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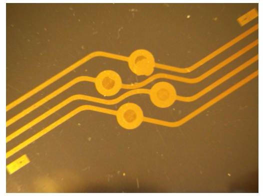

Effects of shear and blocking in a rapidly distorted boundary layer

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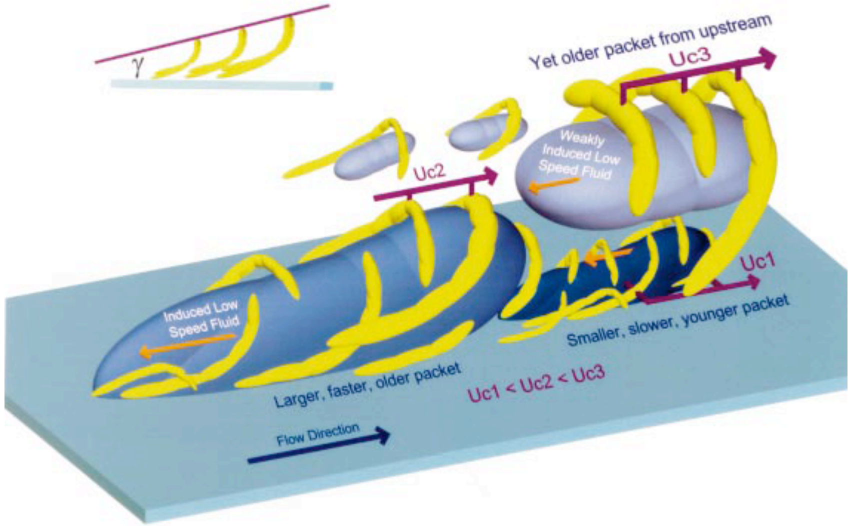
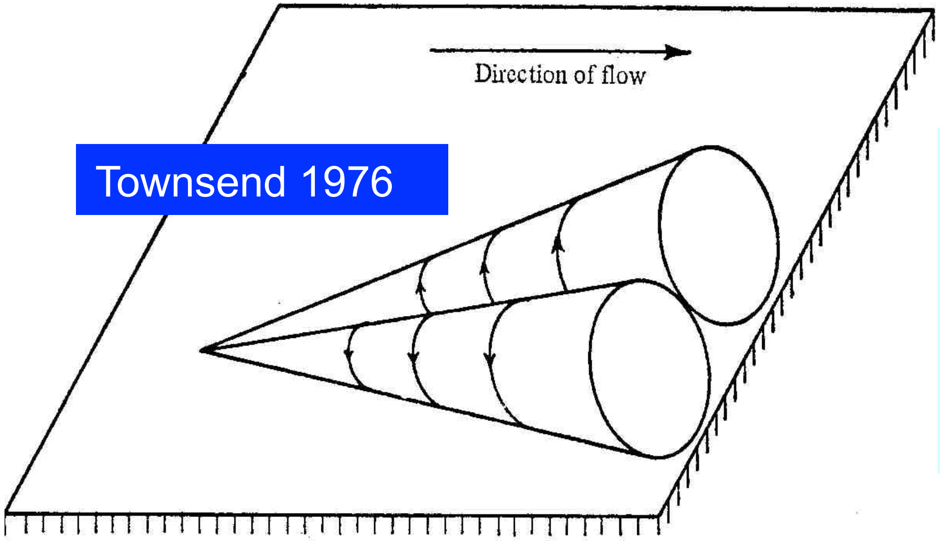
Inner and Outer: attached wall-eddies

"Bottom-up": Adrian *et al.* 2000





Townsend 1976

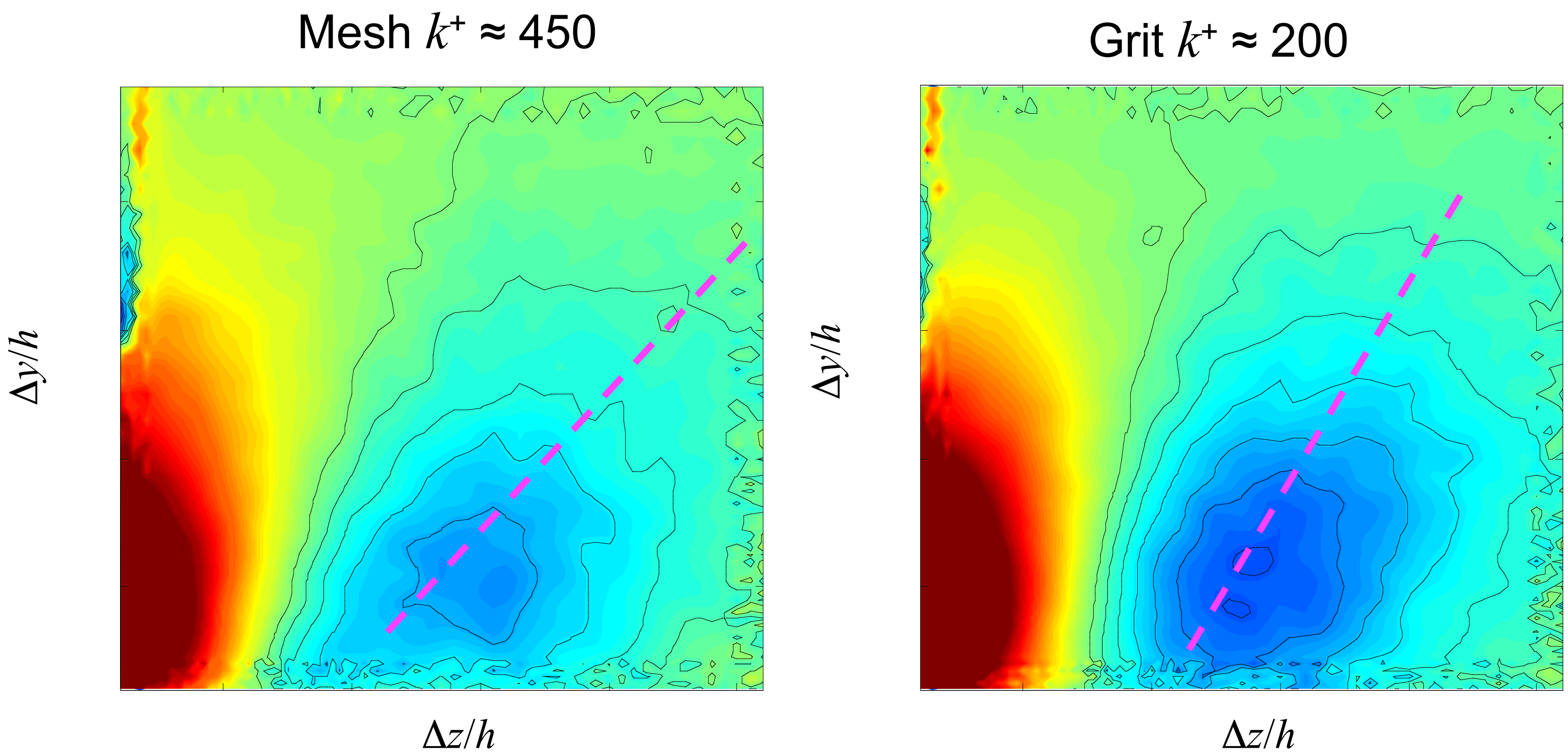
"Top-down": Hunt & Morrison 2000

- packets carry roughly half the turbulence kinetic energy and shear stress
- fill most of the boundary layer
- reach to the wall
- at least 20δ in length – "meandering"

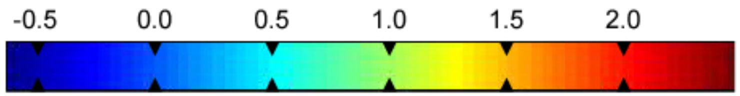
Motivation

- Inner – Outer Interaction top-down and bottom-up
- Two imposed lengthscales: $\delta \Big/ \dfrac{\nu}{u_\tau}$ – how can their effects be separated?
- Single velocity scale, u_τ , but range of convection velocities suggests a range of timescales.
- Shear timescale: $t_s = \left[U'_w\right]^{-1},\ t_s^+ = 1$
- Blocking timescales nonlinear: $t_n = \dfrac{L}{U_\infty},\ t_n^+ \approx 100$
- Impermeability constraint – role of pressure?
- Measurements in a rapidly distorted boundary layer with freestream turbulence: linearised wall turbulence.

Shear: rough channel flow



$$R_{11}(\Delta y,\Delta z) = \frac{\overline{u(y_0,z_0)u(y_0+\Delta y,z_0+\Delta z)}}{\overline{u^2(y_0,z_0)}}$$



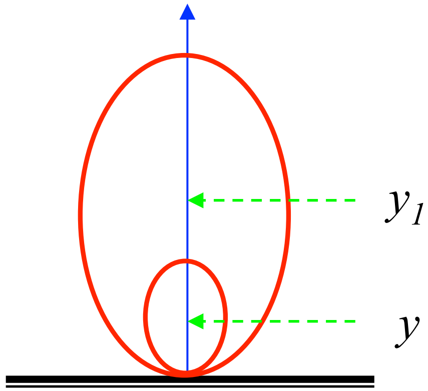
Birch & Morrison 2011

Blocking as a linear effect

- v-component blocked at wavenumber $k \approx 1/y$
- k_1^{-1} implies hierarchy of self-similar, non-interacting attached wall eddies and so linear superposition:

$$\overline{v(y)v(y_1)} = \overline{\left(v_{\text{small}} + \frac{y}{y_1} v_{\text{large}} \right) v(y_1)}$$

$$R_{22} = \frac{\overline{v(y)v(y_1)}}{\overline{v^2}(y_1)} = \frac{y}{y_1}$$



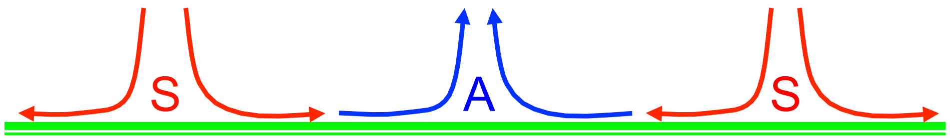
- Spectra: $k_1 \phi_{22}(k_1) \propto k_1 y \phi_{22}(k_1 y) \propto k_1 y$
- Integrating ϕ_{22} for $1/y \le k_1 \le 1/\Lambda \quad (\Lambda \approx 10R)$ gives:

$$\overline{v^2}^+ = B_2 \left(1 - \frac{y}{\Lambda} \right)$$

Blocking

- Does top-down effect lead to:
  - "modulation" of near-wall motion (Hutchins & Marusic 2007, Mathis *et al.* '09, '11, '13)
  - streamwise vortices (Hunt & Morrison 2000) and hence –
  - plane (oblique) waves (Sirovich 1990, Carpenter 2007)?
- What is the role of wall-normal velocity and pressure fluctuations – "Anti-splats" as well as Splats (local surface stagnation points)?

shear-free boundary



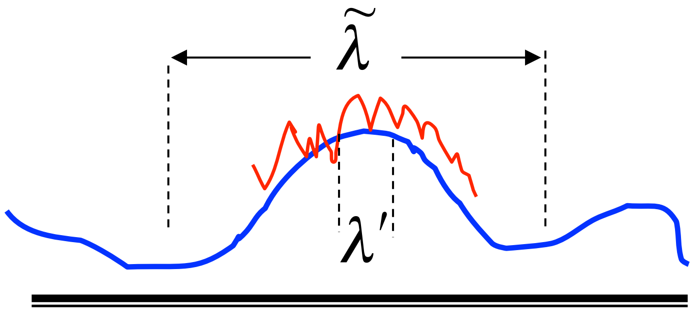
- Viscosity alters the balance between A and S: pressure-strain effects transfer of energy from v – component to u and w (Perot & Moin 1995)

A useful theory for Inner-Outer Interaction?

- Landahl ('93, '90, '75): initial disturbance scales $L,\ u_0$ with timescales: shear interaction $\left\{U_w'\right\}^{-1}$ << viscous $\left\{L^2/(\nu U'^2)\right\}^{1/3}$ << 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 <u>same</u> equations:

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

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



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

- $q,\ r$ 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".

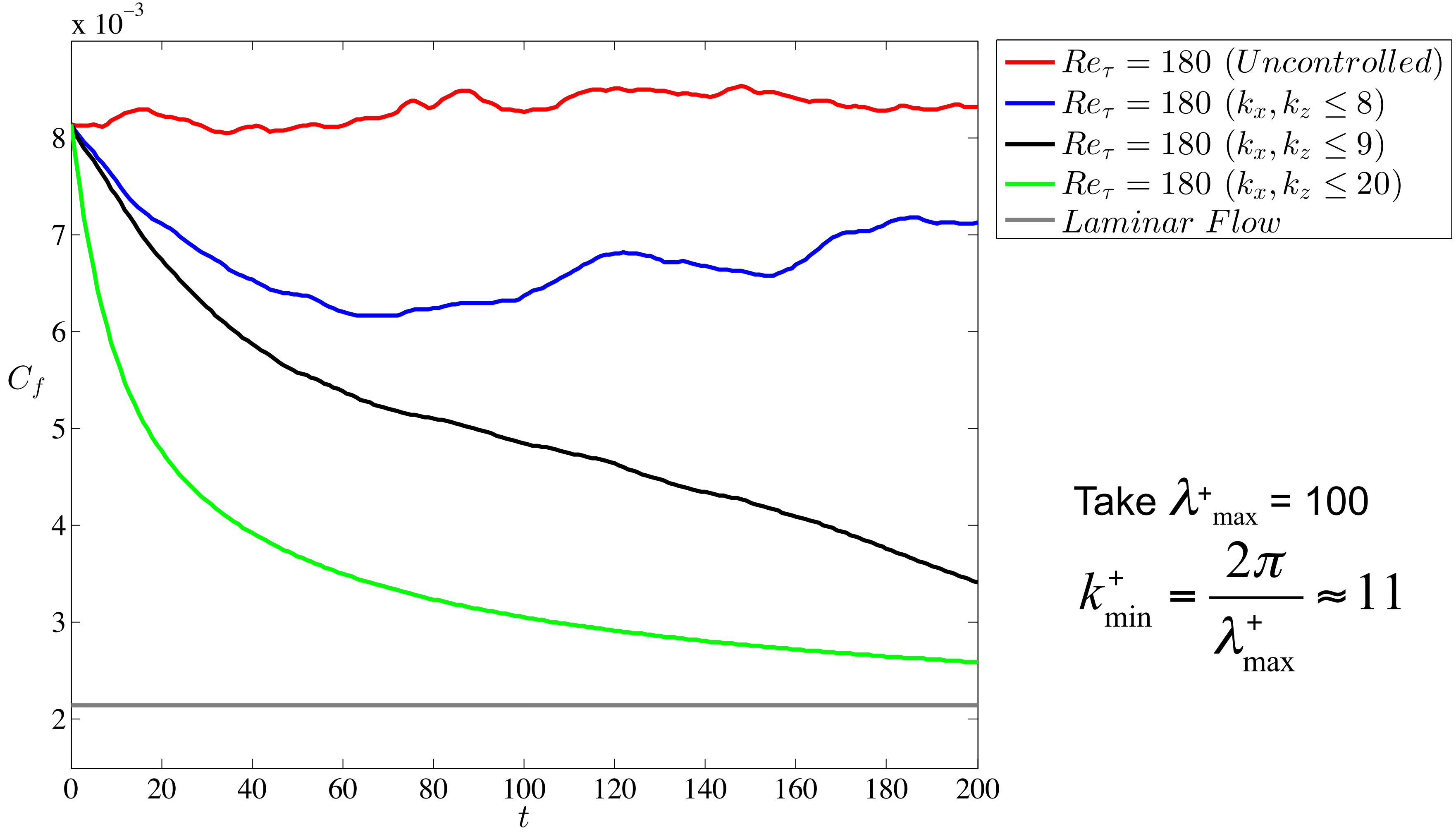
Synopsis

- 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

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 = 400, k_x, $k_z \leq$ 20
- & at $y^+ \approx 25\big|_{\text{init}}$

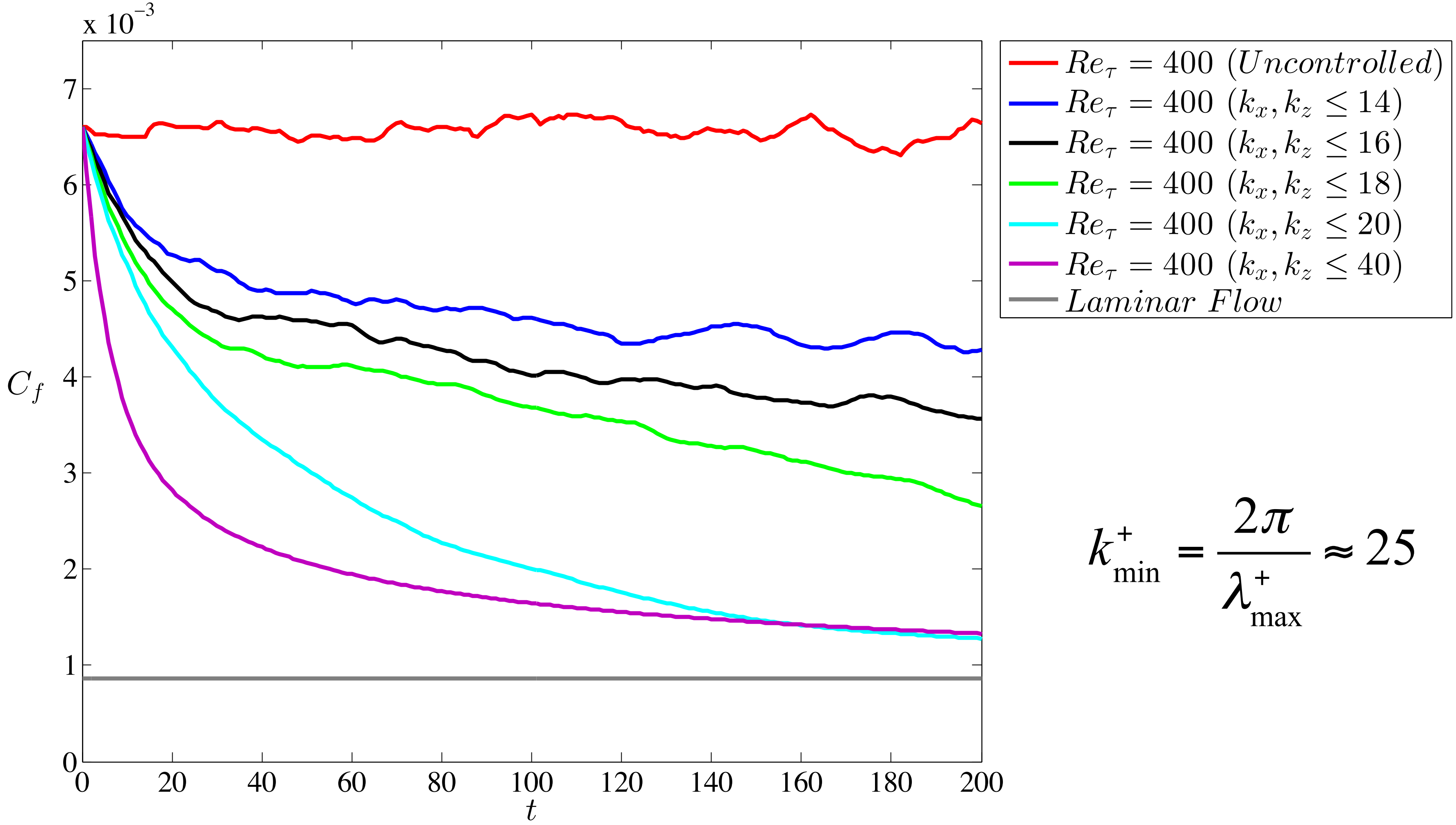
$Re_\tau = 180$



Take $\lambda^+_{max} = 100$

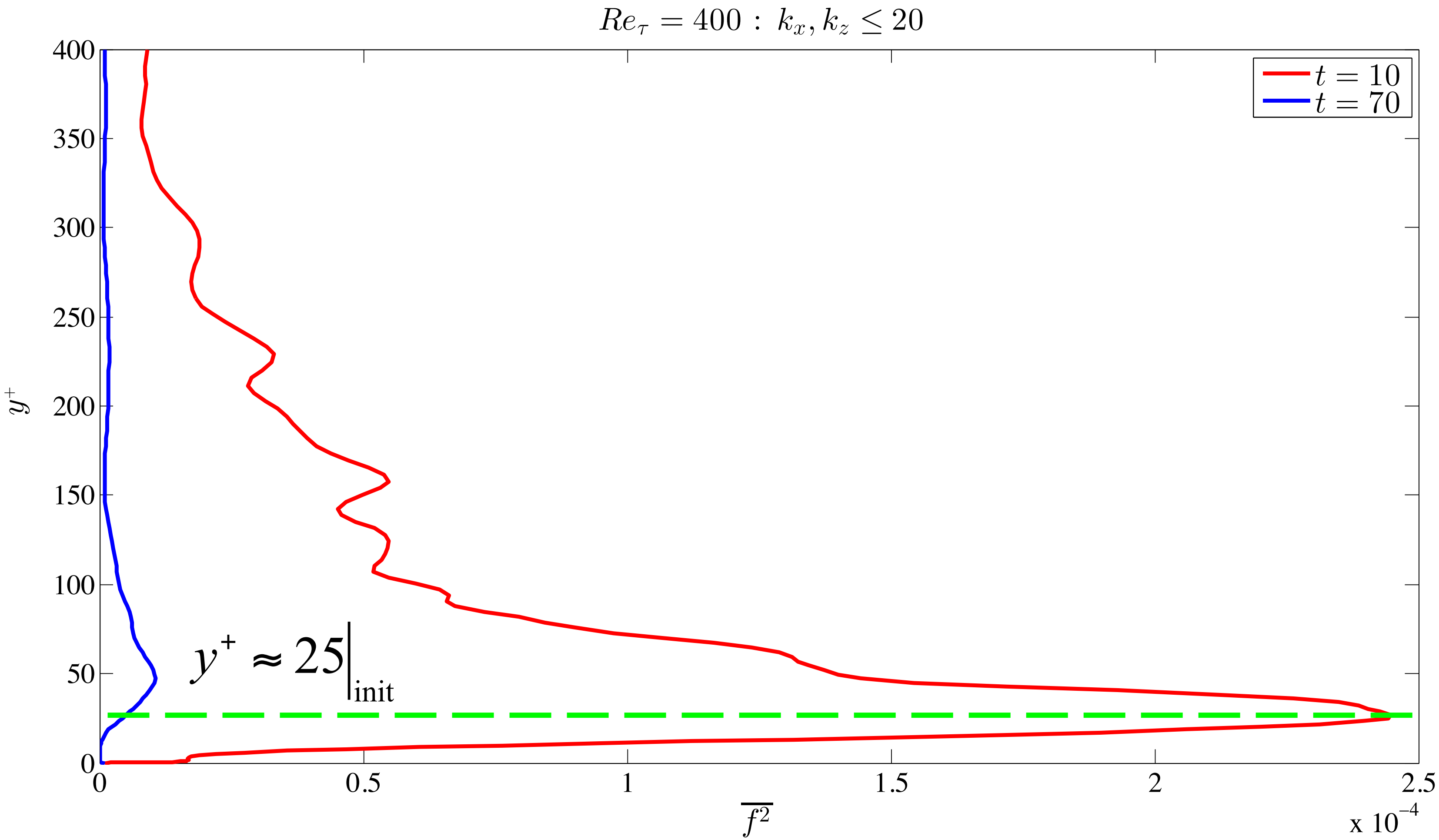
$$k^+_{\min} = \frac{2\pi}{\lambda^+_{\max}} \approx 11$$

$Re_\tau = 400$

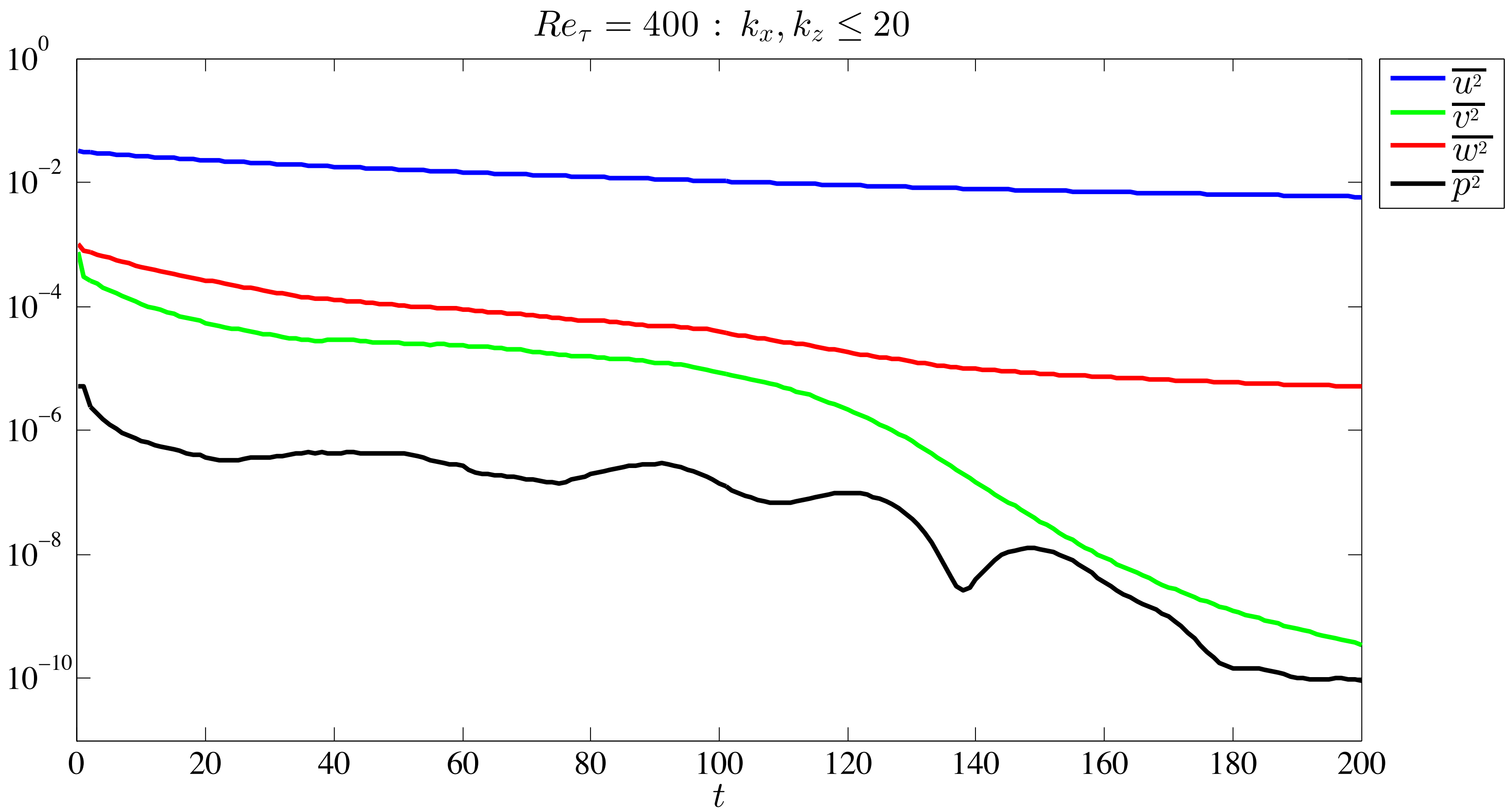


$$k^+_{\min} = \frac{2\pi}{\lambda^+_{\max}} \approx 25$$

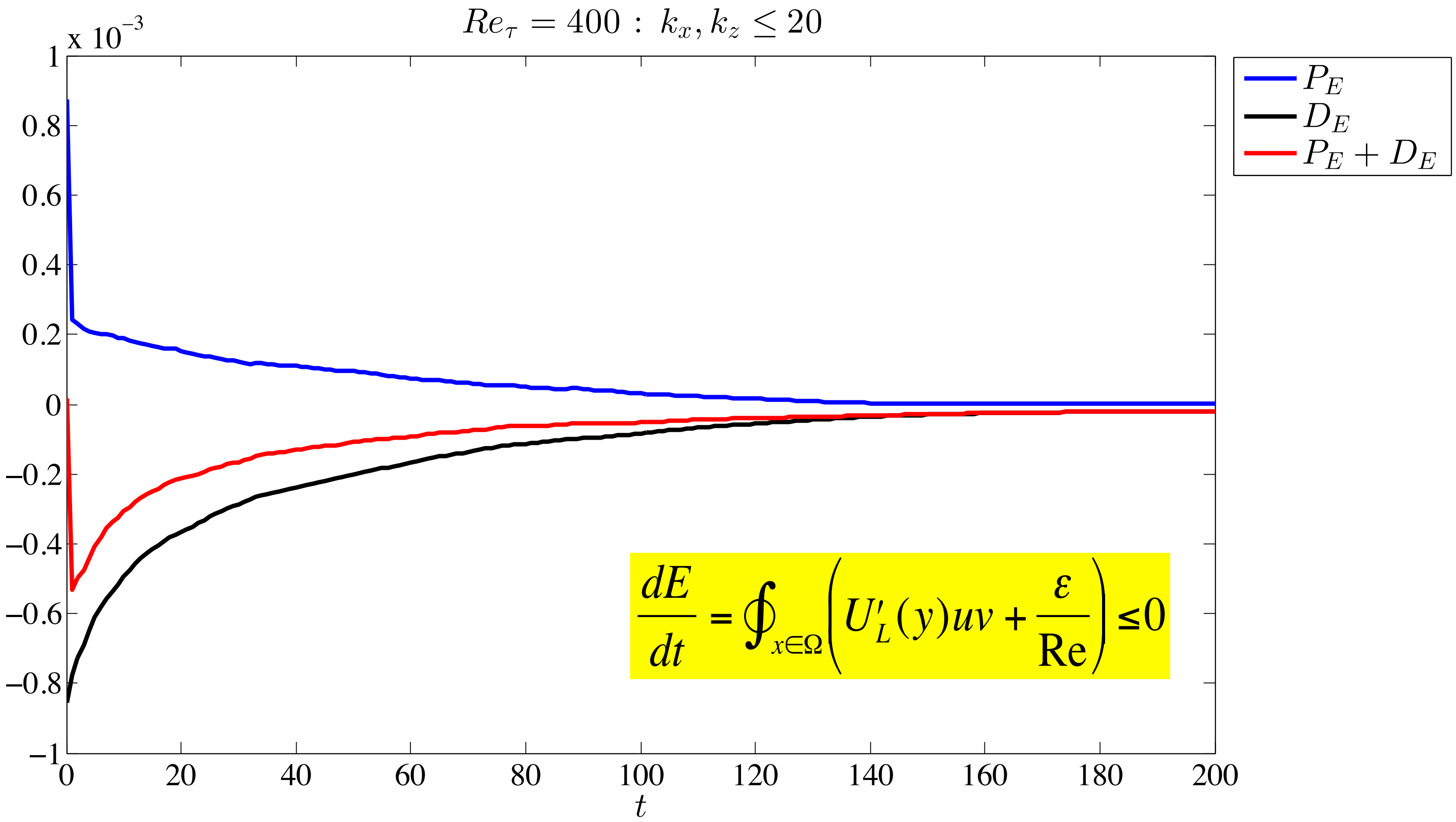
Mean square forcing: $\overline{f^2}(y)$



Rate of decay



Production and dissipation



Pressure gradient fluctuations

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

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

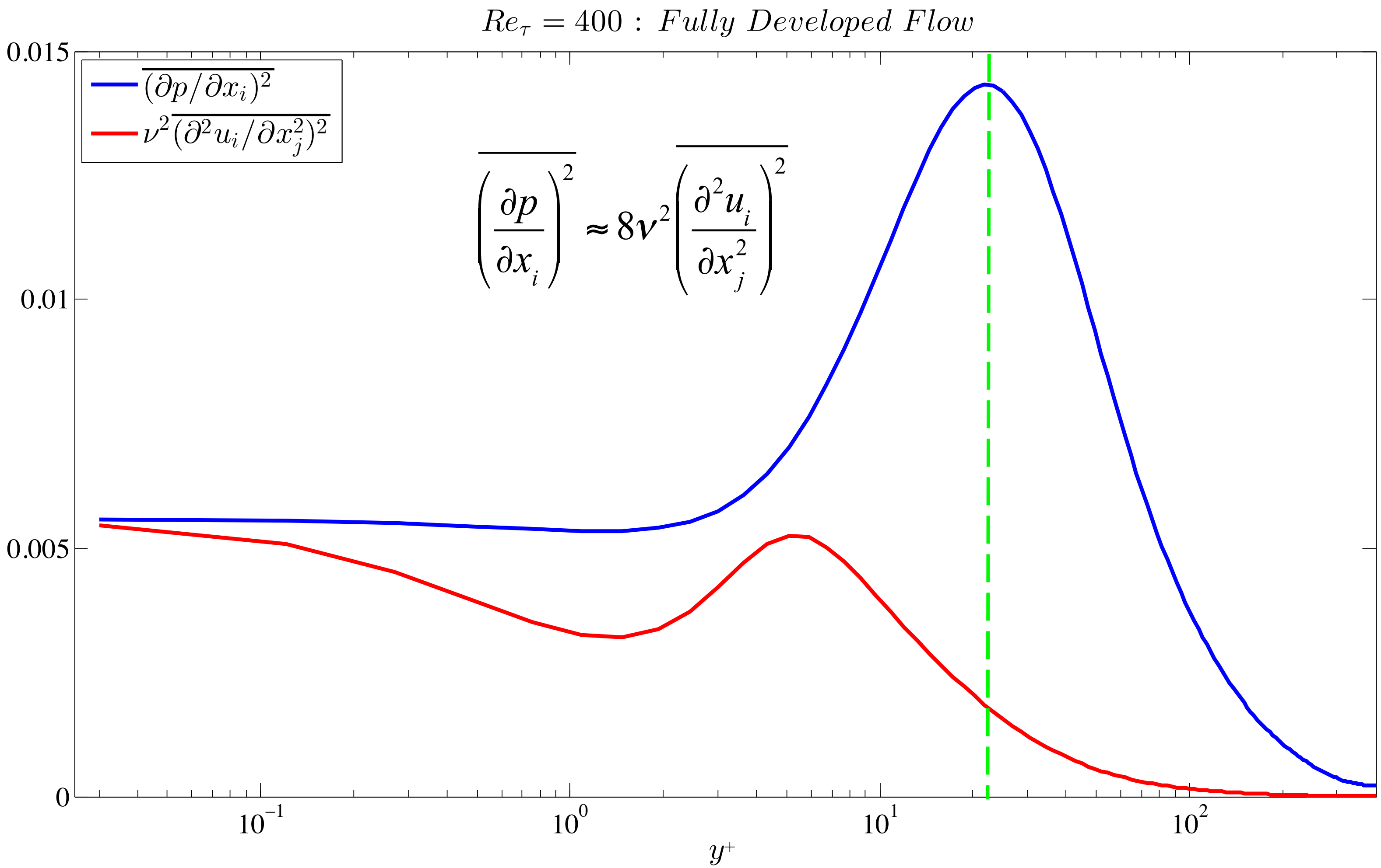
- where

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

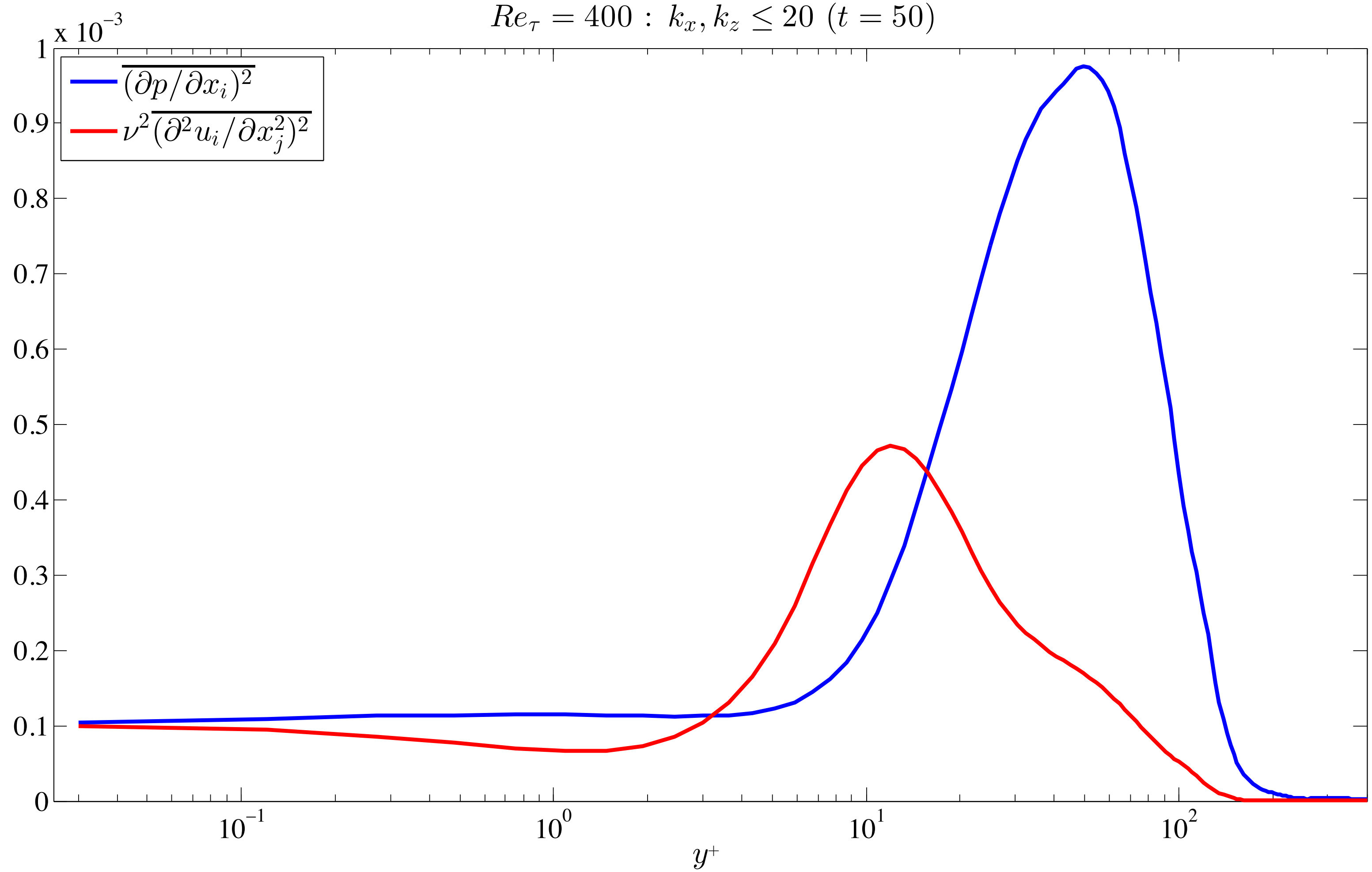
- Therefore, even the smallest scale motion is driven by pressure gradients and not by viscous forces.

Batchelor & Townsend 1956

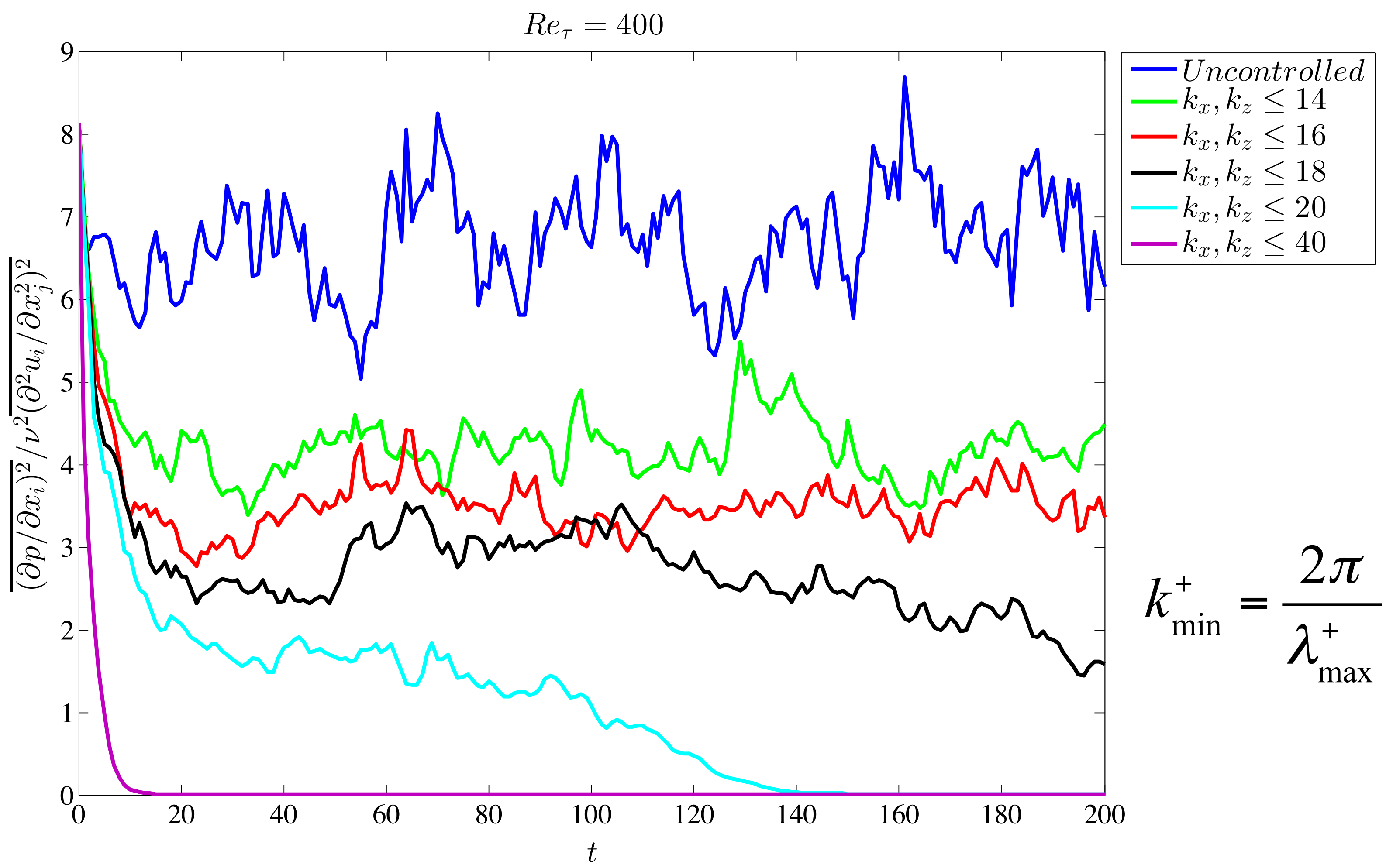
Uncontrolled turbulent channel flow



$$\overline{\left(\frac{\partial p}{\partial x_i}\right)^2} \Big/ \nu^2 \overline{\left(\frac{\partial^2 u_i}{\partial x_j^2}\right)^2} \; : t = 50$$

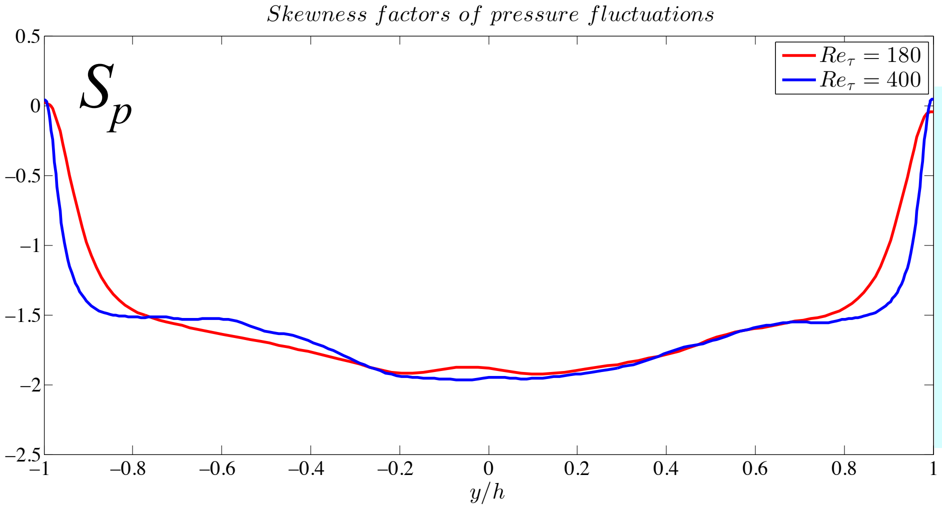


$$\overline{\left(\frac{\partial p}{\partial x_i}\right)^2} \Bigg/ \nu^2 \overline{\left(\frac{\partial^2 u_i}{\partial x_j^2}\right)^2}$$

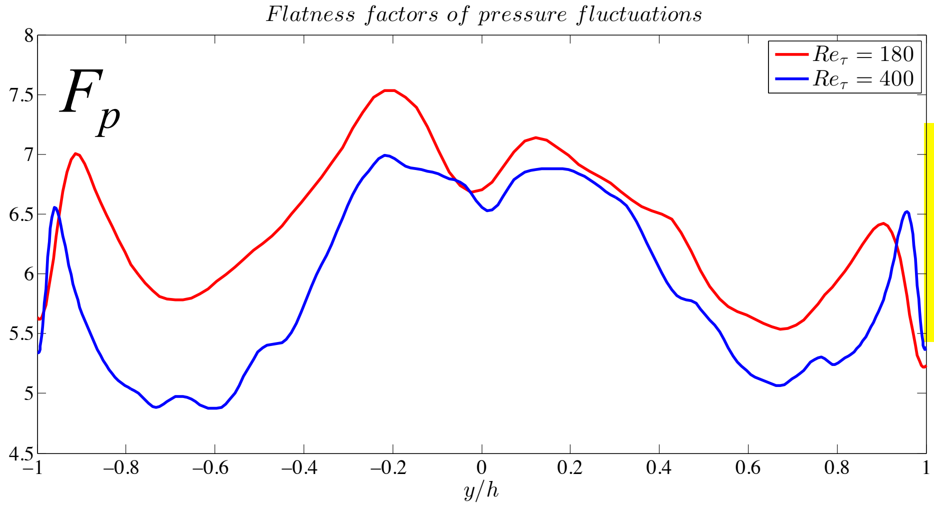


$$k^+_{\min} = \frac{2\pi}{\lambda^+_{\max}} \approx 25$$

Turbulent channel flow pressure statistics



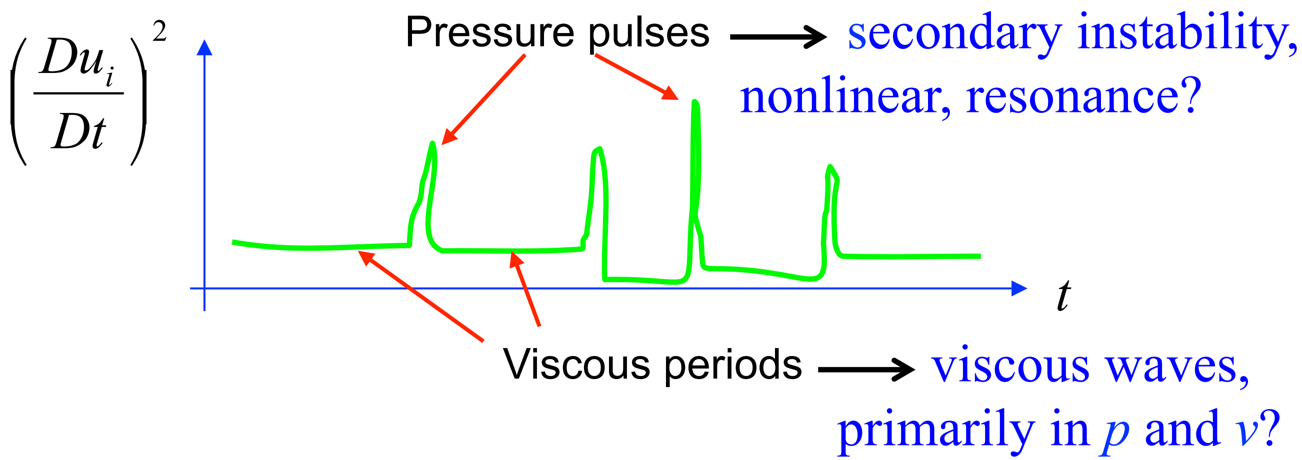
- Spatial intermittency: $S_p \approx 0$, $F_p \approx 6$
- Green's function integral shows that contribution to wall pressure comes mostly from near-wall velocity field, both rapid and slow



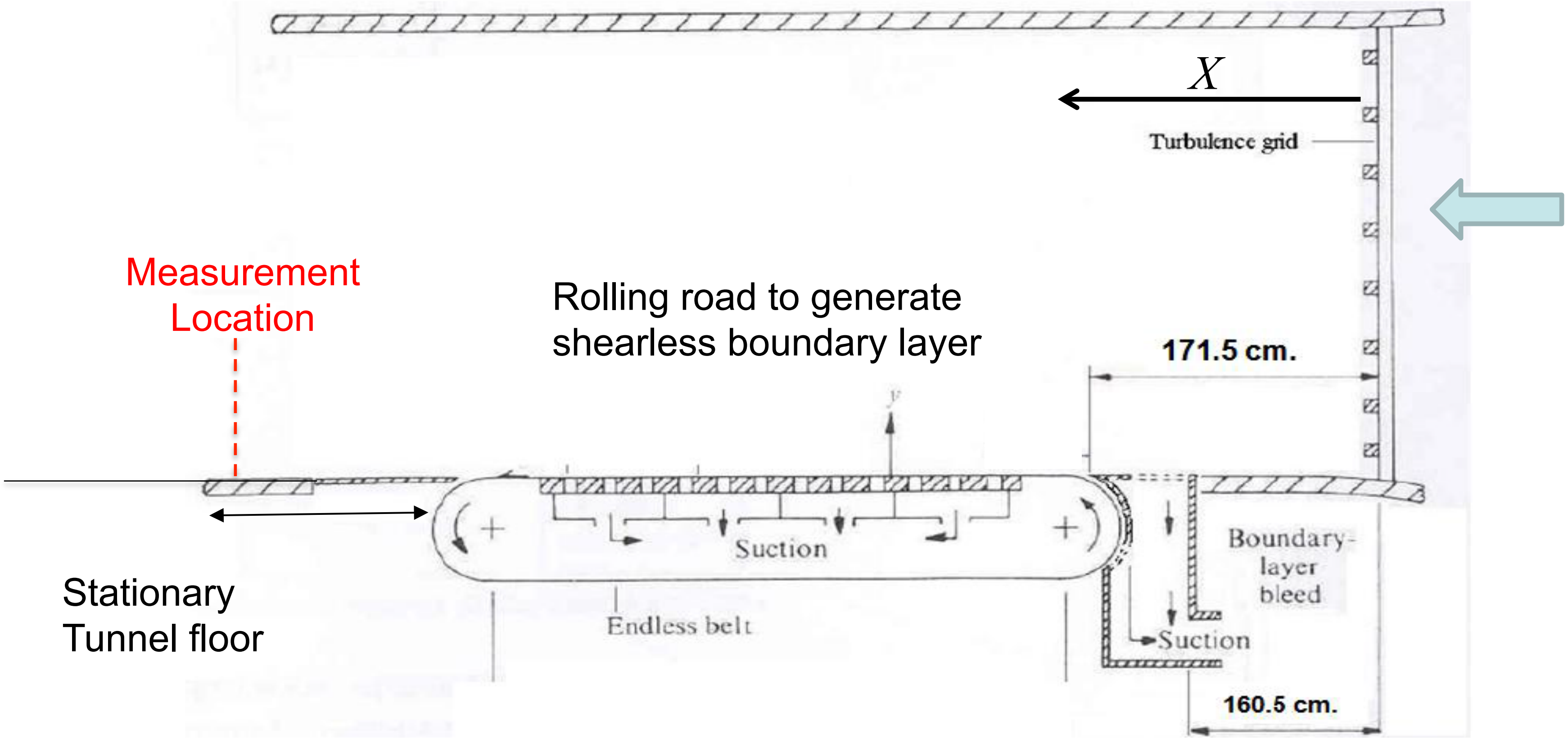
$$-\nabla^2 p = 2U'\frac{\partial v}{\partial x} - \frac{\partial^2}{\partial x \partial y}\left[uv - \overline{uv}\right]$$

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

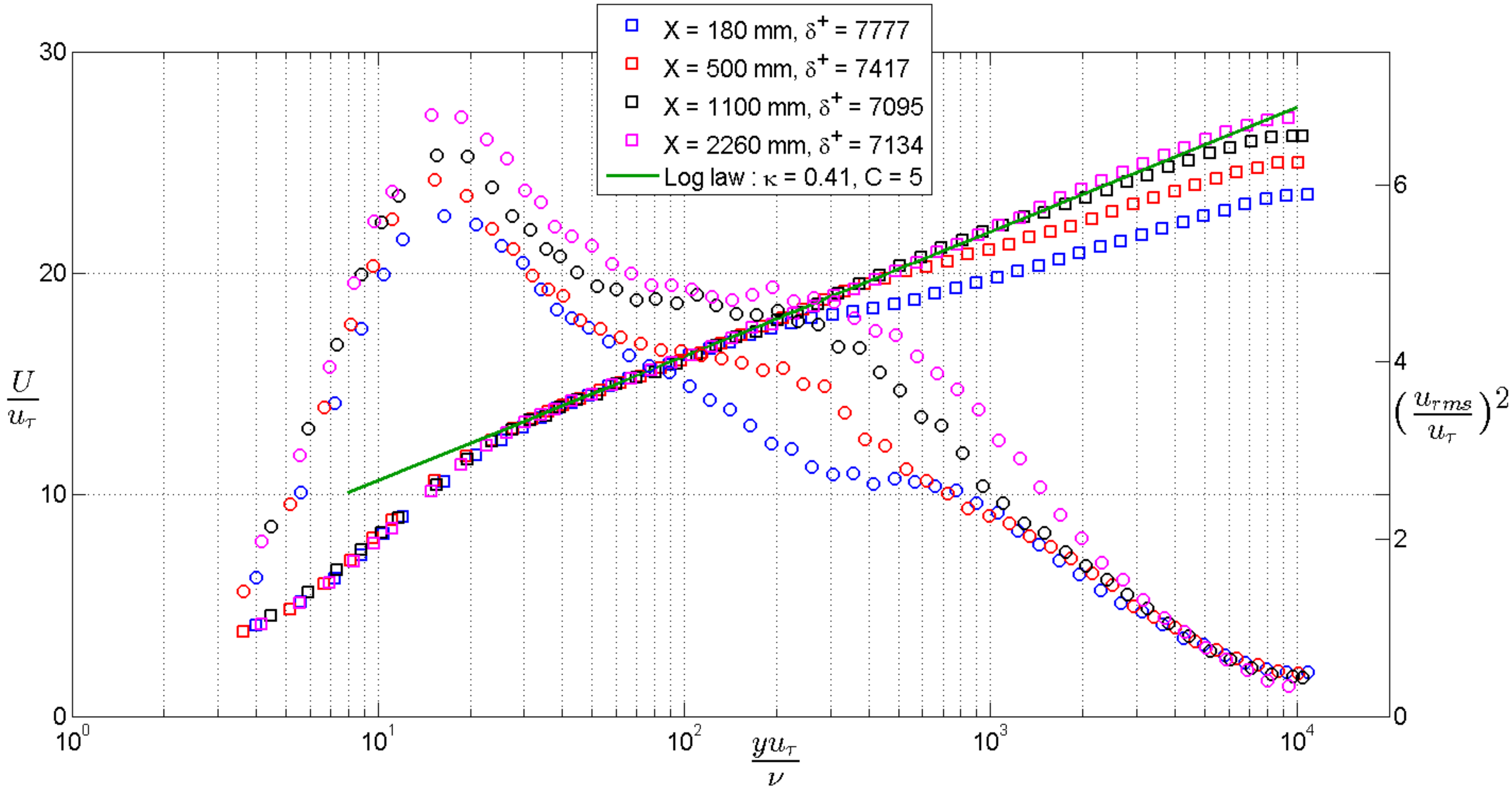


Rapidly distorted boundary layer

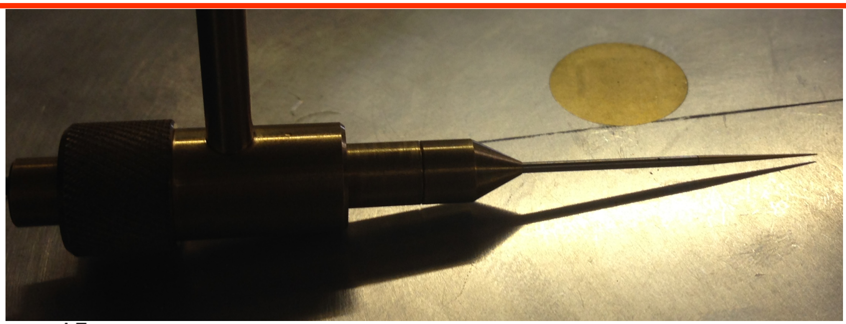


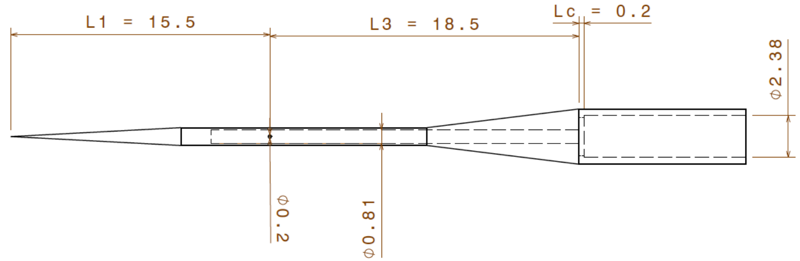
Variable ratio of shear timescale to turbulence timescale

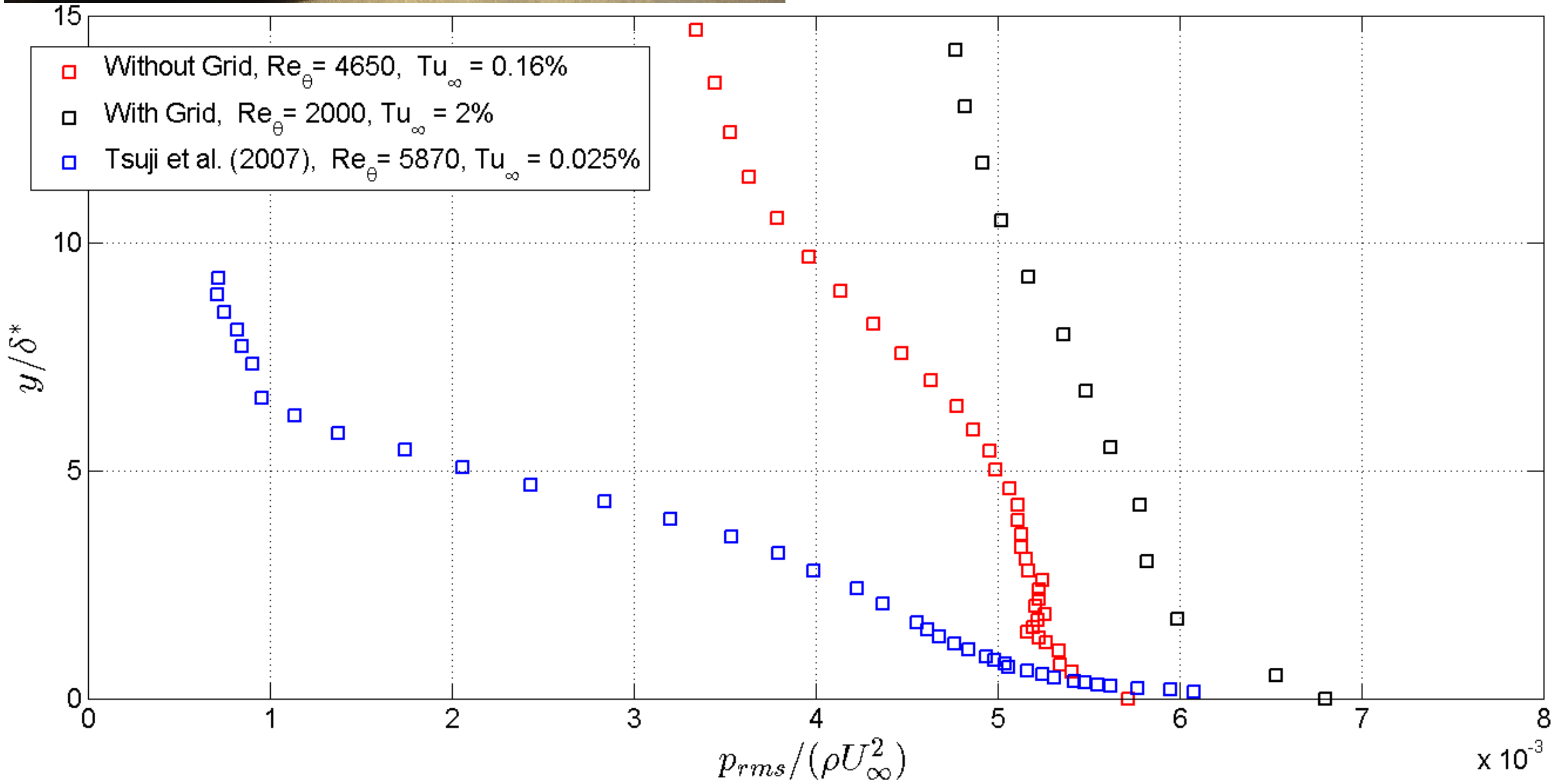
Freesteam turbulence with wall shear



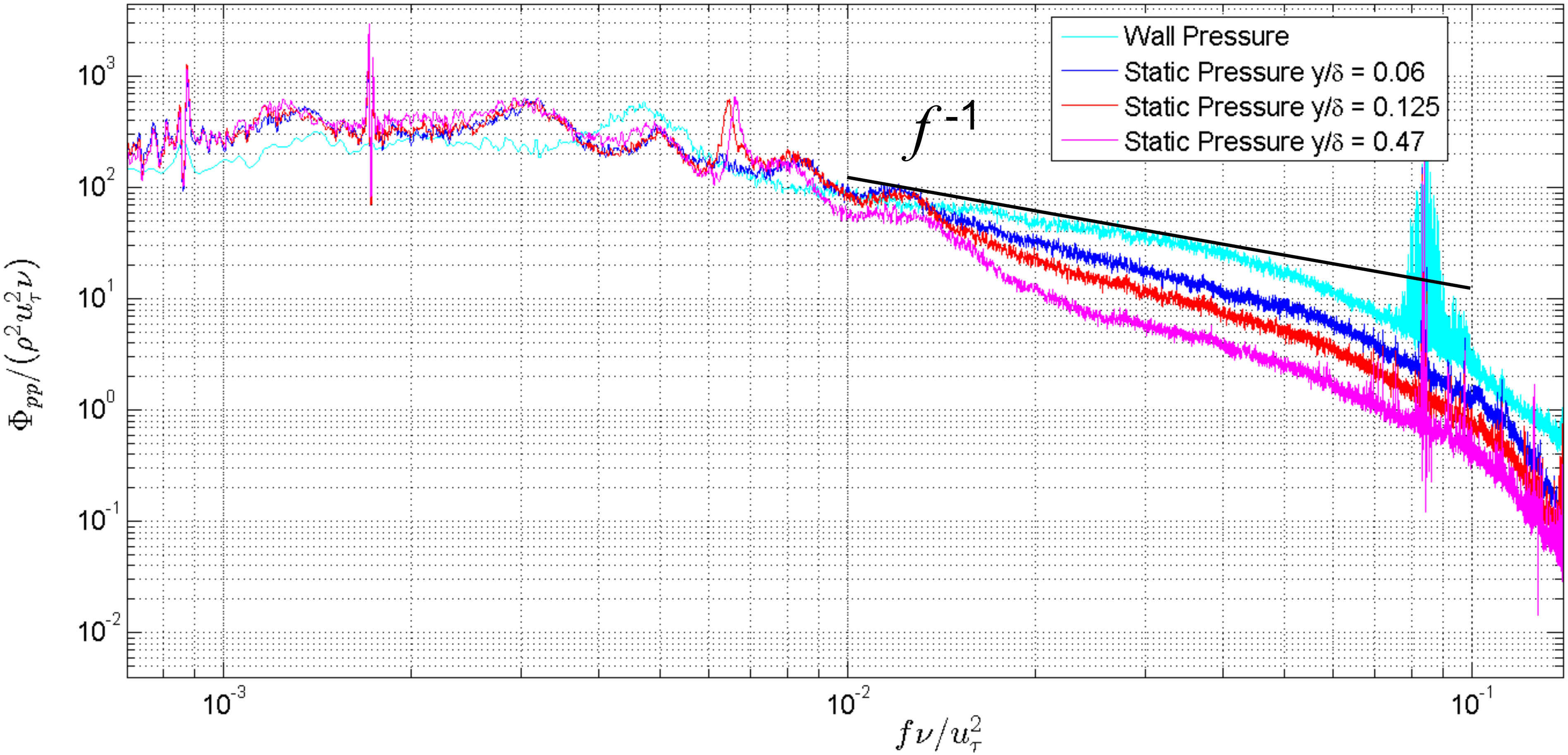
Static pressure fluctuations







Static pressure fluctuations: spectra



Conclusions

- Linear full-domain forcing via vU' at low wavenumbers attenuates turbulent channel flow
- 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 – an RDT approximation
- Rapidly sheared boundary layer with variable shear and nonlinear timescales