Detection of the organized structures in a turbulent boundary layer under an adverse pressure gradient

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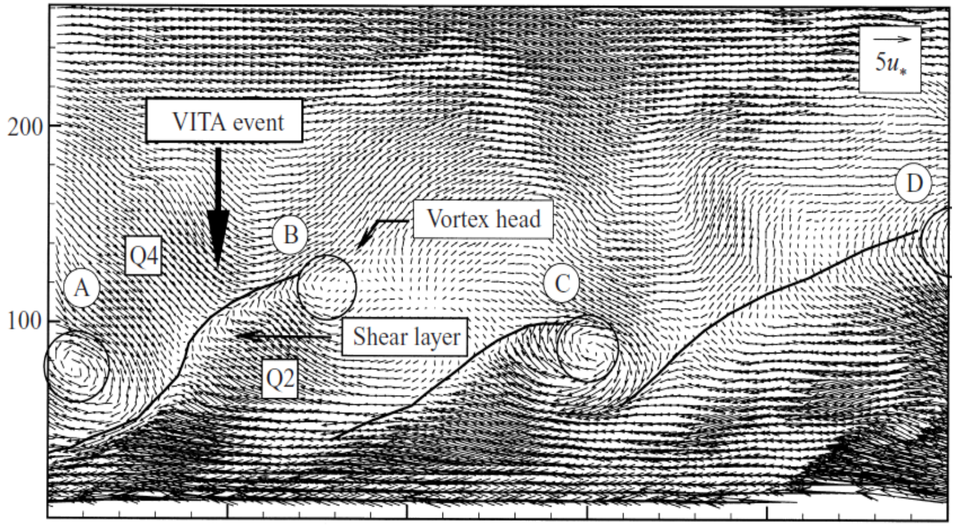
Presentation outline

1. *Structure of turbulent boundary layer*
2. *Objectives*
3. *Test rig description and measuring technique*
4. *VITA detection scheme*
5. *Interpretation of VITA structures*
6. *Analysis of the results of VITA method applied for APG TBL*
7. *Conclusions*

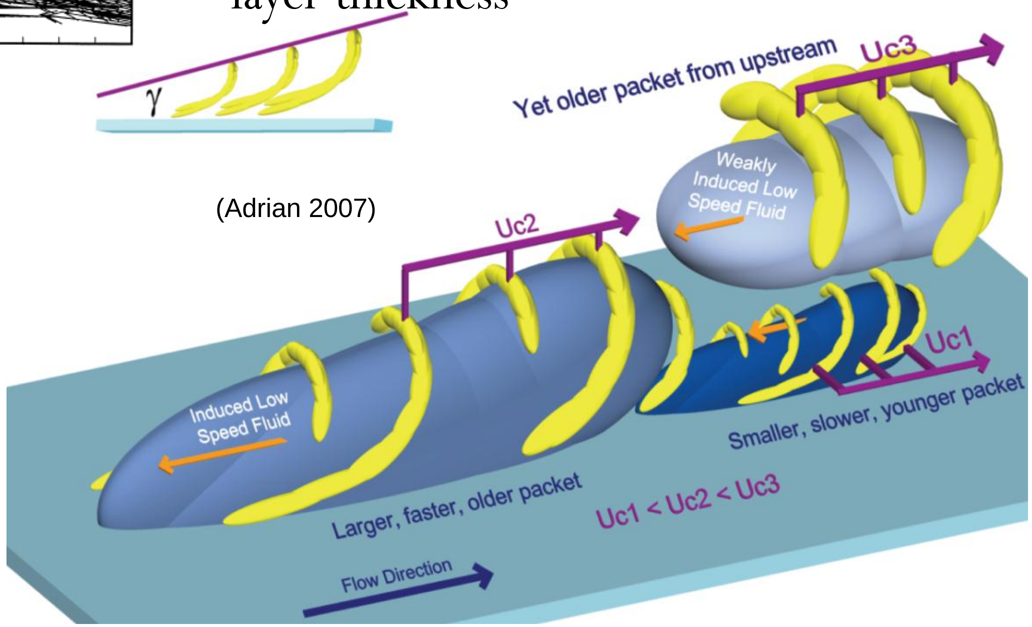
Structure of turbulent boundary layer

Structures in packets



PIV velocity vector field (Adrian 2000)

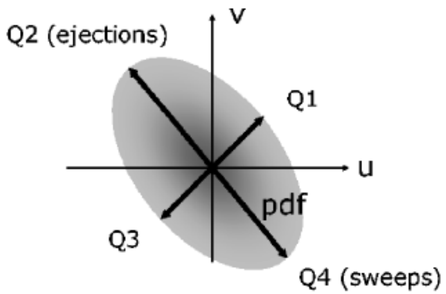
- packet includes hairpin or horseshoe structures with the equal convection velocity
- between hairpins there is shear layer and detectable by VITA bursting structures
- size of packets changes along boundary layer thickness



(Adrian 2007)

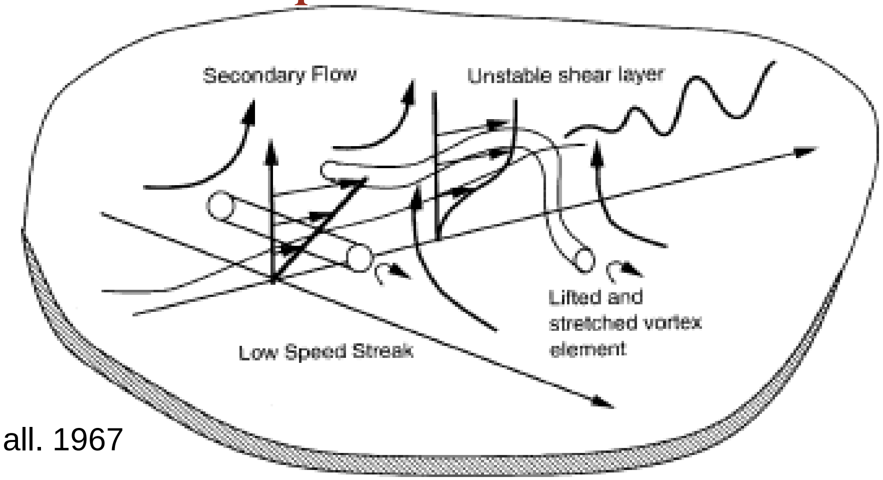
Quadrant analysis

Q1 ($u>0, v>0$)
Q2 ($u<0, v>0$)
Q3 ($u<0, v<0$)
Q4 ($u>0, v<0$)

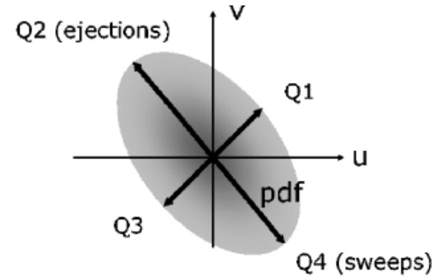


Structure of turbulent boundary layer

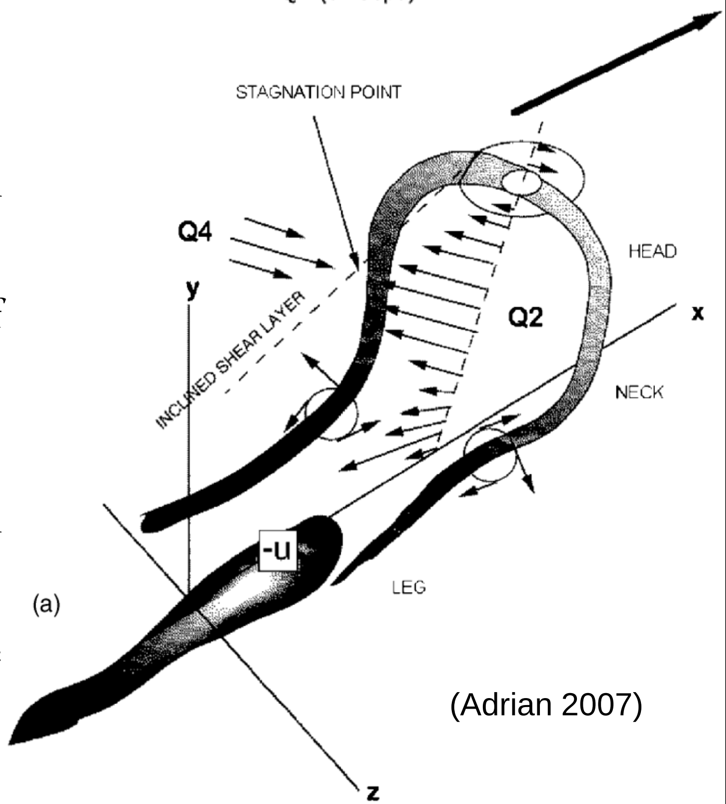
How hairpin structures are created?



Kline at. all. 1967



- spanwise vortex created near the wall is gradually stretched and its middle part (head) is rising
- due to head rise the *Q2* event is produced between necks of structures
- *Q2* event lifts shear layer into higher part of boundary layer
- *Q4* event is produced above secondary hairpins head located upstream primary hairpin
- hairpin vortex produce also longitudinal structures near the wall with the *Q2* and *Q4* events



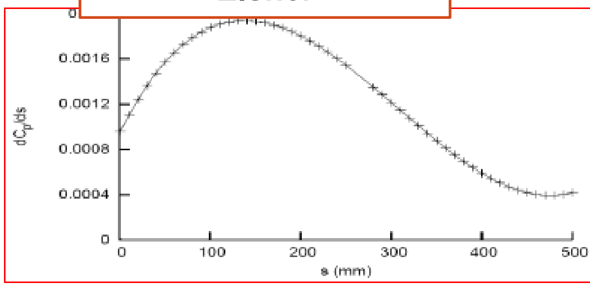
(Adrian 2007)

Turbulent boundary layer in APG conditions

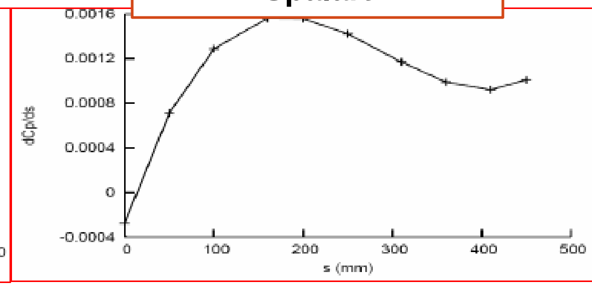
Case	*Nature*	*Geometry*	Re_θ	$U_{in}(m/s)$
Elsner(2008)	HWA	CD	1767-5705	15
Spalart(1993)	DNS	CD	lowest 600	6.5
A.Bernard(2003)	HWA	Bump	7500-32000	10

(Shah, Laval, Stanislas, 2010)

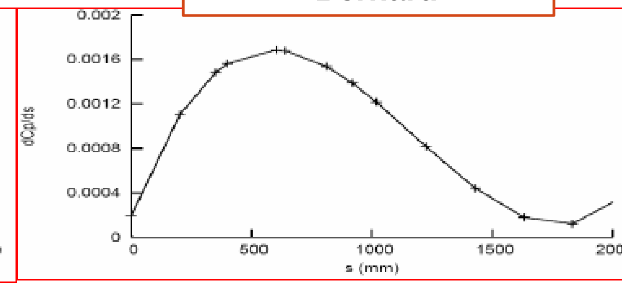
Elsner

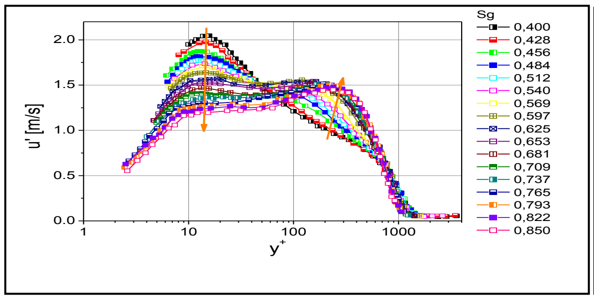


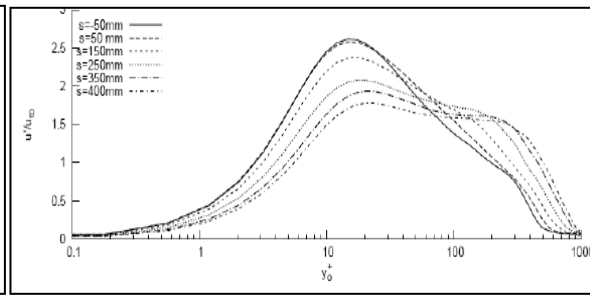
Spalart

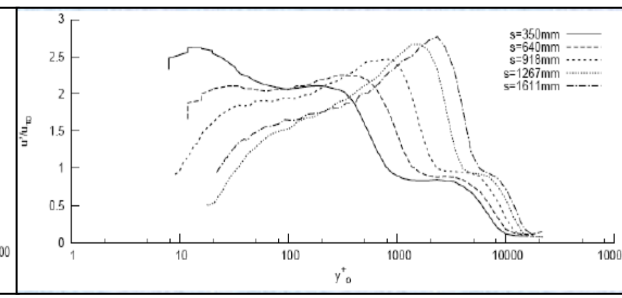


Bernard









Development of a turbulent peak in a logarithmic region of turbulent boundary layer

What is an origin of this peak?

Whether the detection procedure of organized structures helps in the explanation?

Objectives

- **Utilization of hot-wire measurements and VITA method in order to clarify the effect of adverse pressure gradient:**
  - **Identification of the phenomena responsible for the appearance of the outer peak of velocity fluctuation distribution:**
    - analysis of average bursting frequency in APG
    - analysis of bursting event strength in APG
  - **Analysis of VITA structures movements and explanation of the enhancement of Q4 and Q1 events in APG flow**

Test rig description and measuring technique

Inlet conditions:

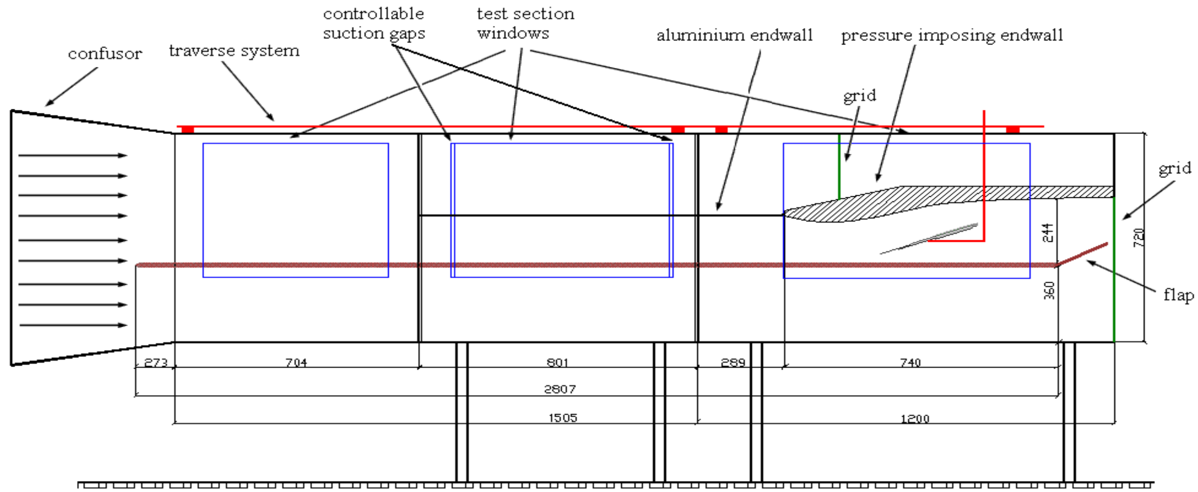
U=15 m/s

Tu≈0.5%

Re_θ=2500

Signal aquisition: time =10s,

sampling frq: 25kHz



Notice:

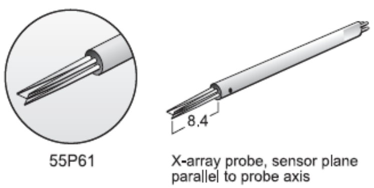
- **trailing flap - 15^0 angle**
- **grid at outlet**

Flat plate dimensions: 2807 mm length, 250 mm width, 10 mm thick

Tripping wire: - located 210 mm from the leading edge on lower and upper plate

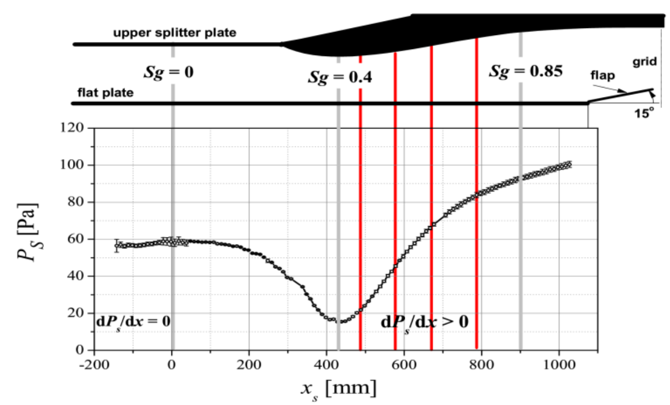
Velocity measurements:

•X- wire probe (Dantec 55P61) diameter 5 μm, sensitive length 1.25 mm



a)

b)



Scheme of VITA detection

RUNNING VARIANCE OF VELOCITY FLUCTUATION

$$\mathrm{var}(t,T)=\frac{1}{T}\int_{t-T/2}^{t+T/2}u(t')^2\,dt'-\left[\frac{1}{T}\int_{t-T/2}^{t+T/2}u(t')\,dt\right]^2$$

DETECTION FUNCTION

$$D(t,T)=\begin{cases}1\Leftrightarrow \mathrm{var}(t,T)\geq ku_{rms}^2\\ 0\Leftrightarrow other\end{cases}$$

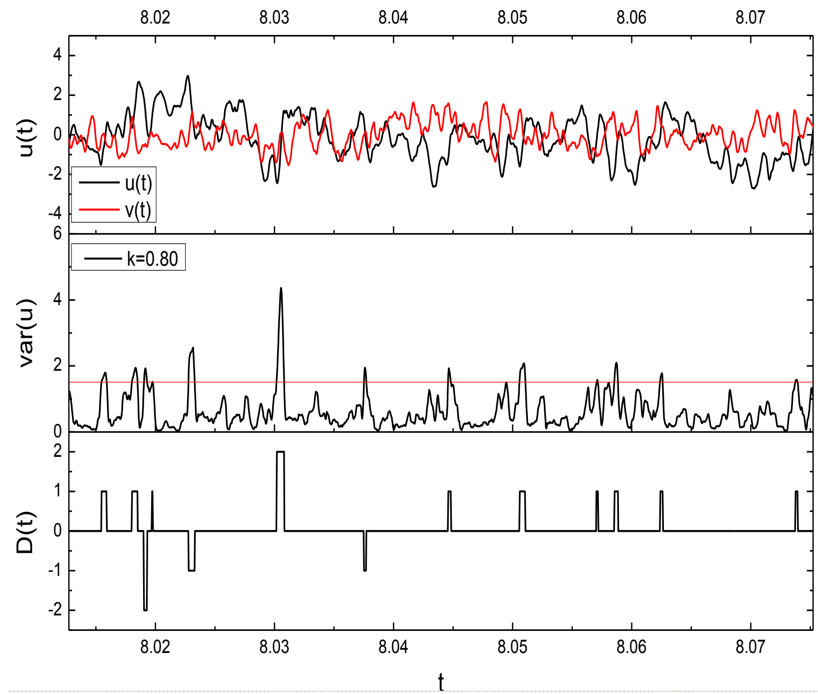
SIGN DETECTION FUNCTION

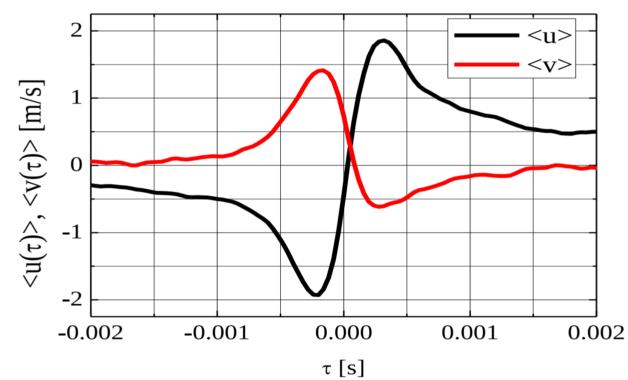
$$D^s(t,T)=\begin{cases}2\Leftrightarrow du/dt>0\wedge dv/dt>0\\ 1\Leftrightarrow du/dt>0\wedge dv/dt\leq 0\\ -1\Leftrightarrow du/dt<0\wedge dv/dt\geq 0\\ -2\Leftrightarrow du/dt<0\wedge dv/dt<0\end{cases}$$

CONDITIONAL AVERAGING

$$<u(\tau)>^{+}=\frac{1}{N^{+}}\sum_{j=1}^{N^{+}}u(t_j^{+}+\tau)\qquad j=1,2,\ldots,N^{+}$$

$$<u(\tau)>^{-}=\frac{1}{N^{-}}\sum_{j=1}^{N^{+}}u(t_j^{-}+\tau)\qquad j=1,2,\ldots,N^{-}$$





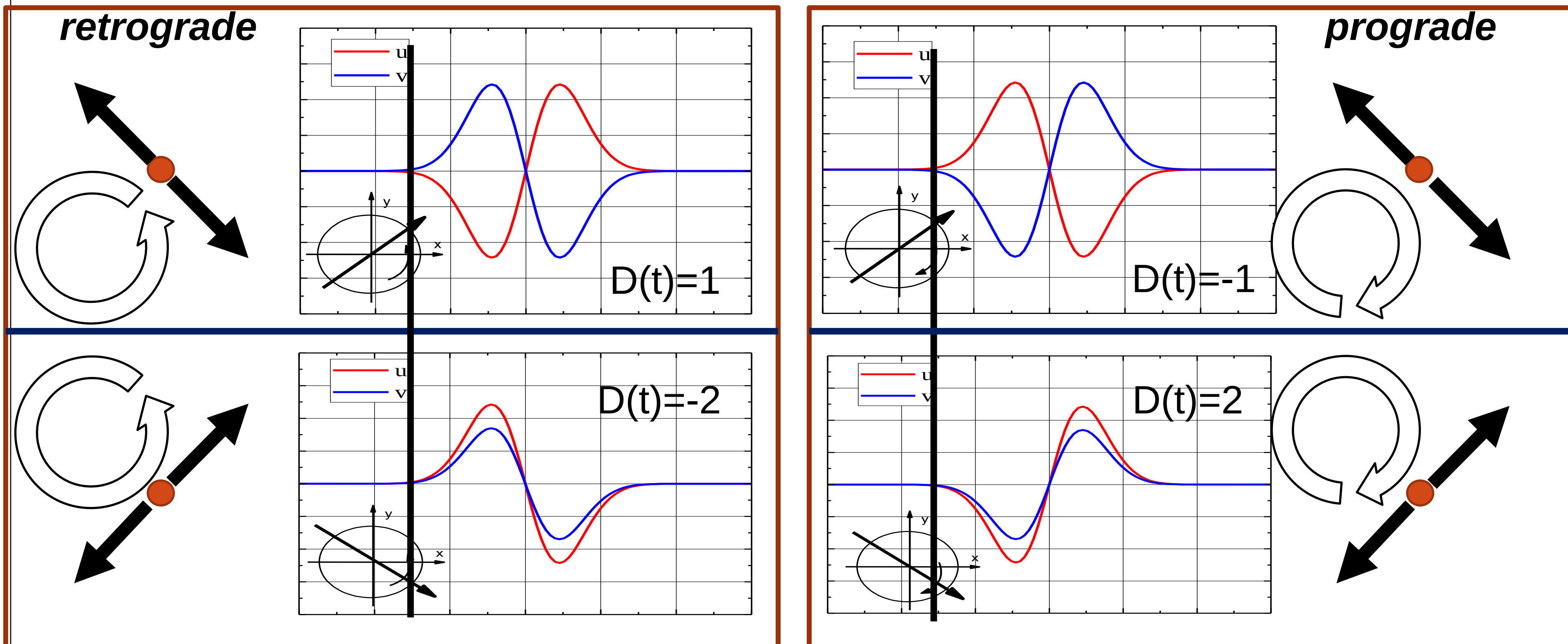
Averaging window of running variance: *T = T(Nmax)*

***N* – number of events**

Detection level: *k = 0.8*

Interpretation of VITA structures

Detection based on *u* and *v* velocity components (four types of detections)



Physical interpretation of VITA structures:

- retrograde VITA vortical structure is vortex produced by inclined shear layer
- prograde VITA vortical structure is head of hairpin

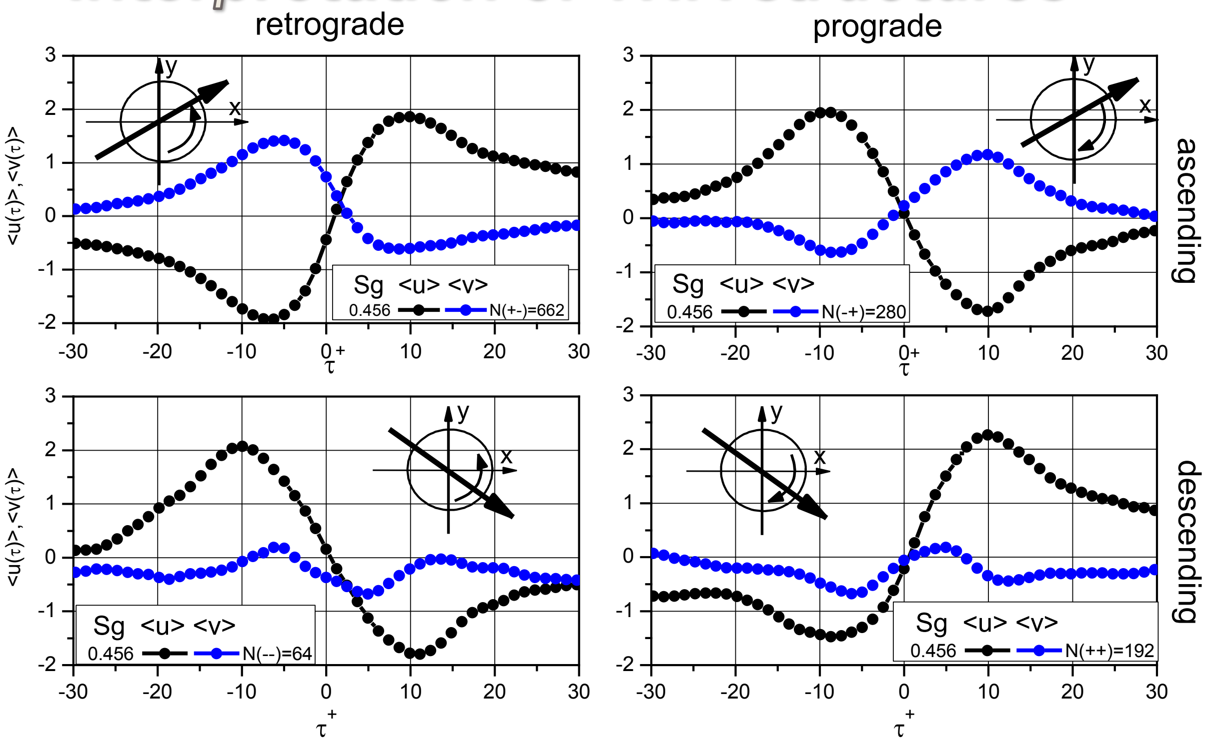
$$D^s(t,T)=\begin{cases}2 \Leftrightarrow du/dt>0 \wedge dv/dt>0\\ 1 \Leftrightarrow du/dt>0 \wedge dv/dt\le 0\\ -1 \Leftrightarrow du/dt<0 \wedge dv/dt\ge 0\\ -2 \Leftrightarrow du/dt<0 \wedge dv/dt<0\end{cases}$$

Interpretation of VITA structures

N=662

N=280

$y^+ = 21.6$



N=64

N=192

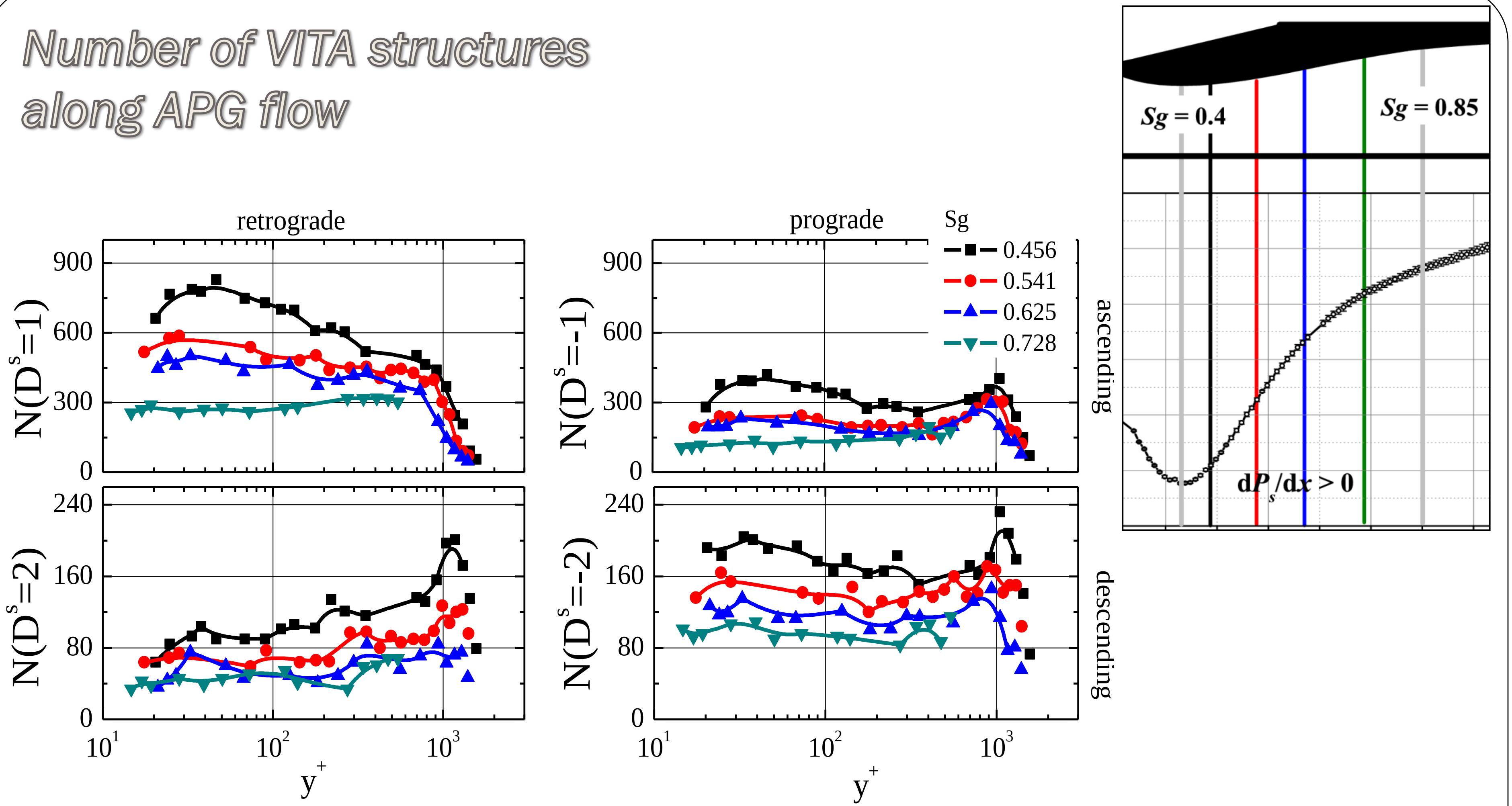
Confirmation of ascending or descending character of vortex movement:

- distribution of <u> velocity component for descending vortices is shifted towards positive values and <v> is shifted towards negative values (vortices comes from higher momentum zone)

- the opposite situation is visible for ascending vortices (weaker due to deceleration under APG)

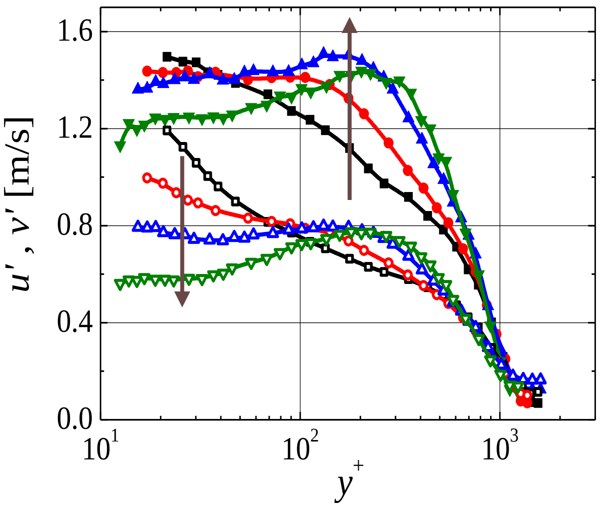
Ascending vortices give negative Reynolds stresses and descending vortices give positive Reynolds stresses. (high contribution of (–uv) due to ascending vortex domination)

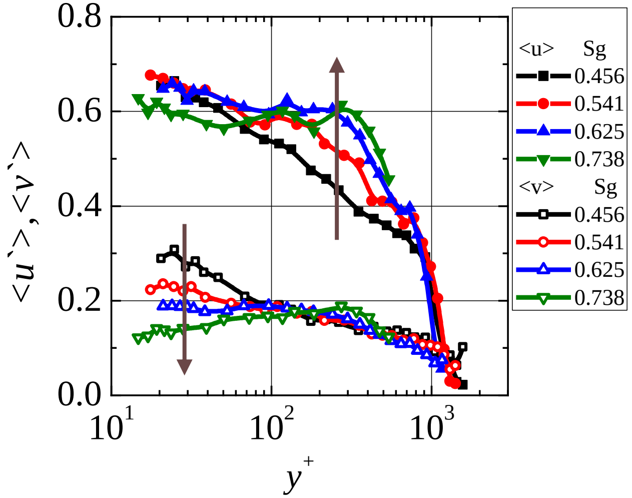
Number of VITA structures along APG flow

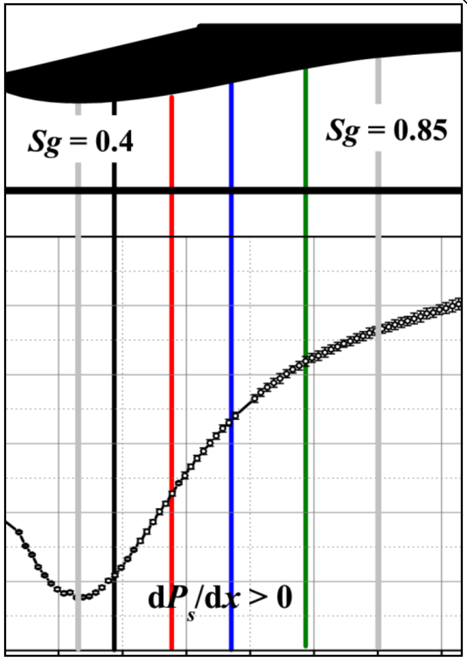


- the number of structures decreases along the APG flow – the effect of velocity drop
- the stronger decrease is observed for $N(D^s=1)$ - retrograde ascending vortex (in the inner part of boundary layer ($y^+ < 200$))

Fluctuations of phased averaged detections along APG flow

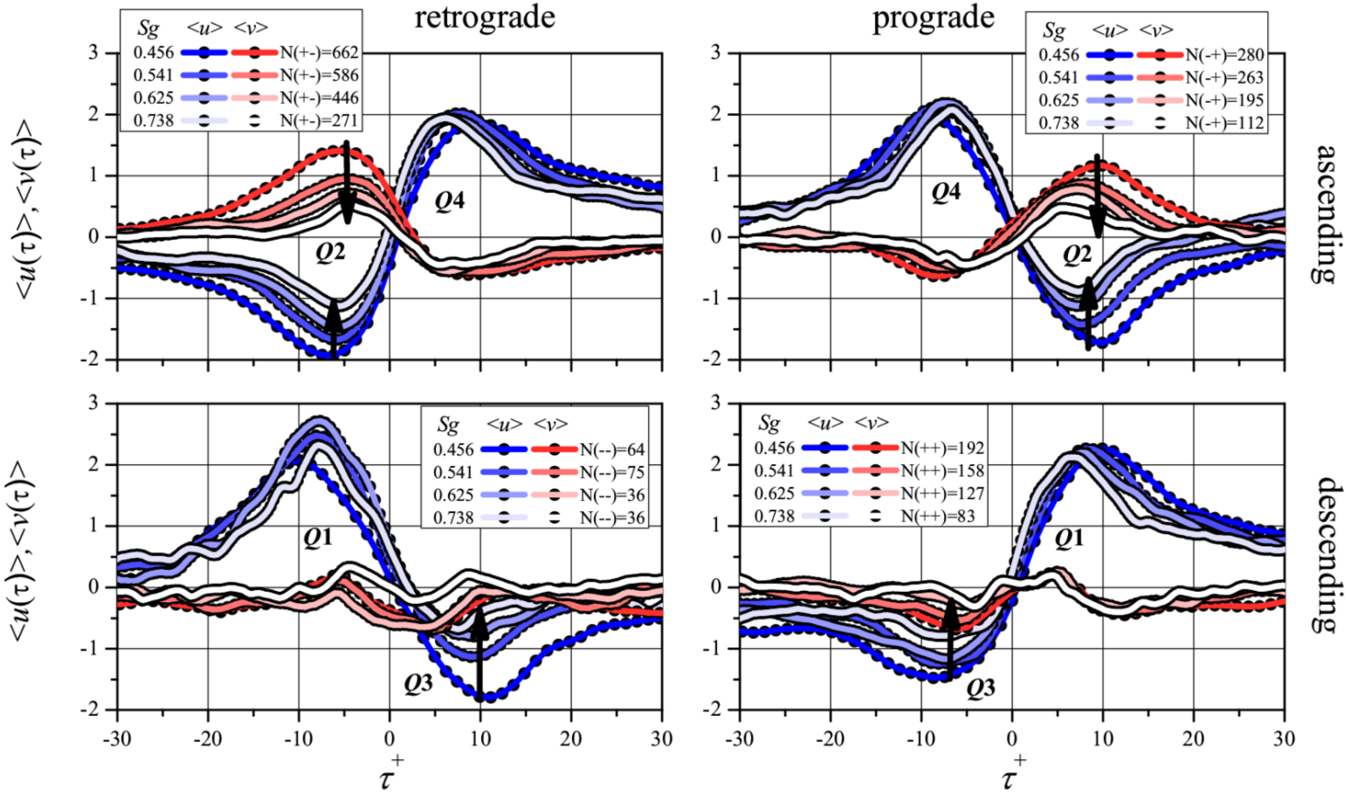


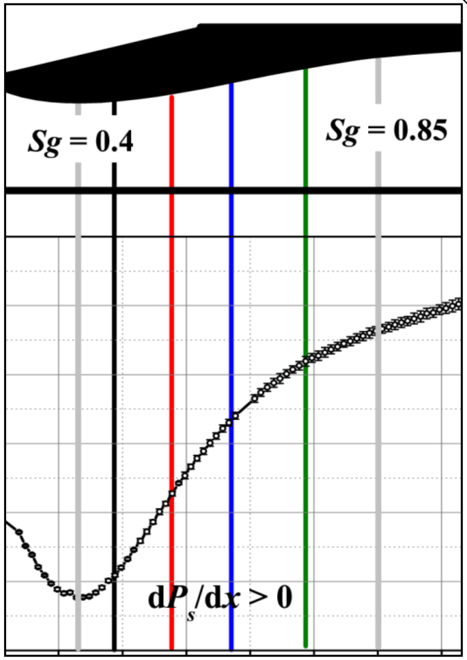




- **the shape of phase averaged velocity fluctuations distributions is similar to the mean fluctuations – bursts impacts the fluctuations profiles**
- **the higher contribution of *u* and lower v components in Reynolds stresses could be explained by the fact that under APG the fast growth of boundary layer thickness is caused by the higher than in ZPG positive normal to the wall mean velocity component**

Phase averaged detections along APG flow for y+=21





- **domination of Q4 and Q1 events in APG (Krogstad, Skare , 1995) – decaying of Q2 and Q3 event**
- **Q2 and Q3 events decrease because of the observed higher than local vortex velocity (<*u*> distributions are shifted toward positive values of velocity - effect of inertia)**

Conclusions

- *shape and direction of structures movement can be determined based on phase averaged u and v velocity components*
- *number of structures in boundary layer decreases along the flow, but the strongest decrease is observed near the wall for structures $D^s=1$*
- *in the presence of APG the energy of VITA structures near the wall decays along the flow*
- *opposite situation is observed for outer peak region, where energy of VITA structures increases, what indicates the dominant role of this region on APG TBL development*
- *observed domination of Q4 and Q1 event is caused by slower than the mean flow deceleration of the vortical structures*

Thank you very much for your attention

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