Yacht sail flow: recent findings and unanswered questions

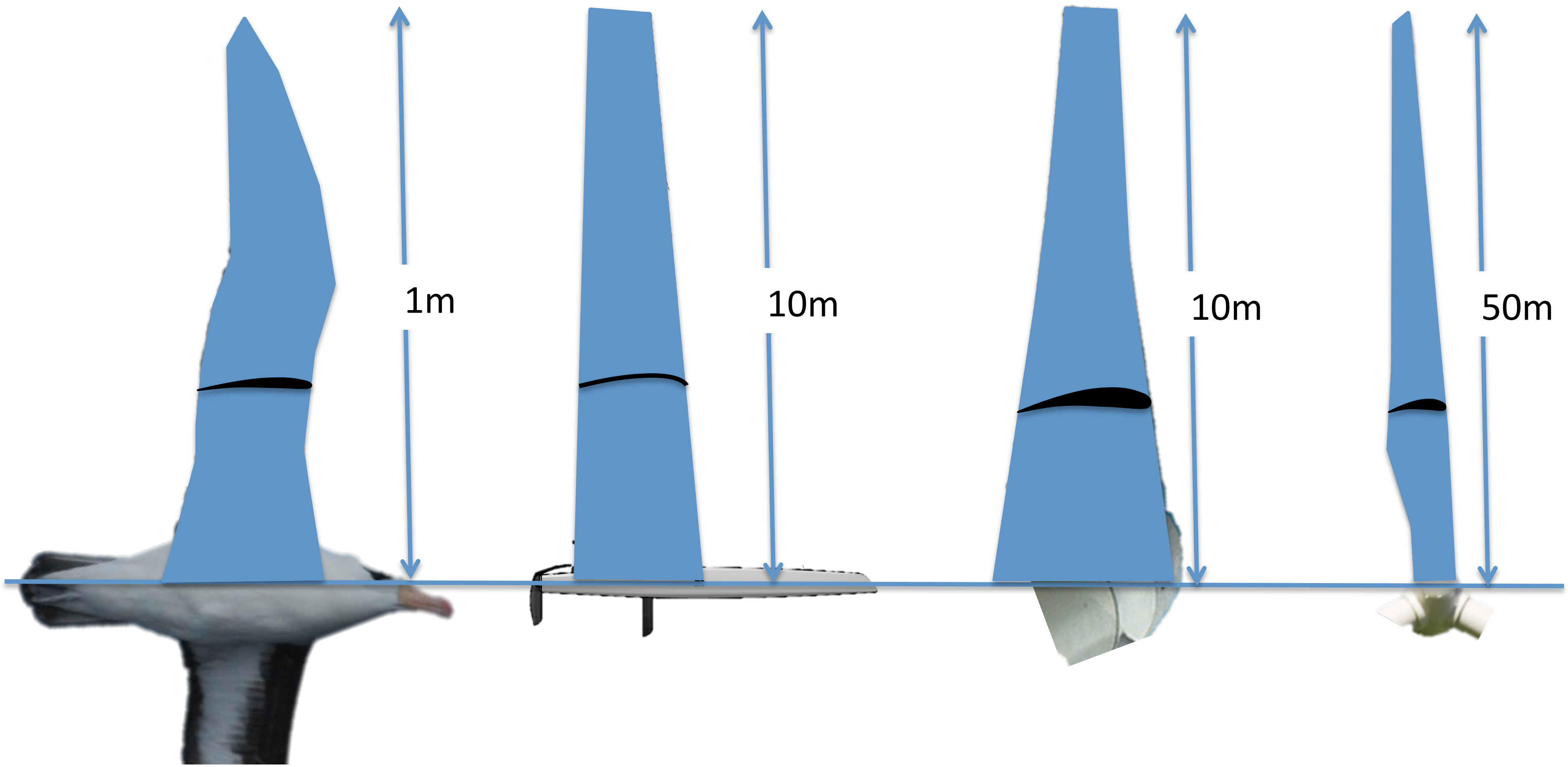
THE UNIVERSITY OF EDINBURGH
SCHOOL OF ENGINEERING
INSTITUTE FOR ENERGY SYSTEMS

Yacht sail flow:
Recent findings and unanswered questions

Dr Ignazio Maria Viola

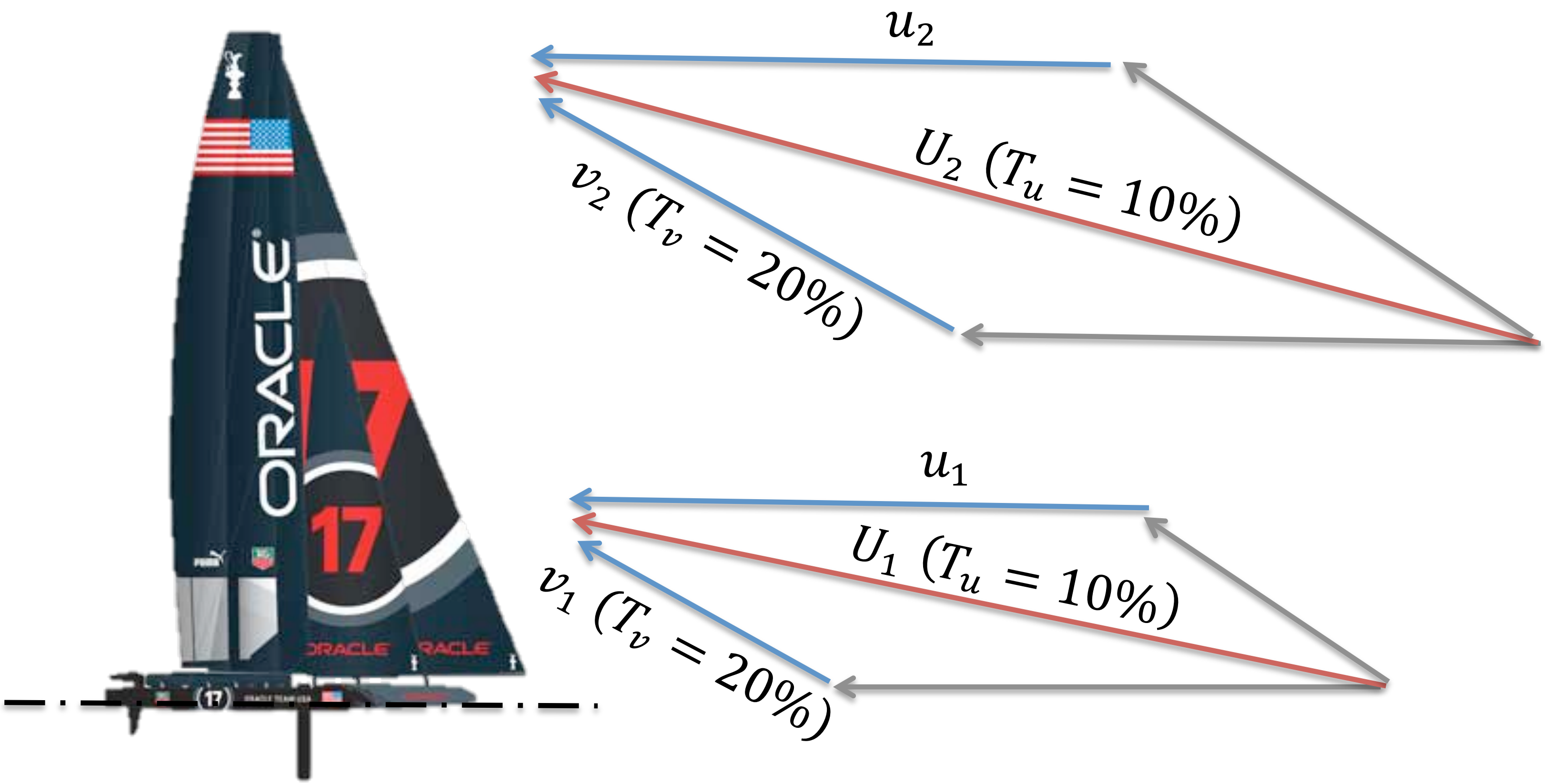
Sails

Sails are 3D wings operating at transitional Re in high turbulent conditions

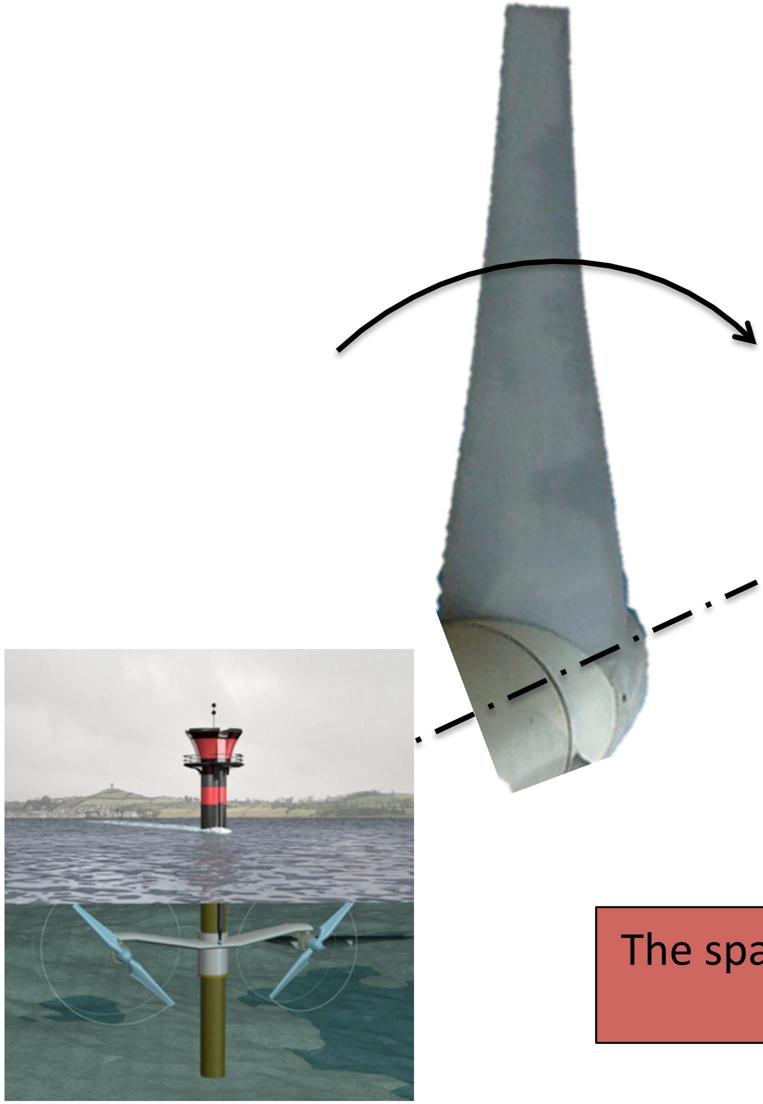


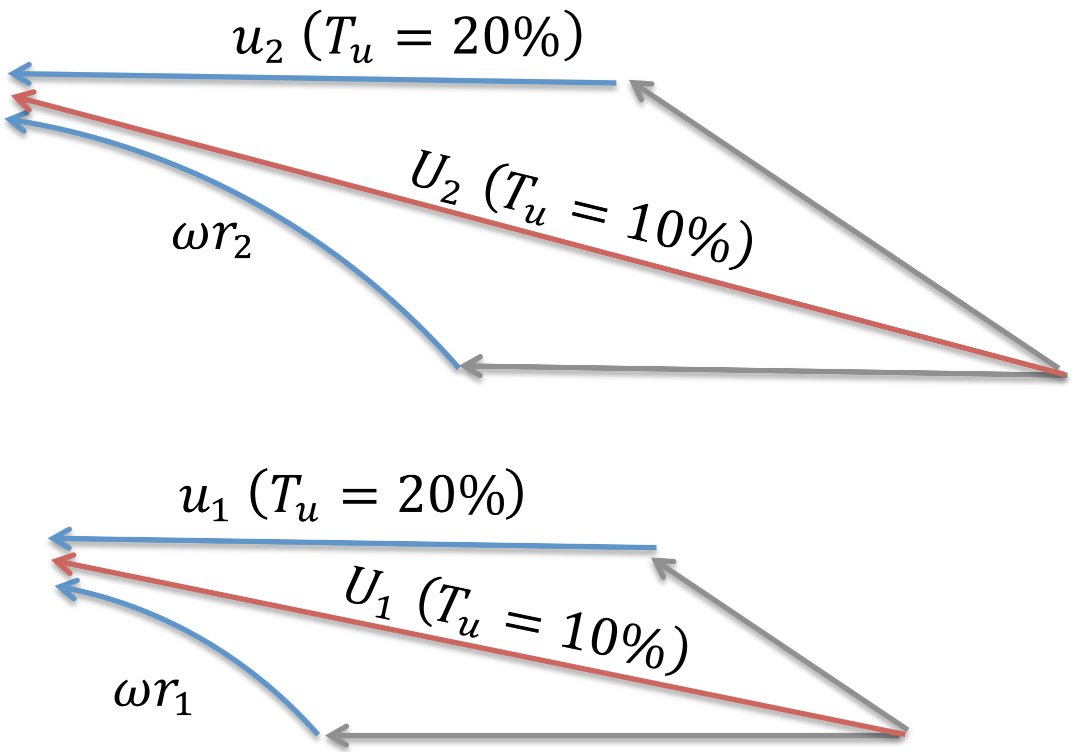
Birds	**Yachts**	**Tidal blades**	**Wind blades**
$Re=10^5$	$Re=10^5$-10^6	$Re=10^5$-10^6	$Re=10^6$
Tu>10%	Tu>10%	Tu>10%	Tu<1%

Spanwise velocity profile



Spanwise velocity profile





The spanwise velocity profile exeperienced by sails is the same as the one experienced by tidal turbine blades

Flexible

Fluid-structure interaction of sails is largely unknown
(follow Dr Matthieu Durand's work for future developments)

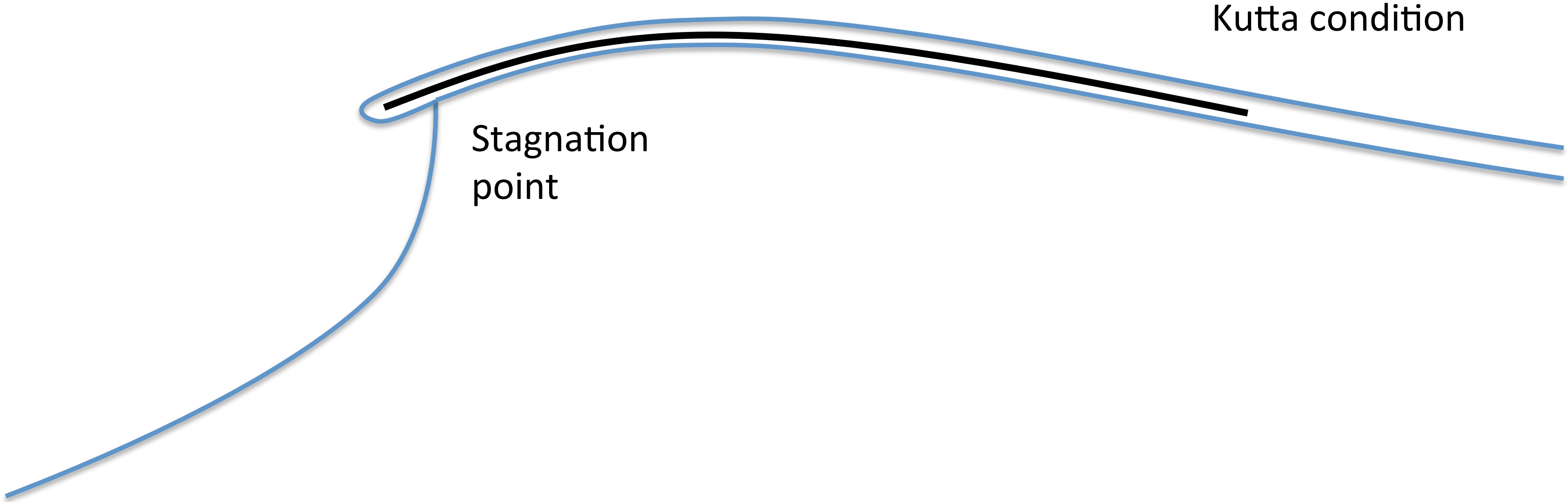
Thin

The extreme sharpness of the leading edge is what makes sail flow exceptional

SAIL Thickness/chord=10^{-4}

THIN FOIL Thickness/chord=10^{-2}

Potential flow interpretation

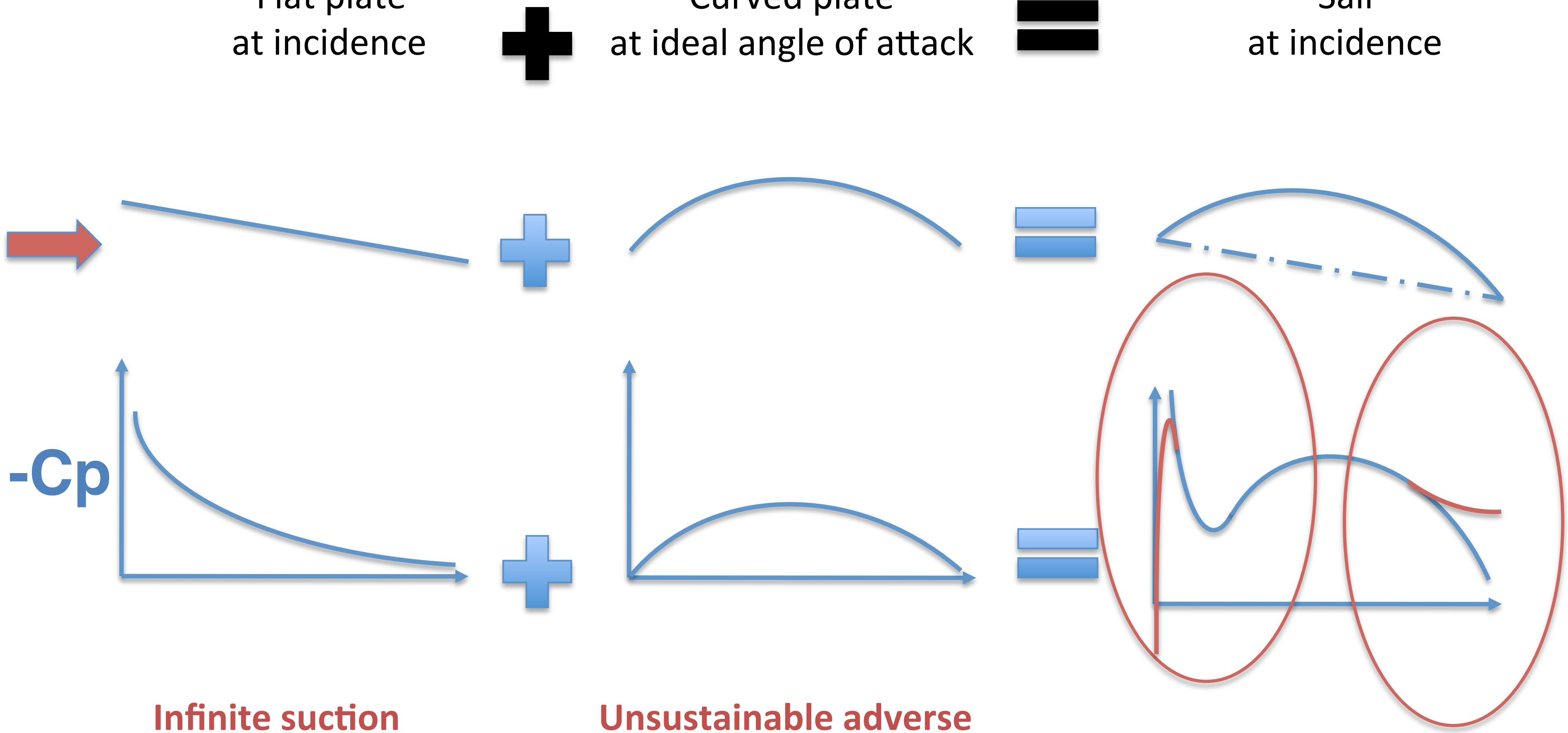


Combination of Laplace solutions

Flat plate
at incidence

Curved plate
at ideal angle of attack

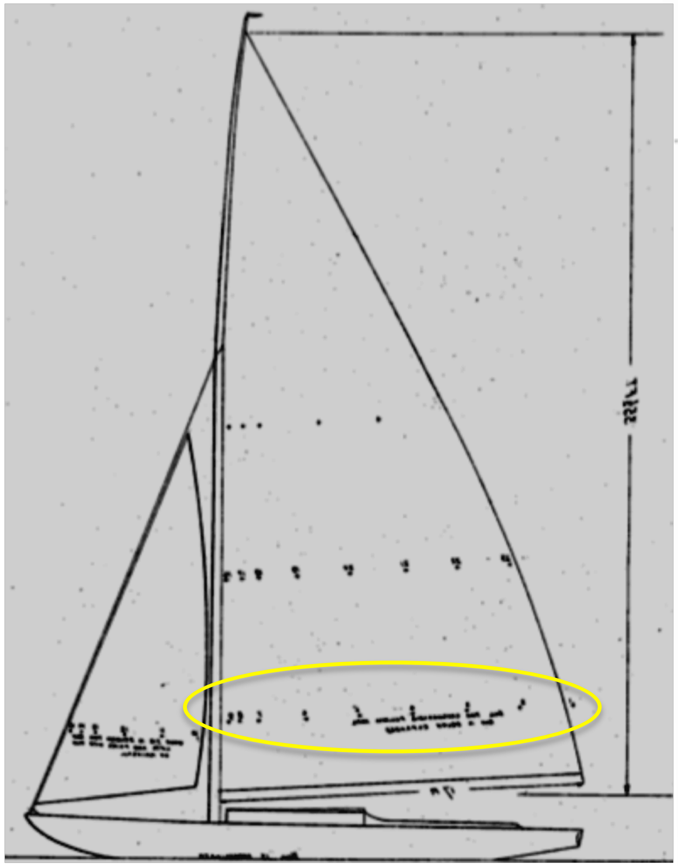
Sail
at incidence

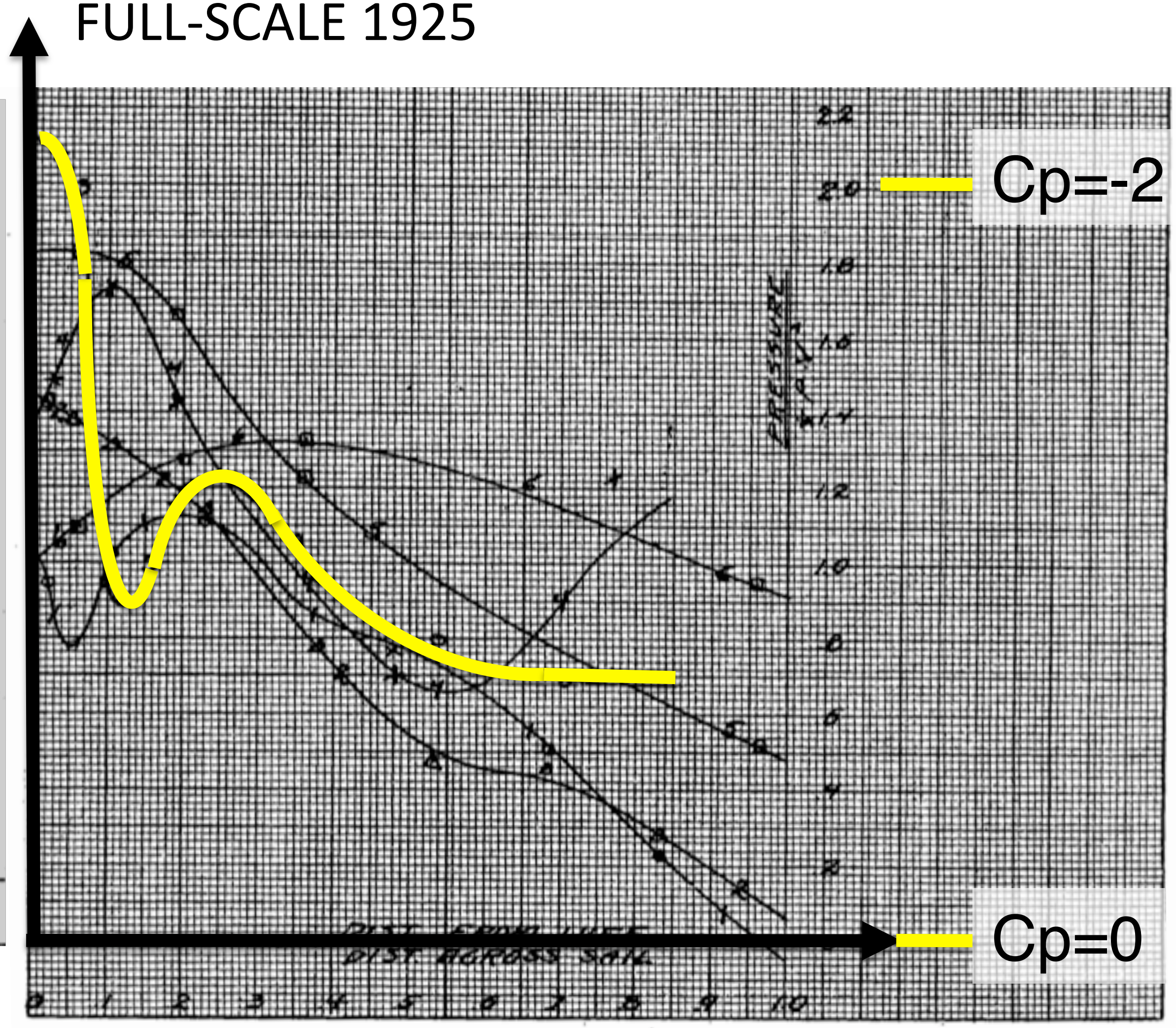


Infinite suction at the leading edge unless separation occurs

Unsustainable adverse trailing edge pressure gradient unless separation occurs

Experimental evidence

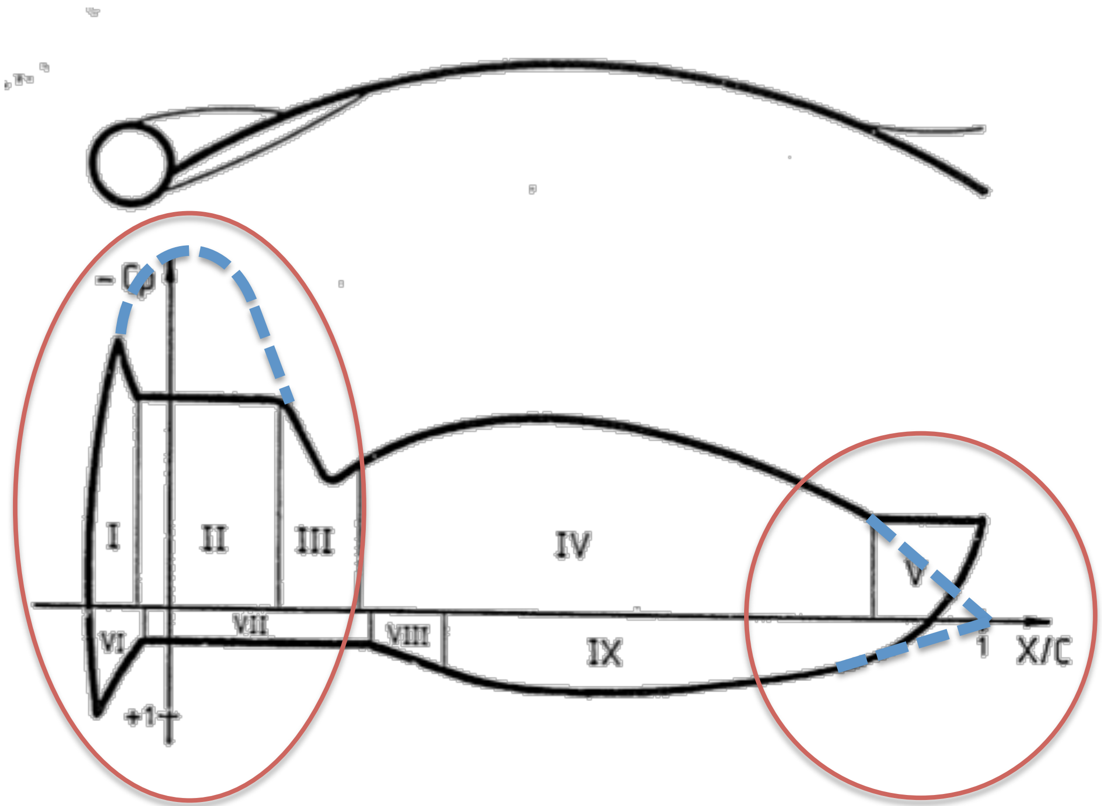


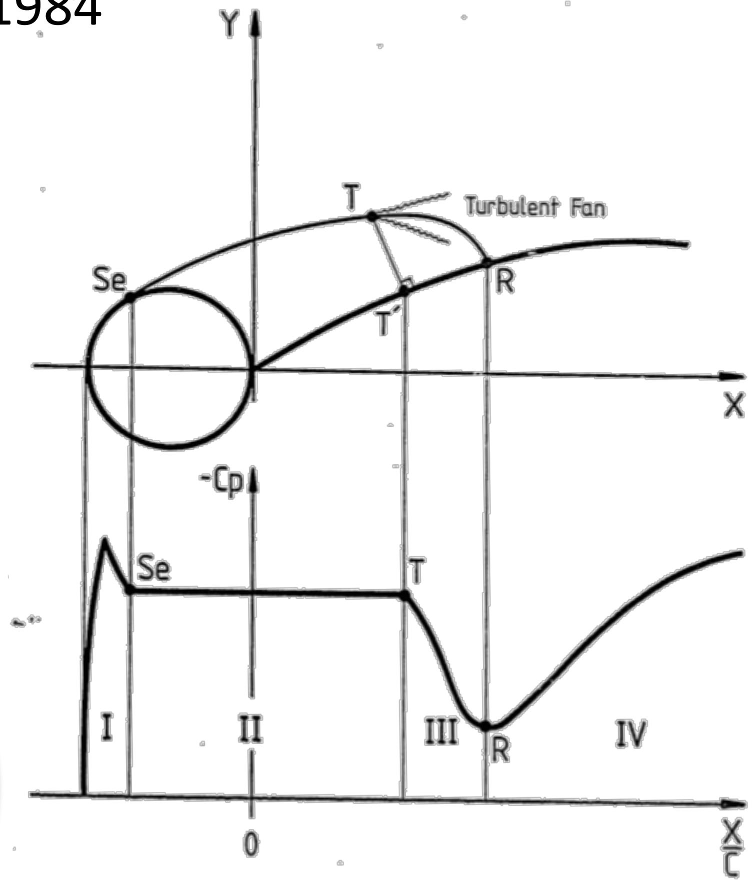


Warner EP & Ober S, 1925, The Aerodynamics of Sails, *Soc. Nav. Arch. Mar. Eng., NY*

Experimental evidence

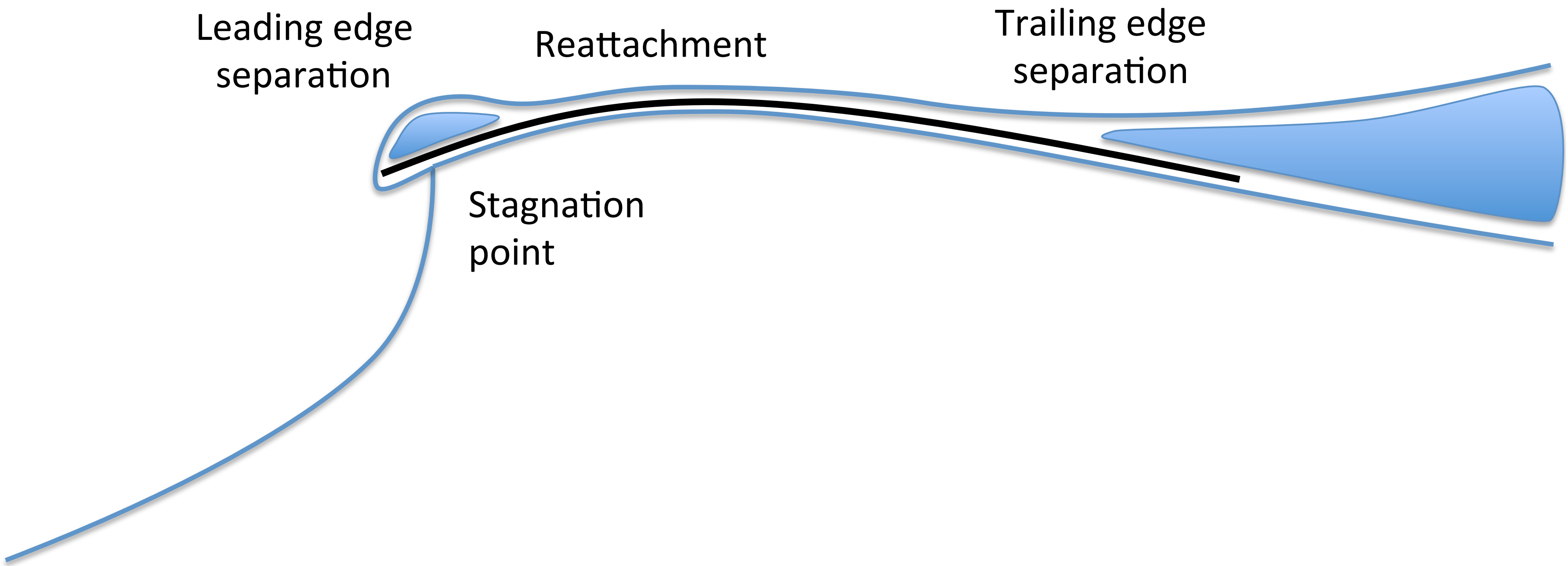
WIND TUNNEL 1984





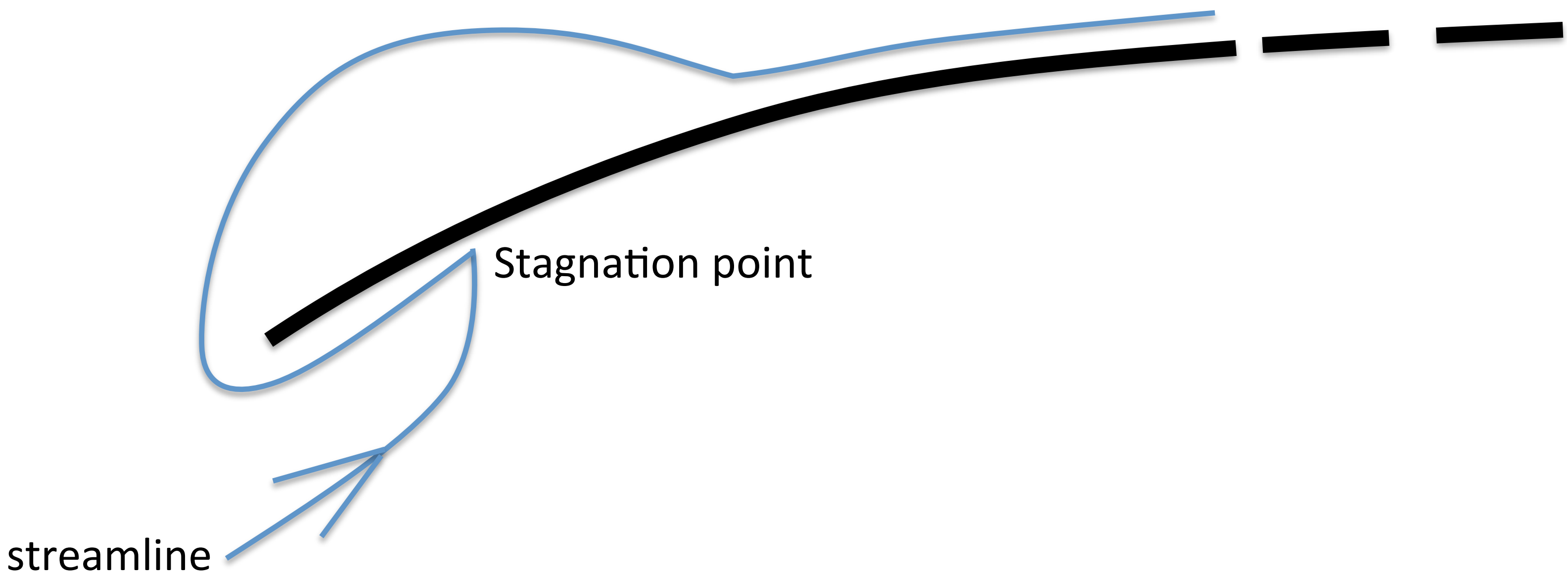
S. Wilkinson, 1984, Partial Separated Flow Around Mast and Sail, *PhD Thesis, Univ. Southampton*

Viscous effects



Leading edge separation

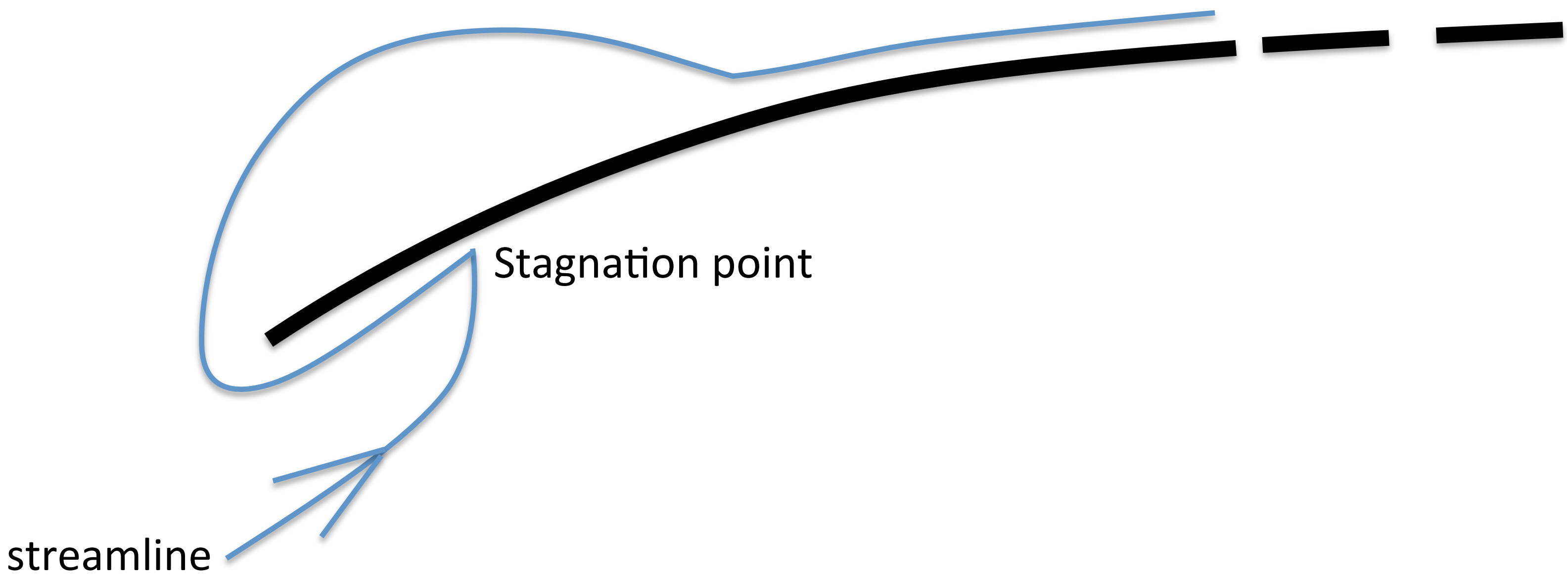
- At an angle higher than the ideal angle of attack, the stagnation point must be on windward side (no exp evidence on sails)
- From the stagnation point to the leading edge the pressure decreases abruptly (highly favourable pressure gradient) and thus the boundary layer must be laminar (no exp evidence on sails)
- At the sharp leading edge the flow must separate (no exp evid. on sails)
- Full-scale and wind tunnel flow visualisation shows reattachment



Leading edge separation

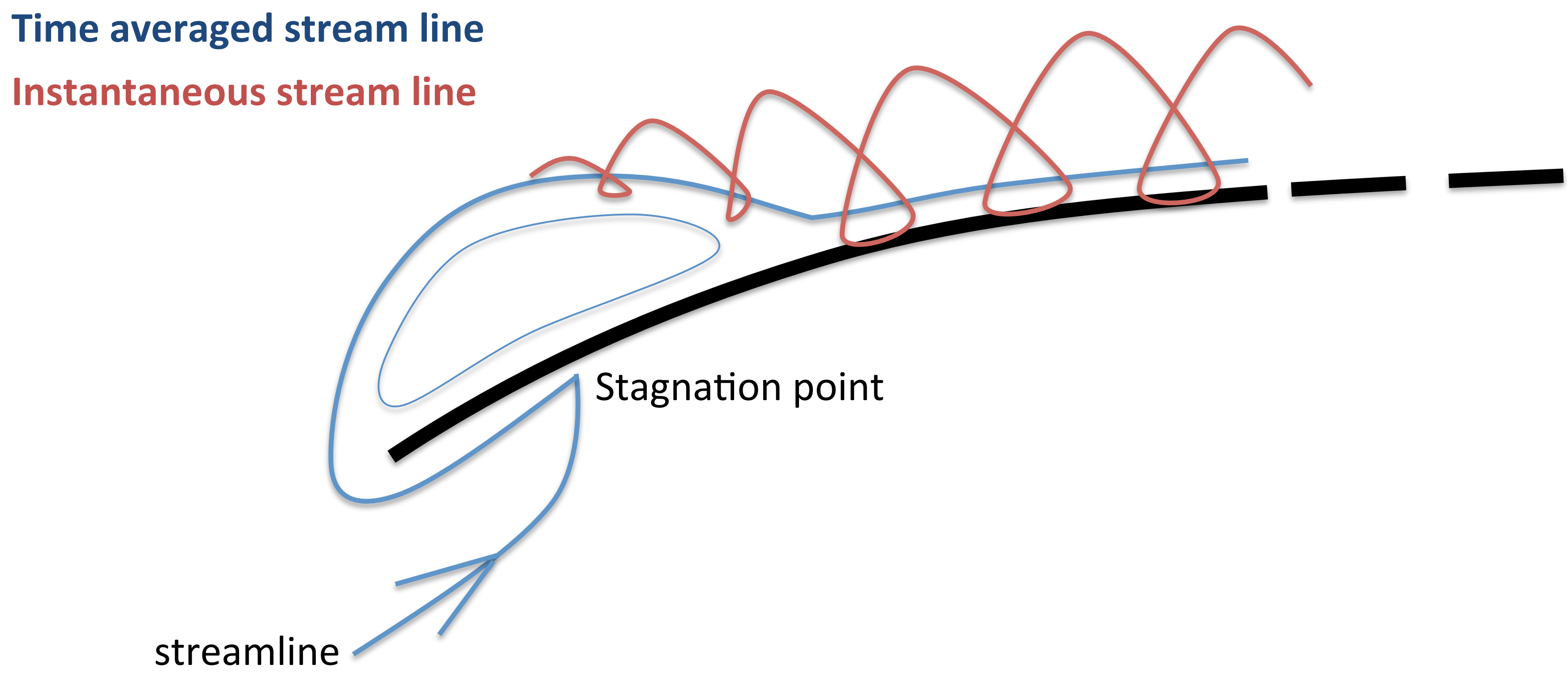
Given the Reynolds number at which sails operate:

- Transition is likely to occur in the separated shear layer
- Turbulence is likely to promote (time-averaged) reattachment
- This can lead to either:
  - **(A) Laminar Separation Bubble**
  - (B) Leading Edge Vortex



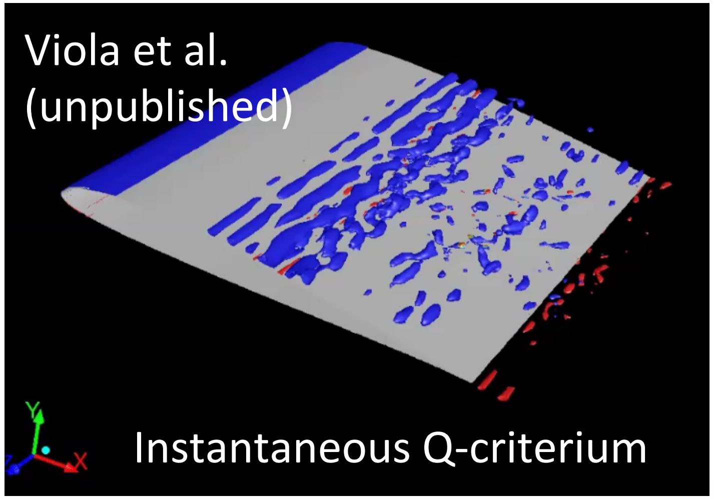
Laminar Separation Bubble (LSB)

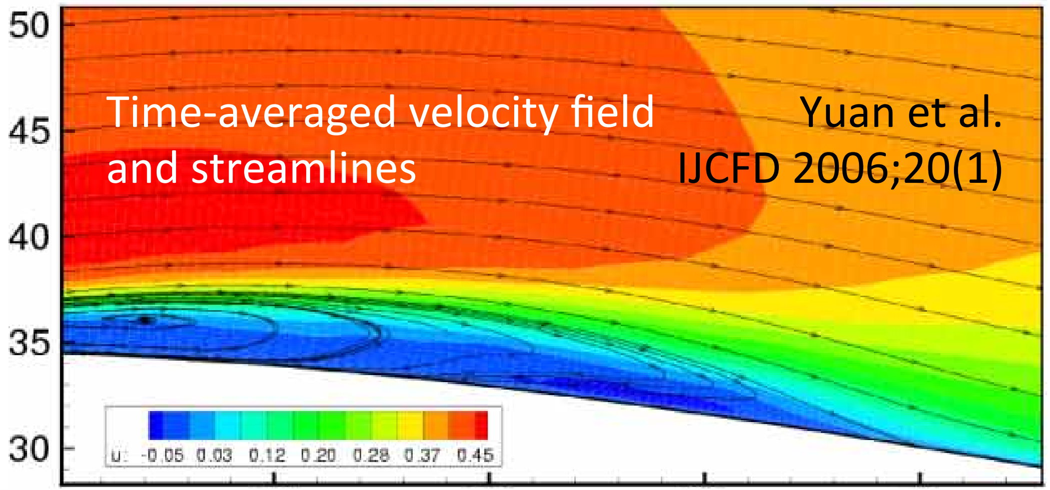
- Discrete pockets of clockwise vorticity are generated from the separated shear layer and are convected downstream transferring momentum from the outer flow to the reattached boundary layer
- The reattachment downstream of the bubble is defined only in a time-averaged sense

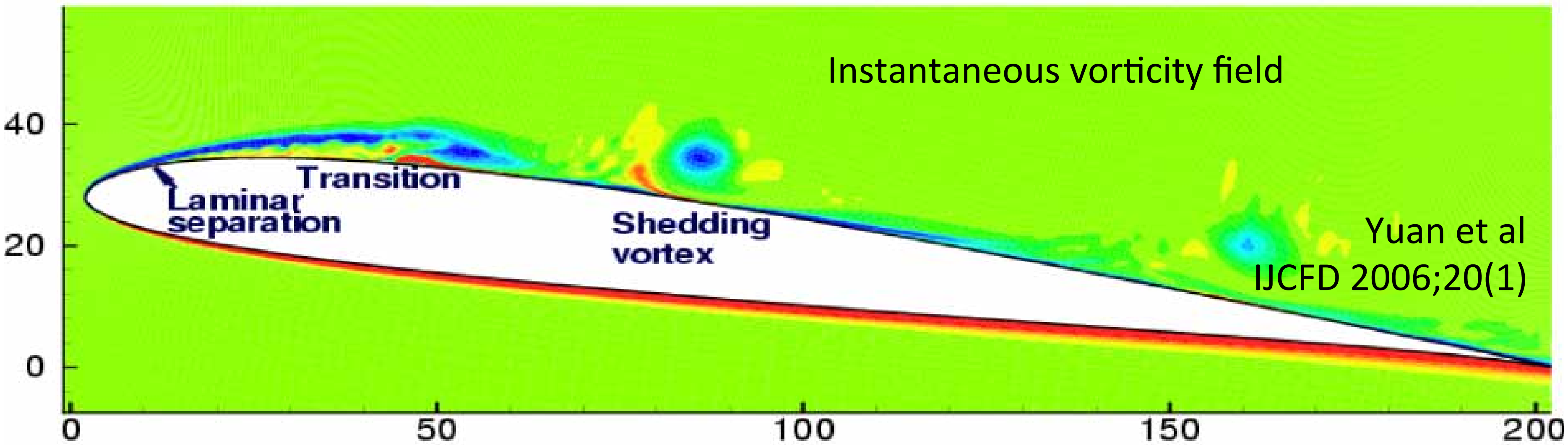


LSB on foils

- The LSB occurs on foils at transitional Reynolds numbers ($10^5<Re<10^5$)

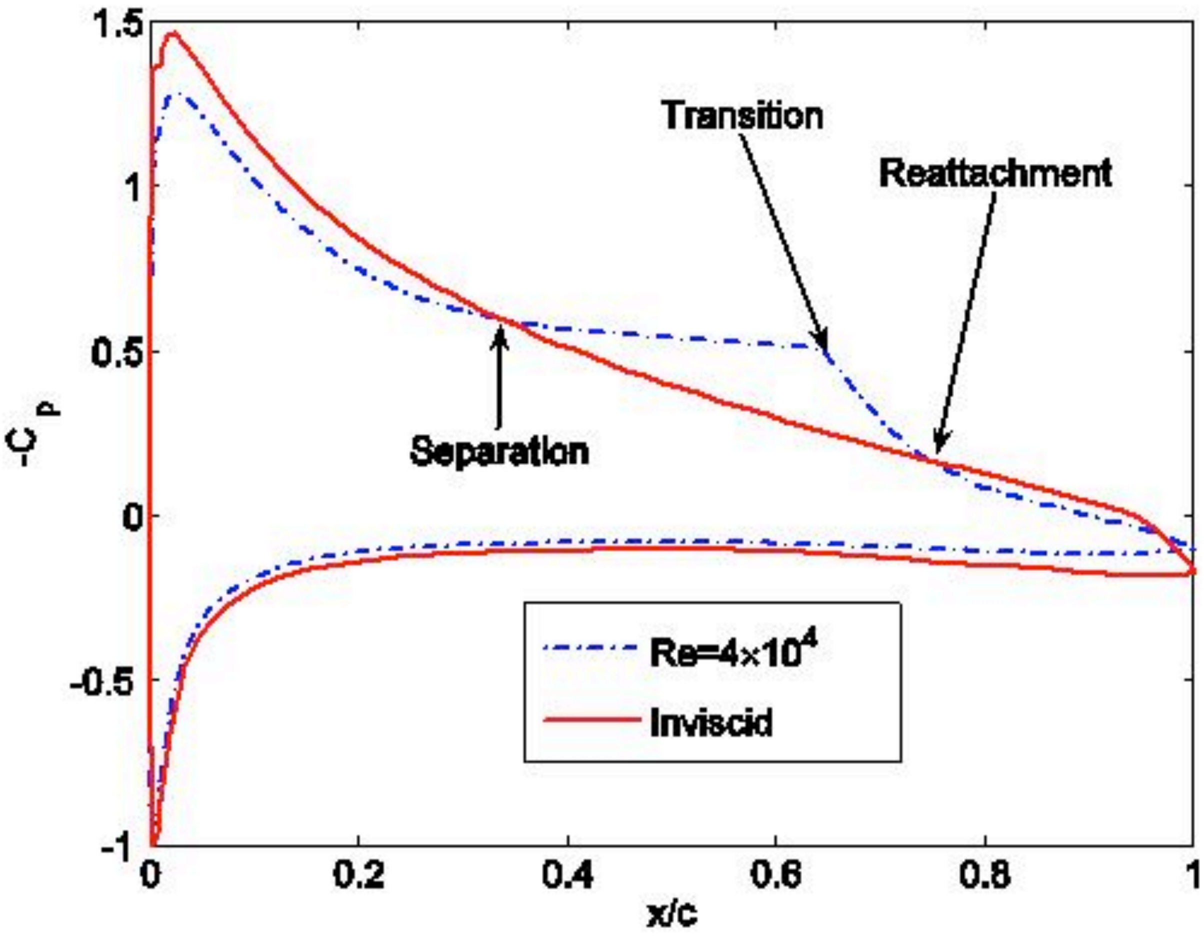






LSB on foils

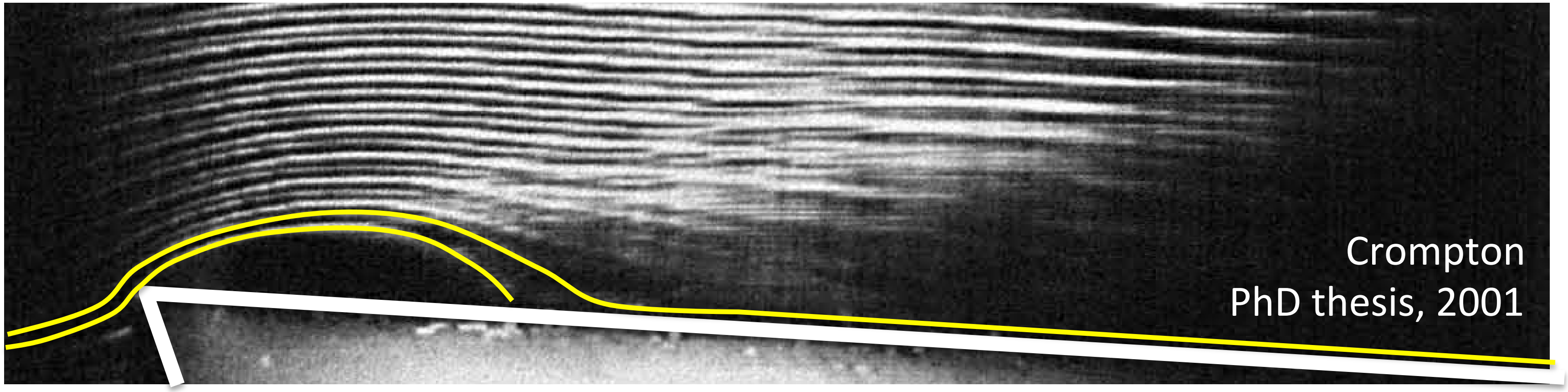
- The LSB on foils is characterised by low recirculation inside the bubble and a pressure plateau is observed in correspondence of the bubble



Lian and Shyy
AIAA 2007;47(7)

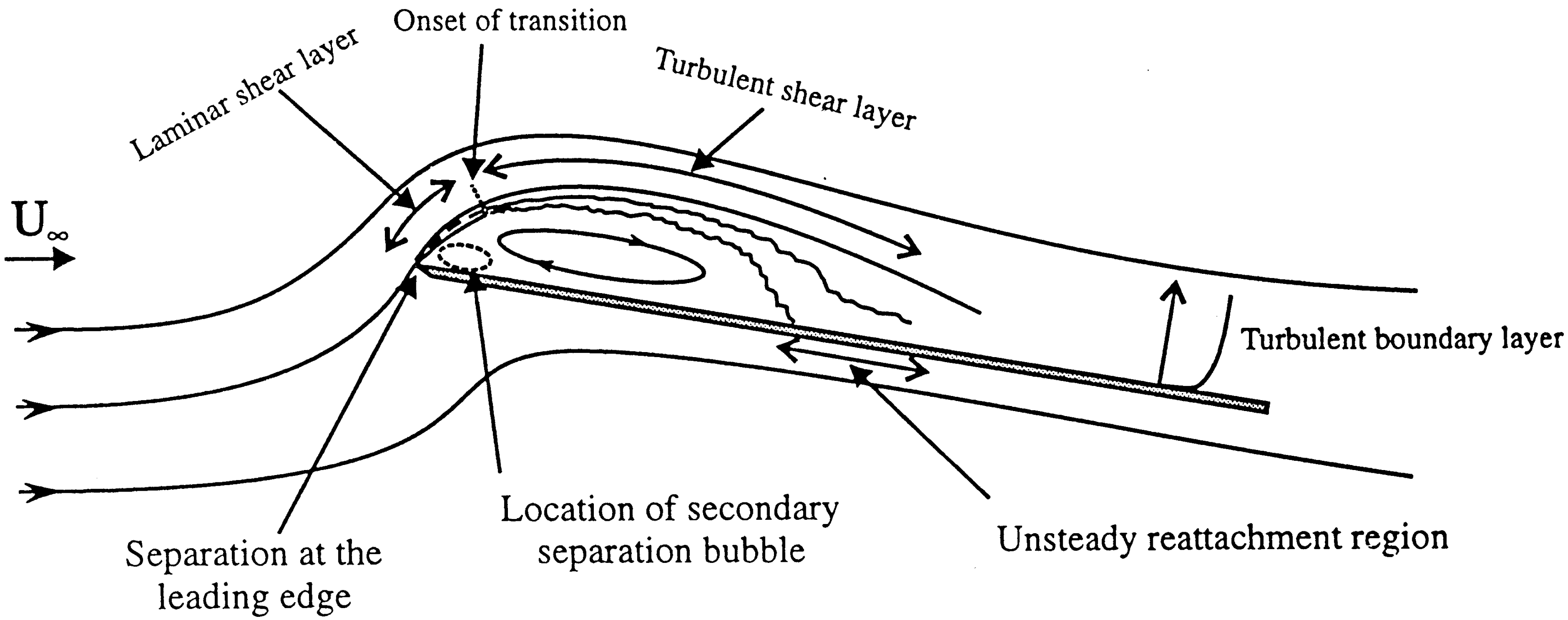
LSB on plates (long type)

- When the LSB is formed at the leading edge, such as on profiles with a sharp leading edge (sails and plates), the bubble is characterised by a higher recirculation



LSB on plates (long type)

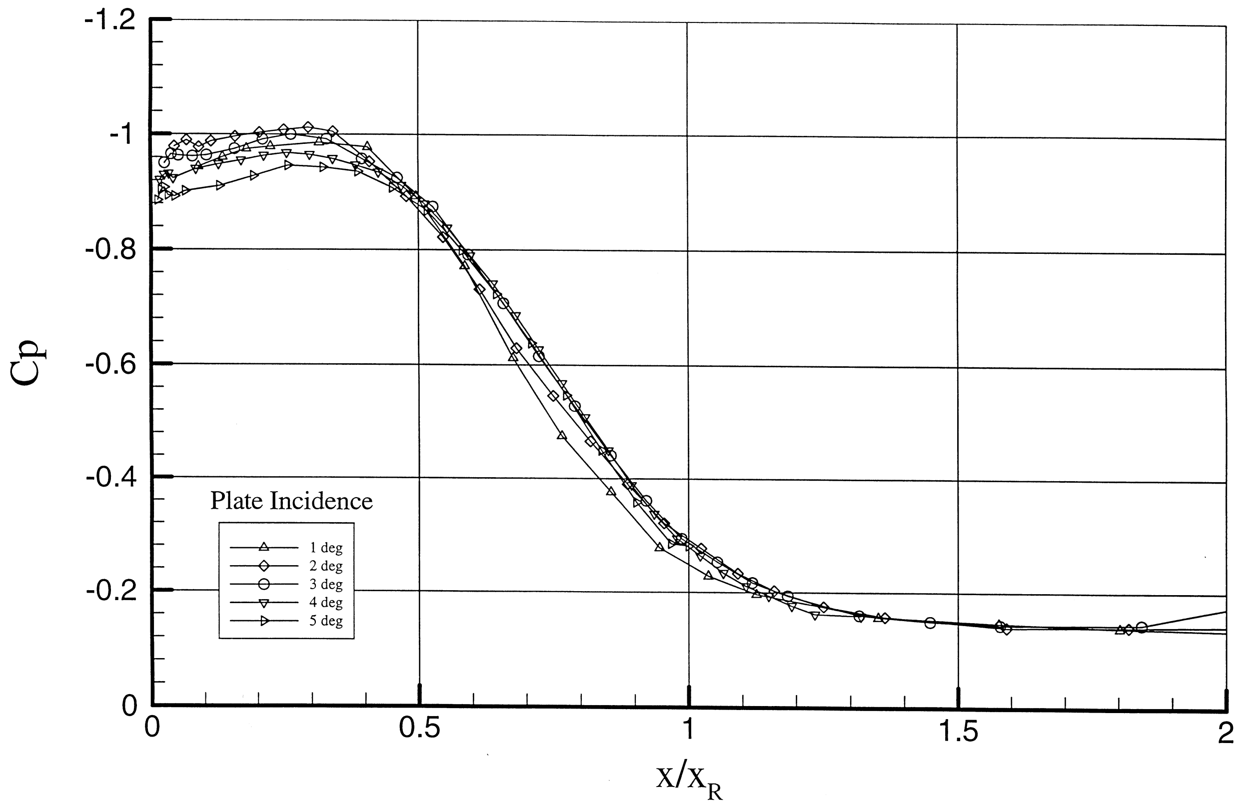
- A secondary separation bubble, which leads to a thicker bubble, is likely to occur



Crompton and Barrett
PIME 2000;2014(G)

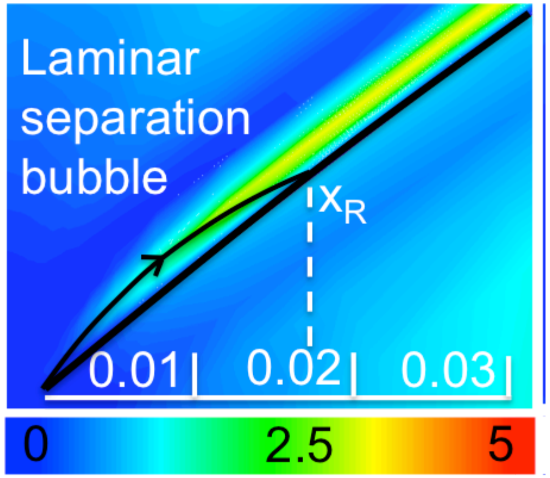
LSB on plates (long type)

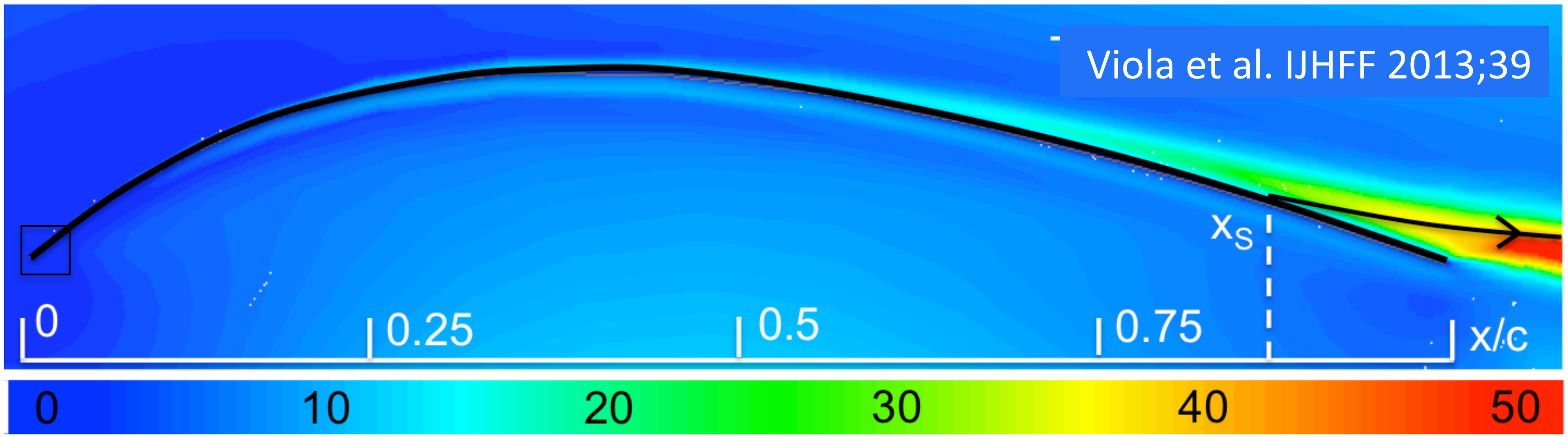
- The pressure plateau typical of the LSB on foils is significantly less pronounced on flat plates



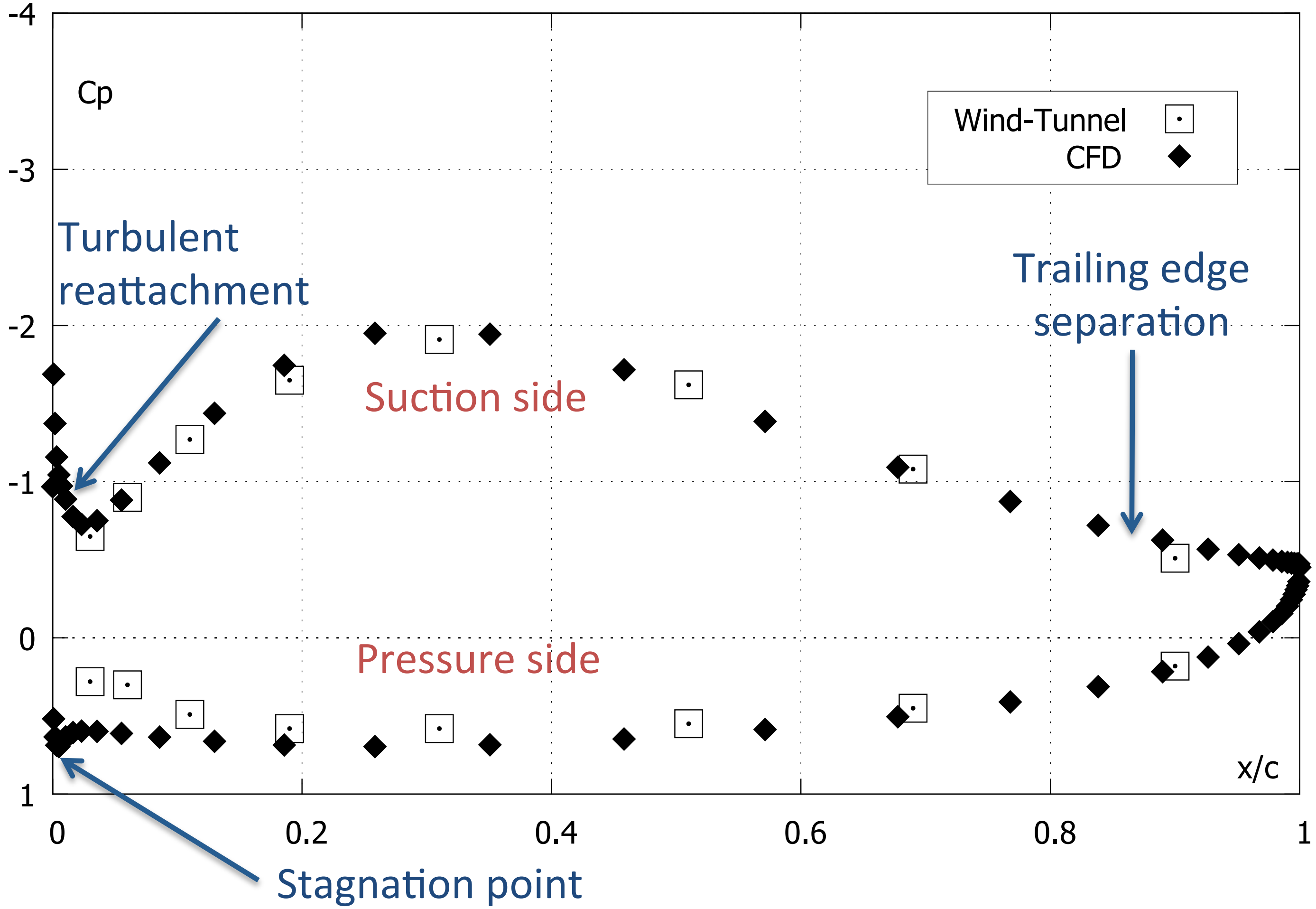
Crompton and Barrett
PIME 2000;2014(G)

LSB on (upwind) sails



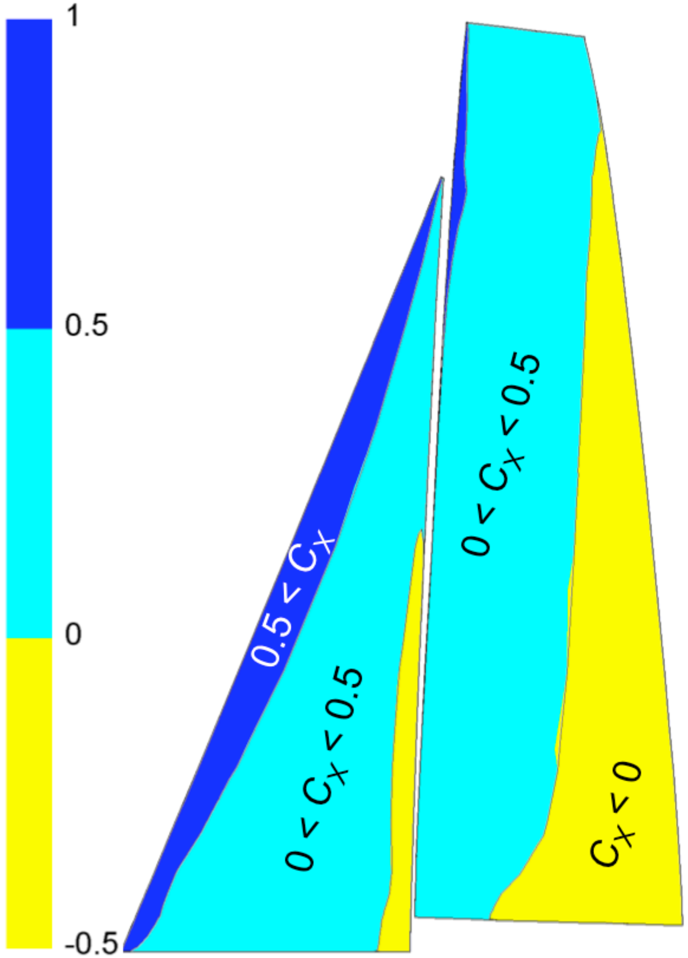


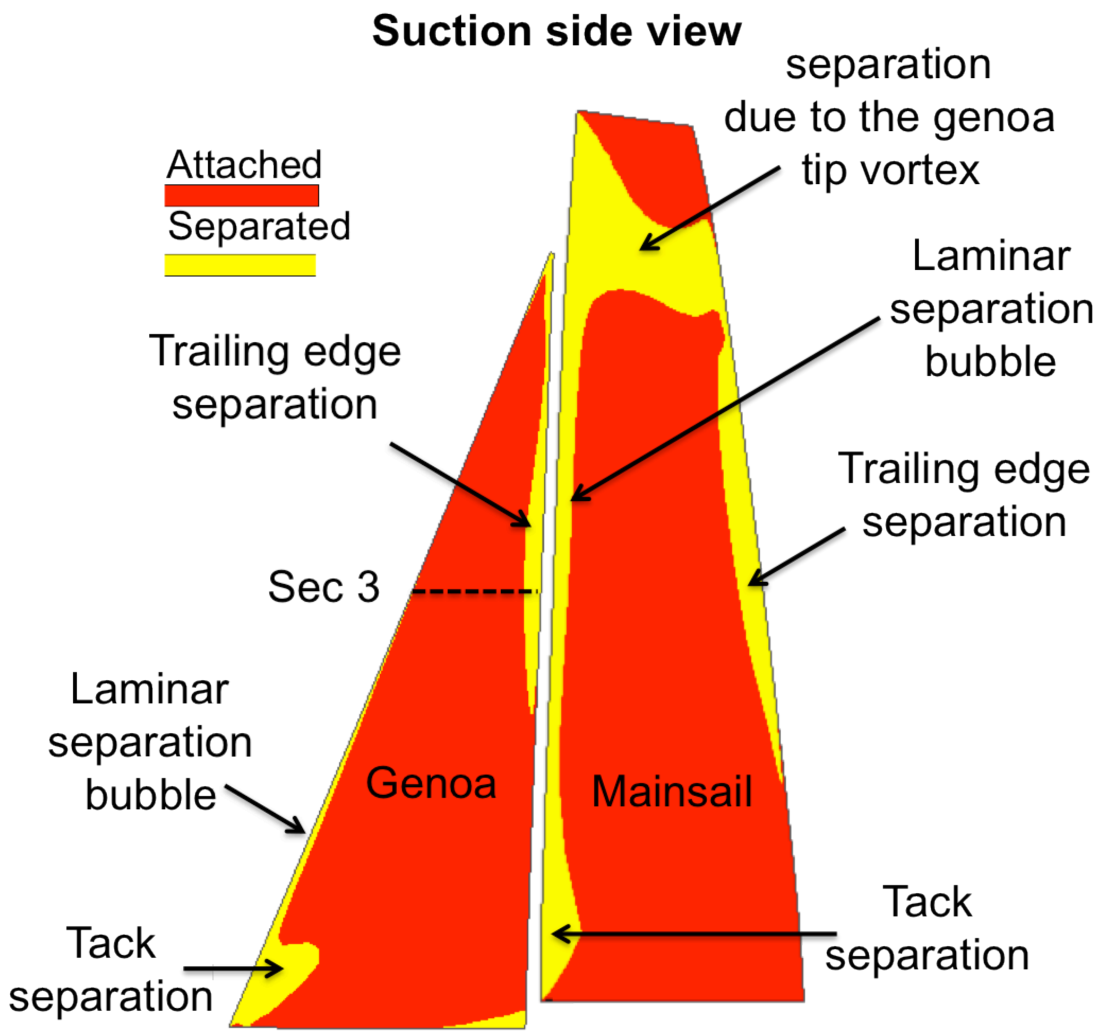
LSB on (upwind) sails



Viola et al. IJHFF 2013;39

LSB on (upwind) sails

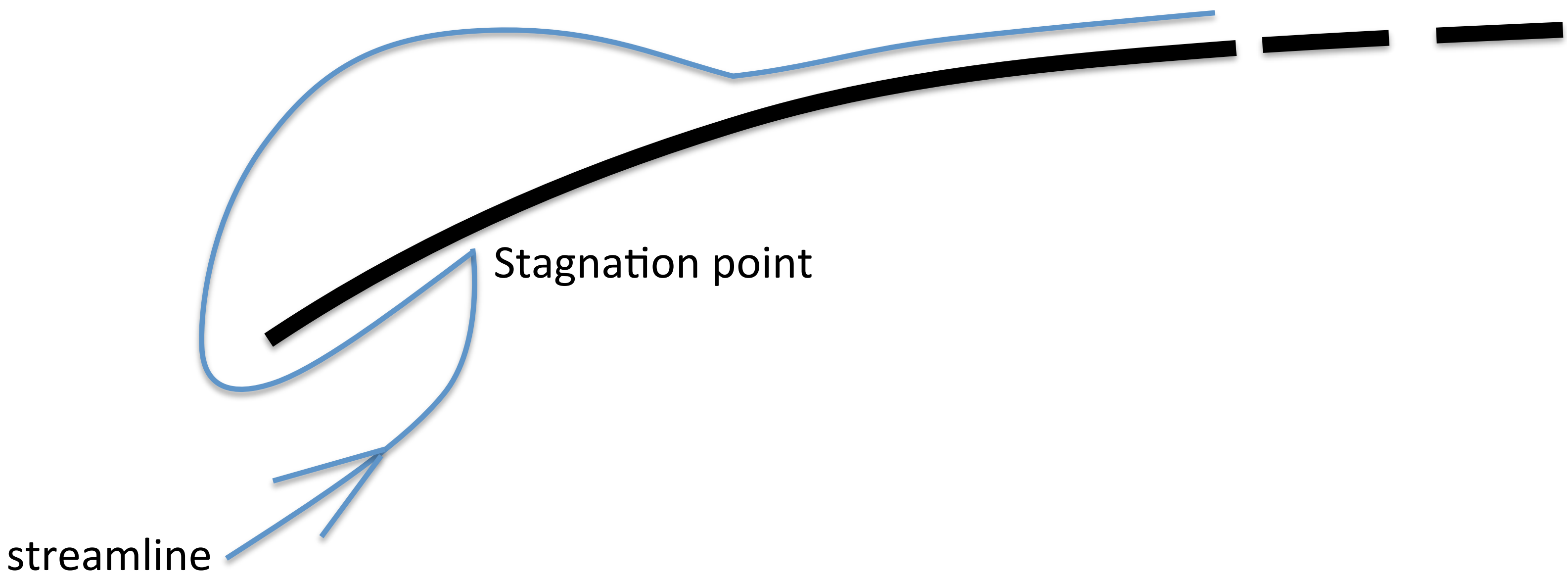




Viola et al. IJHFF 2013;39

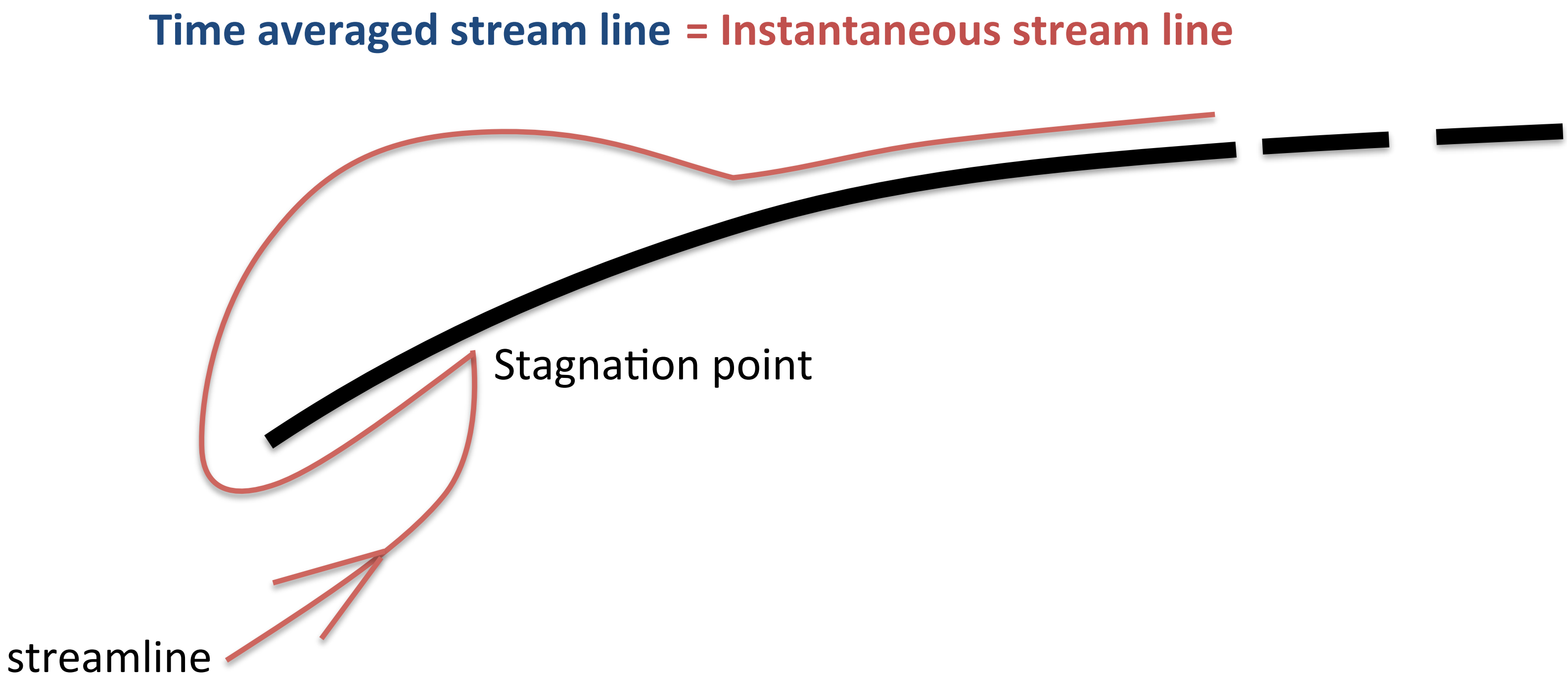
Leading edge separation

- (A) Laminar Separation Bubble
- **(B) Leading Edge Vortex**

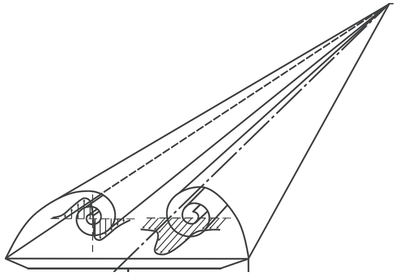


Leading Edge Vortex (LEV)

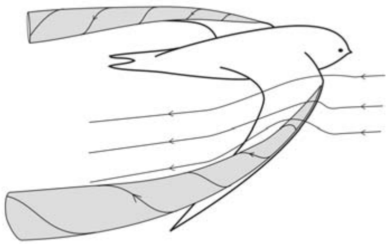
- The LEV was observed for the first time on yacht sails by Viola et al (2013), who performed the first DES on an asymmetric spinnaker
- The LEV is a 3D flow feature whose instantaneous pathlines form a spiral structure
- Vorticity is convected towards the centre of the vortex and extracted from axial velocity at the head of the sail



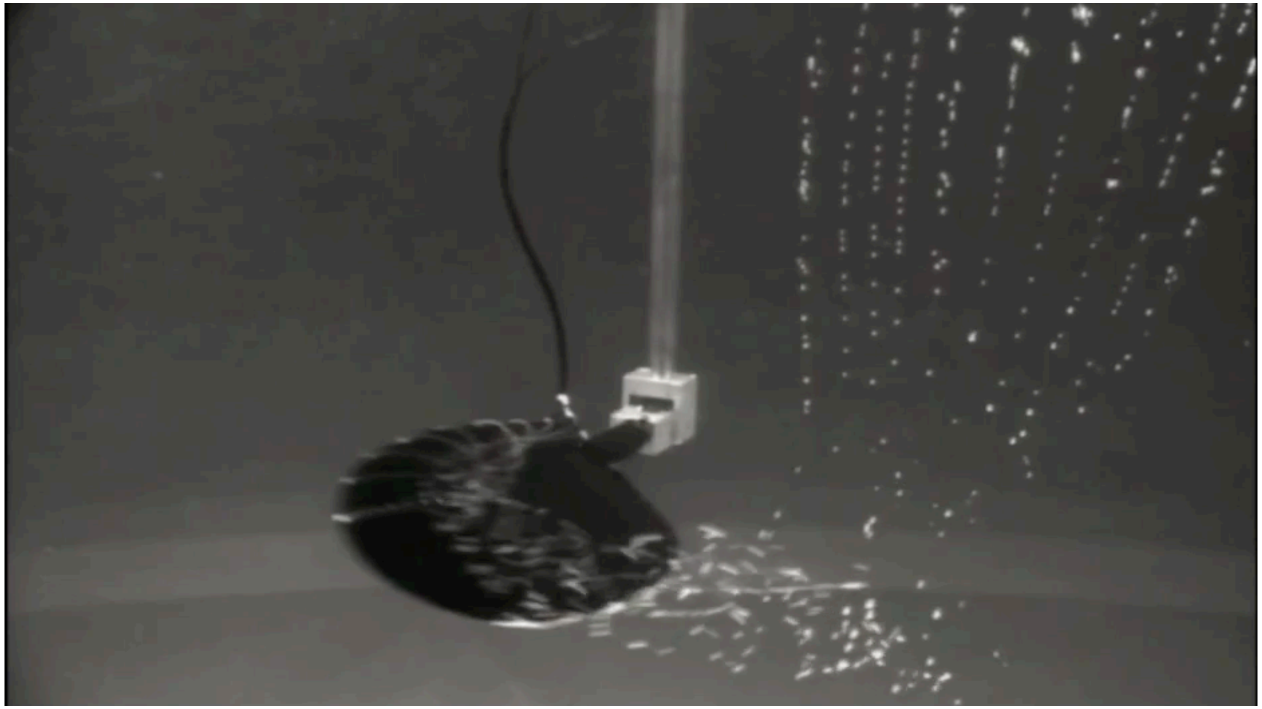
LEV on delta wings and insects/birds



LEV on a delta wing
(Gursul et al., 2007)

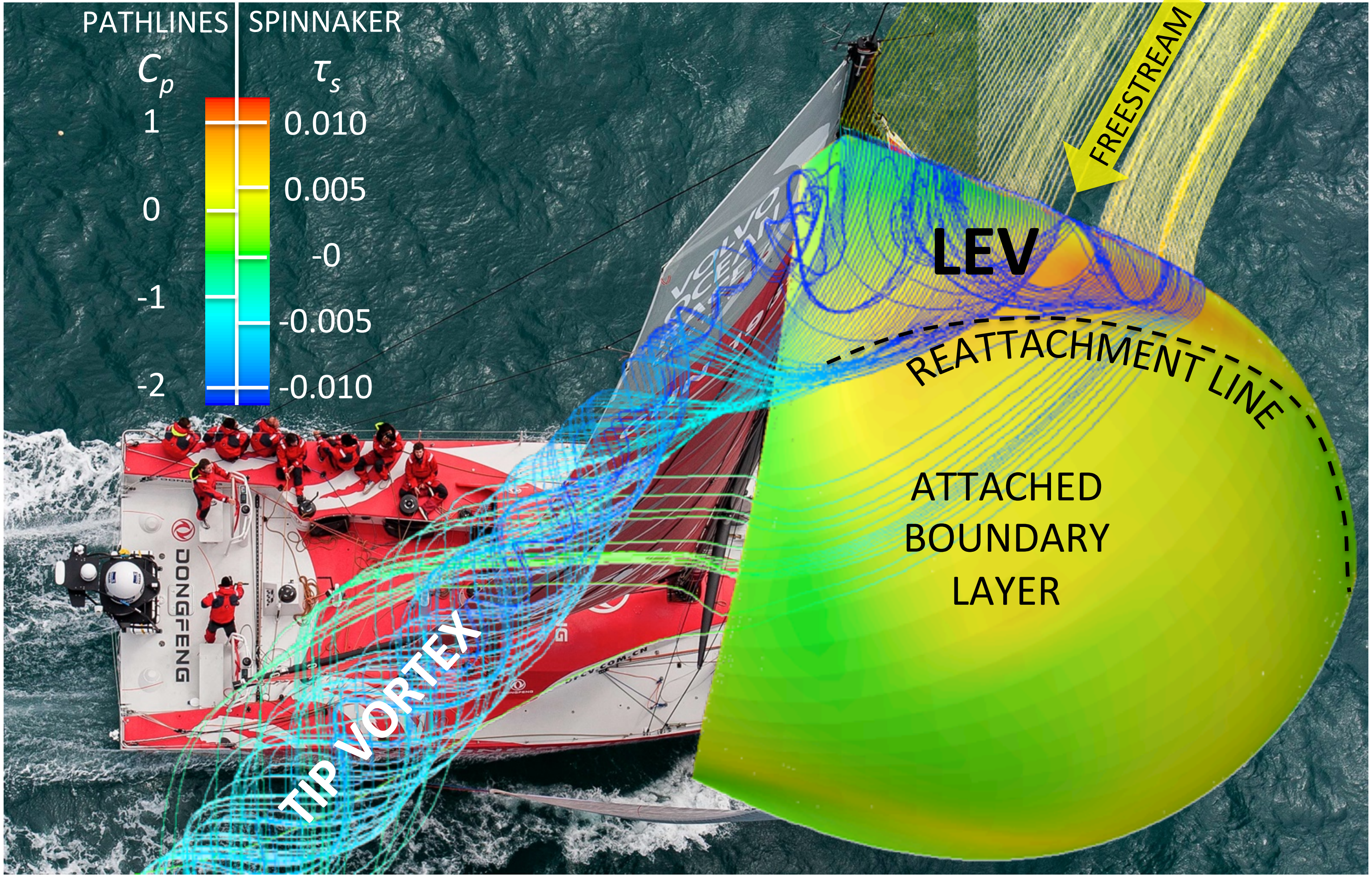


LEV on a bird wing
(Videler et al., 2004)



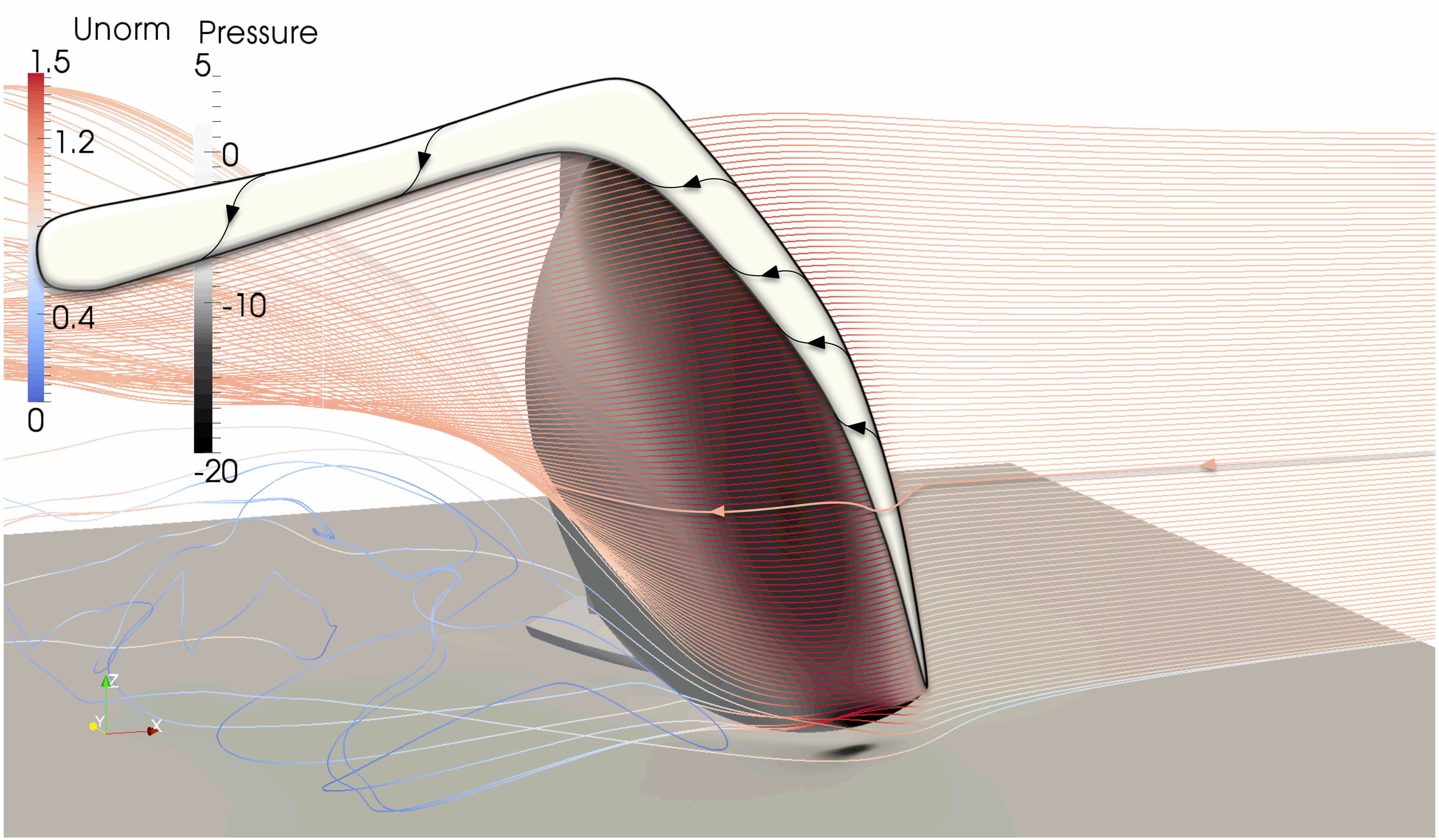
Lentink Lab (Stanford)

LEV on (downwind) sails



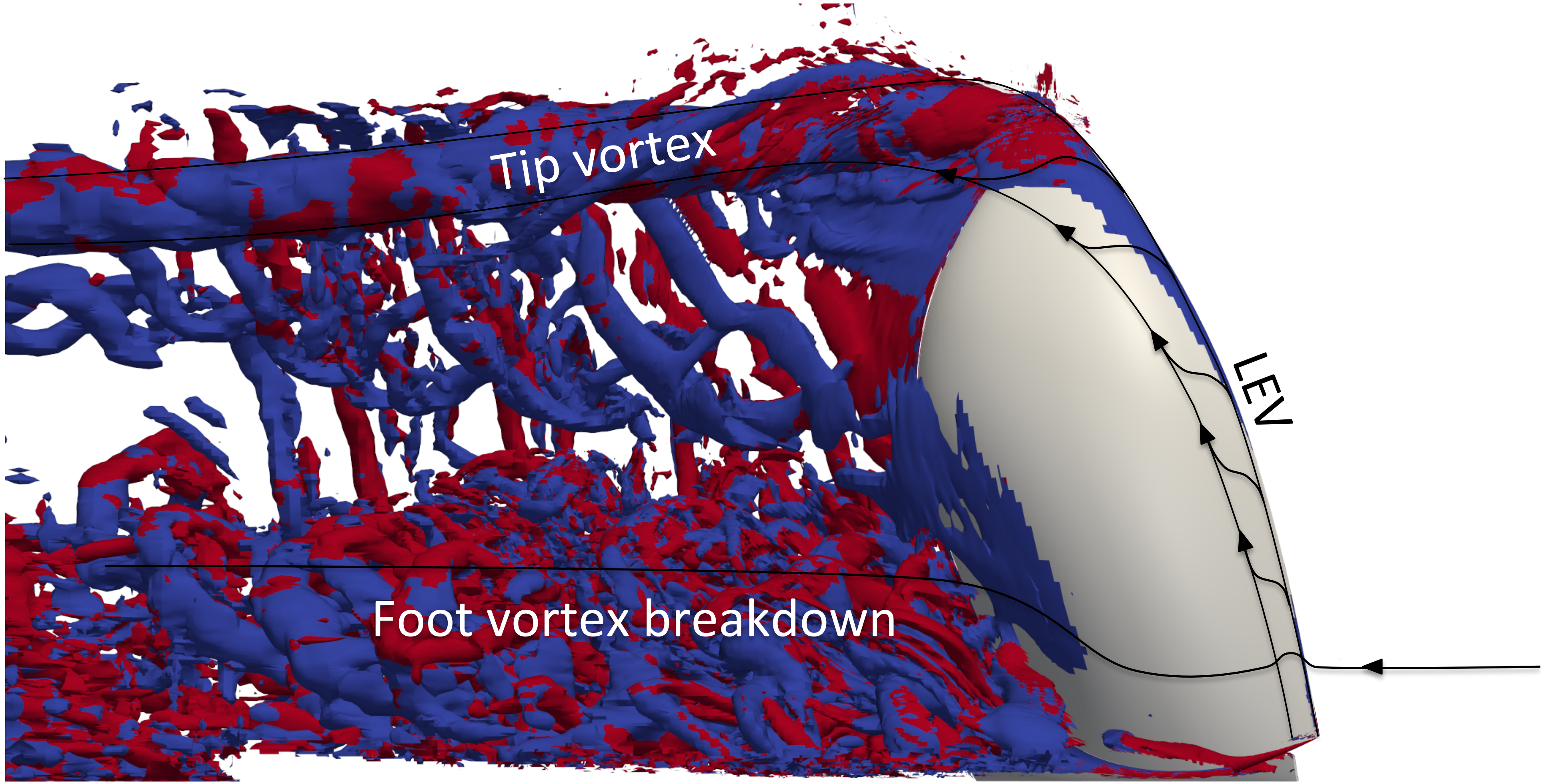
Viola et al., OE 2014;90

LEV on (downwind) sails



Viola et al., OE 2014;90

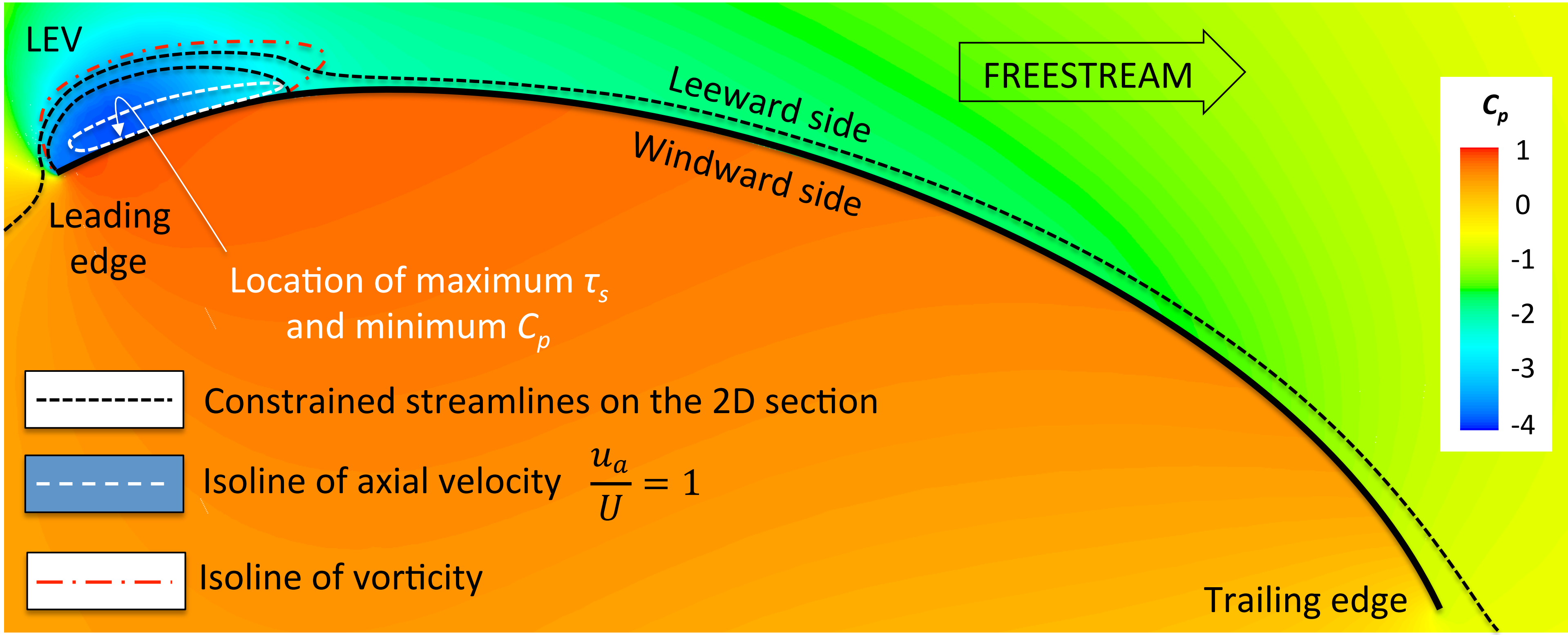
LEV on (downwind) sails



Viola et al., OE 2014;90

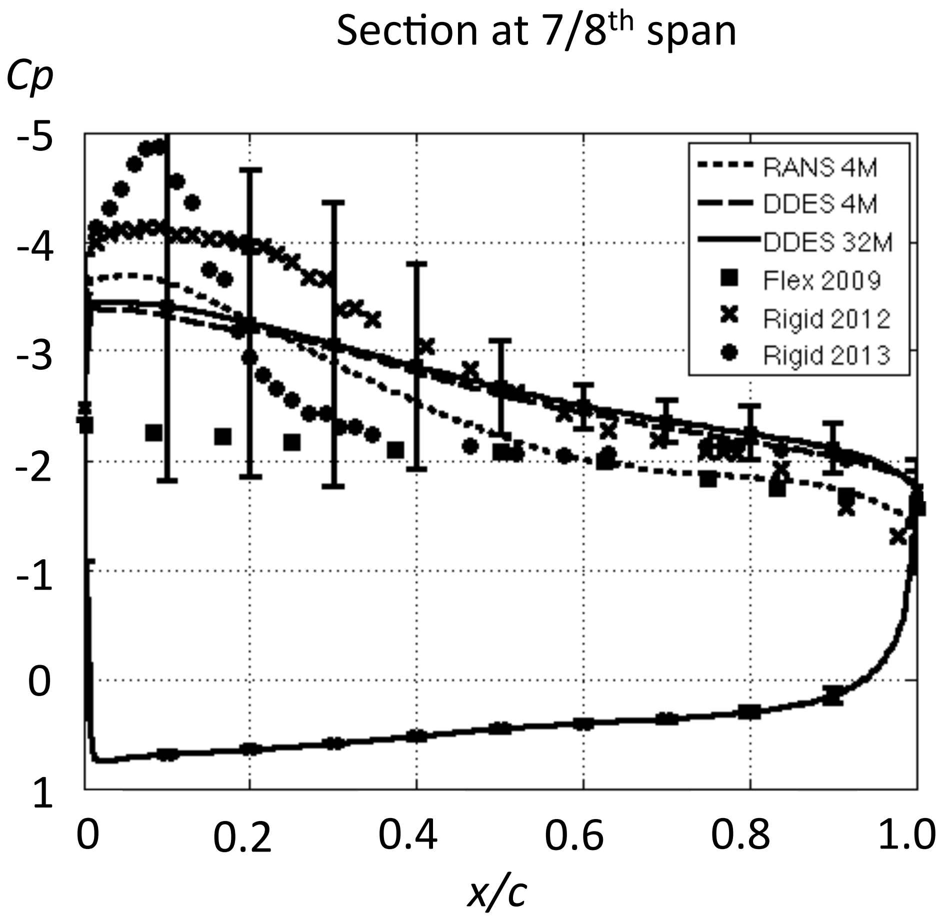
LEV on (downwind) sails

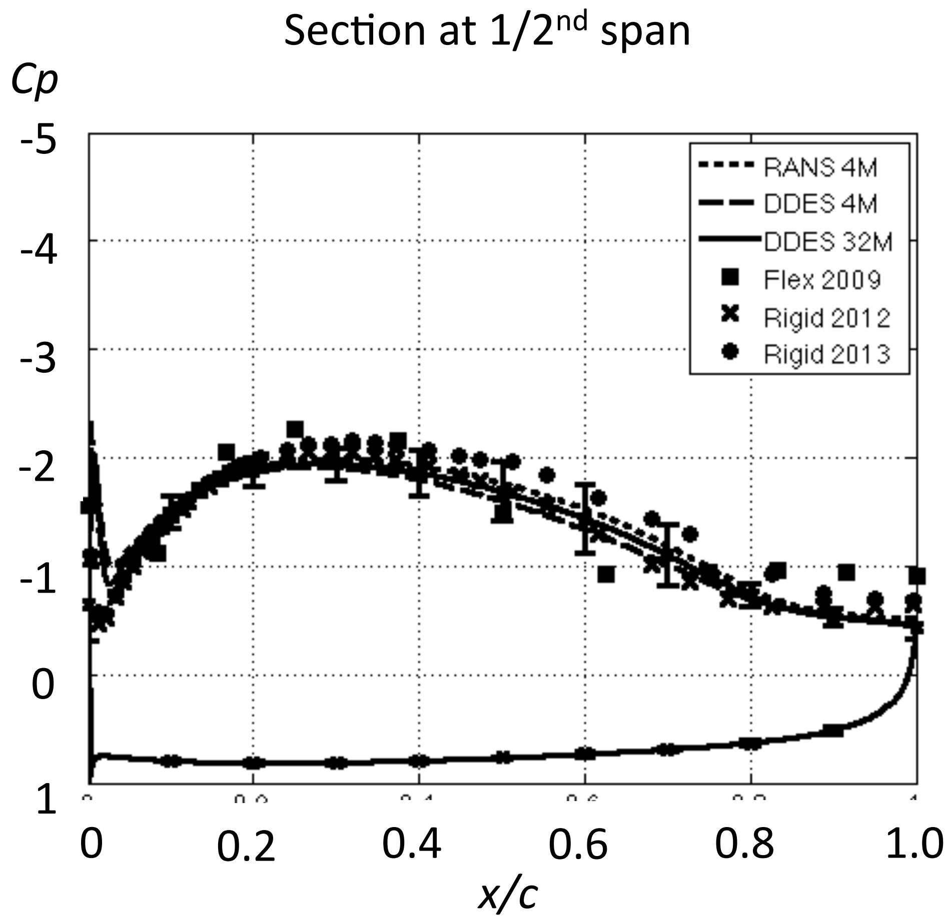
Section at 7/8th span



Viola et al., OE 2014;90

LEV on (downwind) sails



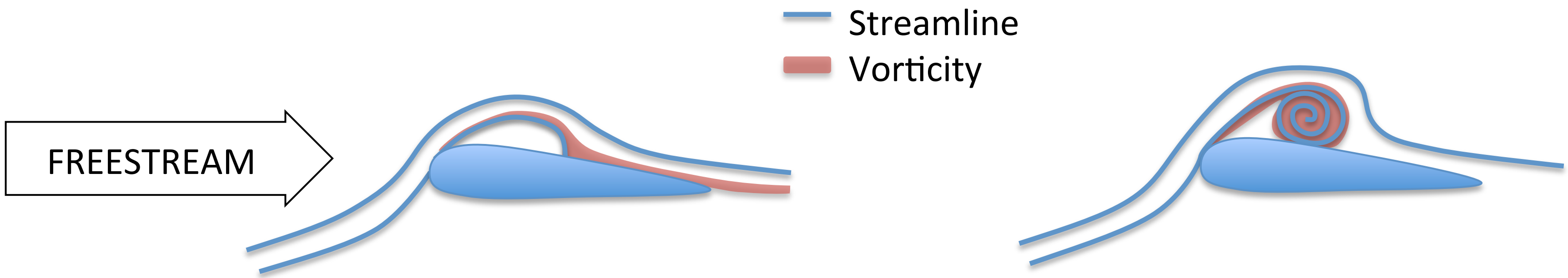


Viola et al., OE 2014;90

LEV vs LSB

LSB (upwind sails)

LEV (downwind sails)



Vorticity is convected towards the centre of the vortex and extracted from axial velocity at the head of the sail

Discrete pockets of clockwise vorticity are generated from the separated shear layer and are convected downstream

Conclusions

- Sails are 3D THIN CHAMBERED TWISTED FLEXIBLE WINGS experiencing large spanwise velocity gradients and high turbulence

- Leading edge separation and reattachment occur
  - LSB has been computed (non measured) on upwind sails
    LSB is thin and narrow, leading to a minor effect on pressure
  - LEV has been computed (non measured) on downwind sails
    LEV grows toward the tip leading to large suction and uplift shear
- Trailing edge separation may occur

- Forces on sails can be predicted within the experimental uncertainty
  - Upwind sails: ±1%
  - Downwind sails: ±20%

- Effect of flexibility and Reynolds number on near-wall flow are unknown

Acknowledgments

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- Susan Tully (RA)
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- Emmanouil Falagkaris (PhD st)

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