How does Knowledge from DNS Enter RANS Models?

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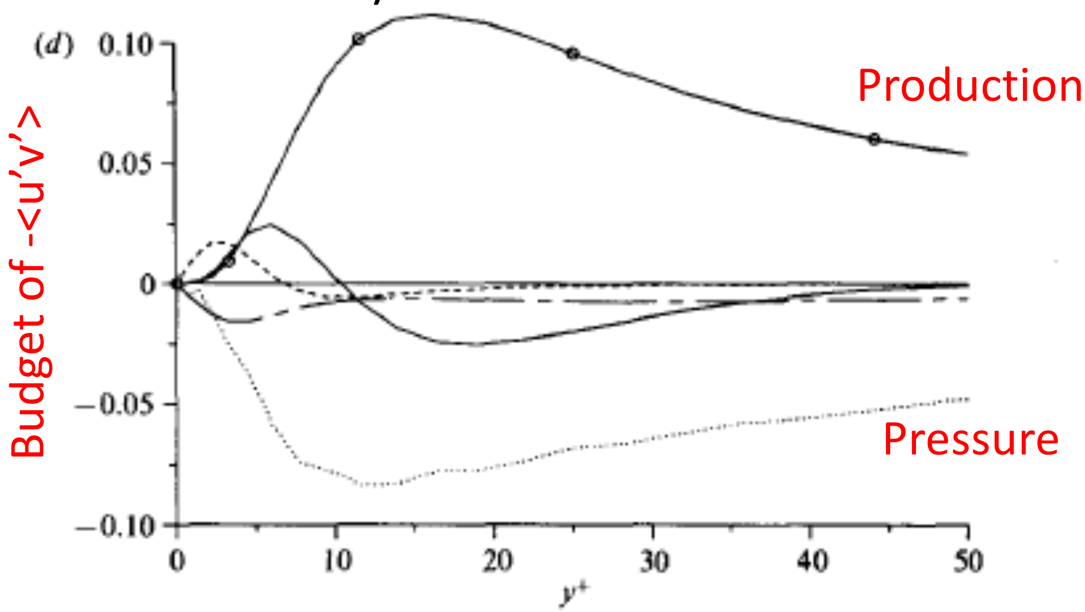
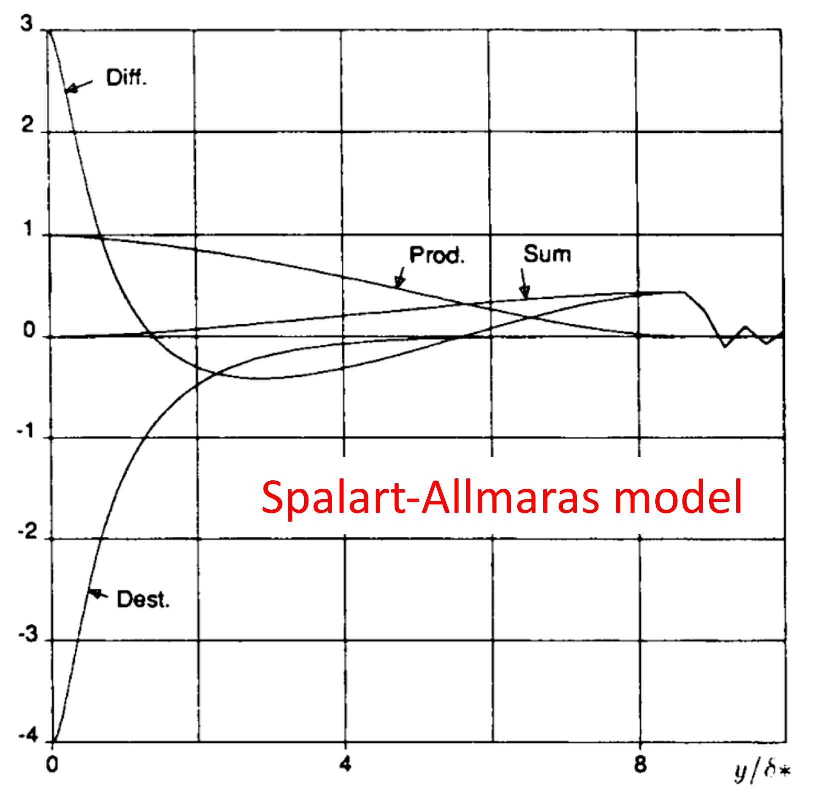
Outline

- Direct Numerical Simulation as a source of data
  - Advantage over experiments: complete information
  - Potential: new ideas, or calibration of existing constants, or validation of full model?
    - Idea in SA model
    - Validation of Reynolds-Stress model
  - Limitations: Reynolds number and geometry
- Puzzling findings in DNS
  - Log layer and Karman “constant” have been very elusive
  - Luchini’s near-theoretical unification of Couette, Poiseuille and pipe flows
- Structural conflicts inherent to RANS models
  - Log-layer behavior of the Reynolds stresses
  - Insensitivity to flow Reynolds number
  - Interface with “clean air”
- Contributions of DNS to complex models
- Attempts to concretely steer simple models
  - Effective eddy viscosity
- Artificial intelligence

DNS as Source of RANS Ideas

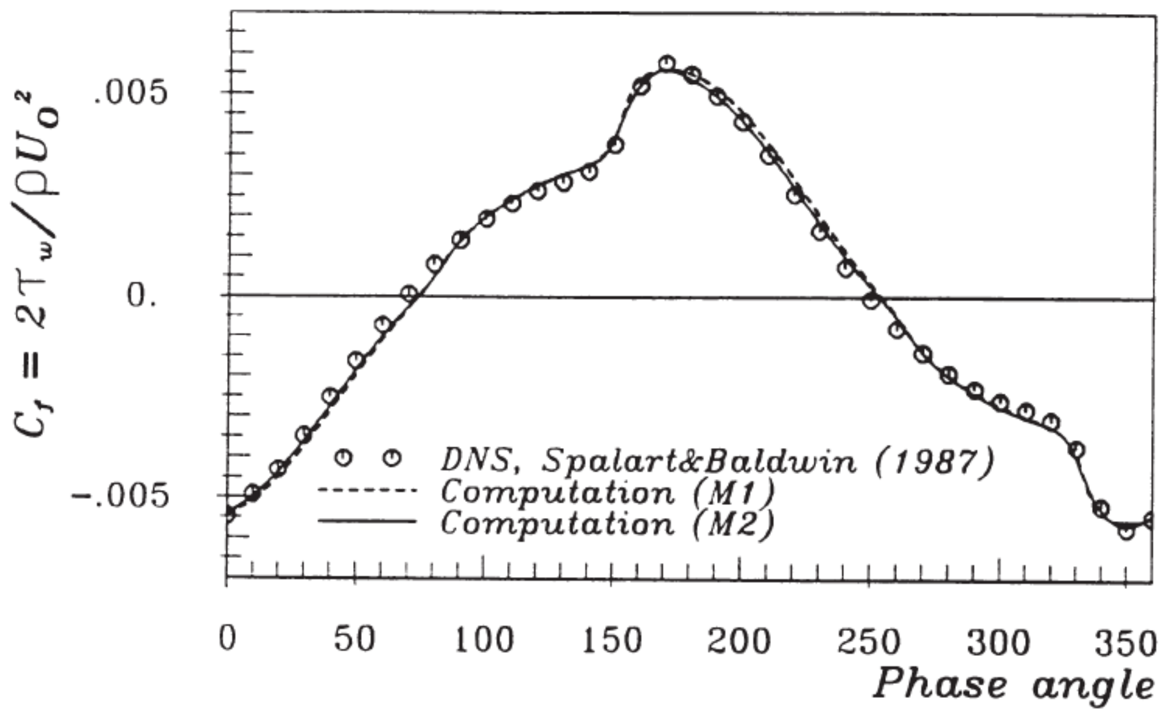
- DNS of turbulent boundary layer provided budgets for Reynolds stresses
- <u'v'> is dominant, and pressure redistribution opposes production
- SA model mimics this with "wall term"
  - Actually, combined with diffusion term
  - Already in Secundov model of the 1970's





DNS as Reference for Validation

- Hanjalić, Jakirlić and Hadzić 1993 Reynolds-Stress Model
  - Oscillating boundary layer: $U_e = U_0 \cos(\omega t)$
  - Excellent comparison with DNS, even for flow with laminarescent phase



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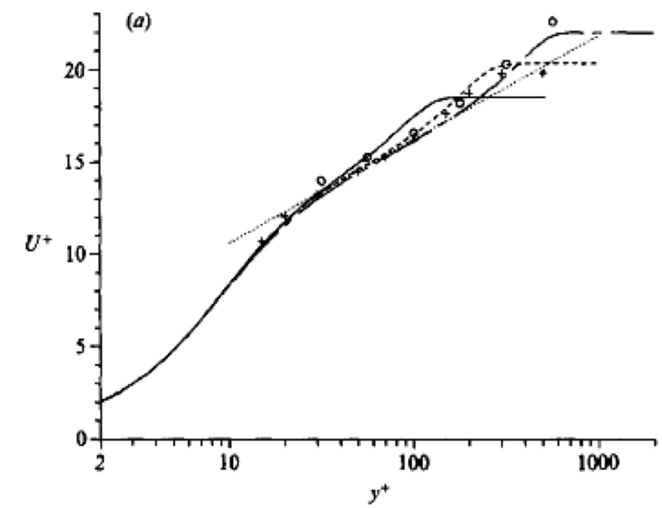
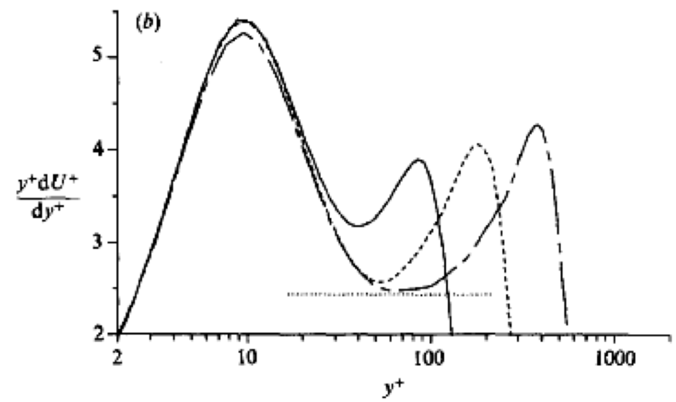
Log Law and Karman Constant

- Early channel and boundary-layer (TBL) DNS had the excuse of "low-Reynolds-number effects"
  - In particular, confirming the log layer and precise value of κ was premature
- Channel Re_τ has risen from 180 to over 5000… and κ is still not found!
  - This is with the "honest" approach of plotting $dU^+/d(\log y^+)$
- Experiments also have conflict between pipe flow ($\kappa \sim 0.42$) and TBL ($\kappa \sim 0.385$)
- Some people suggest κ is flow-dependent!
  - This would mean the theory fails

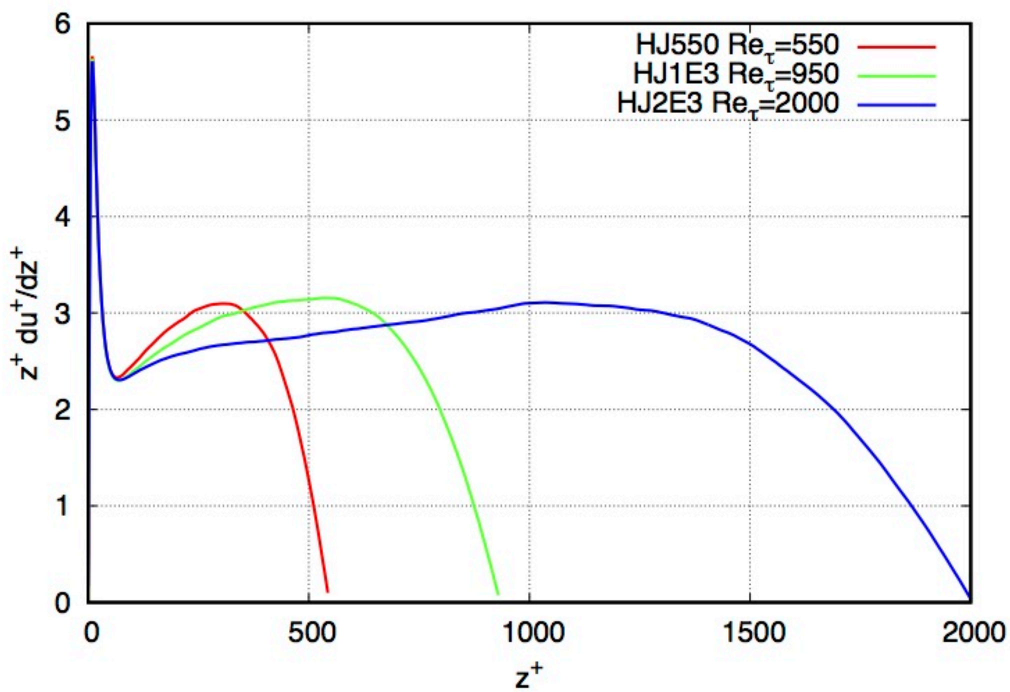


DNS of TBL in 1988 JFM



Effect of Reynolds-Number

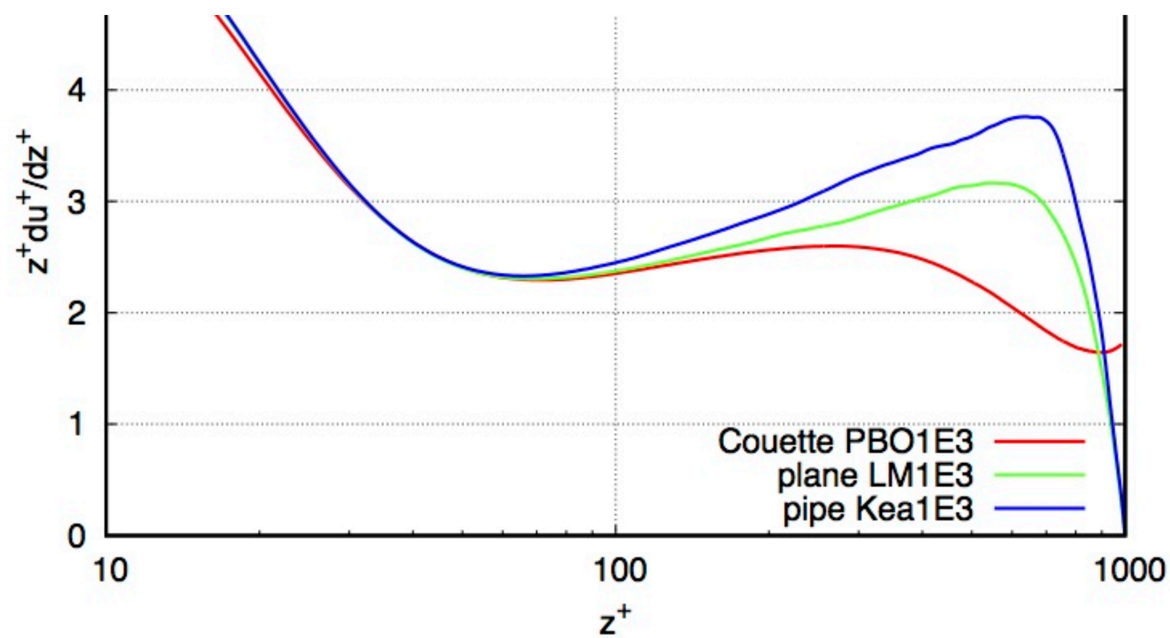
- Channel results of Hoyas and Jimenez up to 2000, rendered by Luchini
- Showing $dU^+ / d(\log y^+)$, which should be $1/\kappa$ (around 2.5)



- There is no plateau, and even the local maxima are much too high

Effect of Flow Type: Pipe, Poiseuille, Couette

- The three flows are “justified” to disagree in the core region
- At z+ = 100 (out of Re_τ = 2000), the disagreement is already palpable
- None of the flows have a plateau anyway



Luchini's Theory

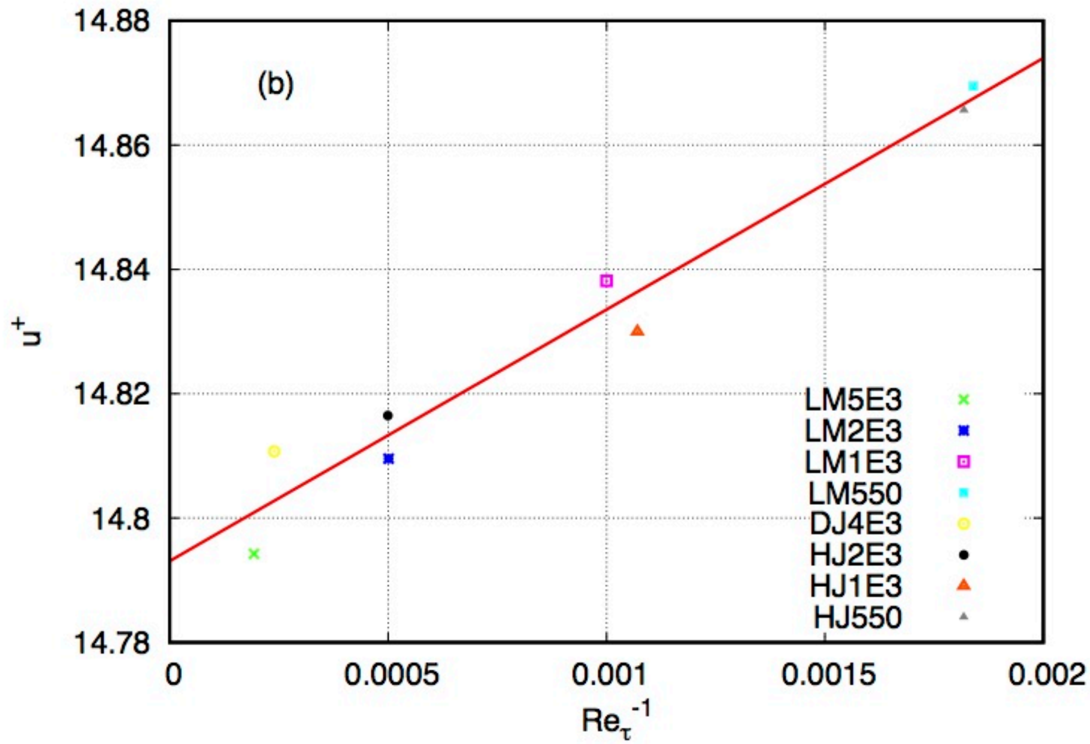
- Luchini in 2017 and 2018 papers proposes a unified correction of velocity profile for pipe, Poiseuille (channel) and Couette flow
  - He extrapolates from two Re values to ∞ in mathematical fashion
  - He adds a linear function of y^+ to U^+:

$$U^+ = U_0^+(y^+) + A_1\,(dp/dx)^+\,y^+$$

  - In channel, $(dp/dx)^+ = 1 / Re_\tau$
- It's empirical, but considerably improves consistency between the three flows and across Reynolds numbers, using only ONE constant, A_1
- My issue: I normally exclude pressure gradient from models and theory
  - Pressure does not influence vorticity
  - Ongoing discussions with Luchini
  - In steady flows, $\partial p / \partial x_i = \partial \tau_{ij} / \partial x_j$, the "turbulence force," so that we can return to the stresses

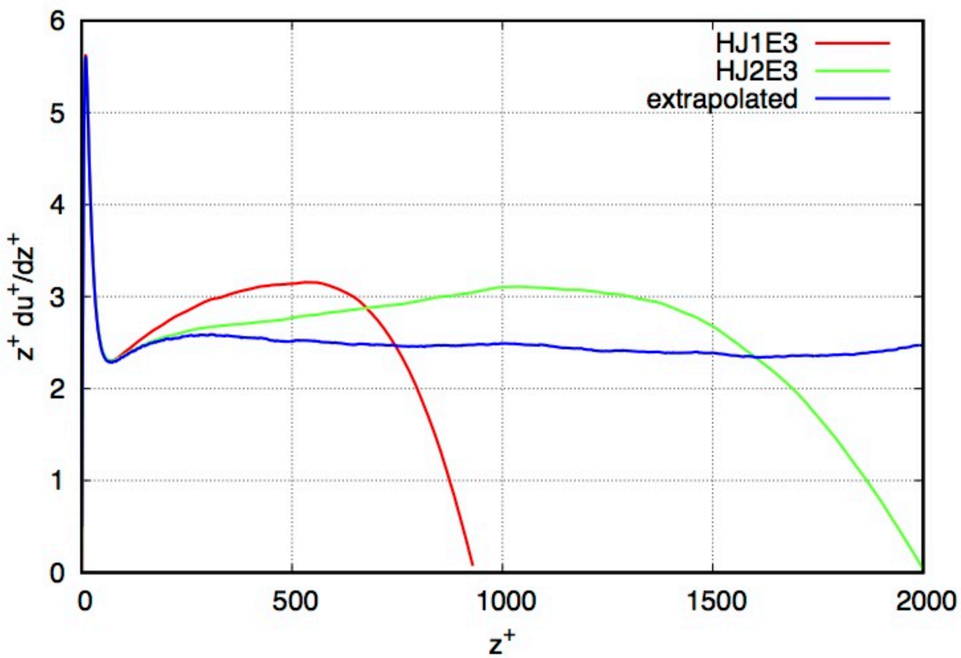
Luchini's Theory

- Shows U^+ at $y^+ = 50$
- DNS evidence for a linear dependence on $(dp/dx)^+ = 1 / Re_\tau$ in channel flow
- This is a conjecture!



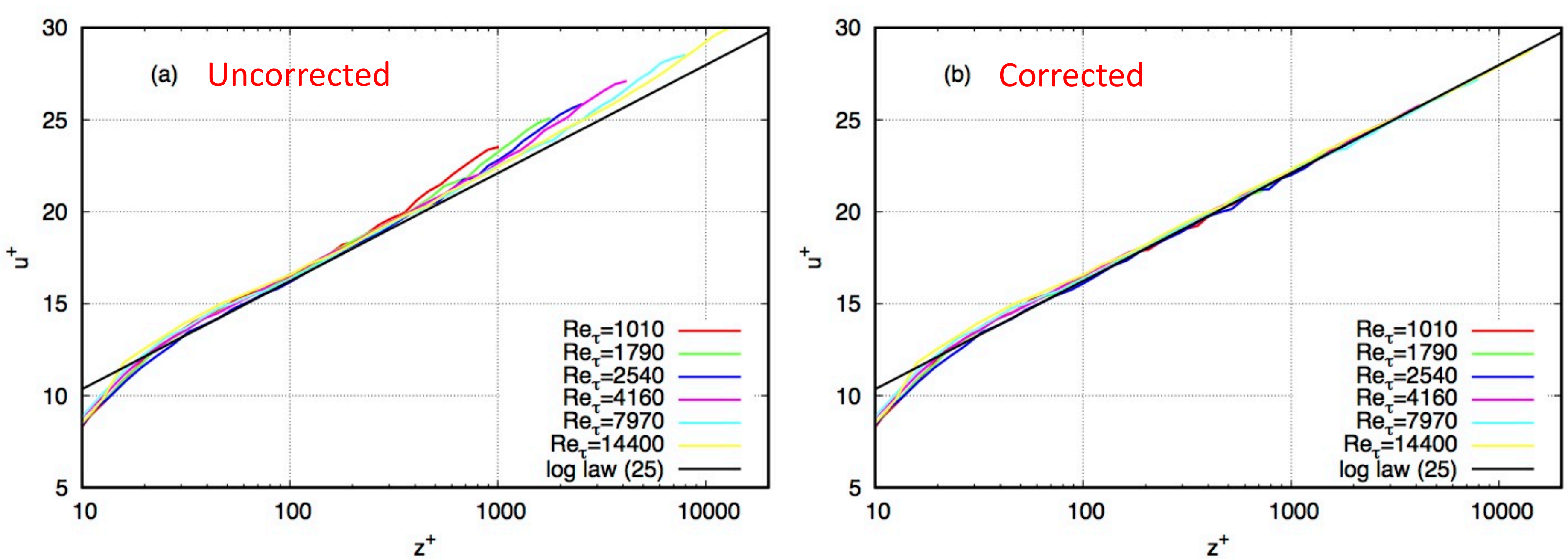
Extrapolation in Channel from Re_τ = 1000/2000 to ∞

- Removal of "wake component" is rigorous
- The curve is considerably closer to a plateau
- It's still not flat enough to really determine κ, say better than 10%



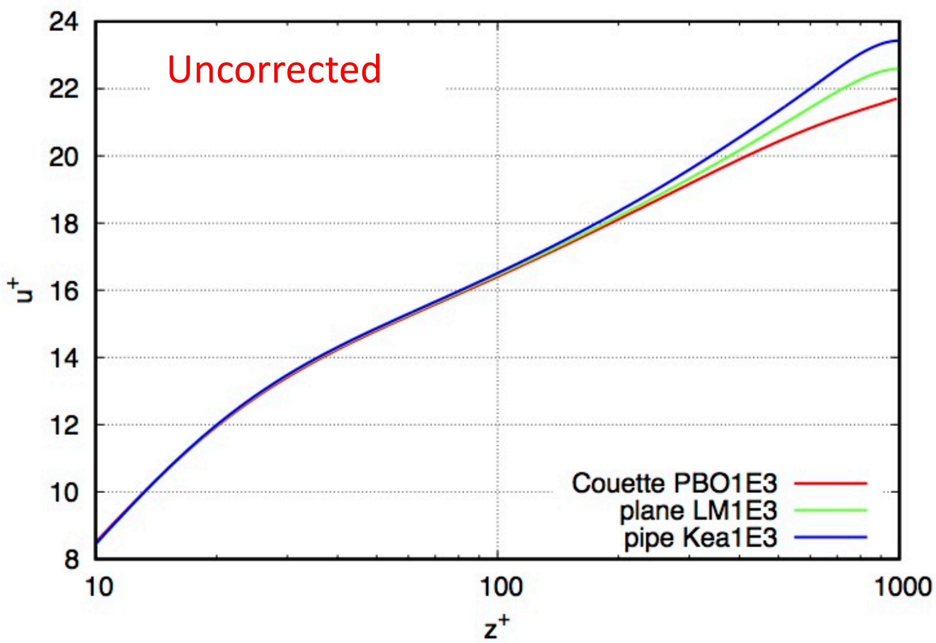
Pipe Flow

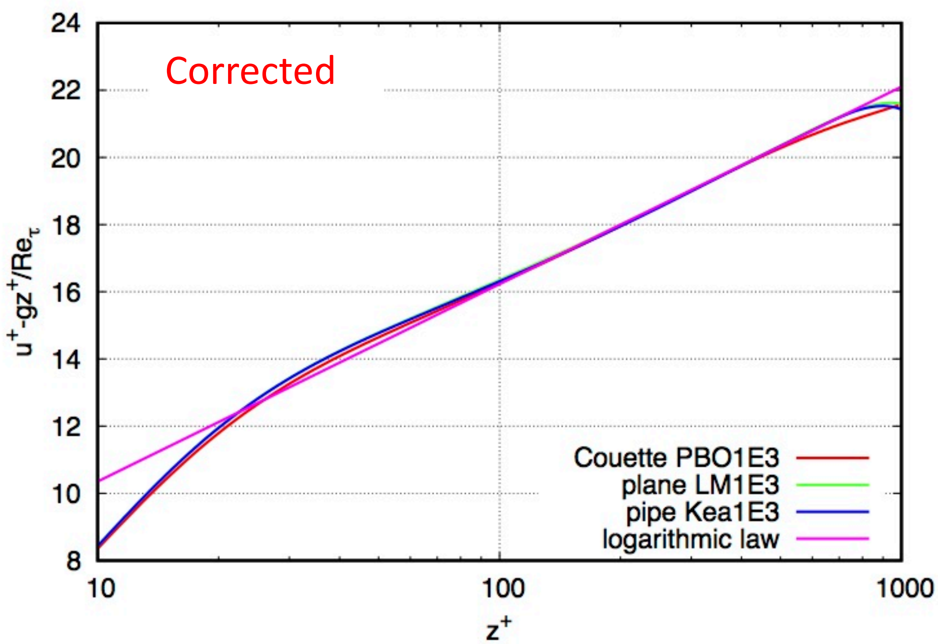
- Superpipe velocity profiles (McKeon, Hultmark, Smits) with Luchini correction



Luchini Correction, $Re_\tau = 1000$

- The three flows are essentially unified in U^+ terms
- His best estimate for κ is 0.392





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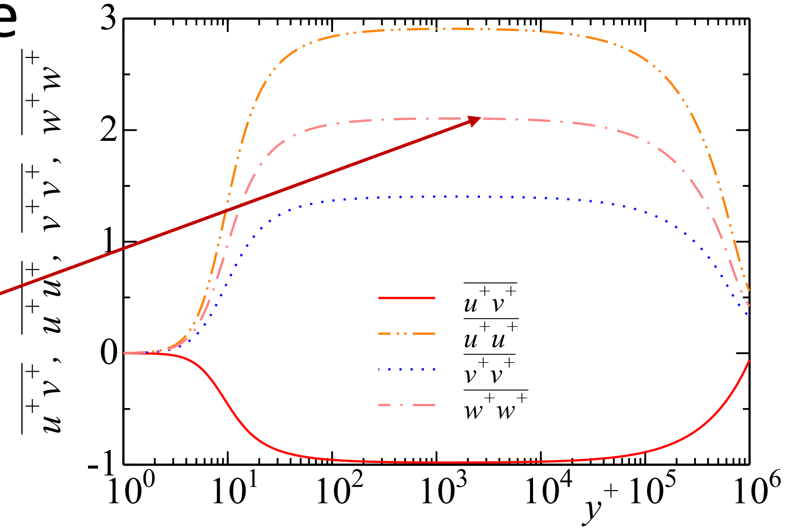
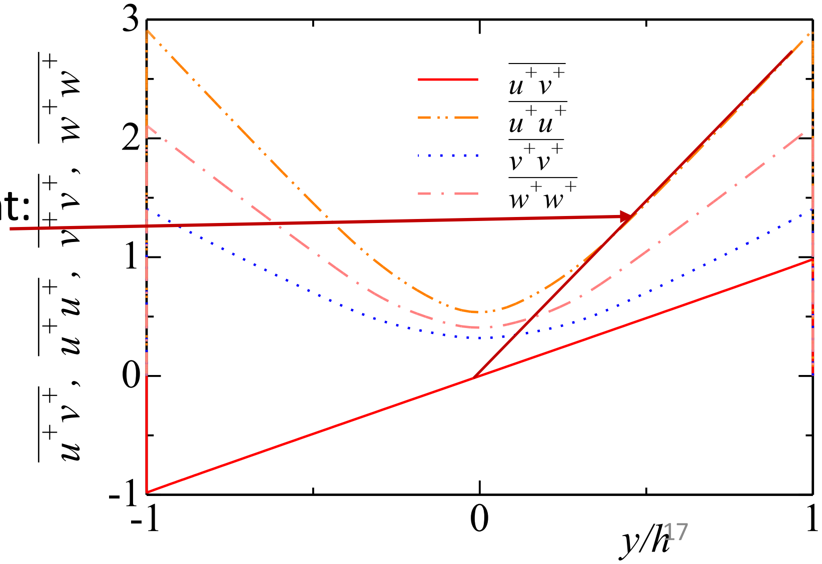
Reynolds Stresses in Channel Flow at High Re

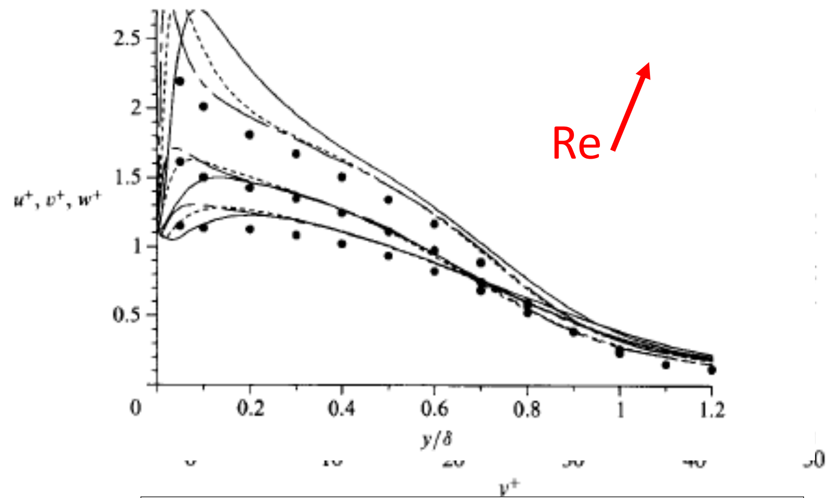
- Work of Rumsey, posted on Turbulence Modeling Resource
- RSM at very high $Re_\tau = 10^6$ (two-equation models do the same, $k^+ = 1 / \sqrt{C_\mu}$)
- 1) In region with $\tau^+ = 1$, all Reynolds stresses are constant, which "theory" would have predicted
  - $d\,\tau_{ij} / d\,y = 0$
- Model is purely driven by $\partial U / \partial y$, which obeys the Law of the Wall. u_τ controls all stresses
- This conflicts with DNS and experiment
  - Plateaus on the stresses in high-Re pipe experiments are still controversial
- 2) Except in center region, anisotropy of tensor is constant: all stresses are proportional to |y|, like |shear stress|
  - $d\,a_{ij} / d\,y = 0$
  - This may allow an analytical solution, but is not Real Life
- Model is here driven by $\partial U / \partial y$, which obeys the Law of the Wake. u_τ, combined with y, again controls stresses!

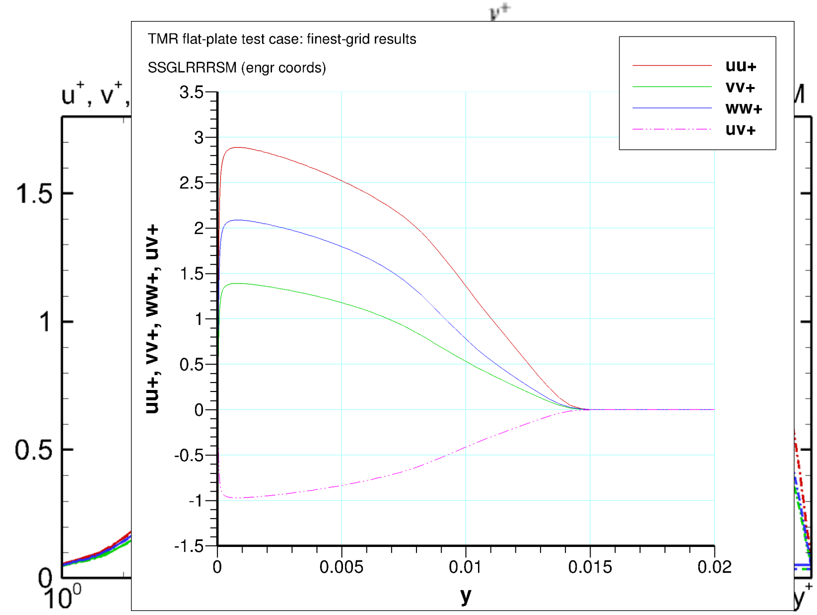




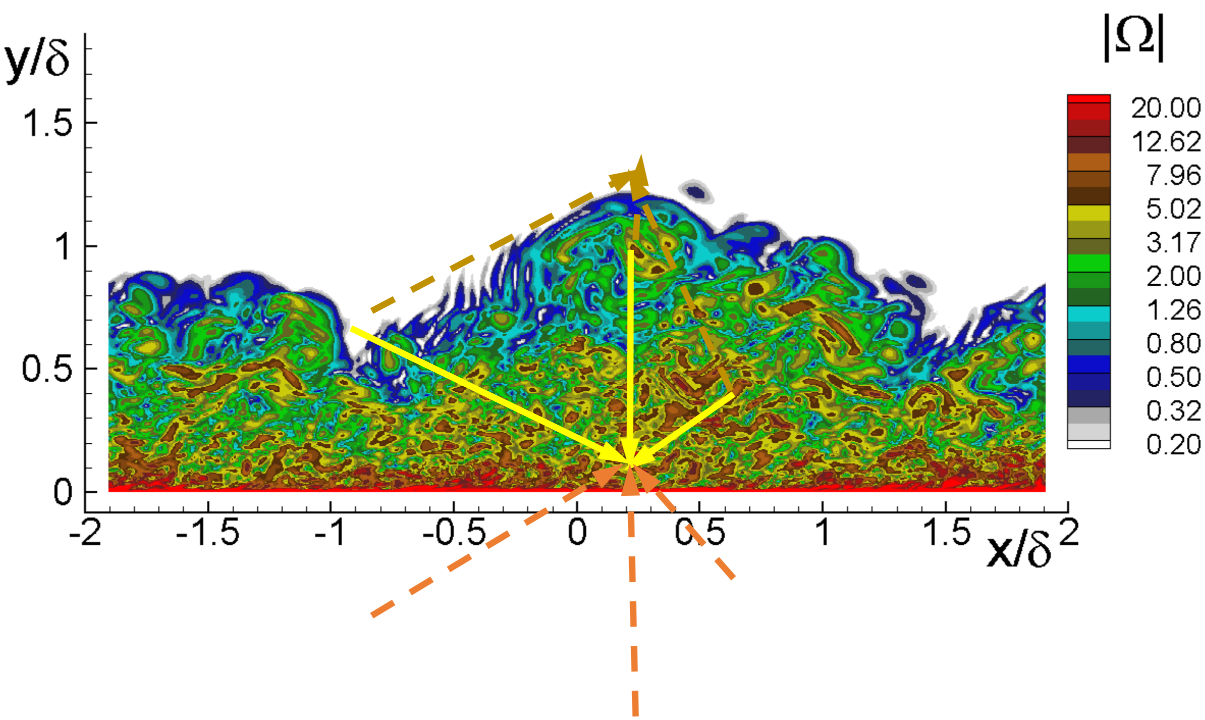
Reynolds Stresses Near Wall, Re Effect

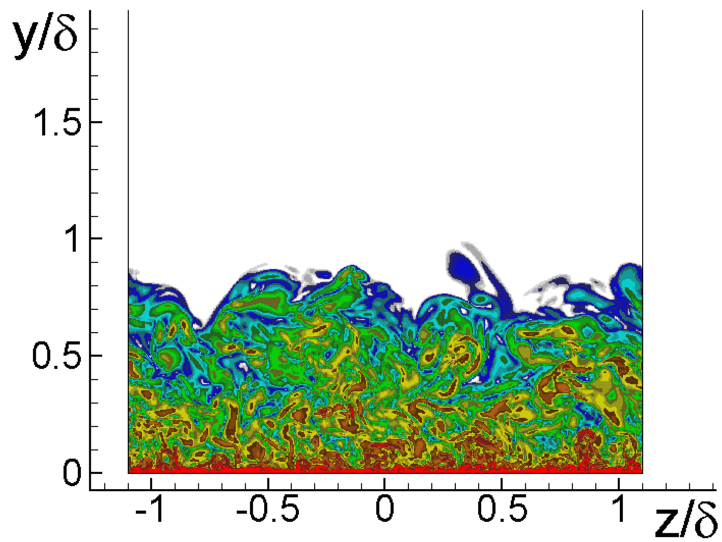
- Old TBL DNS data: 1988!
- Again, the model is driven by $\partial U^+/ \partial y^+$, which very closely obeys the Law of the Wall
- DNS shows a Reynolds-number effect all the way to the wa The slope of w'^+ is especially sensitive
- Wall values such as ε^+ or $p_{rms}{}^+$ are definitely not constant in the DNS Re range
- The Reynolds-Stress Model fails to predict any similar Reynolds-number dependence
  - Or even the near-wall peaks (except for Manceau models)
- DNS trend arguably related to “Inactive Motion”
  - Motion with wall—parallel scales >> y
  - See Bradshaw, JFM 1967, `Inactive motion and pressure fluctuations in TBL’ and Townsend
  - And thinking of Saffman, Wilcox, and Durbin (-> v2f)
- Linear one-eq. models, by chance, avoid this issue
  - QCR does not
- At interface with clean fluid, stresses reach 0 together





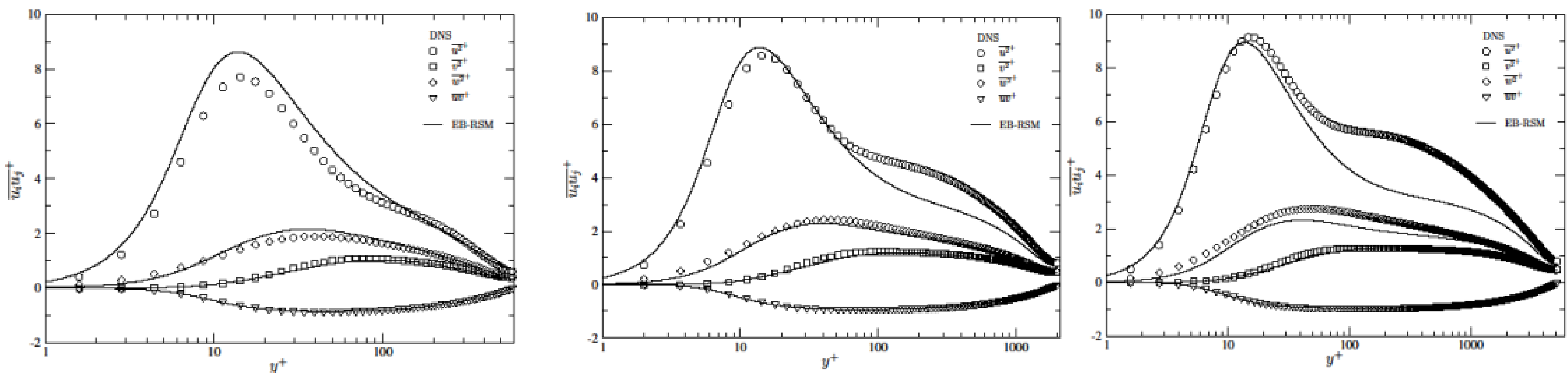
Interactions at a Distance





Manceau's 2015 Elliptic-Blending Reynolds-Stress Model

- Related to work of Manceau & Hanjalić, 2002 and Lardeau & Manceau, 2014
  - Model has 7 + 1 equations
- Compare with channel DNS at Re_τ = 590, 2000, 5200
- Model has much better near-wall peaks than LRR
  - It uses the wall-normal vector **n**
  - Blending function is $f(y^+)$
- Response to Reynolds number is the same as for the other conventional models
  - It is expected the stresses will develop plateaus at higher Re_τ



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Contributions to Complex Models

- DNS normally provides all terms in any budget that is desired
- In theory, we make each term (e.g., pressure-strain and dissipation tensors) play the correct role
  - DNS then opens a new door, relative to experiments
- In reality, we live with compensating errors
  - Example: modeling the dissipation tensor as isotropic
- The modeled budget of the highest moment of turbulence is empirical
  - "Reynolds-Stress Models have more truth in them, and more lies" (anonymous…)
  - The data do not separate "rapid" and "slow" pressure terms
  - Some models use wall distance or wall-normal vector, which are not in the equations
- Another issue is that the true budget of dissipation (ε, or even ε_{ij}) is dominated by small eddies, but real models are dominated by large-eddy quantities (and mean-flow gradients)
  - Richardson-Kolmogorov energy-cascade arguments are effective, but imperfect
  - This was known in 1975

Attempts to Concretely Steer Simple Models

- DNS provides accurate k and ε. Ergo, we can make a better k-ε model!
- This would be true if the equation

$$\nu_t = \frac{C_\mu \quad k^2}{\epsilon}$$

were exact

- In reality, in a log layer the k-ε model gives a correct $\varepsilon^+=1/(\kappa y^+)$, an erroneous $k^+=1 / \sqrt{C_\mu}$, an erroneous C_μ, and a correct ν_t!

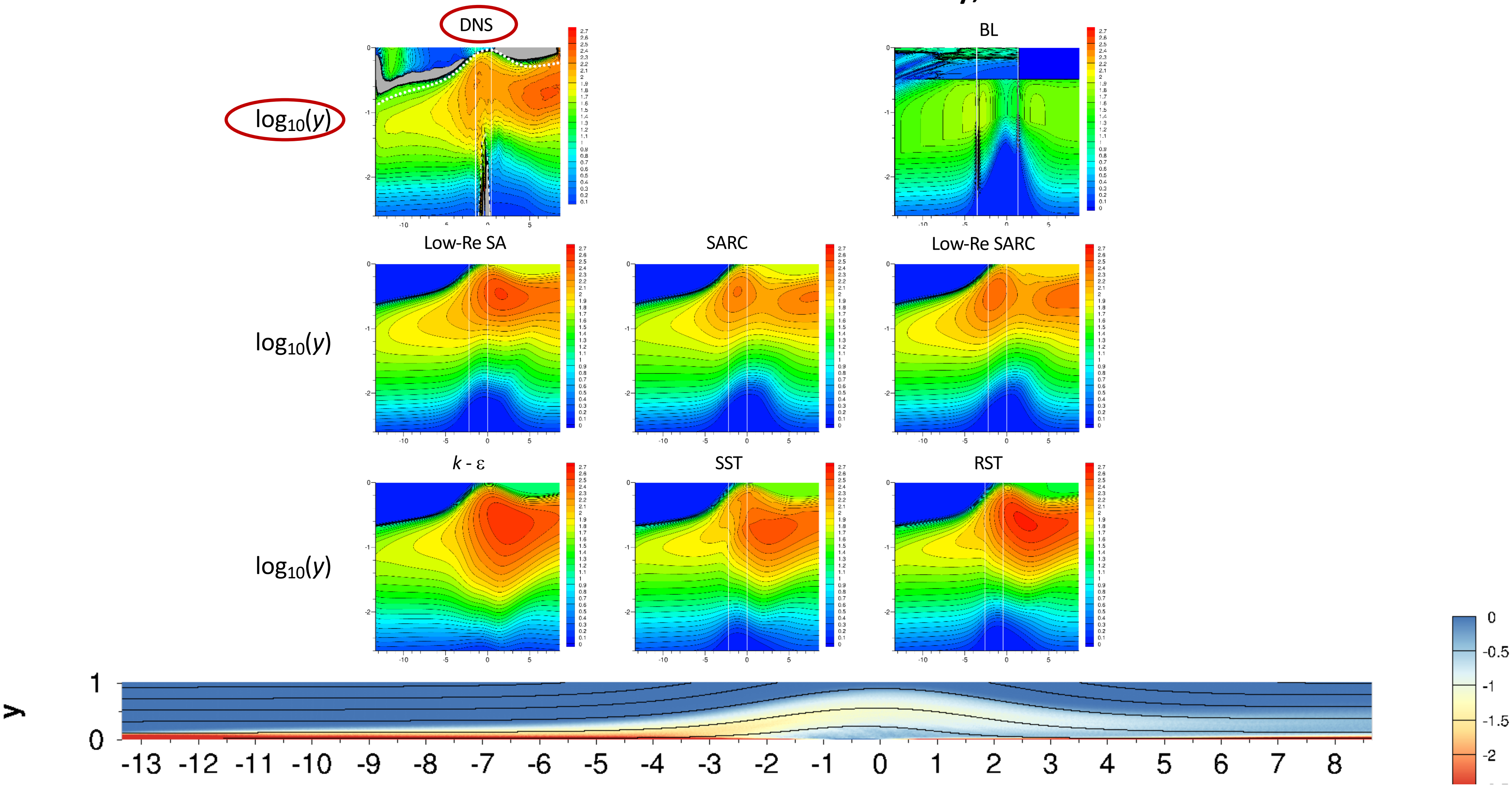
Attempts to Concretely Steer Simple Models

- Define effective eddy viscosity

$$\nu_{t_{eff}} \equiv -\frac{S_{ij} < u_i u_j >}{2 S_{kl} S_{kl}}$$

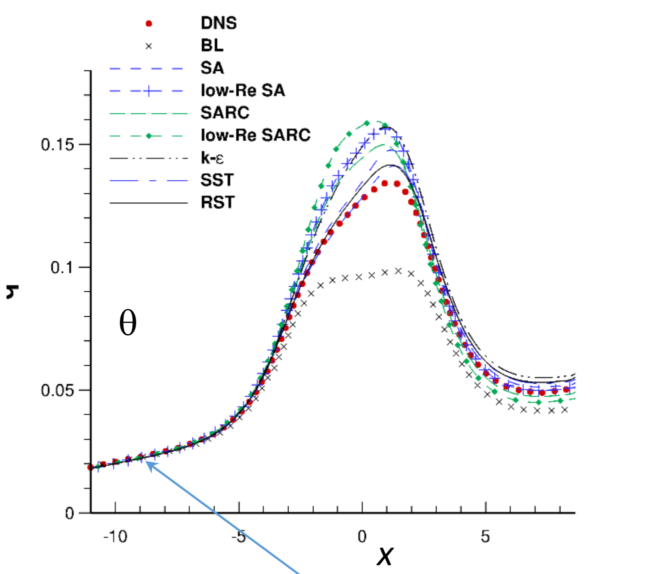
- This can be seen as a least-squares fit of a scalar to the stress tensor, or as the eddy viscosity that would give the correct TKE production
- This gives us a *local* target when working on eddy-viscosity models
- The results to date are mixed: the mean-flow improvement from an improved eddy viscosity is not reliable
  - There is a “norm problem.” Thin regions, especially near the wall, may over-ride much larger regions (point made by P. Durbin)
- The turbulence equations may be solved in the “frozen DNS flow field”
- This concept is in our “tool box,” and we may find fruitful uses for it

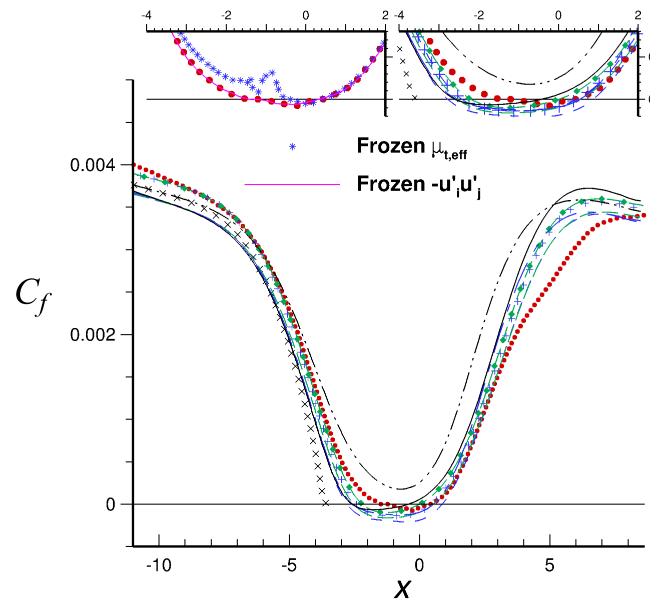
Compare Models and DNS in Separation Bubble
Work with Coleman and Rumsey, in JFM



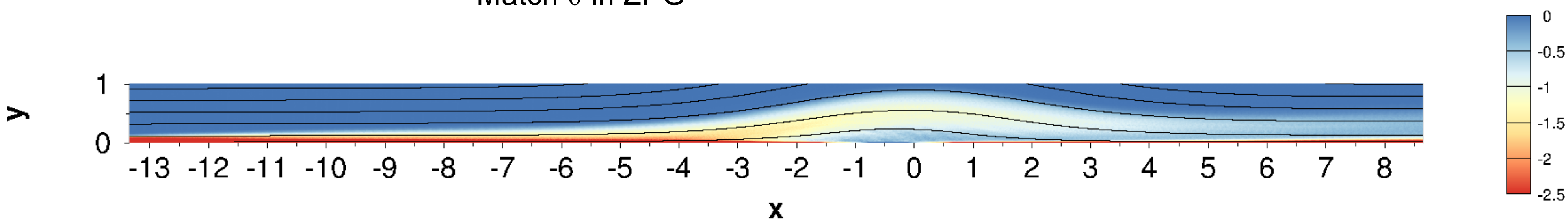
Compare Models and DNS in Separation Bubble

RANS Solutions via CFL3D, using DNS as inflow BC





Match θ in ZPG



Summary and Future

- Since the 1980's, Direct Numerical Simulation has made great progress
  - Reynolds number: Channel Re_τ from 180 to 5000, cylinder Re_D from 3900 to 6 10^5
  - Geometric complexity: from channel to TBL, cylinders, golf balls, high Mach numbers, separation bubbles including shock-induced
- Yet, its impact on everyday turbulence models is still almost invisible
  - One key factor is the empirical nature of these models
  - Even the Reynolds-Stress models suffer from compensating errors
  - Another factor is the probable "structural" inability of RANS models to track DNS (i.e., reality!) for the y- and Re-dependence of the Reynolds stresses, + the laminar interface
  - This is not exactly the same as the "Fundamental Paradox" (e.g. circular-cylinder flow)
  - Danger Machine Learning will spend much of its capital in futile efforts against these conflicts
- It's not that the DNS and RANS communities ignore each other
- The value of RANS to society justifies sustained efforts
  - Breakthroughs are not likely
  - Artificial Intelligence might help
  - It is very hard, for me, to develop new RANS modelers