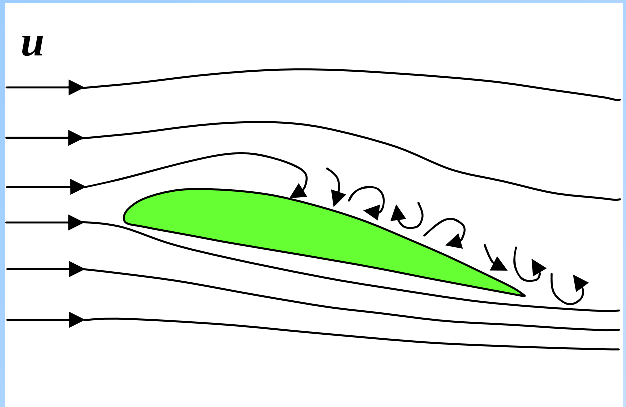
Wall pressure fluctuations in a turbulent boundary layer

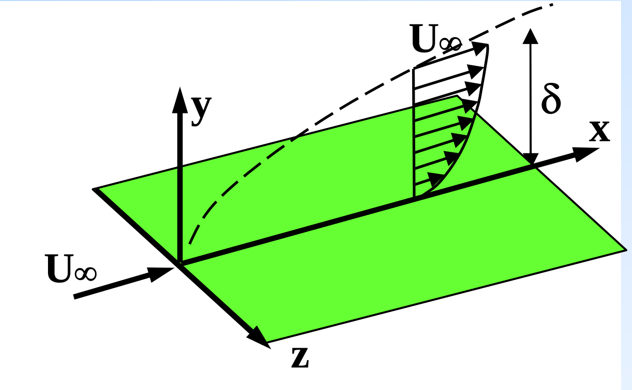
M. Stanislas, J. P. Laval

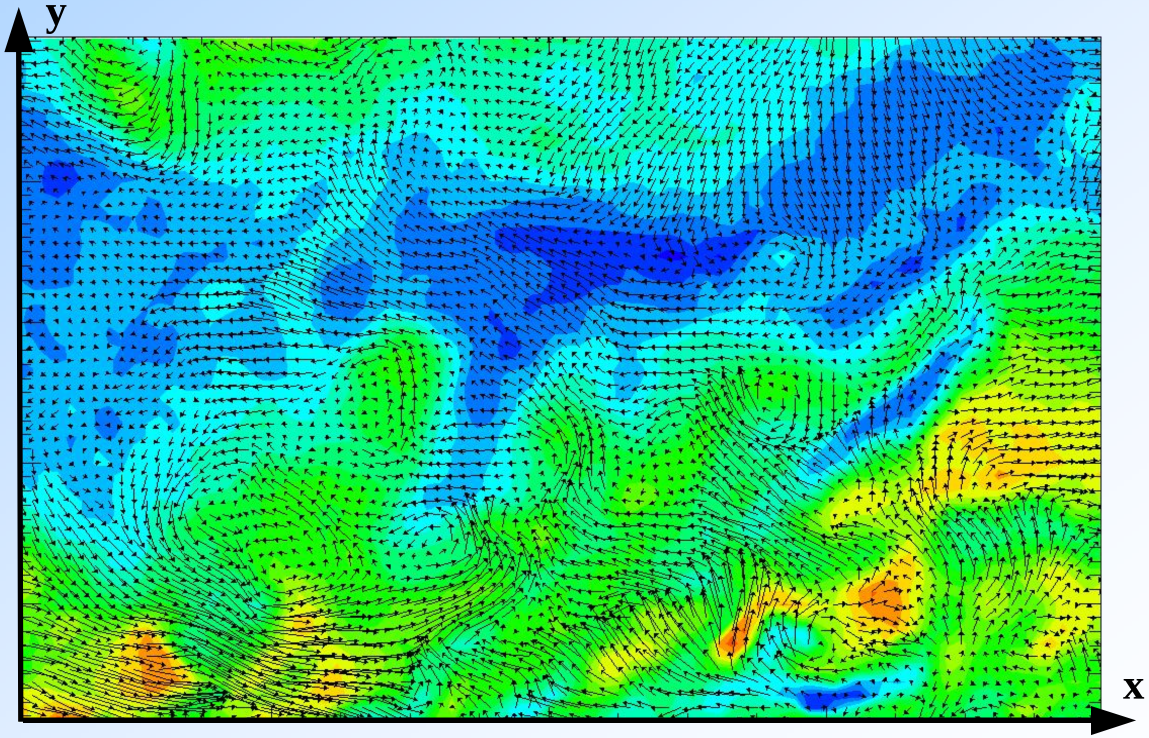
Ecole Centrale de Lille, CNRS

Laboratoire de Mécanique de Lille

Turbulent boundary layer







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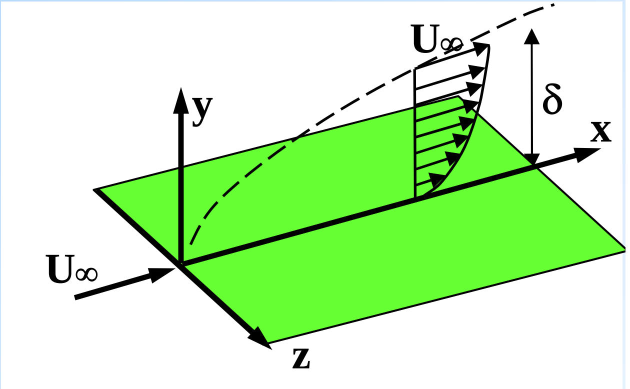
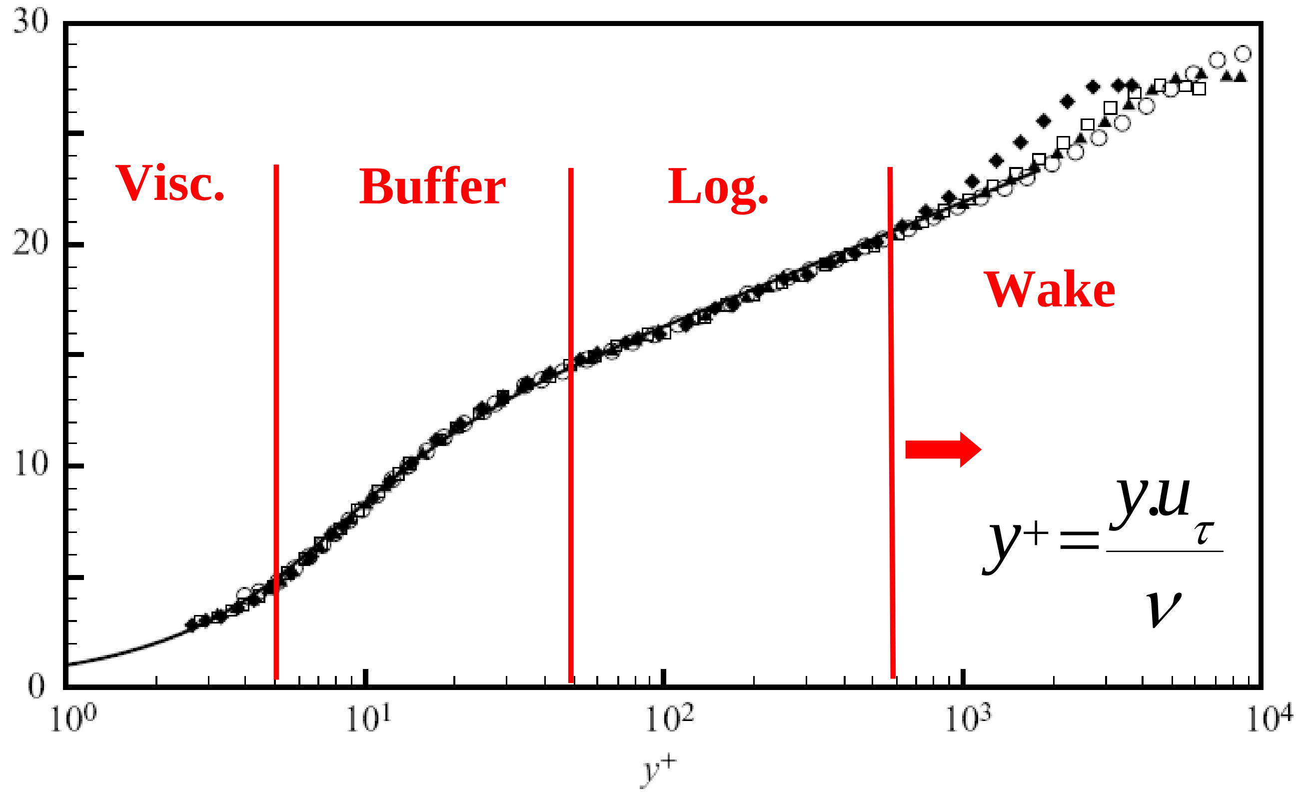
Turbulent boundary layer

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}}$$



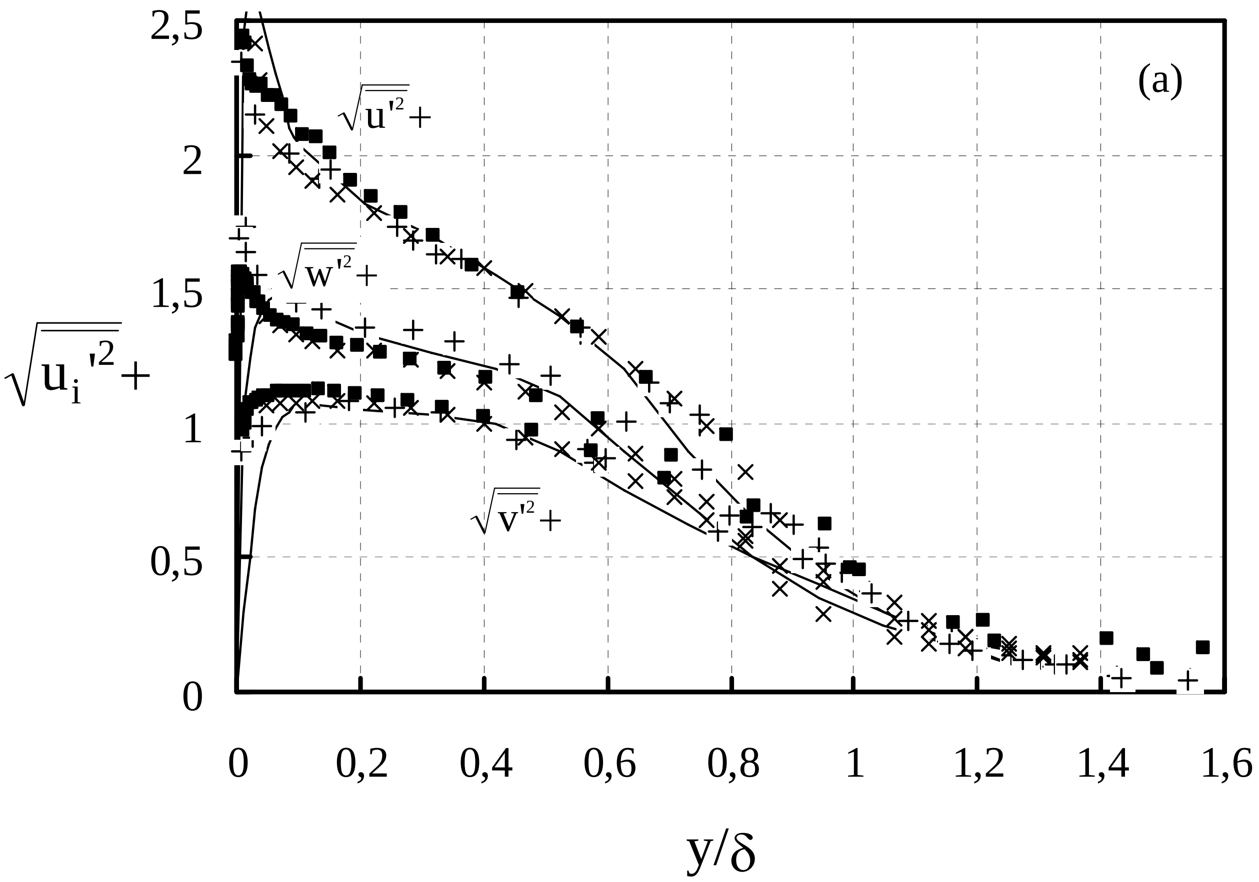
$$U^+ = \frac{U}{u_\tau}$$

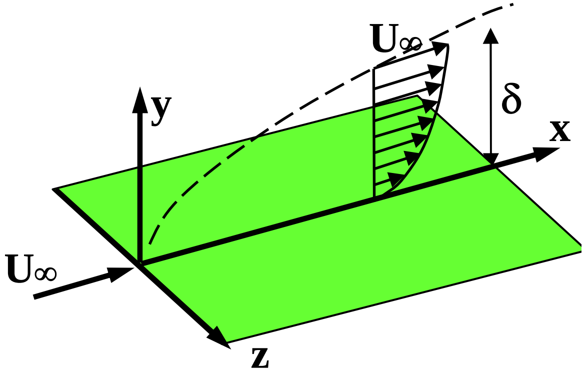


$$y^+ = \frac{y.u_\tau}{\nu}$$

FIGURE 5. Profiles of longitudinal mean velocity U obtained with HWA: ◆, $R_\theta = 8100$; □, $R_\theta = 11\,500$; ▲, $R_\theta = 14\,800$; ○, $R_\theta = 20\,600$; ———, Van Driest profile.

Turbulent boundary layer





Turbulence intensity components in a flat plate turbulent boundary layer, obtained from HWA. ■ Re_θ= 20 800, + Klebanoff (1955), *x* Erm & Joubert (1991), —DNS Spalart (1988).

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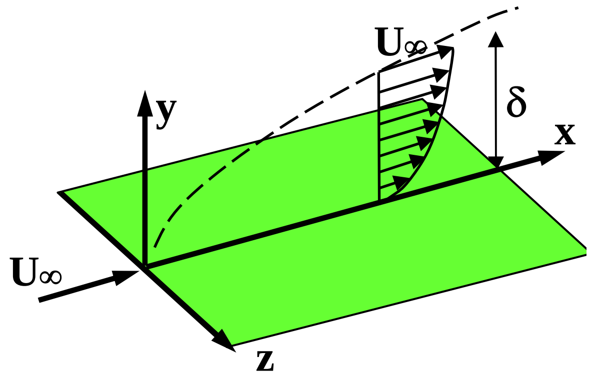
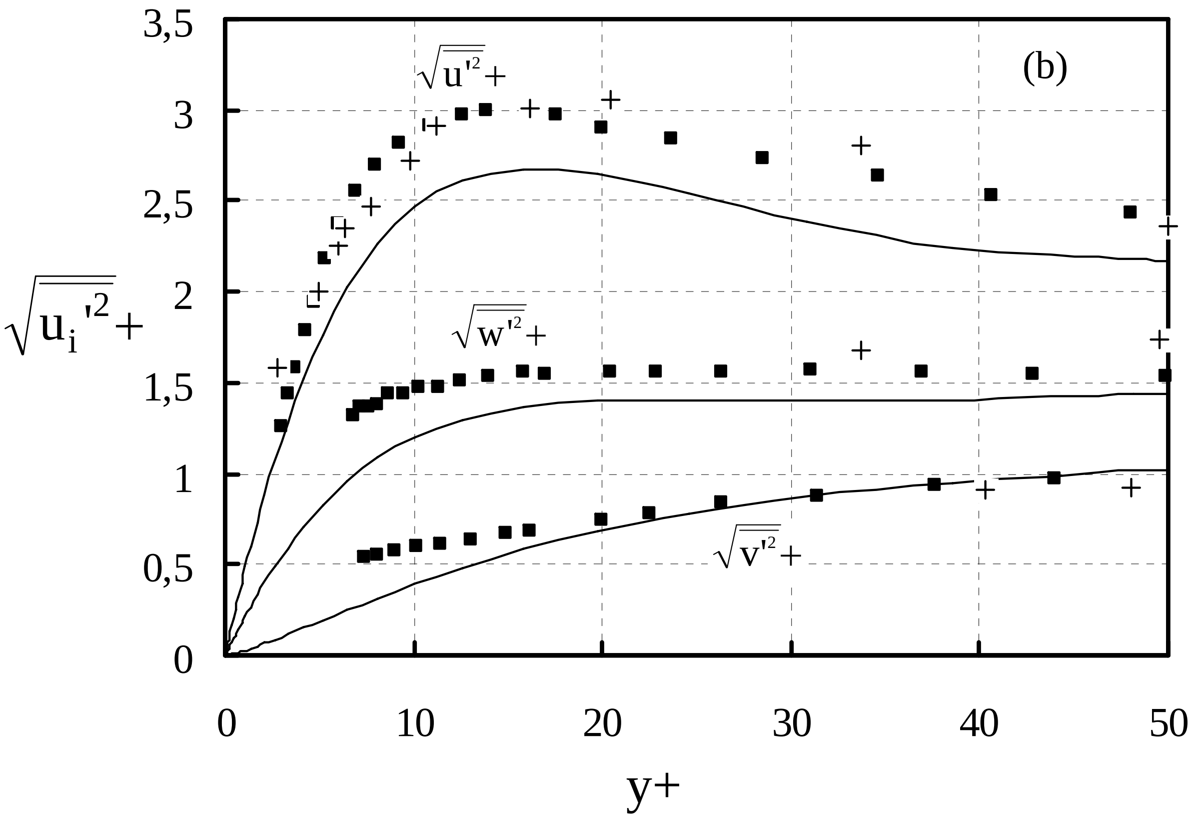
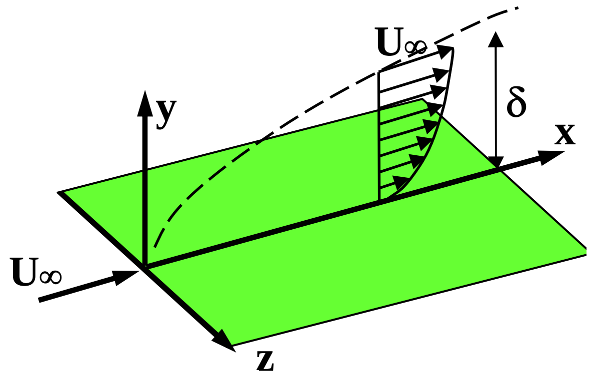
Turbulent boundary layer

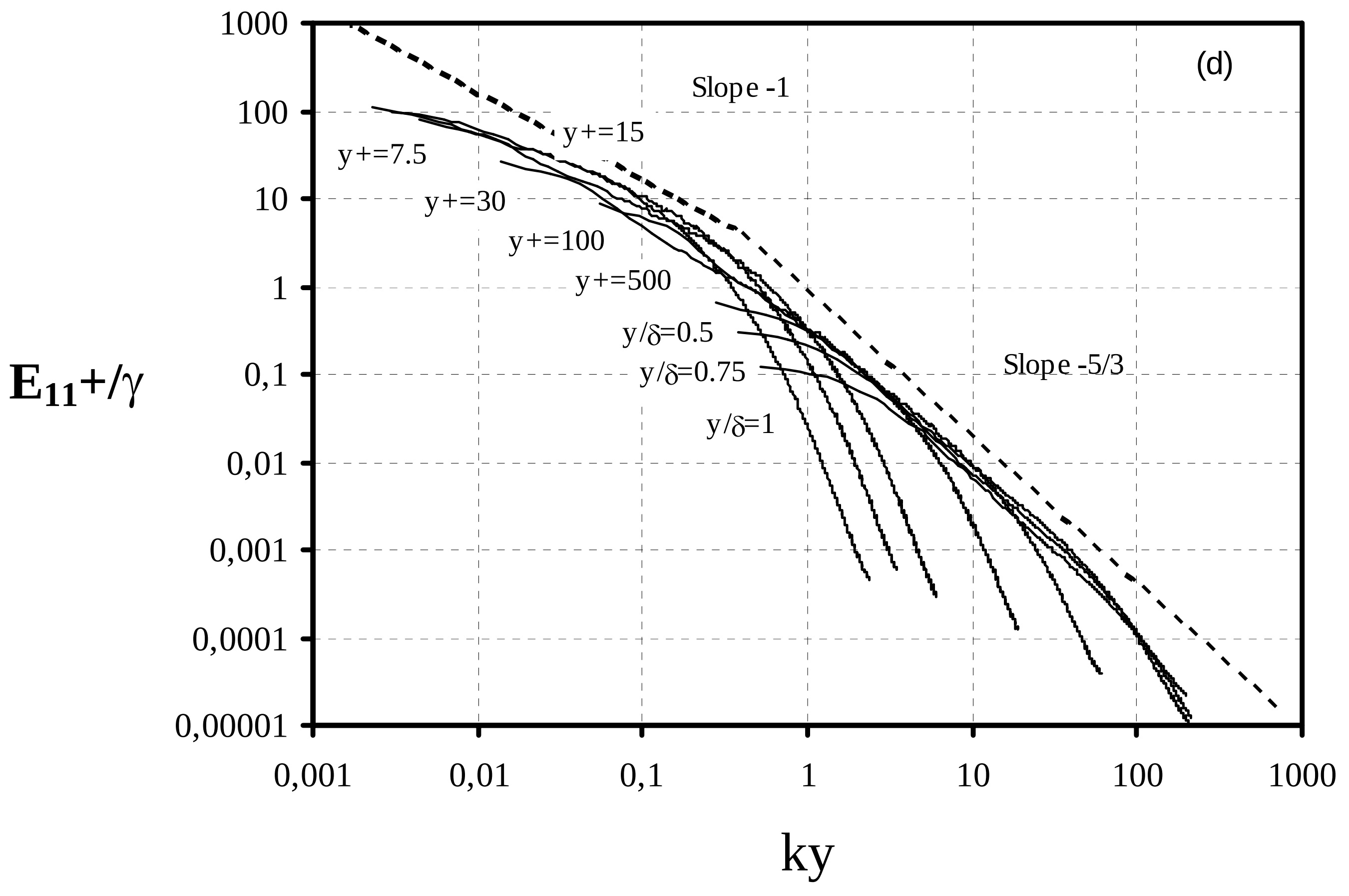




Turbulence intensity components in a flat plate turbulent boundary layer, obtained from HWA. ■ Re_θ= 20 800, + Klebanoff (1955), —DNS Spalart (1988).

Turbulent boundary layer





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Buffer layer

Streaks

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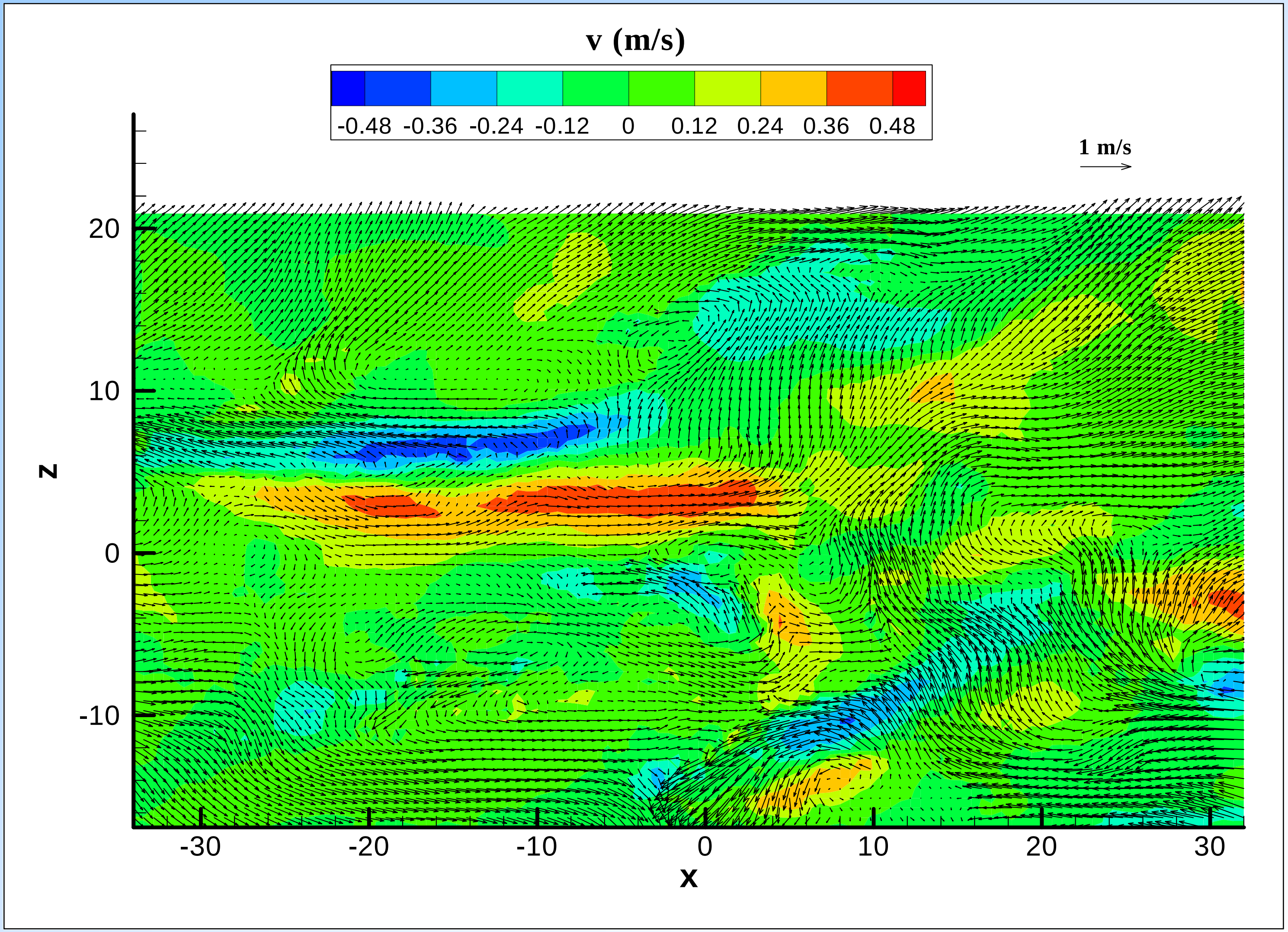
Buffer layer

Vortices



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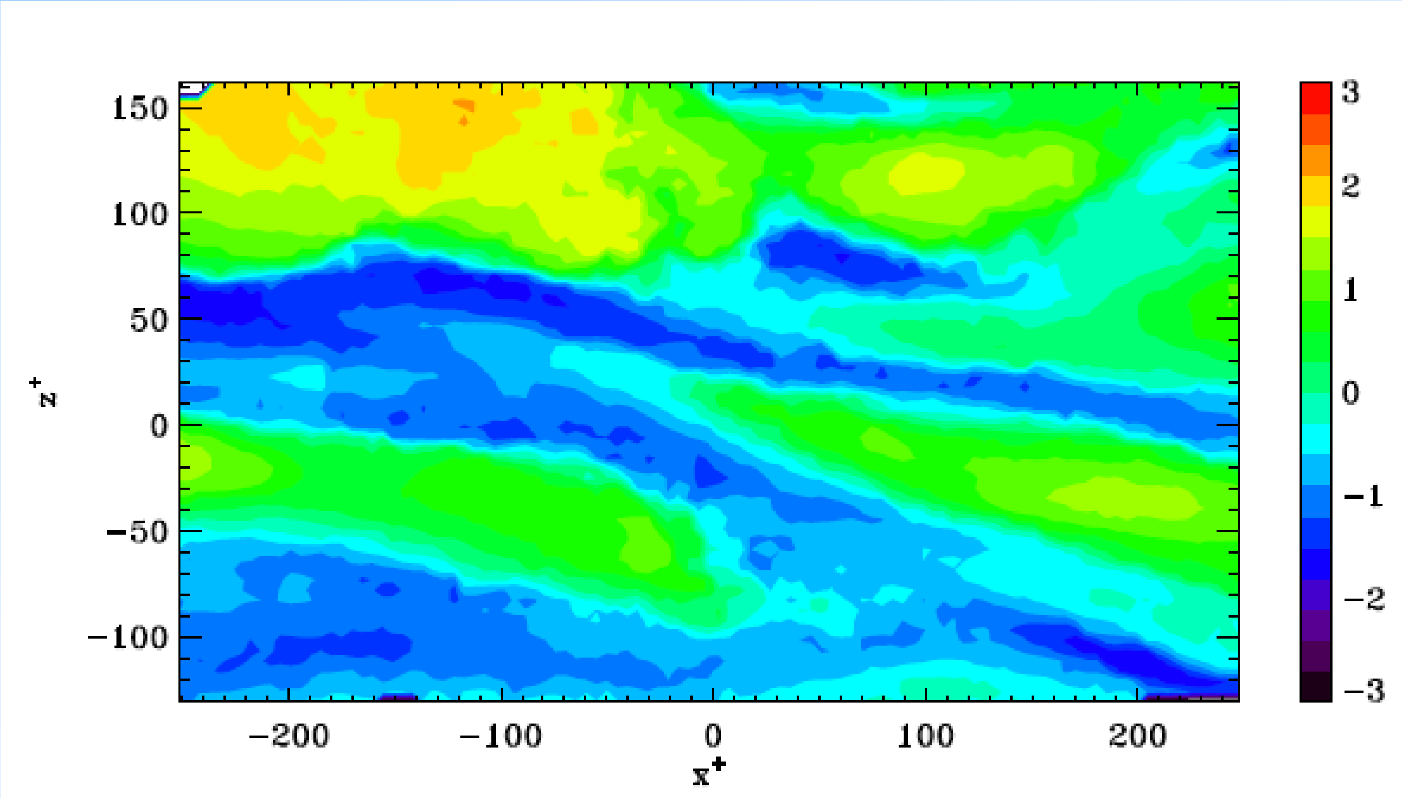
Buffer layer

Streaks

J. Lin (2006)



$$F_d = f(u'(m,n,y^+),\sigma_u(y^+)) = \frac{u'(m,n,y^+)}{\sigma_u(y^+)}$$

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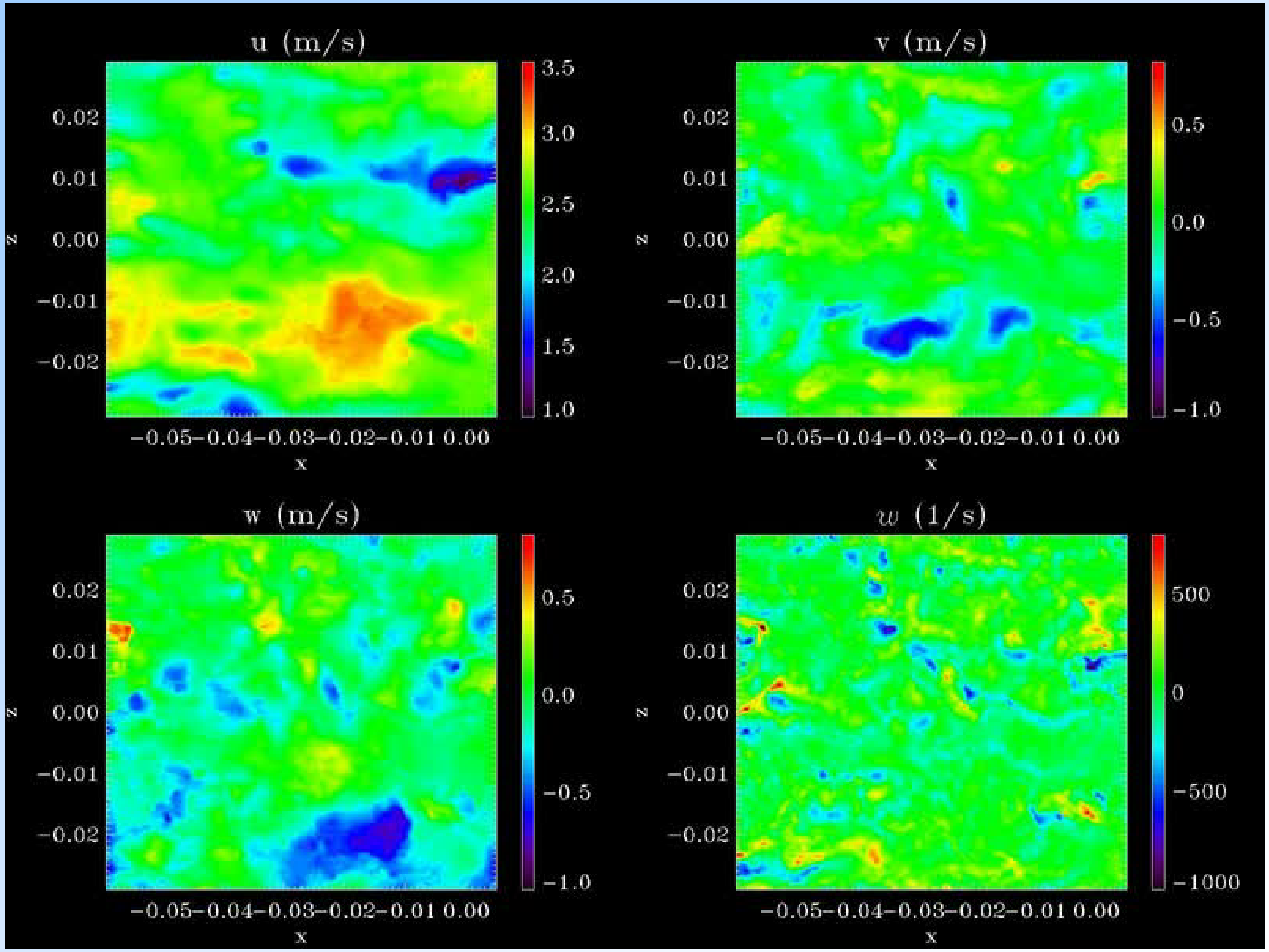
Velocity



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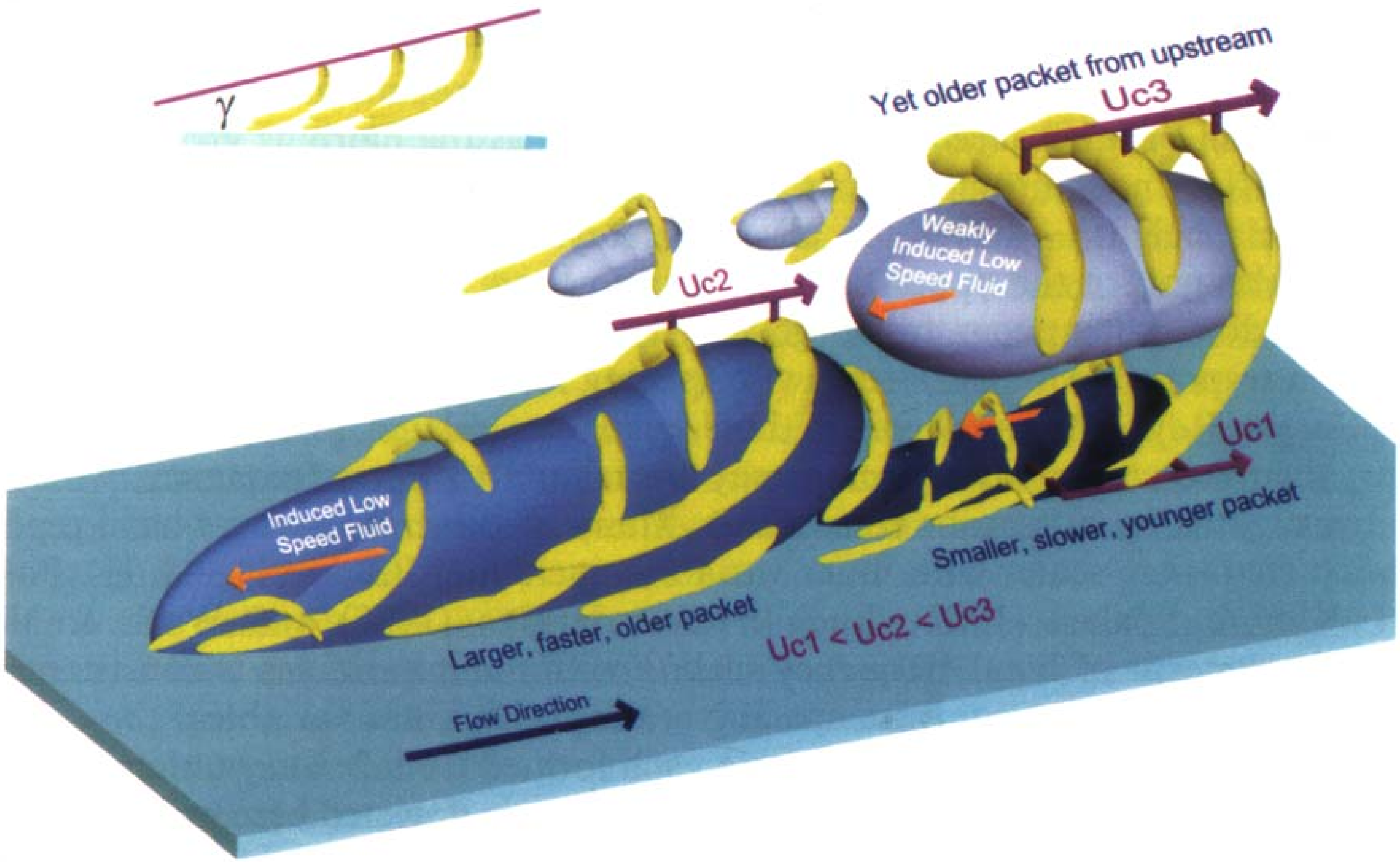
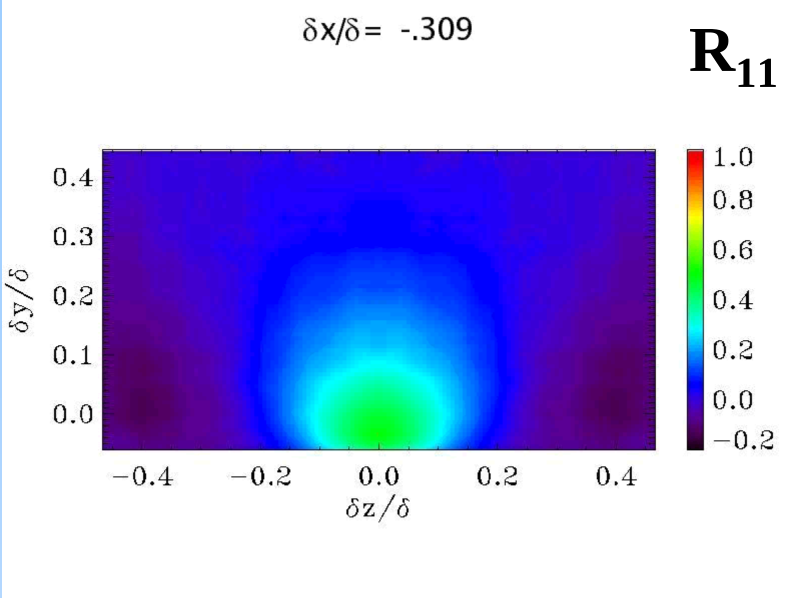
Hairpin vortices

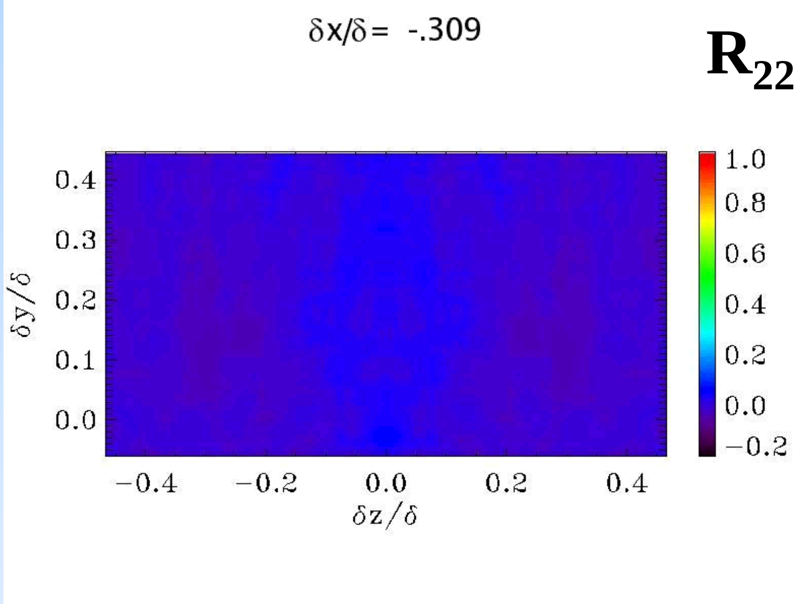
Adrian et al (2000)

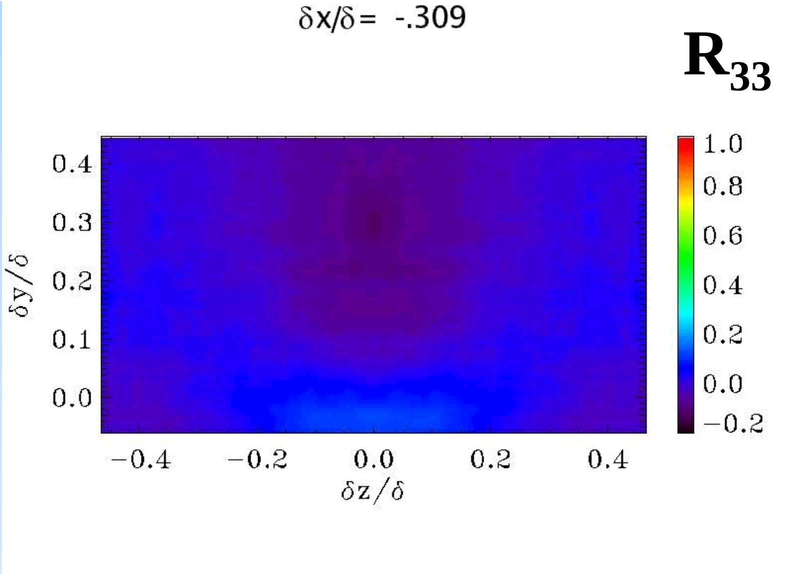


Large scales

3D Two points correlations







$$R_{ij}(\overrightarrow{x},\overrightarrow{dx}) = \frac{\overline{u_i(\overrightarrow{x}).u_j(\overrightarrow{x}+\overrightarrow{dx})}}{\sqrt{\overline{u_i(\overrightarrow{x})^2}}.\sqrt{\overline{u_i(\overrightarrow{x}+\overrightarrow{x})^2}}}$$

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Poisson equation for pressure

$$\frac{\partial^2 p}{\partial x_i \partial x_i} = -\rho \frac{\partial}{\partial x_i}\left(\frac{\partial u_i u_j}{\partial x_j}\right).$$

$$p = P + p'$$

$$u = U + u'$$

$$\frac{\partial^2 p'}{\partial x_i \partial x_i} = -\left\{ 2\frac{\partial U_i}{\partial x_j}\frac{\partial u_j}{\partial x_i} + \frac{\partial^2}{\partial x_i \partial x_i}\left(u'_i u'_i - \overline{u'_i u'_i}\right) \right\}$$

rapid **slow**

T^{MS} T^{TT}

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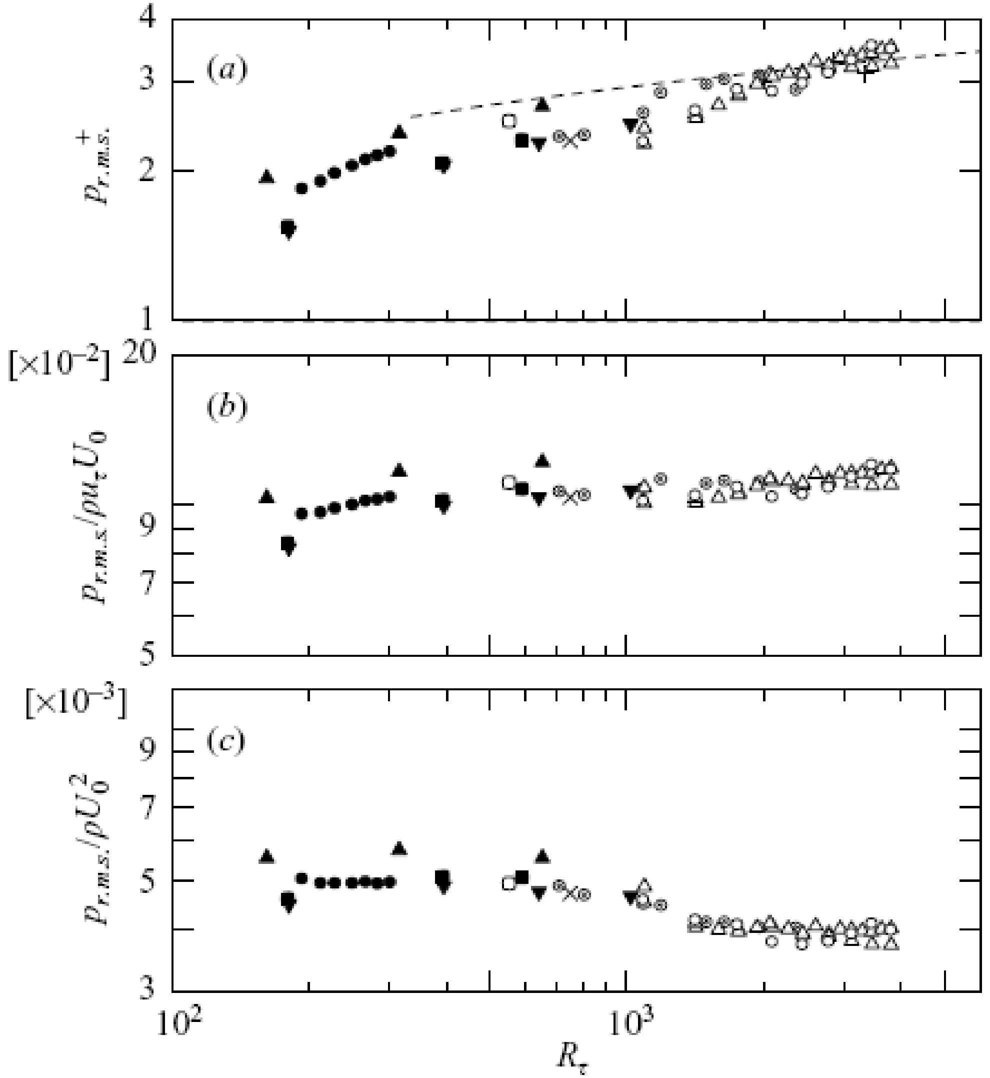
Pressure fluctuations at the wall

Tsuji et al 2007

Measurements
&
DNS

d+ < 30



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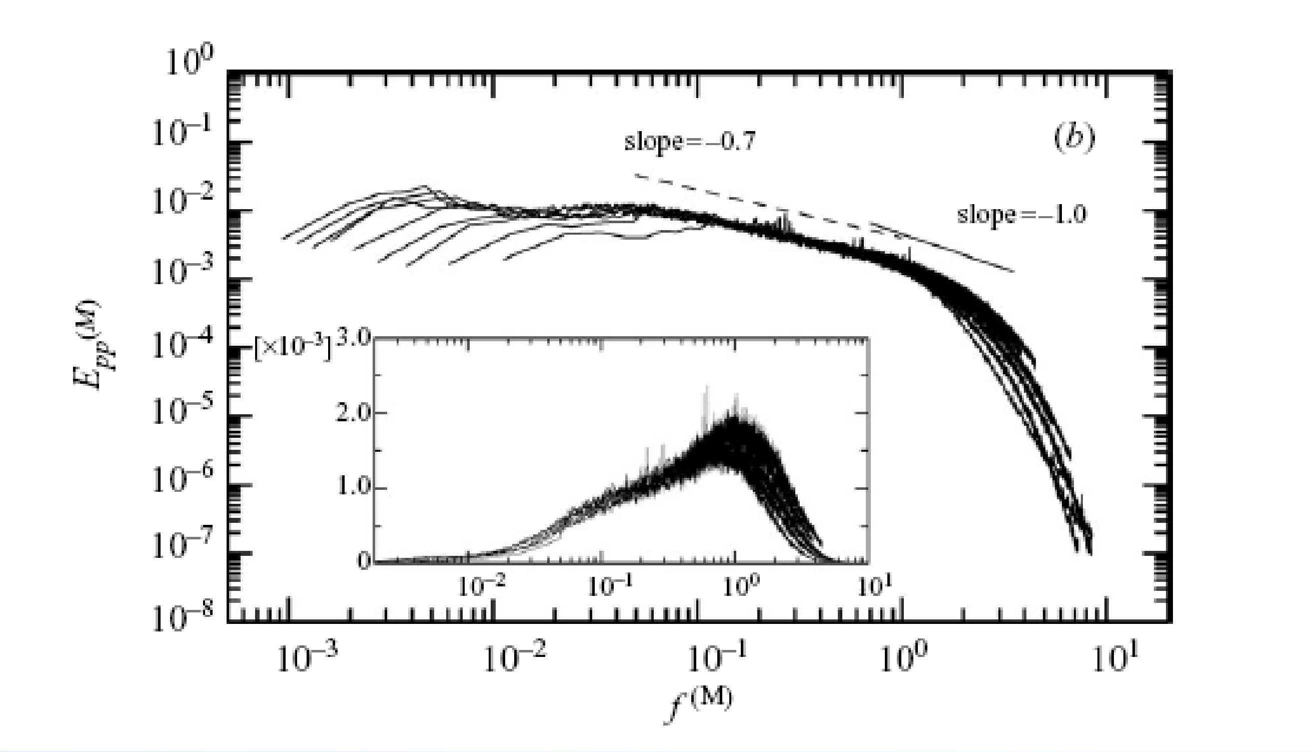
Pressure fluctuations at the wall

Tsuji et al 2007



5 870 < Re_θ < 16 700 mixed scaling

Bradshaw (1967) f^{-1}

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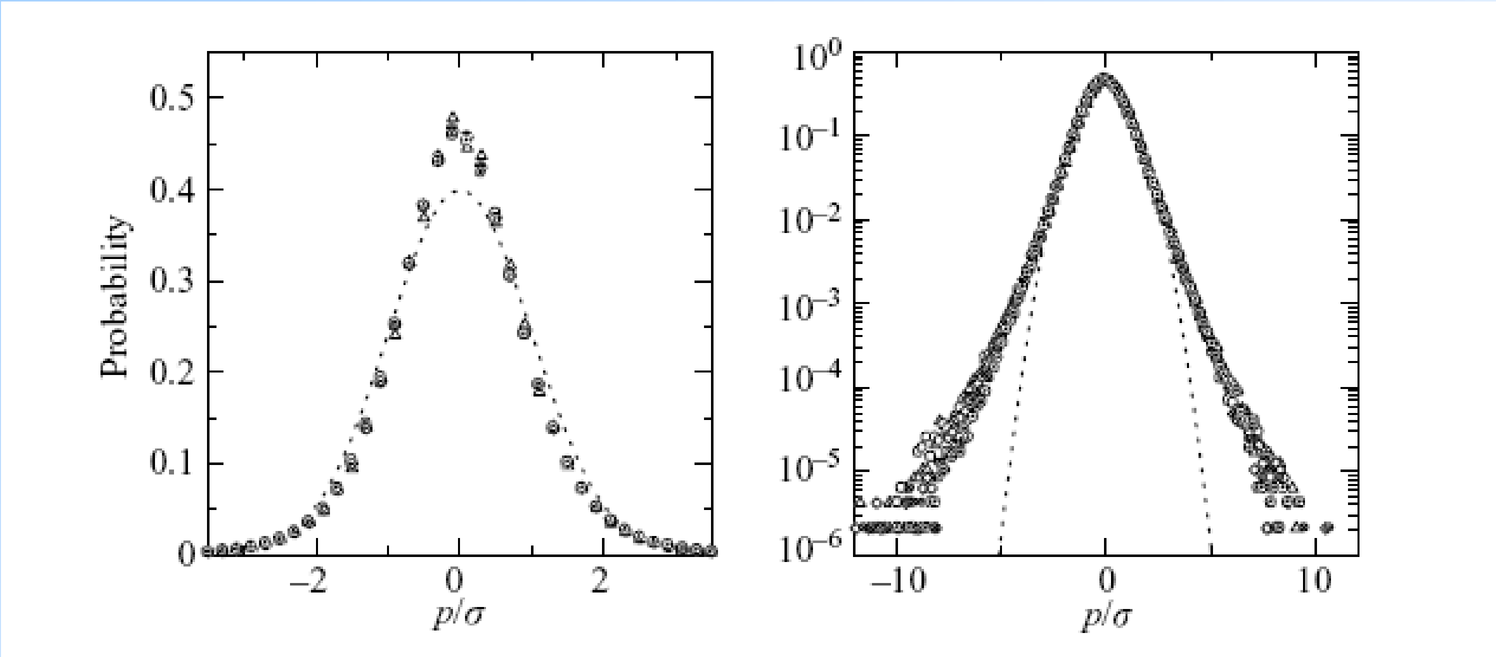
Pressure fluctuations at the wall

Tsuji et al
2007



5 870 < Re_θ < 16 700 PDF of pressure fluctuations

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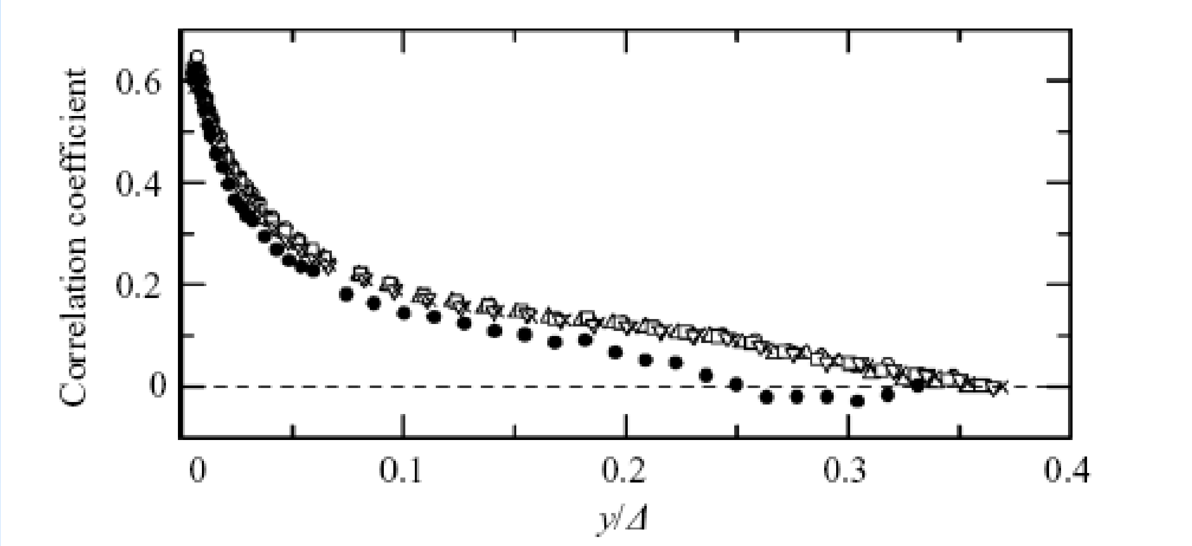
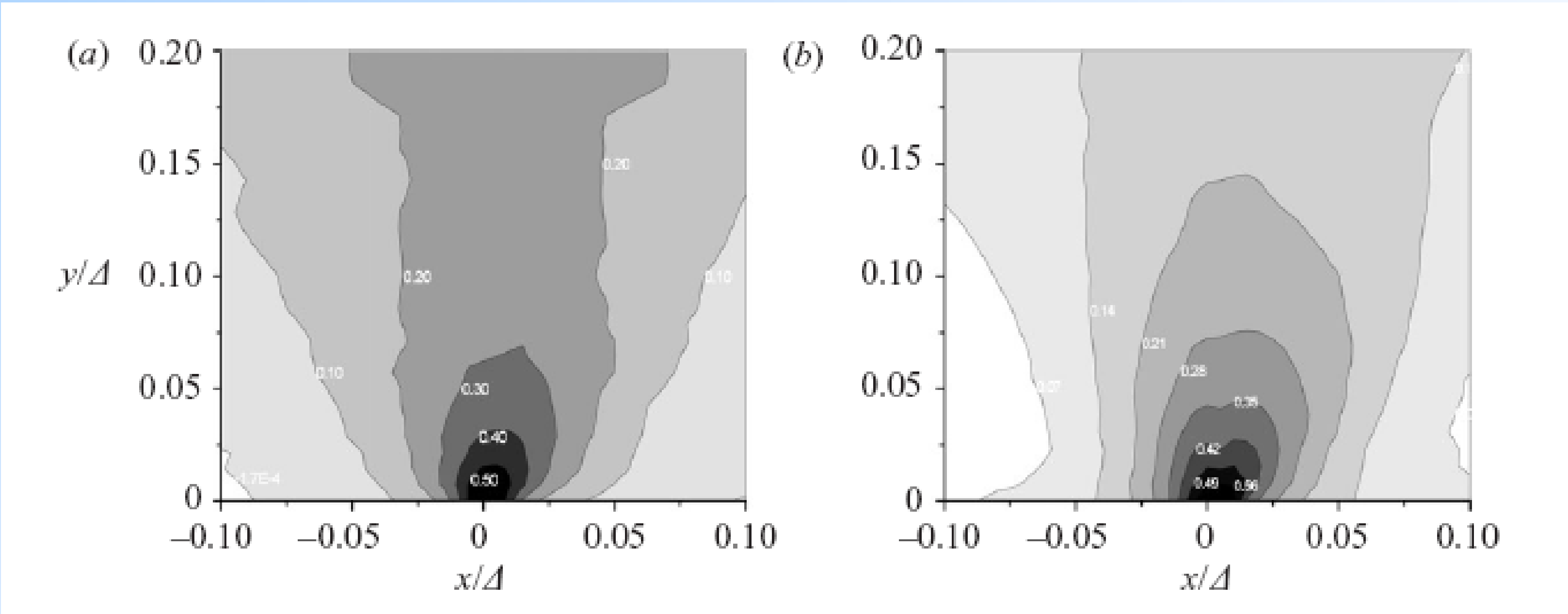
Pressure fluctuations at the wall

Tsuji et al 2007

5 870 < Re_θ < 16 700
Wall/Static
Pressure correlation





Re_θ = 5 870 **Re_θ = 16 700**

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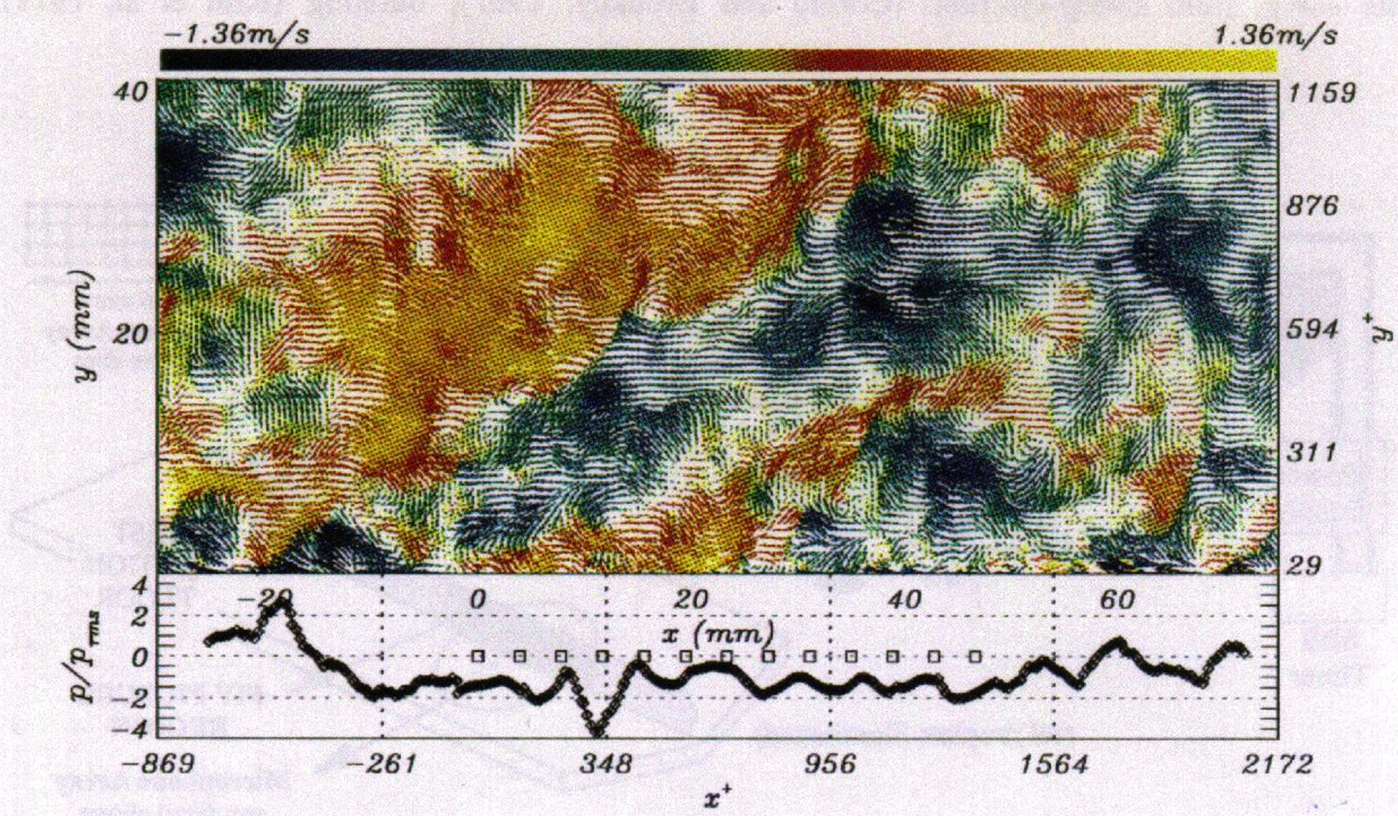

Figure 2 Instantaneous velocity and wall pressure field.

Ojeda (1996)

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Pressure fluctuations

	LES7	DNS5	Kim *et al.* (1987)
$Re_\tau = u_\tau \delta/\nu$	171.8	179.8	$\sim$ 180
$u_\tau/U_o \times 10^2$	5.265	5.525	5.49
U_b/u_τ	16.29	15.57	15.63
U_o/U_b	1.17	1.16	1.16
δ^*/δ	0.1424	0.1396	0.141
θ/δ	0.0858	0.0858	0.087
$C_f \times 10^3$	7.54	8.25	8.18

Table I: Flow parameters for turbulence simulations

Chang (1998)

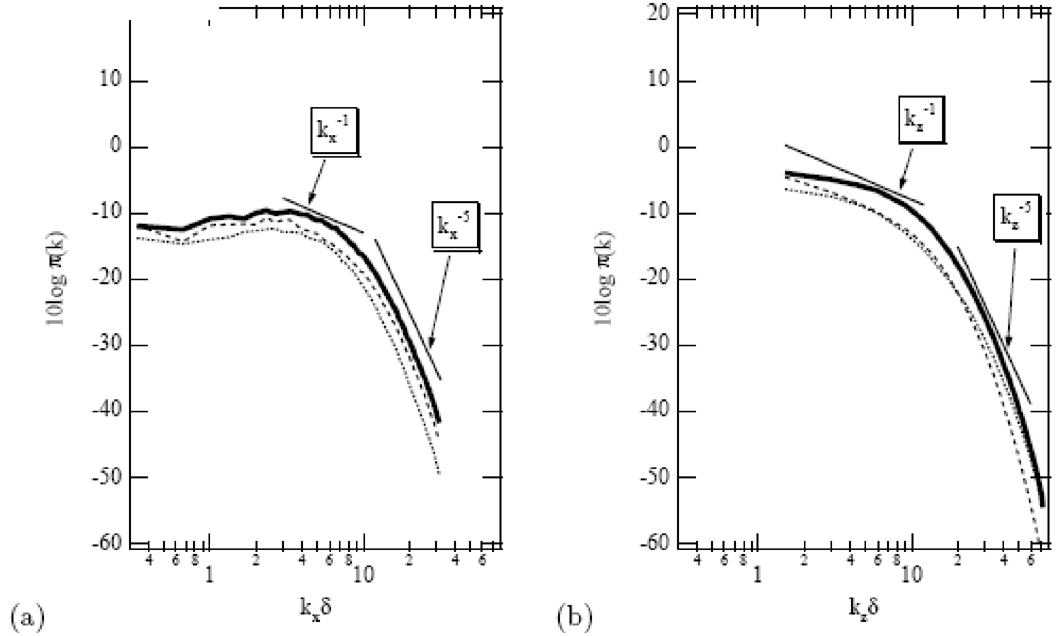

Figure 4.2: Total, MS and TT one-dimensional pressure spectra. ▬ π^{tot}; ········ π^{TT}; - - - - π^{MS}. (a) Streamwise, (b) spanwise.

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Pressure fluctuations sources

Region	Limits	Description
1	$0 \leq y^+ < 5$	Viscous shear-layer
2	$5 \leq y^+ < 30$	Buffer layer
3	$30 \leq y^+ < 180$	Logarithmic region
4	$180 \leq y^+ < 360$	Upper channel

Table I: Regions of the channel.

Chang (1998)

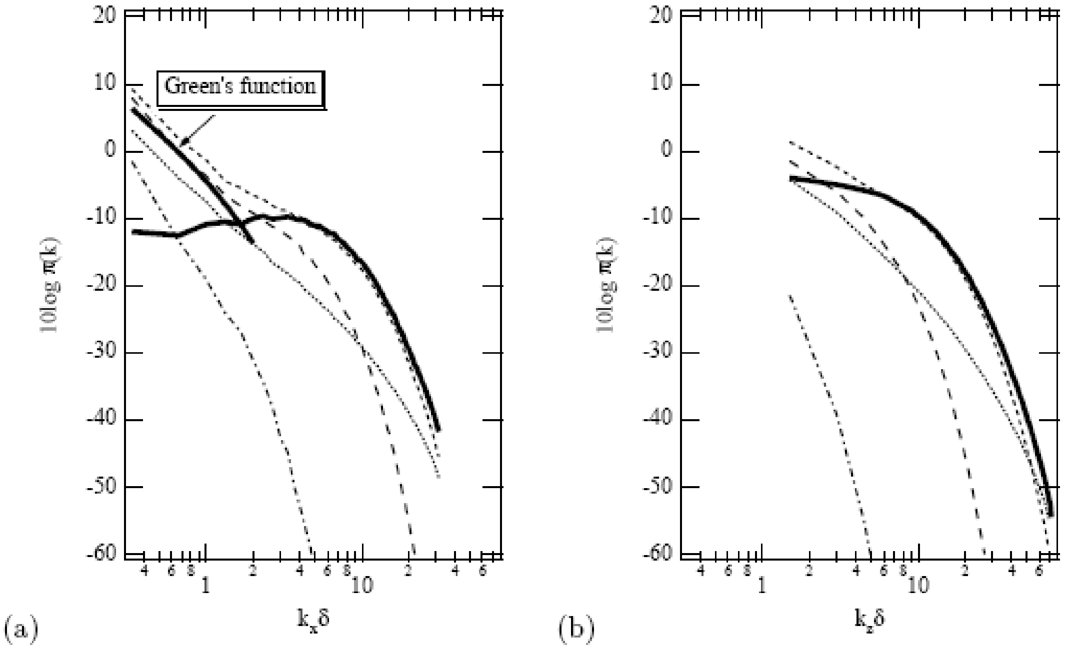

Figure 4.3: One-dimensional spectra of the total pressure for the various regions. ▬ All regions (R1234); ········ viscous shear-layer (R1); --------- buffer layer(R2); – – – – logarithmic region(R3); —·— upper channel(R4). (a) Streamwise, (b) spanwise.

Pressure fluctuations sources

Chang (1998)

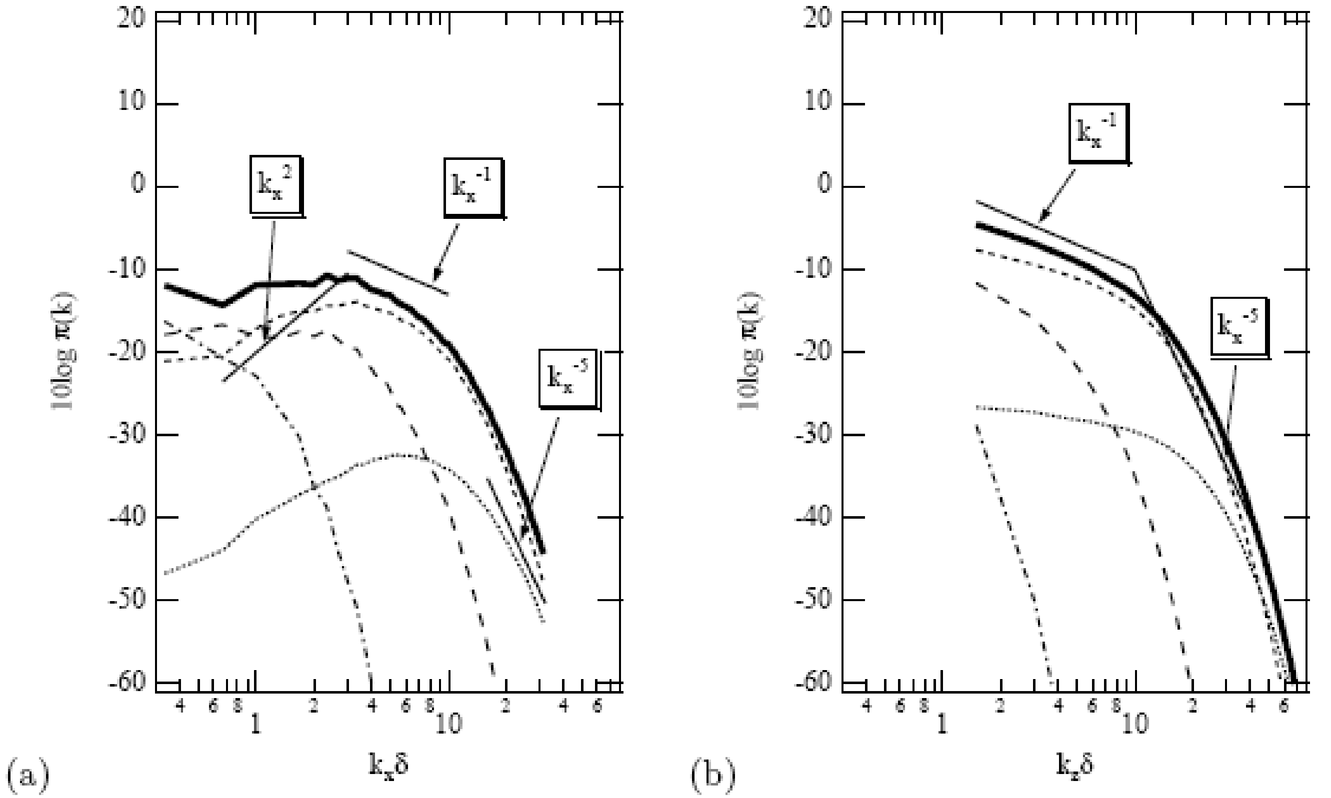

Figure 4.5: One-dimensional spectra of the MS pressure for the various regions. ▬▬ All regions (R1234); ·········· viscous shear-layer (R1); --------- buffer layer (R2); – – – – logarithmic region (R3); –·– upper channel (R4). (a) Streamwise, (b) spanwise.

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Pressure fluctuations sources

Chang (1998)

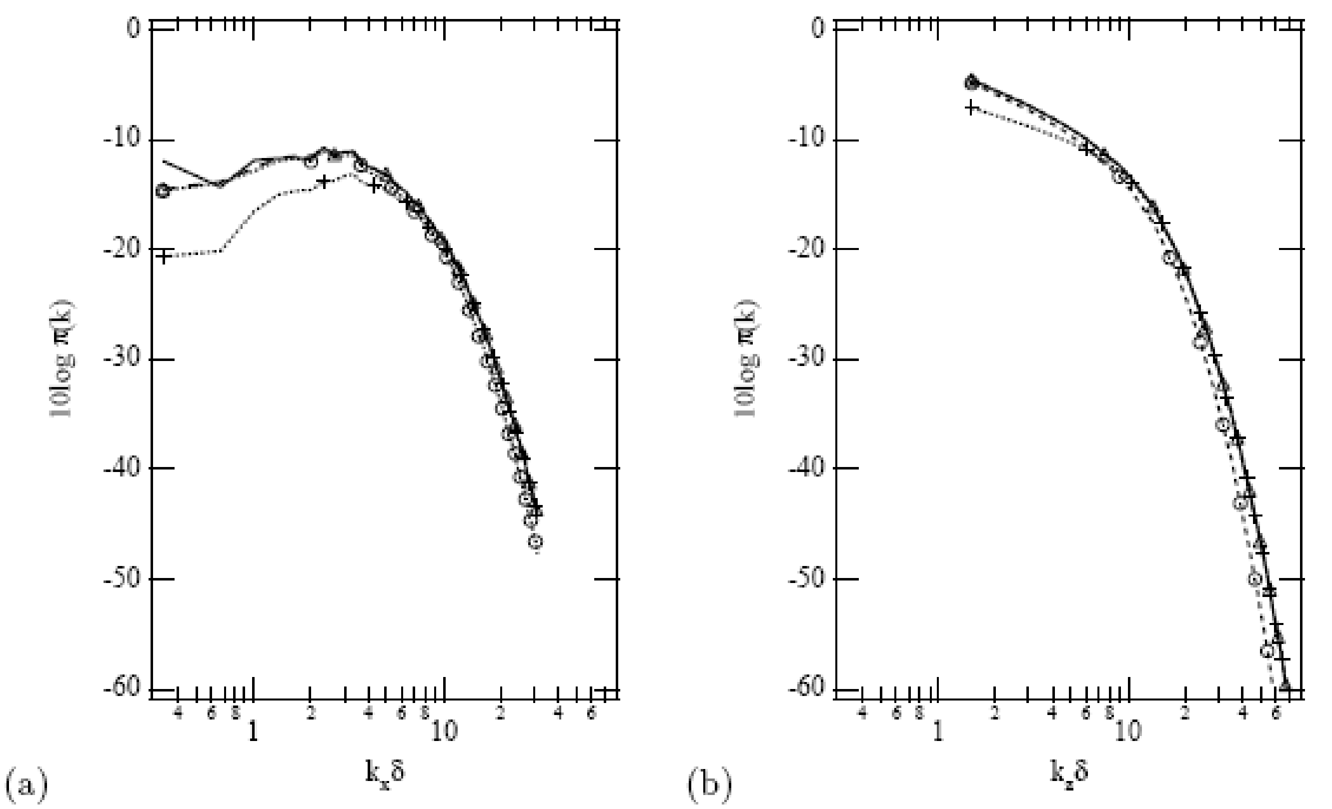

Figure 4.6: One-dimensional spectra of the MS pressure for combinations of regions. ▬ All regions (R1234); △ viscous shear-layer, buffer layer and logarithmic region(R123); + viscous shear-layer and buffer layer(R12) ○ buffer layer and logarithmic region(R23). (a) Streamwise, (b) spanwise.

Pressure fluctuations sources

Chang (1998)

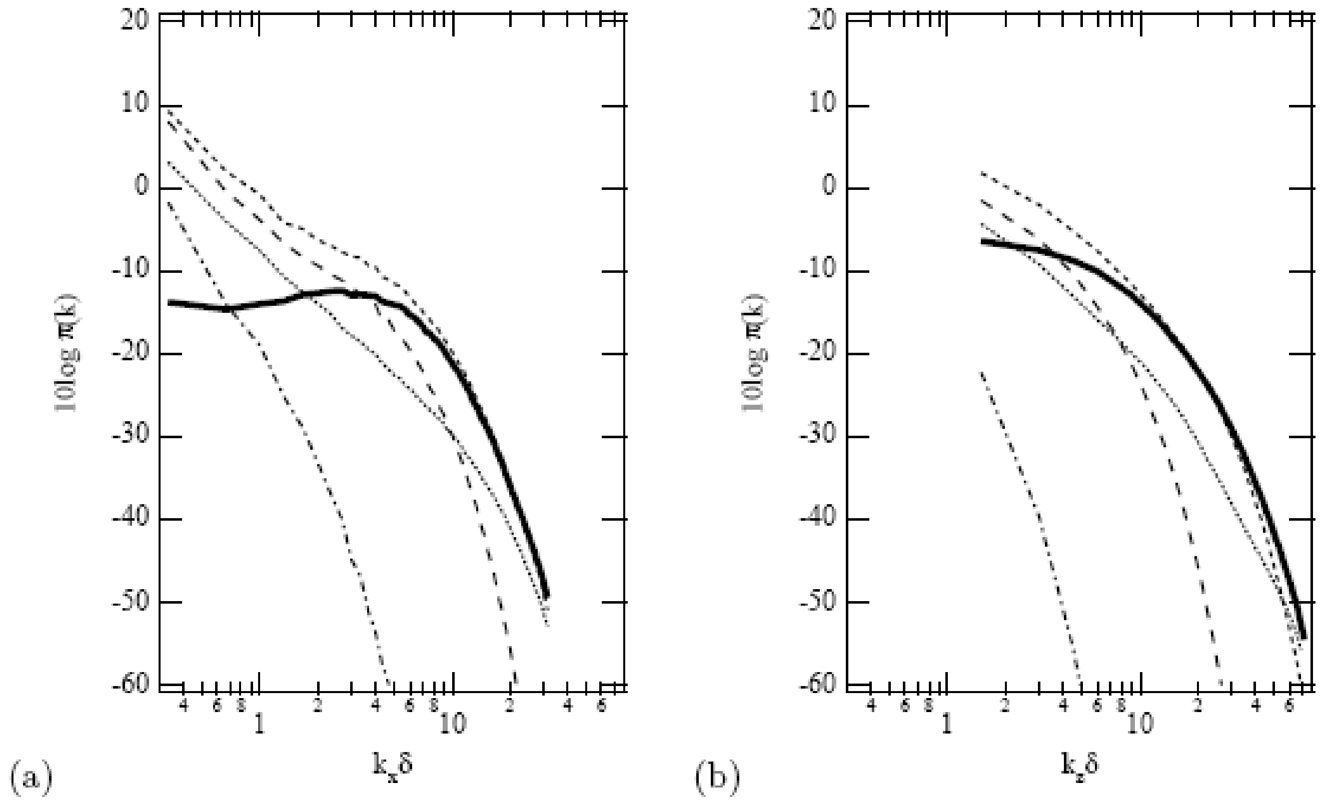

Figure 4.7: One-dimensional spectra of the TT pressure for the various regions. ▬ All regions (R1234); ·········· viscous shear-layer(R1); --------- buffer layer (R2); – – – – logarithmic region (R3); –·– upper channel (R4). (a) Streamwise, (b) spanwise.

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Pressure fluctuations sources

Chang (1998)

http://www.dt.navy.mil/hyd/com-inv-wal/index.html#animations

Pressure fluctuations sources

Chang (1998)

Spectra	Wavenumber range			
	Lowest	Low	Intermediate	High
	$k_x\delta < 1$	$1 < k_x\delta, k_z\delta < 5$	$5 < k_x\delta, k_z\delta < 30$	$30 < k_z\delta < 70$
π^{MS}	2+3	2+3	1+2	1+2
π^{TT}	1+2+3+4	1+2+3	1+2	1+2

Table II: Regions of channel which dominate the MS and TT spectra. 1: viscous shear-layer; 2: buffer layer; 3: logarithmic region; 4: upper channel.

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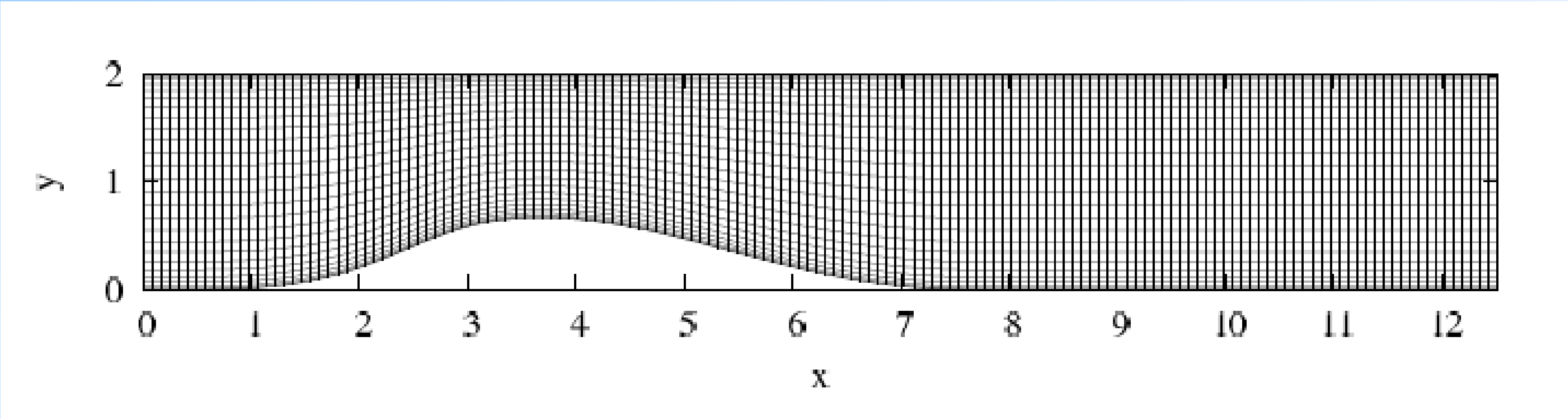
Flow with pressure gradient

Comp. Domain



- Reynolds: $Re_\tau = 395$ at the inlet
- Domain: $4\pi \times 2 \times \pi$
- Resolution: $1536 \times 257 \times 384$

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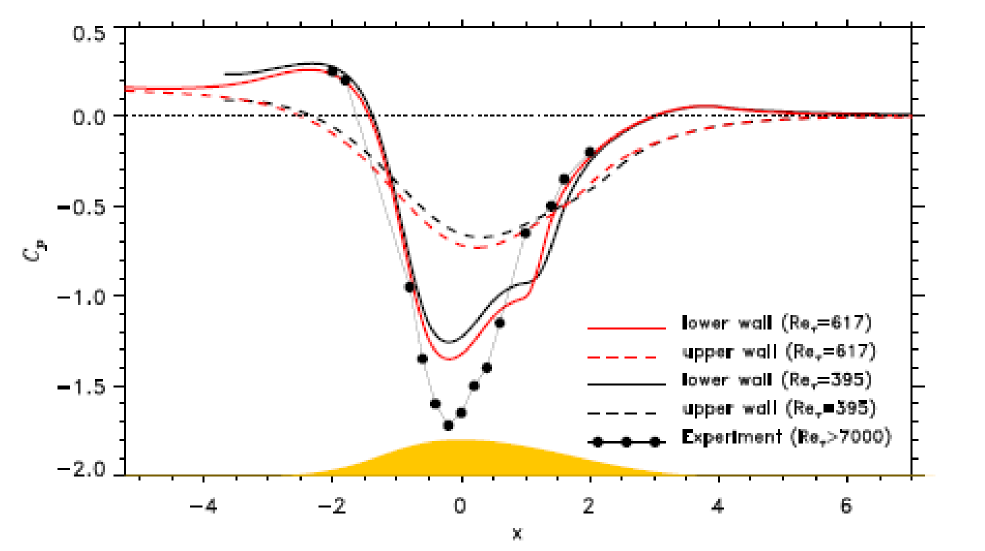
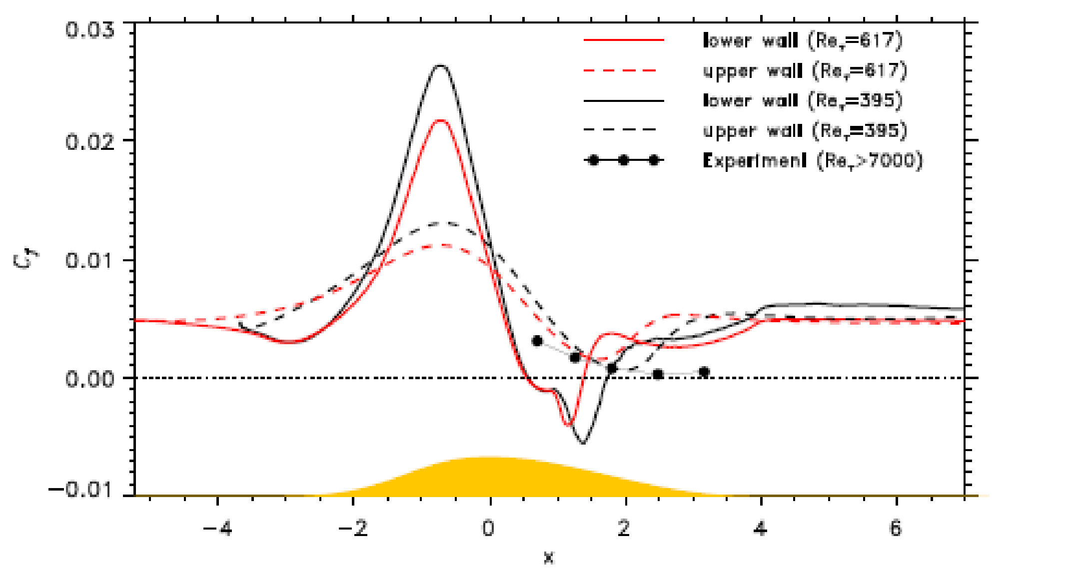
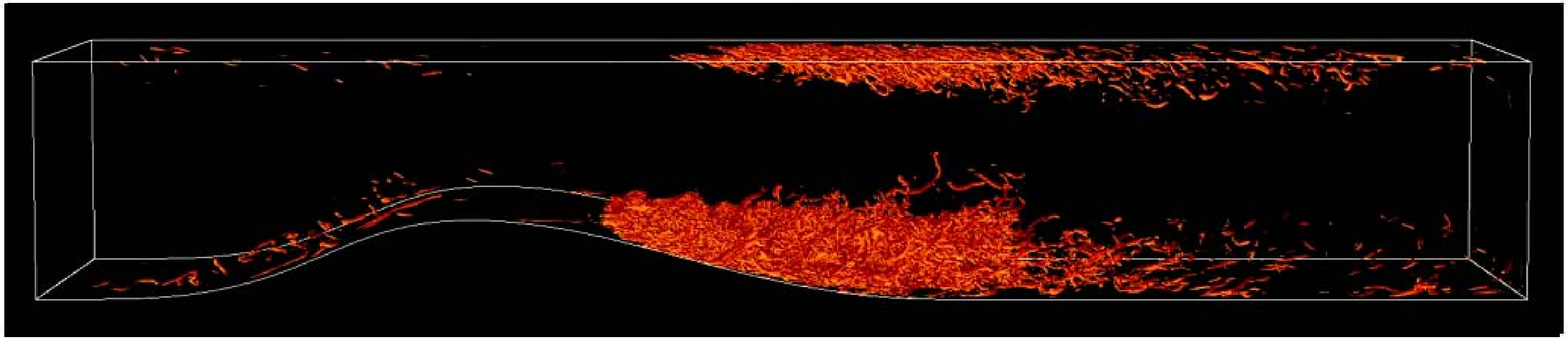
Pressure & friction





Vortices

Isovalue of $Q = \Omega^2 - S^2$



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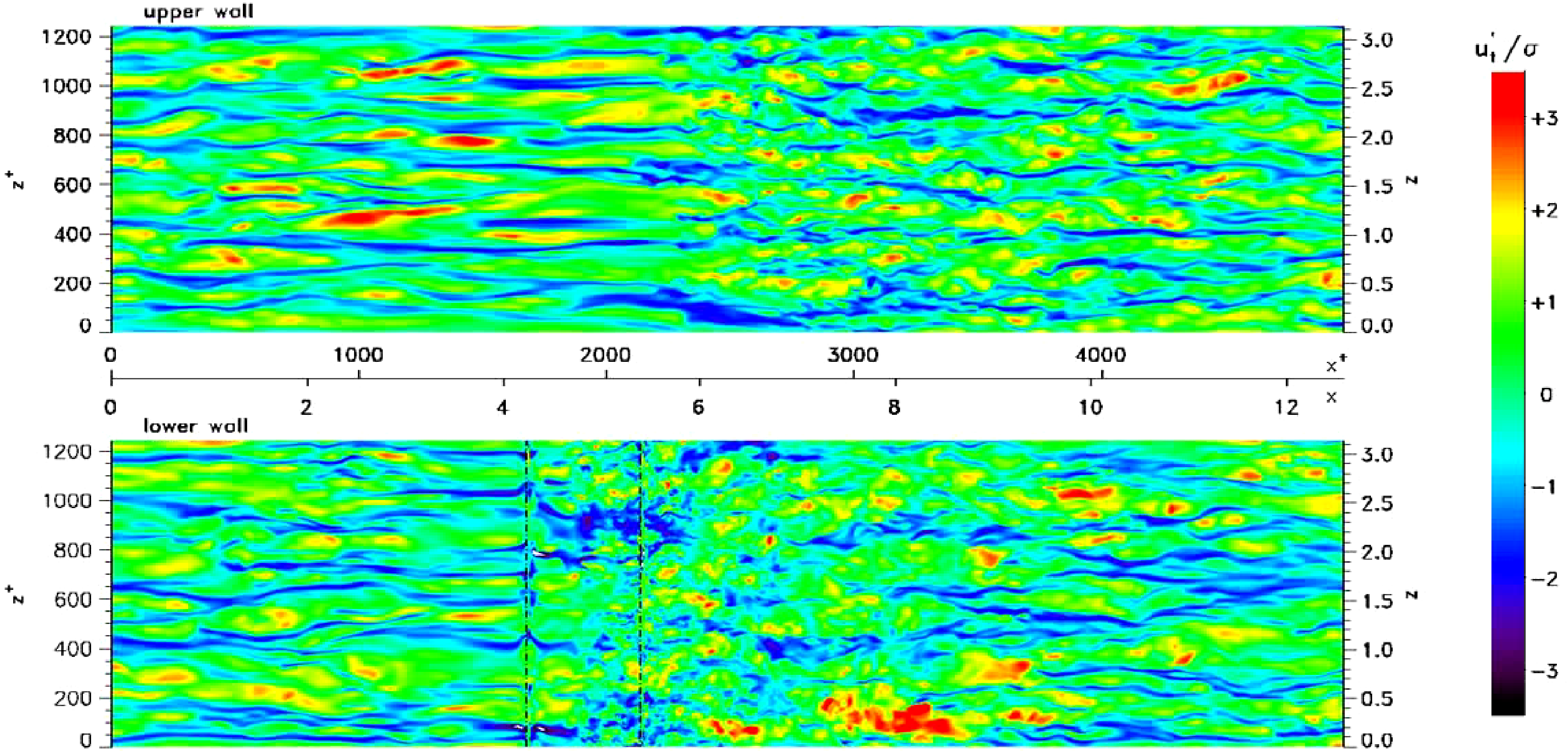
Streaks



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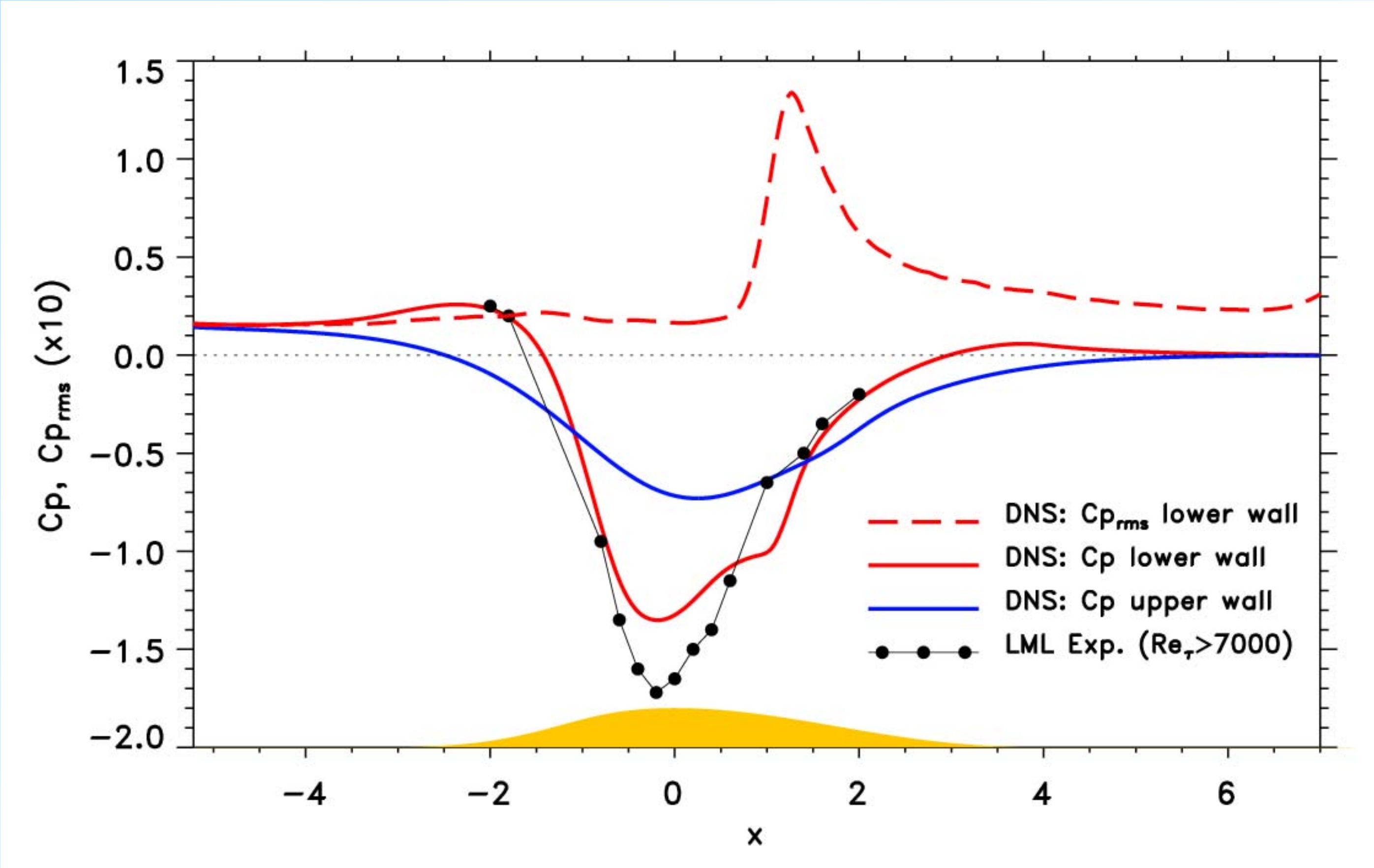
Pressure fluctuations at the wall



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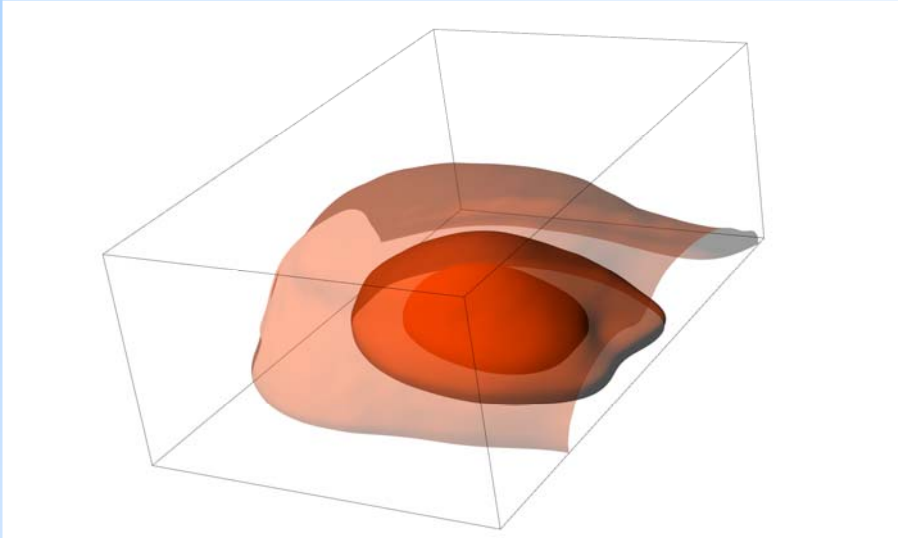
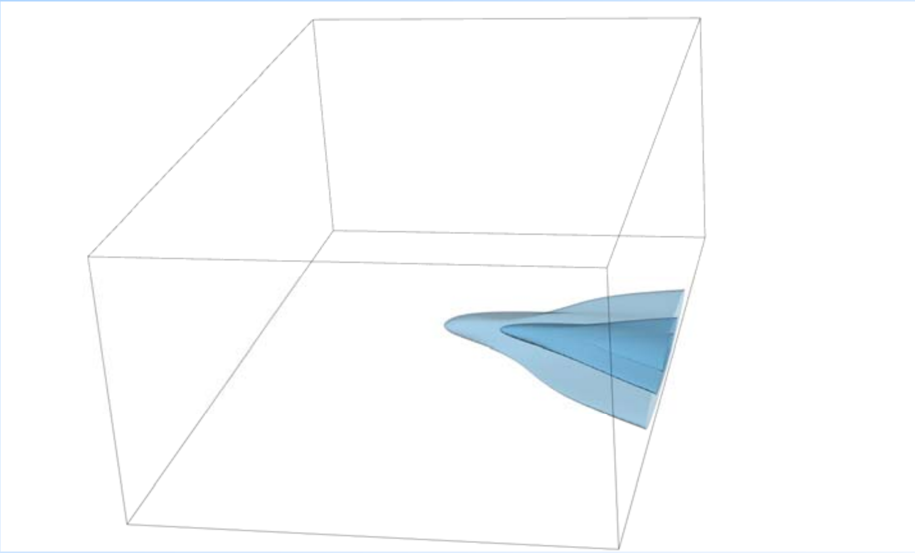
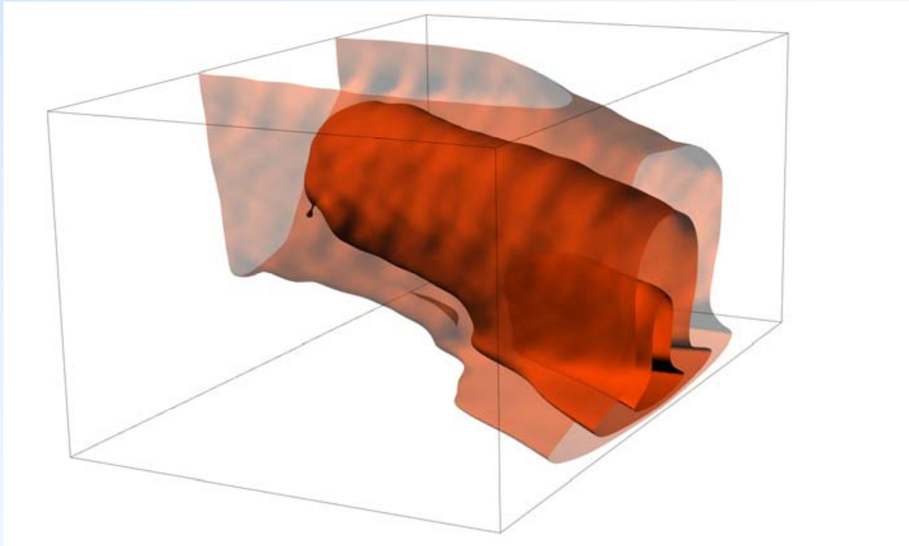
Double spatial correlation
In the APG part of the DNS



$\overline{p'_w p'_f}$



$\overline{p'_w v'_1}$



$\overline{p'_w v'_2}$

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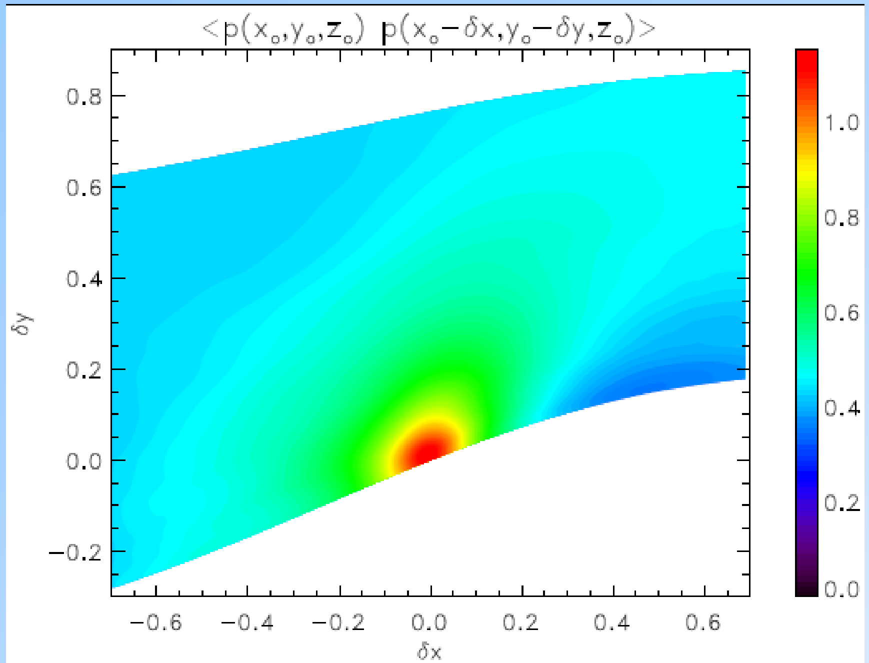
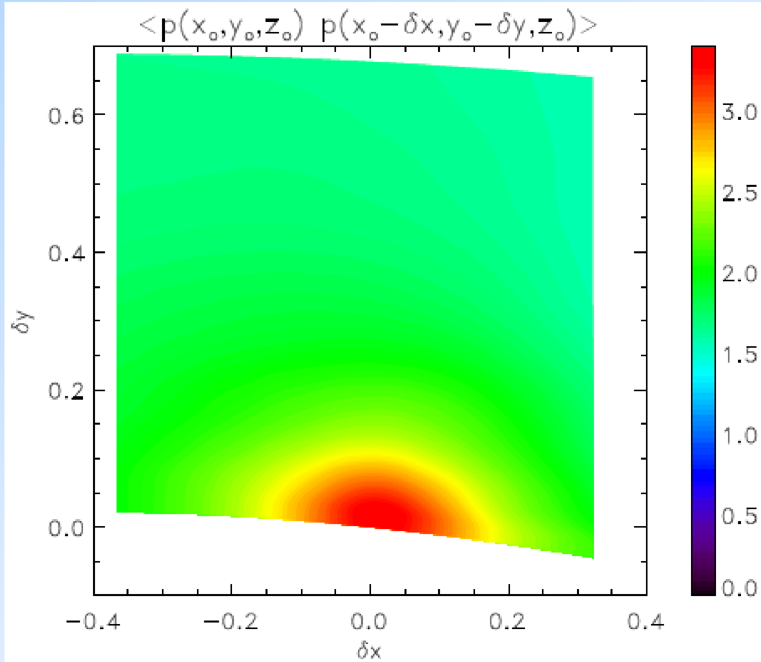
Double spatial correlation: FPG, APG, Channel

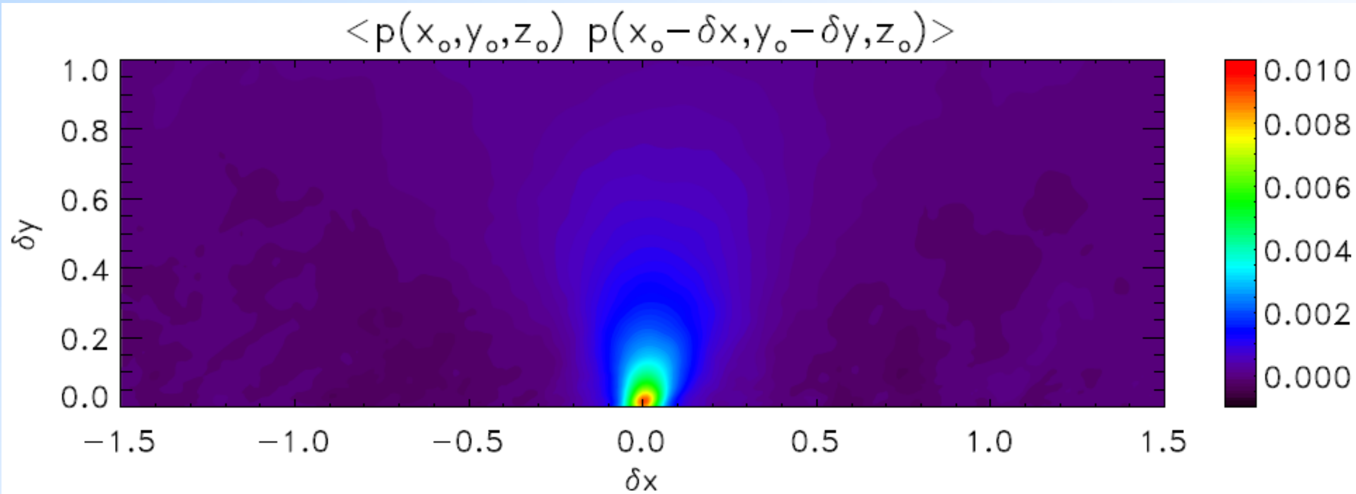


X= -1.



X= +0.4

Channel



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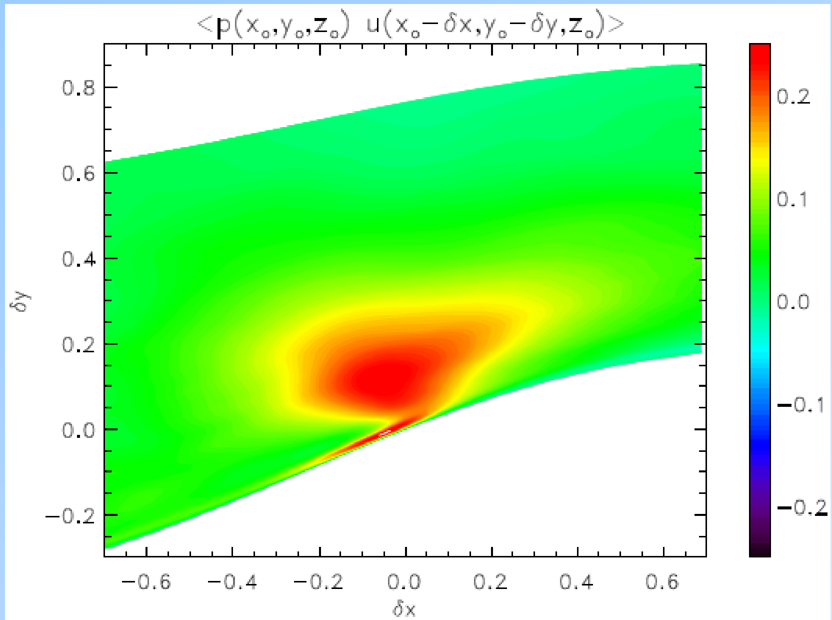
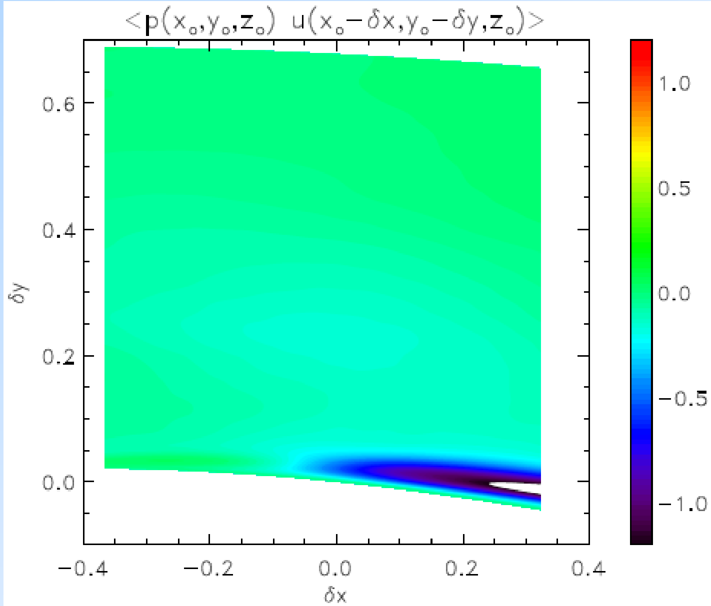
Double spatial correlation: FPG, APG, Channel

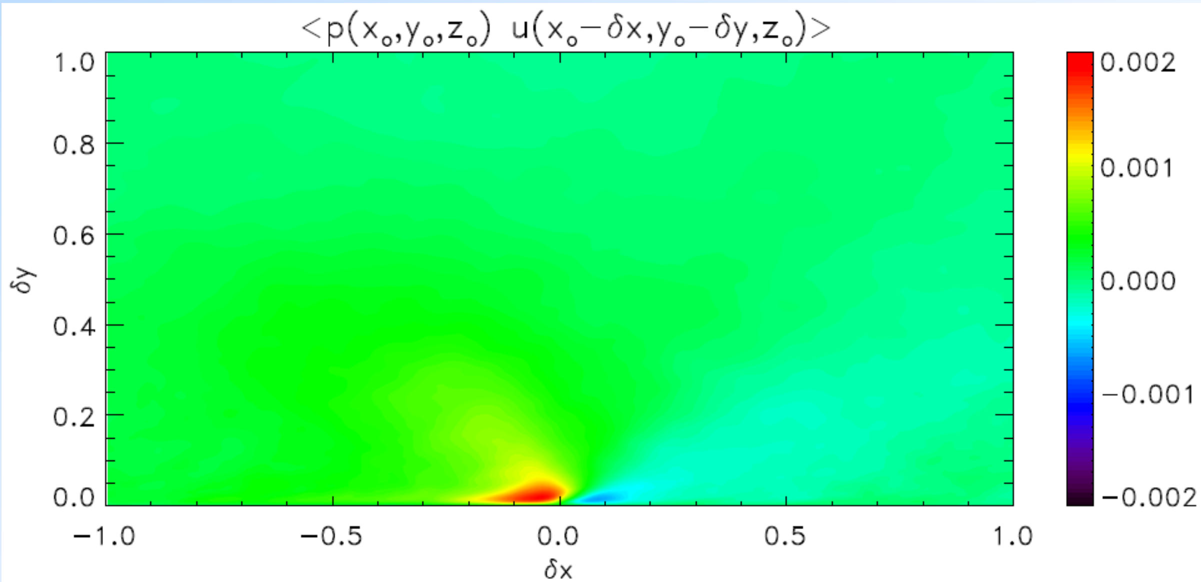




X= -1.

X= +0.4

Channel



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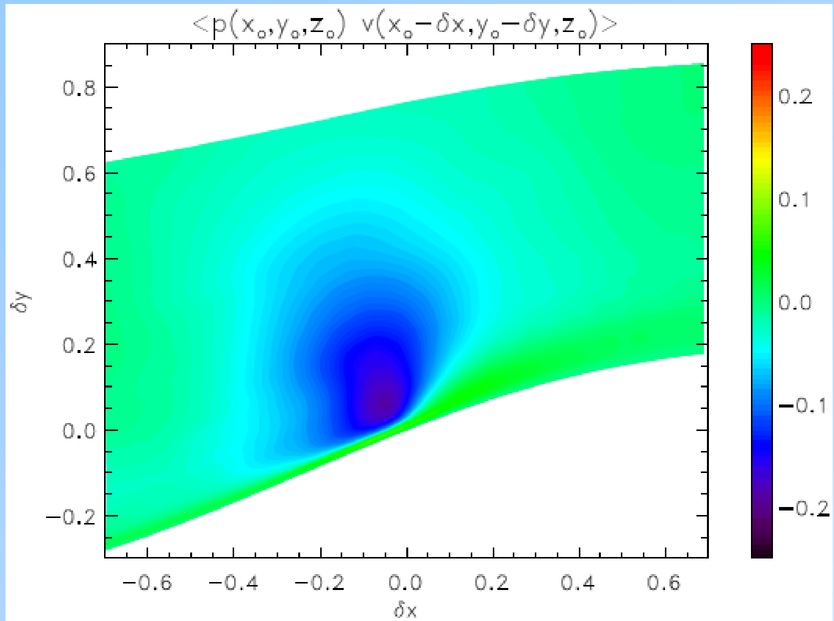
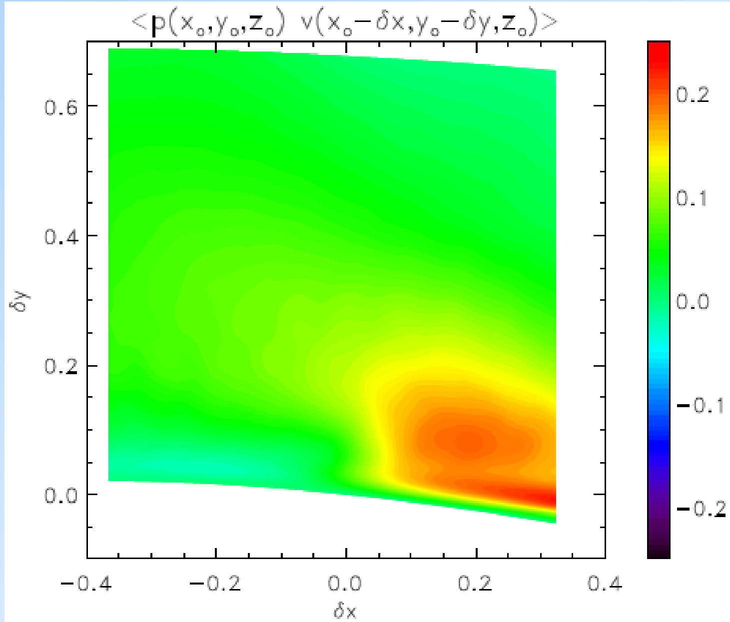
Double spatial correlation: FPG, APG, Channel

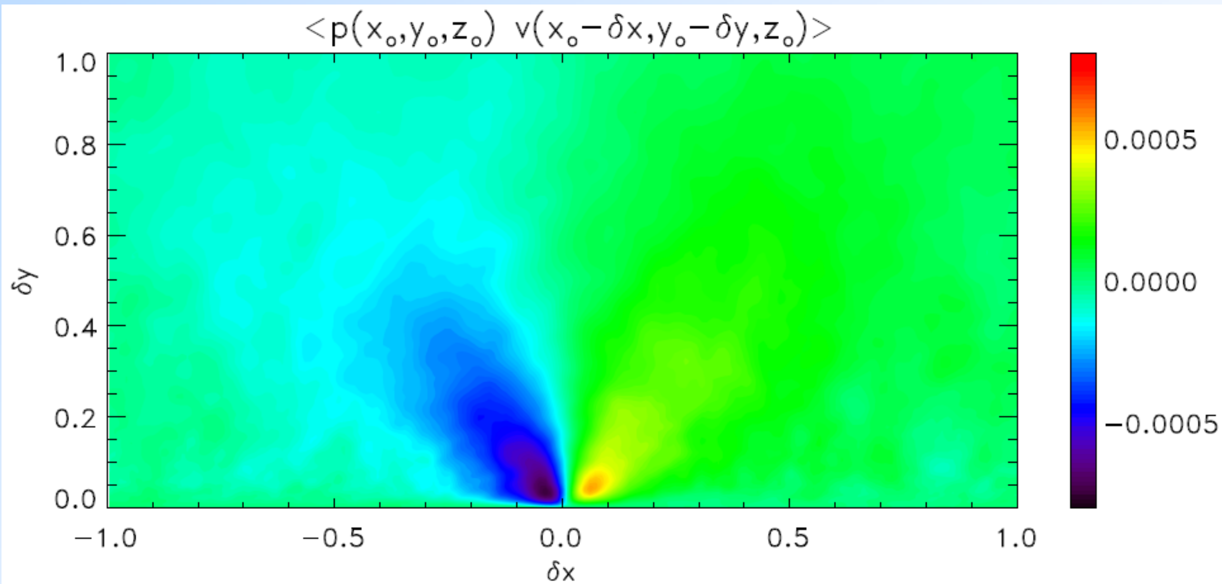




X= -1.

X= +0.4

Channel



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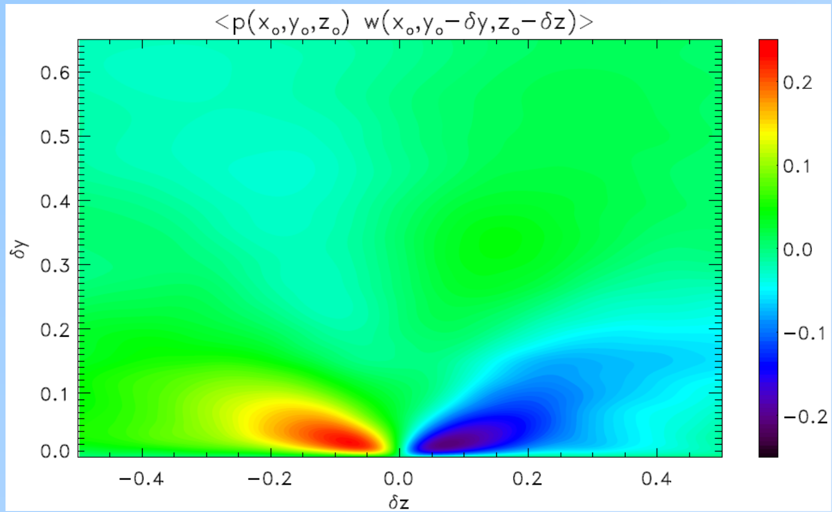
Double spatial correlation: FPG, APG, Channel



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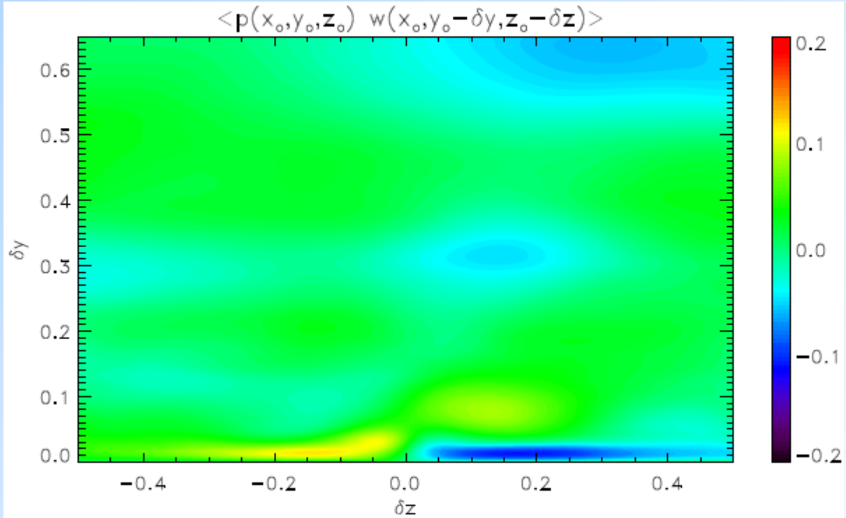
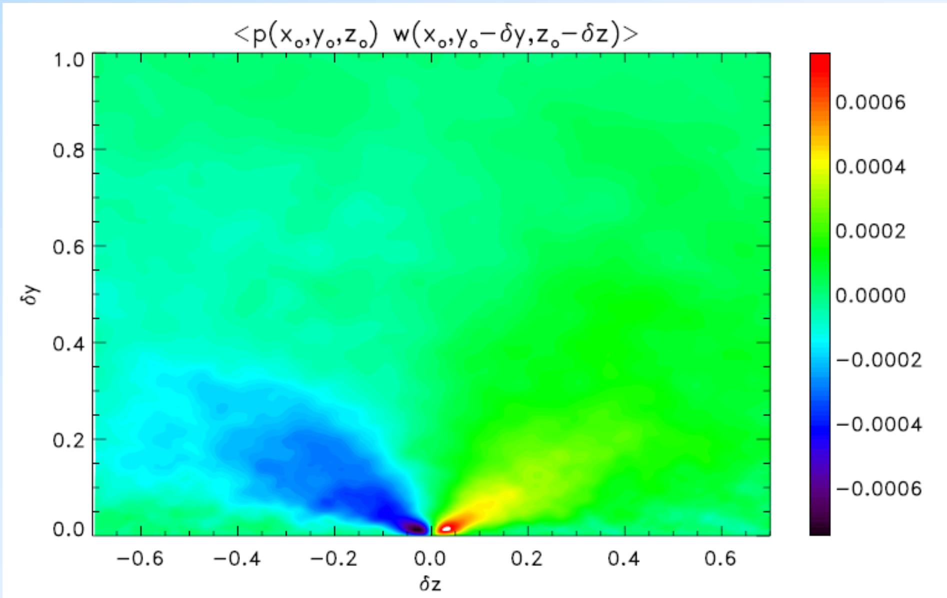


X= +0.4



Channel

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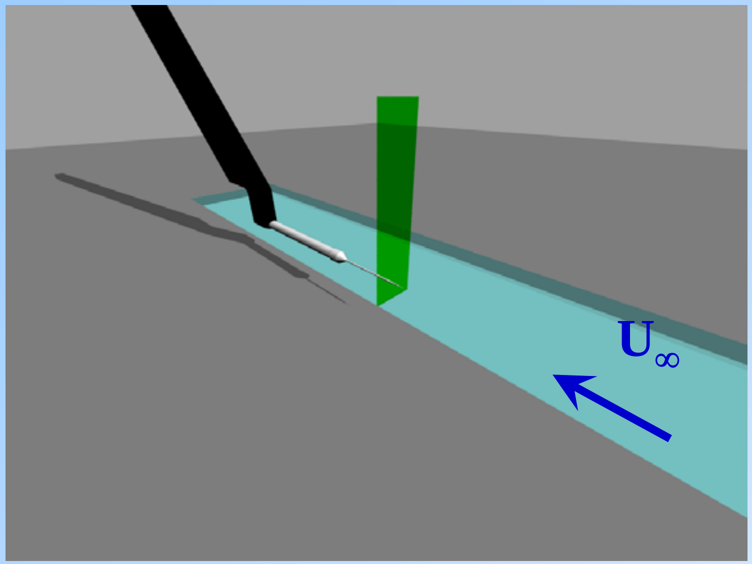
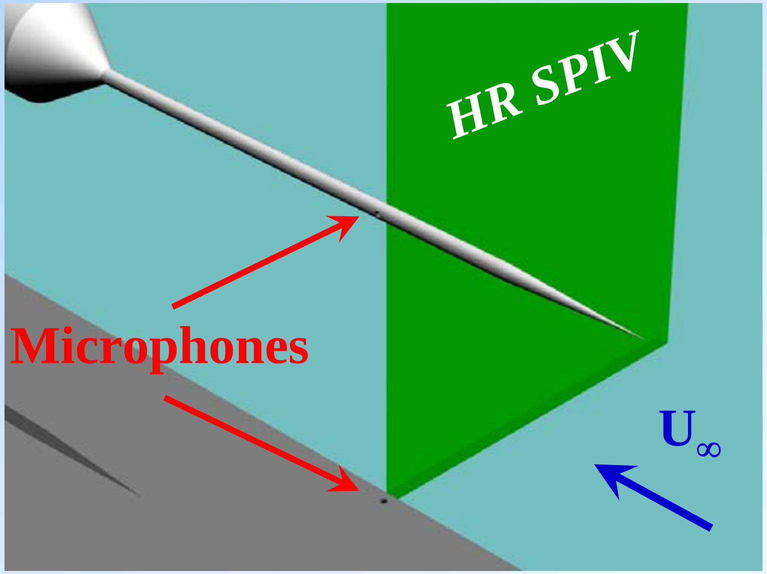
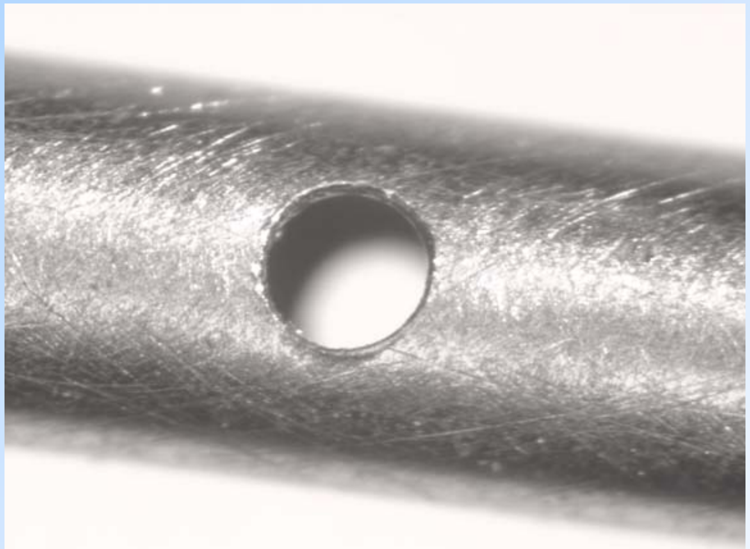
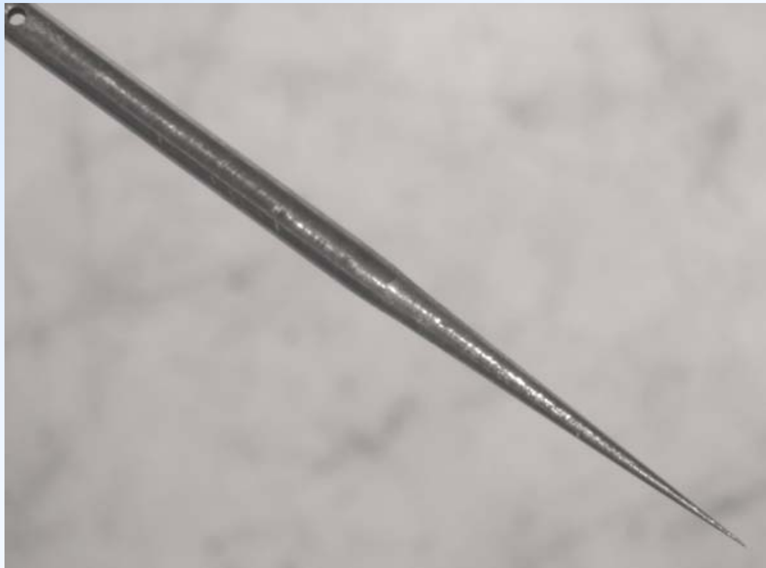
LML 2011 Experiment (Y. Naka)









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Conclusion

• La turbulence de paroi est "relativement " bien connue en gradient de pression nul,

• les fluctuations de pression à la paroi sont couplées à toute l'épaisseur de la couche limite (particulièrement le terme lent),

• l'expérimentation est délicate et limitée,

• les DNS sont à faible Reynolds,

• l'influence du gradient de pression reste à étudier.

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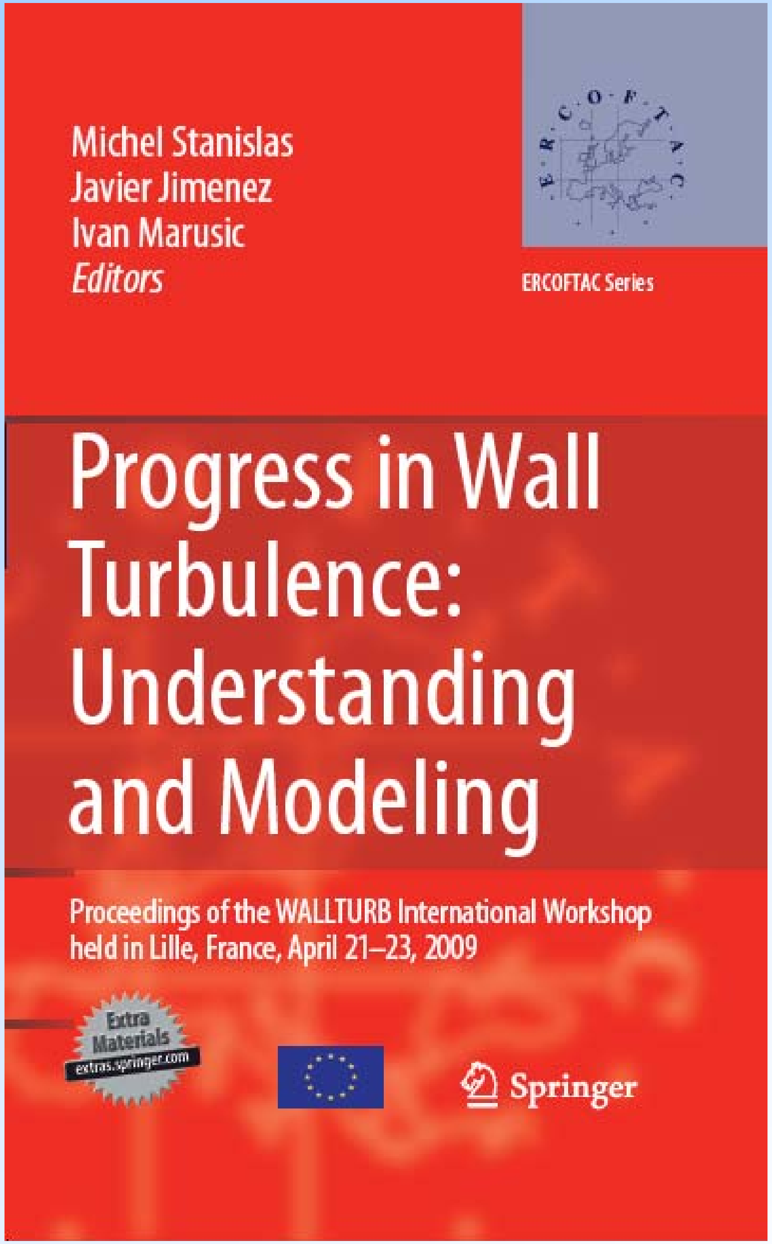

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