WALL PRESSURE OF SEPARATED FLOWS: FLAT PLATE AND AIRFOIL

STAB Workshop 7. – 8. November 2023 im DLR-Standort Göttingen

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MOTIVATION AND CONTEXT

Wind energy: why study separated flows?

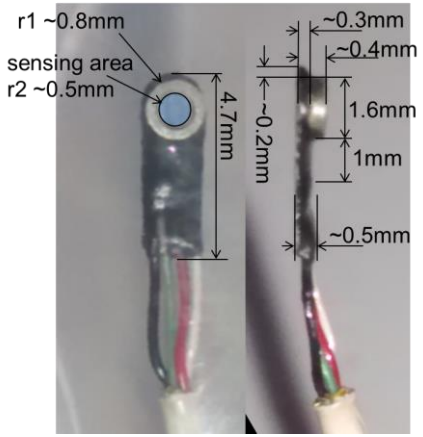
- One third of electricity in Germany comes from wind energy
  - ➢ Need to improve performance and reliability
- Issues with flow separation: source of strong unsteadiness detrimental to wind turbine noise
- Noise emissions regulations must be respected
  - ➢ flow separation noise up to +10 dB (Brooks, Pope and Marcolini, 1989)
- Tracking flow separation is important for *aerodynamics* and *acoustics*
  - ➢ wall-pressure measurements and far-field acoustics were the focus at DLR previously
  - ➢ From wall-pressure : how do we know the flow **separates or not?** Is it a **small** separation (*lower noise*)? Or a **larger** separation (*higher noise*)?
  - ➢ Montréal database → PIV and wall pressure database on a flat plate with separation
  - ➢ **Our motivation**: Is the physics of airfoil and canonical cases self-similar?

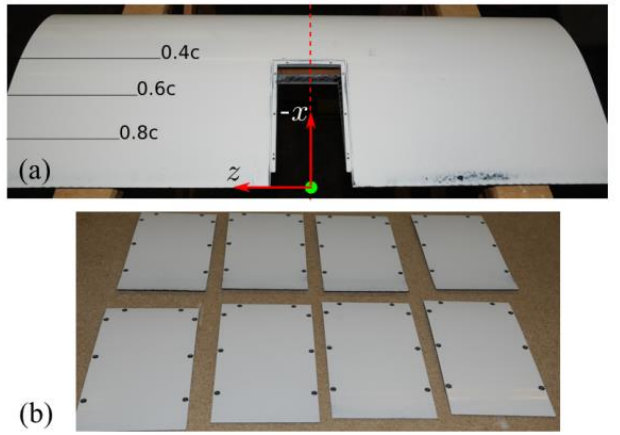
DU96-W-180

- AWB
- U = 40, 50, and 60 m/s
- Tripping: 5%c(SS), 10%c(PS)
- α = 0°, 6°, 8°, attached with APG

  11°,12°,13°, 14°,14.7° } Separated BL

- 5 configurations of 8 LQ-062-0.35BarA Kulite sensors under 0.5mm pinholes
  - 2 configurations on the suction side
  - 2 configurations on the pressure side
  - 1 configuration with 1 sensor on the pressure and 7 on the suction side





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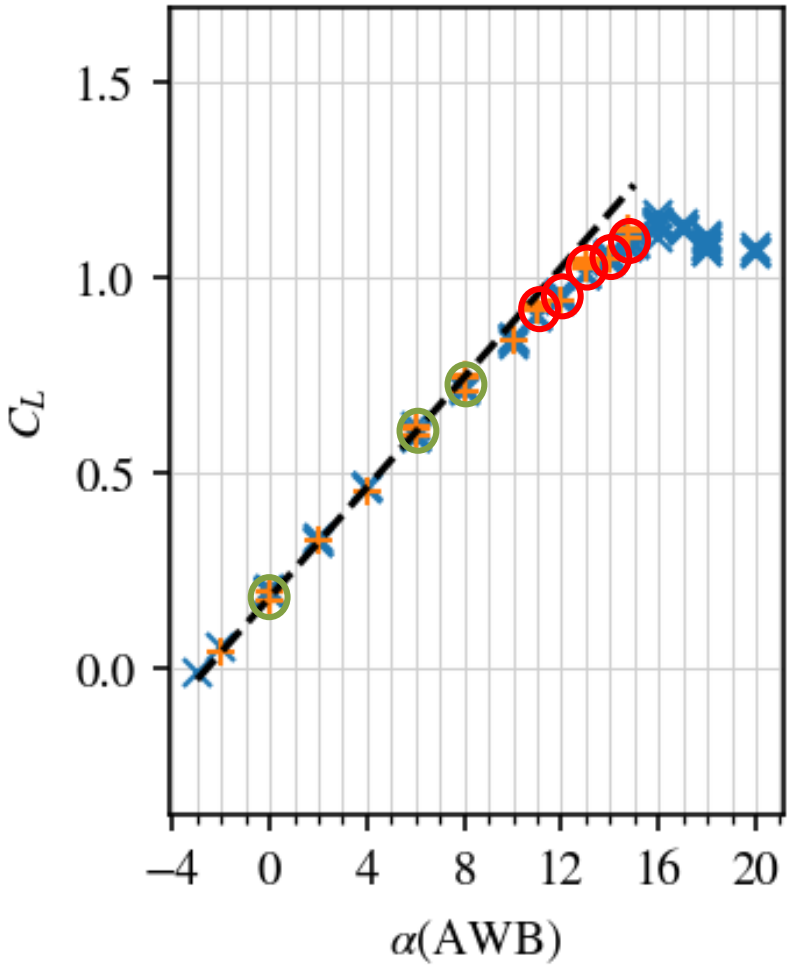

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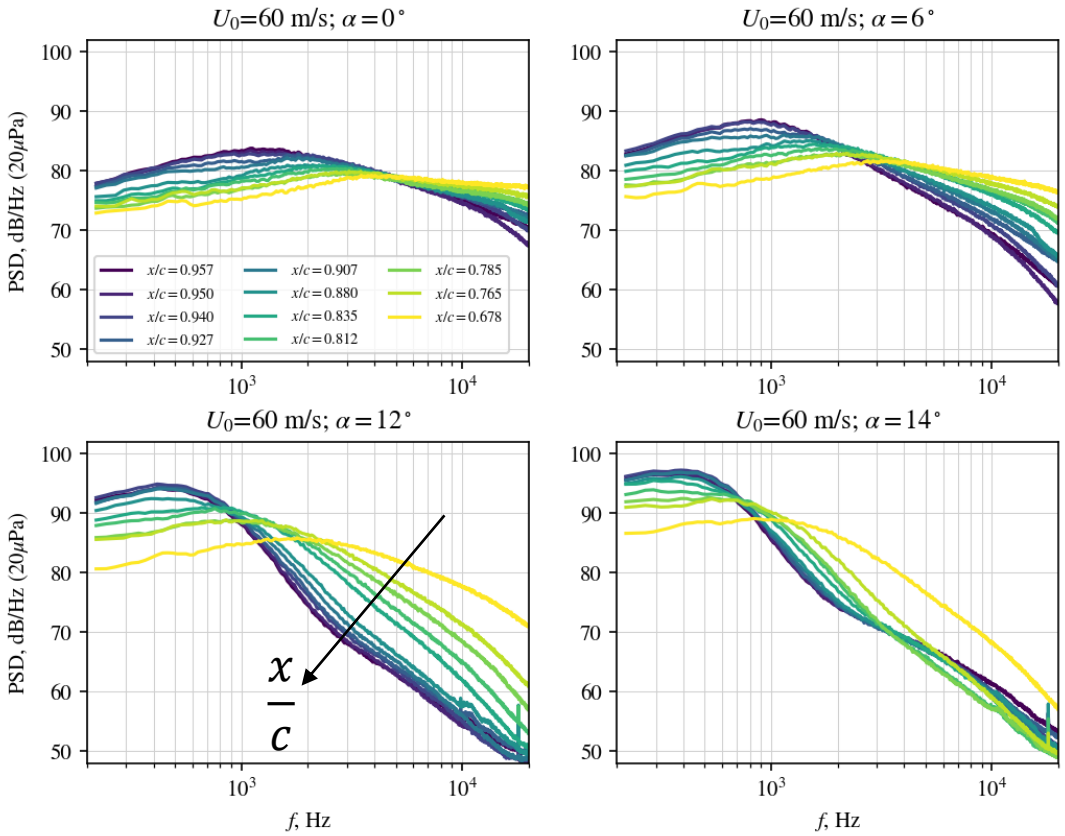
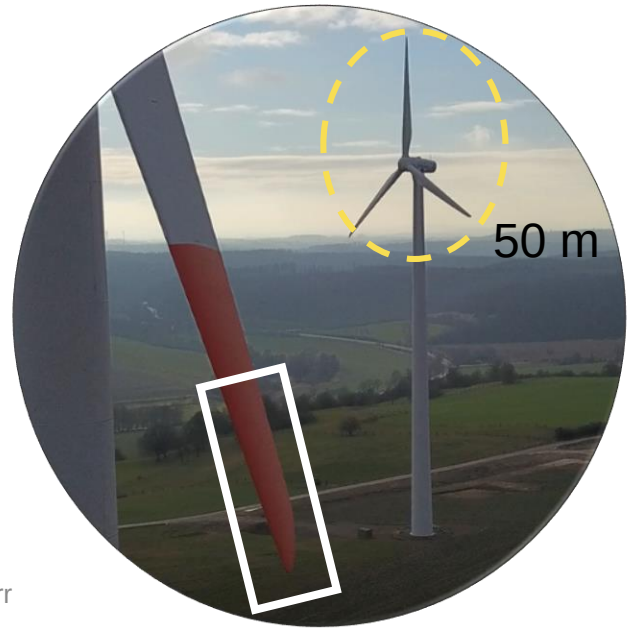


SAFER2
Planned experiment in 09-2024

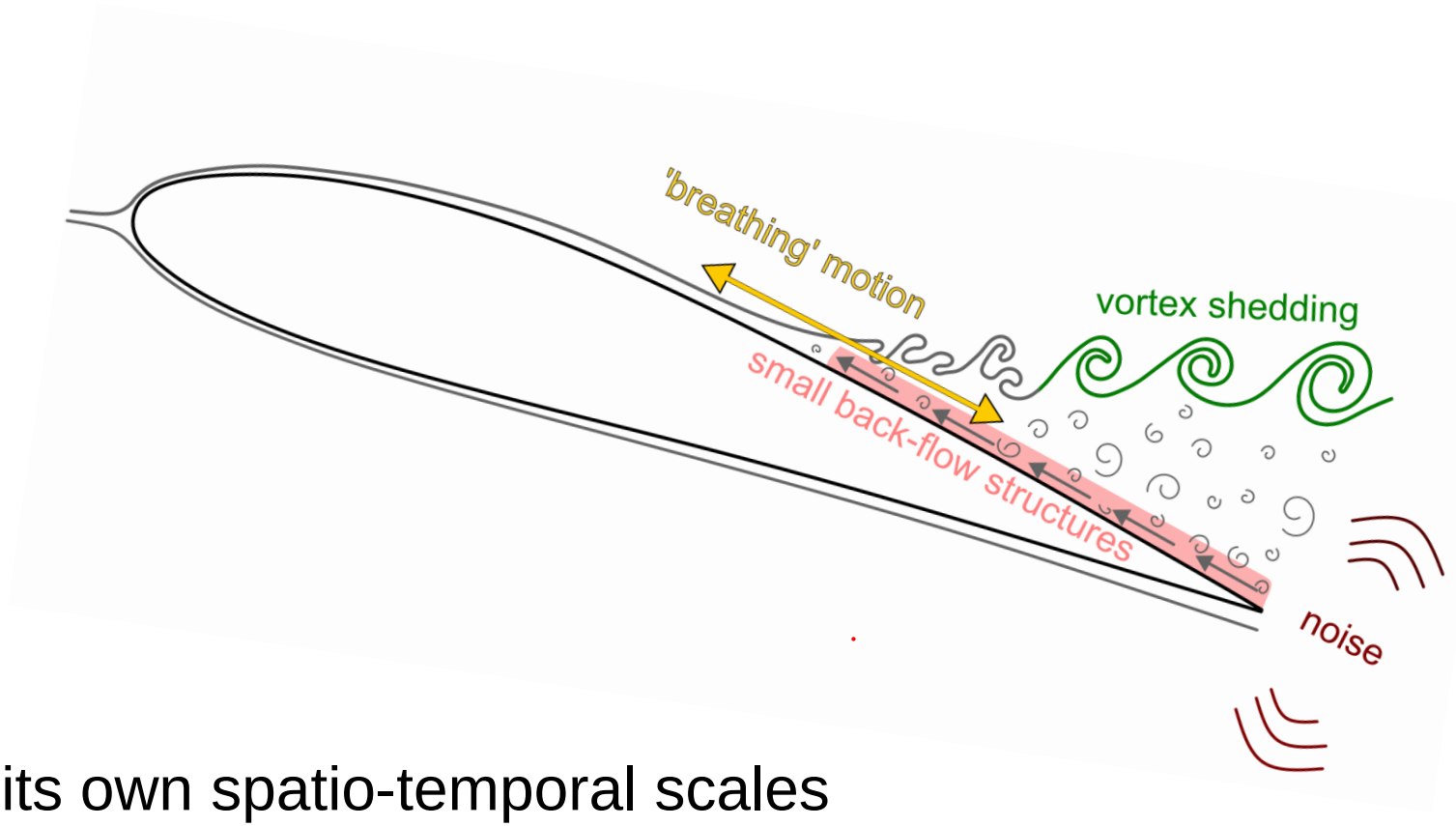
- DNW-NWB (closed≤ 90 m/s, open ≤ 80 m/s)
- HxW=2.8m x 3.25 m
- Blade tip model 2 m
- Wall pressure and shear sensors



FLOW PHYSICS

[Flow Physics] Three main unsteadiness to account for!

1. Low frequency breathing motion
2. Medium frequency vortex shedding
3. High frequency from small back-flow structures



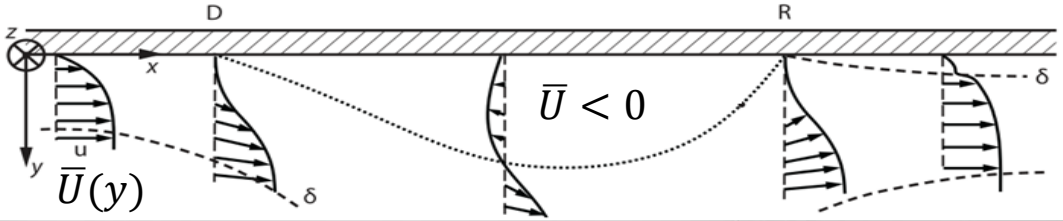
➔ Each phenomemon has its own spatio-temporal scales

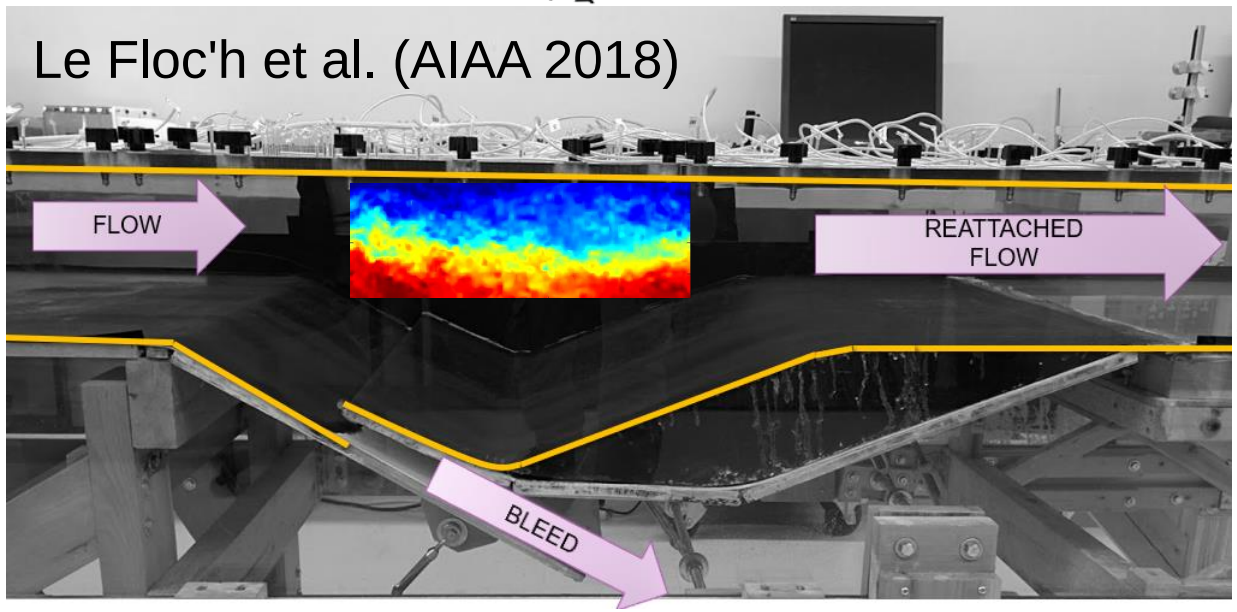
➔ Scaling laws remain to be found: R_e effect, TBL quantities, AoA, etc…

Tracking flow separation ⟷ PARADIGM ⟷ Tracking the associated signatures

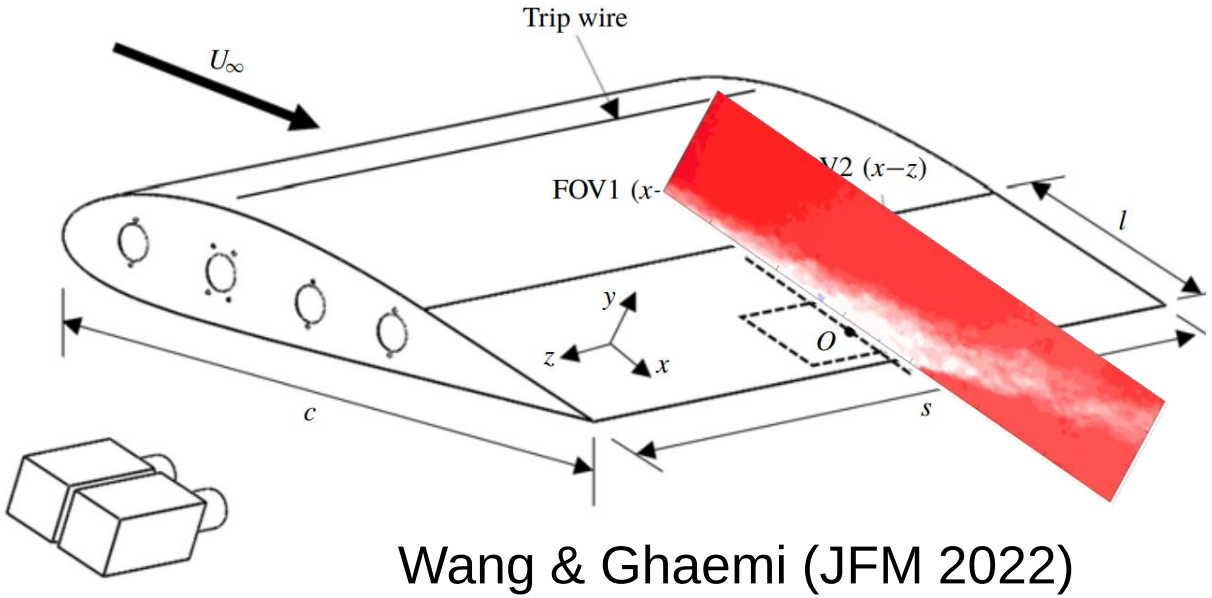
[Flat plate & airfoil] - 2 new pressure & velocity databases

Flat Plate Turbulent Separation Bubble (TSB)





Trailing edge TSB

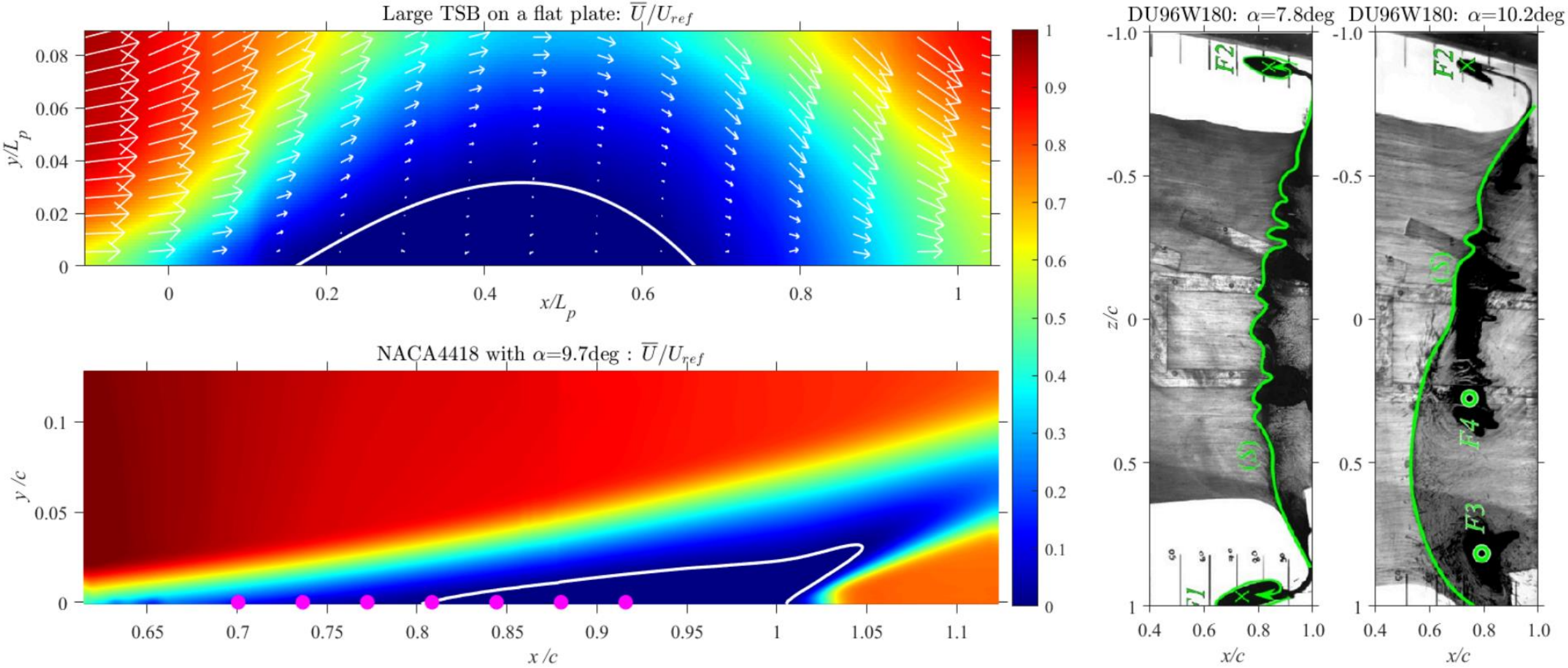


Wang & Ghaemi (JFM 2022)

Aim to derive the flow separation topology from wall-pressure measurements

- predictive laws to determine amplitude of separation
- acoustic factor of correction

Three mean flow topologies



- NACA 4418 and DU96-W-180 at $\alpha = 7.8°$ recirculation regions both cover around 20% of the chord

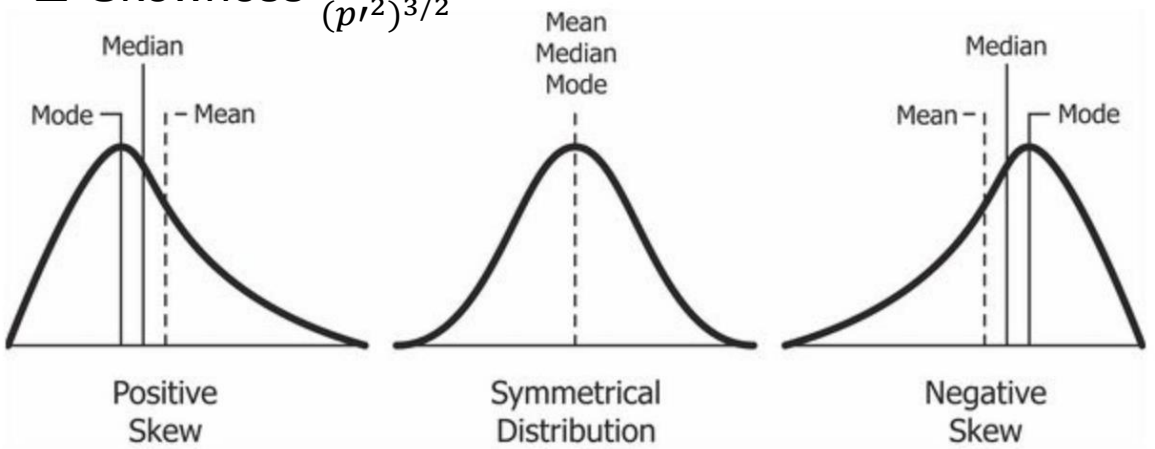
Analyzing wall pressure statistics for separated flows

Non stochastic motion due to organized motions of wall turbulence

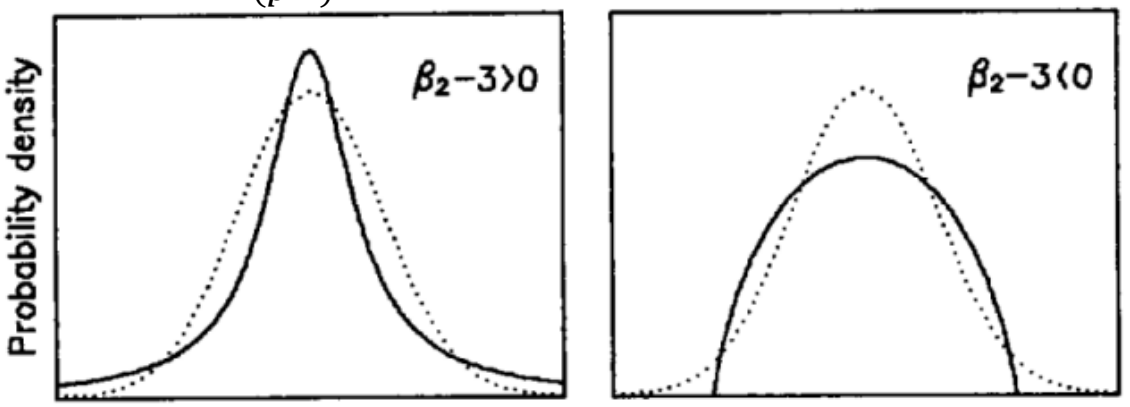
- Skewness measures the length of each tail from the pdf:
  - Positive/negative skewness ➔ domination of positive /negative pressure fluctuations
- Kurtosis measures the possible intermittent extreme events (k-3>0)

- What signatures for separated flows?

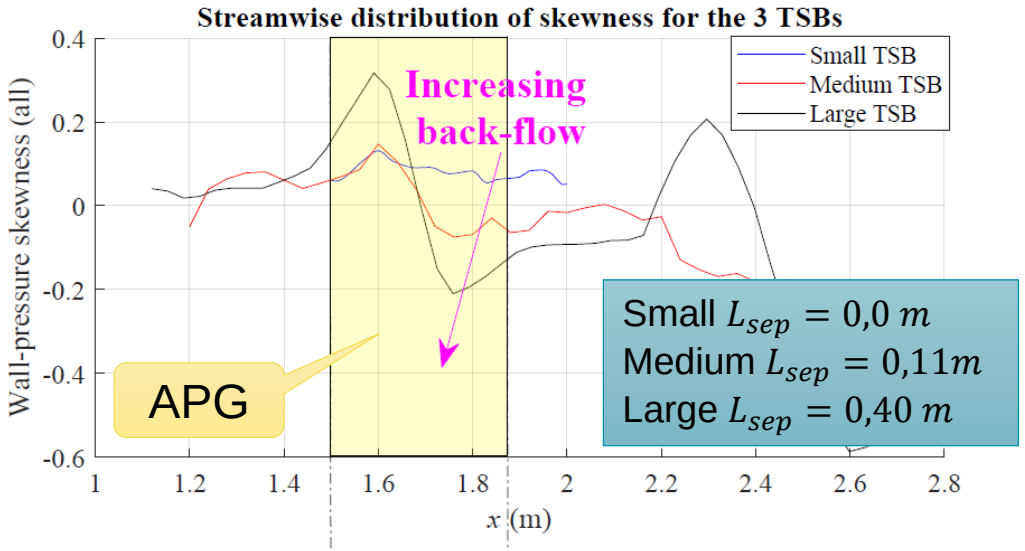
❑ Skewness $\frac{\overline{p\prime^3}}{(\overline{p\prime^2})^{3/2}}$

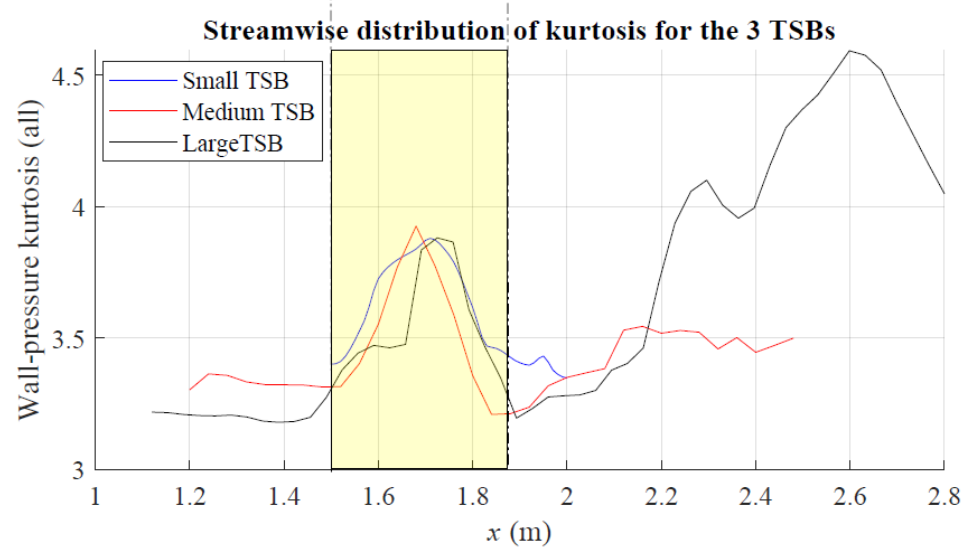


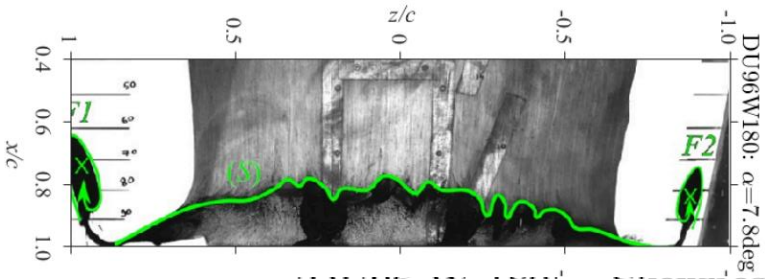
❑ Kurtosis $\frac{\overline{p\prime^4}}{(\overline{p\prime^2})^2}$

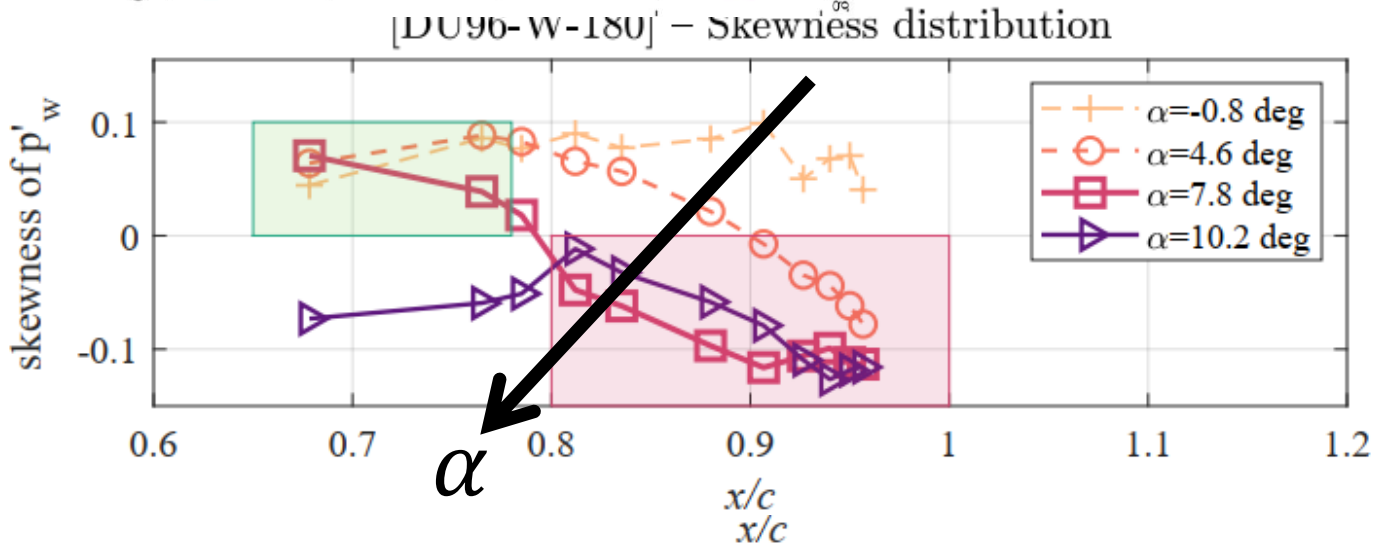


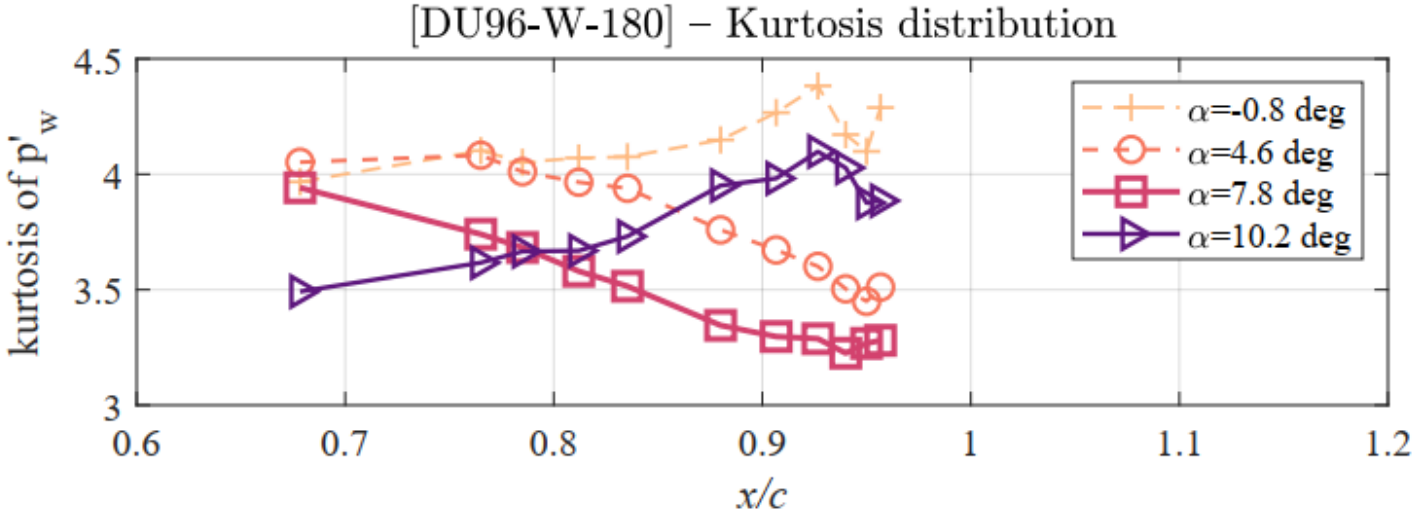
[Flat plate & DU96-W-180] - Skewness of p'_w



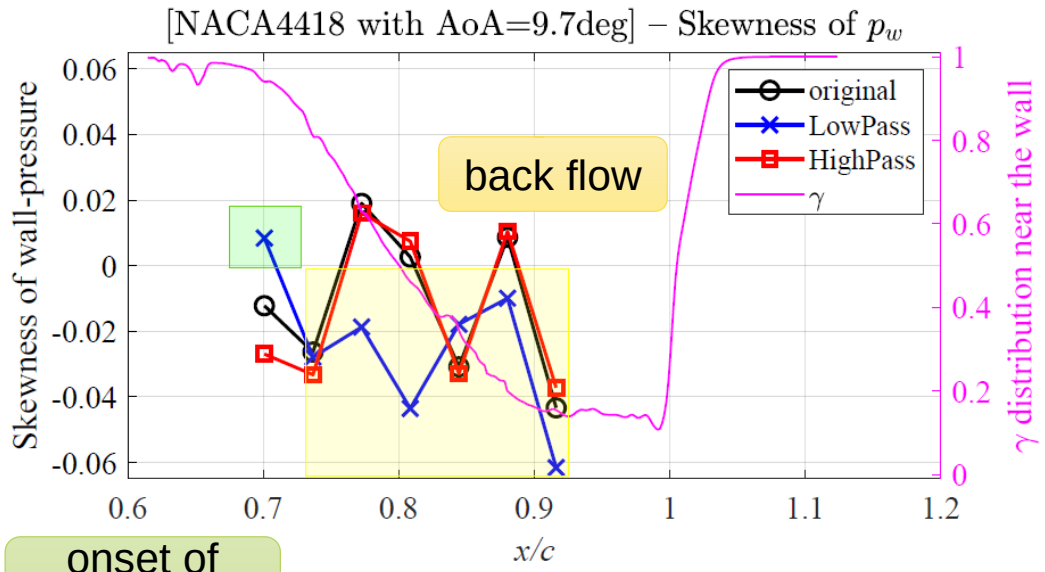


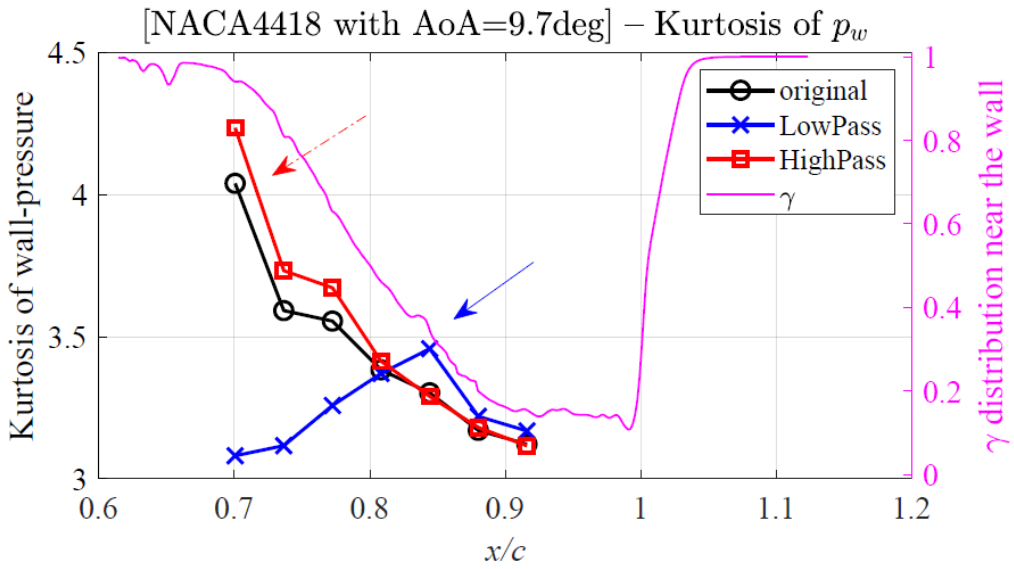


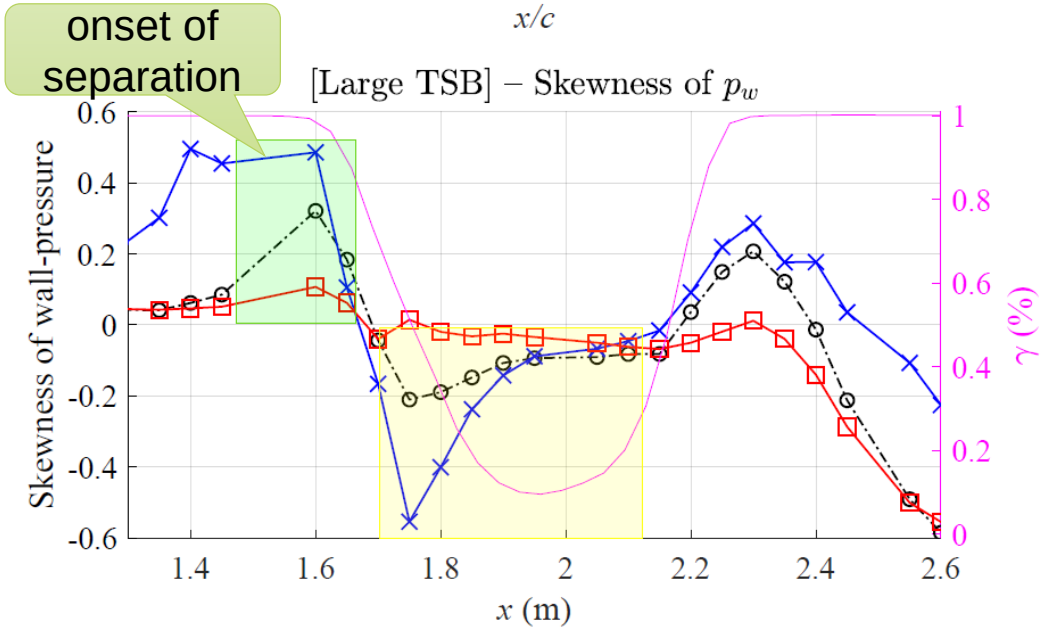


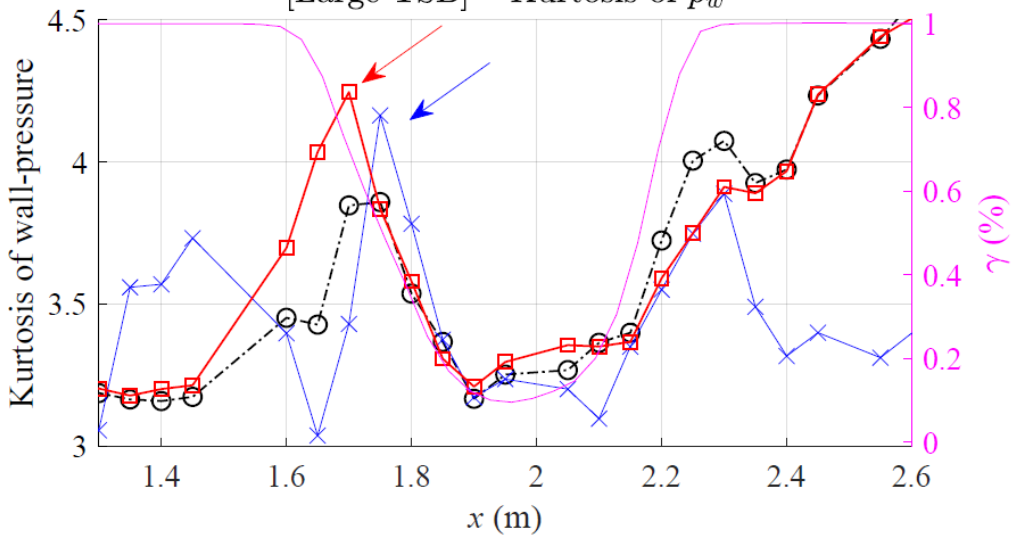


[Flat plate & NACA 4418] - Two massive separations



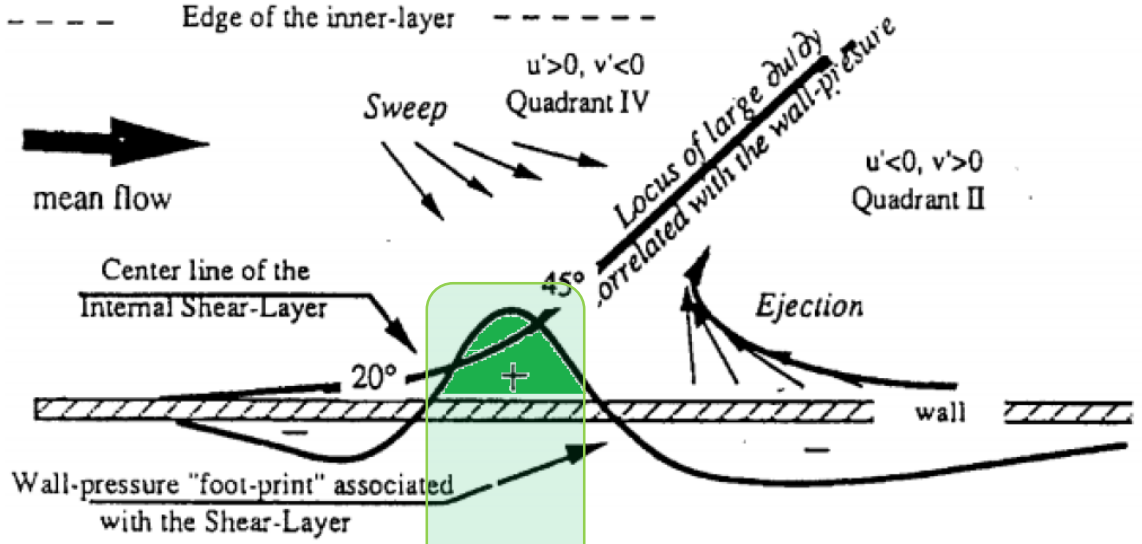






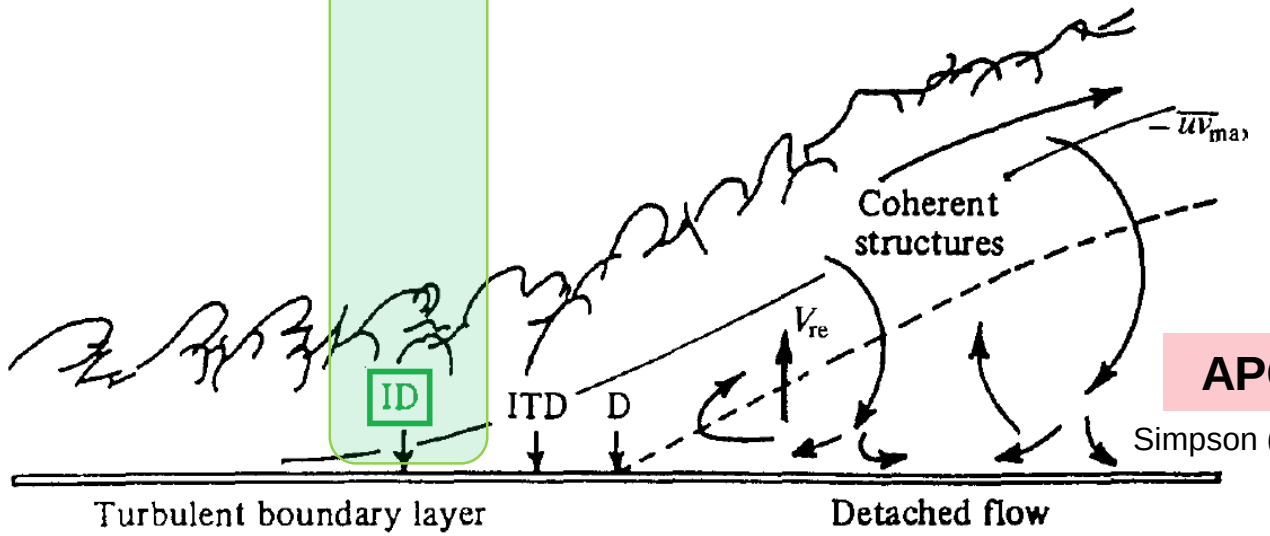
[Flow physics] – Consistent with literature on wall pressure

- Onset of separation linked to important wall pressure events
- Incipient Detachment $\gamma = 99\%$ (fraction of flow moving downstream per unit of time) is where the shear layer is lifted up
- Shift towards negative pressure fluctuations inside the mean recirculation region



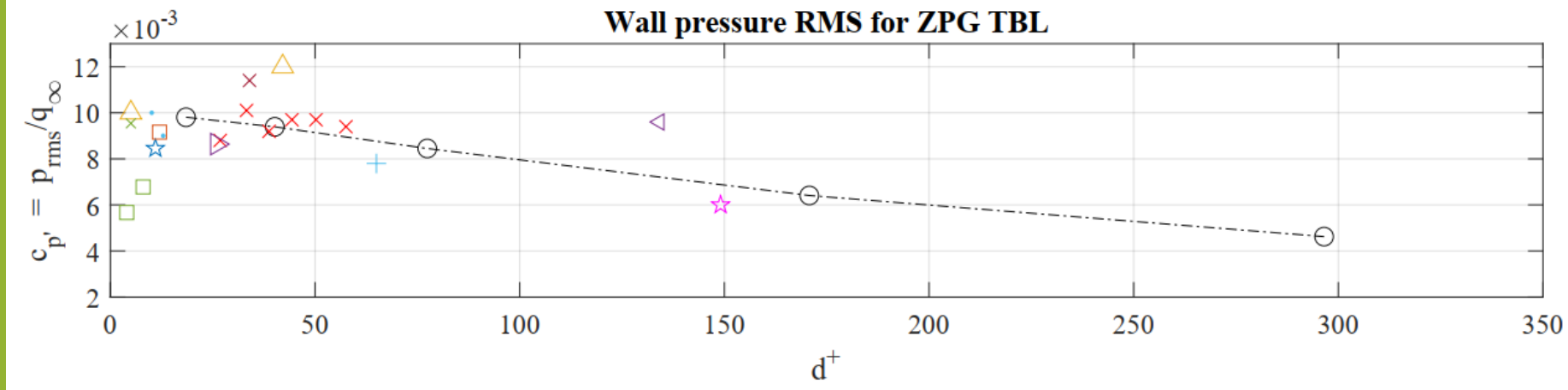
ZPG

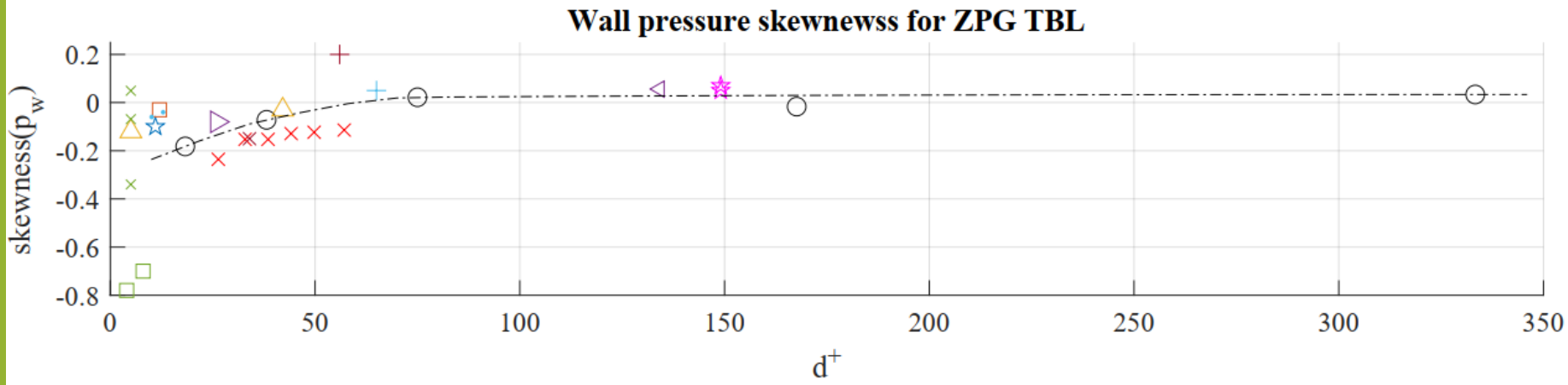
Astolfi (1993)

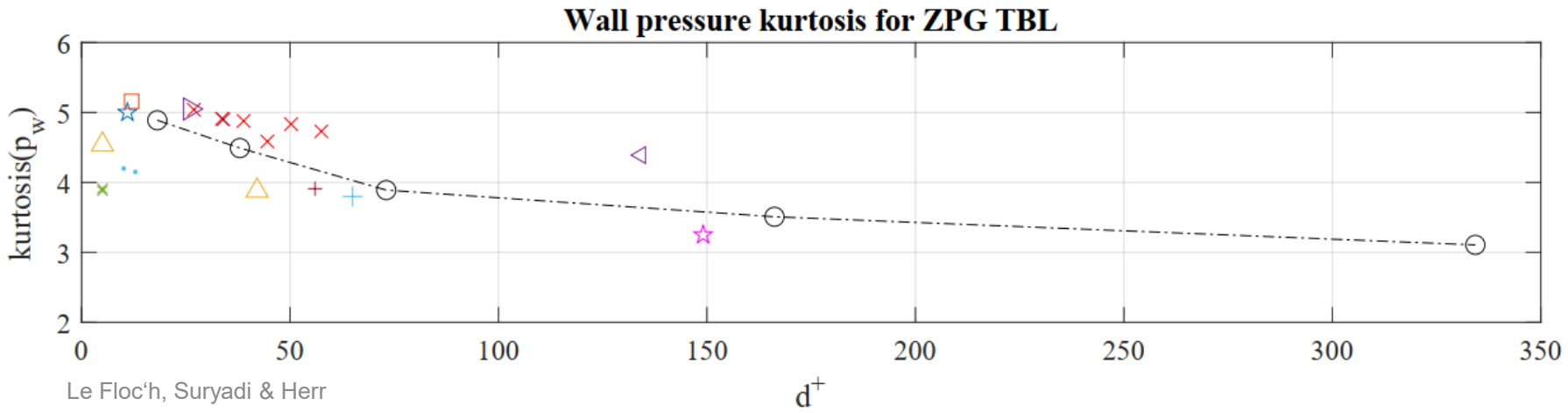


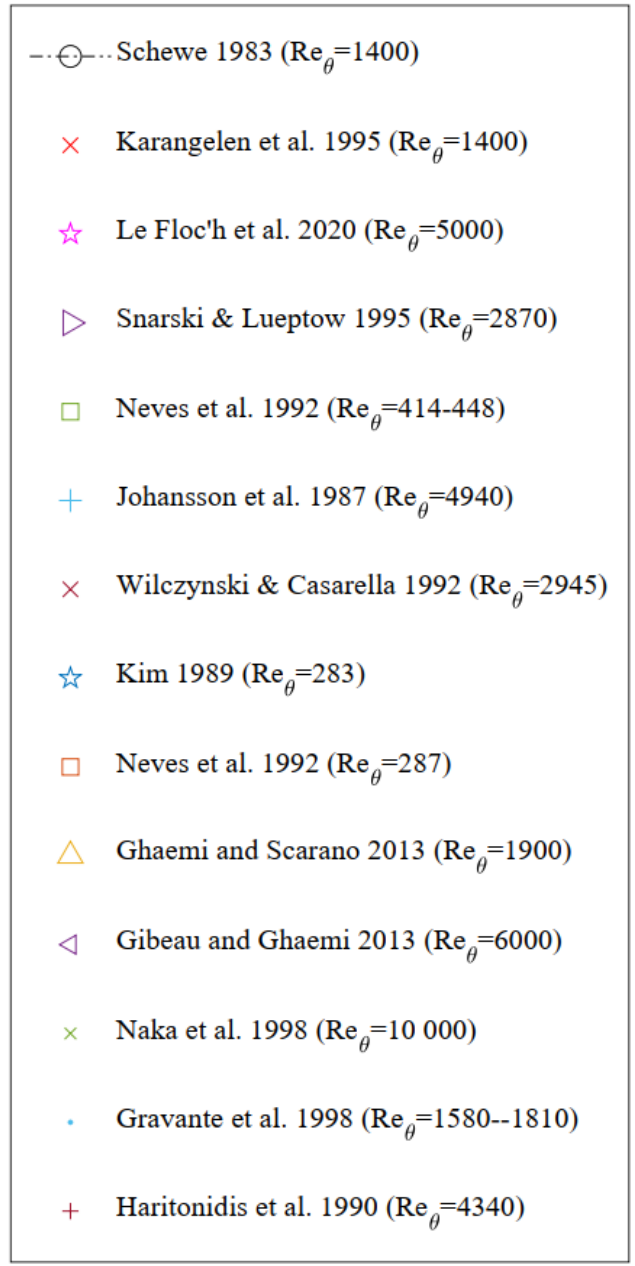
APG

Simpson (1996)


Wall pressure RMS for ZPG TBL
×10^-3
c_p' = p_rms/q_∞
d+

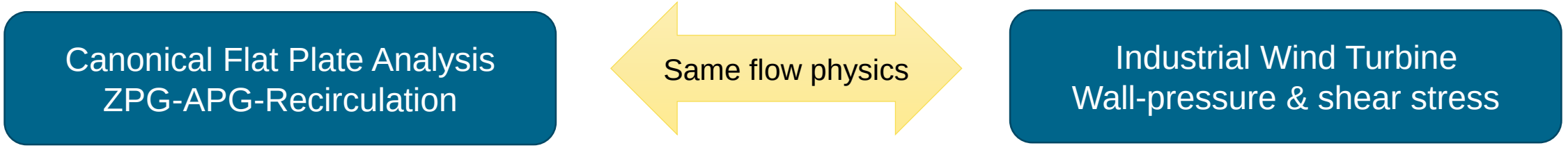

Wall pressure skewnewss for ZPG TBL
skewness(p_w)
d+


Wall pressure kurtosis for ZPG TBL
kurtosis(p_w)
d+


Schewe 1983 (Re_θ=1400)
Karangelen et al. 1995 (Re_θ=1400)
Le Floc'h et al. 2020 (Re_θ=5000)
Snarski & Lueptow 1995 (Re_θ=2870)
Neves et al. 1992 (Re_θ=414-448)
Johansson et al. 1987 (Re_θ=4940)
Wilczynski & Casarella 1992 (Re_θ=2945)
Kim 1989 (Re_θ=283)
Neves et al. 1992 (Re_θ=287)
Ghaemi and Scarano 2013 (Re_θ=1900)
Gibeau and Ghaemi 2013 (Re_θ=6000)
Naka et al. 1998 (Re_θ=10 000)
Gravante et al. 1998 (Re_θ=1580--1810)
Haritonidis et al. 1990 (Re_θ=4340)

Summary

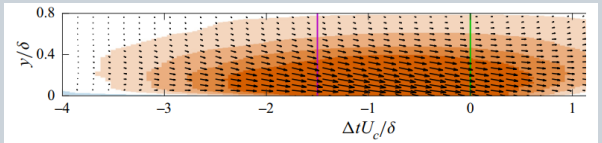
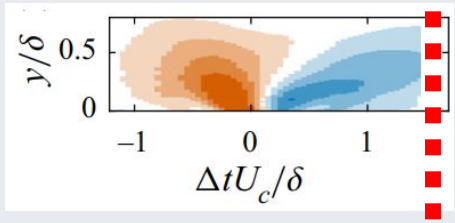
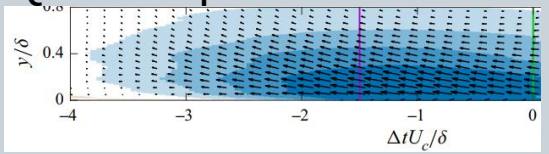
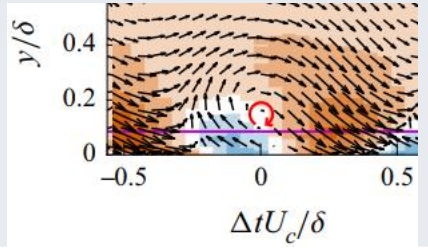
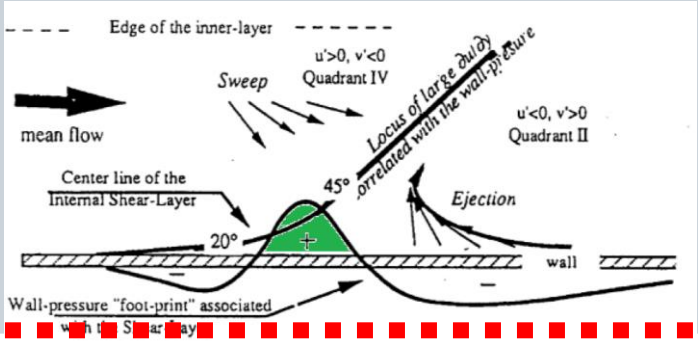
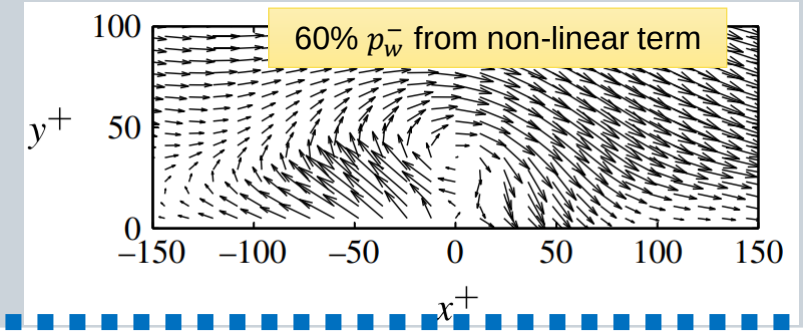
- Preliminary analysis of flat plate and airfoils show **common flow separation unsteady features**
  - Onset of separation characterized by positive pressure fluctuations
  - Reverse flow leads to subsequent negative pressure fluctuations, but not the case with APG still attached
  - Need to further investigate the topology of conditional averages using synchronized velocity measurements
- A more extensive database is favored



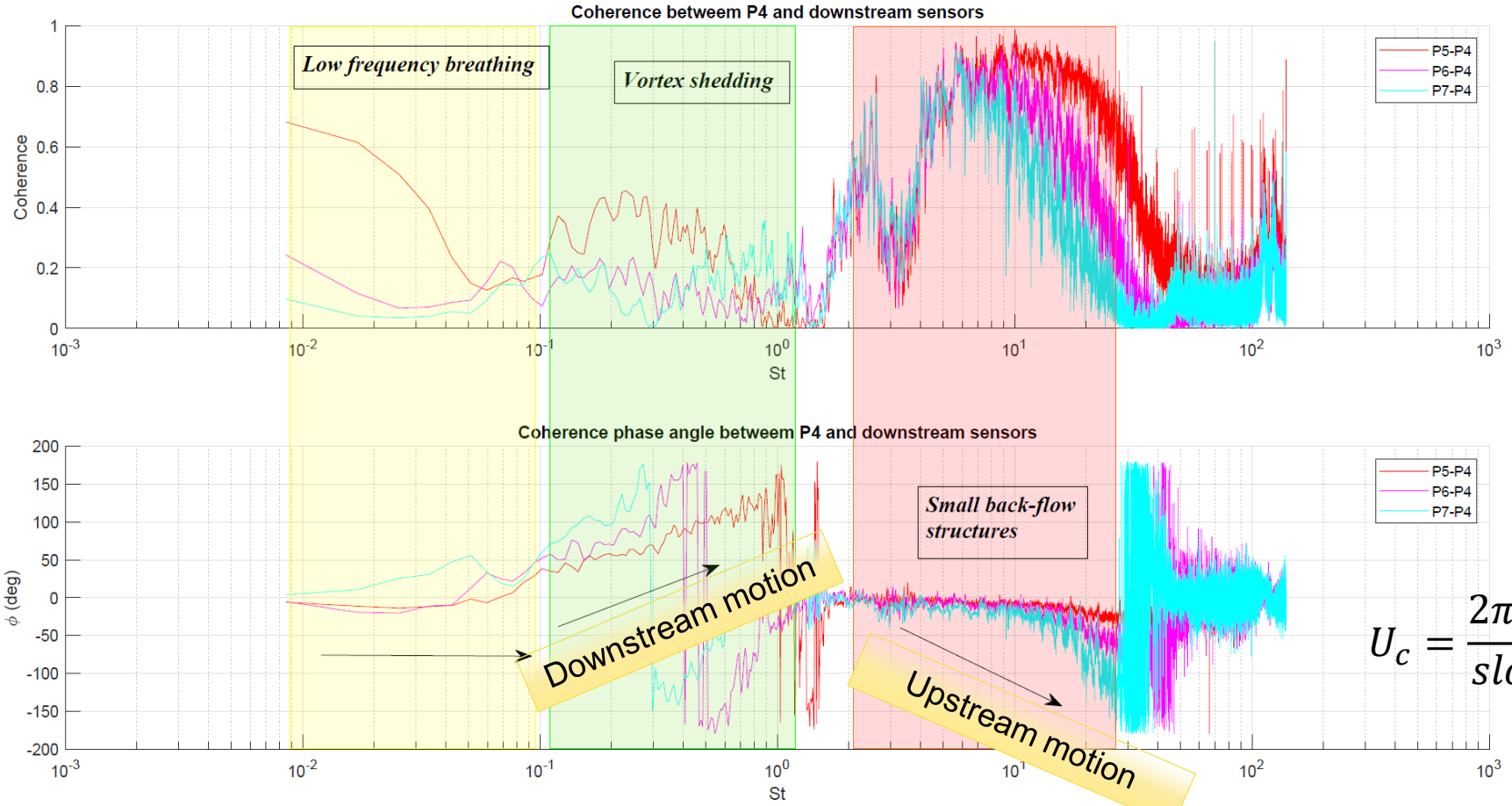
Our objective : A better understanding of the mechanism of flow separation and how it drives flow separation noise.

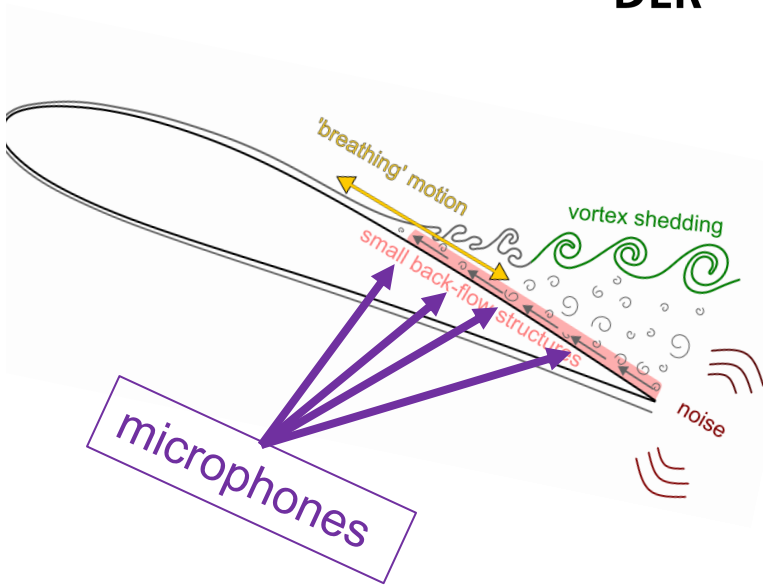
APPENDIX

Wall pressure and coherent structures

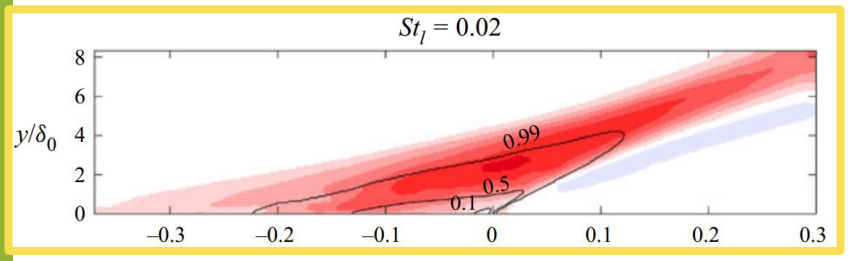
ZPG Boundary Layer:	Velocity Skewness Motion:	Positive event $p_w > 0$ Associated motion:	Negative event $p_w < 0$ Associated motion:
Outer Layer $(y/\delta > 0.2)$	Q2 $(u < 0 \;\&\; v > 0)$	**VLSM**: Q4 high-speed  **LSM**: upstream Q4-downstream Q2 	**VLSM**: Q2 low-speed  20% of p_{rms} **LSM**: upstream Q2-downstream Q4 
Inner Layer $(y/\delta < 0.2)$	Q4 $(u > 0 \;\&\; v < 0)$	**Near-wall**: Region of stagnation upstream Q4-downstream Q2 	**Near-wall**: Sweep Q4 / vortical structural cores 

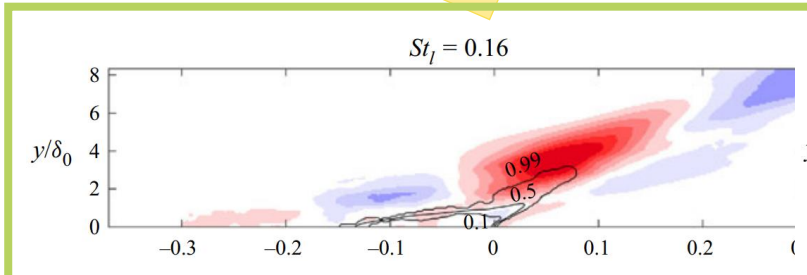
[NACA 4418] - Resolving the 3 types of unsteadiness

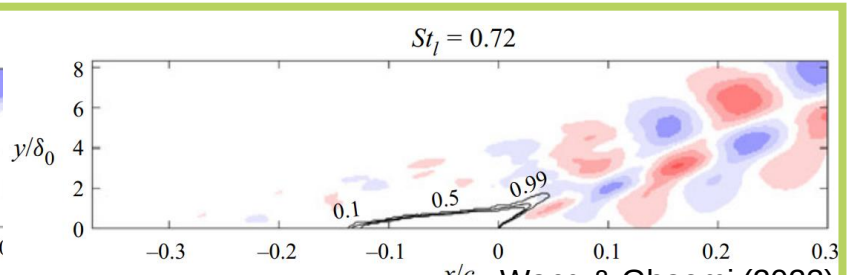




$$U_c = \frac{2\pi\,\Delta x}{slope} \qquad \text{with: } slope = \frac{d\theta}{df}$$







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Wang & Ghaemi (2023)