Can PIV bring something to turbulence understanding and modelling?

M. Stanislas

Also : J.M. Foucaut, S. Coudert, J. Lin, S.Herpin…

Ecole Centrale de Lille

Laboratoire de Mécanique de Lille

Colloquium in honor of Pr Geneviève Comte-Bellot

CENTRALE LILLE

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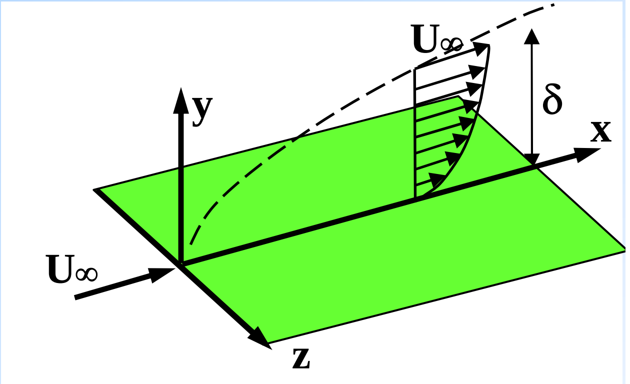
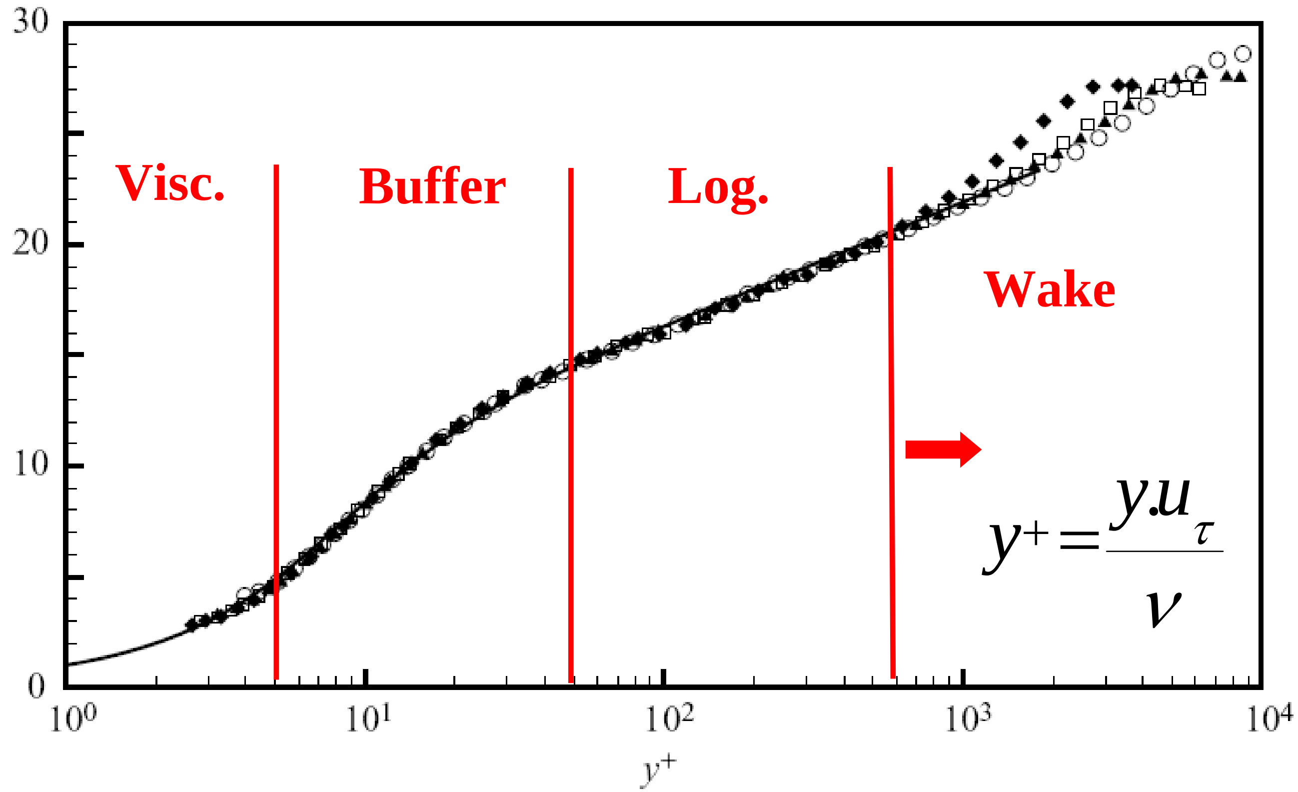
Turbulent boundary layer

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



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



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

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.

Question 1 :

is there today a measurement technique comparable to HWA to characterize statistically turbulence?

SPIV?

Stereo PIV problems :

- limited field of view
- IW averaging
- stereo calibration
- data rate
- recording parameters
- …

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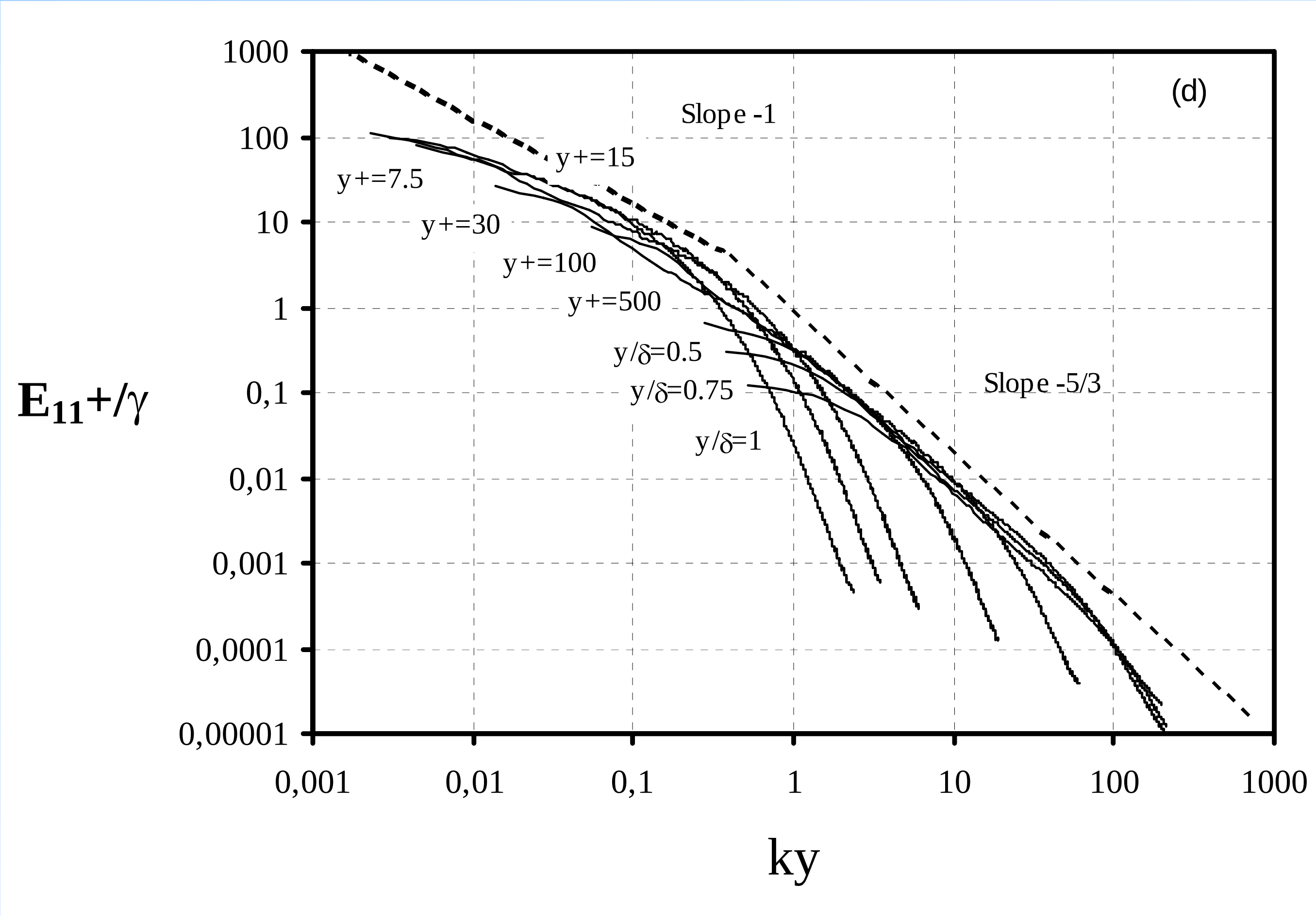
PIV Spectrum



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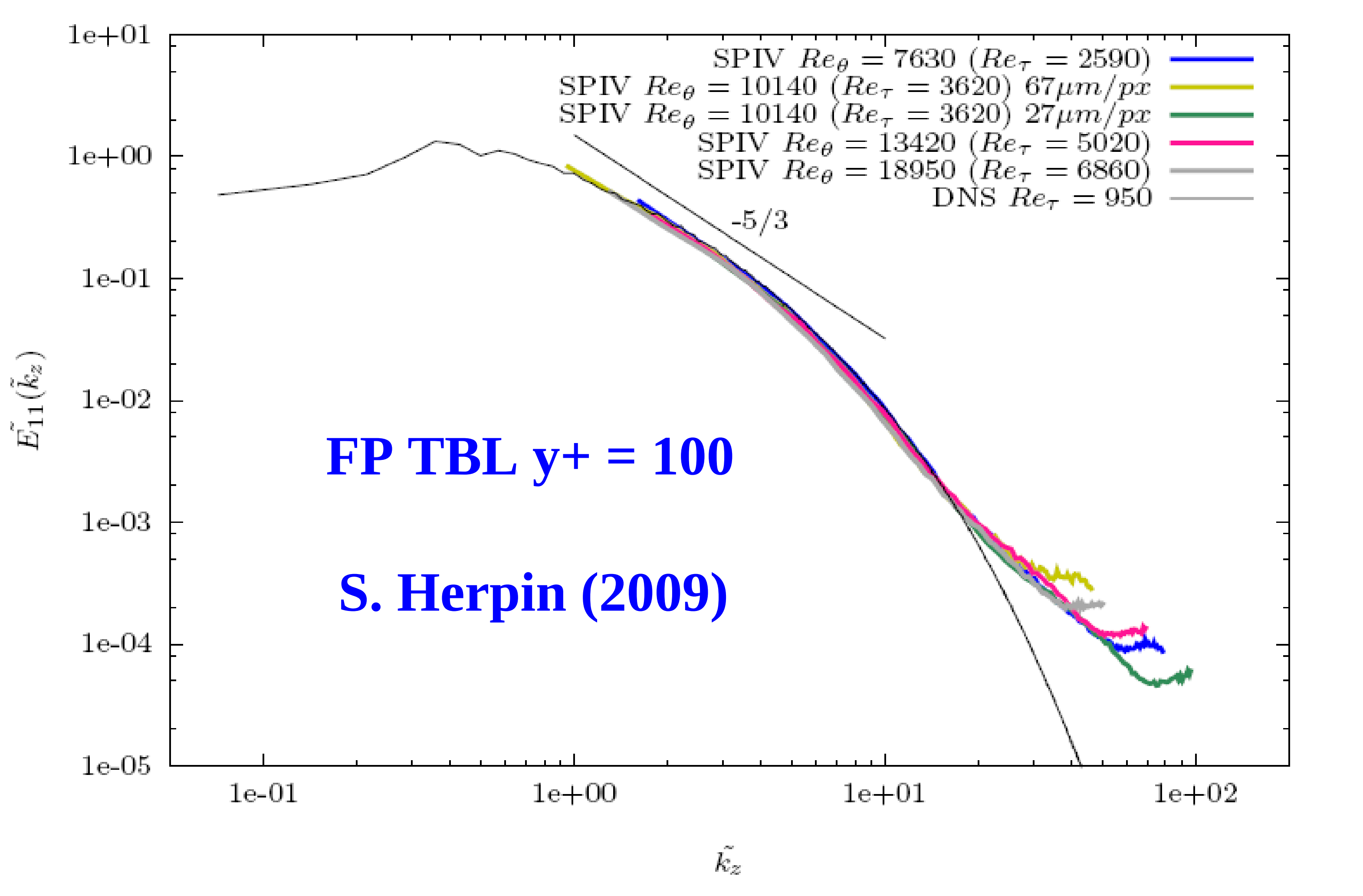
PIV Spectrum



"PIV optimization for the study of turbulent flow using spectral analysis."

J.M. FOUCAUT, J. CARLIER, M. STANISLAS

Meas. Science & Tech. 15-6, 1046-1058, June 2004.

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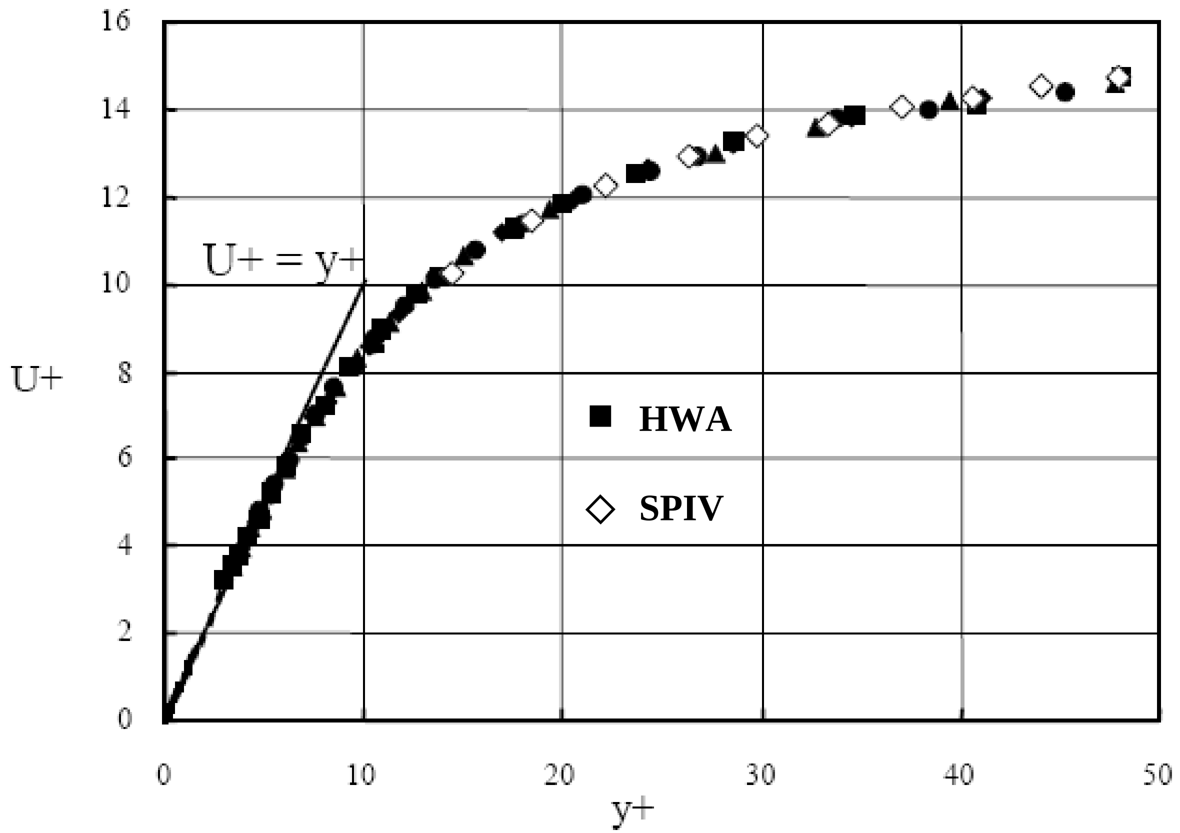
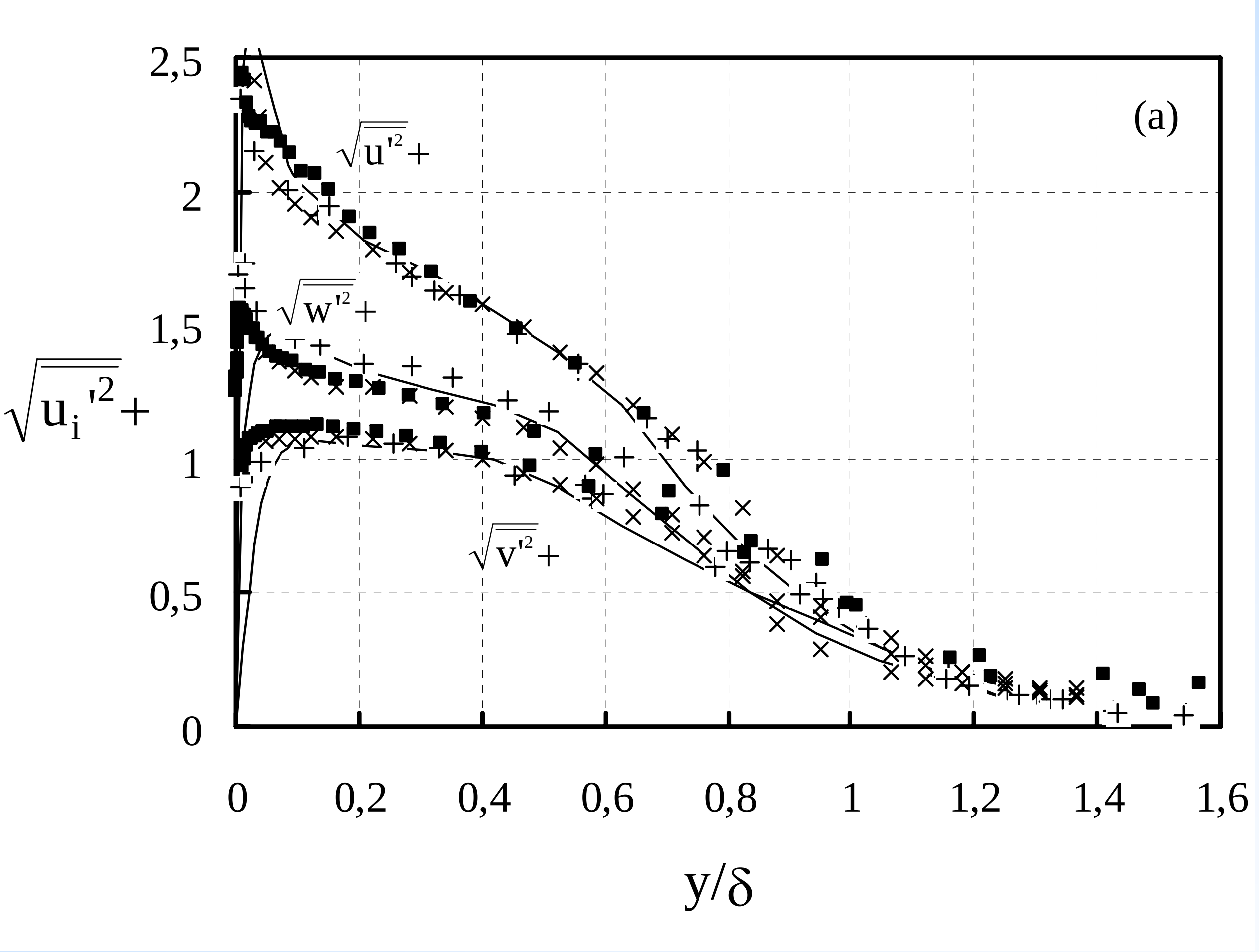
Statistics

Mean velocity



Statistics

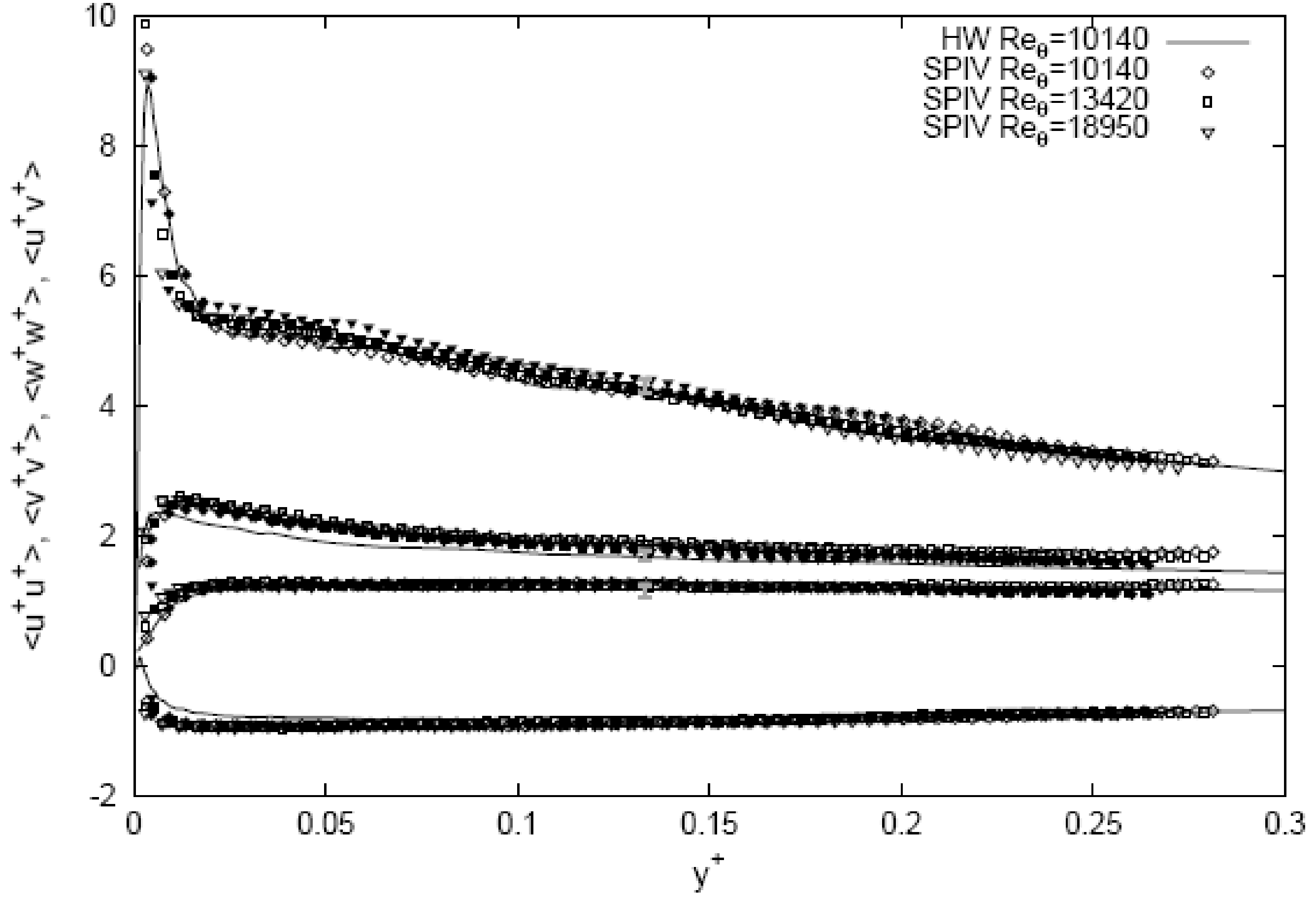
Reynolds stresses



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

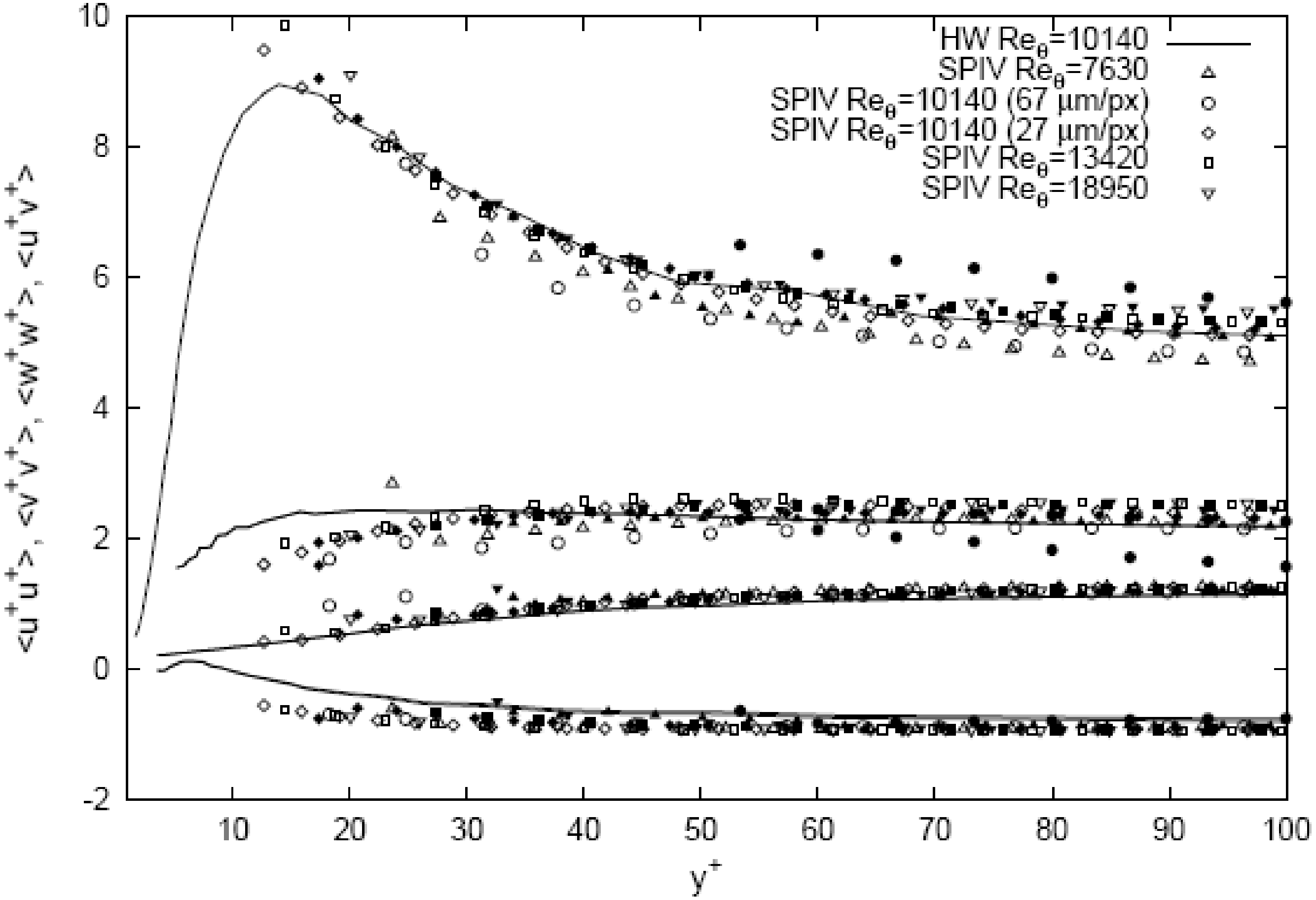
Statistics

Reynolds stresses



Statistics

Reynolds stresses



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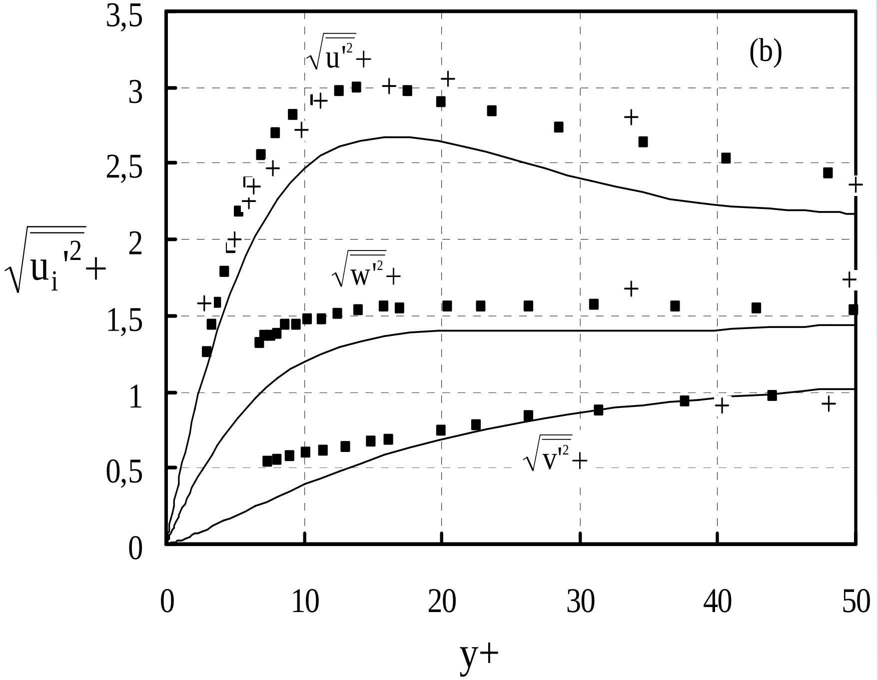
Statistics

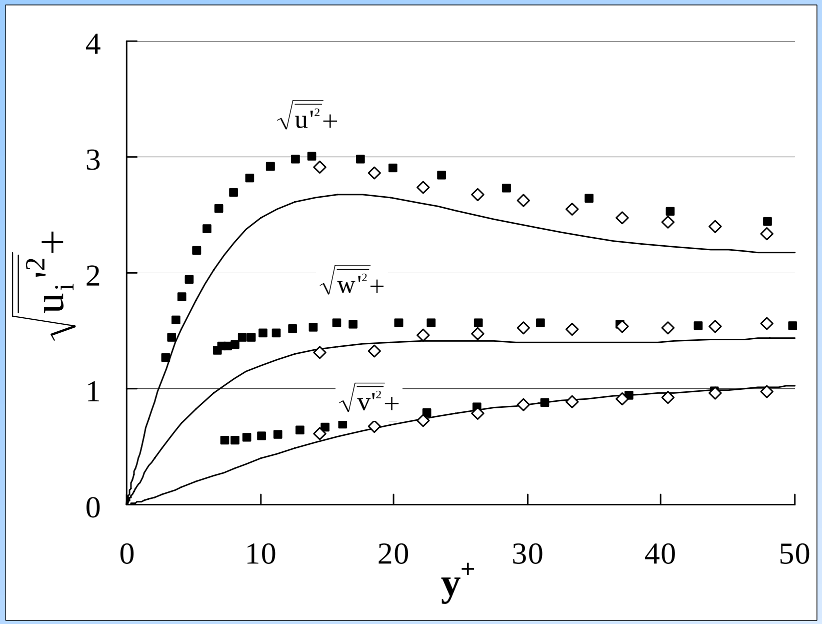
Reynolds stresses

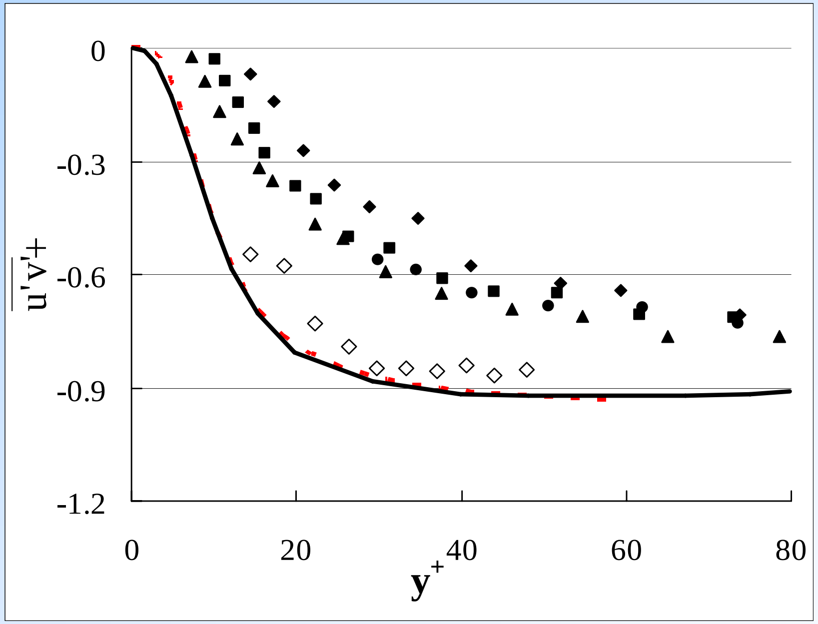


Turbulence intensity components in a flat plate turbulent boundary layer, obtained from HWA. *Re_θ*= 20 800, + Klebanoff (1955), —DNS Spalart (1988).

Statistics

Reynolds stresses





SPIV (◊) ***Re***$_\theta$ **= 7800**

HWA (Carlier, 2001, ■♦●)

7800 < ***Re***$_\theta$ **< 15000**

DNS (Spalart, 1988, —) ***Re***$_\theta$ **= 1400**

Van Driest, 1978 (.....)

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Statistics

Dissipation of TKE

$$\varepsilon = 2\nu < s'_{ij} s'_{ij} >$$

$$\varepsilon = 15\nu < \left(\frac{\partial u'_1}{\partial x_1}\right)^2 >$$

$$\left(\frac{\partial u'_1}{\partial x_1}\right)^2 = 2\frac{u'^2_1}{\lambda_1^2}$$

$$R_{11}(\Delta x_1) = \frac{< u'_1(x_1)u'_1(x_1 + \Delta x_1) >}{< u'^2_1 >}$$

$$R_{11}(\Delta x_1)|_{\Delta x -> 0} = 1 - \frac{\Delta x_1^2}{\lambda_1^2}$$

$$\lambda_1 = \sqrt{\frac{-2}{\frac{\partial R_{11}(\Delta x_1)}{\partial \Delta x_1}|_{\Delta x_1 = 0}}}$$

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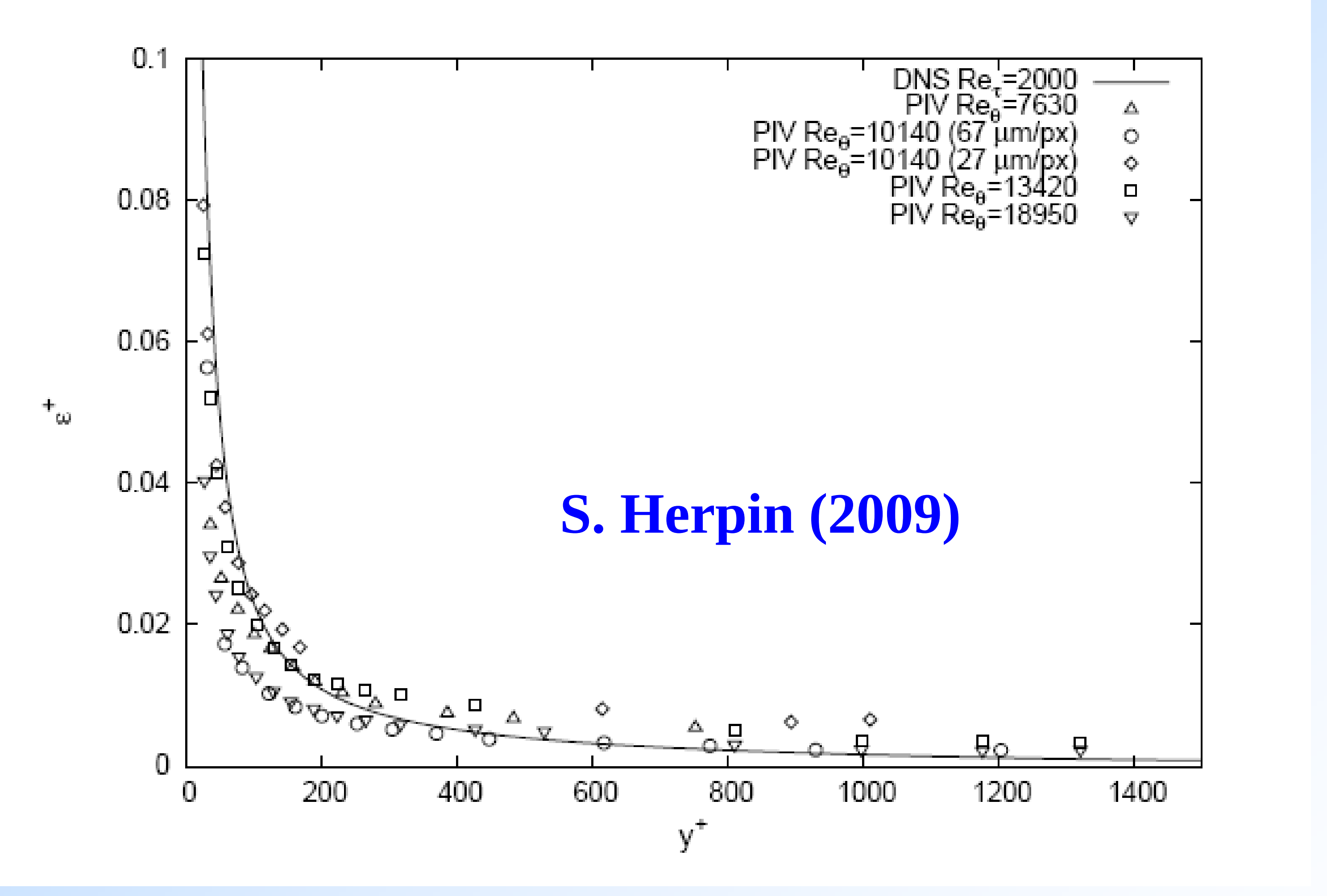
Statistics

Dissipation of TKE



"Study of the influence of the Reynolds number on the organization of wall-bounded turbulence."
HERPIN S. (PhD in english) EC Lille N°95 , 20 avril 2009.

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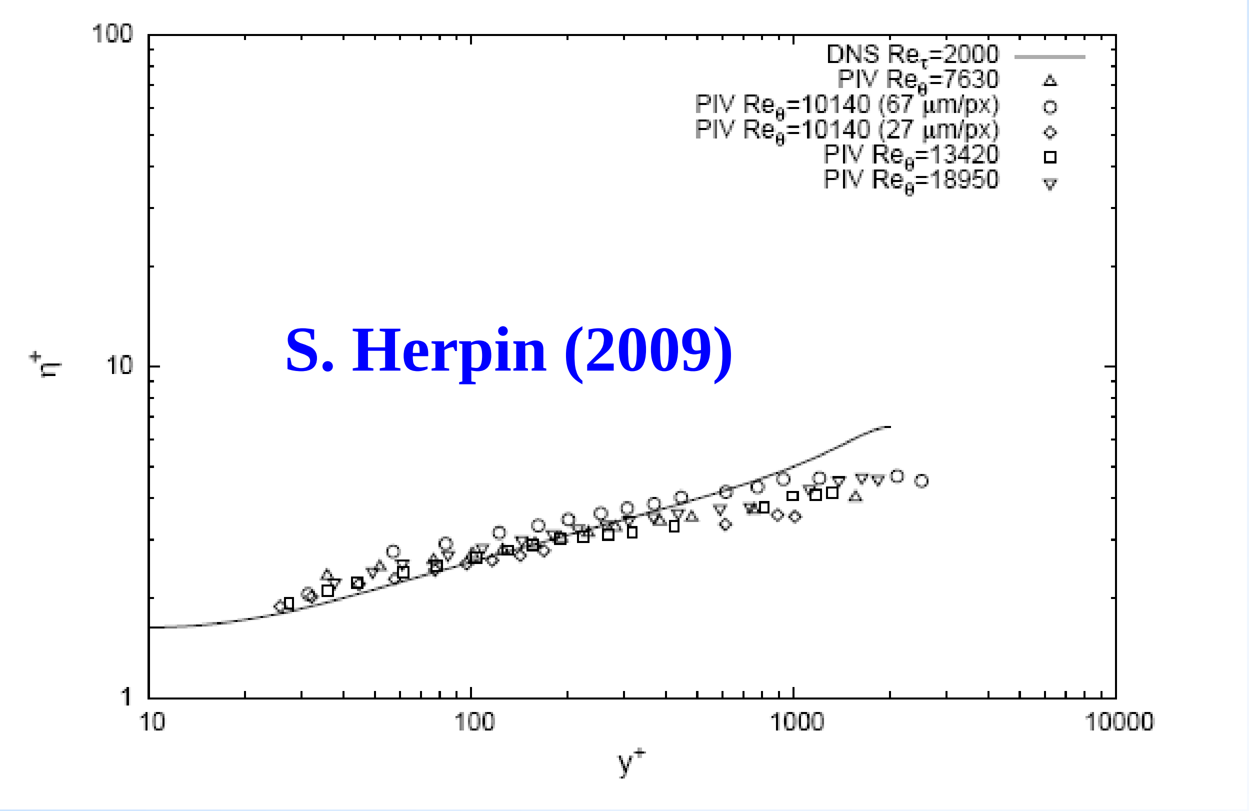
Statistics

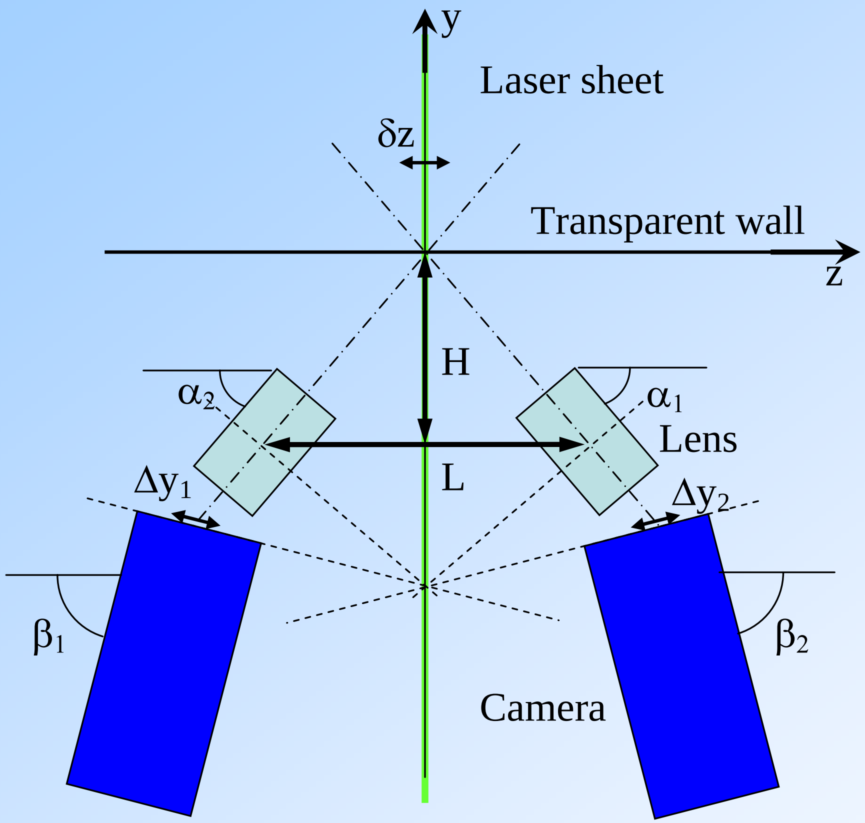
Kolmogorov scales



$$\eta = \left(\frac{\nu^3}{\varepsilon} \right)^{1/4}$$

Statistics

Stereo Macro PIV



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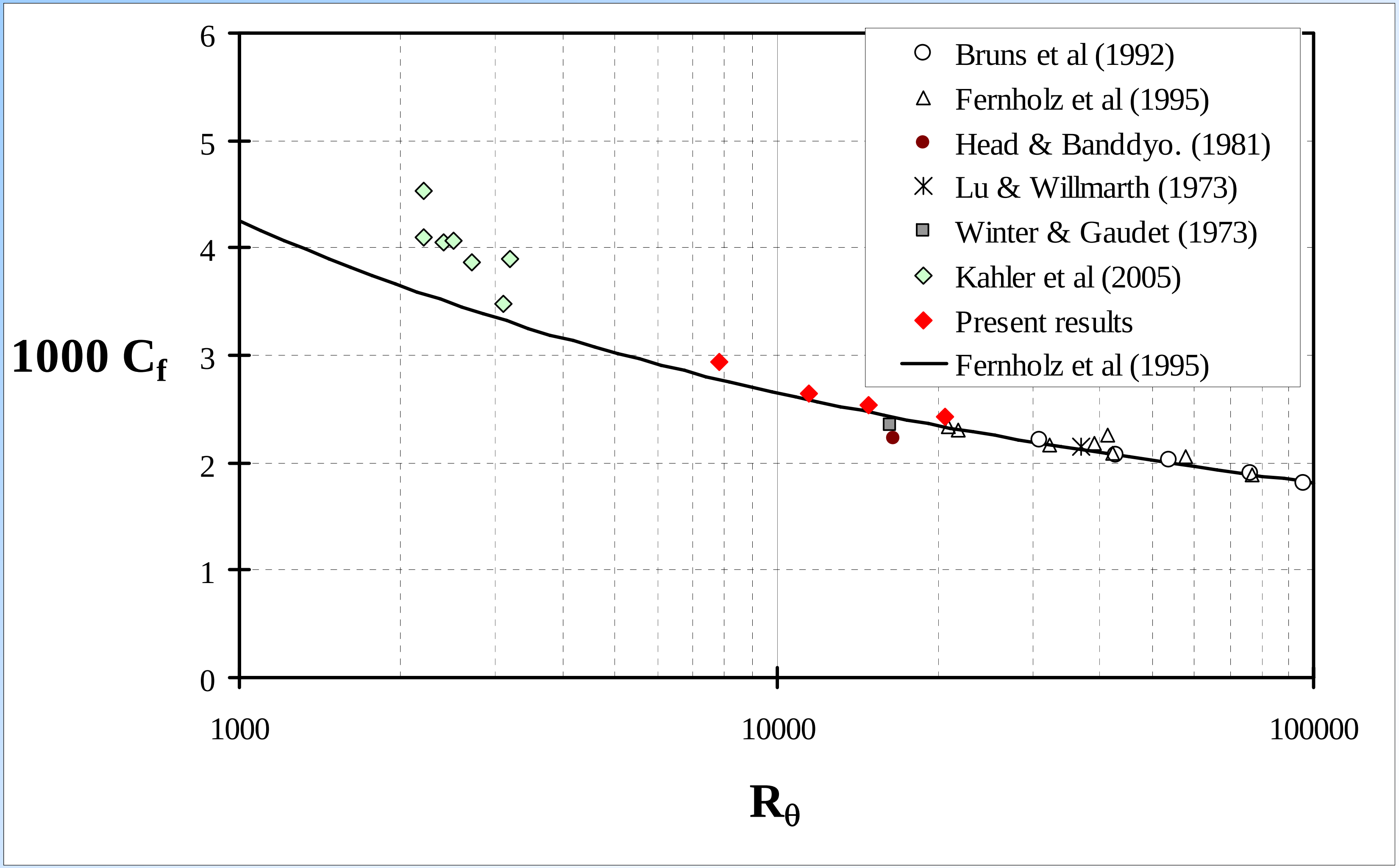
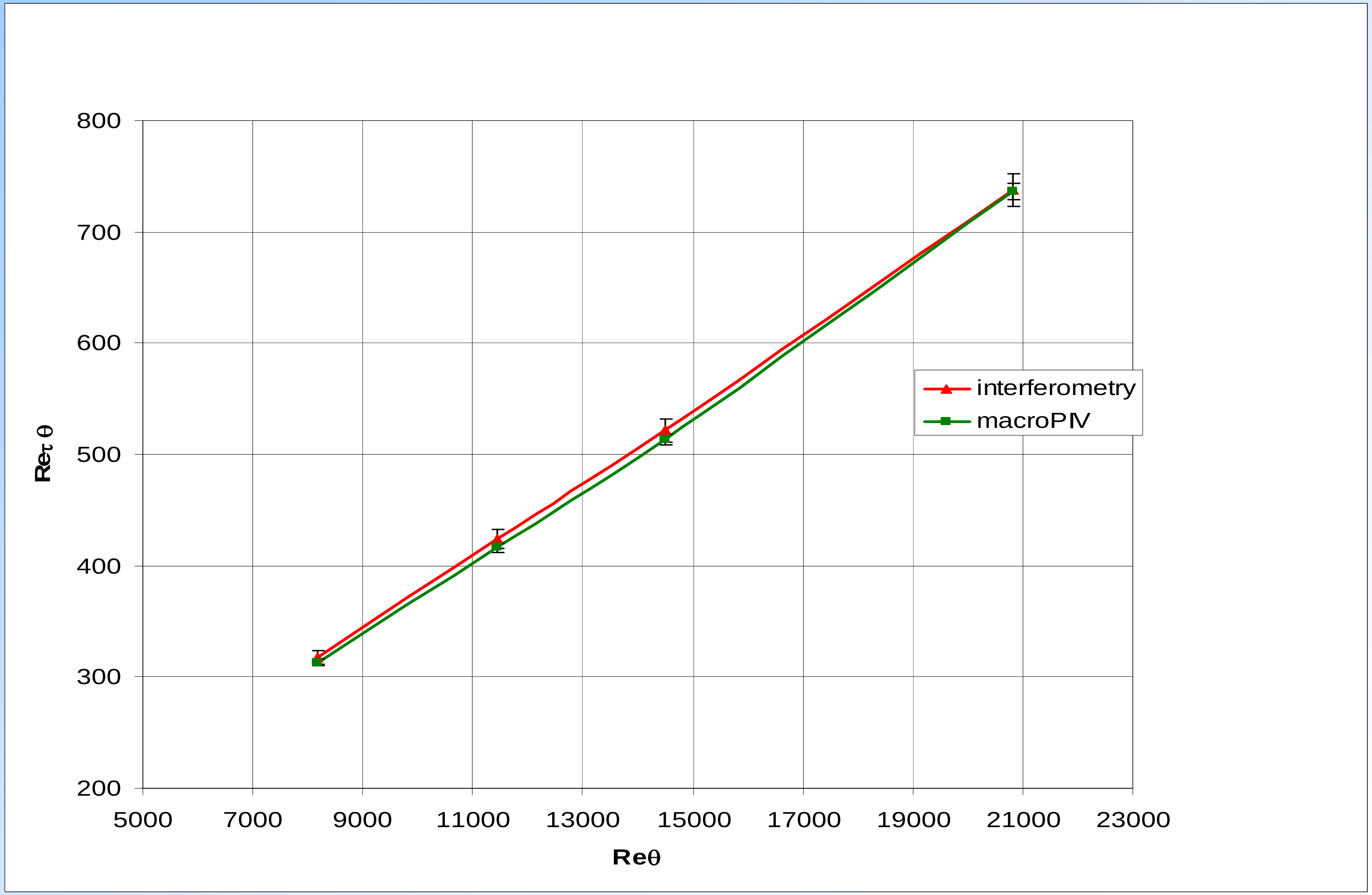
Statistics

Stereo Macro PIV



Statistics

Stereo Macro PIV



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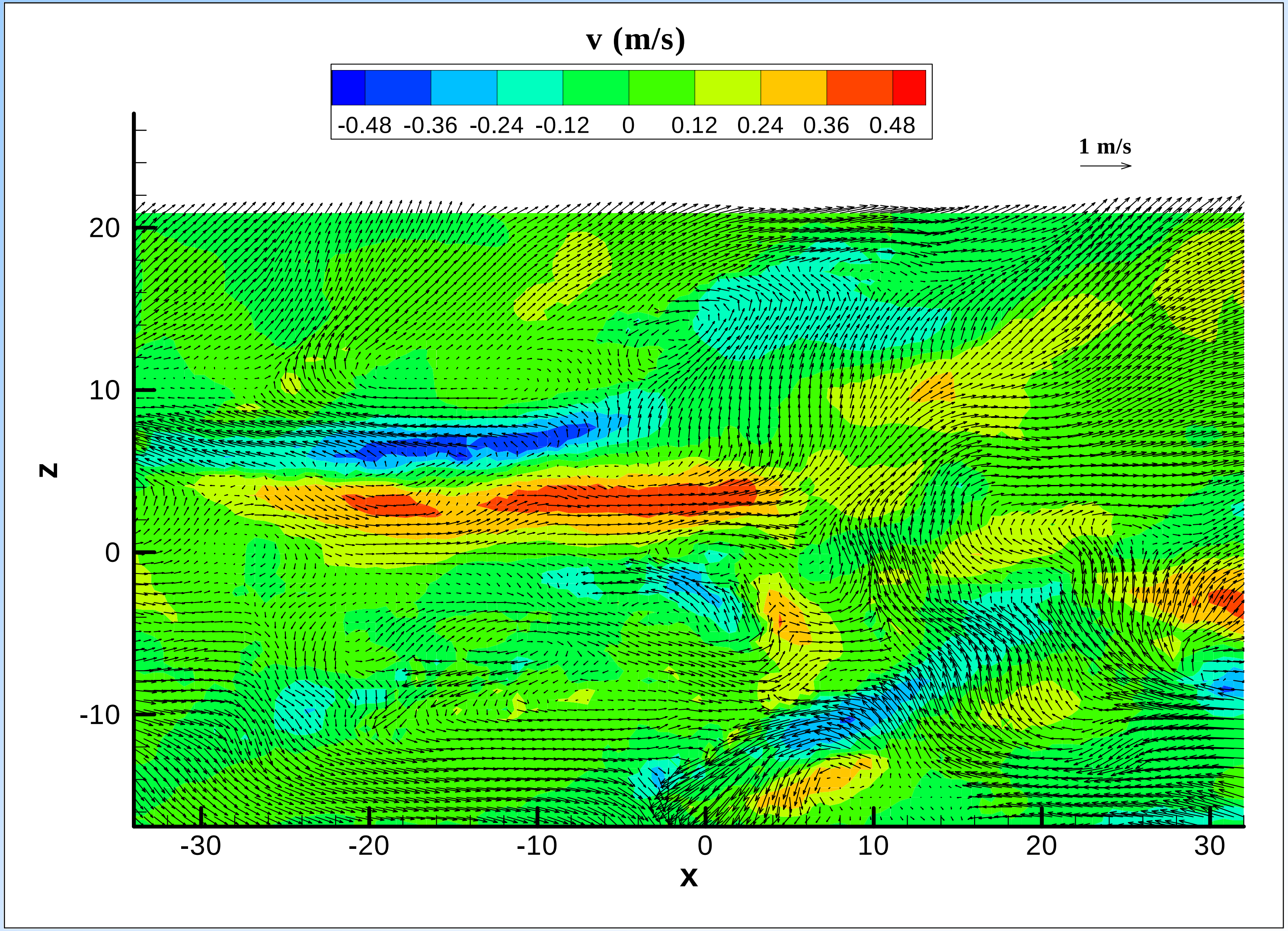
Question 2 :

is SPIV able to bring extra quantitative information on turbulence?



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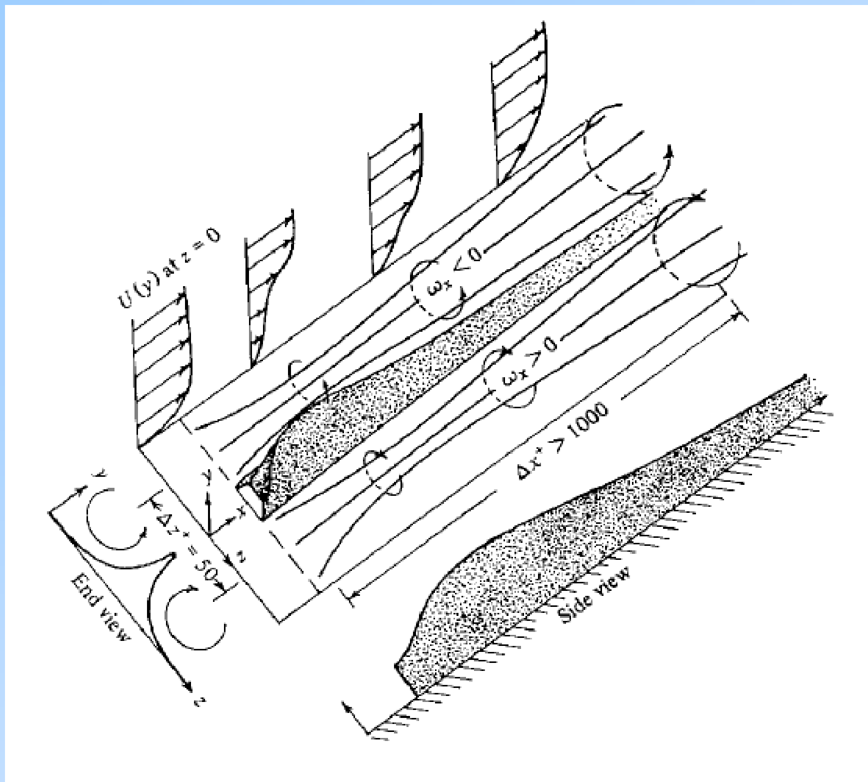
Near wall BL Zoo



BLACKWELDER & KAPLAN (1976)

« Animals »

- **Streaks (low & high speed)**
- **Ejections & sweeps**
- **Vortices**

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Questions

- Shape and size of coherent structures?
- Role of coherent structures?
- Relations and interactions between them?
- Contribution to turbulence production and dissipation?

…

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Buffer layer

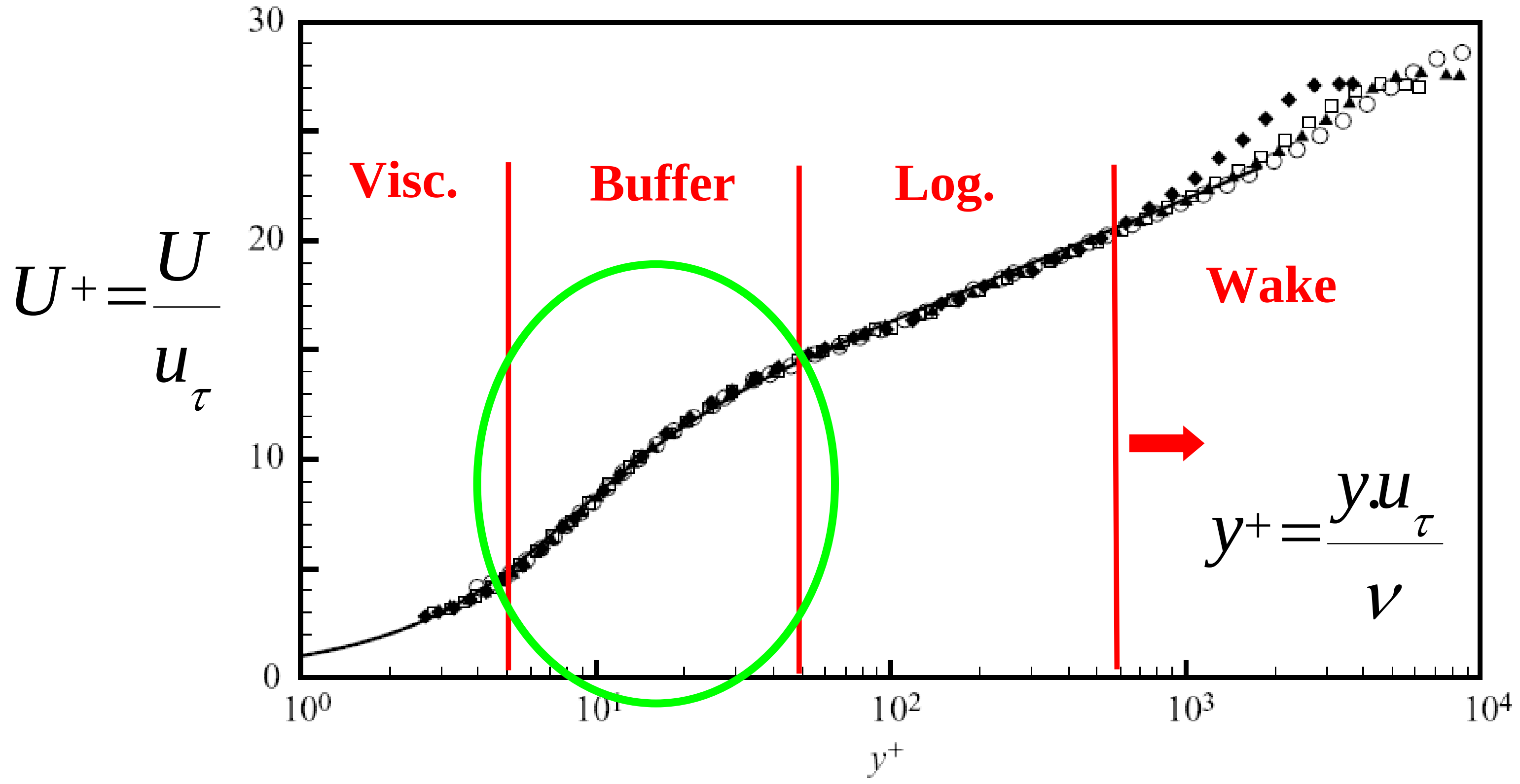

FIGURE 5. Profiles of longitudinal mean velocity U obtained with HWA: ◆, $R_\theta = 8100$; □, $R_\theta = 11\,500$; ▲, $R_\theta = 14\,800$; ○, $R_\theta = 20\,600$; ———, Van Driest profile.

Buffer layer

Streaks

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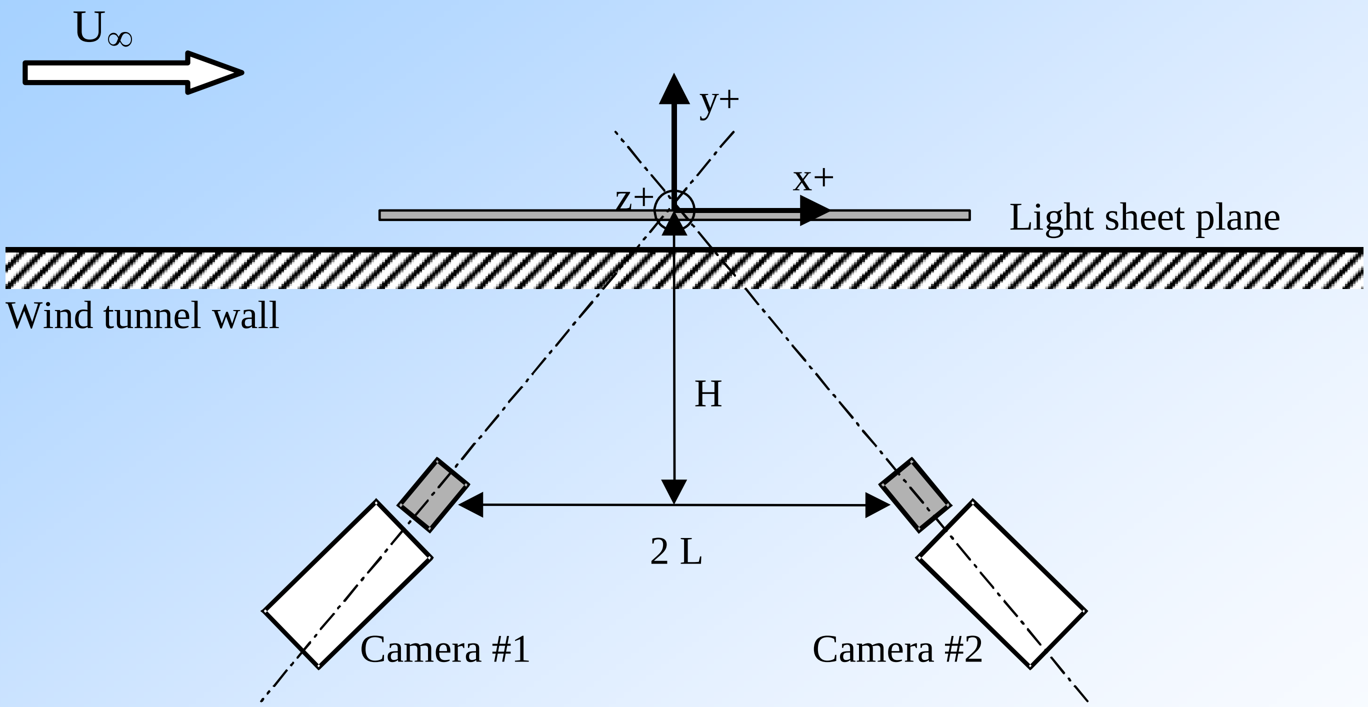
Buffer layer



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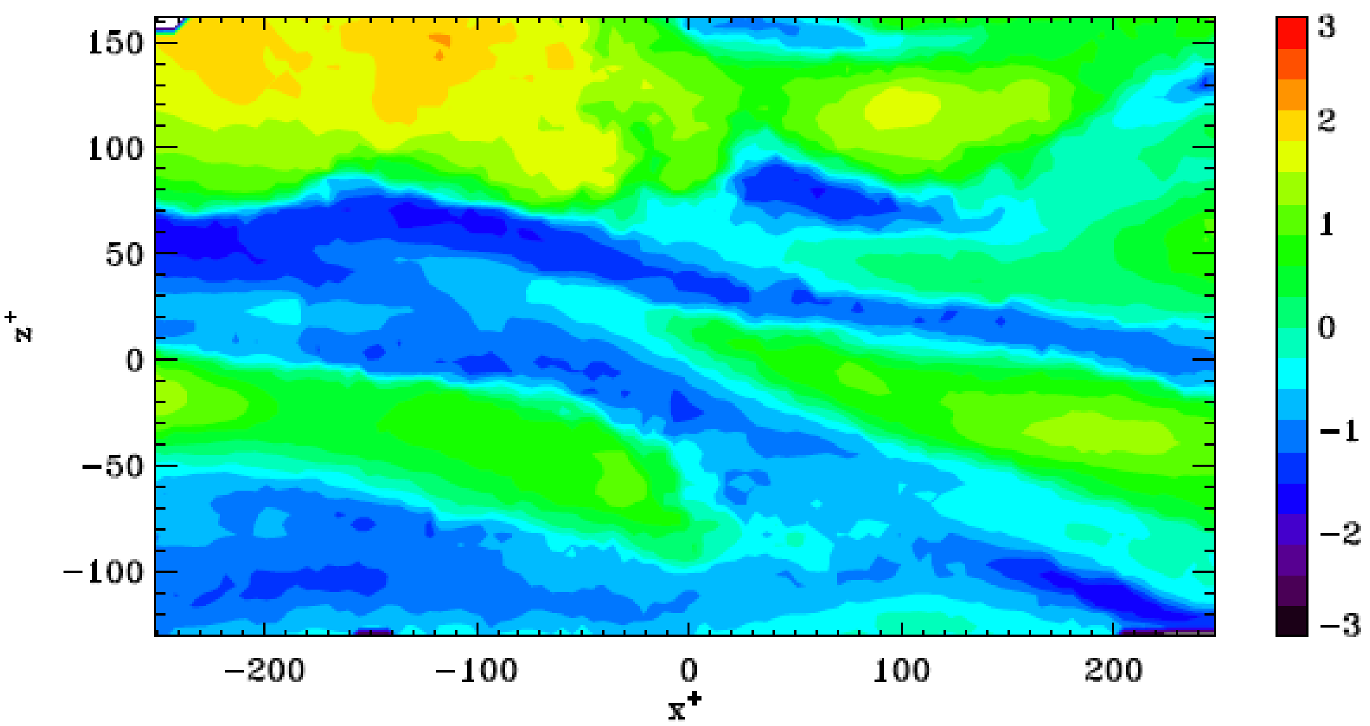
Buffer layer

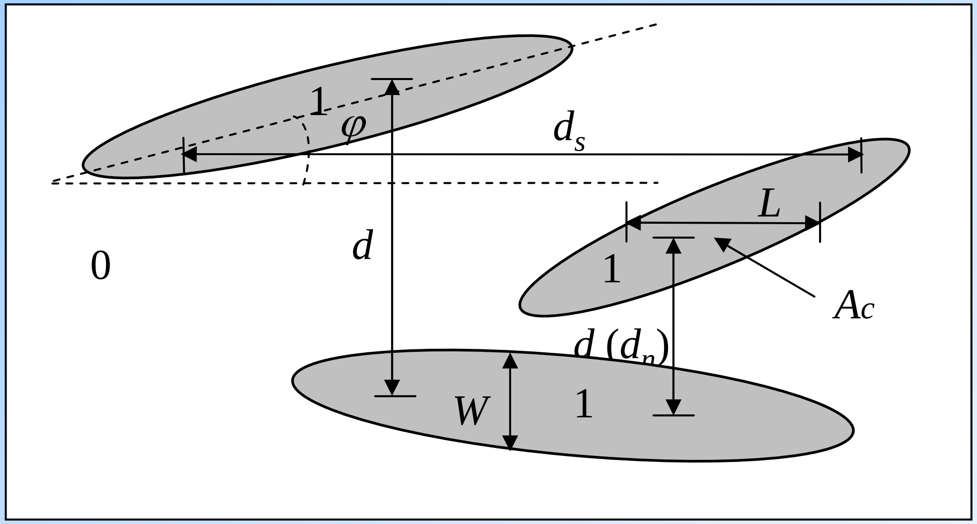
Streaks

J. Lin (2006)



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

Statistical characteristics



Measured parameters :

- Frequency of occur. (N)
- Transverse angle (φ)
- Width (W)
- Length (L)
- Area (A_c)
- Transverse spacing (d)
- …

Statistics :

- Mean
- RMS
- Histogram
- Median
- Variance
- Skewness & flatness
- …

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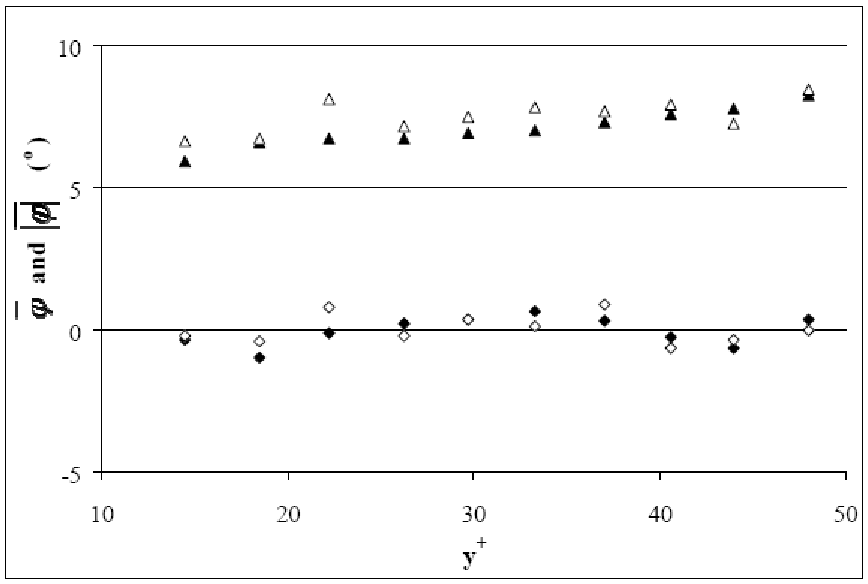
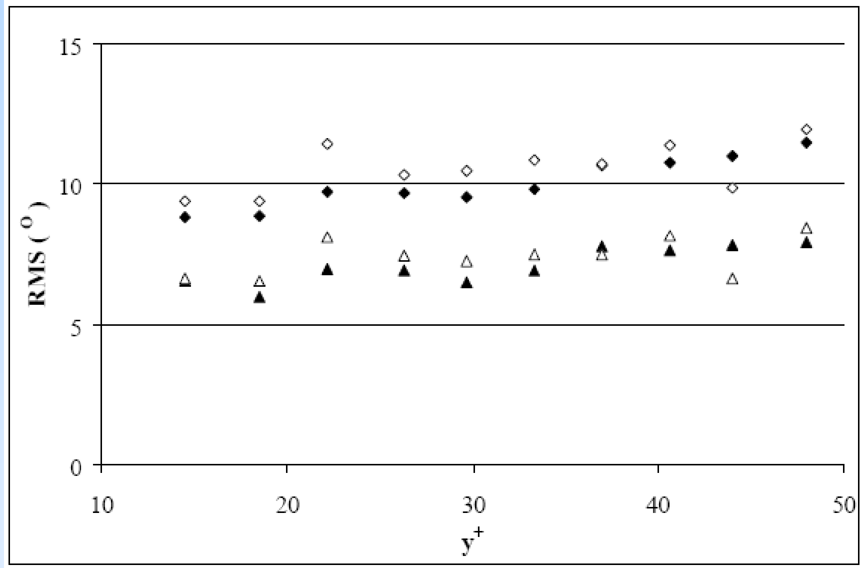
Buffer layer

Streaks

J. Lin (2006)





Mean spanwise angle

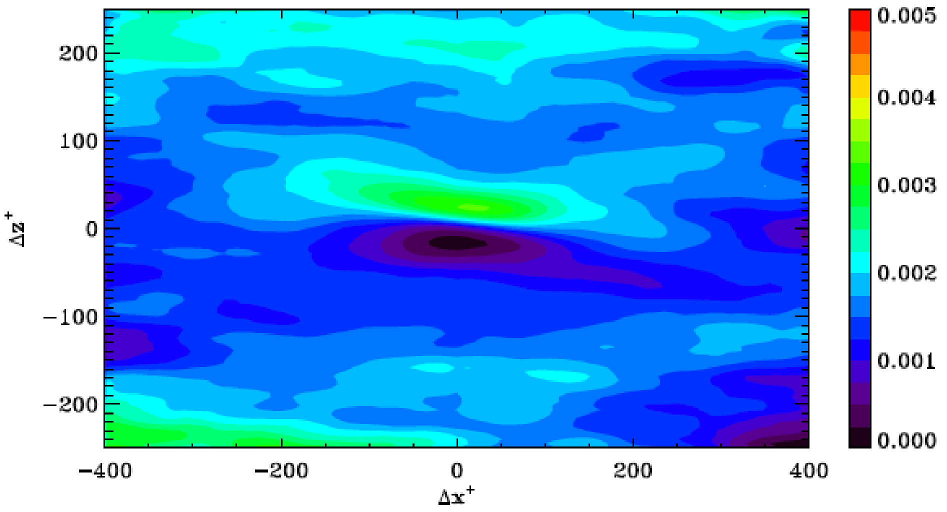
RMS of spanwise angle

Quantitative characterization of coherent structures in the buffer layer of near-wall turbulence. Part 1: streaks.
J. Lin, J. P. Laval, J. M. Foucaut, M. Stanislas
Experiments in Fluids V: 45-6, pp 999-1013, Dec 2008.

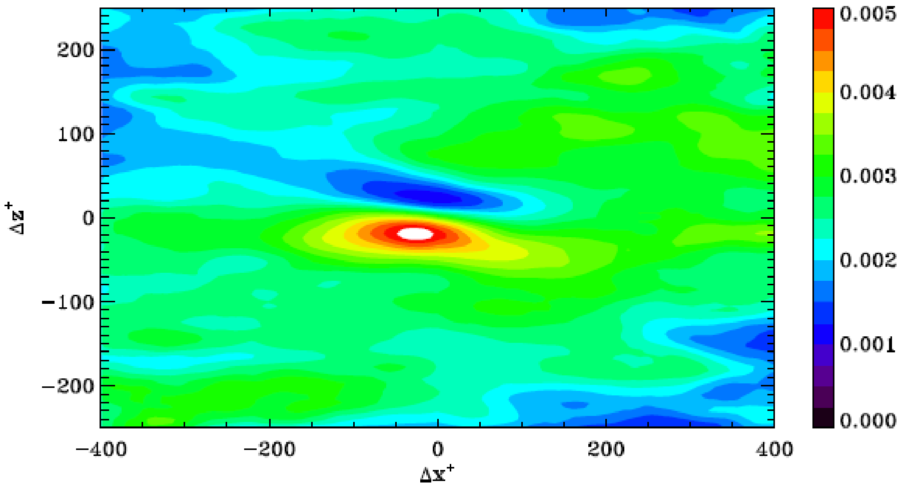
Buffer layer

Relations between CS

J. Lin (2006)



$R_{LSS-PGSV}$



$R_{HSS-PGSV}$

Low speed streaks/vortices

High speed streaks/vortices

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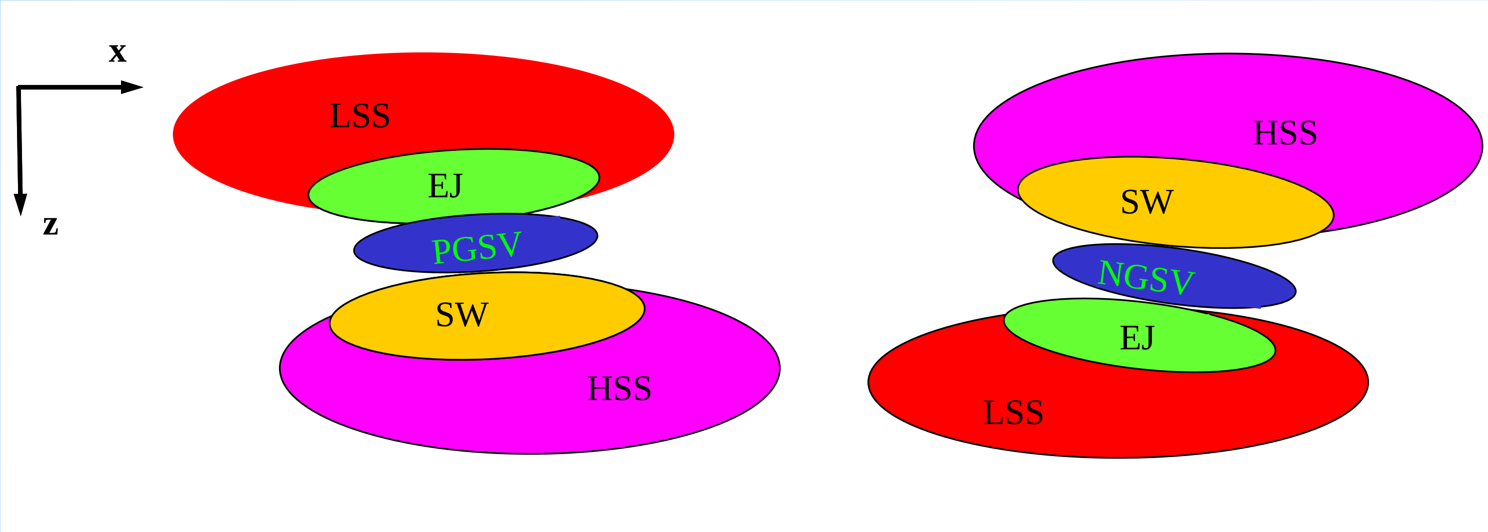
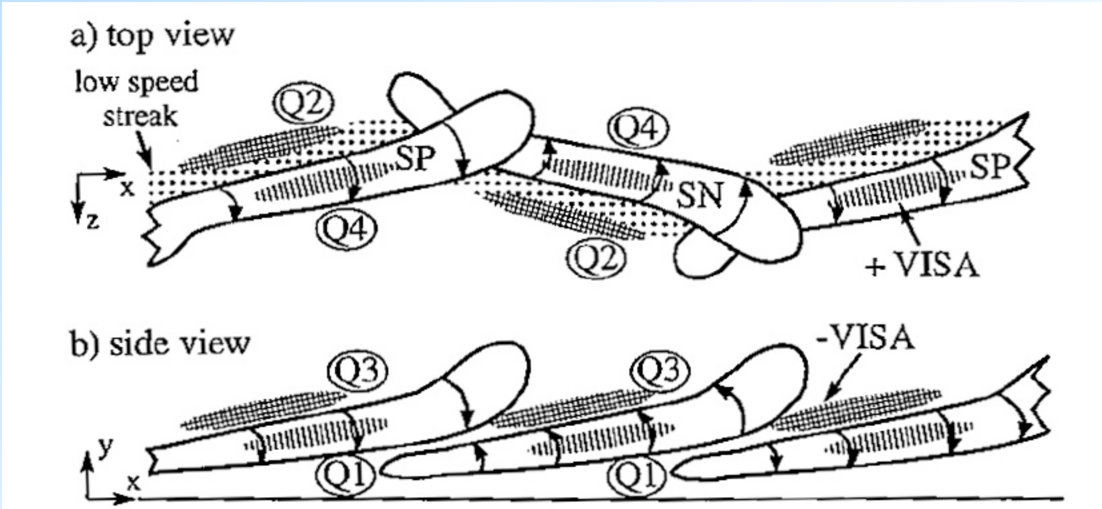
Buffer layer

Relations between CS

J. Lin (2006)





Choppa & Hussain JFM 2000

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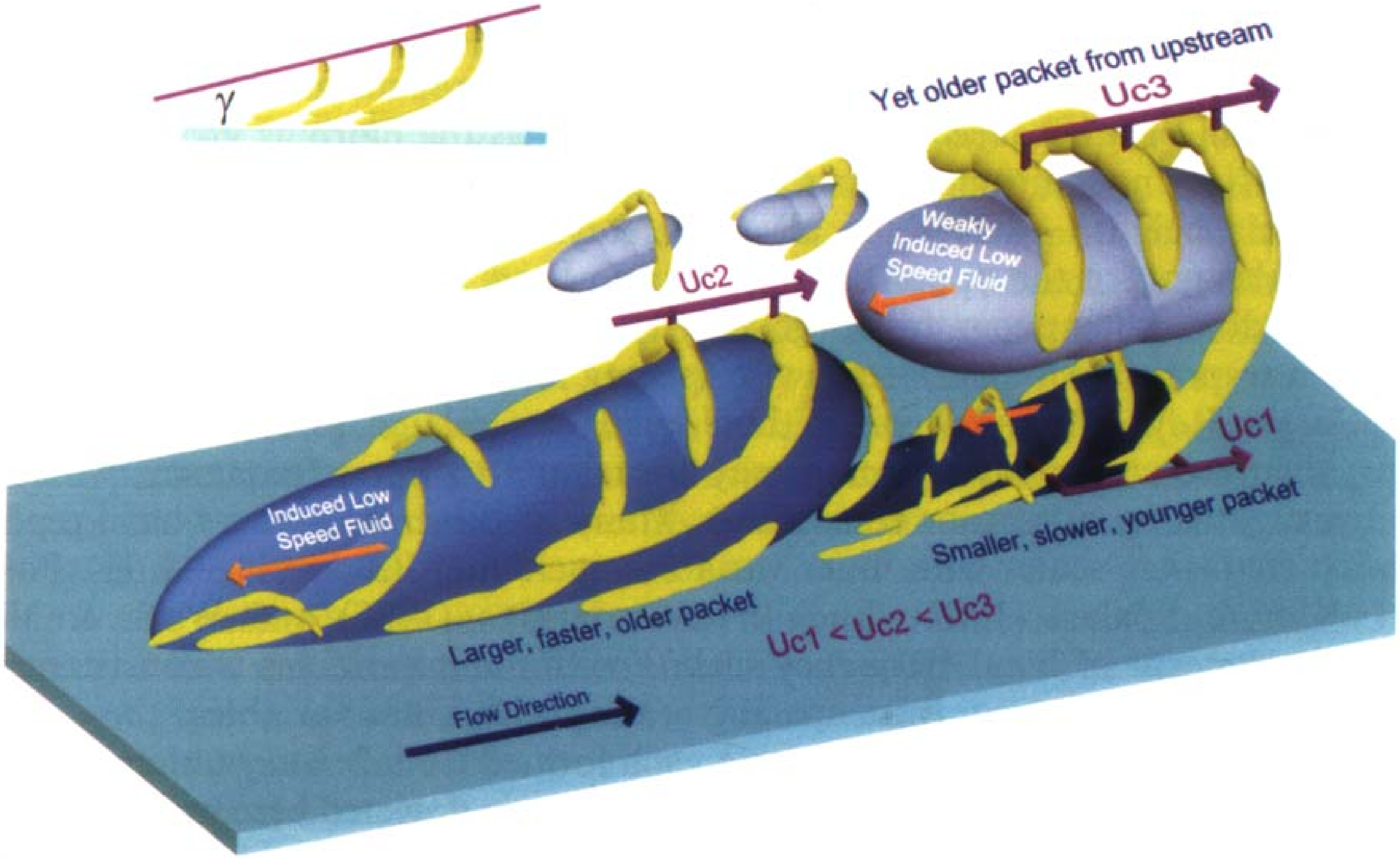
Hairpin vortices

Adrian et al (2000)



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Hairpin vortices

Tools

- **Signed swirling strength**

Velocity gradient tensor : $\partial u'_i / \partial x_j$

$$\begin{bmatrix} \lambda_r & & \\ & \lambda_{cr} & \lambda_{ci} \\ & -\lambda_{ci} & \lambda_{cr} \end{bmatrix}$$

$\lambda_s = \lambda_{ci} . \omega_1 / |\omega_1|$ **with** λ_{ci} **img. part of complex Eig. Val.**

- **Oseen vortex model :** $\underline{u}(\underline{r}) - \underline{u}_0(\underline{x}_0) = \frac{\Gamma_0}{2\pi r}\left[1 - \exp - \left(\frac{r}{r_0}\right)^2\right] \cdot \underline{e}_\theta$

gives : $\underline{u}_o, \Gamma_o, r_o$

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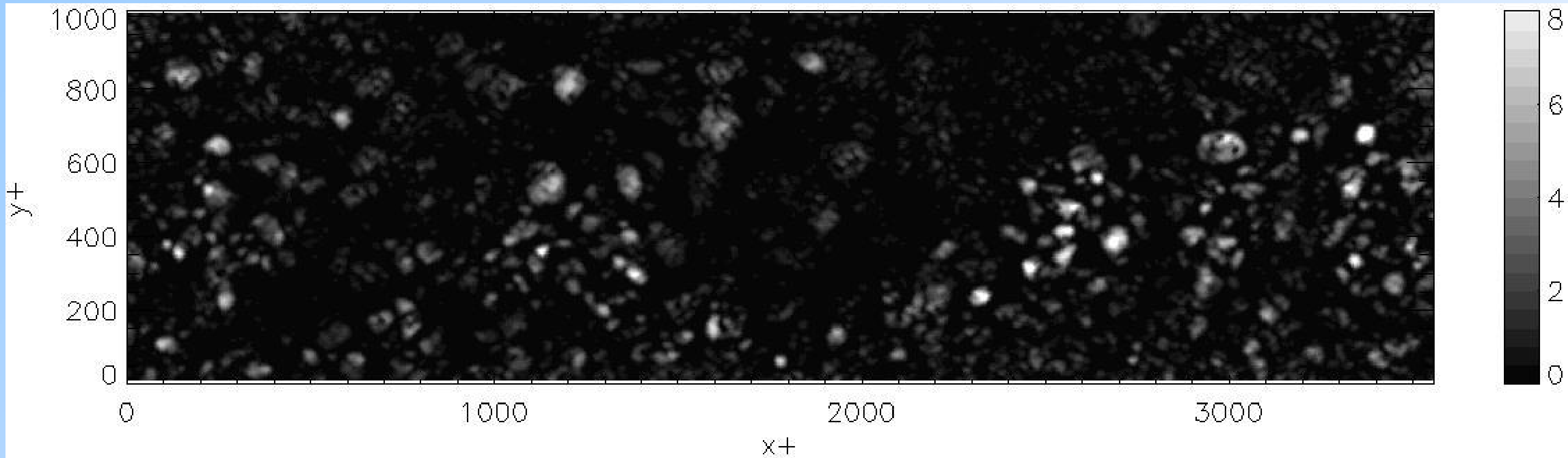
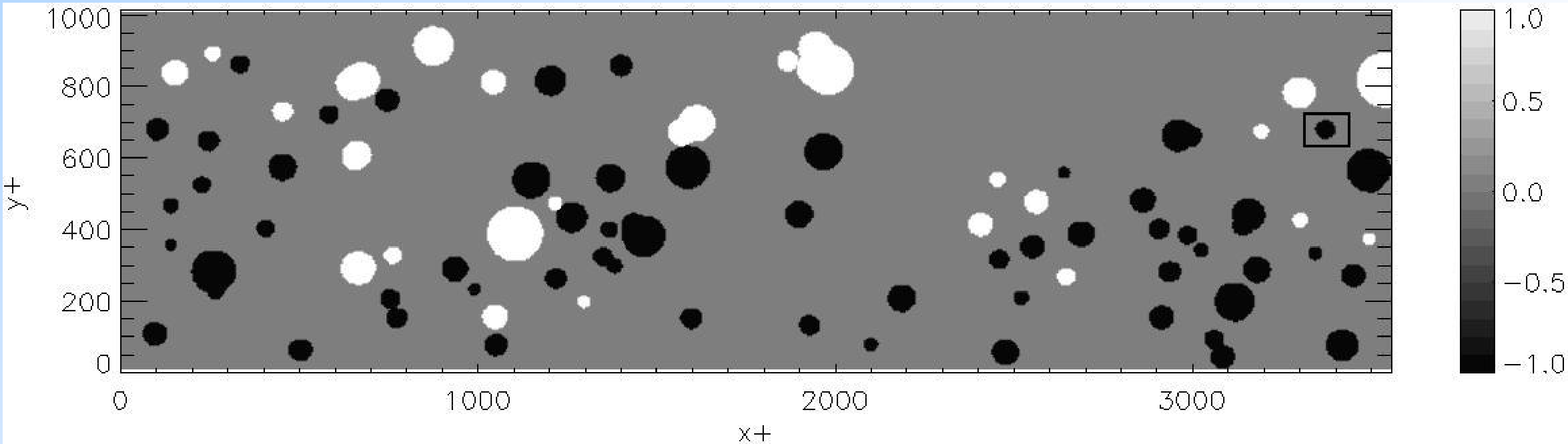
Tools





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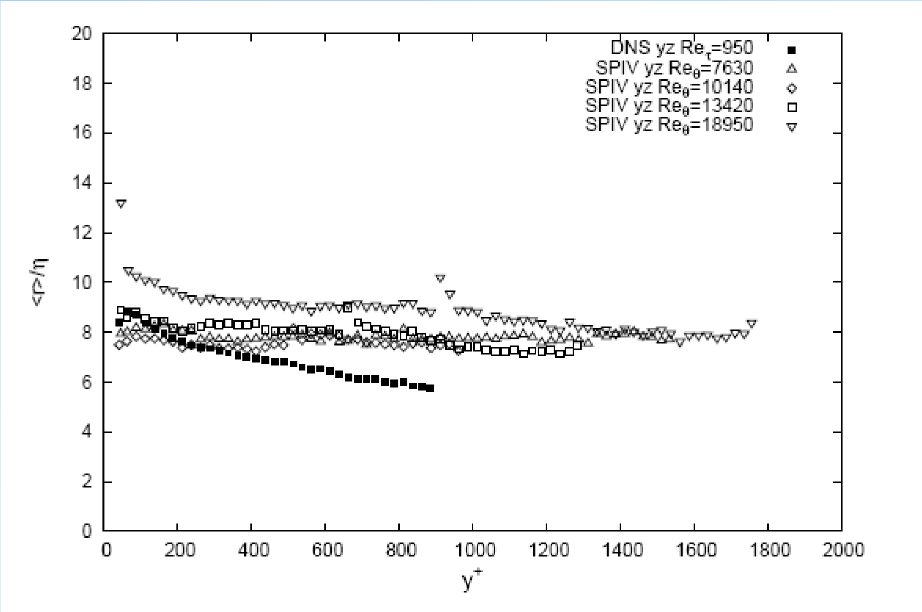
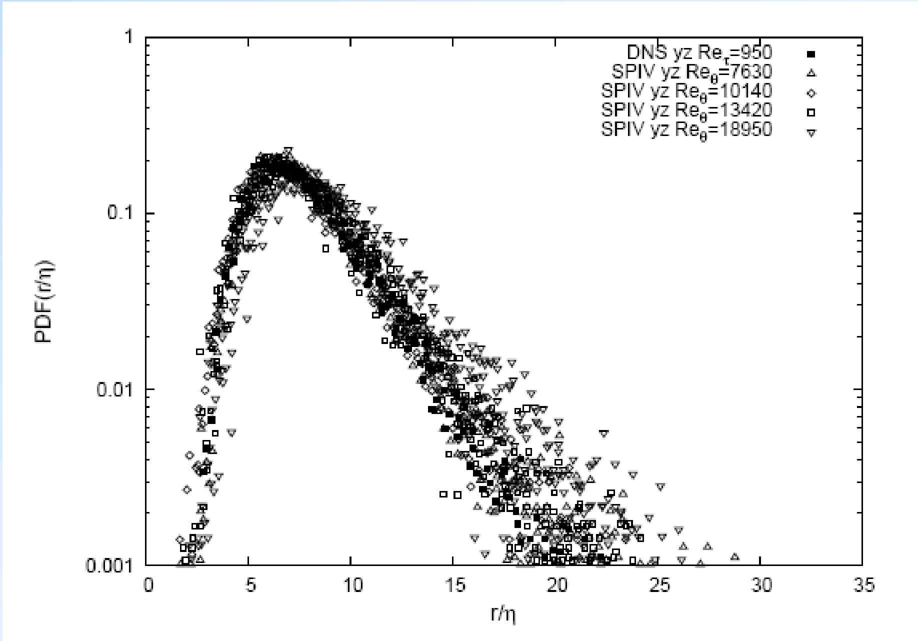
Hairpin vortices

Radius





Scales with Kolmogorov $r \sim 8\,\eta$

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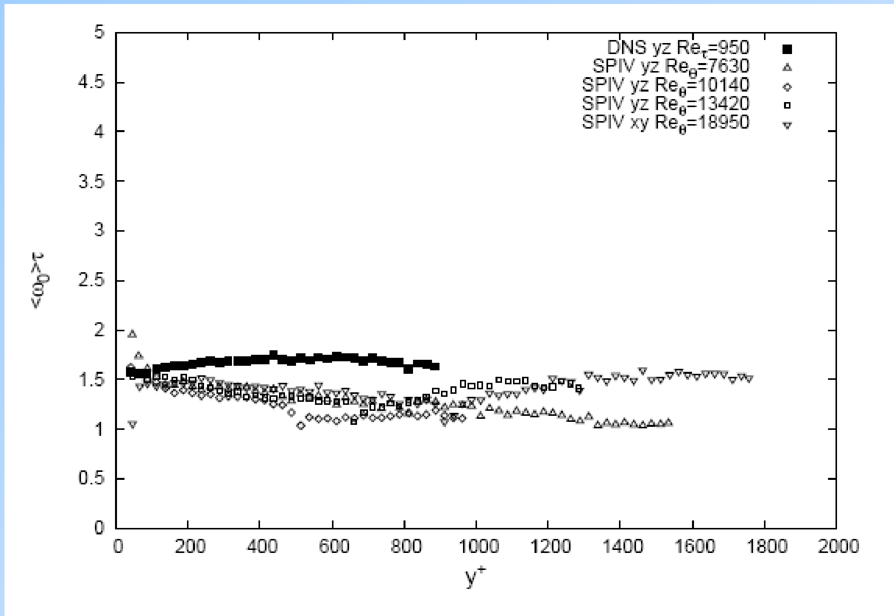
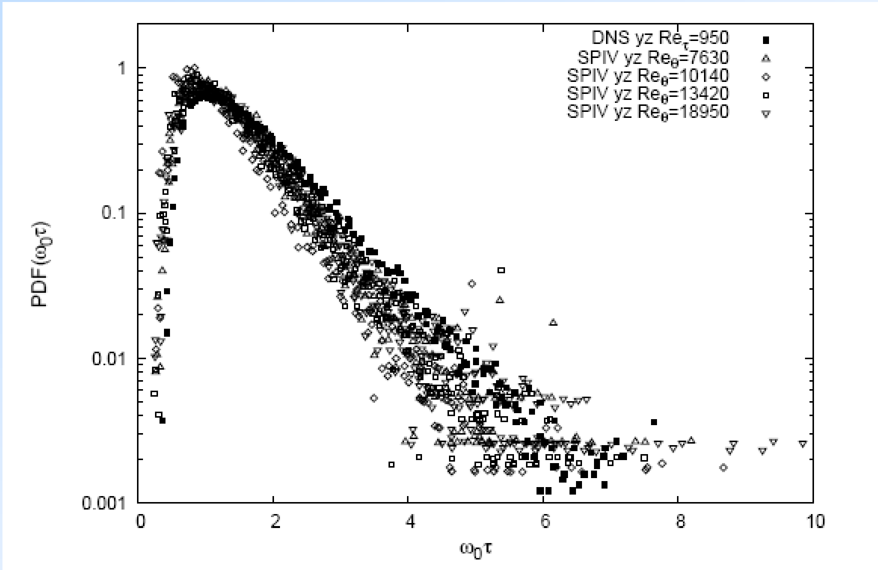
Hairpin vortices

Vorticity





Scales with Kolmogorov $\omega_o.\tau \sim 1.5$

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Hairpin vortices

Vorticity equation

$$\overline{u}_j \frac{\partial}{\partial x_j}\left(\frac{1}{2}\overline{\omega_i'^2}\right) = -\frac{1}{2}\frac{\partial}{\partial x_j}\left(\overline{\omega_i'\omega_i'u_j'}\right) - \overline{\omega_i'u_j'}\frac{\partial \overline{\omega}_i}{\partial x_j} + \overline{\omega_i'\omega_j'}\,\overline{s}_{ij}$$

[1] [2] [3] [4]

$$+\overline{\omega_i'\omega_j's_{ij}'} + \overline{\omega}_j\overline{\omega_i's_{ij}'} + \nu\frac{\partial^2}{\partial x_j^2}\left(\frac{1}{2}\overline{\omega_i'^2}\right) - \nu\overline{\left(\frac{\partial \omega_i'}{\partial x_j}\right)^2}$$

[5] [6] [7] [8]

[1] convection **[2] turb. diff.** **[3] production** **[4] stretching**

[5] stretching **[6] production** **[7] viscous diff.** **[8] dissipation**

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Hairpin vortices

Vorticity equation

$$0 = \underbrace{\overline{\omega'_1 \omega'_2}\,\overline{s}_{12}}_{[4]} + \underbrace{\overline{\omega'_i \omega'_j s'_{ij}}}_{[5]} - \nu \underbrace{\overline{\left(\frac{\partial \omega'_i}{\partial x_j}\right)^2}}_{[8]}$$

[4] stretching **[5] stretching** **[8] dissipation**

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Hairpin vortices

TBL structure

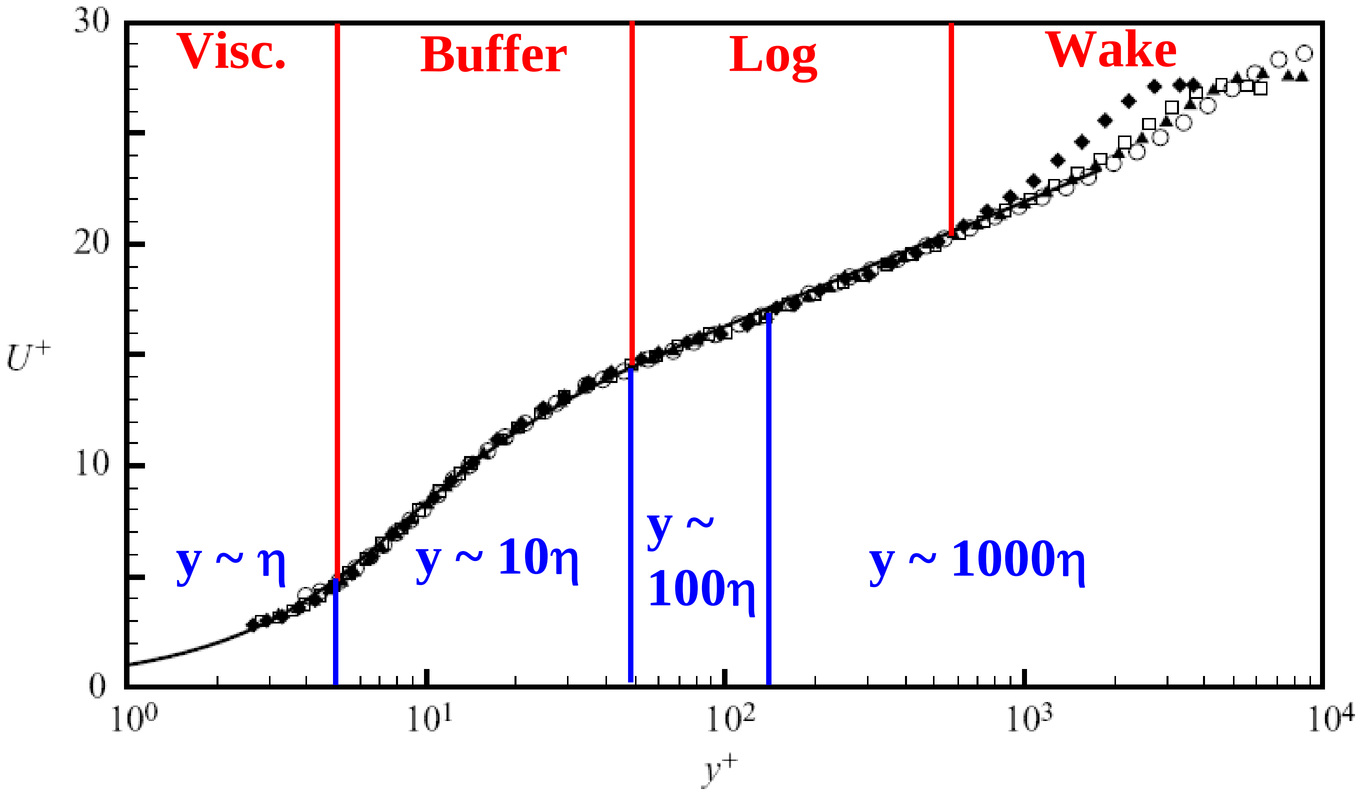

FIGURE 5. Profiles of longitudinal mean velocity U obtained with HWA: ◆, $R_\theta = 8100$; □, $R_\theta = 11\,500$; ▲, $R_\theta = 14\,800$; ○, $R_\theta = 20\,600$; ———, Van Driest profile.

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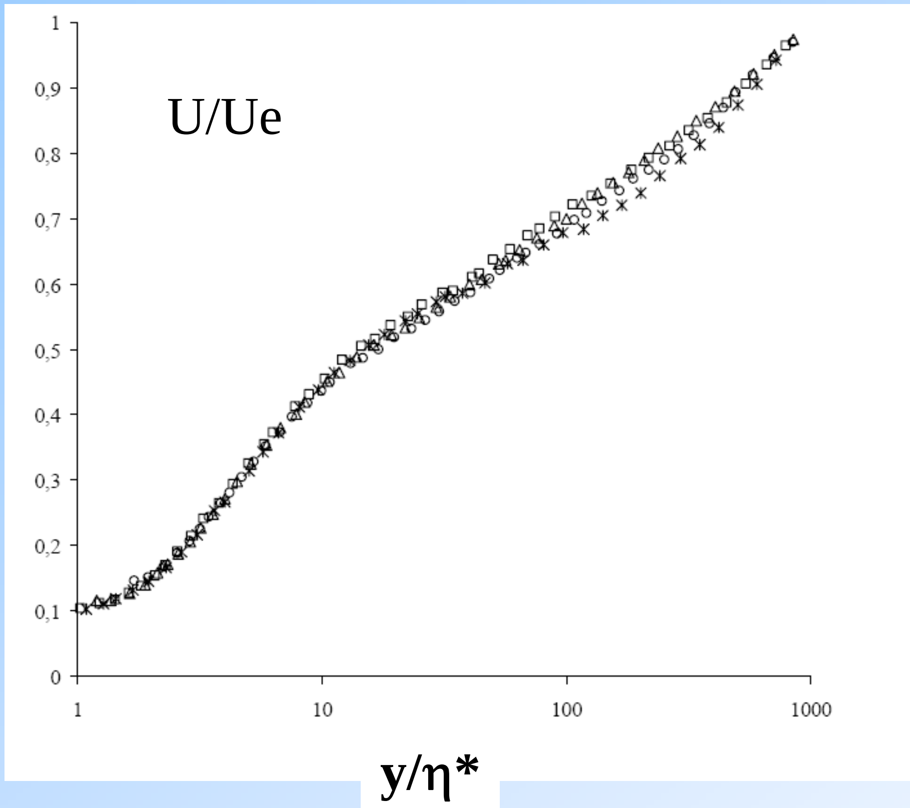
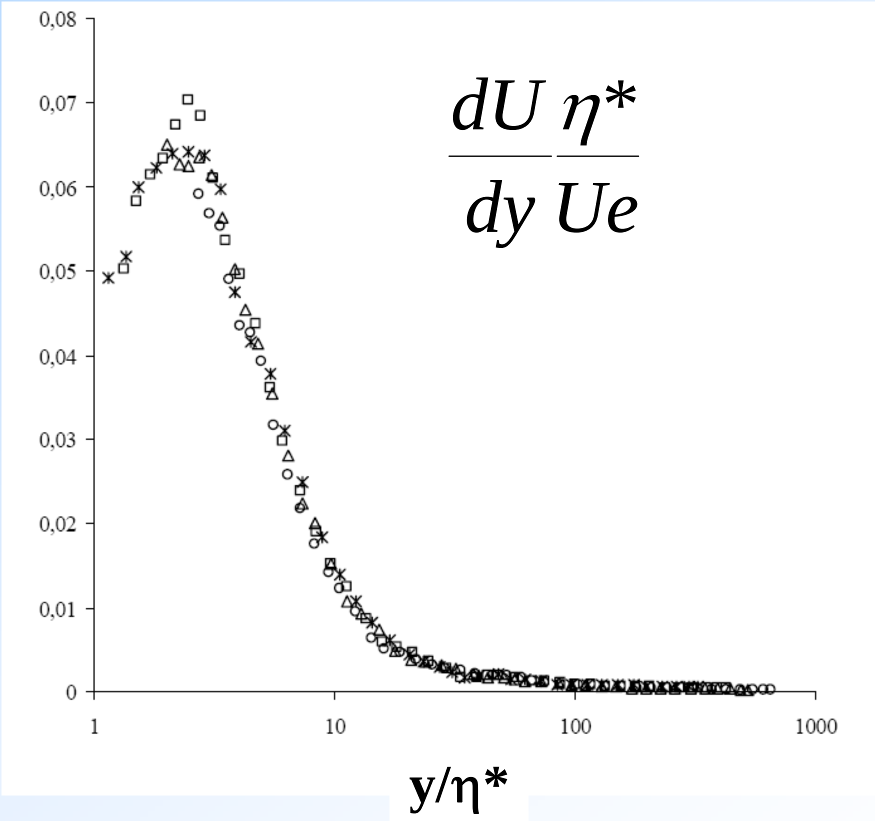
Hairpin vortices

New scaling

R_θ = 8000 – 20 000





Mean velocity

M. Stanislas, L. Perret, J.M. Foucaut
Journal of Fluid Mechanics, Volume 602 (2008), pp 327-382.

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Hairpin vortices

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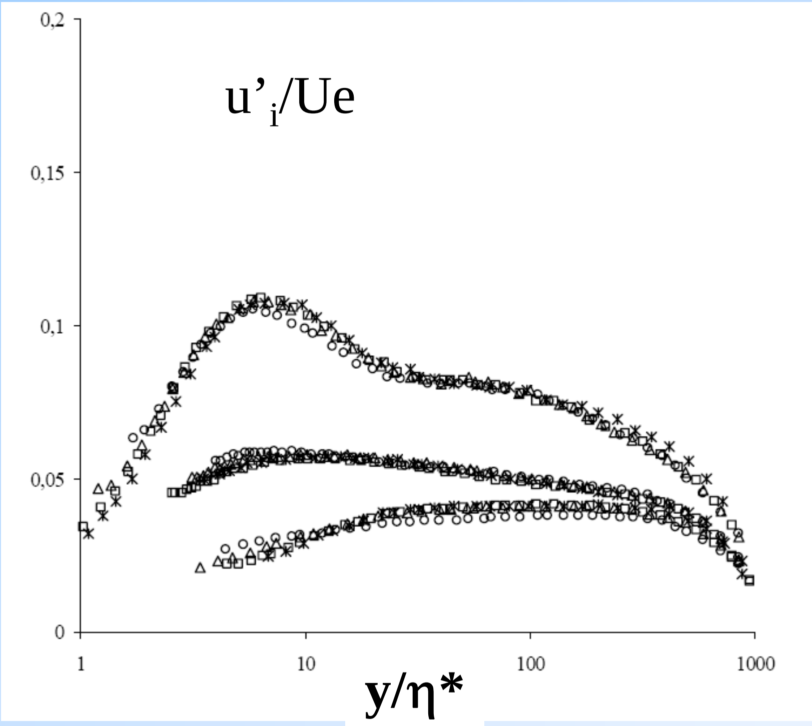

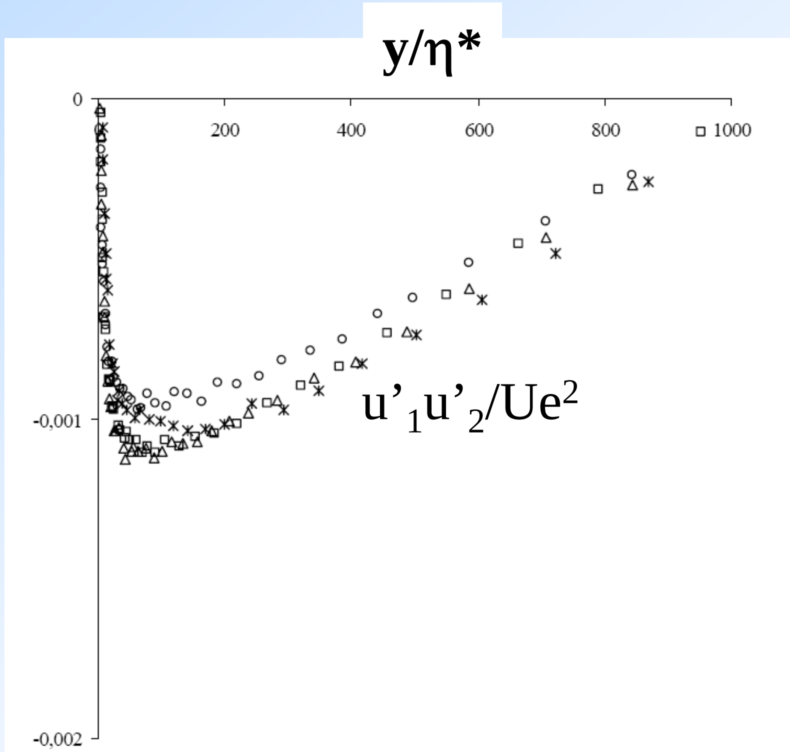

Turbulence

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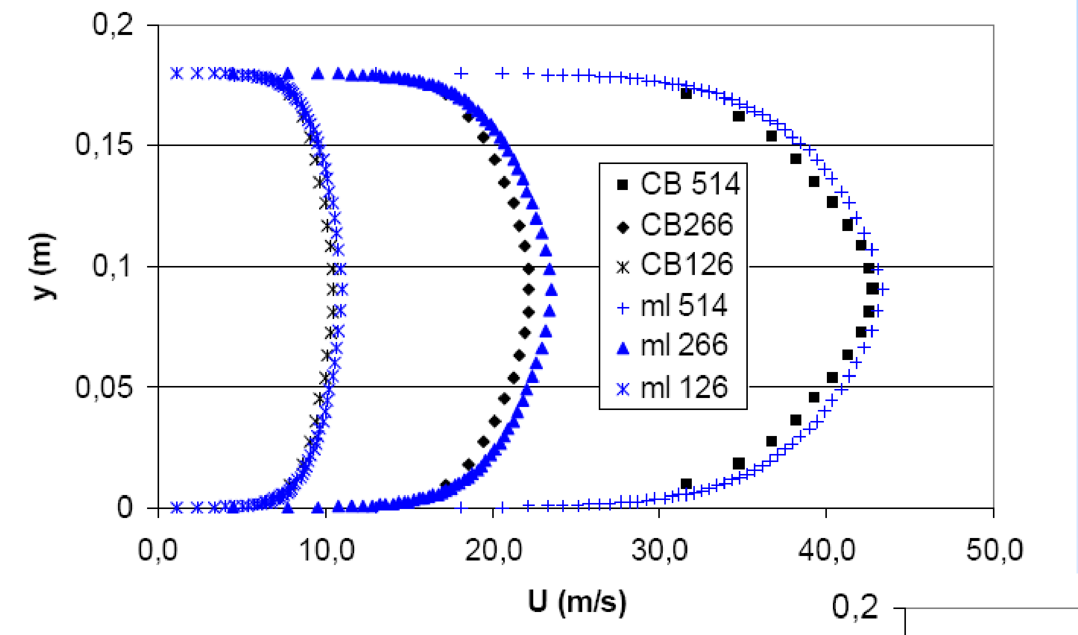
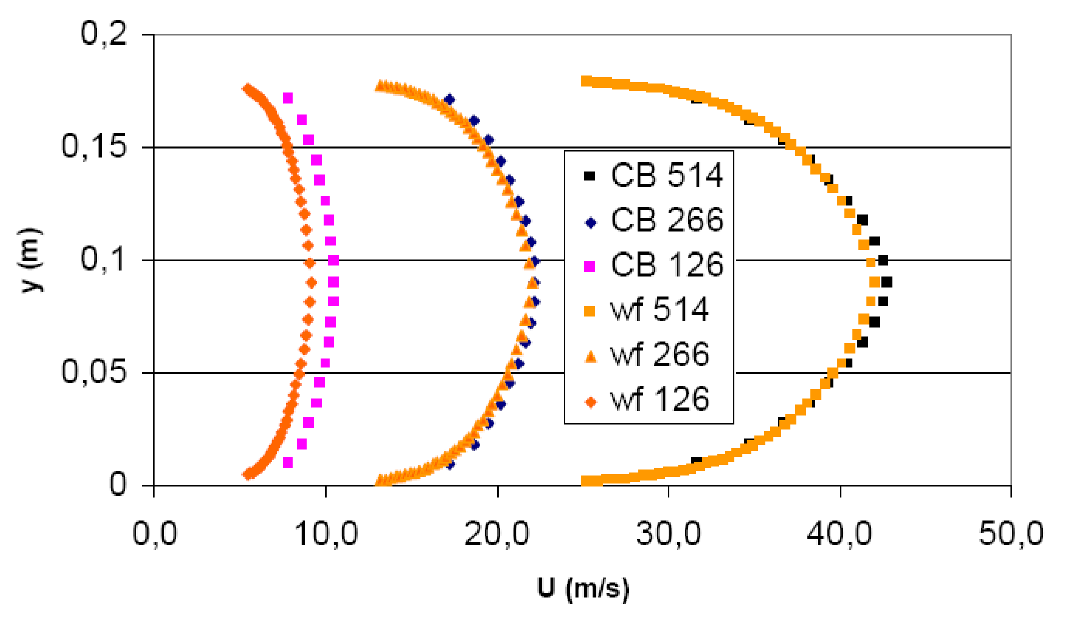
Hairpin vortices

New wall functions



Standard Mixing length

Standard Mixing length with wall functions at y+ = 100



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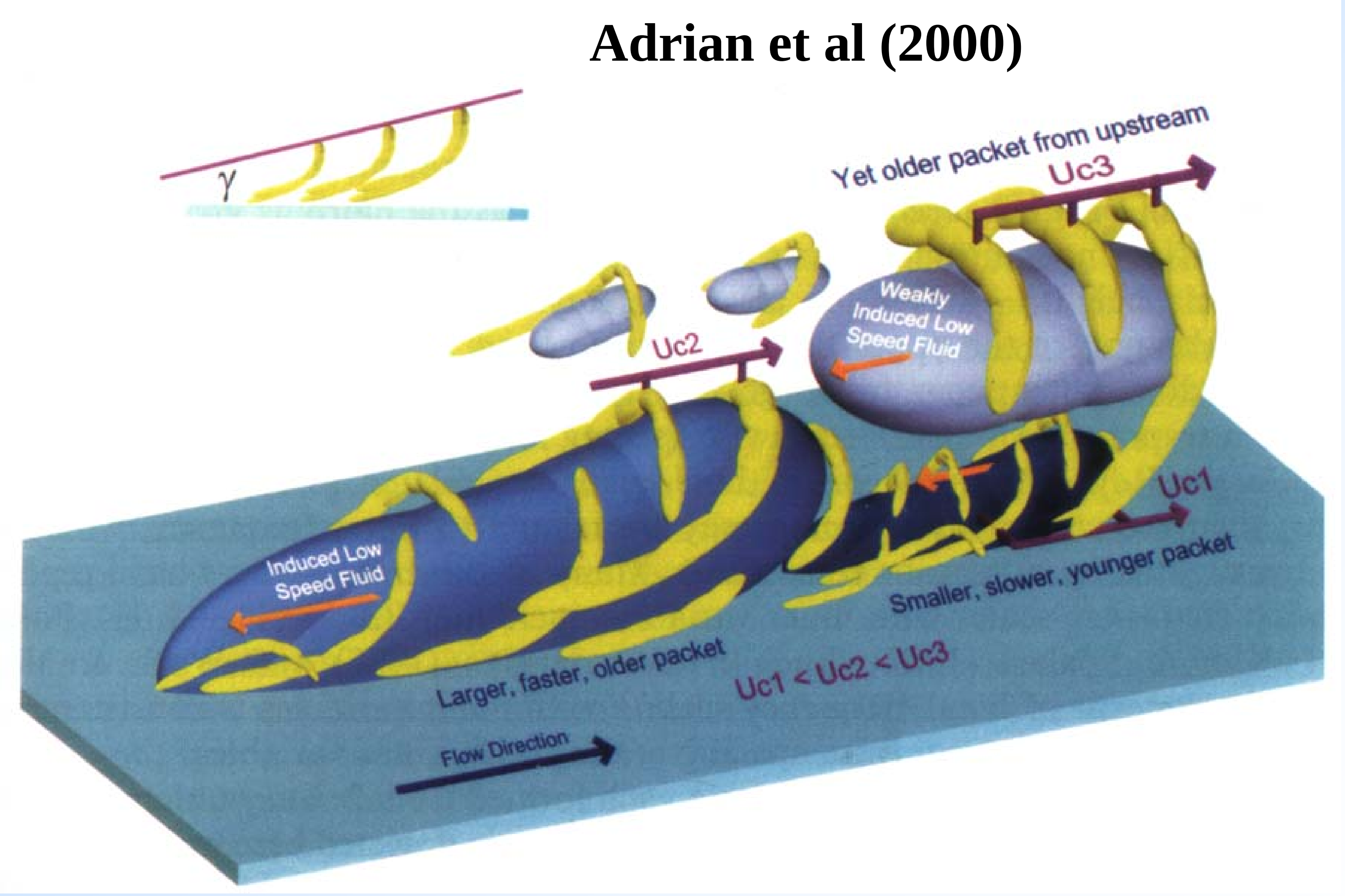
Large scales



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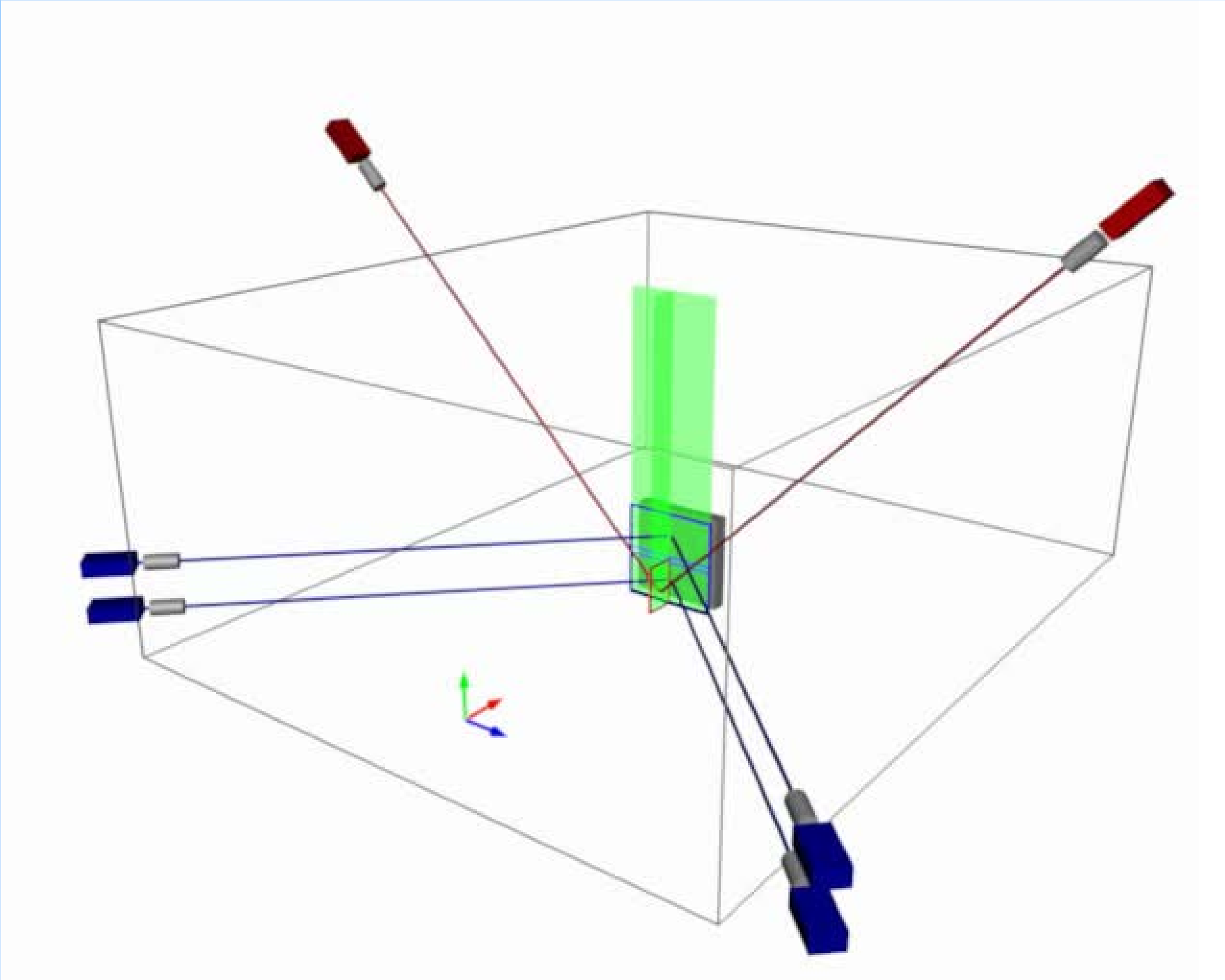
Large scales

Multiple PIV system



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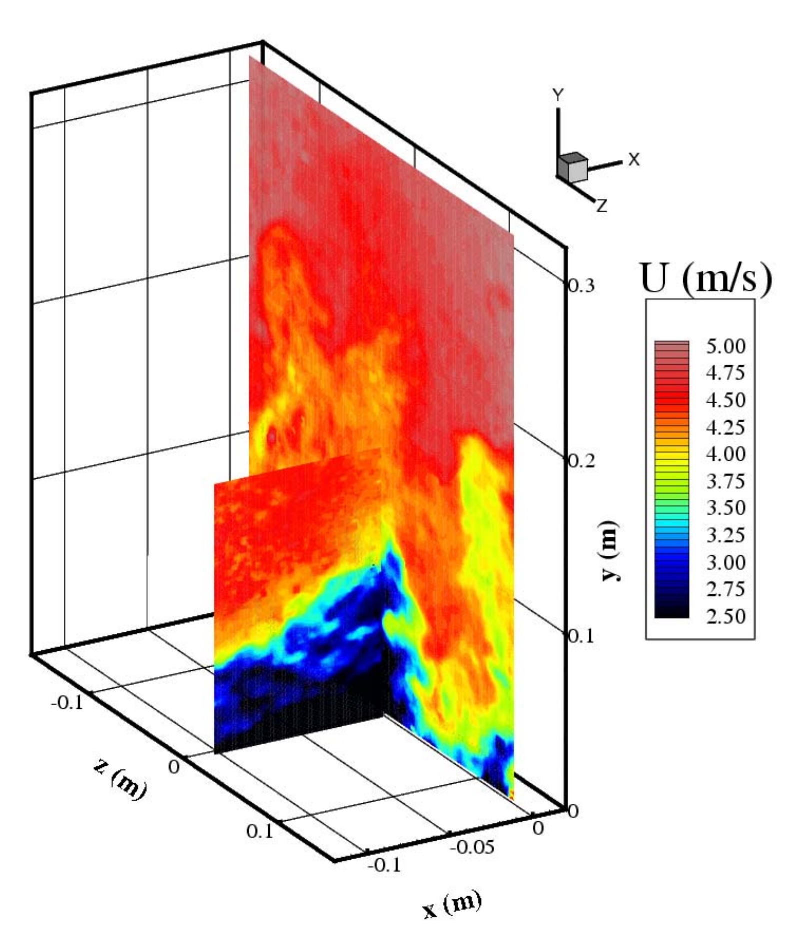
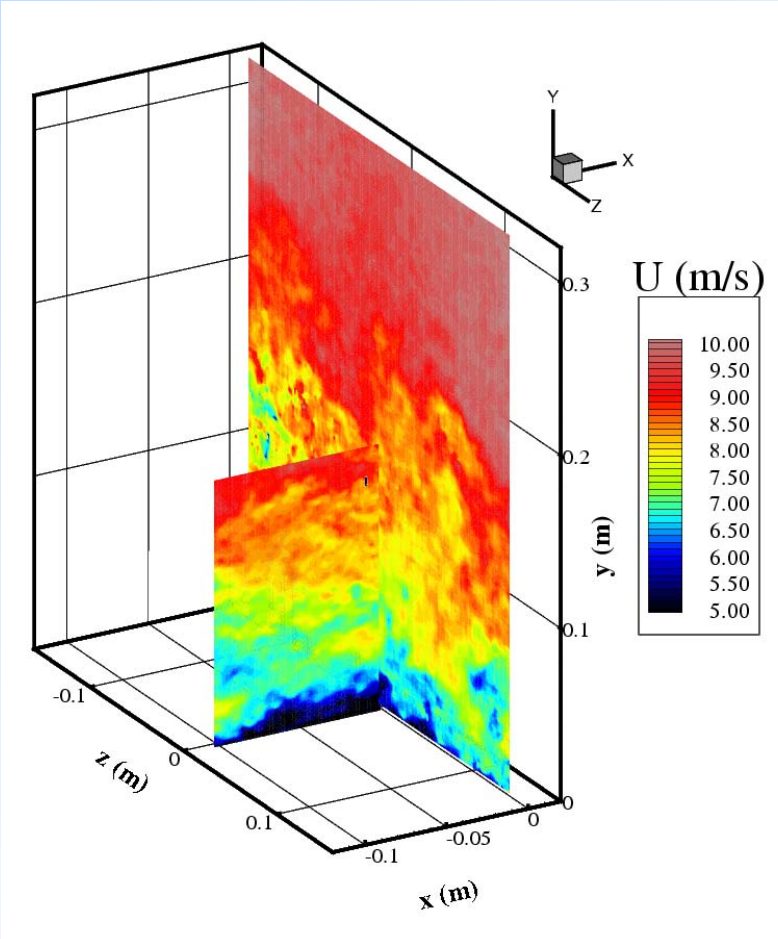
Multiple PIV system





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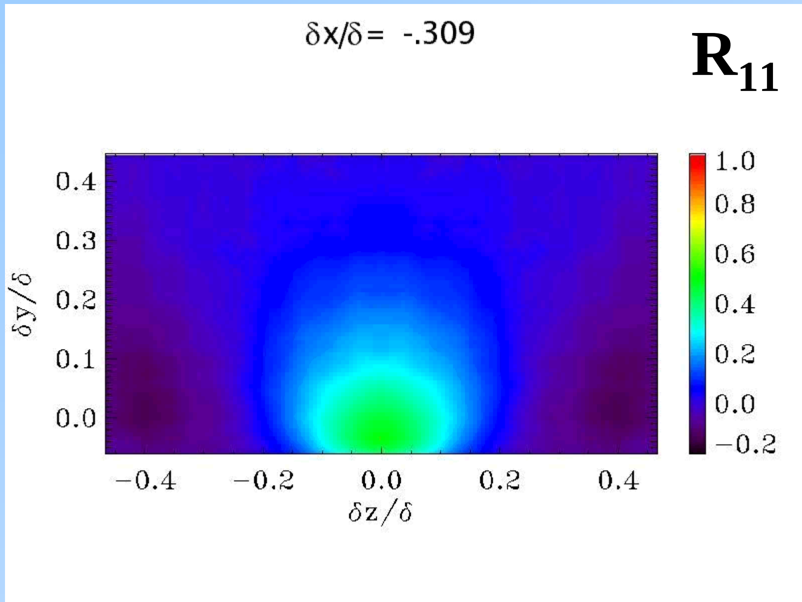
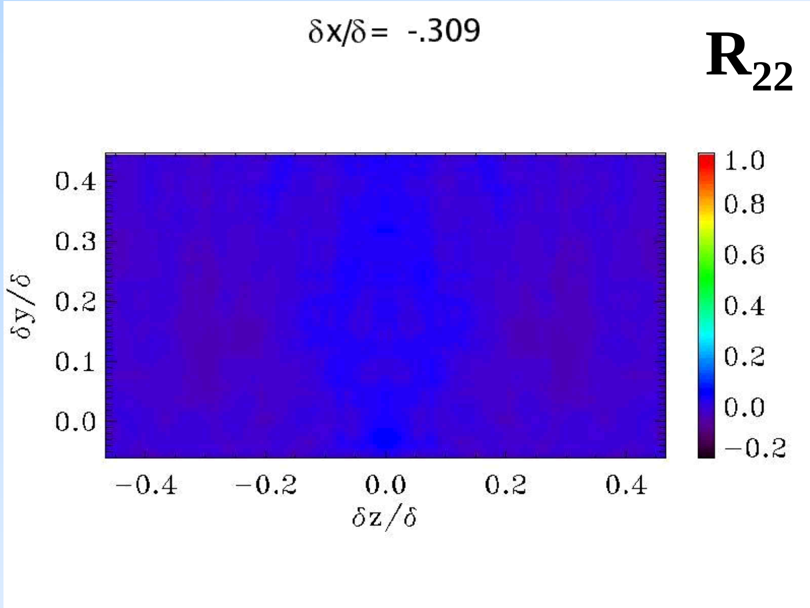
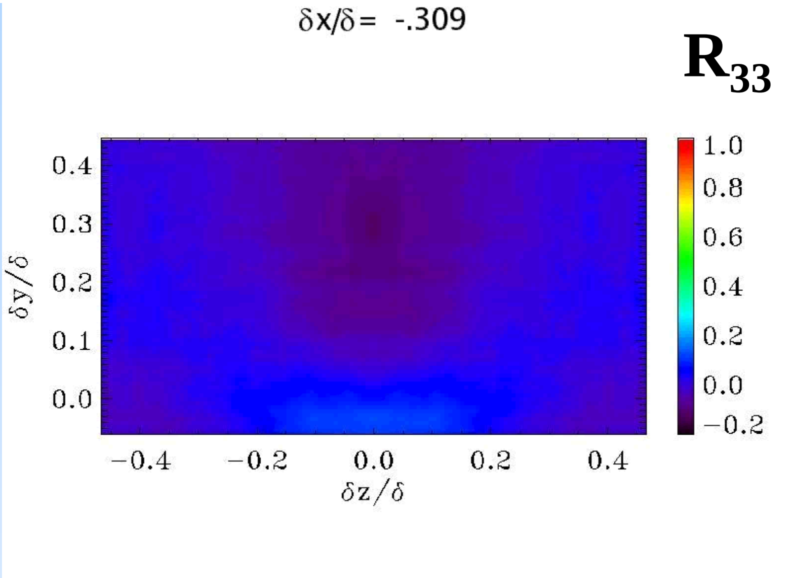
Large scales

3D Two points correlations







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

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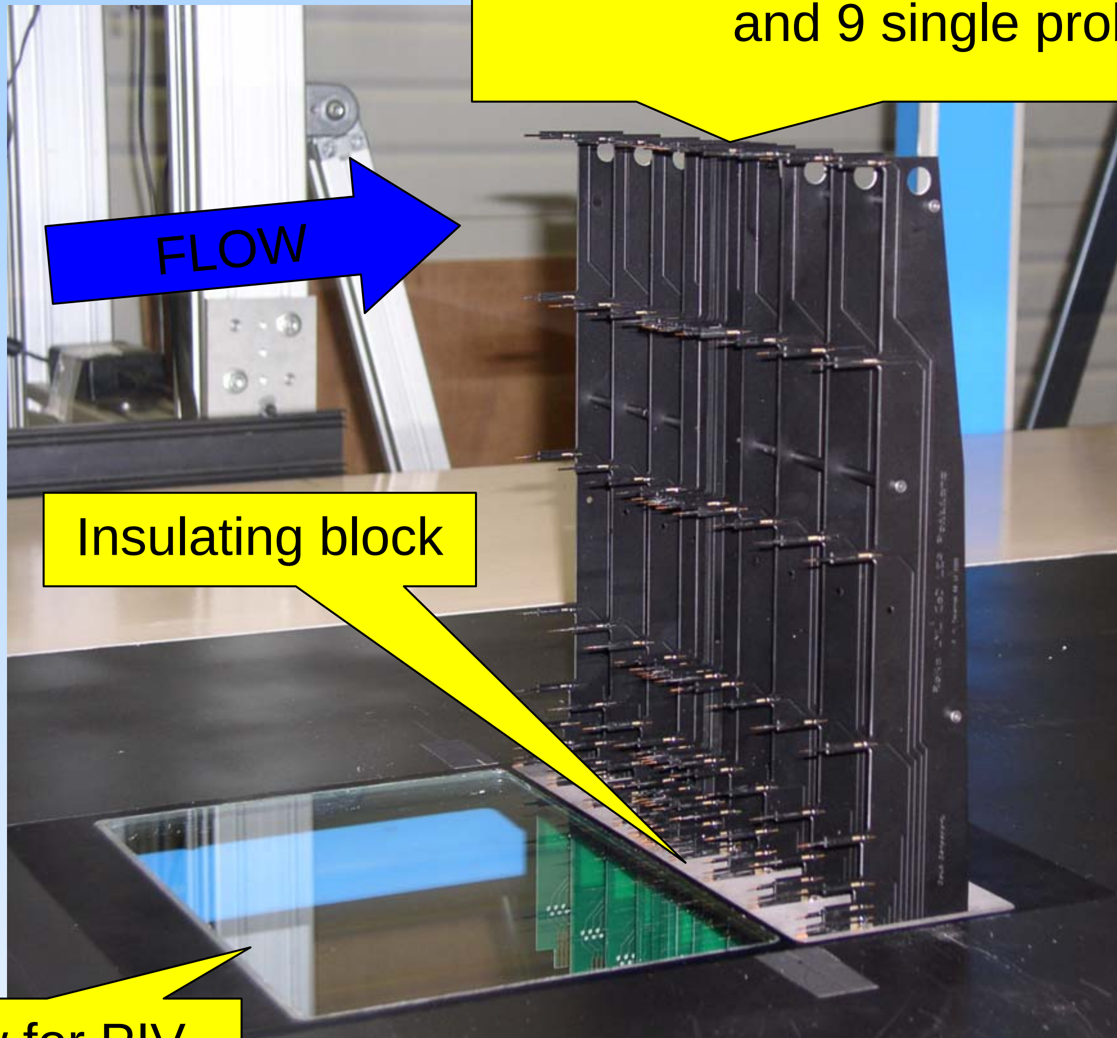
Large scales

Hot Wires rake

143 HWs



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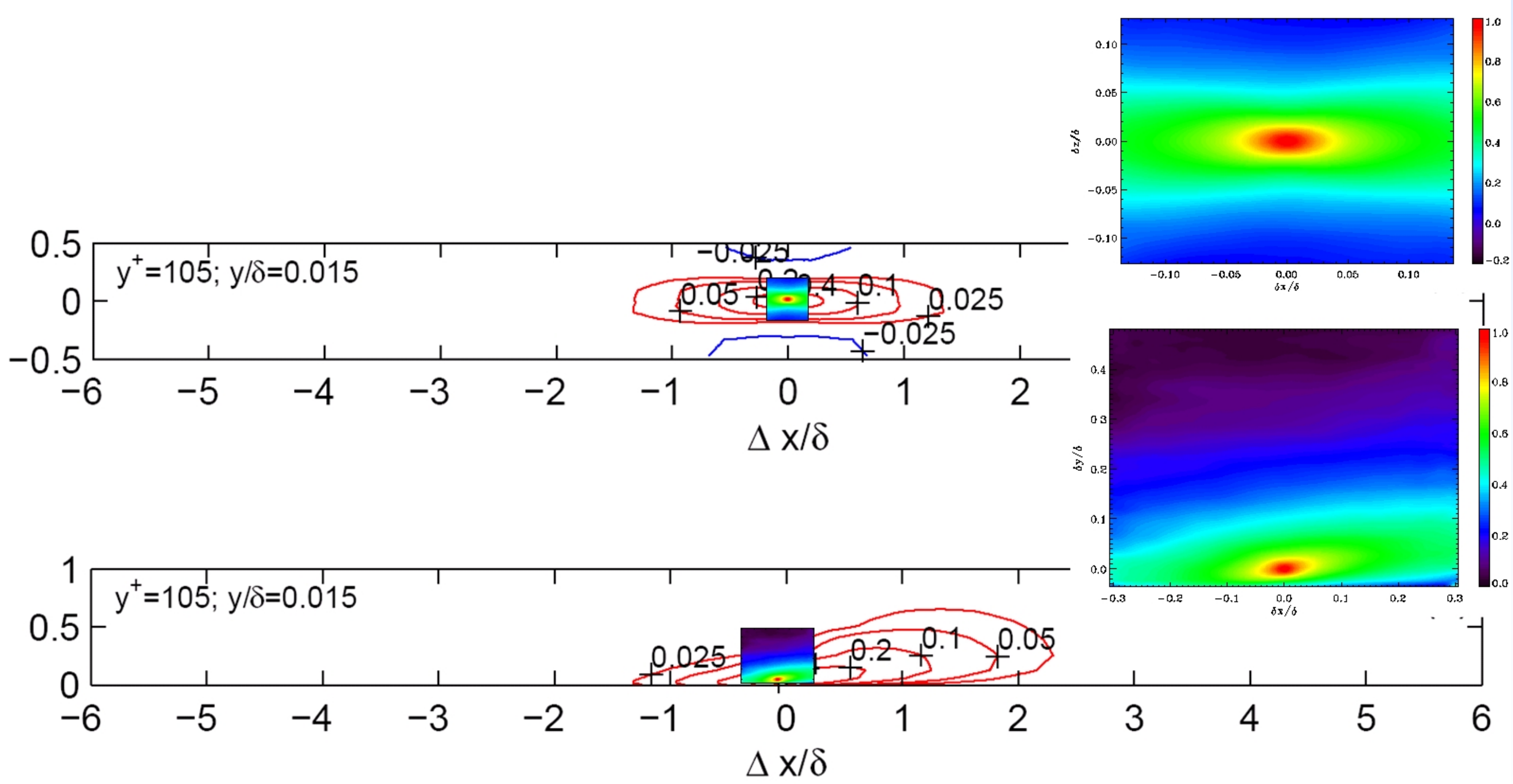
Two points correlations



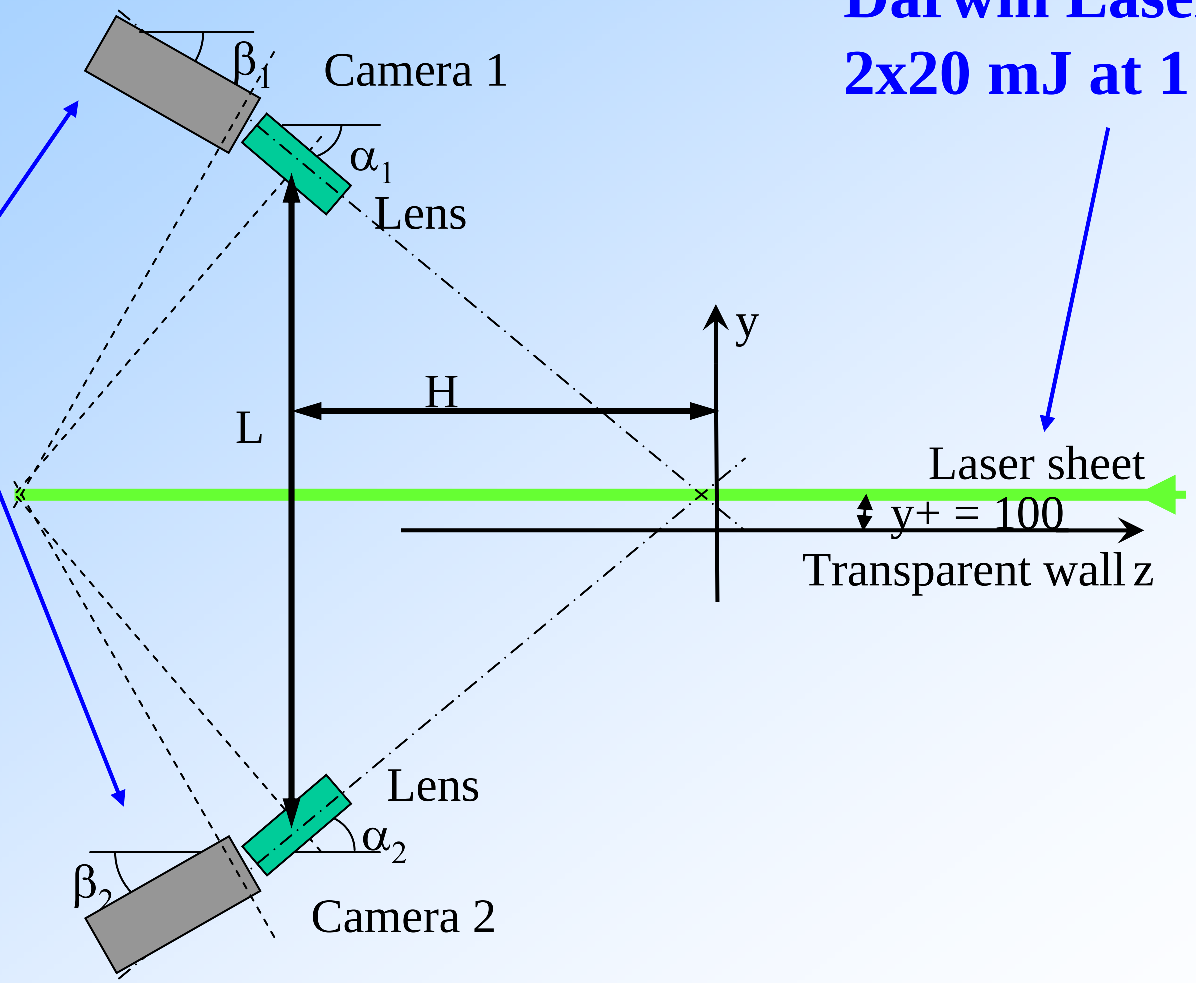
HR SPIV (High Repetition)

Set up

Darwin Laser
2x20 mJ at 1 kHz

Phantom V9

960x960 px
at 2kHz



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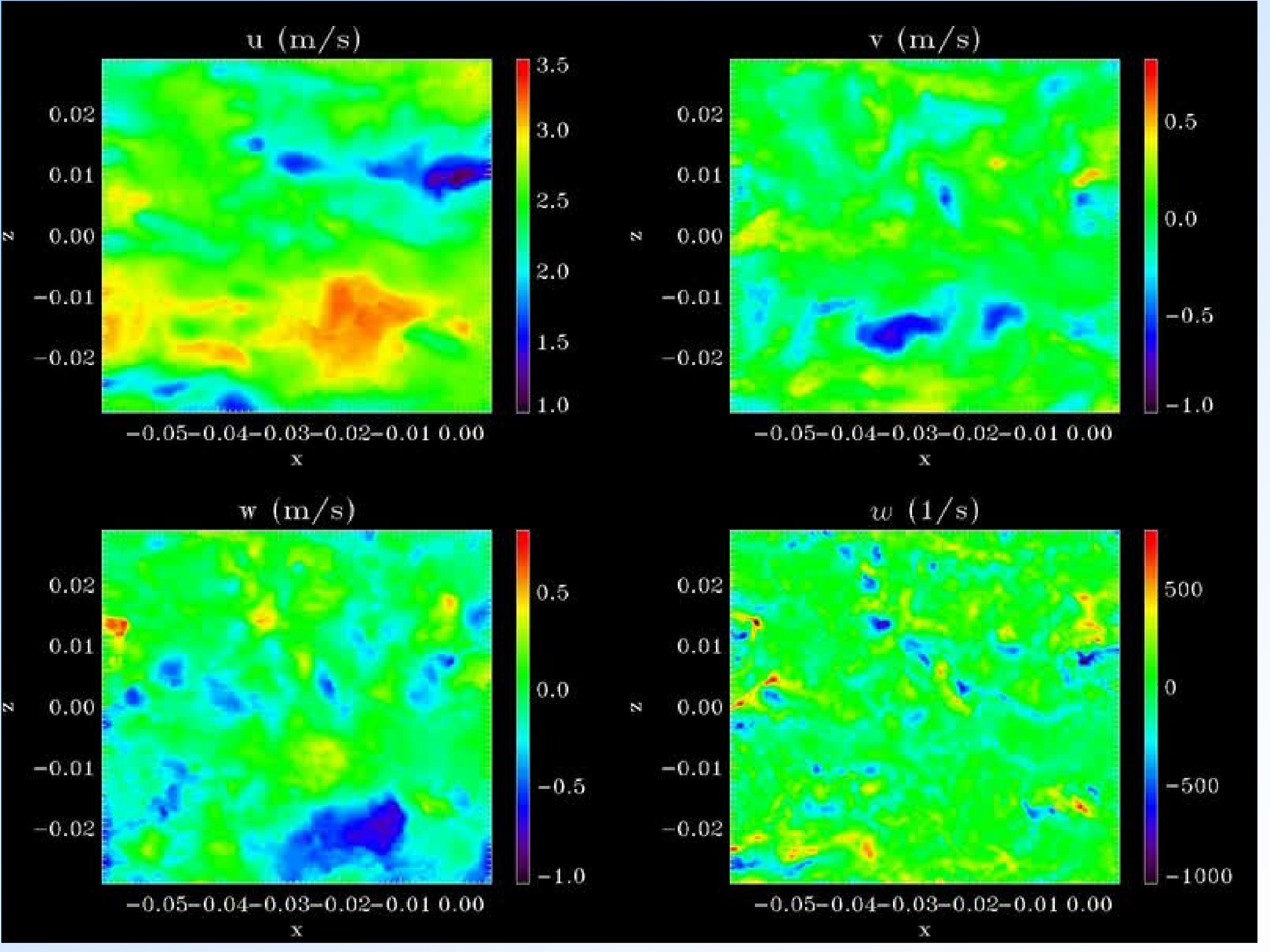
HR SPIV

Velocity



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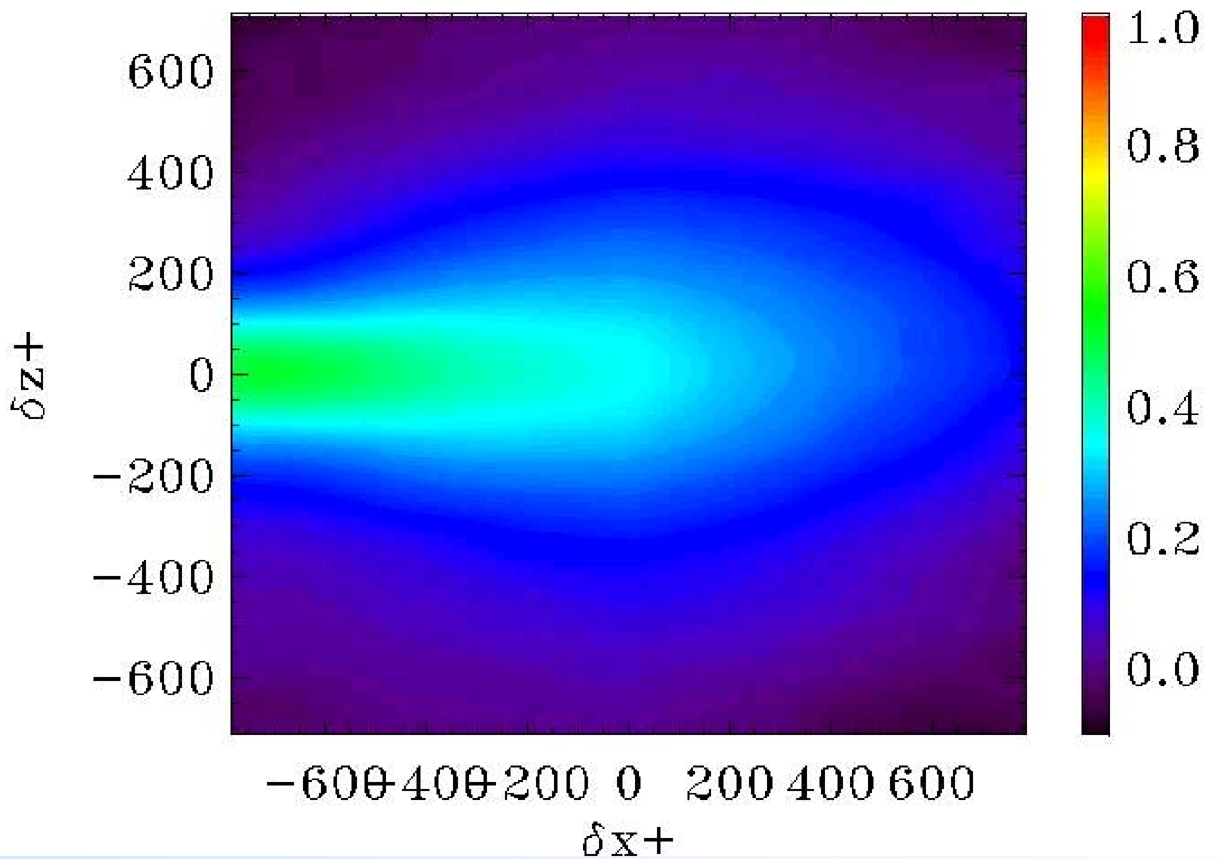
HR SPIV

R_{11} correlation



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Summary

- **Large scales are accessible with multi-SPIV**
- **HR SPIV ➡ space-time correlations**
- **Synchonized SPIV + HW ➡ 4D3C?**

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Conclusions

- Progress of PIV in the last 10 years

Question 1 :

- **SPIV turbulence statistics**
- **SPIV turbulence spectral content**

Question 2 :

- **SPIV coherent structures → l,v**

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Perspectives

Can PIV bring something to turbulence understanding and modelling?

Thank you

and

Congratulation to Geneviève!

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