I C E T

(International Collaboration on Experiments in Turbulence)

Coordinated Measurements in High Reynolds Number Turbulent Boundary Layers from Three Wind Tunnels

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Alexander Smits – Princeton University
Ivan Marusic – University of Melbourne
P. Henrik Alfredsson – KTH
and
ICET Team

NORDITA and Linné FLOW Centre Workshop on Turbulent Boundary Layers
AlbaNova, Stockholm, Sweden - April 29, 2010

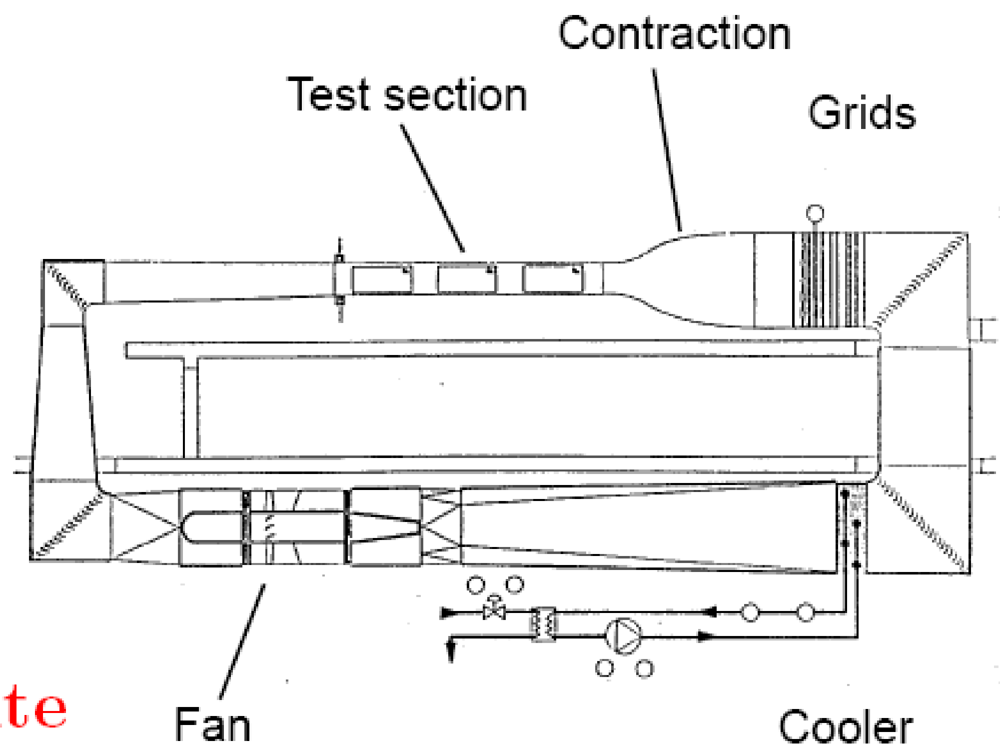
Scope

- Zero pressure gradient (ZPG) boundary layers at high Reynolds numbers are the focus.
- Over the past few years, four groups have made systematic comparison between several measurement techniques and three facilities.
- The development length of the boundary layers and the free-stream velocity in the three facilities range from 5.5 to 22 m, and from 10 to 60 m/s, respectively.
- Various arrangements for adjustable test section ceilings are employed to generate ZPG boundary layers over the range of momentum thickness Reynolds numbers from 11,000 to 70,000.
- Oil film interferometry (OFI) is employed to directly measure the wall shear stress, and various sizes of Pitot probes and types of hot-wire sensors are used.

Objectives

- Compare the high Reynolds number, ZPG boundary layers formed in three facilities.
- Establish a reliable estimate for the accuracy and repeatability of OFI.
- Evaluate the performance of hot-wire probes with different characteristics and of various anemometer units.
- Compare the mean velocity profiles measured by hot wires and Pitot probes.
- Explain differences between overlap region parameters measured by hot wires and Pitot probes; e.g., the value of κ

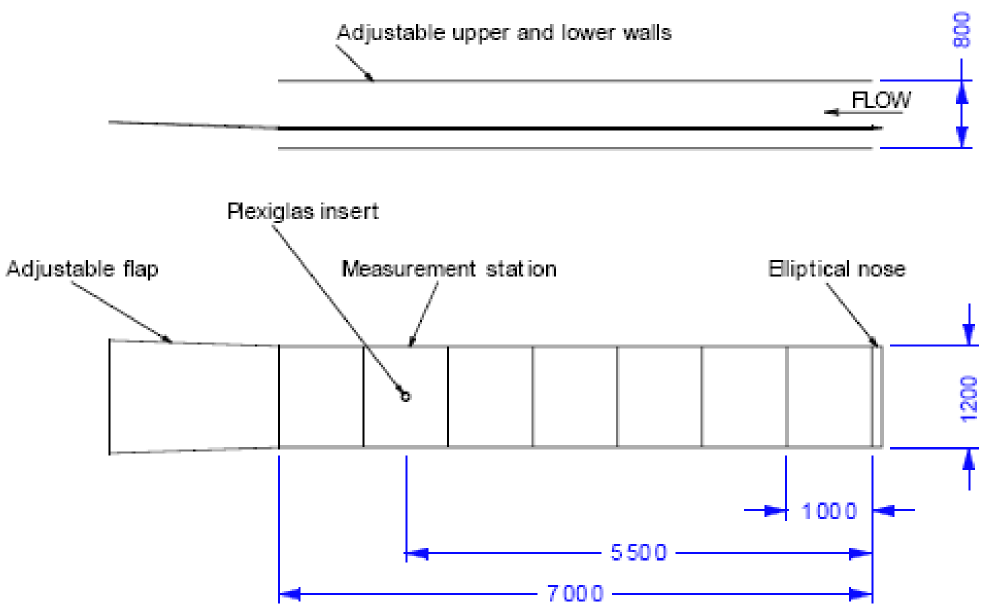
Set-up at KTH / MTL wind-tunnel



0.8m x 1.2m x 7m

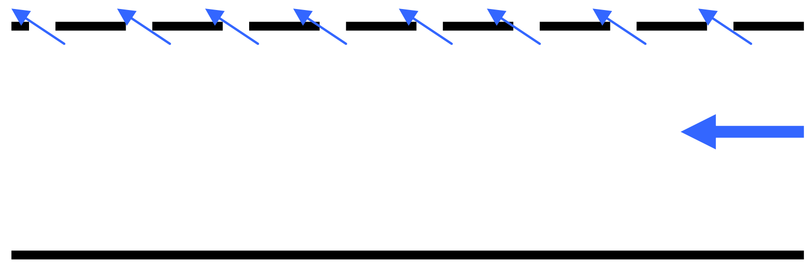
Adjustable Ceiling

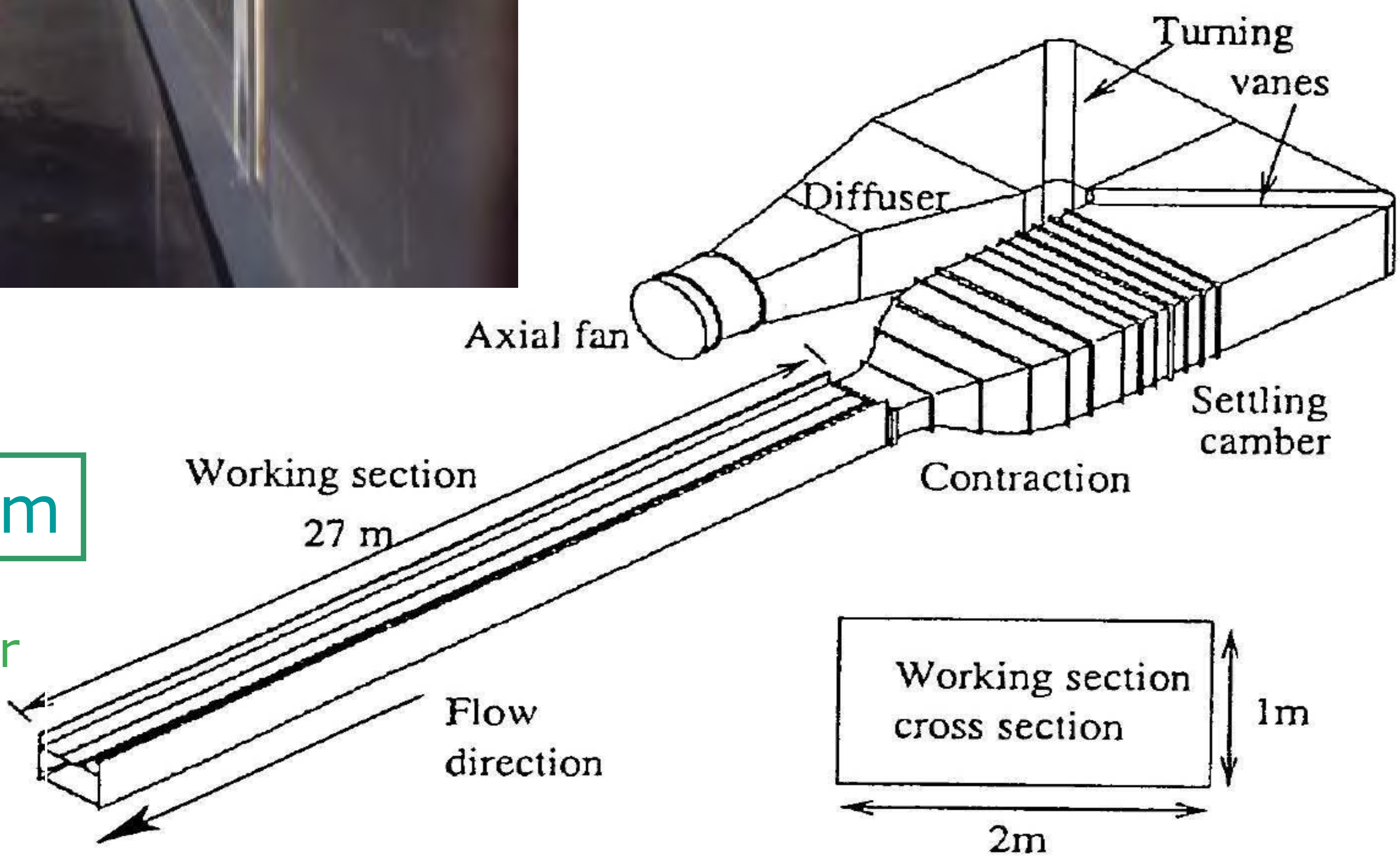
Flat Boundary Layer Plate



High Re wind tunnel, University of Melbourne

Pressure Adjustment Scheme for Test Section

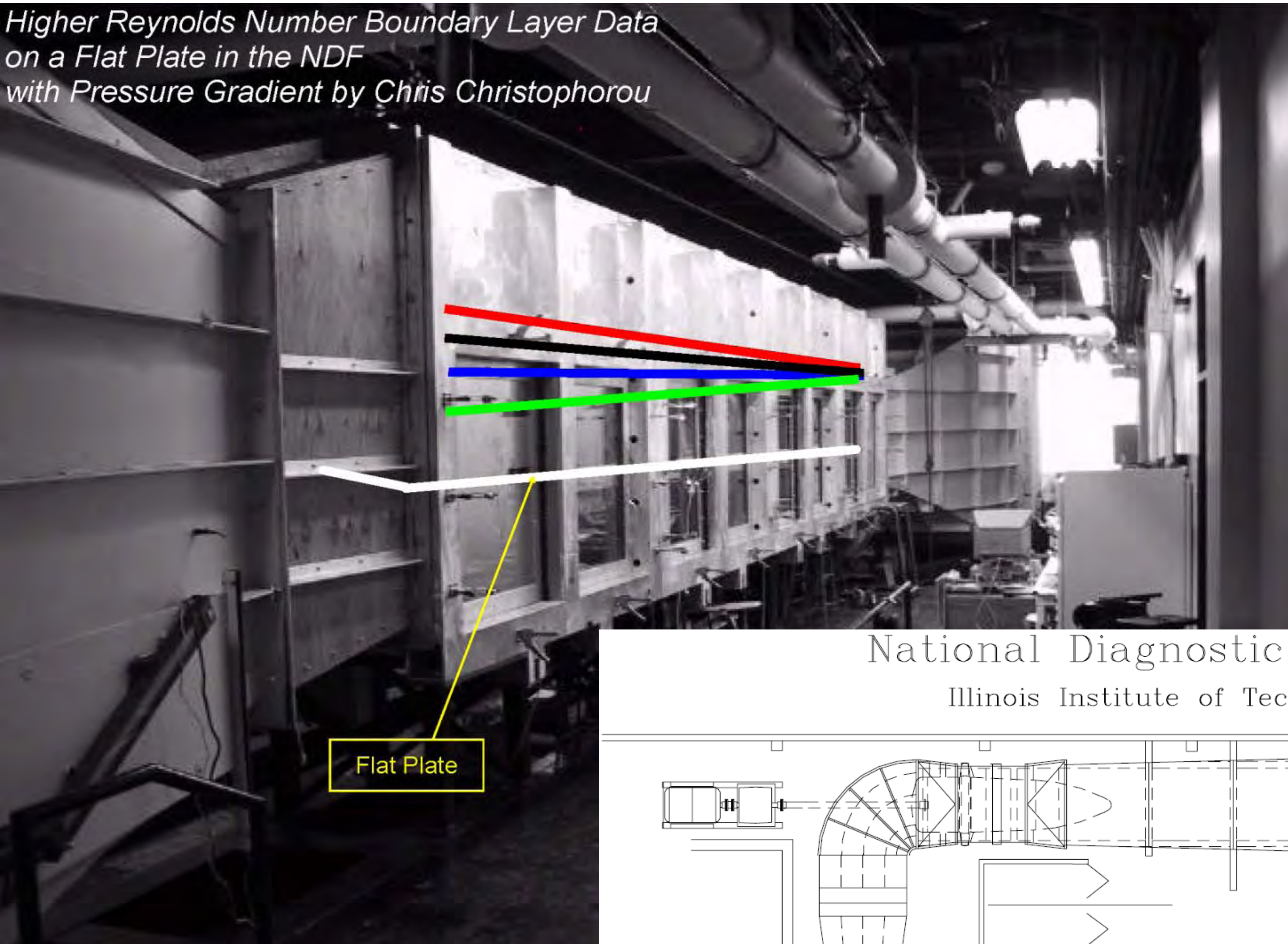




1m x 2m x 27m

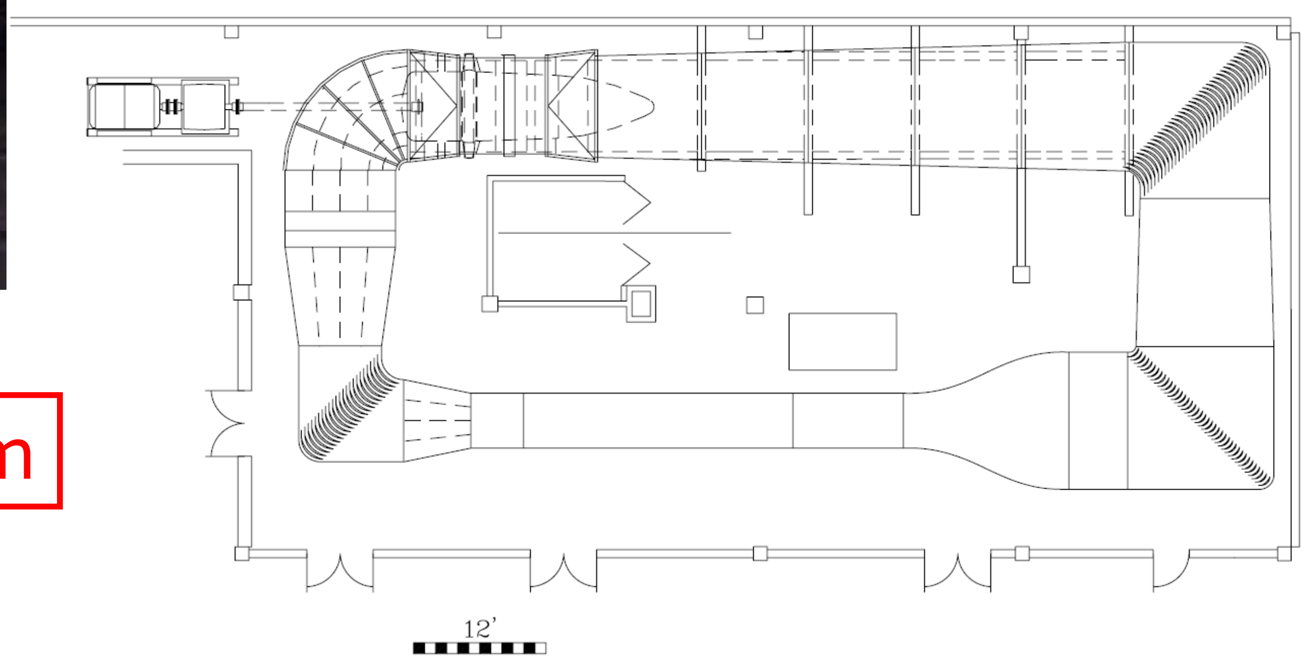
Fixed Ceiling with Transverse Slots for Pressure Gradient Relief

Higher Reynolds Number Boundary Layer Data on a Flat Plate in the NDF with Pressure Gradient by Chris Christophorou



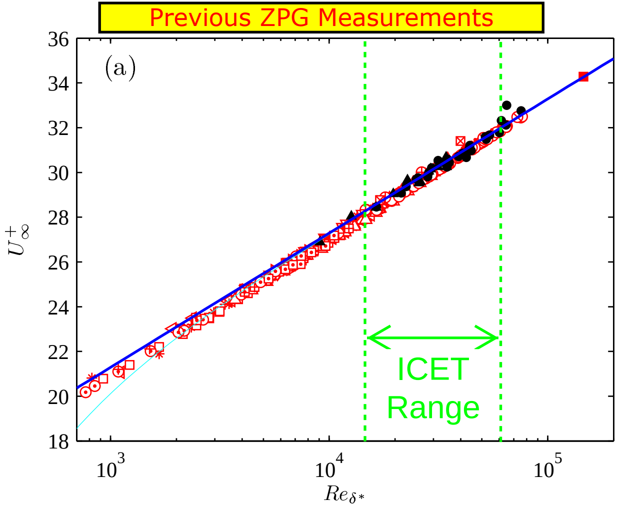
National Diagnostic Facility

Illinois Institute of Technology



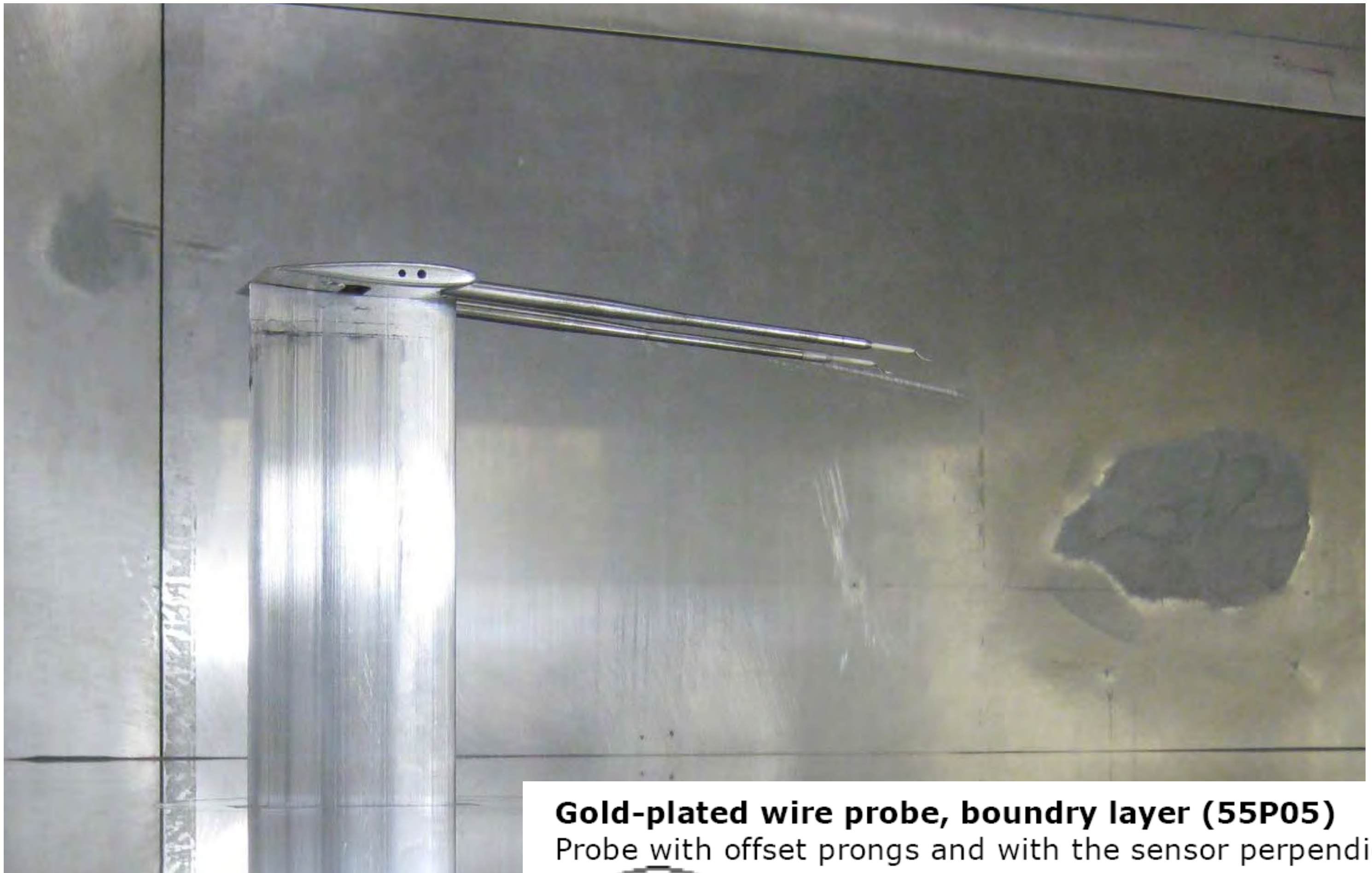
1.3m x 1.5m x 10m

Adjustable Ceiling



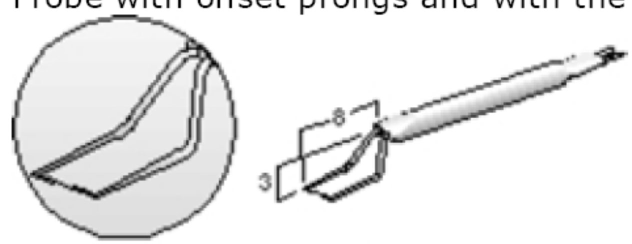
Previous ZPG Measurements
(a)
36
34
32
30
28
26
24
22
20
18
U_∞^+
10^3
10^4
10^5
Re_{δ^*}
ICET
Range

Hot-Wire Probes

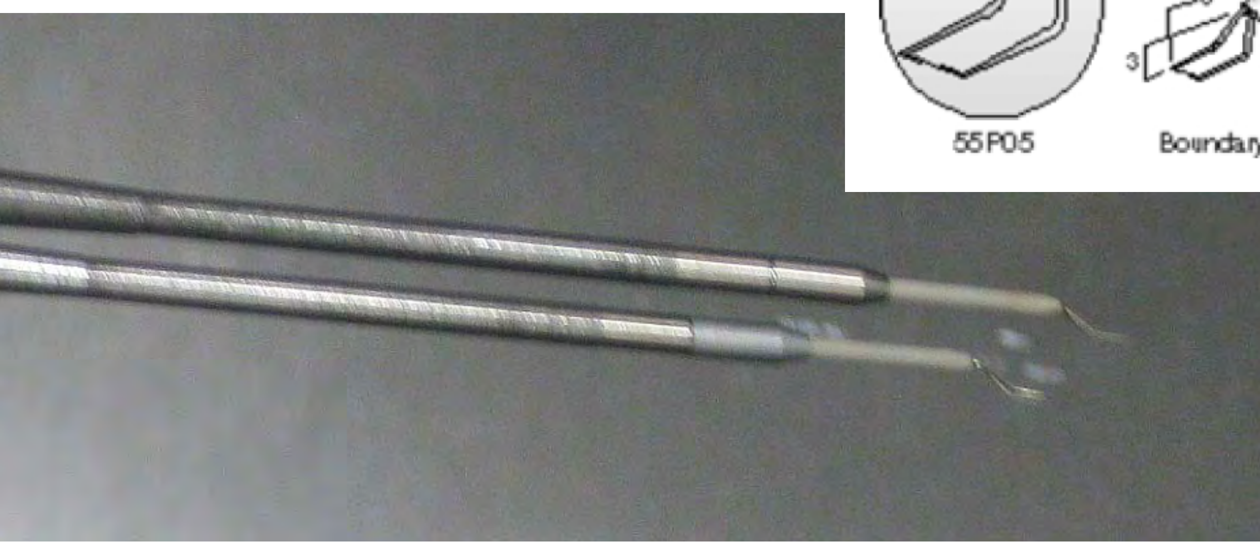


Gold-plated wire probe, boundry layer (55P05)

Probe with offset prongs and with the sensor perpendicular to probe axis.

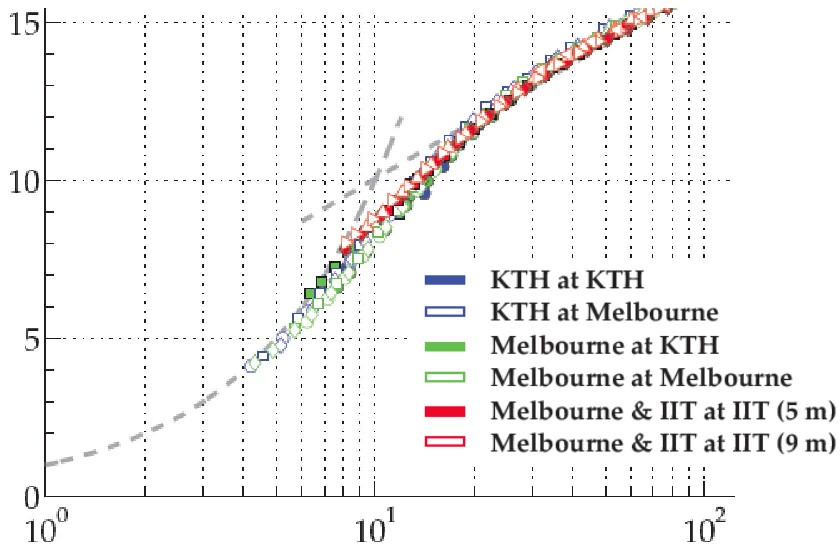


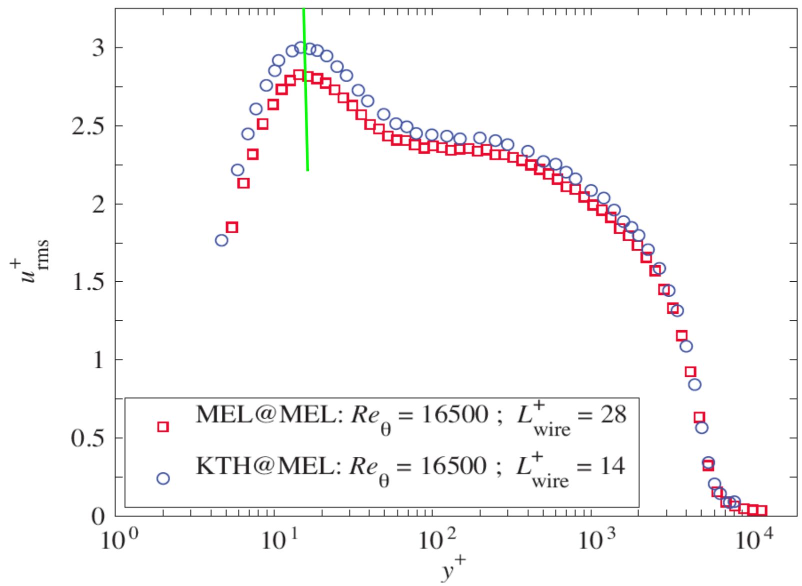
55P05 Boundary layer type



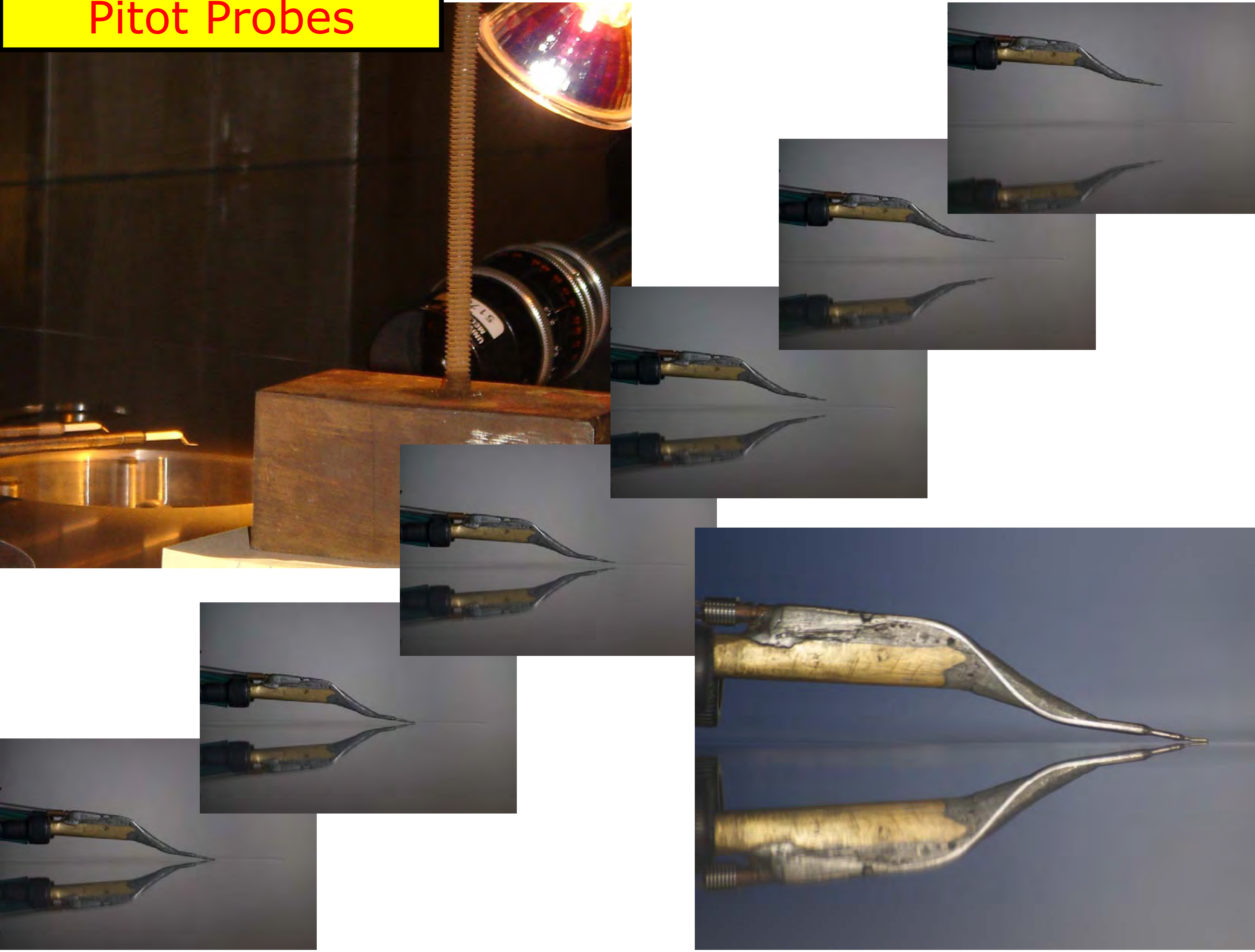
Requirements for Accurate Measurements of Wall Distance in High Reynolds Number Wall-Bounded Turbulence

- Continuous and accurate monitoring of wall distance.
- Accurate measurement of velocity near the wall; i.e., minimize probe interference effects.
- Utilize theoretical, DNS or low Re results to correct wall distance:
    - Linear velocity region; often not accessible.
    - Rely on location for peak in rms velocity.
    - Utilize DNS and low Re experimental data in buffer region; e.g., talk AA00007 by Fransson et al.
    - See also talk BN00004 by Alfredsson et al.





Pitot Probes



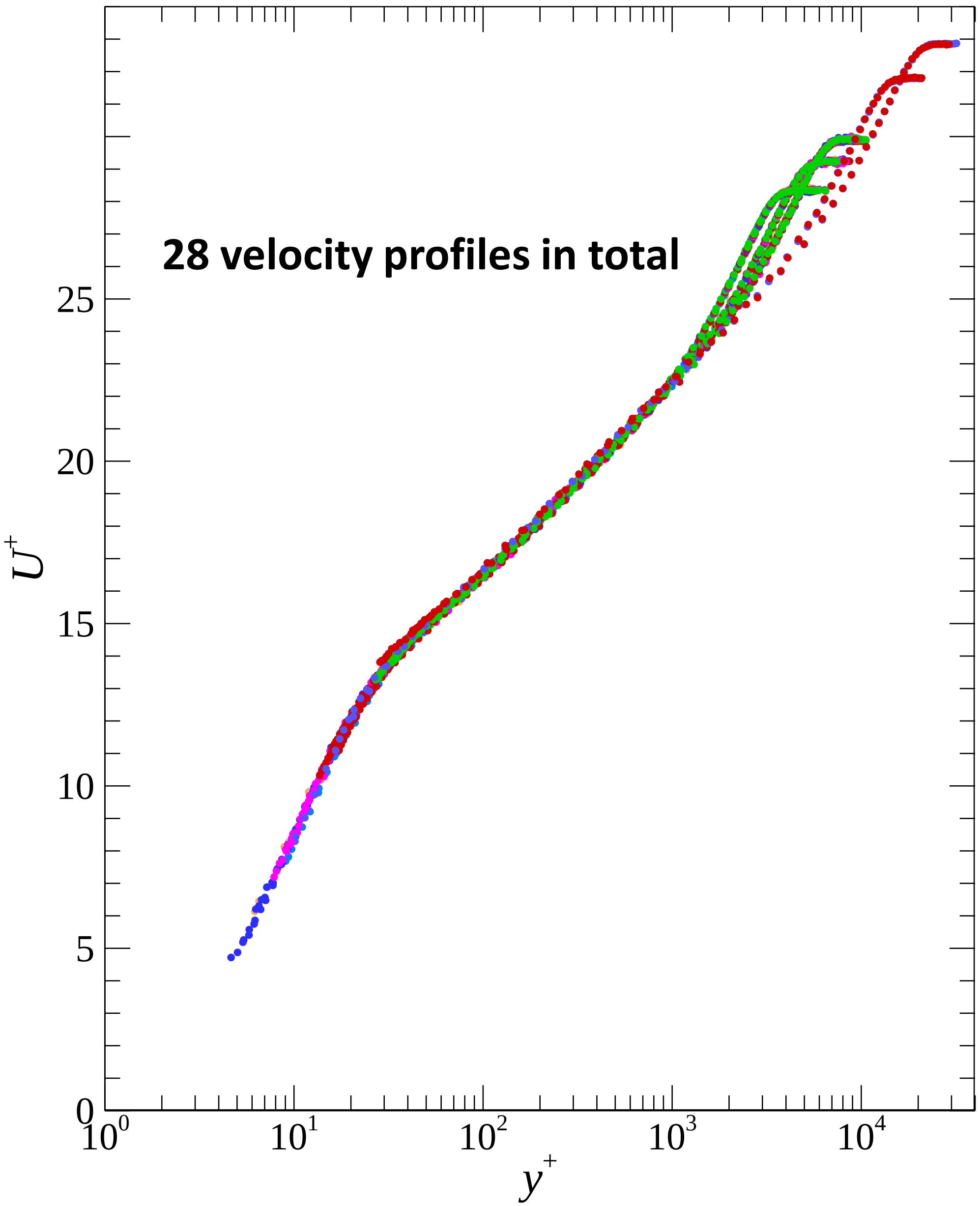
Mean profiles

- All data uses the skin-friction relation in earlier talk

$$U_\infty^+ = \frac{1}{0.38} \ln Re_{\delta^*} + 3$$

			KTH			Melbourne			IIT					
									5.5 m			9 m		
			20 m/s	30 m/s	40 m/s	S1	S2	S3	30 m/s	40 m/s	50 m/s	30 m/s	40 m/s	50 m/s
KTH		20 m/s												
		30 m/s												
		40 m/s												
Melbourne		S1												
		S2												
		S3												
IIT	5.5m	30 m/s												
		40 m/s												
		50 m/s												
	9 m	30 m/s												
		40 m/s												
		50 m/s												
Reynolds numbers			$Re_\theta \approx 12000$		$Re_\theta \approx 16000$		$Re_\theta \approx 22000$		$Re_\theta \approx 25000$		$Re_\theta \approx 32000$		$Re_\theta \approx 38000$	

Dataset



5 Probes, outer diameter:

0.2mm 0.3mm 0.51mm
0 .89mm 1.8mm

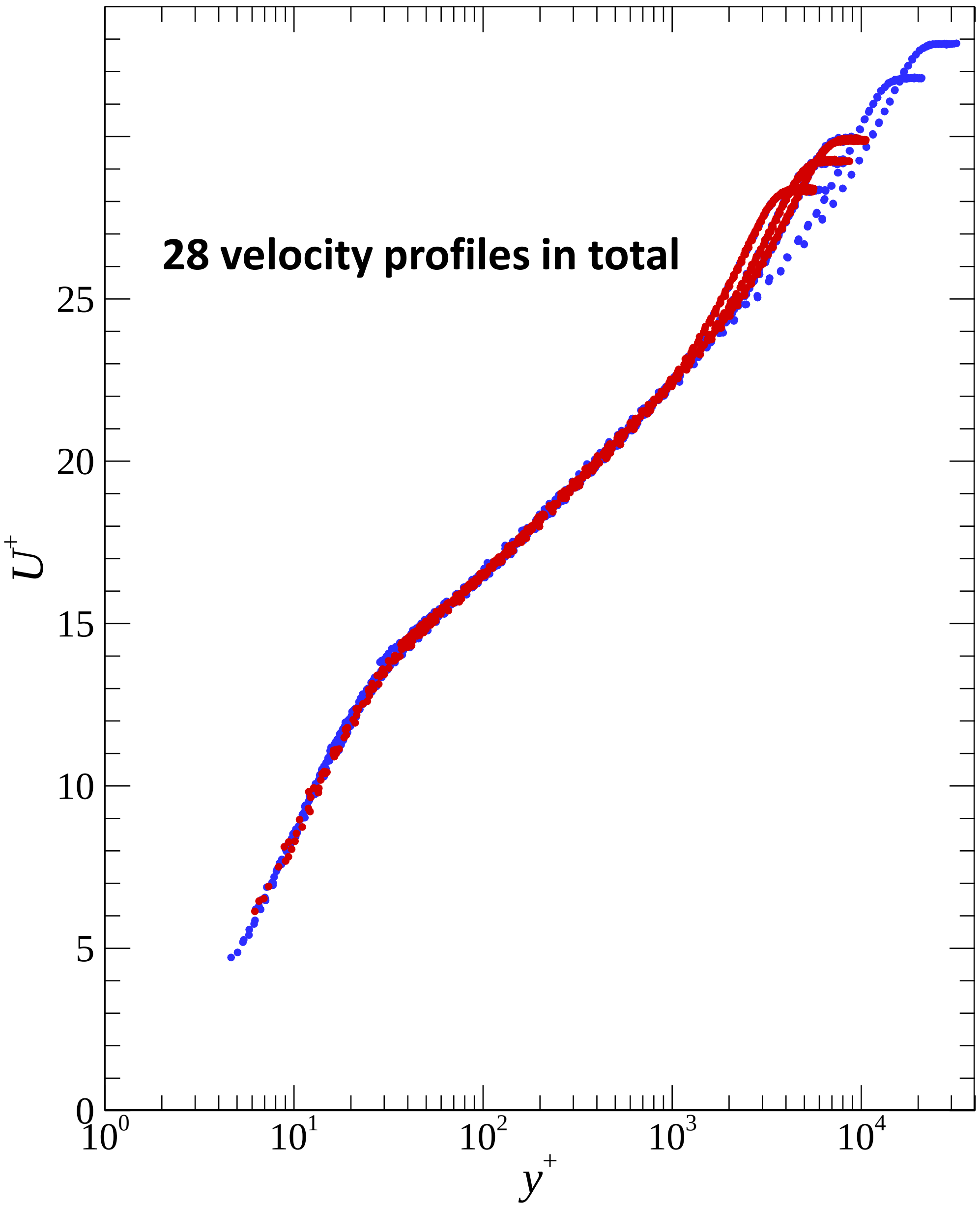
5 Reynolds Numbers, Re_θ:

$11x10^3$ $16x10^3$ $21x10^3$
$44x10^3$ $67x10^3$

2 Facilities:

KTH Melbourne

Dataset



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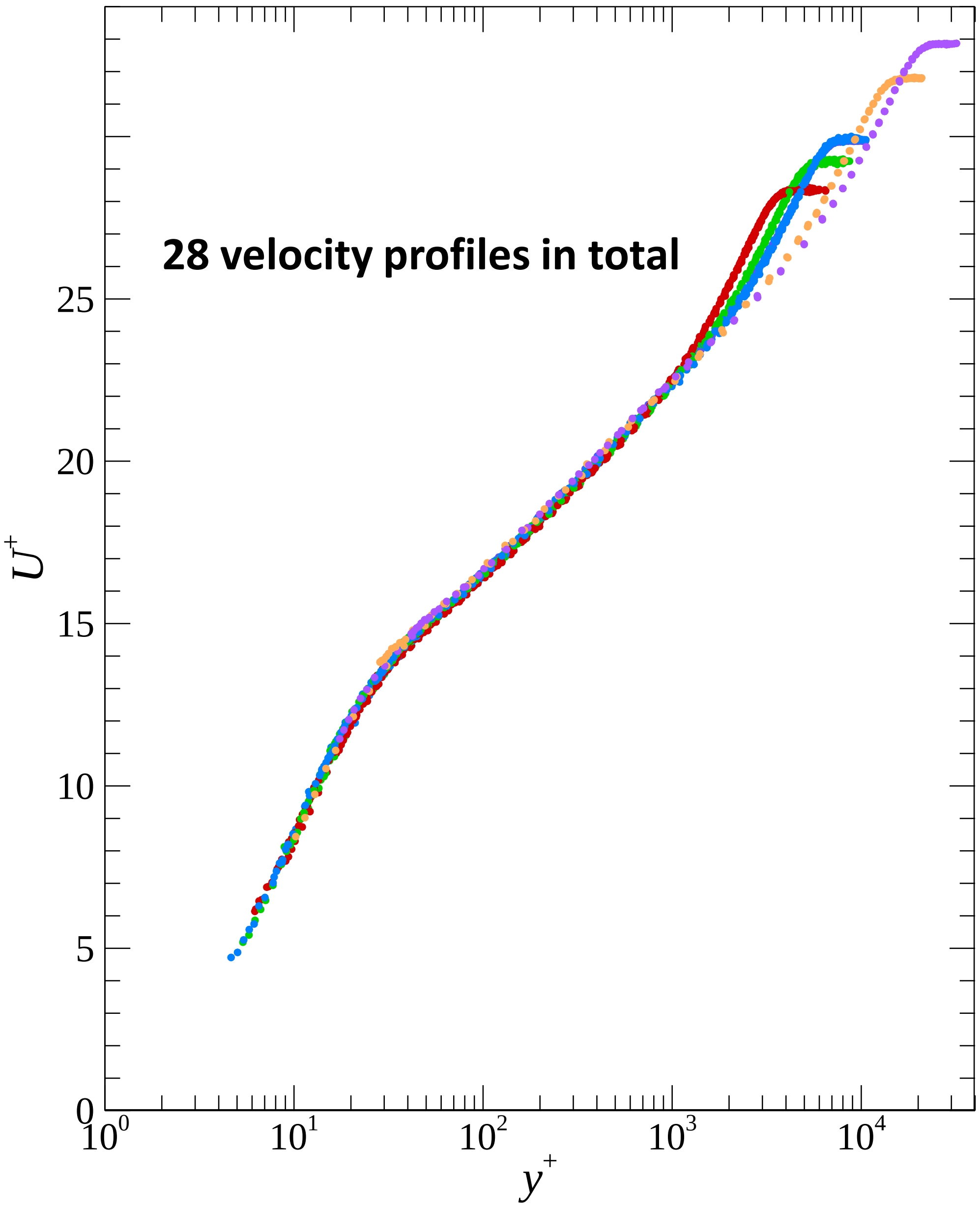
Dataset



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- 0 .89mm
- 1.8mm

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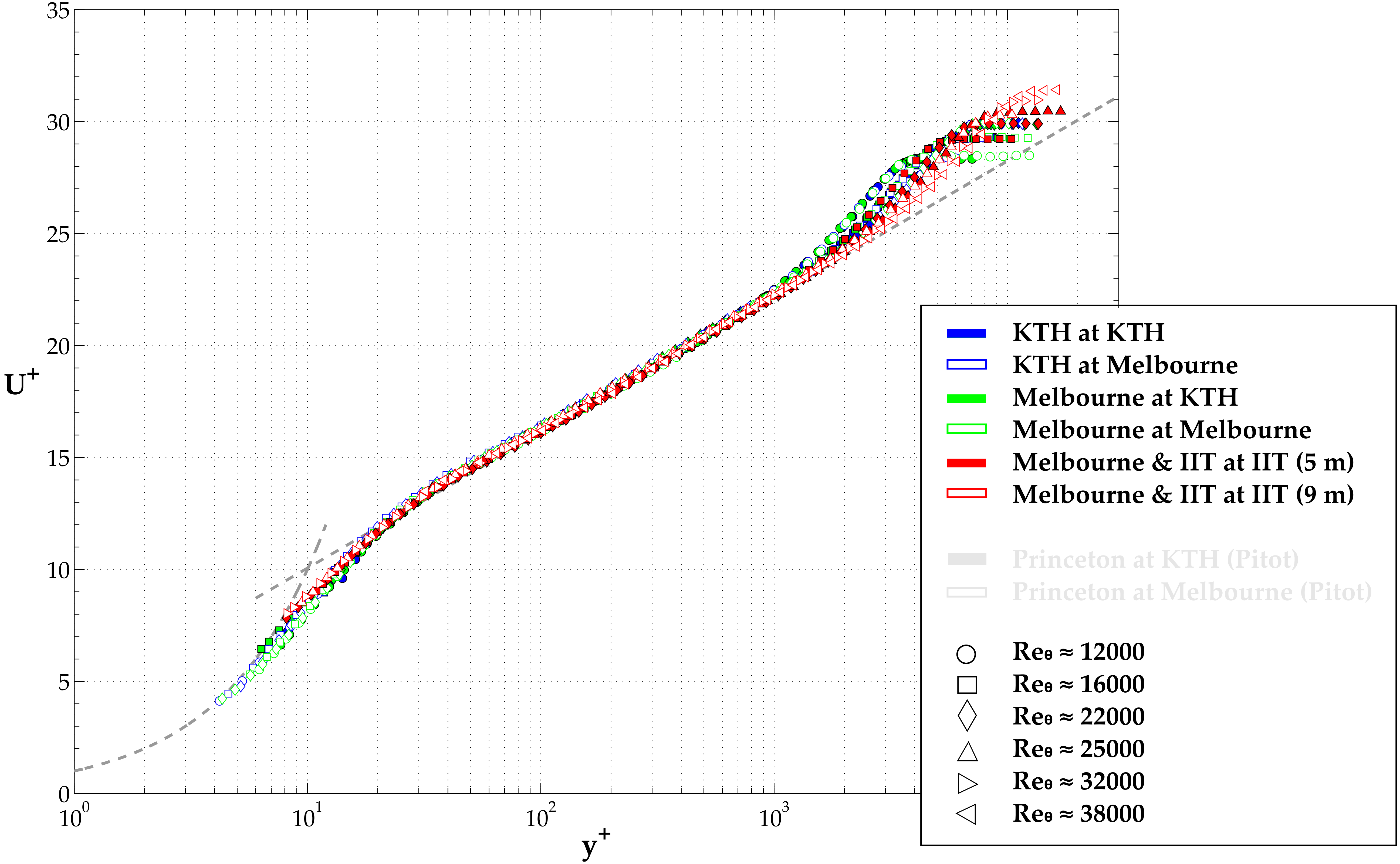
- $21x10^3$
- $44x10^3$
- $67x10^3$

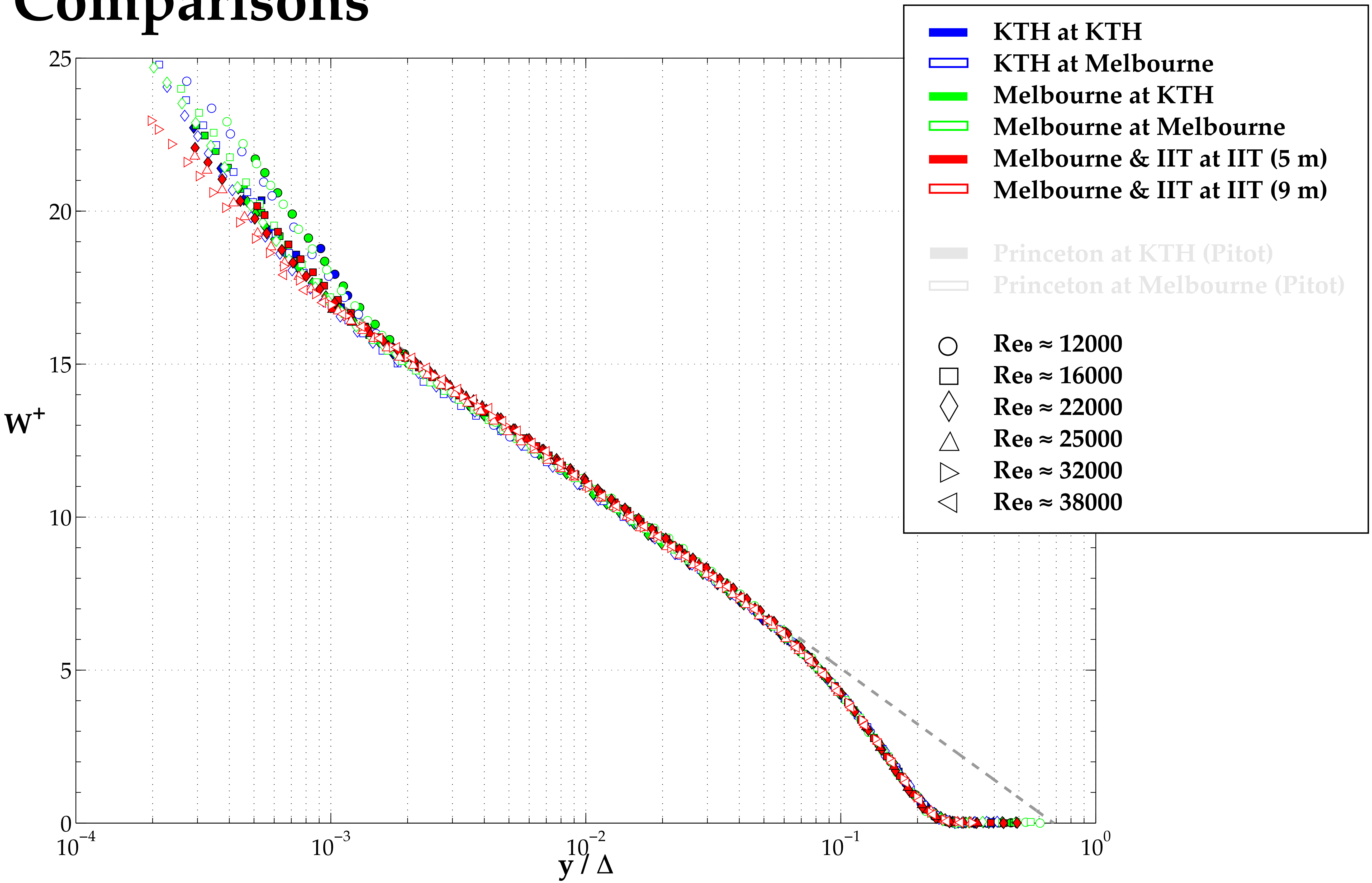
2 Facilities:

- KTH
- Melbourne

Comparisons



Comparisons



Integral and fit parameters

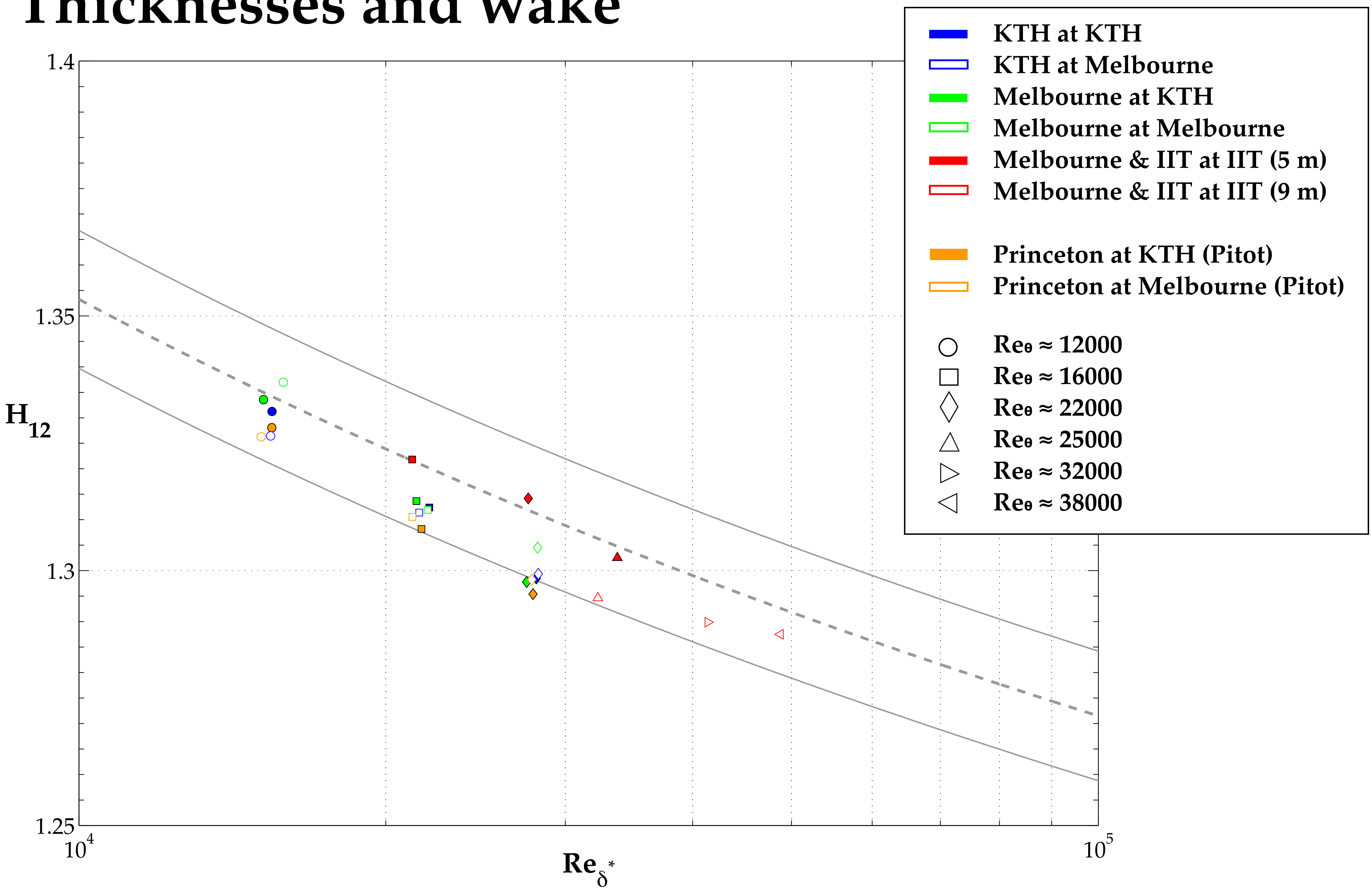
- All parameters computed using fits to the composite function of Chauhan et. al. (2008)

$$U^+ = \frac{1}{\kappa}\ln\left(\frac{y^+ - a}{-a}\right) + \frac{R^2}{a(4\alpha - a)}\left[(4\alpha + a)\ln\left(-\frac{a}{R}\frac{\sqrt{(y^+ - \alpha)^2 + \beta^2}}{y^+ - a}\right) + \frac{\alpha}{\beta}(4\alpha + 5a)\left(\arctan\left(\frac{y^+ - a}{\beta}\right) + \arctan\left(\frac{\alpha}{\beta}\right)\right)\right] + \frac{e^{-\left(\ln\left(\frac{y^+}{30}\right)\right)^2}}{2.85} + \frac{2\Pi}{\kappa}W_{\exp}\left(\frac{y}{\delta}\right)$$

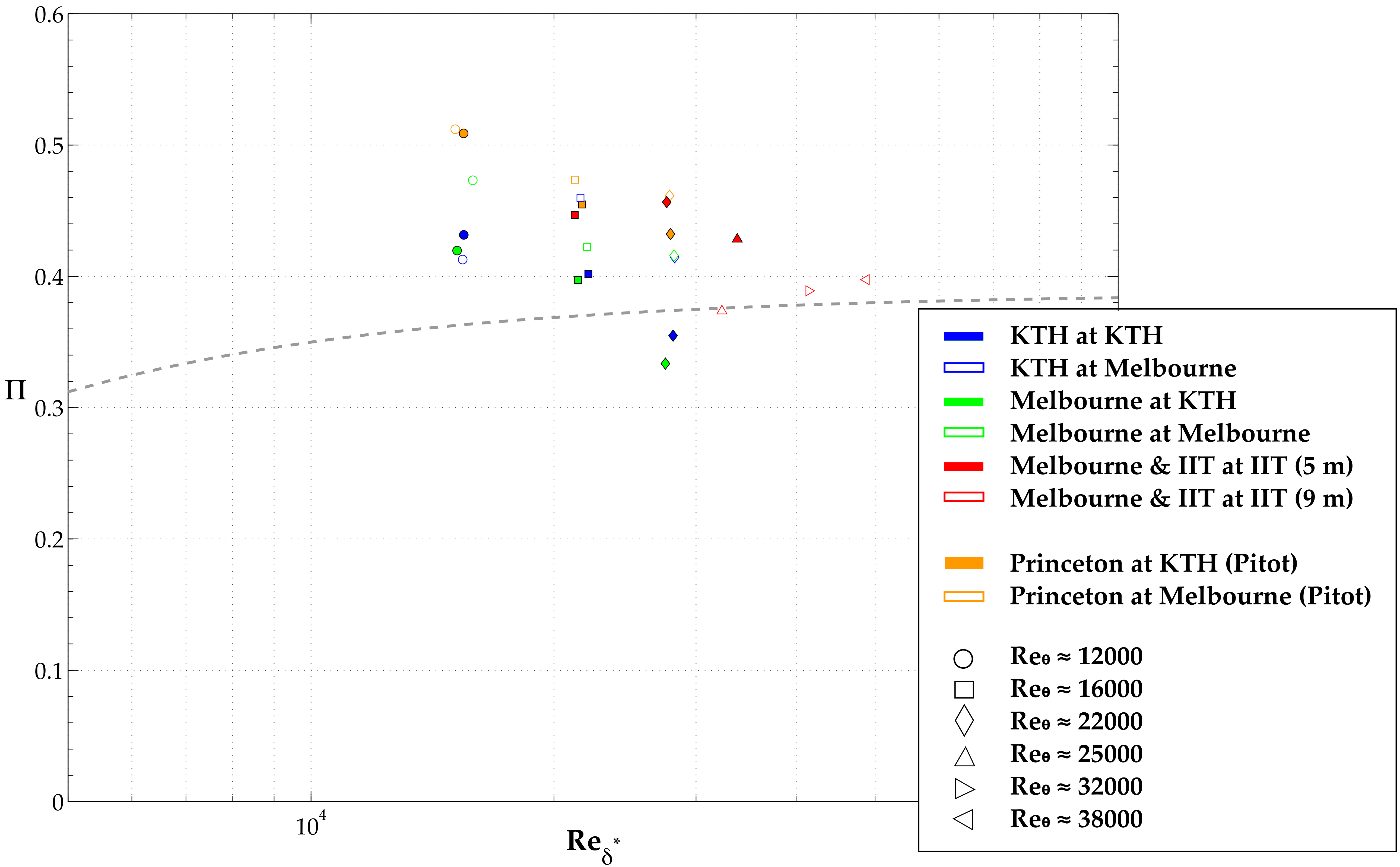
$$\alpha = \frac{1}{2}\left(\frac{-1}{\kappa} - a\right), \beta = \sqrt{-2a\alpha - \alpha^2}, R = \sqrt{\alpha^2 + \beta^2}$$

  - Π determined as a parameter of the fitting procedure of the composite to U vs. y for each profile.
  - δ* and θ determined from direct numerical integration of the composite using parameters unique to each profile.

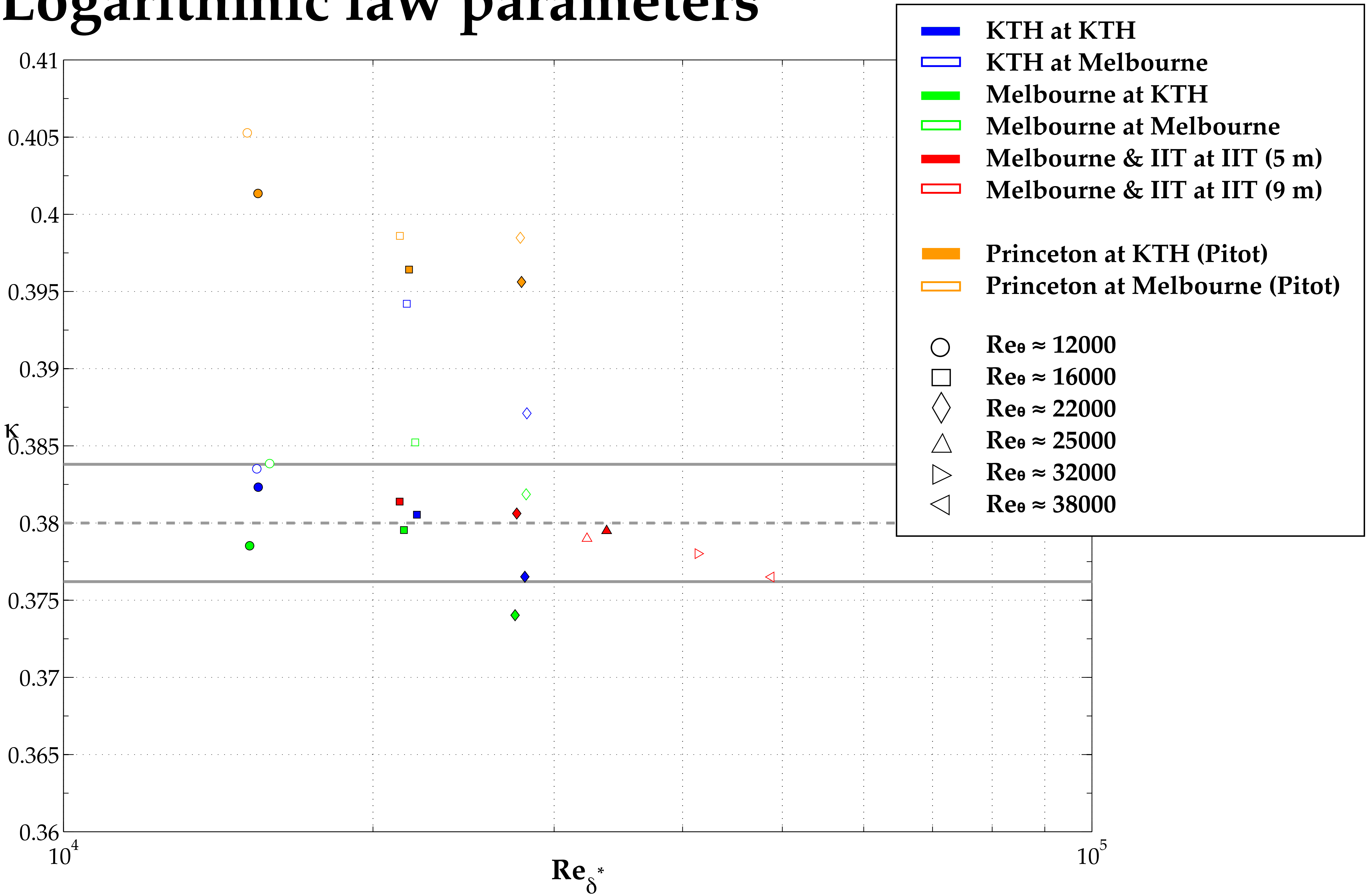
Thicknesses and wake



Thicknesses and wake



Logarithmic law parameters



R. DUNCAN, N. HUTCHINS, A. SEGALINI, J. MONTY and THE ICET TEAM

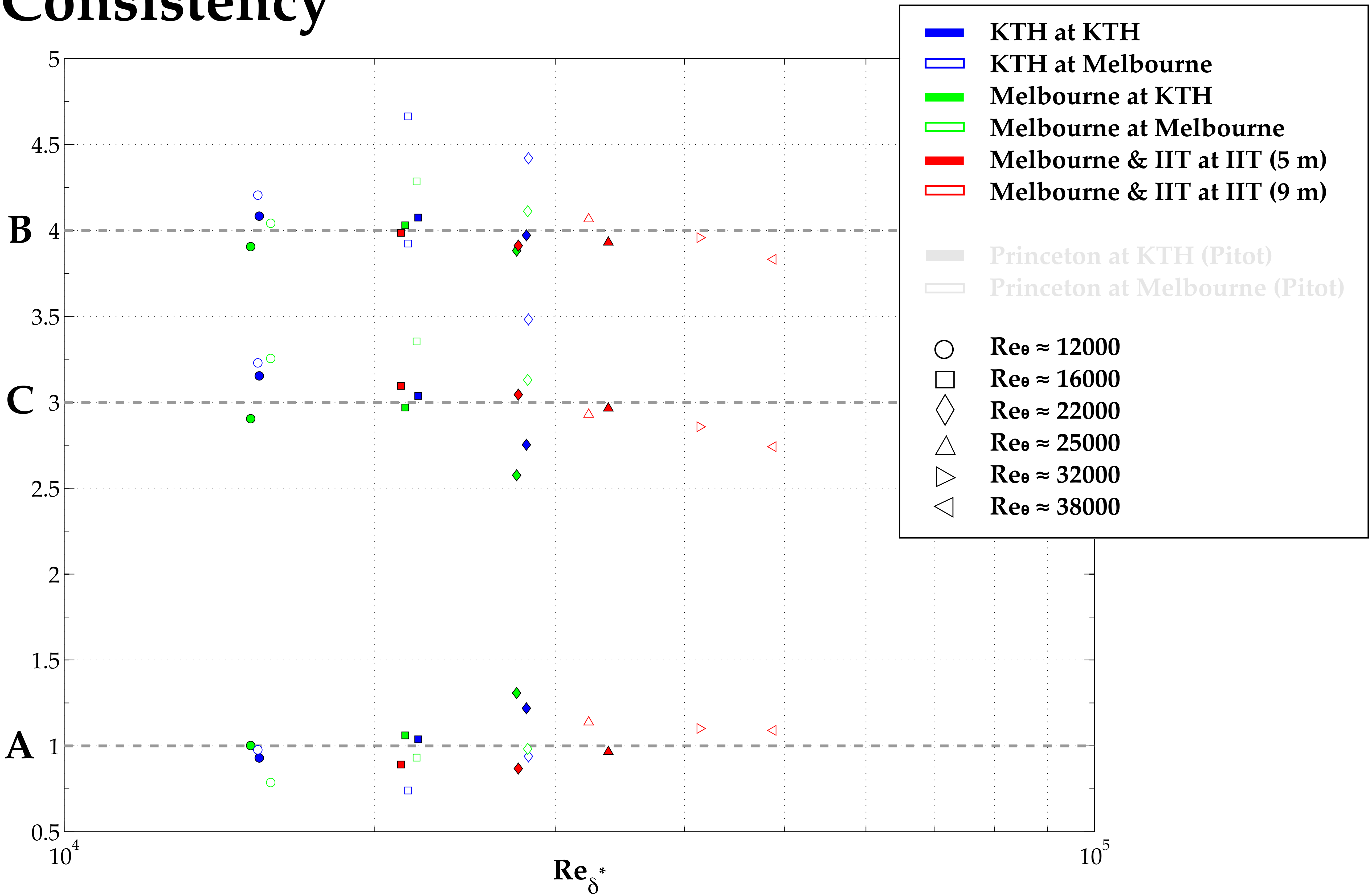
Consistency

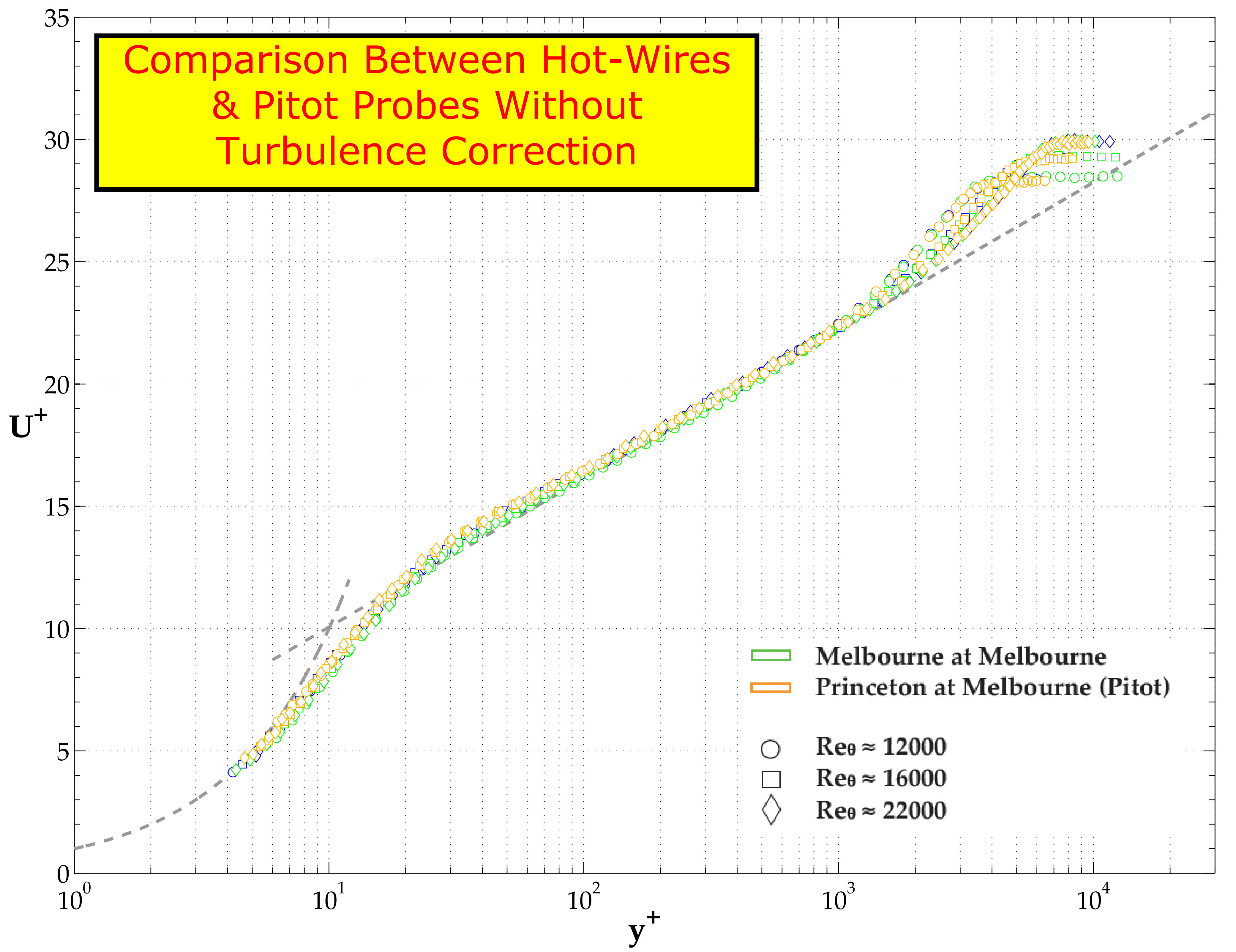
- For consistency between mean profiles and skin friction relation, the additive constants must agree

$$\left.\begin{aligned} U^+ &= \frac{1}{\kappa}\ln y^+ + B \\ W^+ = U_\infty^+ - U^+ &= -\frac{1}{\kappa}\ln\left(\frac{y}{\Delta}\right) - A \end{aligned}\right\} \longrightarrow U_\infty^+ = \frac{1}{\kappa}\ln Re_{\delta^*} + C$$

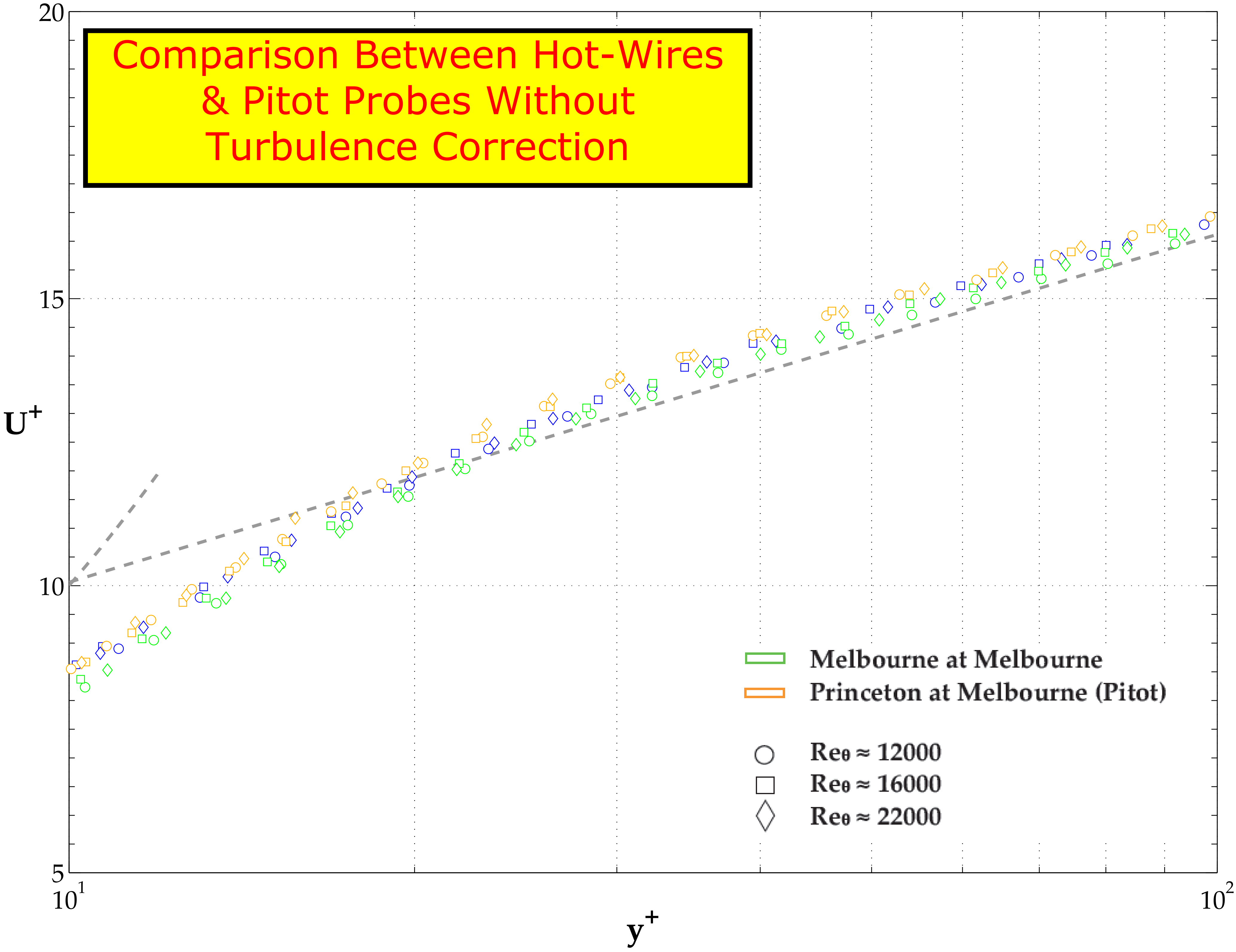
- With κ = 0.38 and C = 3, B - A = 3 would result in perfect consistency
  - Each dashed line shown before for velocity profiles used κ = 0.38 and B = 4, and κ = 0.38 and A = 1 for the defect
  - Monkewitz et. al. (2007) - κ = 0.384, B = 4.17, C = 3.3, A = 0.87

Consistency

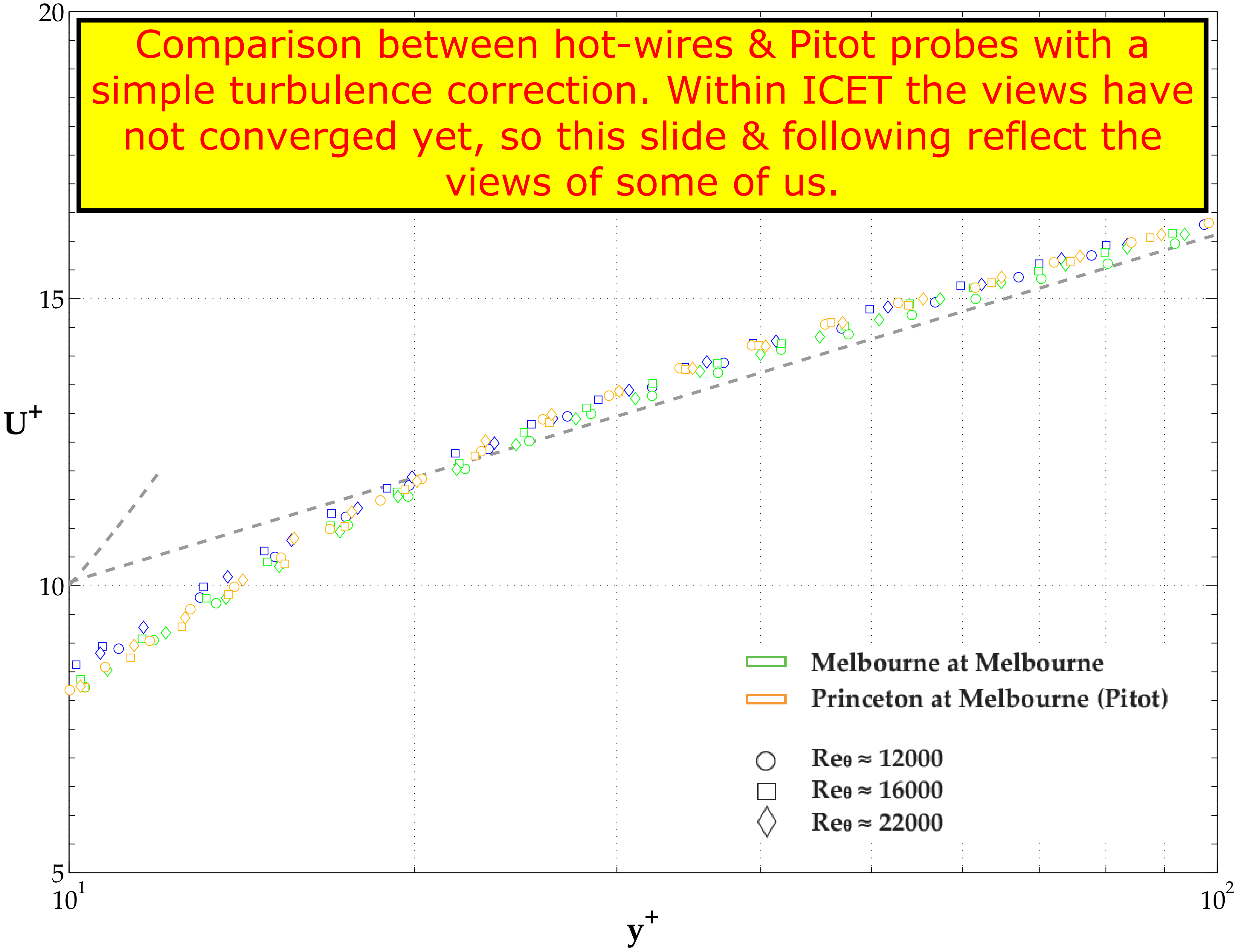




Comparison Between Hot-Wires
& Pitot Probes Without
Turbulence Correction
Melbourne at Melbourne
Princeton at Melbourne (Pitot)
Reθ ≈ 12000
Reθ ≈ 16000
Reθ ≈ 22000
U+
y+
0
5
10
15
20
25
30
35
10^0
10^1
10^2
10^3
10^4



Comparison Between Hot-Wires & Pitot Probes Without Turbulence Correction
20
15
10
5
U+
10^1
10^2
y+
Melbourne at Melbourne
Princeton at Melbourne (Pitot)
Reθ ≈ 12000
Reθ ≈ 16000
Reθ ≈ 22000


Comparison between hot-wires & Pitot probes with a simple turbulence correction. Within ICET the views have not converged yet, so this slide & following reflect the views of some of us.
20
15
10
5
U+
10^1
10^2
y+
Melbourne at Melbourne
Princeton at Melbourne (Pitot)
Reθ ≈ 12000
Reθ ≈ 16000
Reθ ≈ 22000

Turbulence correction

For turbulent flows, Goldstein (1936) and others have suggested

$$\frac{1}{2}\rho\left(U^2 + \overline{u'^2}\right) = \Delta P$$

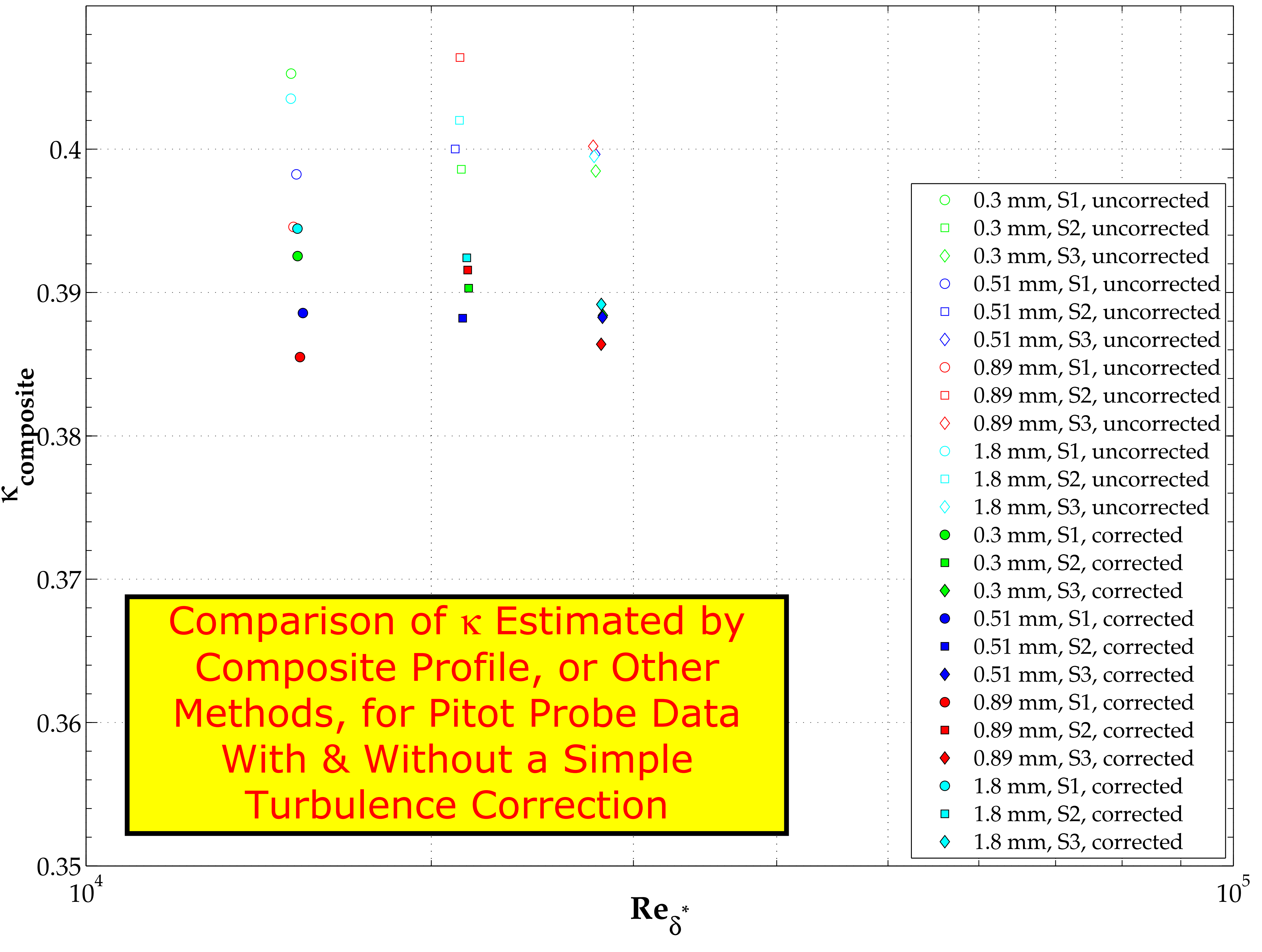
A simple correction to the measured mean velocity is then

$$\frac{U_{TC}}{U_\tau} = \sqrt{\left(\frac{U_m}{U_\tau}\right)^2 - \frac{\overline{u'^2}}{U_\tau^2}} \ ; \text{ where, } U_m = \sqrt{\frac{2}{\rho}\Delta p}$$

i.e., subtract off the turbulence intensity.

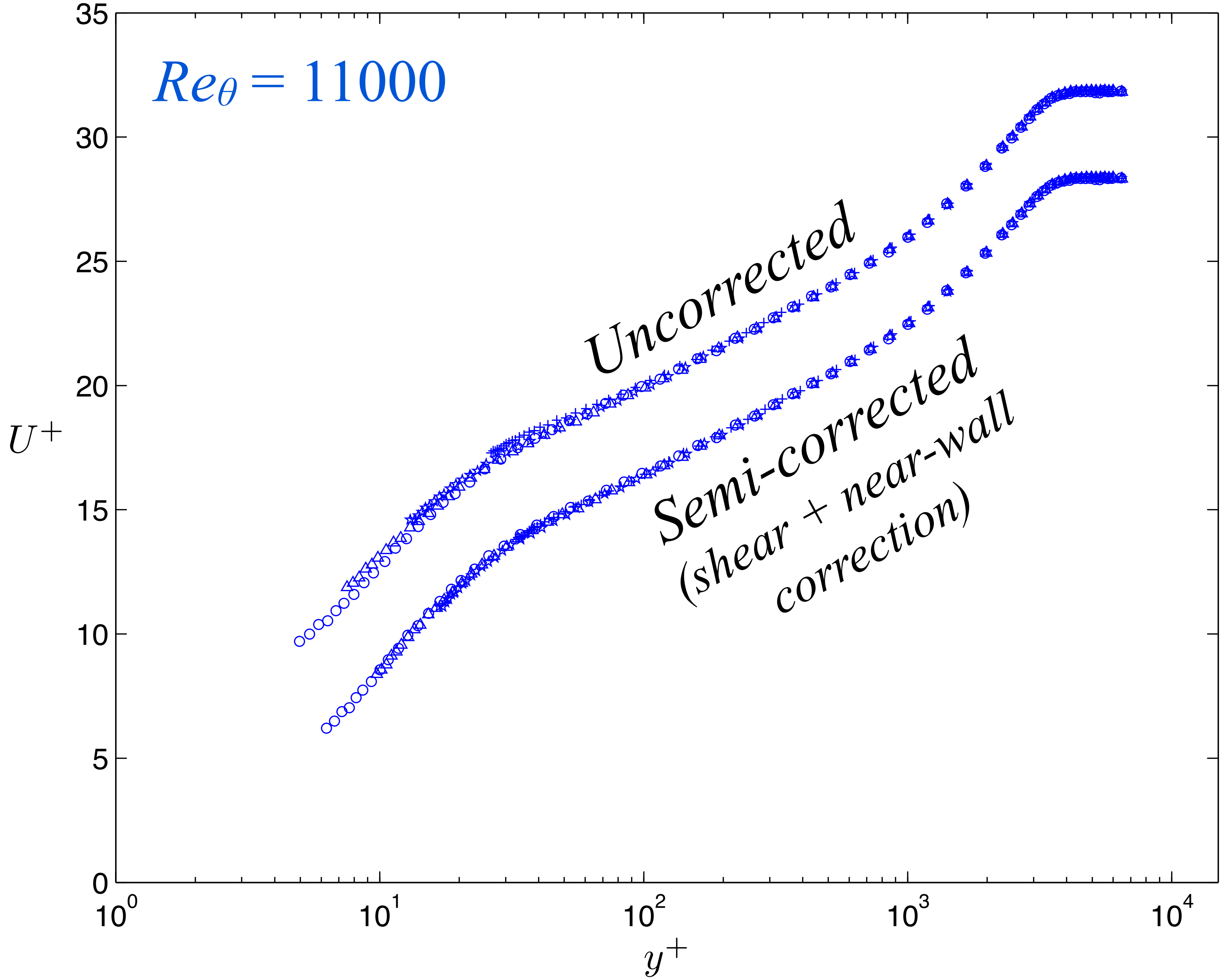
Refer to ***TC corrected*** as

shear + near-wall + turbulence corrected



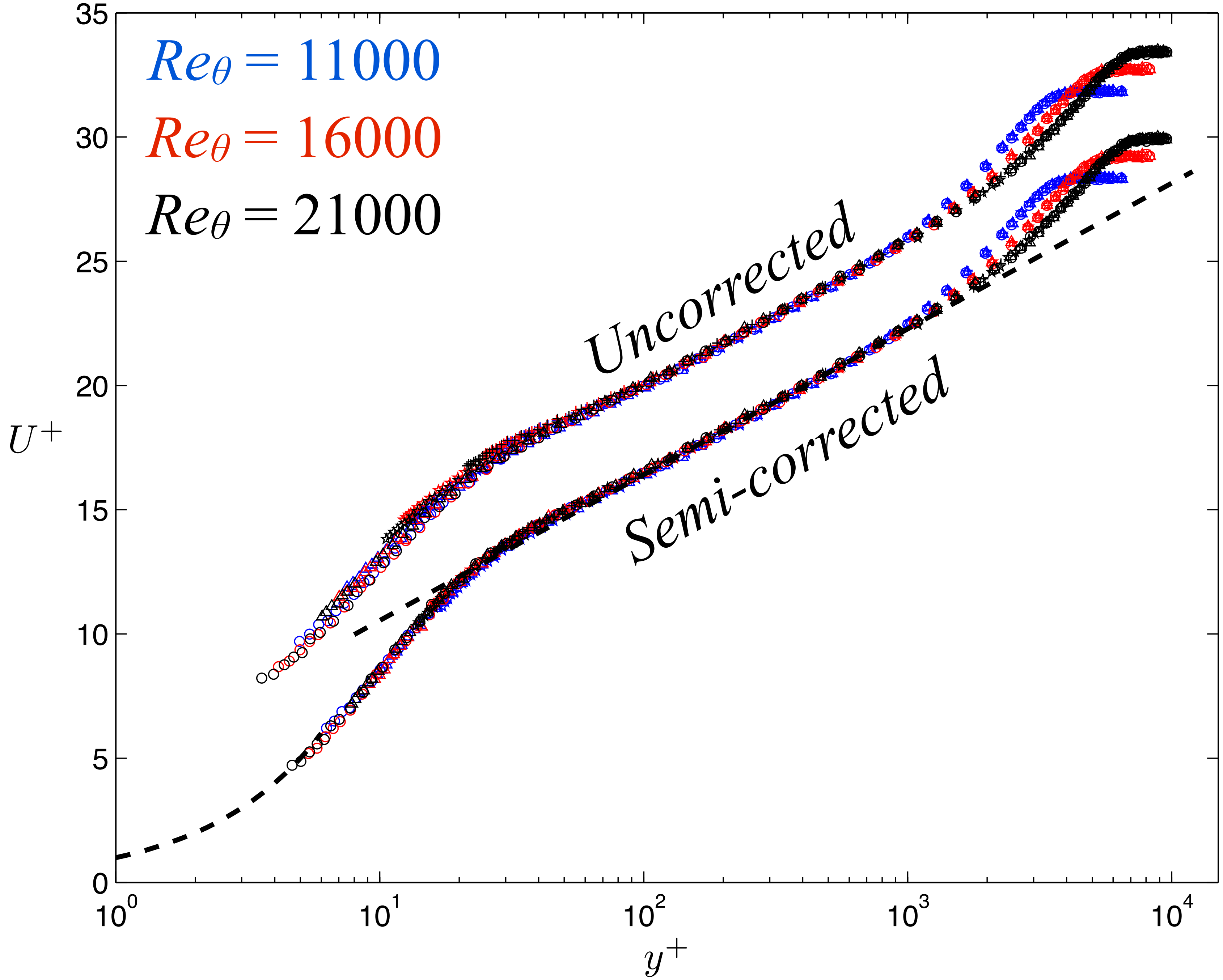
Comparison of κ Estimated by Composite Profile, or Other Methods, for Pitot Probe Data With & Without a Simple Turbulence Correction
0.3 mm, S1, uncorrected
0.3 mm, S2, uncorrected
0.3 mm, S3, uncorrected
0.51 mm, S1, uncorrected
0.51 mm, S2, uncorrected
0.51 mm, S3, uncorrected
0.89 mm, S1, uncorrected
0.89 mm, S2, uncorrected
0.89 mm, S3, uncorrected
1.8 mm, S1, uncorrected
1.8 mm, S2, uncorrected
1.8 mm, S3, uncorrected
0.3 mm, S1, corrected
0.3 mm, S2, corrected
0.3 mm, S3, corrected
0.51 mm, S1, corrected
0.51 mm, S2, corrected
0.51 mm, S3, corrected
0.89 mm, S1, corrected
0.89 mm, S2, corrected
0.89 mm, S3, corrected
1.8 mm, S1, corrected
1.8 mm, S2, corrected
1.8 mm, S3, corrected
κ composite
Re δ*
0.4
0.39
0.38
0.37
0.36
0.35
10^4
10^5

Pitot data from Melbourne



- Uncorrected data compared with shear + near-wall correction

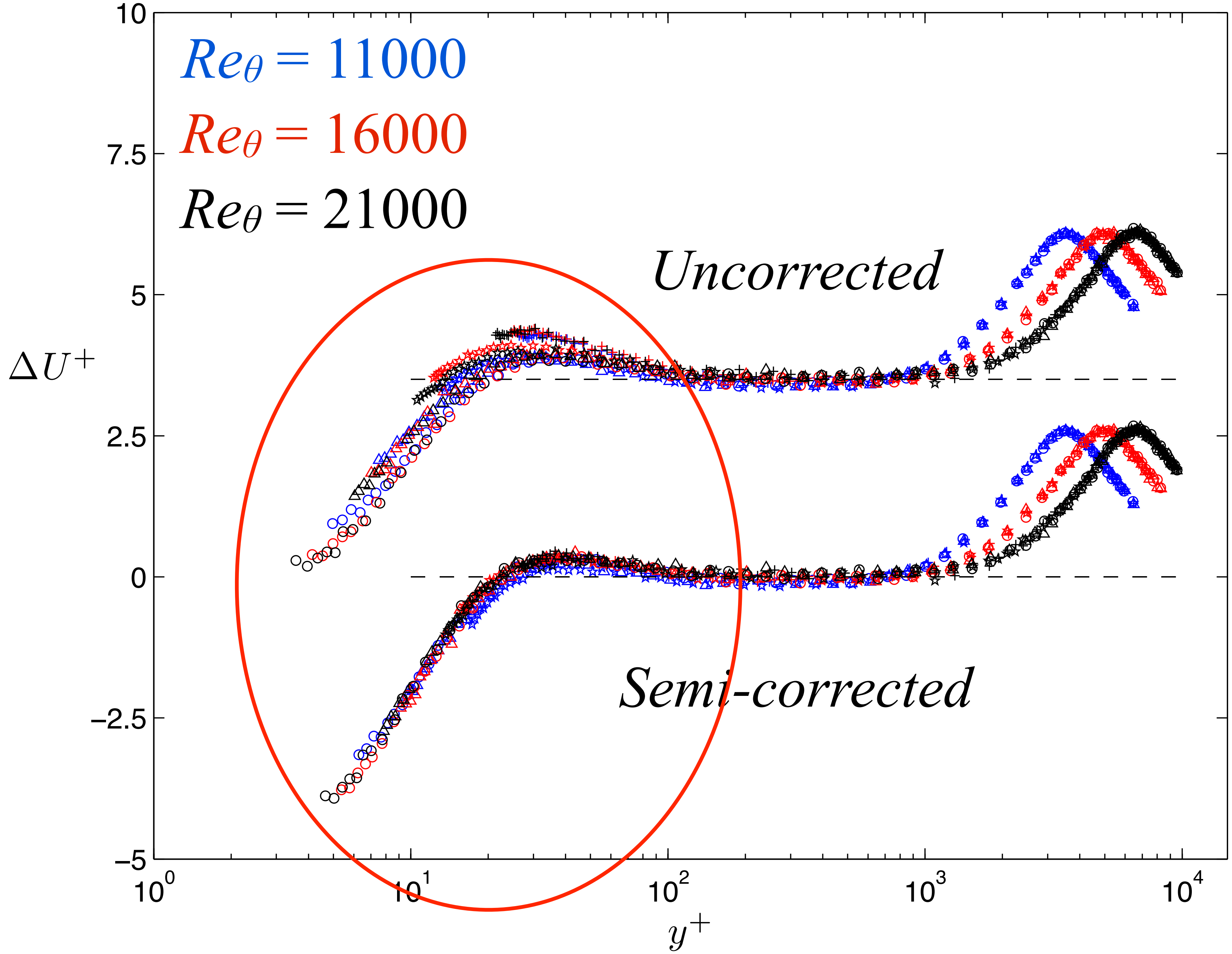
Subtract log law from the data



- Log law determined from ALL semi-corrected data:

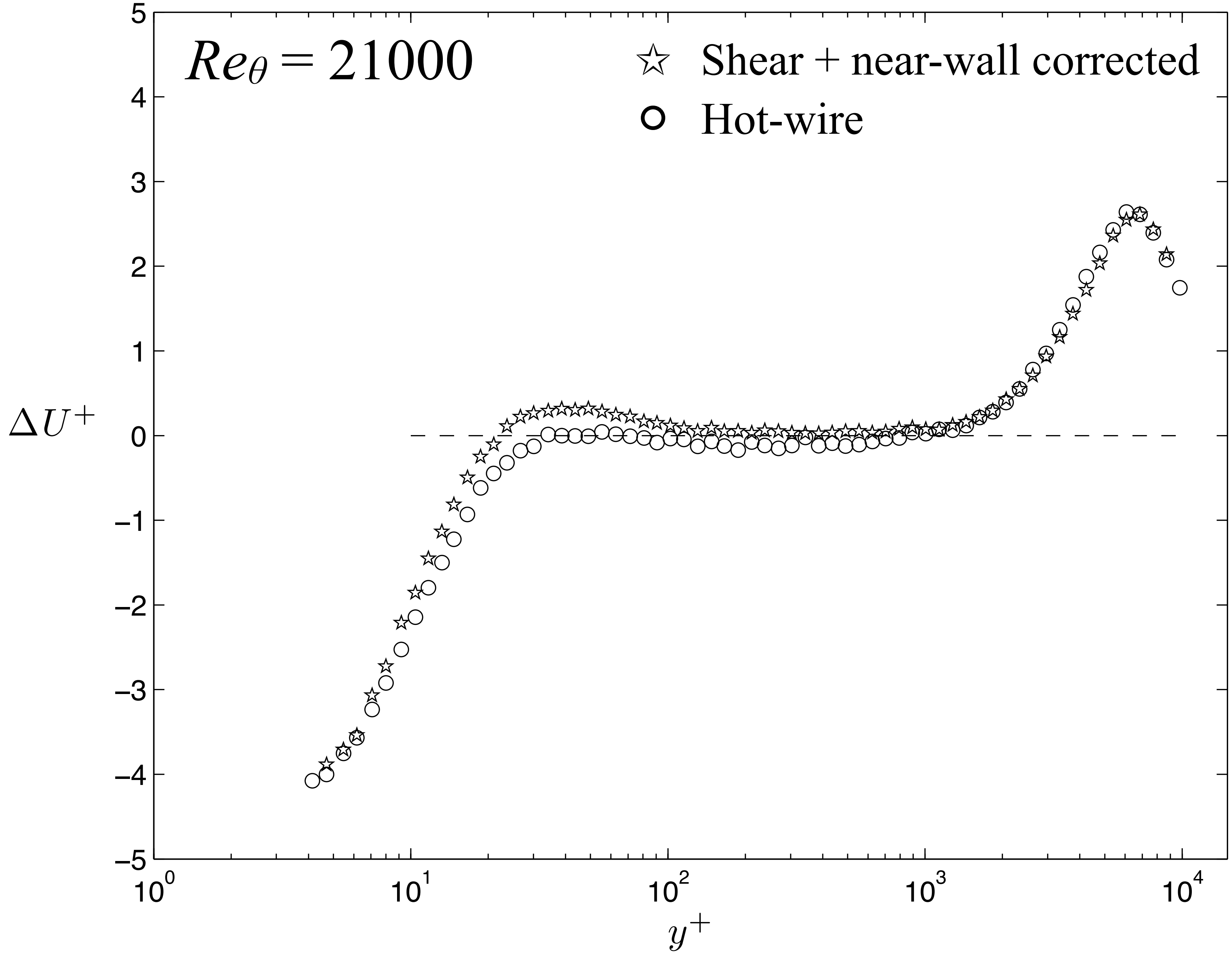
$$\frac{U}{U_\tau} = \frac{1}{0.393} \log\left(y^+\right) + 4.67$$

Difference between Pitot data and log law



The shear and near-wall corrections collapse the data

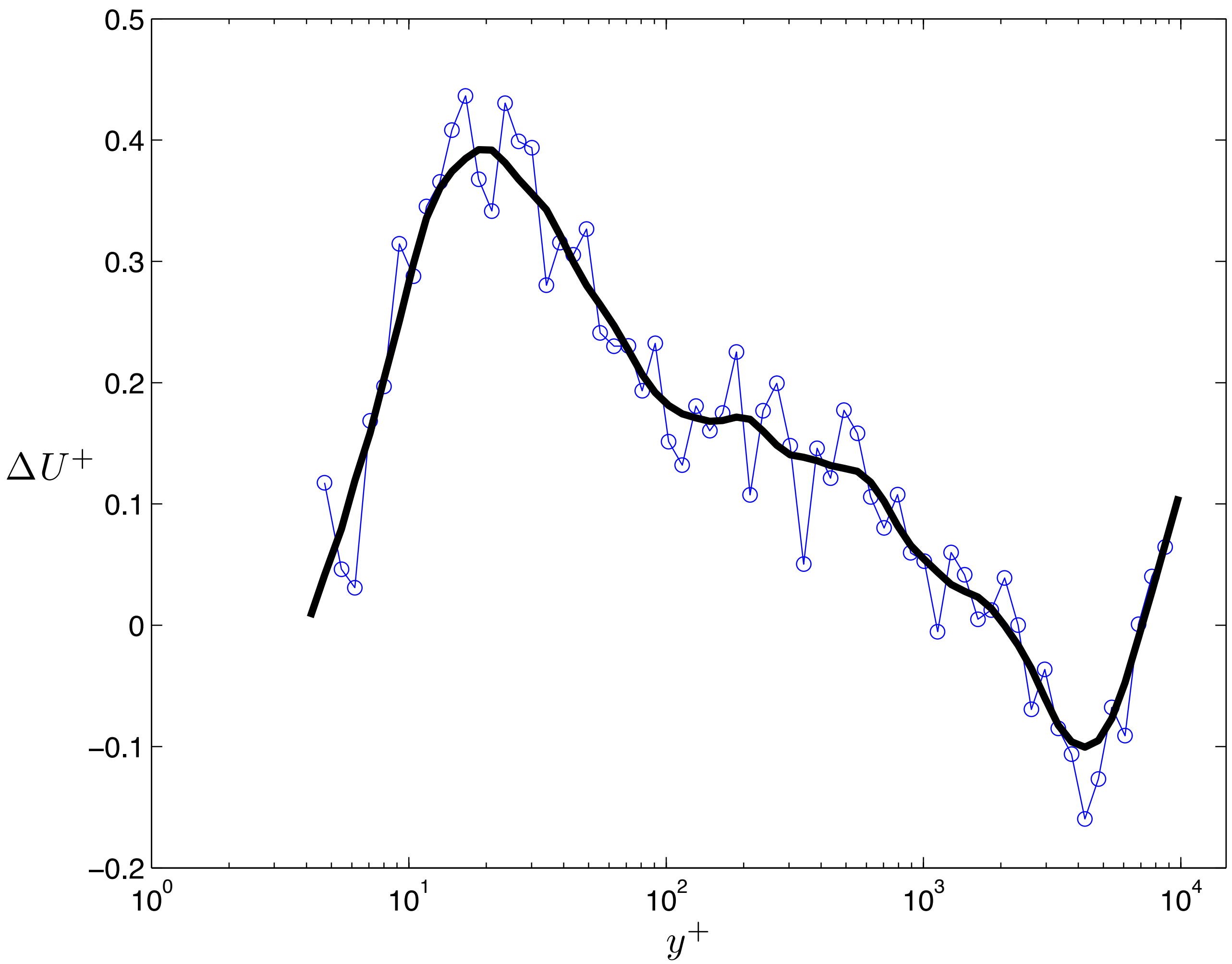
Pitot and Hot-wire



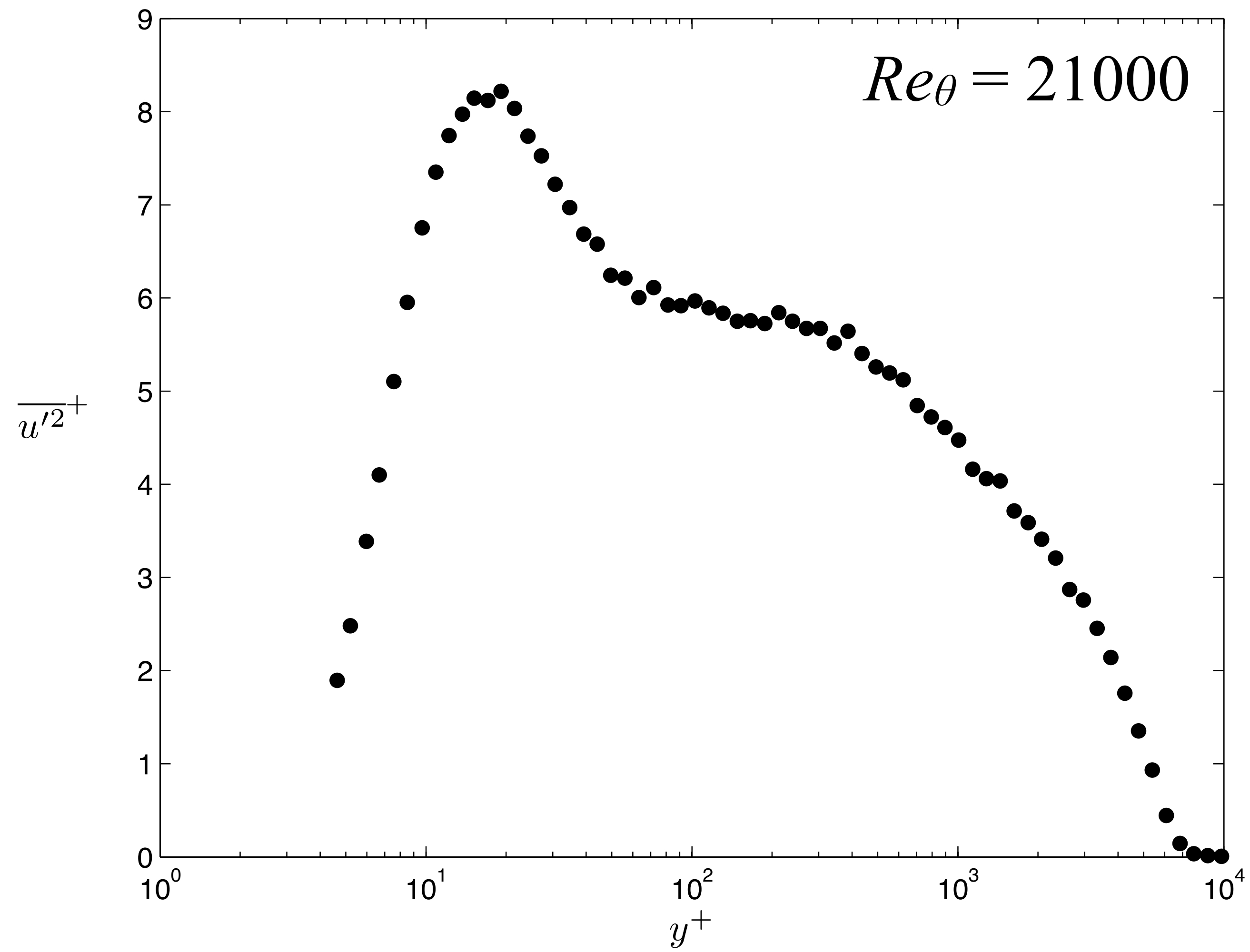
Comparing hot-wire and pitot difference from log law

(ensemble average of all pitot data interpolated onto hot-wire data coords.)

Difference between Pitot data and log law



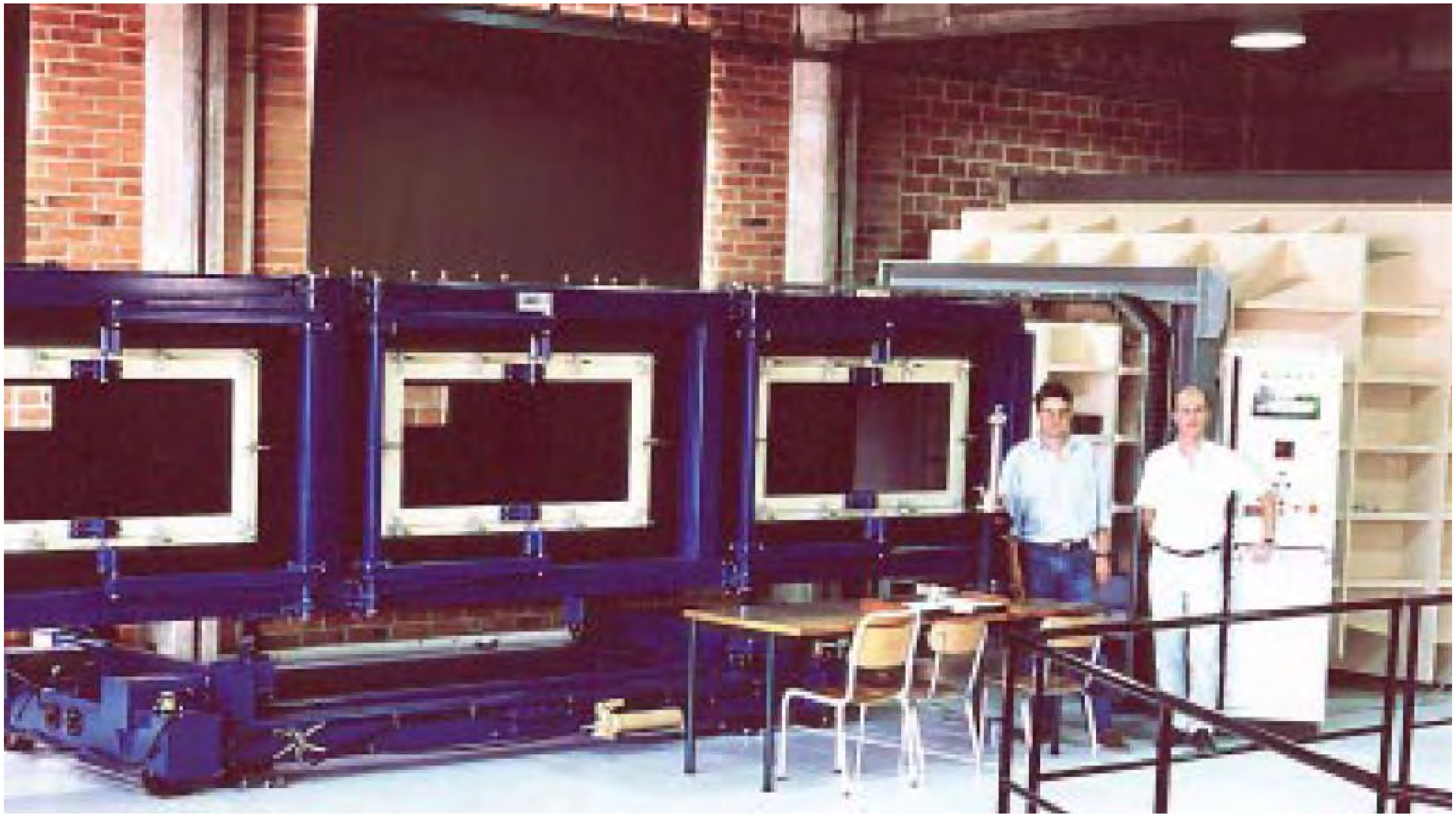
Difference between
Pitot data and hot-wire

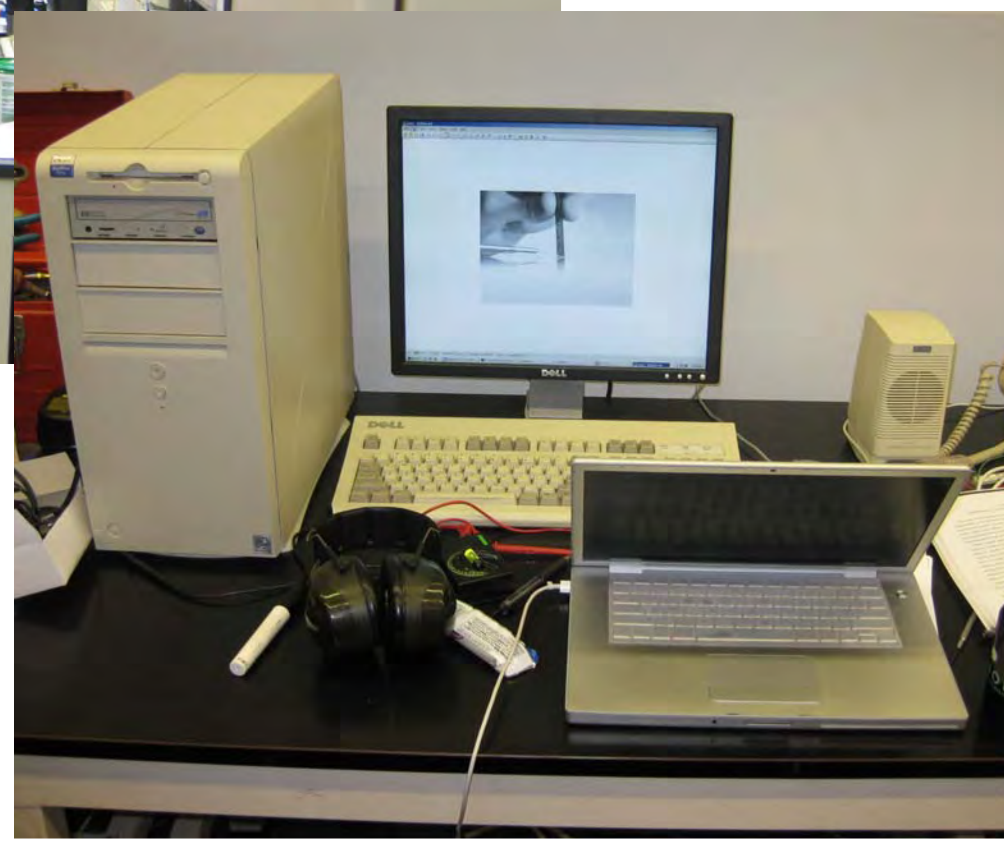


Hot-wire measured
turbulence intensity
(variance of velocity fluctuations)

Conclusions

- See next six talks.
- Criteria regarding the acceptable tolerance in streamwise pressure gradient for ZPG boundary layers have been better defined.
- The requirement of direct and accurate measurements of wall-shear has been reinforced, and caution has again been demonstrated for use of correlations based on other experiments, that may not be representative.
- We have a great deal more to learn from the data we have gathered over last two years and their comparison to other measurements and recent DNS results.
- The need for turbulence correction for Pitot measurements is an important aspect of continuing efforts within ICET. These turbulence corrections could bring the values of the estimated κ closer to those based on hot-wire measurements in the same boundary layer.





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i.e., subtract off the turbulence intensity.

Refer to ***TC corrected*** as

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APS Session
on

Turbulent Boundary Layers: Experimental Studies

1. ICET - International Collaboration on Experiments in Turbulence: Coordinated Measurements in High Reynolds Number Turbulent Boundary Layers from Three Facilities. H. NAGIB, A. SMITS, I. MARUSIC, P. H. ALFREDSSON and ICET Team.

2. Accurate and Independent Measurements of Wall-Shear Stress in Turbulent Flows. J-D. RÜEDI, R. DUNCAN, S. IMAYAMA, K. CHAUHAN and ICET Team.

3. Pitot Probe Corrections for Measurements in Turbulent Boundary Layers. J. MONTY, S. BAILEY, M. HULTMARK, B. McKEON and ICET Team.

4. Challenges in Hot Wire Measurements in Wall-Bounded Turbulent Flows. R. ÖRLU, N. HUTCHINS, T. KURIAN, A. TALAMELLI and ICET Team.

5. Mean Flow Measurements with Pitot Probes in High Reynolds Number Boundary Layers. S. BAILEY, M. HULTMARK, R. DUNCAN, B. McKEON and ICET Team.

6. Mean Flow Measurements with Hot Wires in High Reynolds Number Boundary Layers. R. DUNCAN, N. HUTCHINS, A. SEGALINI, J. MONTY and ICET Team.

7. Turbulence Measurements with Hot Wires in High Reynolds Number Boundary Layers. J. FRANSSON, N. HUTCHINS, R. ÖRLU, M. CHONG and ICET Team.