PECASE: MULTI-SCALE EXPERIMENTS AND MODELING IN WALL TURBULENCE

AFOSR # FA9550-09-1-0701 (P.M. J. Schmisseur)

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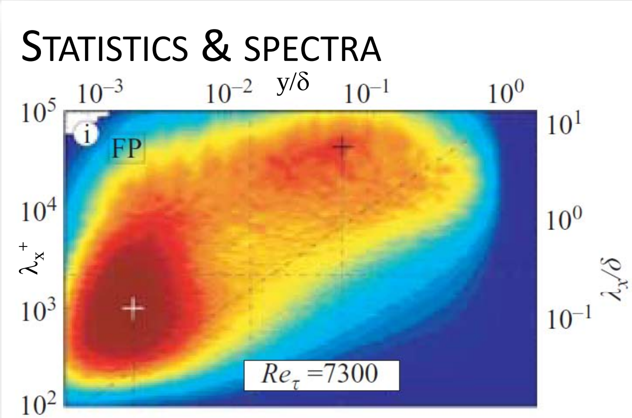
OBJECTIVES

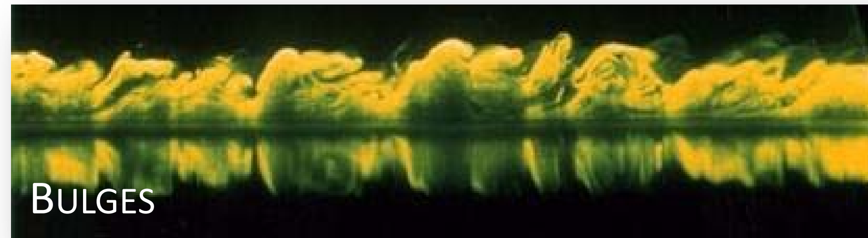
Experimental & analytical investigation into building blocks of wall turbulence

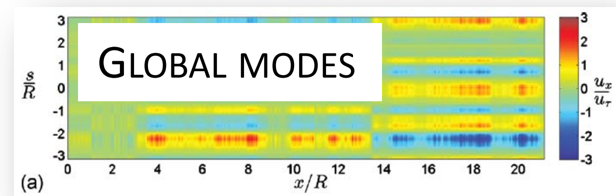
Attempt to unify statistical and spectral understanding via explicit description of turbulent flow field in physical (x,y,z) and spectral (k,n,ω) space

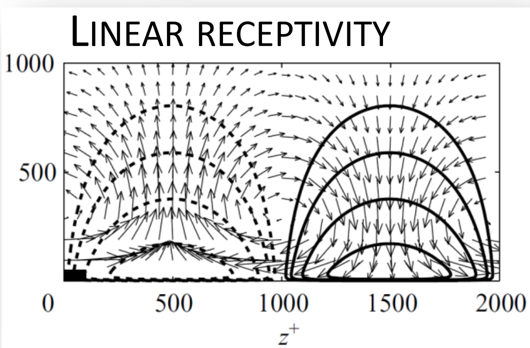
- Formulation of a multi-scale model of wall turbulence
  - singular value decomposition of the linear operator governing a canonical wall-bounded turbulent flow (*McKeon & Sharma, 2010*)
- Experimental investigation of spatio-temporal spectrum
  - TRPIV (*LeHew et al, 2011*)
- Investigation of response of ZPGTBL to “dynamic” roughness
  - Spatially-impulsive, time dependent wall perturbation (*Jacobi & McKeon, 2011*)
- Maintenance of the mean velocity profile
  - Two-dimensional, three-component, 2D/3C, model (*Bourguignon & McKeon, 2011*)

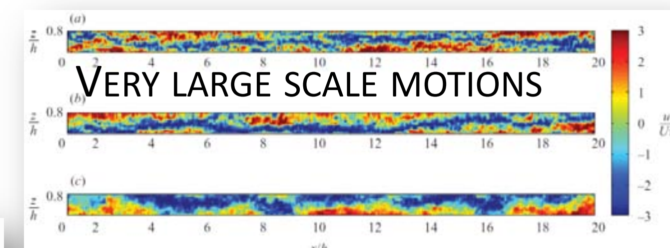
TOWARDS THE BUILDING BLOCKS OF TURBULENCE

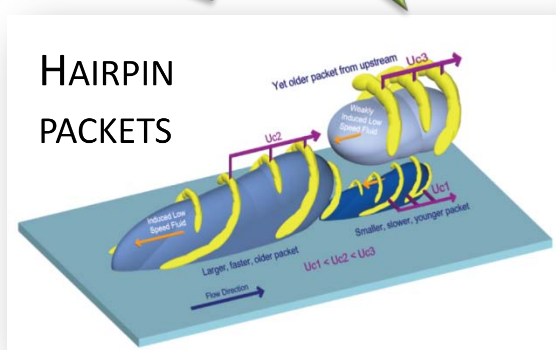








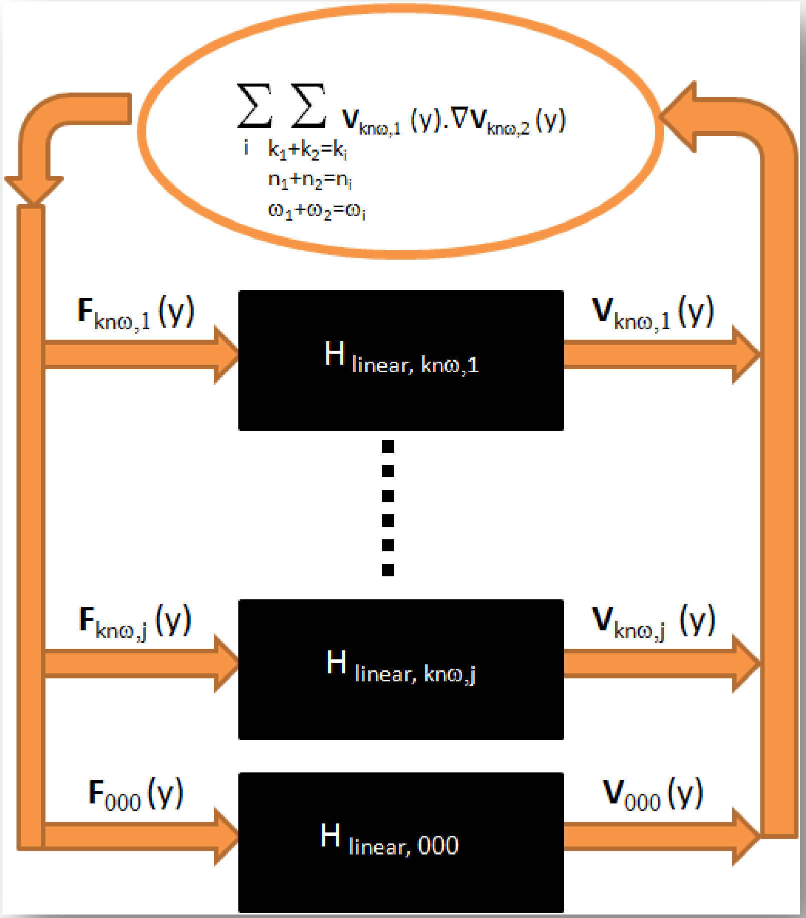


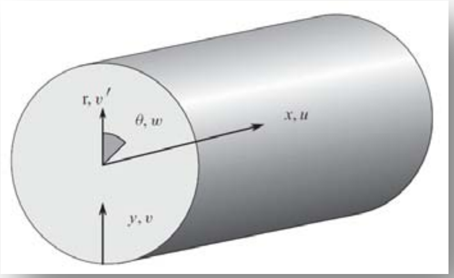


"So, actually the elephant has all the features you mentioned…"

Credits, CW from top left
Hutchins & Marusic
Gad-el-Hak
Hellstroem, Sinha & Smits
Monty, Stewart, Williams & Chong
Adrian, Meinhart & Tomkins
Del Alamo & Jimenez

OBJECTIVES –CARTOON FORM



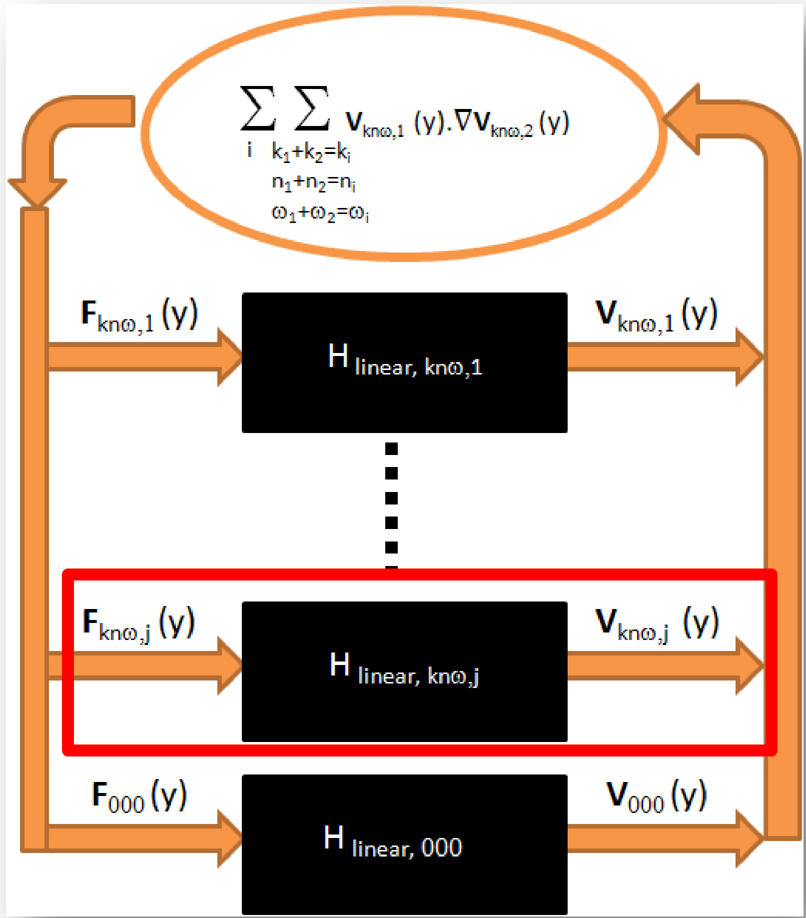


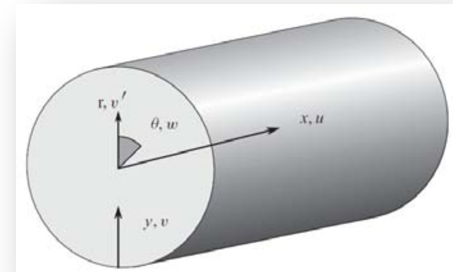
Assume propagating modes with (k,n,ω) in a divergence-free basis

$$v(r,x,\theta,t) = \frac{1}{2\pi} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} c_{mkn\omega}\xi_m(r) e^{i(\omega t\text{-}kx\text{-}n\theta)} dk\, d\omega \qquad v_{kn\omega} = \left(v, e^{i(\omega t\text{-}kx\text{-}n\theta)}\right)$$

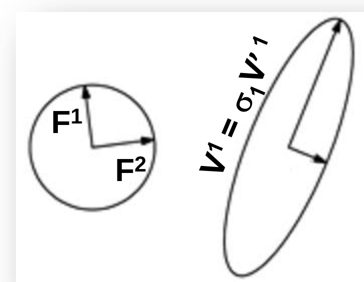
McKeon et al, J. Fluid Mech. 2004
McKeon & Sharma, J. Fluid Mech. 2010

WORK TO DATE: I





Identify F(y) which leads to largest amplification – assume this appears in and dominates real flow



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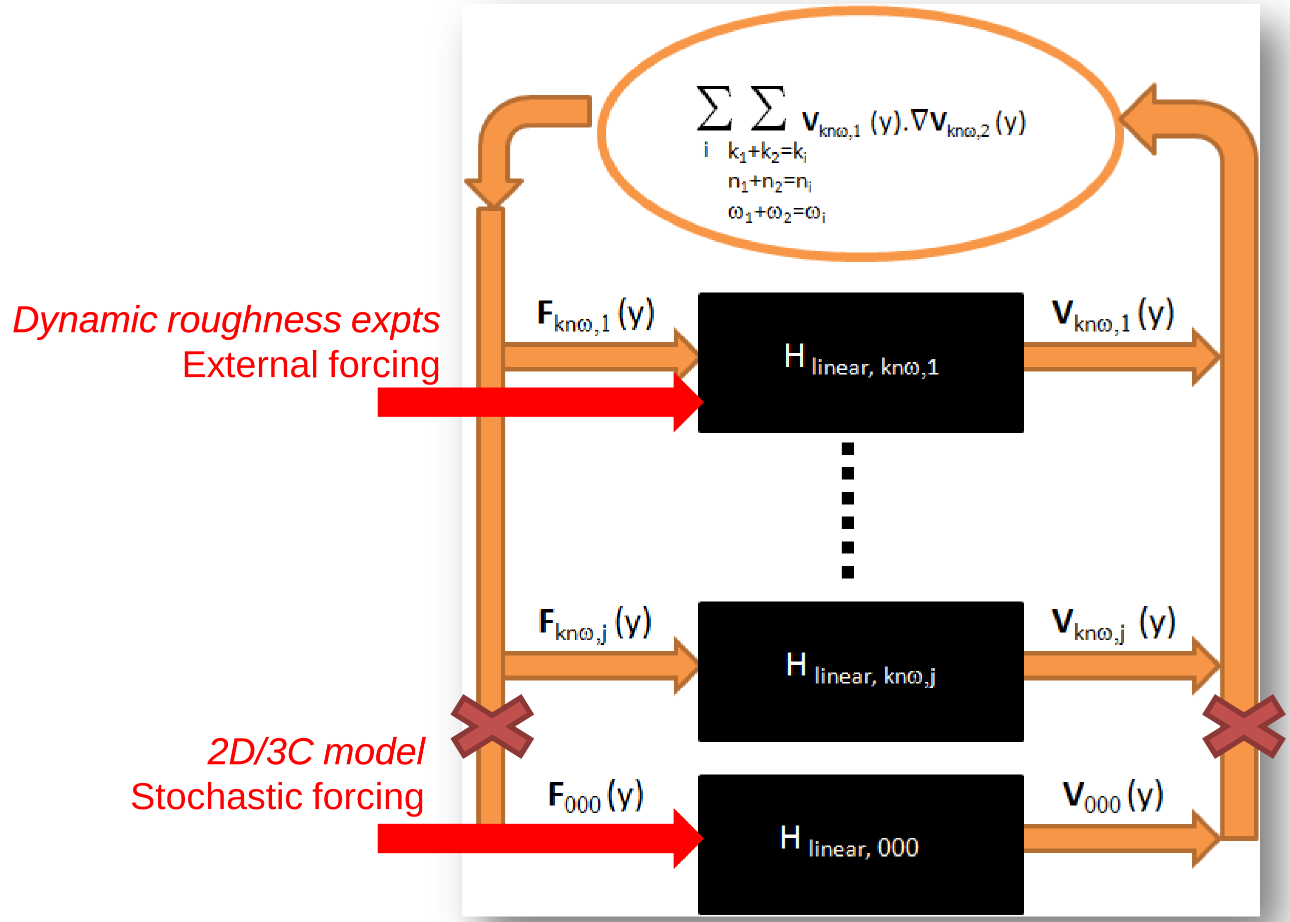
Work to date: II



Jacobi & McKeon, J. Fluid Mech. 2011
Gayme et al, J. Fluid Mech. 2010
Bourguignon & McKeon, Phys. Fluids 2011

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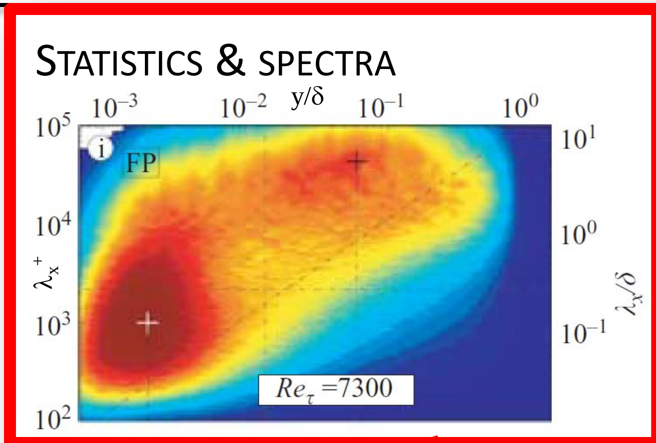
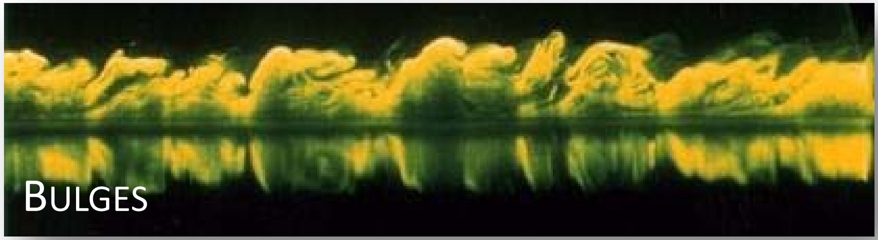
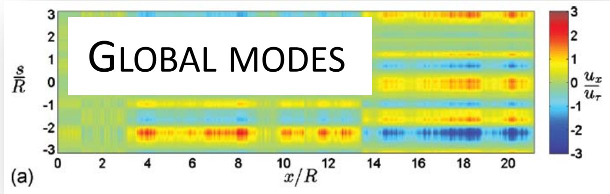
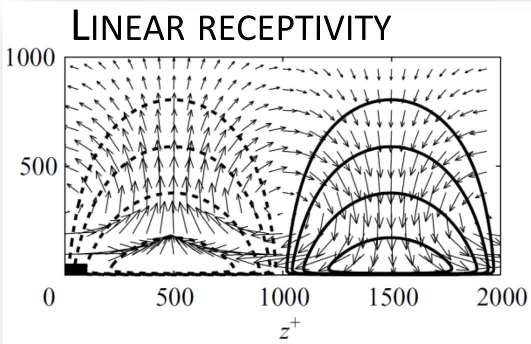
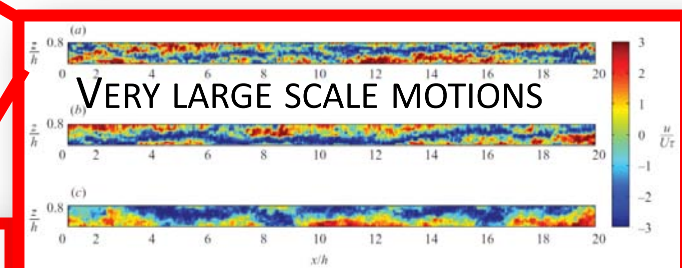
TOWARDS THE BUILDING BLOCKS OF TURBULENCE

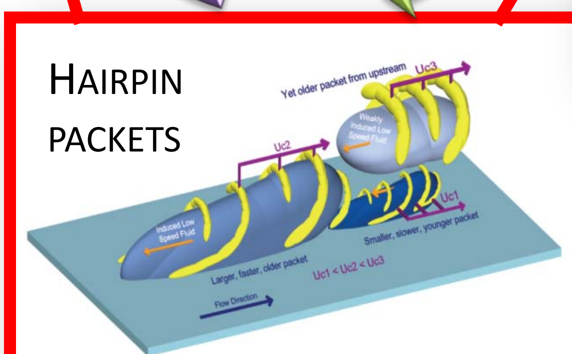












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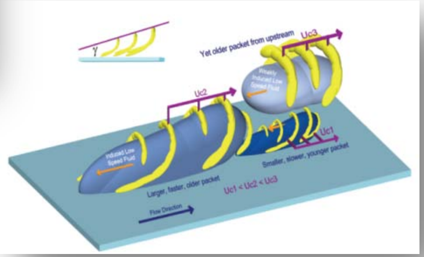
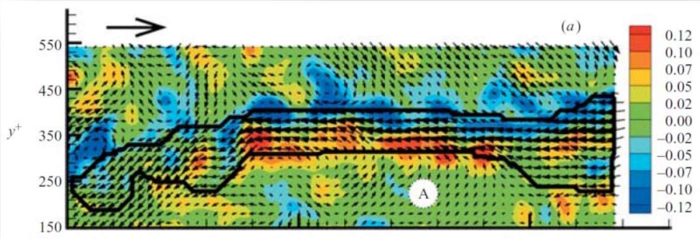
BACKGROUND: VORTICAL STRUCTURE IN WALL TURBULENCE

- Hairpin vortices and the attached eddy model (Theodorsen, 1952; Townsend, 1976; Perry & Chong, 1982, et al)
- Vortex packets, constant momentum zones, alignment of vortices along internal shear layers (Adrian, Meinhart & Tomkins, 2000)
- Packet alignment in wall-parallel planes (Ganapathisubramani, Longmire & Marusic, 2003; Tomkins & Adrian, 2003)
- Prograde and retrograde vortices (Falco, 1977; Carlier & Stanislas, 2005; Natrajan, Wu & Christensen, 2007)

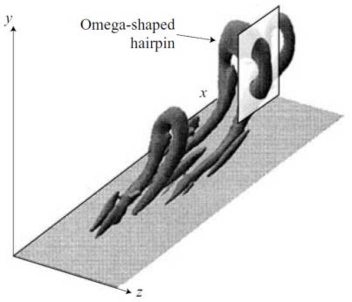
Theodorsen (1952)



Adrian et al (2000)

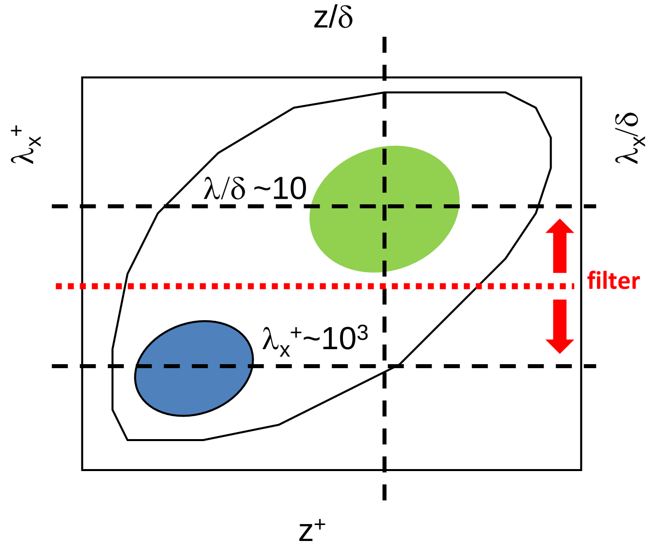


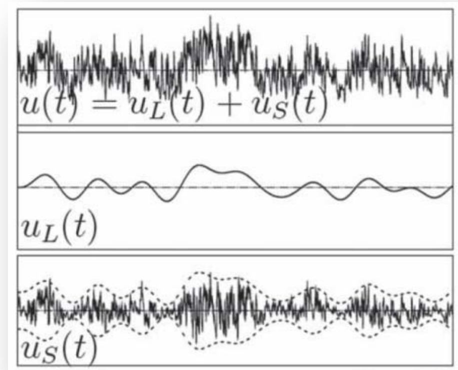
Ganapathisubramani et al (2003)



Natrajan et al (2007)

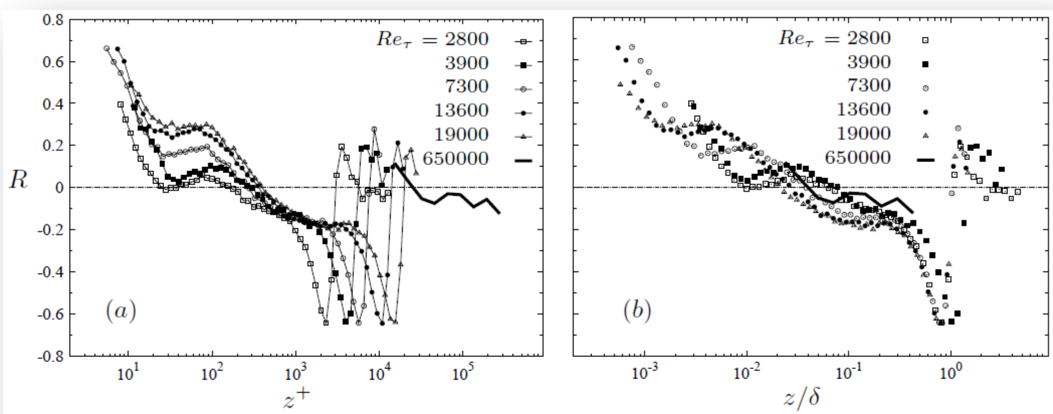
Background: Amplitude Modulation and Skewness

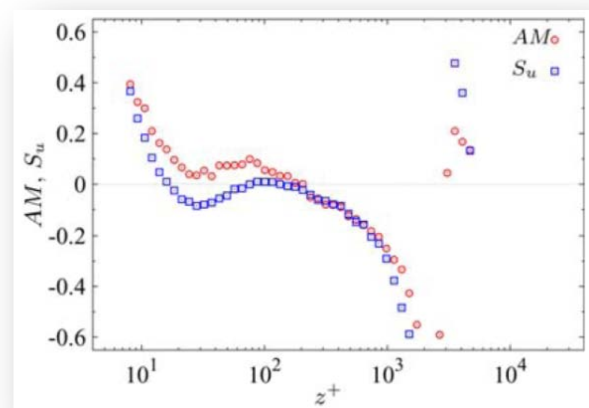




$$AM(z^+) = \frac{\overline{u_L^+ E_L(u_S^+)}}{\sqrt{\overline{u_L^{+2}}}\sqrt{\overline{E_L(u_S^+)^2}}}$$

$$\hat{S}_u(y) = \frac{\langle u^3 \rangle}{\langle u^2 \rangle^{3/2}}$$



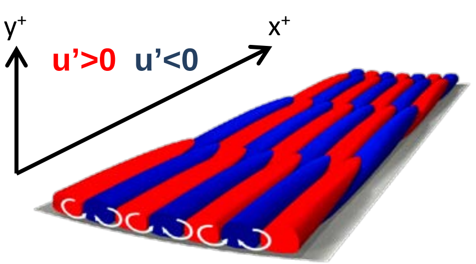


Mathis, Hutchins & Marusic, J. Fluid Mech. 2009
Marusic, Mathis & Hutchins, Science 2010
Mathis, Marusic, Hutchins & Sreenivasan, Phys. Fluids 2011

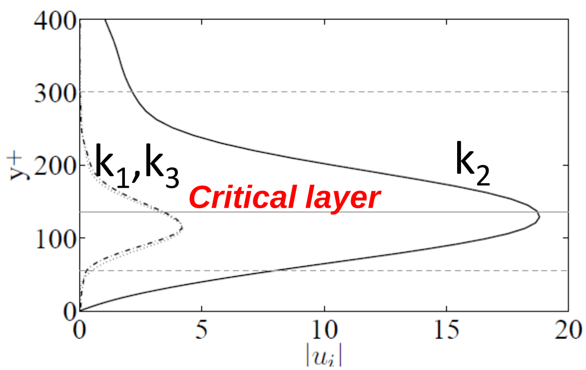
Shape of the response modes

$$v(r,x,\theta,t)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}c_{mkn\omega}\xi_m(r)e^{i(\omega t-kx-n\theta)}dk\,d\omega$$

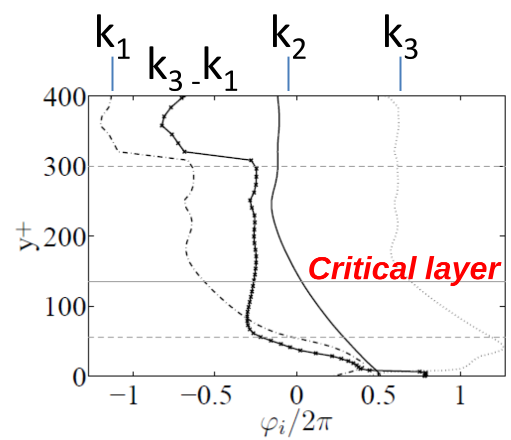
- Select three velocity response modes, $\mathbf{v}_i$, and linearly superpose
- Wavenumber/frequency combinations are triadically consistent: $k_3=k_1+k_2$, $n_3=n_1+n_2$, $c_3=c_1+c_2$,
- "Ideal"/persistent combination: all modes have the same convection velocity



Sample mode shape



Amplitude distributions



Phase distributions

SHAPE OF THE RESPONSE MODES

(k, n, c, A) *u* *v* *<-uv>*

k$_1$

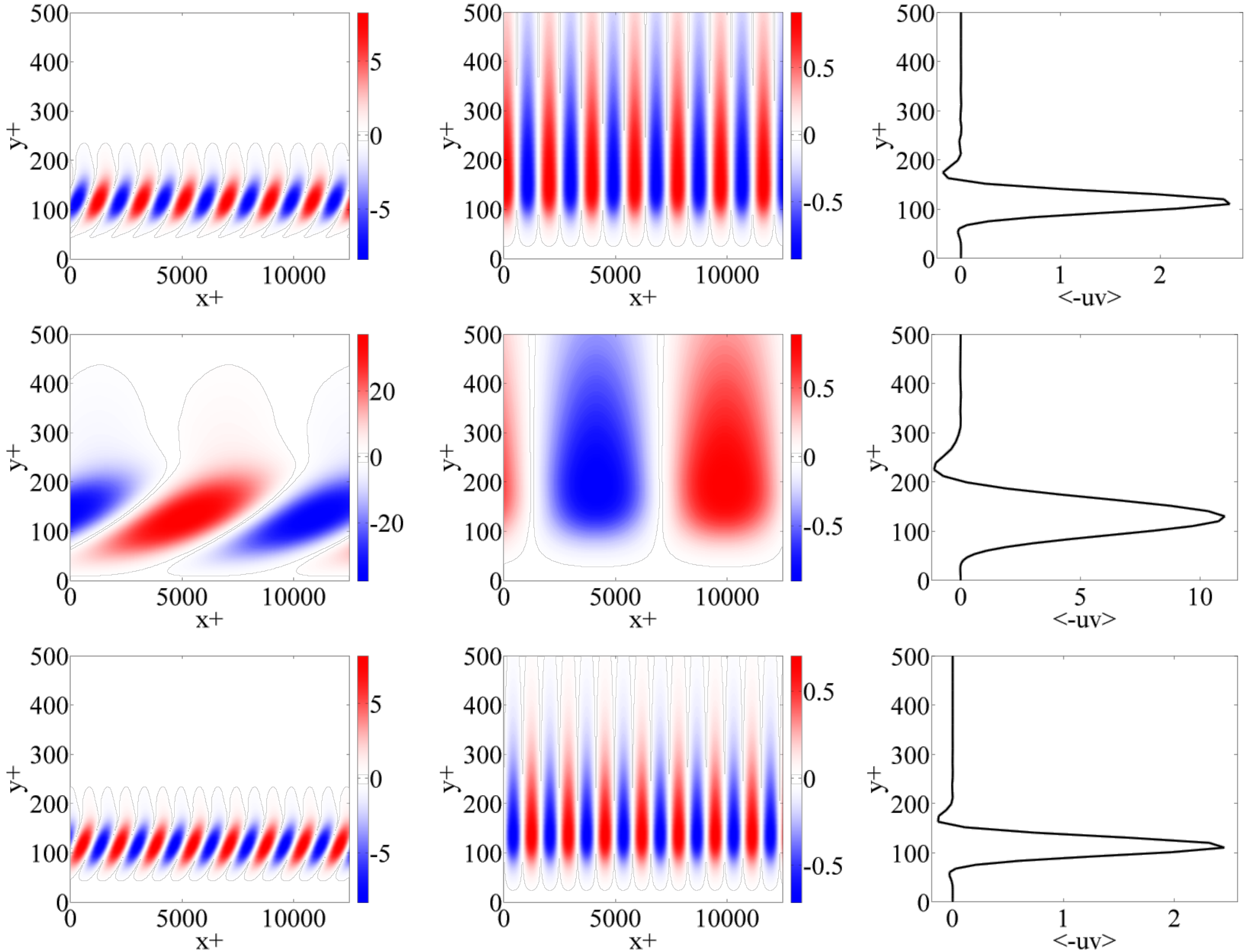
(+/- 6 , +/-6, 2/3, -1.00i)

k$_2$

(+/- 1 , +/- 6, 2/3, 4.50)

k$_3$

(+/- 7, +/-6, 2/3, 0.83i)



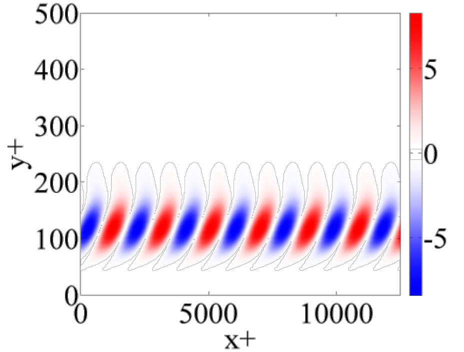
STRUCTURE FROM RESPONSE MODES

(k, n, c, A)

u

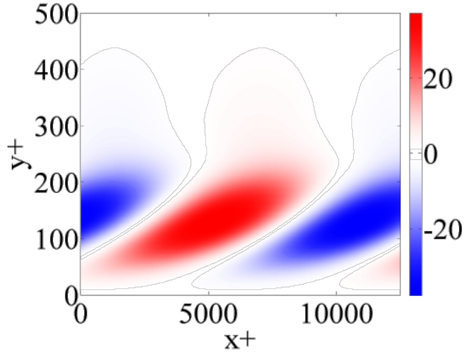
k$_1$

(+/- 6 , +/-6, 2/3, -1.00i)



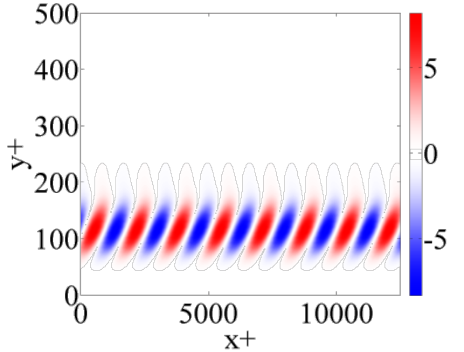
k$_2$

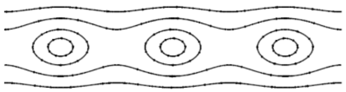
(+/- 1 , +/- 6, 2/3, 4.50)



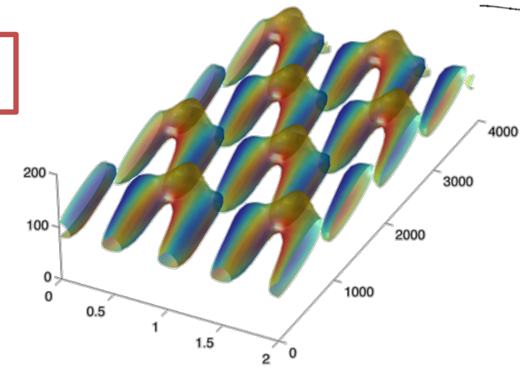
k$_3$

(+/- 7, +/-6, 2/3, 0.83i)



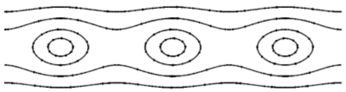


k$_1$



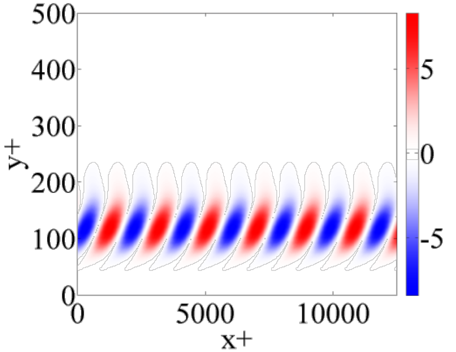
STRUCTURE FROM RESPONSE MODES

(k, n, c, A) *u*



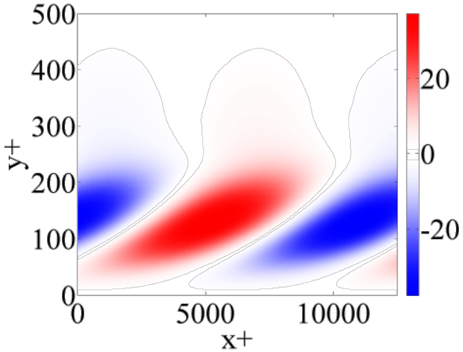
k_1

(+/- 6 , +/-6, 2/3, -1.00i)



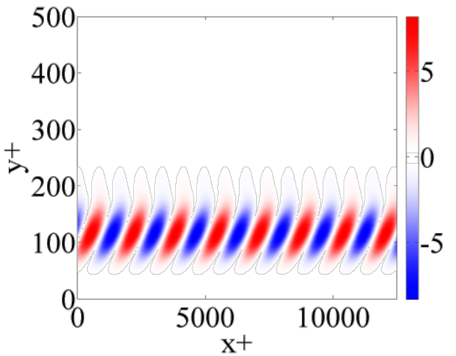
k_2

(+/- 1 , +/- 6, 2/3, 4.50)

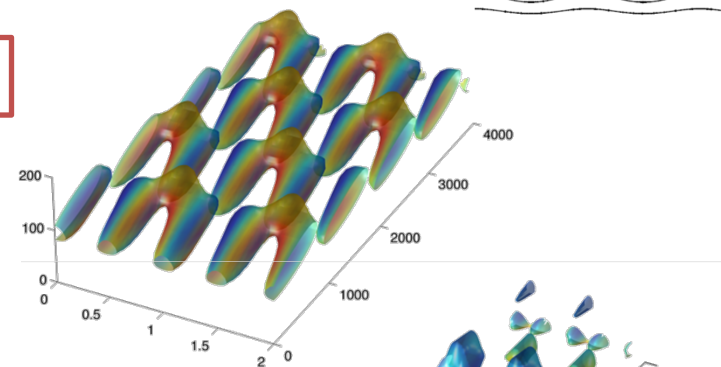


k_3

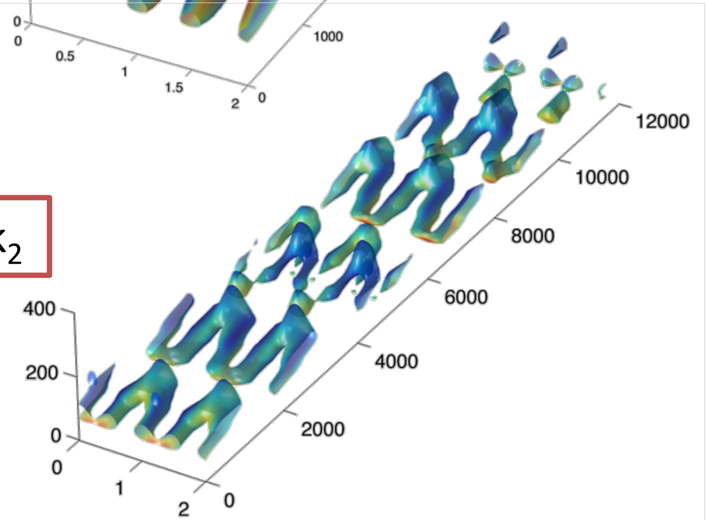
(+/- 7, +/-6, 2/3, 0.83i)



k_1



$k_1 + k_2$

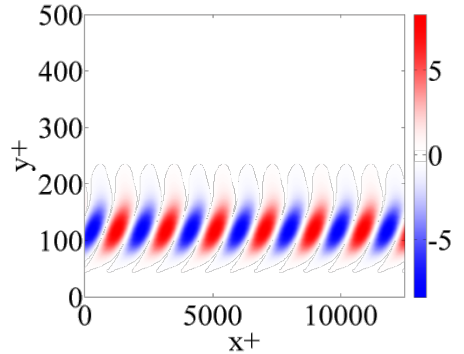


STRUCTURE FROM RESPONSE MODES

(k, n, c, A)   *u*

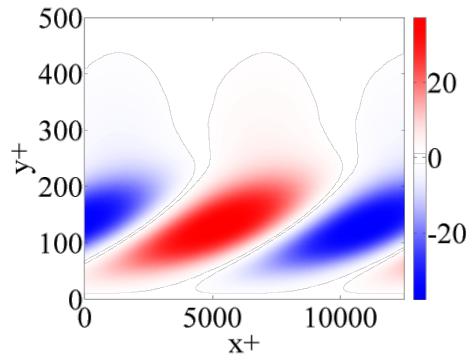
k_1

(+/- 6 , +/-6, 2/3, -1.00i)



k_2

(+/- 1 , +/- 6, 2/3,   4.50)



k_3

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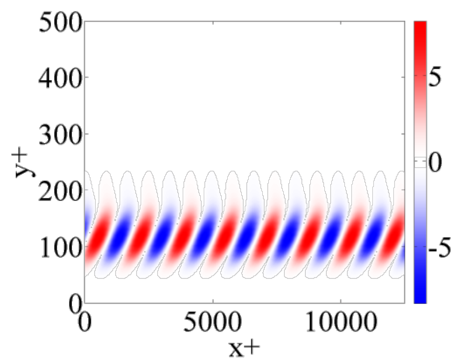
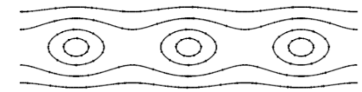
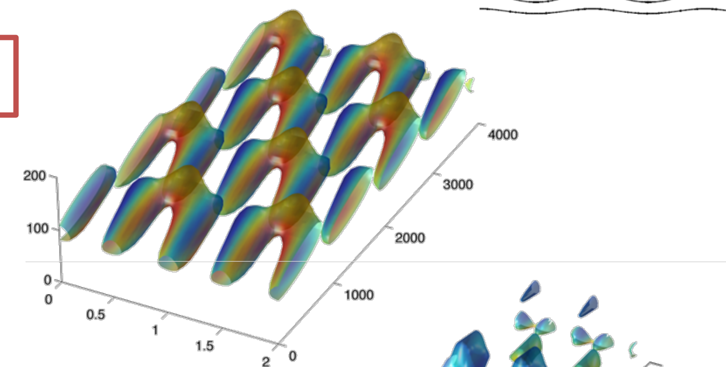
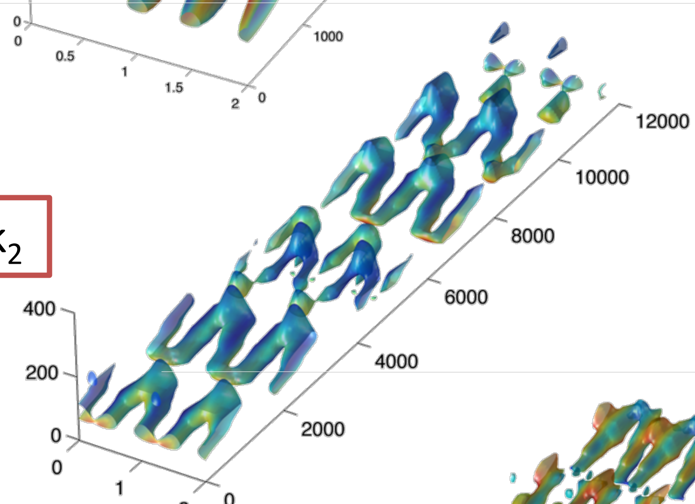




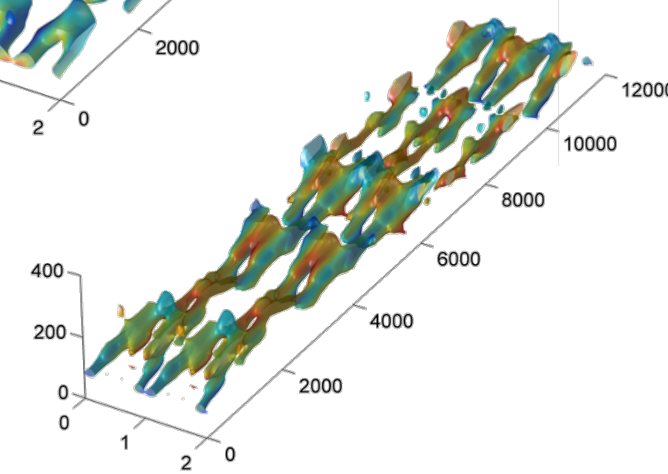
k_1



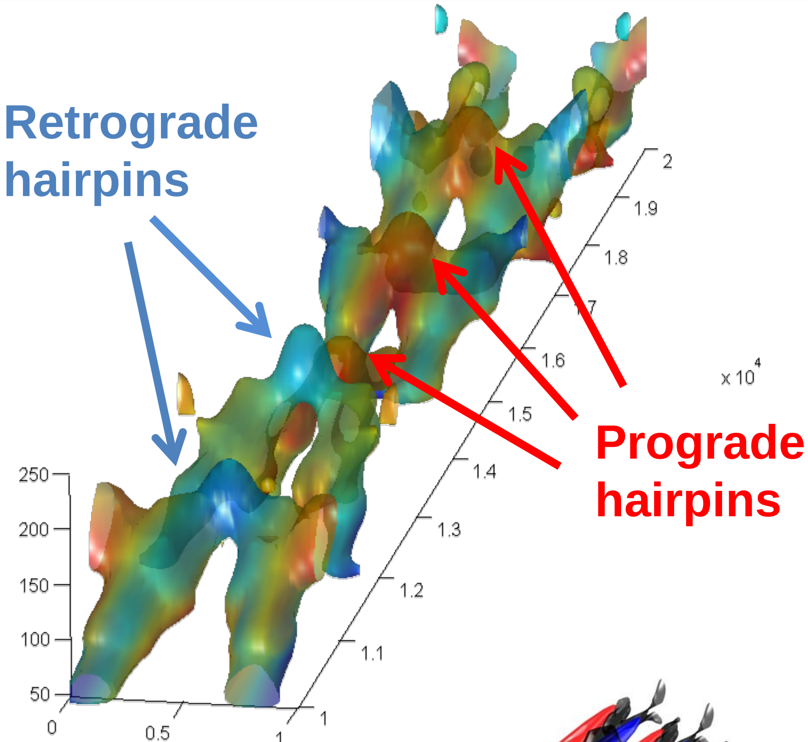
$k_1 + k_2$

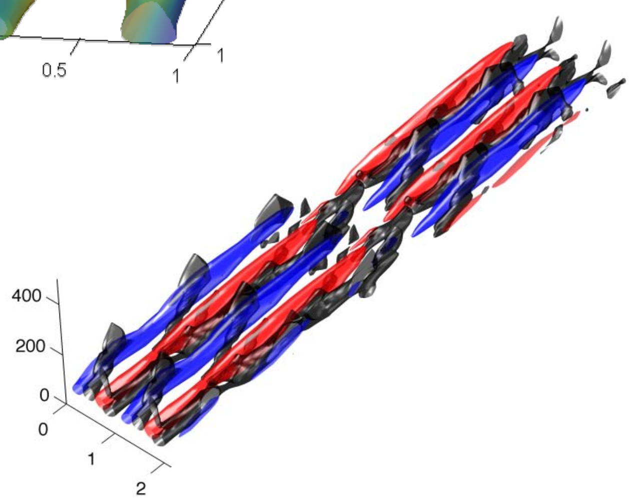


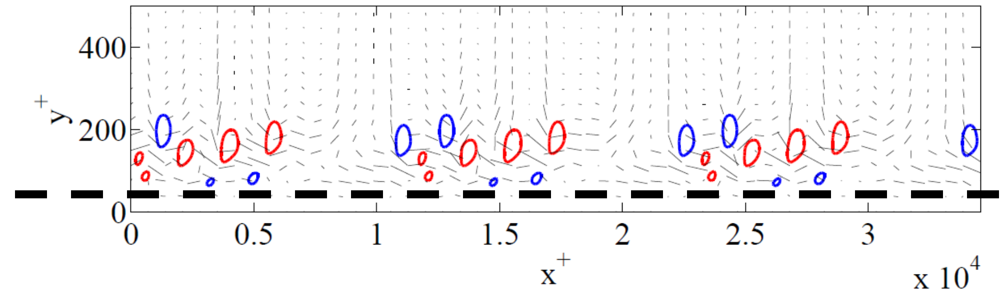
$k_1 + k_2 + k_3$

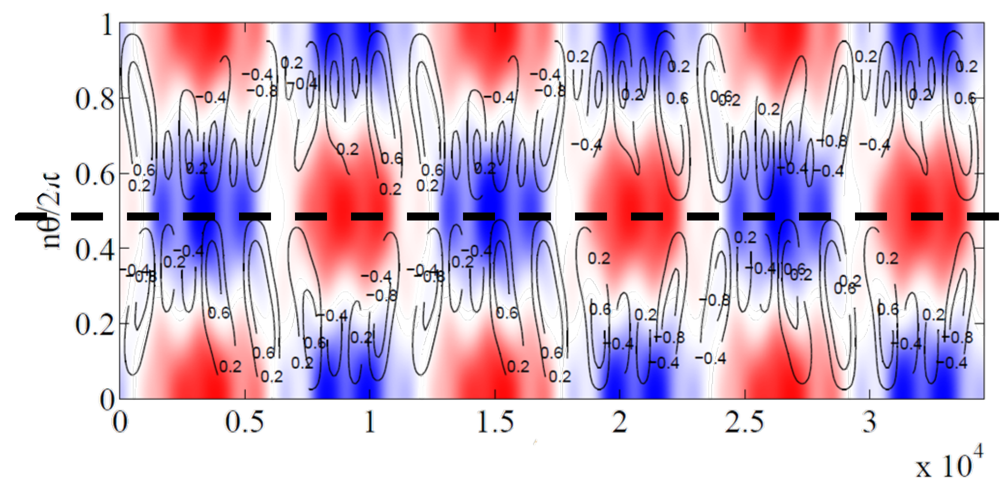


MODULATING PACKET

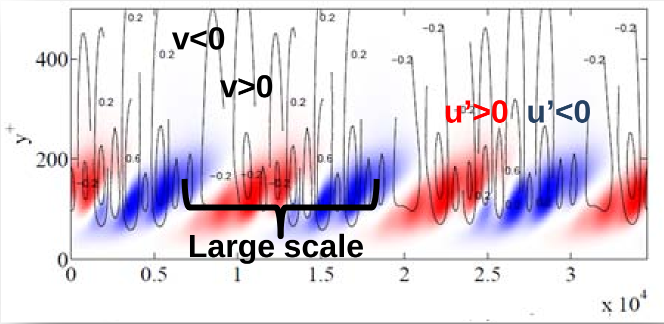




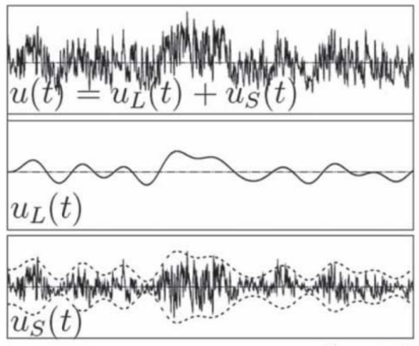




STATISTICS FROM THE MODULATING PACKET



u and v "amplitude modulated" by large scale



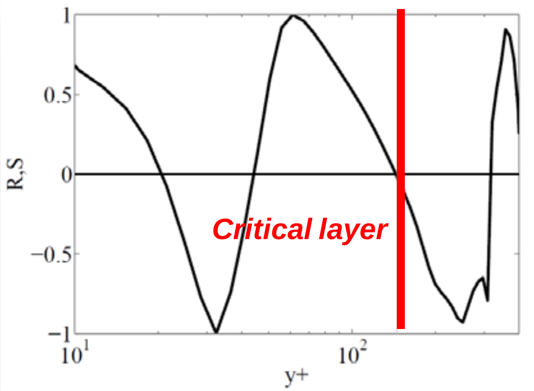
Marusic, Mathis & Hutchins, Science 2010

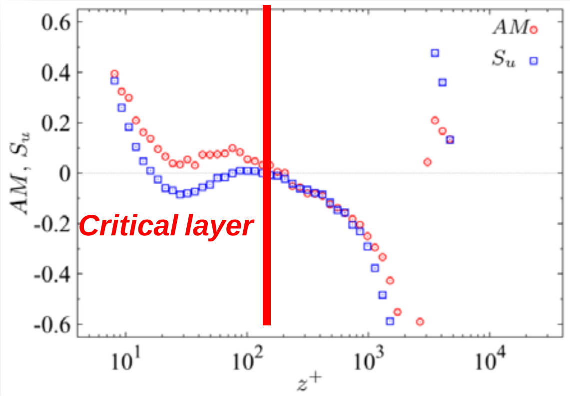
Amplitude modulation coefficient

$$R = \frac{\left(\langle A_2^2(y)\rangle \langle A_{env}^2(y)\rangle\right)^{1/2} \cos[\varphi_2(y) - \Delta\varphi(y)]}{\left(\langle A_2^2(y)\rangle \langle A_{env}^2(y)\rangle\right)^{1/2}} = \cos[\varphi_2(y) + \varphi_1 - \varphi_3(y)]$$

Velocity skewness

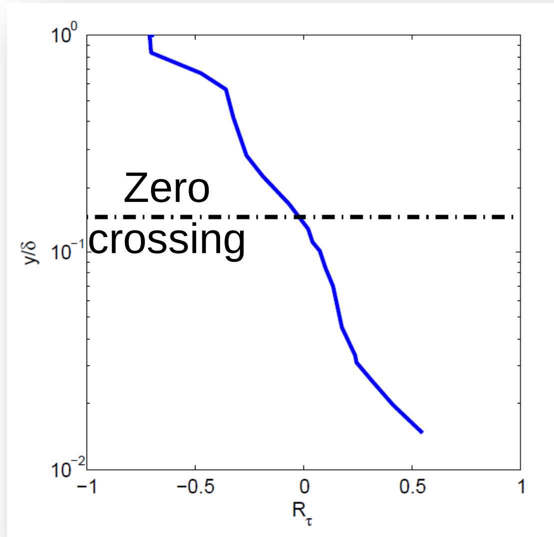
$$\hat{S}_u(y) = \frac{\langle u^3\rangle}{\langle u^2\rangle^{3/2}} = \frac{2A_1A_2A_3\cos[\varphi_2(y)+\varphi_1(y)-\varphi_3(y)]}{(A_1^2+A_2^2+A_3^2)^{3/2}} \qquad S = \cos[\varphi_2(y)+\varphi_1(y)-\varphi_3(y)]$$

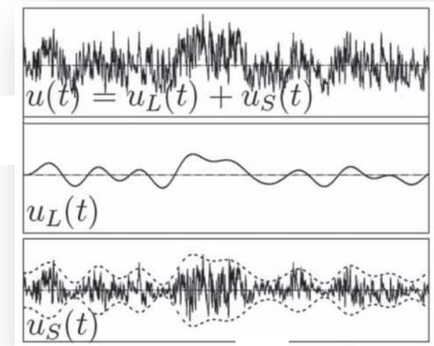




Amplitude modulation in the unperturbed TBL

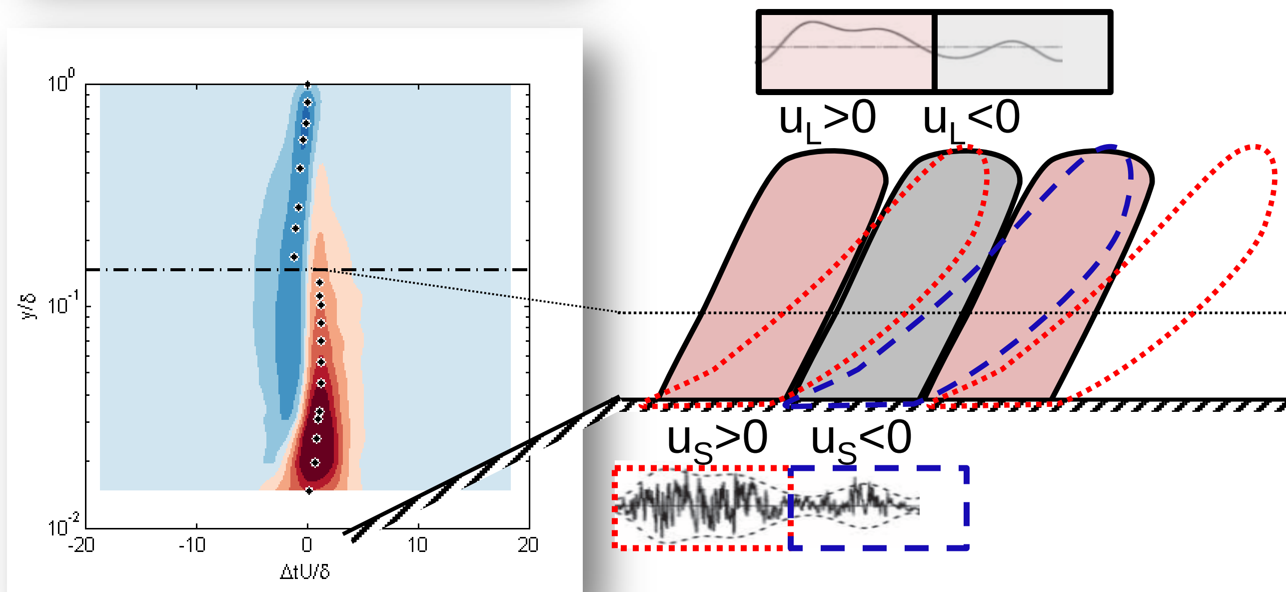
$$R_\tau = \frac{\langle u_L u_s \rangle}{\left\langle \left(u_L{}^2\right)^{1/2} \right\rangle \left\langle \left(u_s{}^2\right)^{1/2} \right\rangle}$$





Marusic, Mathis & Hutchins, Science 2010

$$R_\tau(\Delta t) = \frac{\langle u_L(t+\Delta t) u_s(t) \rangle}{\left\langle \left(u_L{}^2\right)^{1/2} \right\rangle \left\langle \left(u_S{}^2\right)^{1/2} \right\rangle}$$



Bandyopadhyay & Hussain, Phys. Fluids, 1984

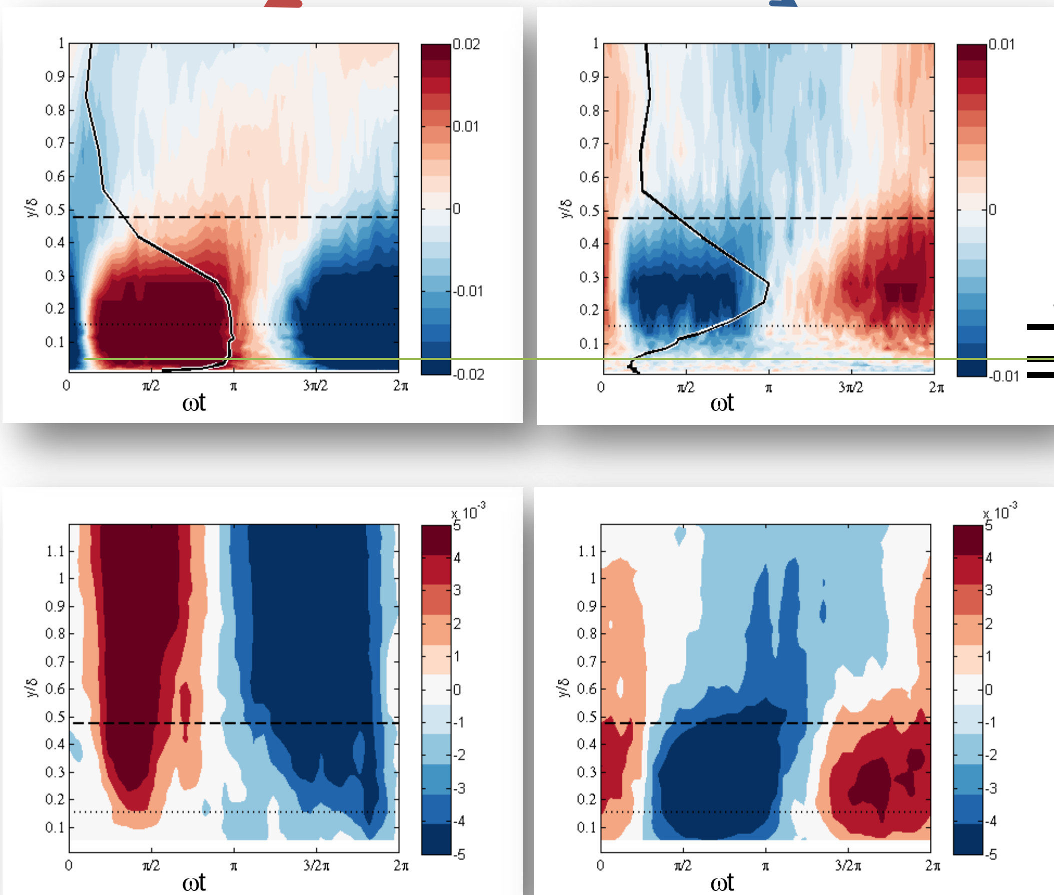
Chung & McKeon, J. Fluid Mech. 2010

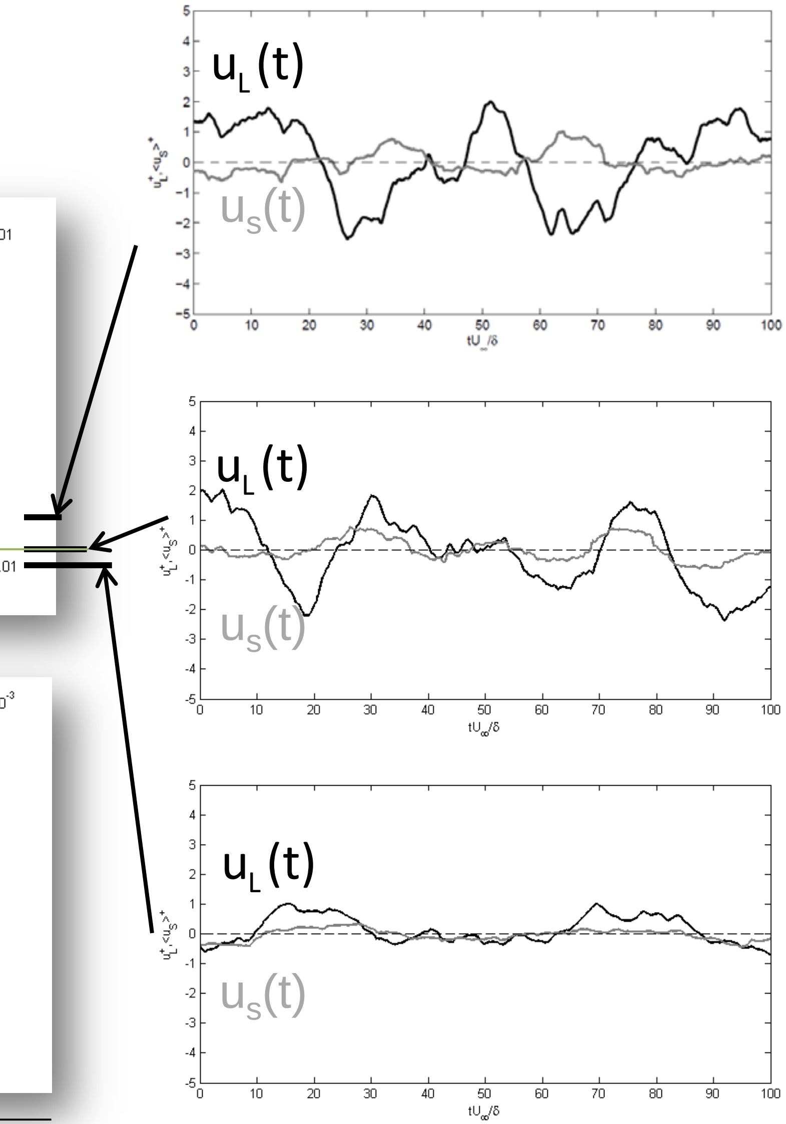
AMPLITUDE MODULATION IN THE PERTURBED TBL

$$u_i(y,t) = \overline{U}_i(y) + \boxed{\tilde{u}_i(y,t)} + \boxed{u_i'(y,t)}$$

STREAMWISE

WALL-NORMAL





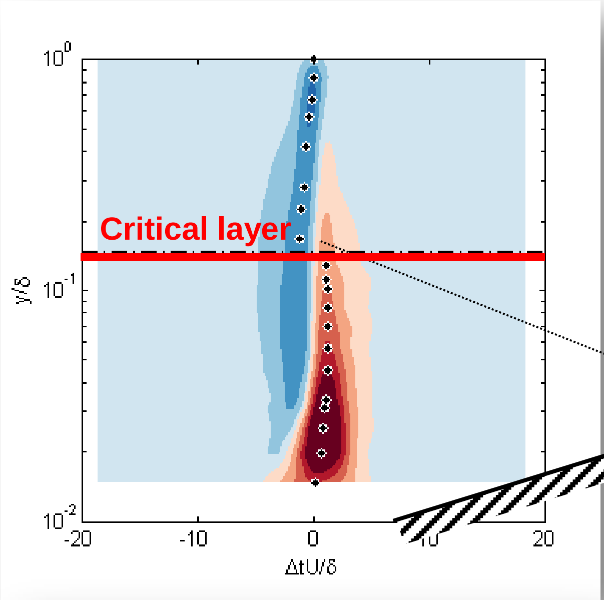
$x=3\delta_0$

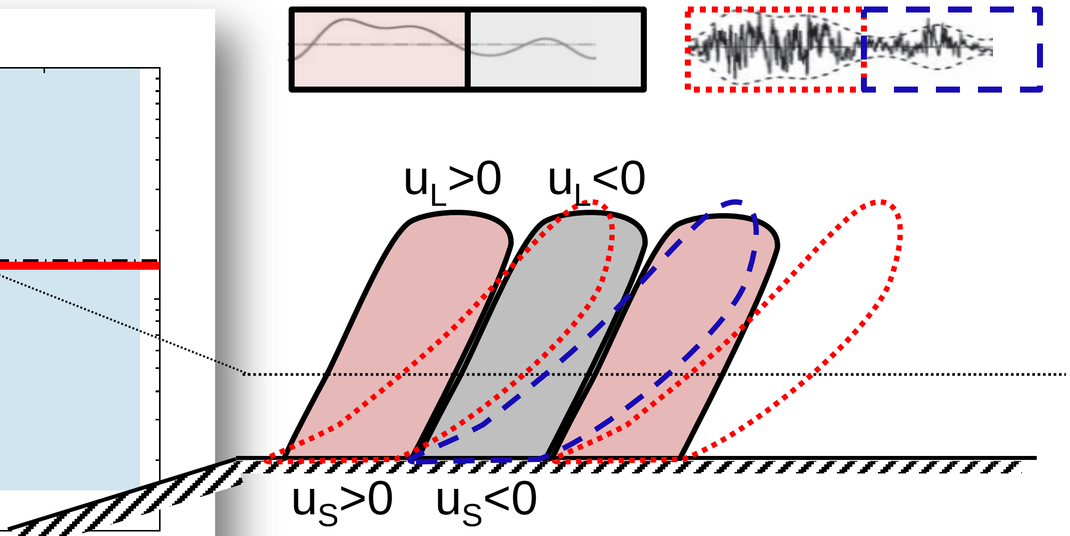
$$\hat{u}_i(y,\omega t) = u'_{i,rms}(y,\omega t) - \overline{u'_{i,rms}}(y)$$

MODULATION EFFECT OF THE ARTIFICIAL LARGE SCALE

UNPERTURBED

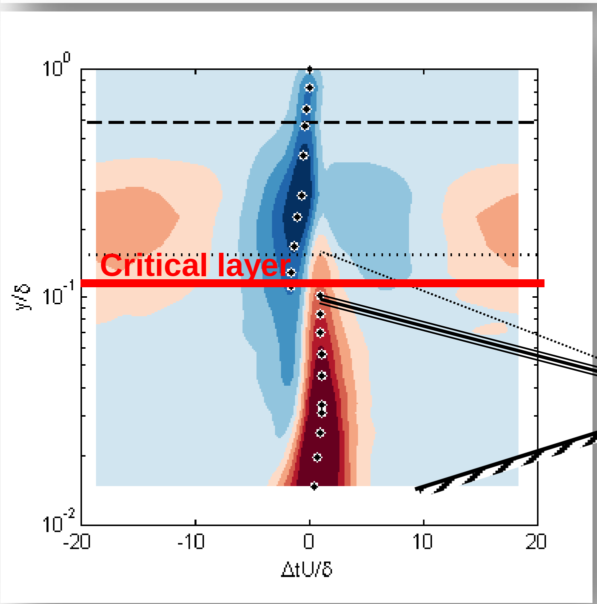
Zero crossing

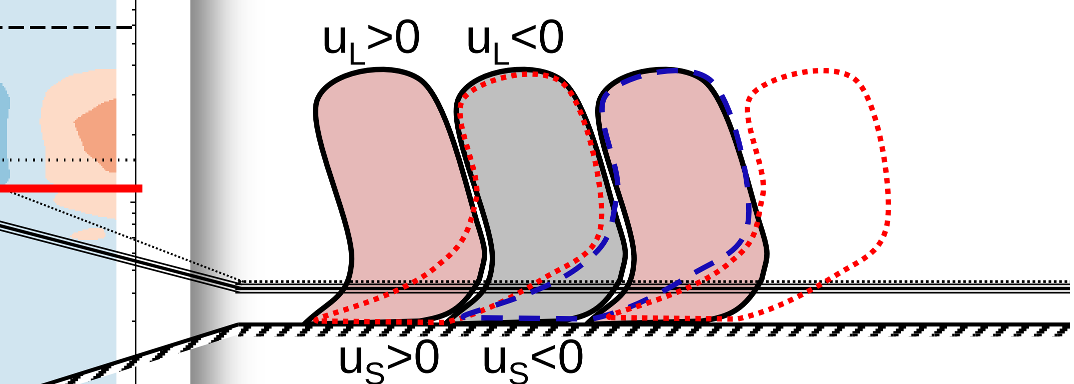




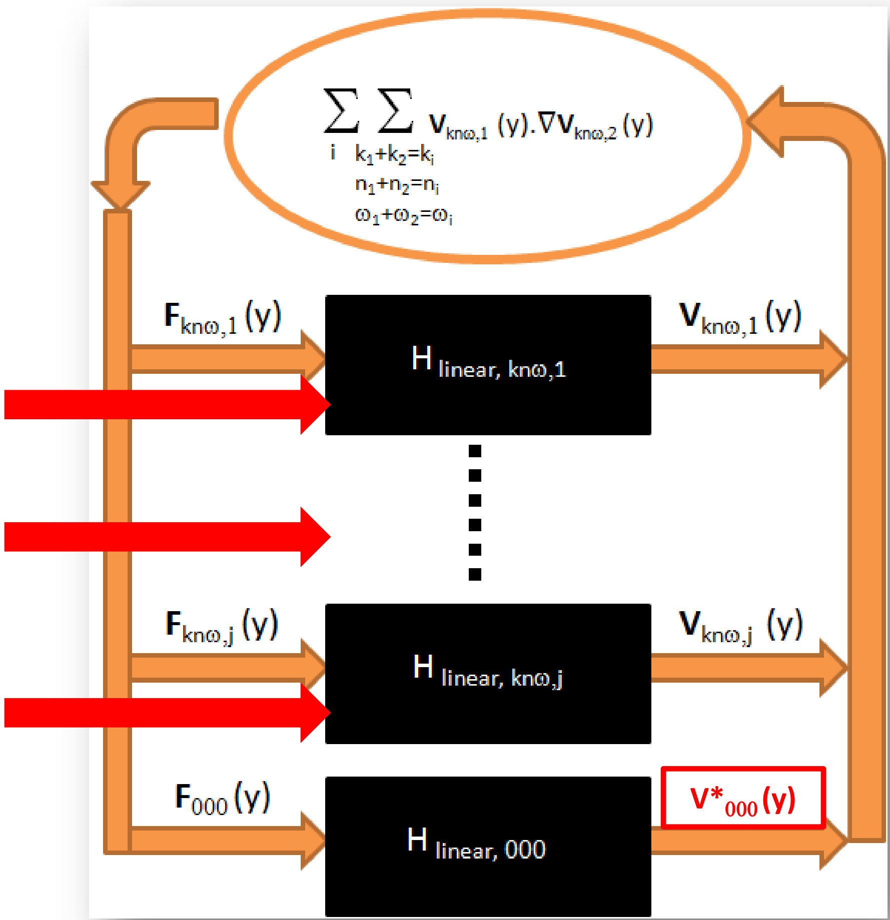
DYNAMICALLY PERTURBED

Zero crossing





A BLUEPRINT FOR CONTROLLING TURBULENCE



CONCLUSIONS

- Critical layer framework of McKeon & Sharma (2010) extended from reconstruction of significant features of statistics of wall turbulence
  - Nonlinearity retained (and supports mean velocity profile)
  - Provides basis for coherence in y
  - Prediction of hairpin vortices from decomposition of Navier-Stokes equations at each wavenumber-frequency combination
- Proposed new kernel of turbulence
  - Three mode representation with appropriate relative phases (fixed to agree with experiment at the VLSM critical layer)
  - Leads to recognizable hairpin packet structure
  - Captures skewness and amplitude modulation behavior (these are *linear* phenomena)
  - Consistent with attached eddy hypothesis
  - Importance of critical layer proven by dynamic roughness and predictable (not shown)
- The response of the TBL to a synthetic large scale via a spatial impulse of dynamic roughness (last two years' reviews) confirms results
  - Coupling of external forcing to the most amplified modes
  - Suggests method can be used for control of near-wall structure

OUTSTANDING CHALLENGES

- Phase…
- Need to bridge the gap between theoretical and experimental studies
- Extension of model: other classical results using essentially linear model?
- "Close the loop": determine correct nonlinear forcing for model to support correct mean velocity profile (currently assumed)?
  - Success will provide informed approach to control
  - Restores the difficulty of nonlinearity in the problem
- Coupling of dynamic roughness actuation with amplified modes demonstrated but what is best (practical) way of exciting them?
- Accurate values of shear stress required to make any scaling arguments for controlled/manipulated cases
- Low order model?