

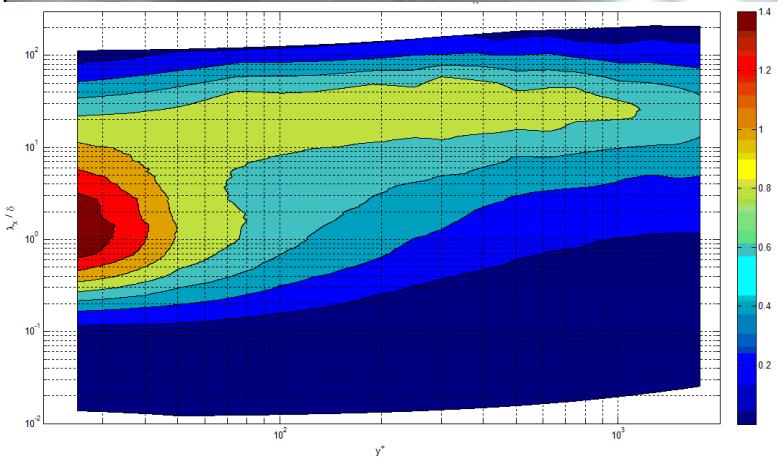
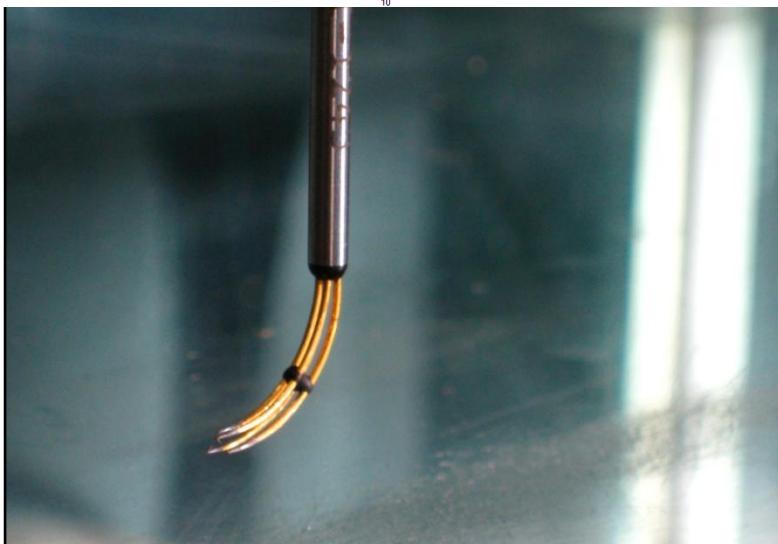
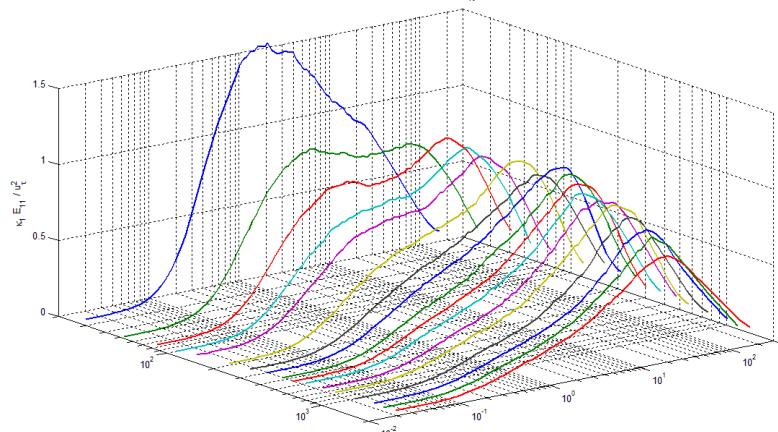


Effects of large-scale free stream turbulence on a turbulent boundary layer

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Cornell University

Presented in partial completion of the
requirements for the degree of Master of
Science in Aerospace Engineering

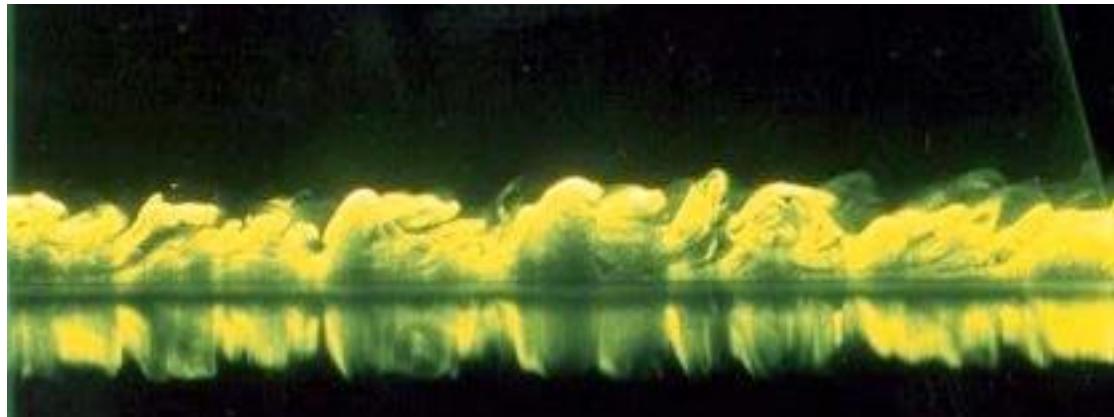
6 February 2009



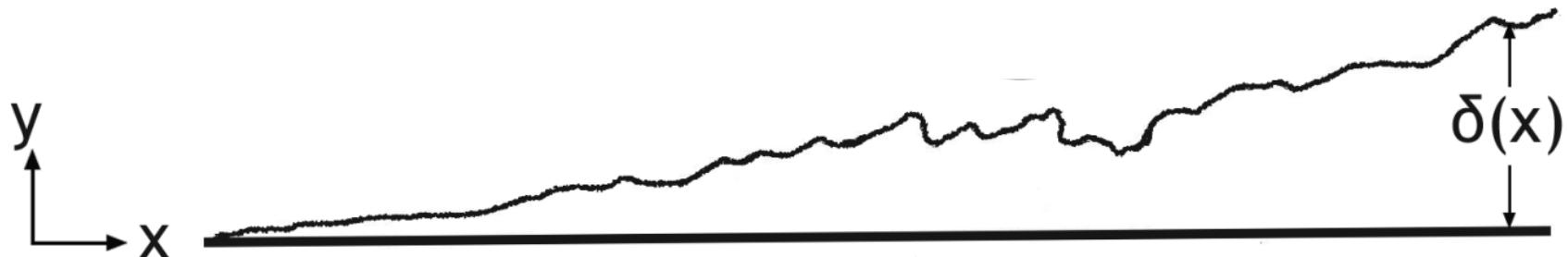


Introduction

The turbulent
boundary layer



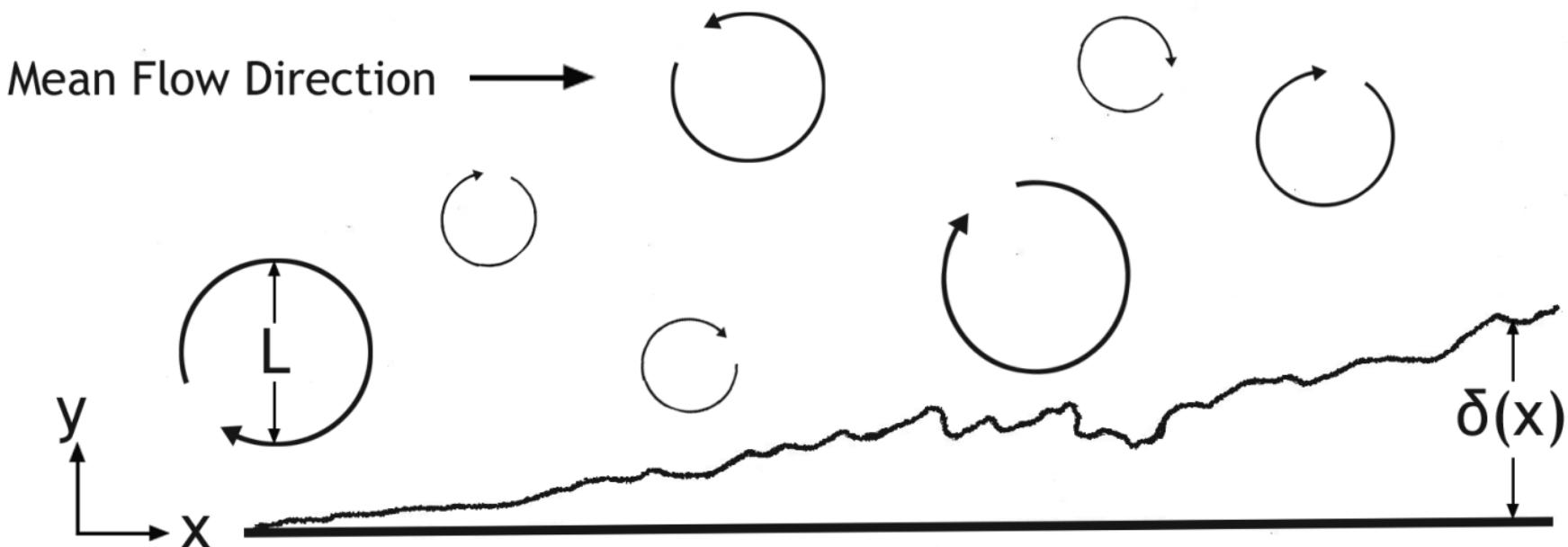
Mean Flow Direction →





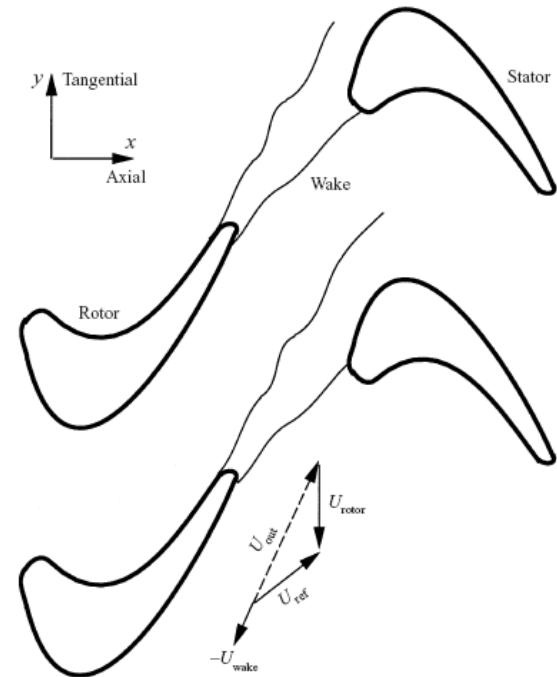
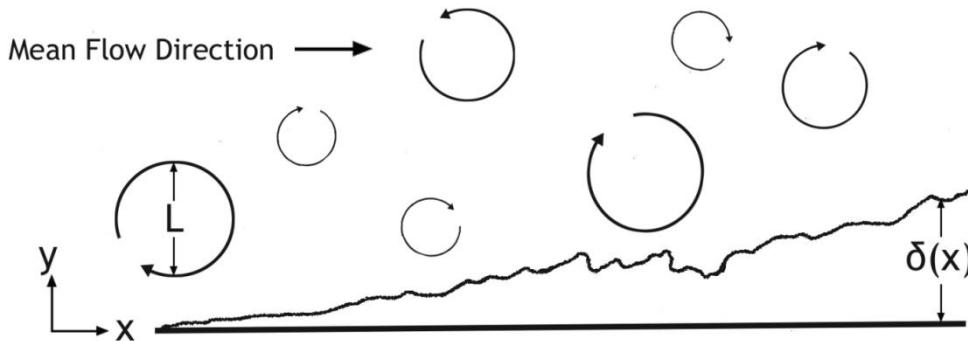
Introduction

L/δ = ratio of free stream lengthscale to boundary layer depth
FSTI = free stream turbulence intensity = $(\langle u^2 \rangle^{1/2} / U)_0$





Introduction





Previous Work

Hancock and Bradshaw (1983, 1989)

- Intensities < 6%
- $Re_\theta > 2,000$
- Studied
 - Mean flow characteristics
 - Variances
 - Conditional averaging
- Correlated some variables using an empirically determined parameter, β

$$\beta = \frac{\langle u^2 \rangle^{1/2}}{\frac{U}{L_e} + 2} \quad L_e^u = - \frac{\langle u^2 \rangle^{3/2}}{U_0 \frac{d \langle u^2 \rangle}{dx}}$$



P. E. Hancock and P. Bradshaw, "The effect of free-stream turbulence on turbulent boundary layers," *J. Fluids Eng.* **105**, 1983.

P. E. Hancock and P. Bradshaw, "Turbulence structure of a boundary layer beneath a turbulent free stream," *JFM*, **205**, 1989.

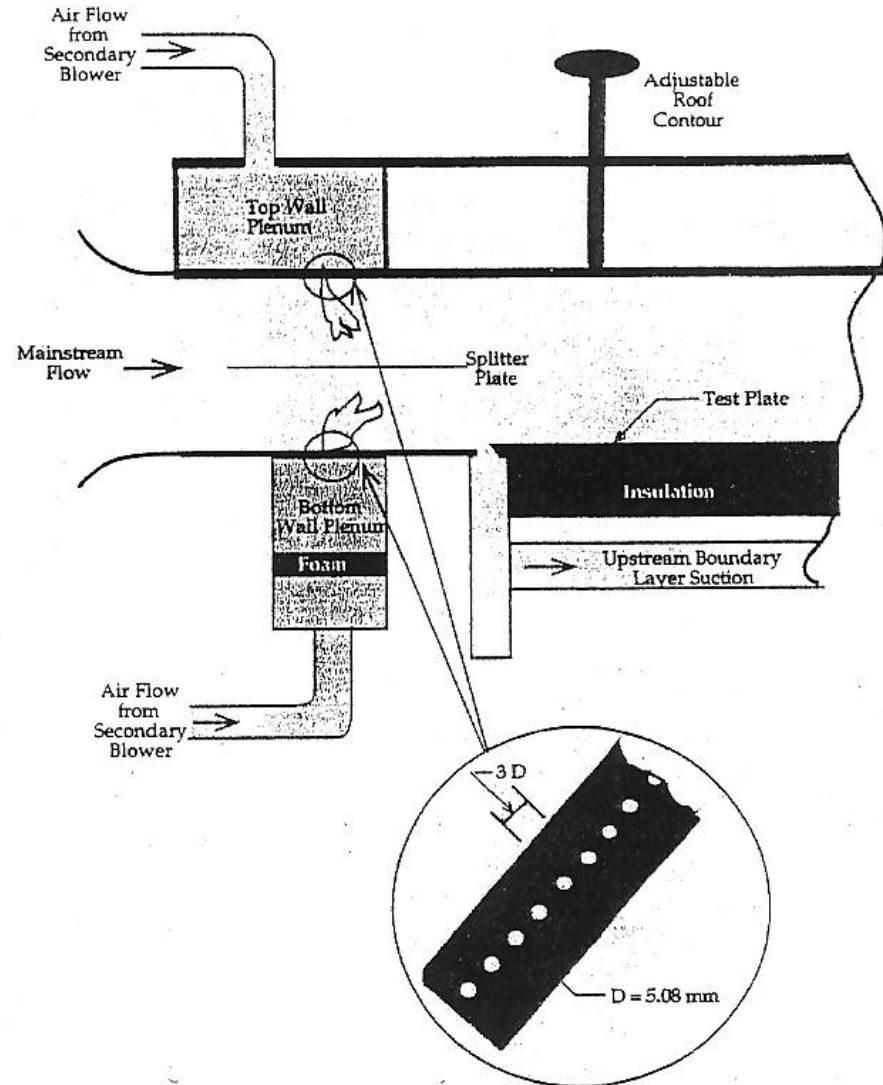


Previous Work

Thole and Bogard (1996)

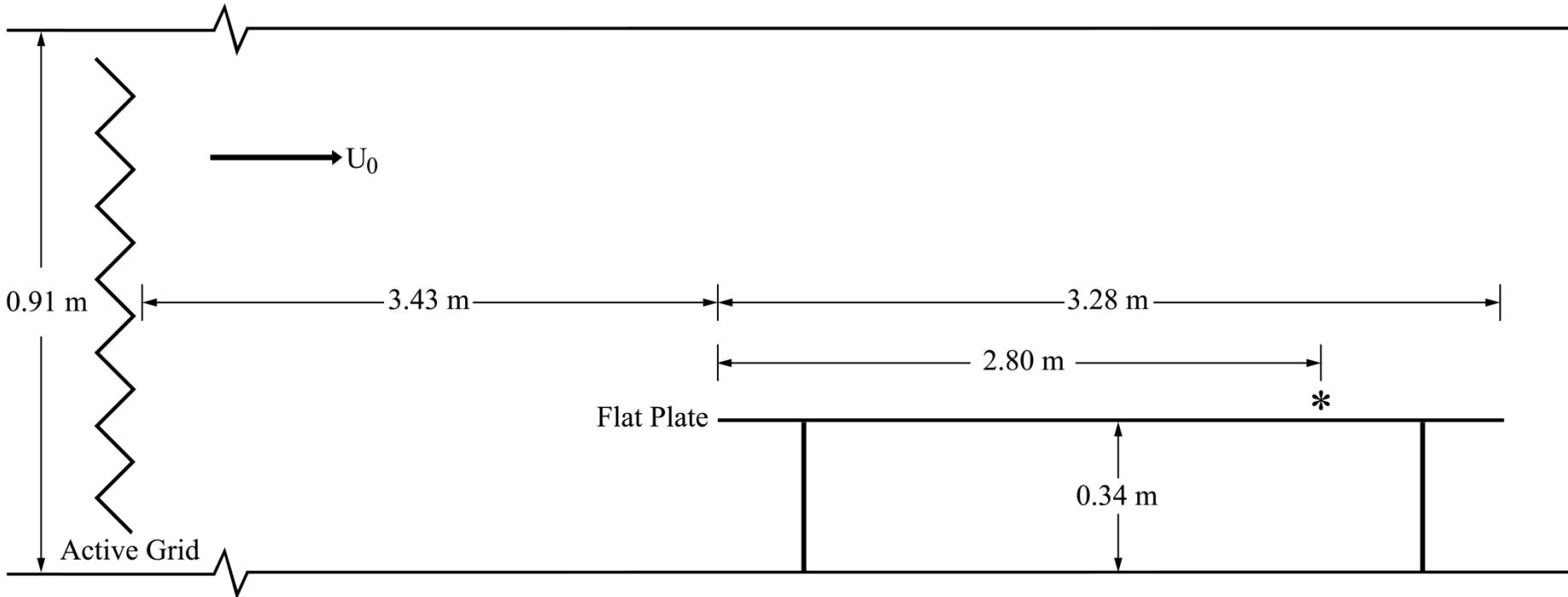
- Intensities < 20%
- $Re_\theta \sim 600$
- Studied
 - Mean flow characteristics
 - Variances
 - Cross-correlation
 - Length scales
 - Spectra
- Found integral length scales at free stream values until $y/\delta \sim 0.3$

K. A. Thole and D. G. Bogard, "High free stream turbulence effects on turbulent boundary layers," *J. Fluids Eng.*, 118, 1996.





Experimental Set-Up



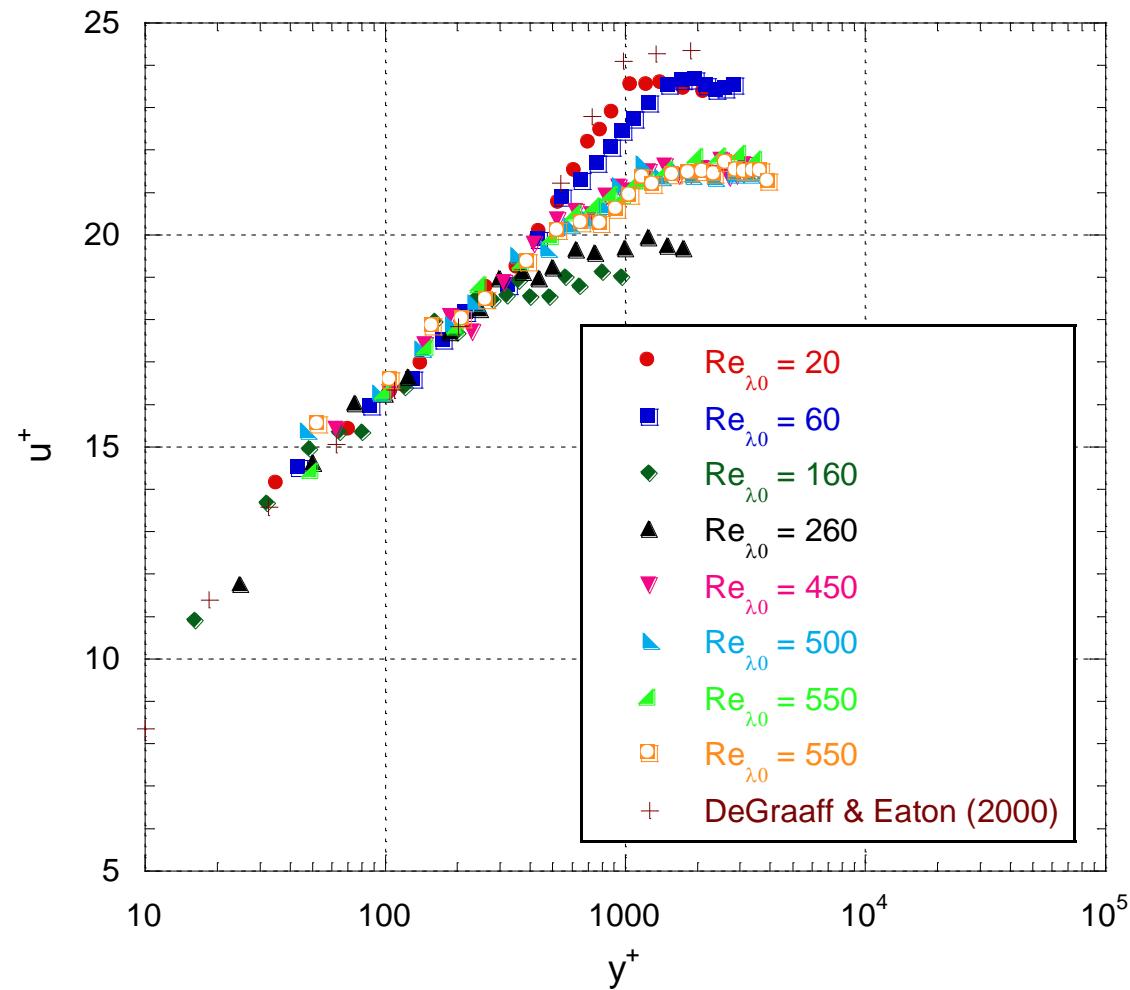
Active grid introduces
large-scale turbulent
eddies
→ higher $Re_{\lambda 0}$

Plate is 30M
downstream to allow
development of FST



Results

Law of the Wall



8 Cases

$$20 < Re_{\lambda_0} < 550$$

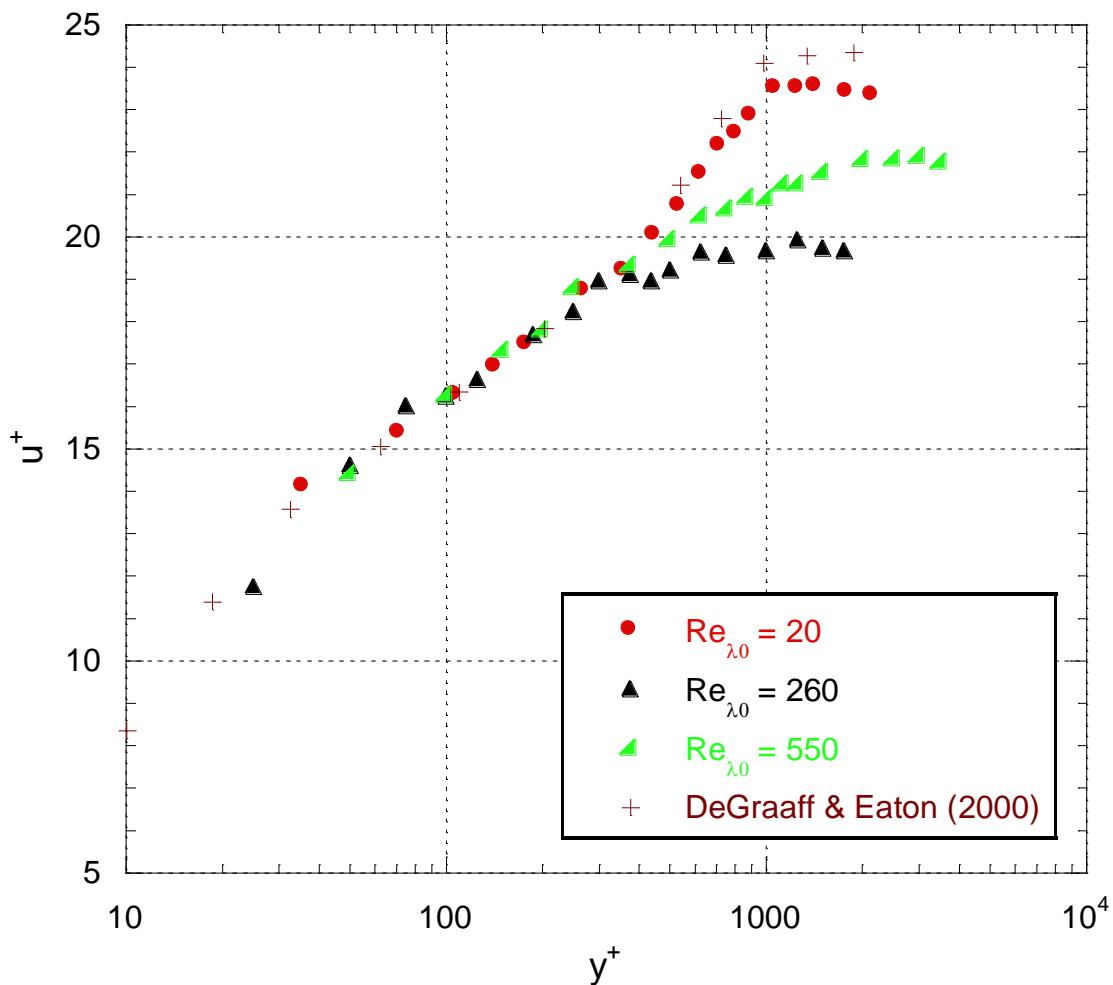
$$0.25\% < FSTI < 10.5\%$$

$$550 < Re_{\theta} < 2840$$



Results

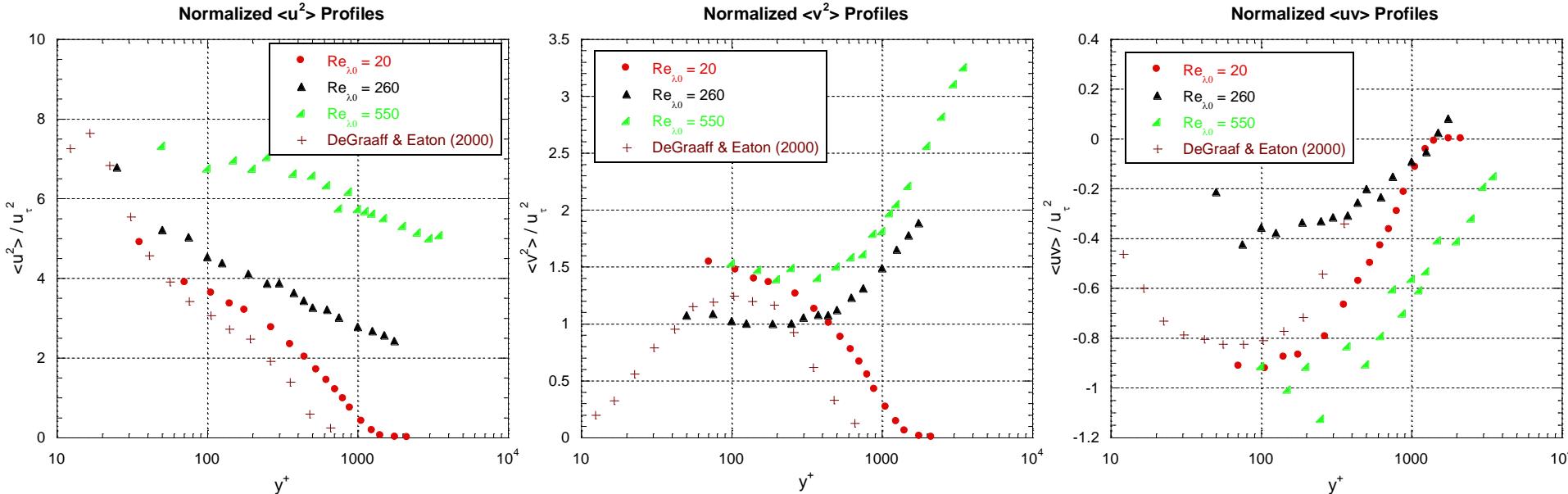
Law of the Wall



Re_{λ_0}	20	260	550
U_0 (m/s)	6.25	3.70	8.15
FSTI	0.25%	8.0%	10.2%
Re_θ	2460	775	1980
Re_τ	1245	915	2020
Grid	none	active, off	active, on



Velocity Variances

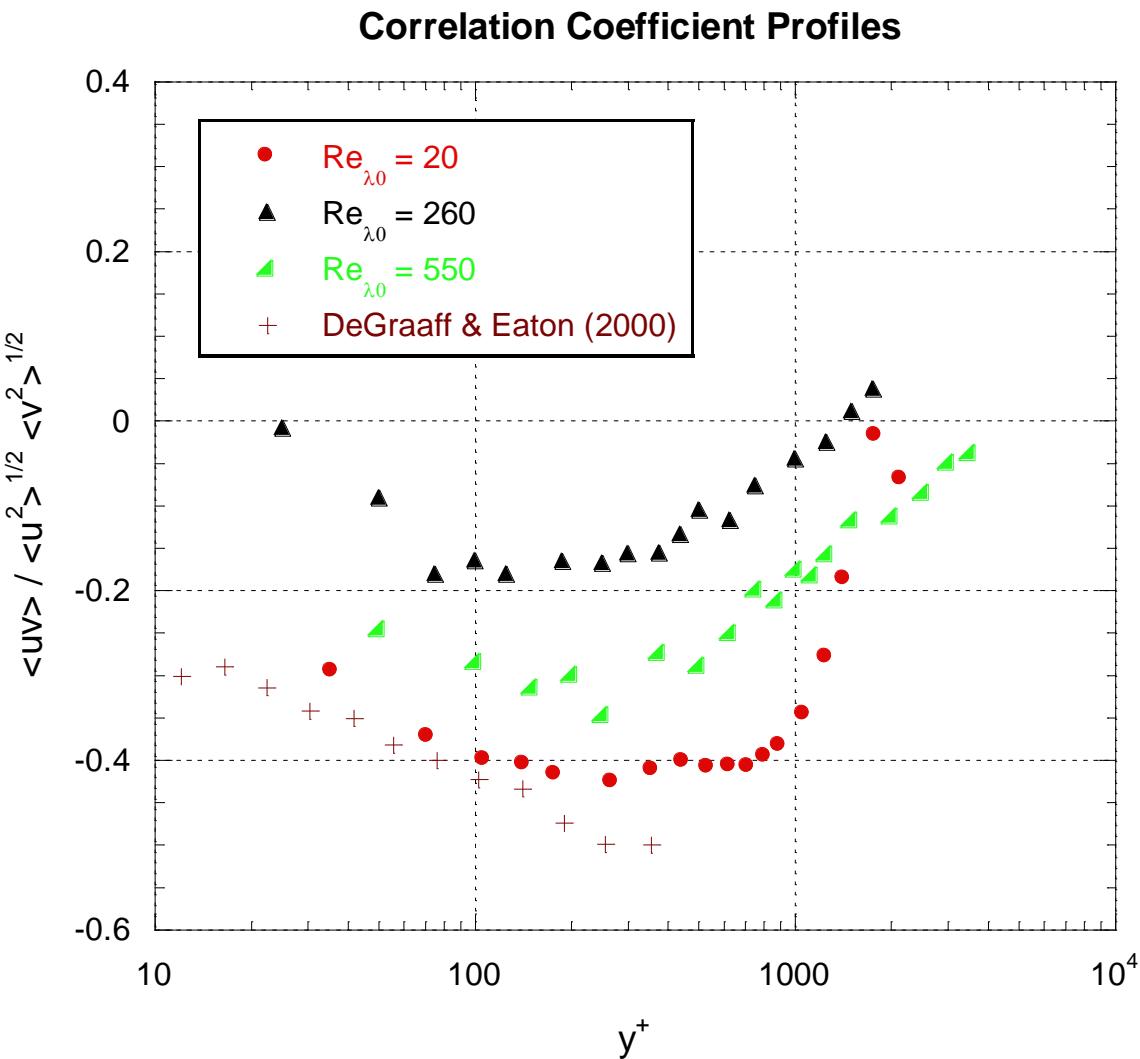


- Velocity variances and covariance show trends in agreement with previous investigations.

D. B. DeGraaff and J. K. Eaton, “Reynolds-number scaling of the flat-plate turbulent boundary layer,” *J. Fluid Mech.* **422**, 2000.



Cross-Correlation



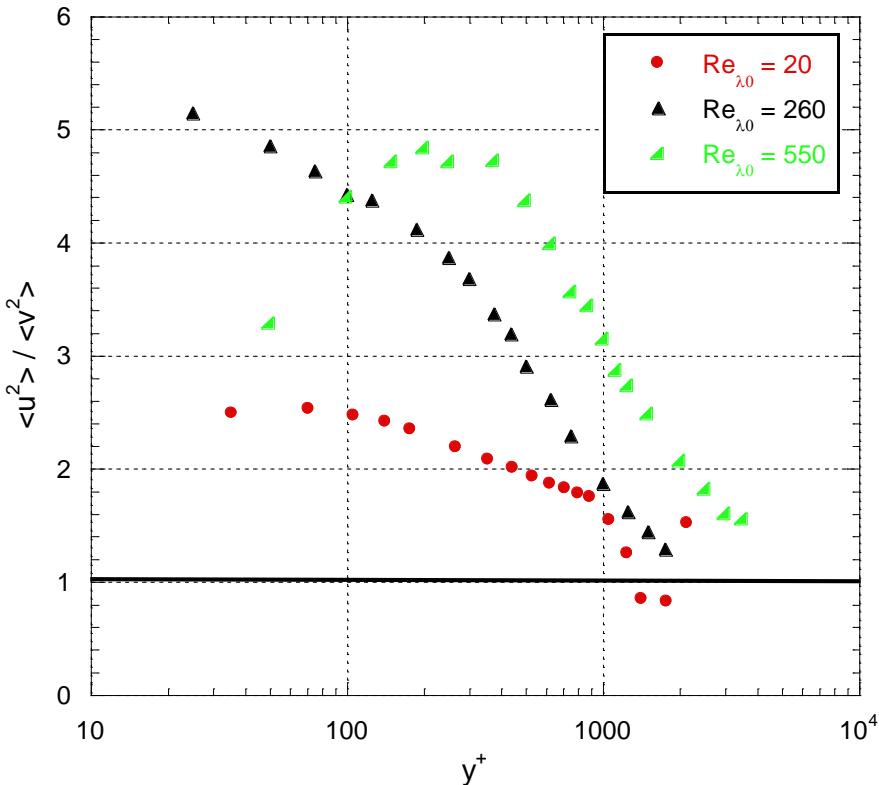
- Penetration of uncorrelated u - and v -components of FST decreases the cross-correlation coefficient throughout the boundary layer.

D. B. DeGraaff and J. K. Eaton,
“Reynolds-number scaling of the flat-plate turbulent boundary layer,” *J. Fluid Mech.* **422**, 2000.

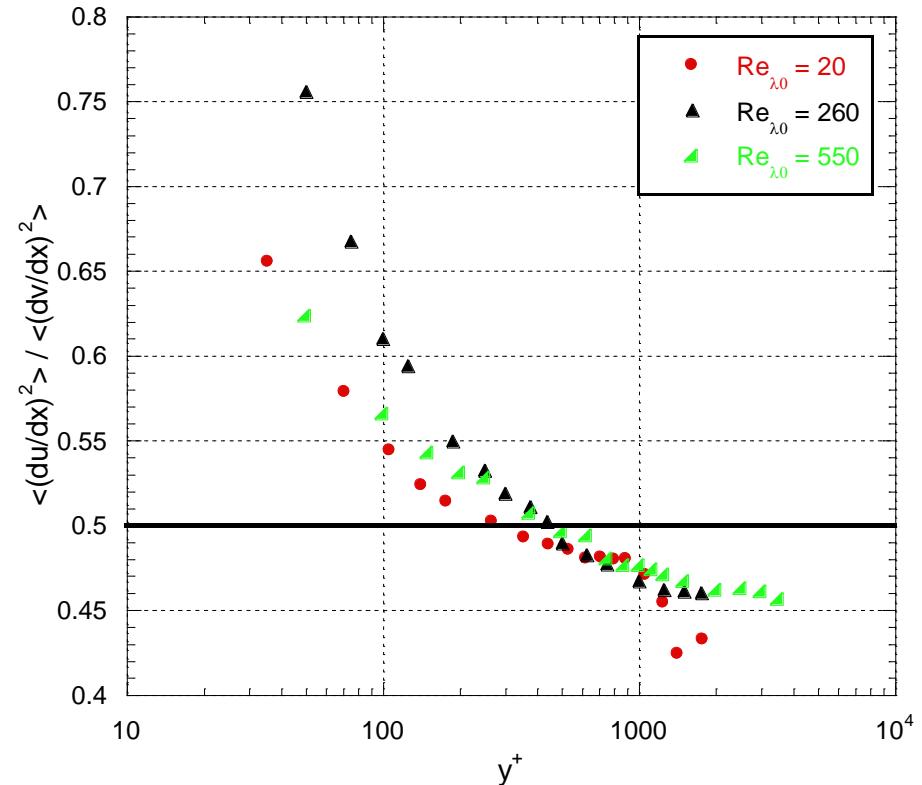


Anisotropy

Large-Scale Anisotropy Profiles



Small-Scale Anisotropy Profiles

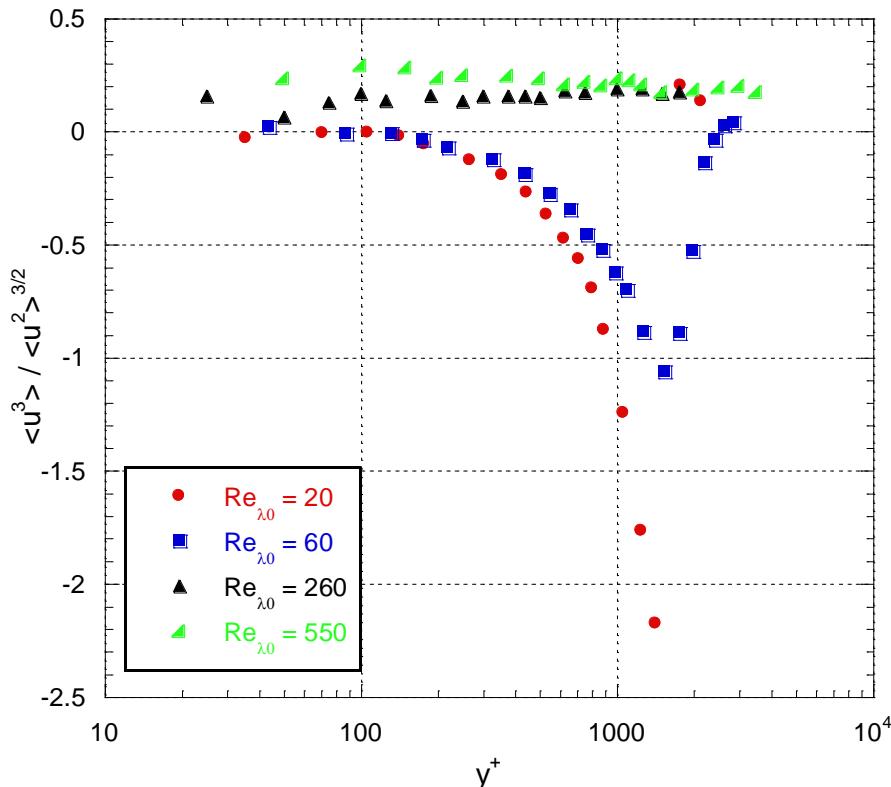


- FST increases levels of anisotropy throughout the boundary layer at both the large- and small- (derivative) scales.

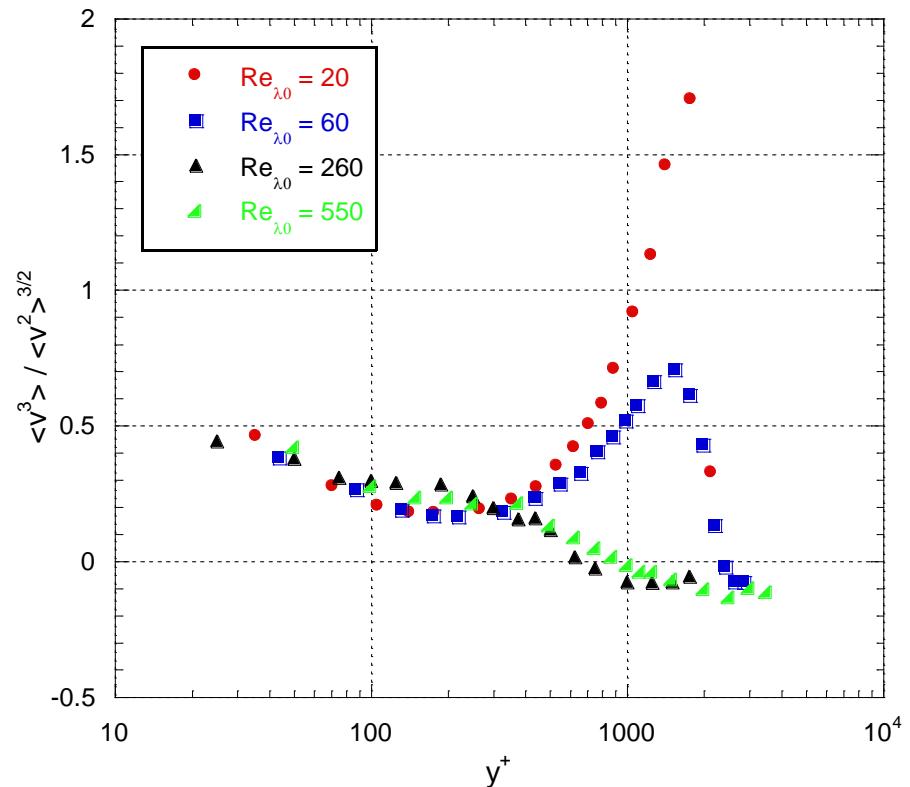


Skewness

Large-Scale U-Direction Skewness Profiles



Large-Scale V-Direction Skewness Profiles

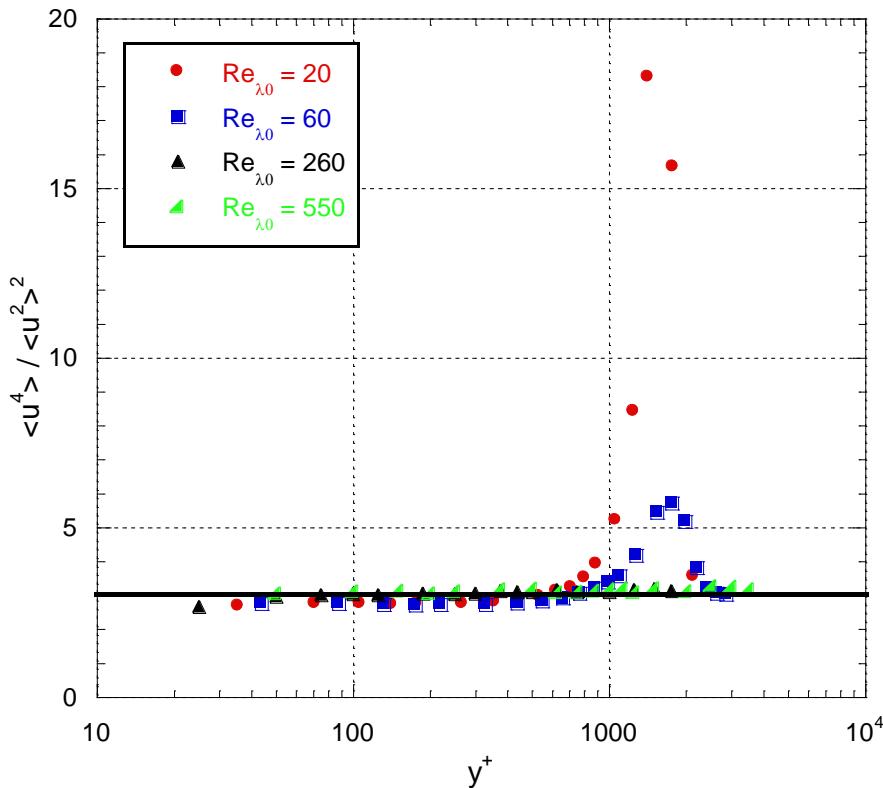


- FST smears out the statistical effects of transition between a boundary layer and the free stream.

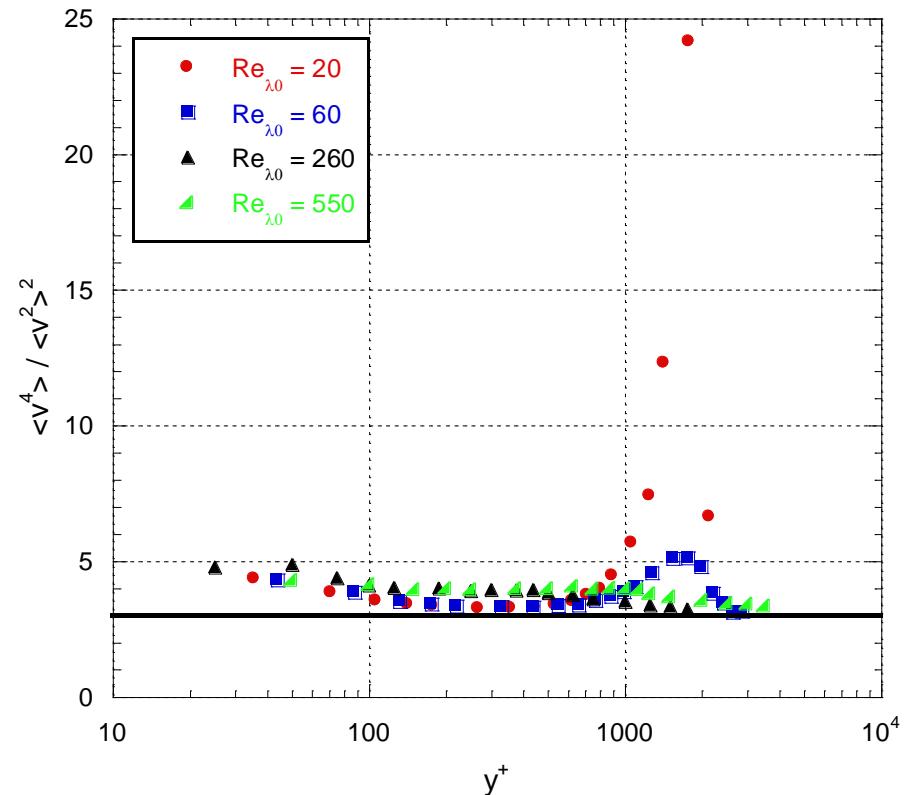


Kurtosis

Large-Scale U-Direction Kurtosis Profiles



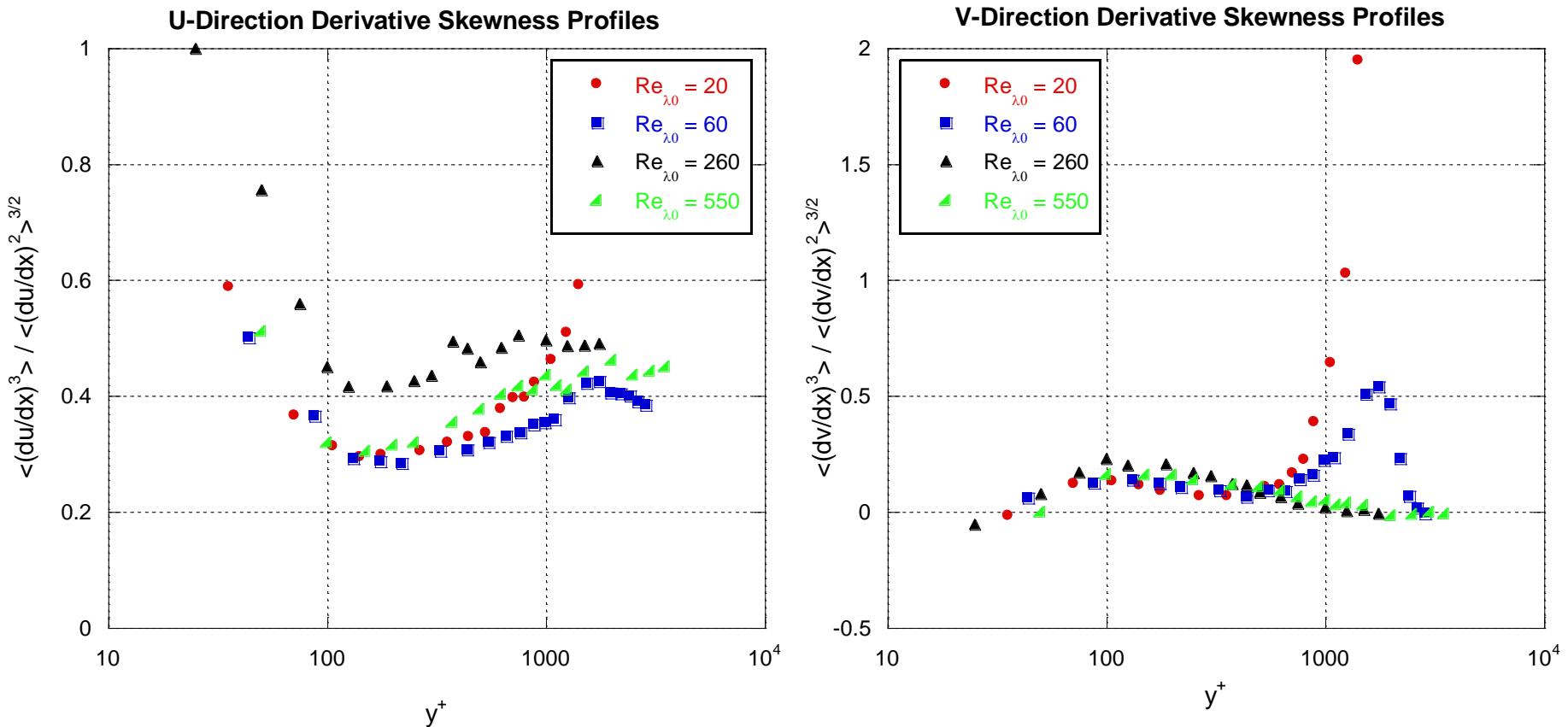
Large-Scale V-Direction Kurtosis Profiles



- Boundary layers with FST have u - and v -direction kurtosis values very near 3, indicating essentially Gaussian behavior at the large-scale.



Derivative Skewness

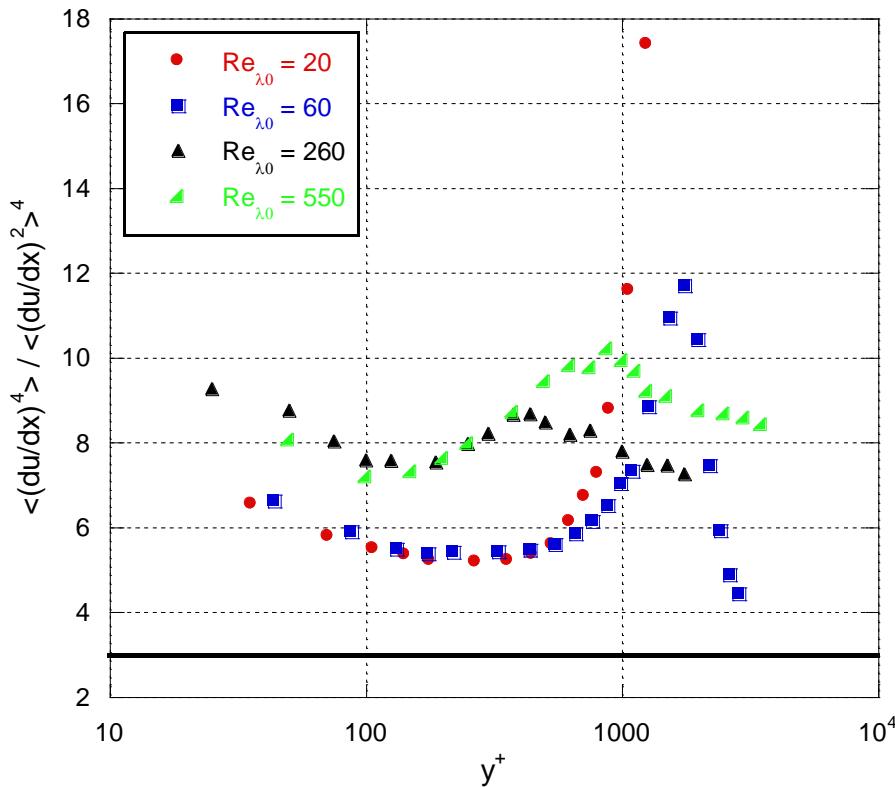


- FST smears out the statistical effects of transition between a boundary layer and the free stream.

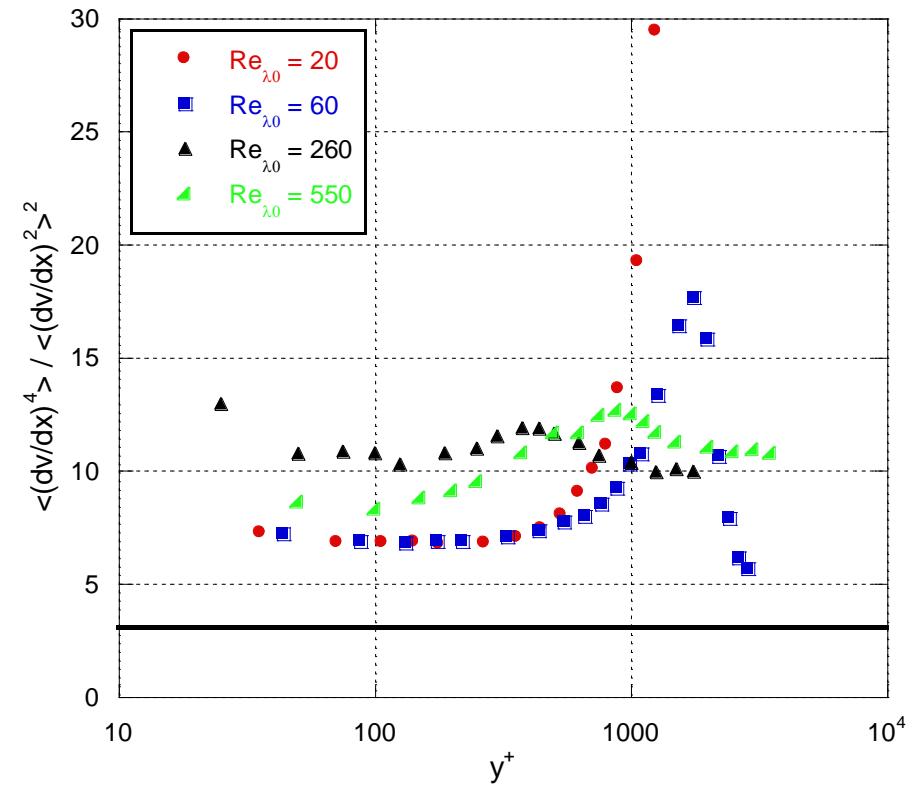


Derivative Kurtosis

U-Direction Derivative Kurtosis Profiles



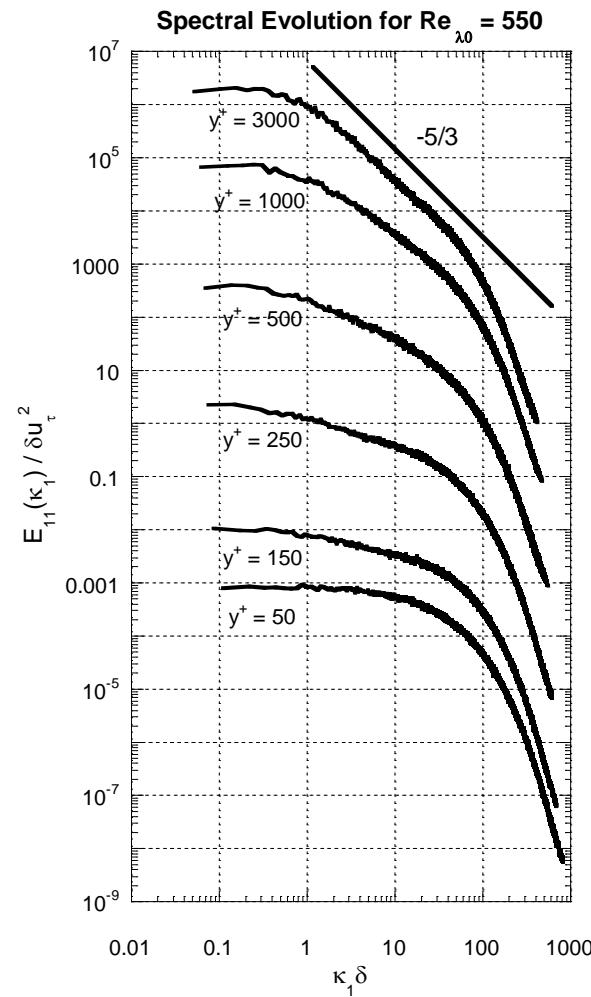
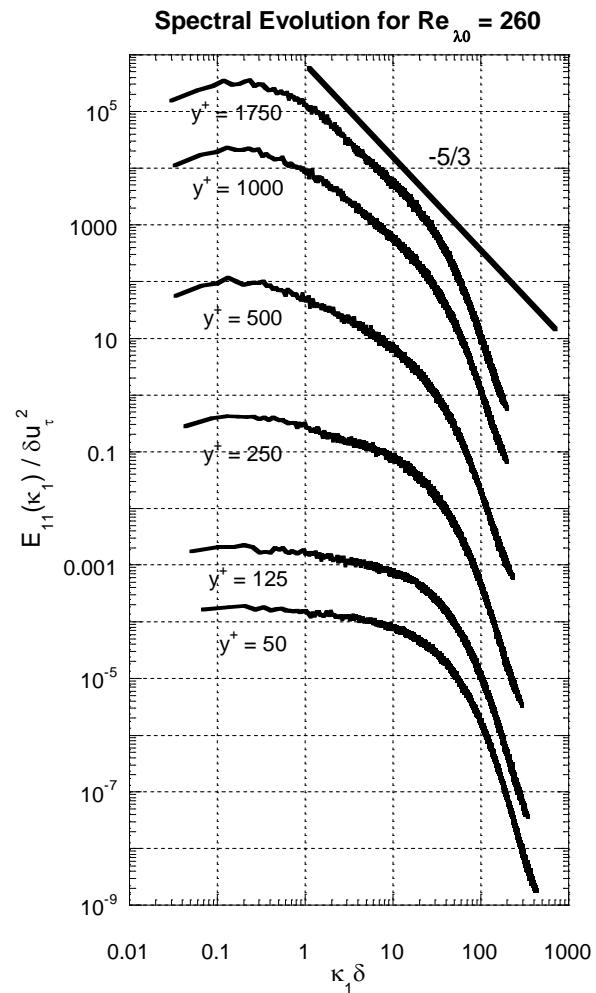
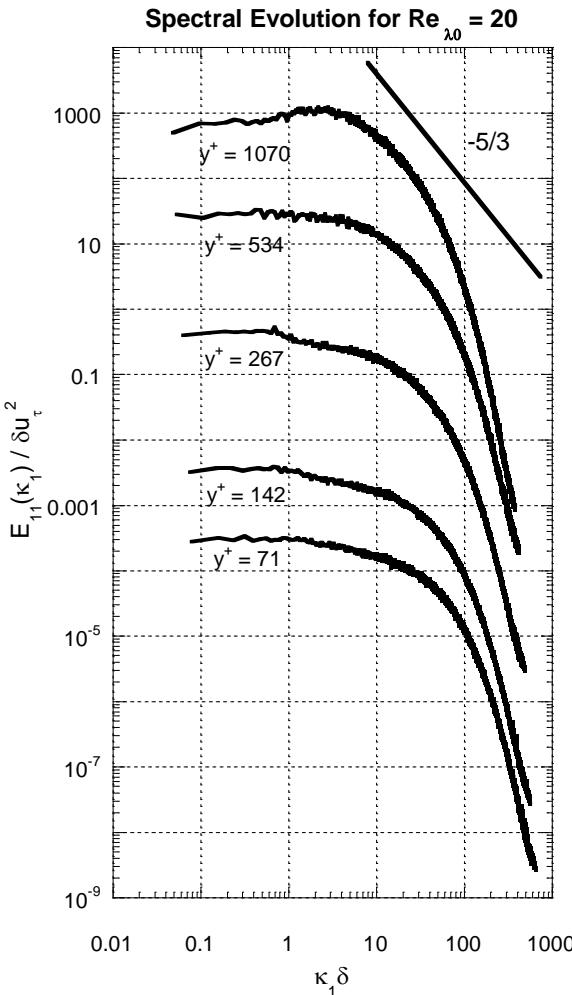
V-Direction Derivative Kurtosis Profiles



- Unlike at the large-scale, the derivative kurtosis in the u - and v -directions show strongly non-Gaussian behavior.



Power Spectra





Energy Spectra: Canonical

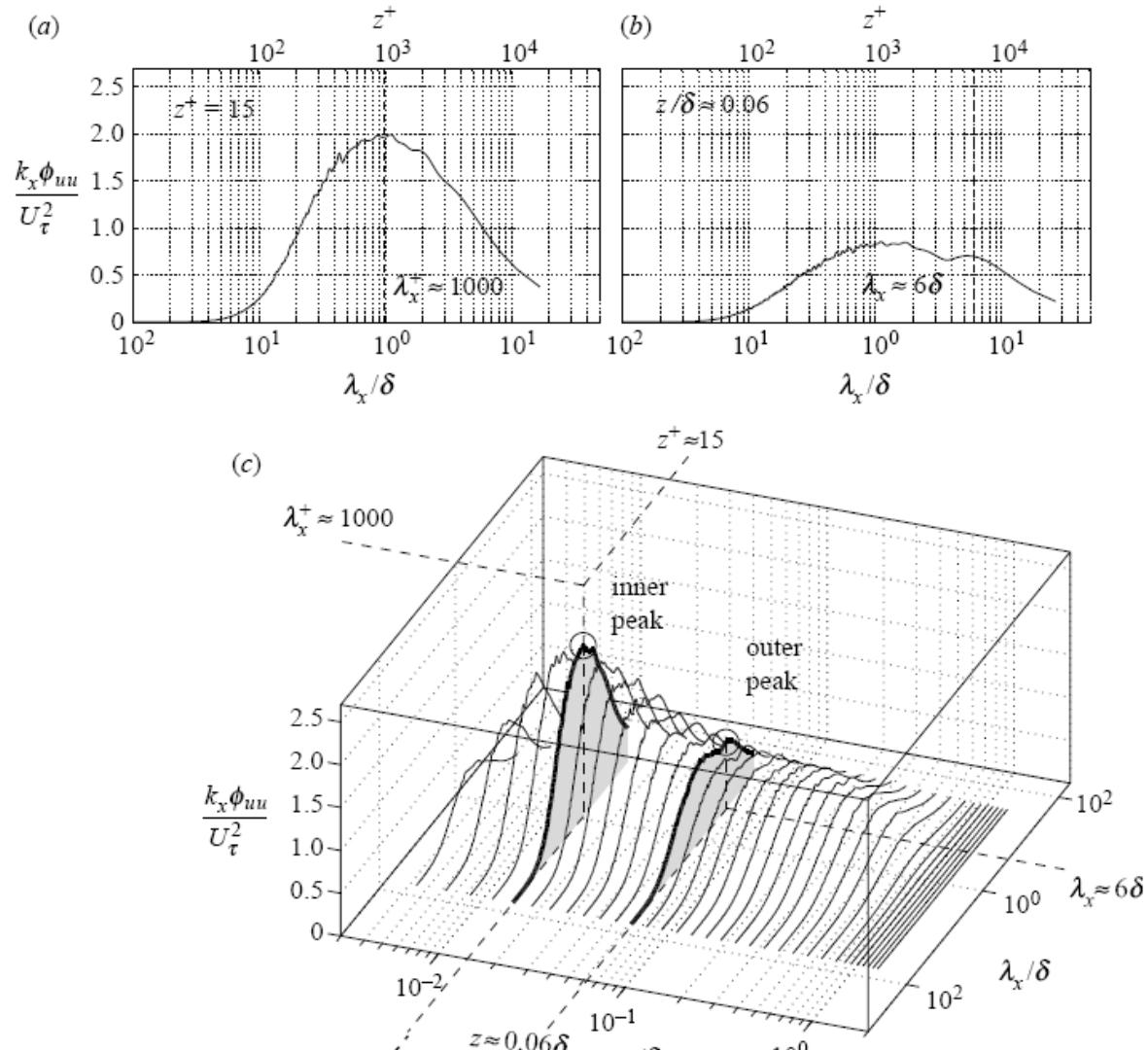
- Canonical boundary layer shows two peaks in the energy spectra

$$\lambda_x^+ = \frac{2\pi}{K_x} \frac{u_\tau}{\nu}$$

Inner peak: $\lambda_x^+ \sim 1000$

Outer peak: $\lambda_x \sim 6\delta$

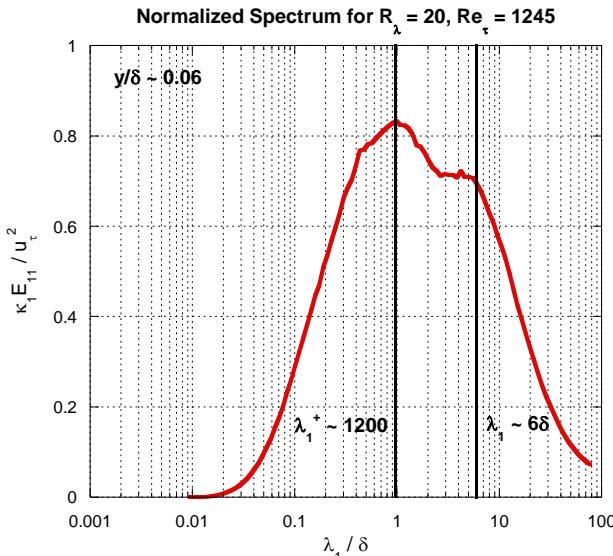
Hutchins N, and Marusic I. "Large-scale influences in near-wall turbulence." *Phil. Trans. R. Soc. A.* v. 365, 2007.



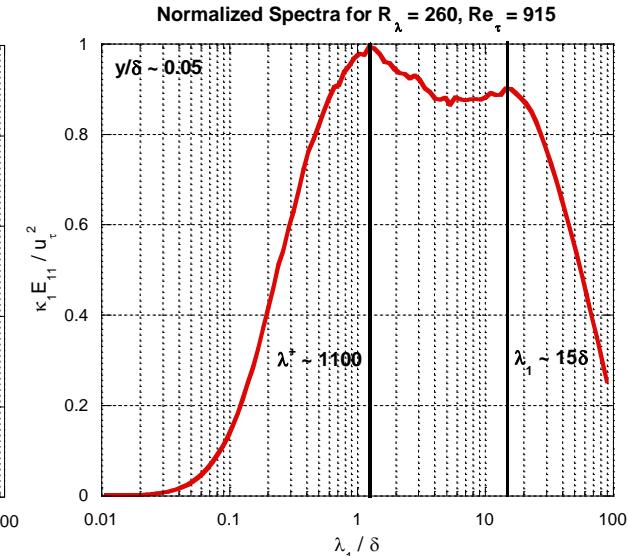


Energy Spectra: Non-Canonical

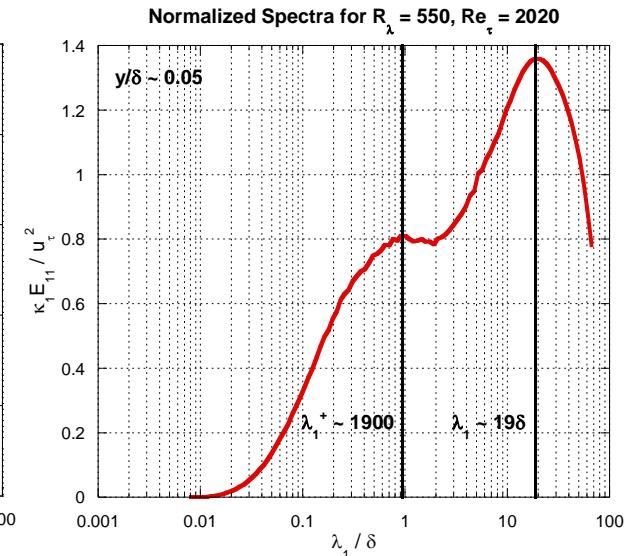
$Re_{\lambda_0} = 20$



$Re_{\lambda_0} = 260$



$Re_{\lambda_0} = 550$



Inner peak: $\lambda_x^+ \sim 1200$

Outer peak: $\lambda_x \sim 6\delta$

Inner peak: $\lambda_x^+ \sim 1100$

Outer peak: $\lambda_x \sim 15\delta$

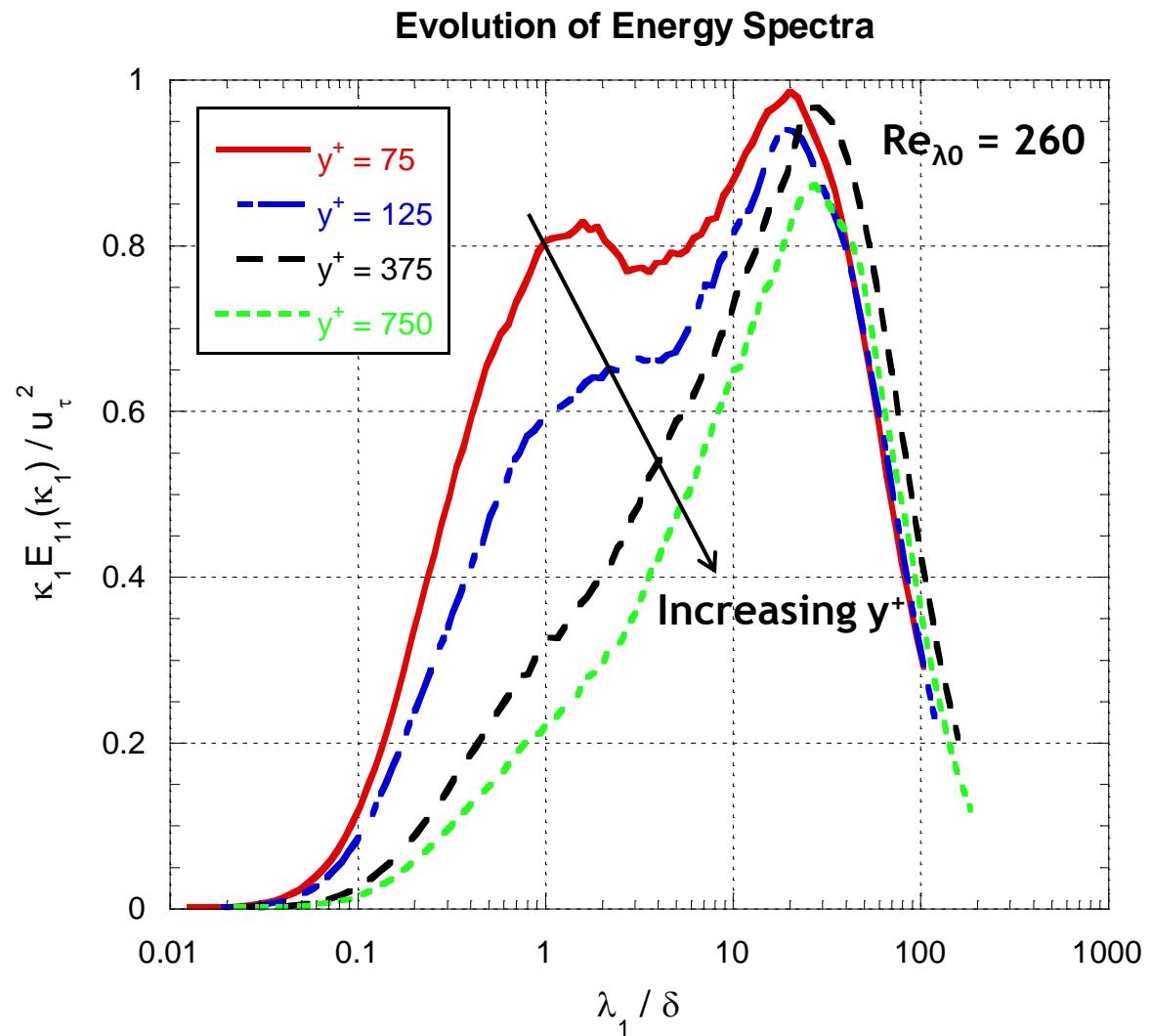
Inner peak: $\lambda_x^+ \sim 1900$

Outer peak: $\lambda_x \sim 19\delta$



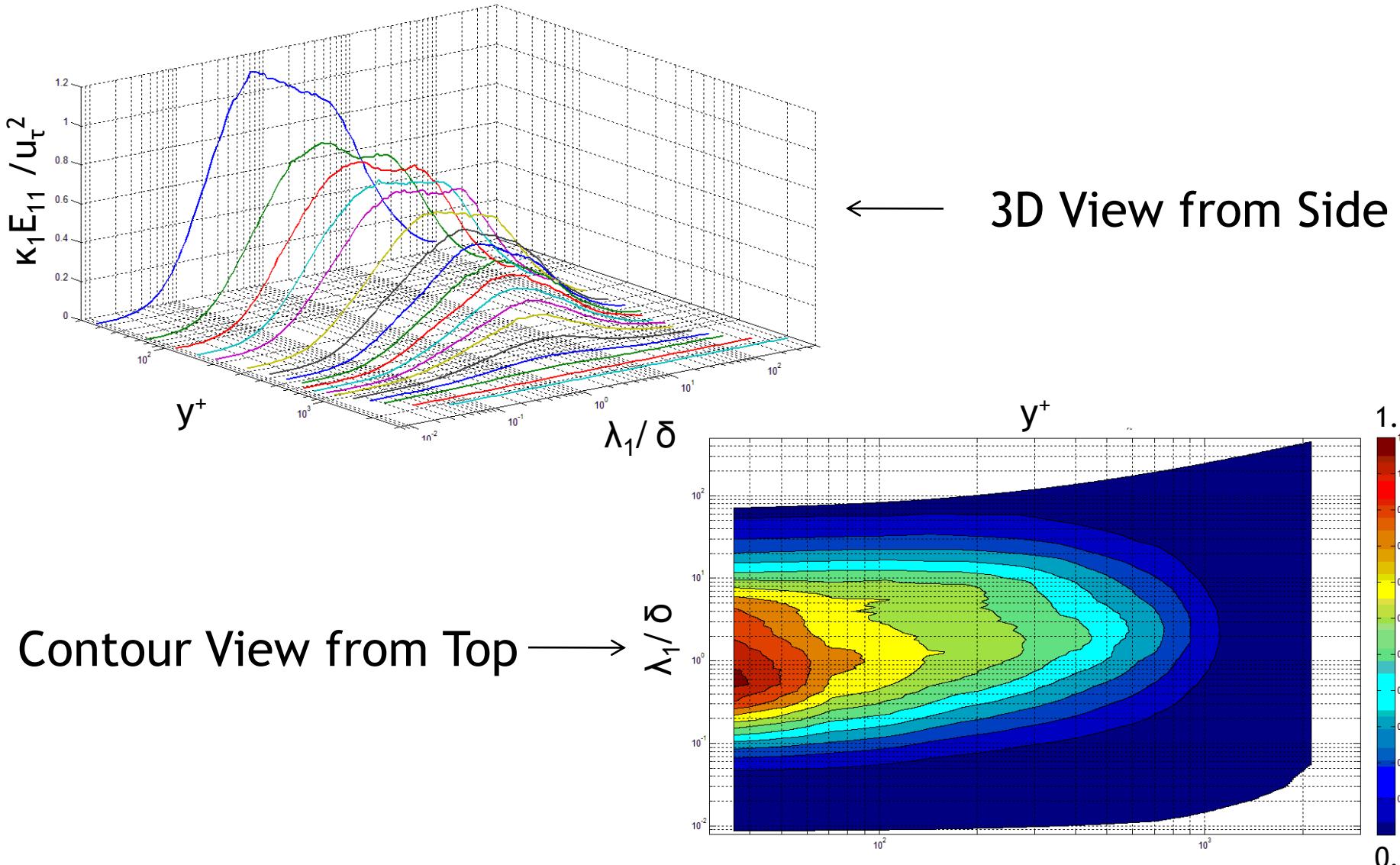
Evolution of Spectra

- Inner peak fades further from the wall, indicating the presence of a scale native to the boundary layer.



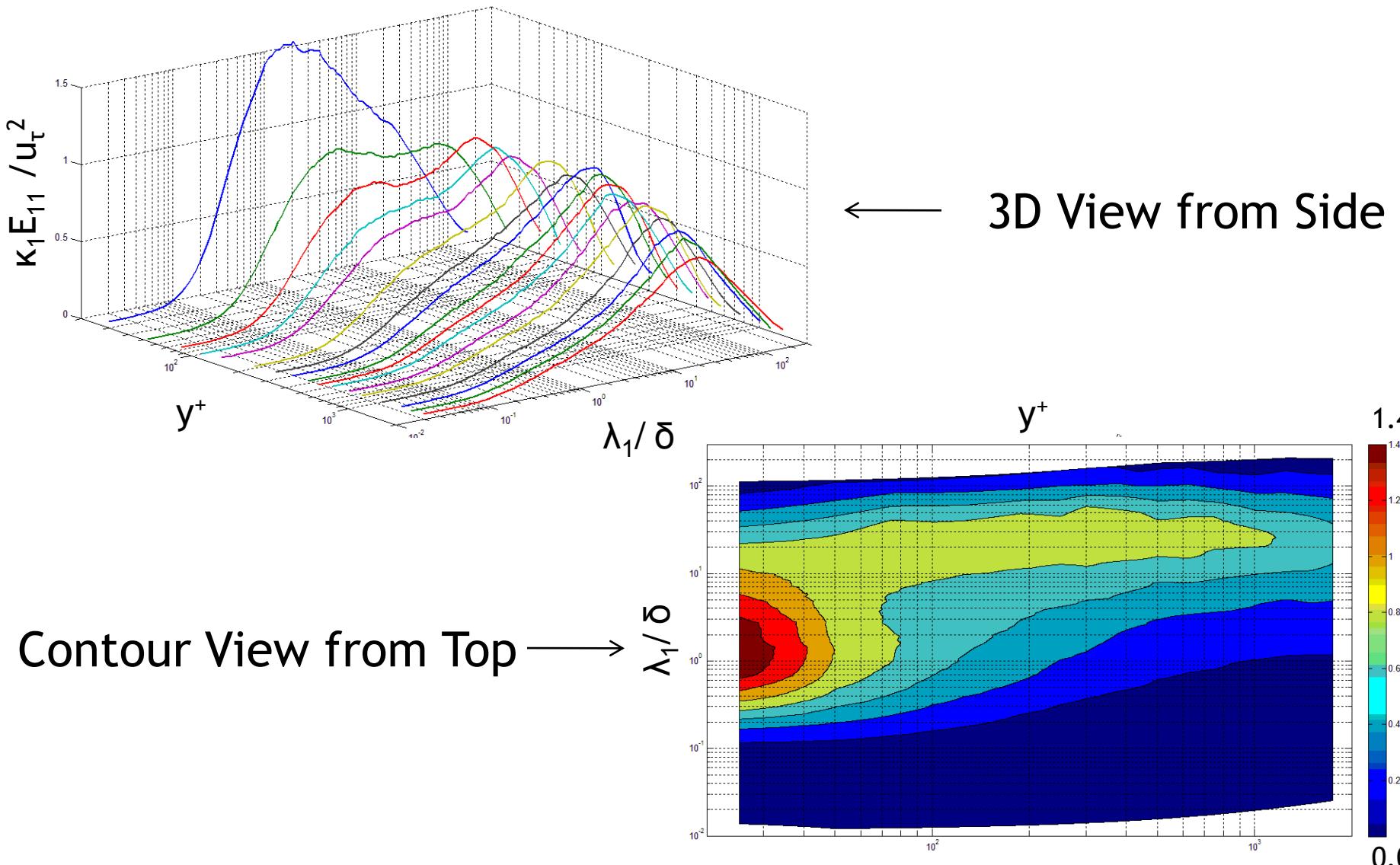


Evolution of Spectra, $\text{Re}_{\lambda_0} = 20$



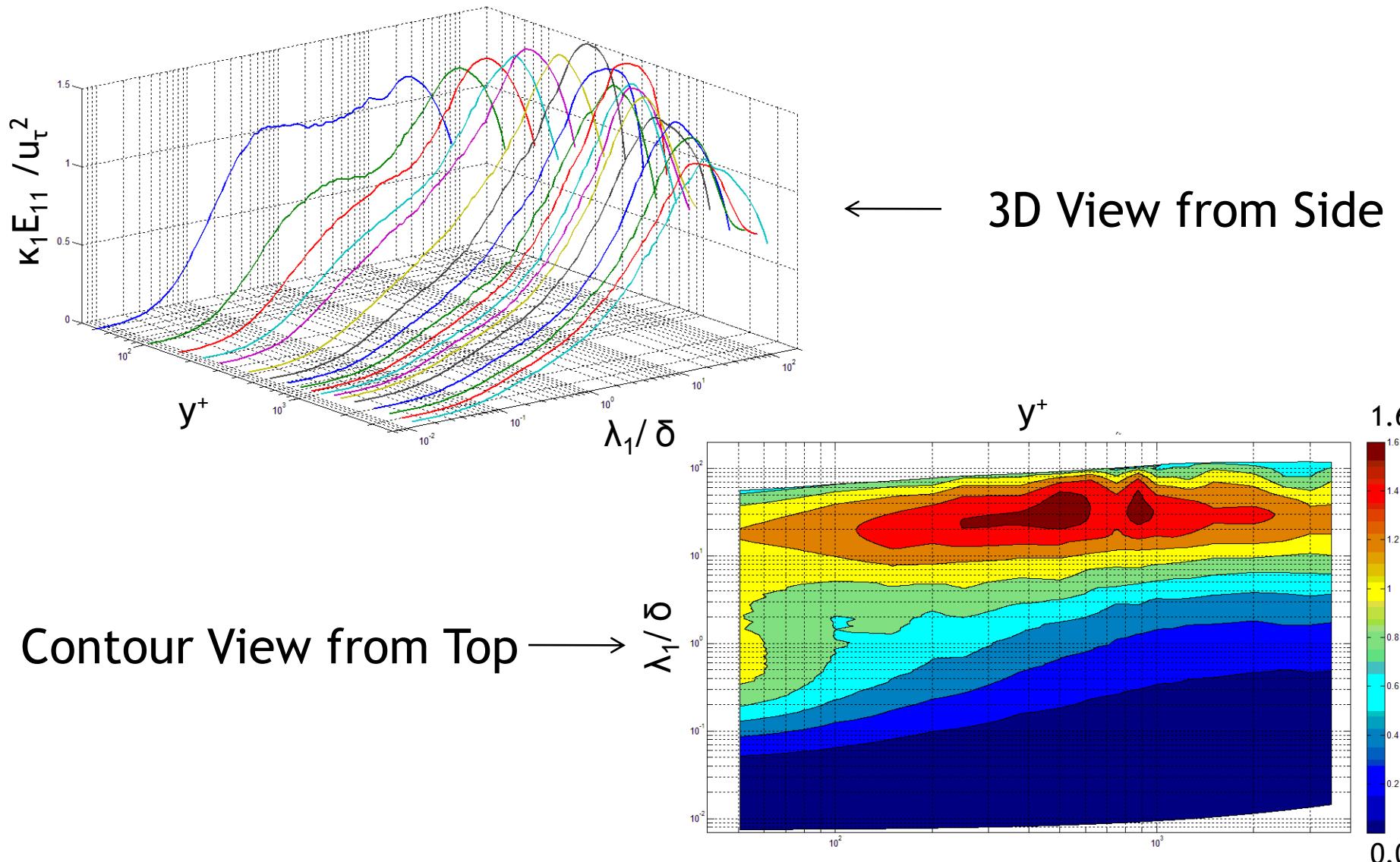


Evolution of Spectra, $\text{Re}_{\lambda 0} = 260$





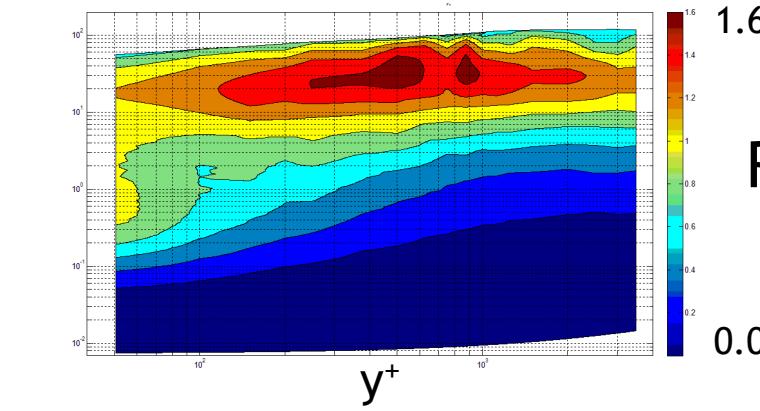
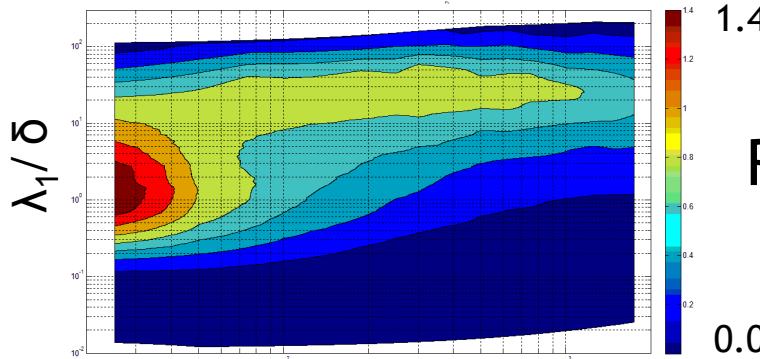
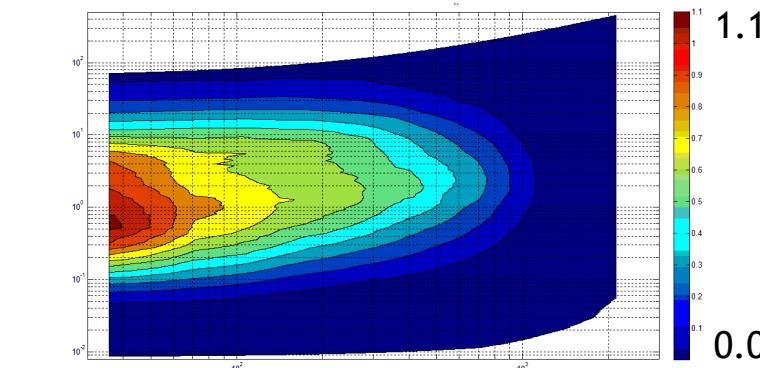
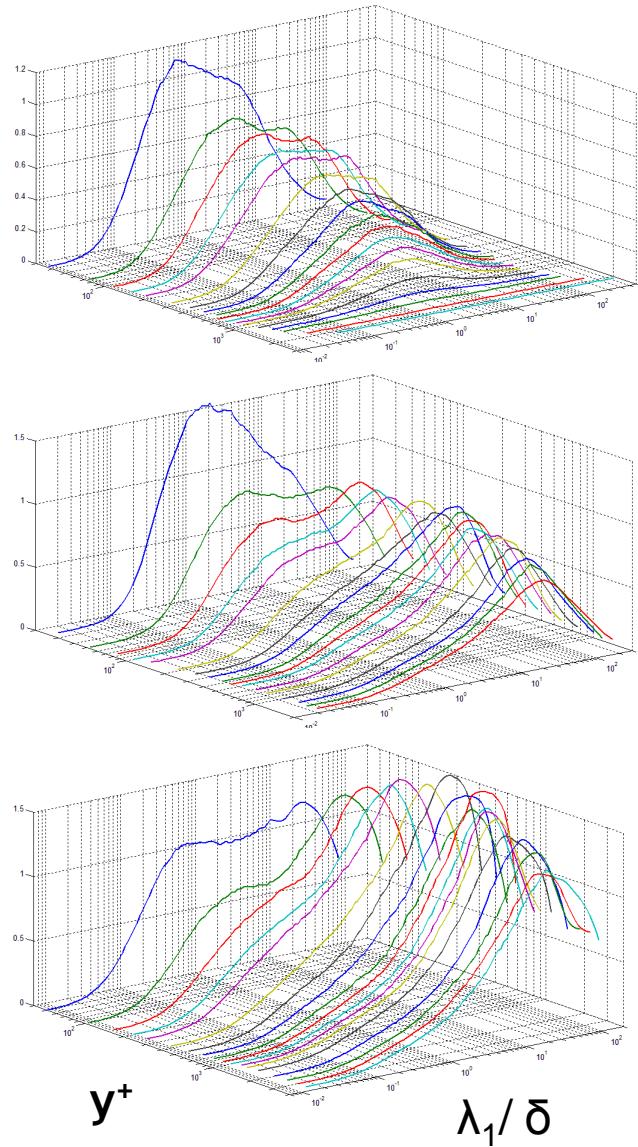
Evolution of Spectra, $\text{Re}_{\lambda 0} = 550$





Evolution of Spectra

$$\kappa_1 E_{11} / u_\tau^2$$



$Re_{\lambda 0} = 20$

$Re_{\lambda 0} = 260$

$Re_{\lambda 0} = 550$



Conclusions

- Observed effects of free stream turbulence on structure throughout the boundary layer
- Found that FST affected higher-order moments at the large- and the small-scale throughout the boundary layer.
- Matched findings of Hutchins and Marusic for near-canonical boundary layer case
- Observed two broadened peaks rather than three distinct peaks in energy spectra of boundary layers with free stream turbulence
- Noted complex interactions between free stream and boundary layer structure extending even below $y^+ = 100$



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The sources for these are acknowledged below:

Slide 2

Large eddies in a turbulent boundary layer, M. Gad-el-Hak, Virginia Commonwealth University,
http://www.efluids.com/efluids/gallery/gallery_pages/eddies_page.jsp

Slide 4

Turbomechanical figure from Wu, Jacobs, Hunt, and Durbin. *JFM*, v. 398, 1999.

Turbomachinery visualization, Mitsubishi,

https://www.mhi.co.jp/en/ngsrdc/producttechnology/turbo/turbo_01.html

Boundary layers in atmosphere, Caroline Bain, University of Leeds,

<http://homepages.see.leeds.ac.uk/~lecclb/>

Wind turbines, Rochester Solar Technologies,

<http://www.solarrochester.com/Wind%20Turbine%20information.asp>

Slide 6

K. A. Thole and D. G. Bogard, "High free stream turbulence effects on turbulent boundary layers," *J. Fluids Engi.*, 118, 1996.



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Unforeseen Delays

