Stability of the boundary layer flow at the leading-edge of a swept Joukowski airfoil

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ONERA – DAAA/MAPE

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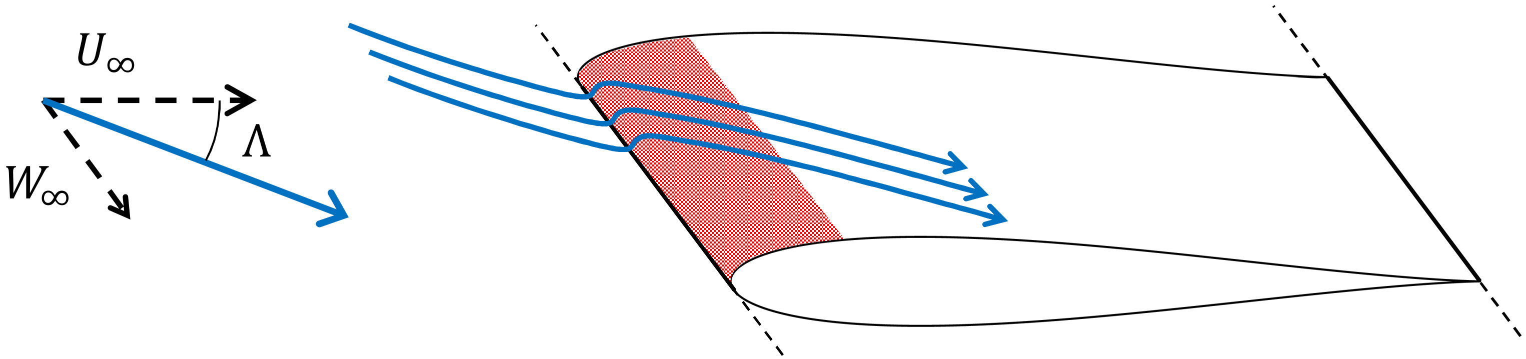
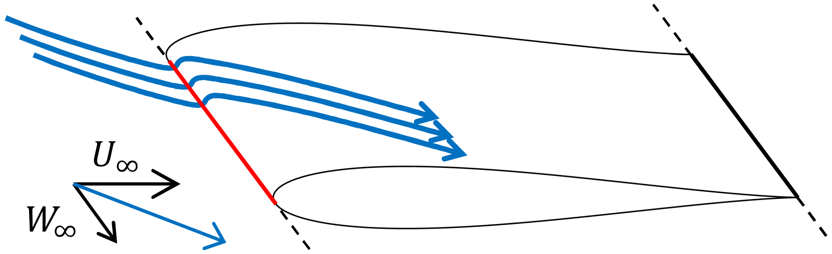
Introduction

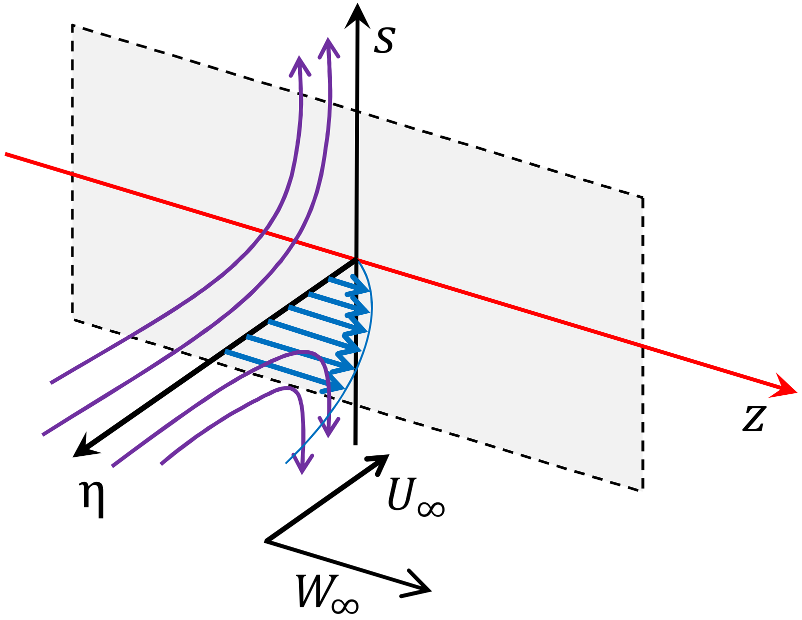
- Transition to turbulence on swept wings occurs near the leading edge due to the growth of instability waves in this region
  - ➢ Stability of the flow in the leading-edge region ?
  - ➢ Mechanisms responsible for amplification ?



Two mechanisms of amplification

- Attachment-line flow
  - Swept Hiemenz flow
  - Control parameter $Re_s = \frac{W_\infty \delta}{\nu}$





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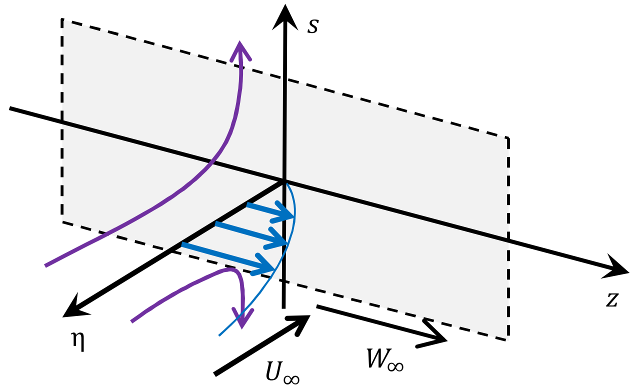

- Stability of spanwise travelling perturbations $\mathbf{q}(s,\eta)e^{i(\beta z - \omega t)}$

  - Viscous instability of the spanwise profile above $Re_s^{critical} = 583.1$
    (Hall & Malik, PRSA 1984)

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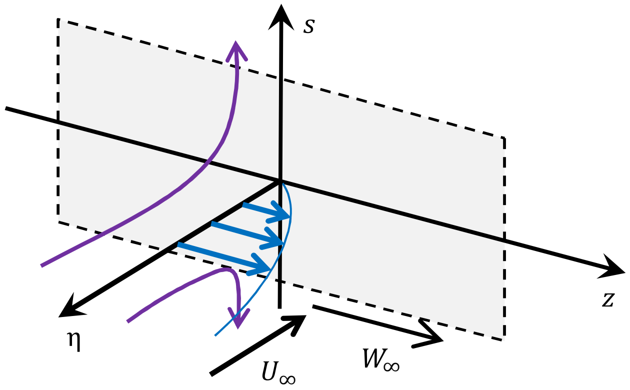

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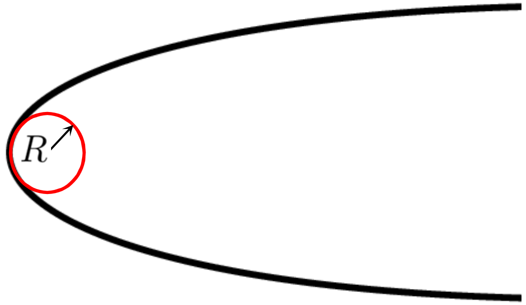
  - Viscous instability of the spanwise profile above $Re_s^{critical} = 583.1$
    (Hall & Malik, PRSA 1984)

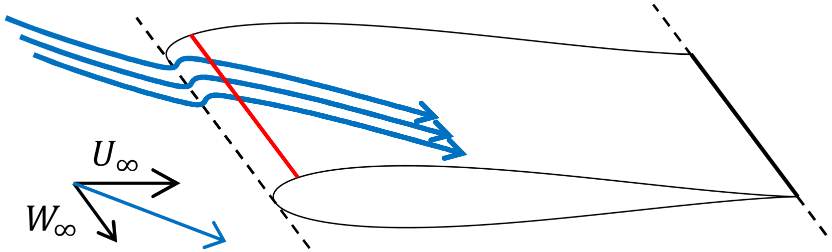
  - Stabilizing influence of leading-edge curvature
    (Lin & Malik, JFM 1997)

$$\frac{\delta}{R} \propto \frac{1}{\sqrt{Re_R}} \qquad Re_R = \frac{U_\infty R}{\nu}$$

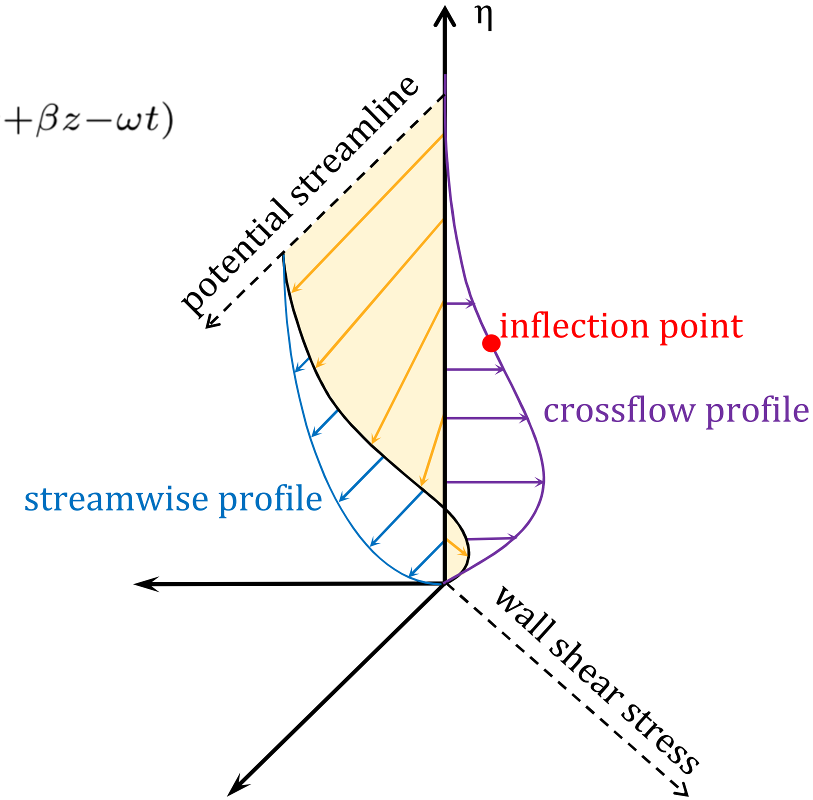


Two mechanisms of amplification

- Further downstream
  - Crossflow velocity profile
  - Falkner-Scan-Cooke flow



- Local stability to perturbations $\mathbf{q}(\eta)e^{i(\alpha s+\beta z-\omega t)}$
  - Inviscid instability of the inflectional profile
  - Absolute instability chordwise (Lingwood, JFM 1997)

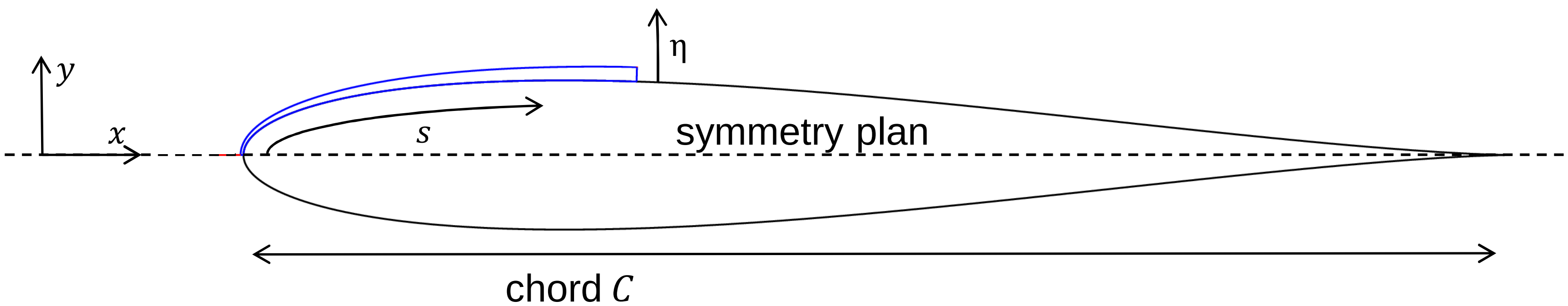


Global stability of a realistic airfoil

- Need for global stability analysis of a realistic leading-edge
  - Full account of leading-edge geometry
  - Interplay between attachment-line and crossflow mechanisms
  - Possibility of global instability due to the crossflow mechanism

Numerical method

- Global stability of a Joukowski profile
  - Fixed airfoil geometry $R/C = 0.016$



Numerical method

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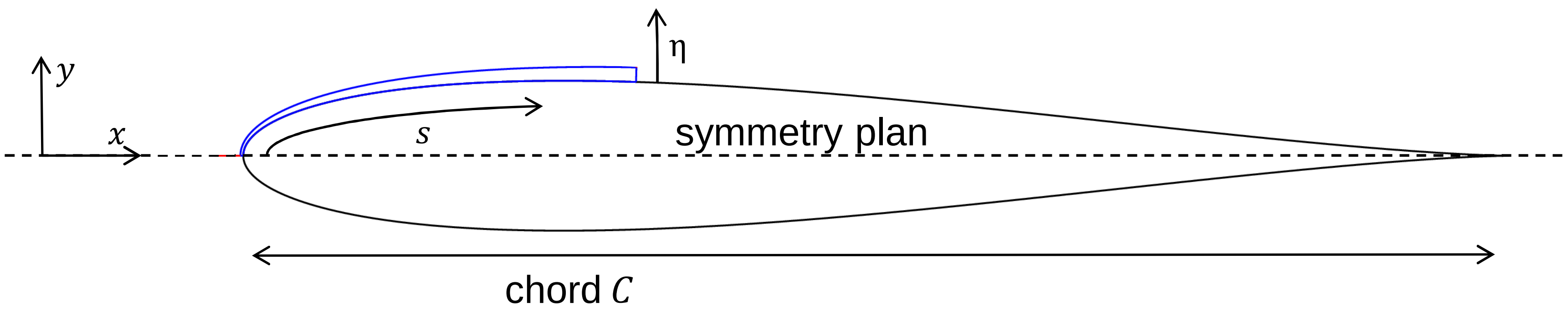

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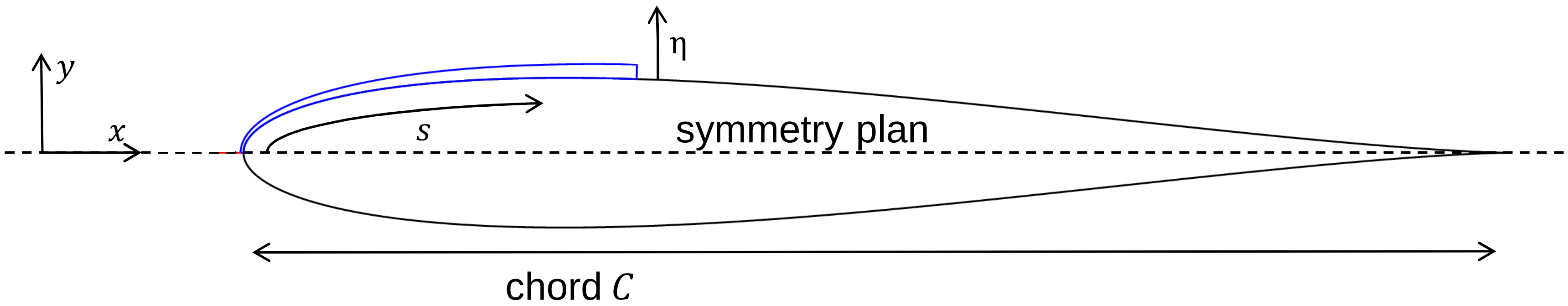

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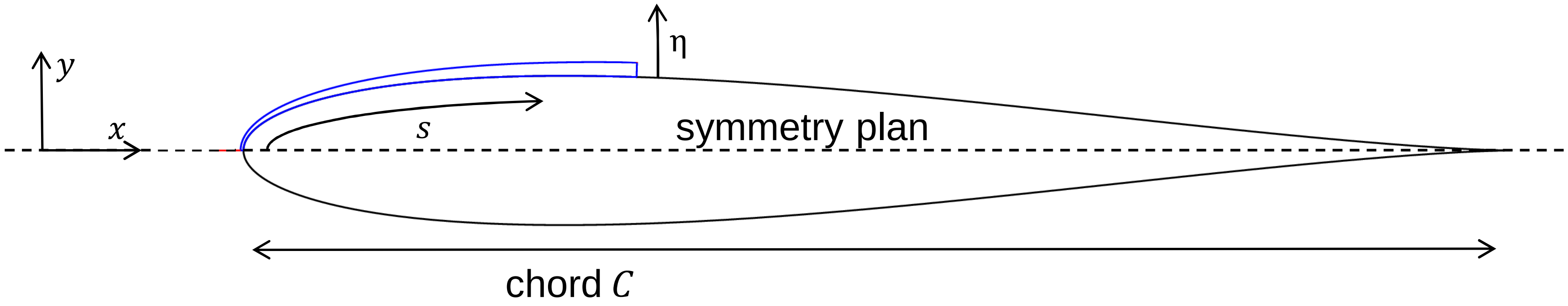
  - Numerical domain extending up to $s = 0.32C$



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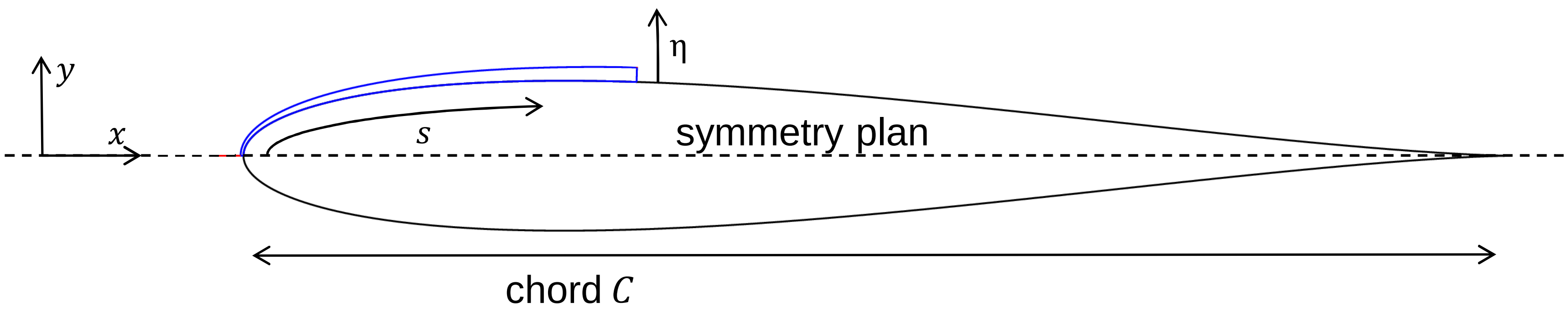
  - Symmetric modes only



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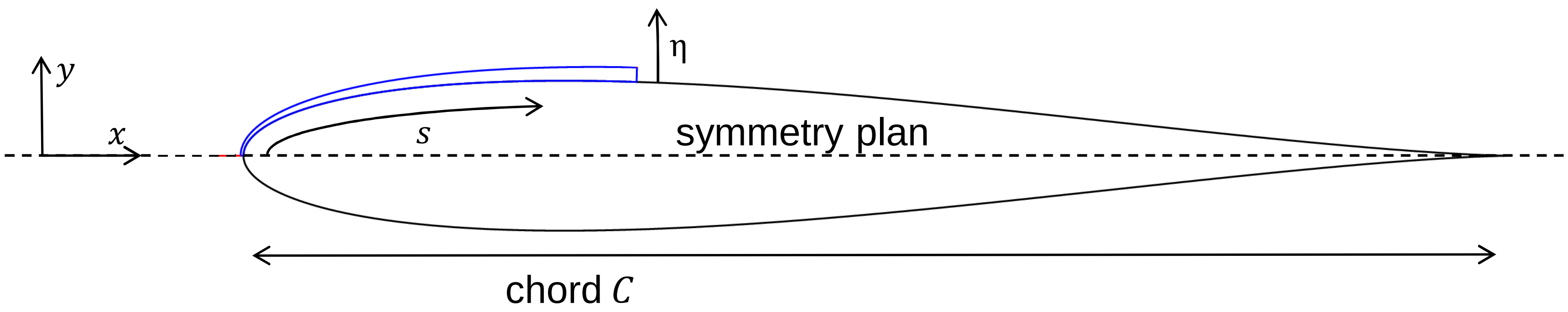
  - Symmetric modes only
  - Finite element discretization with FreeFem++ (Hecht, JNM 2012)



Global stability of leading-edge flow

- Stability threshold for $Re_R = 10^4$ ($Re_C = 6.2 \times 10^5$)

Computed threshold on Joukowski airfoil $Re_s^{critical} = 411$

SH flow with curvature (Lin & Malik, JFM 1997) $Re_s^{critical} = 638$

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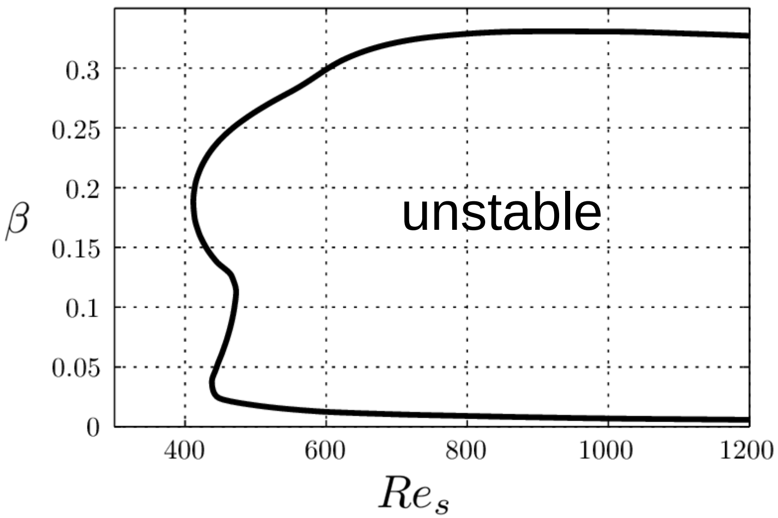
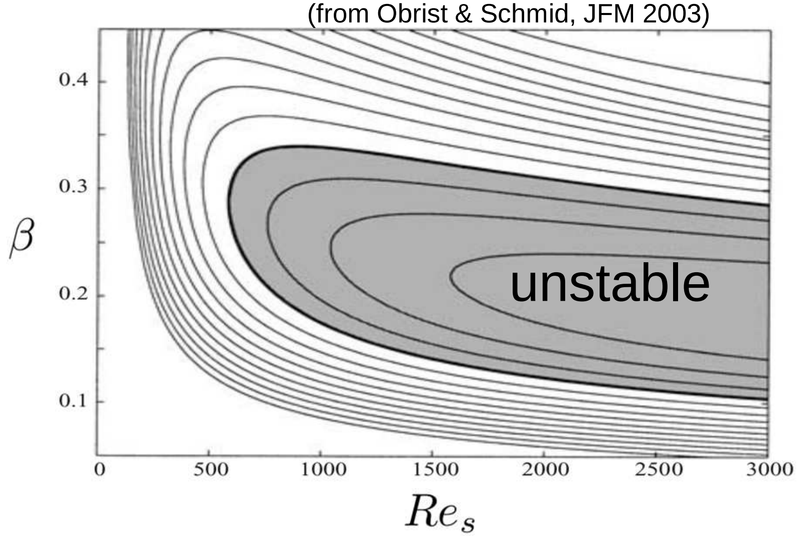
- Critical stability curve

Joukowski airfoil $Re_R = 10^4$



Swept Hiemenz flow w/o curvature

(from Obrist & Schmid, JFM 2003)



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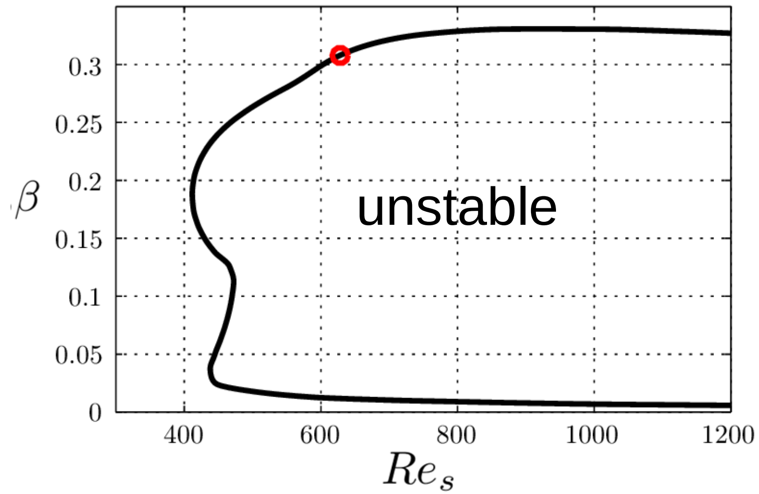
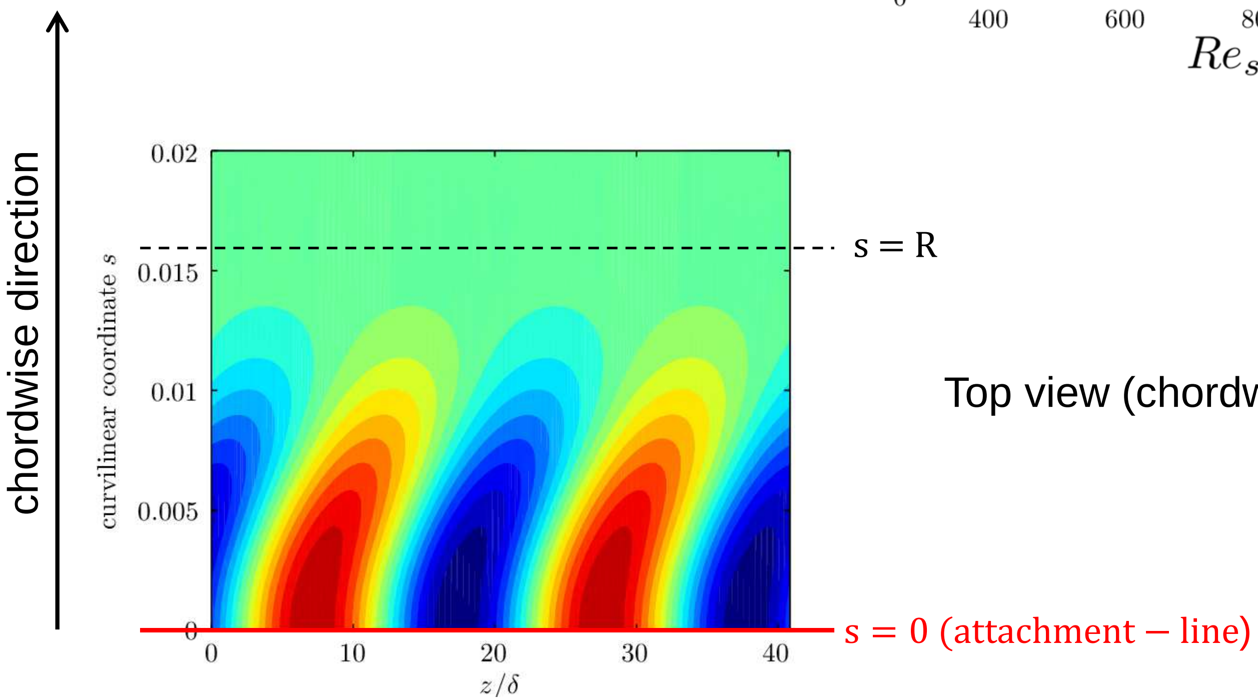
Critical modes analysis

$Re_s = 628$ $\beta = 0.31$

- Mode located within $s < R$
- Wavefront aligned with chord





Top view (chordwise vorticity)

Critical modes analysis

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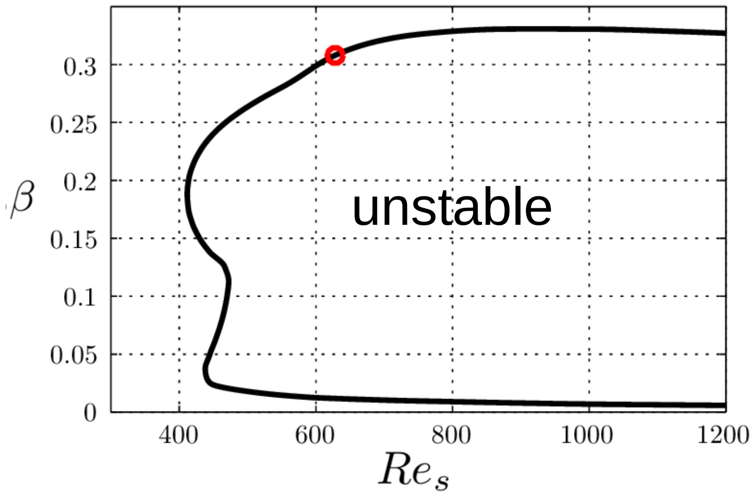
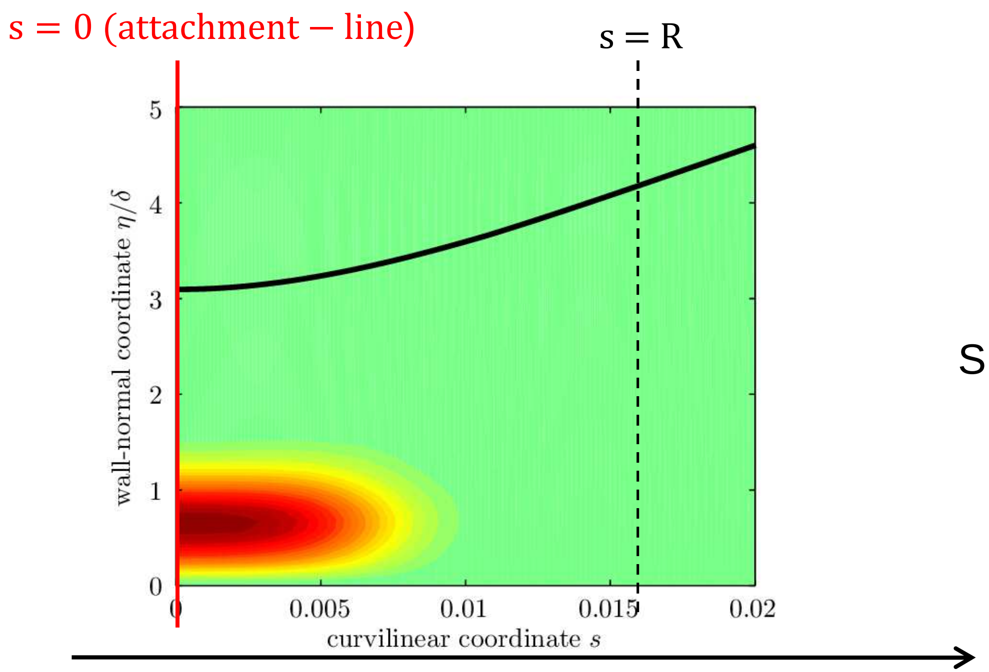
- Mode located within $s < R$
- Wavefront aligned with chord
- Instability core located at the AL





Side view (structural sensitivity)

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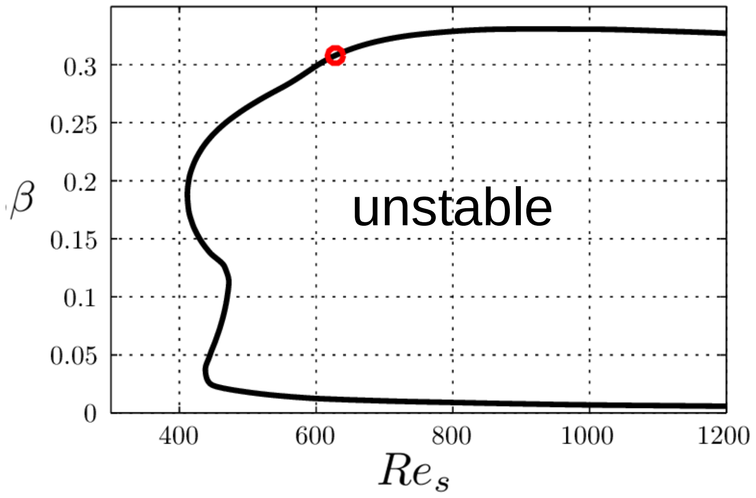

ATTACHMENT-LINE MODE

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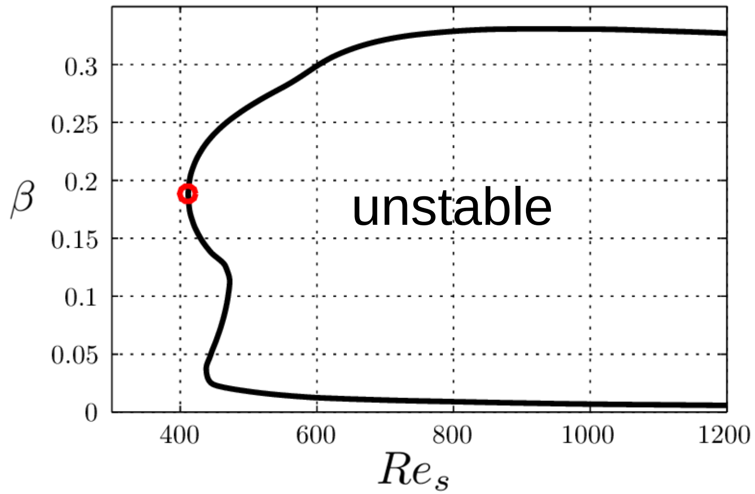
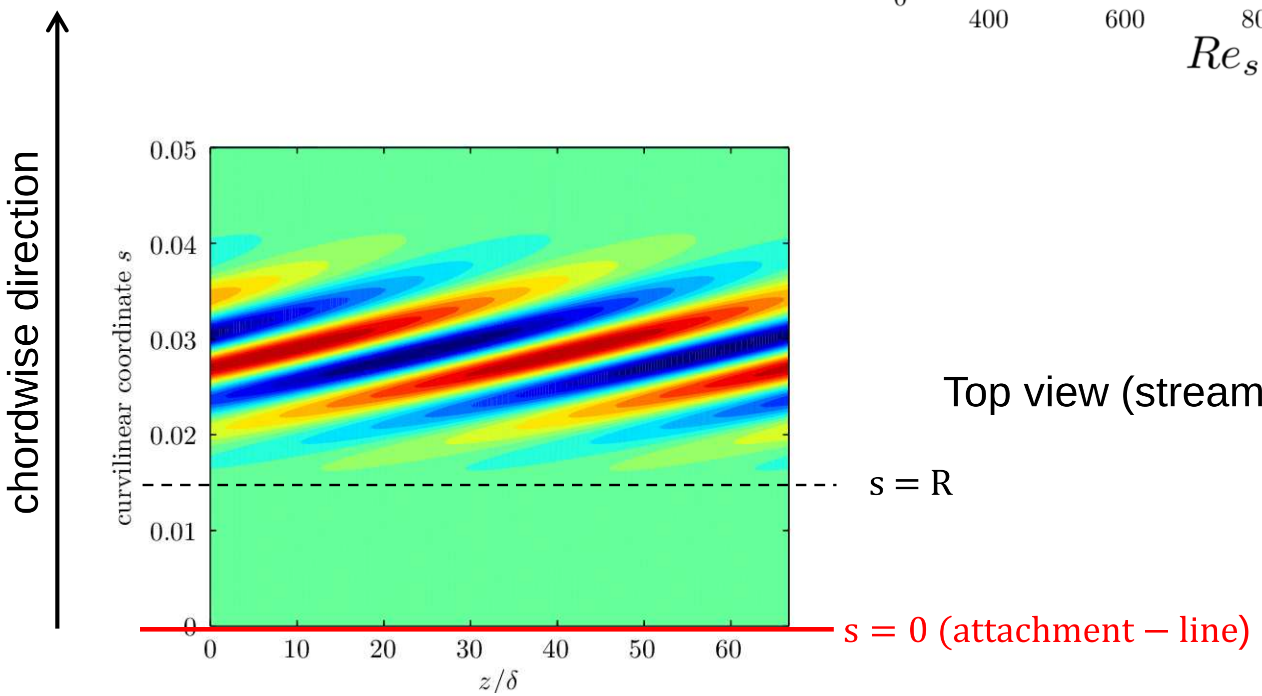
$Re_s = 411$ $\beta = 0.19$

- Mode located further downstream
- Wavefronts angle with chord $\sim 34°$



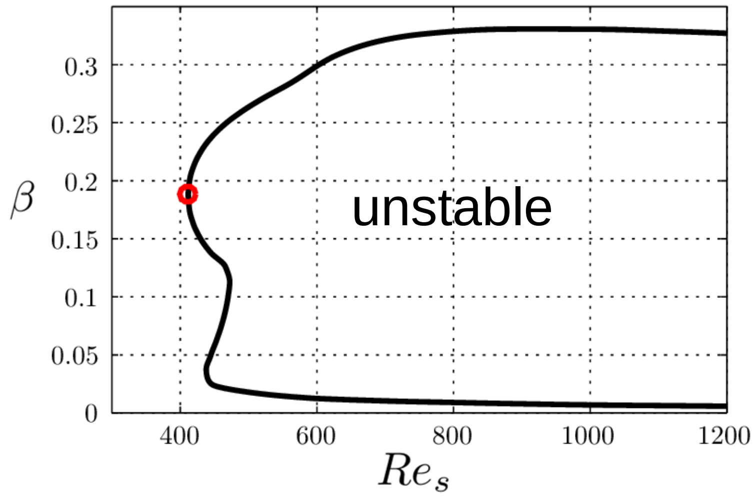


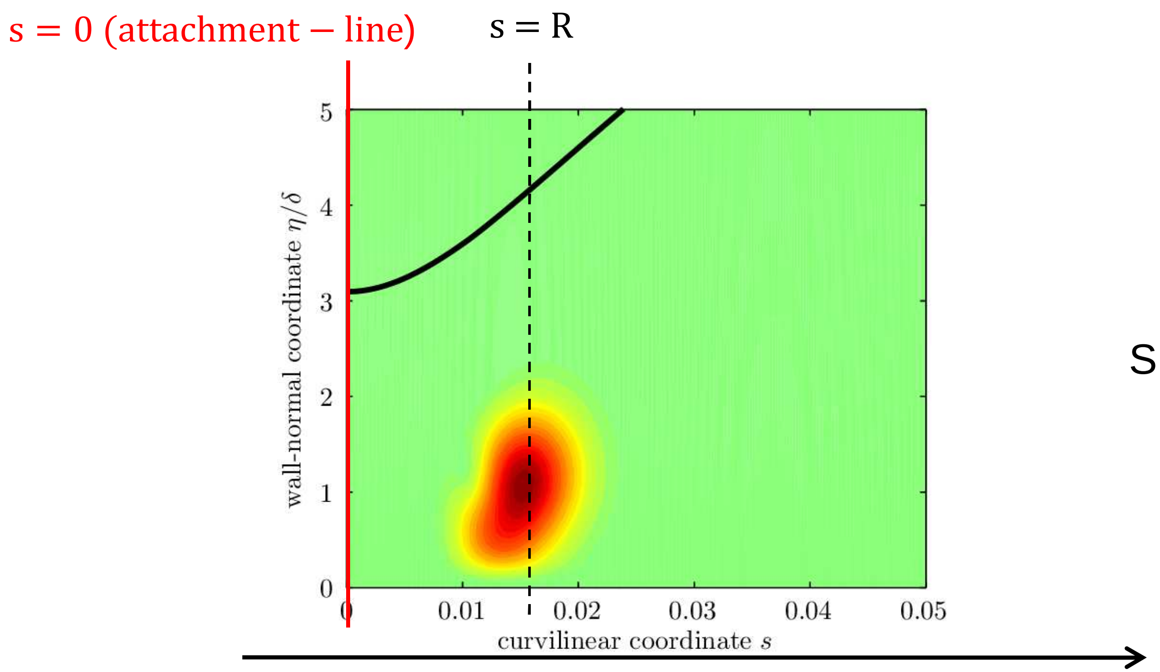
Top view (streamwise vorticity)

Critical modes analysis

$Re_s = 411$ $\beta = 0.19$

- Mode located further downstream
- Wavefronts angle with chord $\sim 34^\circ$
- Instability core downstream of AL





Side view (structural sensitivity)

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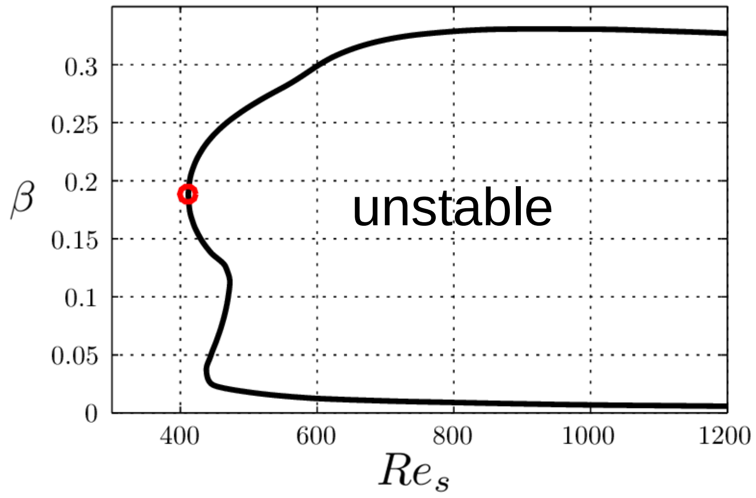
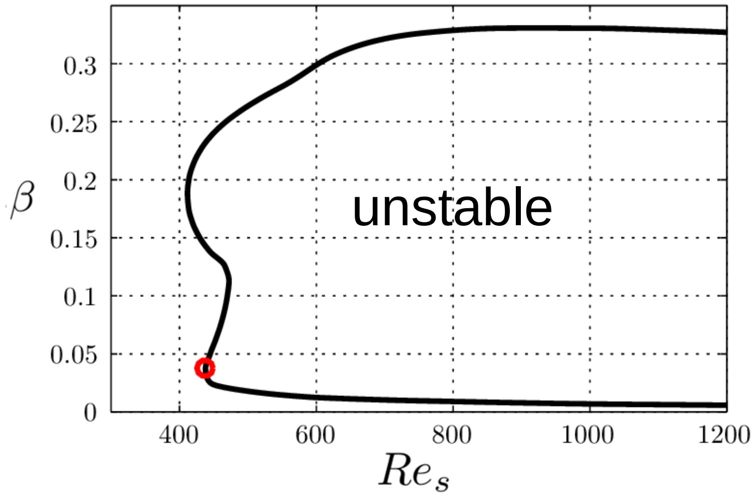


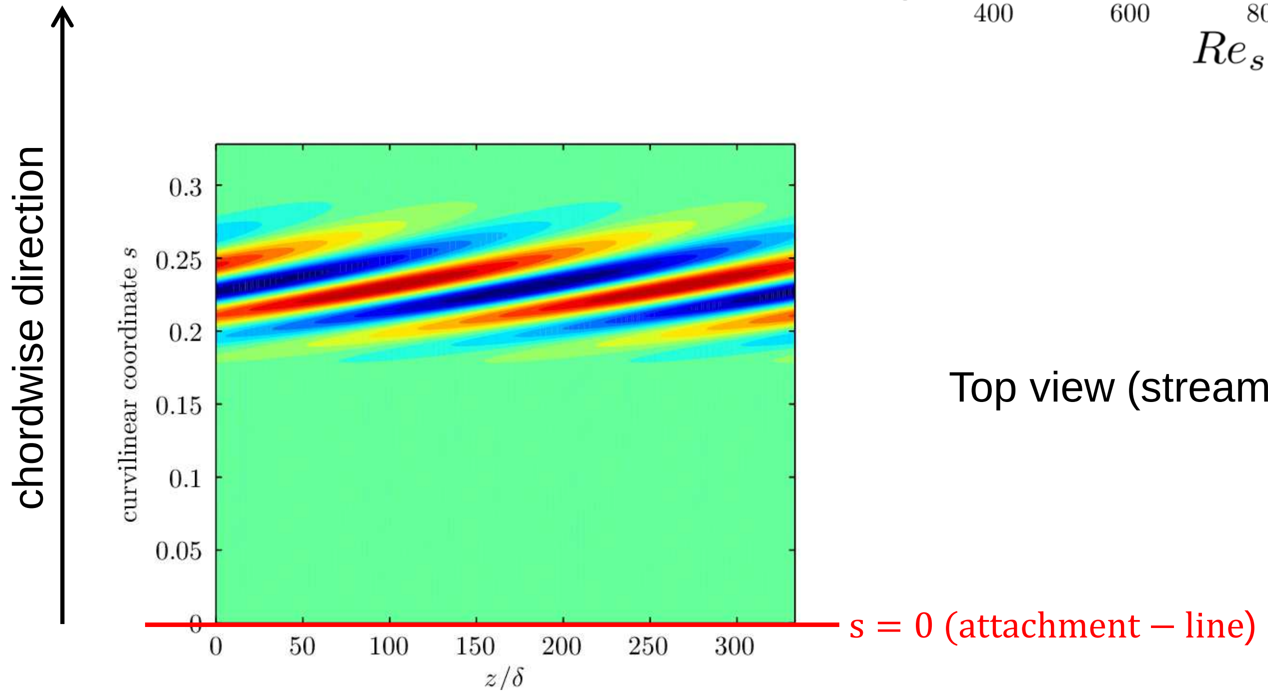
CROSSFLOW MODE

Critical modes analysis

$Re_s = 437$ $\beta = 0.04$

- Similar features: crossflow mode
- Located much further downstream





Top view (streamwise vorticity)

Conclusions

- The stability thresholds of the attachment-line modes are not valid for realistic leading edges when wall-curvature effects are significant

- Another type of unstable global modes appears, driven by the crossflow mechanism downstream of the attachment-line

- These modes are unstable at lower critical sweep Reynolds number, and for lower wavenumbers

- The lower the spanwise wavenumber, the further downstream the mode is located

Thank you for your attention !

Any questions ?