Transport of perpendicular momentum across the last closed surface

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Questions

- What is the rate of perpendicular momentum transport across the last closed surface (LCS)?
  - characterize edge poloidal momentum "source"
- What is the role of Reynolds stress generation and transport by blobs?
  - Coppi [EPS 2006 paper P4.017 & NF 2002] blob momentum and recoil force, spontaneous toroidal rotation
- What determines the direction of the momentum transport (sign of edge source)?
- What is the role of sheath and volume dissipation?
- How does the dynamics of zonal momentum $\langle n_e v_y \rangle$ govern zonal flow $\langle v_y \rangle$ and turbulence regulation?
  - steep n(x) at edge and $\delta n/n \sim 1$
- What can we learn from quasilinear averages?

Model

- minimal 2D turbulence model in plane normal to B for edge and SOL
  - Lodestar SOLT code
- equations:
  - continuity equation for density n
    - lost particles re-supplied at zero velocity
  - vorticity equation for "fluctuating" potential $\tilde{\Phi} = \Phi - \langle \Phi \rangle$
    - curvature drive
    - adiabaticity parameter for electrons α_{dw} controls drift wave (DW) drive
    - sheath charge loss rate parameter α_{sh}
  - momentum conservation equation for zonal-averaged $\langle n v_y \rangle$
    - advances <Φ> from $\langle v_y \rangle = \langle \partial \Phi / \partial x \rangle$

$$\boxed{\langle \Phi \rangle = \int dy \ \ \Phi / L_y}$$

- important features
  - poloidal directionality from electron drift v_{*e}
  - radial blob propagation from curvature
  - radially varying dissipation (sheaths)

radial asymmetries drive momentum flux:
  v shear   Gürcan et al., PoP (2007)
  B shear
  dissipation shear

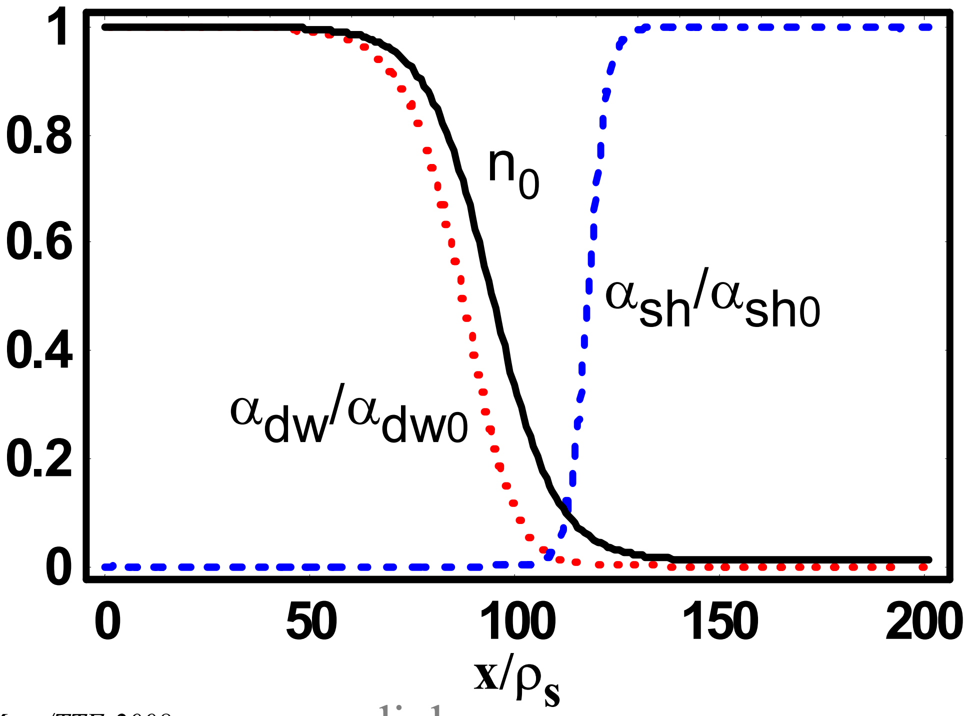
Equations and profiles

$$\frac{\partial n}{\partial t} + \mathbf{v}\cdot\nabla n = \alpha_{dw}(\tilde{\Phi} - \tilde{N}) - \alpha_{sh} n + D\nabla^2 n + S$$

$$\frac{\partial}{\partial t}\nabla^2\tilde{\Phi} = \left\{ -\mathbf{v}\cdot\nabla\nabla^2\Phi + \alpha_{dw}\left(\frac{\tilde{\Phi}-\tilde{N}}{n}\right) + \alpha_{sh}\tilde{\Phi} - \beta\frac{\partial\tilde{N}}{\partial y} + \mu\nabla^4\tilde{\Phi} \right\}$$

$$\frac{\partial}{\partial t}\langle n v_y\rangle + \frac{\partial}{\partial x}\langle n v_x v_y\rangle = \int_0^x dx\, \alpha_{sh}\langle n\Phi\rangle + \bar{\mu}\frac{\partial^2}{\partial x^2}\langle v_y\rangle$$

$$\boxed{\langle J_x\rangle = -\int_0^x dx'\langle\nabla_{\|}J_{\|}\rangle}$$

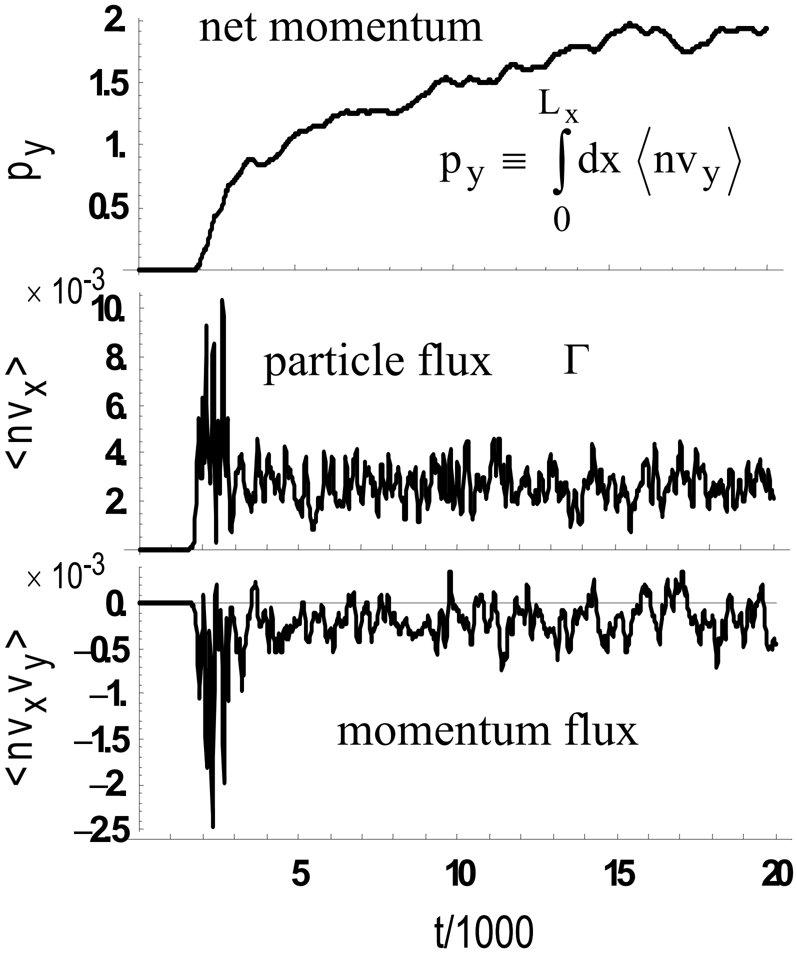


radial →

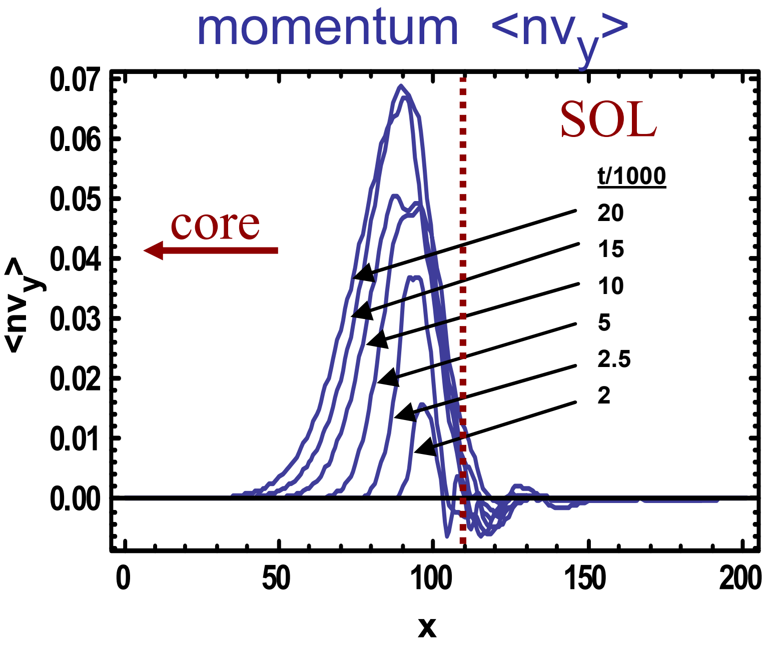
- closed surfaces ("edge") have drift physics α_{dw}
- open SOL field lines have sheath physics α_{sh}
- curvature parameter β = constant
- diffusion: D, μ, $\bar{\mu}$

SOLT Code Results

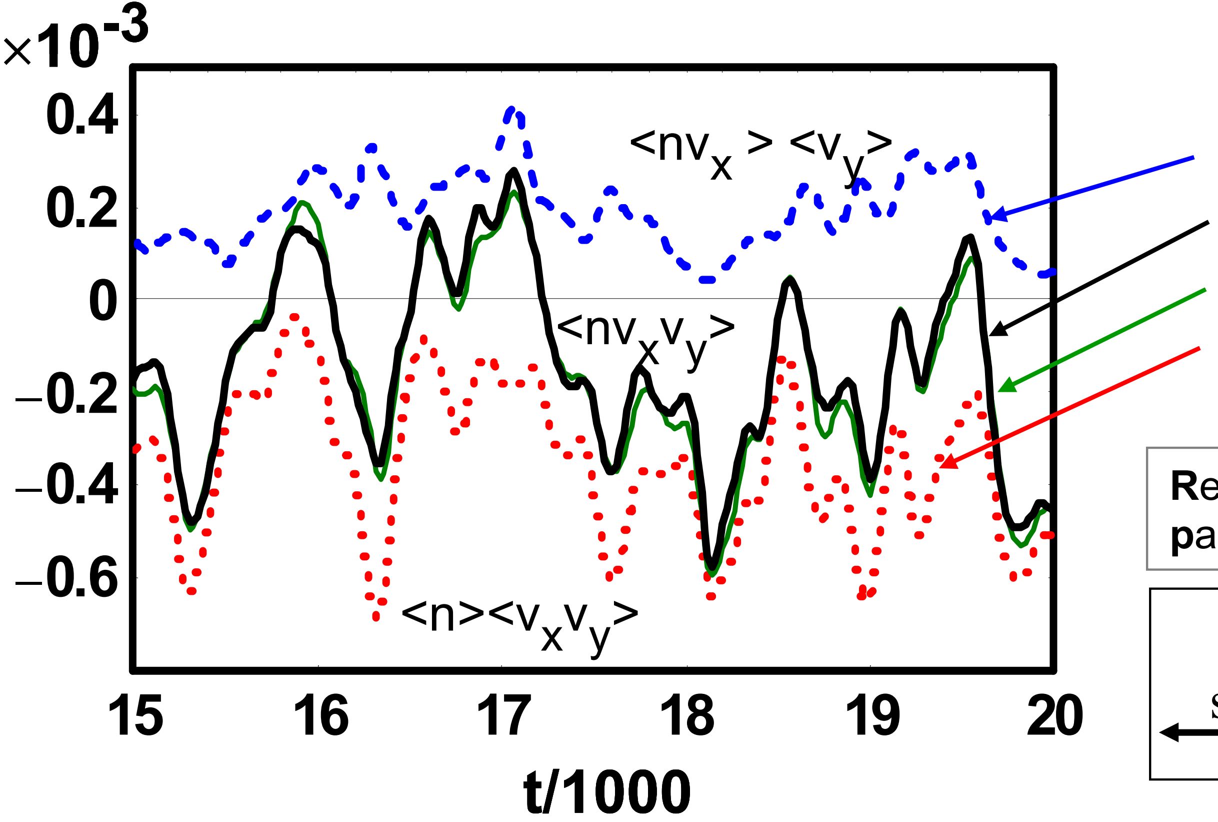
Ejection of moment across LCS and plasma spin-up



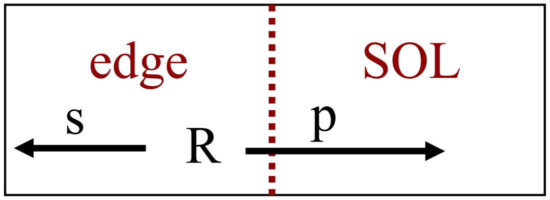
- net plasma momentum buildup (balanced by sheath momentum loss)
- initial transient blob “kick”
- intermittency
- inward momentum diffusion $\bar{\mu}$



Residual from Reynolds and passive momentum flux provides edge source



Reynolds → passive + edge source



- full momentum flux ≈ quasilinear average

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

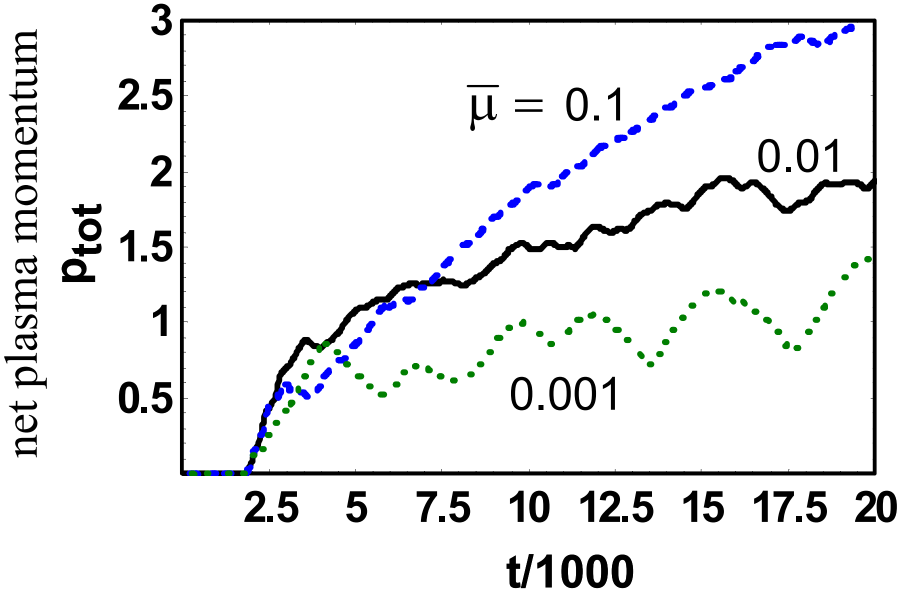
- Reynolds and passive oppose
- Reynolds term generates flows, $\langle v_y \rangle$ builds up
  - passive momentum losses increase: v_y carried with the particle flux (blobs)
  - shear stabilization increases: v_y' vs. γ [see Russell et al., Edge IV]
- total, in direction of Reynolds (after cancellation) = edge source

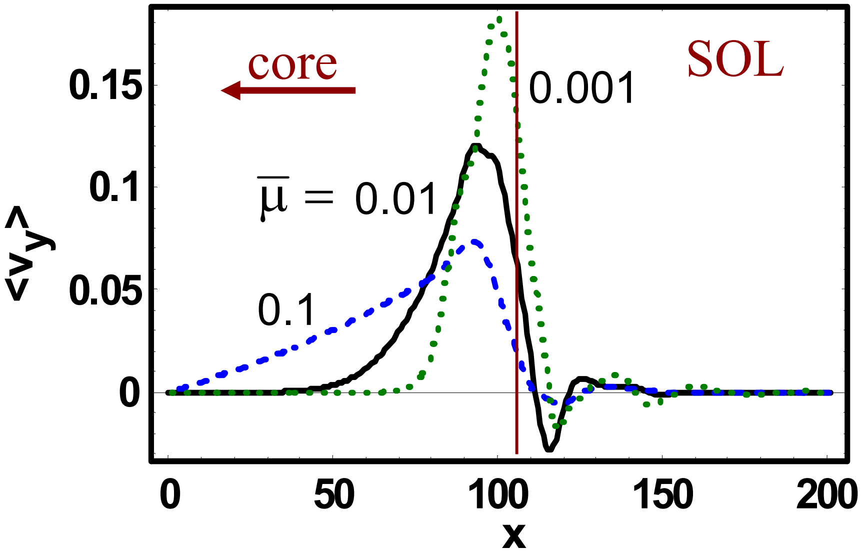
Edge momentum source strength depends on inward transport rate and edge velocity shear

- edge momentum transport into “core” is controlled by $\overline{\mu}$ in our model

$$\frac{\partial}{\partial t}\langle n v_y \rangle = \frac{\partial}{\partial x} \underbrace{\overline{\mu}\frac{\partial \langle v_y \rangle}{\partial x}}_{\text{inward momentum flux}} + \ldots$$

~ NC or turb. pinch, diffn, off-diag.





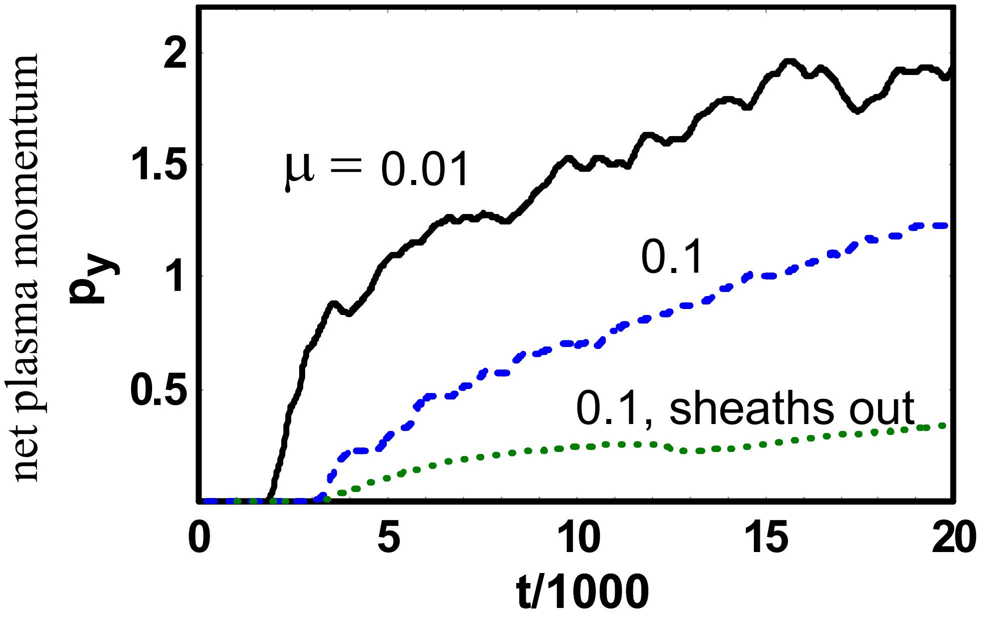
- larger inward transport ⇒ stronger edge source (to a point)
- system tries to maintain sheared flow in instability zone: $v_y' \sim \gamma$

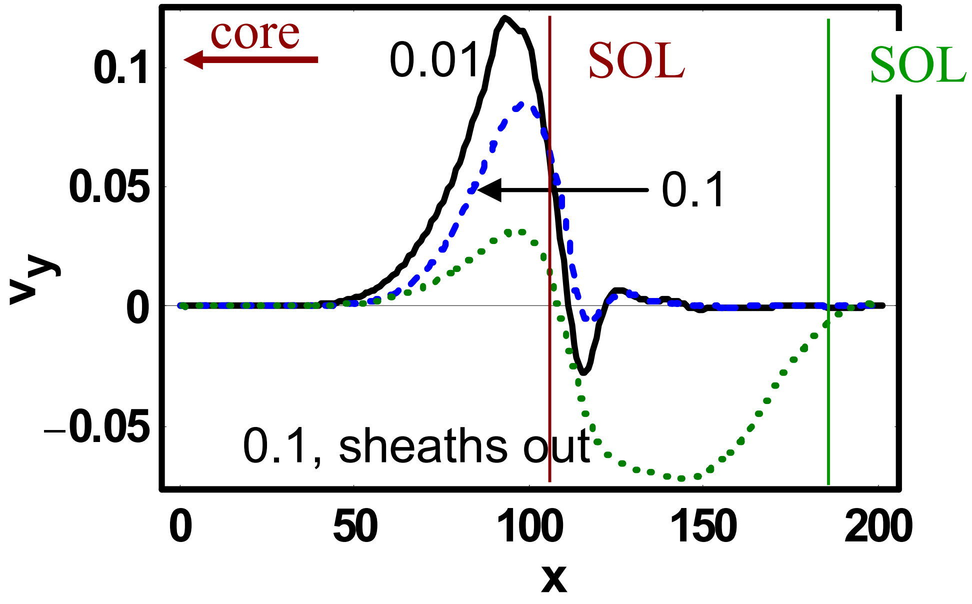
nv_y vs. v_y'

edge – core coupling

Viscous and sheath dissipation control the size and structure of the flows

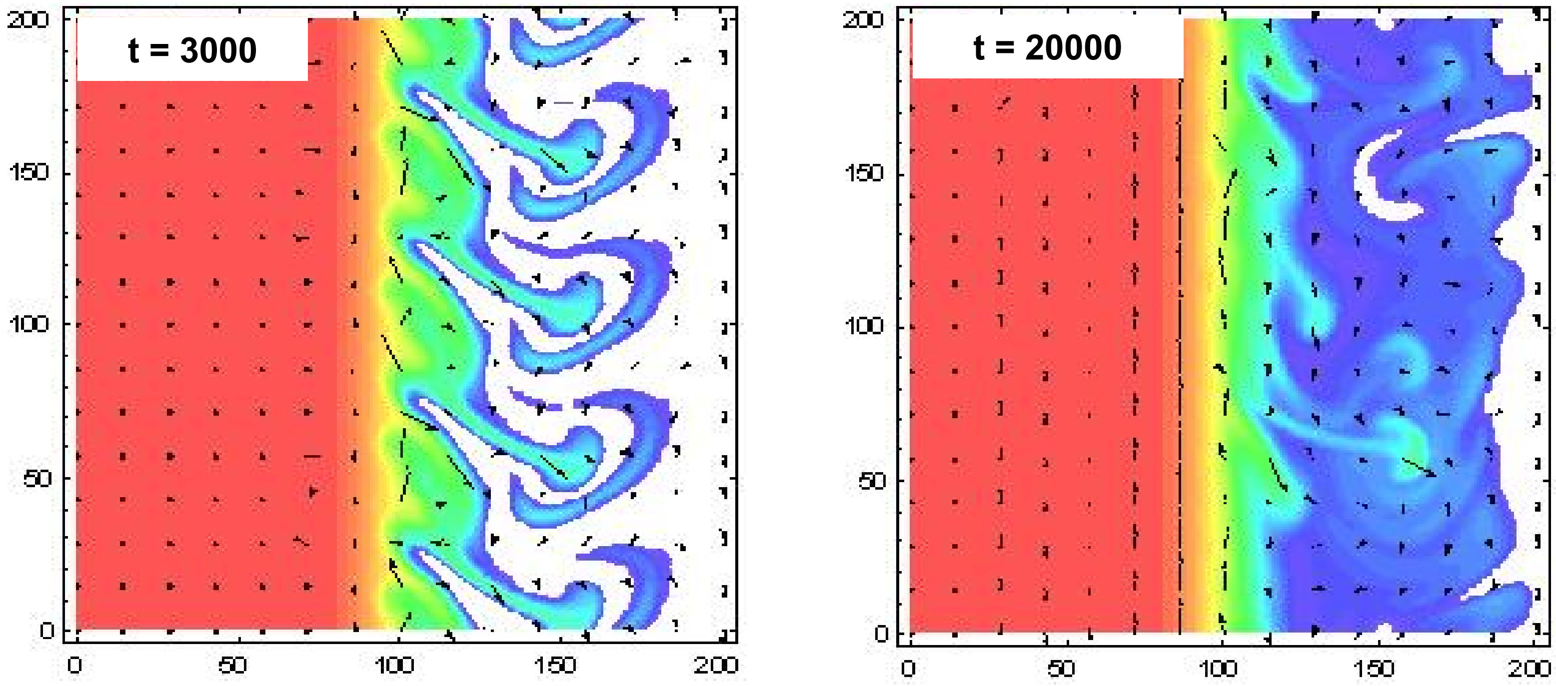
- increased viscous dissipation (μ) of fluctuations reduces γ, turbulence and momentum transport
- artificially moving sheaths out (reduced sheath dissipation) ⇒ bipolar flows (less net plasma momentum)





Dynamics of blob formation and momentum transport

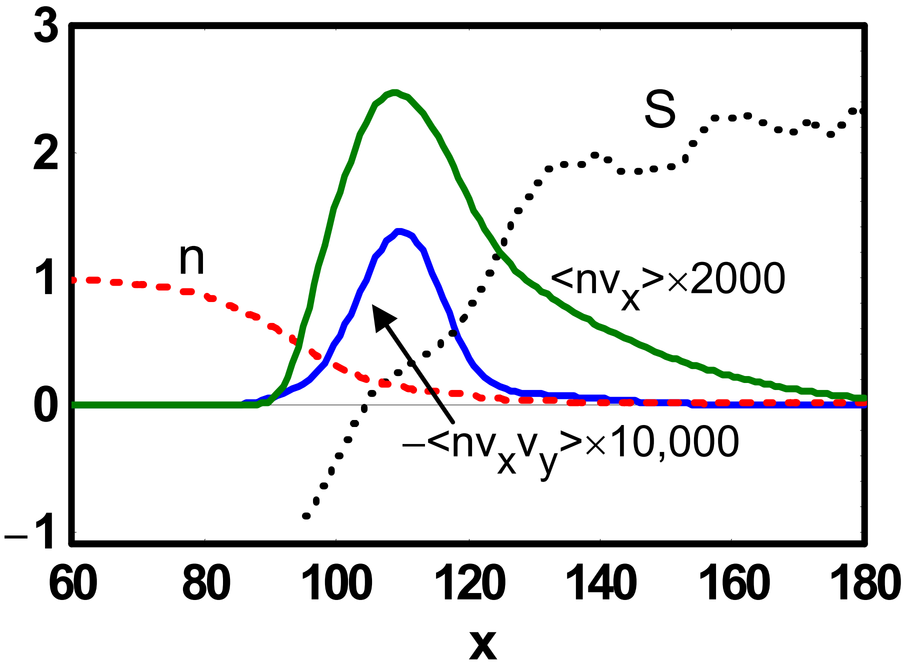
snapshots: density palette, momentum arrows

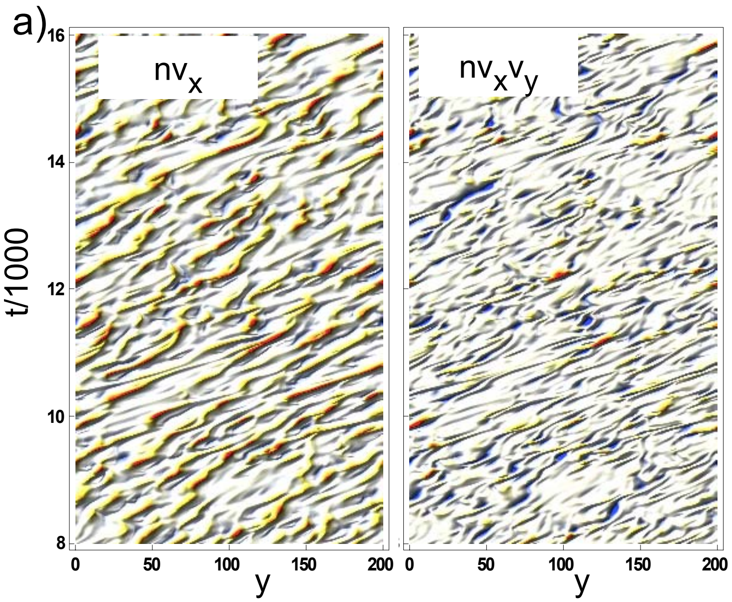


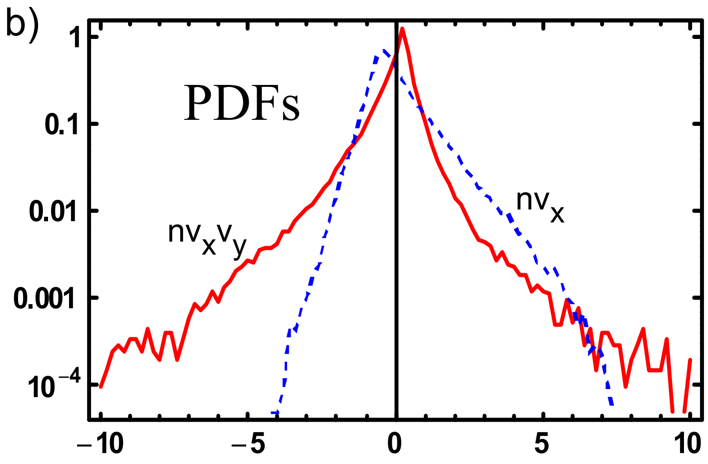
- early nonlinear development of seeded m = 4 mode
  - downward ejection of blobs (streamers); upward momentum “kick”
  - upward moving wave crests twisted around and down in ejection process
- later quasi-steady intermittency
  - sheared flows pinch off streamers ⇒ blobs

Density & momentum intermittency statistics

- momentum kick is mostly from blob birth zone where |skewness| < 1
- particle transport across LCS is by larger more coherent structures than momentum transport

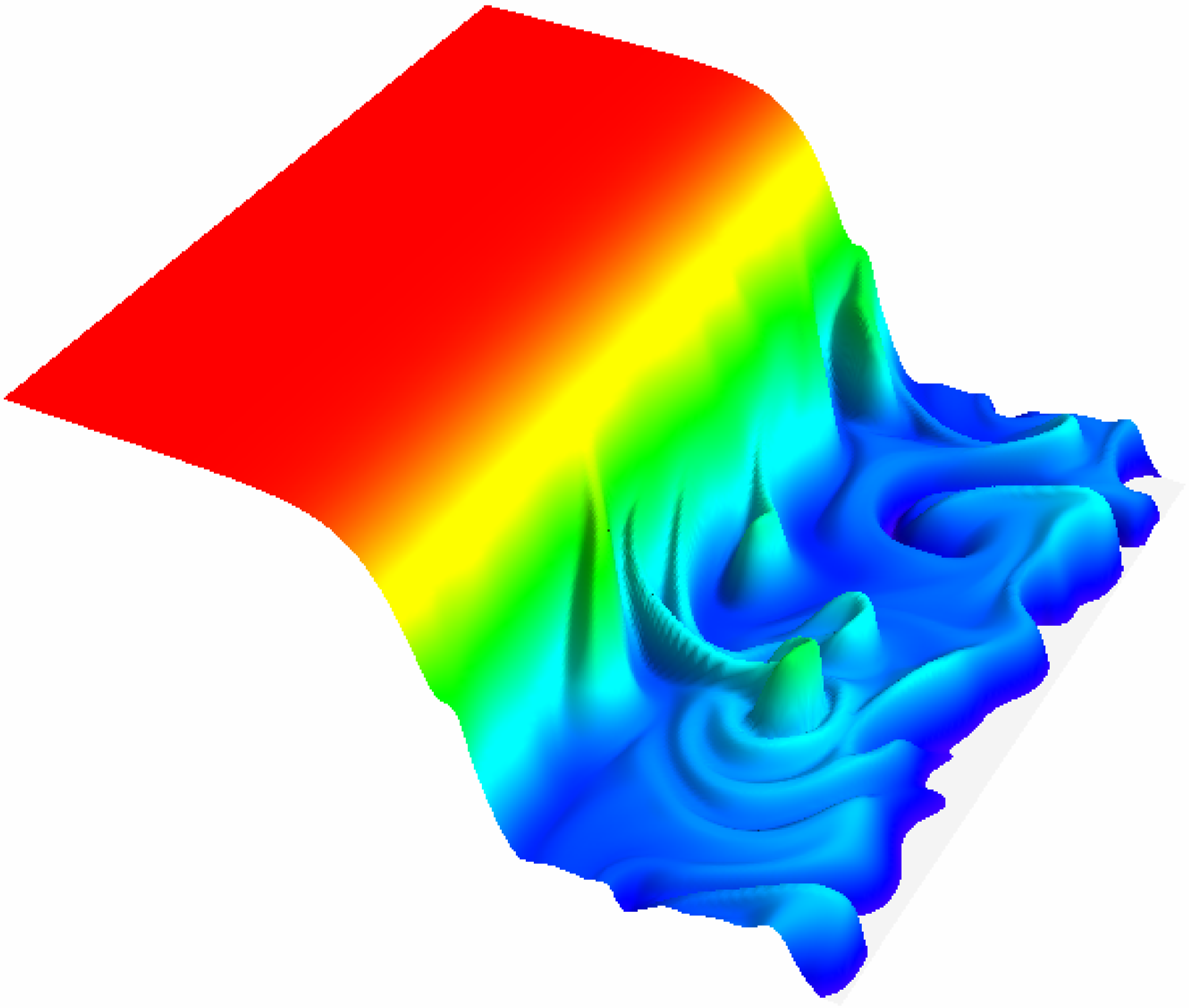






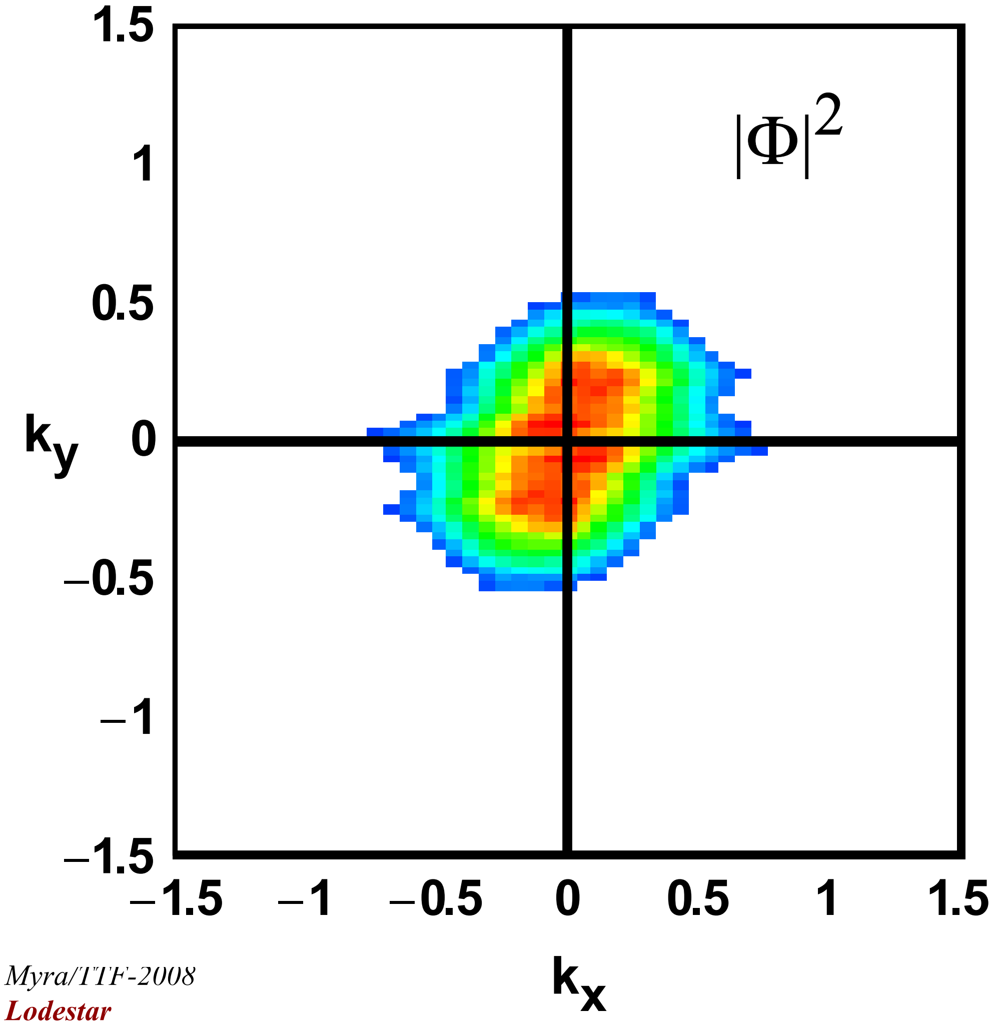
Conclusions & remarks

- *Poloidal* momentum transport studied here; *toroidal* momentum has some significant differences.
- Separatrix-spanning turbulence ⇒ edge momentum source for core rotation.
  - sheath momentum loss ⇒ net flow (vs. bipolar)
- Reynolds stress provides net force on the core plasma, and is opposed by the passive loss of momentum carried by exiting particles.
- Edge momentum source is coupled to core physics, inward transport rate.
- Steep edge n(x) impacts dynamics:
  - regulation by edge sheared flows, viz. v_y' (no density weighting)
  - momentum conservation applied to nv_y
- Quasilinear averages work reasonably well; coherent structures are more important for particle transport than momentum.
- Turbulence-induced poloidal spin-up direction = direction of drift wave $v_{phase} \approx v_{*e}$



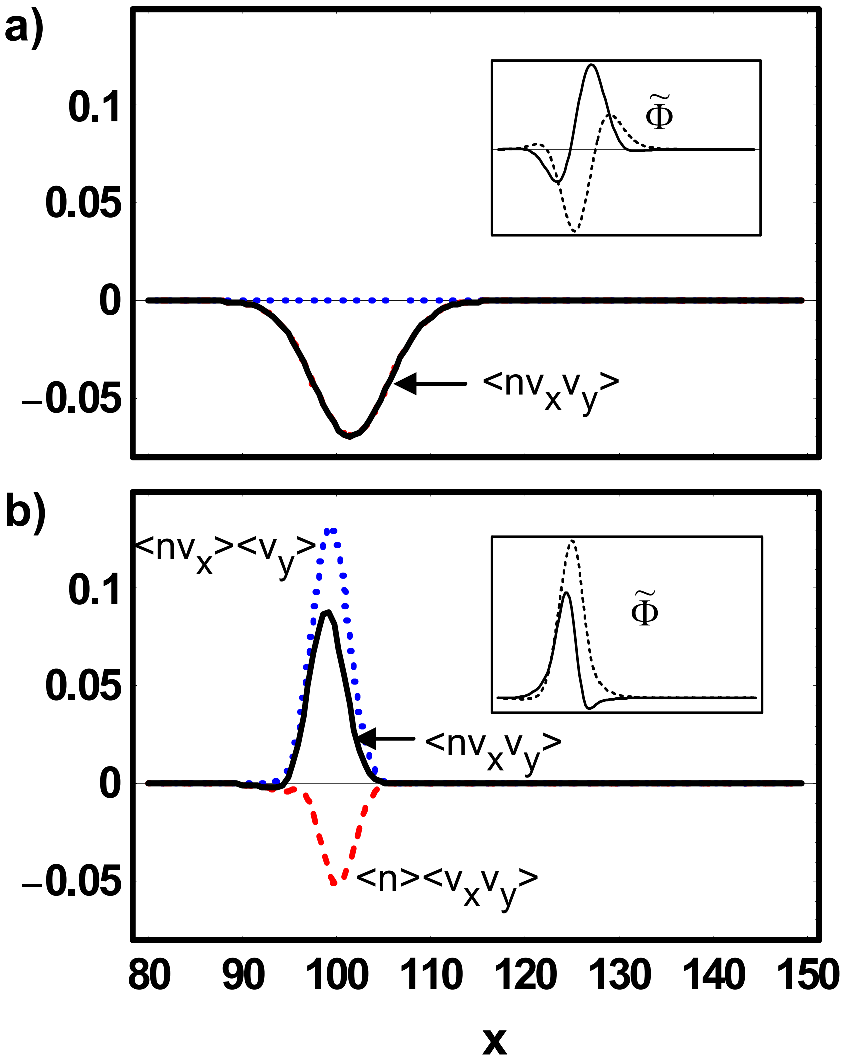
Supplemental

Spectral energy shows asymmetry necessary for momentum transport



- tilted ellipse necessary to get non-zero Reynolds stress $\langle v_x v_y \rangle \propto -k_x k_y \langle |\Phi|^2 \rangle$

Quasilinear averages provide a reasonable description



- total and constituent pieces of momentum flux from radial eigenvalue code + QL averages
- a) $v_y = 0$ (no passive term)
  b) large v_y (passive term dominates)
- critical v_y depends on ratio particle/momentum flux
  - QL does reasonable job

Toroidal (≈ parallel) momentum transport

- consider $<nv_x v_\zeta> = <n><v_x v_\zeta> + <nv_x><v_\zeta>$

Reynolds passive

$$\left\langle \tilde{v}_x \tilde{v}_\zeta \right\rangle = -b_\theta \left\langle \tilde{v}_x \tilde{v}_y \right\rangle + b_\zeta \left\langle \tilde{v}_x \tilde{v}_{||} \right\rangle$$

- need closure model for $\tilde{v}_{||}$
  - $v_{||}$ response of plasma to $k_{||}$

$$\tilde{v}_{||} = \frac{k_{||}}{\omega} c_s^2 \frac{\tilde{n}}{n} + \text{term} \propto \tilde{v}_x \, \partial v_{||} / \partial x$$

- resulting Reynolds term has diffusion + extra "pinch" effect

$$\left\langle \tilde{v}_x \tilde{v}_{||} \right\rangle = \frac{c_s^2}{n v_{||ph}} \left\langle \tilde{v}_x \tilde{n} \right\rangle + \ldots$$

wave momentum carried by particles, blobs

- Coppi, Nucl. Fusion 42, 1 (2002).
- Coppi, IAEA Lyons, (2002).
- Gurcan et al., PoP (2007)
- Coppi et al, EPS 2006 paper P4.017
- Myra et al., IAEA Chengdu (2006).