TURBULENT BOUNDARY LAYERS: CURRENT RESEARCH AND FUTURE DIRECTIONS

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In the distinguished and, as yet, untamed field that is turbulent flow, the nature of turbulence close to a surface continues to yield its secrets piecewise and slowly. The notion that, somehow, one single clever idea will produce a flood of understanding is receding to the background. Or, is it that we are so burdened by what we immediately observe that penetrating the fog to see the light is becoming more difficult?*

AFOSR #s FA9550-08-1-0049, FA9550-09-1-0701 (P.M. J. Schmisseur)

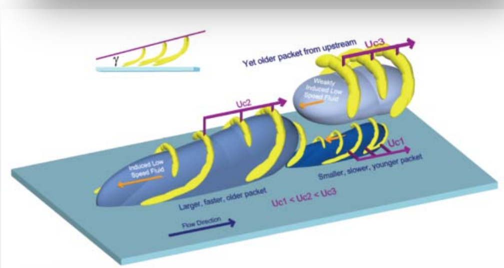
**McKeon & Sreenivasan, PTRSA (2007)*

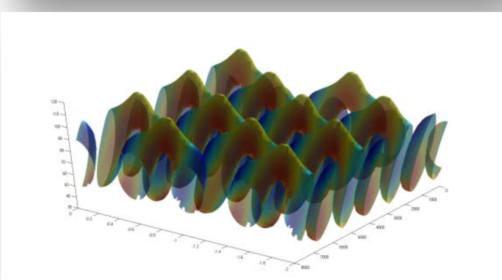
MOTIVATION: HIGH REYNOLDS NUMBER BOUNDARY LAYERS

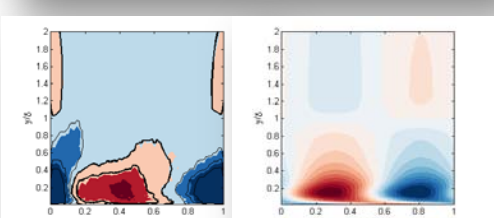
Industrial piping	$Re_D > 10^7$	$D^+ > 10^5$
Boeing 777 fuselage	$Re_x > 10^8$	
Boeing 777 wing	$Re_x > 10^7$	
Near-neutral ASL	?	$\delta^+ \sim 10^6$

- Fundamentally important studies of the behavior of "high Reynolds number" wall-bounded flow
- Extension to other wall-bounded flows: "universal" law of the wall?
- Direct relevance to industrial applications (most simulations not predictive)
  - change in logarithmic mean velocity slope from 1/0.410 to 1/0.436 leads to 1% increase in drag at $Re_x \sim 10^8$ (Spalart)
  - high Reynolds number turbulence modeling and simulation (minimum Reynolds number for realistic turbulent development)
  - application to control strategy

Outline







- Introduction to the state of the art in wall turbulence
  - Statistical description
  - Structure
  - Linear analyses of transient growth

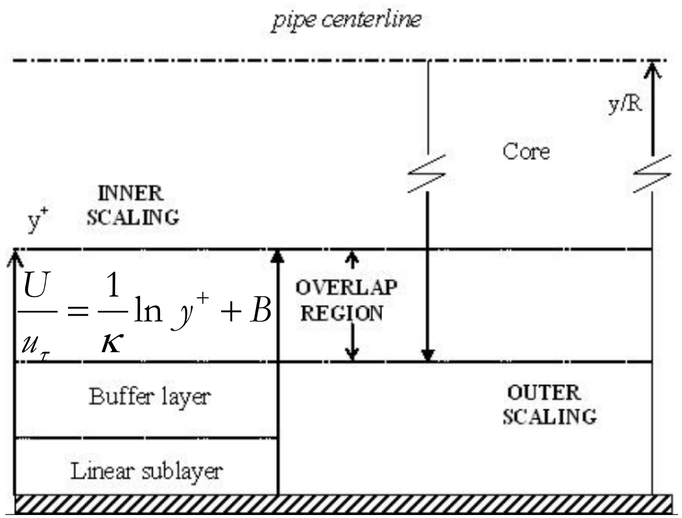
McKeon, B. J. & Sreenivasan, K. R. ‘Scaling and structure in high Reynolds number wall-bounded flows’ *Phil. Trans. Royal Soc. A, 365, 635-646 (2007)*

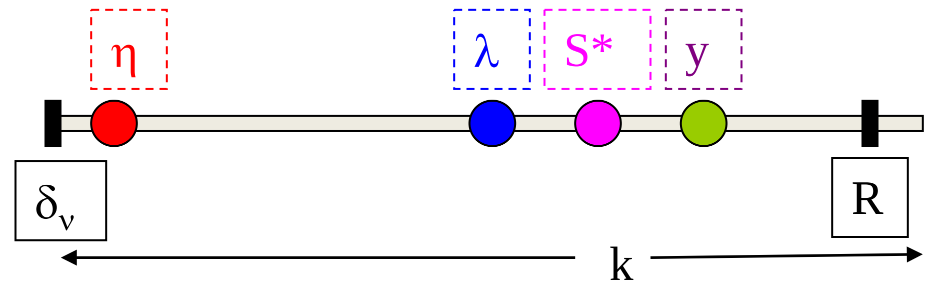
Smits, A. J., McKeon, B. J. and Marusic, I. ‘High Reynolds number wall turbulence’ *Annual Review of Fluid Mechanics, 43, 353-375 (2011)*

Marusic, I., McKeon, B. J., Monkewitz, P. A., Nagib, H. M., Smits, A. J. & Sreenivasan, K. R. ‘Wall-bounded turbulent flows: recent advances and key issues’ *Phys. Fluids, 22, 65103 (2010)*

- A simple linear model for pipe flow
  - Asymptotic results
  - Prediction of statistical scaling
  - Structure
  - Excitation of dominant modes using morphing surfaces

INTRODUCTION (OUR STARTING POINT)





PHYSICAL SPACE

y: distance from the wall

R: outer lengthscale

$$y^+ = \frac{y u_\tau}{\nu} \qquad u_\tau = \sqrt{\frac{\tau}{\rho}}$$

$$\eta_O = \frac{y}{R}$$

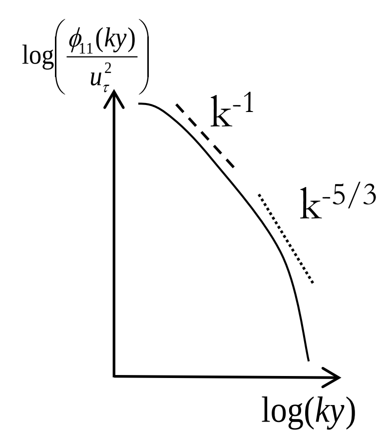
SPECTRAL SPACE

k: streamwise wavenumber

$$\delta_\nu = \frac{\nu}{u_\tau} \qquad \eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$$

$$\lambda = \sqrt{u^2 / (\partial u/\partial x)^2}$$

$$S^* = \sqrt{\frac{\varepsilon}{S^3}} \qquad S = \frac{\partial U}{\partial y}$$



What's new in TBLs? Results and pressing questions

- What is a "**high** Reynolds number"?
  - *The importance of scale separation, finite Re effects*
  - *New facilities*
  - *Challenges to measurement techniques*
- The importance of the (very) large scales
  - *Packets of hairpin vortices*
  - *Energetic contributions from "VLSMs"/"superstructures"*
- Structure and its origin
  - *Instability and transient growth phenomena*
  - *Vortex regeneration mechanisms*
- Successes and failures of models of (aspects of) wall turbulence
- Universality? Differences between canonical flows
- Roughness effects

How do we generate these flows?

TABLE I. Compilation of experiments considered extensively in the Workshops. OFI indicates oil-film interferometry, HW hot wires, ΔP pressure drop, κ is the von Kármán constant, and U_τ is the friction velocity.

Reference	Flow type	Highest Re_τ	κ	y^+: start of log law	No. of decades of log law	U_τ method	U meas. tech.
McKeon *et al.*[a] Morrison *et al.*[b] *Princeton Superpipe*	Pipe	300 000	0.421	600	1.8	ΔP	Pitot/HW
Monty[c] *Melbourne*	Pipe	4000	0.384	100	0.8	ΔP	Pitot/HW
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Zanoun *et al.*[d] *Erlangen*	Channel	4800	0.37	150	0.8	ΔP	HW
Nagib *et al.*[e] *NDF, Chicago*	BL	22 000	0.384	200	1.4	OFI	HW
Österlund *et al.*[f] *KTH, Stockholm*	BL	14 000	0.38	200	1.0	OFI	HW
Nickels *et al.*[g] (2007) ICET (Duncan *et al.*[h]) *Melbourne*	BL	23 000	0.39	200	1.5	OFI	Pitot/HW
Metzger & Klewicki *SLTEST, Utah*	BL	$\mathcal{O}(10^6)$	⋯	⋯	~3	⋯	HW

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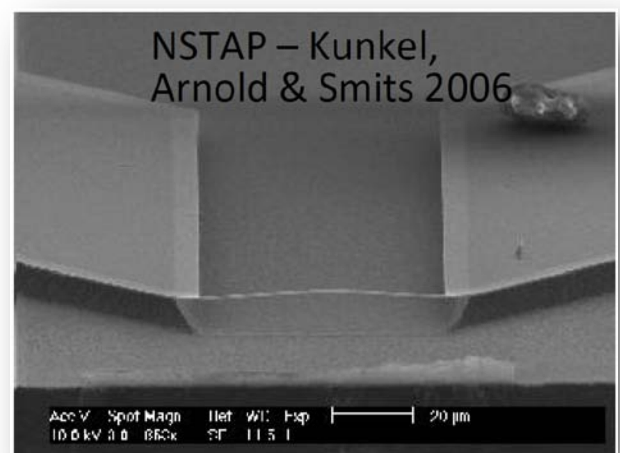
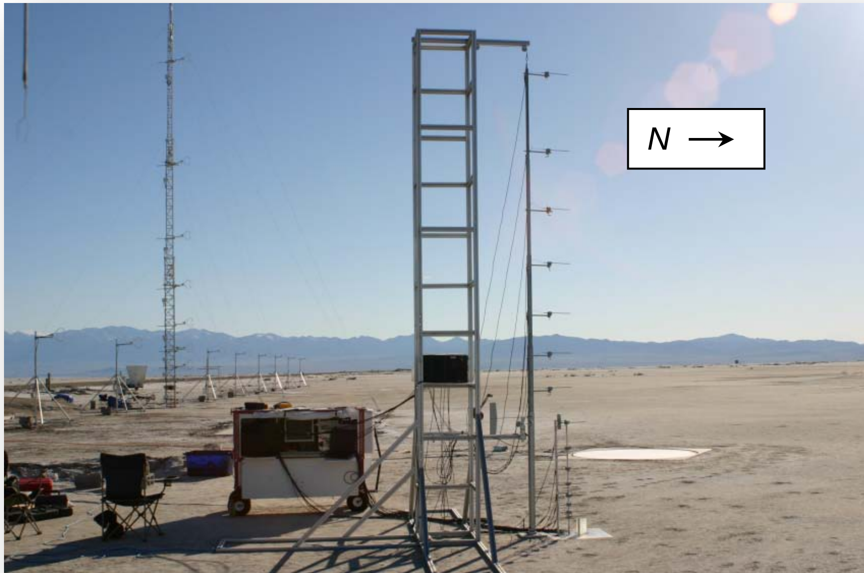
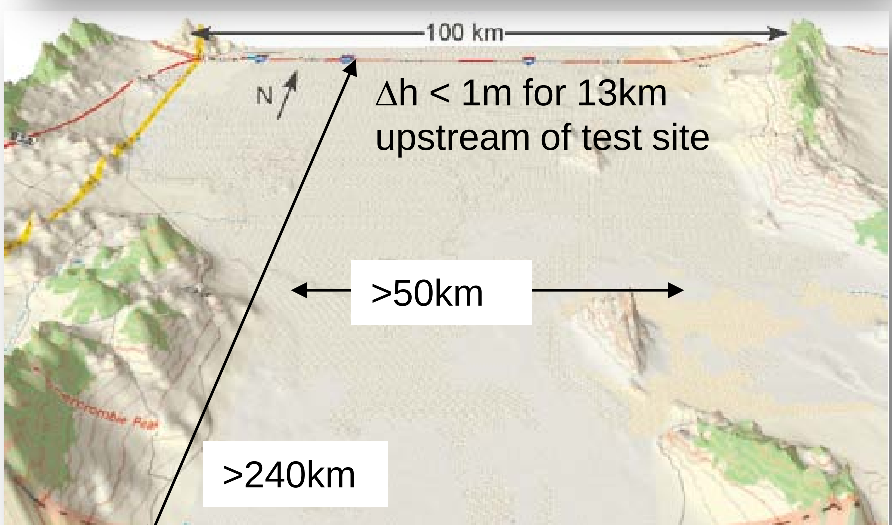
Go BIG (δ) or go SMALL (ν/u_τ)



SURFACE LAYER TURBULENCE & ENVIRONMENTAL SCIENCE TEST SITE





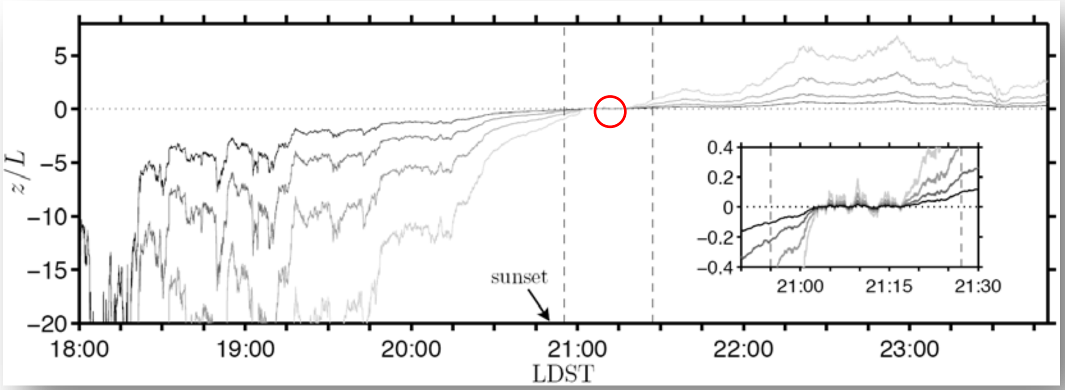
ADVANTAGES

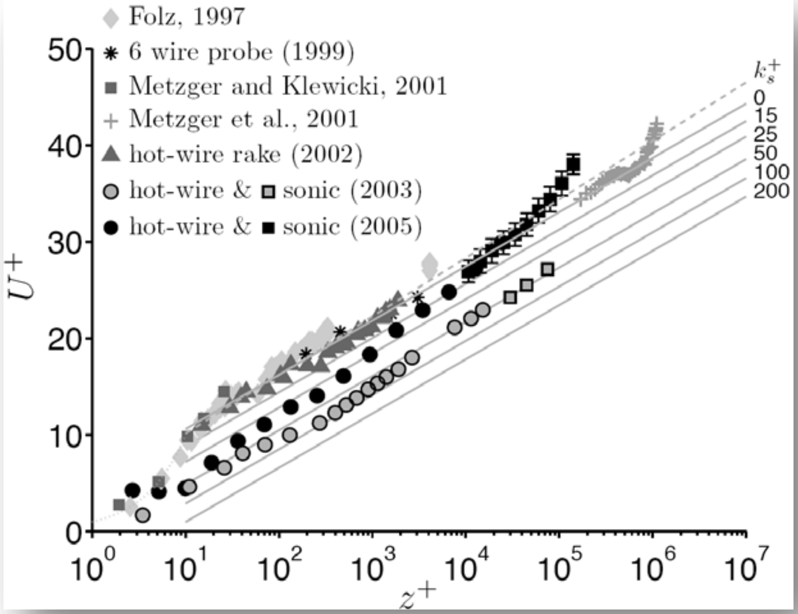
- Highest terrestrial Reynolds numbers
- Large physical and temporal scales
- "Free"!
- 100km fetch, predominantly northerly winds during evening neutrally stable period $|z/L| < 0.01$
- $U_{5m} \approx 5$ m/s $\delta \approx$ 50-100m
  $\delta^+ = \delta u_\tau/\nu \approx O(10^6)$ $k_s^+ \sim 25$

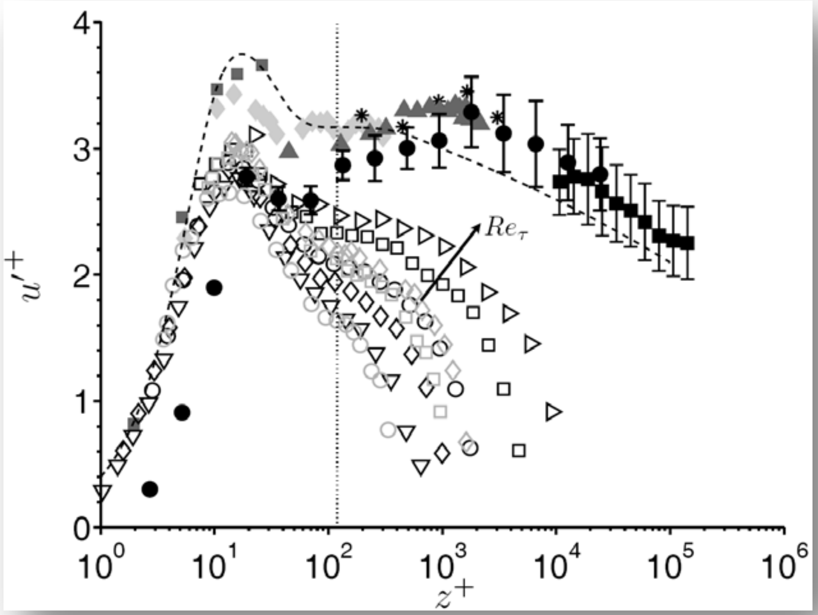
DISADVANTAGES

- Buoyancy effects
- Boundary conditions
- Field campaigns difficult

ASL AS A MODEL FOR A CANONICAL FLOW

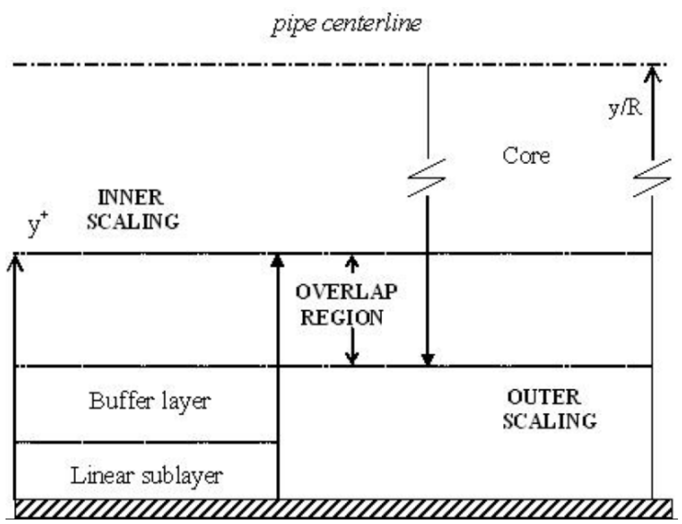


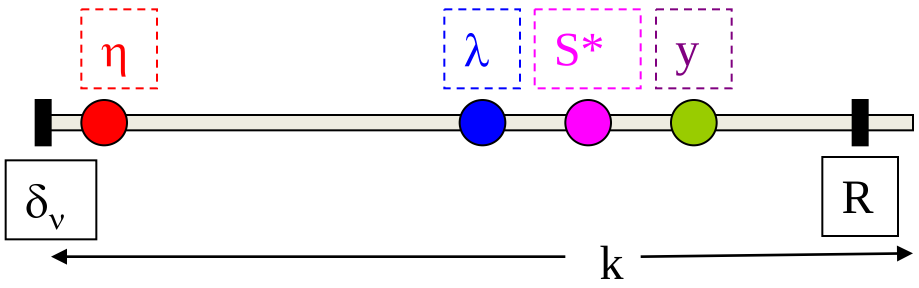




Metzger, McKeon & Holmes, Phil. Trans. R. Soc. A, 2007

WHAT IS A "HIGH REYNOLDS NUMBER"?

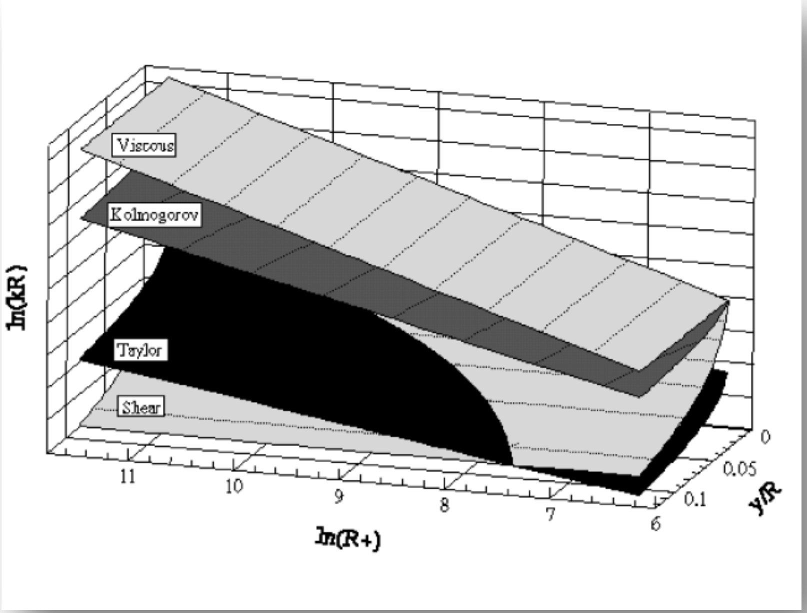




R^+ ~ 5000 (McKeon *et al*, JFM 2004)

δ^+ ~ 4000 (Hutchins & Marusic, PTRSA 2007)

R^+ ~ 5000 (McKeon & Morrison PTRSA 2007)

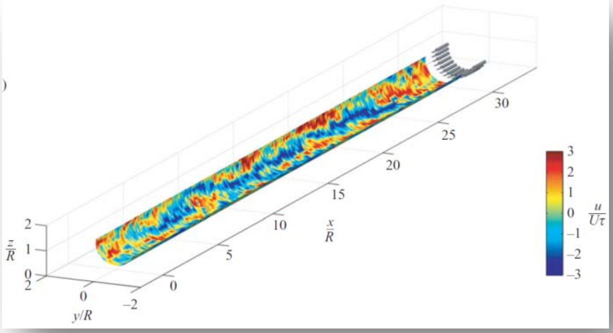


"High Reynolds number, fully-developed flow" only for R^+ $O(10^4)$

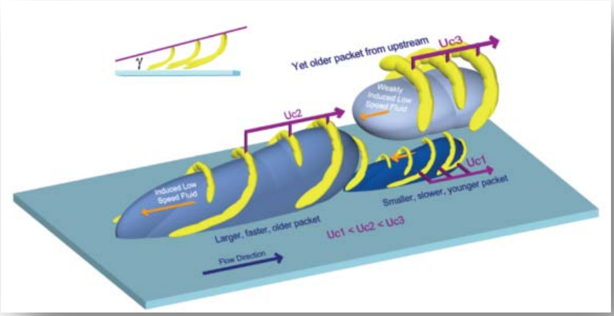
A "SKELETON" OF WALL TURBULENCE

"Skeleton" consisting of (at least) three components (cf classical picture)

- VLSMs:
  - Origin (robust feature of shear flows)
  - Extent
  - Convective velocity/evolution?
- LSMs
  - Hairpins, packets
  - Uniform momentum zones
  - Convective velocity/ies
- Near wall cycle
- (+ small-scales)



Monty et al



Adrian

INTRODUCTION TO VLSM

Very Large Scale Motion: *coherence of O(10 R)*

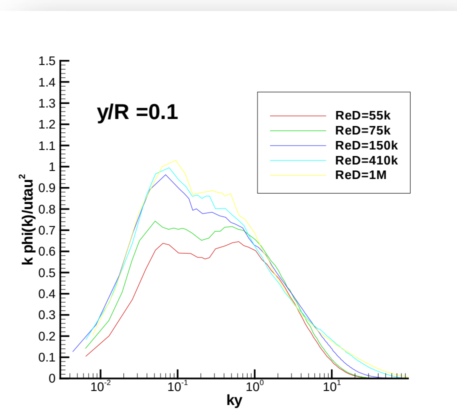
The energetic content and importance of scales much larger than the outer lengthscale (R, δ, h) has been known for almost 40 years

- long correlation tails: Favre et al, 1967
- correlation in the wall-normal direction: Kovasznay et al, 1970

More recent studies have emphasized distinct properties of these scales

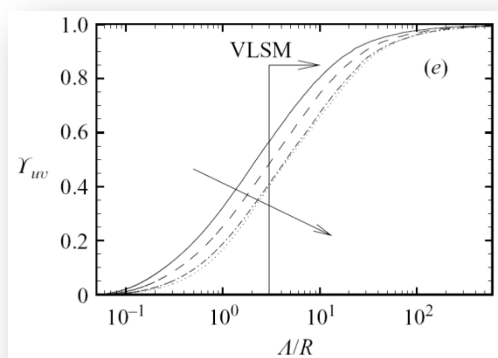
Very energetic in the streamwise velocity

Kim & Adrian, 2000;
Morrison, McKeon et al 2004



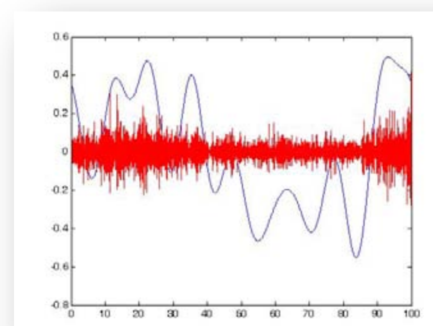
“Active”: contribute to Re shear stress, uv

Guala et al 2006

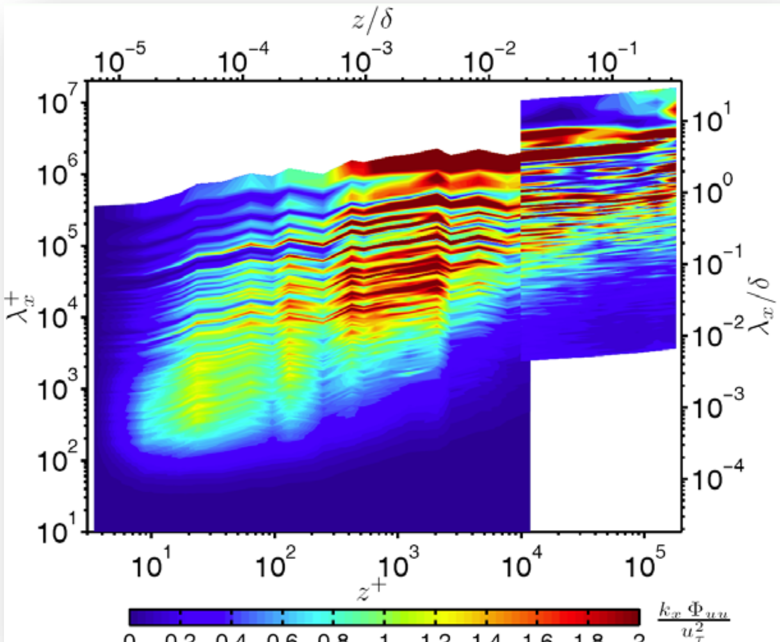


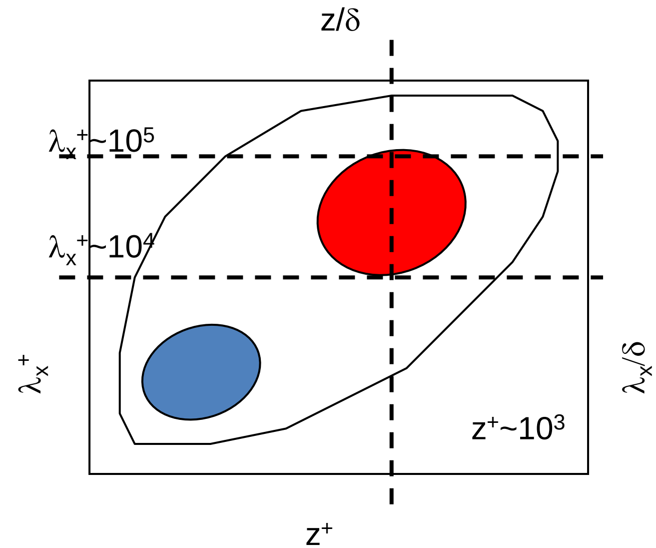
Challenge traditional scaling assumptions

Marusic et al, 2007;
Guala, Metzger & McKeon, 2009



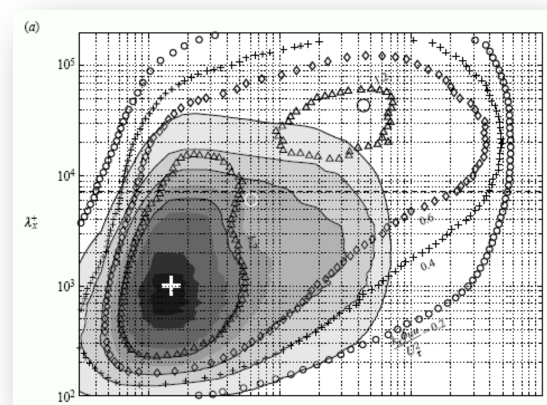
STREAMWISE ENERGY SPECTRA



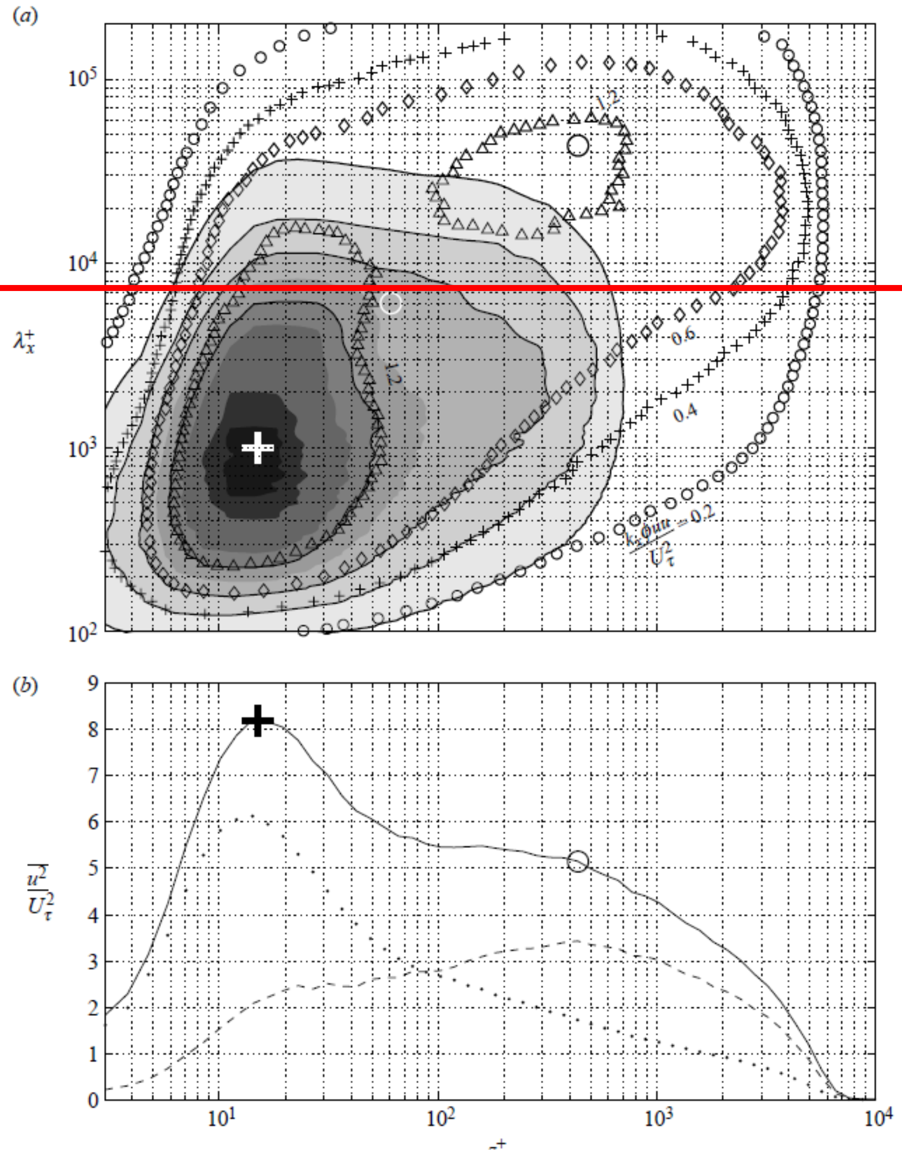


Scaling of the location of the second streamwise spectral peak has implications for self-similarity of the streamwise fluctuations

Similar to $\delta^+ \sim 7300$ results of Hutchins & Marusic, 2007

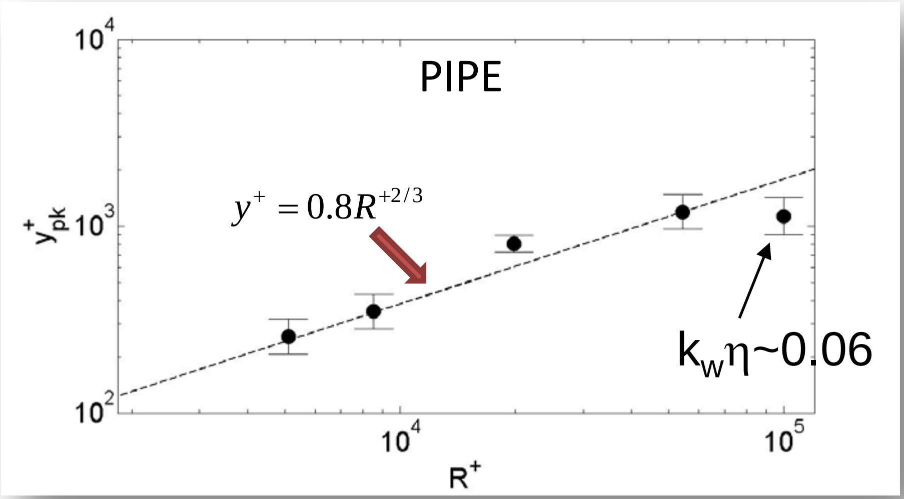


EFFECT OF THE VLSMS ON u'

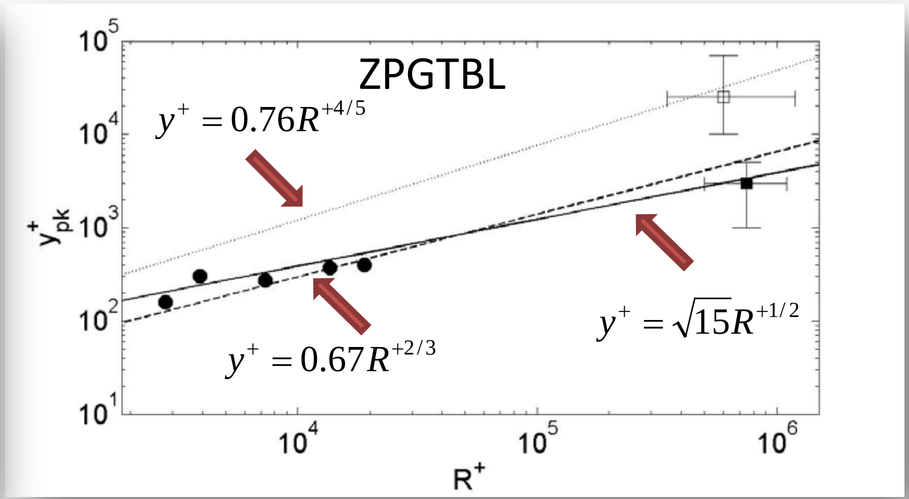


Hutchins & Marusic, PTRSA, 2007

LOCATION OF THE VLSM PEAK ENERGY: PIPE AND TBL



McKeon, AIAA 2008-4237



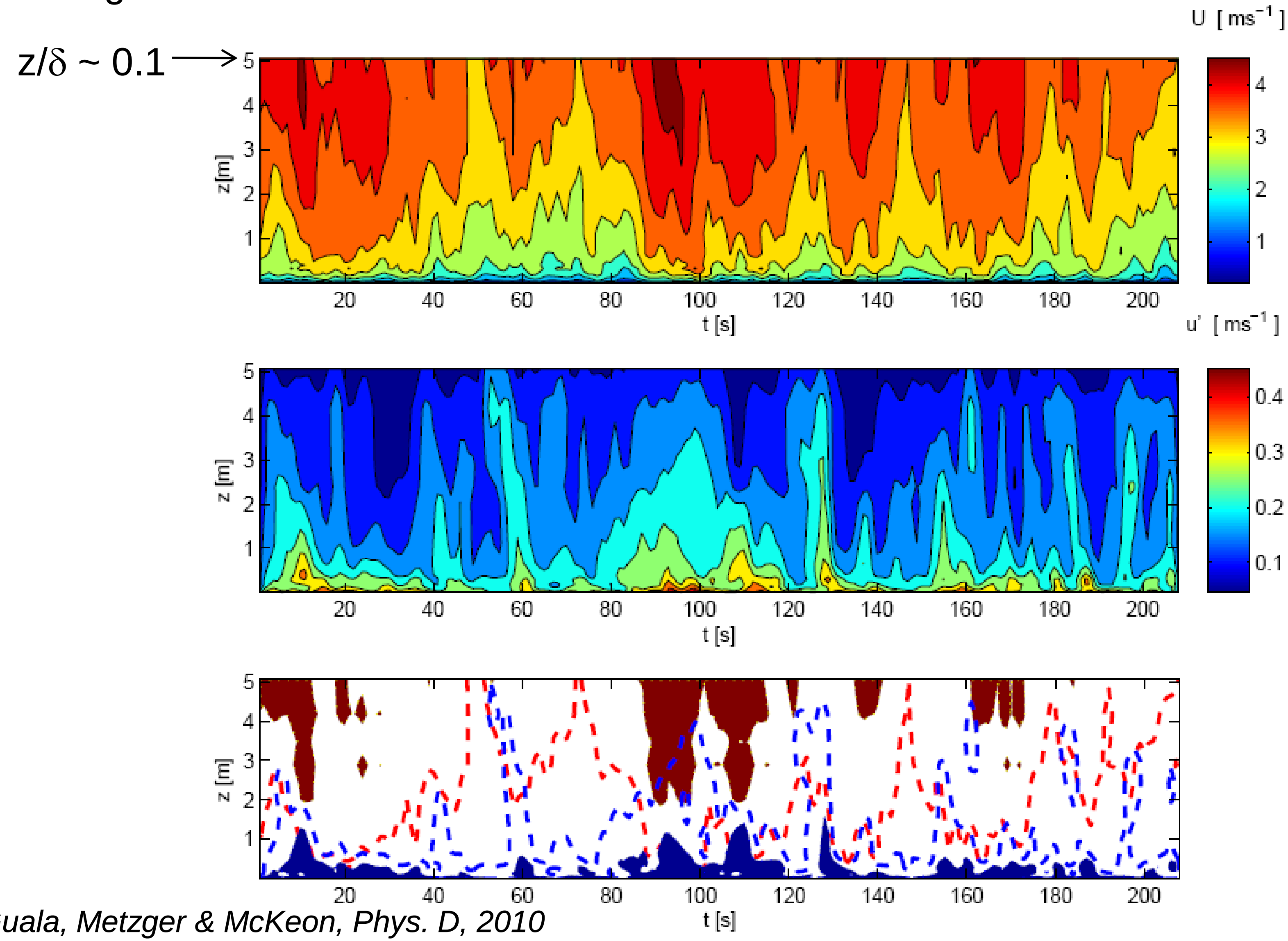
Mathis et al, JFM 628 2009

- Results from the Princeton/ONR Superpipe (McKeon, 2008) and ZPG boundary layers (Mathis, 2009) over a range of Reynolds number suggest location of the VLSM peak resists inner and outer scaling

- Resolution effects may become important in the pipe, although we are considering the lowest frequencies which will be the last to be affected by finite wire length

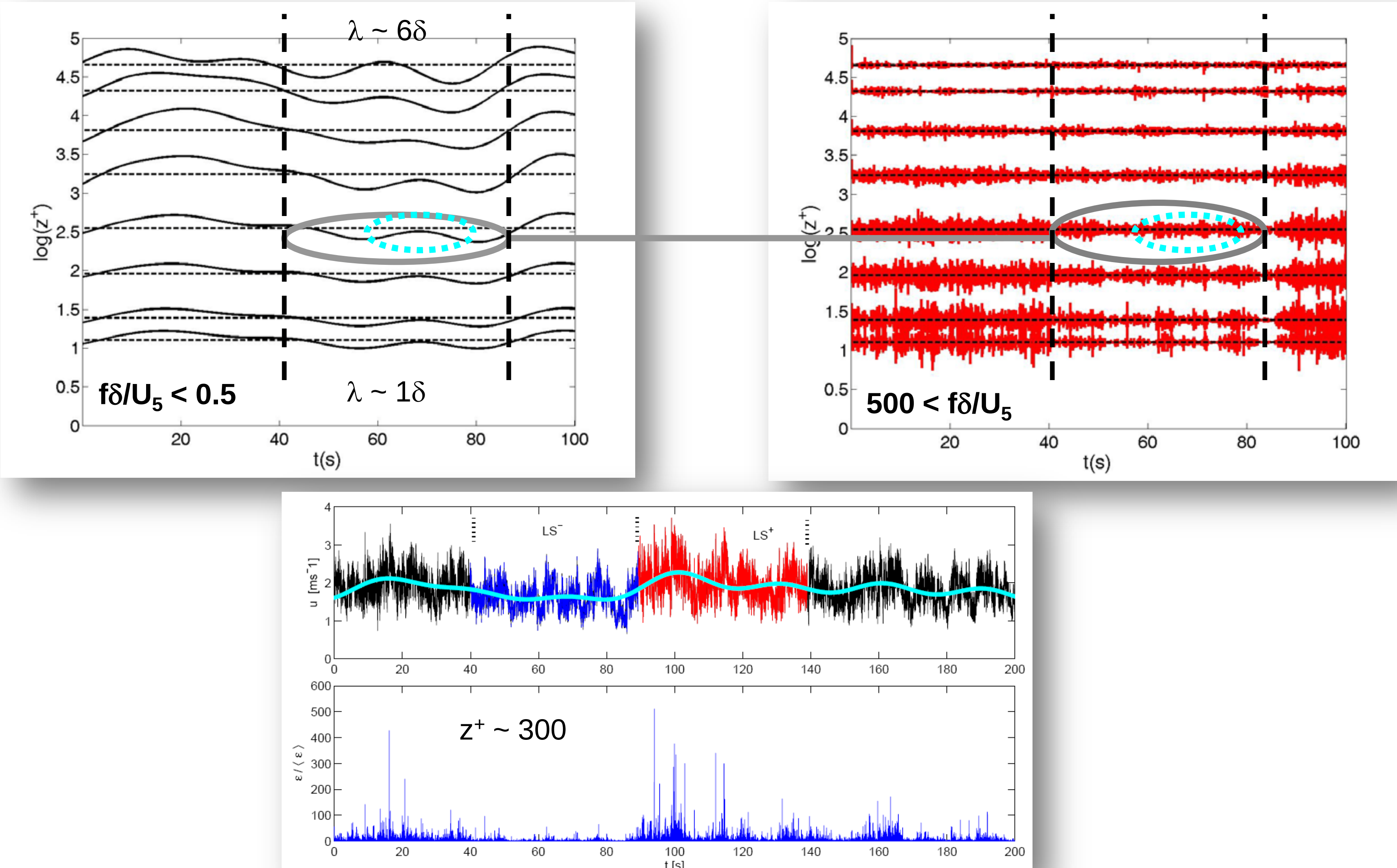
COMPOSITE TEMPORAL RECORD OF U

Sliding window: T=1s



Guala, Metzger & McKeon, Phys. D, 2010

DEMONSTRATION OF AMPLITUDE MODULATION BY FILTERING

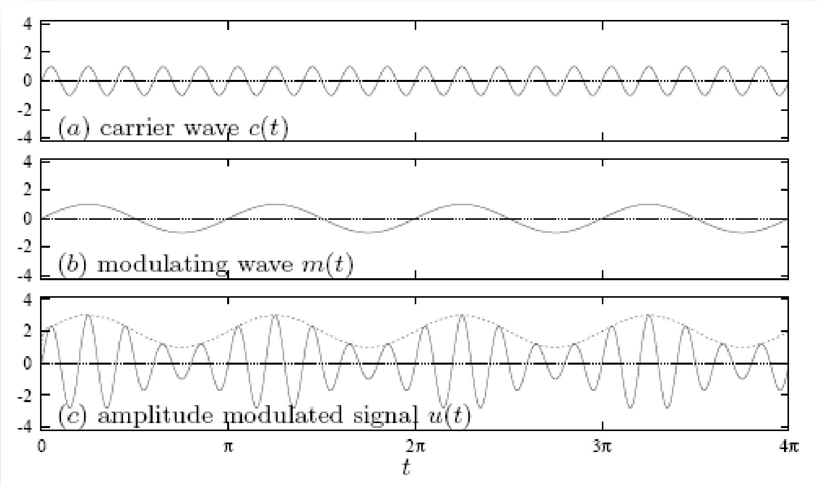


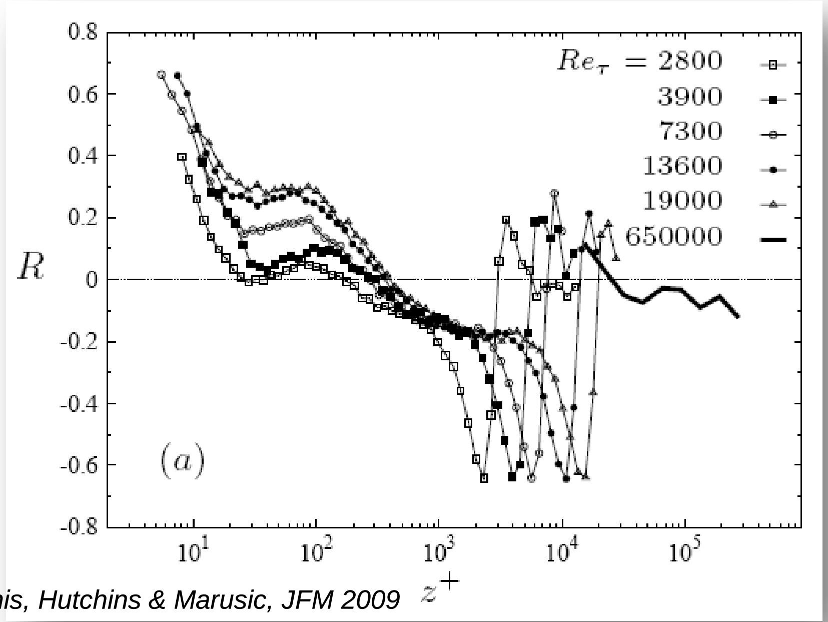
WALL-NORMAL VARIATION OF MODULATING EFFECT

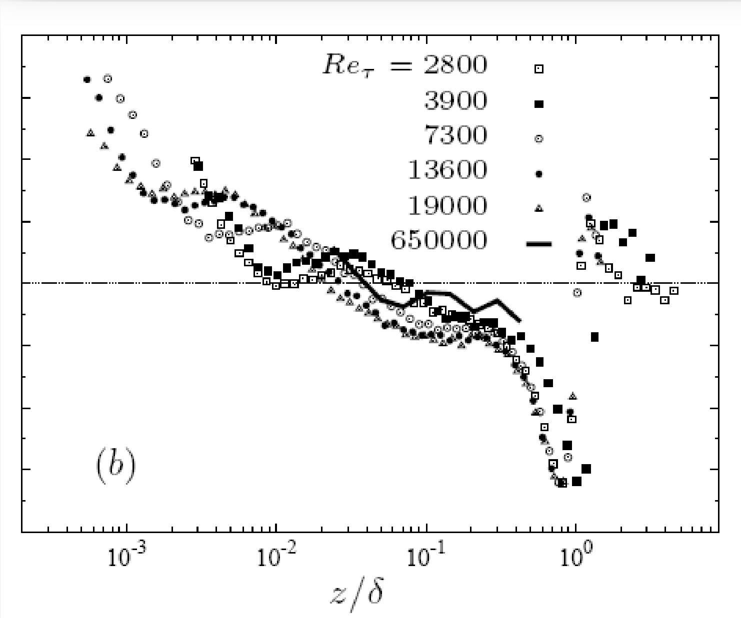
Magnitude of amplitude modulation changes with wall-normal distance

- Bandyopadhyay & Hussain (1987)
- Mathis et al (2009)

$$R = \frac{\overline{u_L^+ E_L^+}}{\sqrt{{u_L^+}^2}\sqrt{{E_L^+}^2}}$$





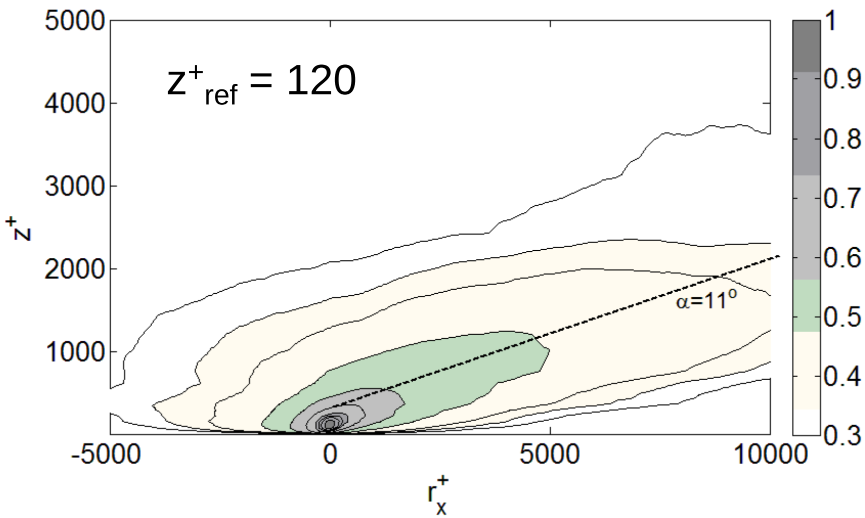


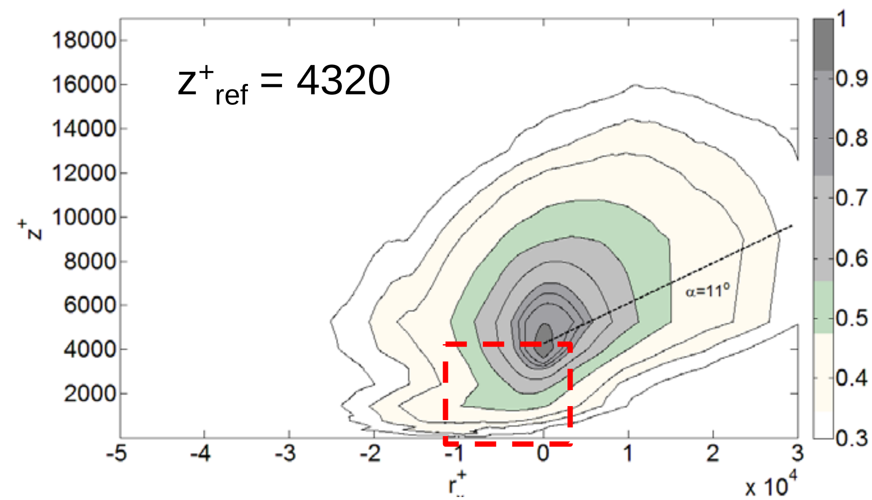
Mathis, Hutchins & Marusic, JFM 2009

Estimate of the dominant VLSM mode shape

Consider the two-point correlation with two reference z^+ locations

$$\rho_{uu}(r_x^+, z^+, z_{ref}^+) = \frac{\Sigma_x u(x, z_{ref}) u(x + r_x, z)}{\sqrt{\Sigma_x u^2(x, z_{ref})} \sqrt{\Sigma_x u^2(x, z)}}$$





Guala, Metzger & McKeon, JFM 2011

EVIDENCE FOR NEAR-WALL STRUCTURE IN THE ASL

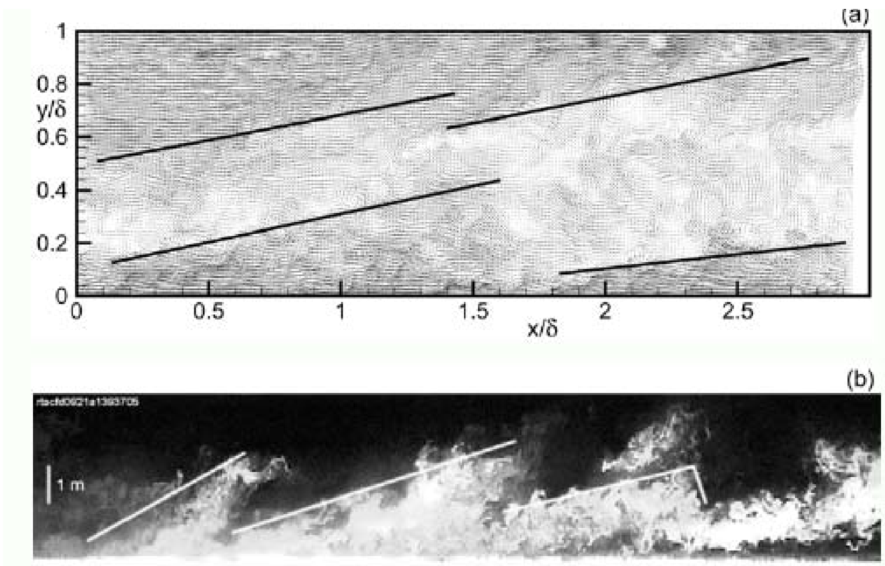
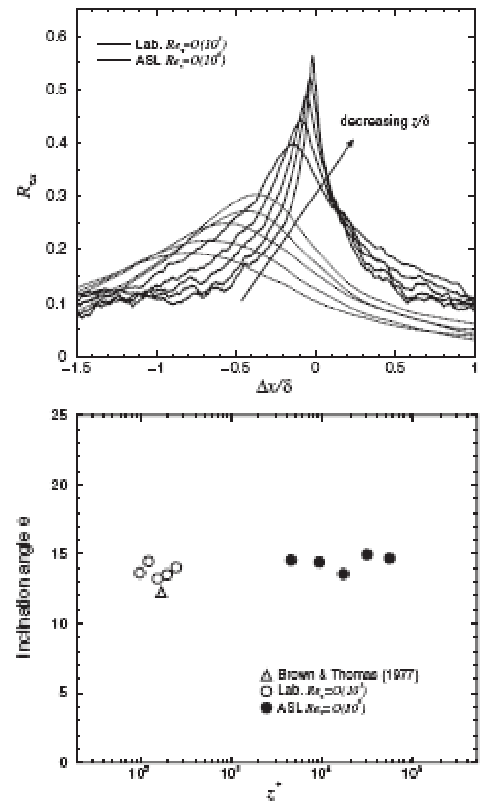


Figure 10. (a) PIV realization in the streamwise–wall-normal plane of a zero-pressure-gradient turbulent boundary layer at $Re_\theta = 7705$ (AMT). Note that the entire boundary layer is shown ($0 < x/\delta < 3$, $0 < y/\delta < 1$). (b) Smoke visualization of the wall-region ($0 < x/\delta < 0.01$, $0 < y/\delta < 0.015$) of the atmospheric boundary layer at $Re_\theta = 9 \times 10^6$. In both cases, air flow is from left to right. A constant convection velocity of $0.79U_\infty$ has been subtracted from the vectors in (a). A hierarchy of ramp-like structures with similar orientation and structure is observed in both figures. The approximate extent of these structures has been indicated with solid lines.

Hommema & Adrian, B. Layer Met. 2003



Marusic & Heuer, Phys. Rev. Letters, 2007

LARGE-SMALL SCALE PHASE RELATIONSHIP: CHANNEL

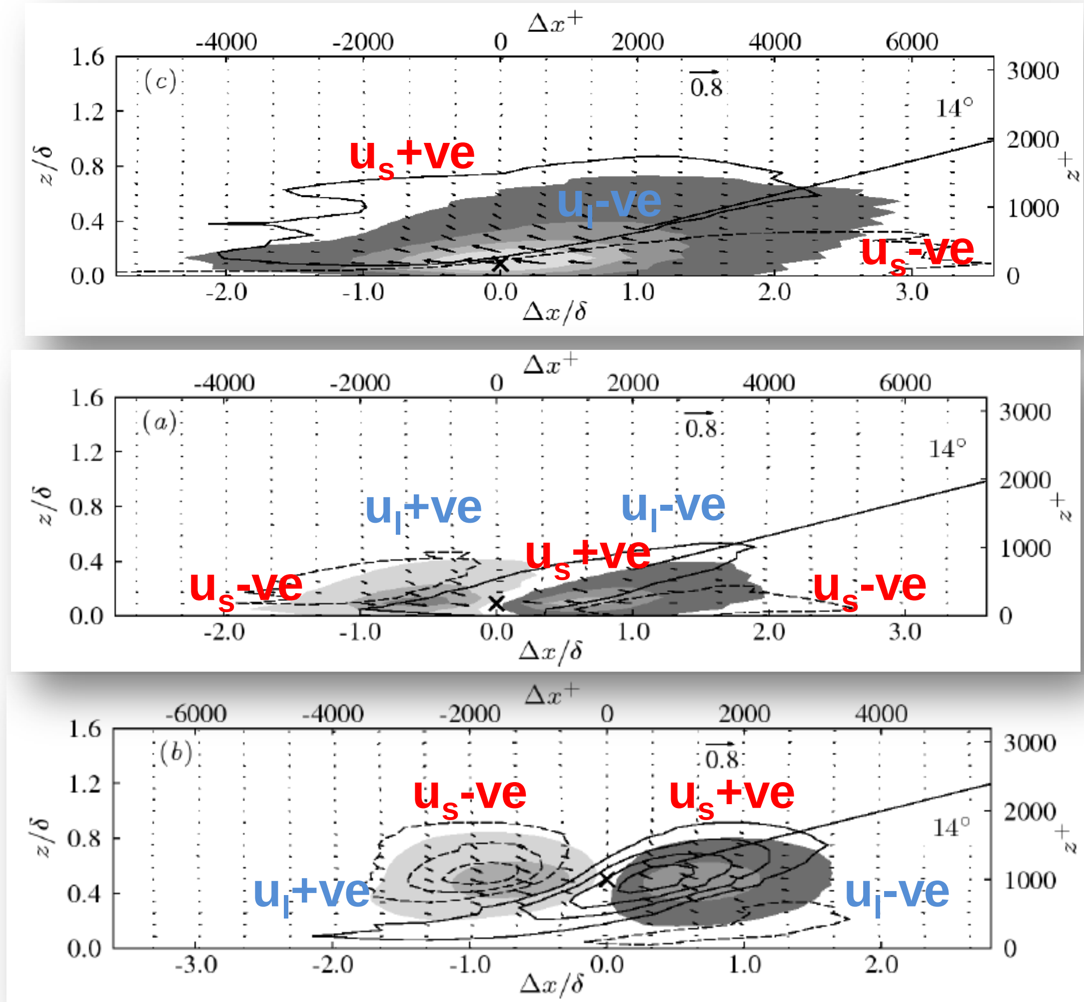
Similar mode shapes found in channel flow LES of Chung & Pullin (2009), $\delta^+ = 2000$

Contours: large-scale velocity field
Lines: small-scale velocity field
(Filter window δ)

Condition 1: $u_L - U < 0$ at $z/\delta = 0.09$

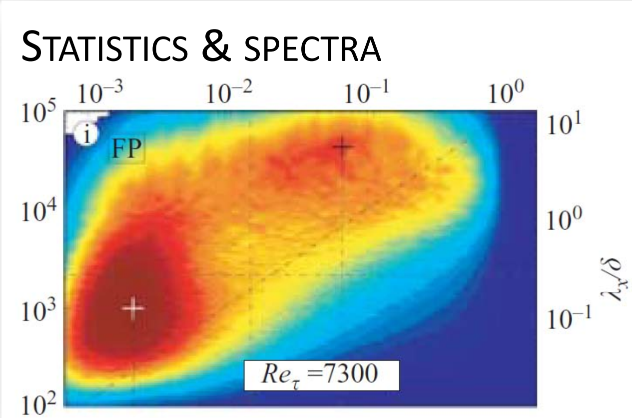
Condition 2: $\frac{\partial u_L}{\partial x} < 0$ at $z/\delta = 0.09$

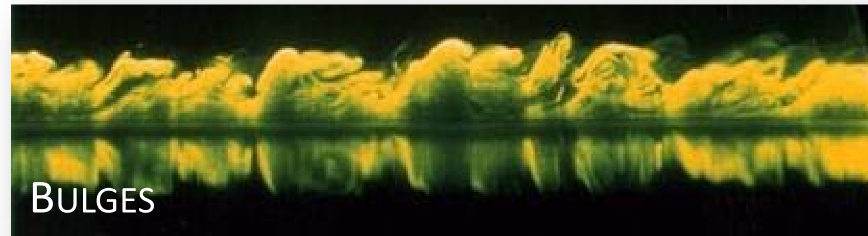
Condition 2: $\frac{\partial u_L}{\partial x} < 0$ at $z/\delta = 0.50$



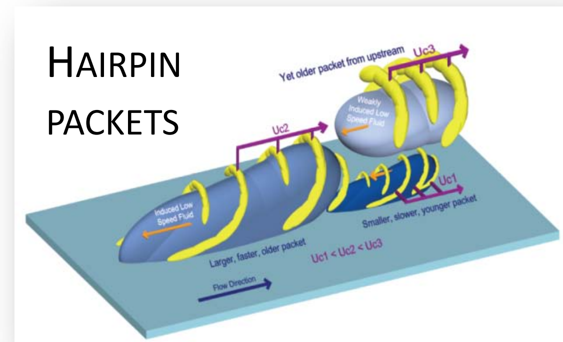
Chung & McKeon, JFM 2010

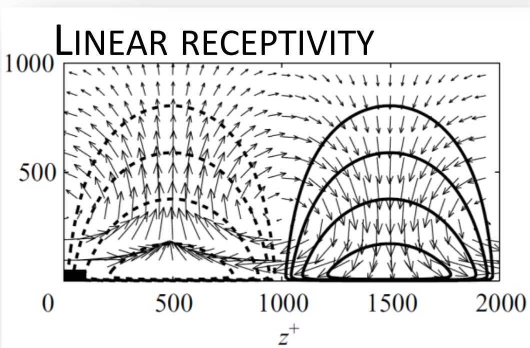
PUTTING IT ALL TOGETHER...

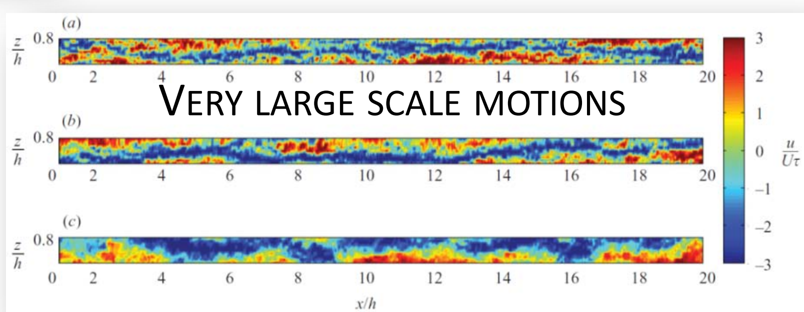




Unified picture







Credits
Hutchins & Marusic
Gad-el-Hak
Adrian et al
Monty et al
Del Alamo & Jimenez

A SIMPLE MODEL FOR PIPE FLOW

- Consider full turbulence field in pipe flow
- Project onto divergence-free basis

$$\dot{\mathbf{v}}(\mathbf{x},\mathbf{t}) = \mathcal{L}\mathbf{v}(\mathbf{x},\mathbf{t}) + \mathbf{f}(\mathbf{x},\mathbf{t})$$

- Consider propagating modes

$$\mathbf{v} = \Sigma_{kn\omega}\mathbf{v}_{kn\omega}e^{i(kx+n\theta-\omega t)}$$

- Write in terms of the linear operator for (k,n,ω)
  - identify $(k,n,\omega)= (0,0,0)$ mode as the turbulent mean profile
  - use experimental data (McKeon *et al*, 2004)

$$0 = \mathbf{f}_{000} - \mathbf{v}_{000} \cdot \nabla \mathbf{v}_{000} + \frac{1}{Re}\nabla^2 \mathbf{v}_{000}$$ **MEAN FLOW**

$$i\omega \mathbf{v}_{kn\omega} = \mathcal{L}_{kn\omega}\mathbf{v}_{kn\omega} + \mathbf{f}_{kn\omega} \quad \forall (k,n,\omega) \neq (0,0,0)$$ **FLUCTUATIONS**

McKeon & Sharma, JFM 2010

ANALYSIS OF THE FORM OF THE RESOLVENT

- At each wavenumber-frequency combination:

$$\mathbf{v}_{kn\omega} = (i\omega I - \mathcal{L}_{kn\omega})^{-1}\mathbf{f}_{kn\omega}$$

RESOLVENT

$$(i\omega I - \mathcal{L}_{kn\omega})^{-1} = \begin{pmatrix} -ARe^{-1} + ikU - i\omega & B & 0 \\ -B & -ARe^{-1} + ikU - i\omega & 0 \\ \mathcal{D}U & 0 & -ARe^{-1} + ikU - i\omega \end{pmatrix}^{-1}$$

- Determine forcing mode shapes that lead to maximum response using singular value decomposition (SVD) at each (k,n,ω)

- If the operator is low rank, first singular value will be large, i.e. it will dominate the response to forcing

- Pseudospectral rather than a spectral interpretation

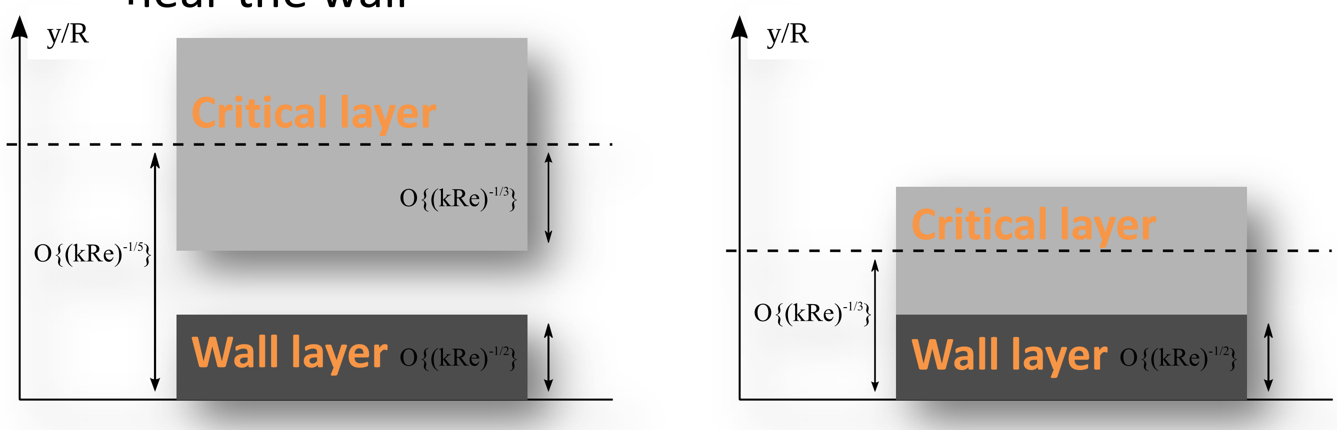
ANALOGY TO CRITICAL LAYER THEORY

RESOLVENT

$$(i\omega I - \mathcal{L}_{kn\omega})^{-1} = \begin{pmatrix} -ARe^{-1} + ikU - i\omega & B & 0 \\ -B & -ARe^{-1} + ikU - i\omega & 0 \\ \mathcal{D}U & 0 & -ARe^{-1} + ikU - i\omega \end{pmatrix}^{-1}$$

Analogy with the Orr-Sommerfeld equations for an unstable flow, where propagating solutions of the Rayleigh equations require viscous modifications at two locations:

- critical layer (where $U(y_c)=U_p$)
- near the wall



UPPER BRANCH **LOWER BRANCH**

Same physical effect for stable flow manifested as high system response with similar modal characteristics

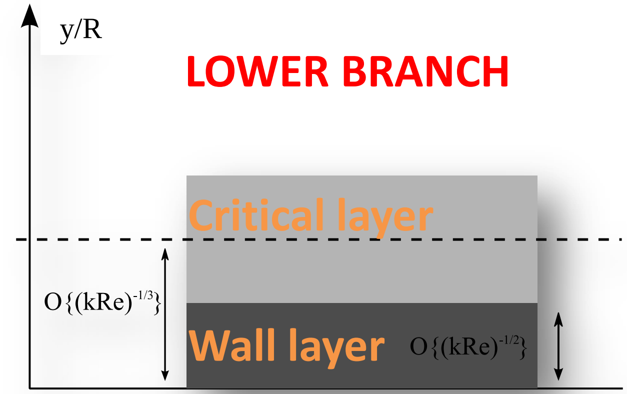
Implications of critical layer analogy

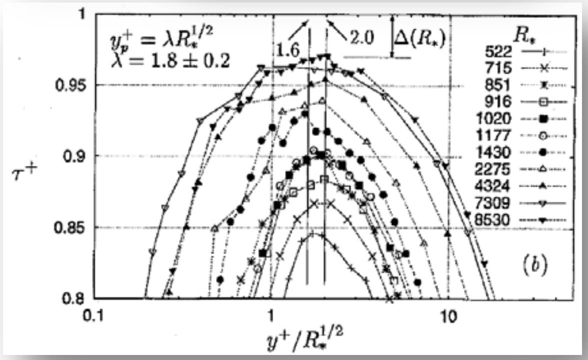
- For the lower branch, we expect
  - a wall layer centered on $y^+ \sim R^{+1/2}$
  - a critical layer centered on $y^+ \sim R^{+2/3}$

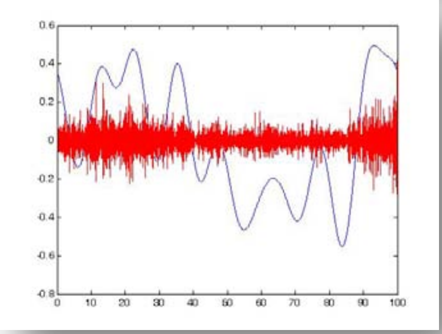
- Sreenivasan (1988), Sirovich *et al* (1990), etc., have also suggested general critical layer behavior

- Wall layer scaling of the Reynolds stress reported by Sreenivasan & Sahay (1997)

- Full description *requires* the coupling between wall and critical layers identified as amplitude modulation

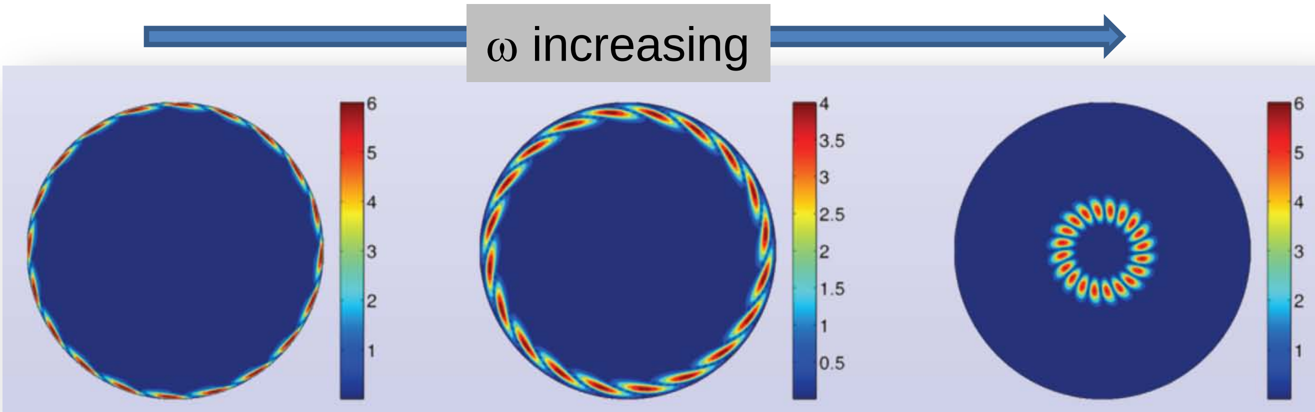


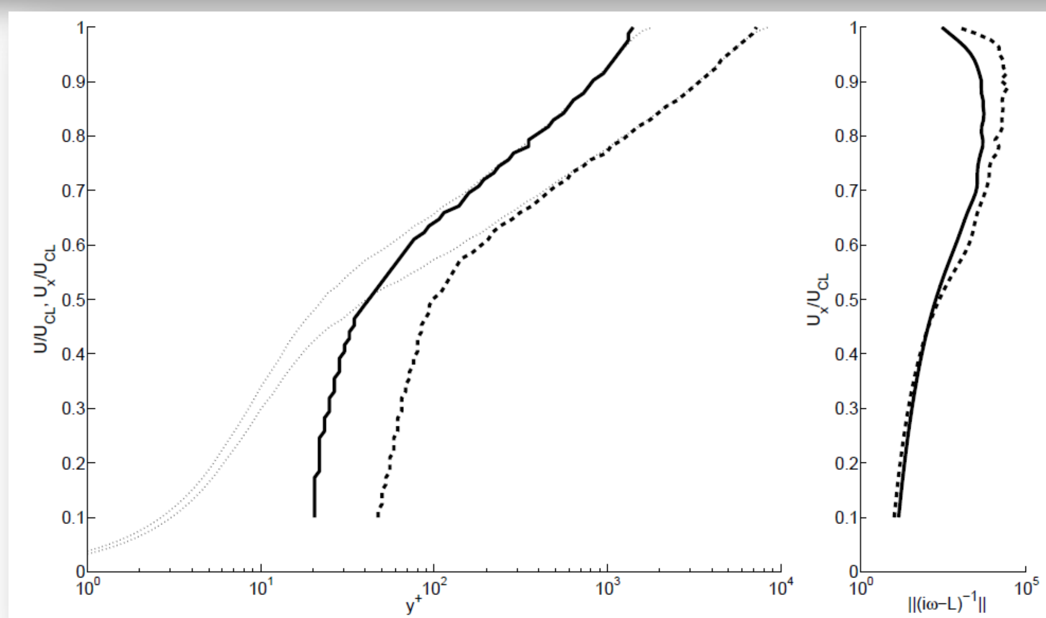




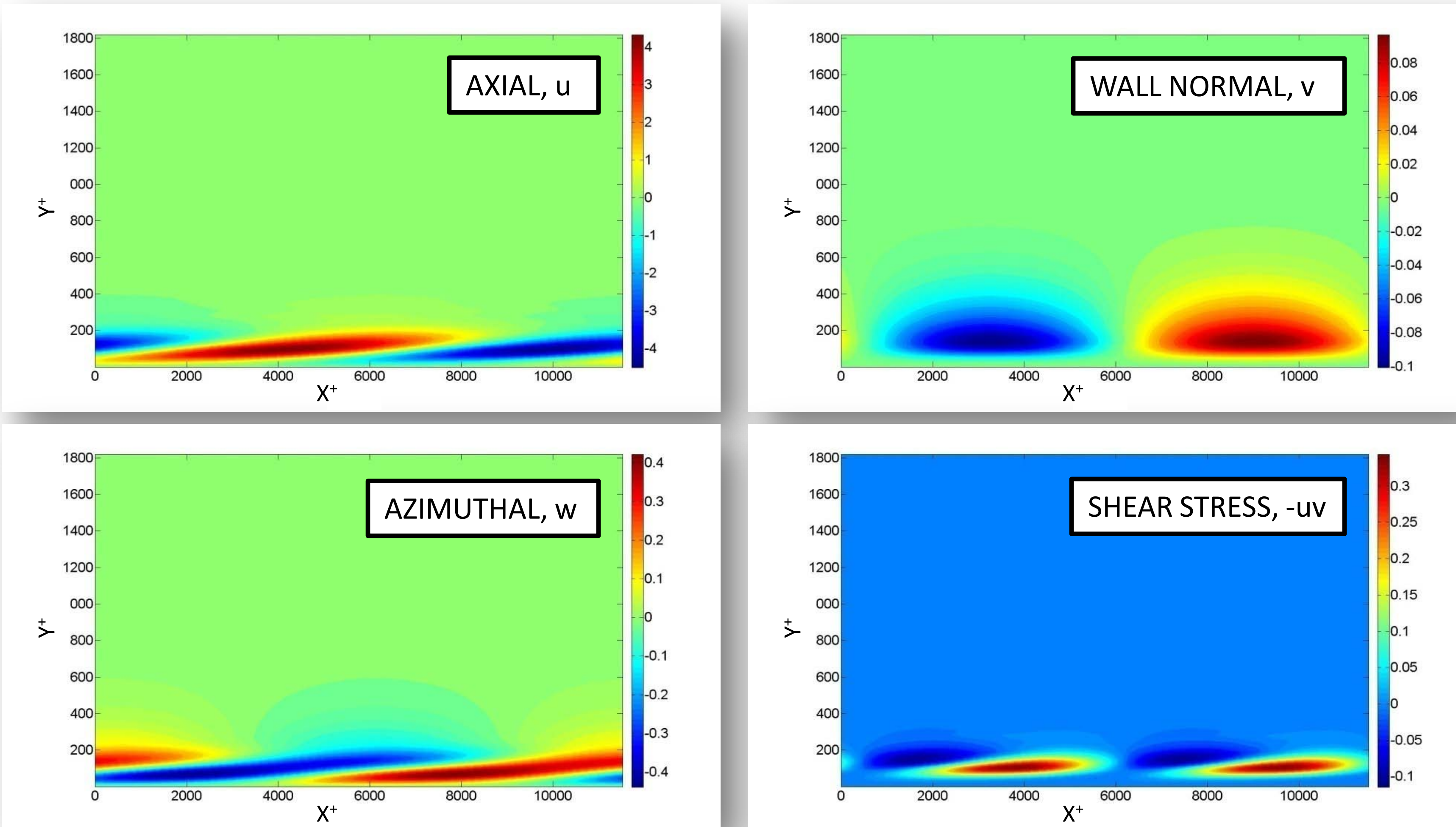
OUTPUT OF THE MODEL: EFFECT OF CONVECTION VELOCITY

- Consider distribution of TKE in pipe cross-section for wavenumbers representative of very large scale motions (VLSMs) with (k,n)=(1,10)

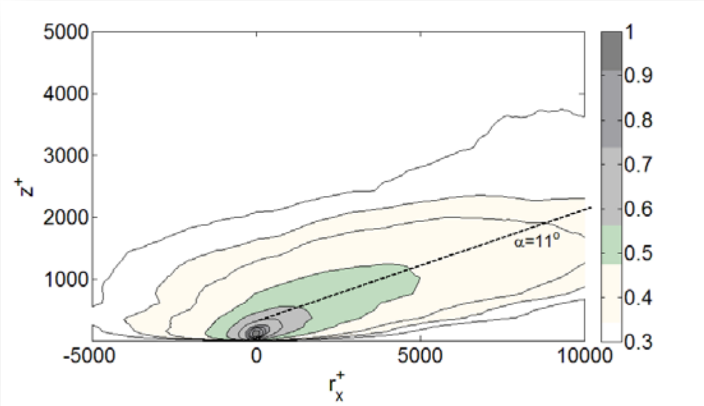


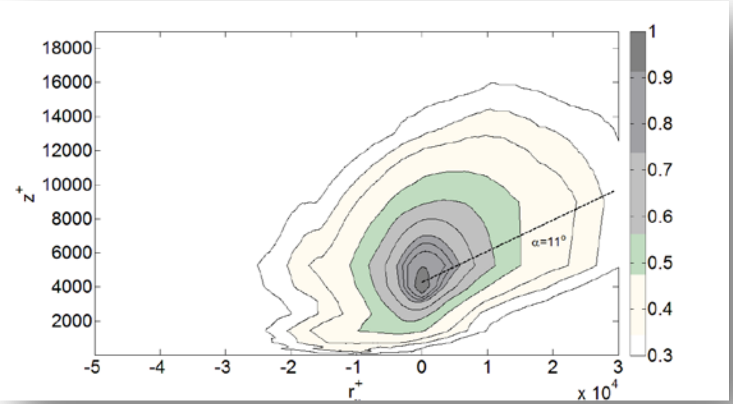


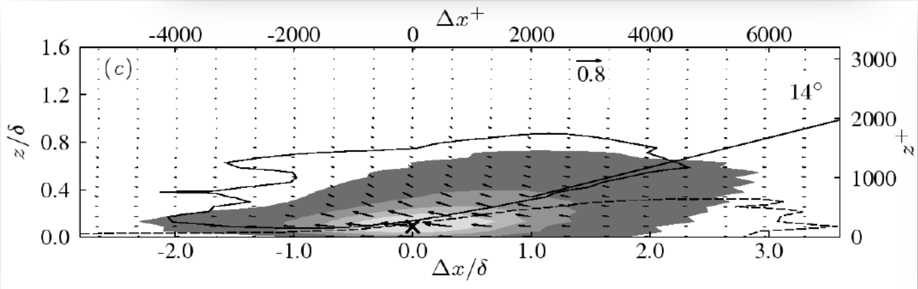
VLSM-LIKE MODE (k,n)=(1,10), U_p = 2/3 U_{CL}, R^+=1800

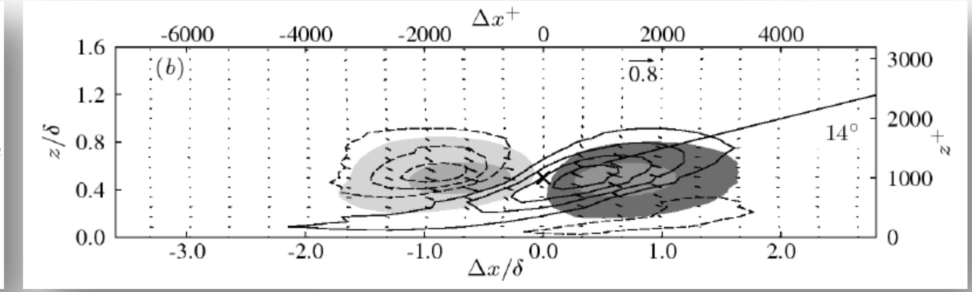


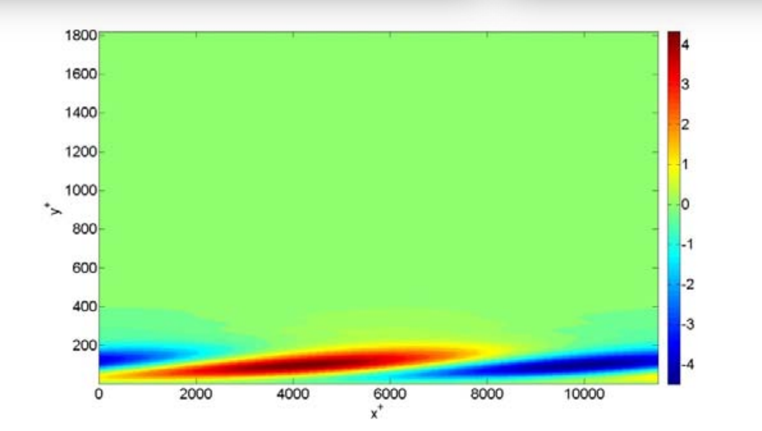
VLSM MODE SHAPE: RECAP









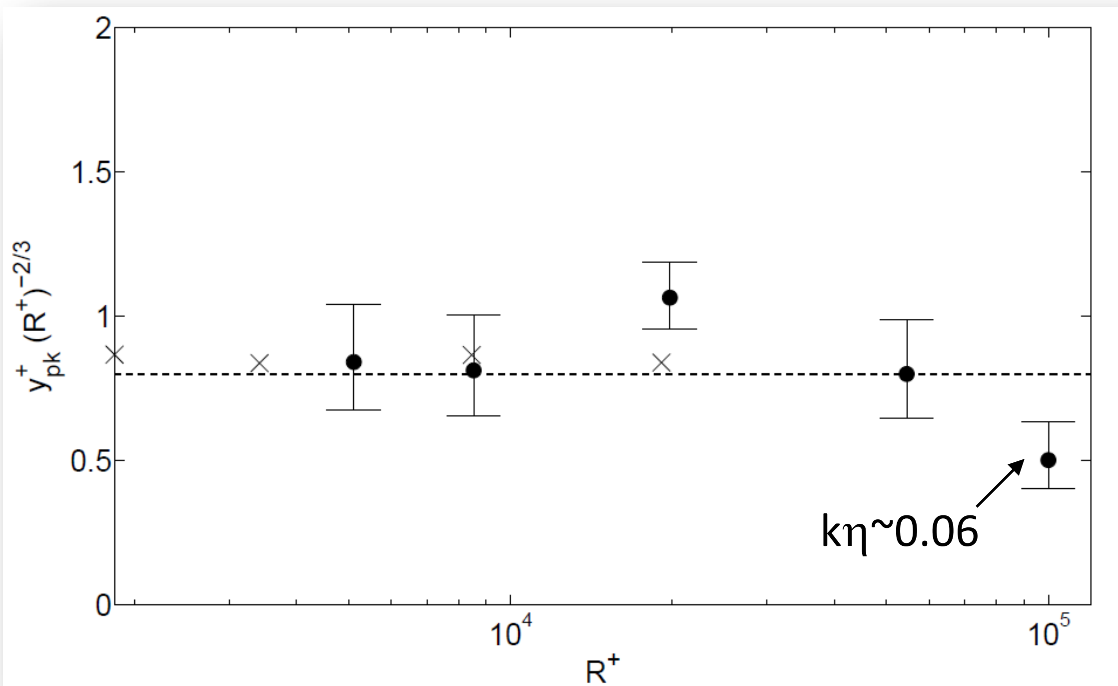


SCALING OF THE VLSMS: PIPE FLOW

- Appropriate length and velocity scales are R and U_{CL}
- $U(y^+_{pk}) = 2/3\ U_{CL}$, irrespective of Reynolds number
- If VLSM convect with mean velocity at y^+_{pk}

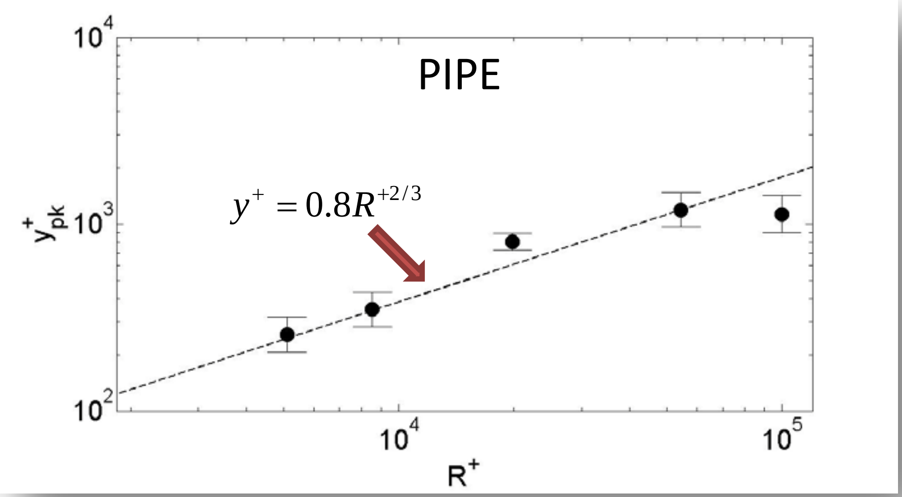
$$\frac{1}{\kappa}\ln y^+ + B = \frac{2}{3}\left(\frac{1}{\kappa}\ln R^+ + B + C\right)$$

$$y^+_{pk} = 0.8R^{+2/3}$$

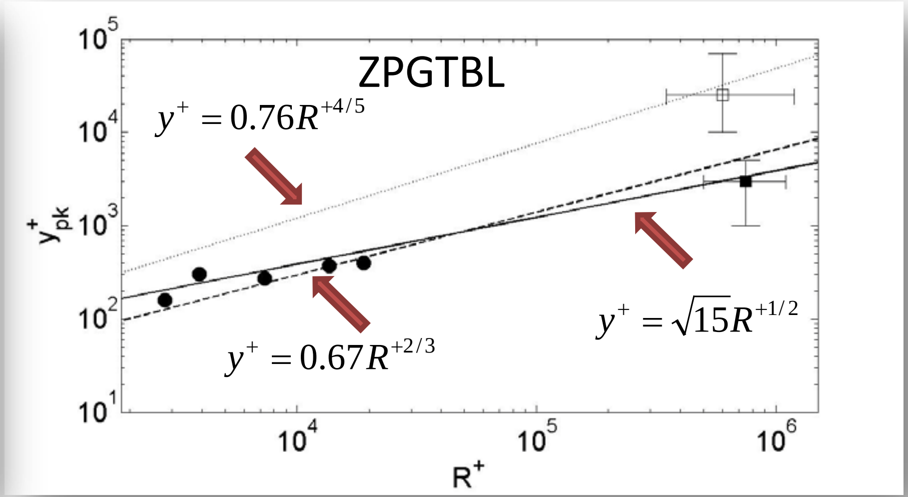


Data from McKeon, AIAA 2008-4237

Extension to other flows



McKeon, AIAA 2008-4237



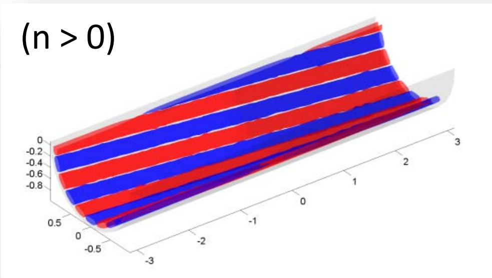
Mathis et al, JFM 628 2009

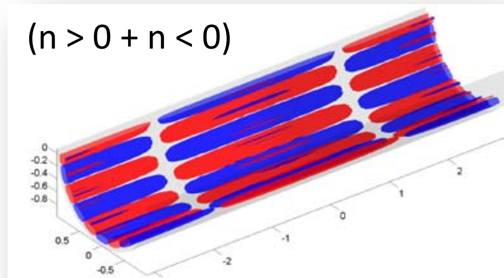
- $R^{+2/3}$ scaling works well for pipe flow
- $R^{+1/2}$ is significantly better for the turbulent boundary layer data of Mathis *et al* (2009)
- Suggests some difference in the critical layer analogy between flows

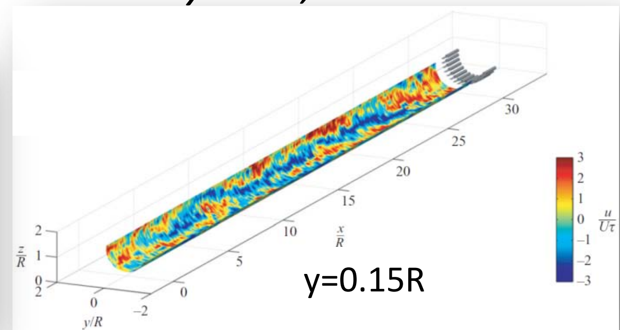
STRUCTURE: IDENTIFYING THE VLSMs

Model – isosurfaces of u

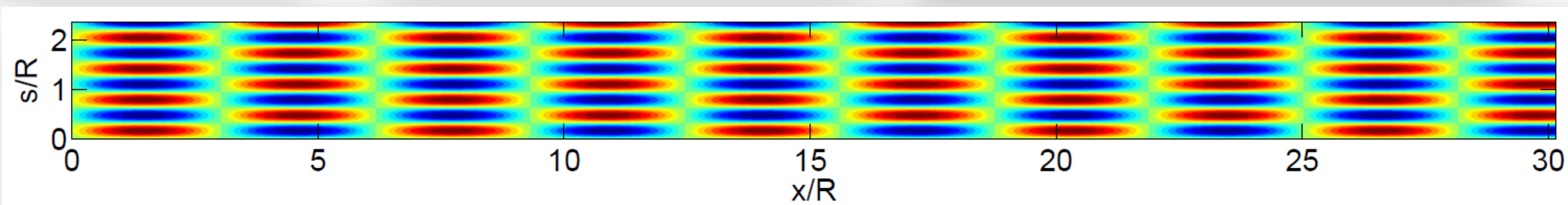
Monty et al, 2007



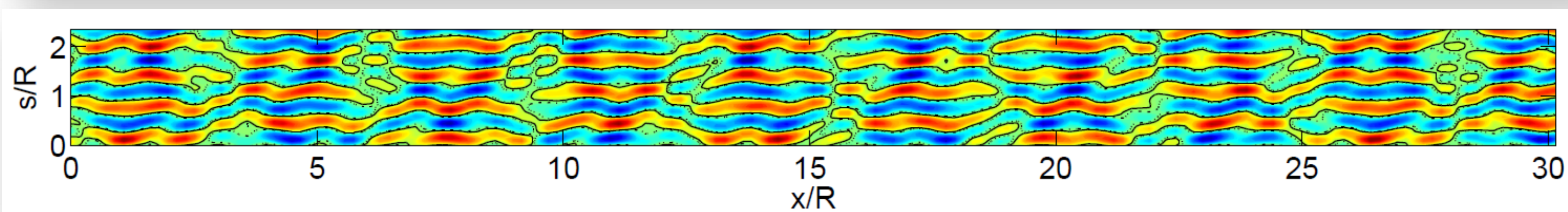




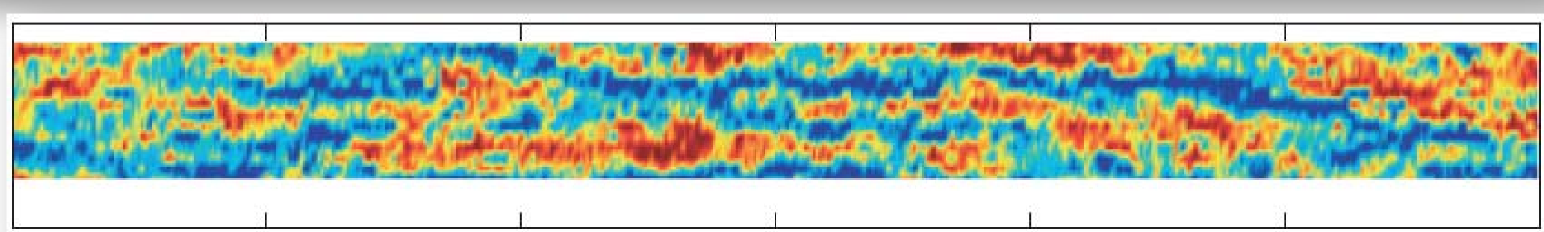
VLSM mode only



3 modes



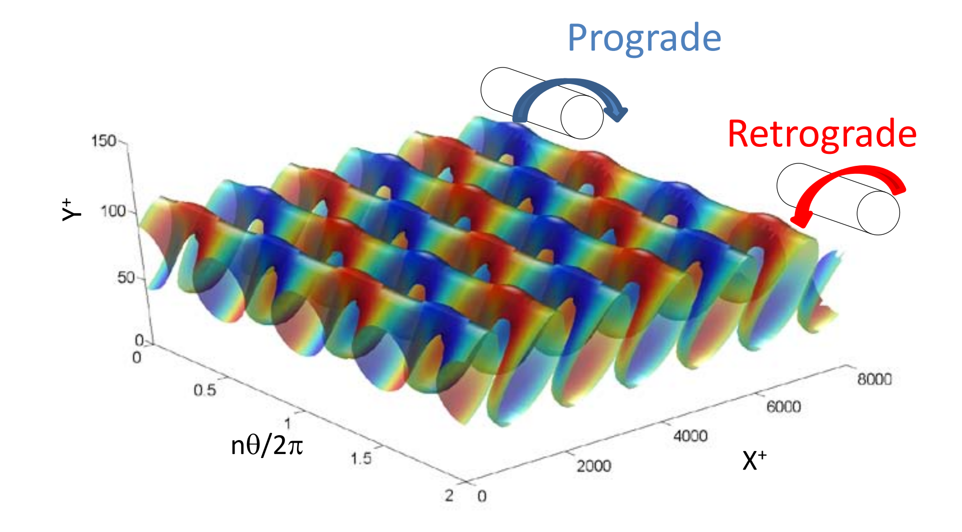
Monty et al



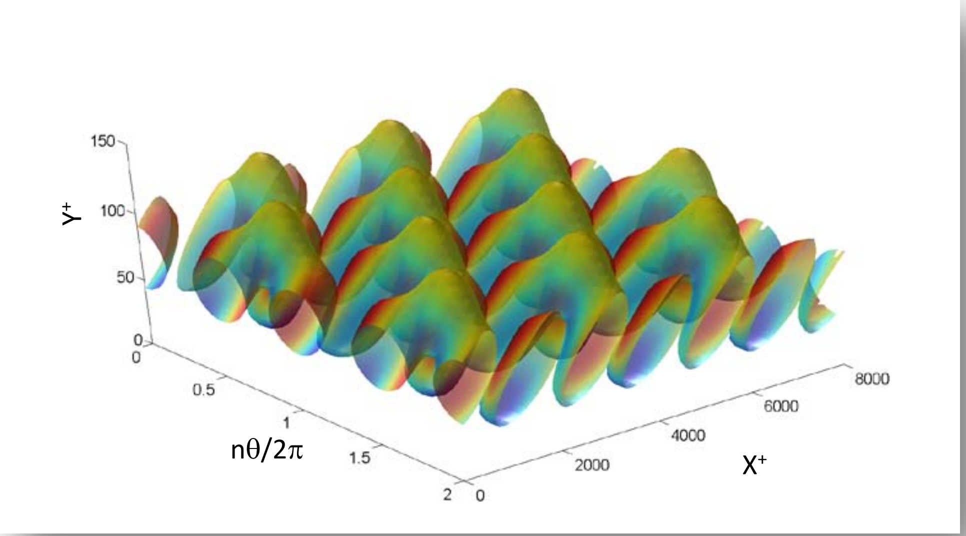
APPEARANCE OF HAIRPIN VORTICES

$$\lambda_{ci} = \frac{1}{2}\text{Im}\left(\sqrt{\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)^2 - 4\left(\frac{\partial u}{\partial x}\frac{\partial v}{\partial y} - \frac{\partial u}{\partial y}\frac{\partial v}{\partial x}\right)}\right)$$

Hairpins with both sense of rotation are naturally associated with the wall velocity response modes



Superposition of mean shear leads to suppression of retrograde vortices



McKeon, Sharma & Jacobi, ArXiV 2010

CONCLUSIONS

- VLSMs become increasingly energetically dominant as Re increases
  - ASL data, channel LES and pipe model in broad agreement on mode shape
  - In general, small scale energy ~ $-\frac{\partial u_L}{\partial x}$ near the wall
- Study of propagating modes leads to a **linear** model where critical layer concepts become relevant
  - Analysis does not require high power computing
  - Can be extended to high Reynolds number
- Our framework explains several results in the literature
  - R and U_{CL} are the correct scales for VLSMs
  - Resolvent model predicts large-scale/small-scale interactions near the wall, spectral scaling, inner and outer scaling (not discussed here)
  - Dominance of different branches appears to depend on geometry
- New results
  - Prediction of Re-dependence of VLSM peak
  - Hairpin vortex structure predicted (uniform distribution of prograde and retrograde vortices)
- Broad implications for wall turbulence