Edge Sheared Flows and Blob Dynamics

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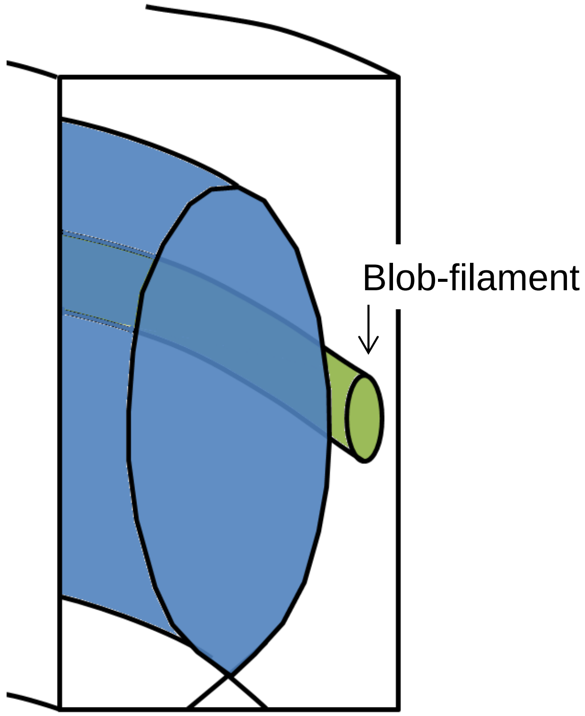
Motivation & Background

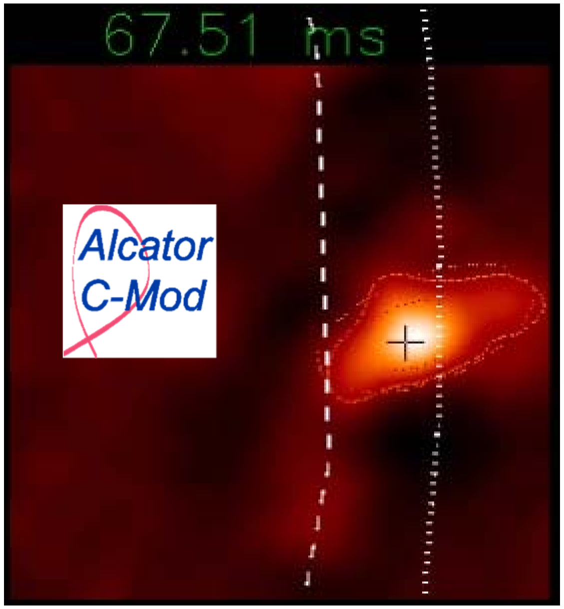
- Edge sheared flows:
  - important for the L-H, and H-L transitions
  - generated by, and regulate the turbulence
  - control the character and trajectories of emitted coherent structures such as blob-filaments

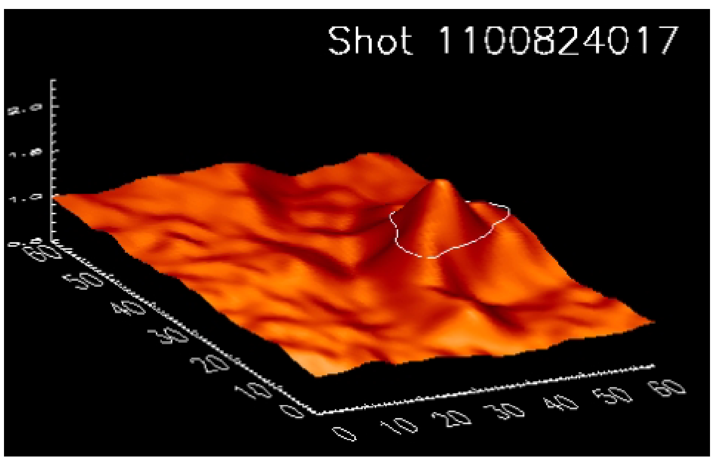
- Blob generation and dynamics impacts:
  - the (near-separatrix) scrape-off-layer (SOL) width, which is critical for ITER power handling in the divertor
  - far SOL blob interaction with plasma-facing components



This work demonstrates that mechanisms related to blob motion, SOL currents and radial inhomogeneity are sufficient to explain the presence or absence of mean sheared flows in selected NSTX and Alcator C-Mod shots

Gas Puff Imaging (GPI) and blob-tracking analysis tool

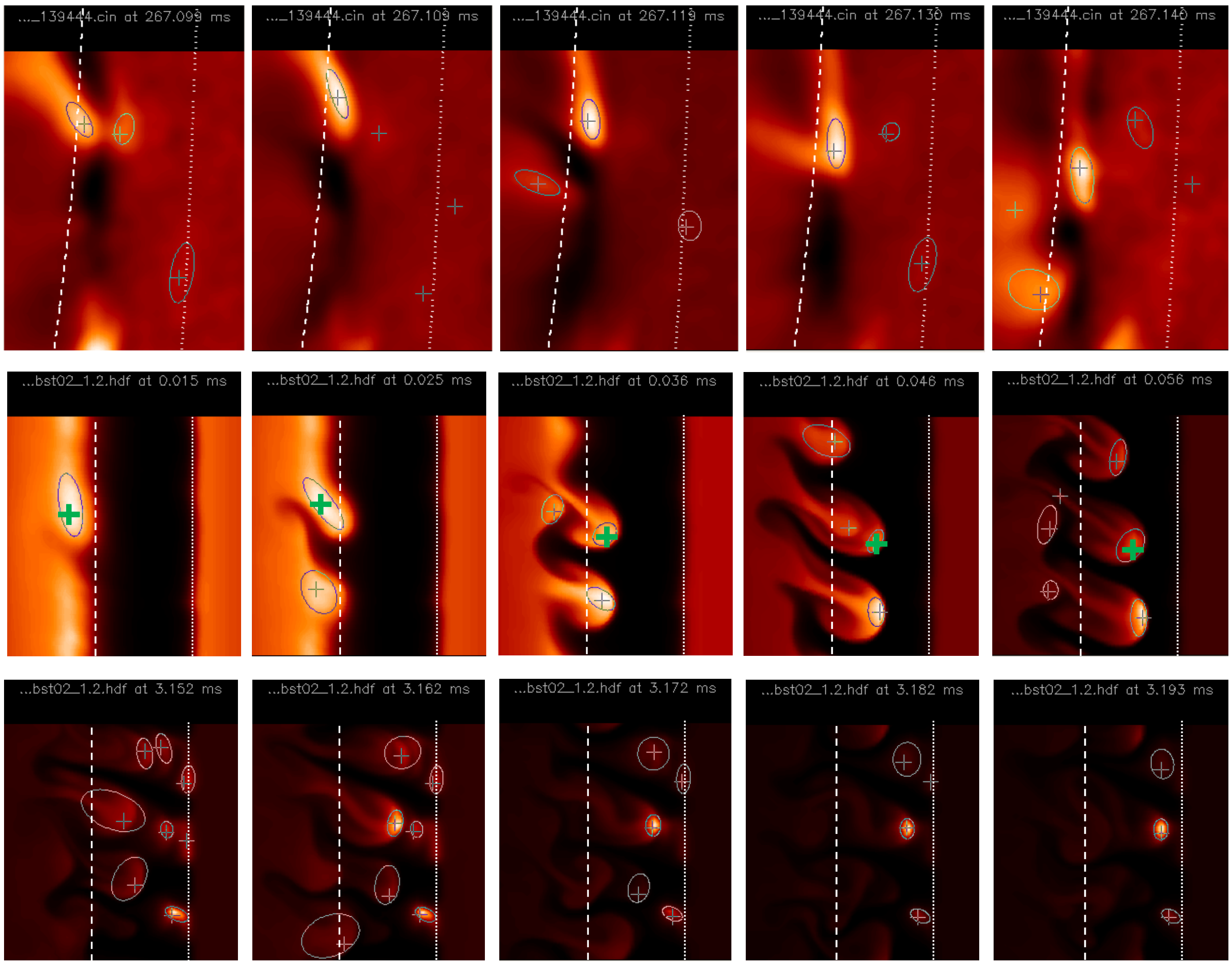




- GPI: Small puff of neural gas (D or He) used to illuminate edge turbulence (via line emission)
- Use relative GPI intensity $\delta I/\langle I \rangle$ as the signal to analyze (in 2D space + time)
- For each frame: locate local maxima (blobs), fit ellipse to each ⇒ “blob”
- Track the motion and structure evolution from frame to frame
- Analyze and compare blob tracks from
  - NSTX
  - C-Mod
  - SOLT simulations

Sample experimental and simulated GPI images

normalized intensity, blob center (+) and fitted ellipse (0); 10 μs per frame



NSTX

SOLT

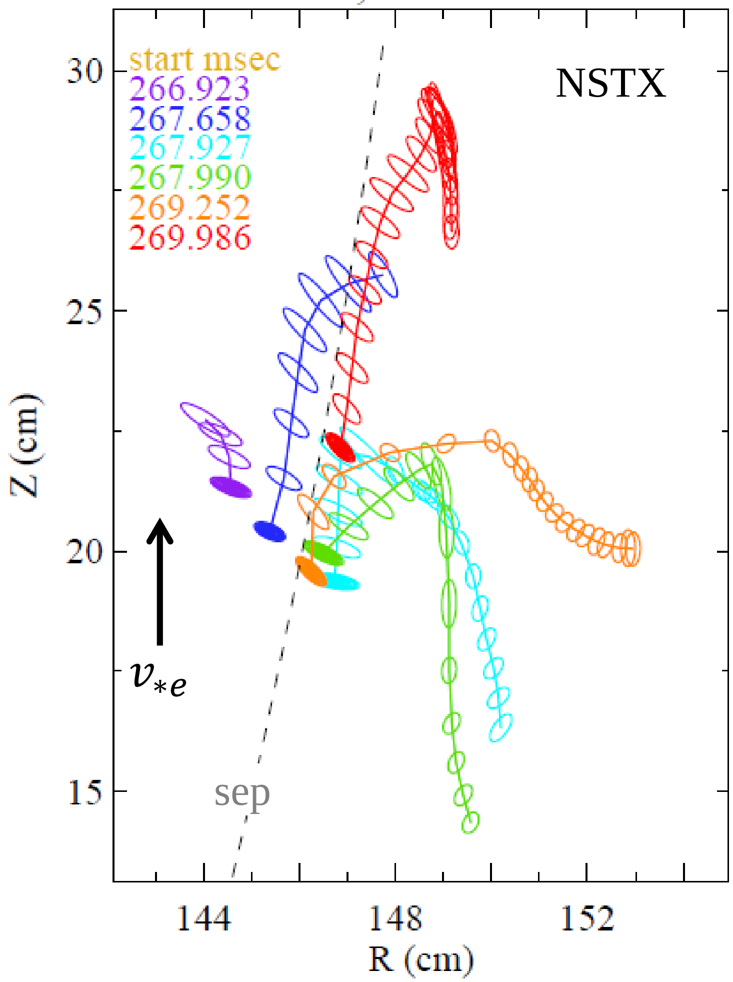
Seeded blob +

SOLT

Turbulence

Experimental NSTX blob tracks

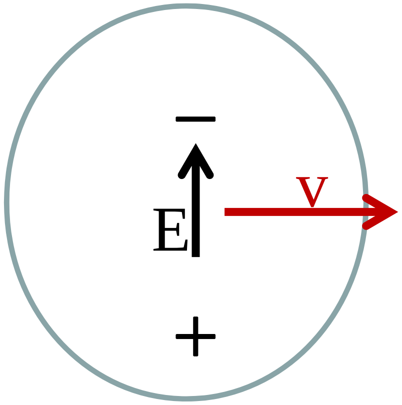
Preheated Ohmic 139444; 267 - 270 ms



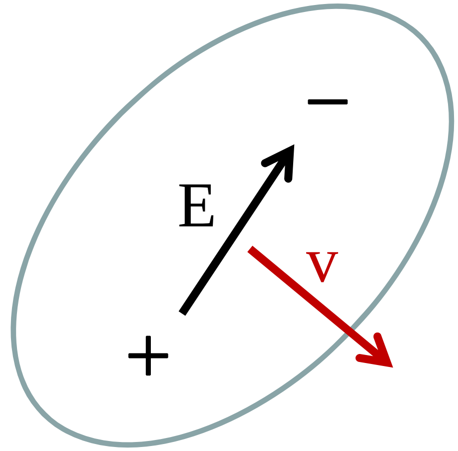
- Some blob tracks show:
  - outward motion (ejection)
  - confinement
  - reversal of v_y near the separatrix
- Mean blob flow v_y changes sign near separatrix

	NSTX 139444	C-MOD 1100824017
$n_{e,sep}$ (cm^{-3})	5.8×10^{12}	1.0×10^{14}
$T_{e,sep}$ (eV)	19.	47.
$\rho_{s,sep}$ (cm)	0.26	0.025
$\Lambda_{SOL} \sim \nu_{e*}(m_e/m_i)^{1/2}$	0.3 – 0.8	1-3
blob size $a_{b,sep}$ (cm)	2.2 ± 0.5	0.4 ± 0.1
$\delta I/\langle I\rangle\vert_{sep}$	0 – 1.6	0 – 0.6

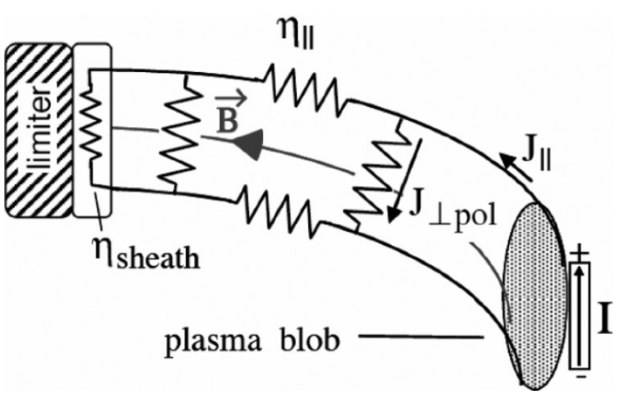
Blob motion is controlled by polarization charges



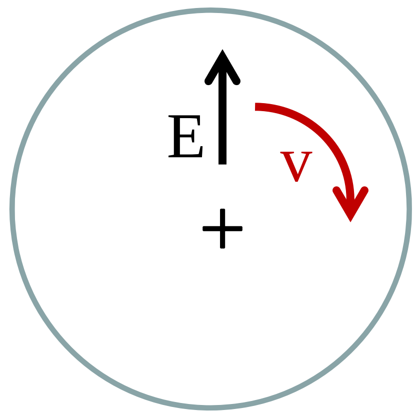
∇B and κ forces charge-polarize the blob ⇒ outward convection



Background flows rotate and shear converting radial motion to poloidal



Current flows neutralize charges; asymmetrically in SOL



Additional monopole charge component ⇒ rotation of dipole

Related Refs.: Diamond and Kim, PF 1991; Terry, RMP 2000; Furno, PRL 2011; Bisai, PoP 2012; Myra PoP 2004; Manz TTF 2012, Horton RMP 1999

Simulation model

D. A. Russell, et al, Phys. Plasmas 16, 122304 (2009)

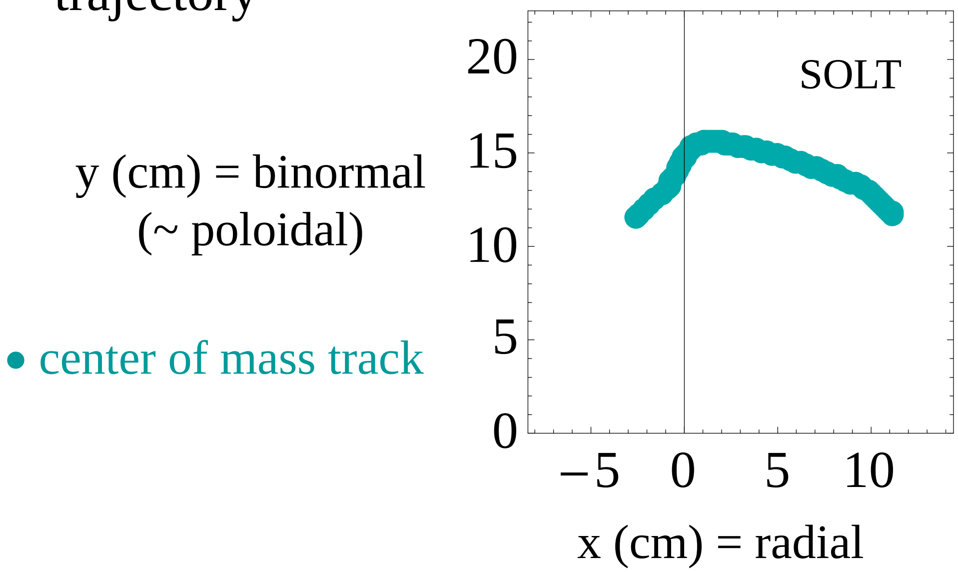
Scrape-Off-Layer Turbulence (SOLT) code

- 2D fluid turbulence code: model SOL in outer midplane
  - classical parallel + turbulent cross-field transport
- Evolves n_e, T_e, Φ with parallel closure relations
  - sheath connected, with flux limits, plus collisional regimes
- Strongly nonlinear: $\delta n/n \sim 1 \Rightarrow$ blobs
- Model supports drift waves, curvature-driven interchange modes, sheath instabilities

- Here:
  - Seeded blob simulations (initial value)
  - Quasi-steady turbulence simulations

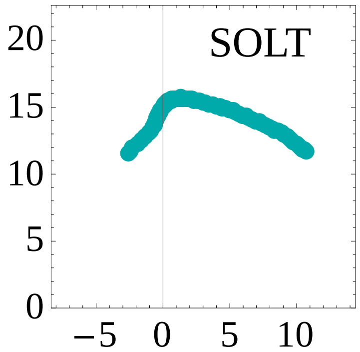
Trajectory for base case NSTX seeded blob

- experimental (NSTX/C-Mod) blob-tracking database ⇒ mean blob scale size, amplitude, birth location for this shot
- shot diagnostics (NSTX/C-Mod) ⇒ background plasma profiles, SOL connection lengths, machine parameters (R, B)
- In SOLT, initialize a typical blob on the background profiles and follow its trajectory

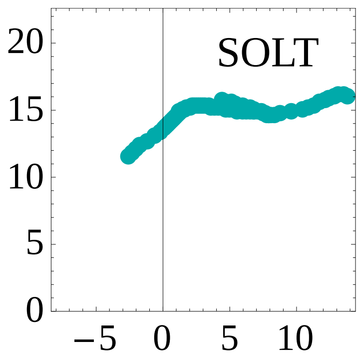


- Blob flows up in the edge (e-direction) and down in the SOL (i-direction)
- Track reversal near separatrix (like data)

Sheath interactions, electron drifts, shear layers, influence trajectories in SOLT

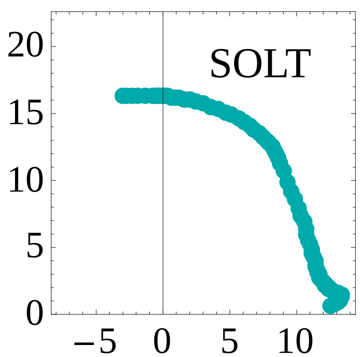


fully sheath connected
(~ NSTX base case)



sheath disconnected

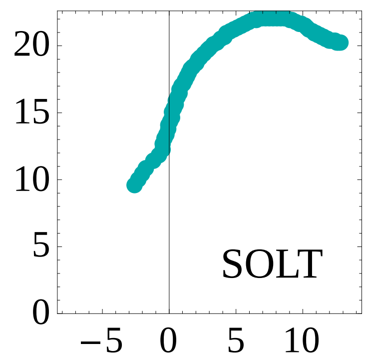
SOL currents matter



electron adiabaticity
and drifts off

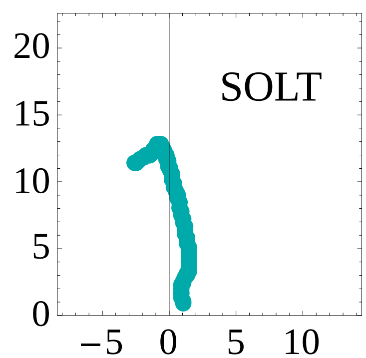
Diamagnetic drift shear matters

- Artificially vary simulation physics to infer mechanisms actually operative in the experimental data
- Acceleration a_y near separatrix related to Reynolds stress and sheared flow generation



imposed $v_{Ey} > 0$

Counter-shear flow ejects blob

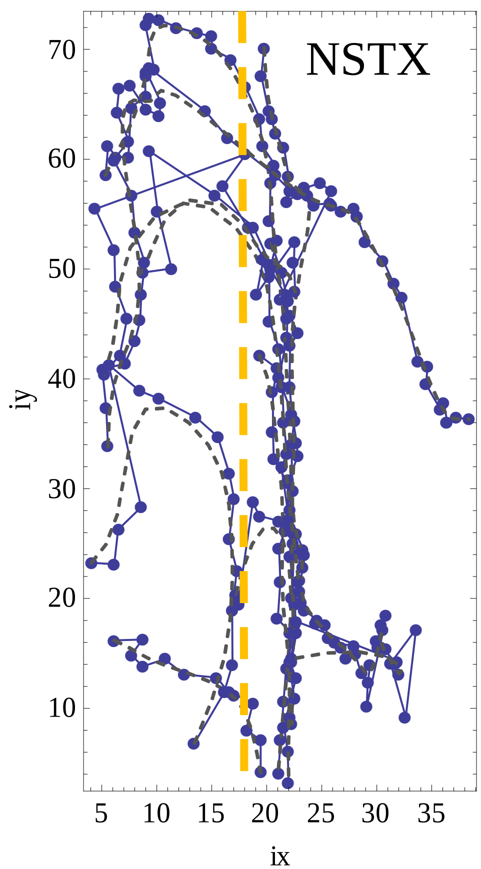


imposed $v_{Ey} < 0$

Co-shear flow traps blob (shear confinement)

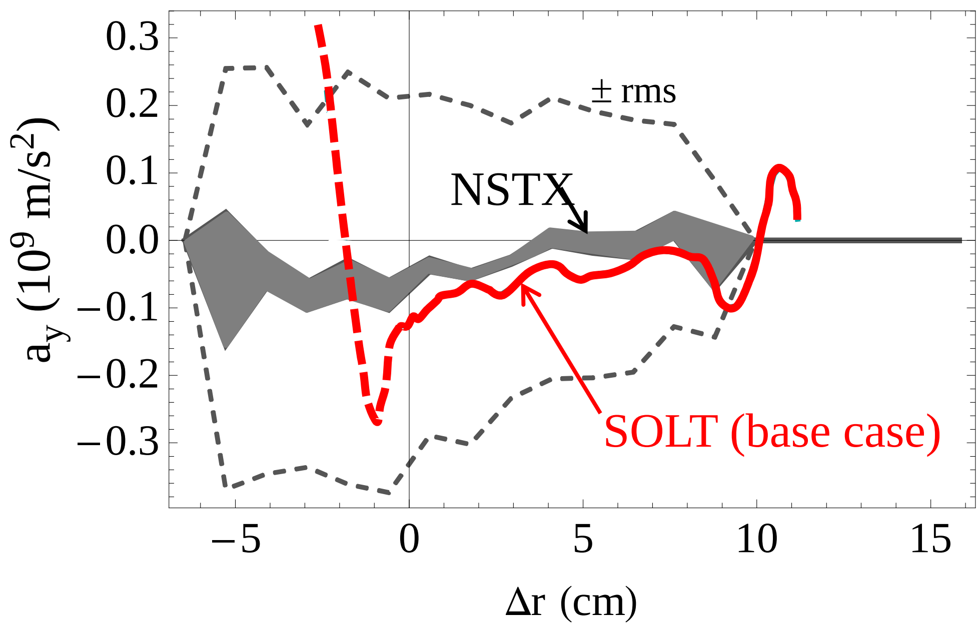
Blob trajectories allow determination of Reynolds stress

- Smoothed fits to blob tracks x(t), y(t) $\Rightarrow$ accelerations and mean RS

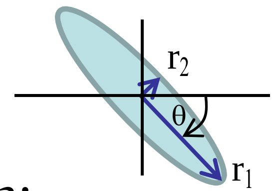


particle *fluid*

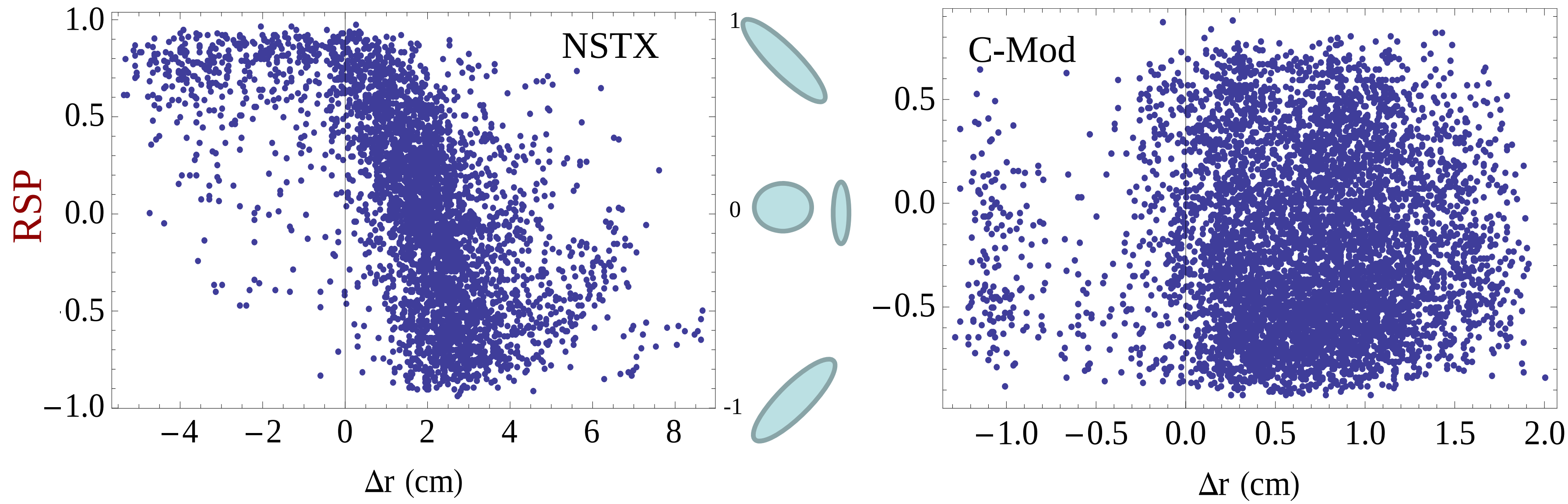
$$\langle a_y \rangle = \left\langle \frac{dv_y}{dt} \right\rangle = \langle \boldsymbol{v} \cdot \nabla v_y \rangle = \partial_x \langle v_x v_y \rangle$$



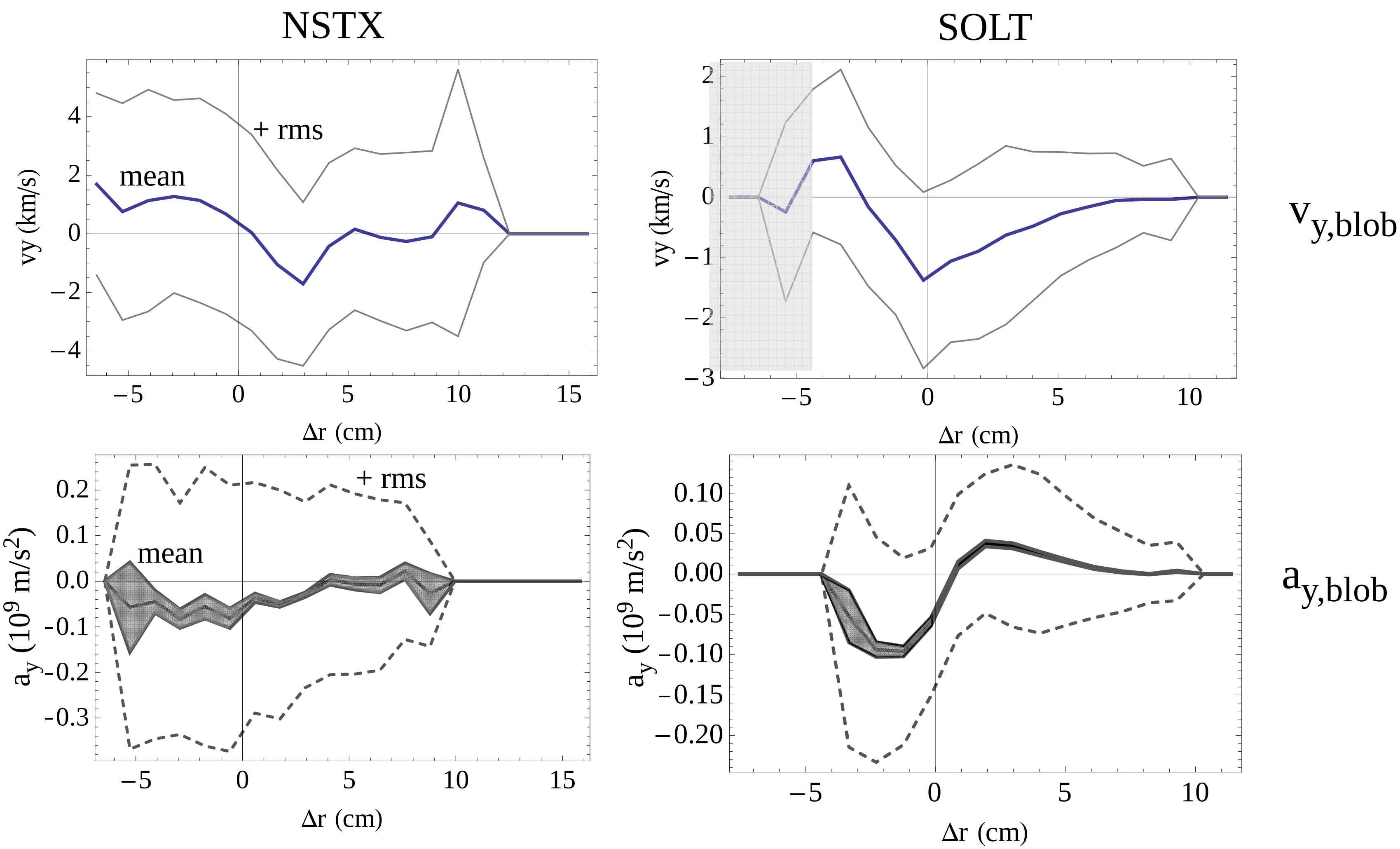
Blob ellipticity and tilt angle variation provide a Reynolds stress proxy (RSP)



- Blob tracking algorithm fits ellipticity and tilt to tracked objects
- Order unity variation in RSP = -sin(2θ)[1-(r_2/r_1)^2] consistent with:
  - Significant blob shearing
  - $\omega_E' \sim 1/\tau_c$ (shearing affect dynamics: distorts blob, regulates flux [Russell 2009])
- Reynolds force is in the right direction to drive observed flows in NSTX



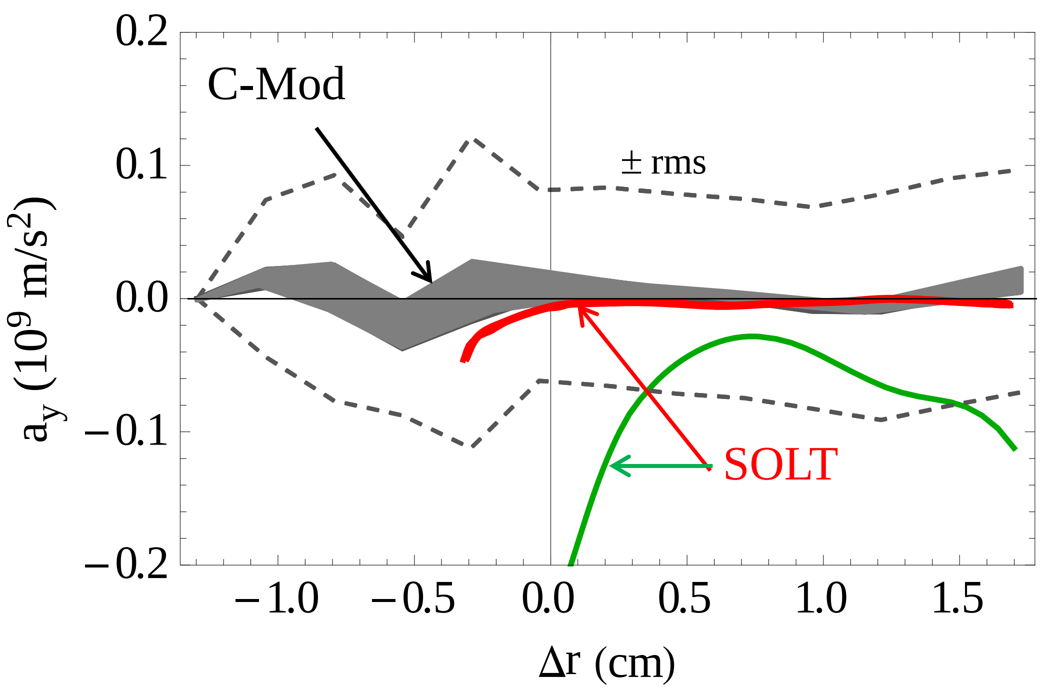
SOLT turbulence simulations run to quasi-steady state: similar blob flows and accelerations as NSTX



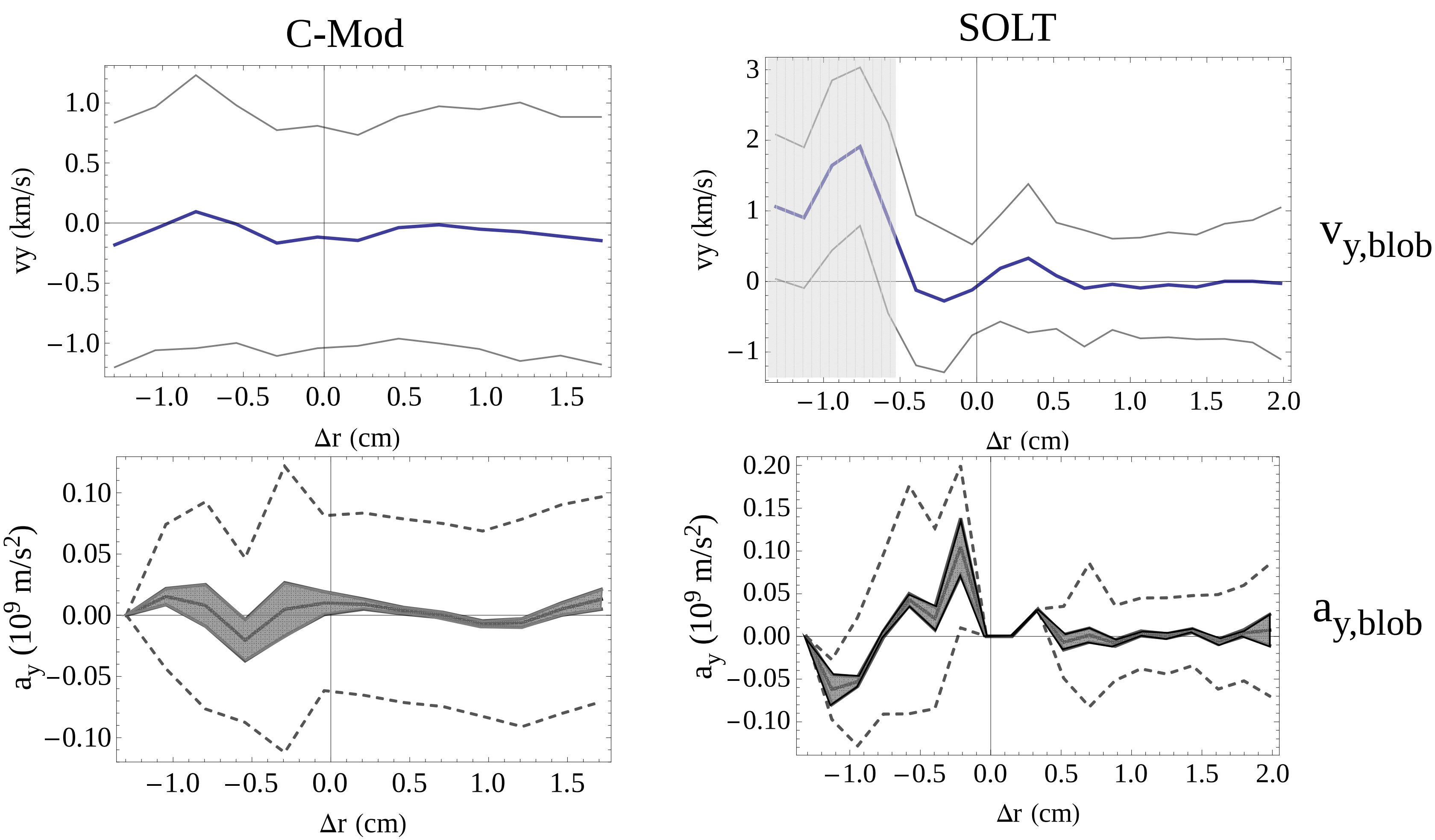
RMS fluctuations are smaller in the simulations

Seeded blob simulations of high collisionality C-Mod shot require modeling extra 3D physics

- High collisionality SOL ⇒ parallel variation, X-point effects
- SOLT model using midplane plasma parameters disagrees with data.
- Assuming sheath disconnection from the plates and extra charge dissipation from friction or cross-field X-point currents gives better agreement.
- Reynolds proxy for this shot shows significant shearing, but no mean shearing



C-Mod turbulence simulations with these assumptions reproduce small mean blob flows with turbulent shearing

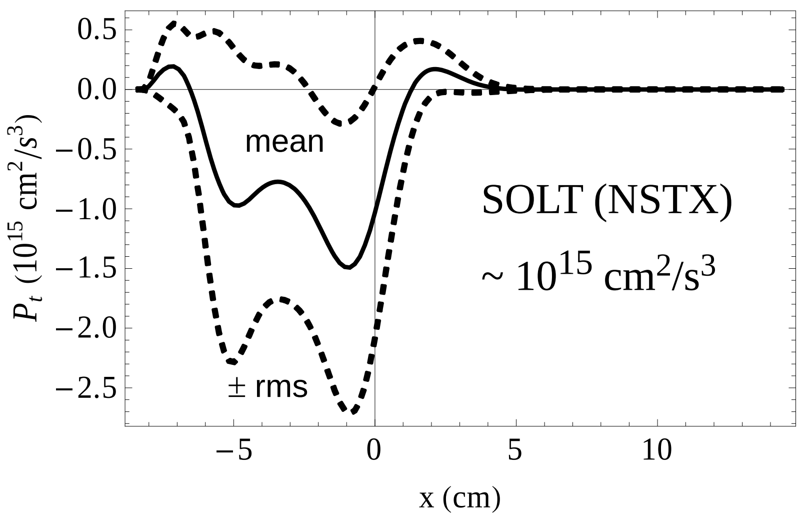


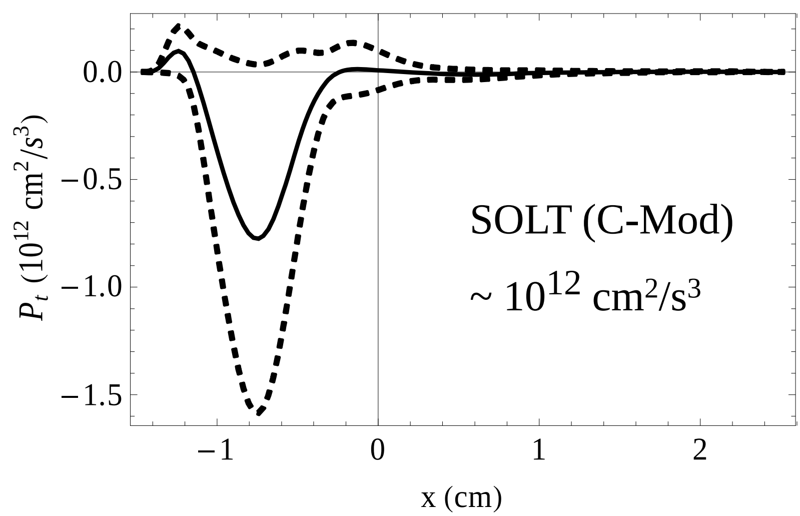
Qualitative agreement near separatrix and in SOL
Core-side flow BC in SOLT $v_E = 0$ is artificial (may contaminate a_y)

Turbulence production rate
SOLT simulations of NSTX and C-Mod

- Turbulence production rate $P_t = -\langle v_x v_y \rangle \frac{\partial \langle v_y \rangle}{\partial x}$

  $P_t < 0 \Rightarrow$ turbulent energy $\rightarrow$ mean flows





- Net perpendicular force on the plasma

  $$F_\perp / P = -\langle n v_x v_y \rangle / \langle 2nT v_x \rangle$$

  – NSTX ~ 0.8 N/MW
  – C-Mod < 0.05 N/MW

Summary and Conclusions

- GPI blob tracking tools
  - motion and changes in structure of blob-filaments
  - applied to NSTX, Alcator C-Mod, SOLT simulations
  - enables a new kind of comparison of edge turbulence theory with data
- Coherent structures crossing the separatrix are sheared and rotated by:
  - radially varying drifts
  - parallel sheath currents from changes in magnetic topology

  $\Rightarrow$ flows
- Simulated accelerations from these mechanisms are large enough to account for the observed Reynolds stress and mean sheared flows in NSTX.
- Sheared flows in the NSTX and C-Mod edge are sufficiently strong to affect blob dynamics and transport
- There is evidence for mean flow damping in a high collisionality C-Mod case, possibly due to 3D effects.
- Model caveats: cold ions, simplified DW physics model, fluid theory, 2D simulations, but captures the essence of nonlinear E×B dynamics