Overview of selected topics in SOL turbulence and blob-filament research

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with acknowledgements to

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Outline

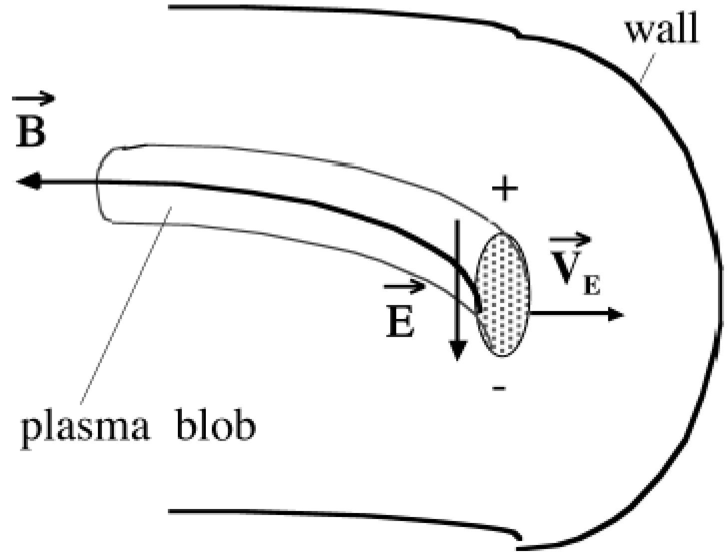
- **Introduction and blob theory 101**
- Experimental comparisons
- Density shoulders
- Statistical properties
- Near SOL
- Other topics
- Ideas for future directions

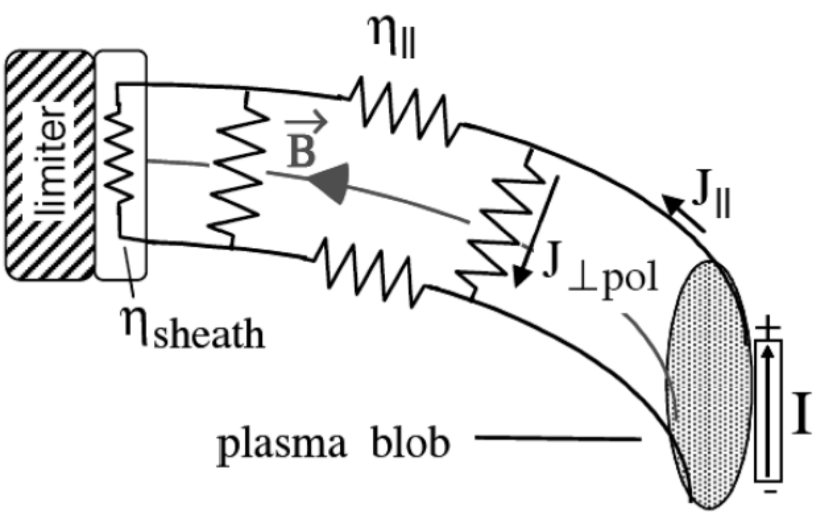
Introduction & Motivation

- Coherent structures in the form of blob-filaments (“blobs”) arise from edge/SOL turbulence: flux tubes filled with “extra” plasma.
- Filaments extended along B can deliver heat and particles to the divertor target.
- Blob-filaments propagate radially delivering heat and particles to the main chamber walls.
- Understanding the structure and characteristics of this turbulence is important. It may impact
  - recycling (divertor and main chamber)
  - deleterious PMI interactions: sputtering and erosion
  - spreading of the near SOL heat flux channel
  - impurity transport
  - divertor operation and detachment
  - RF interactions: scattering of ECH, LH waves; density at antenna, e.g. for ICRF coupling

Blob-filament theory

- definition
- basic propagation mechanism [Krasheninnikov, S. I. *Phys. Lett.* A **283**, 36 (2001)]
- plasma circuit





Current tries to short out polarization charges: affects blob velocity.

Review: Krasheninnikov, D'Ippolito & Myra, J. Plasma Phys. **74**, 679 (2008)

Blob velocity scaling

- Flux depends on blob velocity, size, density/pressure, frequency
- Important quantities determining v_b include
  - blob amplitude $\delta p/p$
  - blob scale size δ_b
  - parallel electrical connection ⇔ resistivity and magnetic geometry $L_{\|}$
- Simplest blob model: interchange driven, no parallel variation of blob pressure, sheath connected (negligible plasma resistivity and X-point effects)

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

balances curvature-drift current with sheath end-loss current

- Disconnected inertial limit (strong parallel resistivity and/or X-point effects)

$$v_b \sim c_s \left(\frac{\delta_b}{R} \frac{\delta p}{p} \right)^{1/2}$$

balances curvature-drift current with ion polarization current, i.e., inertia

… Blob velocity scalings

- Balancing curvature-drift, sheath end-loss & ion polarization current defines characteristic values:

$$v_* \sim c_s \left(\frac{\rho_s^2 L_{\|}}{R^3} \right)^{1/5} \qquad \delta_* \sim \rho_s \left(\frac{L_{\|}^2}{\rho_s R} \right)^{1/5}$$

- and dimensionless blob velocities and sizes

$$\hat{v} = v_b / v_* \qquad \hat{\delta} = \delta_b / \delta_*$$

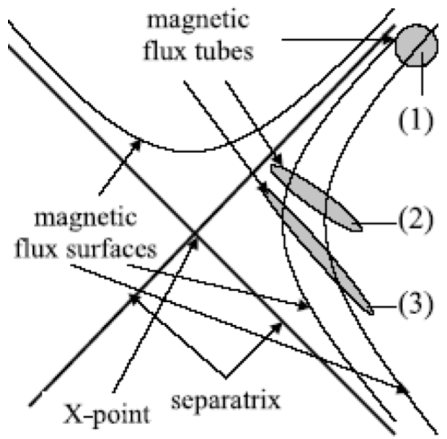
- Dimensionless scaling

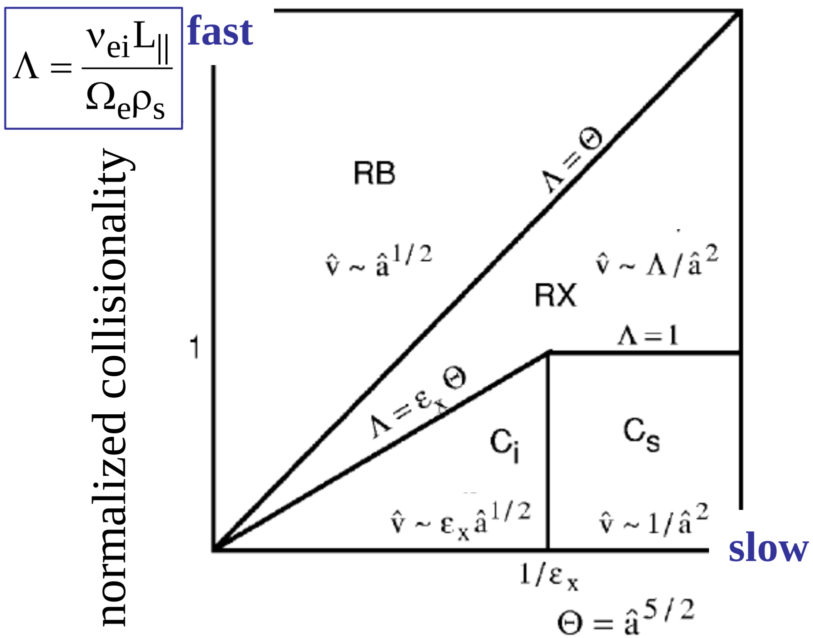
$$\hat{v} = \begin{cases} \hat{\delta}^{1/2}, & \hat{\delta} << 1 \quad \text{inertial} \\ 1/\hat{\delta}^2, & \hat{\delta}^2 >> 1 \quad \text{sheath connected} \end{cases}$$

X-points and magnetic shear can disconnect filaments

- Midplane circular flux tubes map to thin fans

  Krasheninnikov, Ryutov &Yu, *J. Plasma Fusion Res.* 2004





normalized blob size

- Midplane-sheath disconnection
  - parallel resistivity impedes $J_{||}$ ($v_b \uparrow$)
  - fans enhance $J_\perp$ ion polarization ($v_b \downarrow$)
- Ion FLR gyro-averaging of wave or blob **E** [Ryutov & Cohen CPP 2004]

Myra, Russell, & D'Ippolito PoP 2006

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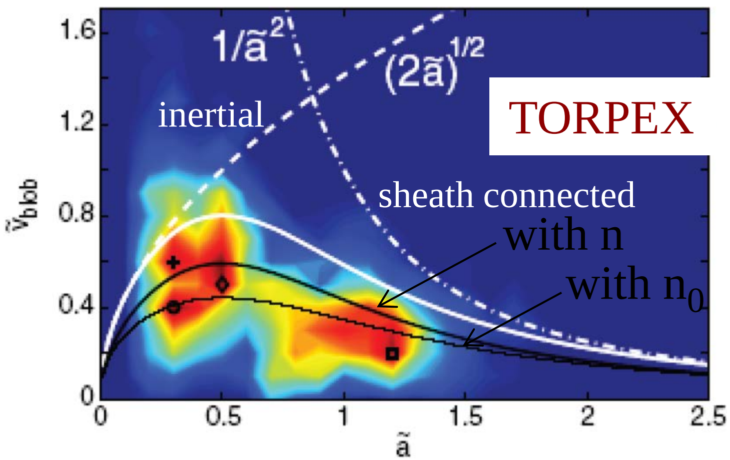
- Density shoulders
- Statistical properties
- SOL width
- Other topics
- Ideas for future directions

Experimental comparisons

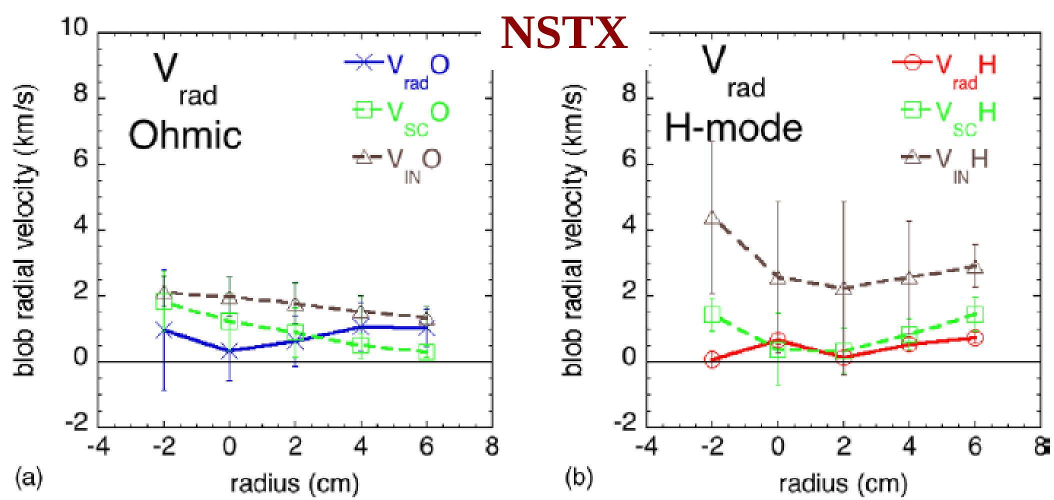


Theiler PRL 2009

- Scaling of v_b confirmed in basic laboratory experiments
- Validation in tokamaks more challenging

Not understood in database:

- V_{rad} distribution, amp. scaling. …
- blob creation rate & size
- V_{pol} dependence amp.



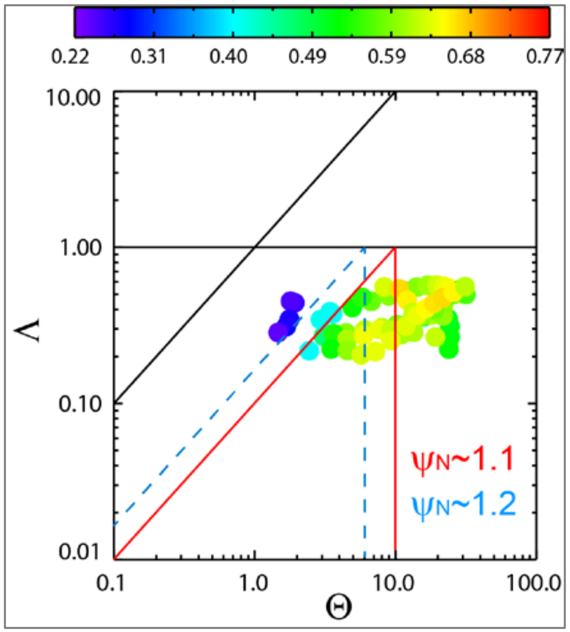
Zweben PPCF 2016

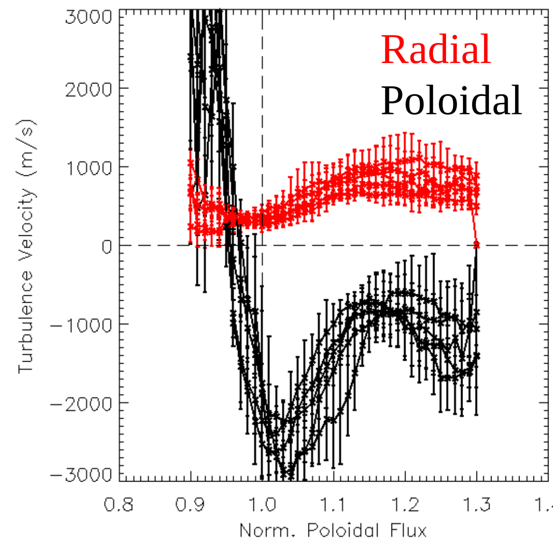
… Experimental comparisons - NSTX

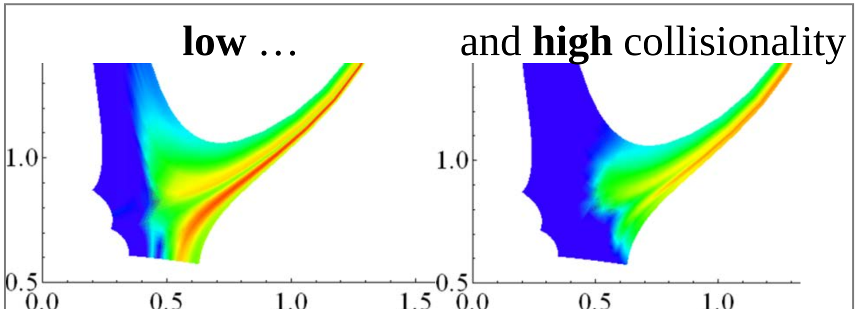
- Disconnection and smaller $V_{b,rad}$ predicted and observed near separatrix

GPI-Div cross correlation

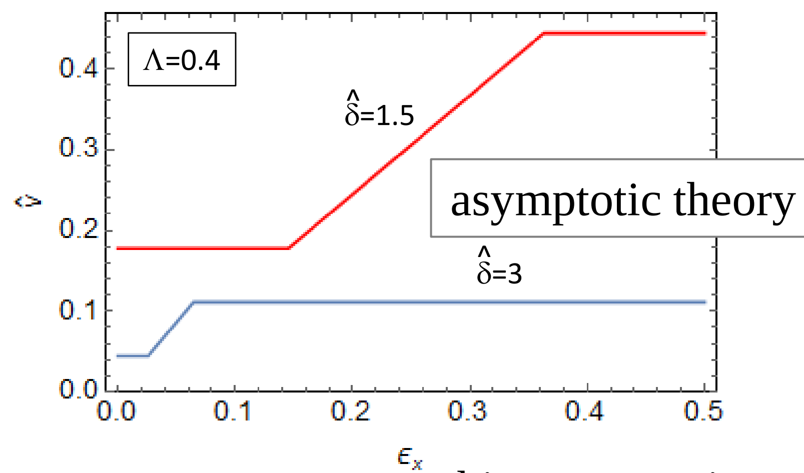
Scotti 2018







Baver 2018 -ArbiTER simulations

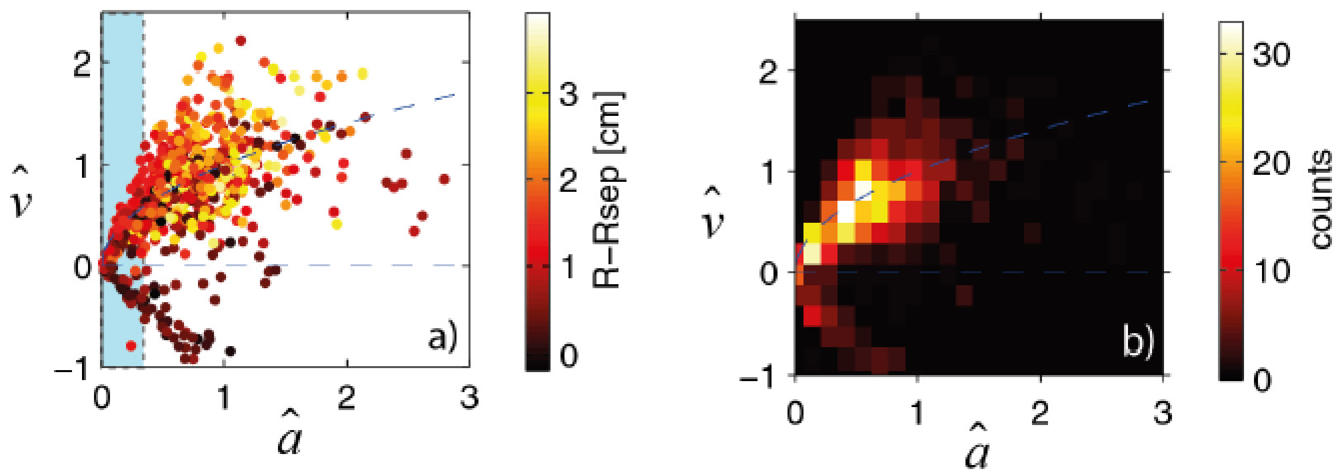


← approaching separatrix

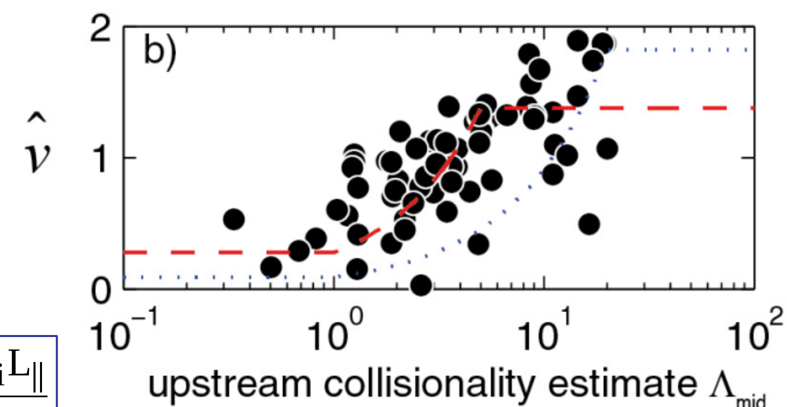
… Experimental comparisons - TCV

C.K. Tsui, et al., PoP 2018

- TCV RB (inertial) conditions, LSN discharge



- comparisons with v scalings for $\hat{a}$ (= $\hat{\delta}$) 1.6 (red) and 3.3 (blue)



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

For better validation and predictive capability:

- Simultaneous measurements of
  - 2D blob size and velocity (e.g. GPI)
  - internal blob plasma parameters n_e, T_e, (T_i) (e.g. probes)
  - parallel structure and X-point or divertor connection
- Theoretical understanding (and numerical simulation) of
  - blob creation rate and location
  - background turbulence saturation level
  - blob size distribution
  - blob velocity distribution (blobs not isolated - interact)

Many other interesting papers on blob dynamics: theoretical and experimental

- Thrysøe Blobs and **neutrals** PPCF 2016
- Hacker Blob **generation rate** PoP 2018
- Zhang & Krasheninnikov Blobs in framework of **nonlinear drift waves** PoP 2016
- Walkden **Isolated filament motion** for MAST NF 2015
- Stepanenkov Blobs in sheath-connected **arbitrary topology** PoP 2017
- Angus Blobs in **3D** PoP 2014
- Zweben NSTX **2D correlations** PoP 2017
- Kube Blob amplitude and size scalings PoP 2016
- Allan **Ion temperature** of blobs in MAST PPCF 2016
- Birkenmeier Filament transport **warm ions** in AUG NF 2015
- Held **Finite Ti** blobs NF 2016
- Carralero Blobs and **SOL heat transport** NF 2018
- Avino X-pt effects on blobs PRL 2016
- Russell C-Mod **blobs and flows** PoP 2016
- Carralero High density transition of blob filaments in ASDEX NF 2014
- Fuchert ASDEX **L- and H-mode** GPI blobs PPCF 2014
- Kocan Intermittent SOL transport in ASDEX NF 2013
- Wiesenberger Unified **blob-hole transport scaling** laws PoP 2017
- Simon Edge **turbulent transport scaling** PPCF 2014

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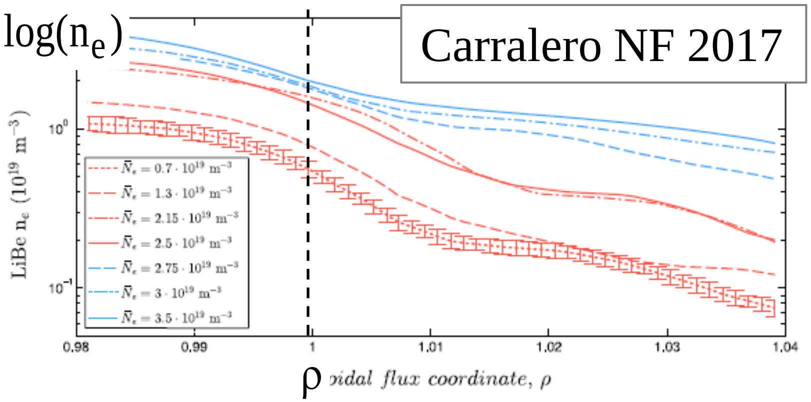
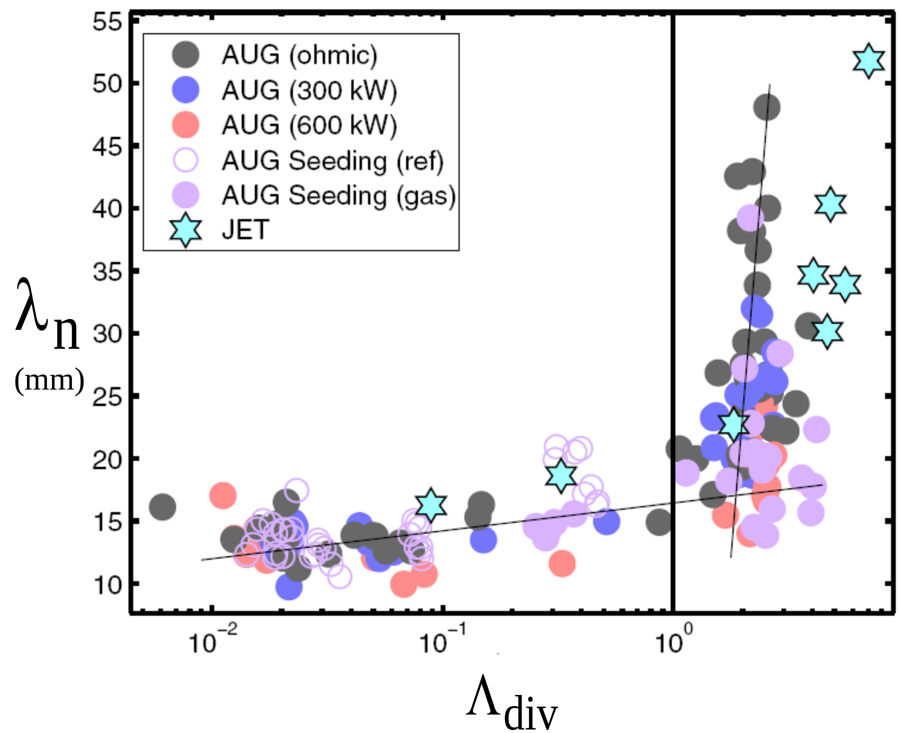
Density shoulders in the SOL

- Density shoulder: increase of λ_n in the far SOL at high n_e
  - observed in many tokamaks; consistent with convective (not diffusive) transport
- Impacts plasma (blob-filament) interaction with main chamber walls



Carralero PRL 2015: L-mode



- Interpreted on ASDEX-U as blob detachment due to divertor collisionality
  - v_b scaling changes SL $\rightarrow$ inertial
  - increased blob speed and particle flux
  - size δ_b also observed to increase

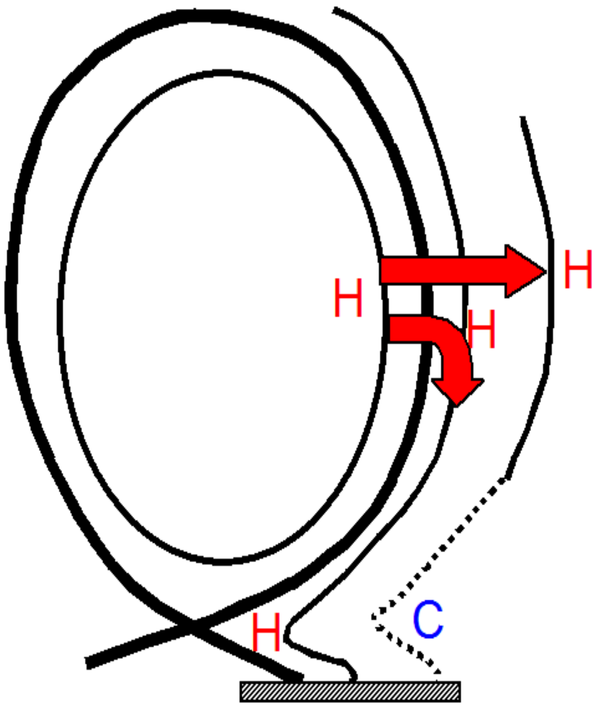
… Density shoulders in the SOL

- Alternative shoulder formation mechanisms:
  - ionization in main SOL [Lipschultz PPCF 2005 – C-Mod]
  - divertor neutral processes, e.g. recycling [Wynn NF 2018]
- Broaden $\lambda_n \sim L_{\|}\, \Gamma_{\perp} / \Gamma_{\|} \Rightarrow$ increase $\Gamma_{\perp}$ or reduce $\Gamma_{\|}$
  - CX friction may clog the flow [Militello PPCF 2016]
- Recent JET [Wynn NF 2018] , TCV [Vianello NF 2017] and ASDEX-U [Carralero JNM 2017] experiments suggest that changes in Λ_{div} are not sufficient to give a shoulder. Also
  - H- and L- mode shoulders may be different
  - Divertor target configuration, fueling/seeding important
- Whether or not larger Λ_{div} causes shoulders, it is still expected to affect blob-filament propagation and main chamber PMI interaction.

Positive feedback loop: upstream-to-divertor power flow

"Thermal transport catastrophe and the tokamak edge density limit," D. A. D'Ippolito and J. R. Myra, Phys. Plasmas **13**, 062503 (2006).

- Blob velocity and transport rate increases with divertor collisionality
- 2 self-sustaining states:
  - connected, slow moving blobs with warm X-pt
  - disconnected, fast moving blobs with cold X-pt
- May be related to ASDEX-U observation of SOL width broadening at detachment [Sun PPCF 2017]



- C-Mod N_2 seeding [LaBombard PSI 2018]: no relationship between divertor conditions and upstream profiles
  - But all blob-filaments were electrically disconnected in these datasets by X-point shear

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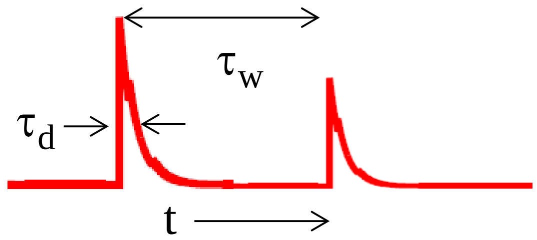
Blob statistical properties

- Surface and atomic physics interactions are nonlinear – should not use mean profiles
- Use statistical description for main chamber PMI and divertor studies
- Garcia PRL **108** 265001 (2012); PoP **23** 052308 (2016) and others
- Single point probe measurements of blob arrivals in far SOL described by
  - Poisson process (exponential distribution of waiting times between uncorrelated pulses)
  - prescribed "pulse" shape (the blob)
  - exponential distribution of amplitudes
- PDFs characterized by intermittency parameter

$$\gamma = \frac{\tau_d}{\tau_w} = \frac{\text{duration time} = \delta_b / v_b}{\text{avg. waiting time}}$$



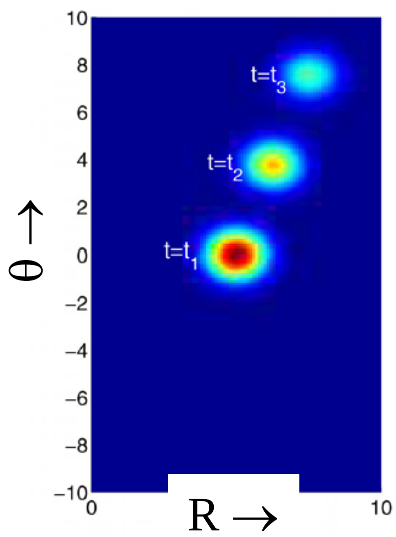
- "Pulse" shape, mean amplitude, $\gamma \Rightarrow$ rms/mean, normalized time correlation function, fluctuation spectrum $S(\omega)$, skewness, kurtosis …
- Quite successful in comparisons with C-Mod and TCV data [Garcia et al.]

Application: Ensemble-averaged profiles

[D'Ippolito PoP 2002, Militello PoP 2008]

- If blobs:
  - non-interacting (e.g. $\gamma << 1$, far SOL)
  - velocity distribution known
  - blob shape and size distribution known
  - amplitude distribution and decay rate known (e.g. parallel losses)
  - waiting time (blob frequency) known

then $\Rightarrow$ radial profile of n_e, Γ, … in SOL



Militello 2008

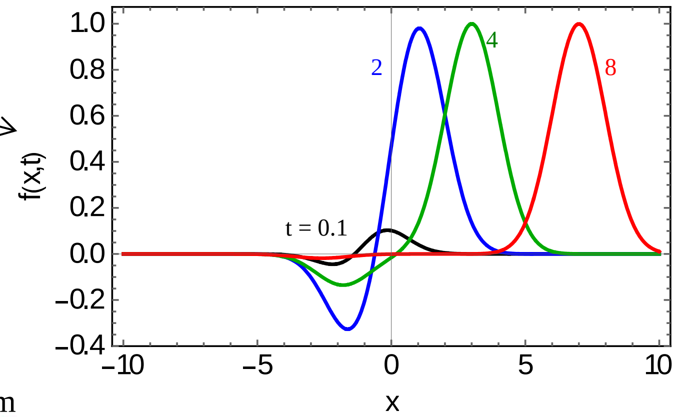
$$n(x) = \frac{2\pi n_{b0}}{\tau_w} \frac{2R}{L_{||}} \frac{\int dr_b r_b^4 f(r_b) e^{-\mu x r_b^2}}{\int dr_b r_b f(r_b)}$$

e.g. for $u_x \sim 1/r_b^2$, Gaussian shape, constant amp, decay rate $\sim \mu$, size dist. $f(r_b)$

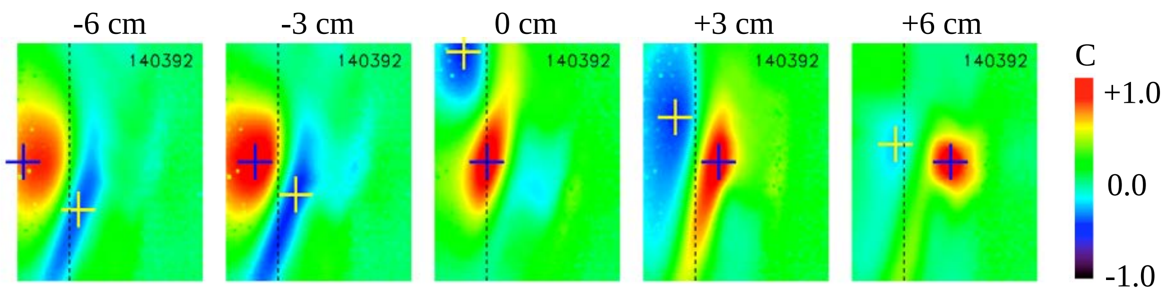
D'Ippolito Myra, and Krasheninnikov 2002

Application: Blob-hole dynamics

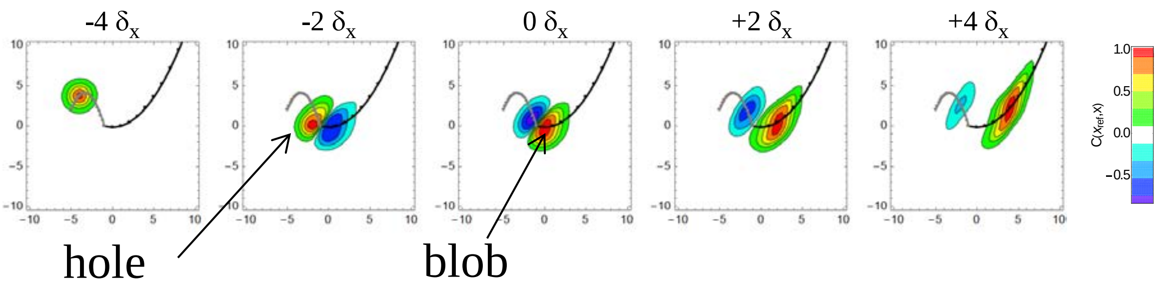
- Blob-hole creation model



- Two-point spatial correlation functions
- Vary the reference location (+)



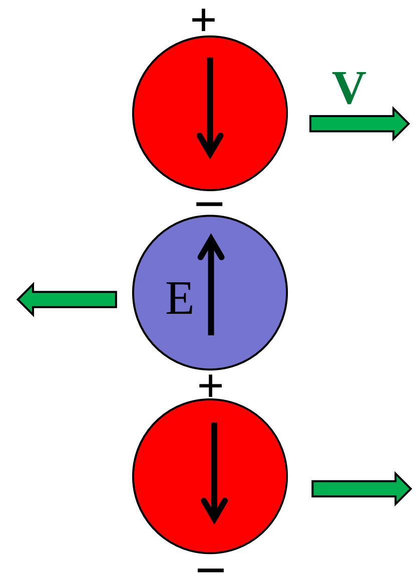
GPI correlations
Zweben PoP 2017



Statistical model
Myra PPCF 2018

- However, GPI did not show inward "hole" motion in time-lag correlations

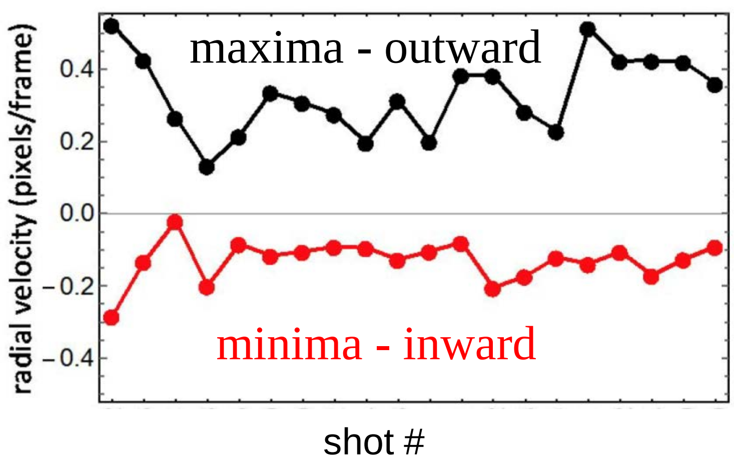
Motion of holes



- Inward motion expected theoretically
  - inward impurity transport
  - turbulence spreading into pedestal
- Probes [e.g. Boedo PoP 2014]
  - Skewness S < 0 (~ inside separatrix) for holes
  - S > 0 (~ outside) for blobs
  - Inward/outward V_{rad} for holes/blobs

- Recent GPI analysis (Zweben)
  - Negative S not seen
  - Inward motion of minima *on average*
  - Some *individual* minima/maxima have positive/negative V_{rad}

Average Vrad per discharge



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Near SOL, SOL width, turbulence

- Midplane SOL width λ_q from

$$\frac{q_\perp}{\lambda_q} = \frac{q_{||}}{L_{||}}$$

  $L_{||}$ = parallel scale length, or if SL entire field line
- Parallel flux is "classical" (e.g. collisional, sheath …)

$$q_{||} \equiv g\, p c_s$$

- Focus on turbulent heat (or particle, $p \rightarrow n$) flux at the separatrix
  - QL theory

$$q_\perp = \langle \tilde{p}\, \tilde{v}_x \rangle$$

- If pressure advection dominates

$$\tilde{p} = \frac{i\tilde{v}_x}{\omega} \nabla p$$

- and e.g. for interchange-type modes $\omega = i\gamma_{mhd}$ giving a (near SOL) *diffusive* flux

$$q_\perp = -\frac{1}{\gamma_{mhd}} \left\langle \tilde{v}_x^2 \right\rangle \nabla p$$

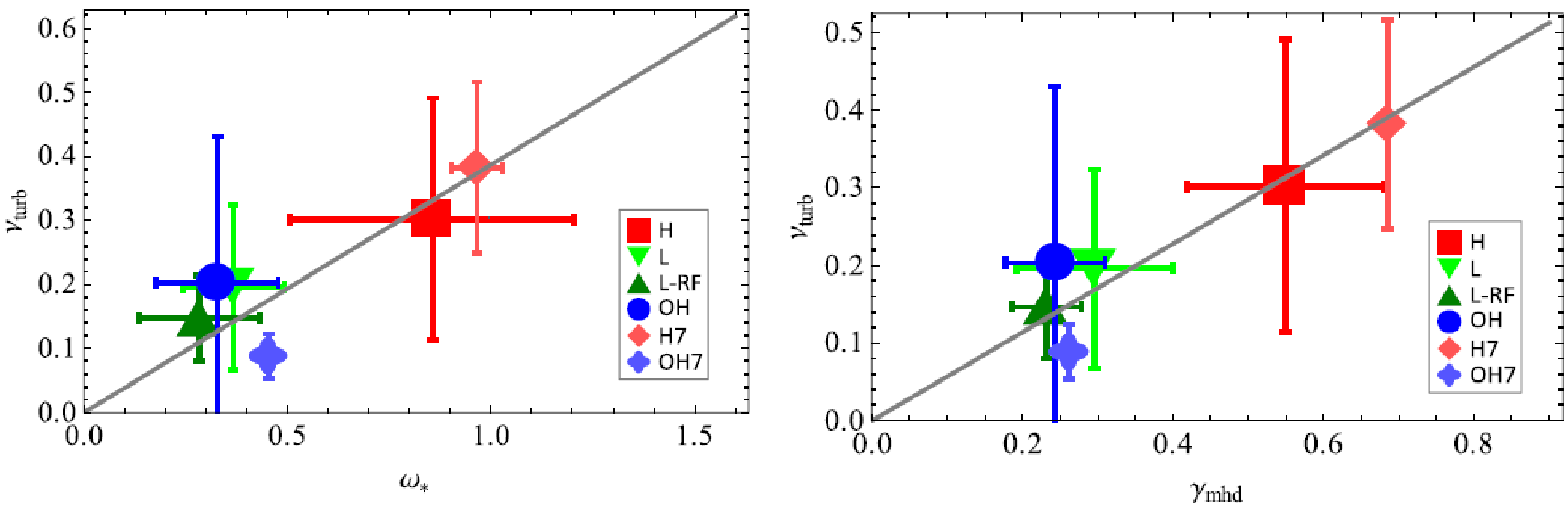
$\Rightarrow$ scaling for λ_q

Drift-interchange turbulence on NSTX

- Instead of assuming interchange turbulence, *define* ν_{turb}

$$\tilde{p} = \frac{i\tilde{v}_x}{\nu_{turb}}\nabla p \qquad\qquad \frac{\tilde{p}}{p} \to \frac{\tilde{I}_{GPI}}{I_{GPI}} = \frac{V_{rad}}{\nu_{turb}\lambda_p}$$

and *test* relationship to drift and interchange frequencies

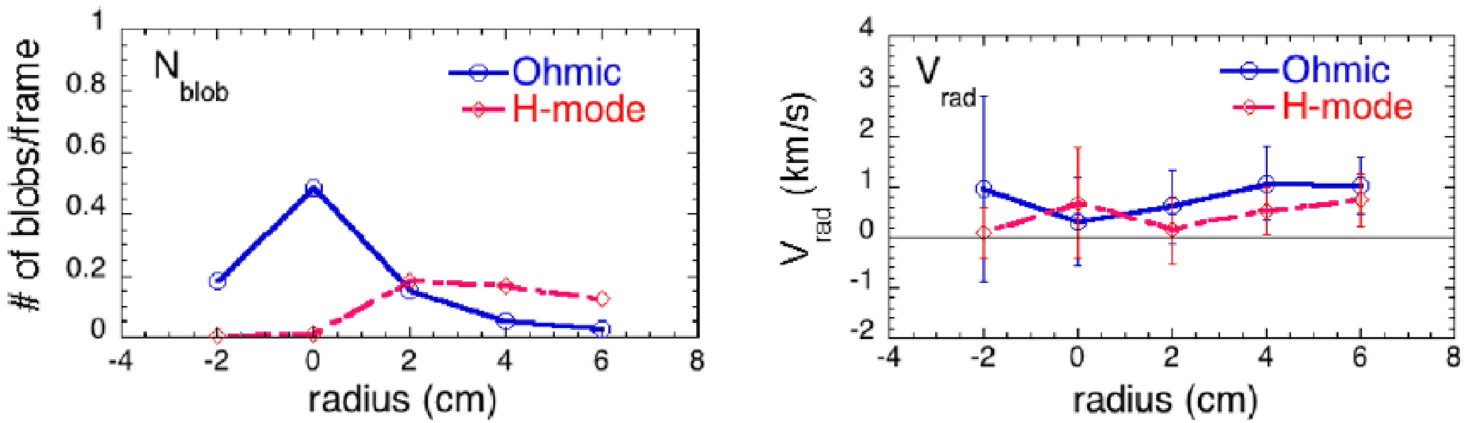


Myra, Russell, and Zweben, PoP 2016

- Assuming drift-interchange + additional caveats $\Rightarrow$ scaling for $\lambda_{q,\text{ turbulence}}$
  - small but not negligible for NSTX
  - could dominate Eich and Goldston HD at large I_p and large R

Relation of QL turbulent flux to blob flux

- Turbulence Gaussian towards core → intermittent in the far SOL
  - Skewness S increases into the SOL (many experiments)
  - Intermittency parameter $\gamma_{int} = \tau_d/\tau_w$ decreases into the SOL
  - $S = 2/\gamma_{int}^{1/2}$ for Poisson statistics, exponential pulse amplitudes and exponential pulse shape [Garcia, 2016]
- Consistent with notion that
  - Large amplitude fluctuations form outward propagating blobs
  - Blobs accelerate and hence separate into the SOL



[Zweben PPCF 2016]

- Number of blobs/frame decreases into the SOL; in the same region the velocity increases

Status

- Need to understand physics and scaling of
  - p_b the peak pressure in the blob, radial birth location
  - f_p the packing fraction, or equivalently (assuming δ_b/v_b is known) the blob frequency f_b or waiting time
  - blob size distribution
    - know the most stable blob size for SOL propagation
  - blob generation rate:

- Work on blob generation rate by [Fuchert PPCF 2016]
- Drift wave dynamics and blob formation [Krasheninnikov PLA 2016]; [Zhang PoP 2016]
  - relates blob amplitudes, sizes, separations and poloidal speeds

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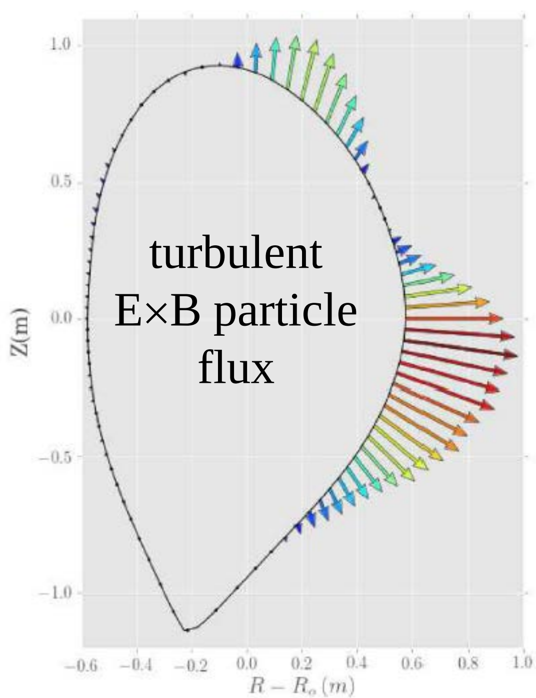
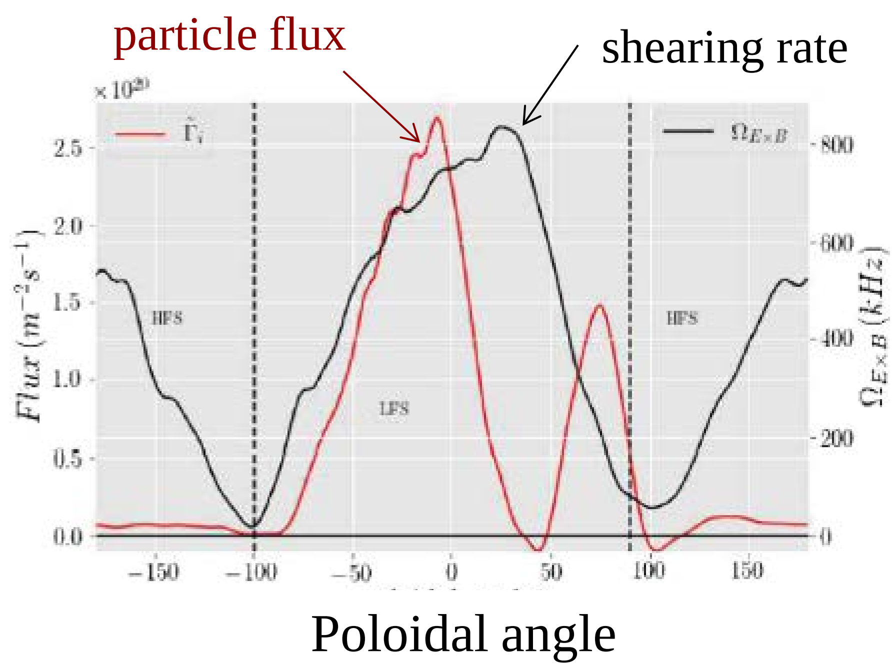
Neoclassical drift effects and turbulence

XGC1 simulation analysis (DIII-D) [Keramidas Charidakos PoP 2018]

- Ions cross the separatrix due to banana motion; and can be subsequently lost to the divertor
- Electrons cross the separatrix due to turbulence; maintain ambipolarity
  - controls density SOL width
- Ion orbit losses set up electrostatic potential $\Phi(\theta)$ near separatrix
  - complex interaction between $\Phi(\theta)$, E_r shearing and turbulence

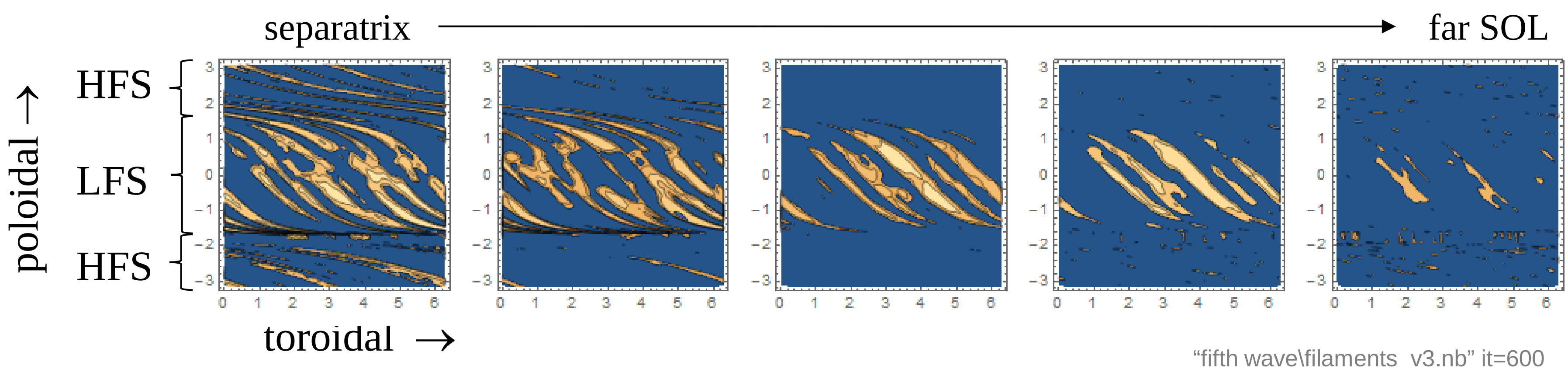




… XGC1 analysis: filamentary structures in SOL

Myra, Russell … TTF 2018

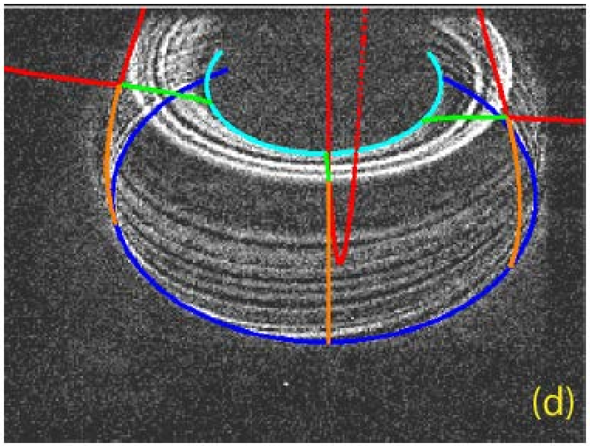
- 5 flux surfaces starting near the separatrix and moving out: Contours → {0.005, 0.01, 0.022, 0.05, 0.10} to show blobs (not holes)



"fifth wave\filaments_v3.nb" it=600

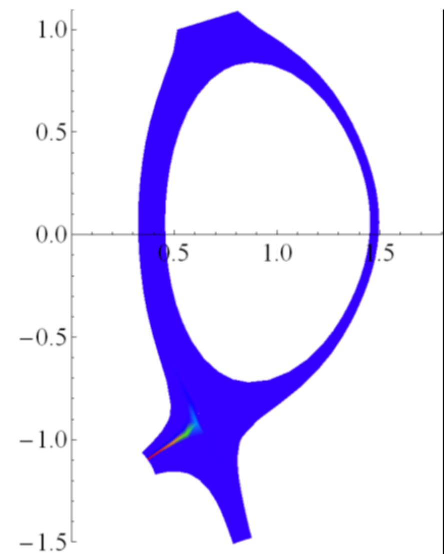
- High field side (HFS) is populated only near the separatrix
  - Blob-filaments propagate out only on low field side (LFS)
  - Consistent with turbulent flux at separatrix
- Turbulent near separatrix; fades in SOL
- "Neoclassical" drifts dominate ion motion
  - Local quasi-neutrality ⇒ ion entrainment in electron filaments
  - Not axisymmetric

Divertor localized modes



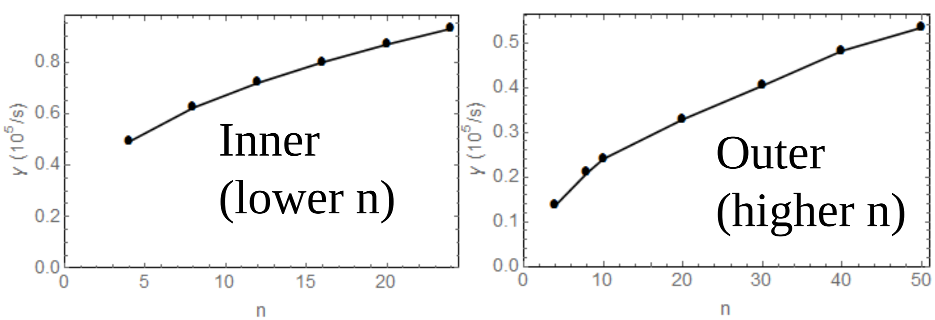
Scotti NF 2018

- Observed experimentally on NSTX-U, MAST, C-Mod
- Understanding of anomalous divertor transport needed: are these modes important?
- Modeling in progress



$$k_\theta = \frac{nB_\zeta}{RB_\theta}$$

γ



Toroidal mode # n

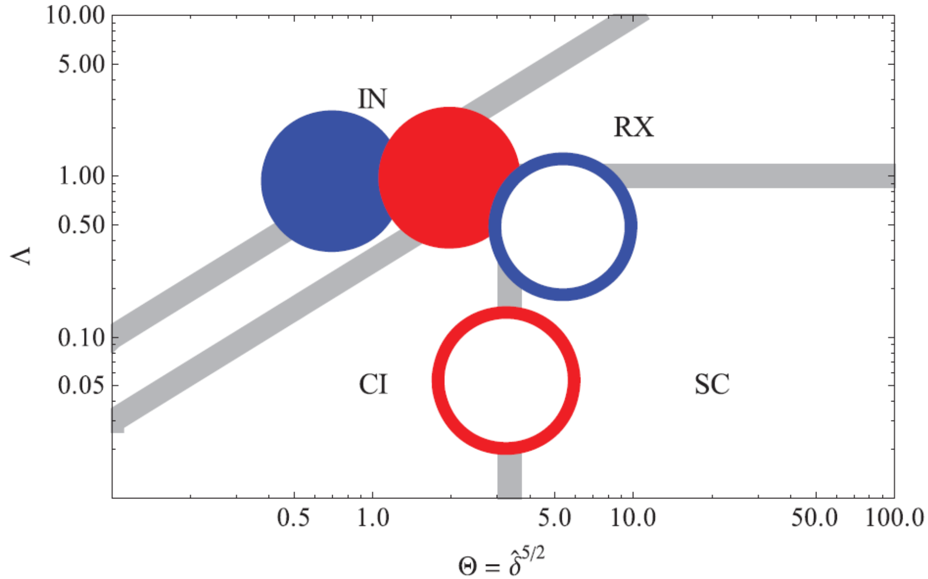
Bayer 2018

Ideas for future work (experiment and theory)

- Basic blob physics
  - blob creation rate and location; packing fraction
  - turbulence saturation level; blob amplitude
  - blob size and velocity distributions
- Hole dynamics and impurity transport
- Drift orbits, turbulence and SOL width:
  - Coexistence and transitions
  - Scaling of near and far SOL turbulent/blob flux with I_p , R, …
- Density shoulder formation and relation to disconnection, divertor regime
- Divertor transport: effect of fluctuations, divertor modes …
- Neutral and atomic physics
  - divertor; instabilities and interaction with filaments
  - fueling and edge profiles, sources for simulation

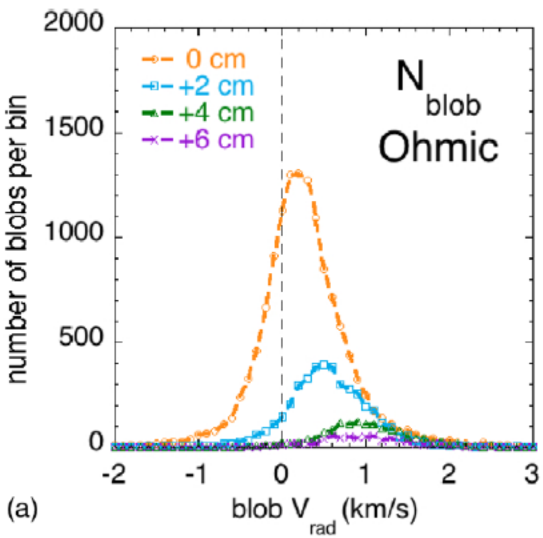
Extras

Regimes for Zweben PPCF 2016 blob database

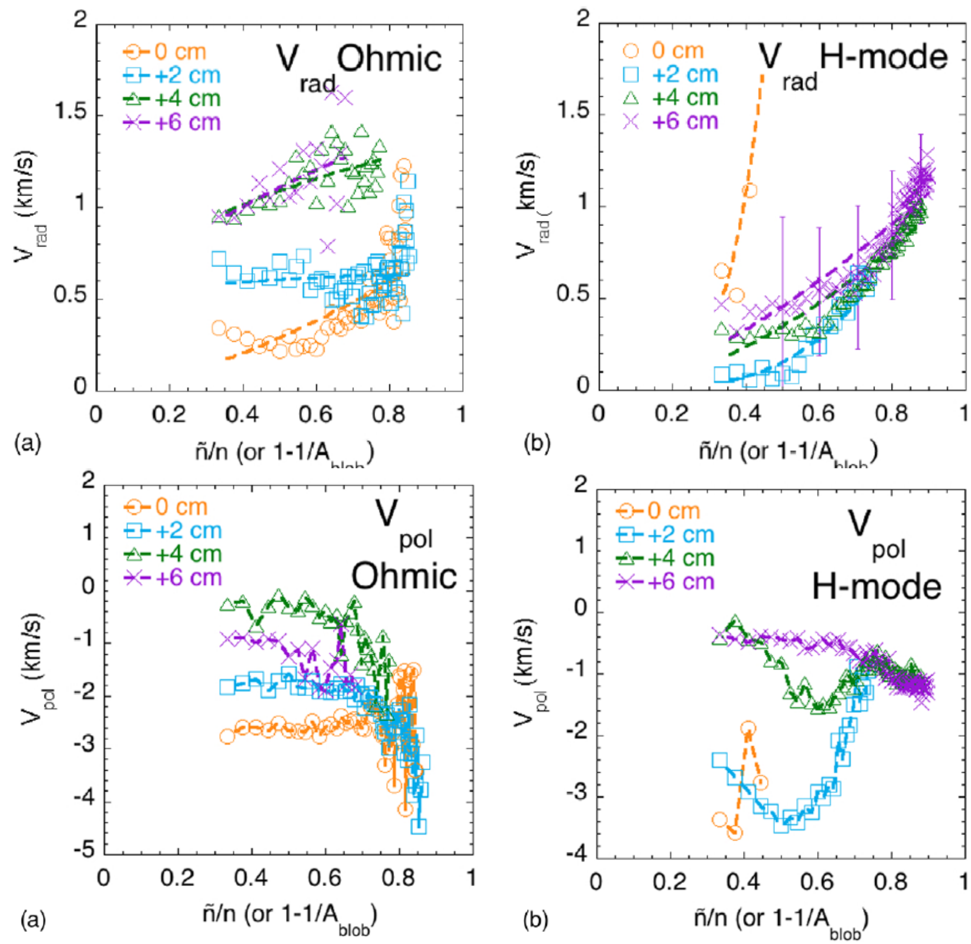


- L-mode SC near sep and disconnected in far SOL
- H-mode SC near sep and marginally disconnected in far SOL

Zweben PPCF 2016: theoretical challenges



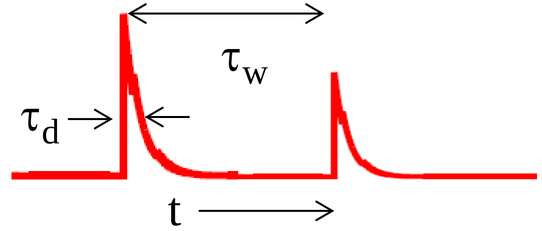
- Velocity distribution (with negative Vrad)



Vrad and Vpol scaling with amplitude and distance from separatrix

… QL turbulent flux to blob flux

- For isolated blobs



$$q_\perp = p_b v_b f_p$$

with peak pressure p_b, velocity v_b, packing fraction $f_p \sim \gamma$

- QL flux is $$q_\perp = \langle \tilde{p}\,\tilde{v}_x \rangle$$

- For blobs identify $\tilde{p} \sim p_b$, $\tilde{v}_x \sim v_b$ and at the birth region $f_p \sim 1$
- Packing fraction (or intermittency parameter) is key

$$\gamma = \frac{\tau_d}{\tau_w} = \frac{\text{duration time} = \delta_b / v_b}{\text{avg. waiting time}}$$

proportional to blob generation frequency $1/\tau_w$