NORDITA-FLOW Workshop on Turbulent Boundary Layers
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DNS of spanwise-shear-induced drag reduction, revisited

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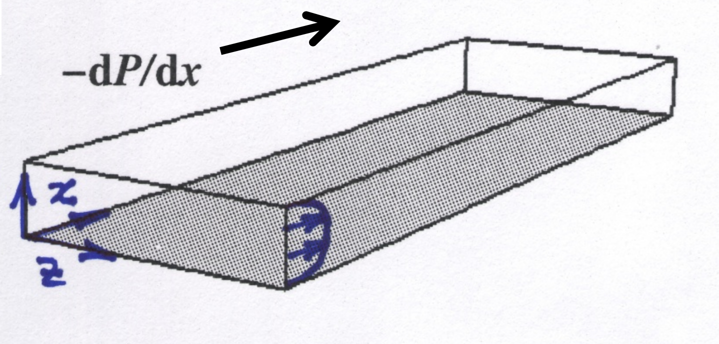
**Advatech Pacific Inc.*

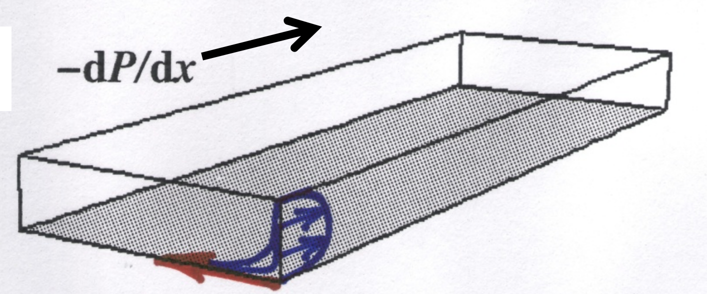
Channel with spanwise moving wall

$t < 0$:



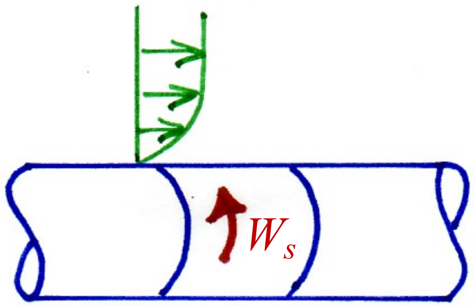
Apply W_s at $t = 0\ldots$

$t > 0$:

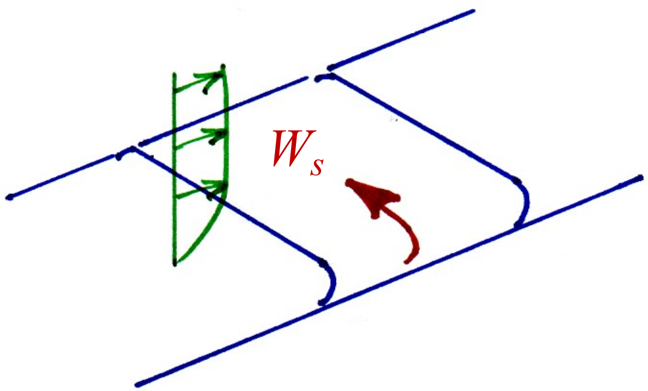


W_s = constant

Actual/spatial counterparts



Furuya *et al* (1966), Lohmann (1976), Driver & Hebbar (1991), …



Kiesow & Plesniak (1998), …

Spanwise-moving-wall channel DNS

- Sudden constant $\mathrm{d}P/\mathrm{d}z$ ($\Rightarrow W_s(t)$)
  - Moin *et al* (1992), Sendstad & Moin (1992)
- **Sudden constant W_s**
  - Coleman *et al* (1996), Le *et al* (2000); Coleman (2010)
  - Howard & Sandham (2000)
- Temporally oscillating $W_s(t)$
  - Jung *et al* (1992)
  - Choi *et al* (2002)
  - Quadrio & Ricco (2004), Ricco & Quadrio (2008)
- Temporally and spatially oscillating $W_s(t,x)$
  - Quadrio *et al* (2009)
  - Yakeno *et al* (2009)

Present focus: constant-W_s DNS

Case	$\mathrm{Re}_\tau(0)=u_\tau(0)\,h/\nu$	$W_s/u_\tau(0)$
Le, Coleman & Kim (2000)	180*	-8.5
New	390†	-8.4

* 5-field ensemble

† 24-field ensemble

- **Statistical perspective**

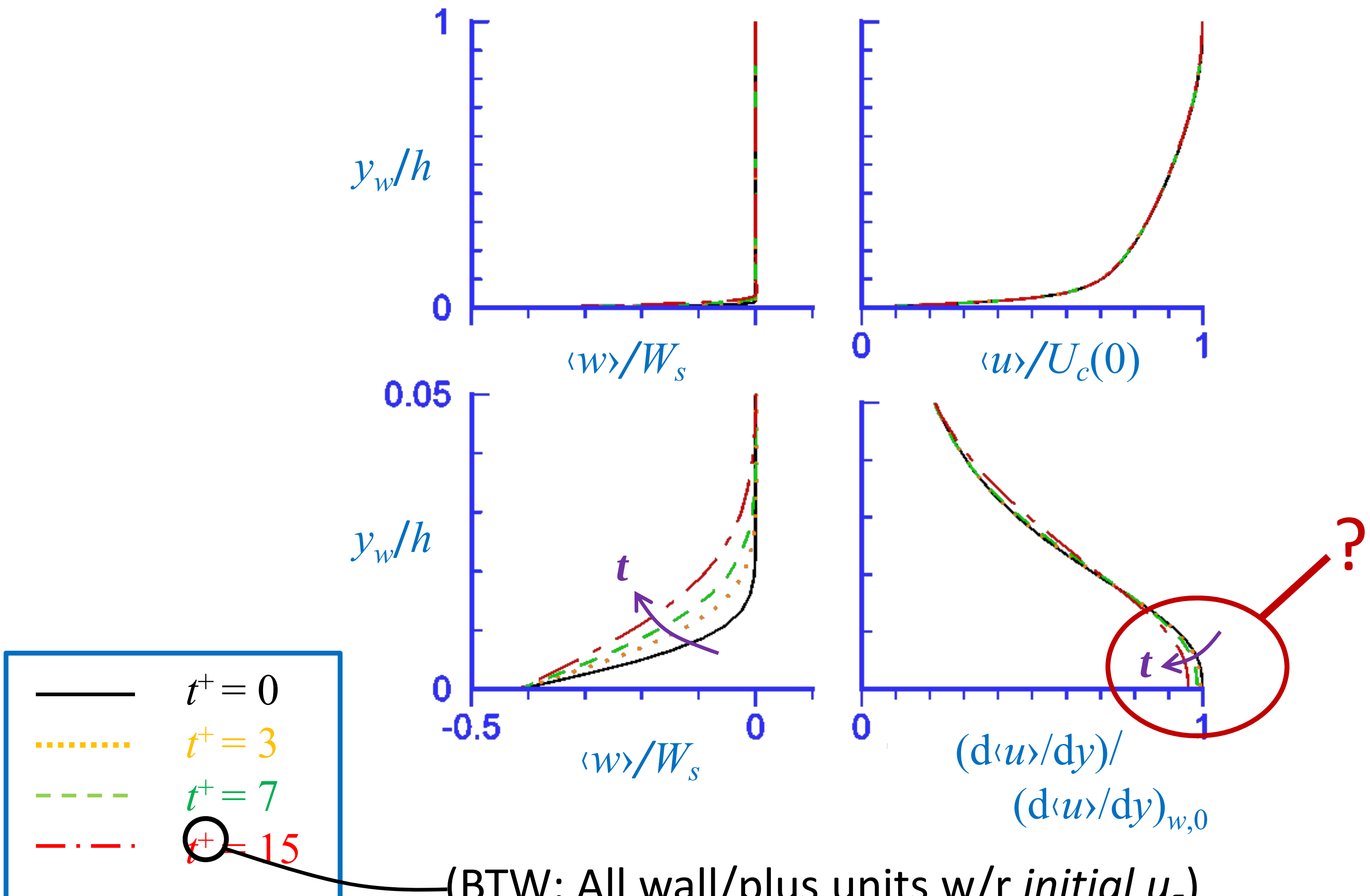
Structural perspective

Statistical perspective

- ▷ Evolution/history of mean quantities

Evolution of mean spanwise and streamwise velocities

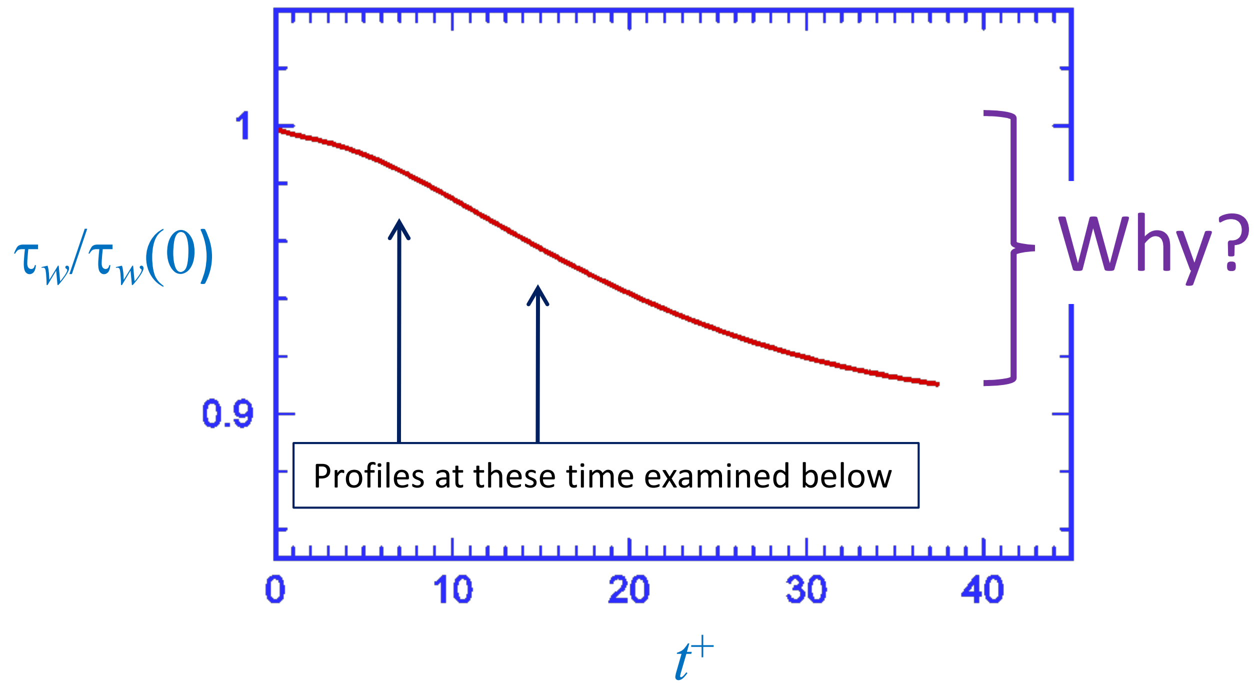
$Re_\tau(0)=390$



(BTW: All wall/plus units w/r *initial* u_τ)

Streamwise drag history

$Re_\tau(0)=390$



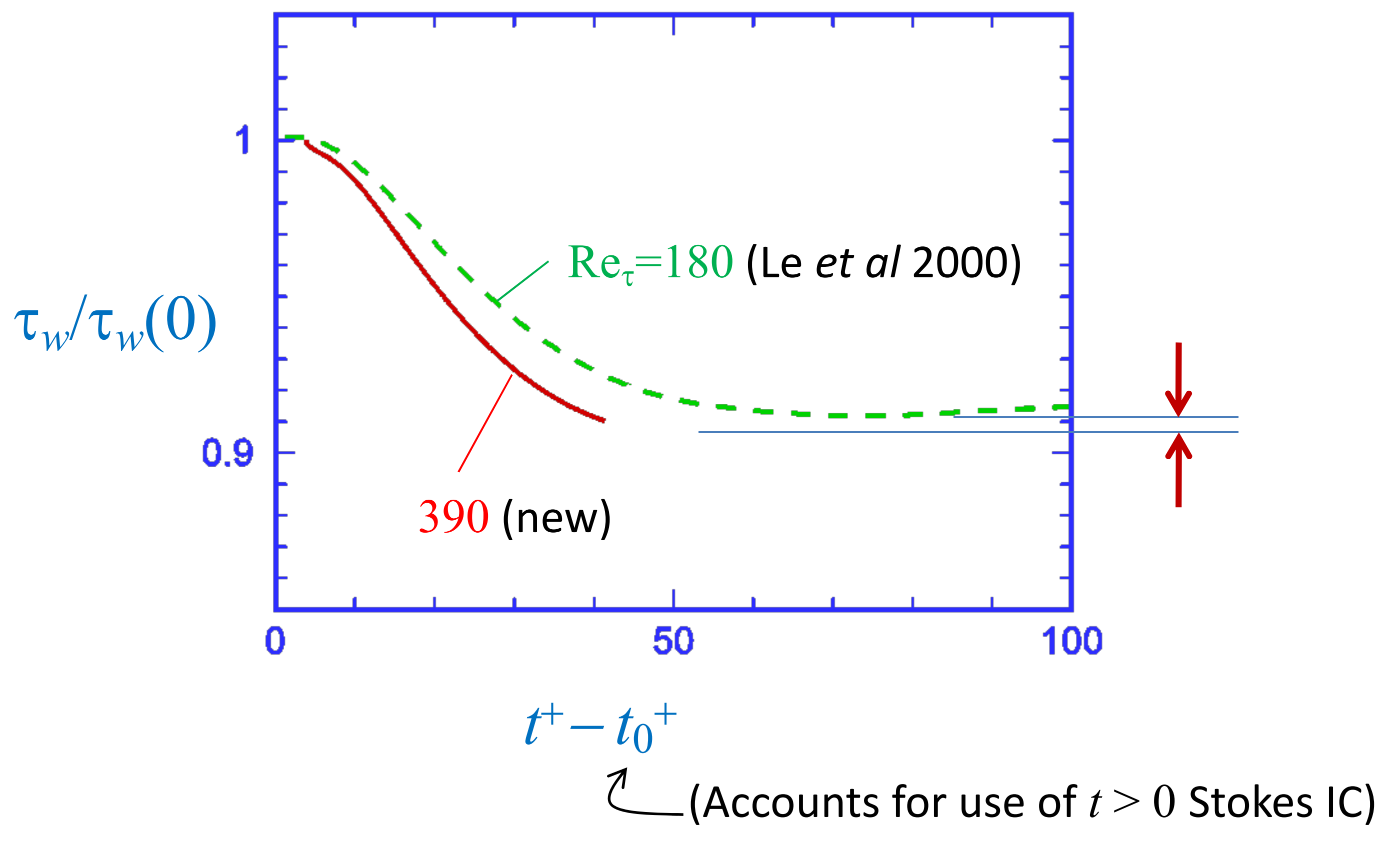
Statistical perspective

Evolution/history of mean quantities

▷ **Reynolds-number dependence**

– Reynolds-number dependence –

Compare Re_τ=180 and 390 results…



No decrease with Re of net drag-reduction magnitude…

Statistical perspective

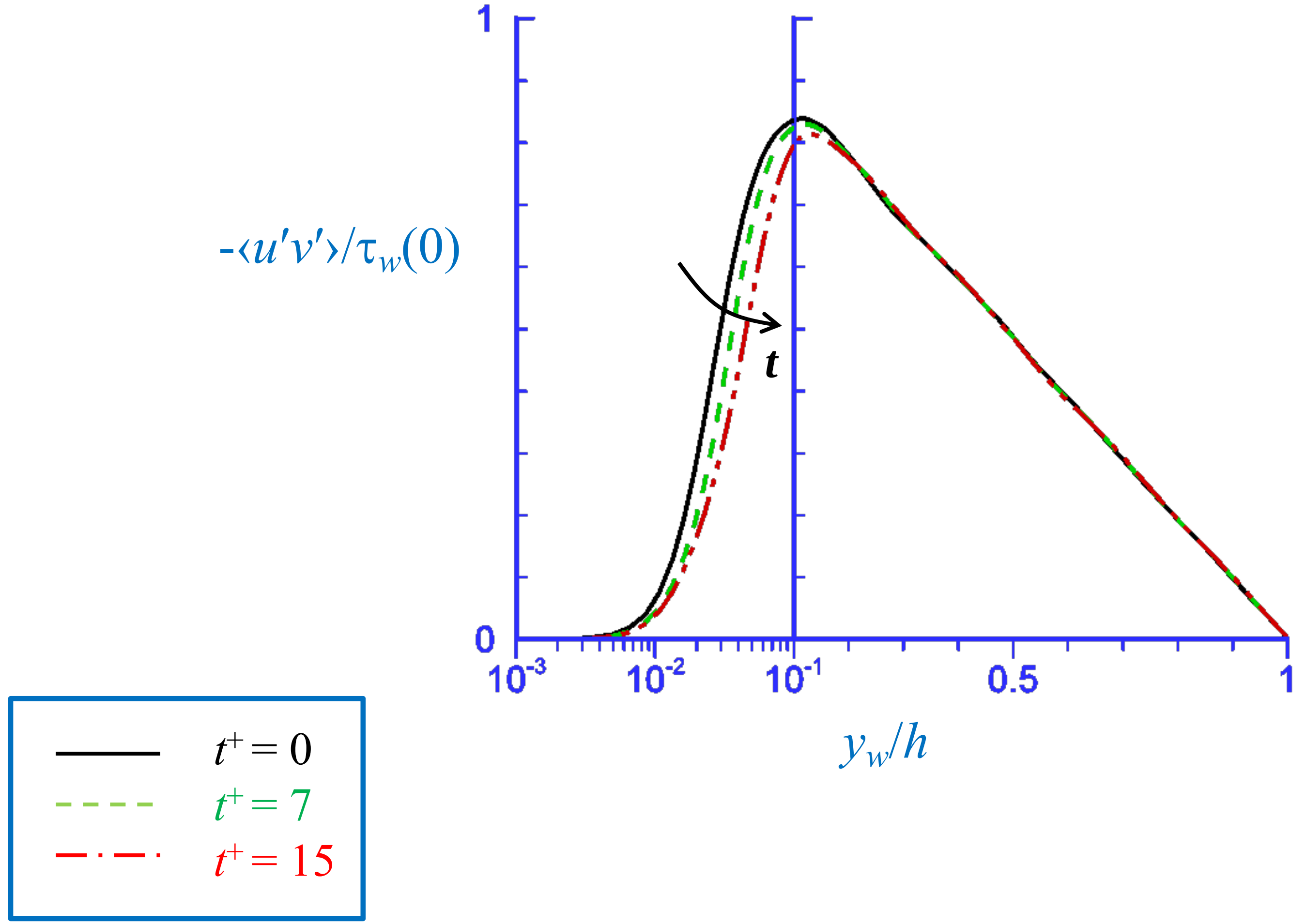
Evolution/history of mean quantities

Reynolds-number dependence

▷ **Reynolds-stress budgets**

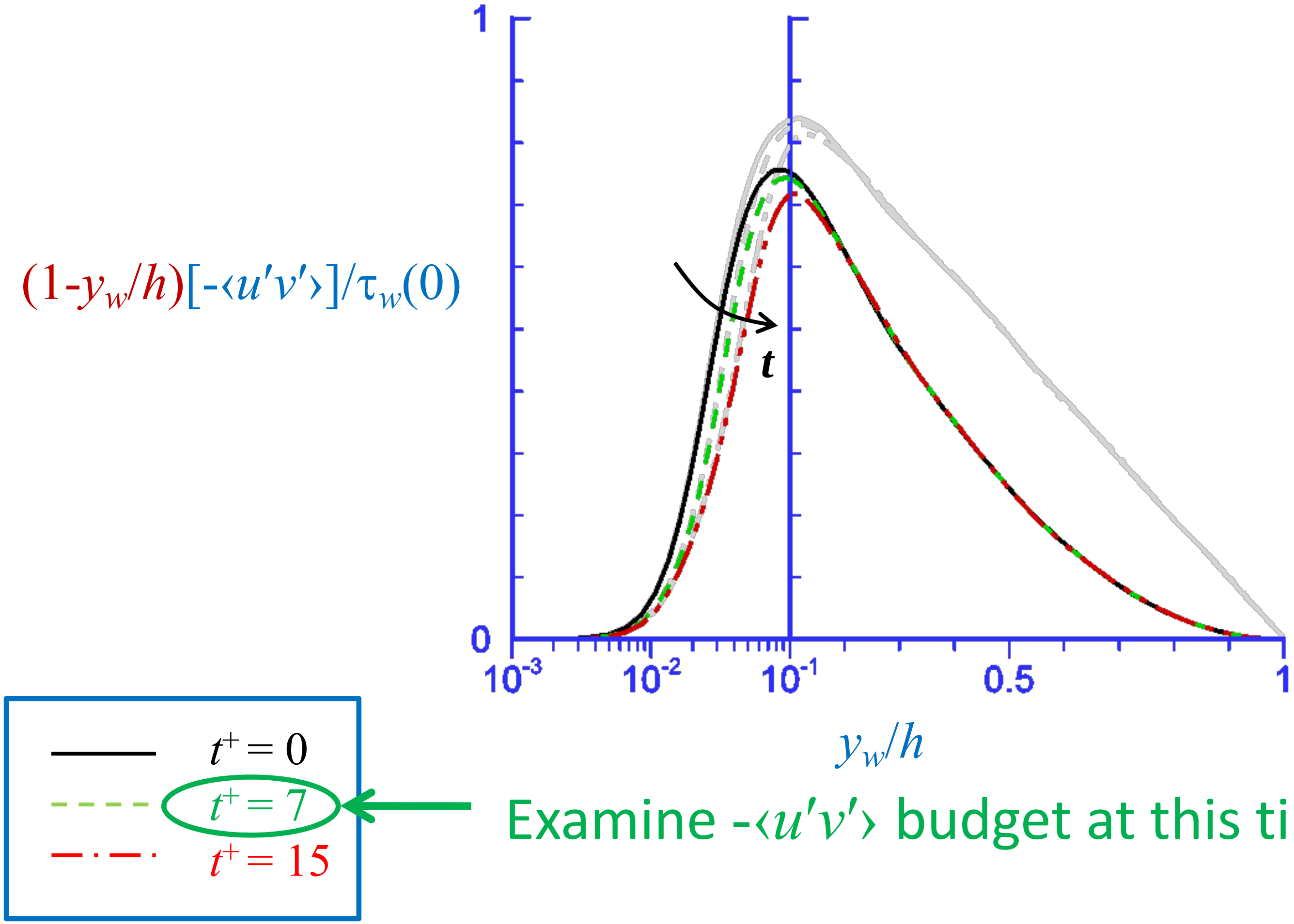
$-\langle u'v' \rangle$ evolution

$Re_\tau(0)=390$



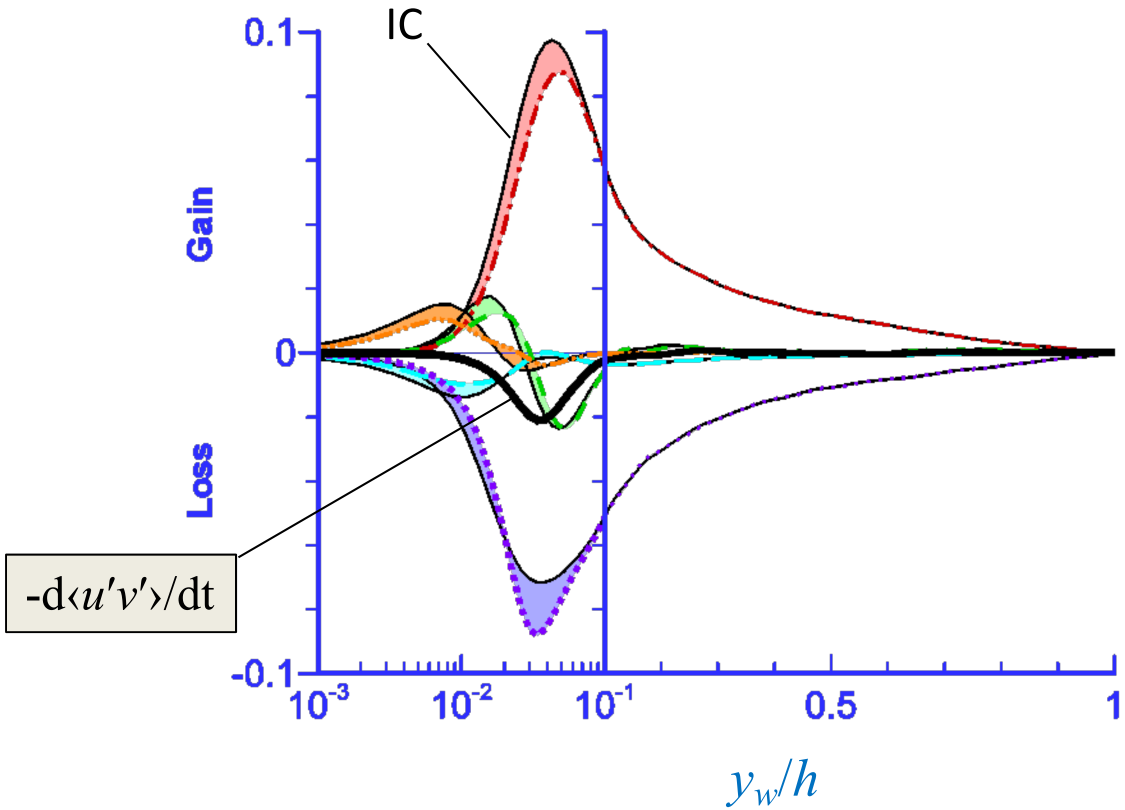
…F.I.K. weighting

Fukagata *et al* (2002): $C_f = \frac{12}{\mathrm{Re}_b} + \frac{6}{U_b^2}\int_0^1 \underbrace{(1 - y_w/h)}_{*}\,[-\langle u'v' \rangle]\,\mathrm{d}(y_w/h)$

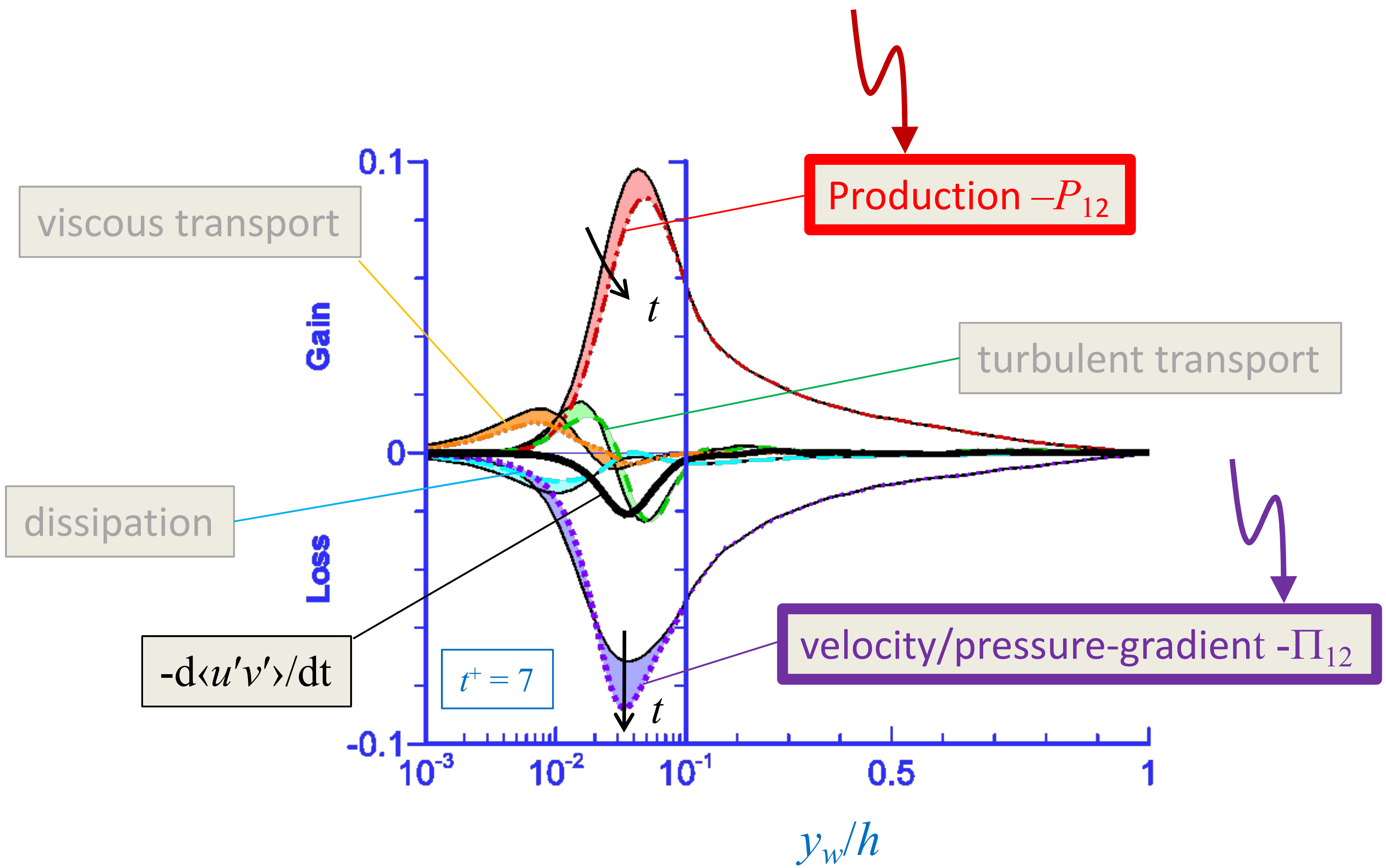


Examine $-\langle u'v' \rangle$ budget at this time…

-⟨$u'v'$⟩ budget at $t^+ = 7$

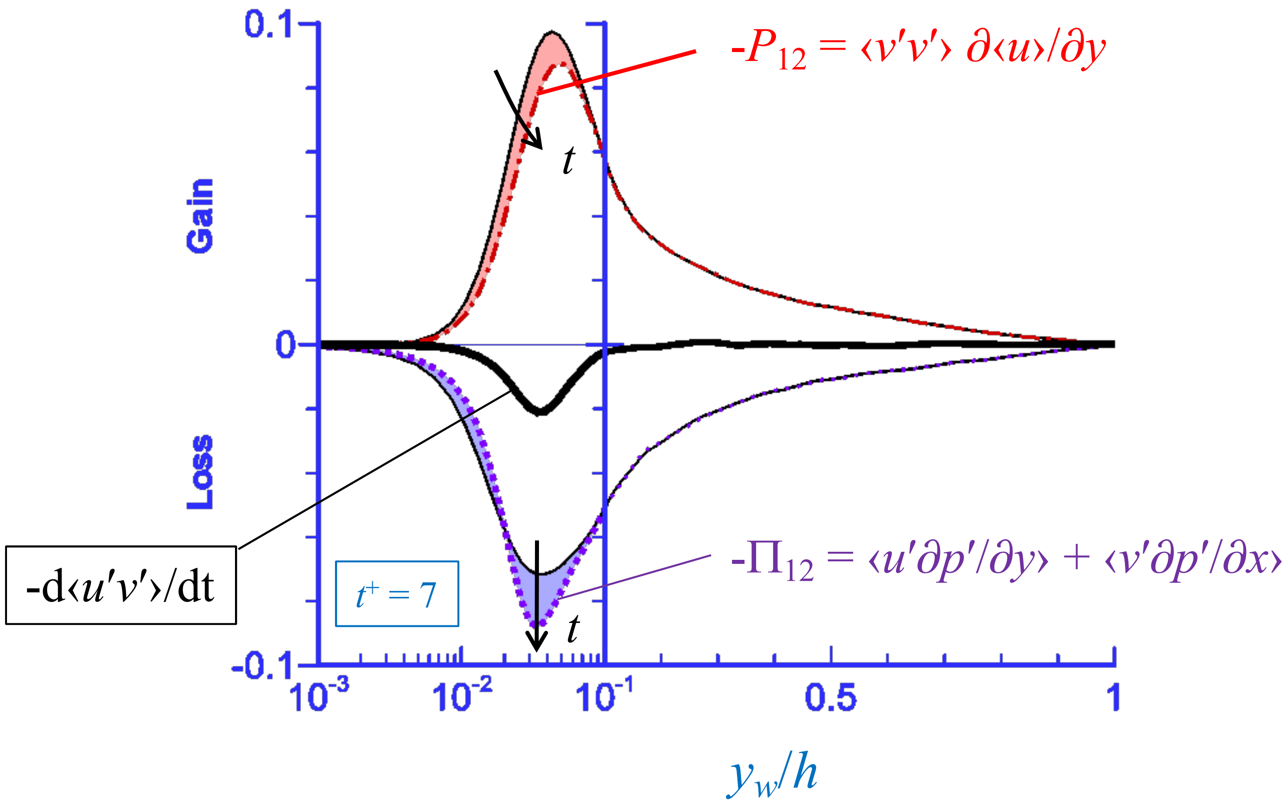


Dominant terms in -‹$u'v'$› budget



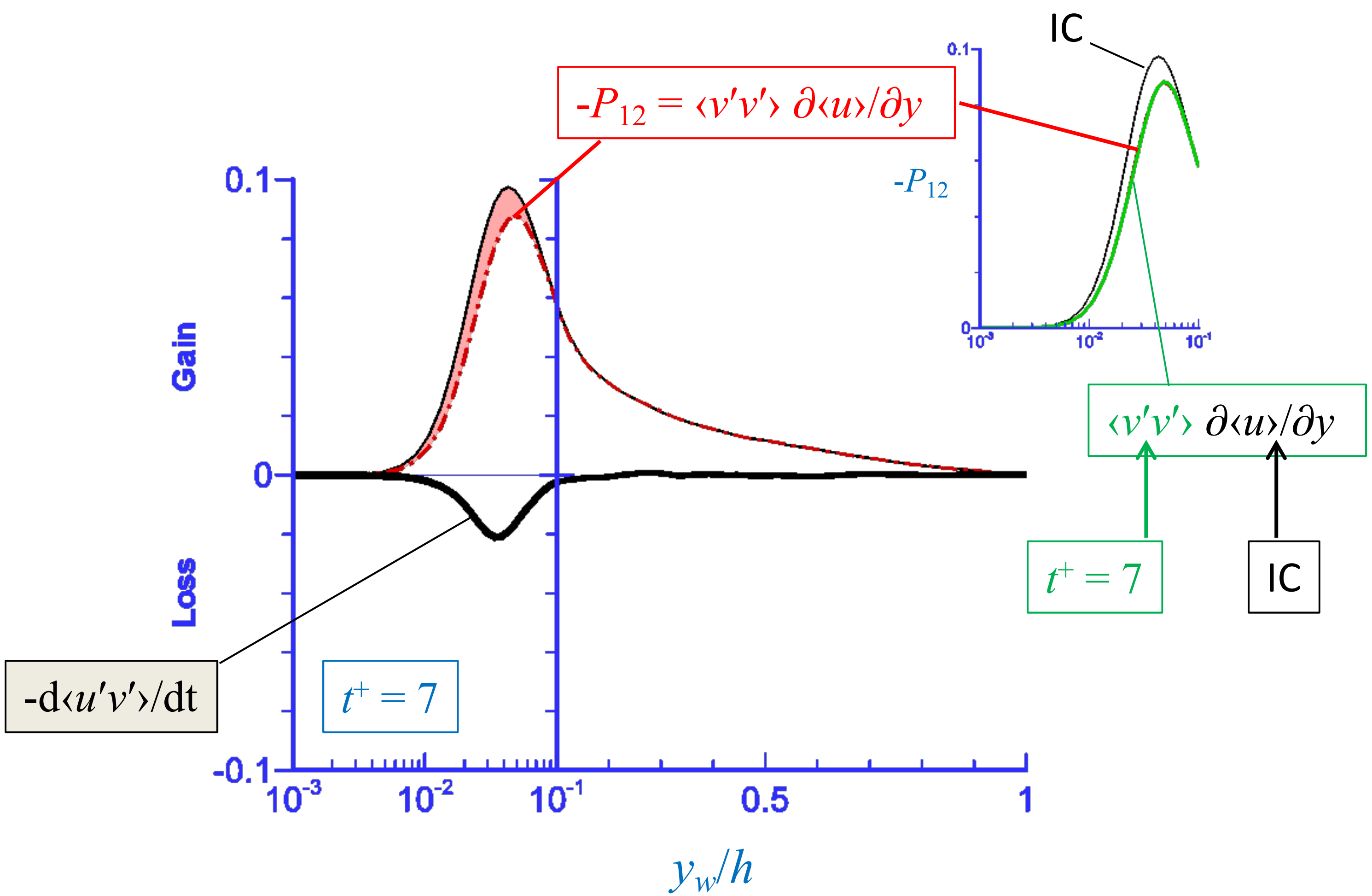
Conclusion: drop of -‹$u'v'$› (and thus τ_w) primarily due to reductions of $-\Pi_{12}$ and $-P_{12}$…

Examine two dominant terms in -$\langle u'v' \rangle$ budget…



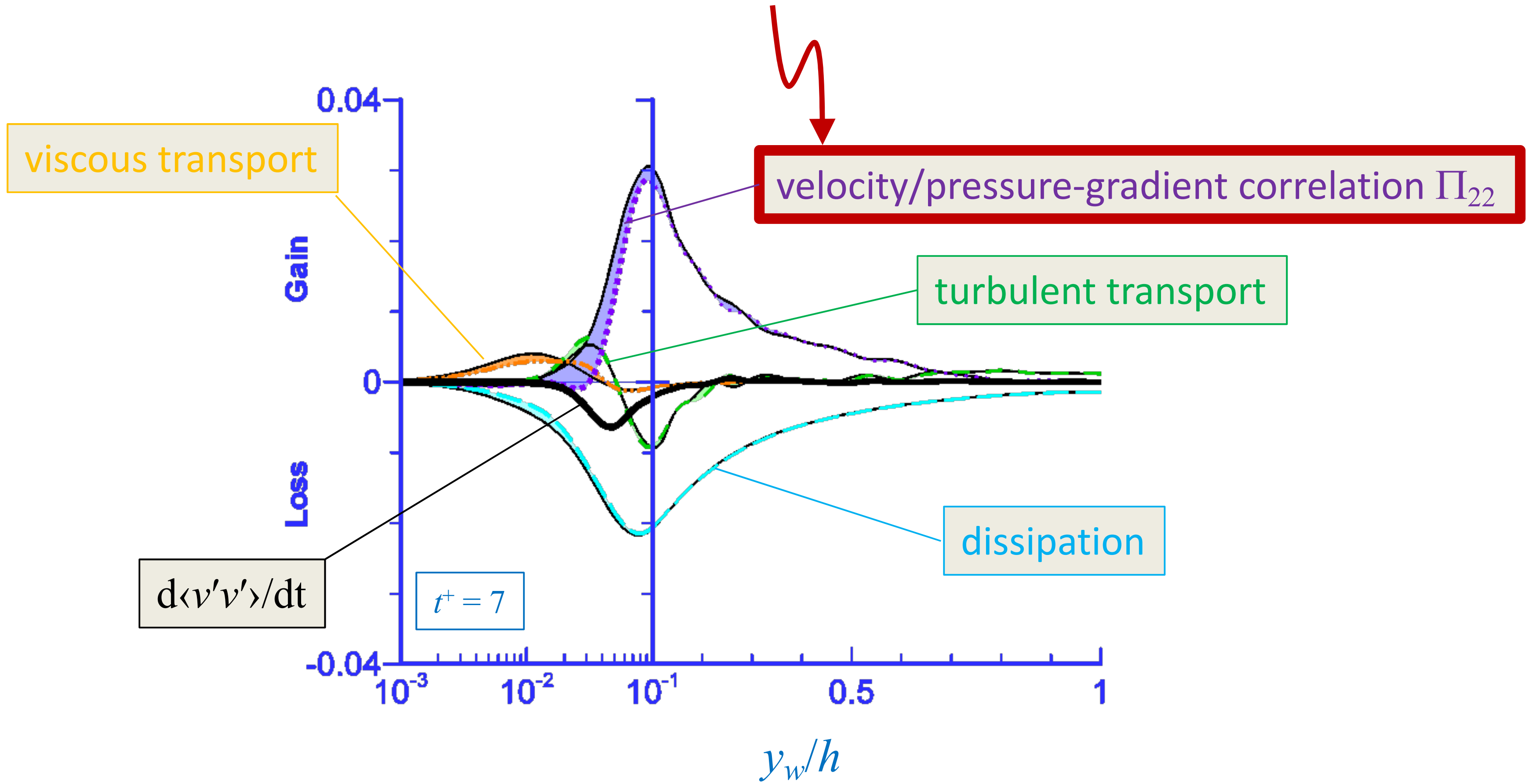
-P_{12} drop is due to $\langle v'v' \rangle$ …

…-P_{12} production term…



Conclusion: -P_{12} drop due to ‹$v'v'$› drop, **which is mostly due to…**

… (looking at ⟨$v'v'$⟩ budget)…



Bottom line: ⟨$v'v'$⟩ budget dominated by $\Pi_{22=}$ -2⟨$v'\partial p'/\partial y$⟩

Recap: Reynolds-stress budgets

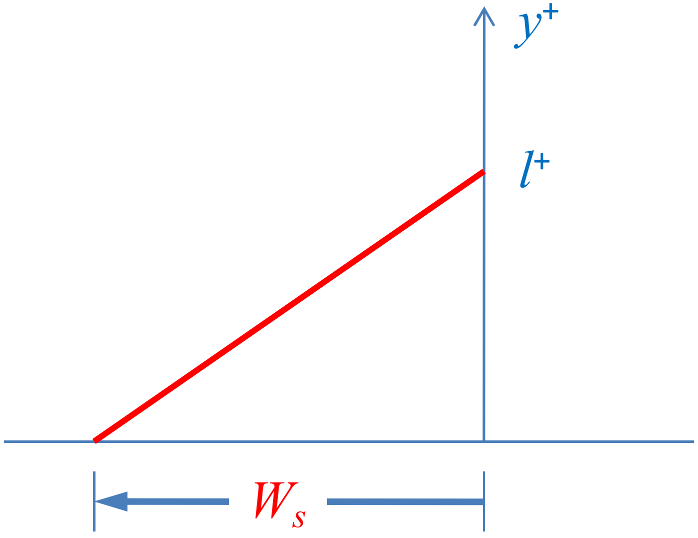
- ►*Ultimately* (from *statistical* point of view), spanwise-shear-induced drag reduction is due to $\Pi_{ij=}$ $-\langle u_i'\partial p'/\partial x_j\rangle$ $-\langle u_j'\partial p'/\partial x_i\rangle$ terms – which implies τ_w reduction will ***not* be easy for RANS models** to capture (cf. Moin *et al* 1990; Howard & Sandham 2000).

Statistical perspective

- Evolution/history of mean quantities
- Reynolds-number dependence
- Reynolds-stress budgets
- ▷ **Optimal shearing**

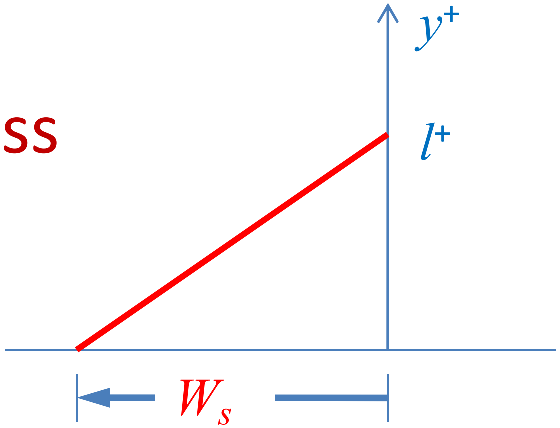
Objective: Determine *optimal* spanwise shearing, producing *maximum* τ_w decrease

Strategy: Impose *constant* (in space and time) $\mathrm{d}W/\mathrm{d}y$ across different near-wall regions of 2D turbulent channel…



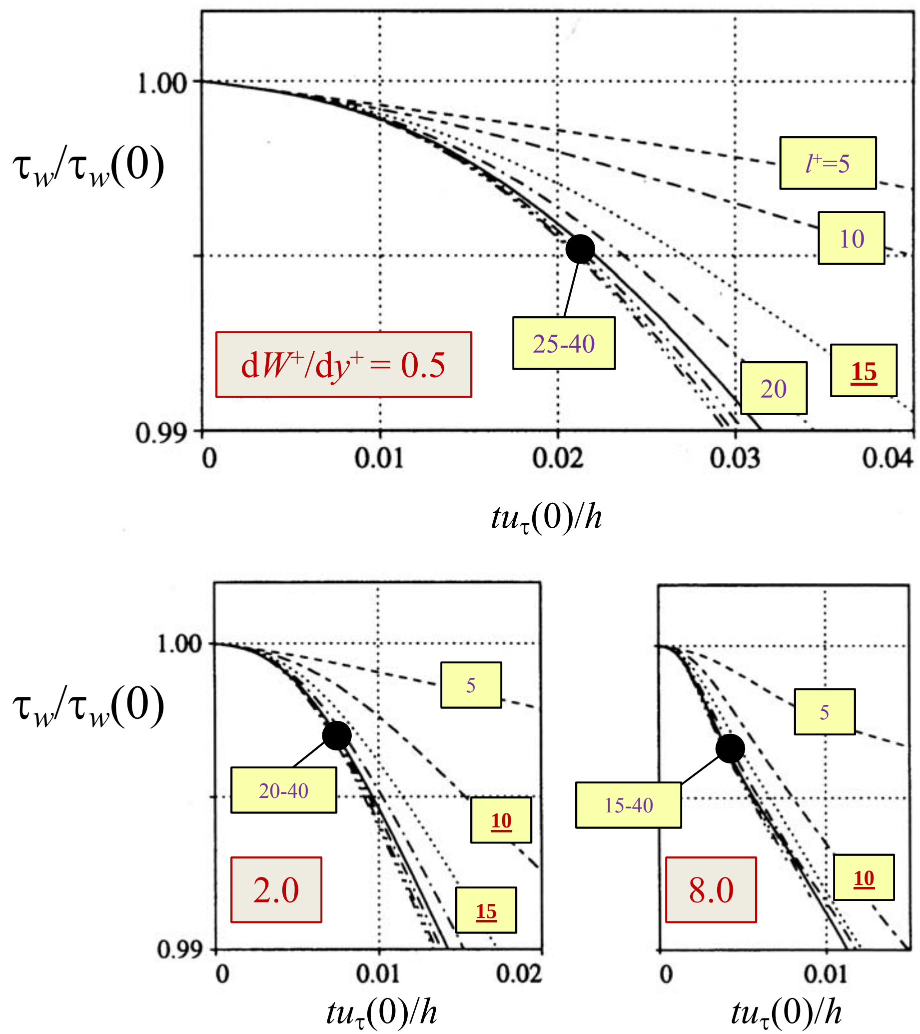
Vary l^+ and spanwise/streamwise stress ratio $dW^+/dy^+ = (dW/dy)/(dU/dy)_{y=0,t=0}$

$Re_\tau=112$ (Coleman *et al* 1996)



l^+ / dW^+/dy^+	5	10	15	20	25	30	35	40
0.5	✓	✓	✓	✓	✓	✓	✓	✓
2.0	✓	✓	✓	✓	✓	✓	✓	✓
8.0	✓	✓	✓	✓	✓	✓	✓	✓

Optimal spanwise shearing…



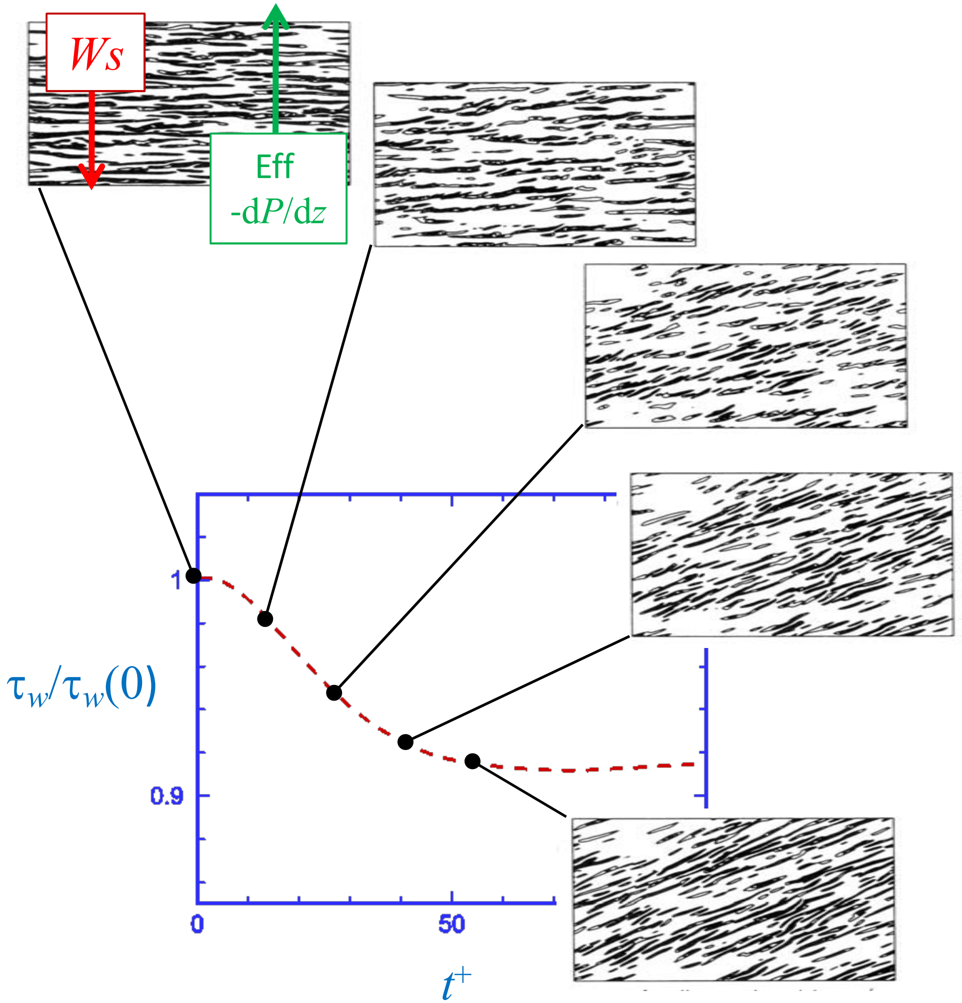
- Implies *optimal shearing* between $5 \leqslant y^+ \leqslant 15$, with *downward shift with increasing* $\mathrm{d}W/\mathrm{d}y$
- Consistent with oscillating-Stokes-layer behaviour…

Statistical perspective

Structural perspective

▷ **A QSV-based model** (and open questions…)

Near-wall structural changes associated with drag reduction?



(from Coleman *et al* 1996)

Proposals*

– *Reduction of vorticity* of Quasi-Streamwise Vortices (QSV)
– *Alteration of trajectories* of QSV-induced motions
– *Shifting of streaks* beneath QSV
– *Breaking communication* between QSV and streaks

*Anderson & Eaton (1989), Shizawa & Eaton (1990), Sendstad & Moin (1992), Kang *et al* (1998), Coleman *et al* (1996), Choi (2002), Yakeno *et al* (2009)

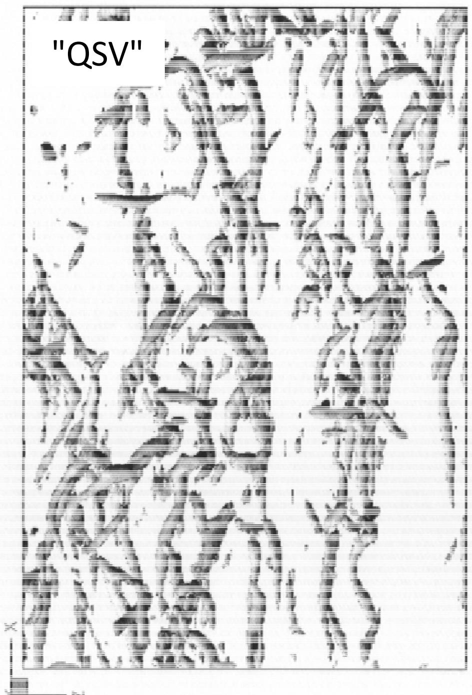
Common characteristics:

- *2D model* of QSV assumed
- Tendency to view QSV and streaks as *separate entities*

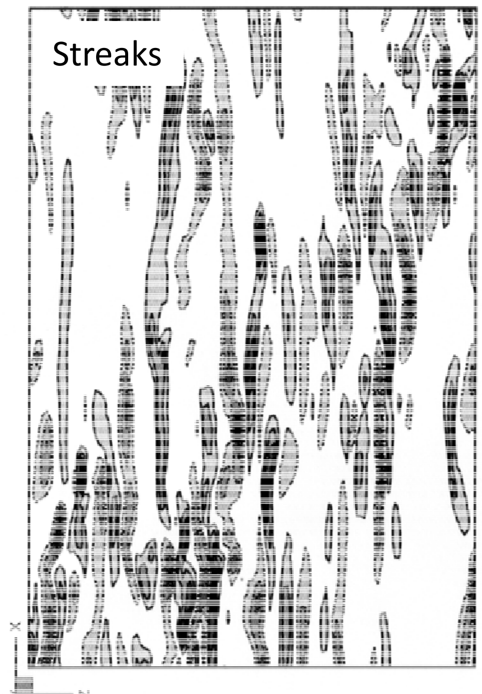
Quasi-Streamwise Vortices and streaks (2D channel)

Top views:

U

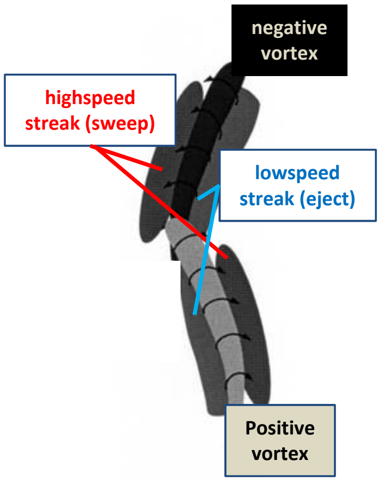


Iso-surfaces of λ_2 above wall



Wall-normal vorticity at $y^+=5$

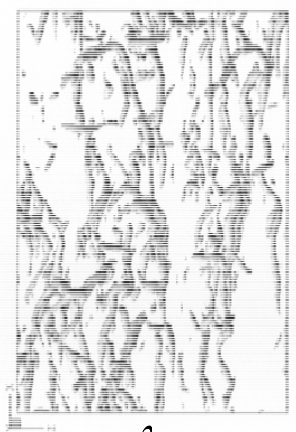
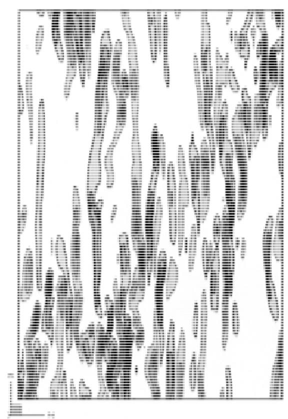
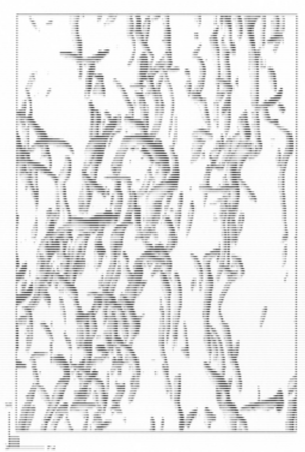
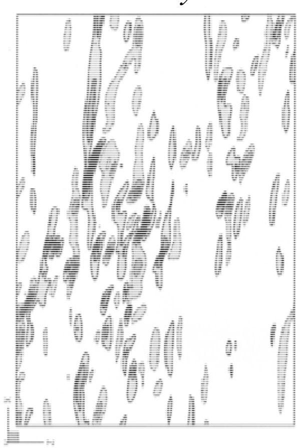
Idealisation:



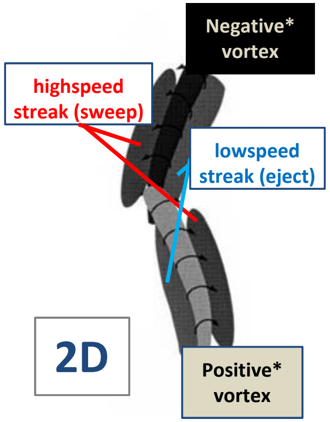
(cf. Jeong *et al* 1997)

Note ***interdependence*** of QSV and ("near-QSV regions" of) streaks…

Effect of spanwise-wall motion…

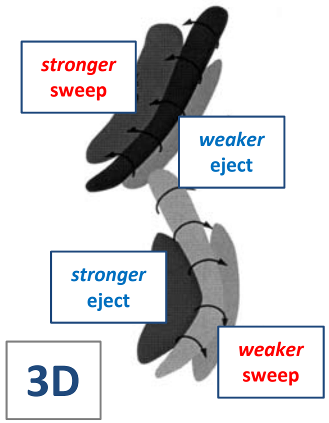
	λ_2	ω_y
2D:		
3D:		

Idealisation:

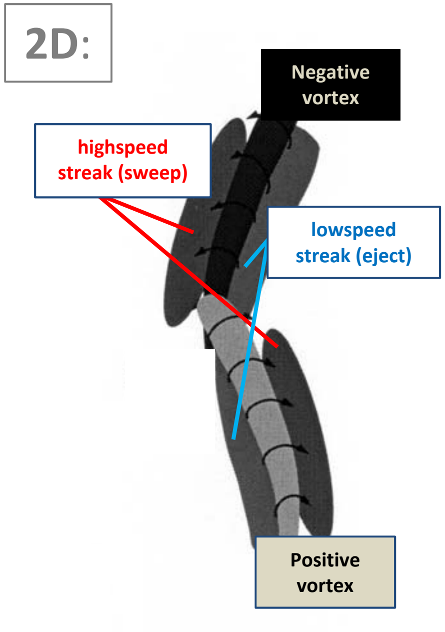


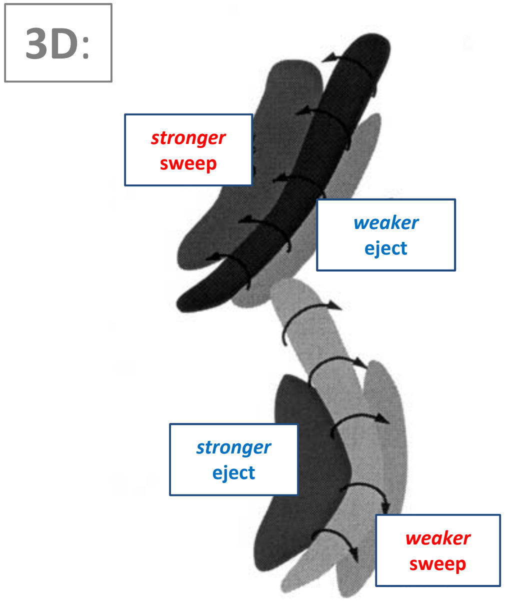
* w/r W_s-induced vorticity

"("s become "S"s and ")"s become "J"s…



Summary: Model of near-wall structural changes induced by spanwise shear





✓ Consistent with drag reduction, asymmetries in statistics
✓ Treats QSVs and streaks as unified structures

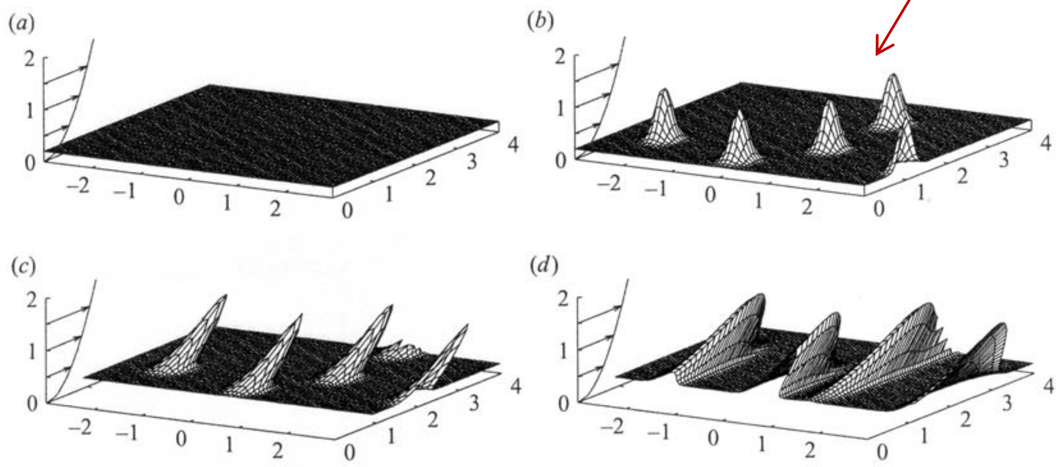
…*but*, on the other hand…

…are QSVs *really* essential?

Alternative framework (Chernyshenko & Baig 2005)

Non-QSV streak-formation:

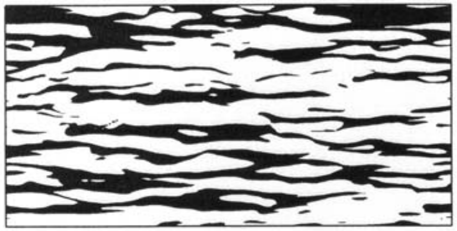
random v'



(with streak spacing set by mean $\mathrm{d}U/\mathrm{d}y$ and diffusion, **not** location of QSVs)

DNS of non-QSV streaks

(Chernyshenko & Baig 2005)



← u' (velocity) streaks

← θ' (scalar) streaks, where

(**Random** irrotational velocity)

$$\frac{\partial \theta}{\partial t} = (\mathbf{U} + \nabla\phi) \cdot \nabla\theta = S(y) + \nu\nabla^2\theta$$

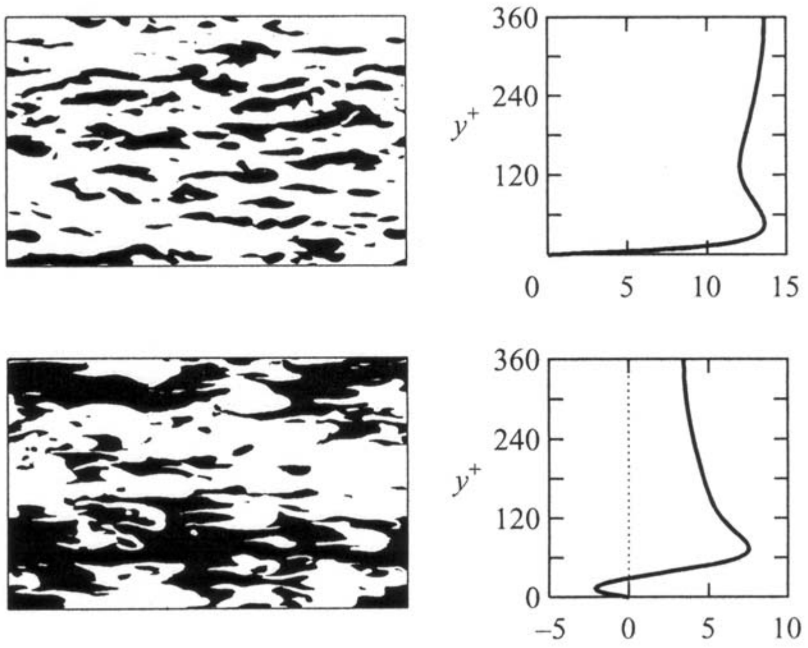
$(U(y),0,0)$

such that $U(y) = \overline{\theta}(y)$

Conclusion: streaks also formed by random fluctuations!

…DNS of non-QSV streaks (contd)
(Chernyshenko & Baig 2005)

Effect of mean-θ profile on scalar streaks, with **same velocity field:**



Implication: *perhaps QSV-structures not essential?...*

►Compare recent TBL DNS of Schlatter *et al* (2009), Simens *et al* (2009) and Wu & Moin (2009): **good agreement of statistics,** despite Wu & Moin's results being "extra rich" in hairpins…

Summary

- Successful RANS modelling of spanwise-shear effects requires correct representation (implicitly or otherwise) of velocity/pressure-gradient correlation Π_{ij} (represents *severe modelling challenge*)
- Present DNS reveals no Re-dependence of $\Delta\tau_w$ reduction
- Optimal spanwise shearing observed when $\mathrm{d}W/\mathrm{d}y$ applied in range $5 \leqslant y^+ \leqslant 15$, with downward shift with increased magnitude.
- Open questions remain regarding dynamic significance of quasi-streamwise vortices and relationship with near-wall streaks