Lodestar Report #LRC-06-111, (to be published in Phys. Plasmas)
http://www.lodestar.com/LRCreports/TwoRegionModel_I_blobs.pdf





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

GPI modeling (Stotler et al.)

Time Response of Excited GPI Atoms

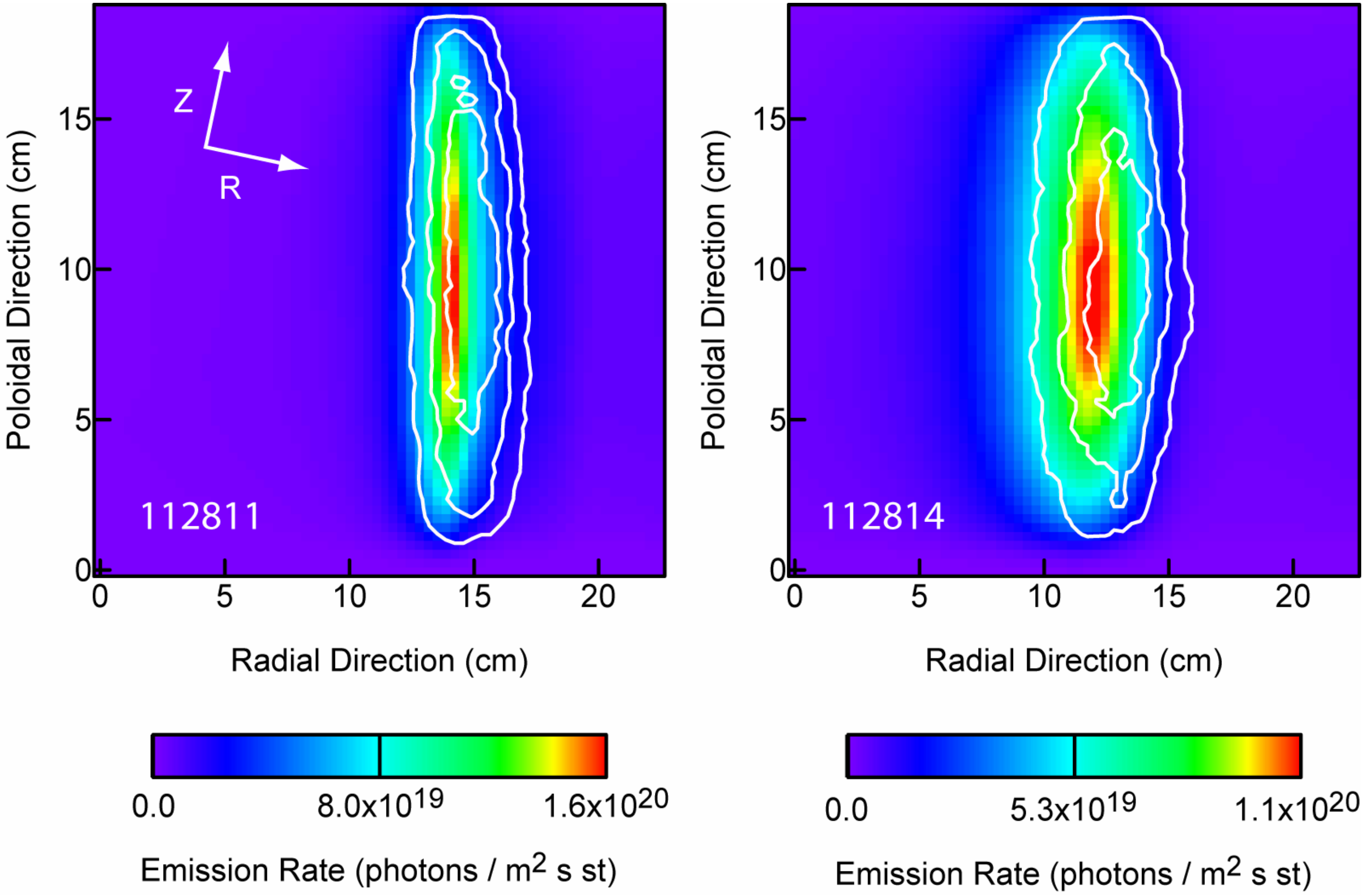
- GPI assumes light emission instantaneous compared with time scales of interest, ≥ 4 μs.
- May not always be true,
  - e.g., helium has 2^1S and 2^3S metastable states.
  - If not, temporal & spatial scales inferred for turbulence could be wrong.
- Apply analysis of [Greenland 2001] to single state "collisional radiative" model for helium,
  - For GPI-relevant parameters, this representation closely approximates solution of full system,
  - **and can resolve time scales longer than 1 μs.**
- **⇒ Can write emission rate as: $S = n_0 F(n_e,T_e)$.**

Get n_0 from Three-Dimensional DEGAS 2 Simulations of GPI Experiments

- Procedure similar to [Stotler 2004]
- Begin with EFIT equilibrium at time of interest ⇒ mesh,
- Incorporate geometry of vacuum vessel, including manifold,
- Single-time $n_e(R_{mid})$, $T_e(R_{mid})$ from Thomson Scattering,
  - Assume $n_i = n_e(\psi)$, $T_i = T_e(\psi)$ only,
  - Simulations are time independent.
  - Two shots: 112811 (H-mode), 112814 (L-mode).
- Emulate 64 x 64 pixel camera view,
  - Record helium 587.6 nm emission,
  - Account for nonlinear response of GPI camera,
  - GPI vignetting incorporated via a filter.
  - Compare with median average of 300 GPI frames.

Radial Widths & Peak Locations Agree to within Estimated Uncertainties, < 1 cm

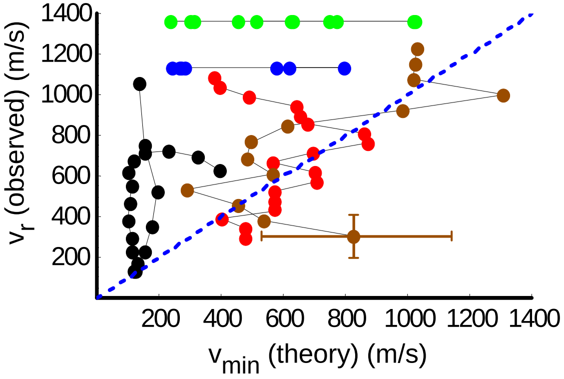
Simulated (color images) and observed (line contours) camera data for NSTX shots 112811 and 112814.



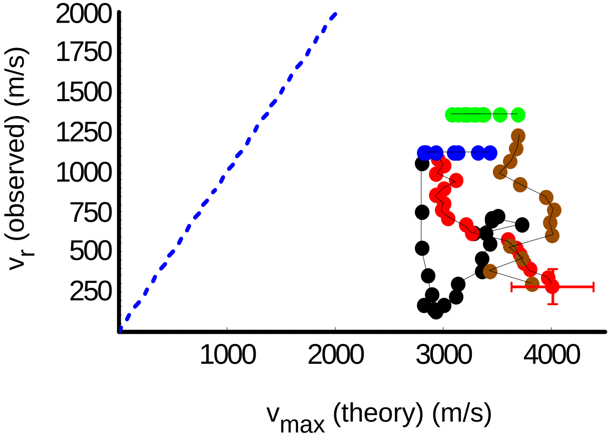
Blob velocity bounds verified from the GPI imaging analysis

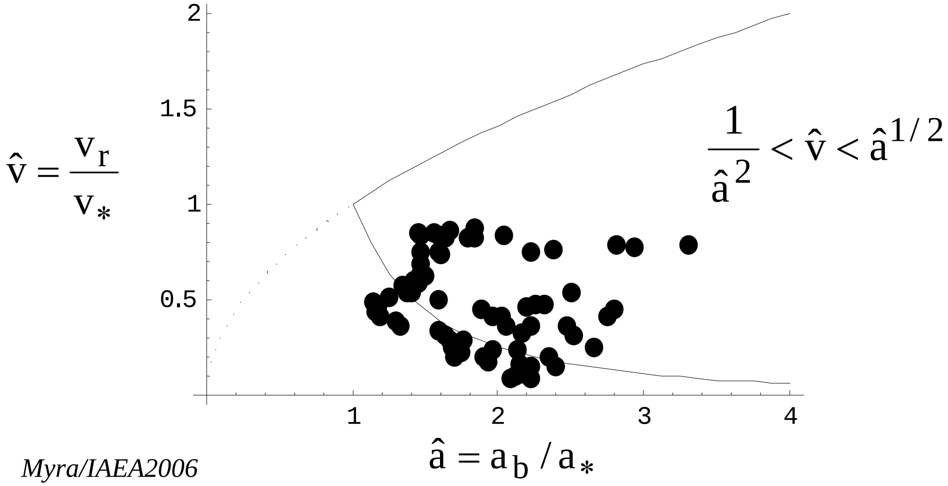
Myra, D'Ippolito, Stotler, Zweben, LeBlanc, Menard, Maqueda and Boedo,
Phys. Plasmas **13**, 092509 (2006)

v_r (GPI) vs. v_{min}



v_r (GPI) vs. v_{max}



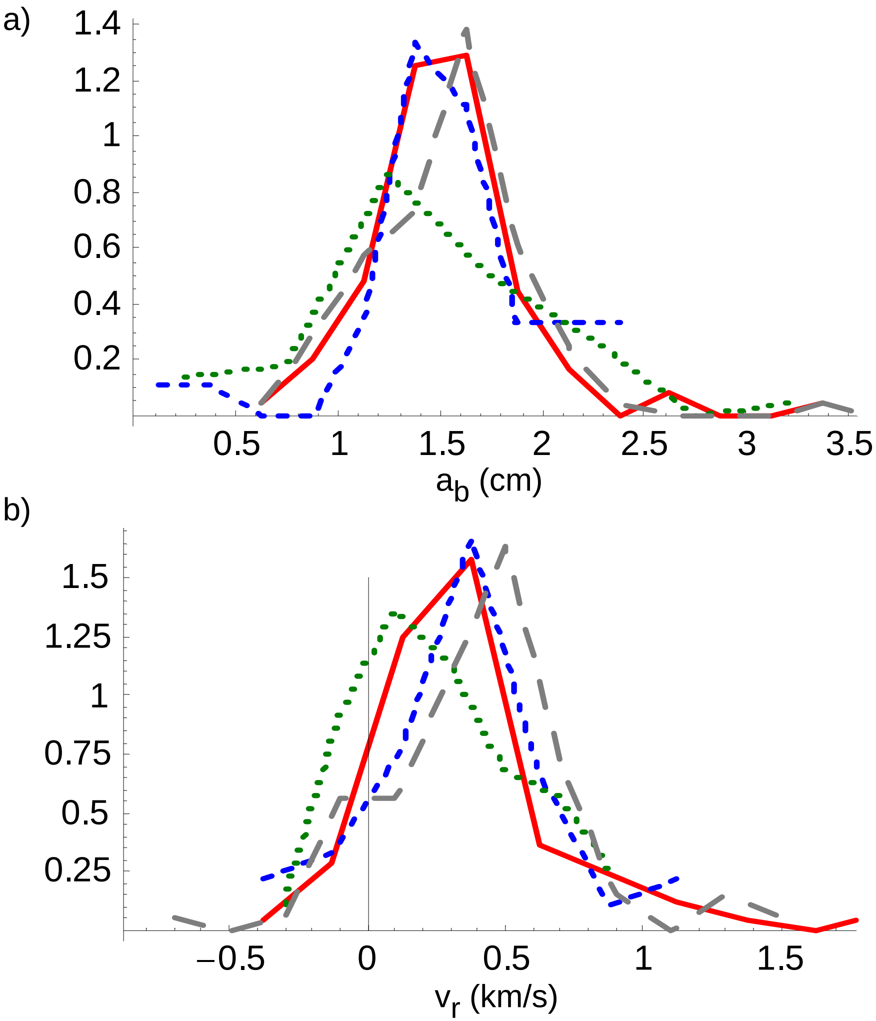


note also:

high-beta RX-EM blob scaling is

$$\hat{v} \sim q^{4/5} \beta^{1/2} (R / \rho_s)^{2/5} \sim 0.2 - 1$$

So far, large changes in blob v_r (or a_b) with plasma conditions are not observed

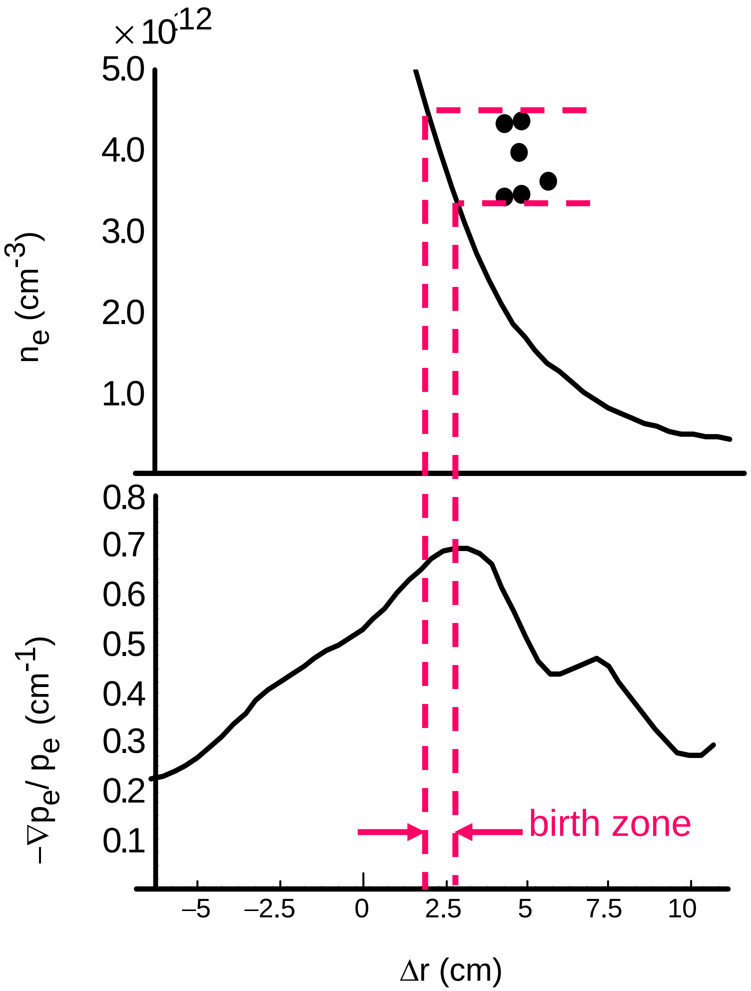


- PDF’s of a_b and v_r
- automated blob finder (R. Maqueda) + selection criteria

shot #	conf. mode	ne (edge) (10^{13} cm–3)	P_{nbi}(MW)	blob activity
112825	L	4.0	0.8	turbulent
112814	L	2.5	0.8	quiescent
112842	H	2.0	0.8	quiescent
112844	L (DX)	3.0	1.7	turbulent

biggest difference is
in number of blobs:
turbulent: 53, 45
quiescent: 20, 17

Blob birth zone is at max of edge instability drive



- Dots in the upper panel correspond to the start of individual blobs tracks at the point of first detection.
- Solid curves are smoothed background profiles obtained from combining TS and probe data.
- Blobs born where local instability drive peaks: max(∇ *ln* p)

Accretion theory and spontaneous toroidal rotation

B. Coppi, Nucl. Fusion **42**, 1 (2002); B. Coppi, IAEA Lyons, (2002).

see additional posters (Coppi et al.)

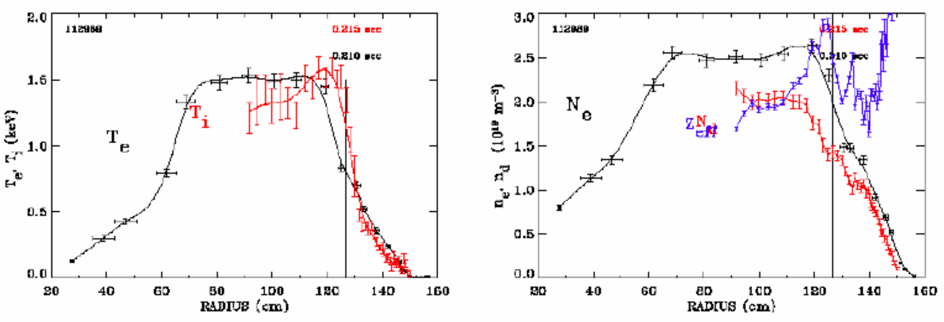
- key features of the theory
  - angular momentum flows inward to core and outward to “wall”
    - carried by wave-generated turbulence
    - diffusion and inflow velocity in core
  - connections with experiments
    - intrinsic connection between thermal energy transport and spontaneous rotation
    - rotation is strongly affected by edge plasma conditions
    - rotation is inverted in transition from L-mode to enhanced confinement
    - phase velocities of modes are inverted in this transition (JET)

Here look at two new features:

- inflow and diffusion of momentum to core by ITG and VTG (Coppi, Lontano, Varischetti)
  - $V_{||}$ shear important
- blobs carry momentum to the wall (sheaths) ⇒ edge momentum source
  - recoil force can spin core plasma
  - need to consider binormal (“poloidal”) $<n\ v_x\ v_y>$ and parallel $<n\ v_x\ v_{||}>$ fluxes

Modeling of ITG instability and QL fluxes in NSTX [Lontano, Varischetti, Coppi]

Analysis of two sets of profiles taken from Mikkelsen et al, poster jP1-020 "Gyrokinetic simulations of turbulence in NSTX", APS-DPP 2004, Savannah.



(1) Symmetric T_i profile around x=0

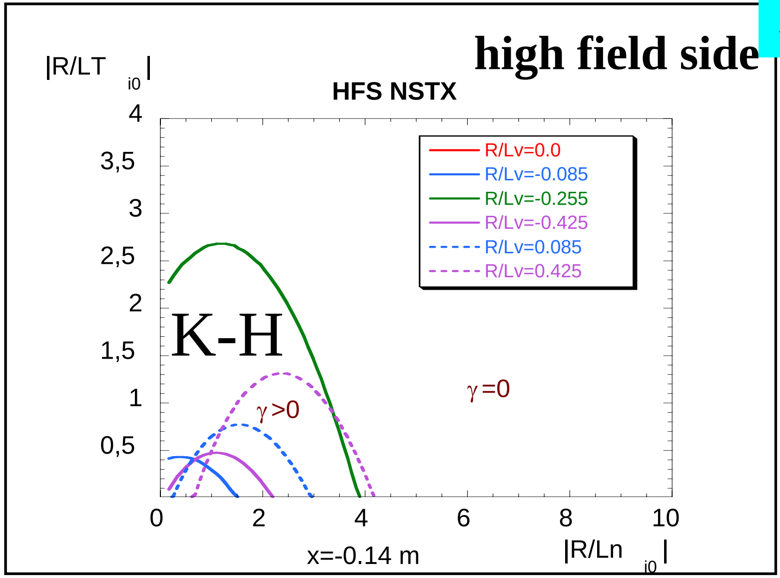
(2) Asymmetric T_i (see left)

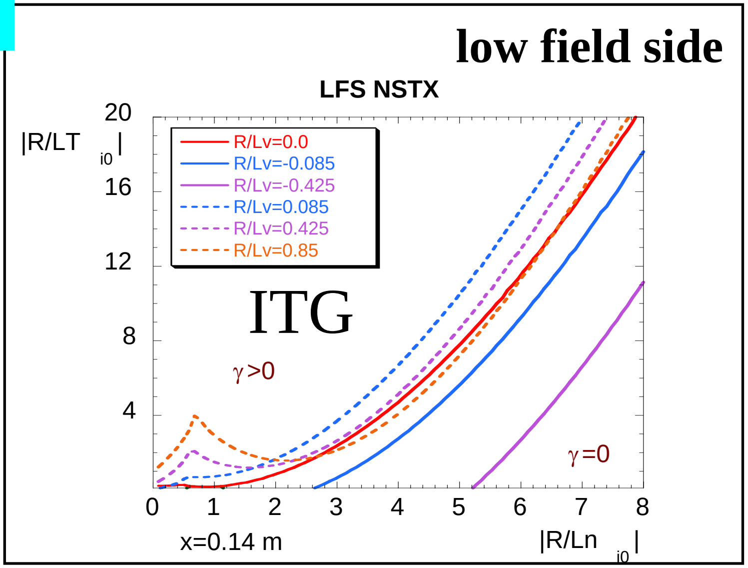
- Local analysis, collisionless ⇒ 3rd degree dispersion relation
- linear growth rate $\gamma_k(R/L_{Ti}, R/L_{ni}, R/L_U, \tau, x)= 0$, gives marginal stability boundaries in different parameter planes, $(R/L_{ni},R/L_{Ti})$, $(R/L_U,R/L_{Ti})$, $(R/L_U, \tau)$, etc.; here $\tau=T_i/T_e$
- Quasi-linear fluxes: $\Gamma_{x,p} = \langle \tilde{v}_{E_x} \tilde{p}_i \rangle = n_i^0 \langle \tilde{v}_{E_x} \tilde{T}_i \rangle$ $\Gamma_{x,v_\parallel} = n_i^0 M \langle \tilde{v}_{E_x} \tilde{v}_\parallel \rangle$,

- Fluxes are normalized to $\Gamma_p^u = (cT_e/eB) k_\perp n_i T_i (e\tilde{\phi}/T_e)^2$ and to $\Gamma_\parallel^u = n_i M (cT_e/eB) k_\perp c_s (e\tilde{\phi}/T_e)^2$, respectively.

Lontano et al. cont'd

NSTX (1)

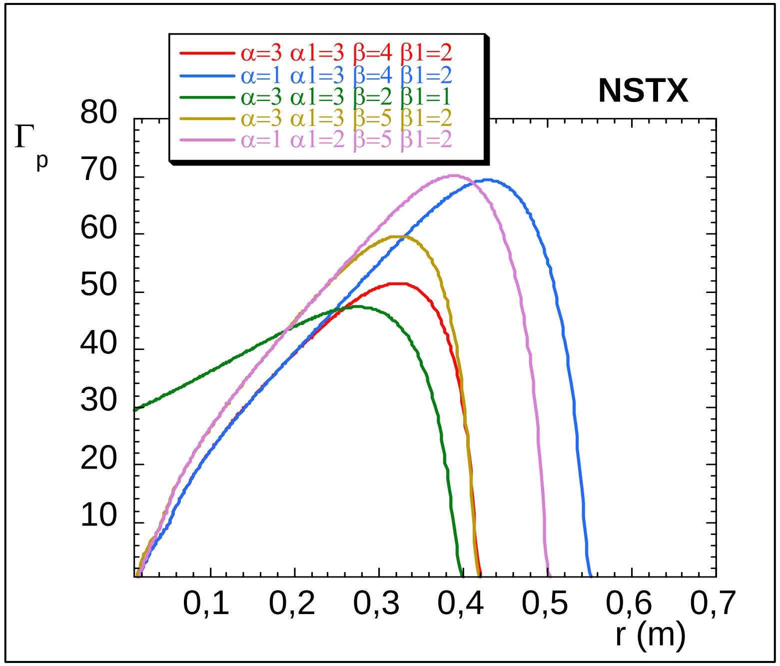


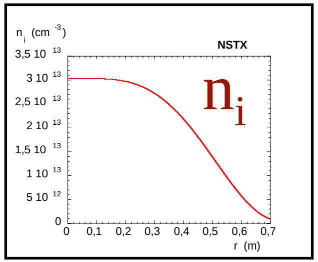


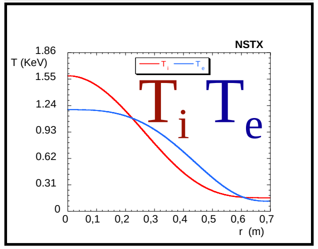
$$\xi = \frac{r}{a} = \frac{x}{a}$$

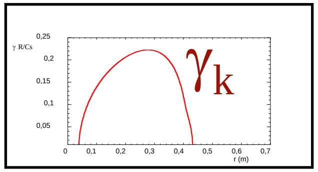
$$(A_c - A_b)(1-(\xi - s)^{\alpha 1})^{\alpha} + A_b$$

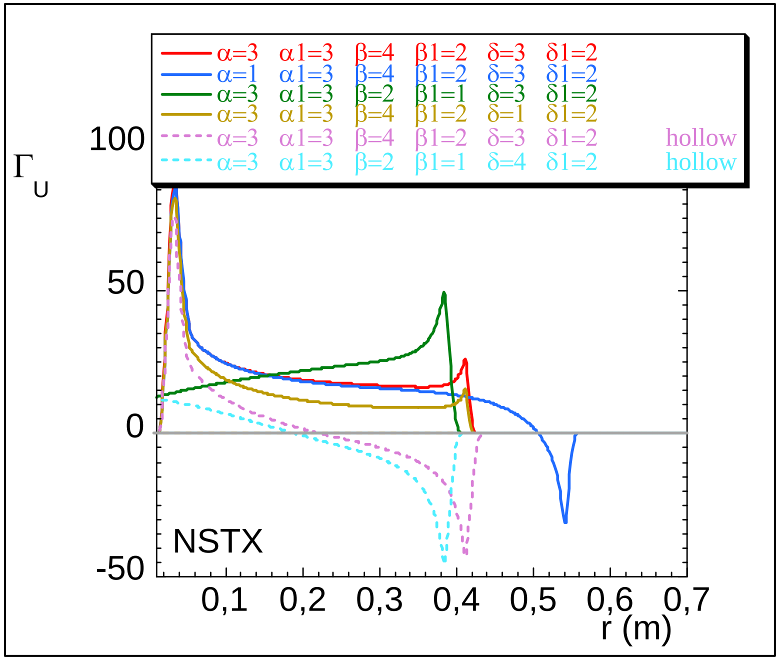
s=0 symmetric profile







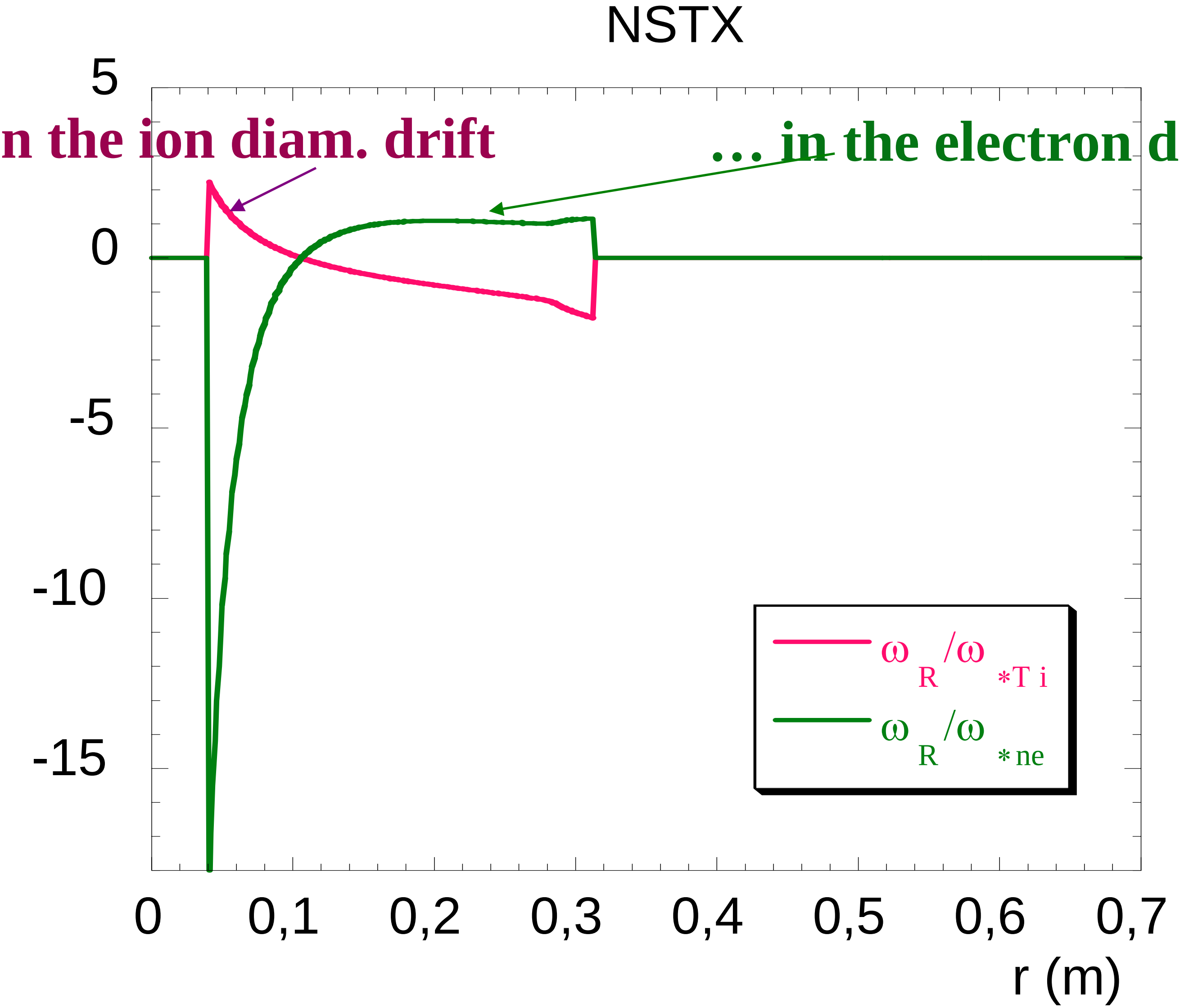




NSTX (1)

Lontano et al. cont'd

mode rotates…

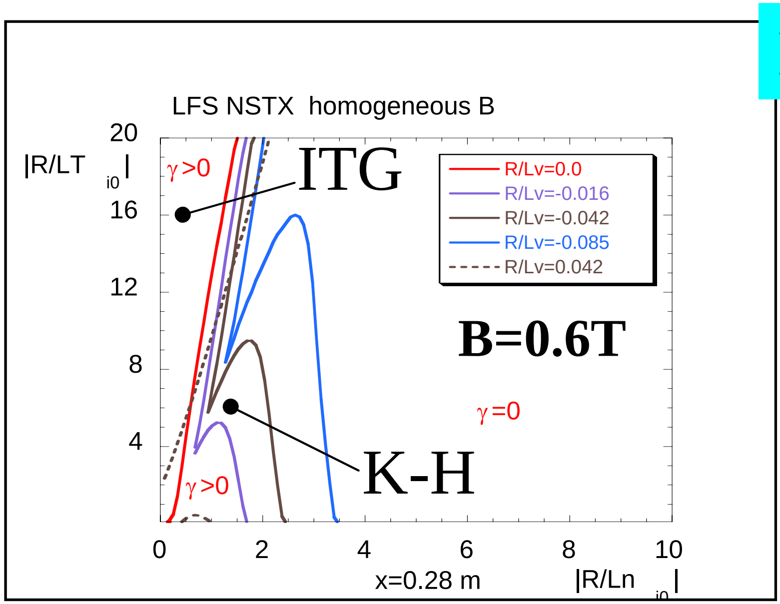


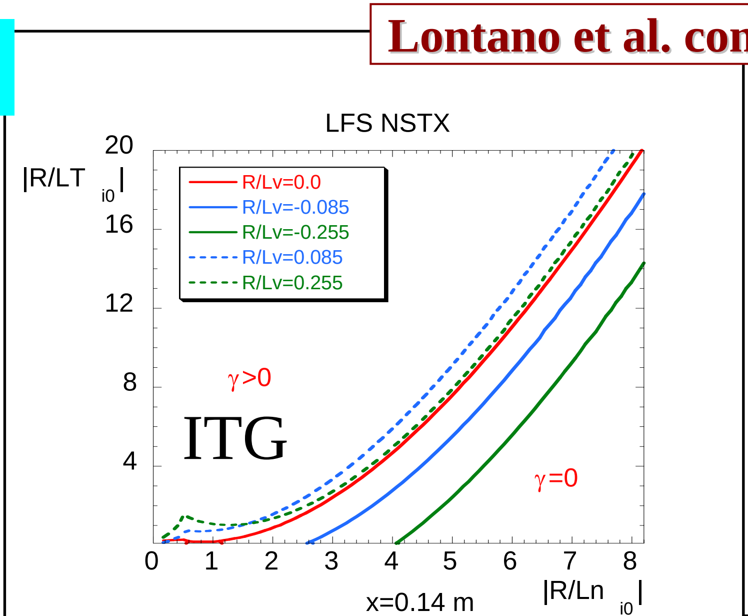
… in the ion diam. drift

… in the electron diam. drift

NSTX (2)

Lontano et al. cont'd

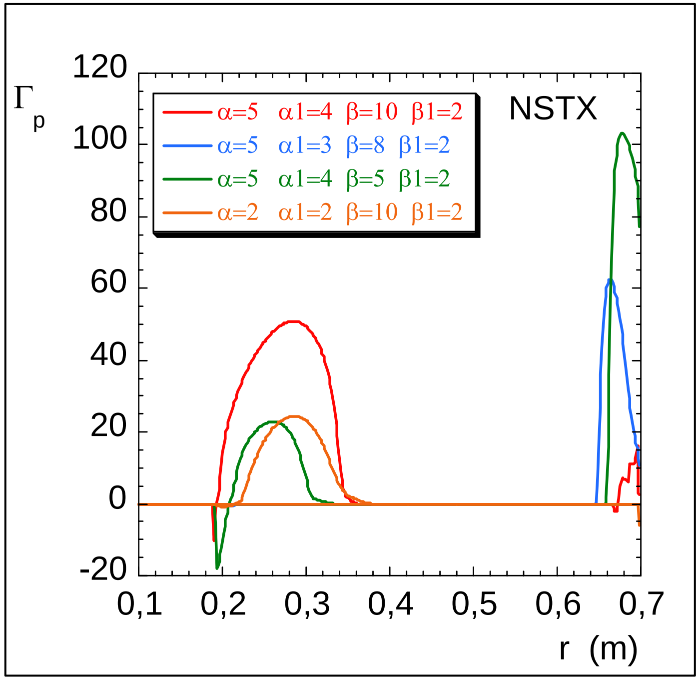


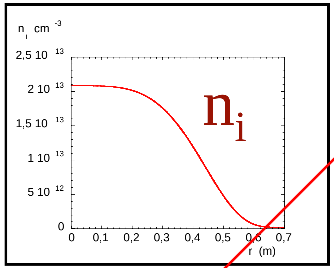


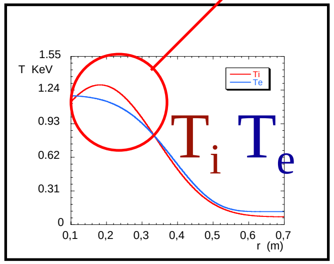
$$(A_c - A_b)\left(1-(\xi - s)^{\alpha 1}\right)^{\alpha} + A_b$$

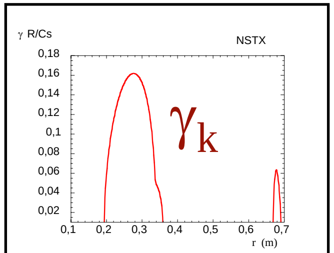
s=0 symmetric profiles

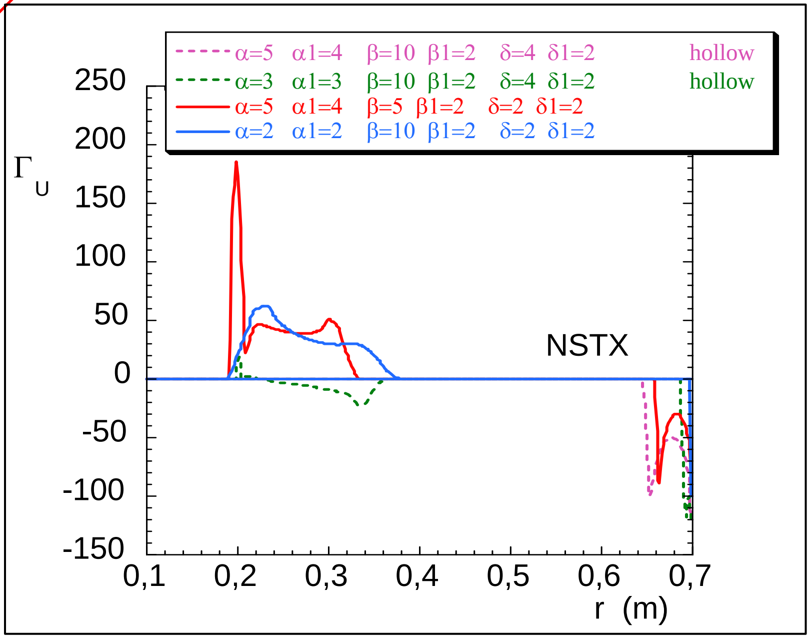
s=0.26 asym. T_i profile in LFS, only











2D turbulence model equations

- hybrid Wakatani-Hasegawa and blob model
  - M. Wakatani and A. Hasegawa, Phys. Fluids **27**, 611 (1984).
  - S. I. Krasheninnikov, Phys. Letters A **283**, 368 (2001).
  - D. A. D'Ippolito, et al., Phys. Plasmas **9**, 222 (2002).
- equations for the fluctuations

$$\frac{dn}{dt} = \underbrace{\alpha_{dw}(\tilde{\Phi} - \tilde{N}) - \alpha_{sh}\, n}_{\nabla_{||}J_{||e}} + S$$

core particle source

$$\frac{d}{dt}\nabla^2\tilde{\Phi} = \underbrace{\frac{\alpha_{dw}}{n}(\tilde{\Phi} - \tilde{N}) + \alpha_{sh}\tilde{\Phi}}_{\nabla_{||}J_{||}} - \beta\frac{\partial N}{\partial y} \cancel{+ S_\rho}$$

curvature drive

$$\frac{d}{dt} = \mathbf{v}_E \cdot \nabla$$

core

SOL
sheath losses

$N = \mathit{ln}\ n$

Zonal <y-averaged> momentum equation defines net momentum kick from blob losses to sheaths

integral of vorticity Eq.

$$\frac{\partial}{\partial t}\langle n v_y \rangle + \frac{\partial}{\partial x}\langle n v_x v_y \rangle = \int_{x_{LCS}}^{x} dx\, \alpha_{sh} \langle n\Phi \rangle \longrightarrow \boxed{\langle J_x \rangle = -\int_{x_{LCS}}^{x} dx \langle \nabla_{\|} J_{\|} \rangle}$$

generation by Reynold’s stress

loss to sheaths

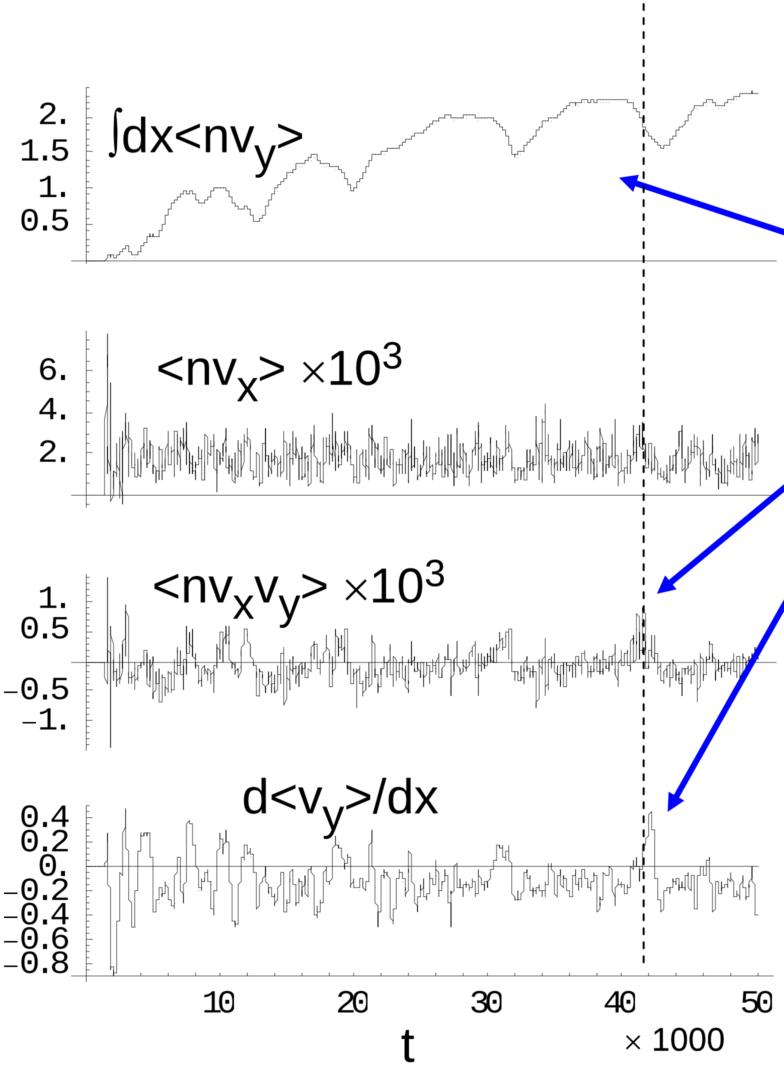
radial location of sheaths determines net flow vs. sheared flow

- use this equation to evolve <Φ>
- turbulence code is explicitly momentum conserving
  - Boussinesque approximation on vorticity equation no good here

$$\nabla \cdot \left(n \frac{d}{dt} \nabla \Phi \right) \neq n \frac{d}{dt} \nabla^2 \Phi$$

- non-local radial modes
- strong (order unity) fluctuations
  - triple product correlations, blob transport, …
  - proper radial density weighting of $v_x v_y$ important

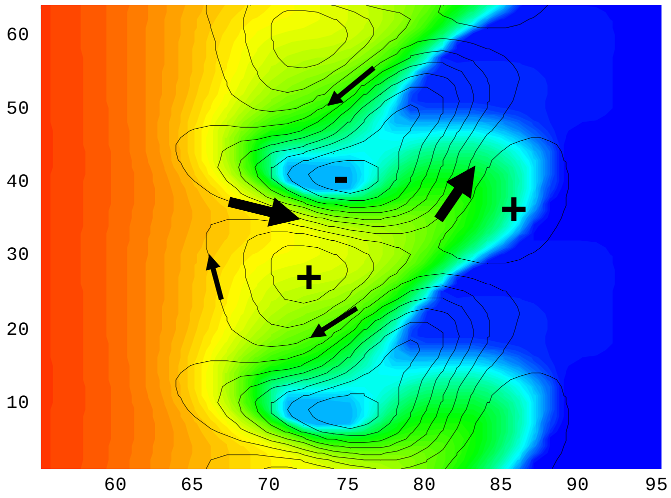
Edge turbulence simulations show spin-up of plasma



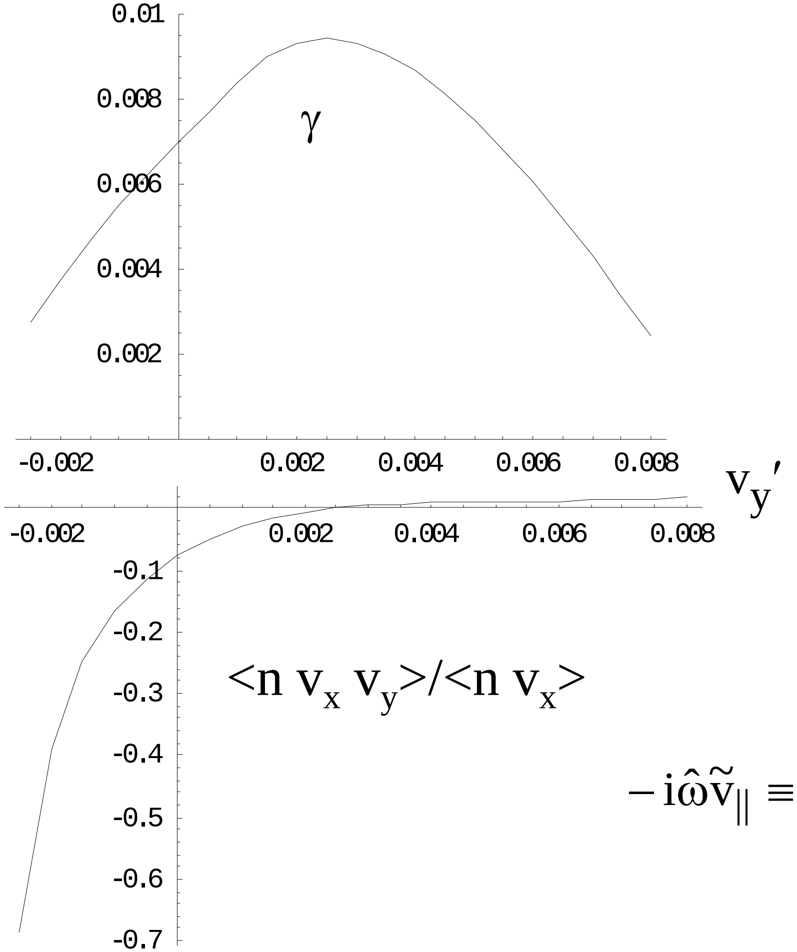
- spikes in particle flux are blob ejection events
- recoil spins up core
- sign of ejected momentum correlated with $\langle v_y \rangle'$

blob ejection dynamics

n (shaded) and Φ (contours) in (x, y) plane



Quasi-linear evaluation of momentum kick



- radial eigenvalue code based on Wakatani-Hasegawa-blob model
- linear growth rate γ peak is offset from $v_y' = 0$ due to drift terms
- kick (momentum/particle flux) changes sign with v_y'

$v_{\|}$ shear: $v_y' \rightarrow (k_{\|}/k_y)\, v_{\|}'$

- parallel momentum transport from diffusive and pinch terms
- pinch term carries wave momentum $k_{\|}/\omega$, and can be dominant

$$-i\hat{\omega}\tilde{v}_{\|} \equiv \left(\frac{\partial}{\partial t} + \bar{v}_y \frac{\partial}{\partial y} + \bar{v}_{\|}\nabla_{\|}\right)\tilde{v}_{\|} = -\tilde{v}_x \frac{\partial \bar{v}_{\|}}{\partial x} - \frac{c_s^2}{n}\nabla_{\|}\tilde{n}$$

pinch

$$\left\langle n v_x v_{\|}\right\rangle = -D\bar{n}\frac{\partial \bar{v}_{\|}}{\partial x} + \left(\bar{v}_{\|} + \frac{c_s^2 k_{\|}}{\hat{\omega}}\right)\left\langle \tilde{n}\tilde{v}_x\right\rangle$$

Summary

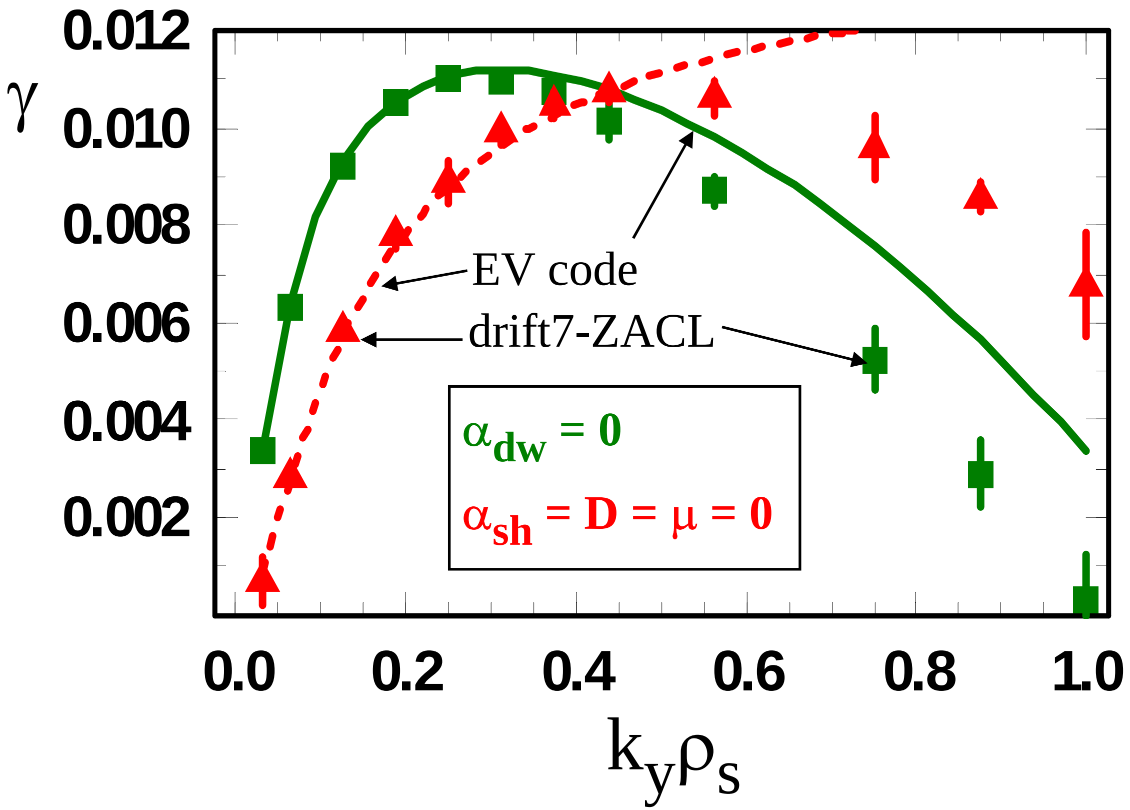
- Electrostatic two-region model elucidates blob regimes in dimensionless parameter space of collisionality and blob scale size. Theoretical bounds on radial blob velocity are given.
- Modeling of gas-puff-imaging (GPI) experiments validate the collisional radiative model; DEGAS-2 simulated images reproduce camera data very well. [Stotler]
- Analysis of GPI data from NSTX shows that within error bars, data obeys the theoretical bounds for blob velocity v_r as a function of size a_b.
- The ITG mode can transport momentum inward, instability spectrum and transport depends on sheared parallel velocity. [Lontano et al.]
- Blobs carry momentum to the wall (sheaths) and the recoil spins the plasma.
- Different types of edge instabilities (e.g. in L and H mode) correlate with observed changes in toroidal rotation. [Coppi et al.]
- The VTG mode, driven by ion flow velocity and temperature gradients, contributes both momentum inflow and diffusion terms which cancel under stationary conditions. [Coppi et al.]
- Nonlinear edge plasma simulations show the dynamics of momentum transport from waves to blobs to sheaths. Both perpendicular and parallel momentum transport interact with sheared velocity profiles.

Supplemental

Poster and paper available at www.lodestar.com

- http://www.lodestar.com/LRCreports/Blobs_Accretion_Poster_IAEA_2006.pdf
- http://www.lodestar.com/LRCreports/Blobs_Accretion_Paper_IAEA_2006.pdf

Drift7 code benchmarks well against radial eigenvalue code



- grid size is $\Delta_x = \Delta_y = 1.57\ \rho_s$
- grid diffusion negligible until $k_y\ \rho_s > 0.6$ or $k_y\ \Delta_y > 1$

notes:

- same case as for D = 0.01 nonlinear run, except as indicated
- results very sensitive to non-stationary equilibrium for finite α_{dw} (requires turning sheaths and diffusion off)

ZACL = Phoenical Shasta with Zalesak’s 2D Limiter (convective update algorithm) [S.T. Zalesak, J. Comp. Phys. v.31 p.335 (1979).]