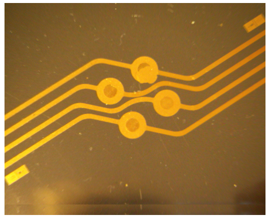
Imperial College
London



Effects of shear and blocking in a rapidly distorted boundary layer

Jonathan Morrison
Kamthon Septham
Sourabh Diwan

Department of Aeronautics
Imperial College, London

High Reynolds Number Boundary Layer Turbulence
University New Hampshire

November 20-22, 2013

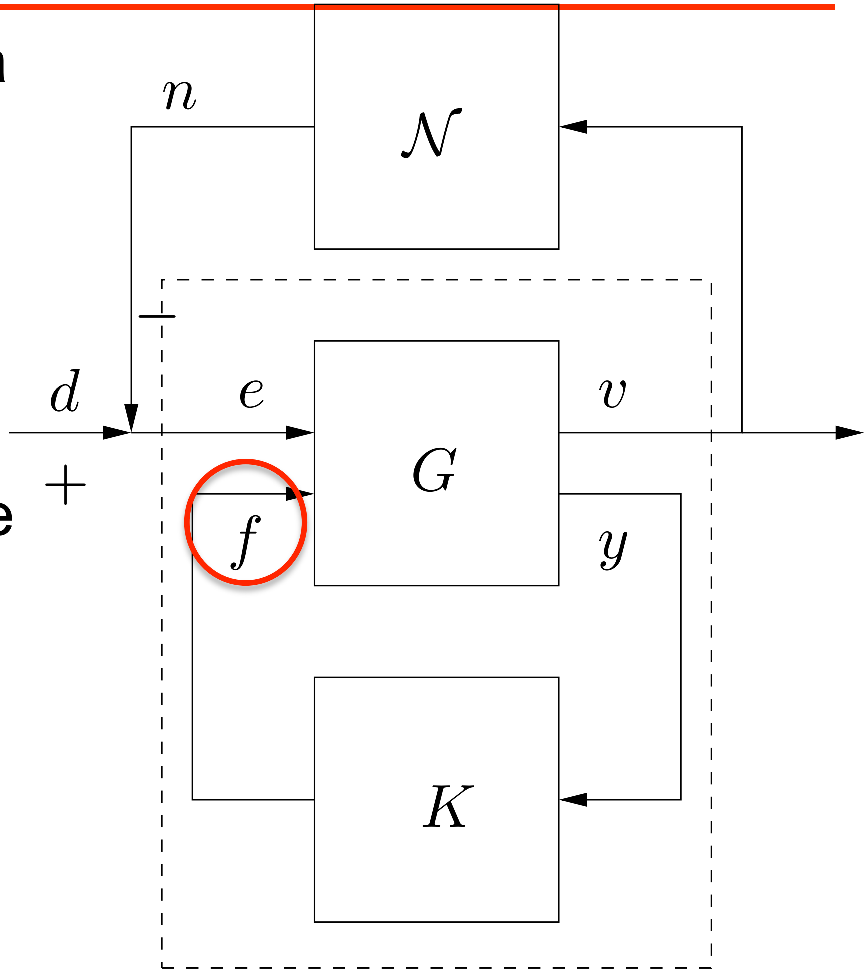
EPSRC
Engineering and Physical Sciences
Research Council

Synopsis

- Motivation
- A full-domain linear controller that relaminarises turbulent channel flow $\mathrm{Re}_\tau \leq 400$
- How does this work?
- Importance of pressure fluctuations – Batchelor, Landahl & Townsend (BLT)
- Comparison of timescales
- Measurements in a rapidly distorted boundary layer

Linear globally stabilising controller

- Navier-Stokes equations written as a linear system G with control K and nonlinear forcing, f
- Nonlinear term N is conservative w.r.t. disturbance energy
- Turbulent shear stresses treated as part of perturbations we wish to force
- Linear controller works in presence of nonlinearity by characterising it as positive real i.e. passive.
- Stability: choose K such that linear part of closed loop is passive
- The linear terms always dissipate disturbance energy



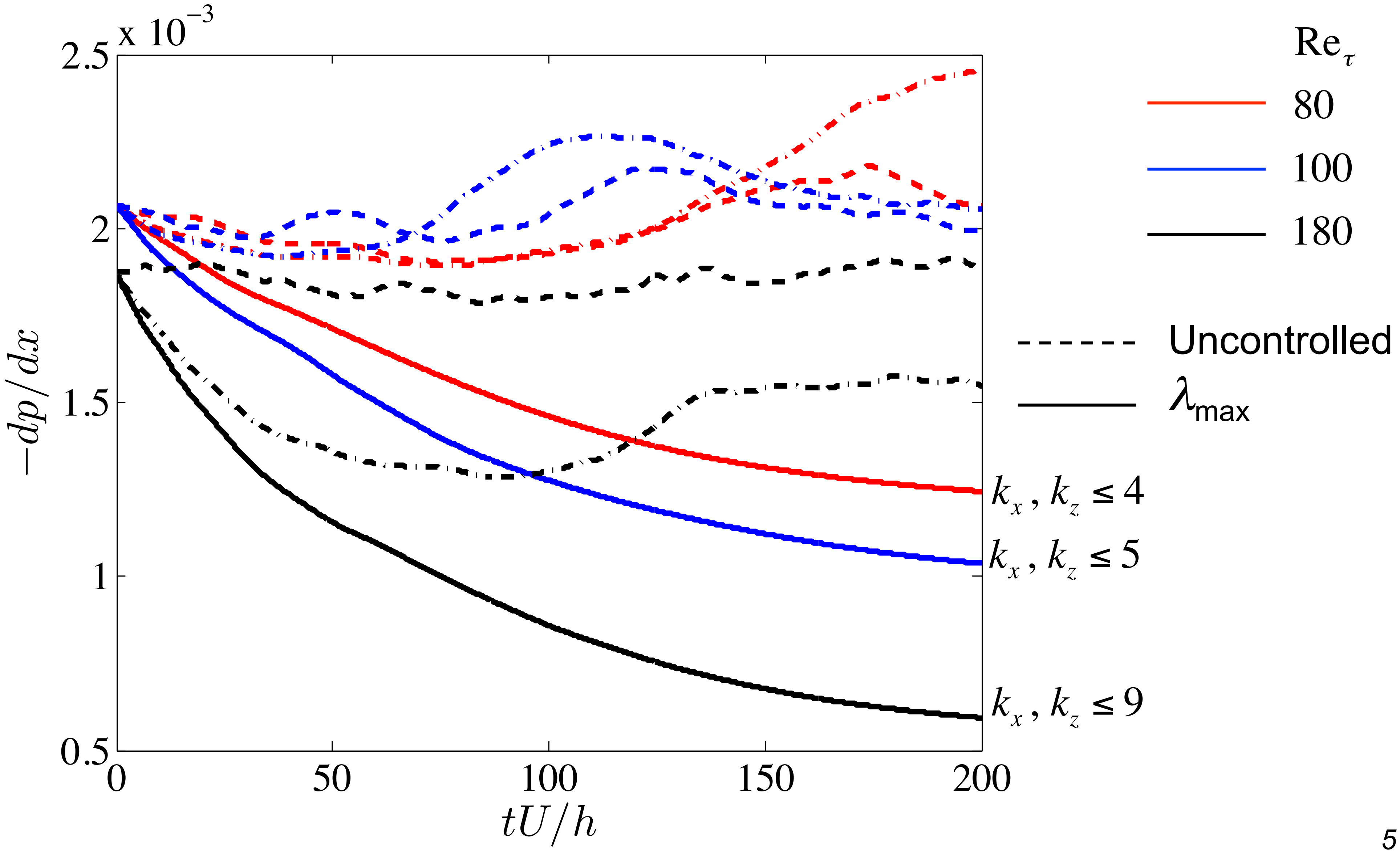
$$\frac{dE}{dt} = \oint_{x\in\Omega}\left(U_L'(y)uv + \frac{\varepsilon}{\mathrm{Re}}\right) \leq 0$$

Sharma *et al.* 2010

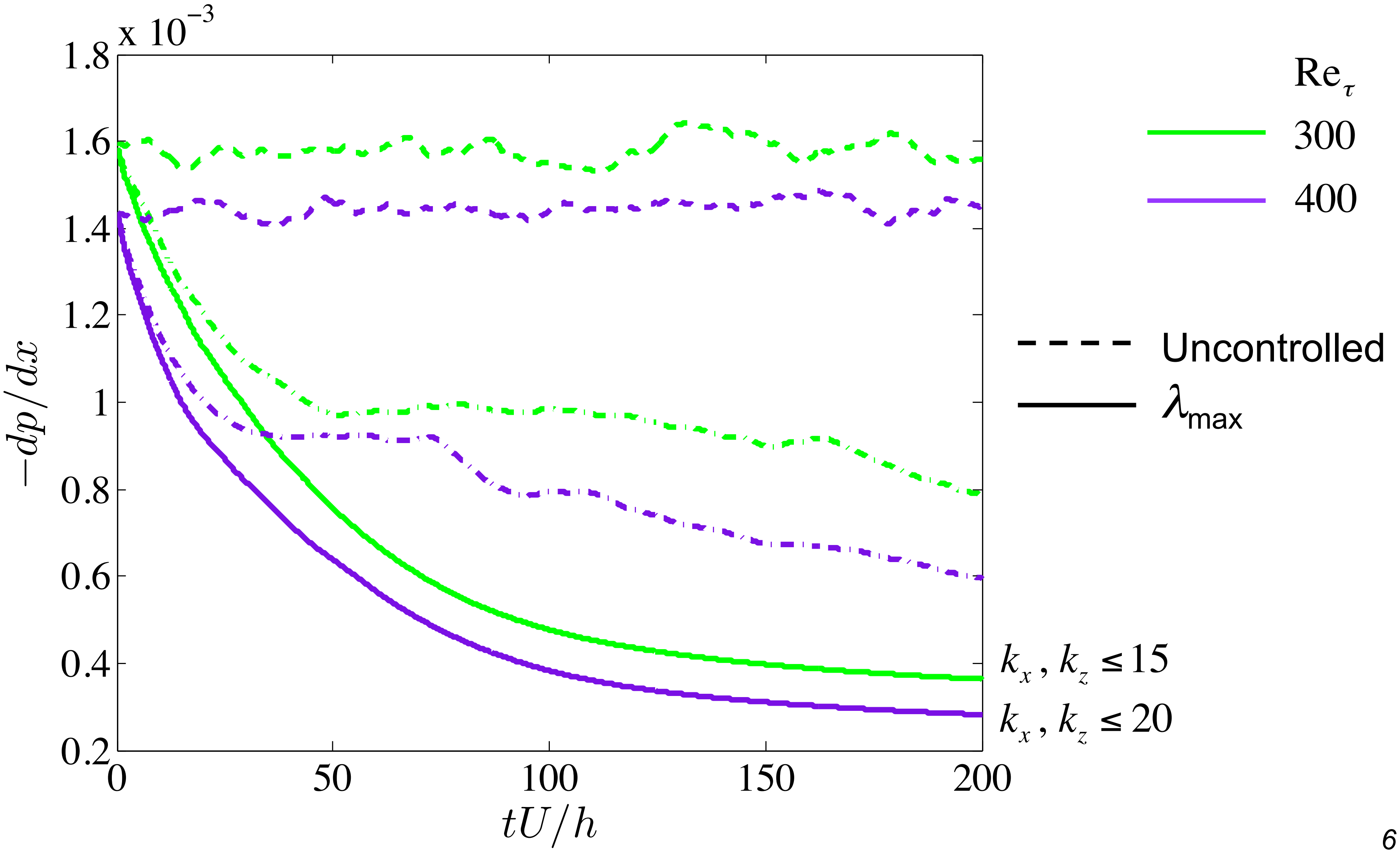
Turbulent channel flow

- Re_τ = 80, 100, 180, 300: Domain $4\pi h$ x $2h$ x $2\pi h$
- Re_τ = 400: Domain $2.5\pi h$ x $2h$ x πh
- Channelflow 0.9.15 (Gibson *et al.* '08)
- Full-domain sensing, actuation on v
- Control focuses on vU'
- Forcing bandwidth progressively increased
- Details for Re_τ = 180, $k_x, k_z \leq 9$
- & at $y^+ = 20\big|_{\text{init}}$

$Re_\tau \leq 180$

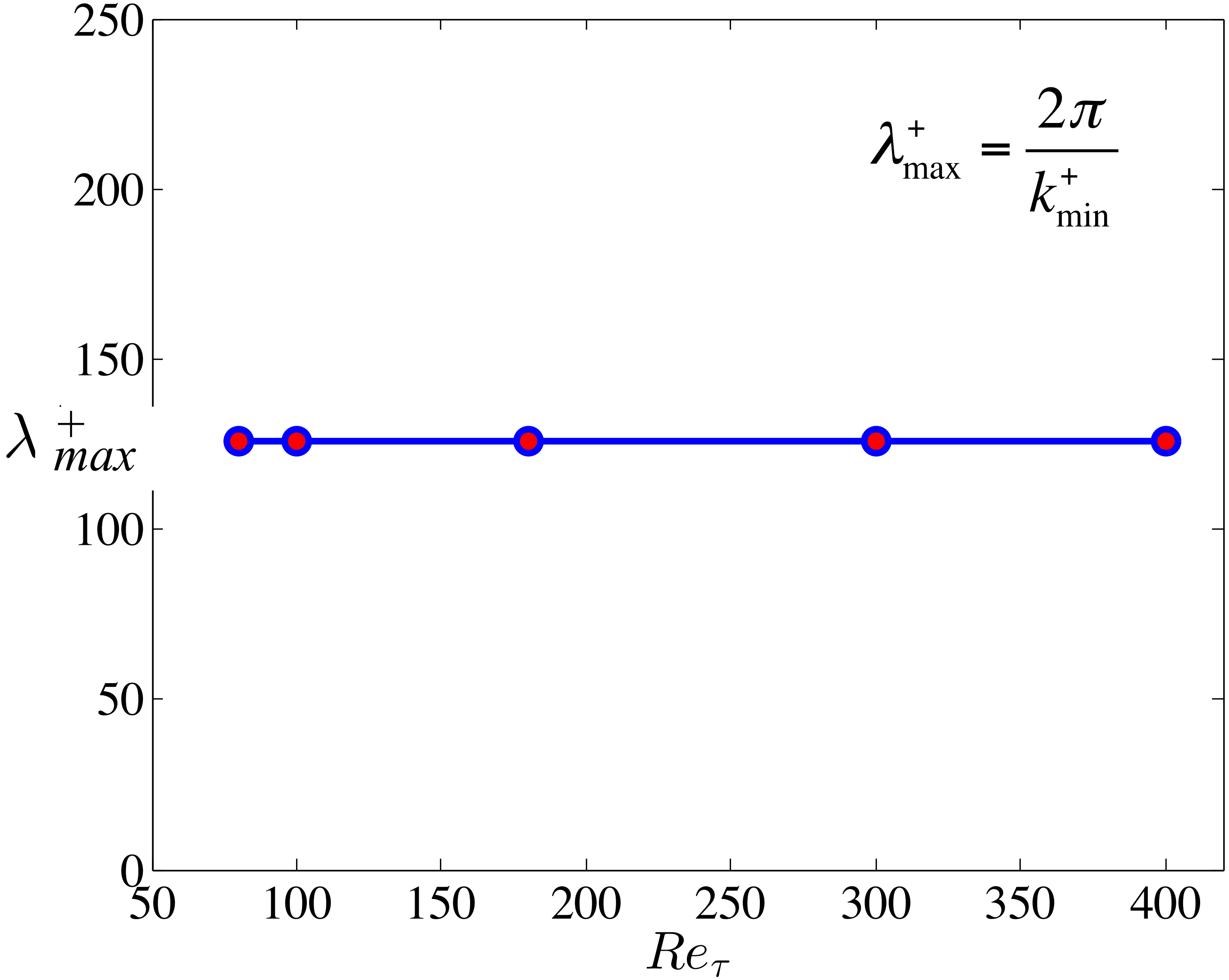


$Re_\tau \leq 400$



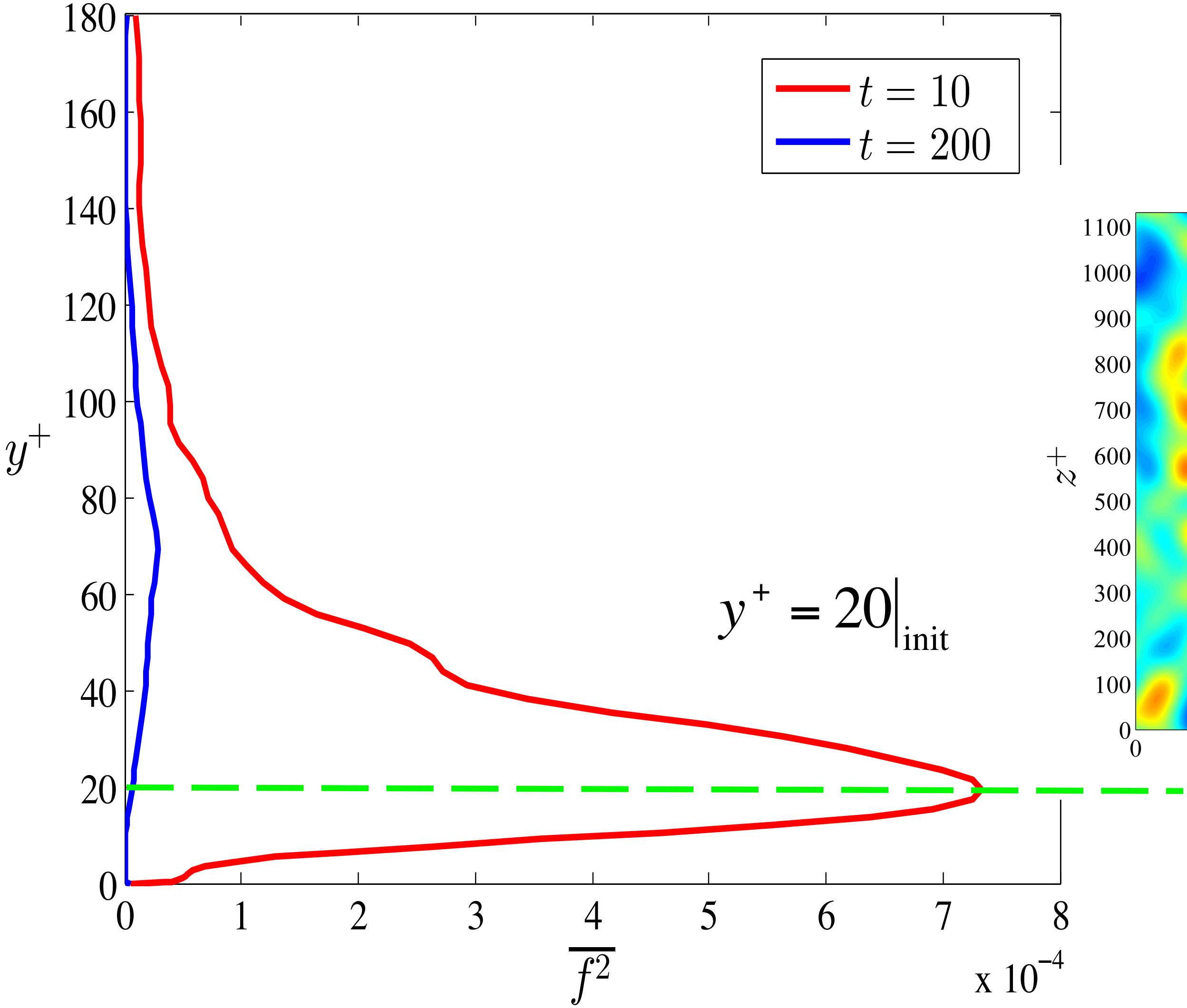
Minimum wavenumber for relaminarisation

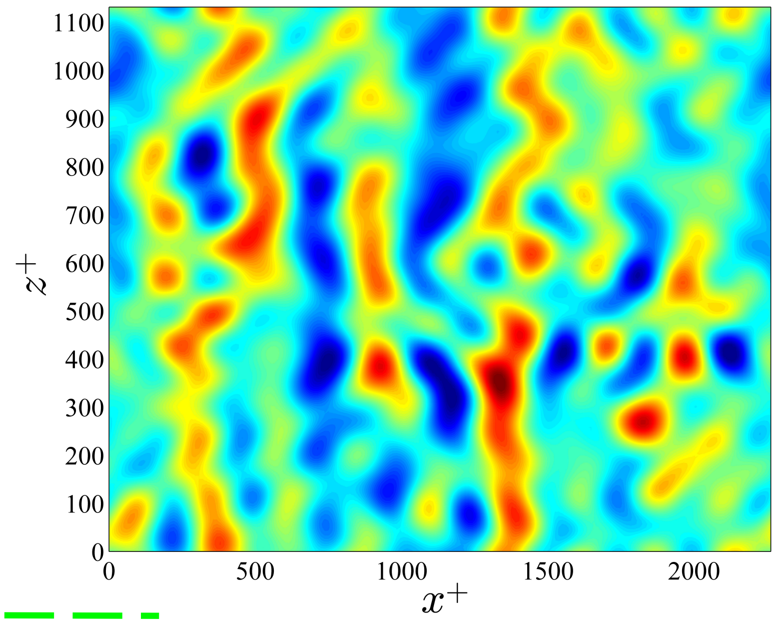
Normalised by u_τ at $t = 0$



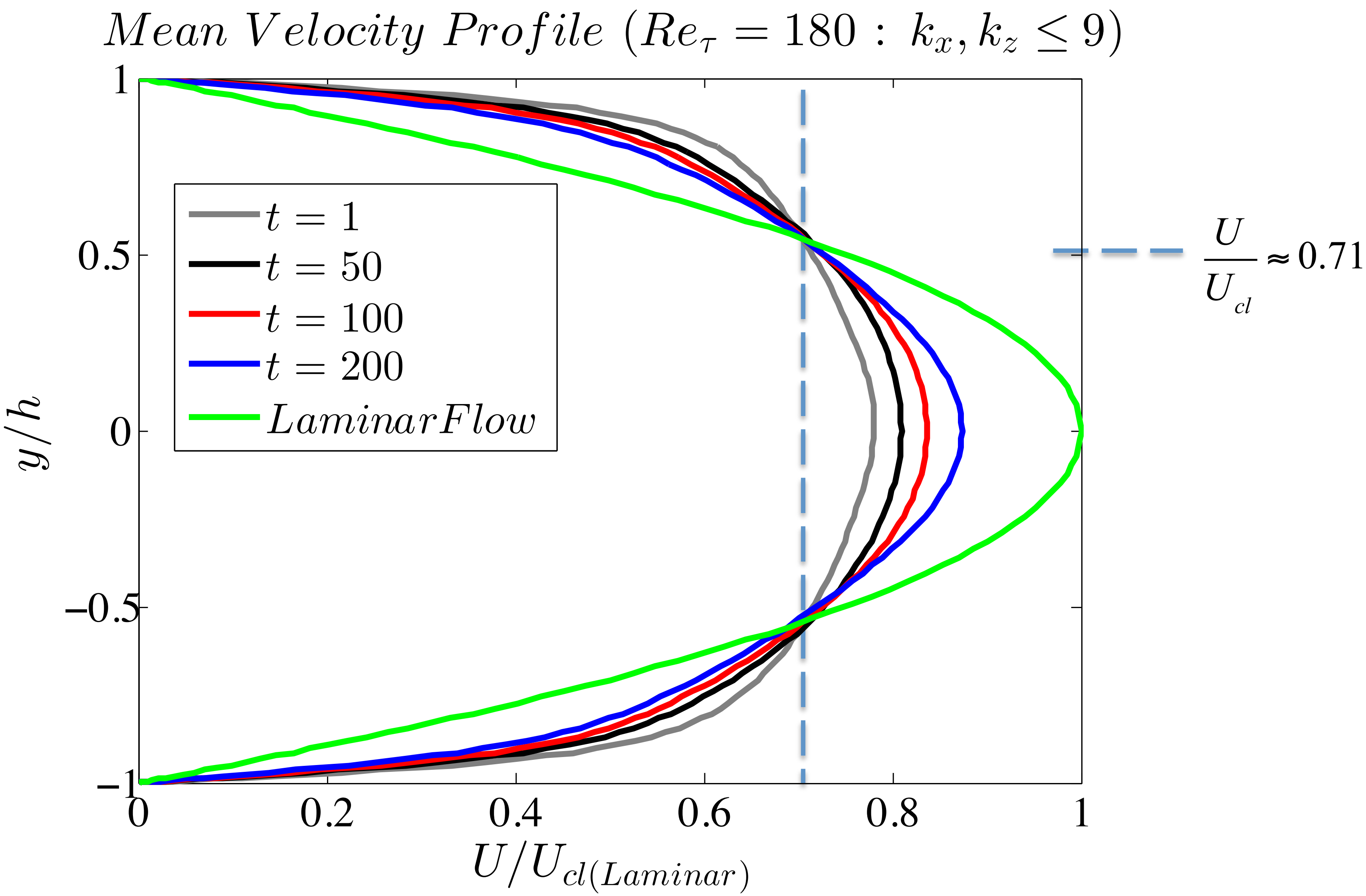
Mean square forcing: $\overline{f^2}(y)$

$Re_\tau = 180$

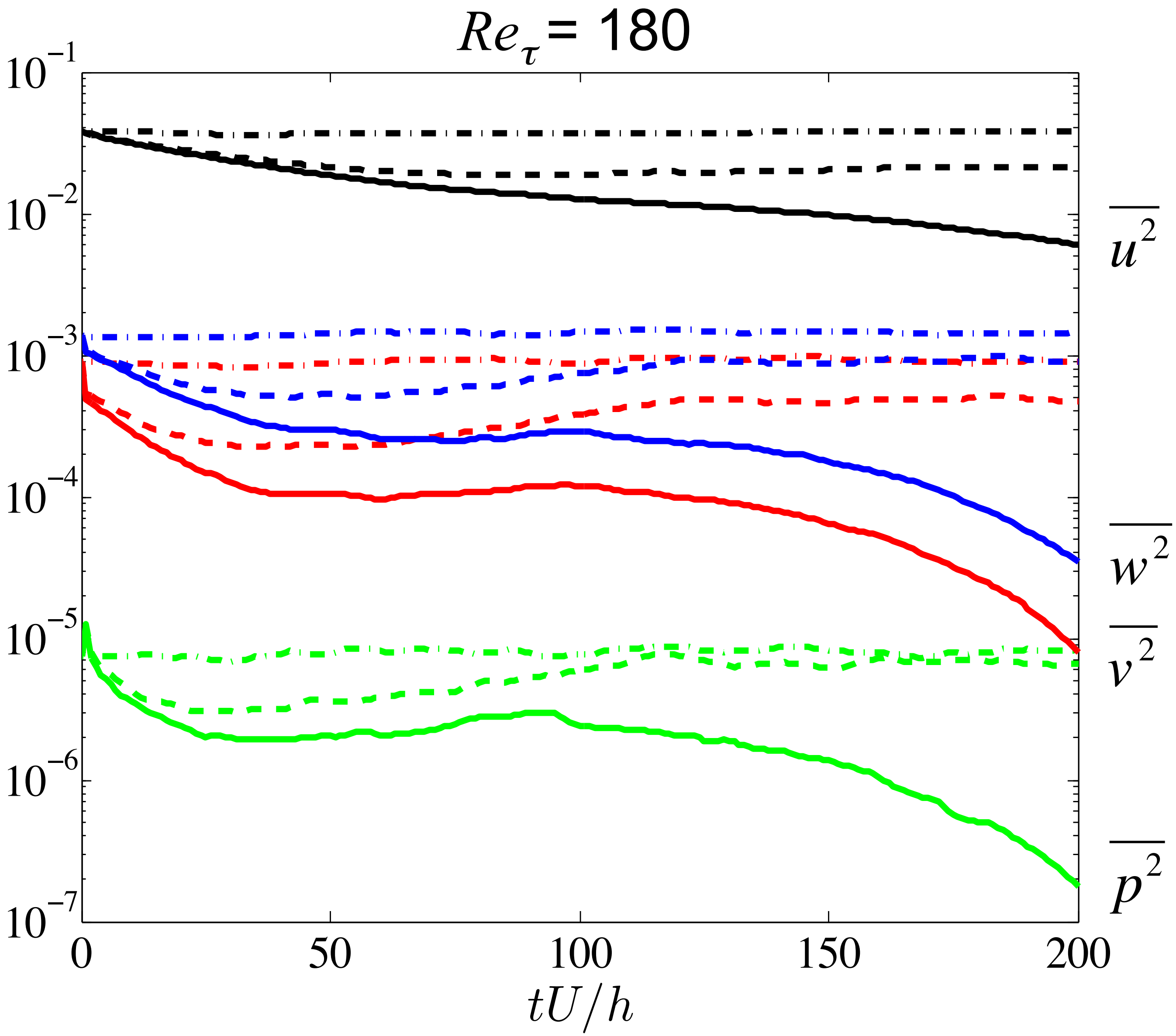




Mean velocity profile



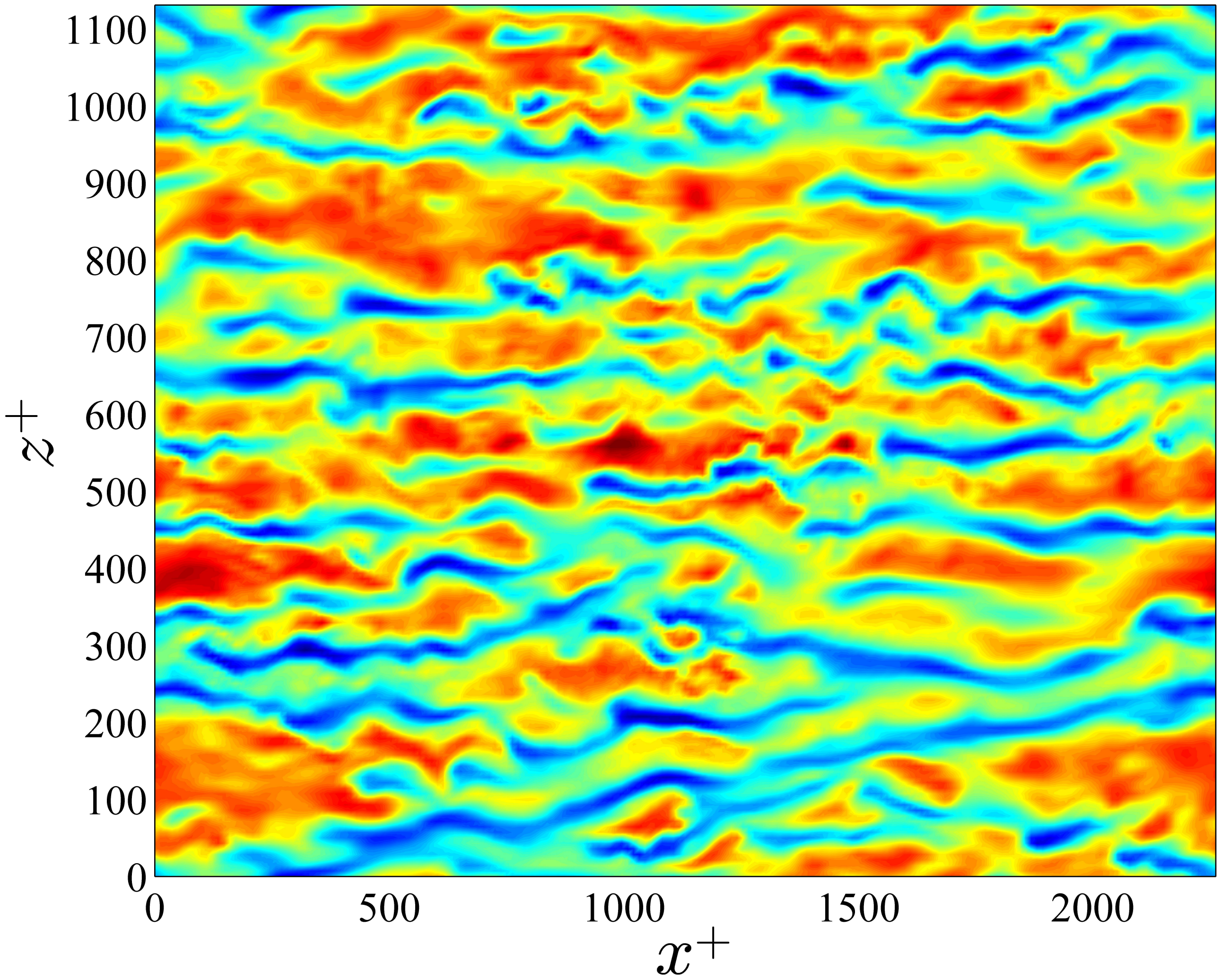
Fluctuations about target laminar profile



Controlled u: $y^{+} = 20|_{\text{init}}$

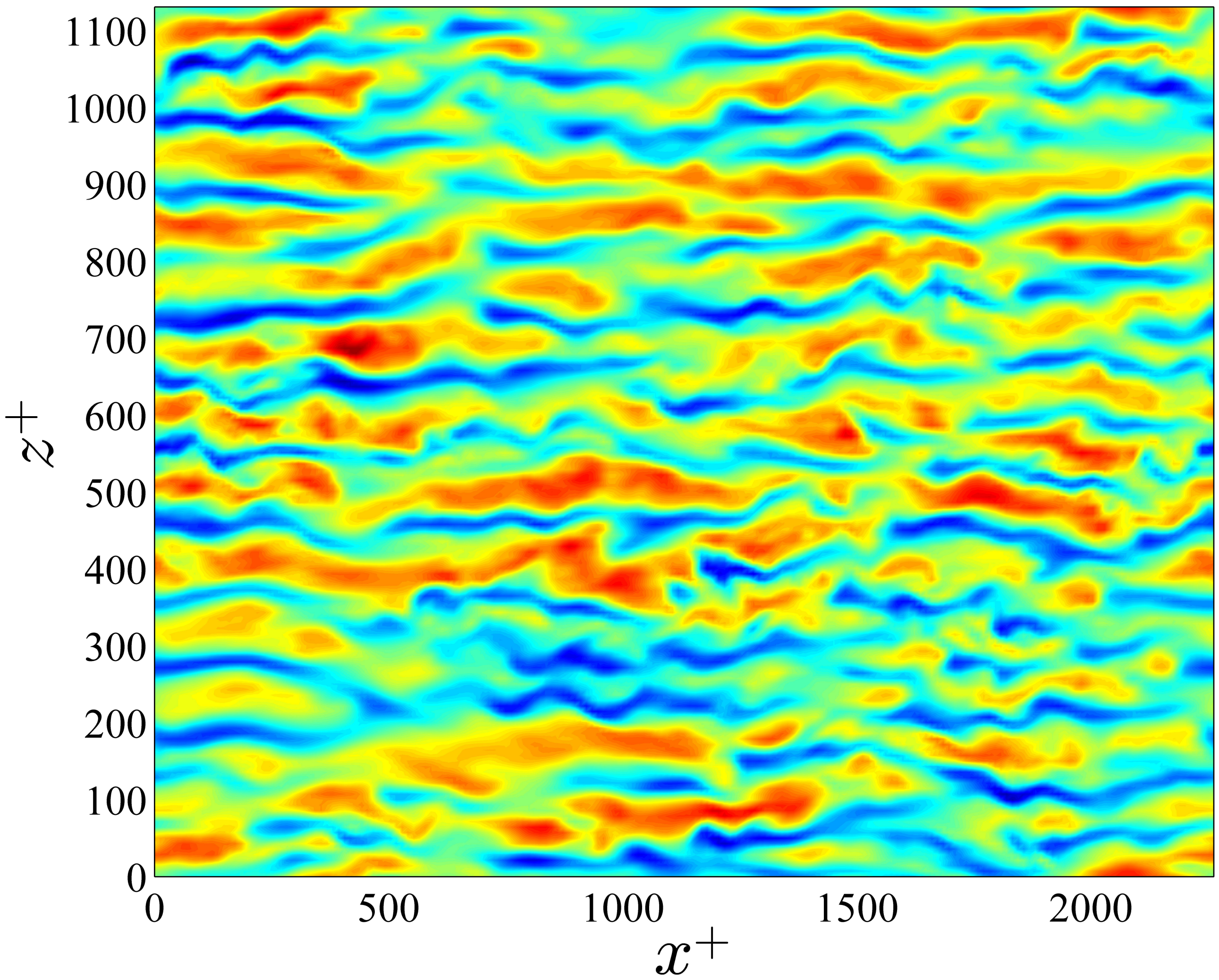
Re_τ = 180

$t = 2$



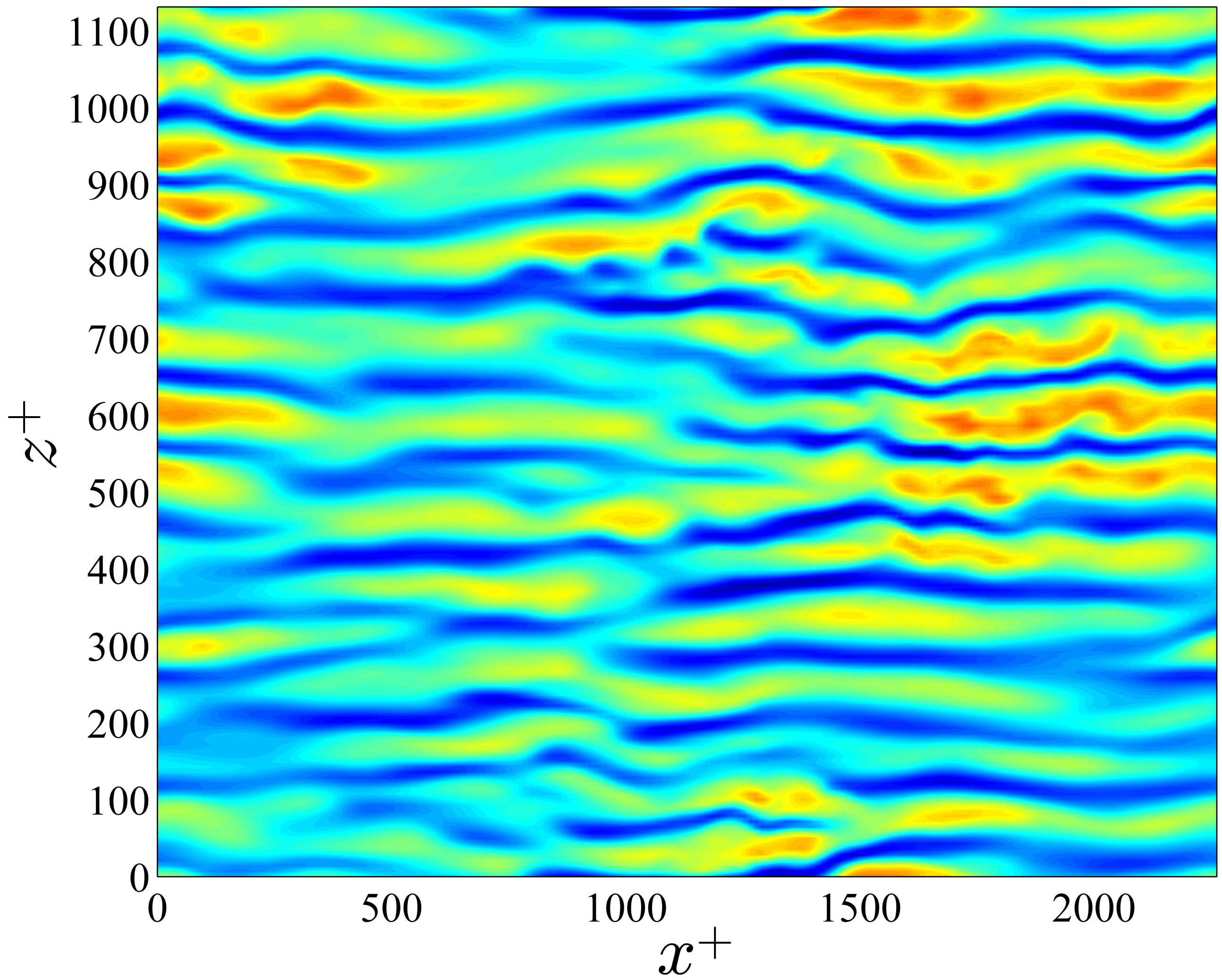
Controlled u: $y^+ = 20|_{\text{init}}$

$t = 10$



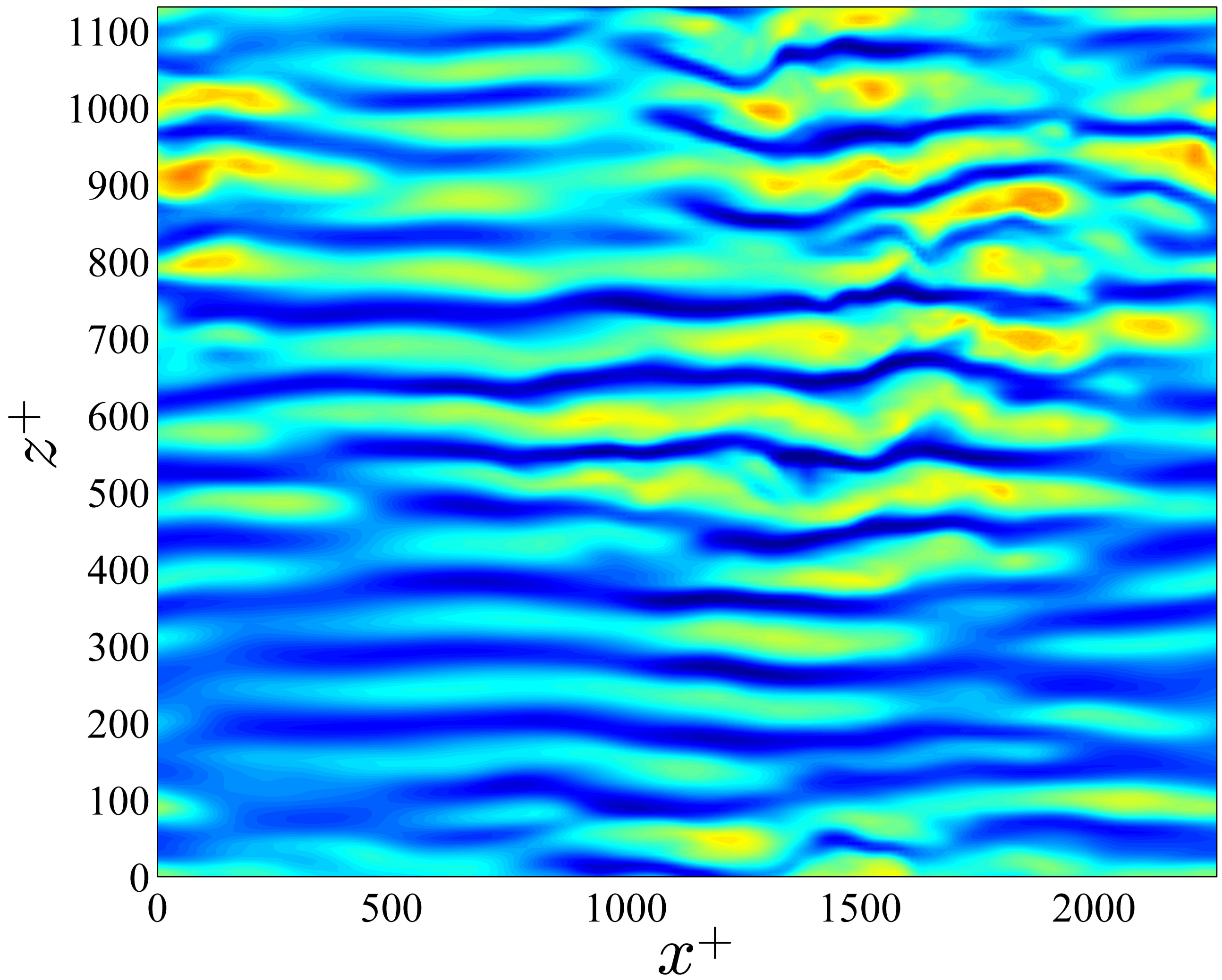
Controlled u: $y^{+} = 20\big|_{\text{init}}$

t =50



Controlled u: $y^+ = 20|_{\text{init}}$

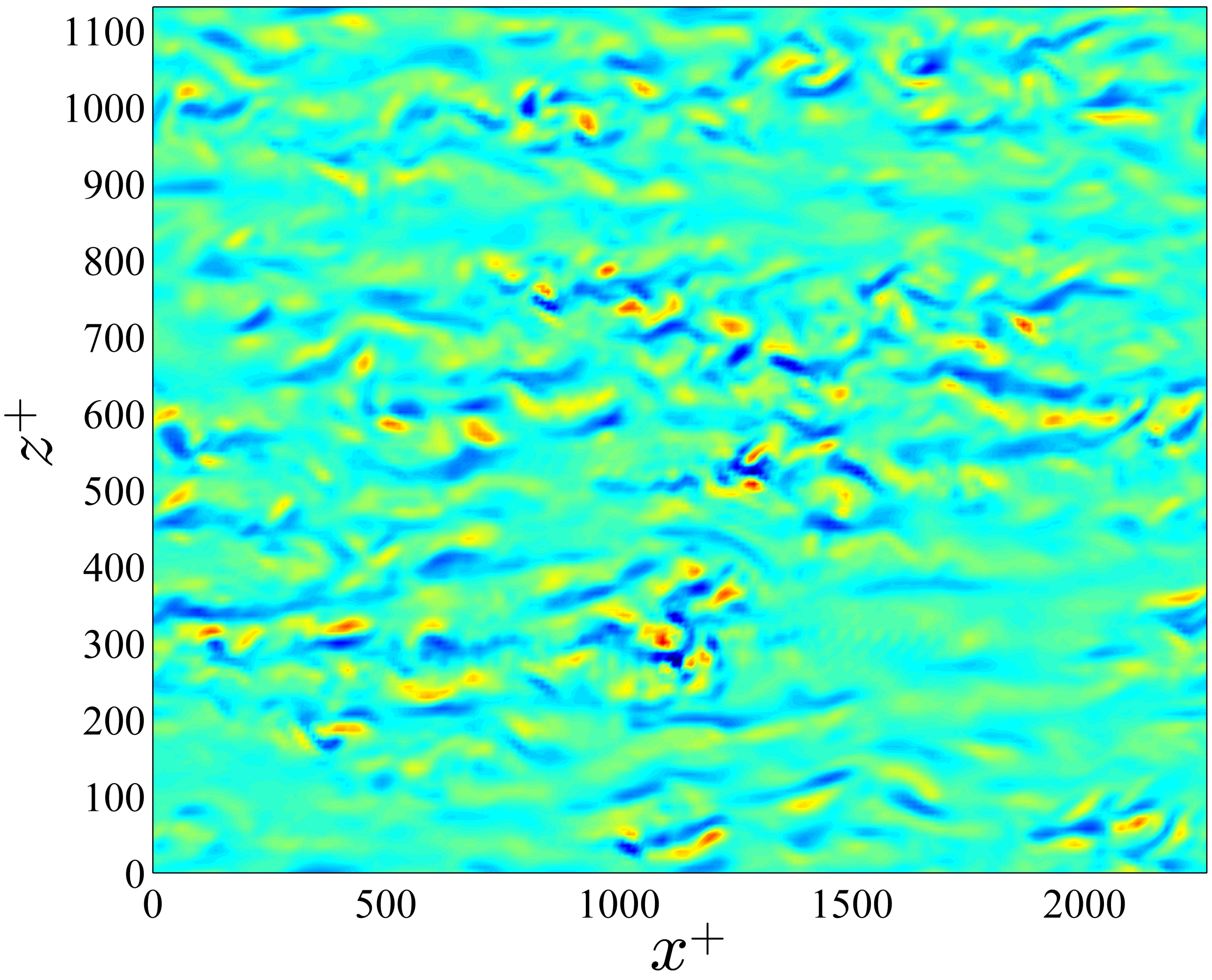
t =100



Controlled v: $y^+ = 20|_{\text{init}}$

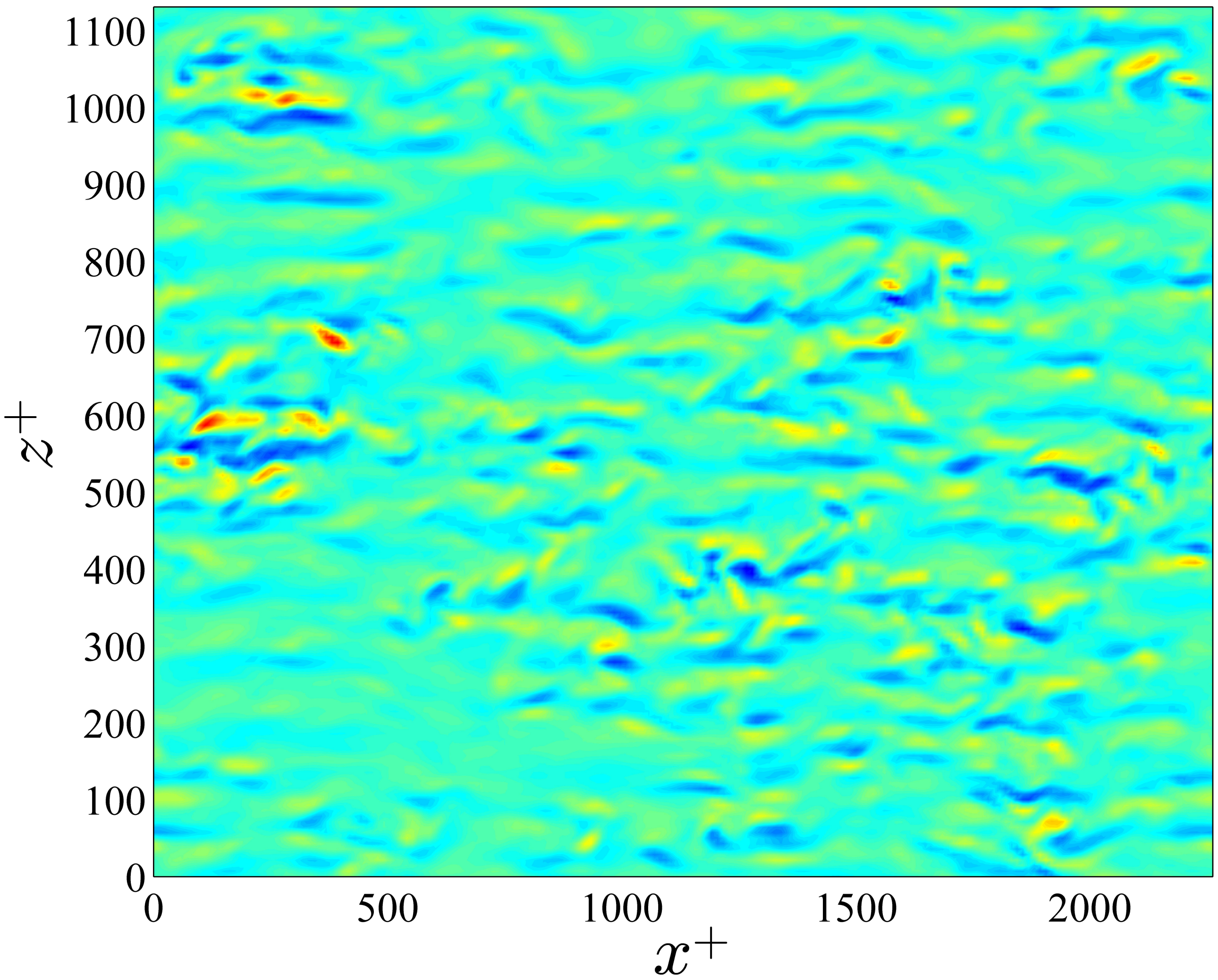
$Re_\tau = 180$

$t = 2$



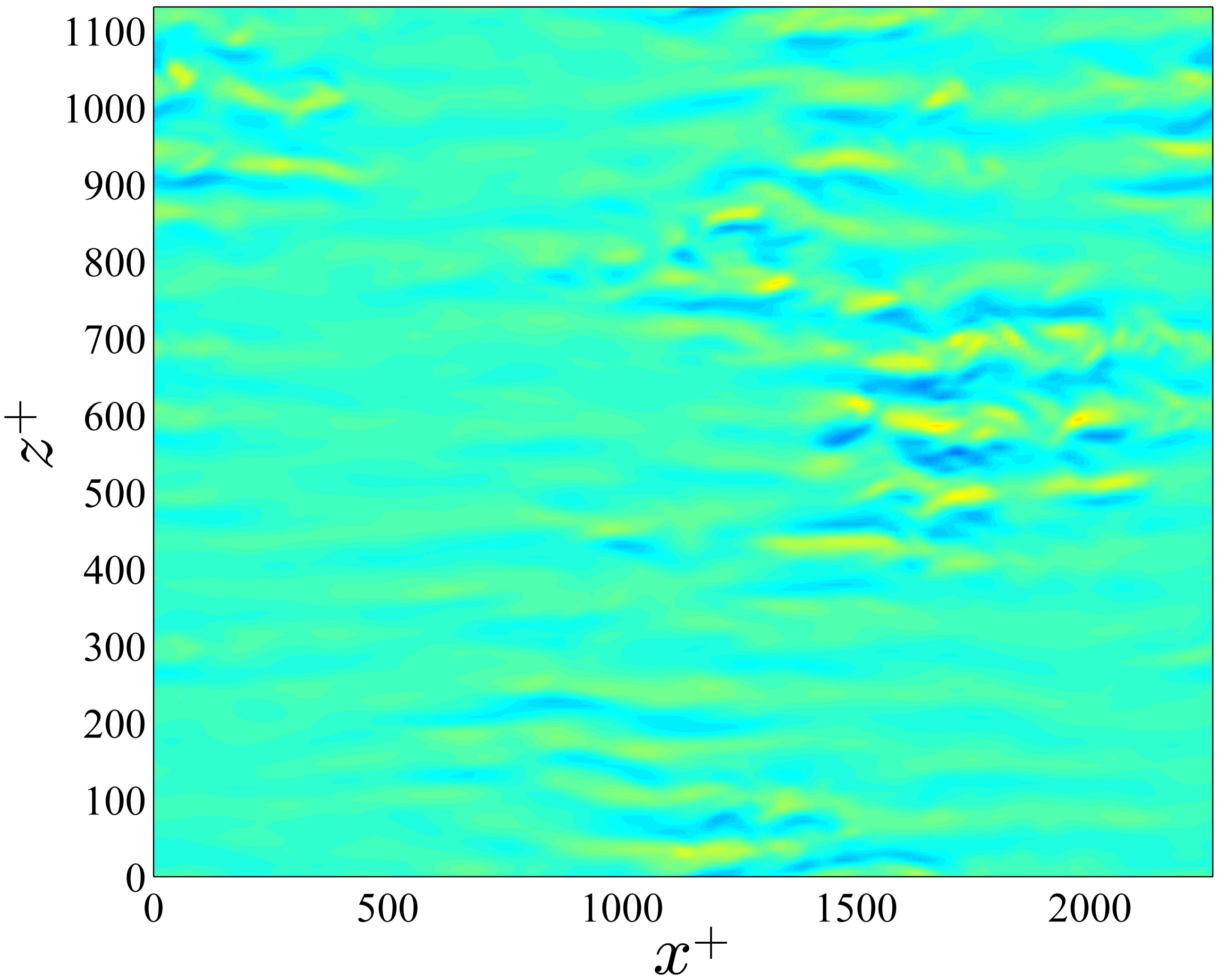
Controlled v: $y^+ = 20|_{\text{init}}$

t=10



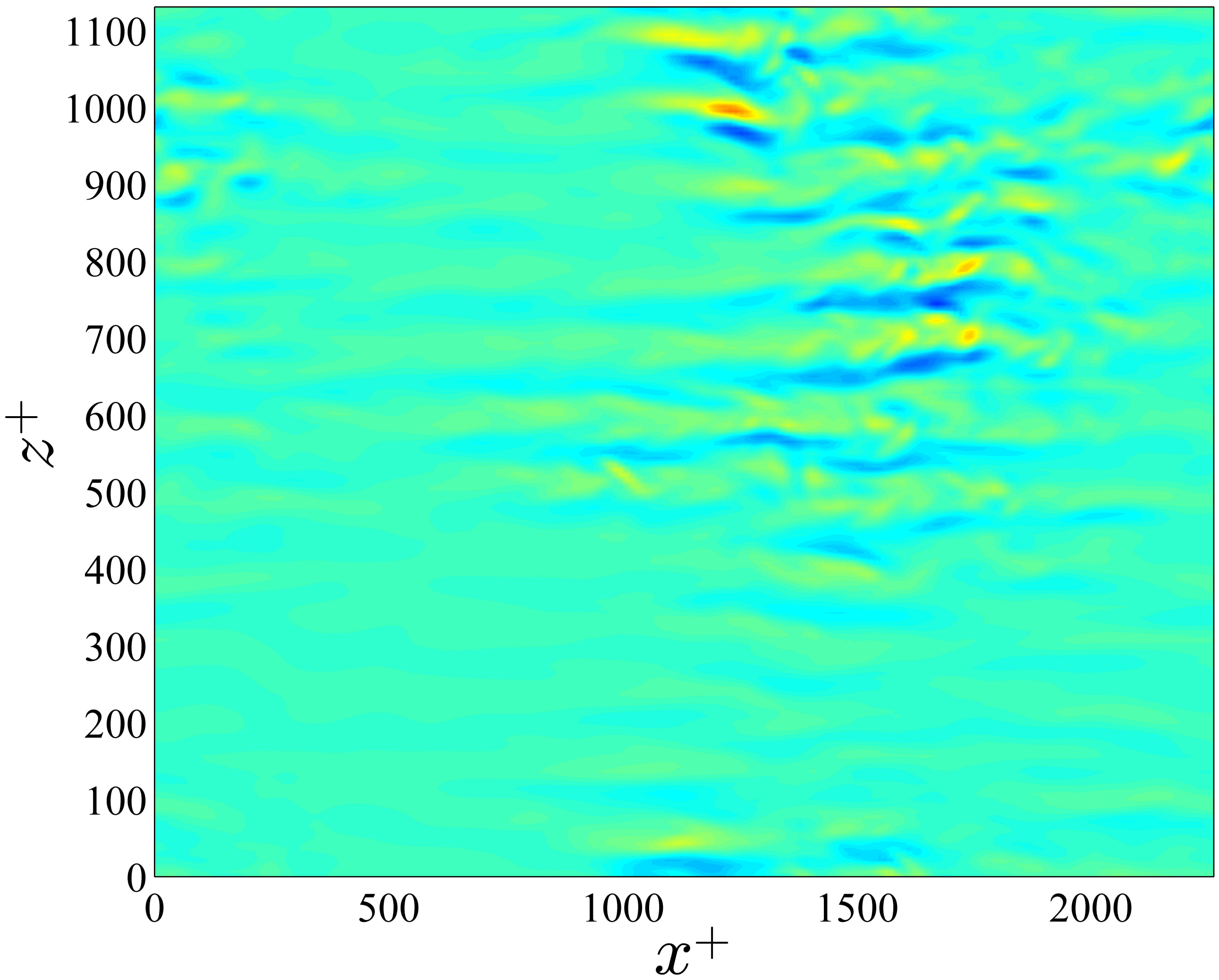
Controlled v: $y^+ = 20|_{\text{init}}$

$t = 50$



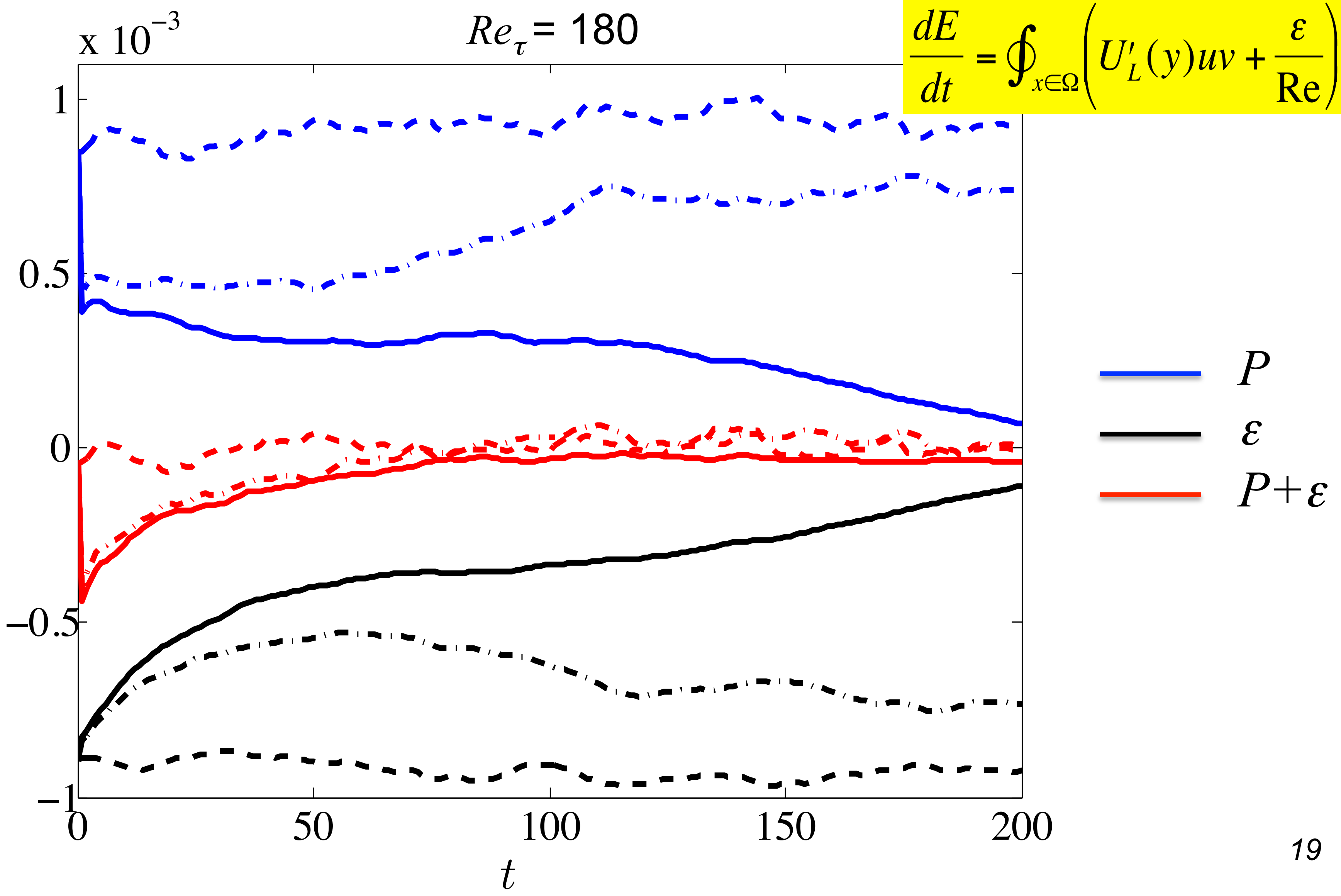
Controlled v: $y^+ = 20\big|_{\text{init}}$

$t = 100$



Fluctuations about target laminar profile

$$\frac{dE}{dt} = \oint_{x\in\Omega}\left(U_L'(y)uv + \frac{\varepsilon}{\mathrm{Re}}\right) \leq 0$$

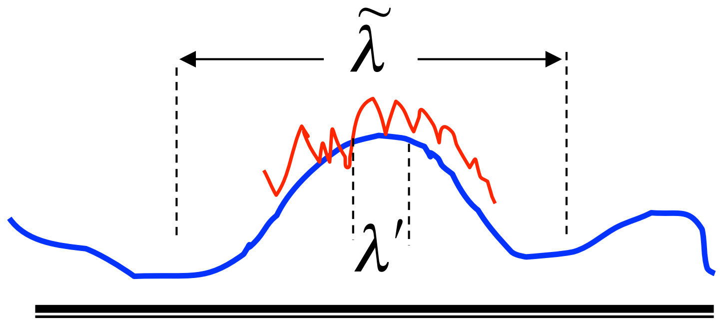


A useful theory for Inner-Outer Interaction?

- Landahl ('93, '90, '75): initial disturbance scales L, u_0 with timescales: shear interaction $\{U'_w\}^{-1}$ << viscous $\{L^2/(\nu U'^2)\}^{1/3}$ << nonlinear L/u_0 .
- Large and small-scale decomposition: $u_i = \tilde{u}_i + u'_i$
- Small scale, λ', large scale $\tilde{\lambda}$ where $\lambda'/\tilde{\lambda} = \varepsilon << 1$
- To first order in ε, large-scale and small-scale fields may be represented separately by the same equations:

$$\left(\frac{\partial}{\partial t} + U\frac{\partial}{\partial x}\right)\nabla^2 v - U''\frac{\partial v}{\partial x} - \frac{\nabla^4 v}{\mathrm{Re}} = q$$

$$\left(\frac{\partial}{\partial t} + U\frac{\partial}{\partial x}\right)\eta + U'\frac{\partial v}{\partial z} - \frac{\nabla^2 \eta}{\mathrm{Re}} = p$$



$$U_i = U(y)\delta_{1i} + u_i(x_j, t)$$

- p, q nonlinear source terms (turbulent stresses) significant only in local regions: "intense small-scale turbulence of an intermittent nature" interspersed with "laminar-like unsteady motion of a larger scale".

Pressure gradient fluctuations

- High Reynolds numbers: local isotropy and negligible viscous diffusion
- Mean-square acceleration becomes

$$\overline{\left(\frac{Du_i}{Dt}\right)^2} \approx \overline{\left(\frac{\partial p}{\partial x_i}\right)^2} + \nu^2 \overline{\left(\frac{\partial^2 u_i}{\partial x_j^2}\right)^2}$$

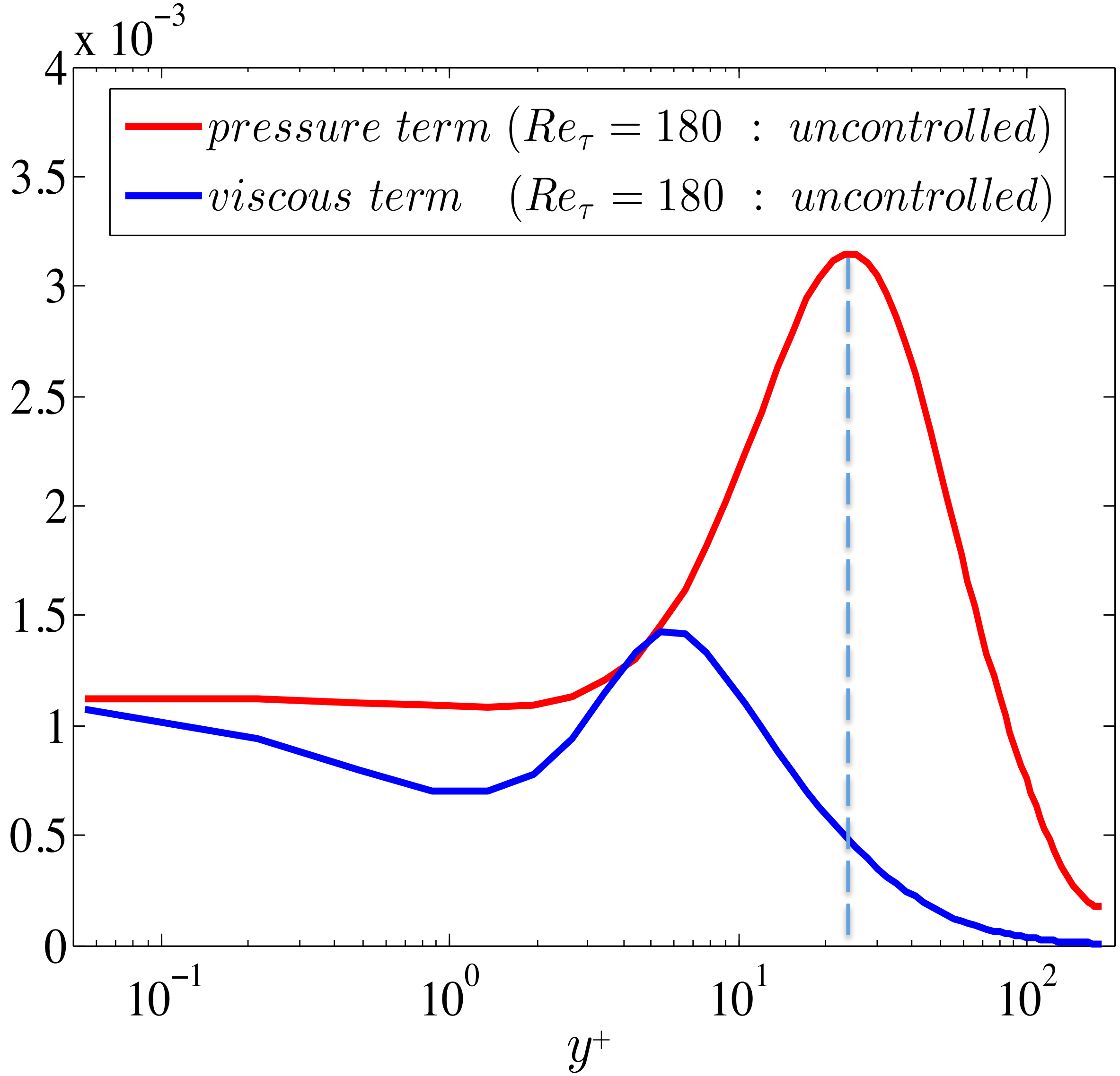
- where

$$\overline{\left(\frac{\partial p}{\partial x_i}\right)^2} \approx 20\nu^2 \overline{\left(\frac{\partial^2 u_i}{\partial x_j^2}\right)^2}$$

- Therefore, even the smallest scale motion is driven by pressure gradients and not by viscous forces.

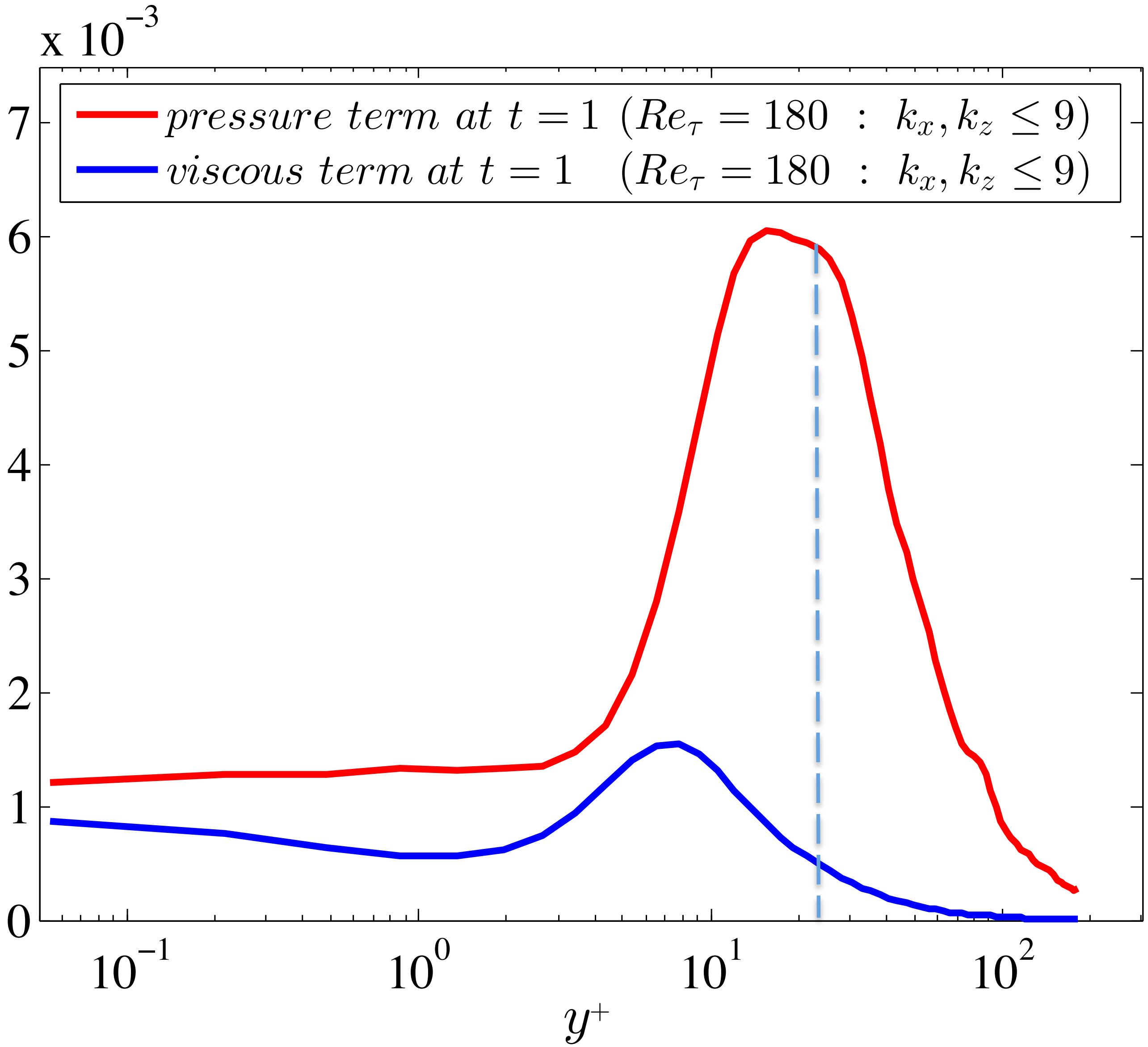
Batchelor & Townsend 1956

Batchelor & Townsend: uncontrolled turbulent channel flow

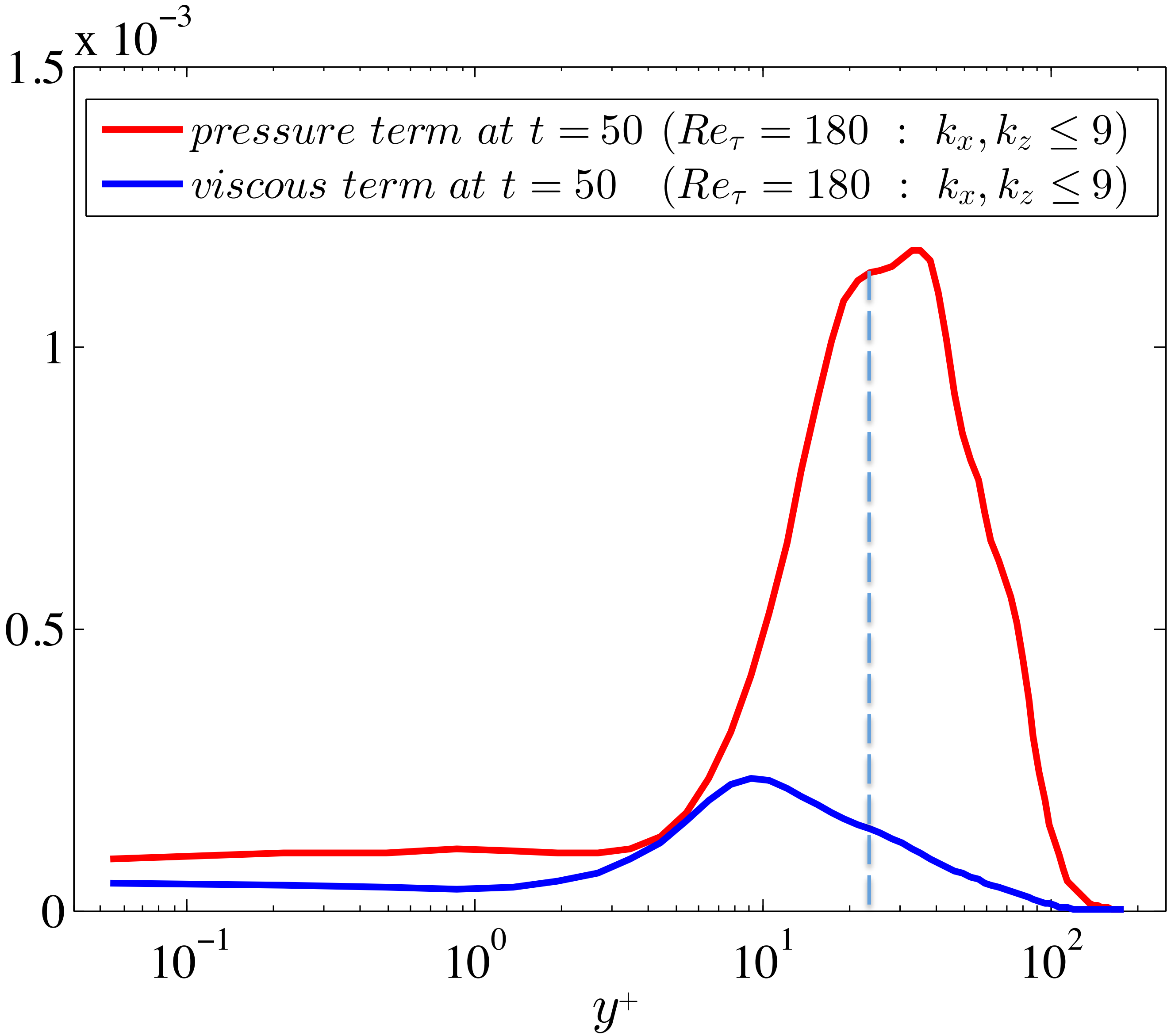


$$\overline{\left(\frac{\partial p}{\partial x_i}\right)^2} \approx 20\nu^2 \overline{\left(\frac{\partial^2 u_i}{\partial x_j^2}\right)^2}$$

Fluctuations about target laminar profile



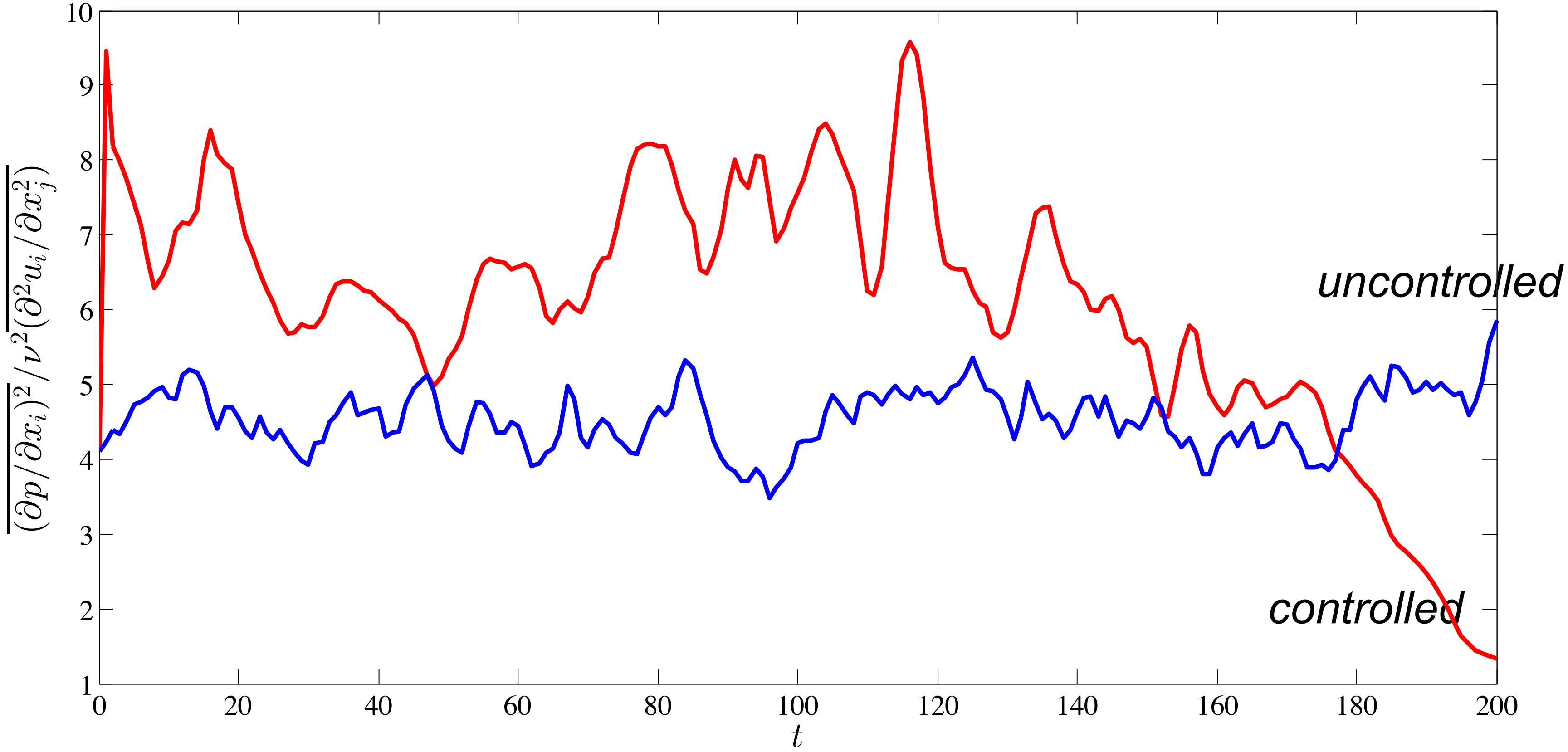
Fluctuations about target laminar profile



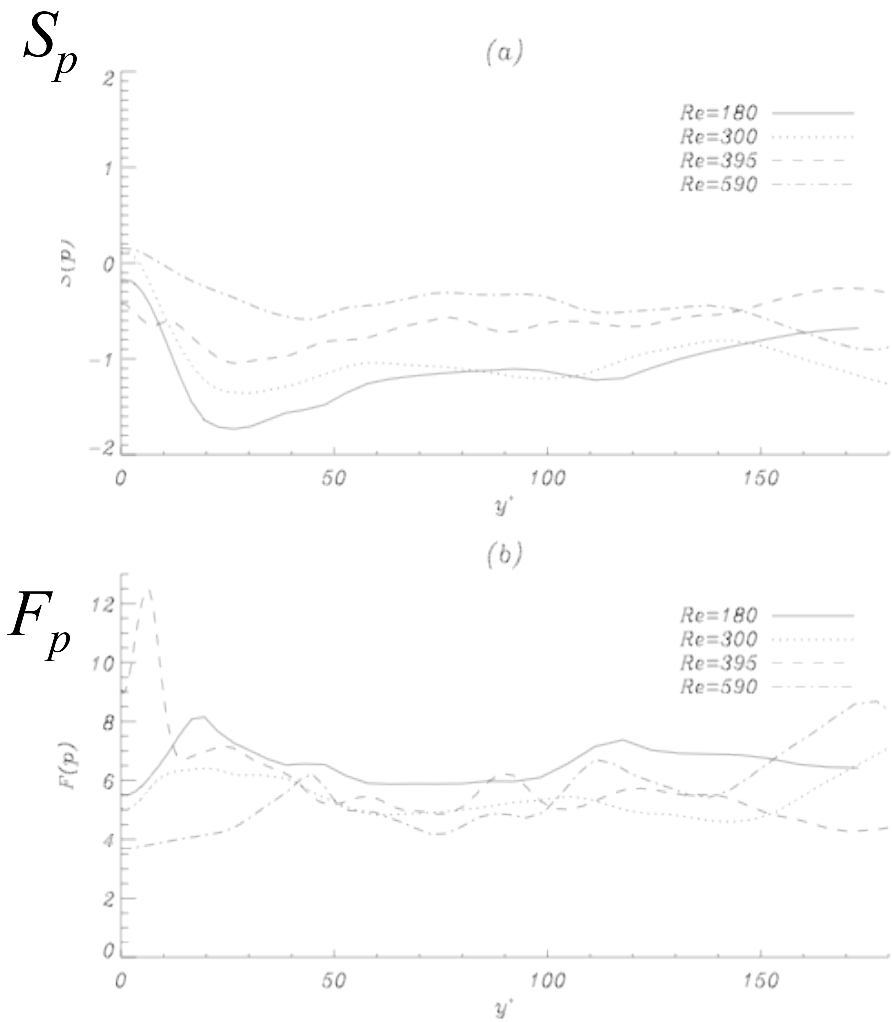
$$\overline{\left(\frac{\partial p}{\partial x_i}\right)^2} \Bigg/ \nu^2 \overline{\left(\frac{\partial^2 u_i}{\partial x_j^2}\right)^2} \text{ at } y^+ = 20$$

U based on mean profile U(t)

$\mathrm{Re}_\tau = 180$



Turbulent channel flow pressure statistics



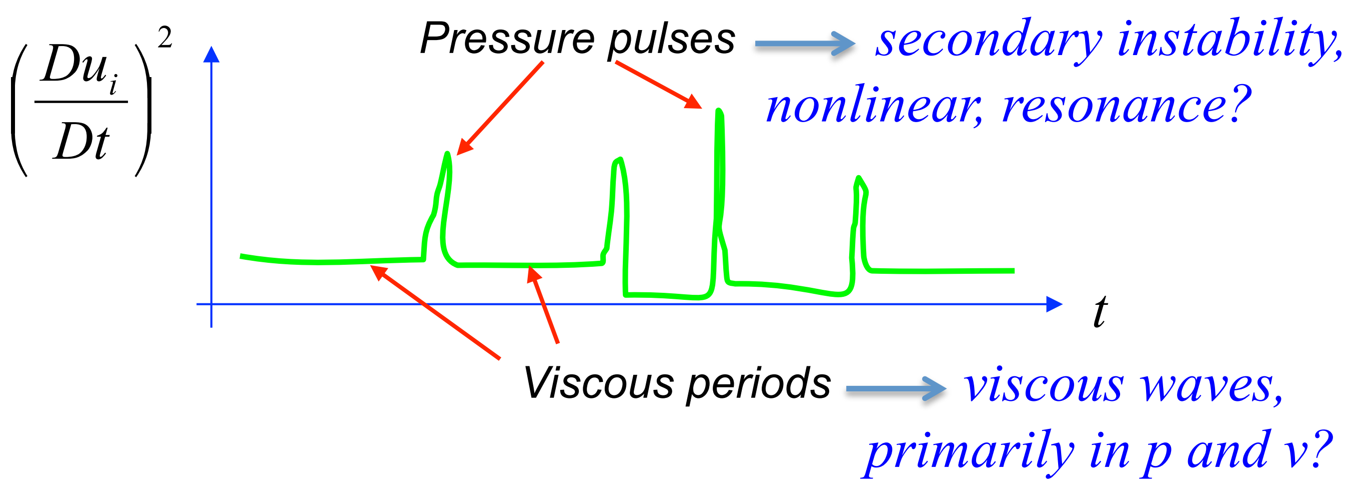
Dunn & Morrison 2003

- Spatial intermittency: pressure has small skewness, large flatness (>6)
- Green's function integral shows that contribution to wall pressure comes mostly from near-wall velocity field

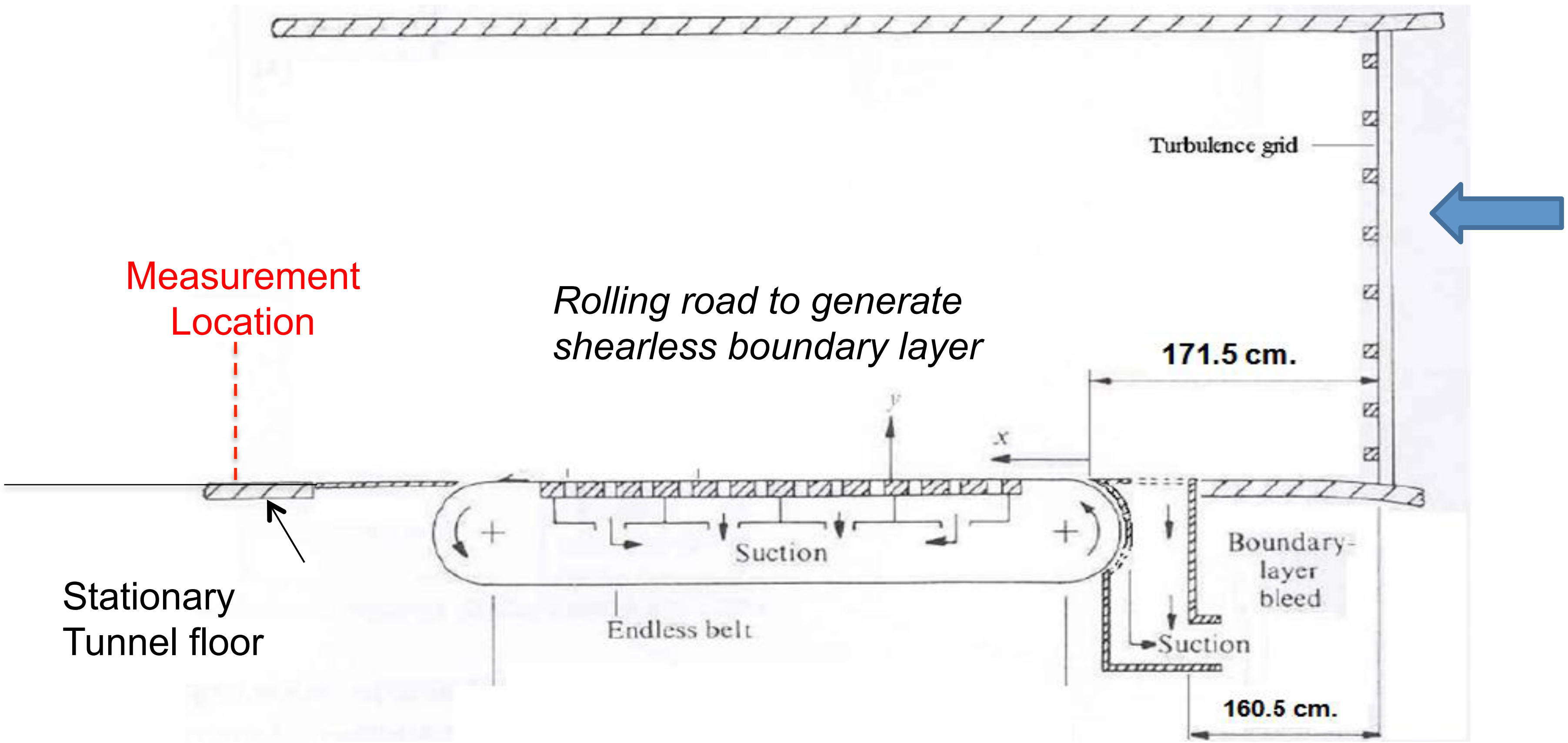
$$-\nabla^2 p = 2U'\frac{\partial v}{\partial x} - \frac{\partial^2}{\partial x \partial y}\left[uv - \overline{uv}\right]$$

BLT theory

- Sublayer as a waveguide: primarily for p and v
- u and w also wave-like but including convected eddy behaviour
- Description of both large & small scales – Inner-outer interaction?
- Pressure sources can ‘trigger’ bursts near wall = short shear – interaction timescale



Rapidly distorted boundary layer

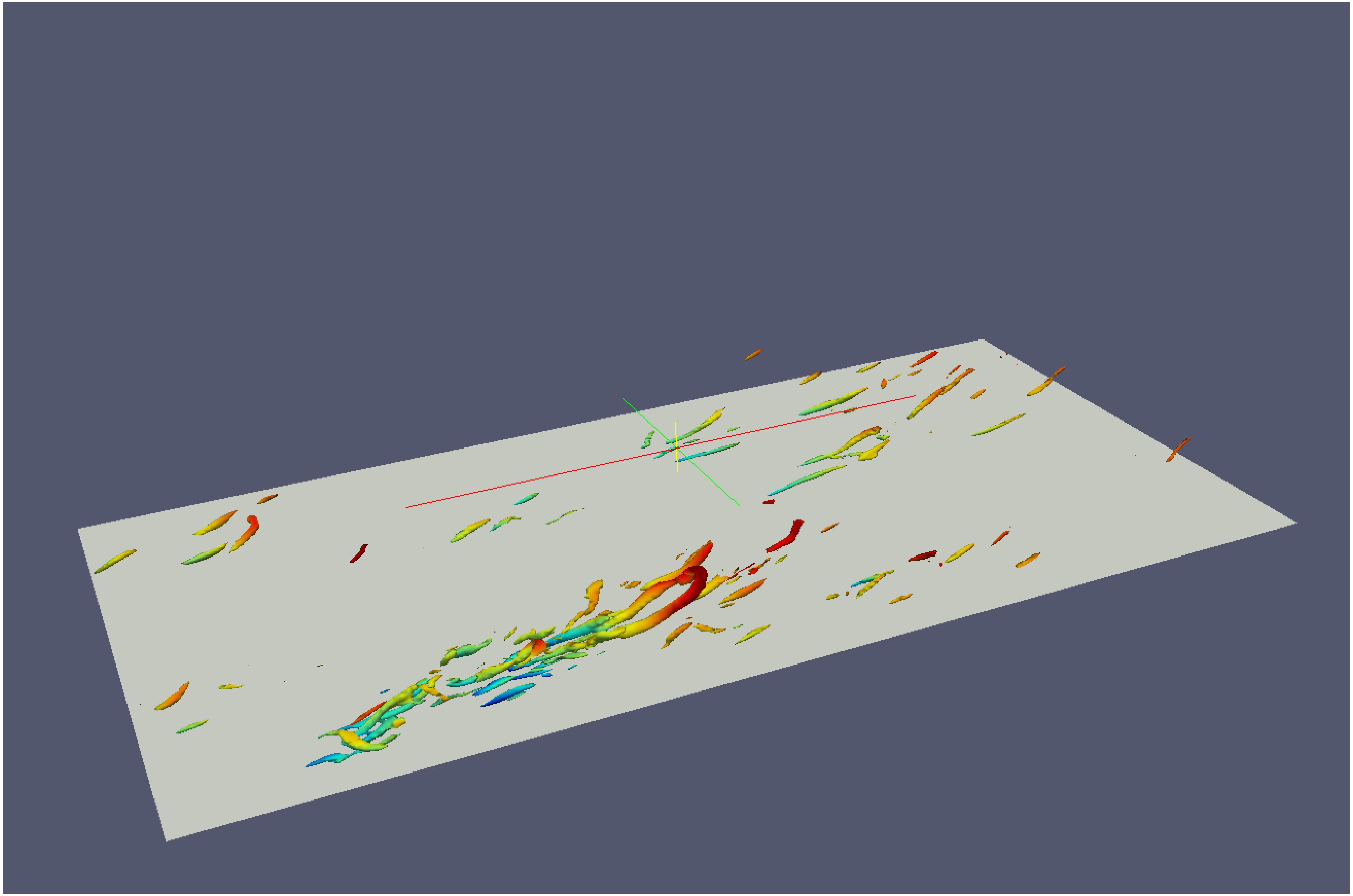


Aims:

1. Experimental study of linear mechanisms in wall turbulence
2. Variable ratio of shear timescale to turbulence timescale

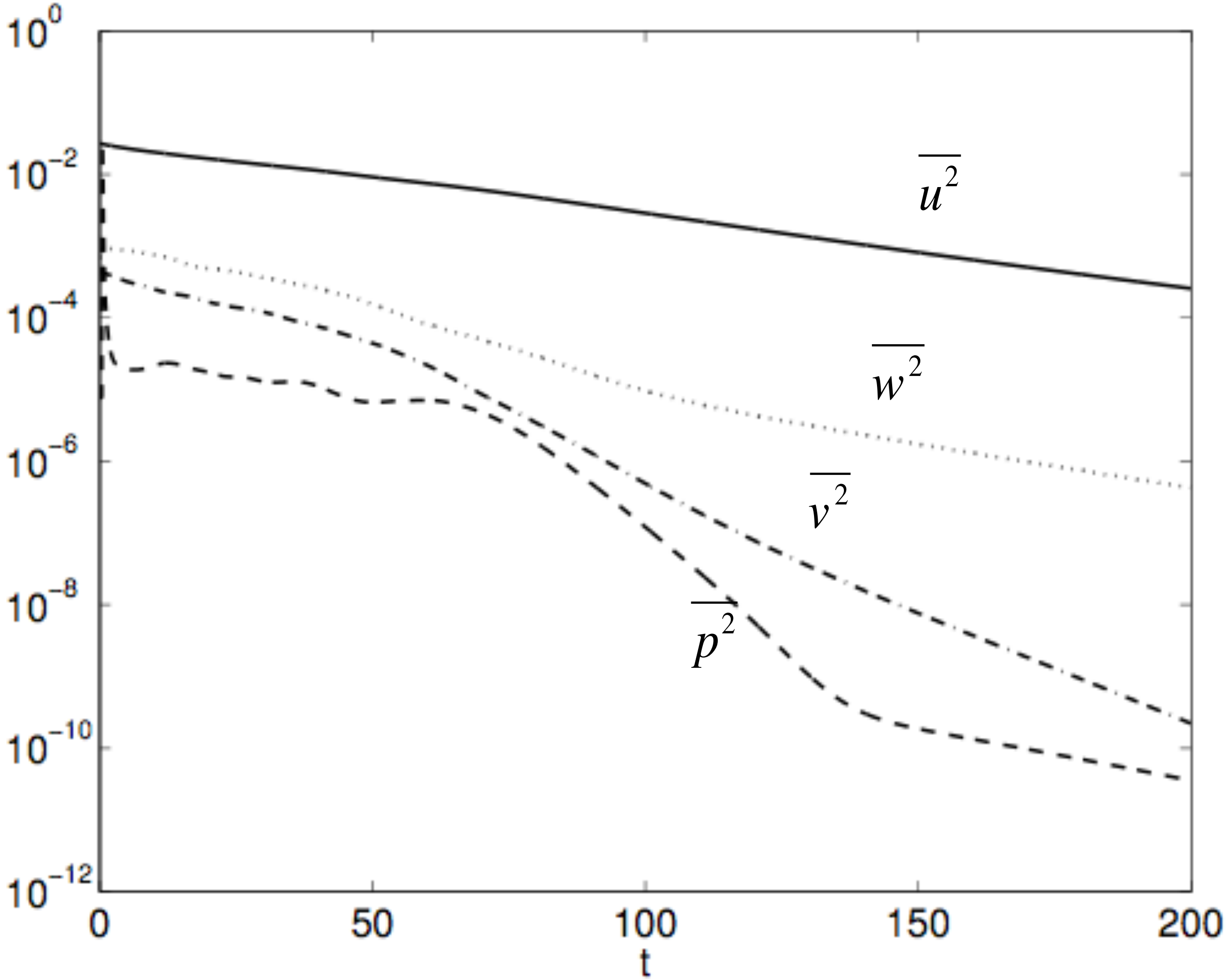
Conclusions

- Linear full-domain forcing via vU' at low wavenumbers effective in attenuating turbulent channel flow
- Control-theoretic approach ("passivity") explained by conservative nature of nonlinear terms contributing to Reynolds-Orr equation
- Control acts on v–component field and hence pressure field via rapid source term of Poisson equation
- Qualitative support for Landahl's theory: inner-outer interaction effected by linear shear-interaction on short timescales
- Relevance of Landahl's theory for linear control lies in the fact that, over the short time for which the controller is effective, the longer turbulence time scale is not significant
- Shear timescale effective because of pressure – linear source term is an RDT approximation



Fluctuations about target laminar profile

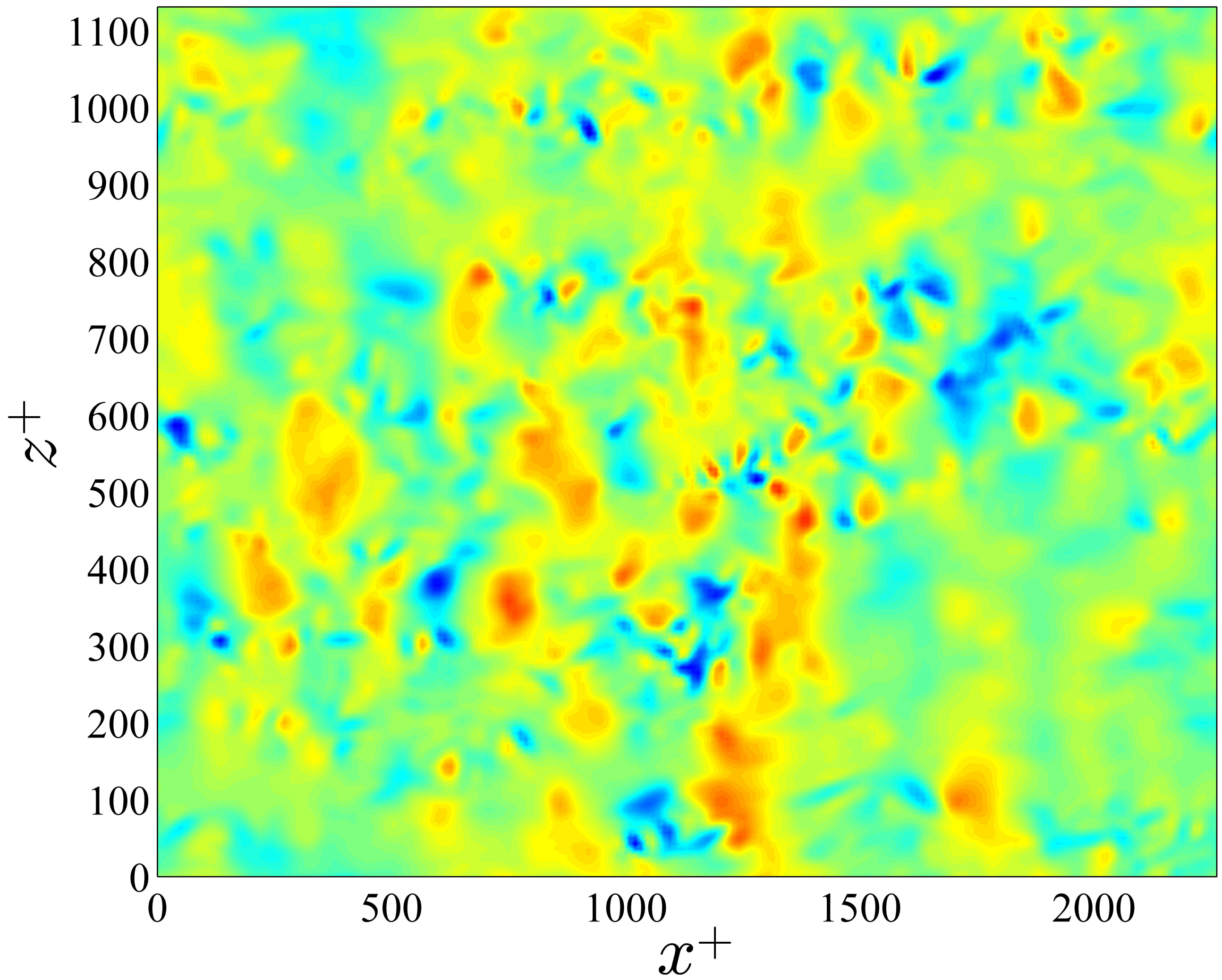
$$Re_\tau = 80$$



Controlled p: $y^+ = 20|_{\text{init}}$

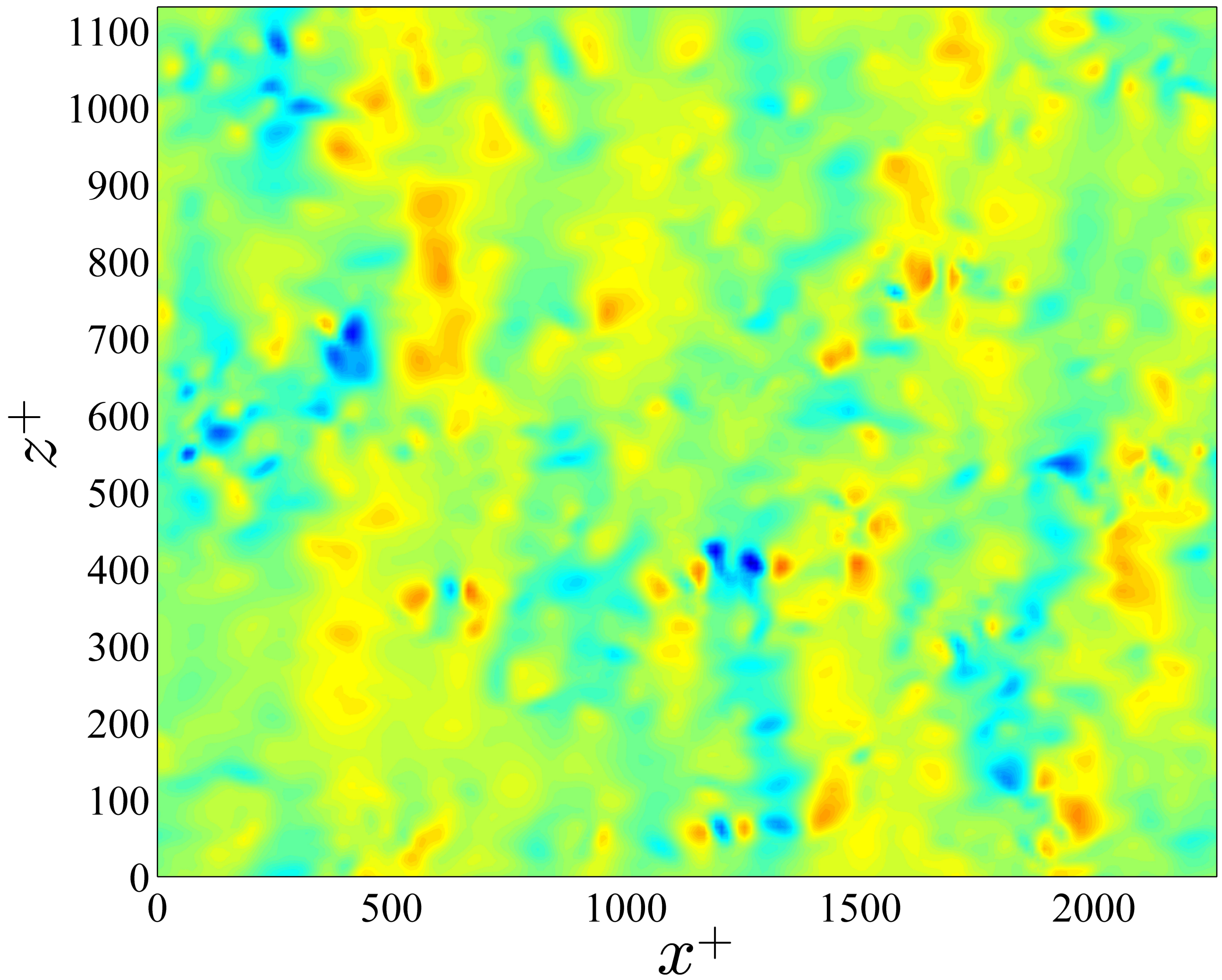
$Re_\tau = 180$

$tU/h = 2$



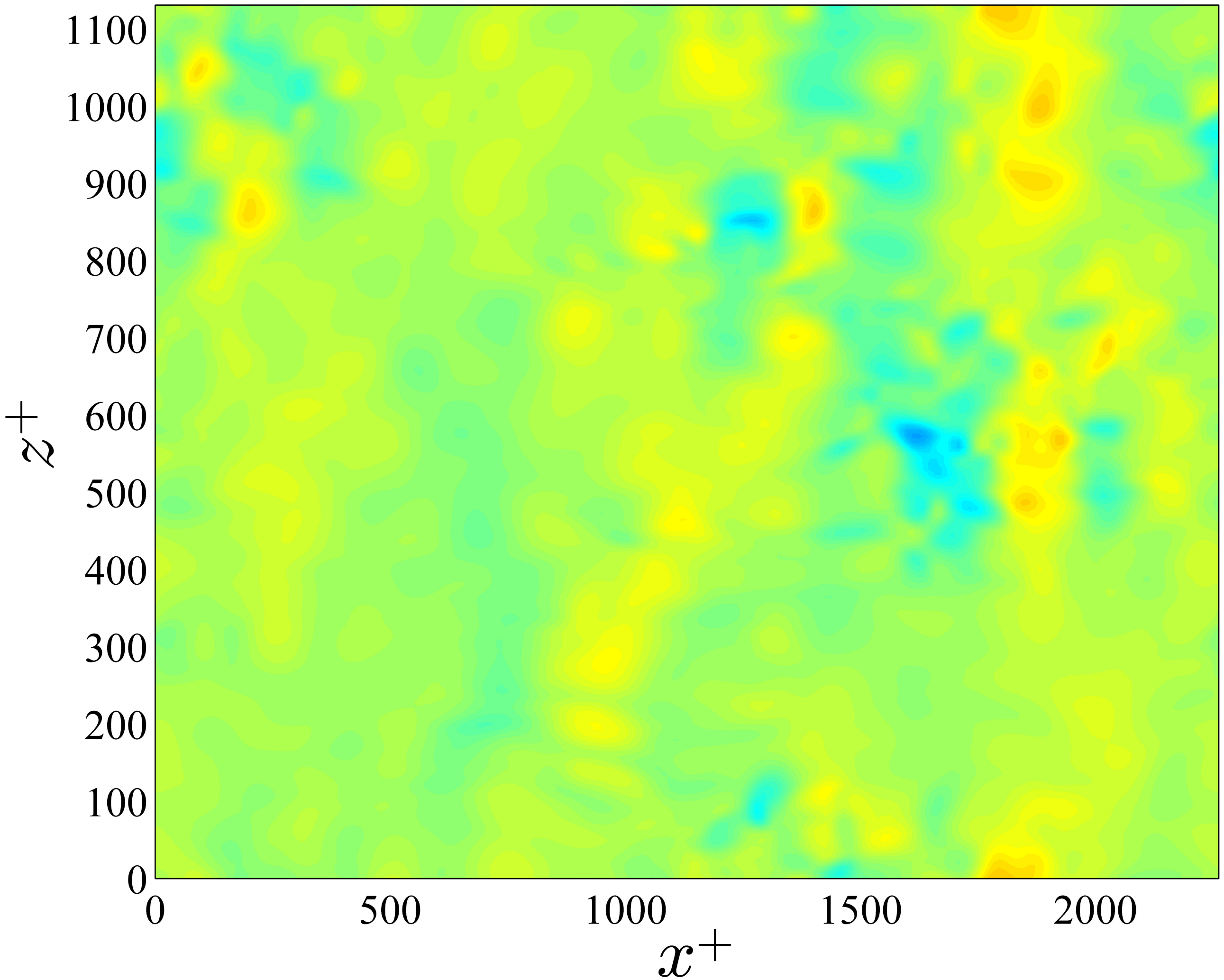
Controlled p: $y^{+} = 20\big|_{\text{init}}$

tU/h =10



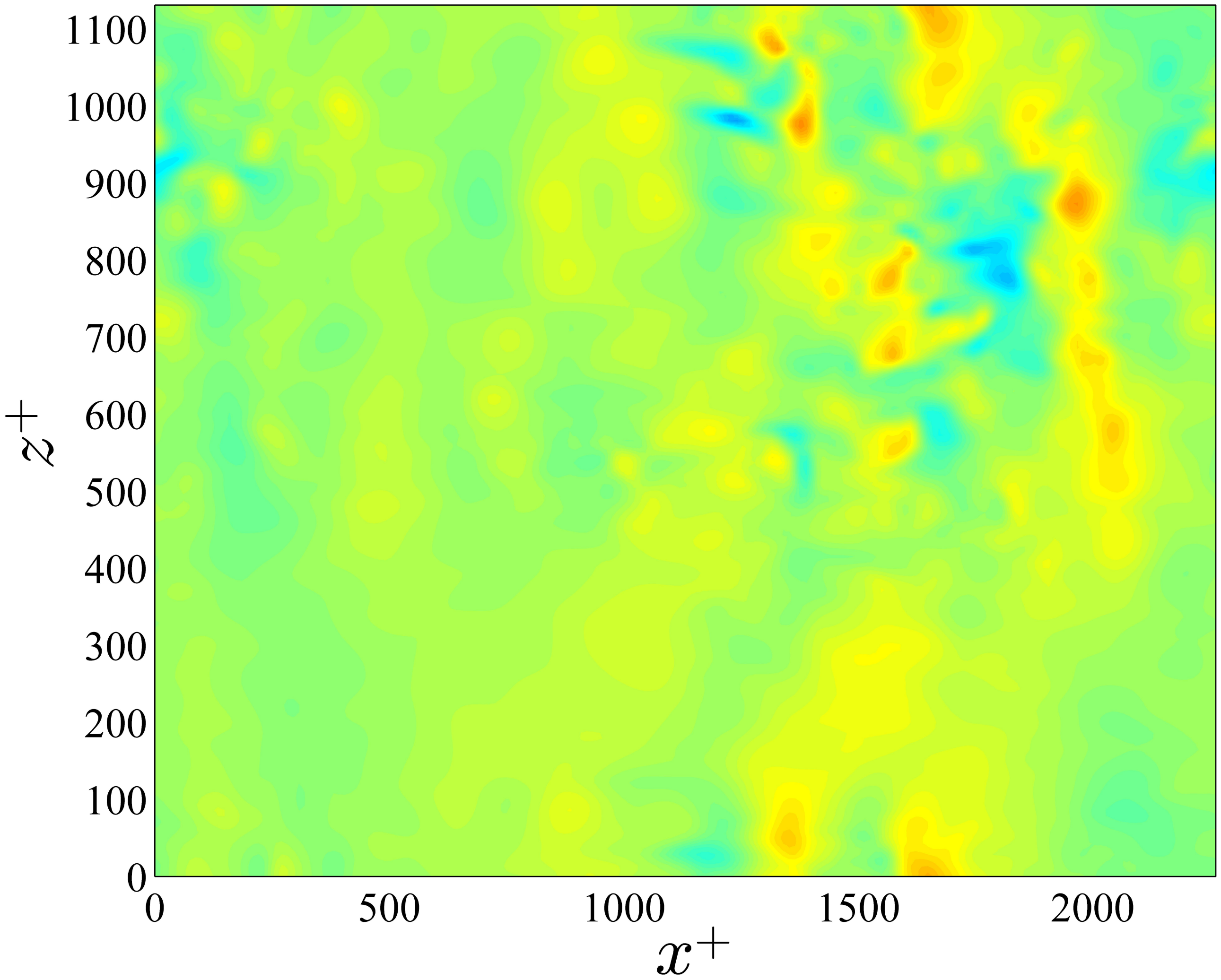
Controlled p: $y^{+} = 20|_{\text{init}}$

tU/h =50



Controlled p: $y^{+} = 20|_{\text{init}}$

tU/h =100

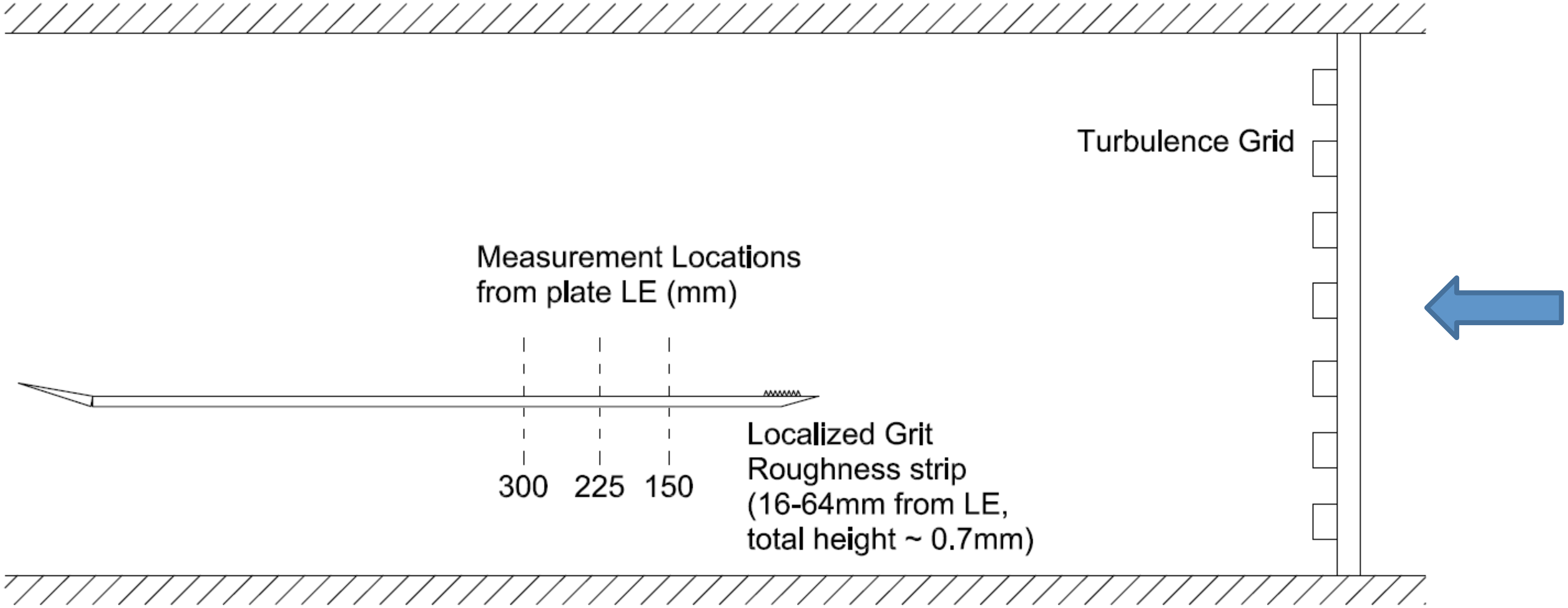


- *Experimental Design:*

1. *Grid-generated turbulence*
2. *Thin boundary layer on a flat surface to provide for rapid shearing*
3. *Localised roughness strip to introduce broad-band disturbance*

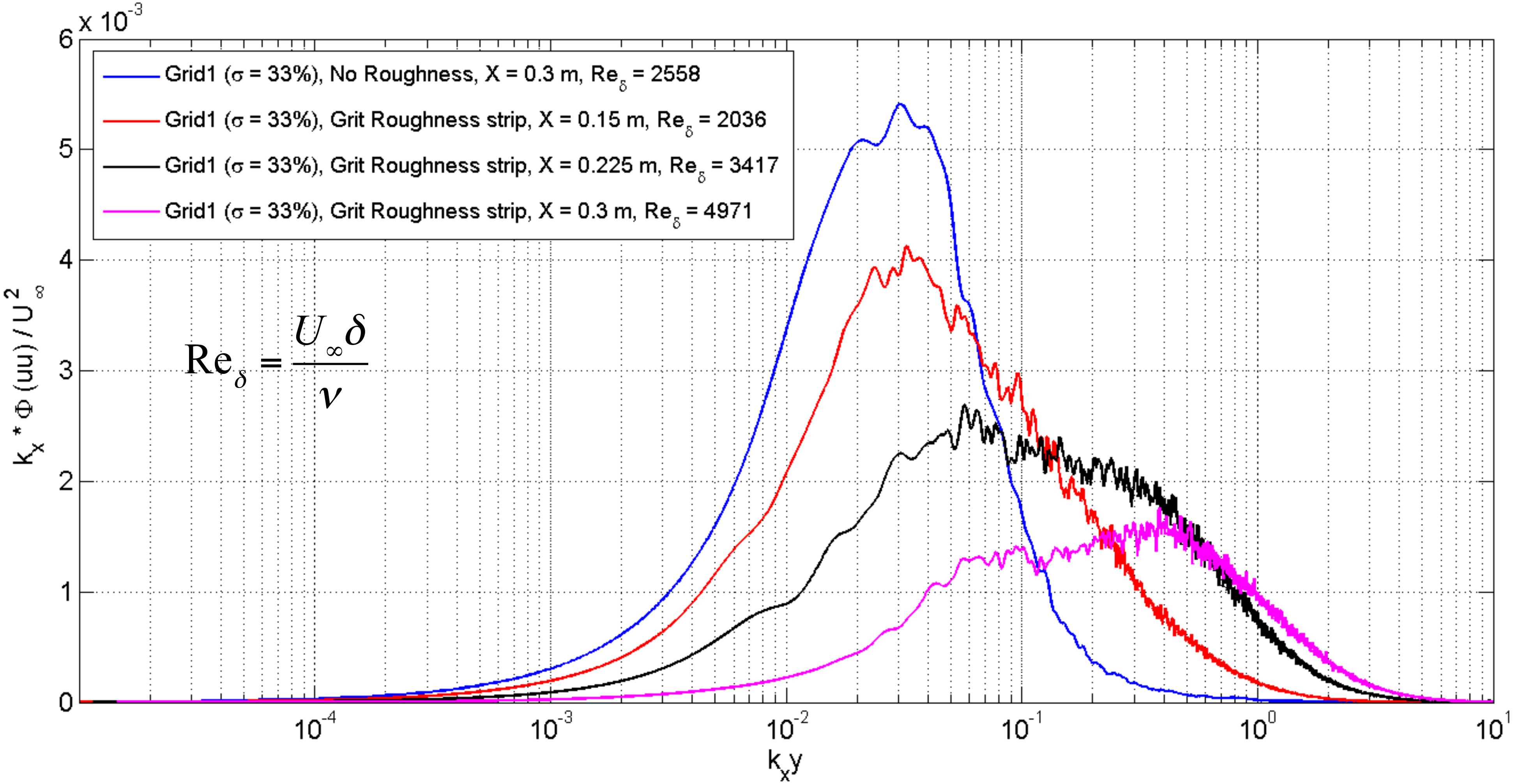
- *Two configurations used:*

1) 18” x 18” tunnel (without a rolling road), on an Aluminium plate



Preliminary Results

- *Single-wire HW measurements*
- *Spectrum calculated using Taylor's hypothesis*

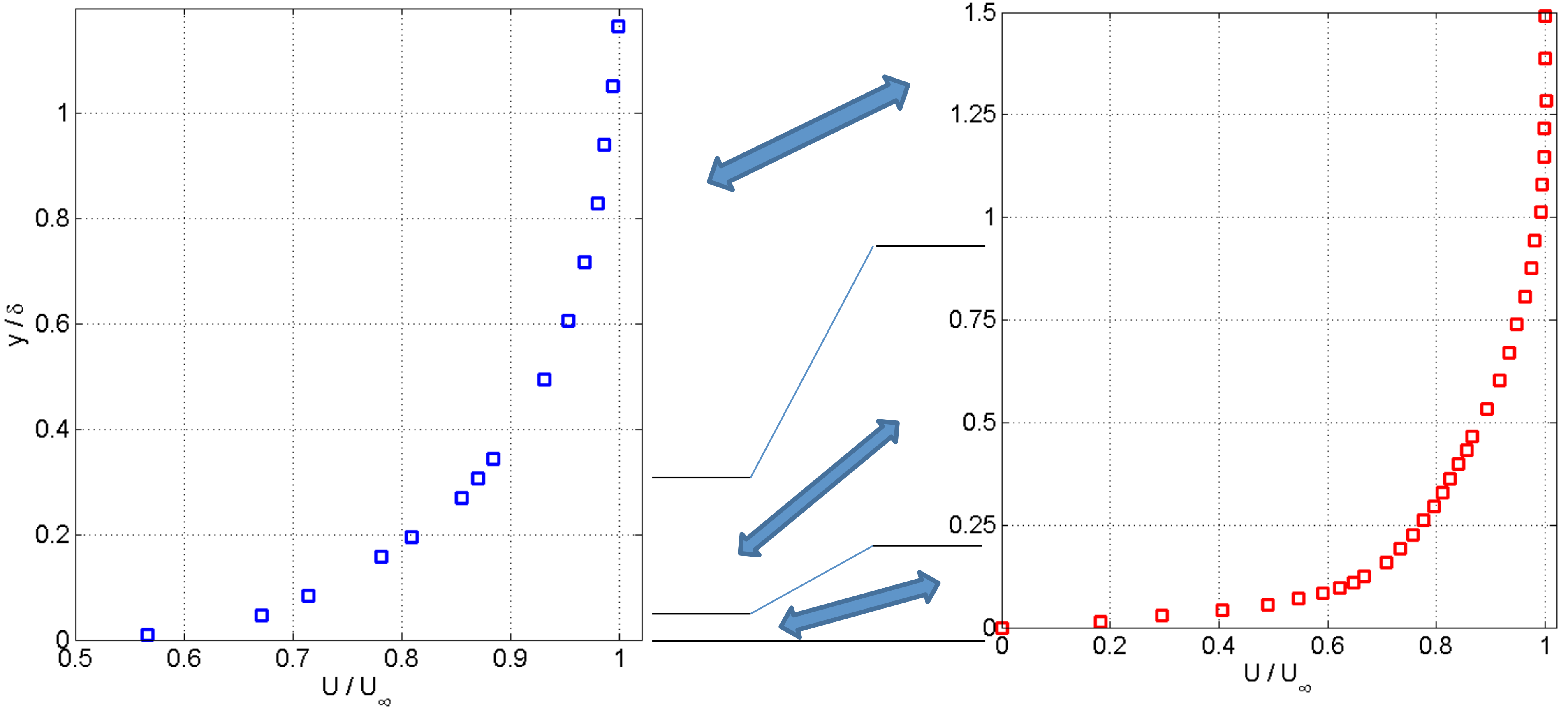


$$\mathrm{Re}_\delta = \frac{U_\infty \delta}{\nu}$$

- *BL evolves gradually towards a fully developed turbulent BL*
- *Localized grit roughness enhances high wave-number content in the spectrum (for a given*

Comparison between fully-developed TBL and a rapidly sheared flow

A typical ZPG TBL *Rapidly sheared flow (X = 0.3m)*



"synthetic" boundary layer that

- *Approximately resembles in turbulence structure to a typical TBL*
- *Expands the buffer layer of the TBL allowing for a closer inspection of structures*

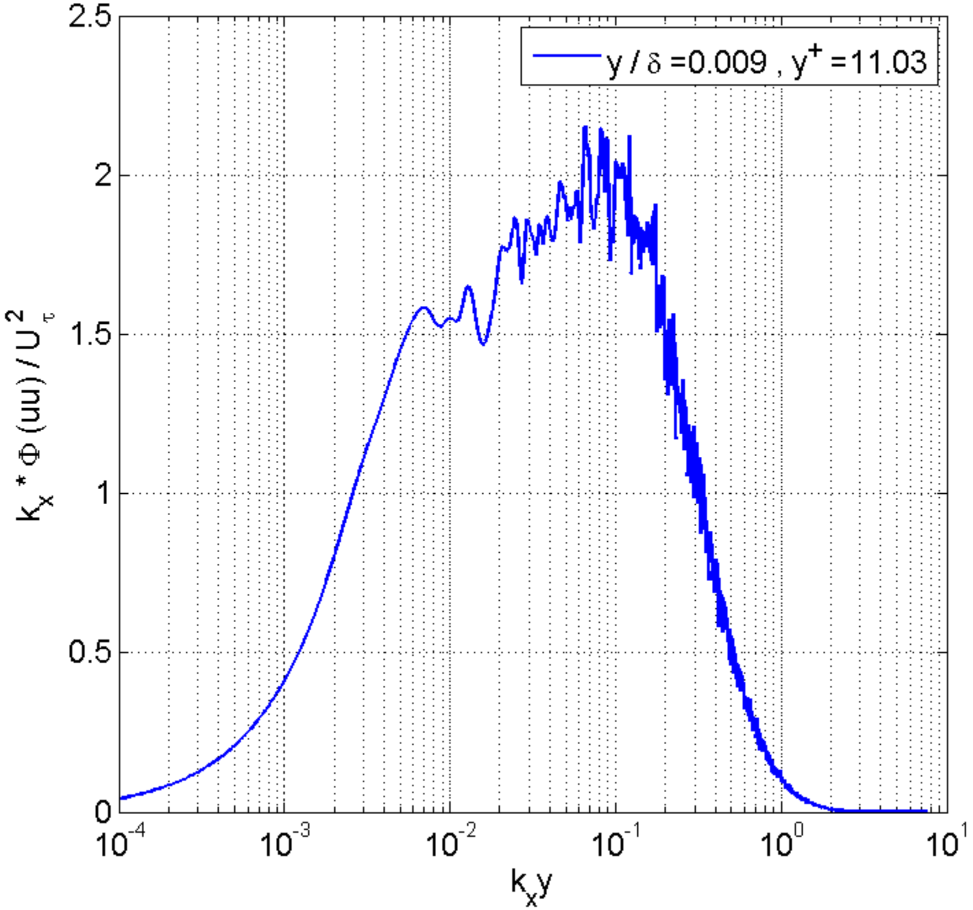
“Synthetic” Boundary Layer compared to a TBL

“Synthetic” Boundary Layer	Turbulent Boundary Layer
Grid-generated turbulence blocked by the presence of wall	Wake region close to the edge of the TBL
A thin wall layer (that rapidly shears the free-stream turbulence to generate long structures)	The buffer region of the TBL
A localized patch of roughness to enhance smaller scales	High wavenumber end of the turbulence spectrum

Comparison between fully-developed TBL and a rapidly sheared flow

Buffer layer

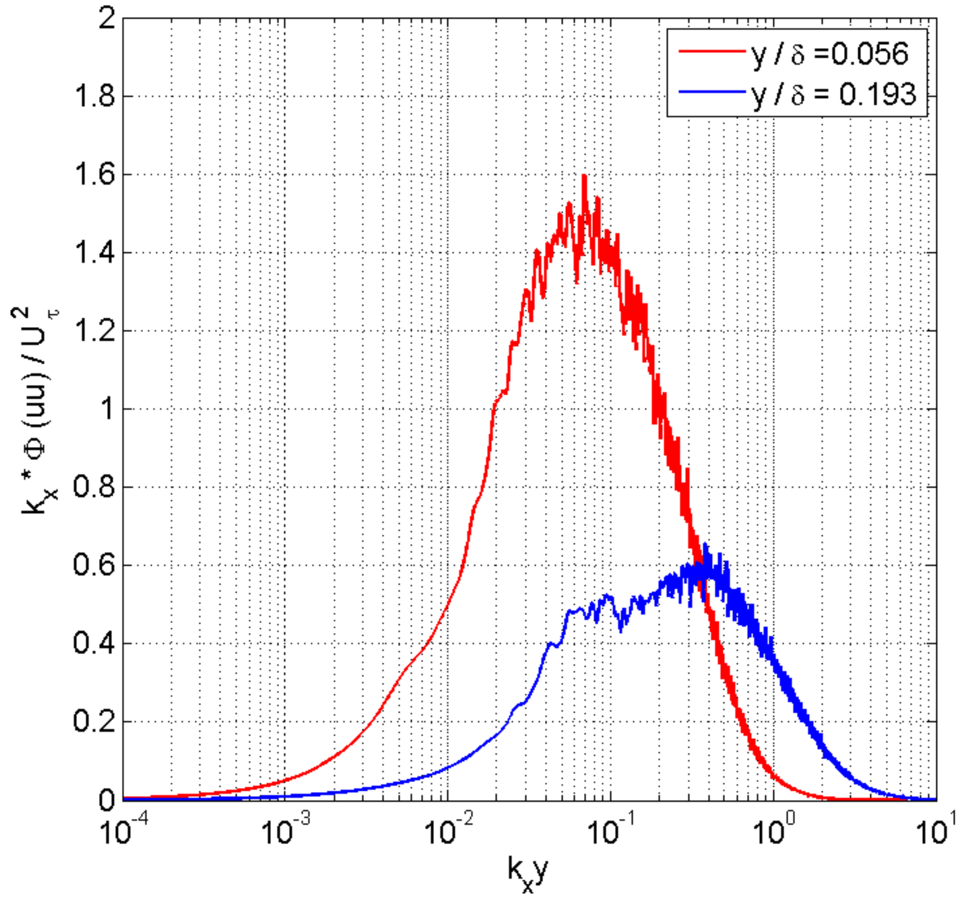
ZPG TBL (with freestream Tu = 3%)



10' x 5'

from Clauser Chart

Rapidly sheared flow (X = 0.3m)
Freestream Tu = 2.2%



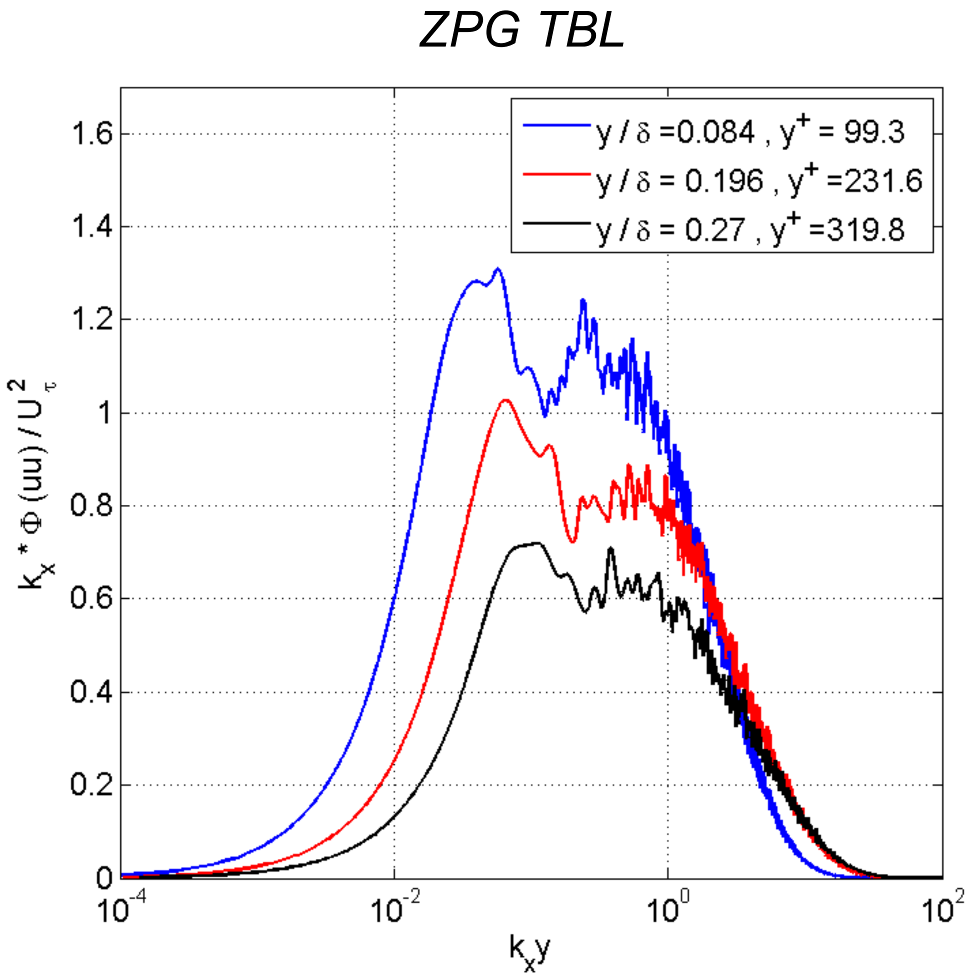
18" x 18"

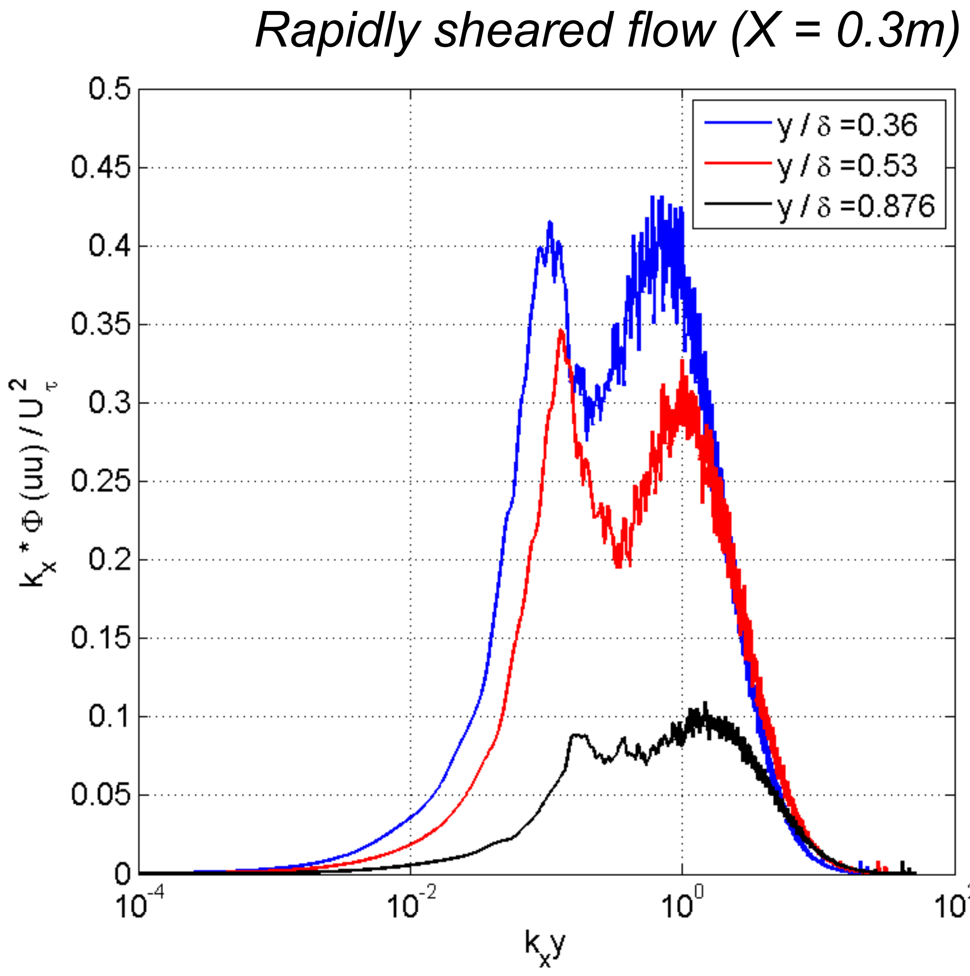
Grid Turbulence with localized roughness

from wall gradient (within ±3 %)

Comparison between fully-developed TBL and a rapidly sheared fl

Log layer





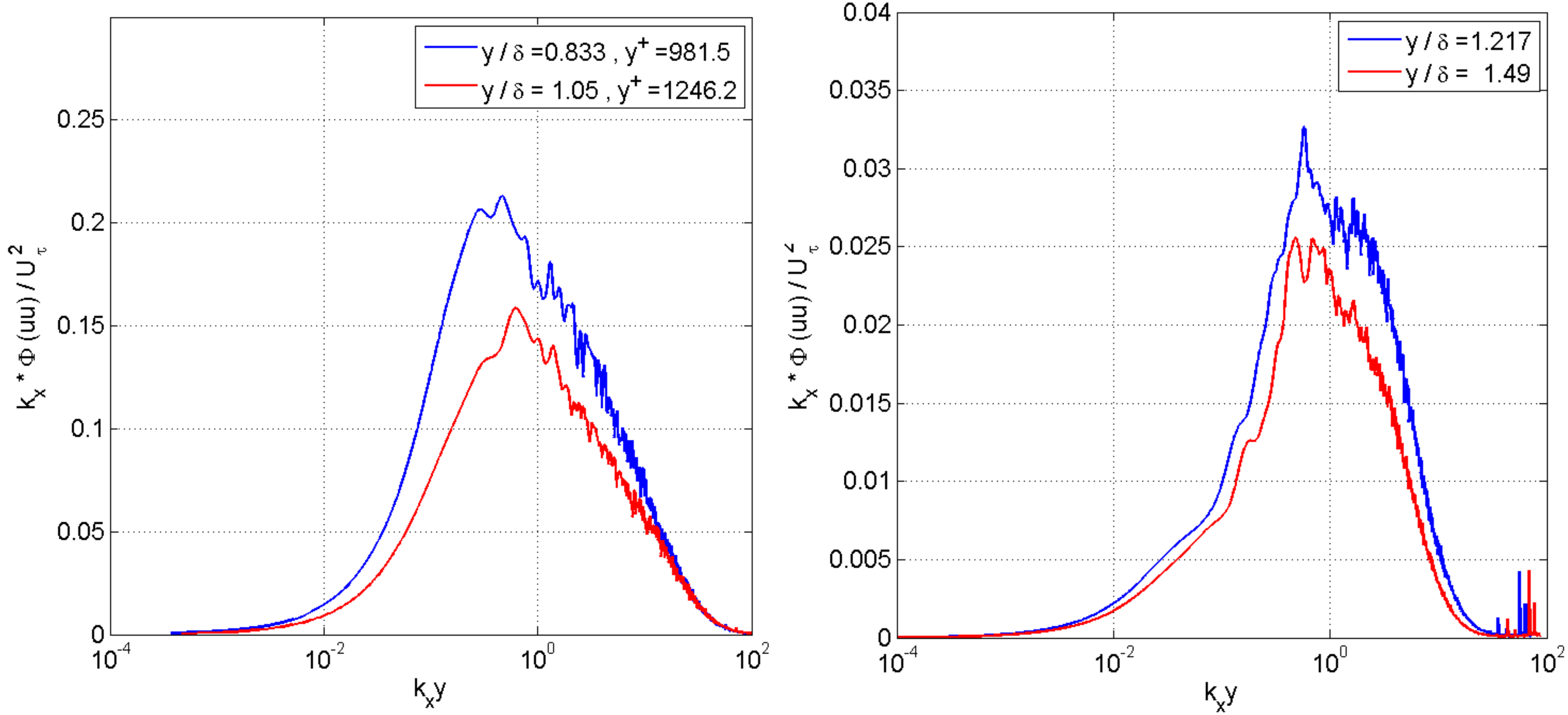
Streamwise length scales of the same order in both flows in appropriate regions

Comparison between fully-developed TBL and a rapidly sheared flow

Outer layer

ZPG TBL

Rapidly sheared flow (X = 0.3m)



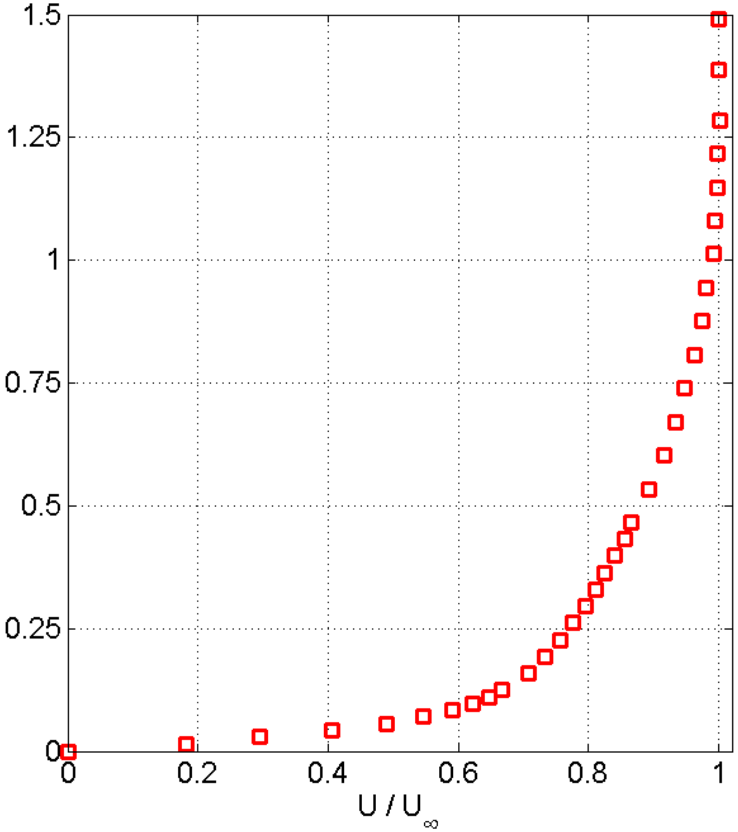
Streamwise length scales of the same order in both flows in appropriate regions

Time-scale Disparity

τ = Integral time scale of Freestream Turbulence

= Shear interaction time scale =

τ



X=0.3 m

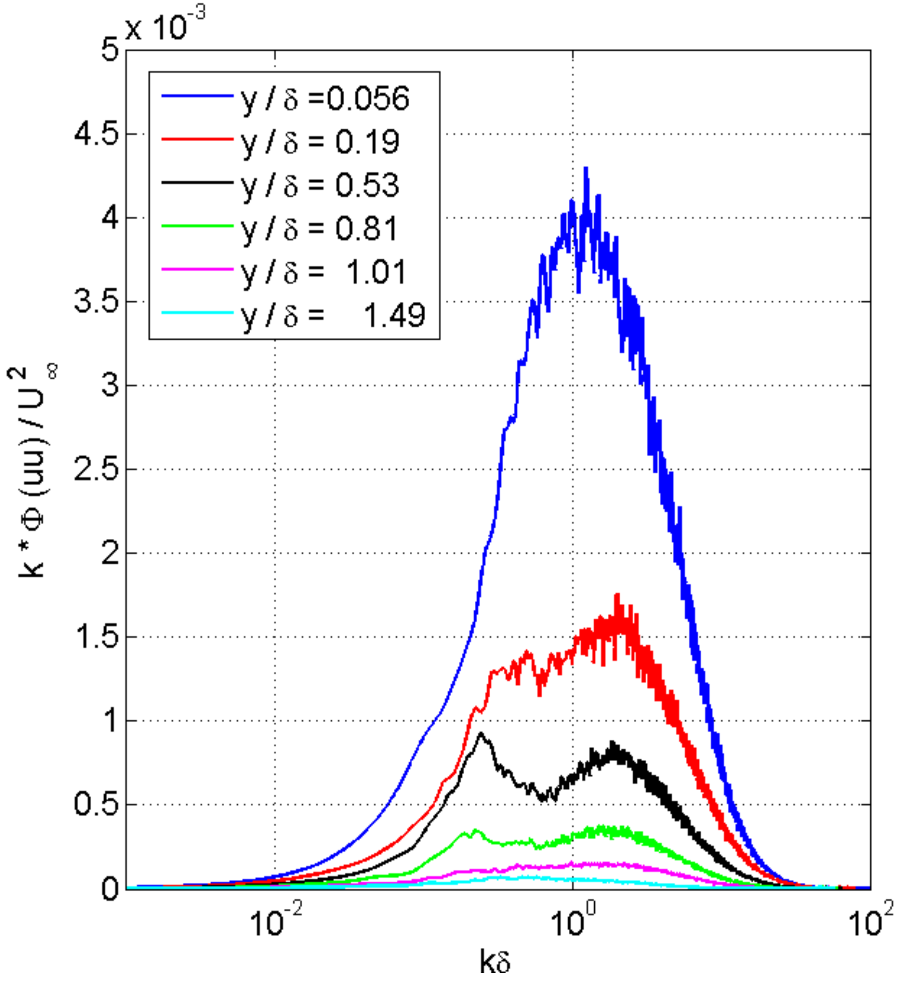
18” x 18”

Grid Turbulence with localized roughness

Time-scale disparity suggests that the ideas of the Rapid Distortion Theory might be applicable to this “synthetic” flow

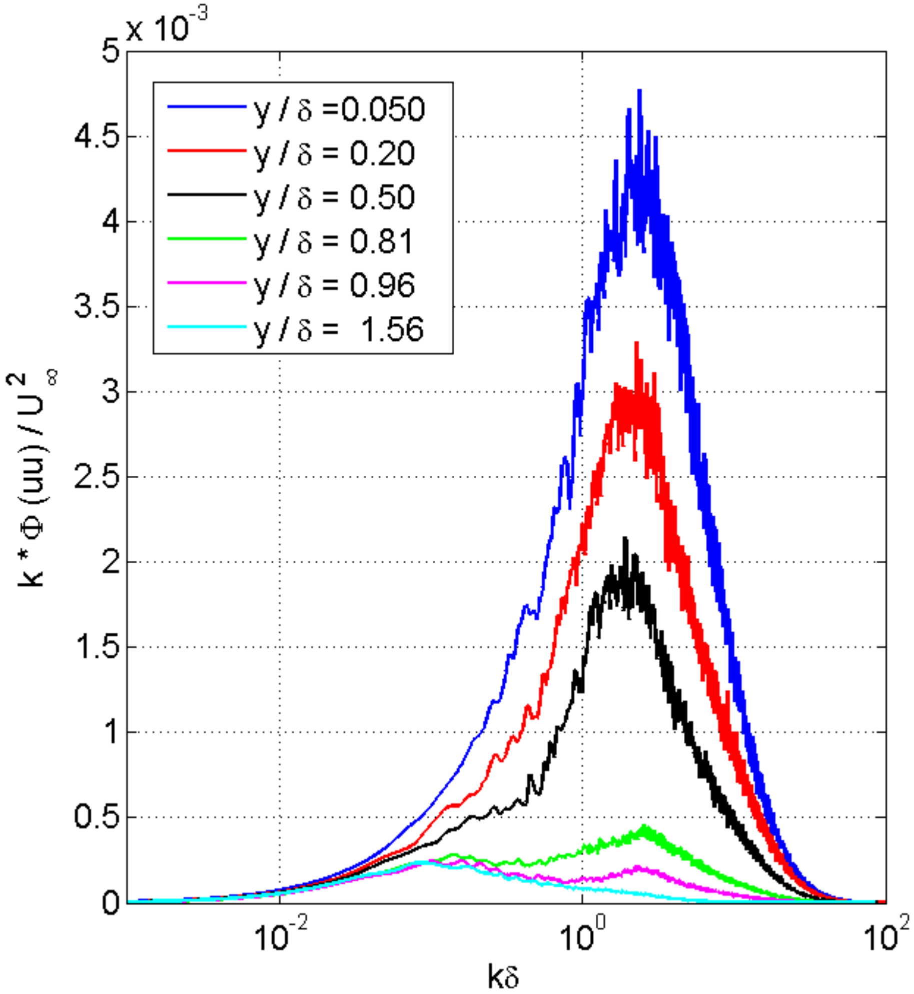
Effect of upstream boundary condition (UBC) on spectra

UBCs: Grid turbulence
Localized Wall Roughness



18" x 18" tunnel

UBCs: Shearless Boundary Layer
No Wall Roughness



10' x 5' tunnel