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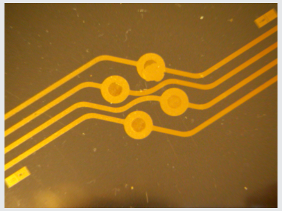

# Similarity and structure in very rough channel flow


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Engineering and Physical Sciences Research Council


-NORDITA Workshop on TURBULENT BOUNDARY LAYERS *Stockholm, Sweden*

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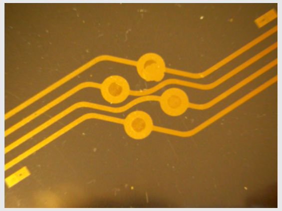
# Synopsis



- Do the details of the roughness leave their imprint on the flow?
- Does self-similarity of the mean velocity profile persist?
- Does Townsend outer-layer similarity persist?
- What aspects of turbulence structure are common to both rough and smooth surfaces?

- Jiménez (2004) suggests that $k/h$ < 2.5% "before similarity laws can be expected"..

- If so, is this limit dependent on other roughness details?
- Is it the same for both internal and external flows?
- So what happens for $k/h$ > 4% ?
- It is likely that self-similarity is a stronger requirement than Townsend outer-layer similarity

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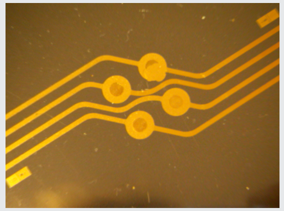
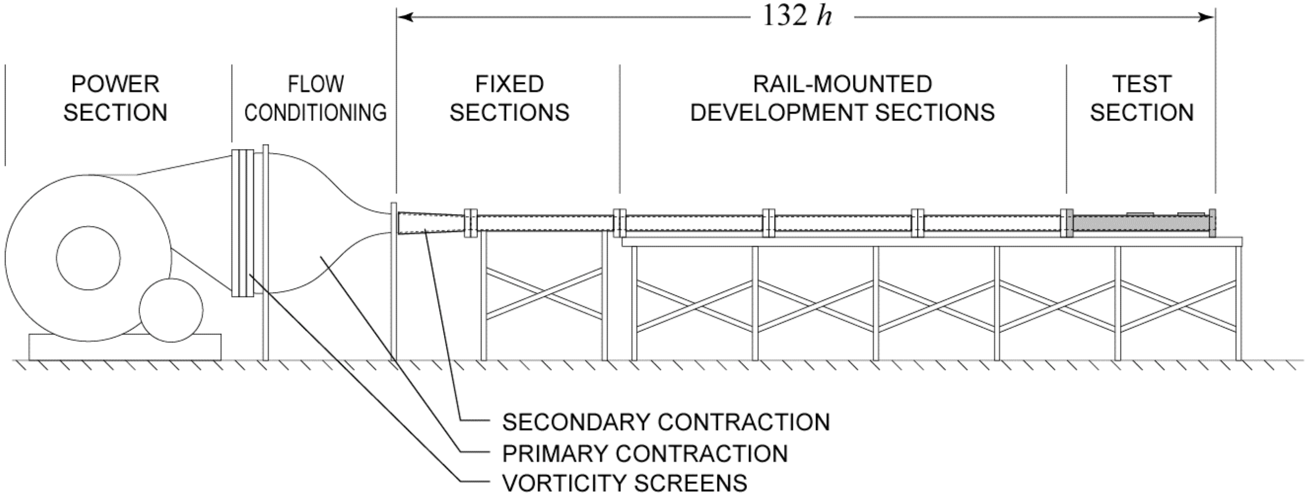
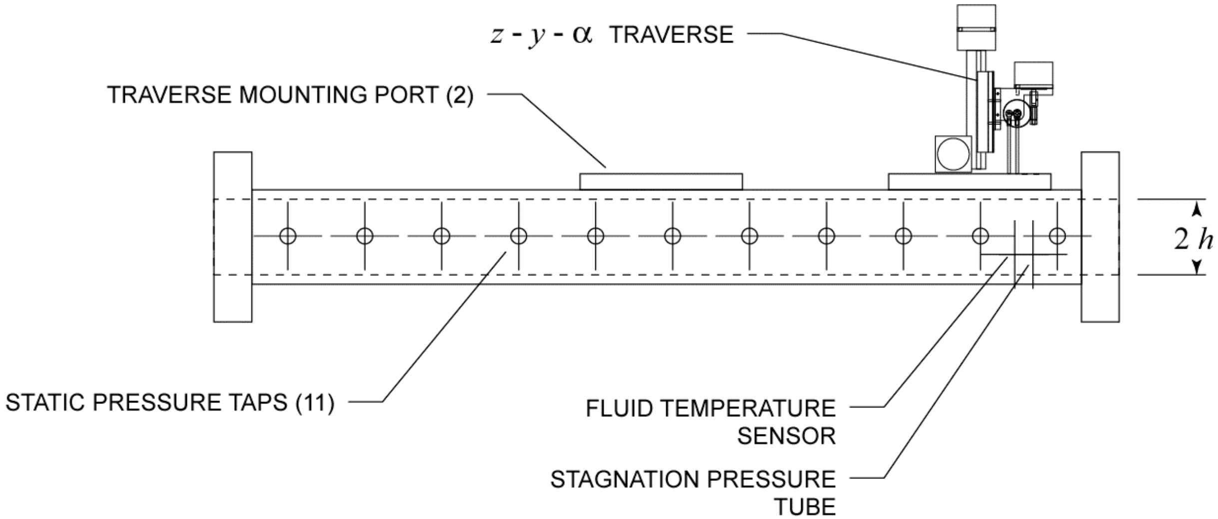


# Channel flow facility




$h$ = 50.8 mm

$x/h$ ~ 132

$U_o$ ~ 30 m/s

$Re_\tau$ = 5,700 - 7,700

$W/h$ = 15

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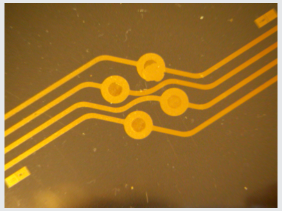
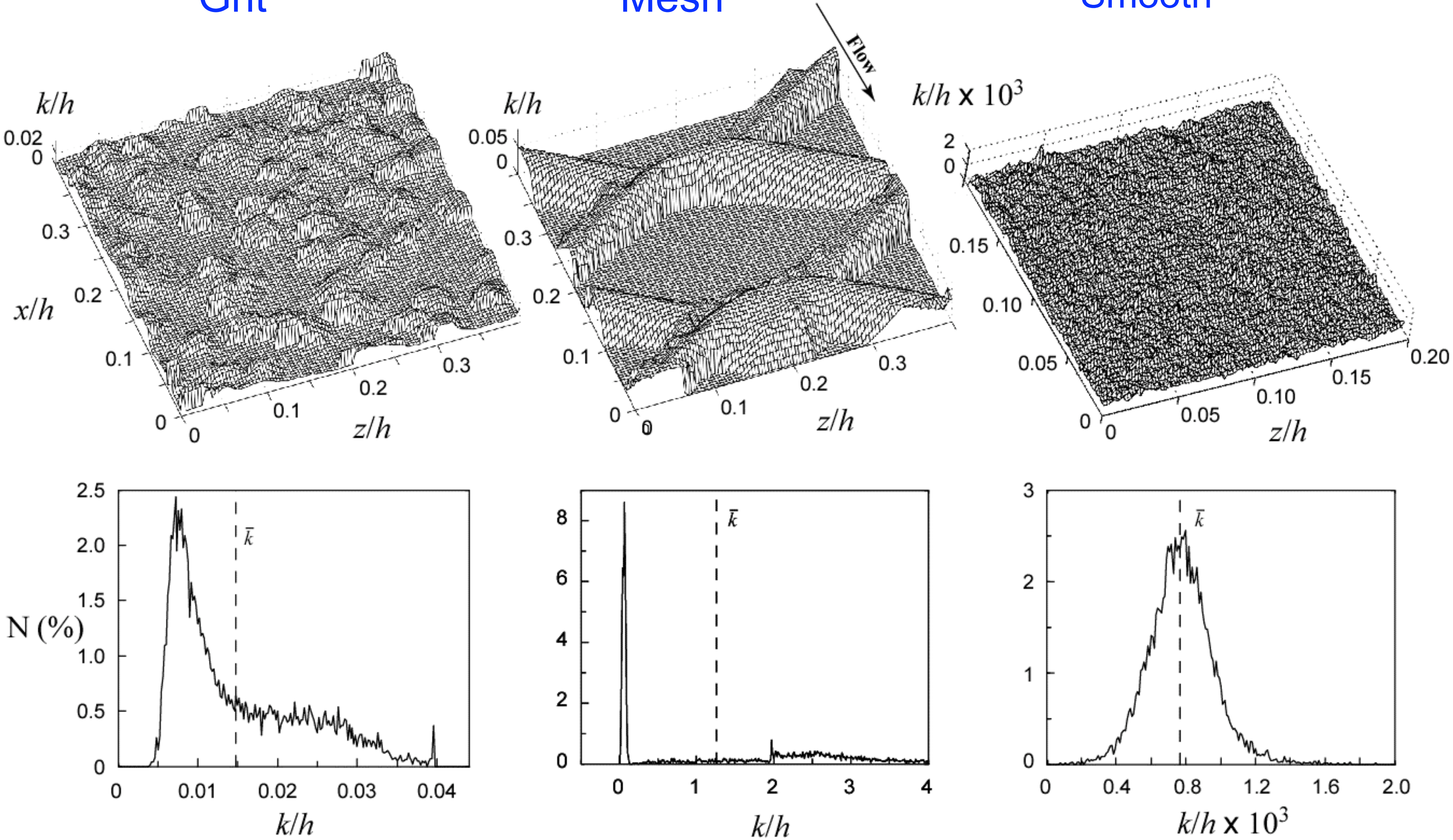


# Surface topologies

Grit | Mesh | Smooth



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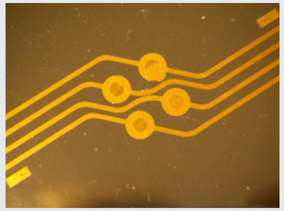

# Grit and mesh roughness

- Grit peak-to-peak $k_{max} \approx$ 1.8 mm, $k/h$ = 3.5%
  - Isotropic
  - Non-Gaussian, positively skewed
- Mesh $k_{max} \approx$ 4.0 mm, $k/h$ = 7.9%
  - Anisotropic
  - $L_z/L_x$ = 2.6, $L_z/k_{max}$ = 7.5, $L_x/k_{max}$ = 2.9 - “2.5D”
- Single-wire results $\ell^+ \approx 40 - 60$

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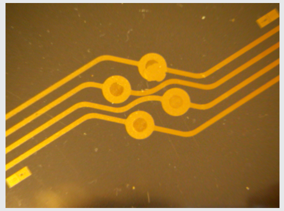

# Experimental parameters

$k_{max}$

| Surface | $U_{cl}$ | $\overline{U}$ | $Re_\tau$ | $Re_h$ x $10^{-4}$ | $ku_\tau/\nu$ |
|---|---|---|---|---|---|
| Grit | 24.7 | 21.0 | 4780 | 7.28 | 186 |
| Grit | 26.7 | 22.8 | 5130 | 7.78 | 200 |
| Grit | 28.6 | 24.4 | 5540 | 8.43 | 216 |
| Mesh | 21.1 | 17.3 | 5230 | 6.12 | 410 |
| Mesh | 23.2 | 18.8 | 5830 | 6.77 | 458 |
| Mesh | 25.0 | 20.5 | 6270 | 7.38 | 493 |
| Smooth | 41.9 | 31.5 | 4480 | 12.4 | – |

$$\mathrm{Re}_\tau = \frac{u_\tau h}{\nu} \qquad \mathrm{Re}_h = \frac{U_{cl} h}{\nu} \qquad \overline{U} = \frac{1}{h}\int_0^h U(y)\,dy$$

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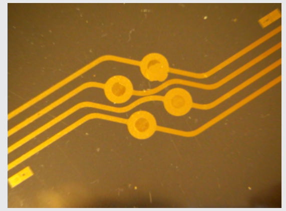
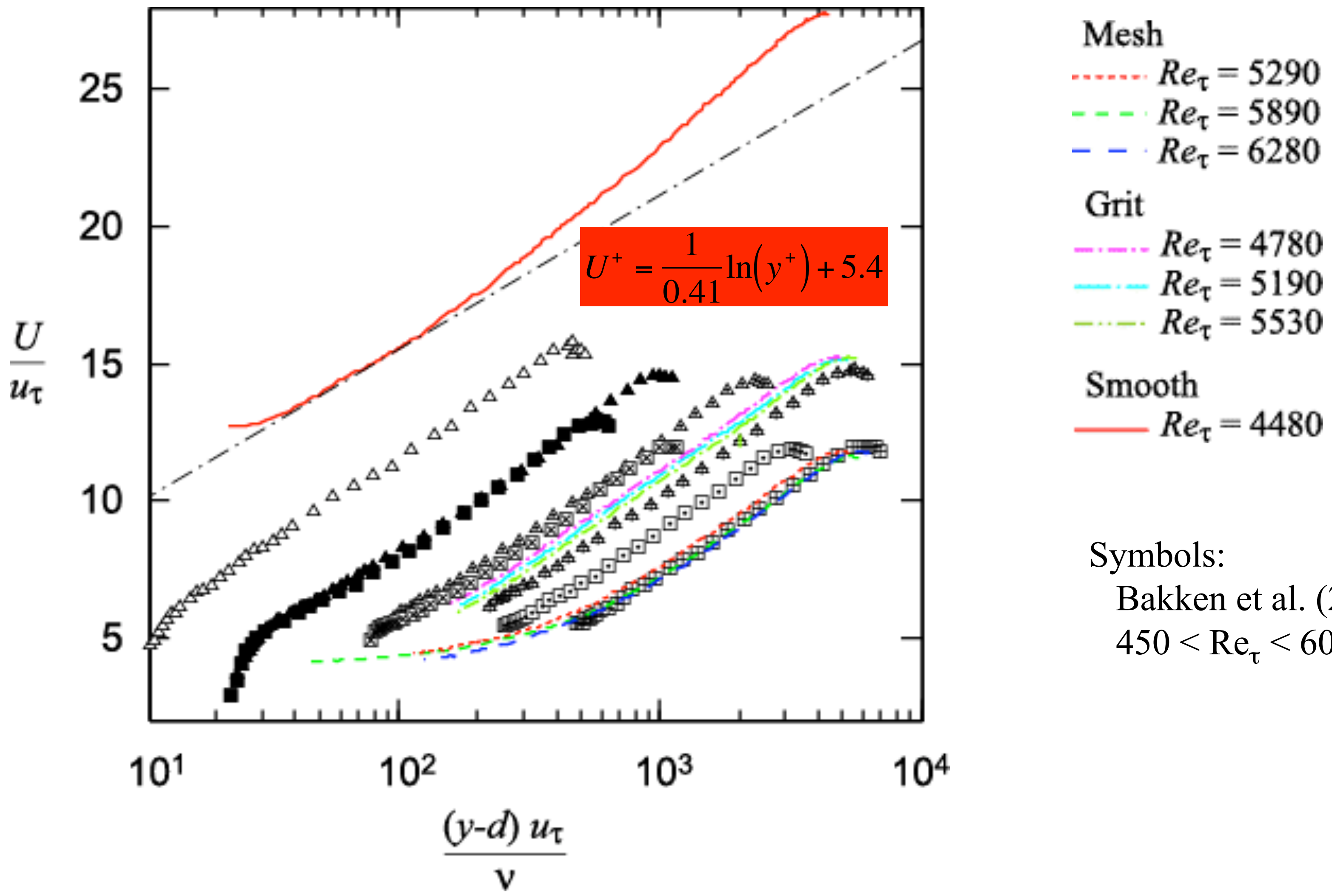


# Mean velocity: viscous scaling




Symbols:

Bakken et al. (2005)

$450 < Re_\tau < 6000$

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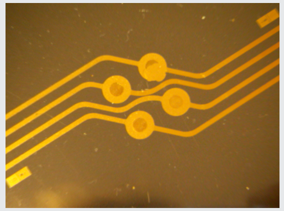
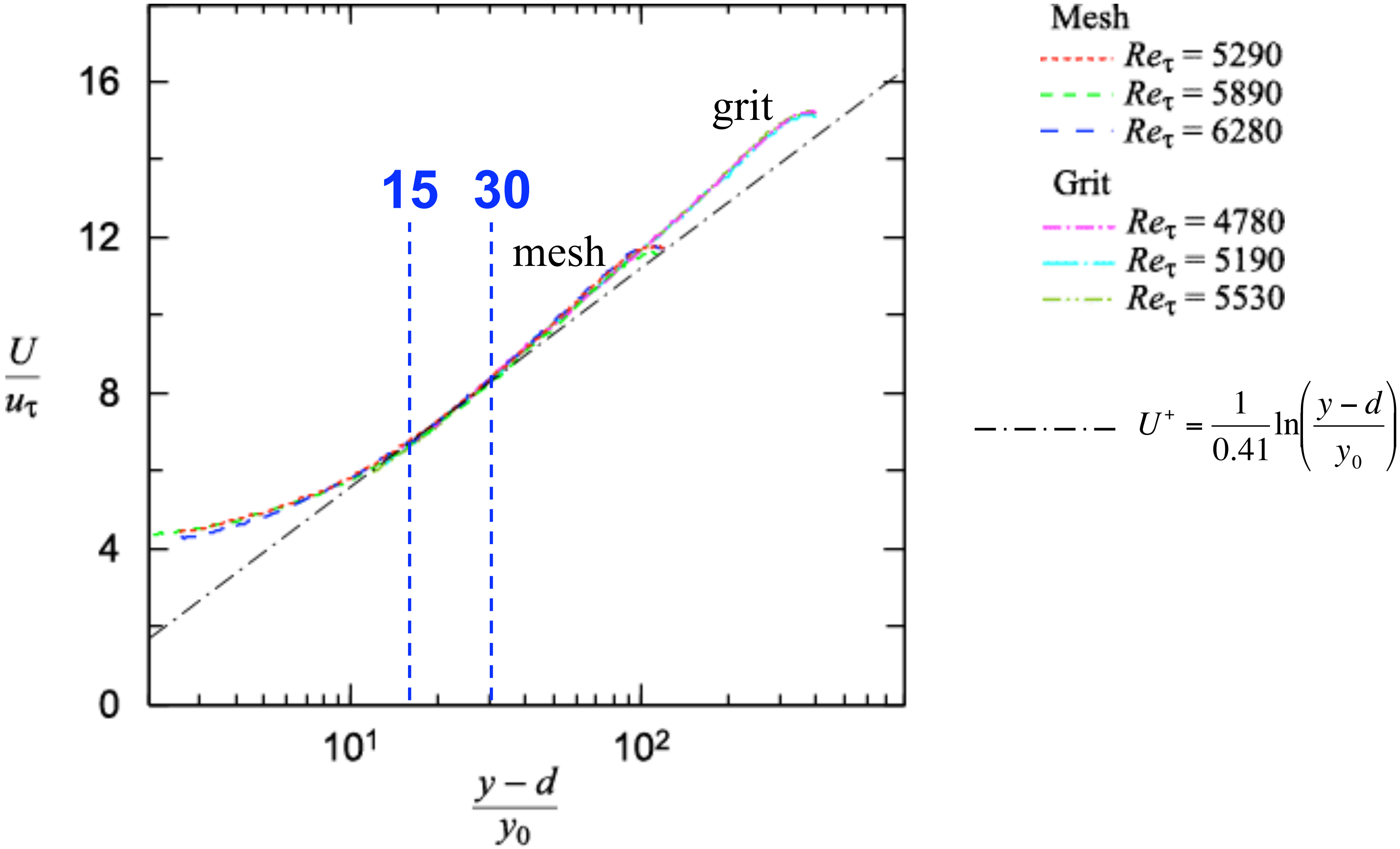
# Mean velocity: inner scaling





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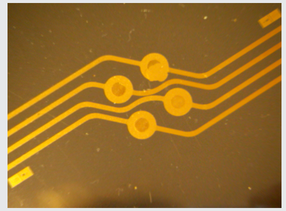
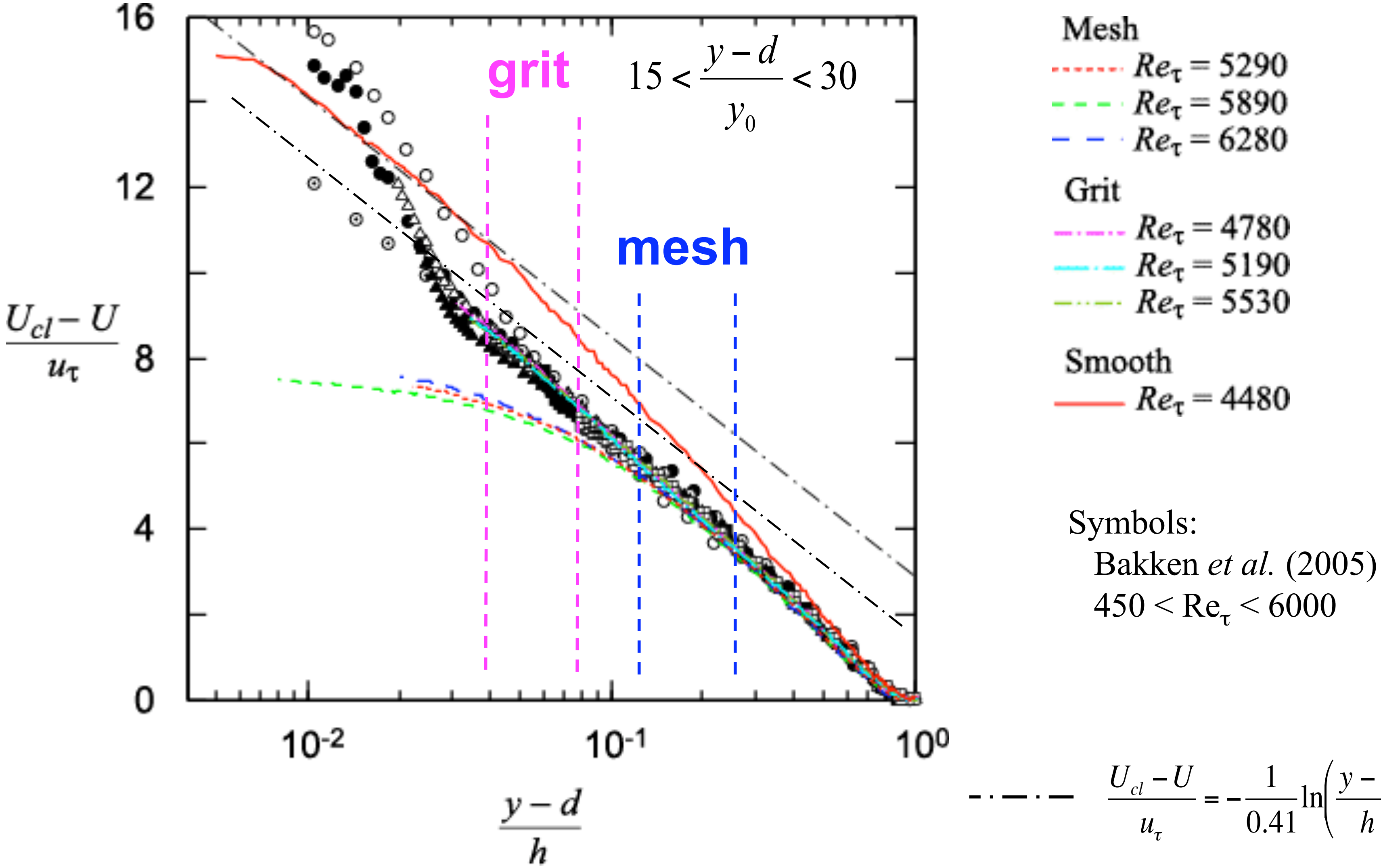


# Mean velocity: outer scaling




-·—·— $\frac{U_{cl} - U}{u_\tau} = -\frac{1}{0.41} \ln\left(\frac{y-d}{h}\right) + B$

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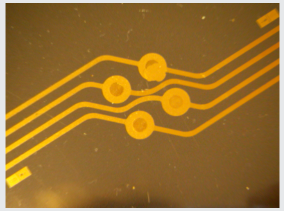
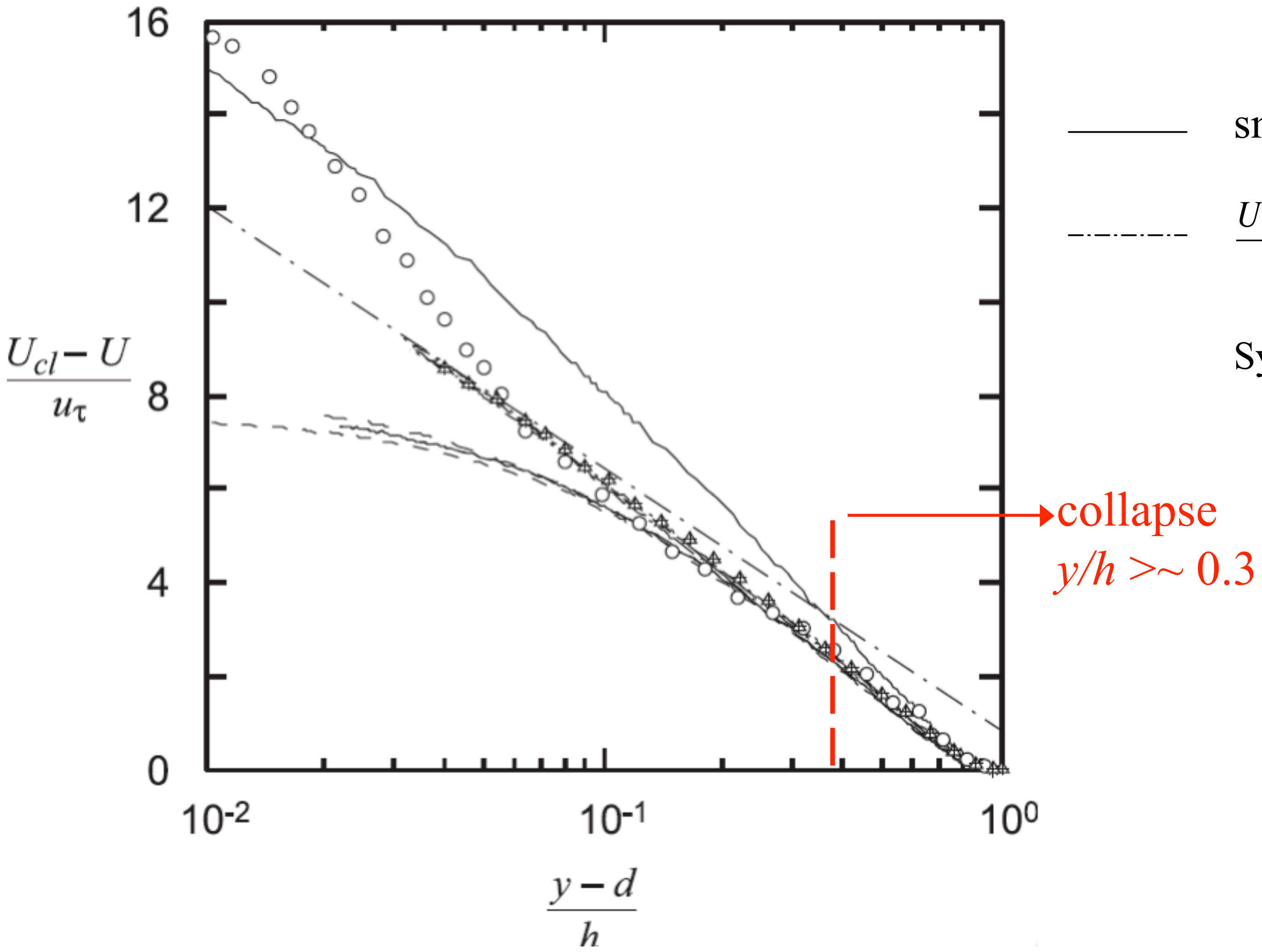
# Outer scaling - detail






smooth

$$\frac{U_{cl} - U}{u_\tau} = -\frac{1}{0.41}\ln\left(\frac{y-d}{h}\right) + B$$

Symbols:
Bakken *et al.* (2005)
$450 < Re_\tau < 6000$

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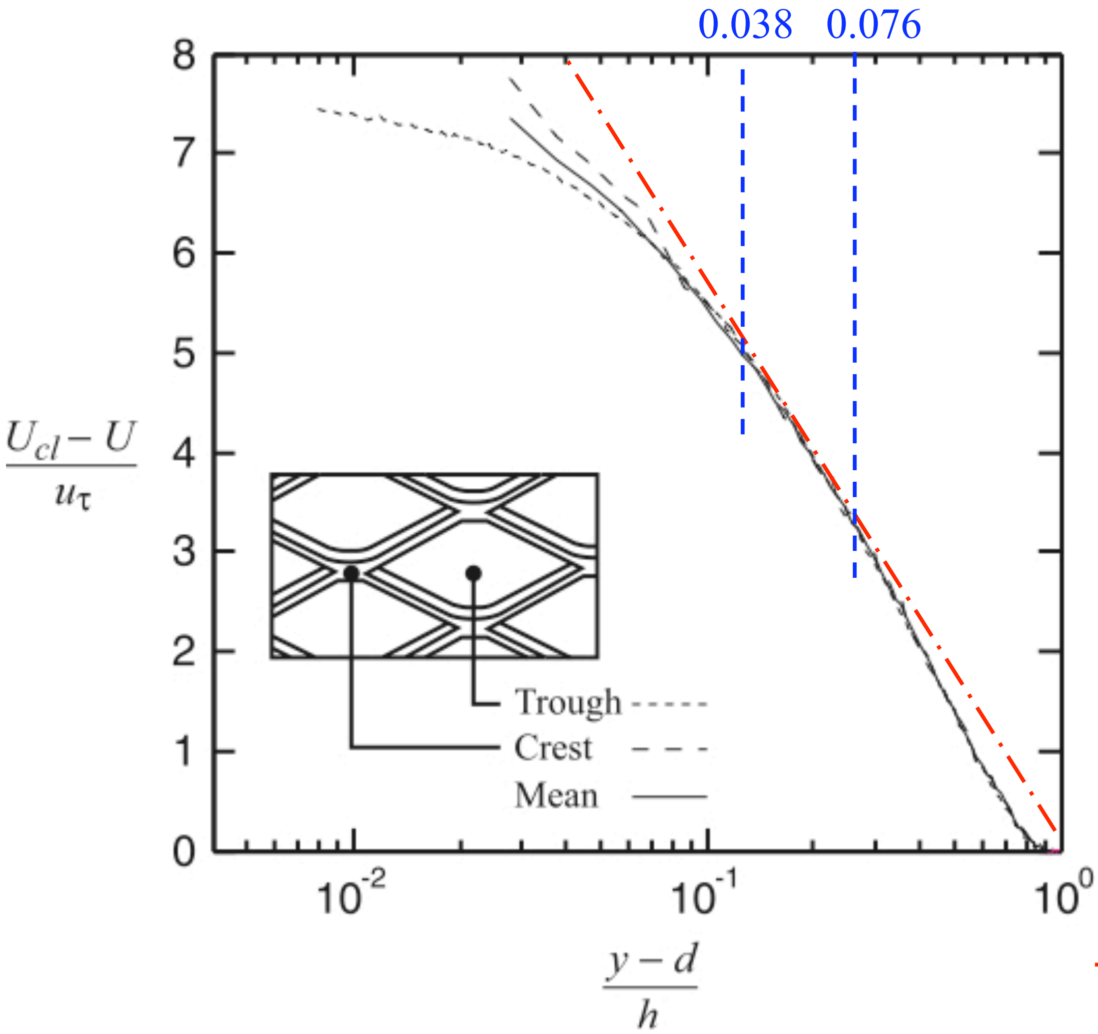
# Mean velocity: outer scaling - mesh detail




Profiles become spanwise homogeneous $(y-d)/h > 0.08$

Profiles collapse $y/h >\sim 0.3$

$$\frac{U_{cl} - U}{u_\tau} = -\frac{1}{0.41}\ln\left(\frac{y-d}{h}\right) + B$$

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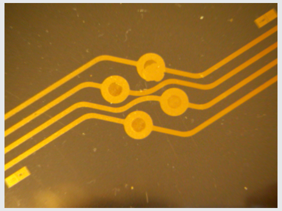
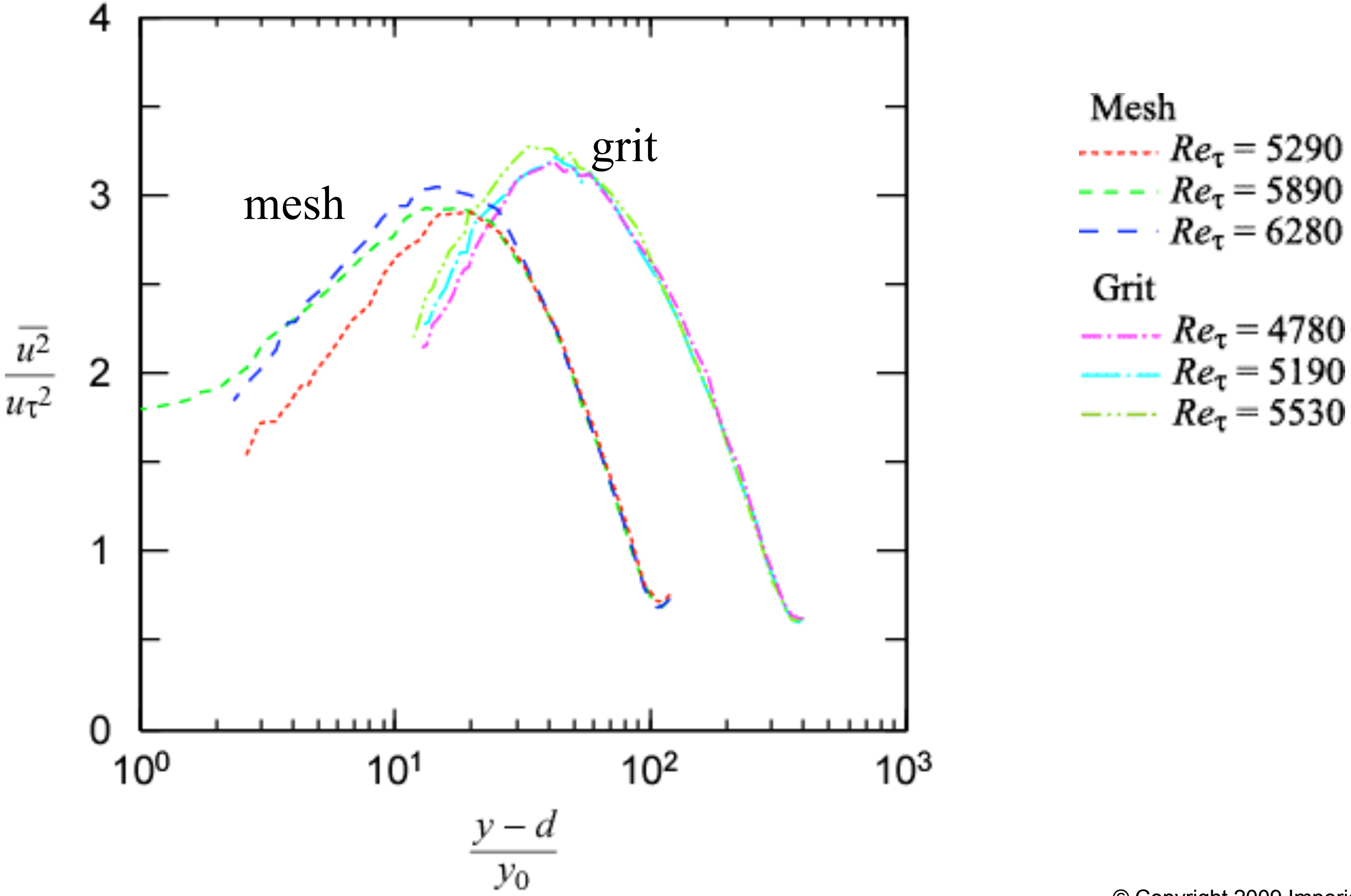


# Second moment: inner scaling



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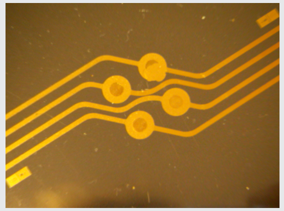
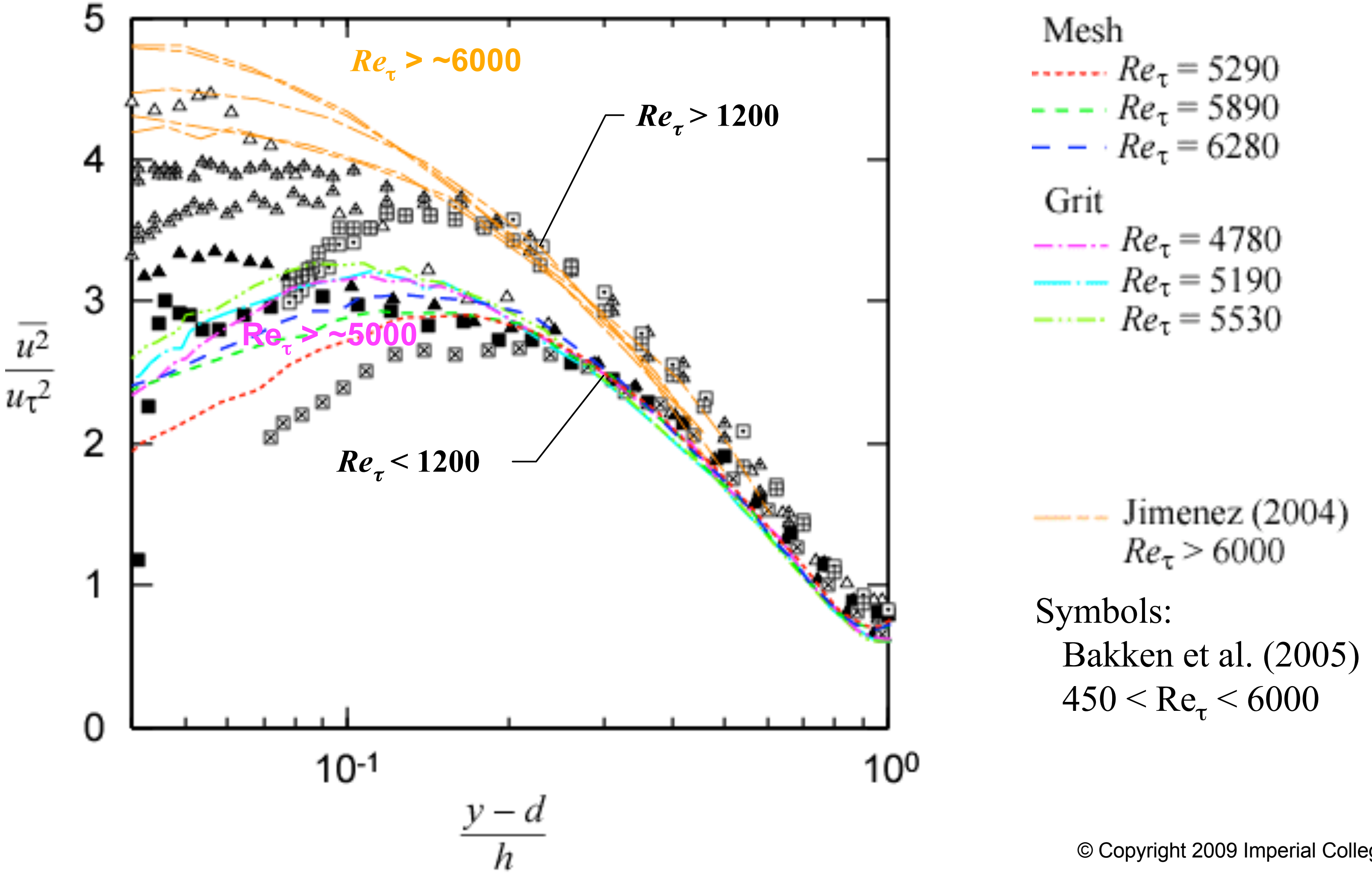
# Second moment: outer scaling





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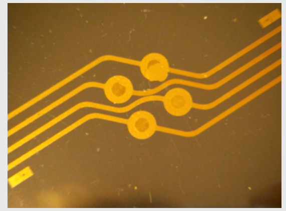
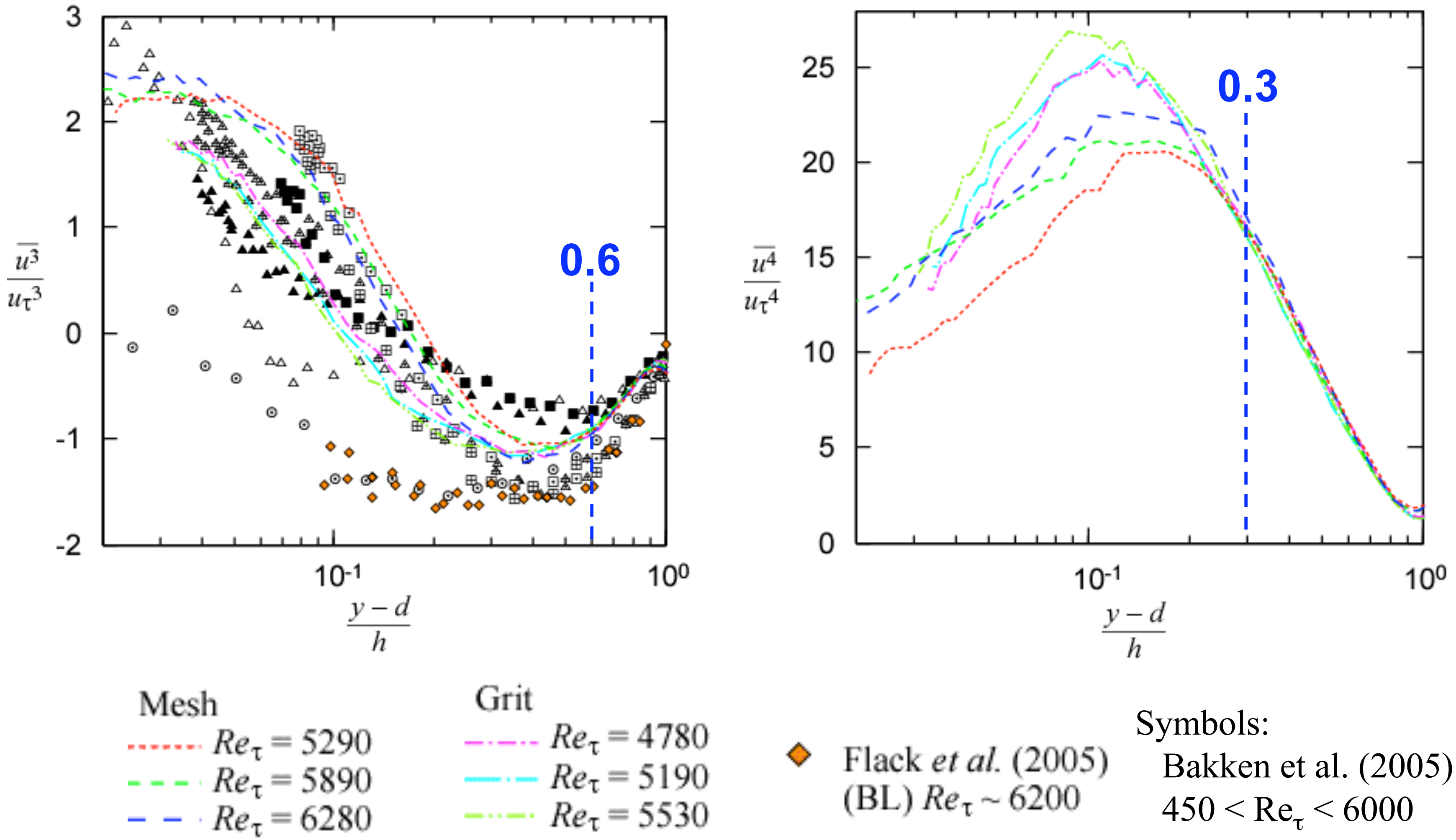


# Higher-order moments: outer scaling



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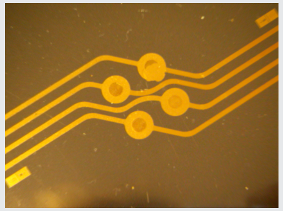
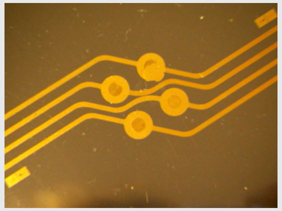
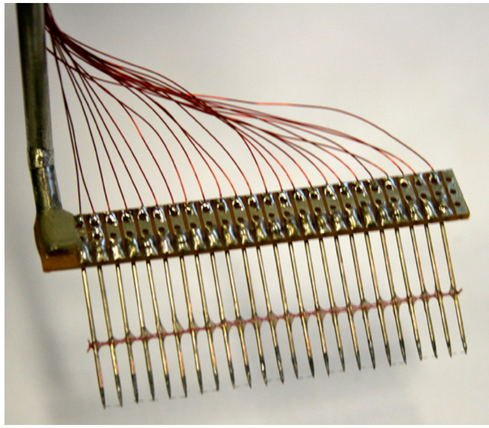


# Similarity: summary

- While mean velocity profile on isotropic grit ($k/h \approx 4\%$) shows self-similarity, that on '2.5D' mesh ($k/h \approx 8\%$) does not
- The lack of self-similarity on the mesh surface extends above the point at which mean velocity profiles become spanwise-homogeneous
- Coles' wake parameter, "wake strength", $\Delta U^+ = 2\Pi/\kappa$ decreases with increasing roughness (smooth: 3.9; grit: 0.7-0.8; mesh 0.2-0.4)
- Note however, that $\Pi$ may only be defined once the log law is established
- All $u$-component moments scale with outer variables - Townsend outer-layer scaling: $y/h$ at which this begins varies with order of moment
- Fully-developed channel flow requires $dp/dx$ to be a constant at all $y$ even if $\frac{1}{\rho}\frac{\partial p}{\partial y} = \frac{\partial \overline{v^2}}{\partial y}$ : therefore it is perhaps unsurprising that scaling with $u_\tau$ is robust

# Large structures: time histories - channel flow





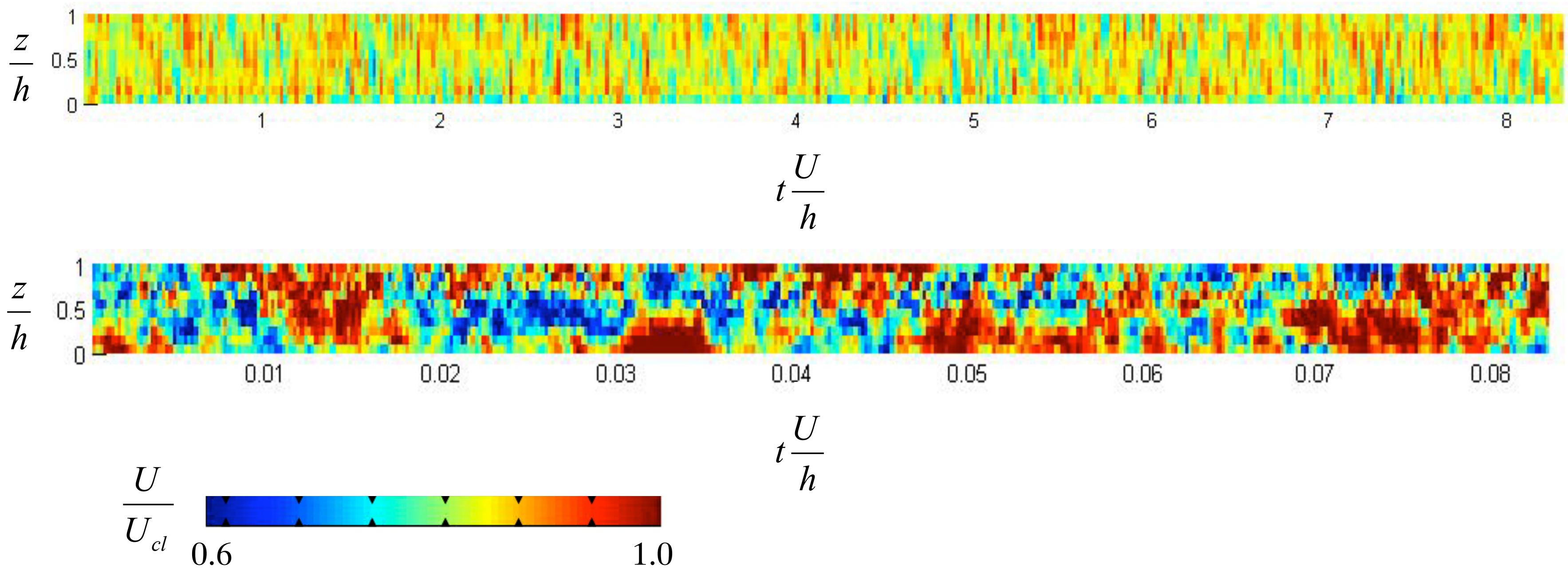
$\Delta z$ = 5.08 mm

$n$ = 12

$y/h = 0.2$

$Re_\tau$ = 5190

Grit surface



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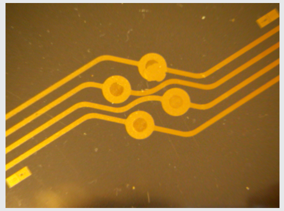
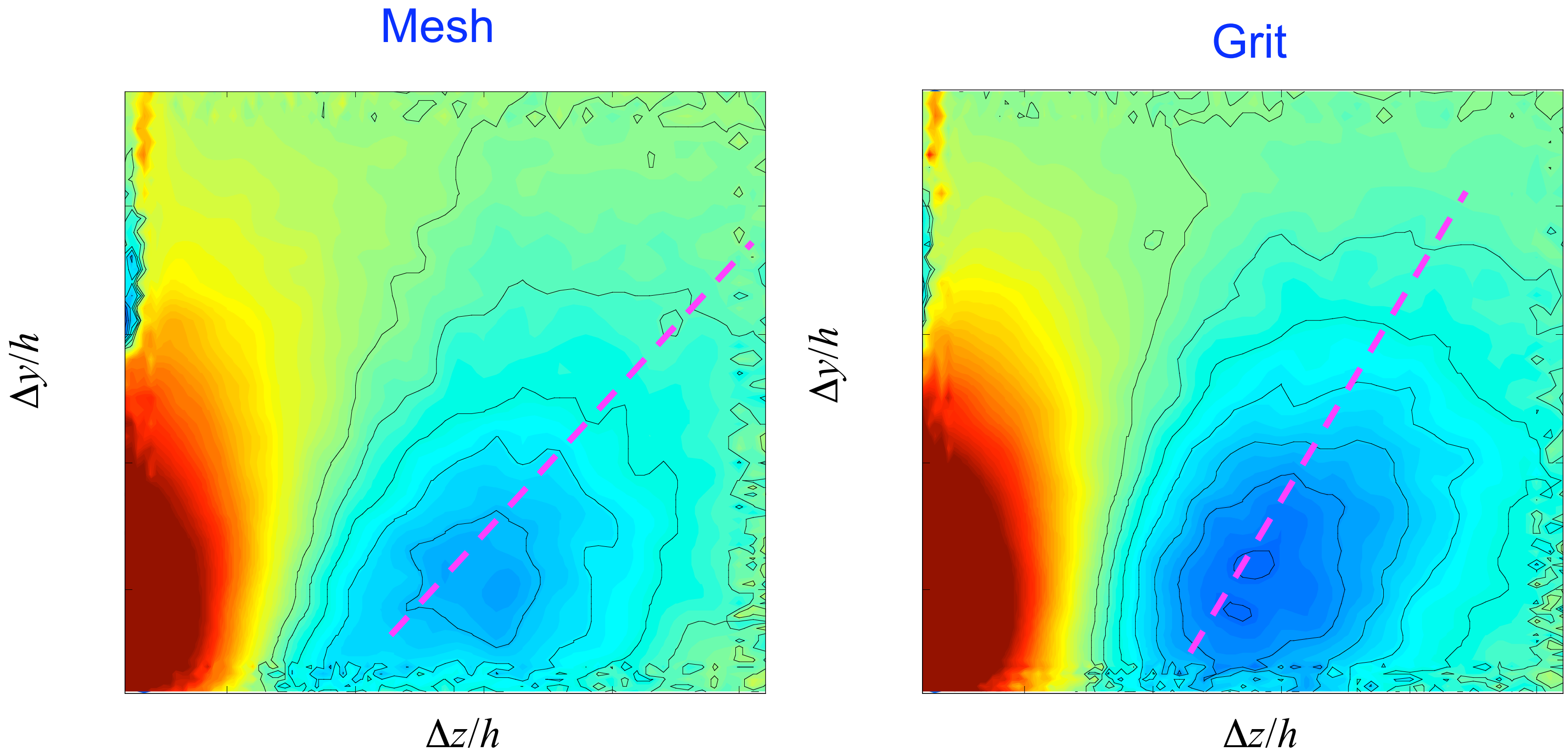
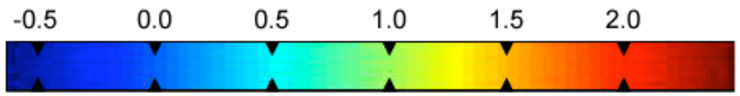
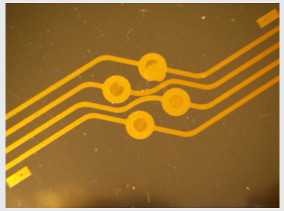


# Two-point correlations: channel flow

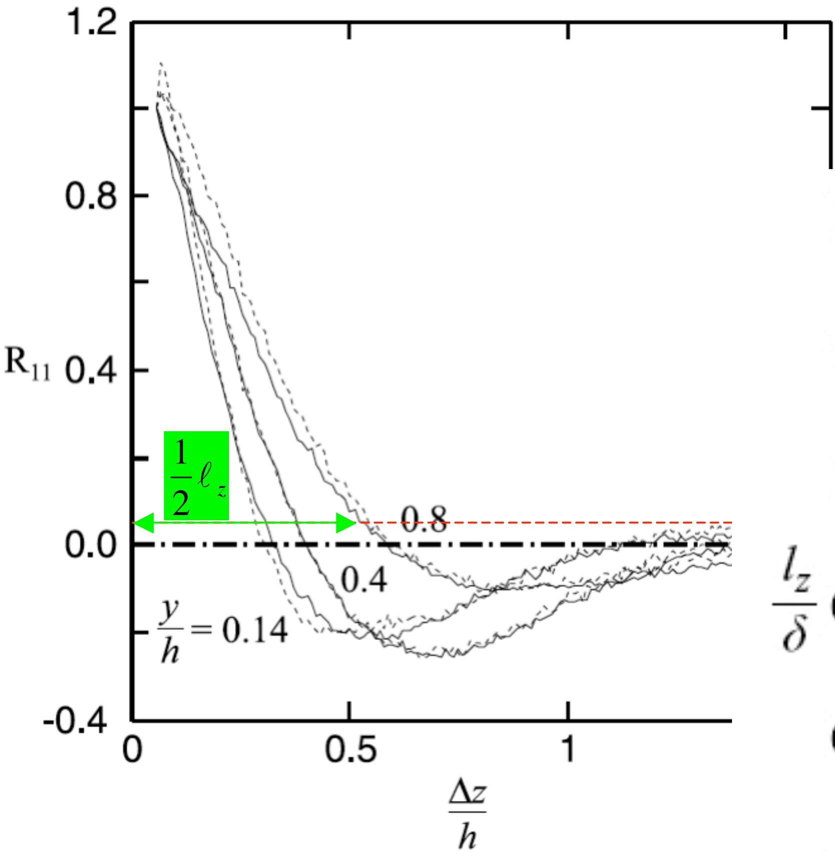


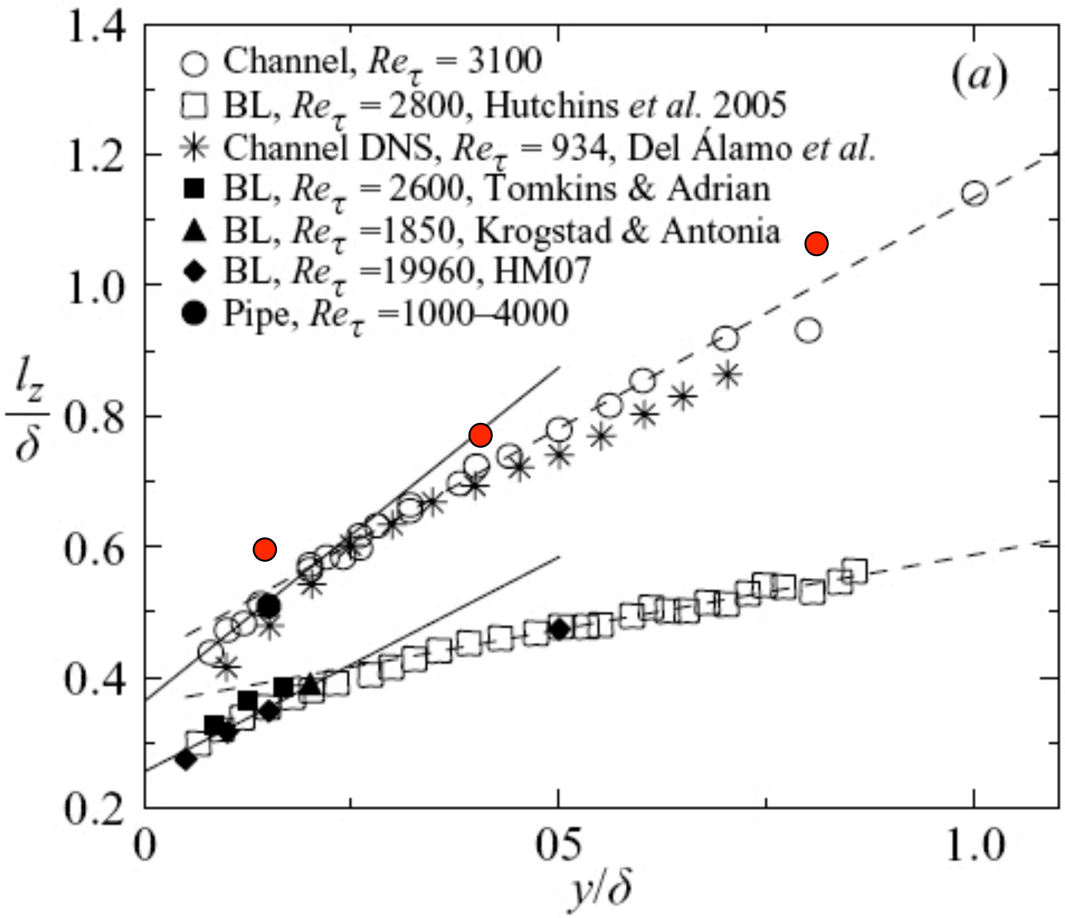

$$R_{11}(\Delta y, \Delta z) = \frac{\overline{u(y,z)u(y+\Delta y, z+\Delta z)}}{\overline{u^2(y,z)}}$$





# Two-point correlations: channel flow




$\Delta z/h$ at $R_{11}$=0.05
"Spanwise width scale"
Monty *et al.* (2008)

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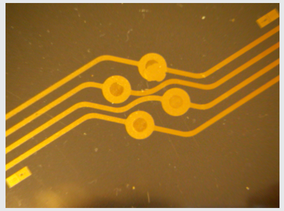

# Conclusions

- Self-similarity requires a demonstration of simultaneous overlap: grit roughness shows a log law, mesh does not
- The extent of Townsend outer-layer similarity has yet to be fully assessed: here it works well even for mesh
- Wake strength decreases as roughness increases
- Large streamwise vortices appear on rough as well as smooth surfaces: spanwise width scale, $\ell_z$ is larger
- Large streamwise structures are likely to be the result of non-normality - essentially not a viscous process and therefore relating to strain rate rather than viscous shear