Universität Stuttgart, Fakultät Luft- und Raumfahrttechnik und Geodäsie
- Vorlesung -

Strömungsinstabilitäten und laminar-turbulenter Strömungsumschlag // Flow Instability and Laminar-to-Turbulent Transition

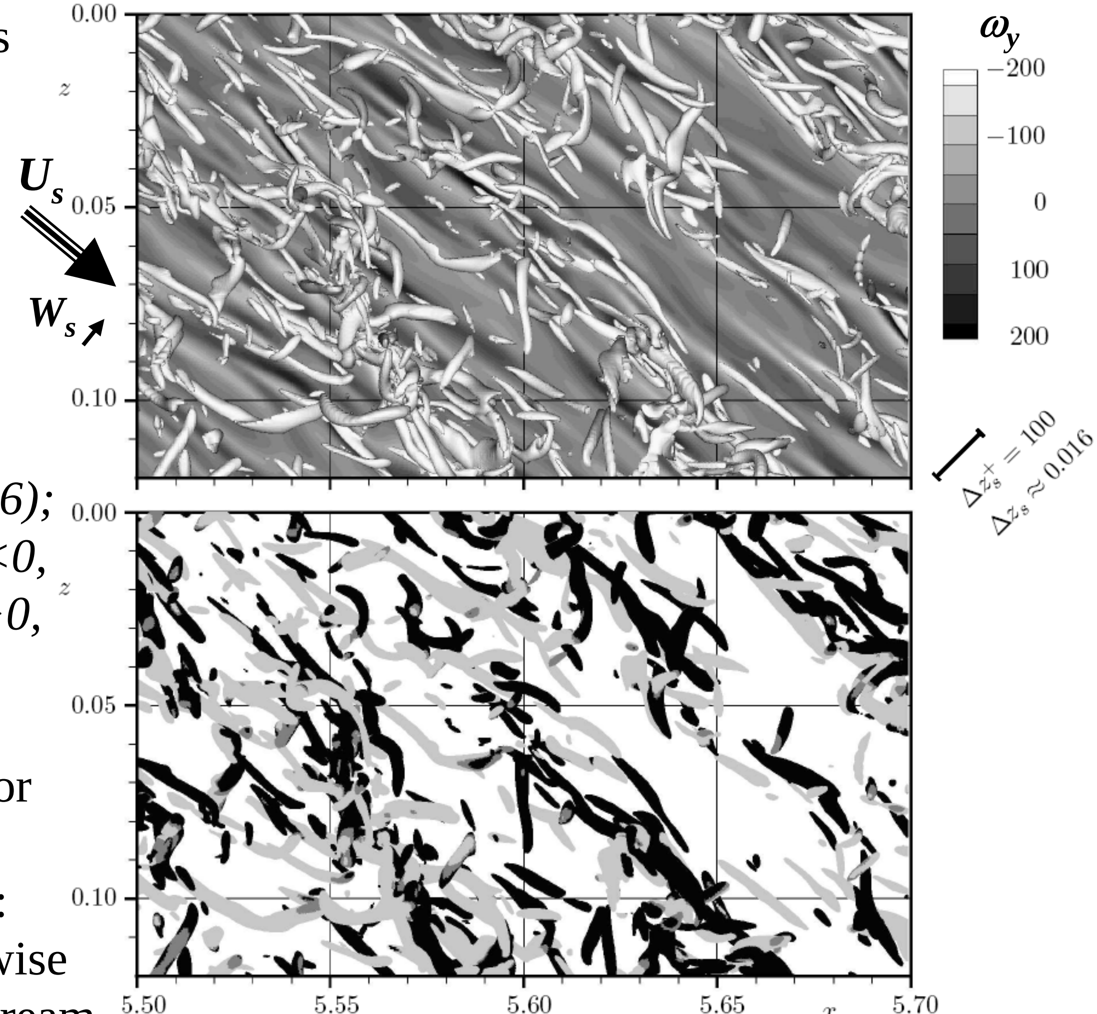
Hauptdiplom, Vertiefungsfach Strömungslehre
2 Semesterwochenstunden im SS

Dozent:
Dr. Markus J. Kloker

Snapshot of near-wall vortices in a turbulent boundary layer (top view, after crossflow transition, Re_θ=*950*).

Upper: *vortices* (λ_2-isosurfaces, y^+*<100)* and, in background, *wall-normal vorticity* ω_y *(*$y^+ \approx$*6);* white: *low-speed streaks,* ω_y *<0,* dark: *high-speed streaks,* ω_y *>0,* generated by the vortices.

Lower: *streamwise vorticity* for the vortices shown above, indicating their rotation sense: black/grey means anti-/clockwise rotation when looking downstream.

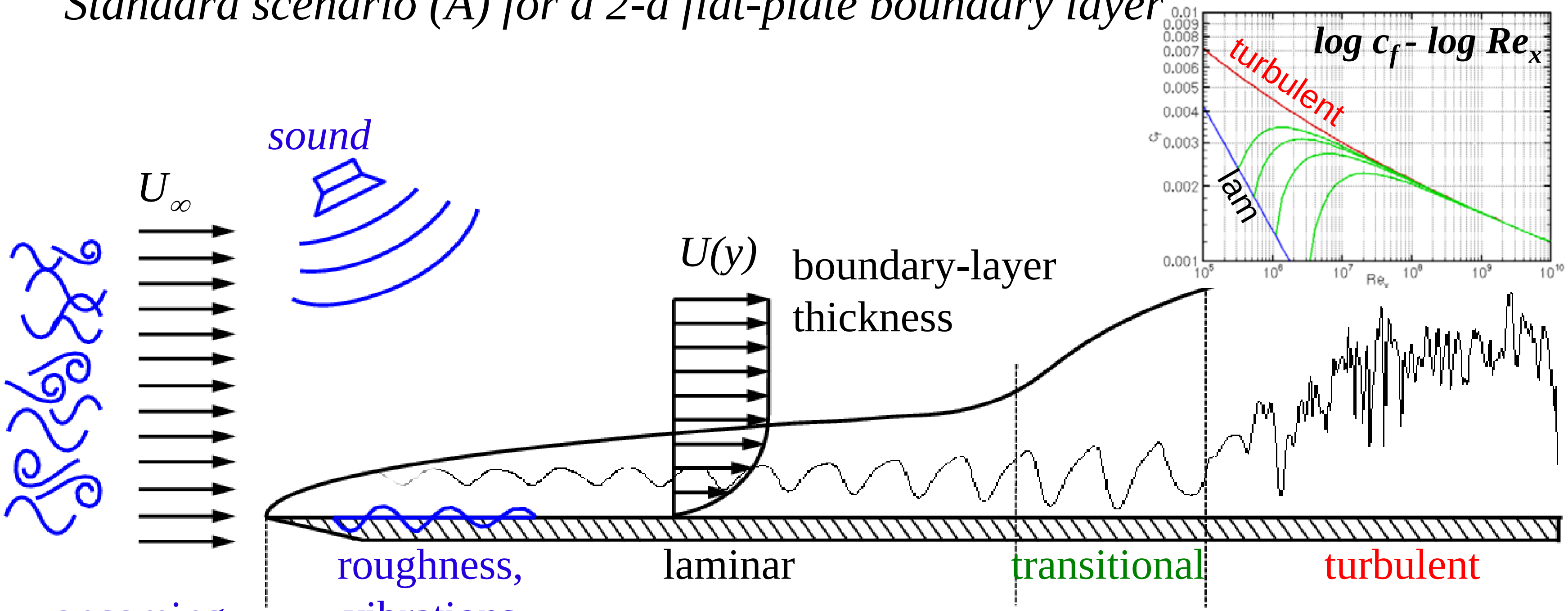


DNS Bonfigli & Kloker, IAG, 2002/6

Content of Lecture

- Review of the routes to "turbulence": ***any unsteady flow is a consequence of an instability of the underlying steady base flow*** if unsteady excitation is small or absent
- Introduction of the concept of (linear) ***primary instability*** of laminar shear flows:
  - modal exponential disturbance growth of wave-like disturbances
  - Orr-Sommerfeld Equation
  - non-modal, transient growth
- Transition prediction: *exp(N)* method based on OSE
- Discussion of the influence of, e.g., crossflow velocity, Mach number, wall temperature on the flow instability
- Weakly nonlinear instability: spectral and local ***secondary instability***
- Fully nonlinear mechanisms of laminar breakdown with ***formation of dynamical structures***
- Examples from experiments and detailed direct numerical simulations
- Discussion of some transition control methods

Standard scenario (A) for a 2-d flat-plate boundary layer



oncoming distubances

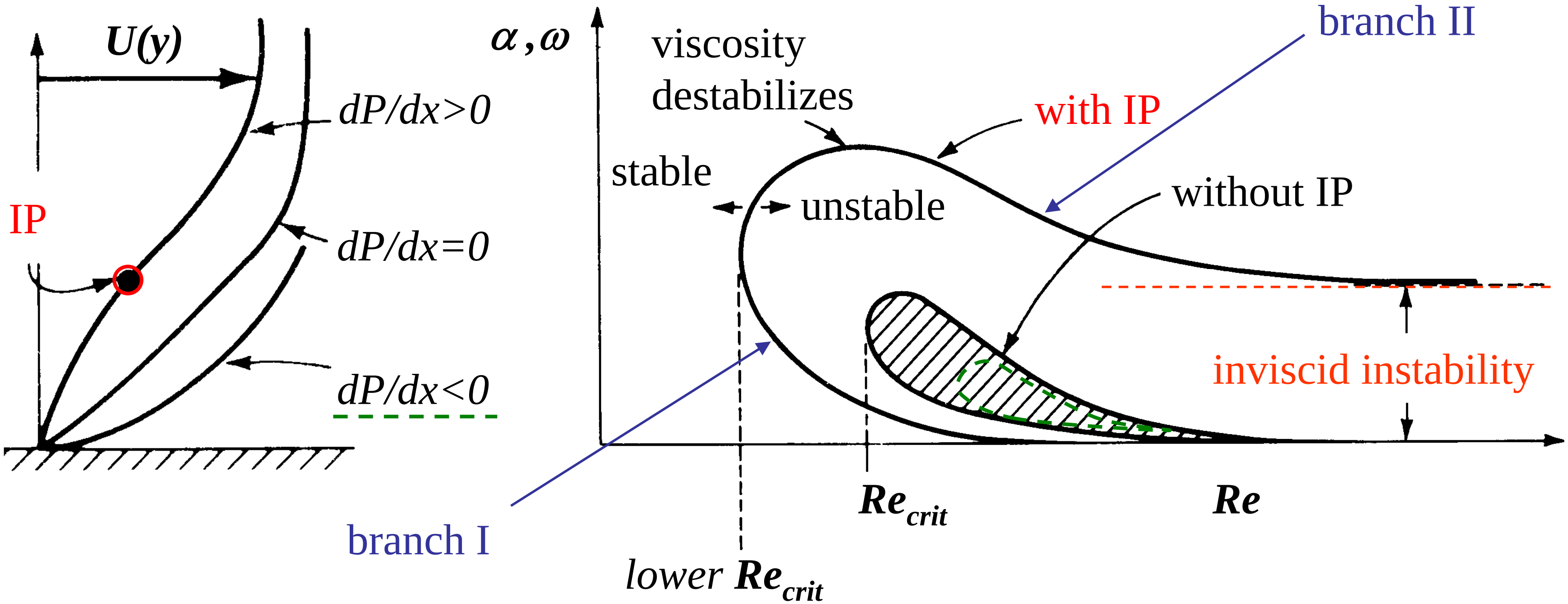
receptivity → primary instability → secondary instability → turbulence

primary instability ↓ TS modes

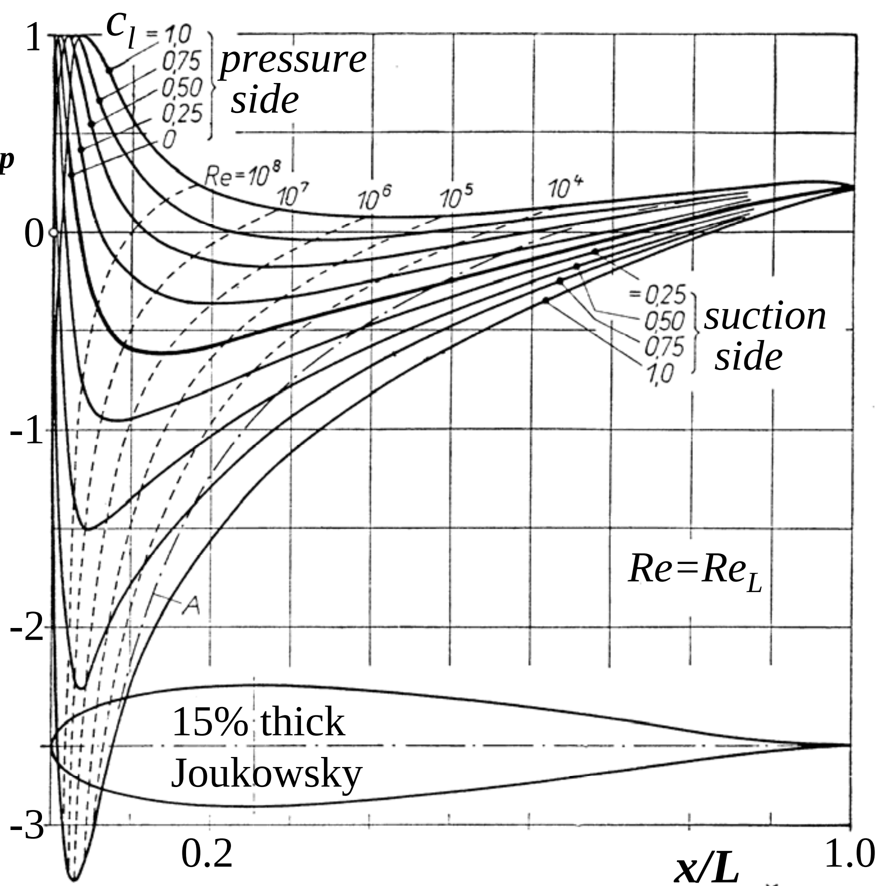
secondary instability ↓ fundamental / subharmonic resonance, Λ vortices

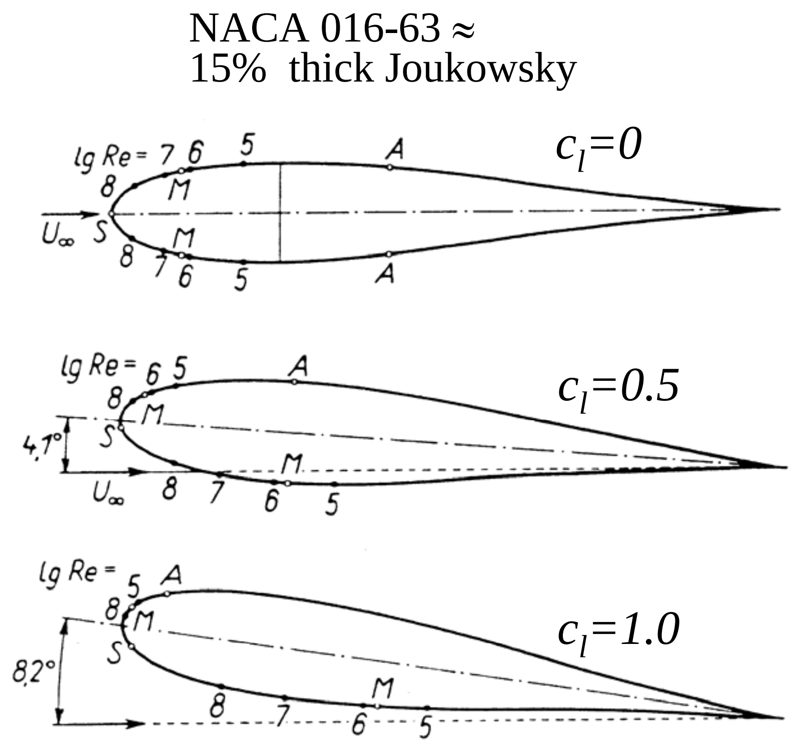
for small initial disturbances: TS modes

- Orr-Sommerfeld equation: TS-waves that represent downstream travelling "infinitely small spanwise vortices" can grow exponentially in a shear flow
- Stability diagram (2-d waves): instability inside "banana"
- Strong "inviscid" instability exists if the base-flow profile *U(y)* has an inflection point (IP) and at this point the modulus of the spanwise vorticity (~|*dU/dy*|) has a maximum as, e.g., for Falkner-Skan profiles with $\beta_H<0$.



Primary Instability, OSE / experiments, 1 *Flow Instability*





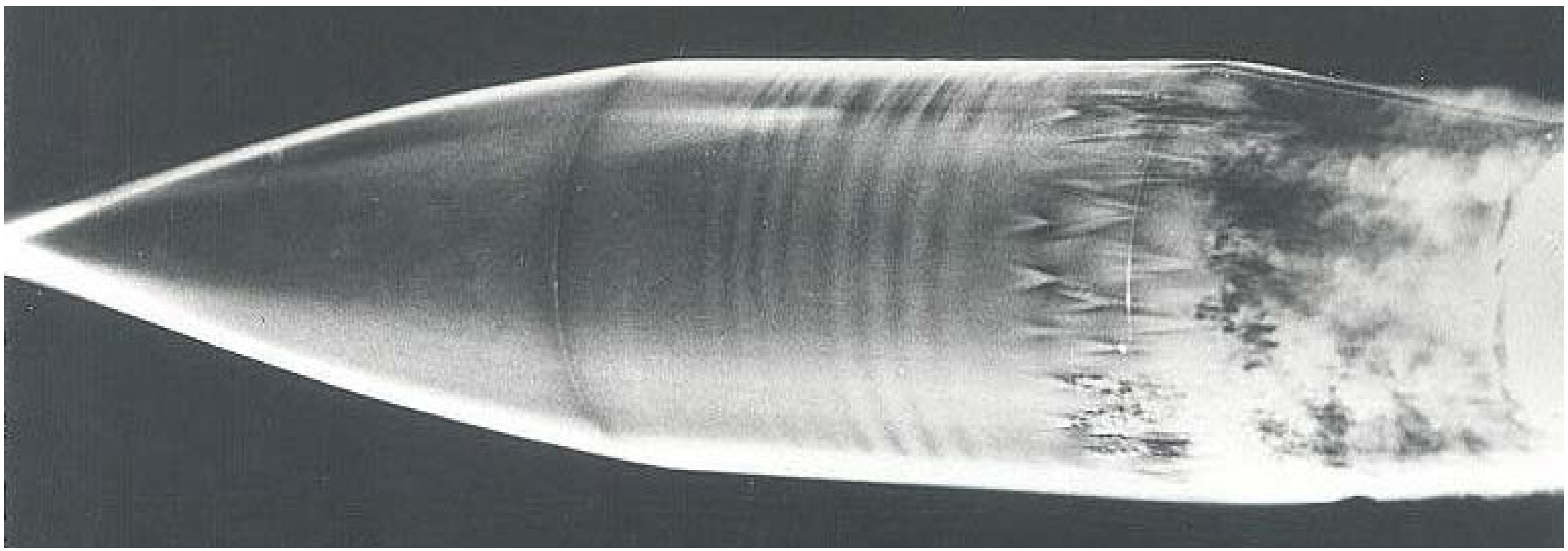
Position of boundary-layer instability onset (left) and transition (right) on a wing profile as function of chord *Re* number and lift coefficient c_l . *A* - boundary-layer separation for *laminar* flow until *A*; *M* - pressure minimum; *S* - stagnation point. For $Re_L \leq 5 \times 10^6$ transition occurs downstream of or around M.

Scenario A – Breakdown (Exp., 1) *Flow Instability*

- Experimental smoke visualization (snapshot) of TS-wave-induced breakdown on an axisymmetric body

TS-waves *Λ-vortices*

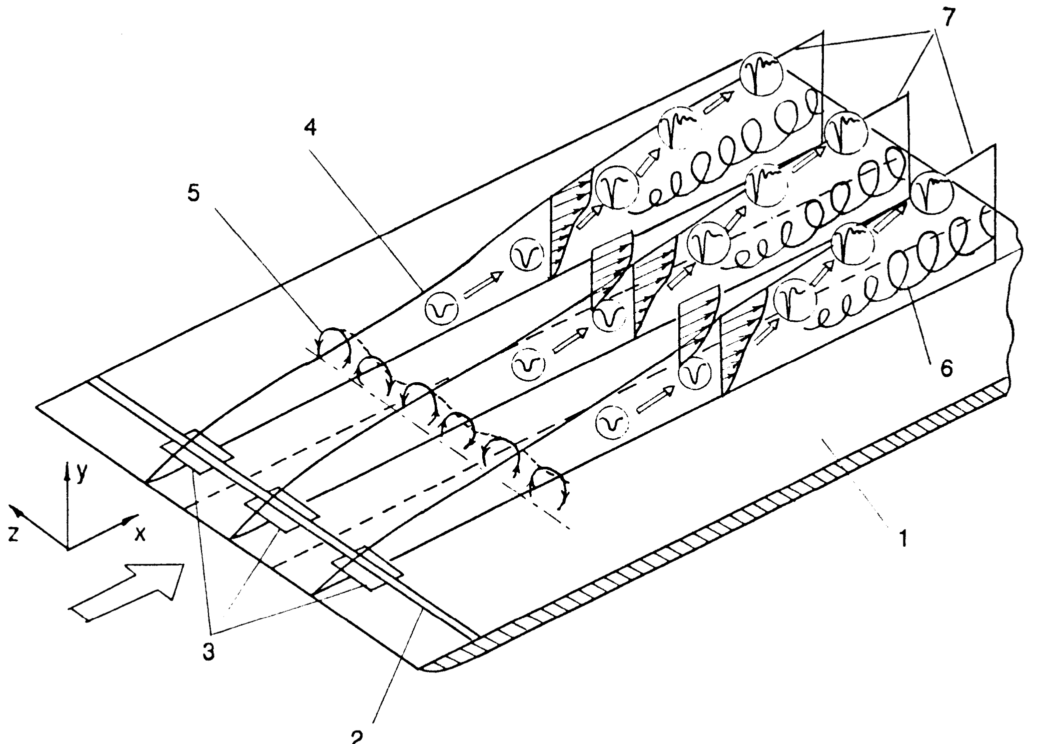
U



(T.J. Mueller, Nelson, Kegelmann, Morkovin 1981)

Scenario A – Breakdown (Exp., 2)

- Breakdown: Klebanoff's (1961) and Kachanov's (1985) controlled vibrating ribbon experiment in the Blasius boundary layer ⇒ K-Breakdown

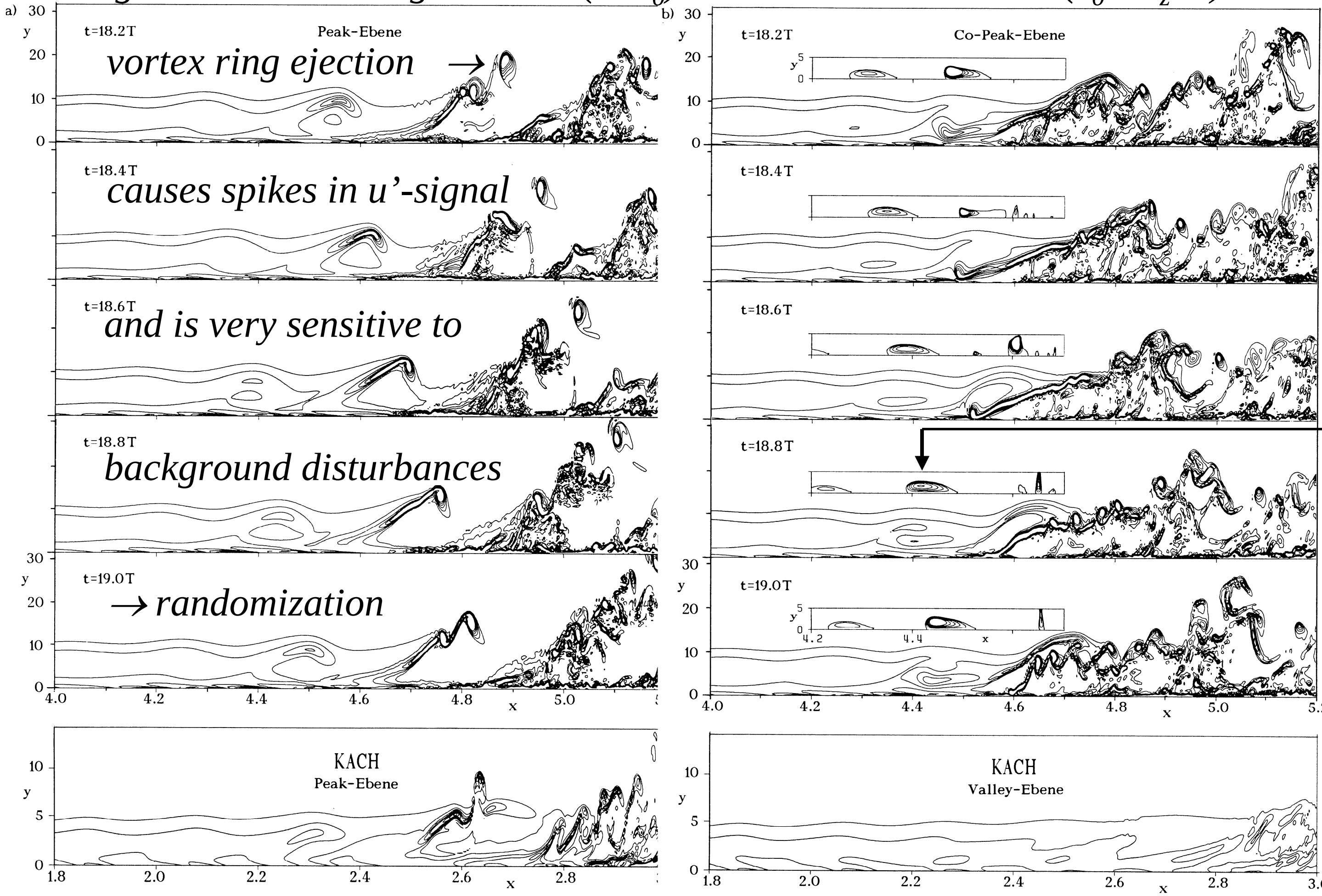


1 - plate, 2 - vibrating ribbon to induce 2-d Tollmien-Schlichting wave, 3 - tape spacers to prevent spanwise drift, 4 - boundary layer thickness, 5- longitudinal vortex pairs, 6 - turbulence start, 7 - disturbance "peak" planes with locally decelerated flow and instantaneous u-velocity "spike" signal

Scenario A – Breakdown (DNS, 1) *Flow Instability*

- Details of K-Breakdown (with adverse pressure): spanwise vorticity / shear-layers

longitudinal cut through Λ head ($z=z_0$) … *between Λ's ($z_0+\lambda_z/2$)*



vortex ring ejection →
causes spikes in u'-signal
and is very sensitive to
background disturbances
→ randomization

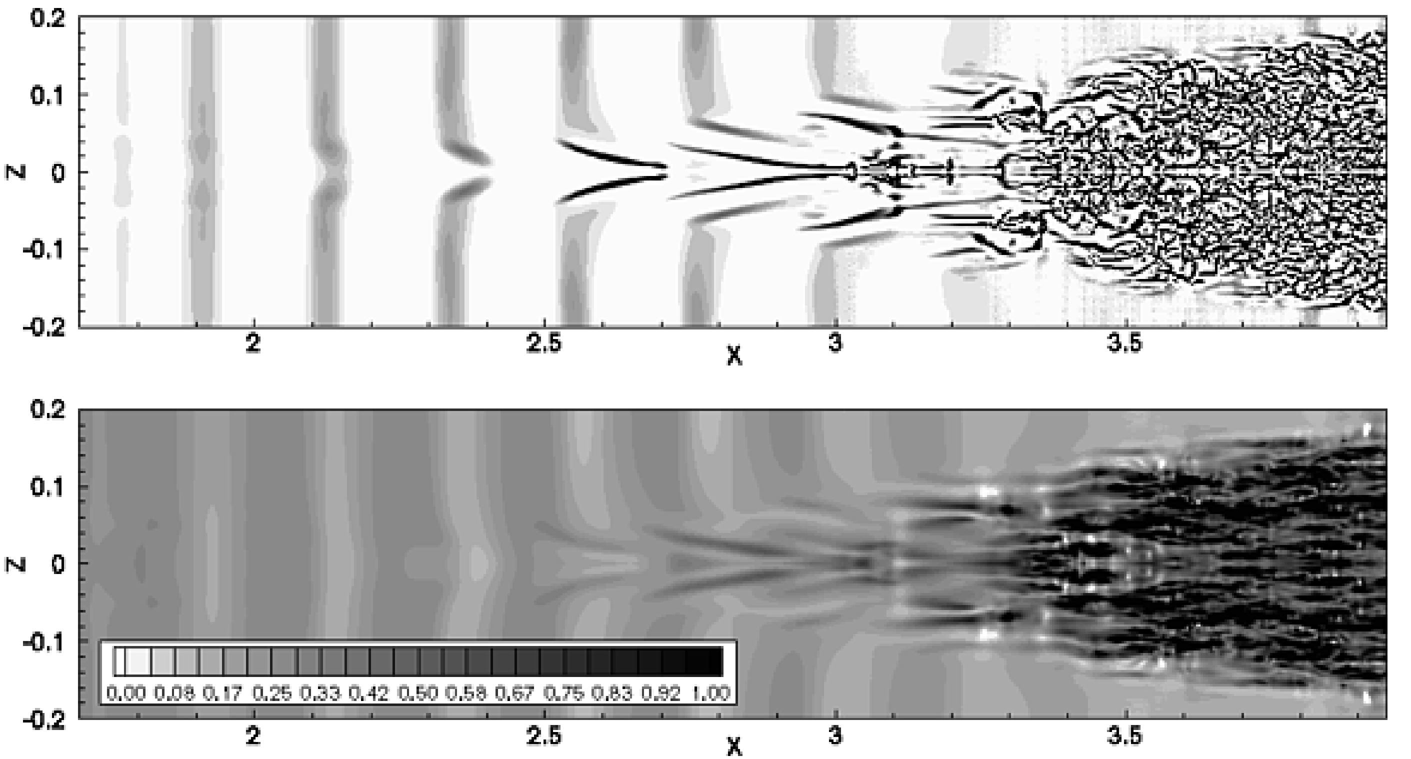
Snapshots during one fundamental time period

with downstream rolling separation zone due to large-amplitude 2-d TS wave in the decelerated Falkner-Skan-layer (not for Blasius flow)

Scenario A – Breakdown (DNS, 2)

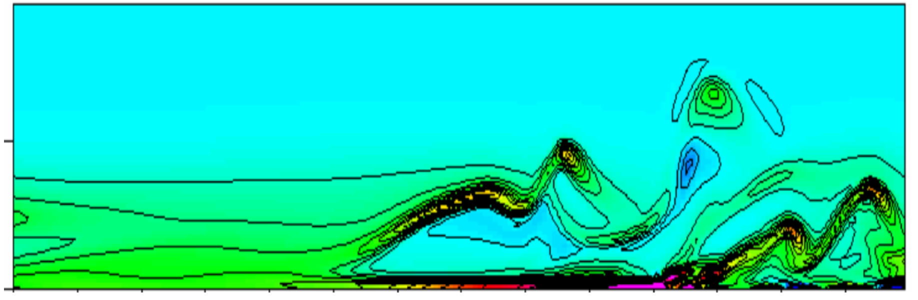
- Details of K-Breakdown with single tape strip: formation of Λ-vortex, top view, Blasius case. Single Λ-vortex induces side structures that break down independently

λ_2-projection

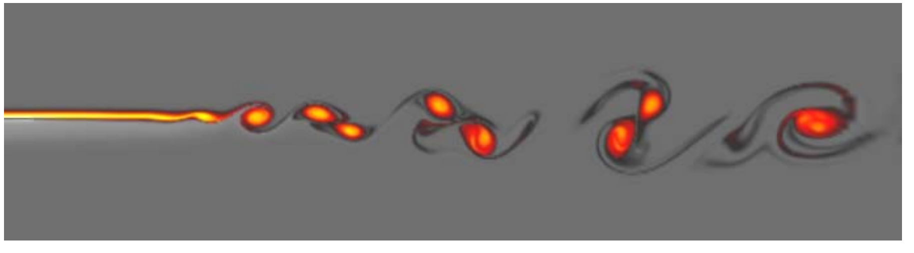


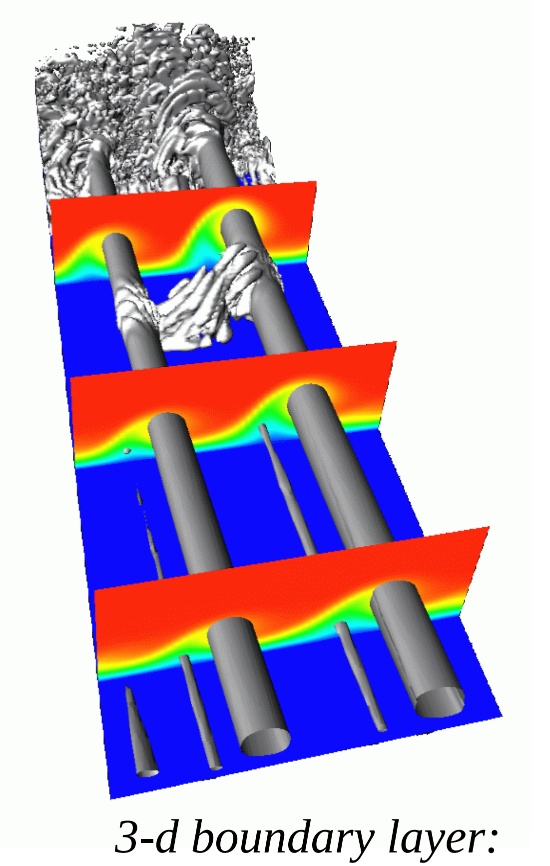
spanwise wall vorticity ~ friction
(z-symmetric DNS, D. Meyer 2002)

2-d boundary layer: hi-shear layer on Λ-vortex



2-d shear wake after a plate: vortex pairing





3-d boundary layer: crossflow-vortex secondary instability

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