Transport in the Coupled Pedestal and Scrape-off layer region of H-mode plasmas

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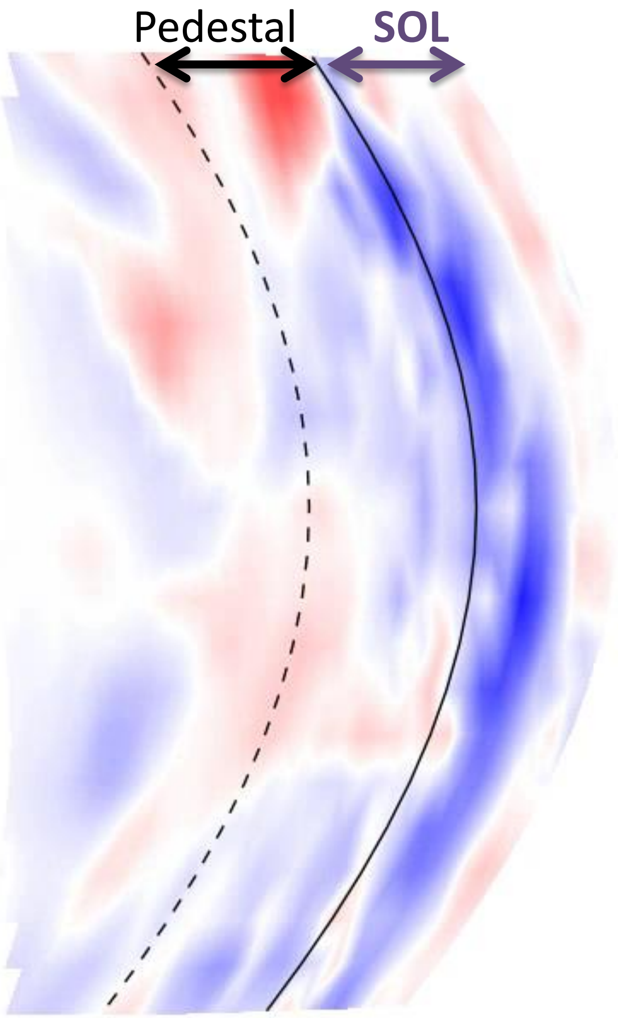
S. Janhunen

H-mode edge pedestal and scrape-off layer are a coupled system

Coupling through, e.g.:

- X-point ion orbit loss
- nonlocal turbulence dynamics

Goal of XGC gyrokinetic codes is to include the physics necessary to model this coupled edge system (pedestal + SOL)



XGC Family of Codes

XGC (X-point Gyrokinetic Code) codes are a family of gyro-kinetic, total-*f* (= 5D full-*f*), highly parallelized particle-in-cell (PIC) codes

- Realistic diverted geometry (X-point, separatrix)
- Logical sheath as wall boundary condition
- Self-consistent electric potential calculations

	Turbulence?	Field Solver	Impurities?	Neutrals?	Collision operator	CPU Hours
XGC1	✔	$\Phi(\psi,\theta,\zeta)$	✔ in XGC1-KAIST ✔ Under optimization in XGC1-PPPL	Built-in Monte Carlo neutrals	Fully non-linear	$\sim 10^6$
XGCa	✖	$\Phi(\psi,\theta)$	Under development	built-in Monte Carlo neutrals	Fully non-linear	$\sim 10^4$
XGC0	✖	$\Phi(\psi)$	✔	DEGAS2	Linear	$\sim 10^4$

OUTLINE

- Neoclassical pressure balance in scrape-off layer (XGCa)
- Nonlocal intermittent edge turbulence (XGC1)
- Data management (follow on CPPG seminar)

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Motivation – Neoclassical SOL pressure balance study

- Three competing requirements in the scrape-off layer (SOL) for a fusion reactor:
  - Sustain adequately high upstream pressure to maximize fusion reactions in the core
  - Keep upstream density much lower than Greenwald density
  - Constrain downstream temperature to avoid destroying the divertor

- Workhorse codes/models for SOL pressure predictions dominantly assume strong collisionality ($\lambda_{ii}/L_{//} \ll 1$) with simplified transport or fluid models

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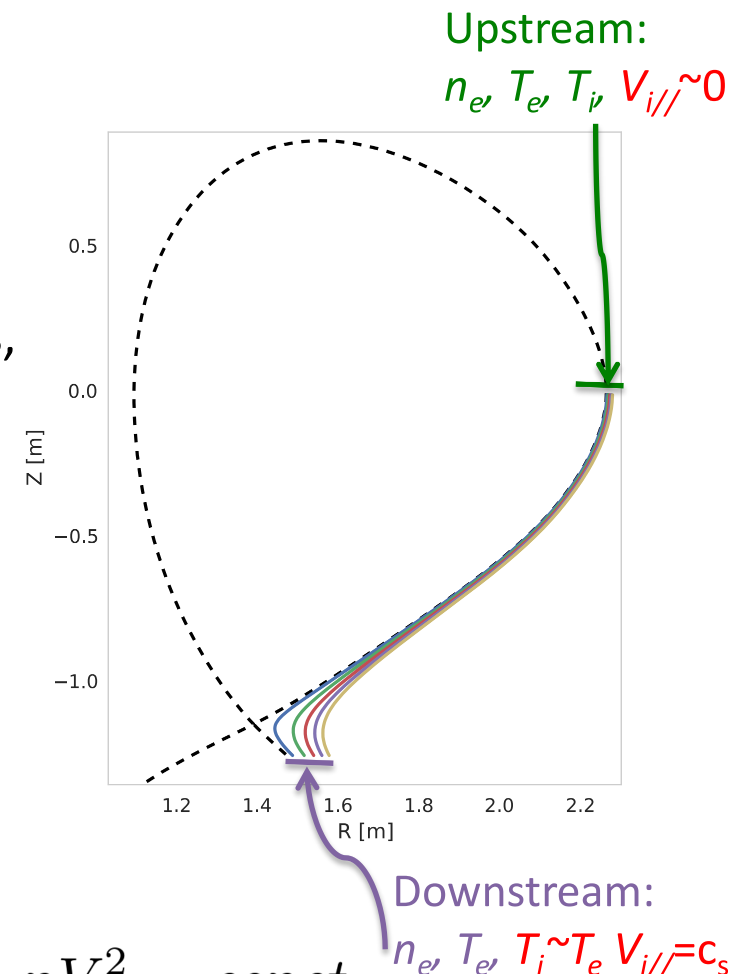
Two-point model (2pm) often used to relate up and downstream quantities

- 2pm based on basic fluid continuity, momentum conservation [Stangeby 2000]

- 2pm formatting useful for characterizing fluid simulation results, including momentum loss terms for i.e. neutrals [Kotov PPCF 2009]

- Experimental evidence for usefulness on DIII-D in ELMing H-mode, but unrealistic assumption needed ($V_{i//,mid}$~0, cross-field drift negligible) and $V_{i//,div}$~c_s, $T_{i,div}$~$T_{e,div}$, [Petrie JNM 1992]



$$p_e + p_i + m_i n V_{i\|}^2 = const$$

1d constancy of total pressure along field line (x-direction) derivation

$$\frac{d}{dx}(nV_{i,\|}) = S_p$$

Continuity

$$m_i n V_{i,\|} \frac{d}{dx}(V_{i,\|}) = -\frac{d}{dx}(p_e + p_i) + m_i V_{i,\|} S_p$$

Total (e+i) momentum

$$m_i n V_{i,\|} \frac{d}{dx}(V_{i,\|}) + m_i V_{i,\|} \frac{d}{dx}(nV_{i,\|}) = -\frac{d}{dx}(p_e + p_i)$$

Substitute Continuity into momentum (Sp)

$$\begin{aligned} abb' + b(ab)' &= abb' + abb' + b^2 a' \\ &= a(b^2)' + b^2 a' \\ &= (ab^2)' \end{aligned}$$

Rearrange velocity terms

$$\frac{d}{dx}(m_i n V_{i,\|}^2) = -\frac{d}{dx}(p_e + p_i) \Rightarrow \boxed{p_e + p_i + m_i n V_{i\|}^2 = const}$$

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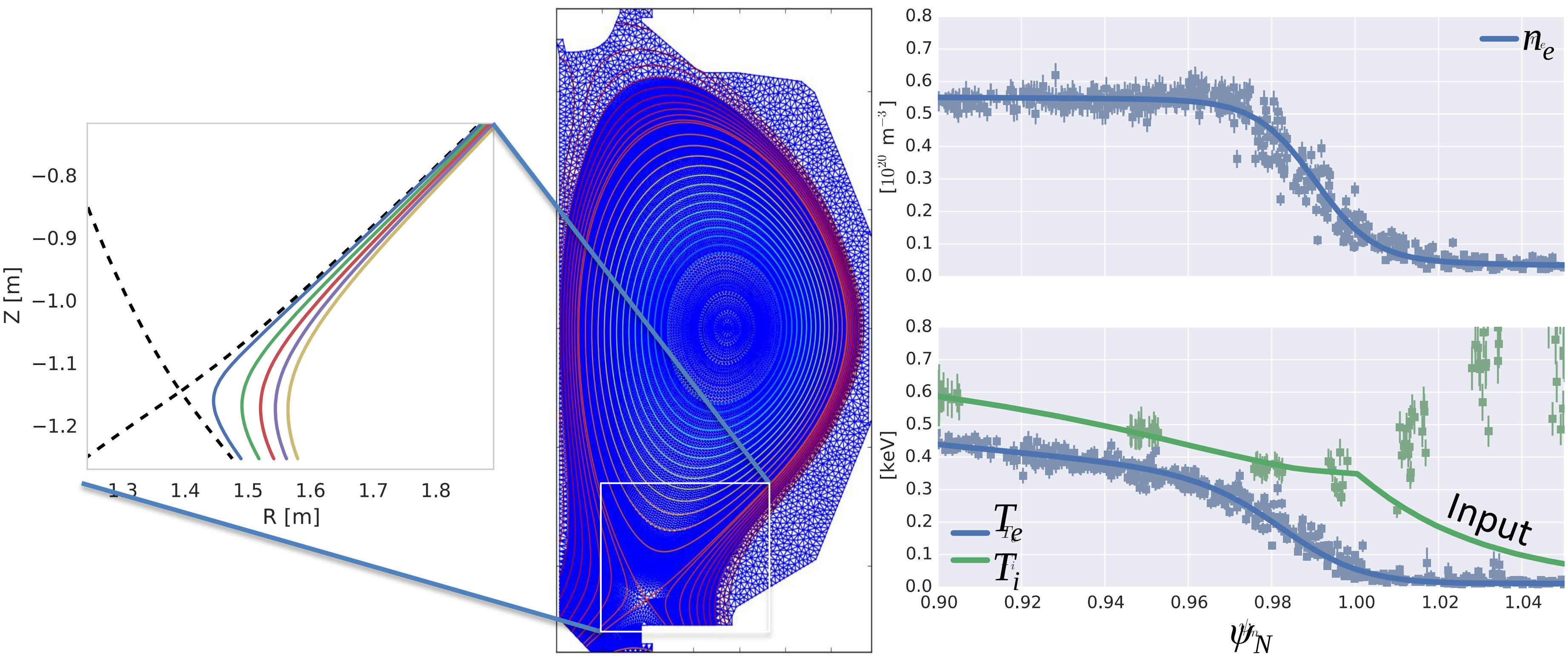
XGCa simulation parameters of low-collisionality DIII-D ELMing H-mode (153820)

[Churchill JNME 2016]

Param:	B_0	I_p	q_{95}	Z_{eff}	P_{inj}	P_{rad}
Value:	2 T	1 MA	4.4	1.6	2.4 MW	1.3 MW



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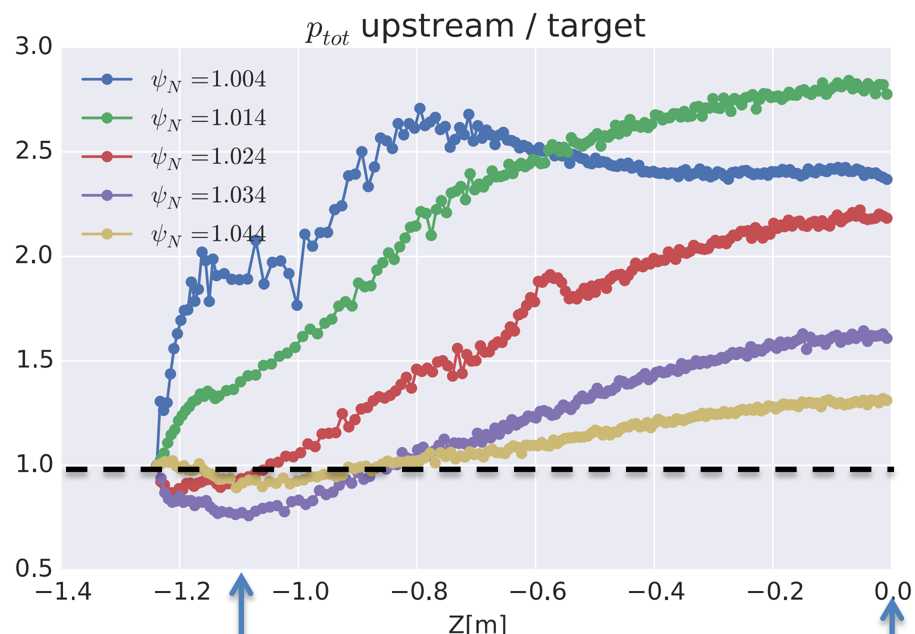
XGCa total pressure upstream is >twice that expected by $p_e + p_i + m_i n V_{i||}^2 = const$

- Tested total pressure constancy (simple + dynamic) along field line by normalizing total pressure between low-field side (LFS) divertor and midplane by divertor total pressure

$$p_{tot} = p_e + p_i + m_i n V_{i||}^2$$

- Disagreement is:
  - worse in the near-SOL (~2.5x)
  - smaller in the far-SOL (~1.3x)



X-point

LFS midplane

The question is why?

What is missing in the simplified momentum equation?

Expanded parallel momentum conservation to include viscosity, neutrals

Total (e+i) conservation of parallel momentum

$$\mathbf{b} \cdot [m_i n_i \mathbf{V}_i \cdot \nabla \mathbf{V}_i \quad + \nabla(p_e + p_i) + \nabla \cdot \pi_i] + m_i V_{i,\|} n_n \left(\nu_{ion} + \nu_{cx}\right) \quad = 0$$

Integrating from divertor ($\ell_{//}$=0) to any point *x* upstream ($\ell_{//}$=x)

Usual

New terms

$$\frac{p_{tot}|_{\ell_\| = x}}{p_{tot}|_{\ell_\| = 0}} + F_{visc} + F_{neu} = 1$$

for near-SOL, need to be size ~-1

CGL form for viscosity!!

$$p_{tot} = p_e + p_i + \frac{1}{2} m_i n V_{i,\|}^2$$

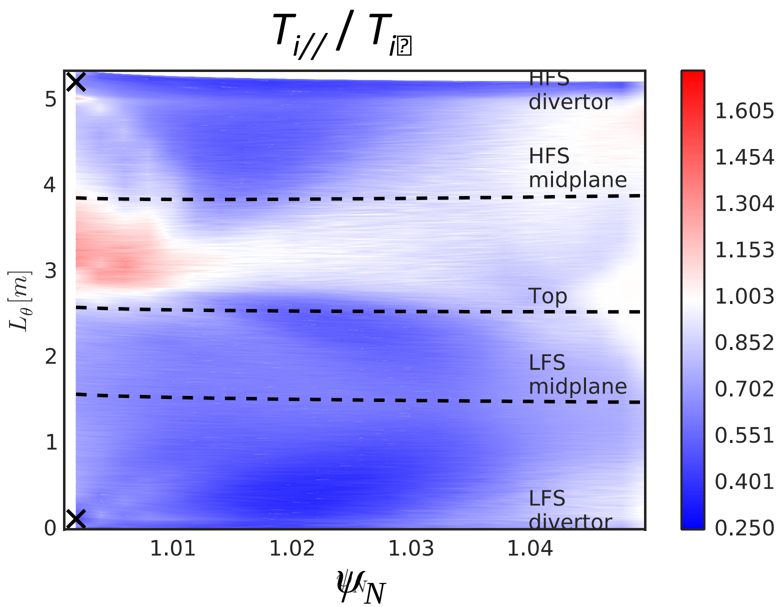
$$F_{visc} = \frac{\overbrace{\frac{2}{3}(p_{i\|} - p_{i\perp})|_{\ell_\|=0}^{\ell_\|=x} - \int_0^x d\ell_\| \left[(p_{i\|} - p_{i\perp})\mathbf{b} \cdot \nabla \ln B\right]}^{\text{CGL form for viscosity!!}}}{p_{tot}|_{\ell_\|=0}}$$

$$F_{neu} = \frac{\int_0^x d\ell_\| m_i V_{i\|} n_n (\nu_{ion} + \nu_{cx})}{p_{tot}|_{\ell_\|=0}}$$

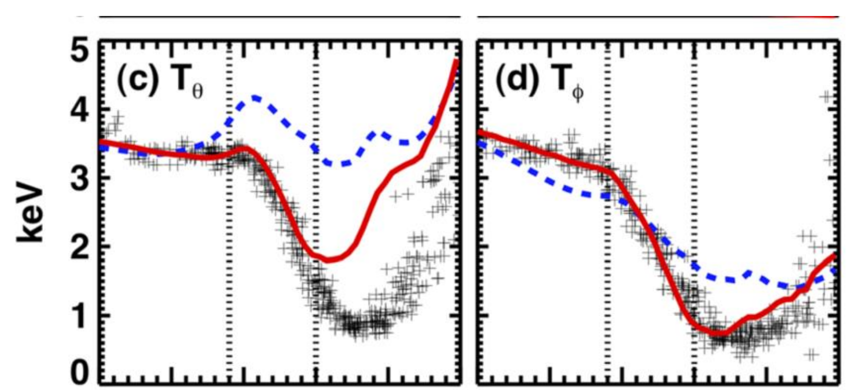
[Churchill NF 2016]

Ion average kinetic energy (temperature) anisotropy large in SOL from XGCa simulation

- Requires a bi-Maxwellian approximation to correctly capture pressure variation



Similar anisotropy from XGC0 and experiment [Battaglia PoP 2014]



Black: C^{6+} T_z (experiment)
Red: C^{6+} T_z (XGC0)
Blue: D T_i (XGC0)

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CGL approximation

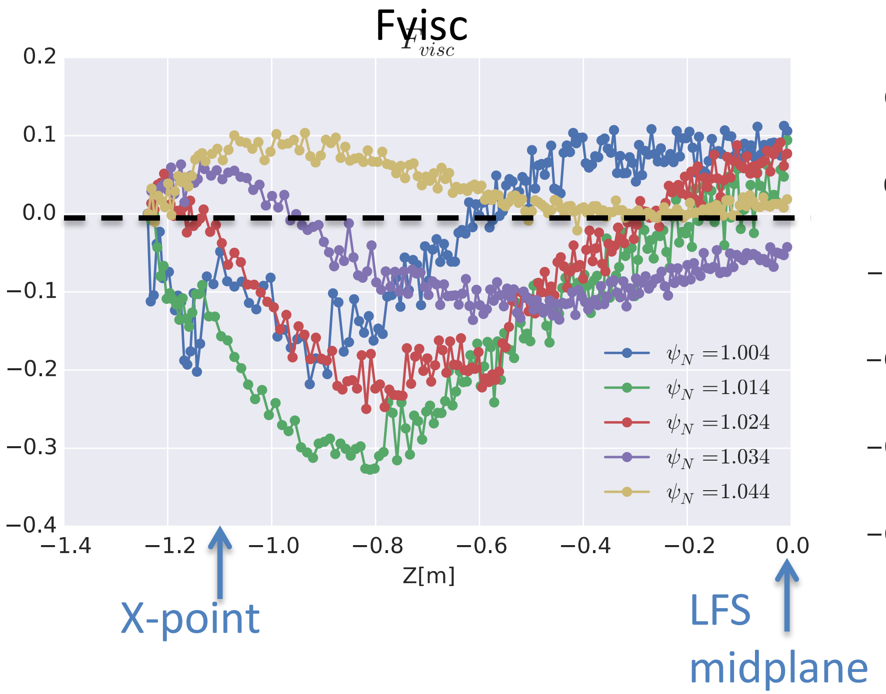
- Assuming no collisions ($\tau_{ii} \rightarrow \infty$) removes "randomizing" of particle velocities; The double adabatic constant assumption in strong-B field leads to diagonal pressure tensor [Chew, Goldberger, Low 1956]:

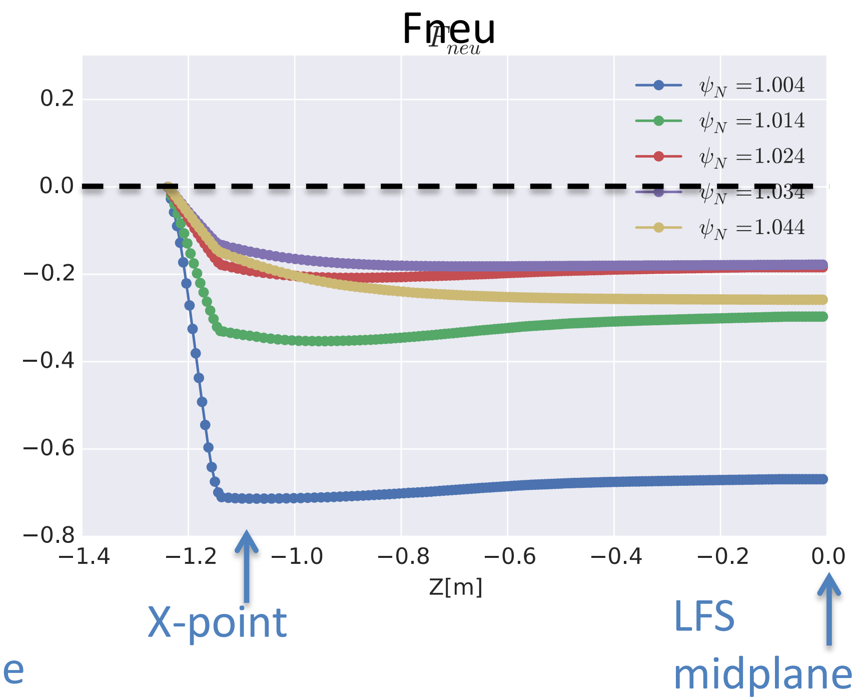
$$\overleftrightarrow{\mathcal{P}} = \int d^3 v (\mathbf{v}-\mathbf{u})(\mathbf{v}-\mathbf{u}) f = \begin{pmatrix} p_\perp & 0 & 0 \\ 0 & p_\perp & 0 \\ 0 & 0 & p_\parallel \end{pmatrix}$$

$$\Rightarrow \mathbf{b} \cdot \nabla \cdot \pi_i = \frac{2}{3} \nabla (p_{i,\parallel} - p_{i,\perp}) + (p_{i,\parallel} - p_{i,\perp}) \mathbf{b} \cdot \nabla \ln B$$

- Landau fluid CGL by Snyder-Hammett-Dorlad [PoP 1997]: $f = f_M + f_1$
- Is CGL valid in the SOL?

CGL viscosity (F_{visc}) and neutral momentum drag (F_{neu}) non-negligible





- Largest lower half (near X-point)
- -0.15 at Z=-0.8m for ψ_N=1.004

- Dominant contribution from divertor
- -0.75 at Z=-0.8m for ψ_N=1.004

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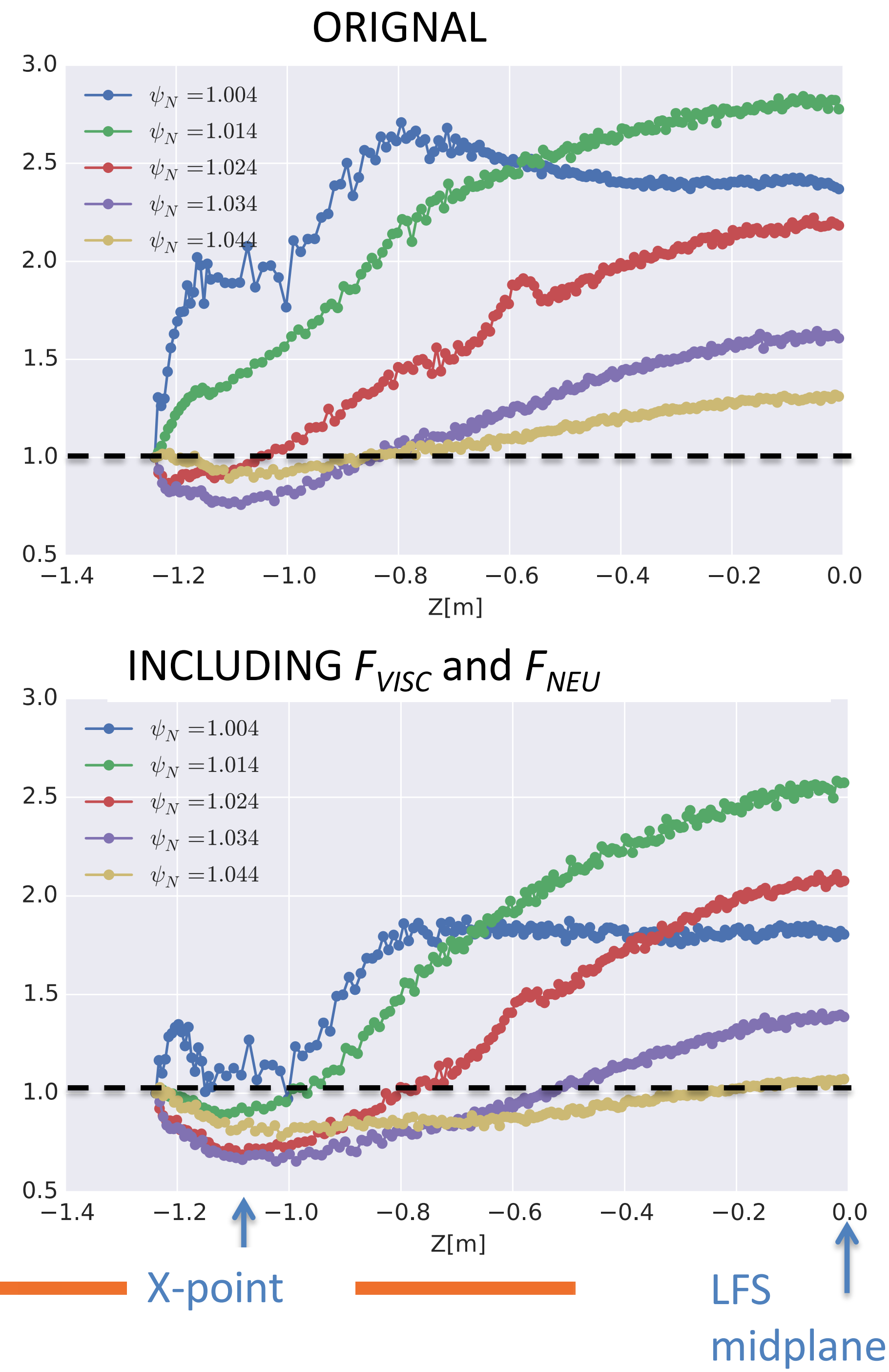
Expanded fluid parallel momentum conservation still not satisfied in XGCa

- Viscosity and neutral effects important, but fail to account for momentum loss in near-SOL (~2.0x, ψ_N=1.004)

- Far-SOL has a better-balanced balanced parallel momentum (~0.8 – 1.05)



Conclusion - Neoclassical SOL pressure balance study

- Simple fluid closure does not give correct parallel pressure balance contribution
    - Off-diagonal pressure tensor components may need to be investigated
- Two-point model fails to capture pressure variation in near-SOL
- Kinetic, non-Maxwellian closure is needed if fluid equations are insisted.
    - Off-diagonal pressure tensor terms to be calculated from XGC
    - Work in progress: how to make fluid edge codes (e.g. SOLPS) agree with kinetic codes

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- **Nonlocal intermittent edge turbulence (XGC1)**
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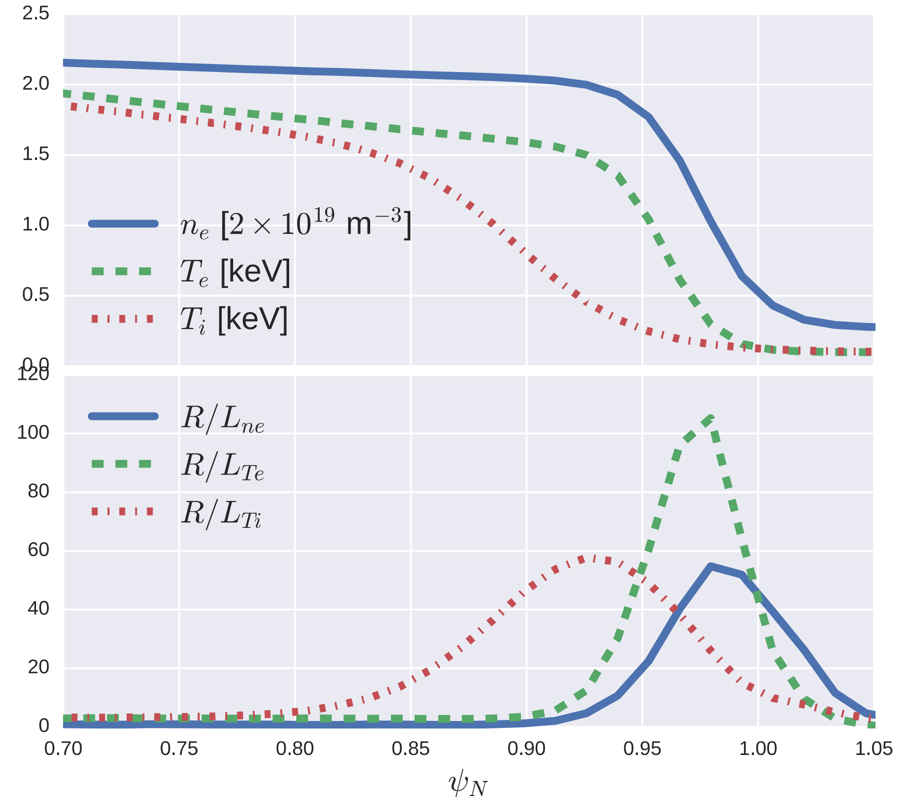
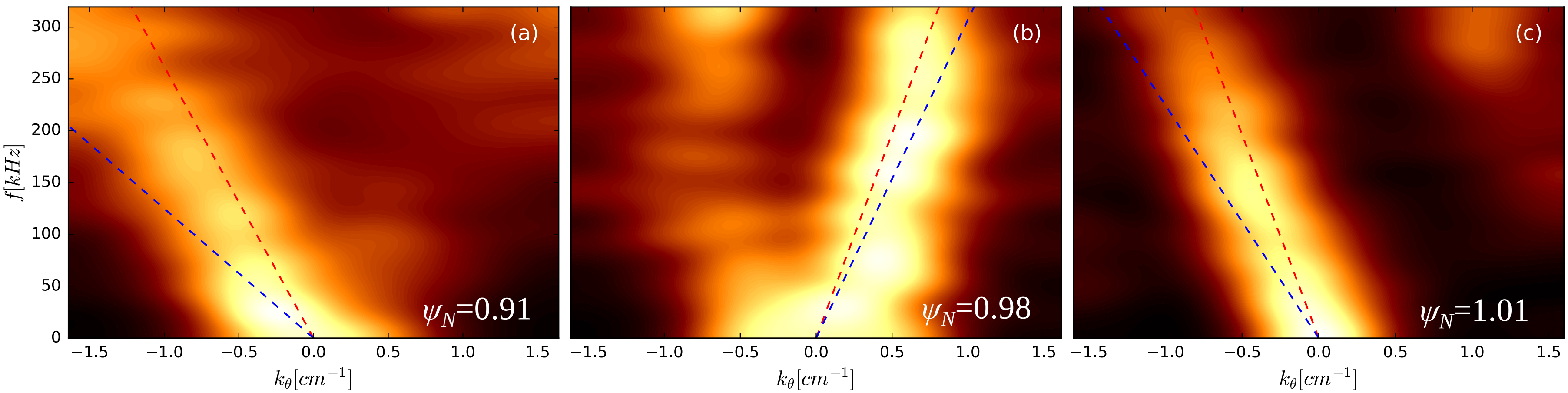
Electrostatic, total-f XGC1 simulation of model H-mode

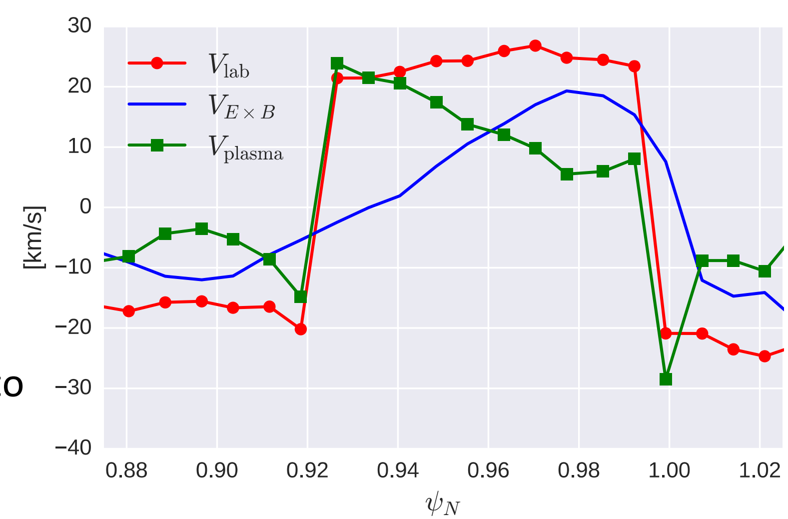
- DIII-D like magnetic equilibrium
  - Full magnetic geometry, including X-point
- Initialized with model electron and ion profiles
- Collisions and neutrals turned off for physics simplicity, to separate out effects
- Most XGC1 simulations are with collisions neutrals; analysis left for future



Frequency spectrum shows dominant turbulence drive changing through the pedestal/SOL



- Conditional spectrum S(k_θ,f) suggest dominant turbulence modes:
  - ITG near pedestal top
  - TEM through pedestal
  - Kelvin-Helmholtz into SOL [W. Wang 2015]
- Dual propagating mode in pedestal region due to nonlocal, counter-propagating turbulent structures [I. Cziegler, PhD thesis, 2012]



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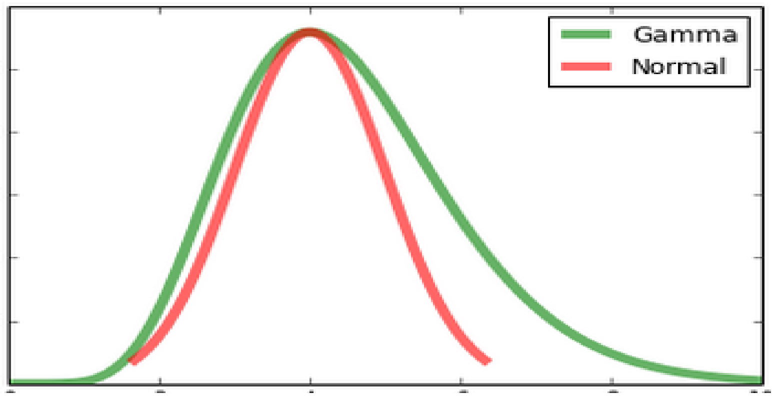
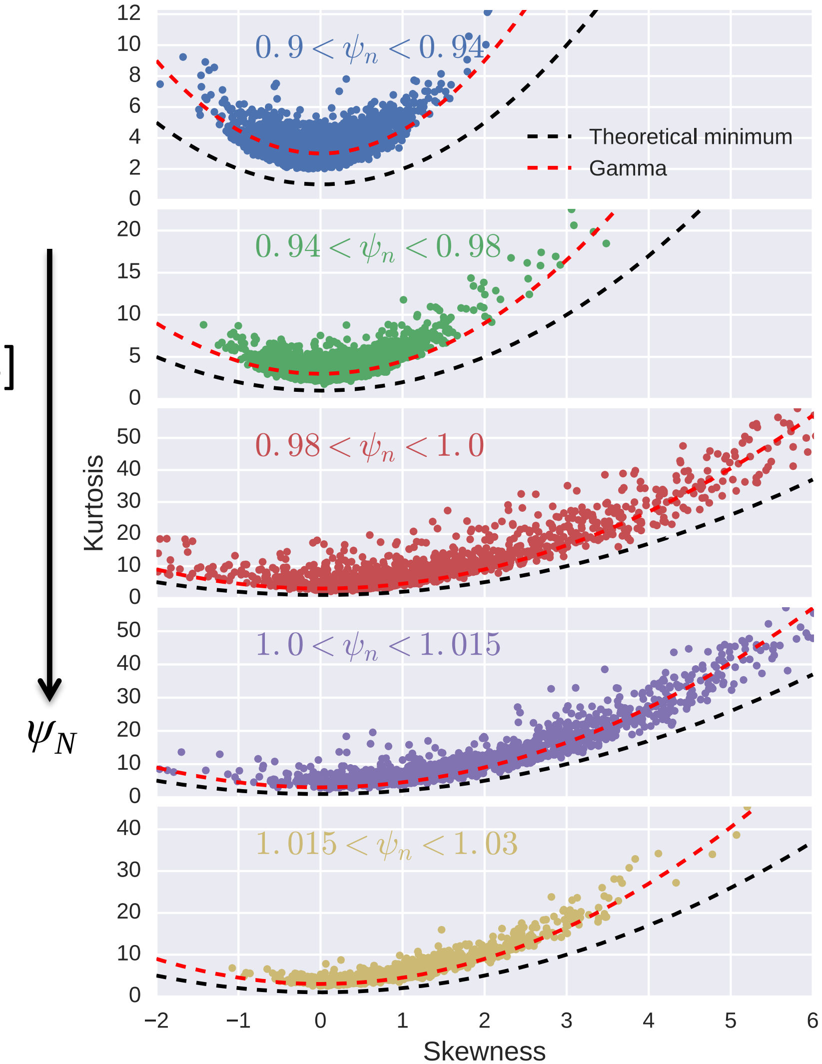
Non-Gaussian statistics in fluctuations across pedestal and SOL

- Skewness/kurtosis relation similar to gamma distribution throughout pedestal and SOL [Labit PPCF 2007, Krommes PoP 2008]



[R.M. Churchill, *PPCF*, submitted]



Simple picture of blobs and holes

Kosuga, Diamond, NF, 2013

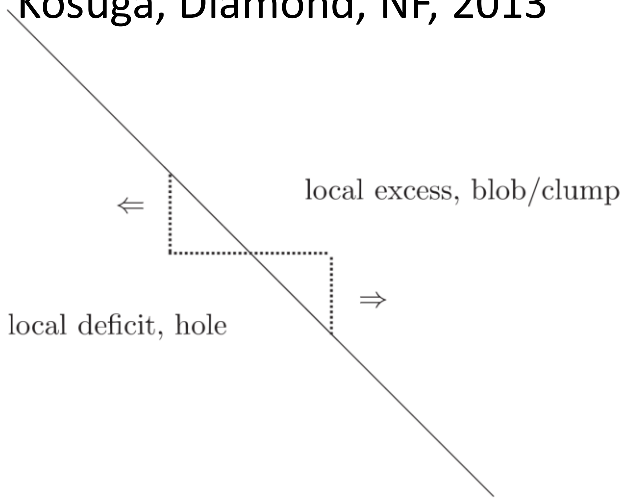
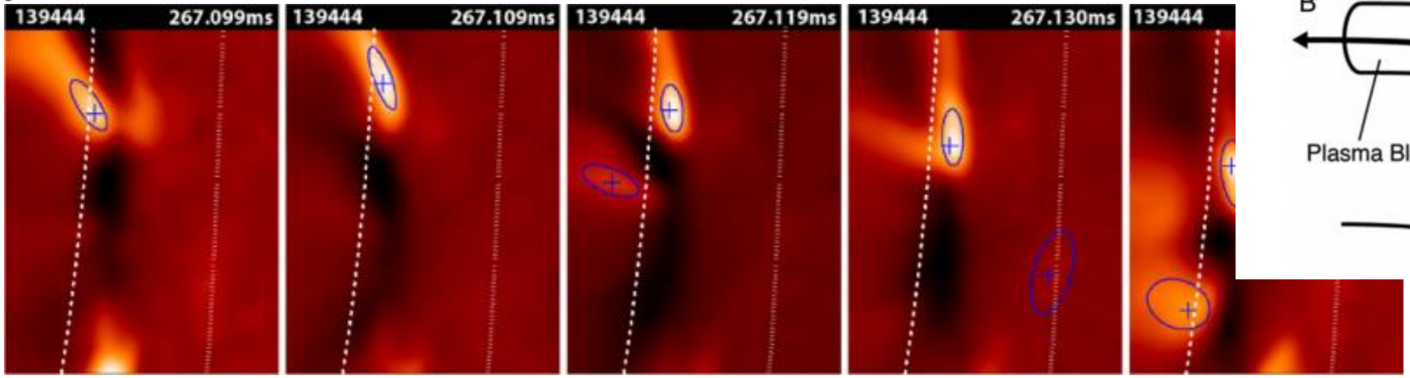
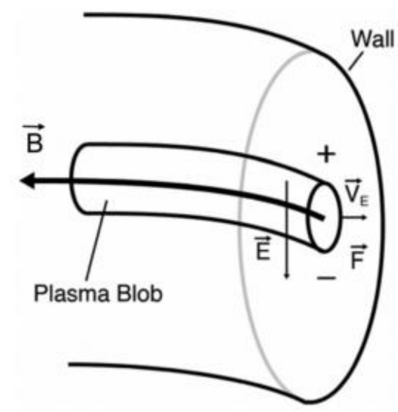


FIG. 1. Formation and growth of structures. The flattening of the gradient leads to the formation of blobs (local excess) and holes (local deficit). Once formed, holes (blobs/clumps) can grow by propagating against (down) the gradient.

- Local flattening of density
- Excess ("blobs") generally move outwards
- Deficit ("holes") generally move inwards



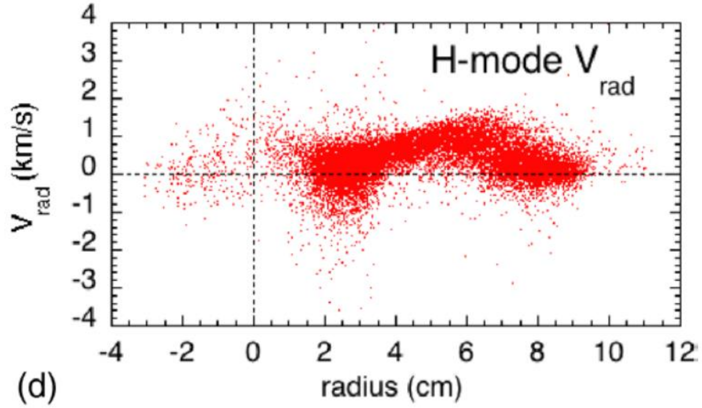


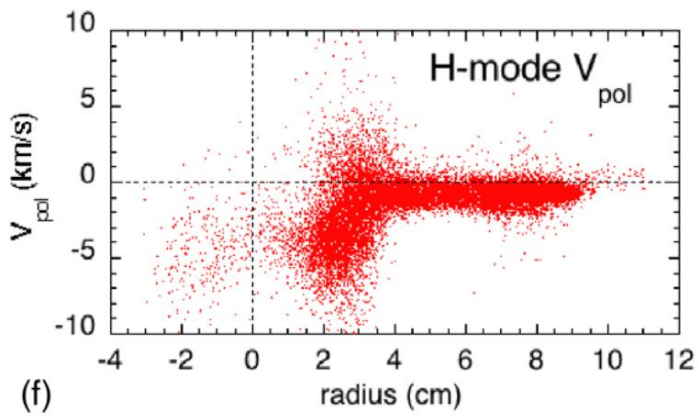
Myra, Zweben, Nucl. Fus, 2013

D'Ippolitto, Myra, Zweben, PoP, 2011

NSTX blobs in H-mode scattered near-zero average radial velocity in near-SOL, large poloidal velocity

- Blobs believed to be as much as 50% transport across SOL
  [Boedo PoP 2003]
  - But no proven fundamental understanding of generation mechanism!!
- Blob detection and tracking used to extract radial and poloidal blob velocities
  [Davis, Zweben Fus. Eng. Design 2014]
- Unlike in L-mode, blobs in near-SOL H-mode move, on average, dominantly poloidally
  [Zweben *PPCF* 2016]





[NSTX experiment Zweben *PPCF* 2016]

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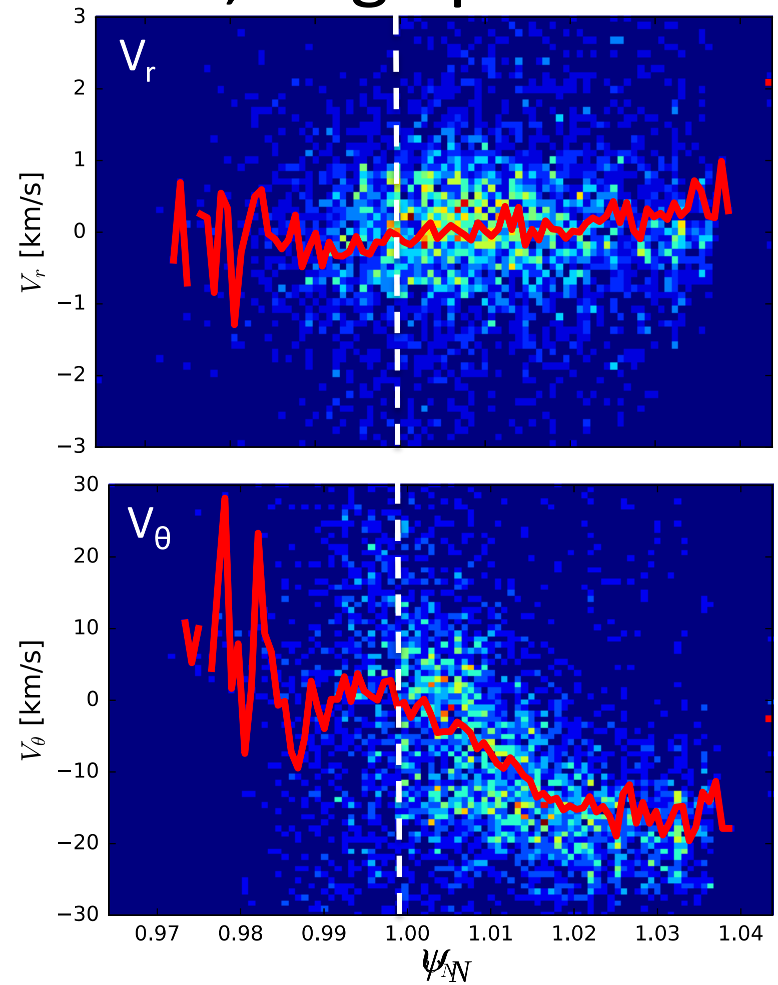
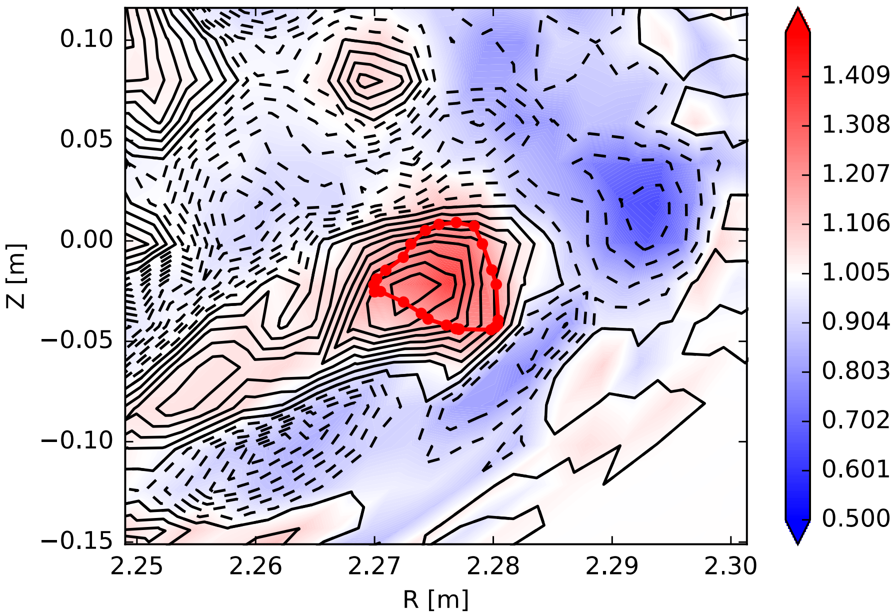
XGC1 blobs in H-mode scattered near-zero average radial velocity in near-SOL, large poloidal velocity

- Blob detection and tracking used to extract radial and poloidal blob velocities [Davis, Zweben Fus. Eng. Design 2014]
- V_r bounded by +-1km/s, average near 0 km/s, increases slightly into SOL, scatter similar to NSTX H-mode blobs [Zweben NF 2016]
- V_θ large, increases into SOL, near -20 km/s, close to ExB velocity

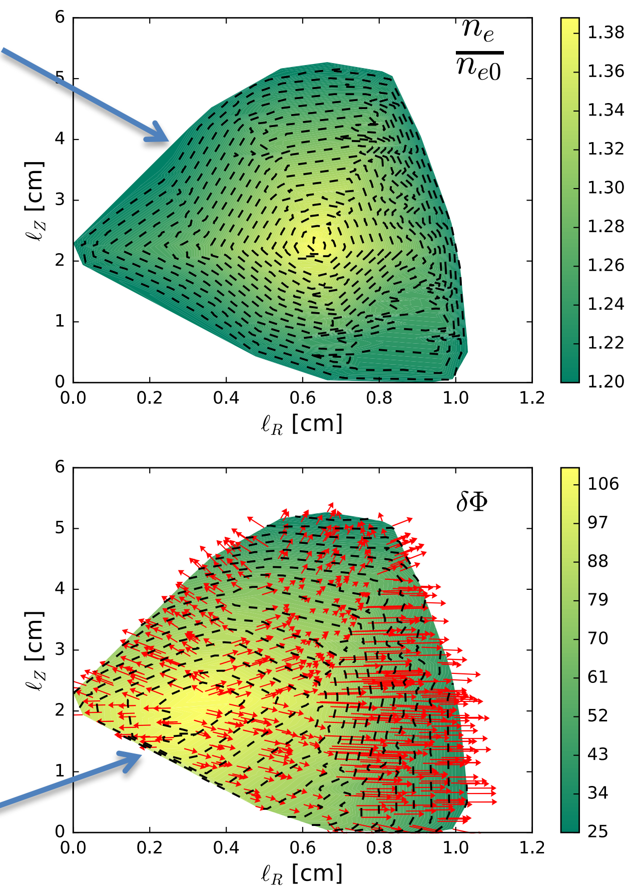


[R.M. Churchill, *PPCF,* submitted; Wu *IEEE Big Data* 2016]

Blob potential structure not dipolar, against simple magnetic drift argument



Density monopole



Blob dipolar potential structure crucial to analytical blob models [Krasheninnikov PRL 2001, D'Ippolito PoP 2011]

Shifted potential monopole (!?)

[R.M. Churchill, *PPCF*, submitted]

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Conclusion – Nonlocal intermittent turbulence

- Blobs do not move purely radially from vertically dipolar electric field in H-mode plasmas:
  - Non-1fluid blob motion behavior found

- How the kinetic blob behavior self-organizes to go along with non-ambipolar ion dynamics is an important future research direction for divertor heat load width [Chang, *submitted NF*, 2017]

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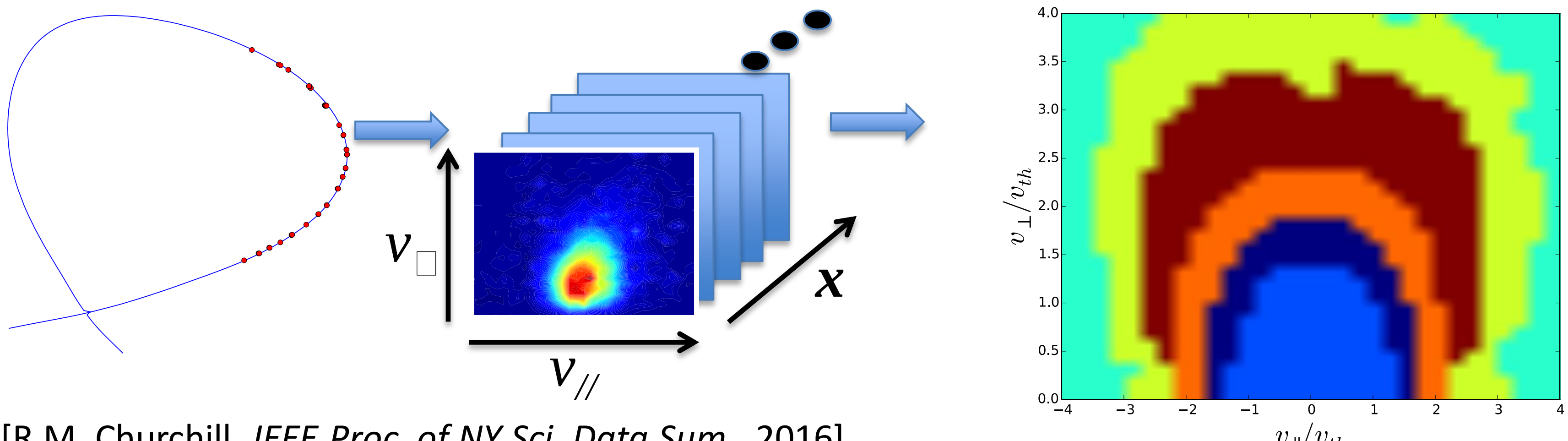
- Nonlocal intermittent edge turbulence (XGC1)
- Data management (follow on CPPG seminar)

Machine learning data management technic large XGC1 data sets

- XGC1 distribution function datasets are huge
    - ITER simulation 500 GB/time step
- Coherent phase space structure suggested to exist [Dupree *Phys Fluids* 1982, Kosuga *PoP* 2012], other indications they wouldn't survive [Krommes *PoP* 1997]
- Unsupervised machine learning algorithm (K-means clustering) helps find common structure among large data sets



[R.M. Churchill, *IEEE Proc. of NY Sci. Data Sum.*, 2016]

Summary

- Scrape-off layer pressure variation along magnetic field lines can depart drastically from simple fluid models in the near-SOL
  - CGL parallel viscosity and neutral drag do not solve the problem
  - Experimental main ion temperature critical to understand

- Blob potential structure can be monopolar, allow for dominant poloidal ExB motion of blobs
  - How this internal structure self-organizes with non-ambipolar ion orbit loss may be important for understanding divertor heat flux width

- Unsupervised machine learning reveals no isolated, coherent blob phase space structure, but rather ring like structure of roughly constant velocity

- Broader data management to be presented as a CPPG seminar

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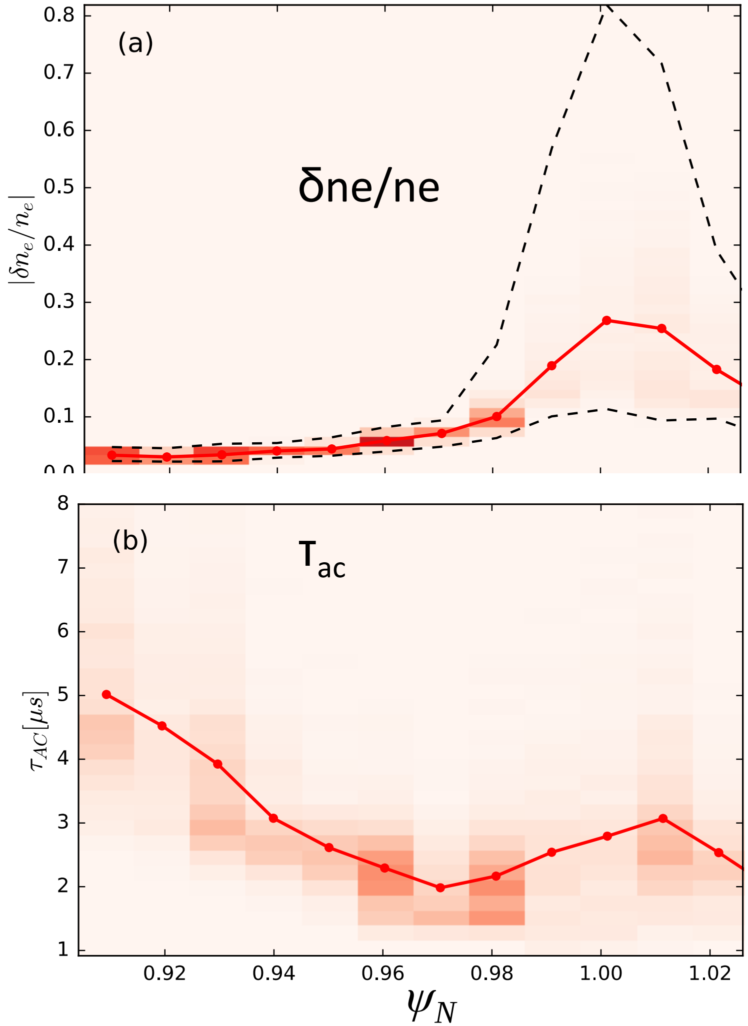
END PRESENTATION

Turbulence characteristics across the edge suggestive of nonlocal effects

- Density fluctuations increase in magnitude near separatrix, where ∇n strongest, stay high in SOL
- Autocorrelation time decreases in regions of strong *negative* ExB shearing
- BUT, radial and poloidal correlation lengths are ~ constant over the pedestal+SOL (L_{pol} ~ 4 L_{rad} ~ 5cm)



[R.M. Churchill, *PPCF,* submitted]

Maching Learning for finding and exploring structure in large XGC1 data sets

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  - ITER simulation 500 GB/time step
- Coherent phase space structure suggested to exist [Dupree *Phys Fluids* 1982, Kosuga *PoP* 2012], other indications they wouldn't survive [Krommes *PoP* 1997]
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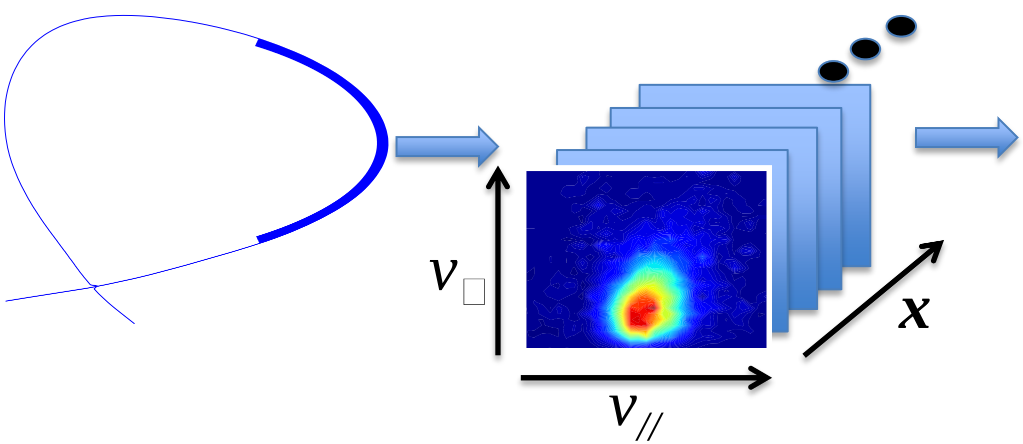
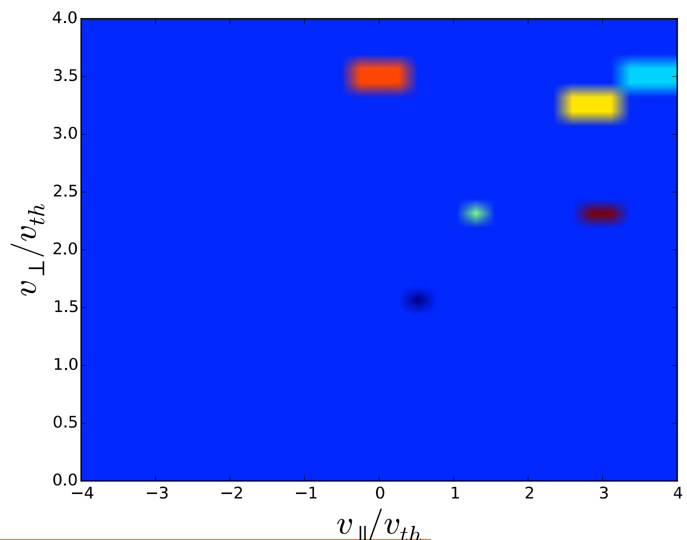


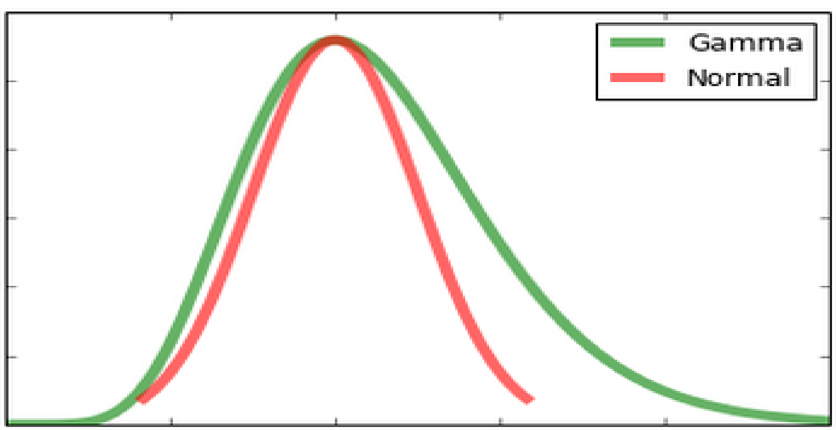


[R.M. Churchill, *IEEE Proc. of NY Sci. Data Sum.*, 2016]

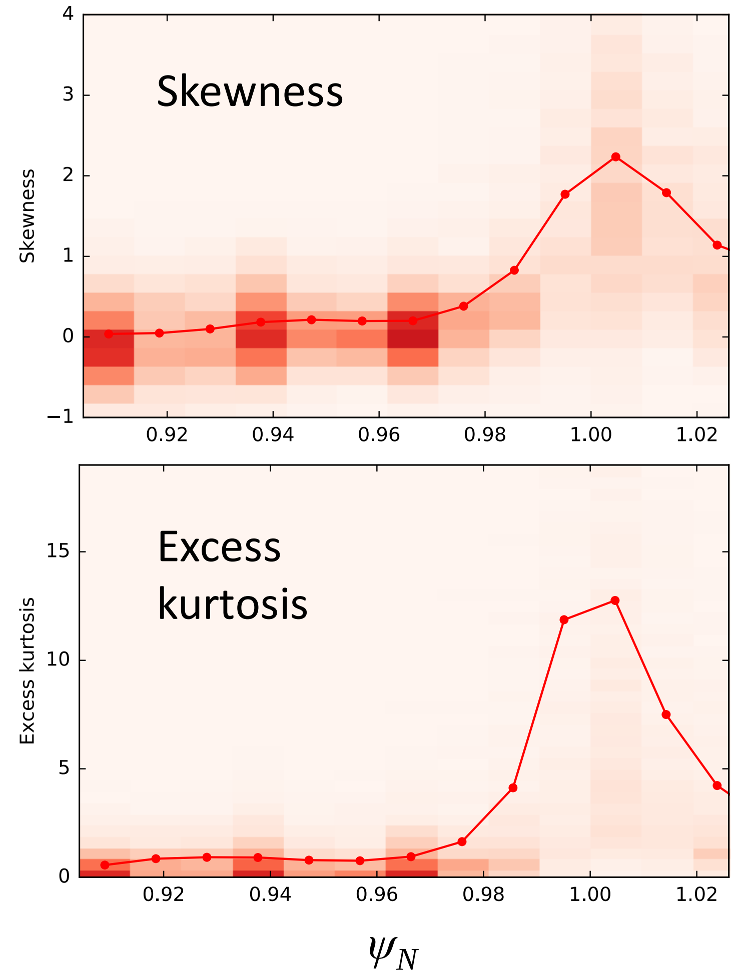
Non-Gaussian statistics in fluctuations across pedestal and SOL

- Skewness and kurtosis increase near separatrix, into the SOL

- Slightly negative skewness at pedestal top suggests existence of density holes there
  [Boedo PoP 2003]



[R.M. Churchill, *PPCF*, submitted]



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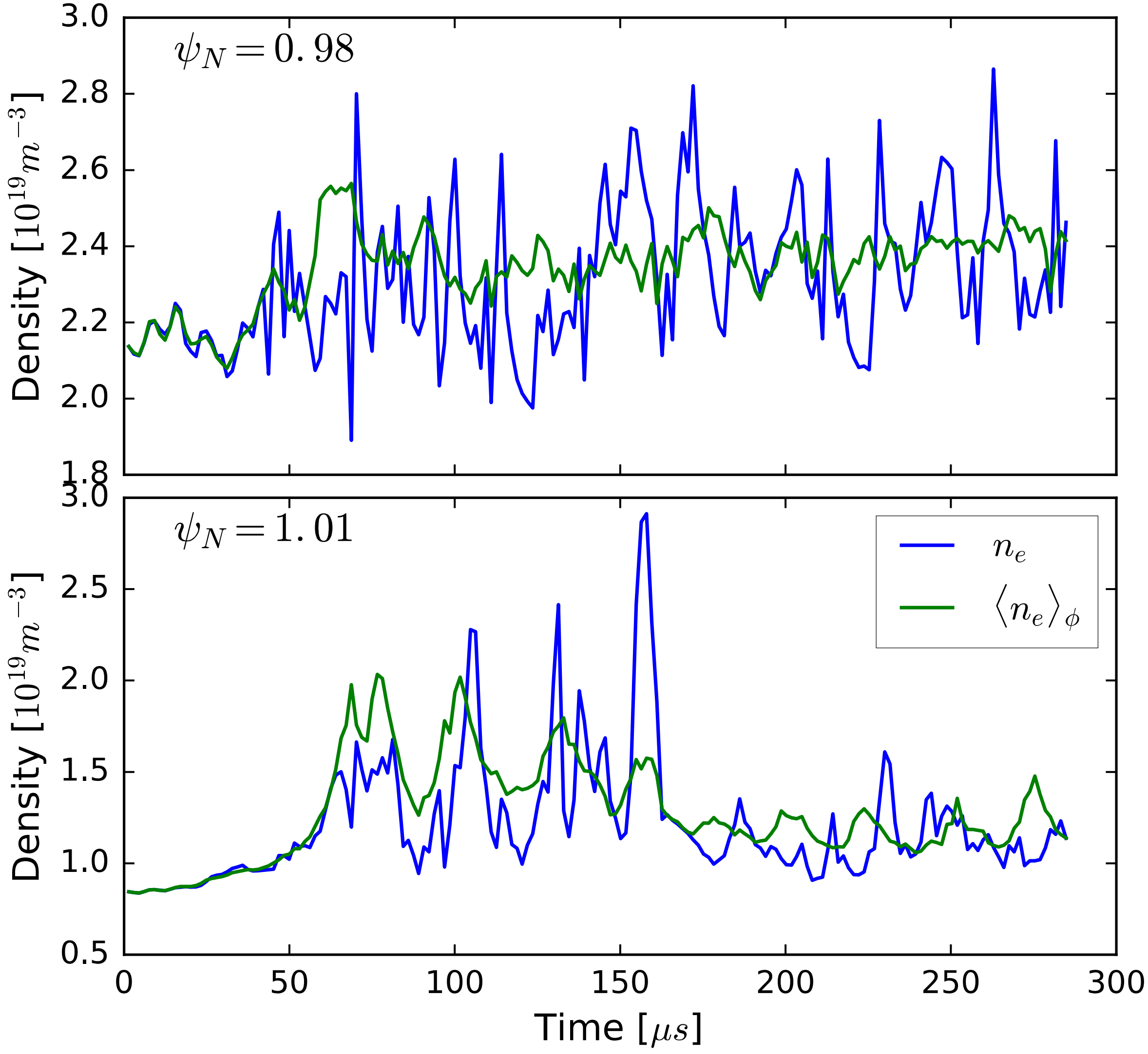
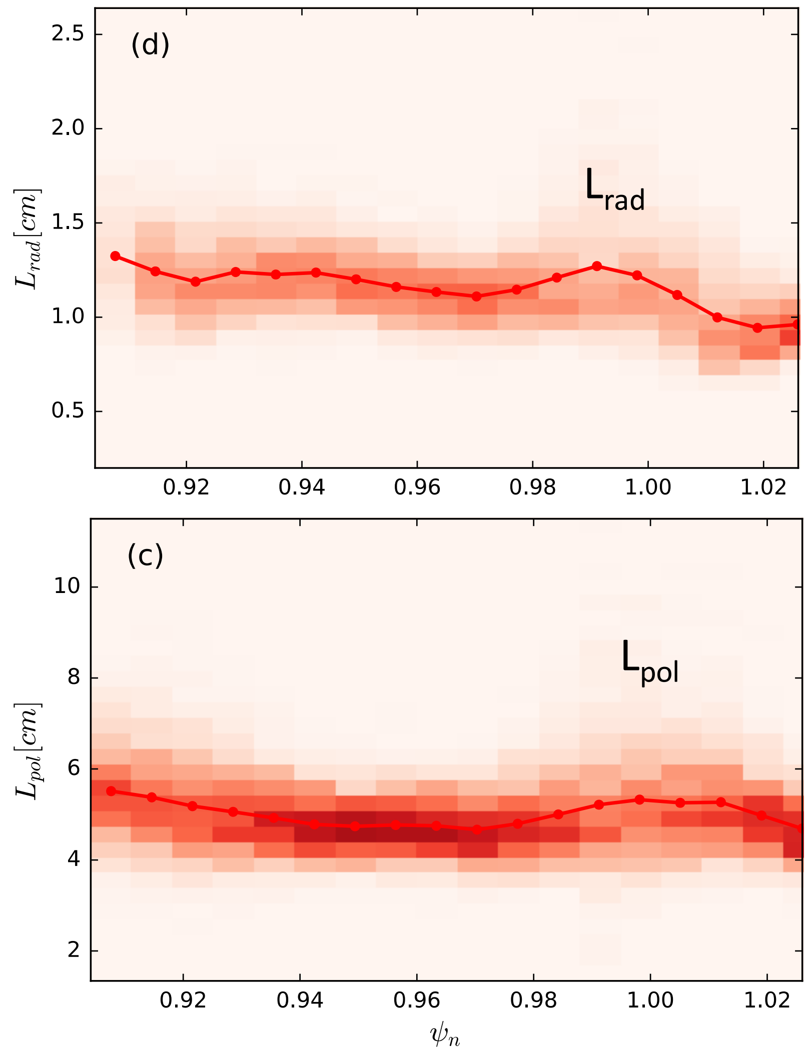
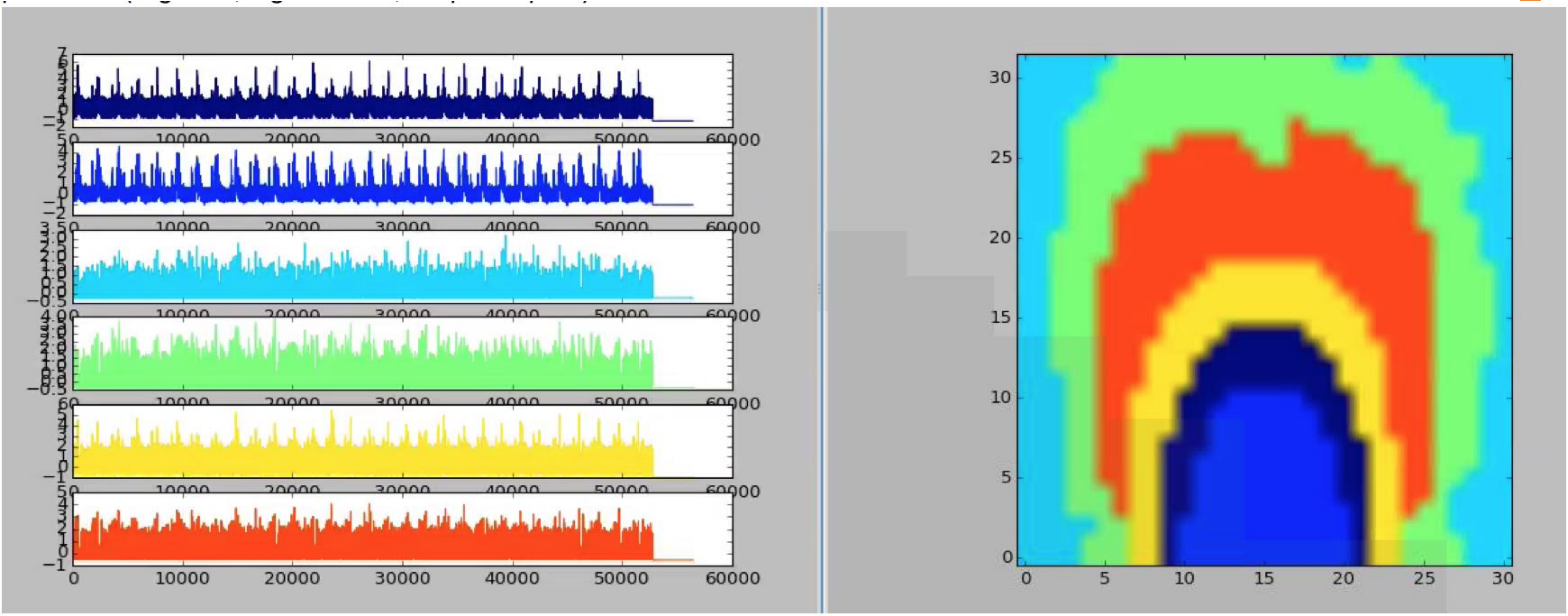

$\psi_N = 0.98$
$\psi_N = 1.01$
Density $[10^{19} m^{-3}]$
Density $[10^{19} m^{-3}]$
Time $[\mu s]$
n_e
$\langle n_e \rangle_\phi$
3.0
2.8
2.6
2.4
2.2
2.0
1.8
3.0
2.5
2.0
1.5
1.0
0.5
0
50
100
150
200
250
300

Turbulence characteristics across the edge

- Correlation lengths are ~ constant over the pedestal+SOL, suggestive of dominant non-local turbulence

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