

Direct numerical simulation of a turbulent separation bubble with sweep

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Project overview

■ Flow: *Separation bubbles*

- Six cases: with/without sweep, sudden/gradual pressure gradient (PG), 2X Reynolds number

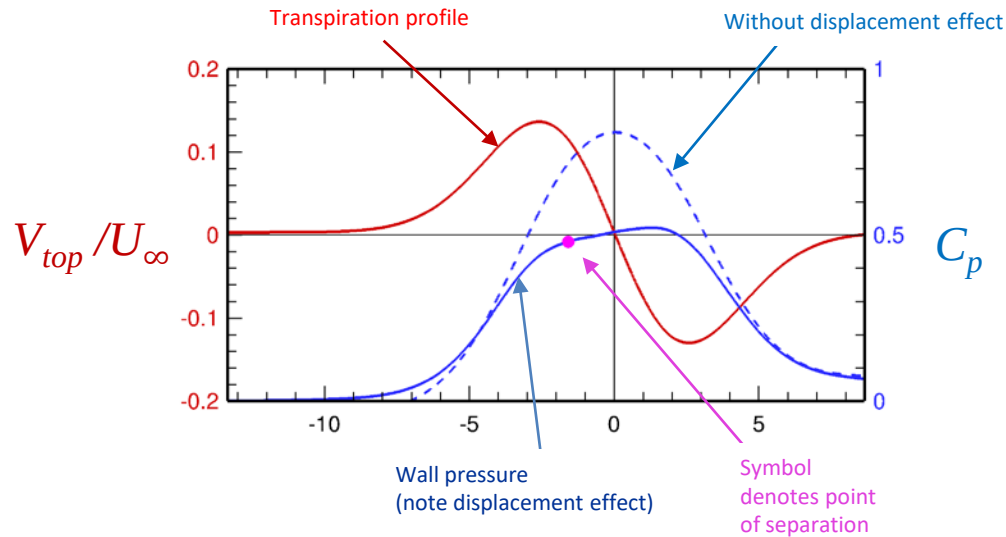
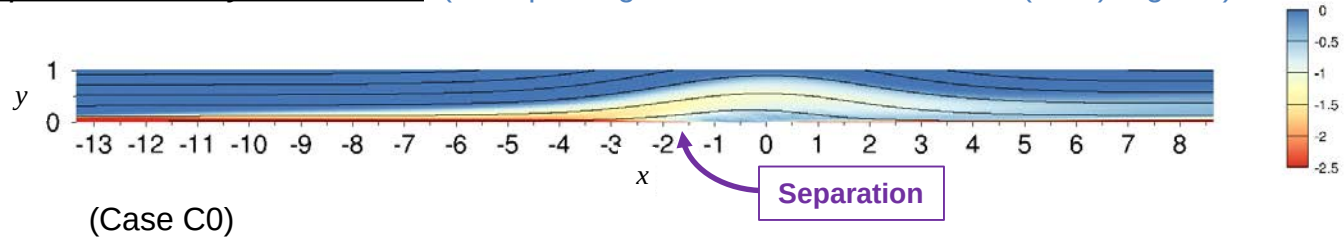
■ Strategy: Use DNS to address...

- *Fundamental questions*, turbulence theory (Stratford scaling, Independence Principle,...)
- *Performance of range of available RANS models* (SA, SST, RSM,...), to predict separation/reattachment locations
- See *JFM* [2018: **847**, 28-70] for unswept cases
- Today's focus: *Effect of sweep...*

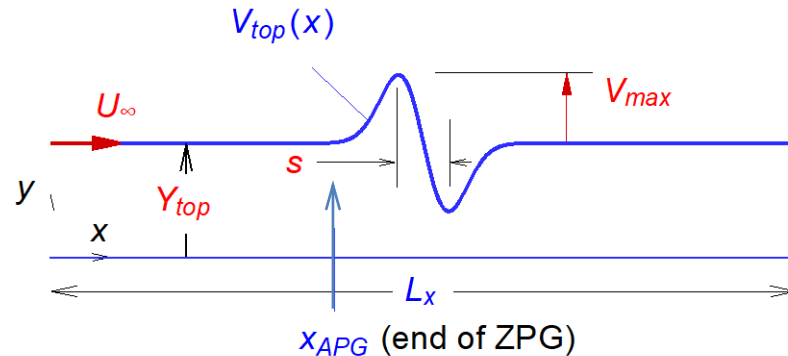
Turbulent flat-plate separation bubbles

Separation & reattachment via upper-wall transpiration:

Mean spanwise vorticity, streamlines: (Note prolonged Zero Pressure Gradient (ZPG) regions)



Cases



Case	$\arctan\left(\frac{W_\infty}{U_\infty}\right)$	s/Y_{top}	V_{max}/U_∞	$R_\theta _{x_{APG}}$	$N_x \cdot N_y \cdot N_z$
SC97	0°	1.7	0.435	500	0.03×10^9
A0	0°	1.7	0.400	1200	0.98×10^9
A35	35°	1.7	0.400	1400	1.97×10^9
B0	0°	5.2	0.133	750	0.98×10^9
B35	35°	5.2	0.133	710	1.97×10^9
C0	0°	5.2	0.133	1800	4.72×10^9
C35	35°	5.2	0.133	1850	9.44×10^9

Spalart & Coleman 1997:
Eur J. Mech. B/Fluids
16(2), 169-189.

SC97: $L_x/Y_{top} = 10$, $L_z/Y_{top} = 1.4$

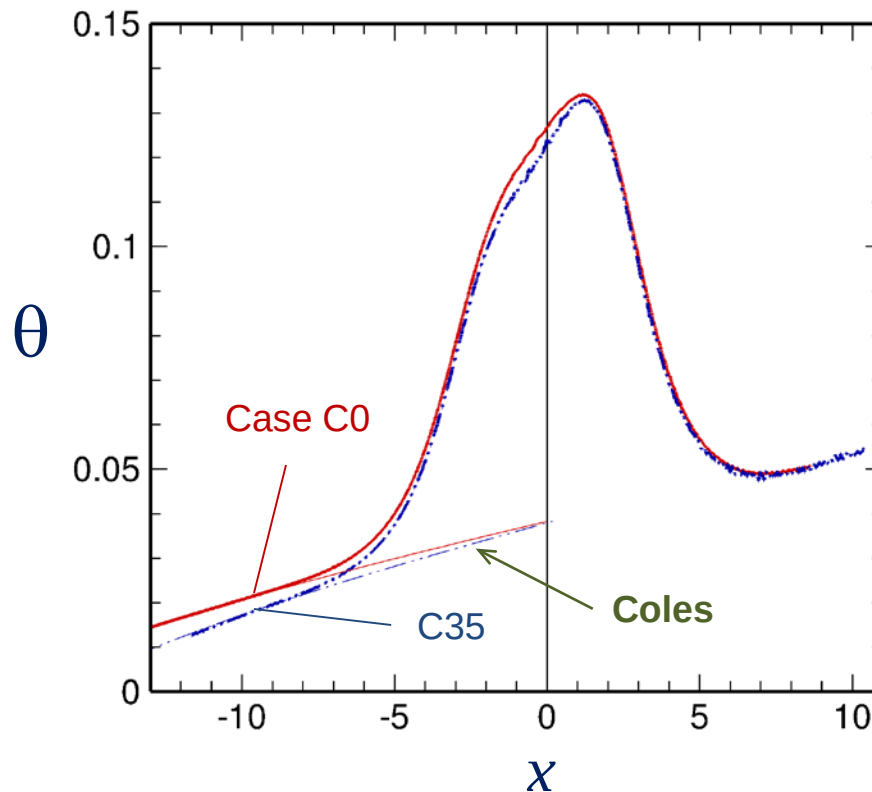
New cases: $L_x/Y_{top} = 26$, $L_z/Y_{top} = 4.0$

Focus: highest Re, most-gradual PG,
 over unswept & 35° infinite-swept wing

Algorithm: Jacobi/Fourier scheme
 with fringe BCs (Spalart *et al.* 1991)

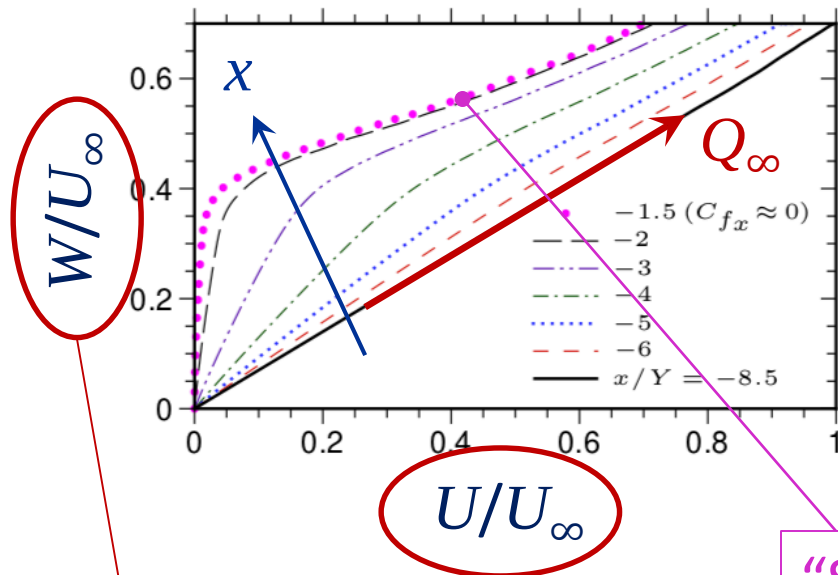
Consider 35° infinite-swept wing...

*Swept and unswept cases compared by matching
virtual ZPG x-component momentum thickness
extrapolated to center of transpiration profile ($x = 0$):*



Mean velocity hodograph development

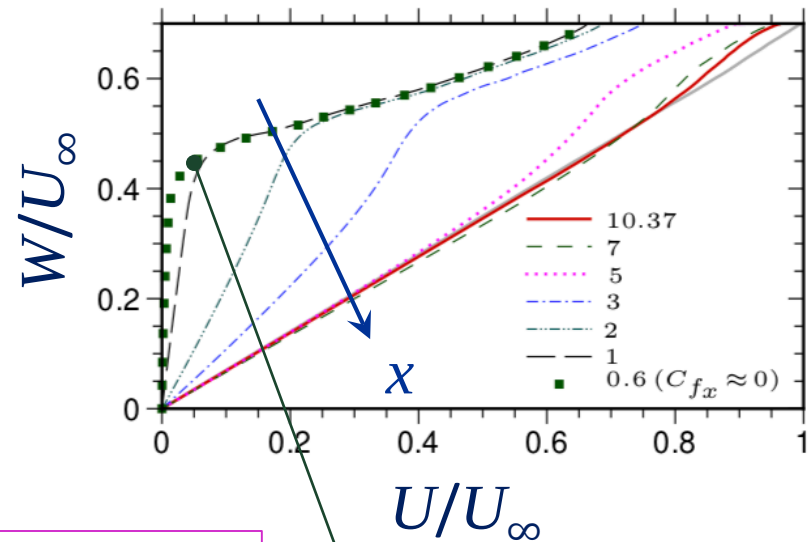
ZPG → APG region:



Spanwise

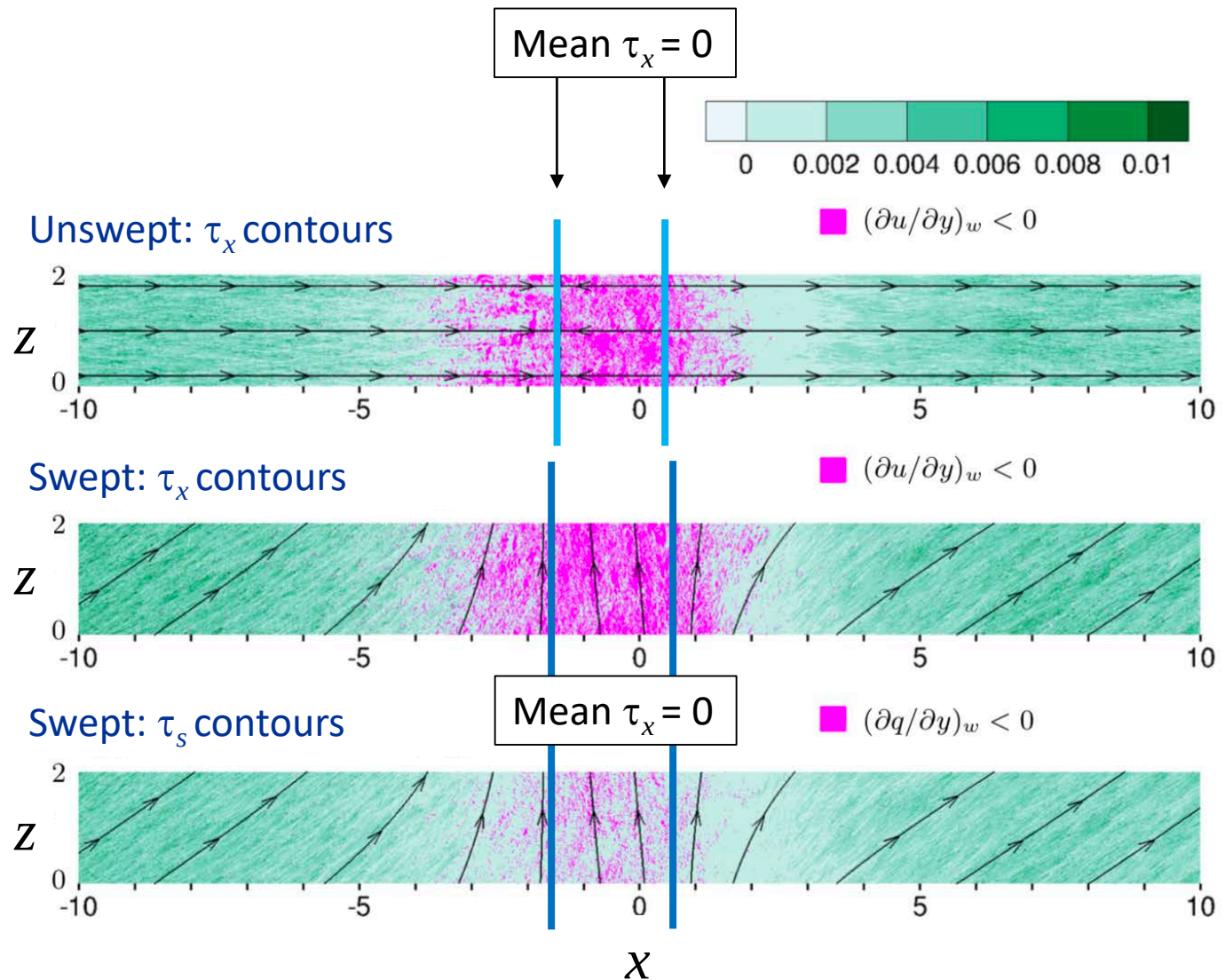
Chordwise

FPG → ZPG region:



"Reattachment"

Instantaneous wall shear stress



Effect of sweep:

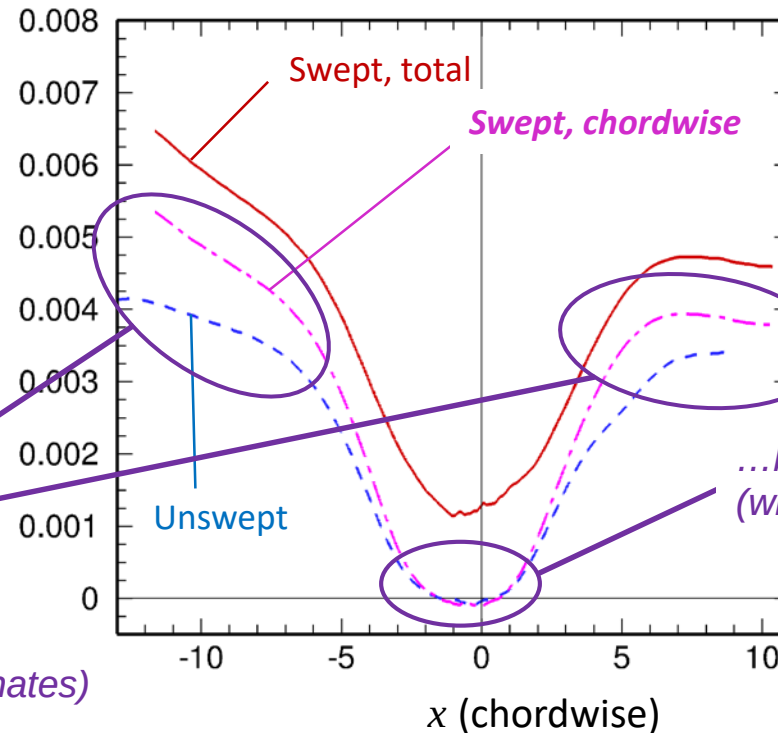
Is Independence Principle (IP) valid for turbulent case?

(Recall IP holds exactly for **laminar BL** on an infinite swept wing, for which chordwise variation is independent of spanwise variation)

$$C_f = \frac{\tau_w}{\frac{1}{2} U_\infty^2}$$

(WRT chordwise freestream)

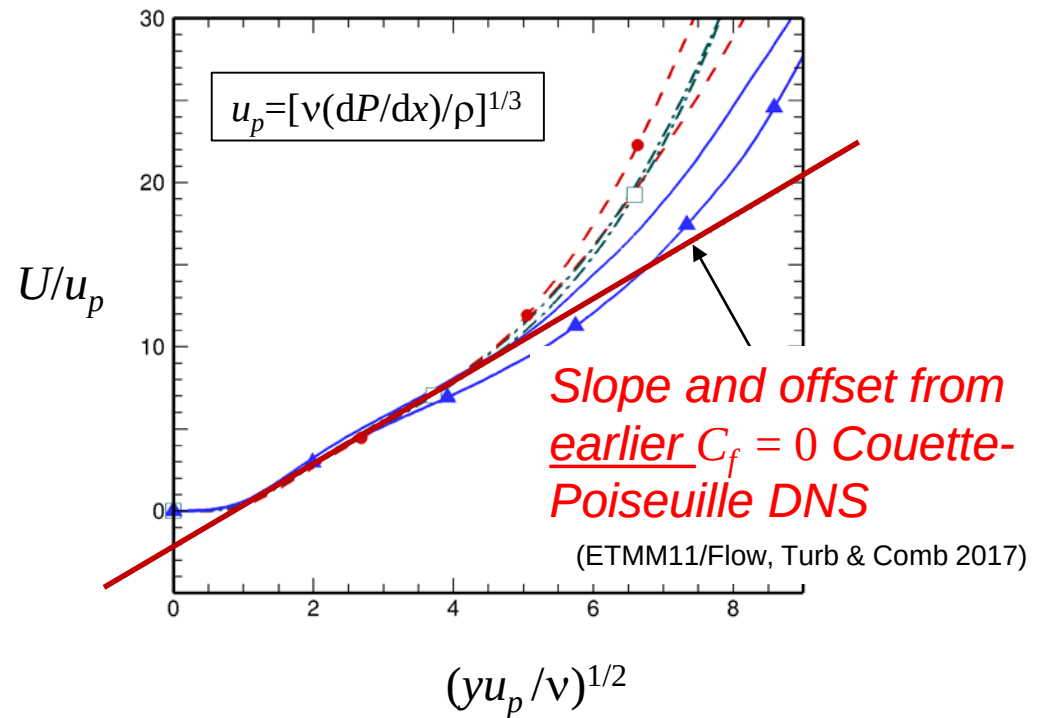
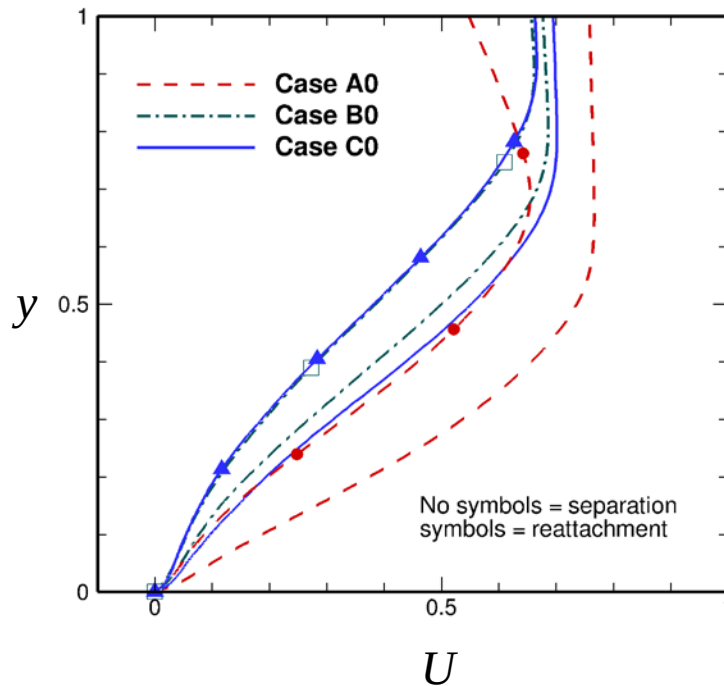
Violates
Independence
Principle here...
(where skin friction dominates)



...but satisfies it here!
(where pressure dominates)

Validity of *Stratford zero-stress velocity scaling* ($U \sim \sqrt{y}$)? for swept-wing flow?

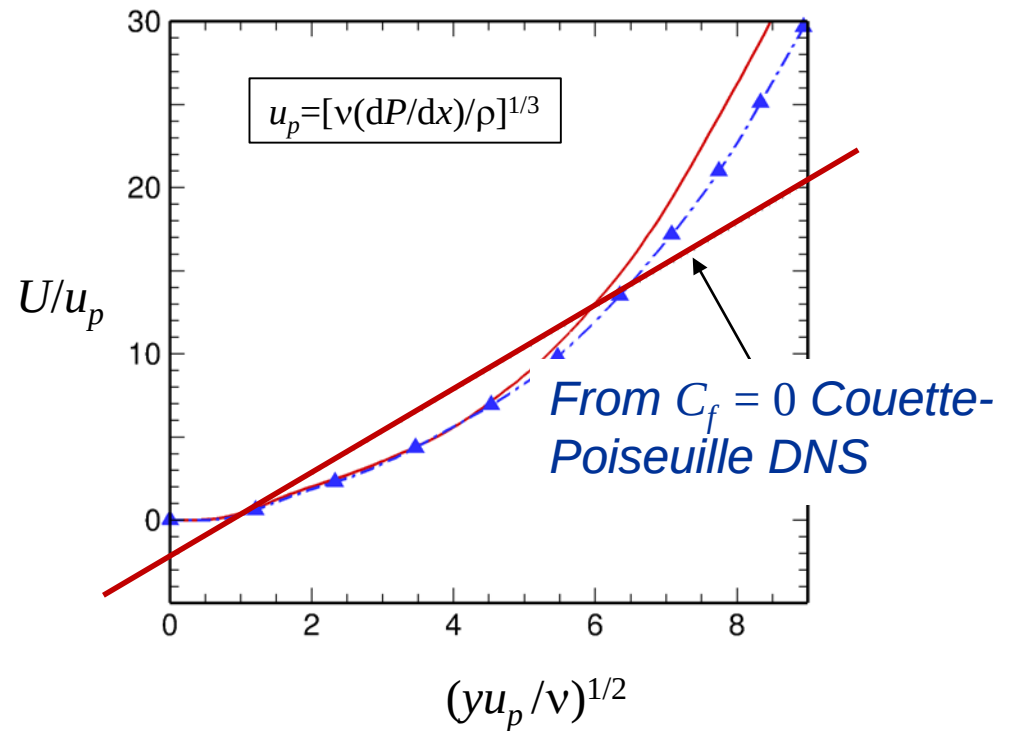
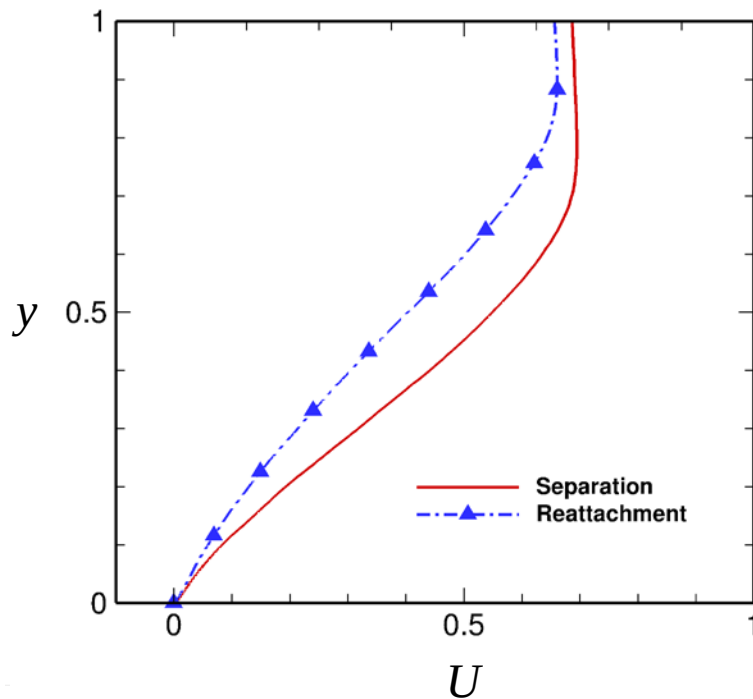
Background: Unswapt cases at separation & reattachment stations:



Implication: *Stratford theory works quite well(!)*
for 2D/unswept bubbles...

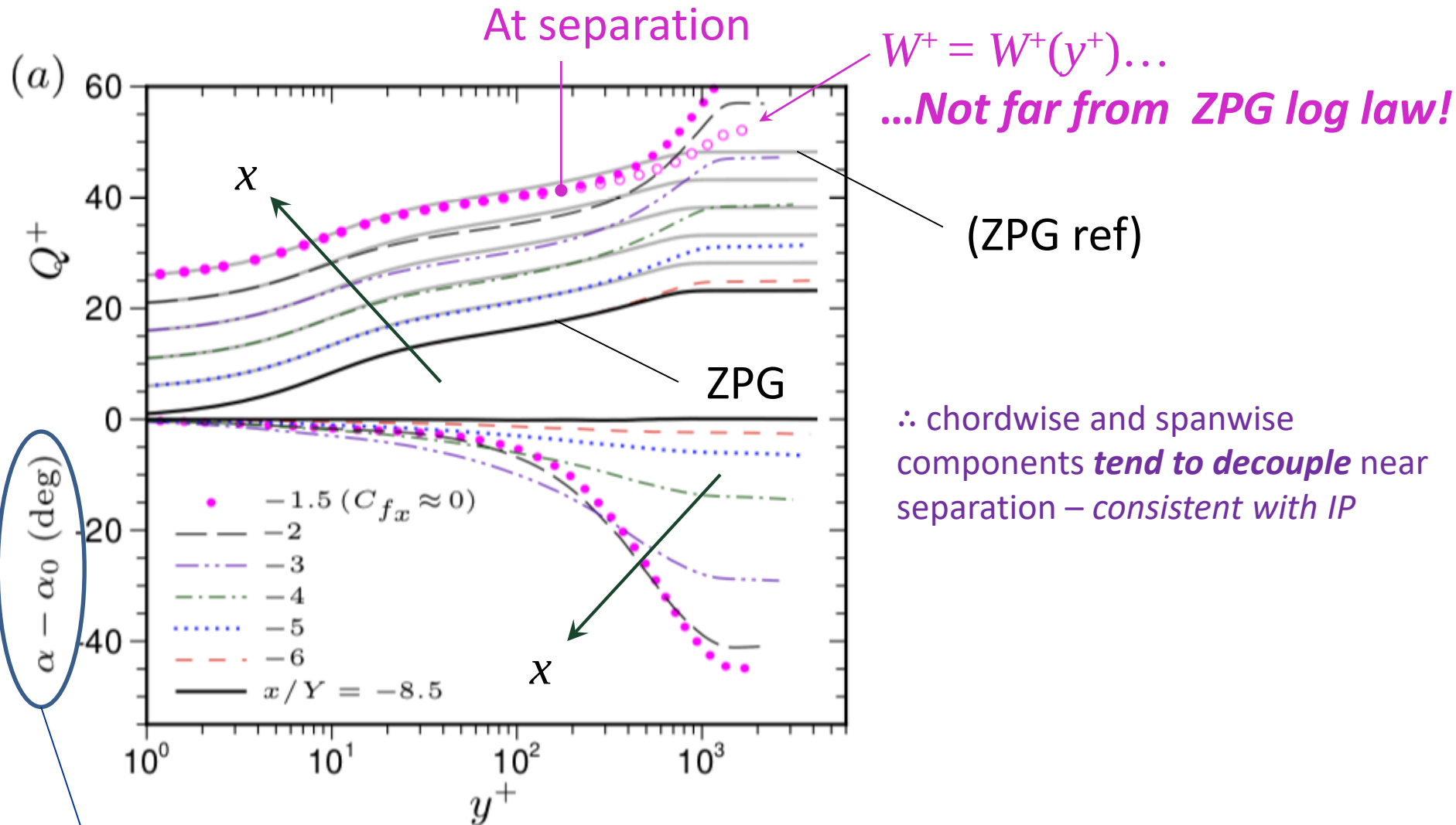
Validity of *Stratford zero-stress velocity scaling* ($U \sim \sqrt{y}$)? *for swept-wing flow?...*

Consider: Swept case at separation & reattachment stations:



Message: Stratford scaling “too fragile” to survive skewing, probably because the spanwise shear dominates the turbulence

Examine development of **spanwise component**
 (inferred from inner scaling of magnitude $Q^+ = \sqrt{[U^{+2} + W^{+2}]}$)



$\therefore$ chordwise and spanwise components **tend to decouple** near separation – consistent with IP

Deviation from surface shear direction

Summary (1/2)

- DNS database for separation bubbles created with (compared with 1997) much larger domain, higher Reynolds number, range of pressure gradients, two sweep angles. Data available on NASA *TMR website*.
- (Unswept result documented in *JFM* [2018: **847**, 28-70], including:
 - Wide selection of models (*one-, two-eqn, RST*) fails to bracket the target (separation point, post-reattachment skin-friction) and cluster on a common erroneous result! Thus, it is possible to get completely wrong picture from multiple-model-sensitivity tests.
 - Effective eddy viscosity extracted from DNS proposed as Machine-Learning (or human!) surrogate for RANS-model testing/development (cf. Spalart lecture).
 - Stratford square-root scaling very successful at $C_f = 0$ locations (only!), with universal behavior – as in Couette-Poiseuille flow.
 - Relatively small streamline divergence/convergence can have significant effect on turbulence statistics and structure.)

Summary (2/2)

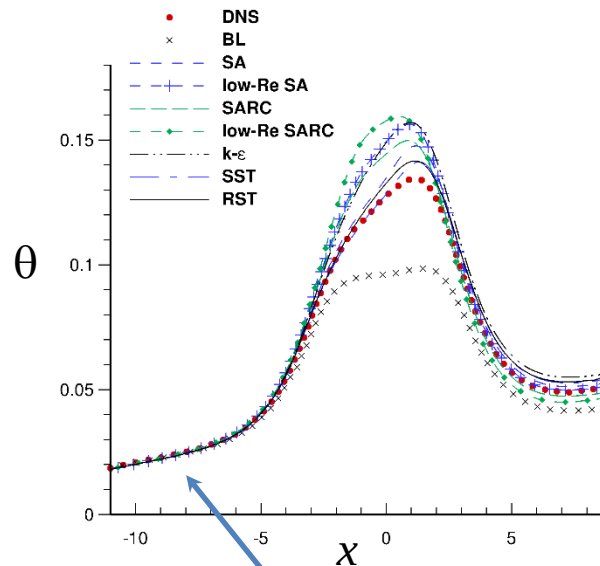
- Swept-wing Independence Principle fails as expected in ZPG regions, **but** succeeds near separation bubble! Turbulence overwhelmed by pressure?
- Chordwise mean velocity near separation/reattachment “not kilometers away from” Stratford $\sqrt{y}$ scaling for swept-wing flow, while spanwise component not far from ZPG log law there.
- Swept-wing layer thus fairly normal in terms ***of magnitude, although not orientation***, everywhere – ***even through the bubble***.
- Findings (not shown) suggest RANS CFD cannot expect easier time of predicting separation for 3D/skewed flows than for 2D flows.
 - Contrary to a conjecture made by one of the authors...

FIN

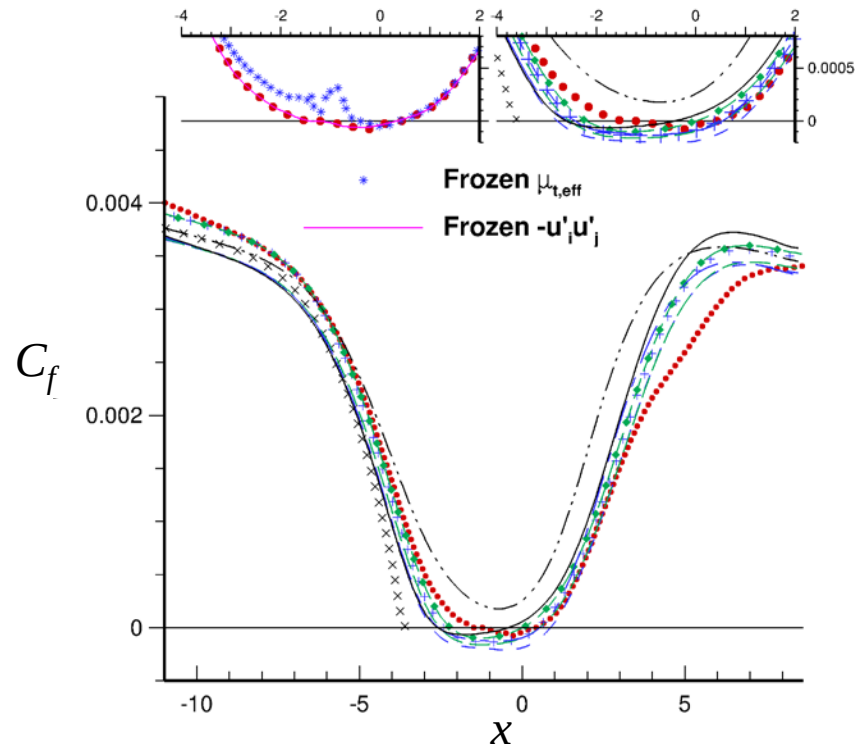
Backup slides

DNS (Case C0) as RANS-model benchmark

Solutions via CFL3D,
using DNS as inflow BC



Match θ in ZPG



Findings:

BL: *sep too early*

k- ϵ (Abid): *no sep*

SA/SST/RSM/etc: *somewhat too early and too deep,*
and *together* (why?)...

(Recovery difficult in its own right)

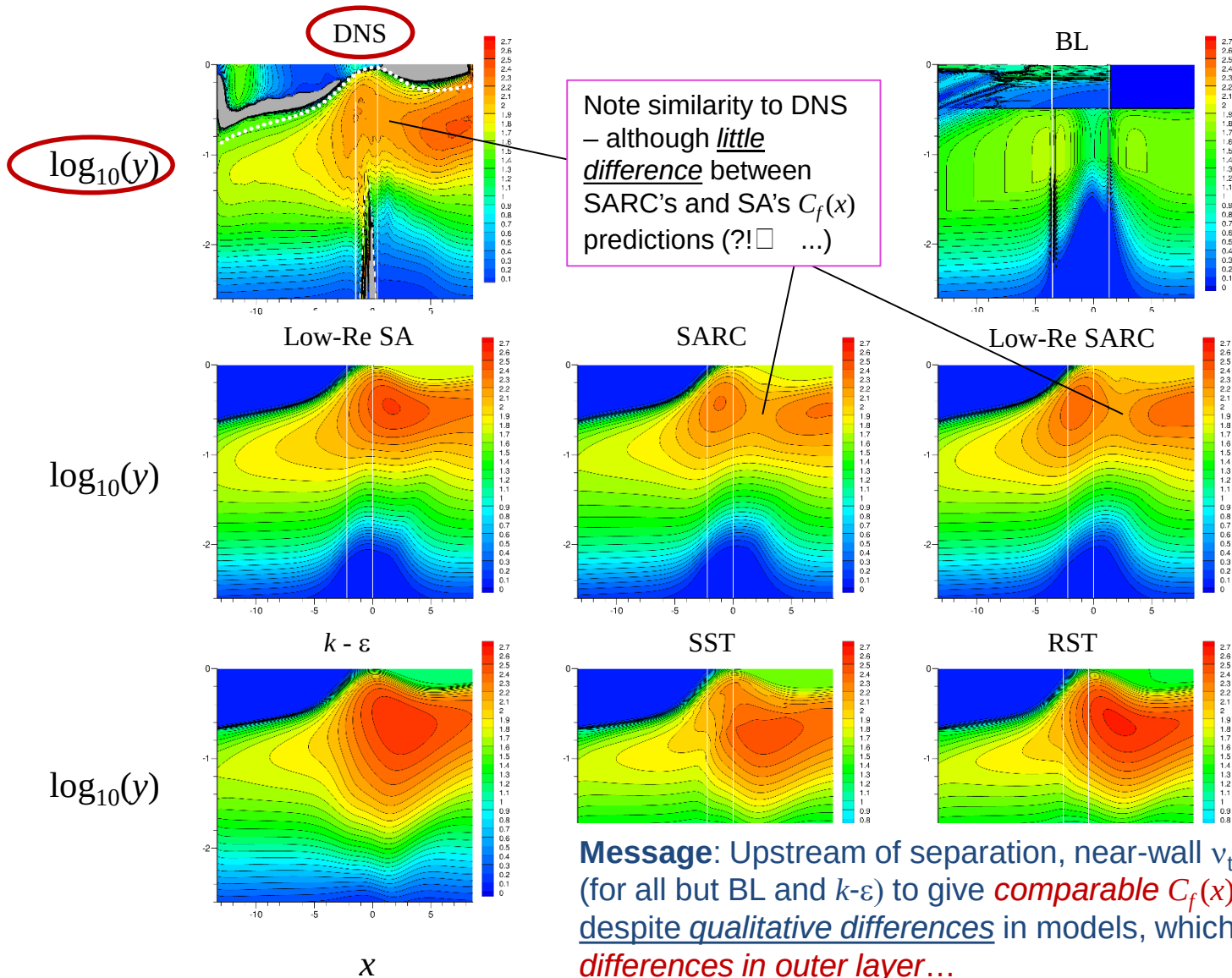
Implies danger when using range
of models to bracket errors

DNS as RANS-model benchmark: Effective eddy viscosity

$$\nu_{t,eff} \equiv \frac{\mathcal{P}_{TKE}}{2S^2} = \frac{-\overline{u'_i u'_j} S_{ij}}{2S_{k\ell} S_{k\ell}}, \text{ where } S_{ij} = \frac{1}{2} \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right).$$

- Follows from Boussinesq approximation and assumed relationship between eddy viscosity and TKE production (to give correct mean-to-turbulence energy transfer)
- Corresponds to least-squares fit of Reynolds stress tensor by scalar eddy viscosity
- Available from DNS, convenient RANS-model diagnostic – *tool for Machine Learning?*
 - (Solutions obtained with Reynolds-stresses from DNS – consistency check)
 - (Models solved in “frozen” DNS fields – check constitutive relationship)
 - **Full RANS-model solutions** (highlight critical regions)

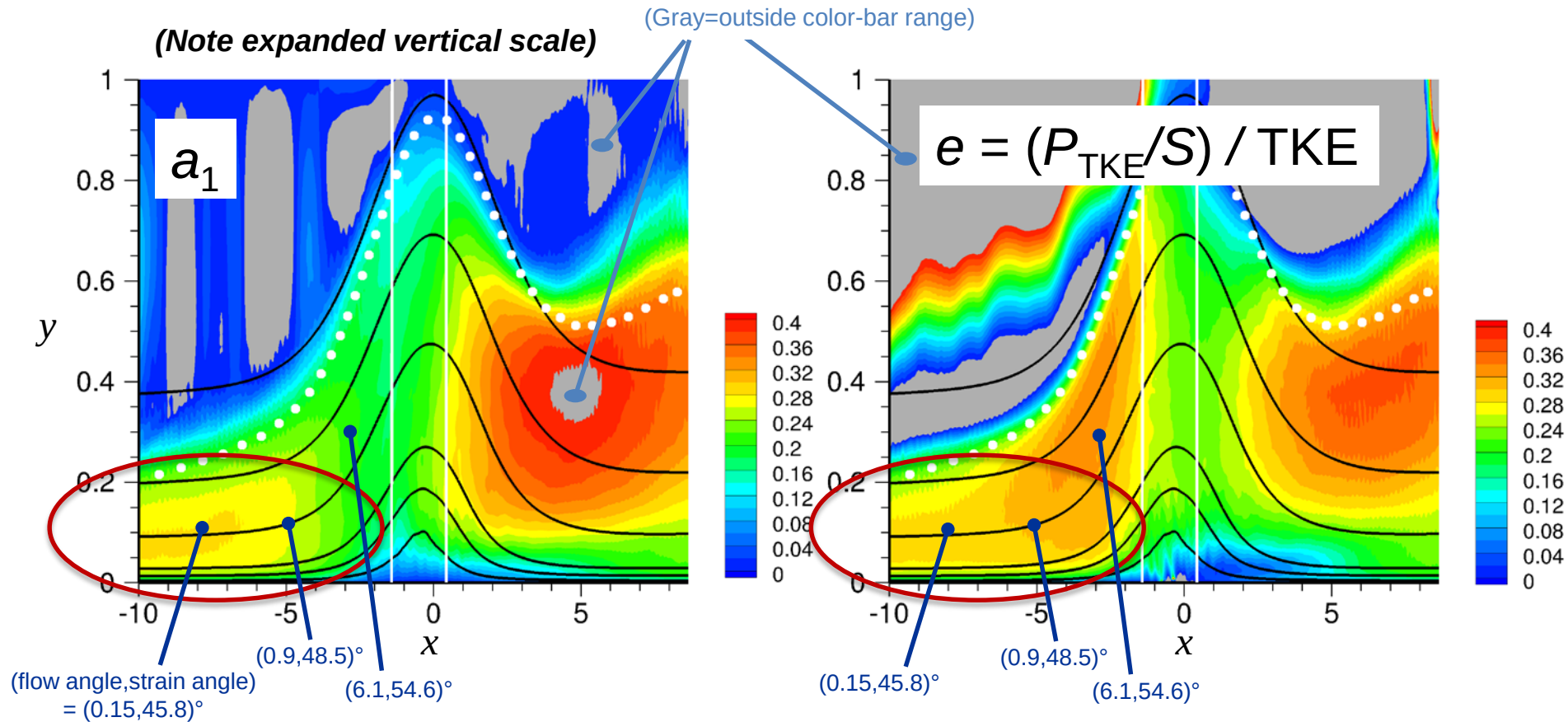
Compare models and DNS: $\log_{10}(v_{t,eff}^+ + 1)$ contours



Message: Upstream of separation, near-wall v_t “similar enough” (for all but BL and $k - \epsilon$) to give *comparable* $C_f(x)$ predictions – despite *qualitative differences* in models, which yield *significant differences in outer layer*...

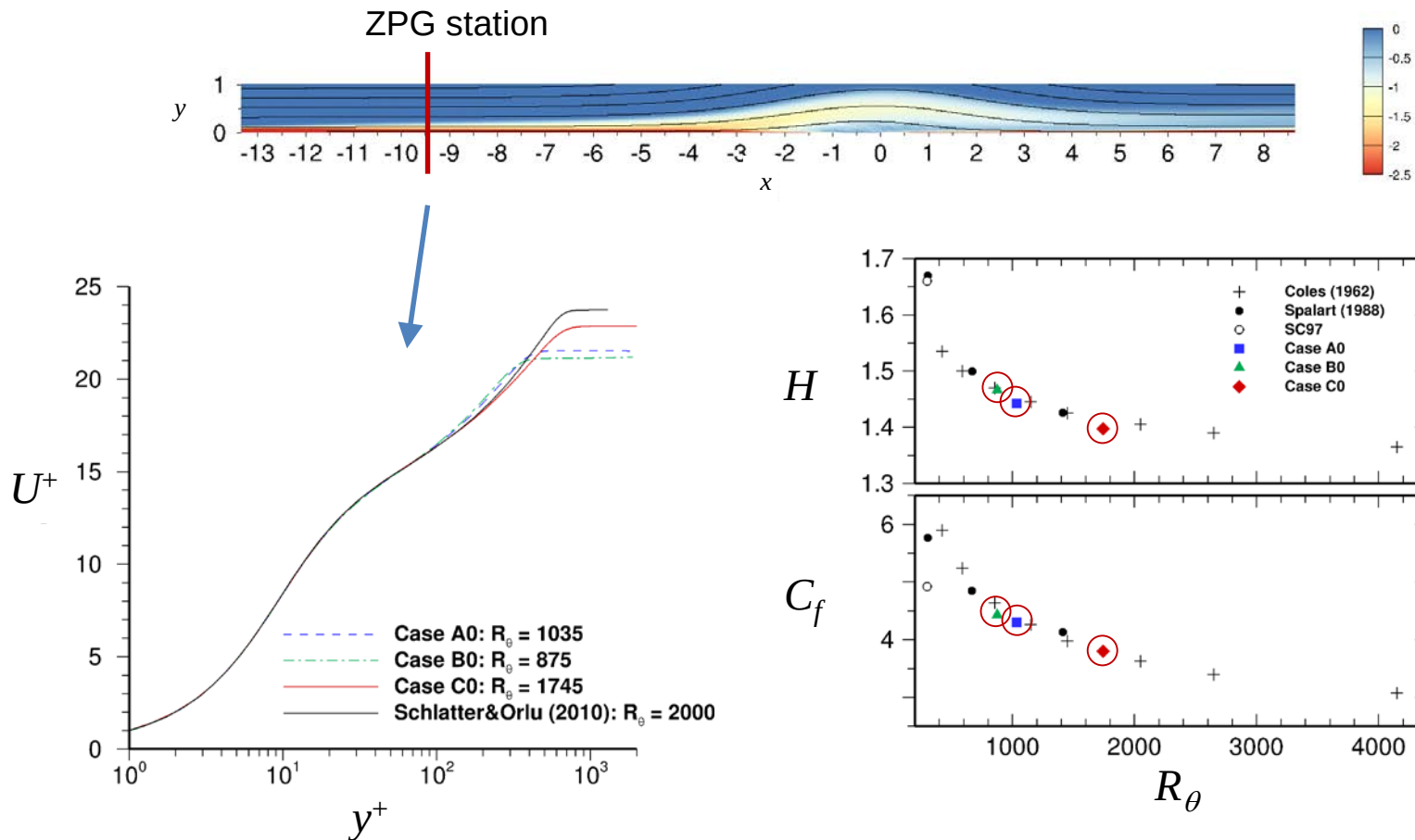
Effect of non-parallel streamlines on RANS-based measures of turbulence?

Define “Efficiency” $e = (P_{TKE}/S) / TKE$ (= fraction of energy to affect mean momentum). Efficiency e is equivalent to Reynolds-stress “structure parameter” $a_1 = -u'v'/TKE$ in parallel $U(y)$ shear flow. Note large deviation from 0.31, and that a_1 goes down in APG, while e goes up!



Conclusion: Experience/results from parallel-flow turbulence can be misleading!

Check upstream conditions...



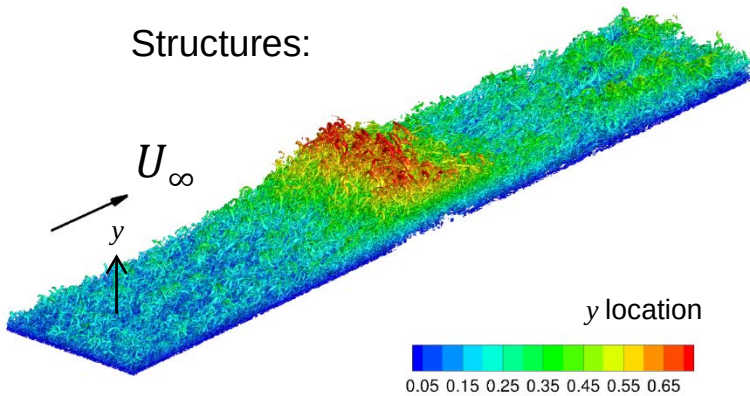
(Also very good agreement with TKE budgets from Schlatter & Orlu's (2010) ZPG BL DNS)

Conclusion: Canonical ZPG BL upstream of separation. Supports *suitability as a RANS-modelling benchmark* (or as the subject for DNS and LES studies by other groups)

Turbulent flat-plate separation bubbles

Turbulent separation and reattachment via prolonged adverse then favorable PGs...

Structures:



(Q criterion,
subdomain of Case A0)

Surface shear:

