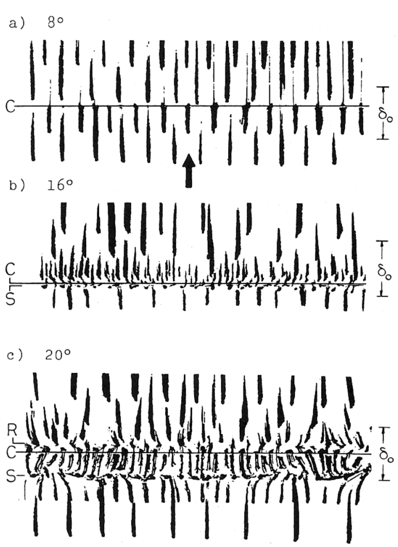
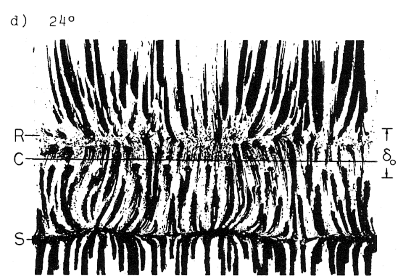
Some observations on experiments

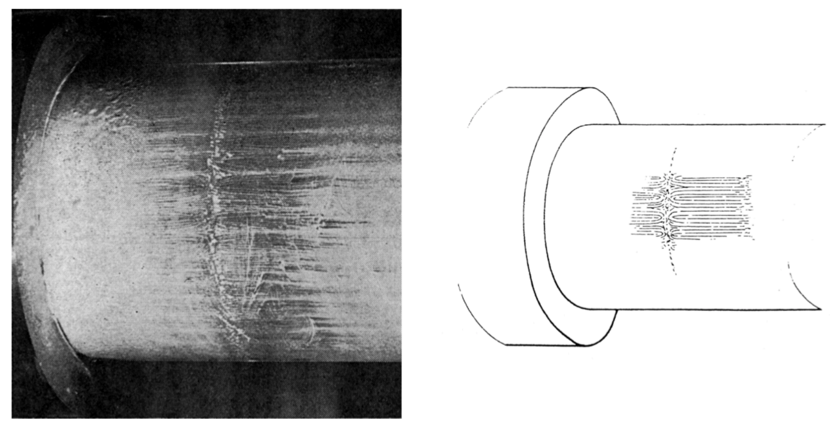
- Never measure anything twice (but of course we must)
- Skin friction versus Reynolds number for flat plates
  - Any one experiment only covers a range of Reynolds numbers
  - Initial conditions are important and wash out slowly
  - Boundary conditions are important, e.g., width of plate or tunnel
  - Need zero pressure gradient, but what is close enough?
  - Need to be smooth (problem at high Reynolds number

- 3D effects in nominally 3D flows



Settles et al. (1979)
at Mach 2.9





Roshko and Thomke (1966) at M = 3.20

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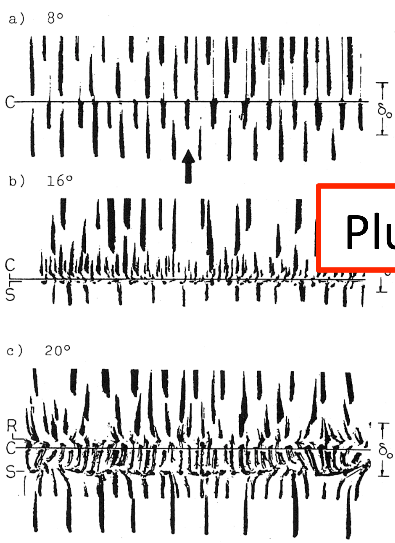
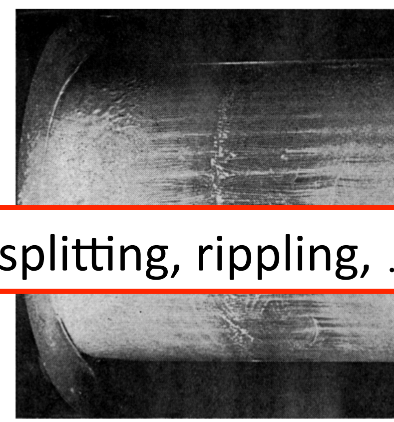
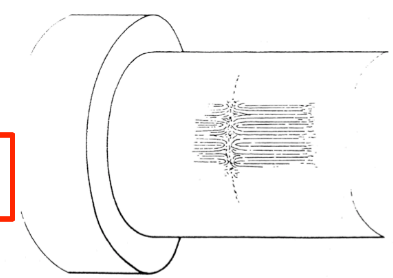


Settles et al. (1979)
at Mach 2.9

Plus unsteadiness, shock splitting, rippling, …



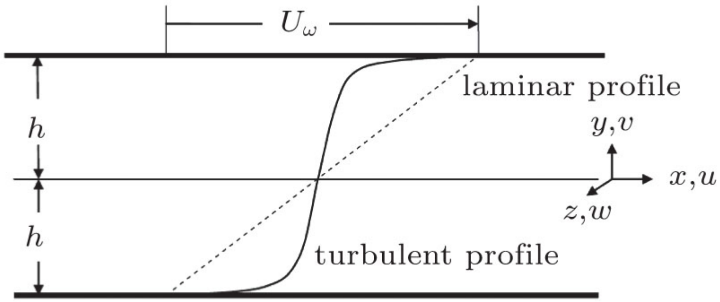


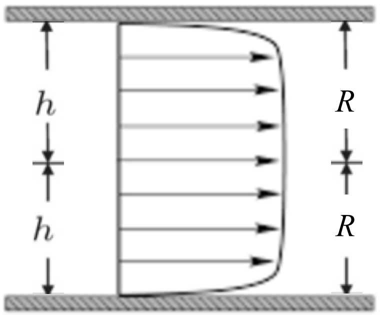
Roshko and Thomke (1966) at M = 3.20

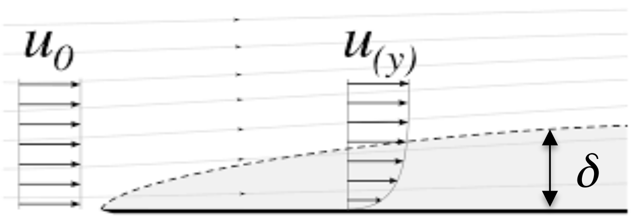
Canonical wall-bounded flows

1. Plane Couette flow, 2D in the mean (w/h >> 1)
2. Fully-developed channel flow of high aspect ratio (L/h >> 1, w/h >> 1)
3. Fully-developed pipe flow (L/D >> 1)
4. Turbulent boundary layer, flat plate, zero pressure gradient, 2D in the mean, free of transitional or tripping effects (L/δ >> 1, w/δ >>1)

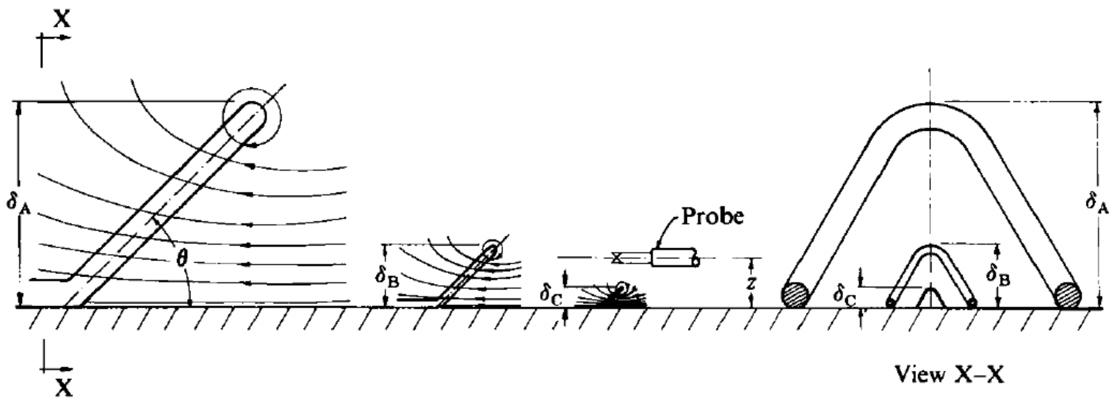
5. Also Ekman layers, Taylor-Couette flows, Rayleigh-Bénard convection, …







Townsend’s attached eddy hypothesis (1976)



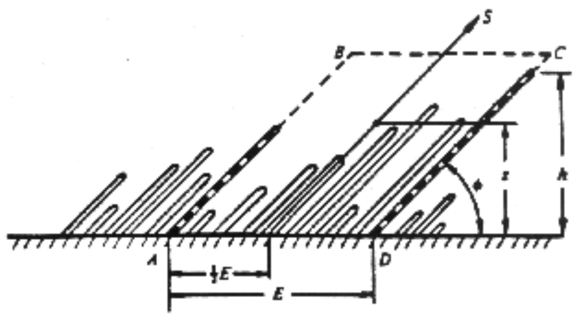
Perry, Henbest & Chong (1986)

Townsend’s attached eddy hypothesis (1976)

Townsend: “It is difficult to imagine how the presence of the wall could impose a dissipation length-scale proportional to distance from it unless the main eddies of the flow have diameters proportional to distance of their “centres” from the wall, because their motion is directly influenced by its presence. In other words, the velocity fields of the main eddies, regarded as persistent, organized flow patterns, extend to the wall and, in a sense, they are attached to the wall.”

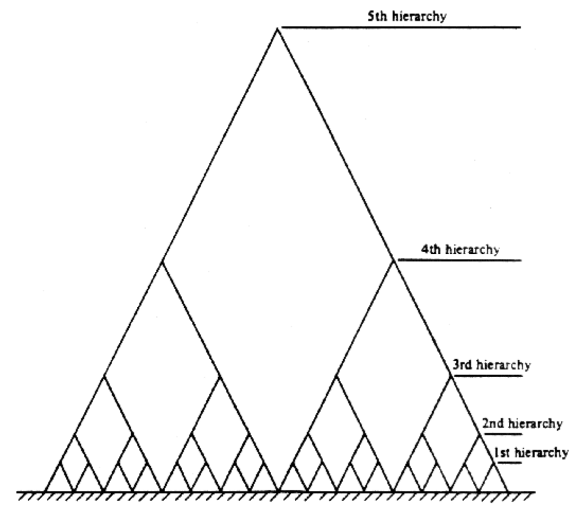
Perry: In this theory, wall turbulence is considered to consist of a 'forest' of randomly positioned horseshoe, hairpin or A-shaped vortices that lean in the streamwise direction and have their legs extending to the boundary.

Attached eddy concepts

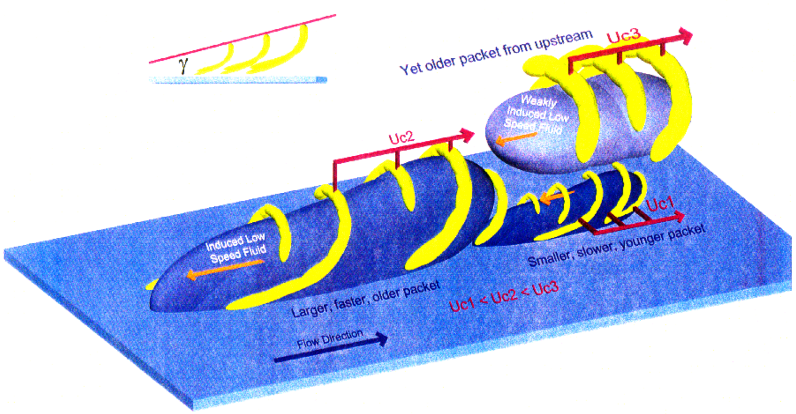


Random distribution of horseshoe vortices, from Perry and Chong's (1982) model of a turbulent boundary layer.

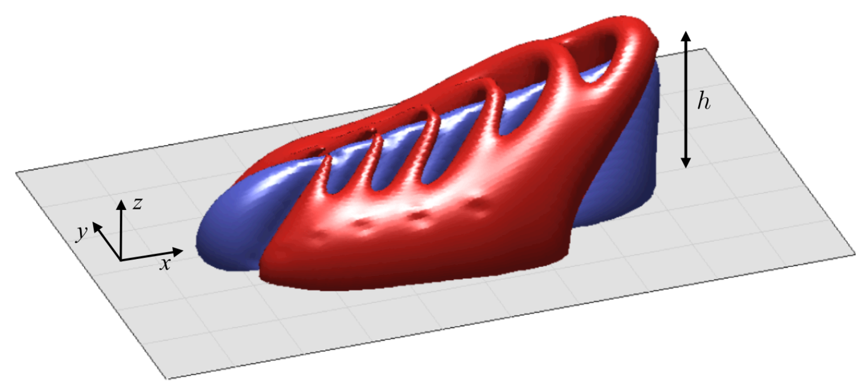
Hierarchical model of outer layer turbulence using Λ-eddies



Symbolic representation of a discrete system of geometrically similar eddy hierarchies from Perry and Chong [1982].

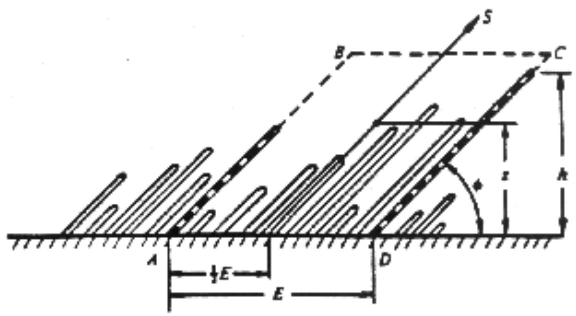


Adrian, Meinhart & Tomkins (1999)



Woodcock & Marusic (2015)

Attached eddy concepts



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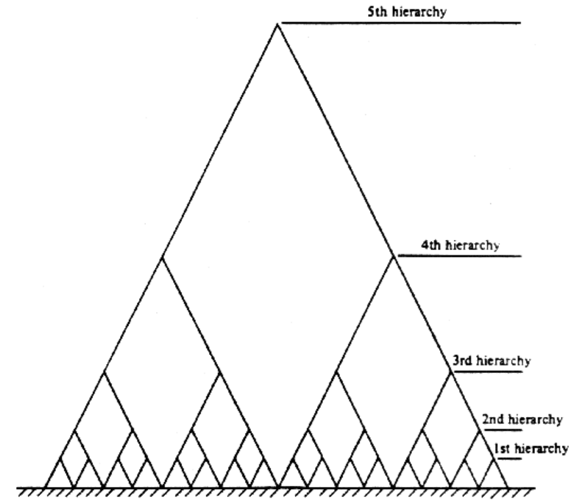

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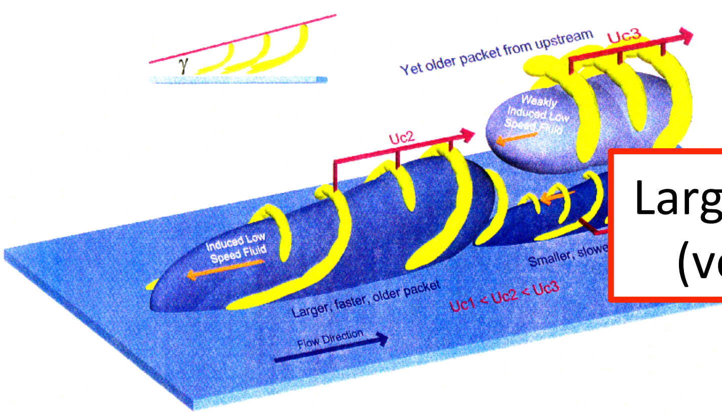
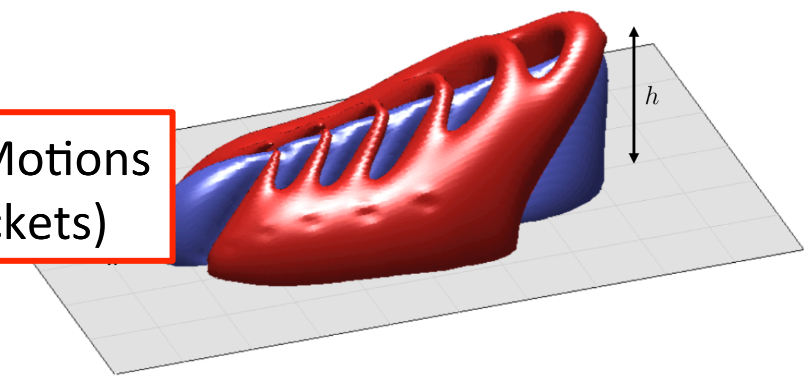


Large Scale Motions (vortex packets)



Adrian, Meinhart & Tomkins (1999)

Woodcock & Marusic (2015)

Attached Eddy Model predictions

At high enough Reynolds number, in the overlap region, where the characteristic motions scale with the distance form the wall:

$$
\begin{aligned}
\frac{\overline{u'^2}}{u_\tau^2} &= B_1 - A_1 \ln\left(\frac{y}{\delta}\right), \\
\frac{\overline{w'^2}}{u_\tau^2} &= B_3 - A_3 \ln\left(\frac{y}{\delta}\right), \\
\frac{\overline{v'^2}}{u_\tau^2} &= A_2.
\end{aligned}
$$

Townsend employed a heuristic model

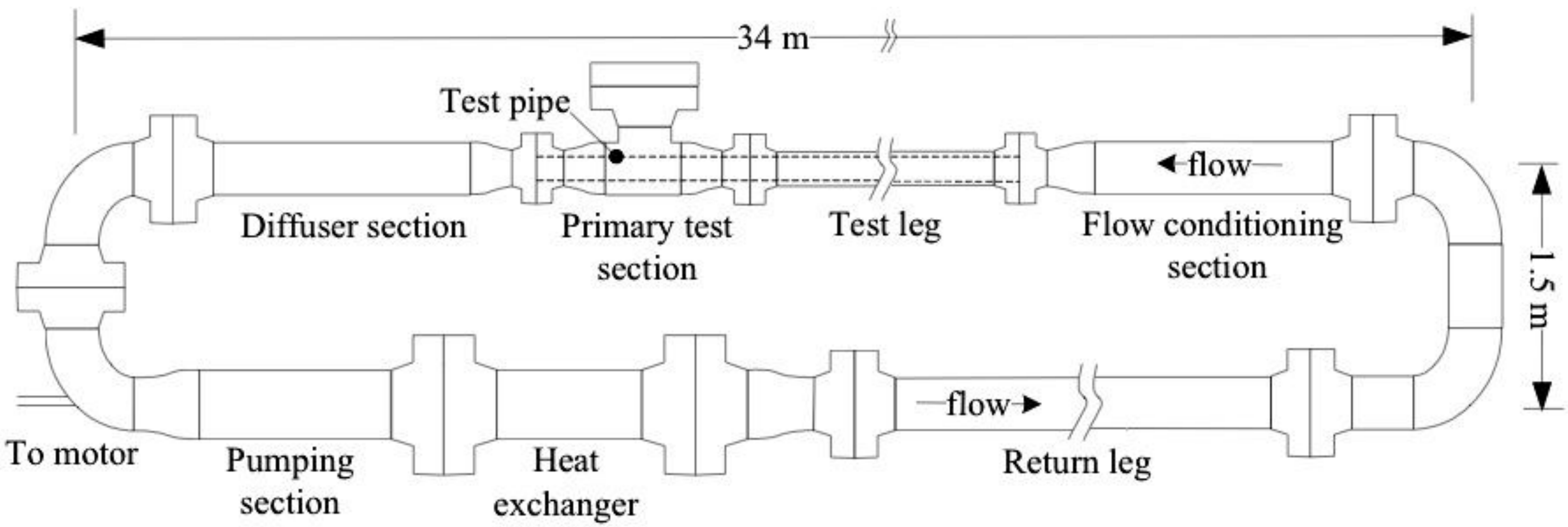
Perry used a spectral overlap argument

$$
U^+ = \frac{1}{\kappa} \ln y^+ + B
$$

Need high Reynolds number experiments

$$\frac{\overline{U}D}{\nu}$$

High Reynolds number in the lab: compressed air up to 200 atm as the working fluid

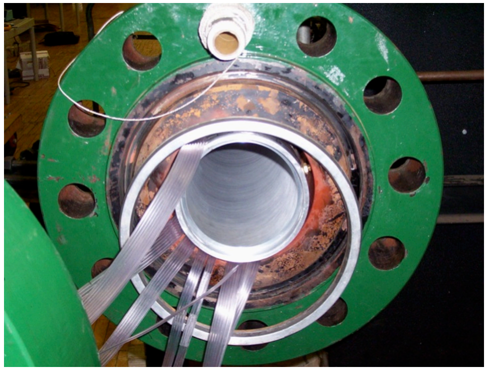


Fully-developed pipe flow experiments

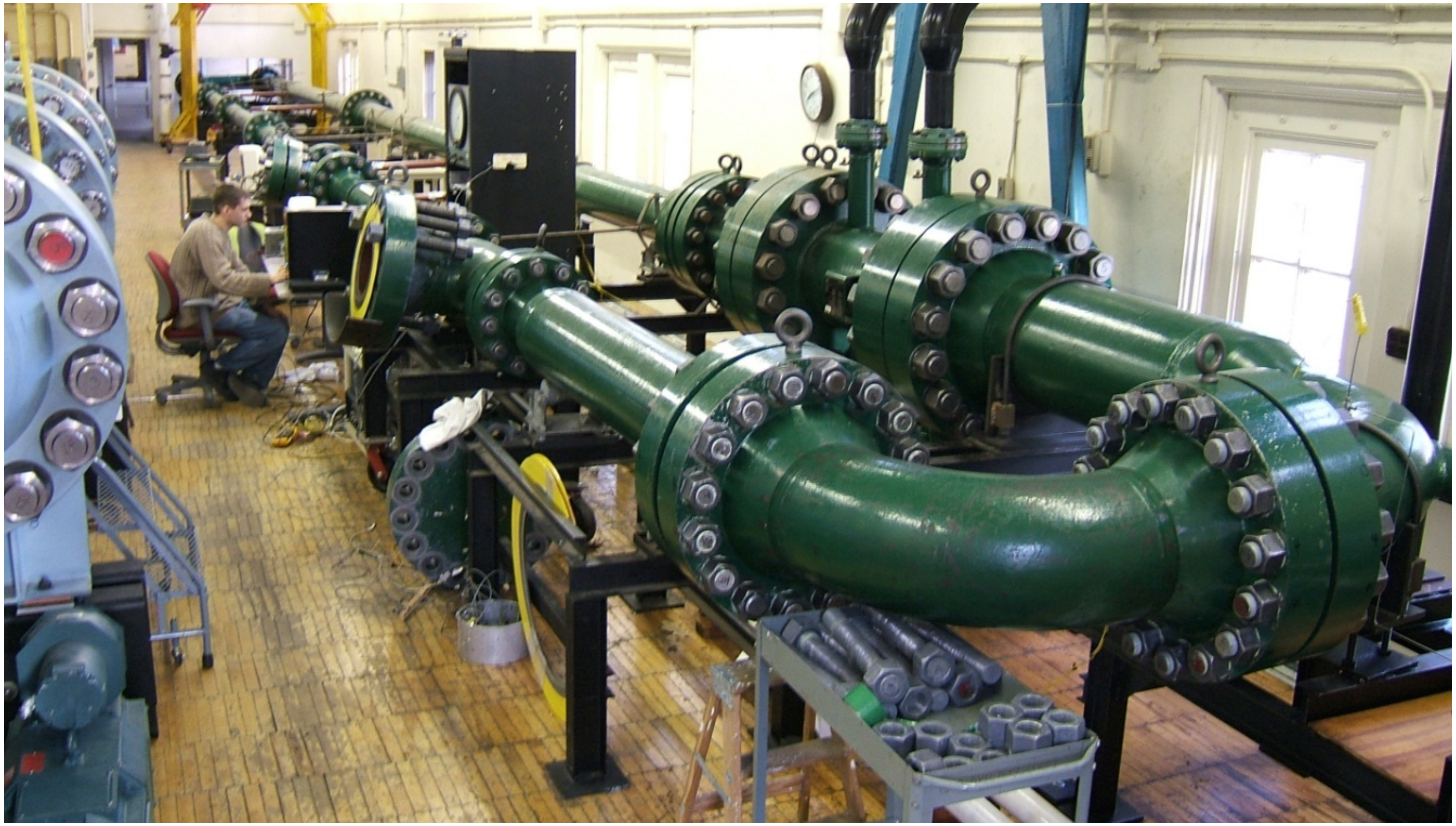
$$\boxed{\begin{gathered}81 \times 10^3 \leq Re_D \leq 6 \times 10^6 \\ 2000 \leq Re_\tau \leq 98,200\end{gathered}}$$

$$31 \times 10^3 \leq Re_D \leq 35 \times 10^6$$

$$10^3 \leq Re_\tau \leq 5 \times 10^5$$



Superpipe



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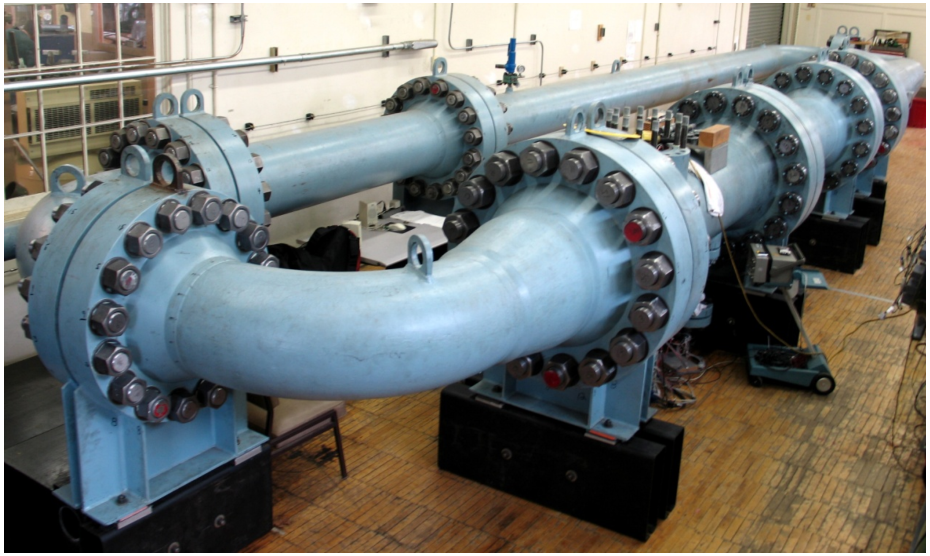
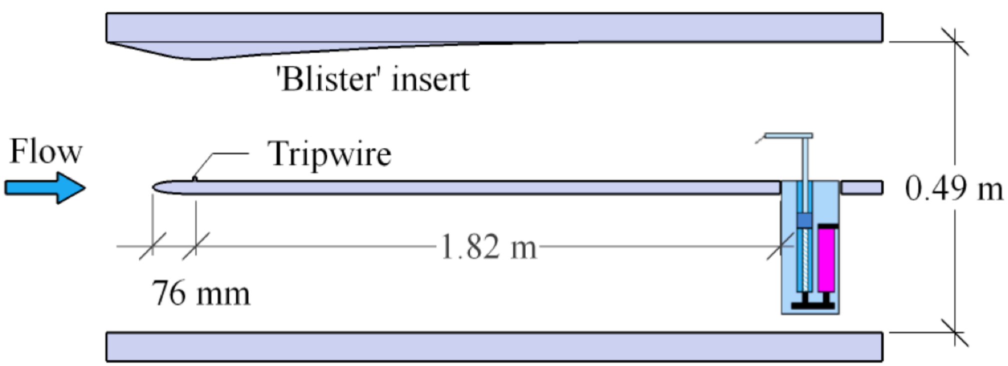
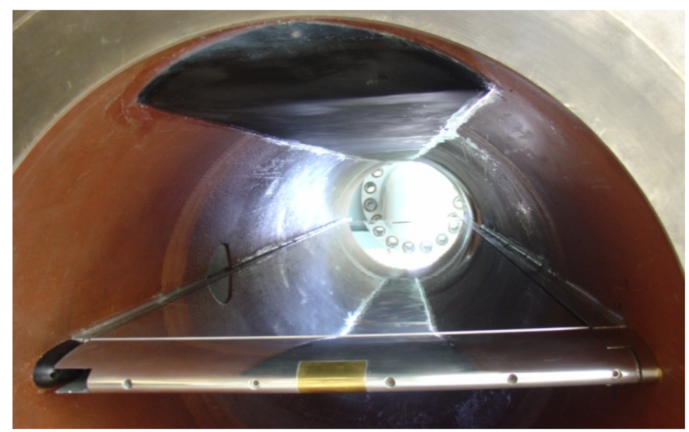
High Reynolds number Test Facility (HRTF)



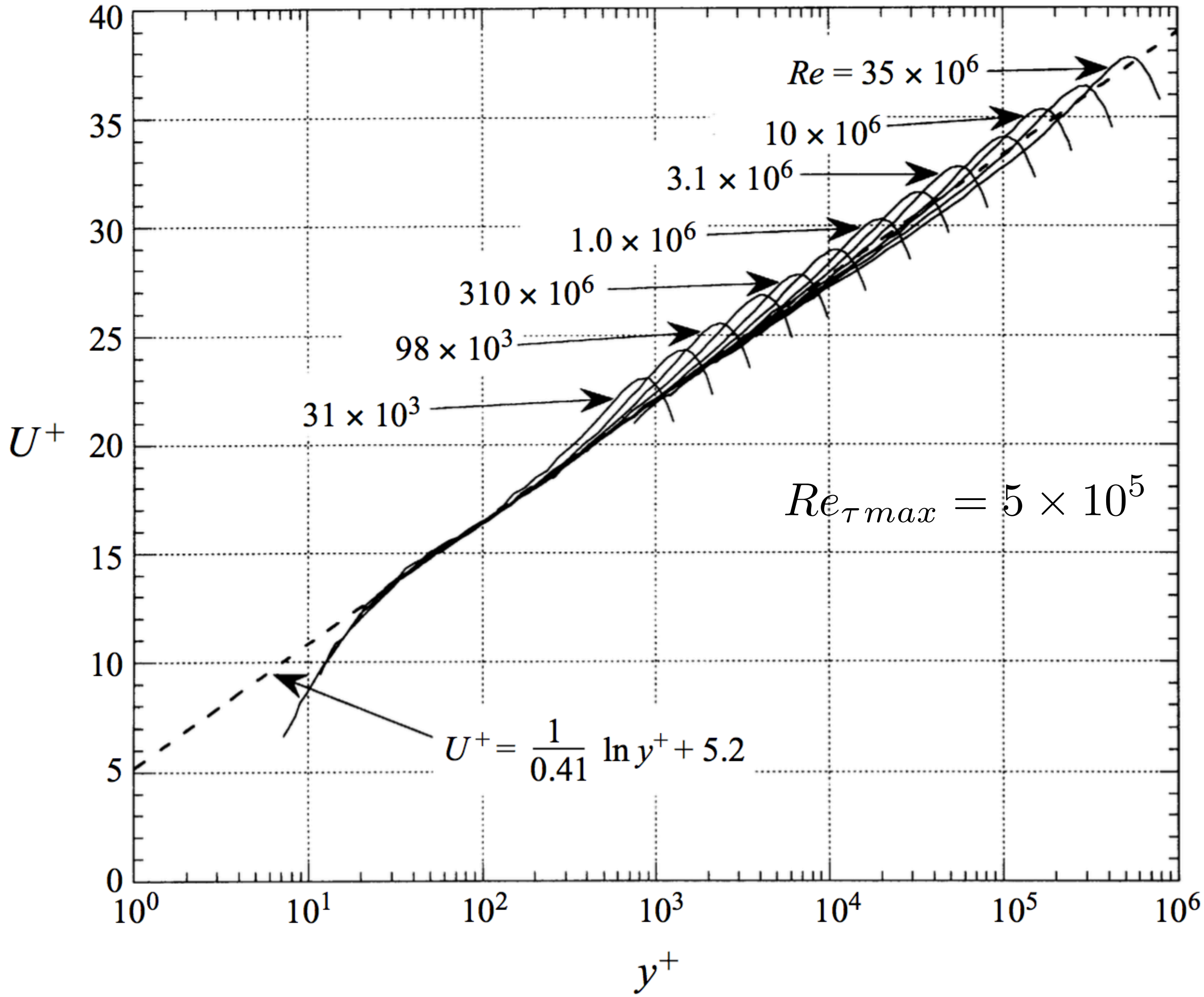
Flat plate boundary layer experiments

$$8400 \le Re_\theta \le 235,000$$
$$2600 \le Re_\tau \le 72,500$$





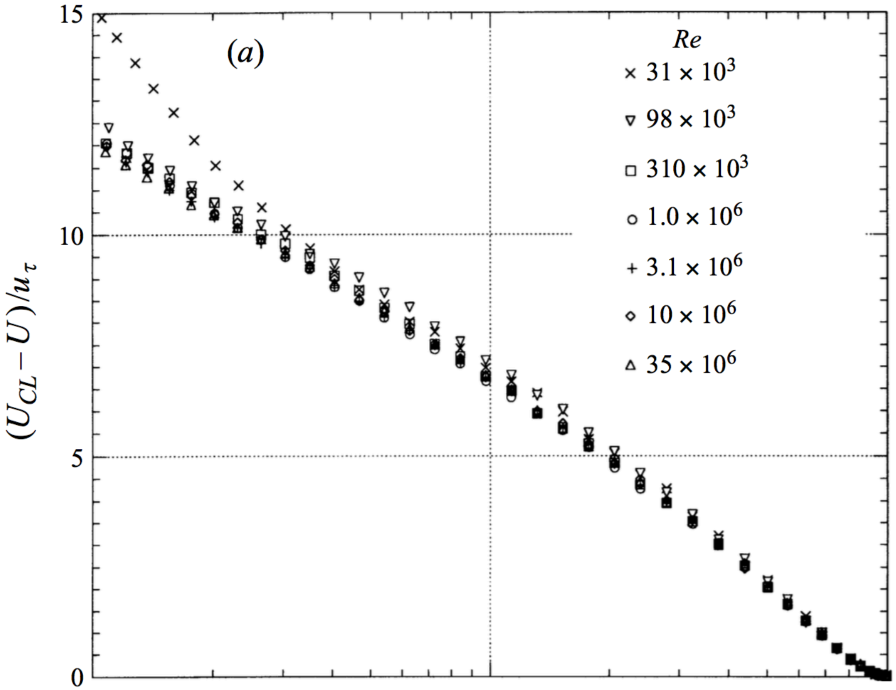
Superpipe mean velocity results



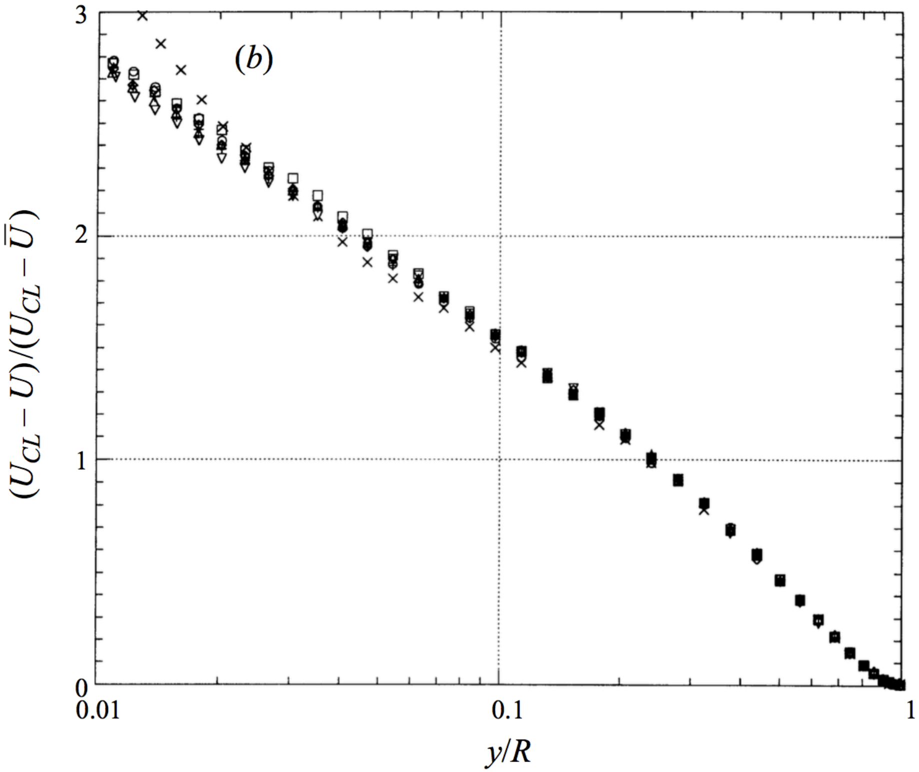
(Zagarola & Smits, JFM 1998)

Superpipe mean velocity results

Outer scaling



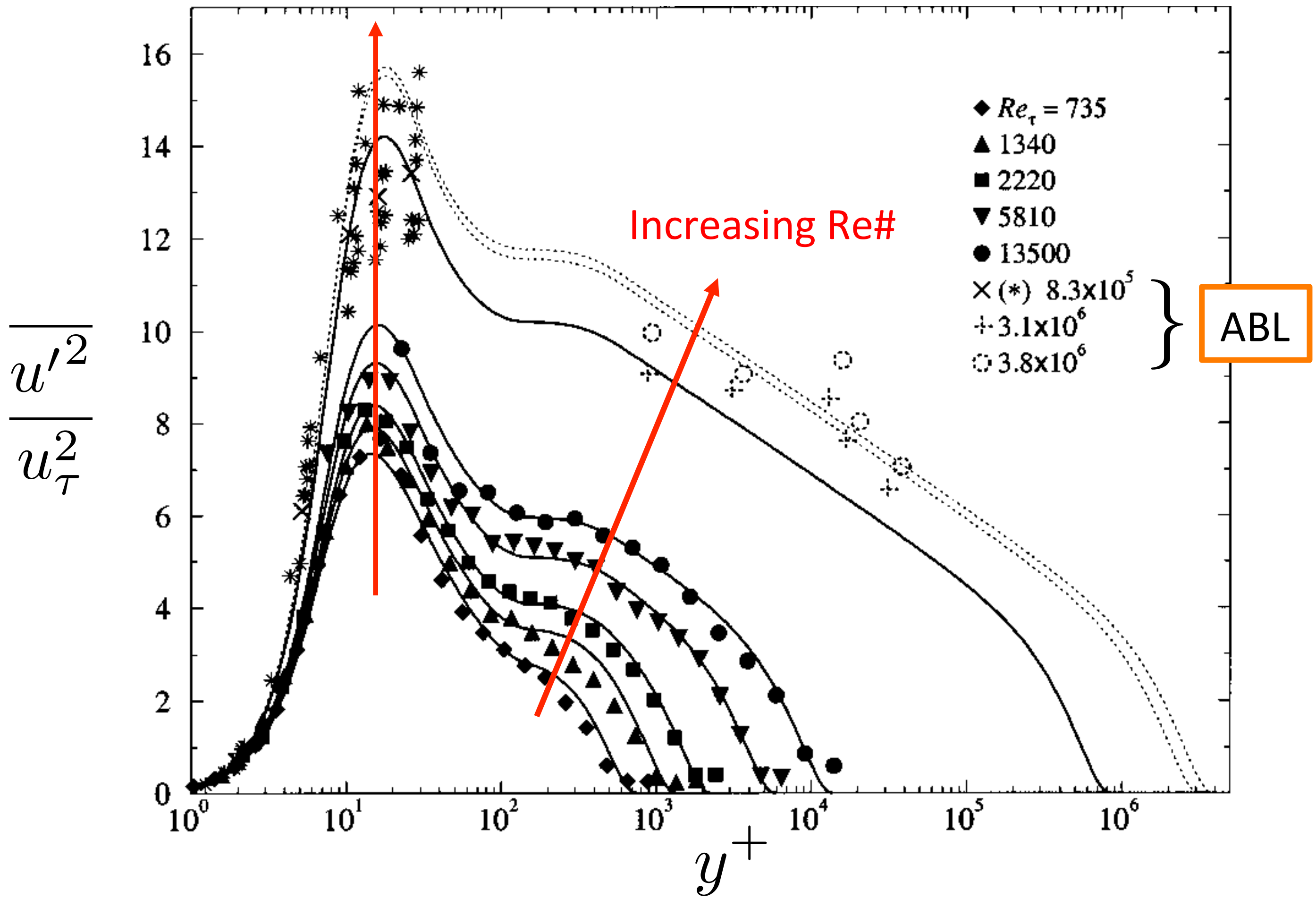
Classic scaling



Zagarola scaling

(Zagarola & Smits, JFM 1998)

Expected turbulence behavior

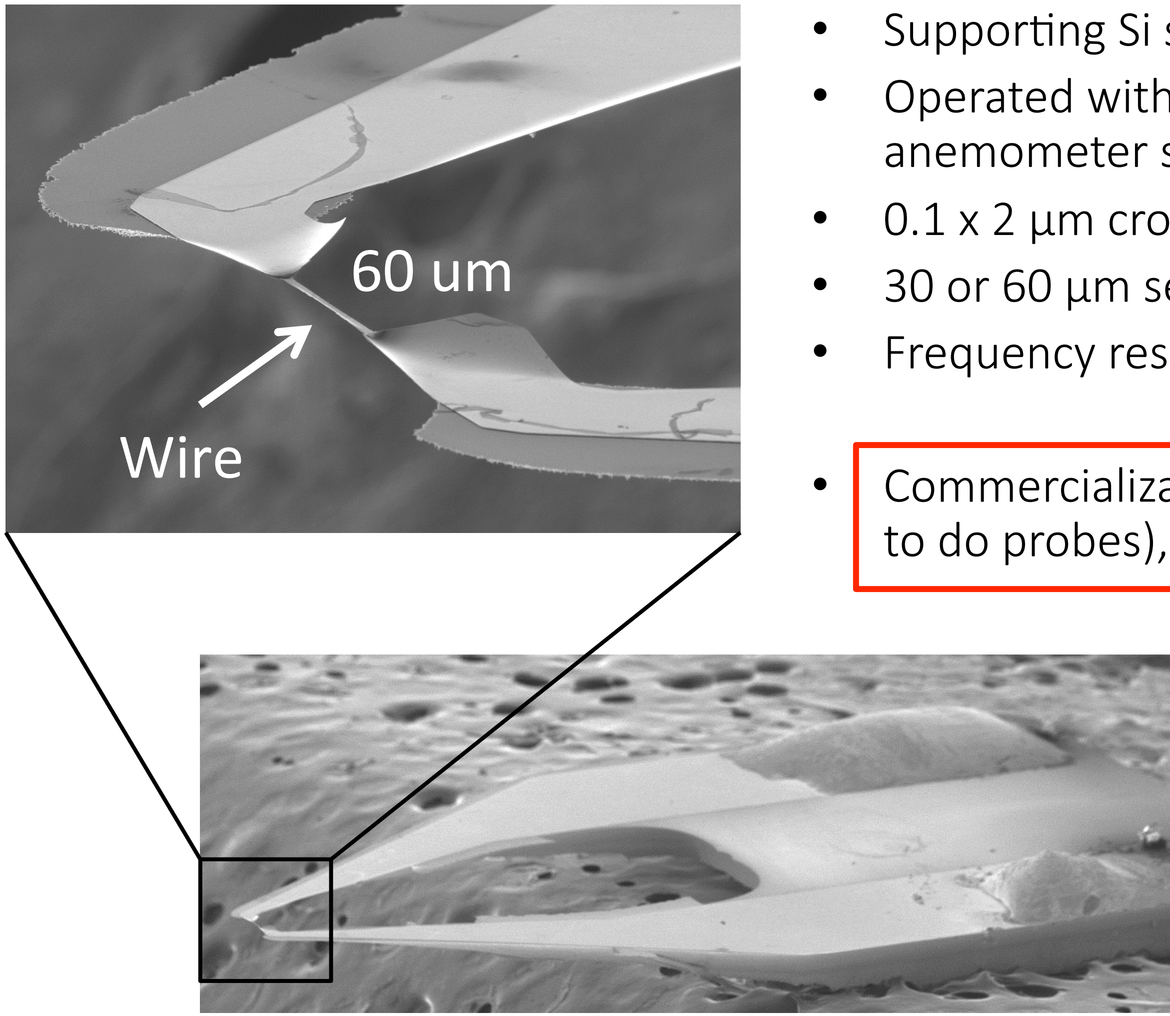


Inner layer peak at $y^+ = 15$, that grows with Reynolds number

Indicates outer layer influence near wall

(Marusic et al. 2003)

Nano-Scale Thermal Anemometry Probe (NSTAP)

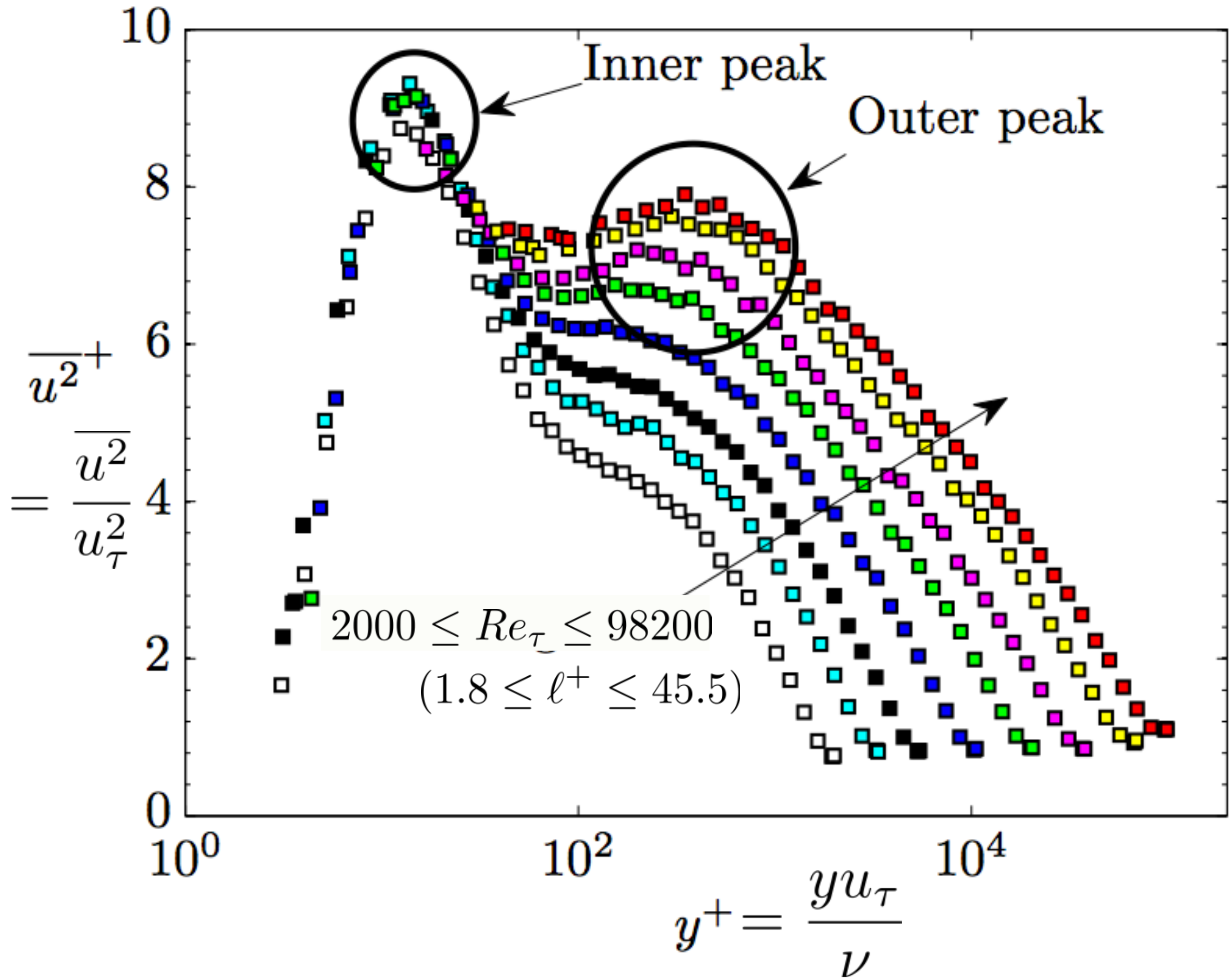


- Freestanding Pt wire
- Supporting Si structure
- Operated with a conventional anemometer system (CTA)
- 0.1 x 2 µm cross-section
- 30 or 60 µm sensing length
- Frequency response > 150kHz

- Commercialization: InstruMEMS (startup to do probes), Dantec (to anemometers)

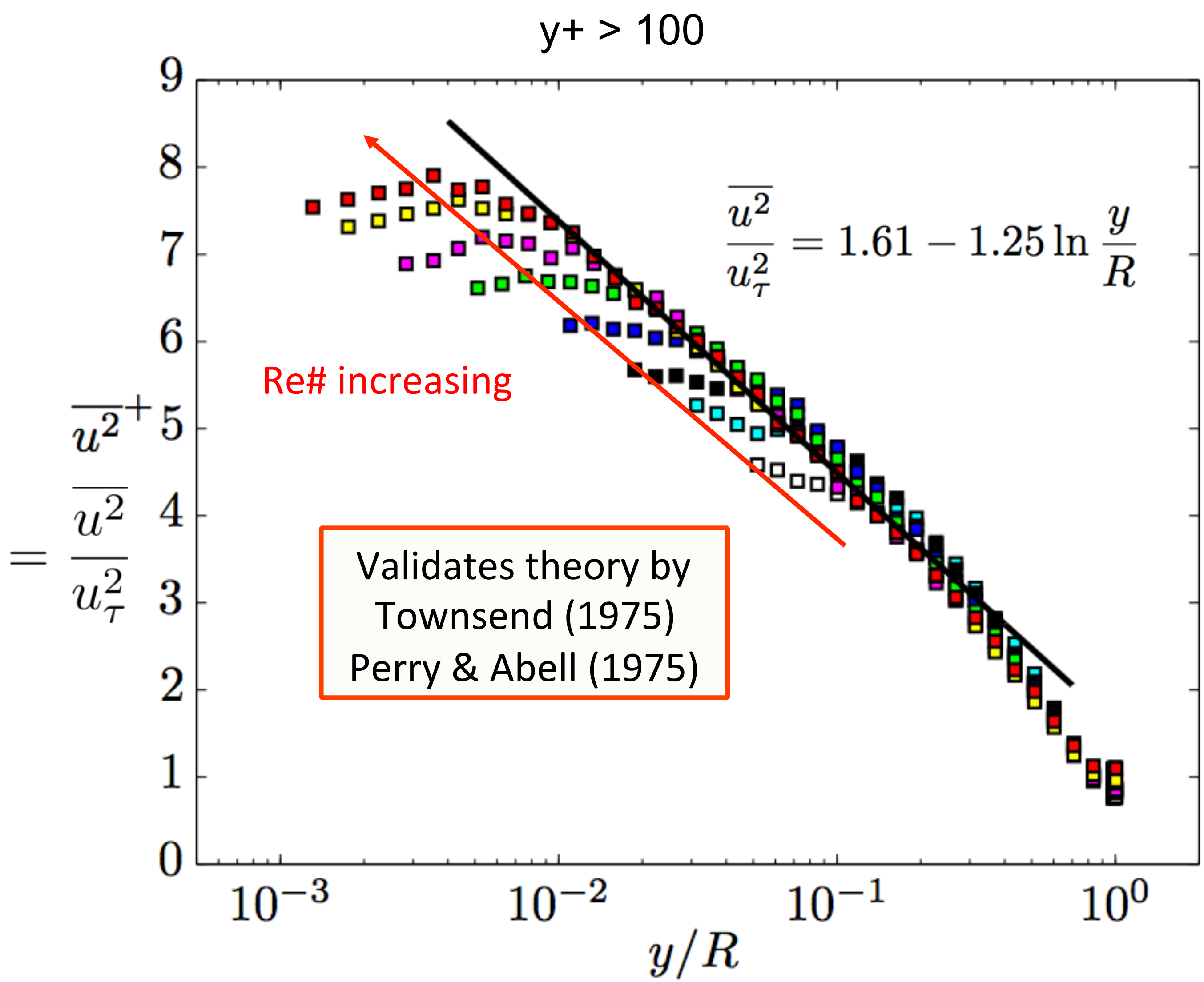
Bailey et al (2010) JFM
Vallikivi et al (2011) Exp. in Fluids
Vallikivi & Smits (2014) JMMS

Turbulence measurements in Superpipe



(Hultmark, Vallikivi, Bailey & Smits, 2012)

Log-law in turbulence for pipe flow



(Hultmark, Vallikivi & Smits, 2012)

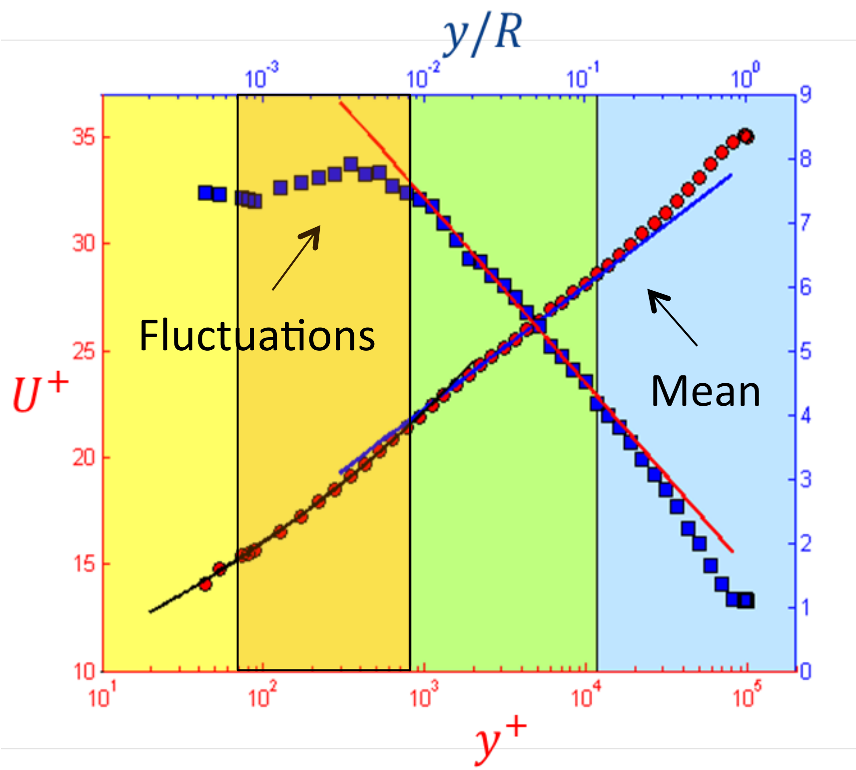
Wall-bounded flows: Boundary layer vs. pipe flow

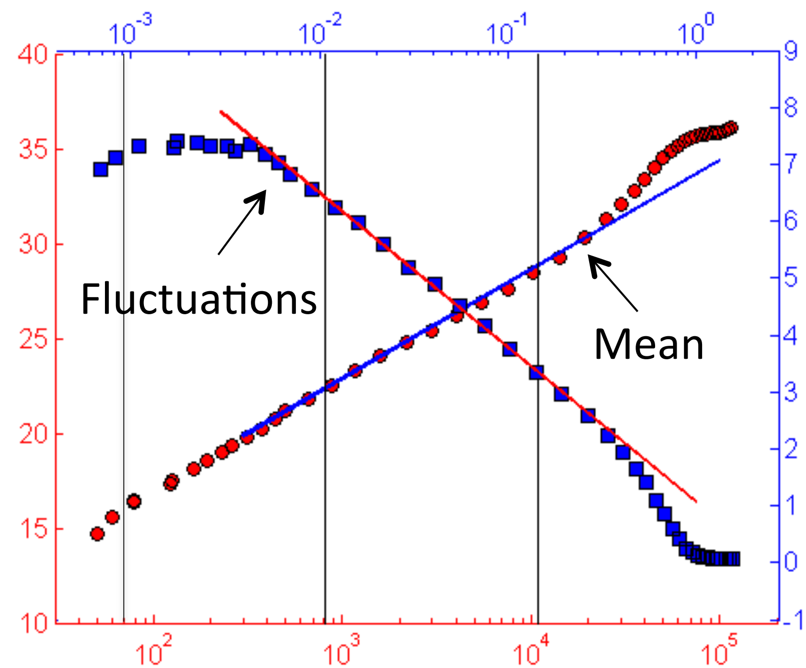
$$\boxed{\frac{\overline{u'^2}}{u_\tau^2} = B_1 - A_1 \ln \frac{y}{\delta}} \qquad A_1 = 1.25$$

Townsend's Attached Eddy Hypothesis

Pipe
$R^+ = 100,000$

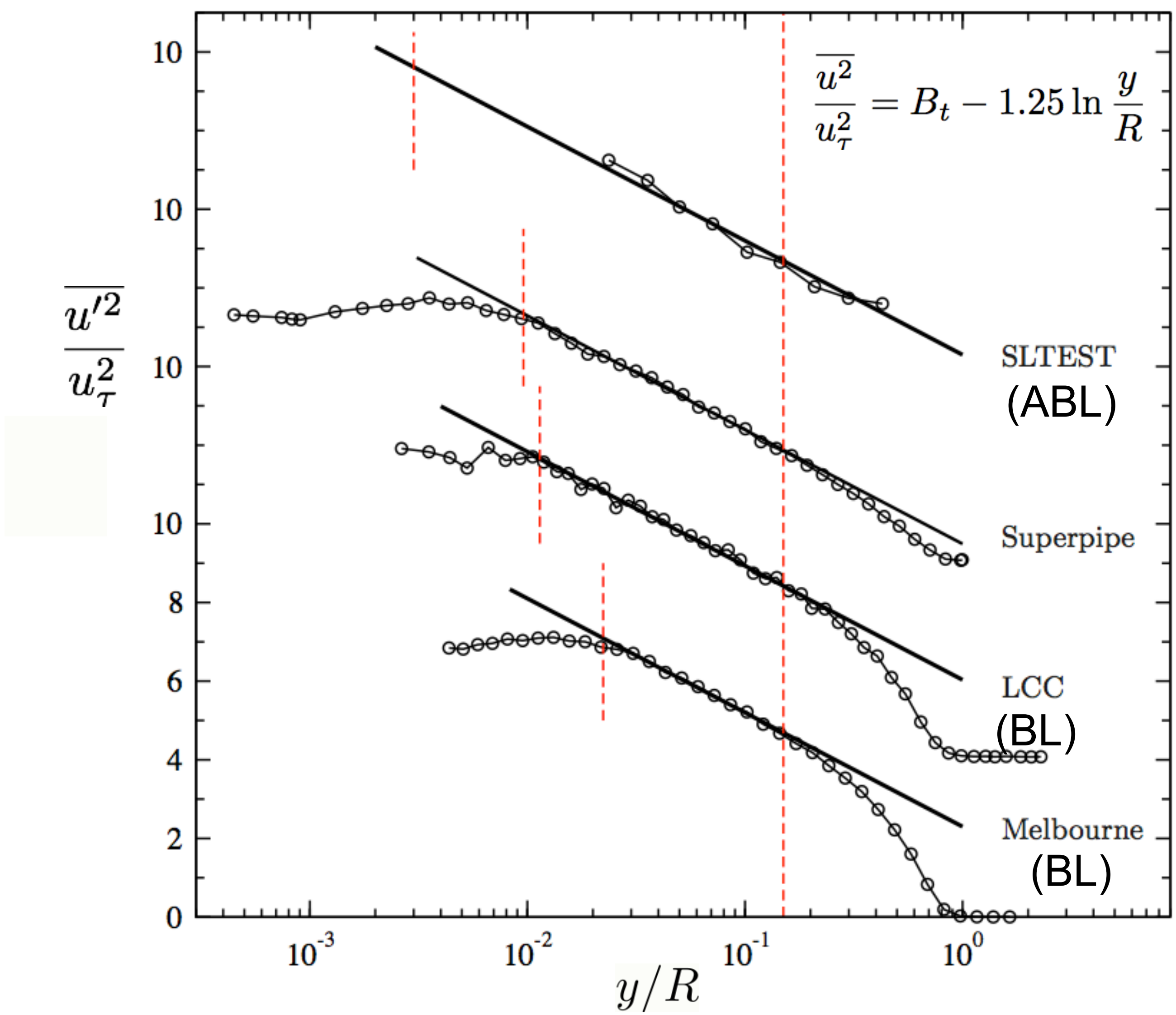
Boundary layer
$R^+ = 73,000$





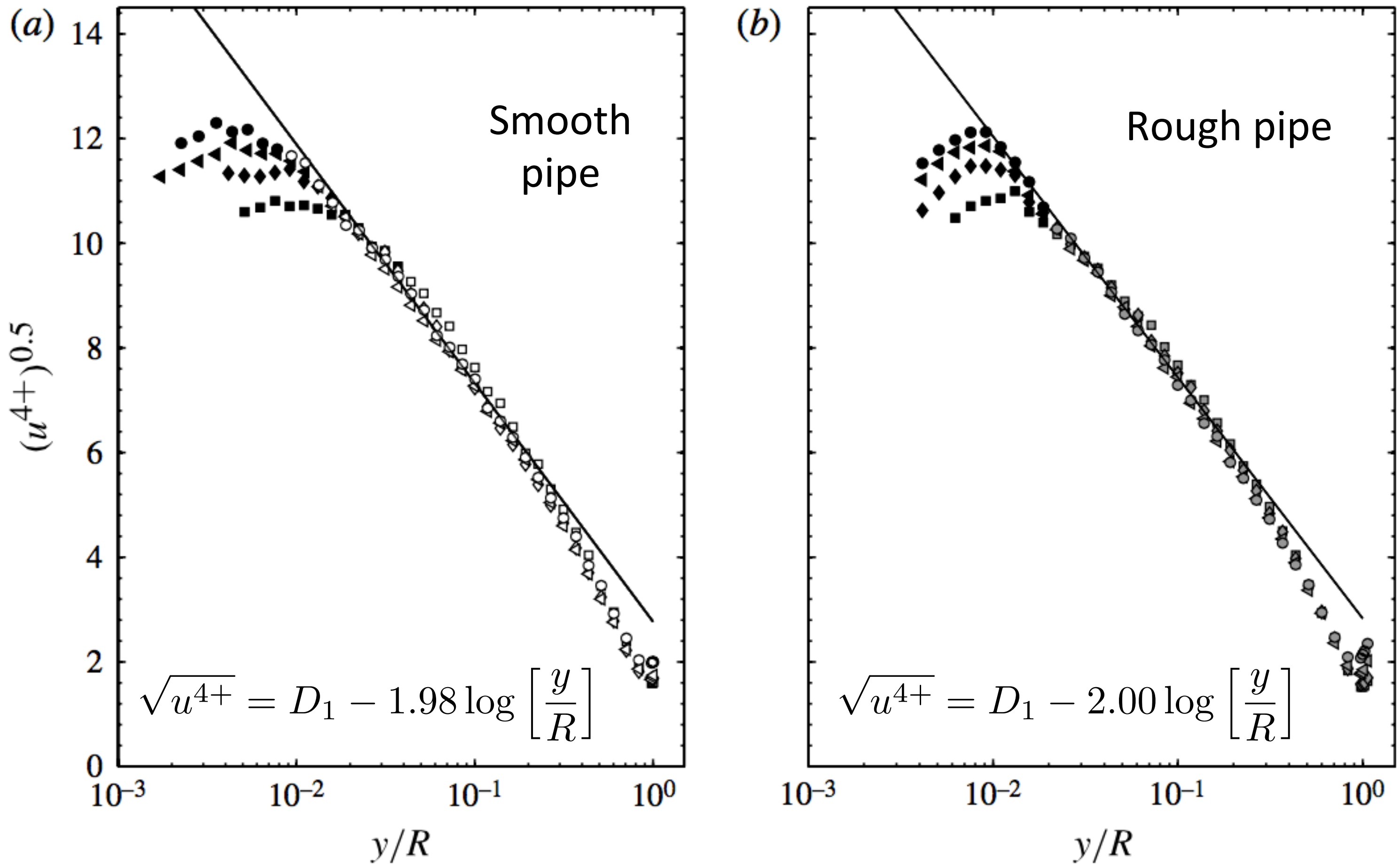
mesolayer | near-wall | overlap | wake

A universal log law for turbulence



(Marusic, Monty, Hultmark & Smits, 2012)

A universal log law for turbulence



$1.25\sqrt{3} = 2.16$ (Gaussian expectation)

Hultmark, Vallikivi, Bailey and Smits (2013)

What about spectra?

Perry et al. AEM spectral overlap arguments

Streamwise component only

$$\boxed{\frac{\Phi_{uu}(k_x\eta_K)}{u_K^2} = g_1(k_x\eta_K) = \frac{K_0}{(k_x\eta_K)^{5/3}}}$$

$$\boxed{\frac{\Phi_{uu}(k_x y)}{u_\tau^2} = g_2(k_x y) = \frac{K_0}{\kappa^{2/3}(k_x y)^{5/3}}}$$

$\Rightarrow$

$\boxed{{k_x}^{-5/3} \text{ region} \quad \Phi_{uu} \sim {k_x}^{-5/3}}$

$$\boxed{\frac{\Phi_{uu}(k_x\delta)}{u_\tau^2} = g_3(k_x\delta) = \frac{A_1}{k_x\delta}}$$

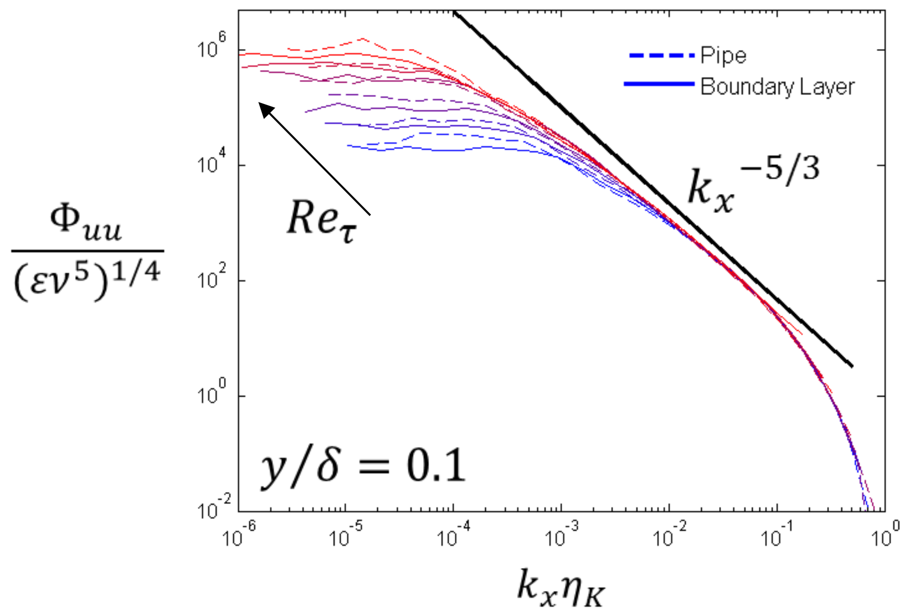
$$\boxed{\frac{\Phi_{uu}(k_x y)}{u_\tau^2} = g_2(k_x y) = \frac{A_1}{k_x y}}$$

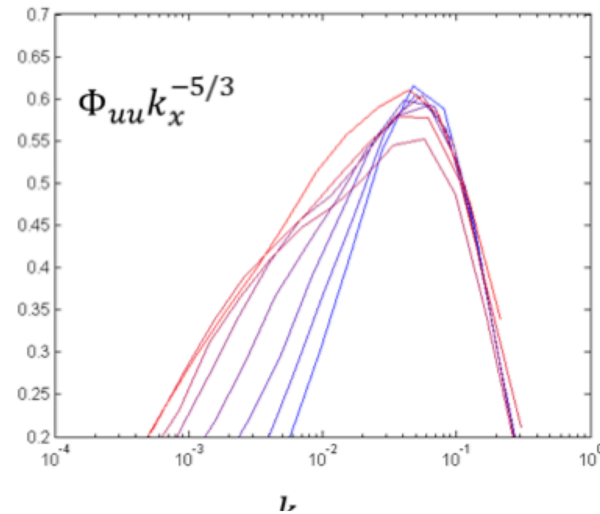
$\Rightarrow$

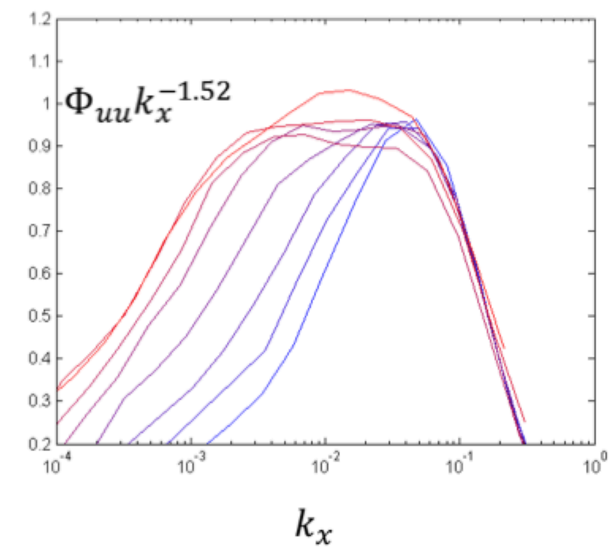
$\boxed{{k_x}^{-1} \text{ region} \quad \Phi_{uu} \sim {k_x}^{-1}}$

Perry & Abell (1977); Perry, Henbest & Chong (1986)

What about -5/3?



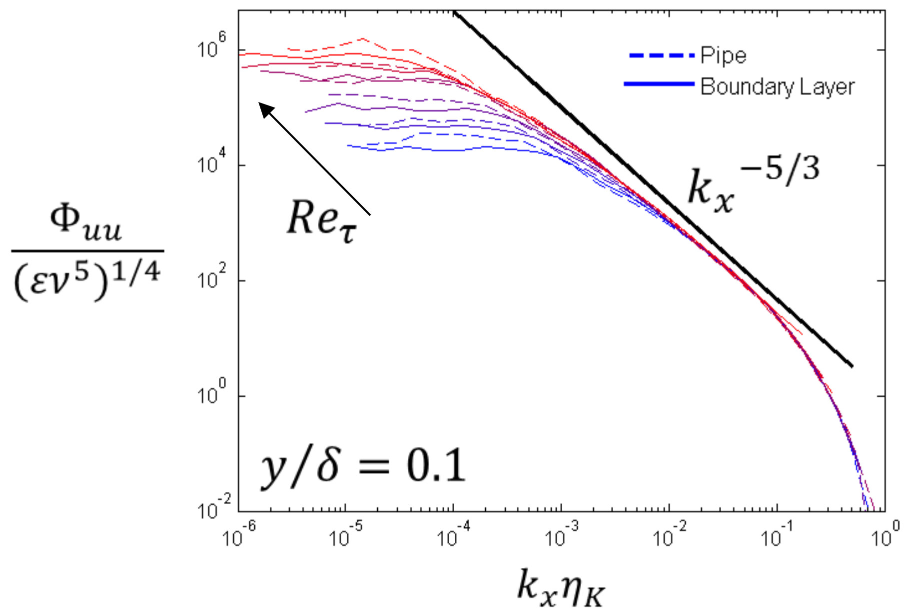


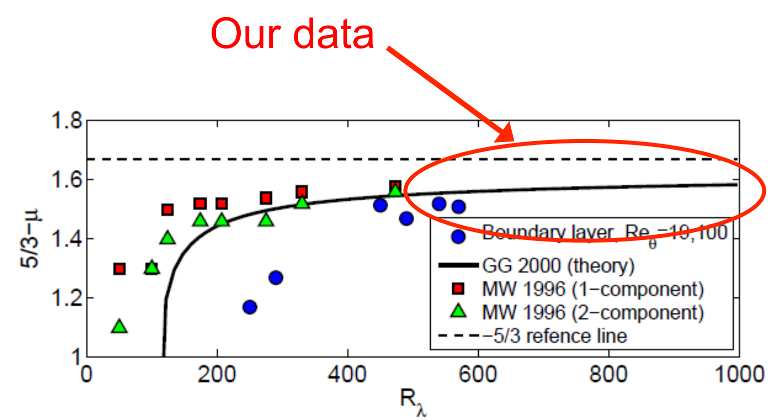


$k_x{}^{-5/3}$ region

$\Phi_{uu} \sim k_x{}^{-5/3}$

What about -5/3?





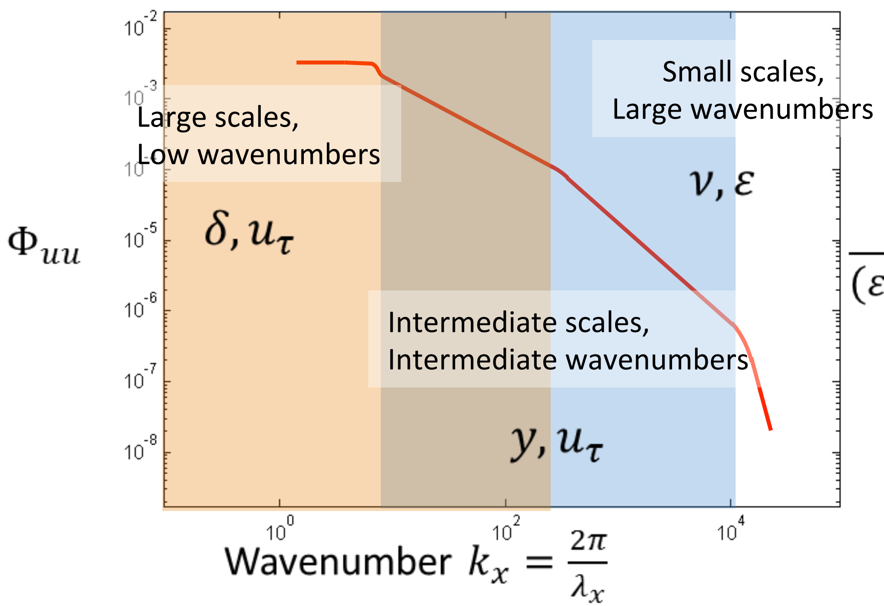
$$k_x^{-5/3} \text{ region}$$

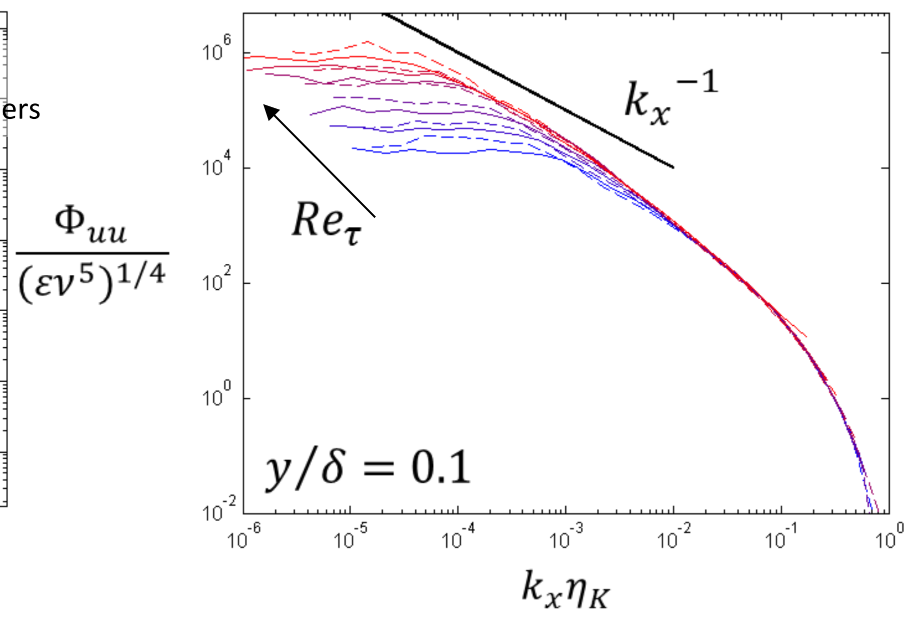
$$\Phi_{uu} \sim k_x^{-5/3}$$

Mydlarski and Warhaft (1996),
Gamard and George (2000)

$$\Phi_{uu} \sim k_x^{-\frac{5}{3}+\mu}, \qquad \mu \sim \frac{1}{\ln Re}$$

What about -1?





$\boxed{\begin{array}{c} {k_x}^{-1}\text{region} \\ \Phi_{uu} \sim {k_x}^{-1} \end{array}}$

What about -1?

$$\boxed{\begin{array}{c} {k_x}^{-1} \text{ region} \\ \Phi_{uu} \sim {k_x}^{-1} \end{array}}$$

According to Nickels et al. (2005), k^{-1} region is found for:

$$k_x \delta < 18.6 \quad (k_x \delta_N < 21)$$

$$k_x y > 0.4$$

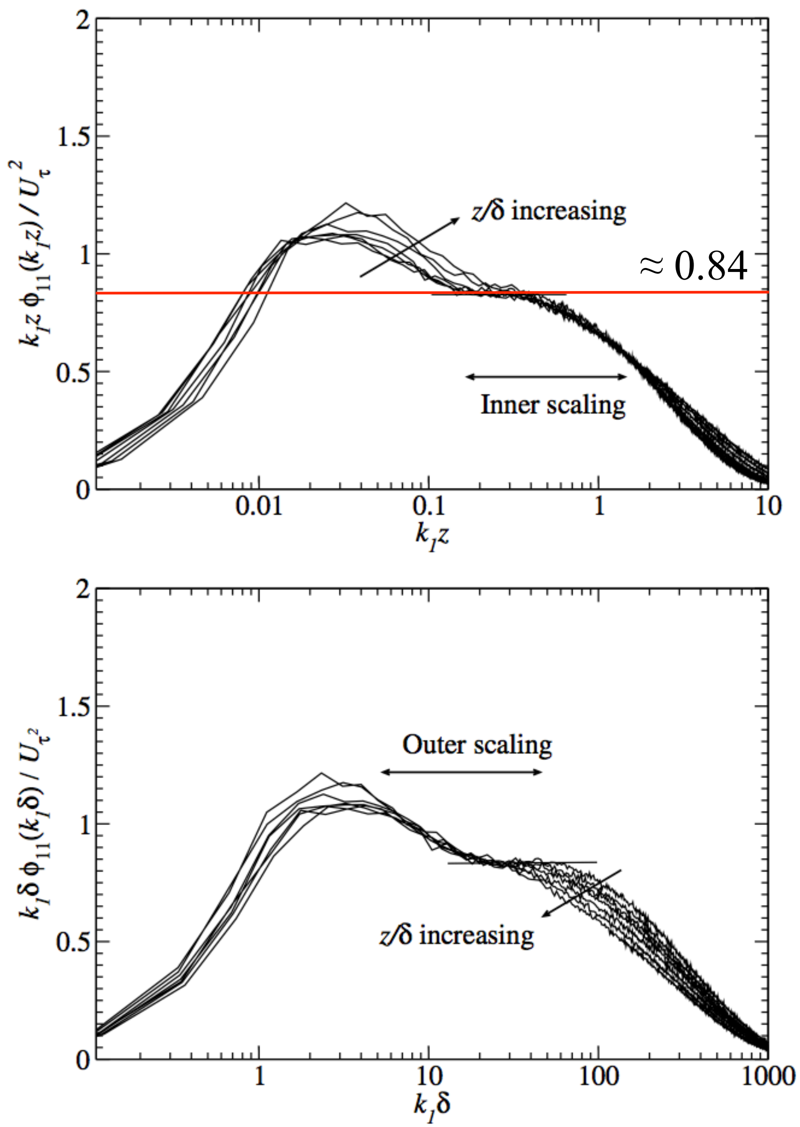
Also

$$y^+ > 100$$

$$y/\delta < 0.021$$

$$k_x \phi_{uu} = A_1$$

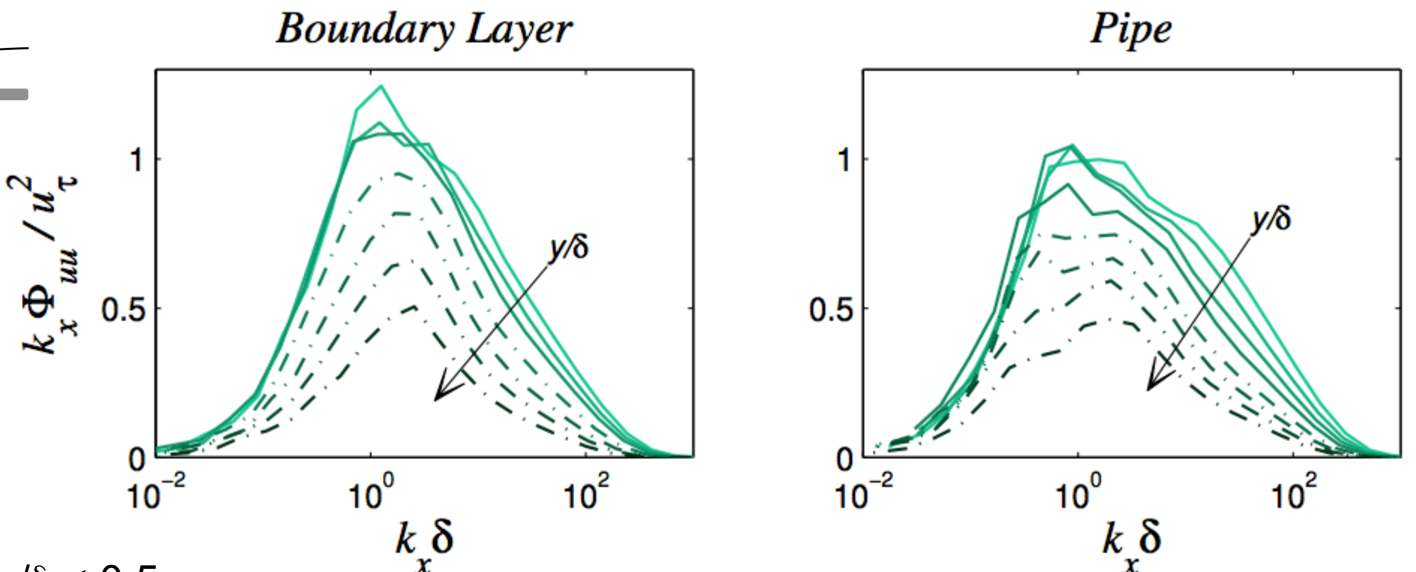
$$(A_1 \text{ is slope of log law for } {u'}^{2^+})$$



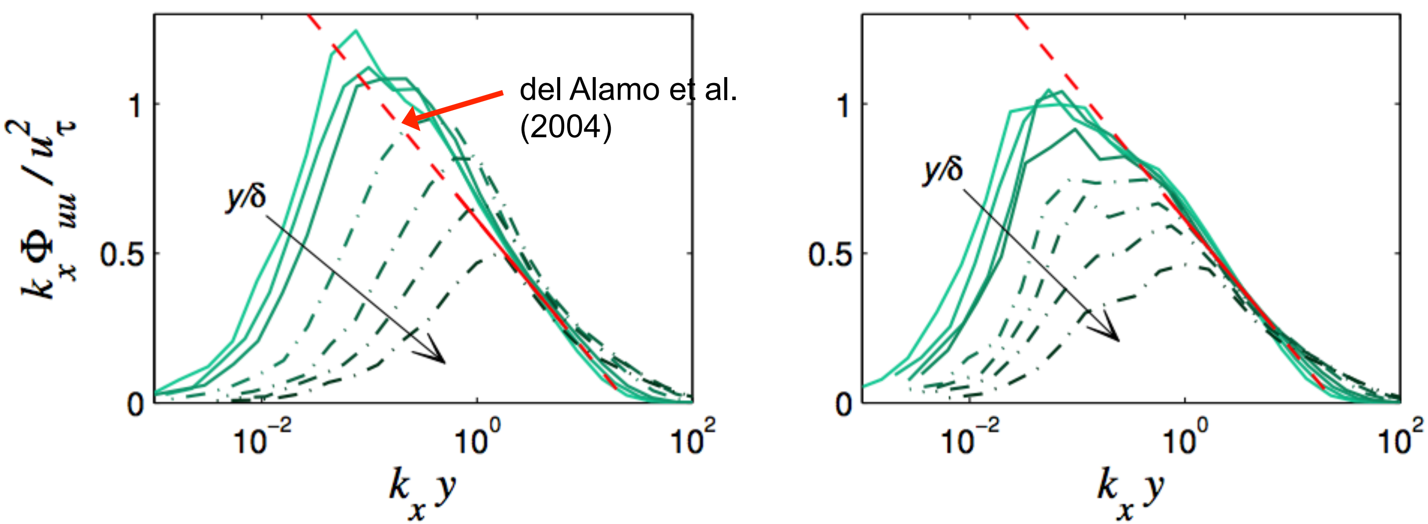
Nickels et al (2005)

Pre-multiplied -1 spectra

$Re_\tau \approx 5{,}000$

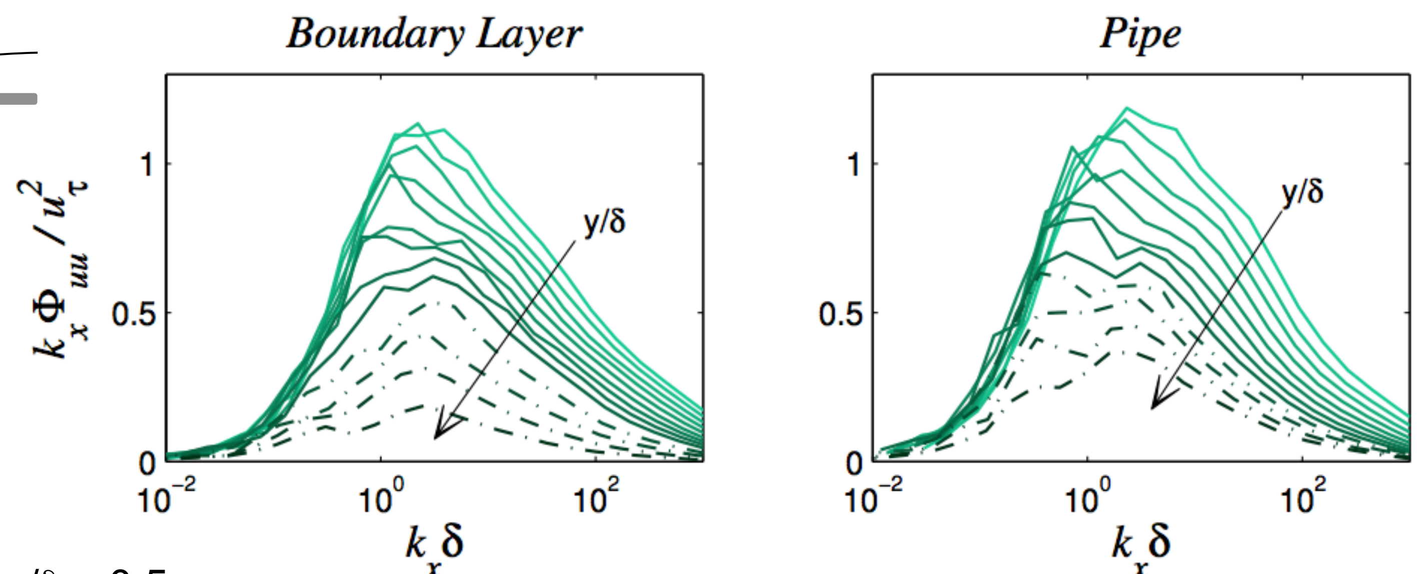


0.001< y/δ < 0.5

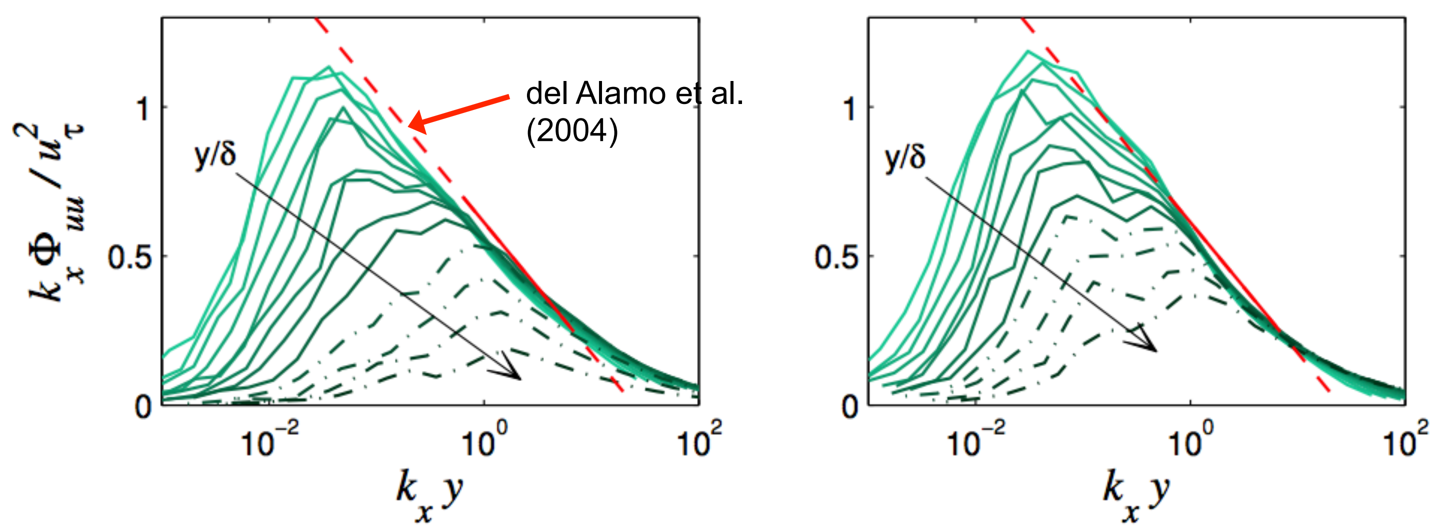


Pre-multiplied -1 spectra

$Re_\tau \approx 70{,}000$



0.001< y/δ < 0.5



Canonical pipe and boundary layers

- A log-law in turbulence is found to occur in the same region where the log-law in mean velocity is found, in accordance with AEM
- Inner peak is weakly dependent on Reynolds number, not in accord with AEM
- Spectra asymptote very slowly to -5/3, as suggested by Mydlarski and Warhaft (1996), Gamard and George (2000)
- No overlap region found where inner (y) and outer (δ) scaling occur over the same range of wavenumbers (no k-1) at these Reynolds numbers, not in accord with Perry scaling
- A mesolayer exists as a blending region between the wall-scaled region and the y-scaled region (only evident at high Reynolds number)

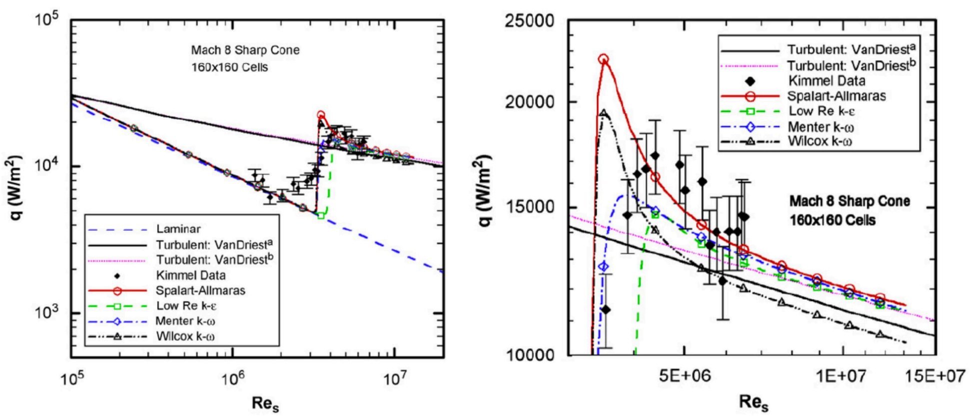
Beyond canonical flows

- Flat plate zero pg flow, or fully developed pipe/channel flows are canonical but singular cases
- Need to move beyond canonical flows
- Wall-bounded turbulence includes roughness, pressure gradients, surface curvature, three-dimensional flows, separation, blowing, suction, etc.
- Much work was done in the past, but the last 20 years or so the basic research community seems to have been fixated on canonical cases

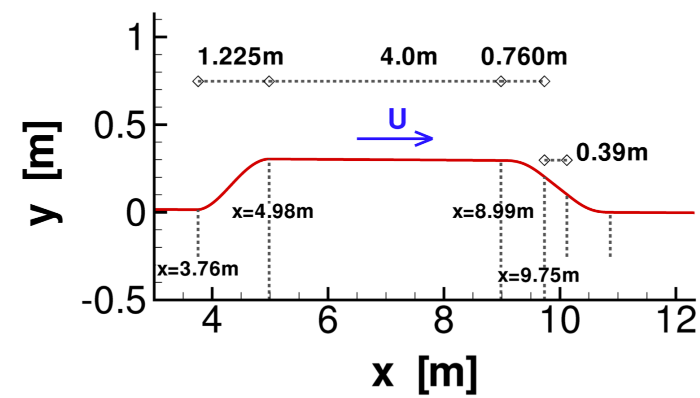
- There may be a glass ceiling on studying canonical flows

Beyond canonical flows

- How robust is the Attached Eddy Model for complex flows?
- Many existing experiments are old, and not fully documented or limited in data extent (Cf, Cp, mean velocity, turbulence, …). Maybe need another sifting, as done by Stanford Olympics I and II, Fernholz and Finley, Settles & Dodson, Roy & Blottner? Certainly need error bars.
- Reynolds number effects for complex flows are not well understood.
- New experiments designed in collaboration with CFD community to examine more complex flows to gain both new understanding AND help improve turbulence models
- Example, APG flows beyond equilibrium, as in DLR experiment (Knopp et al. TSFP10)
- Compute entire flow, including wind tunnel walls (helps to eliminate many sources of uncertainty in initial and boundary conditions)

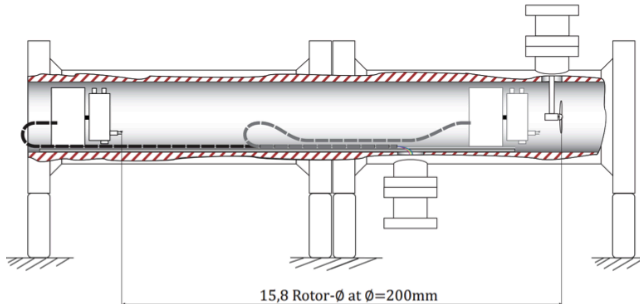


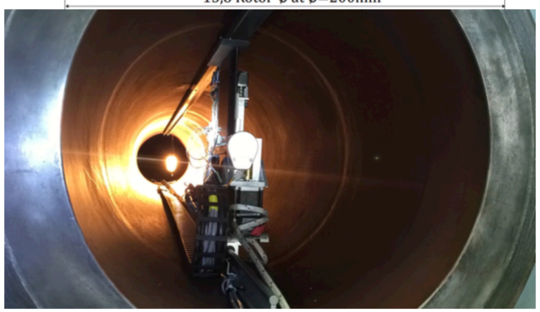
Roy & Blottner (2006)

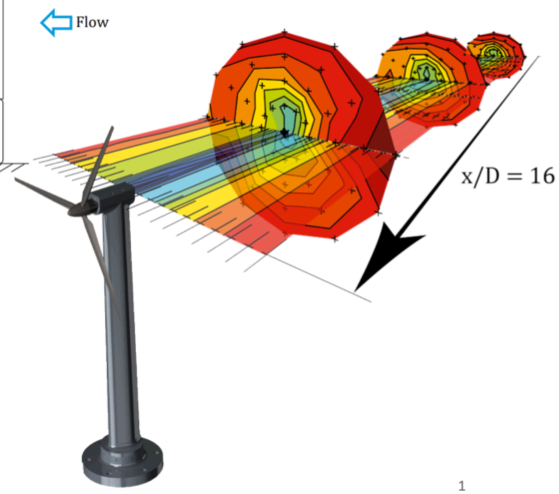


Knopp et al. TSFP10

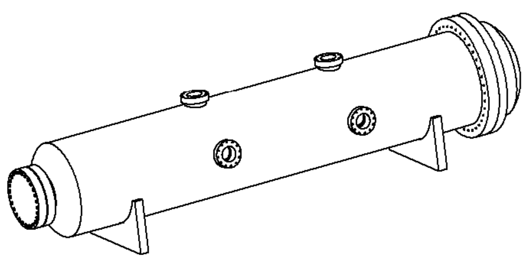
New high pressure experiments

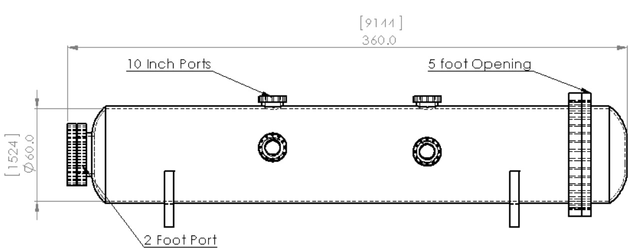






HRTF VAWT experiments in HRTF at full scale Reynolds number and Tip Speed Ratio (Hultmark)

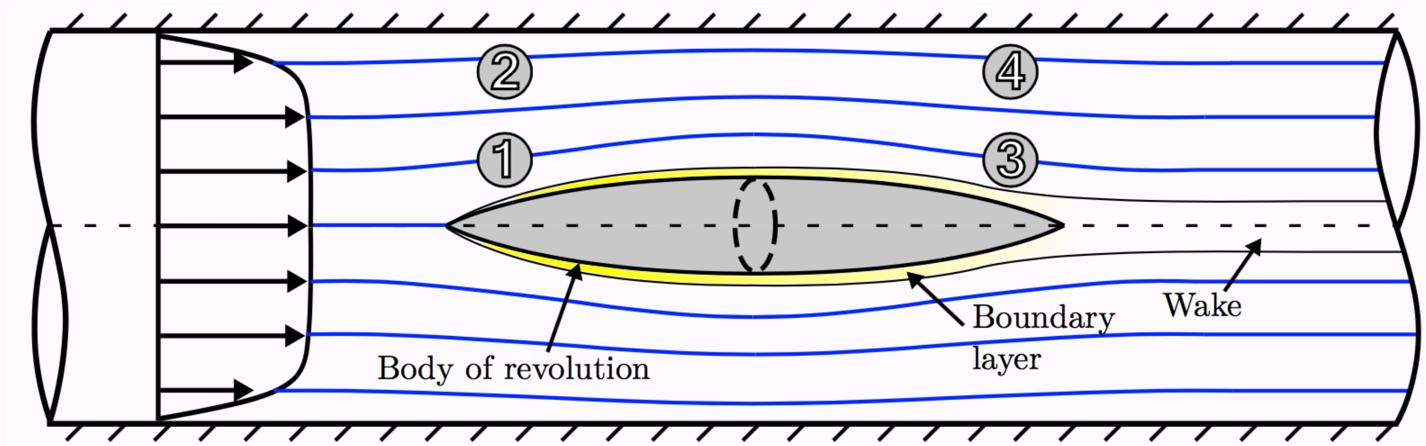




New facility (Marcus Hultmark):

- 1.5 m by 9 m long
- 1000 psi (68 bar)
- Can match propellor conditions at 1/10th scale at (0.7 m diameter) at 15 m/s
- Can match HAWT conditions at 1/100th scale (1 m diameter) at 11 m/s

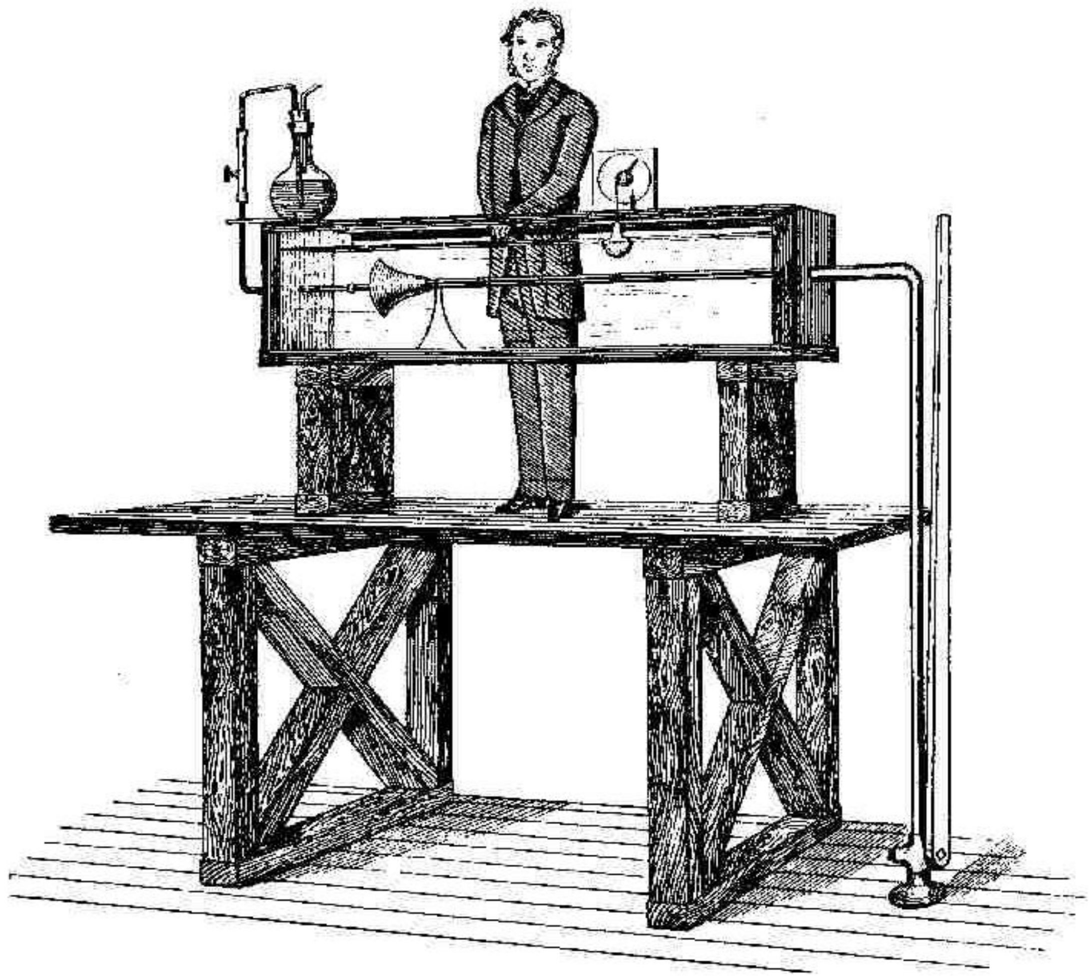
New Superpipe experiments



Region 1: favorable pg, convex S/L curvature, divergence
Region 2: adverse pg, convex S/L curvature, convergence
Region 2: adverse pg, convex S/L curvature, convergence
Region 2: adverse pg, convex S/L curvature, convergence

- High Reynolds number (inflow $Re_\tau = 10^5$; $Re_L = 20 \times 10^6$)
- Inflow fully-developed pipe flow

Questions??



Osborne Reynolds