University of Stuttgart, Aerospace Engineering and Geodesy Department
- Lecture -

Mechanisms of Laminar-to-Turbulent Transition

Master, specialization course
3 lecture hours/week (3 SWS), 6 LPs/ECTS

Lecturer:
Dr. Markus J. Kloker

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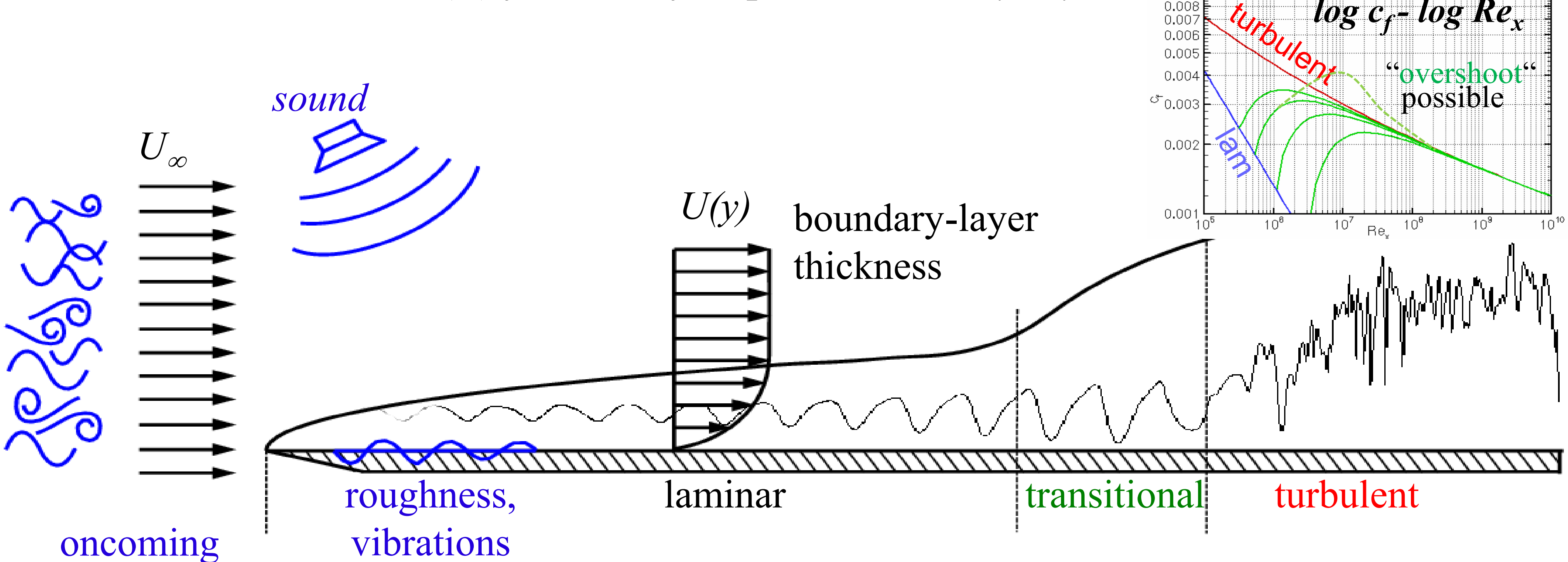
Standard scenario (A) for a 2-d flat-plate boundary layer



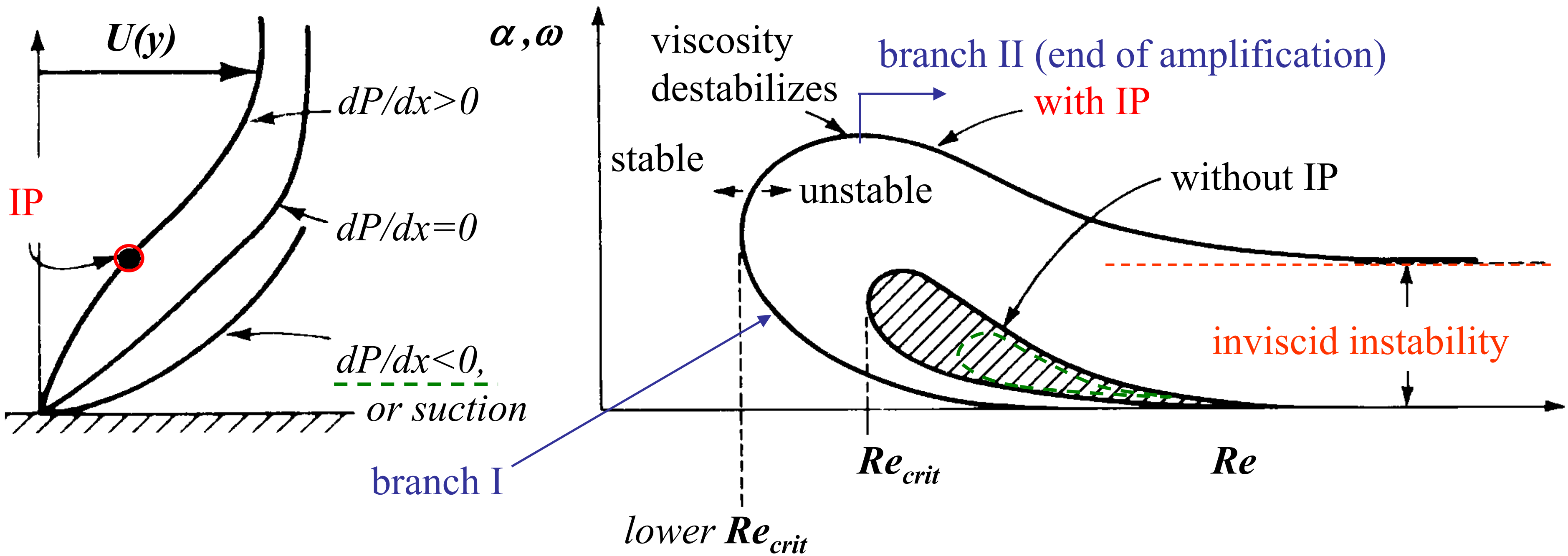
oncoming distubances

receptivity → primary instability → secondary instability → turbulence randomization

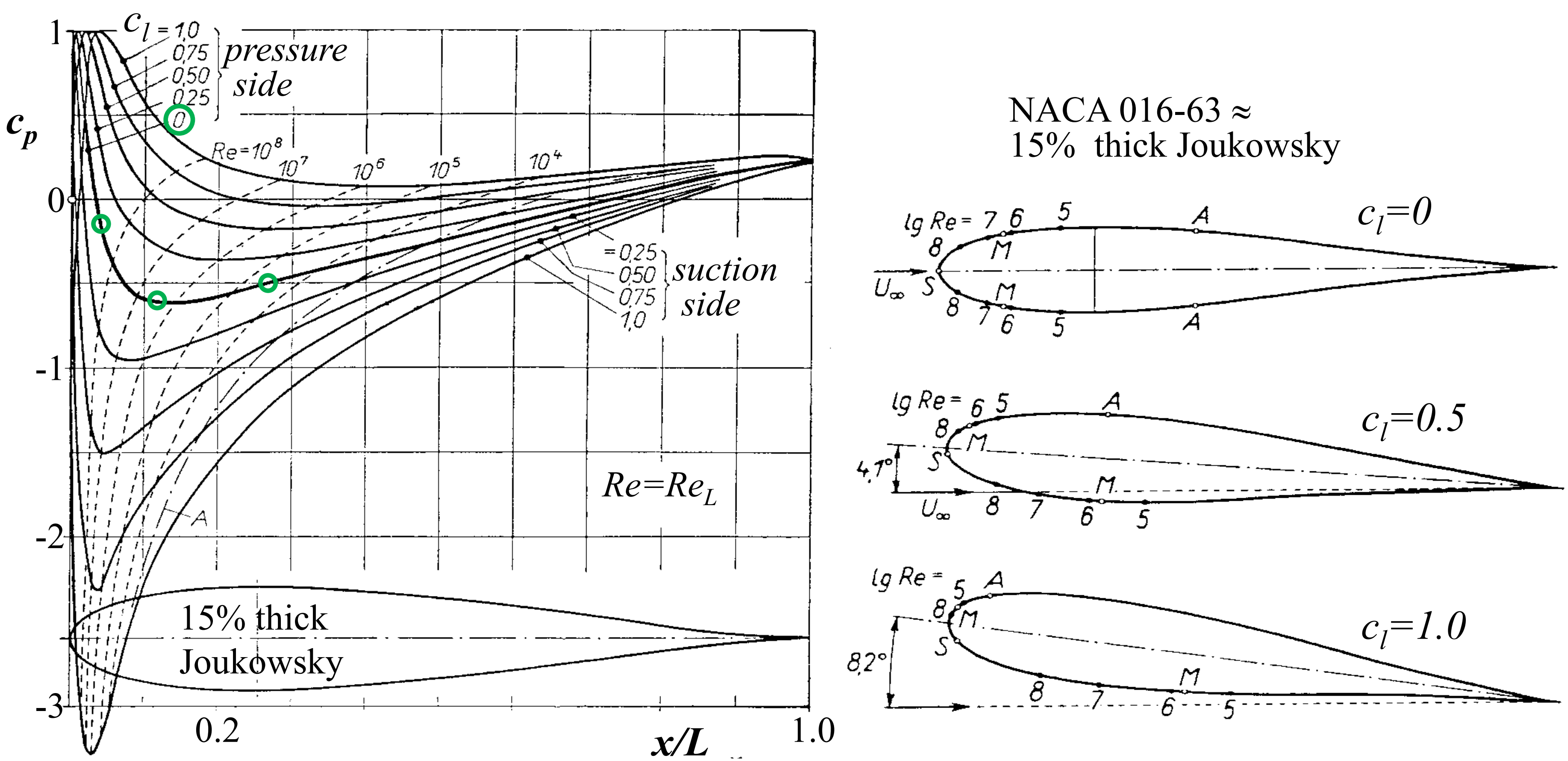
primary instability ↓ for small initial disturbances: Tollmien-Schlichting waves

secondary instability ↓ fundamental / subharmonic resonance, Λ vortices

- Orr-Sommerfeld equation: TS-waves that represent downstream travelling "infinitely small counterrotating spanwise vortices" can grow exponentially in a boundary layer
- Stability diagram (2-d waves): instability inside "banana", see below [5]
- Strong "inviscid" instability if *U(y)* has an inflection point (IP) and here the spanwise vorticity (~|*dU/dy*|) has a maximum as, e.g., for Falkner-Skan profiles with $\beta_H<0$
- Without IP: only viscous instability; the diagram closes for large *Re* because $dU/dy \sim \delta^{-1}\downarrow$

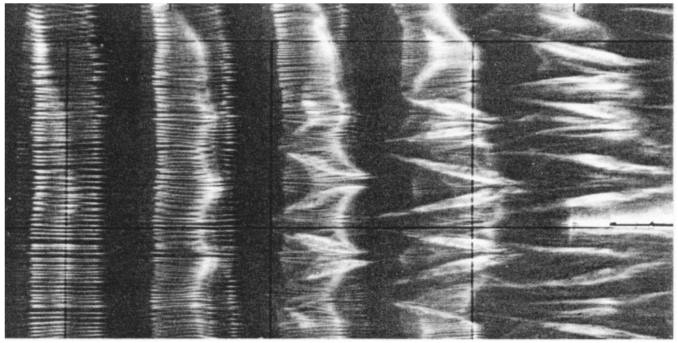


2.6 Wing profiles, experiment, 1



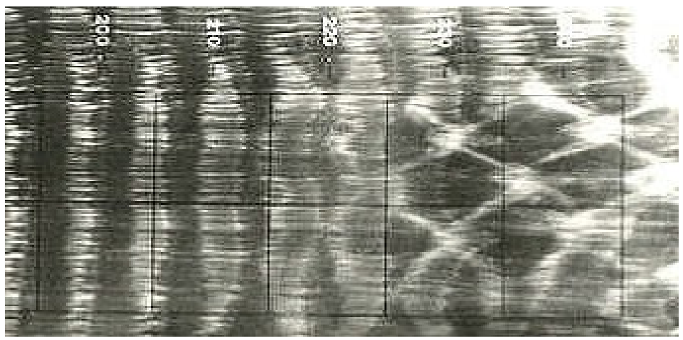
Position of boundary-layer instability onset (left) and transition (right) on a wing profile as function of chord *Re* number and lift coefficient c_l. *A* - boundary-layer separation for *laminar* flow until *A*; *M* - pressure minimum; *S* - stagnation point. For $Re_L \leq 5\times10^6$ transition occurs downstream of or around M [2].

• Visualizations in experiments, Blasius flow (smoke, laser light sheet)

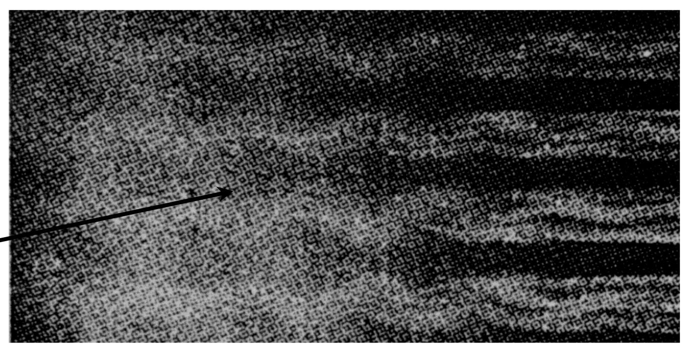


K-Typ (Saric 1984, see [12])

U



H-Typ (Saric 1984, see [12])



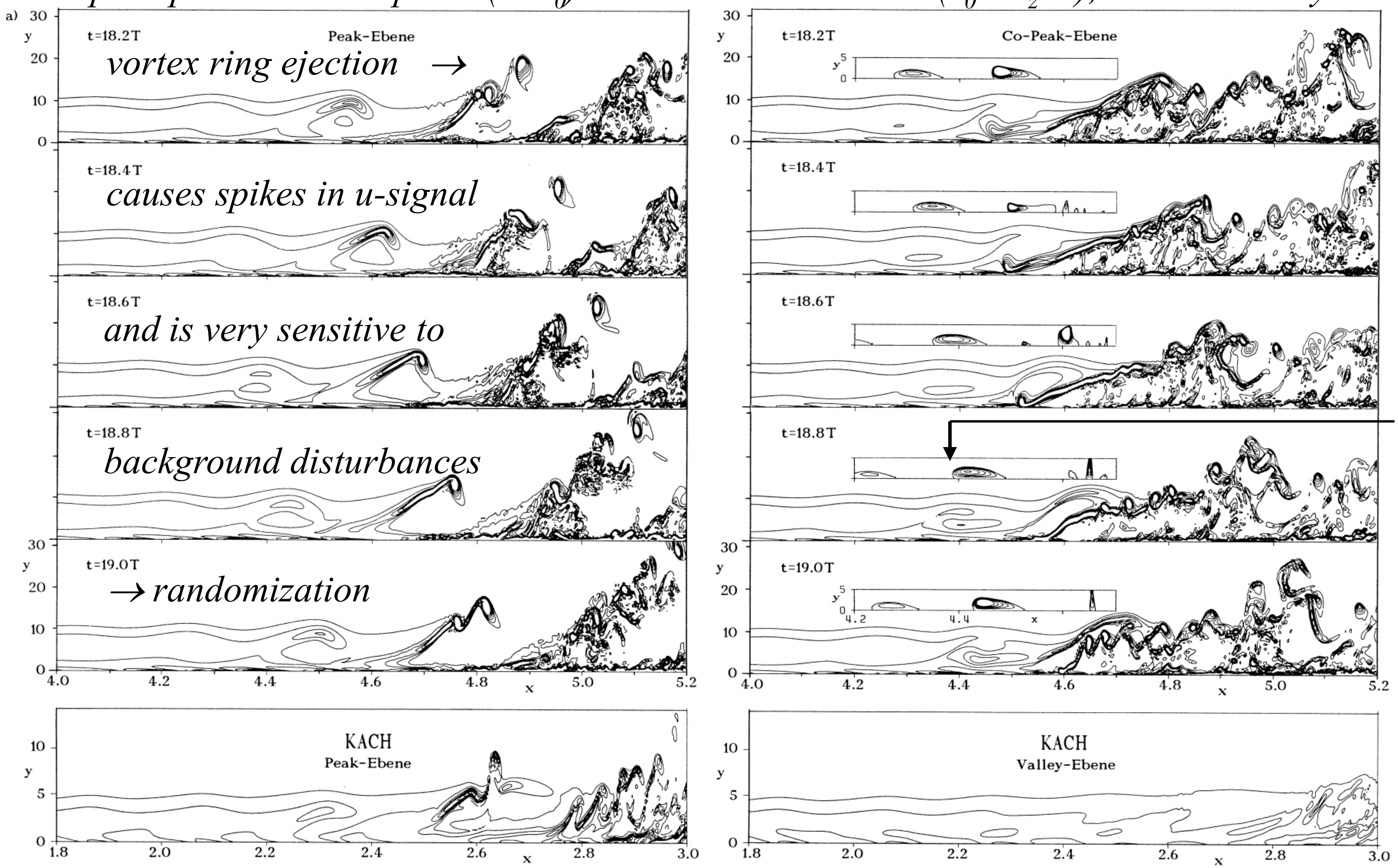
O-Typ (Wiegel, Bippes 1997, see [28])

3-d waves

streaks (0,2)

- Details of *K*-Breakdown (*with adverse pressure*): spanwise vorticity / shear-layers [25, 27]

peak plane /Λ-head plane ($z=z_0$) … *between Λ's ($z_0+\lambda_z/2$), here not valley but co-peak plane*

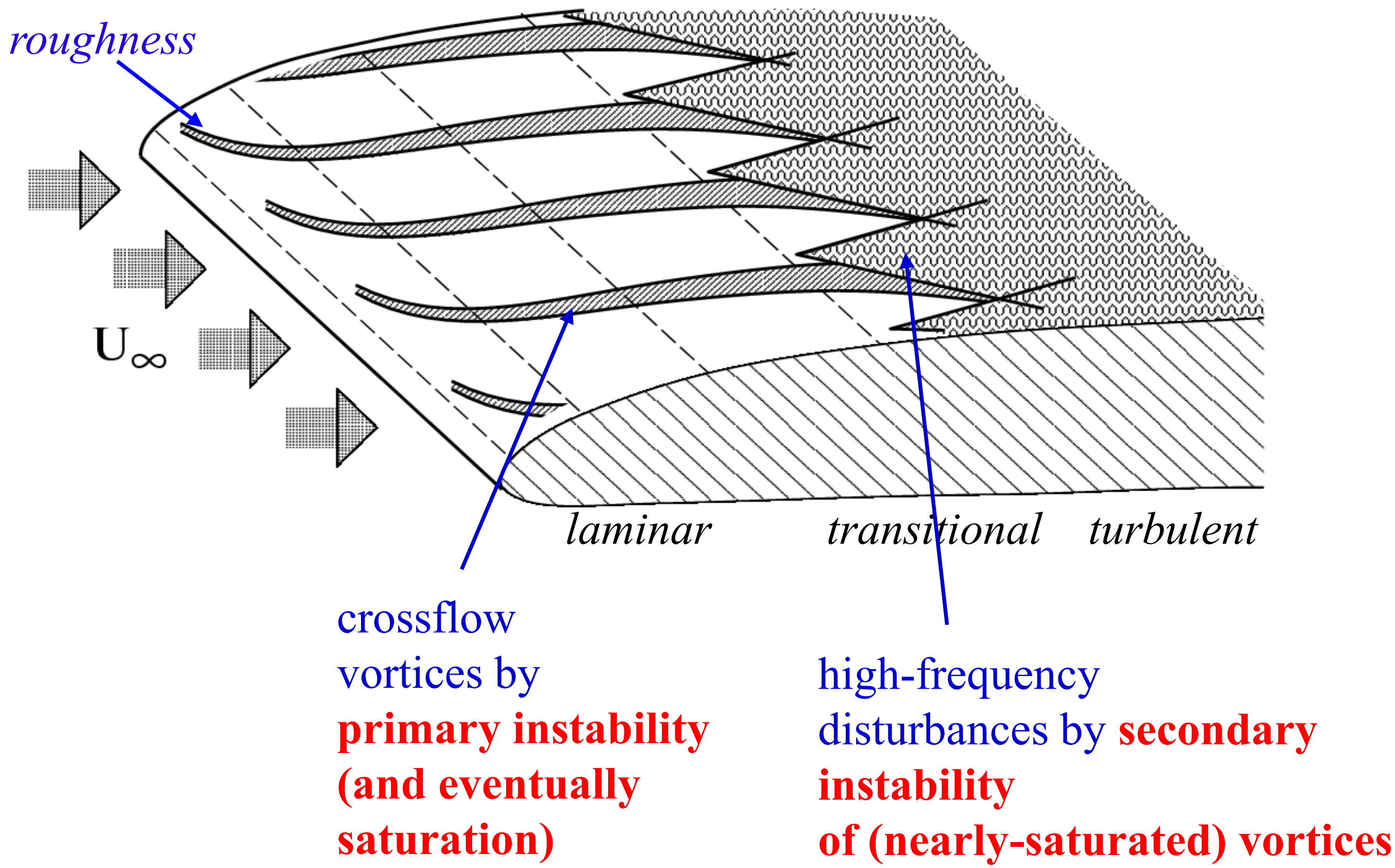


Snapshots during one fundamental time period

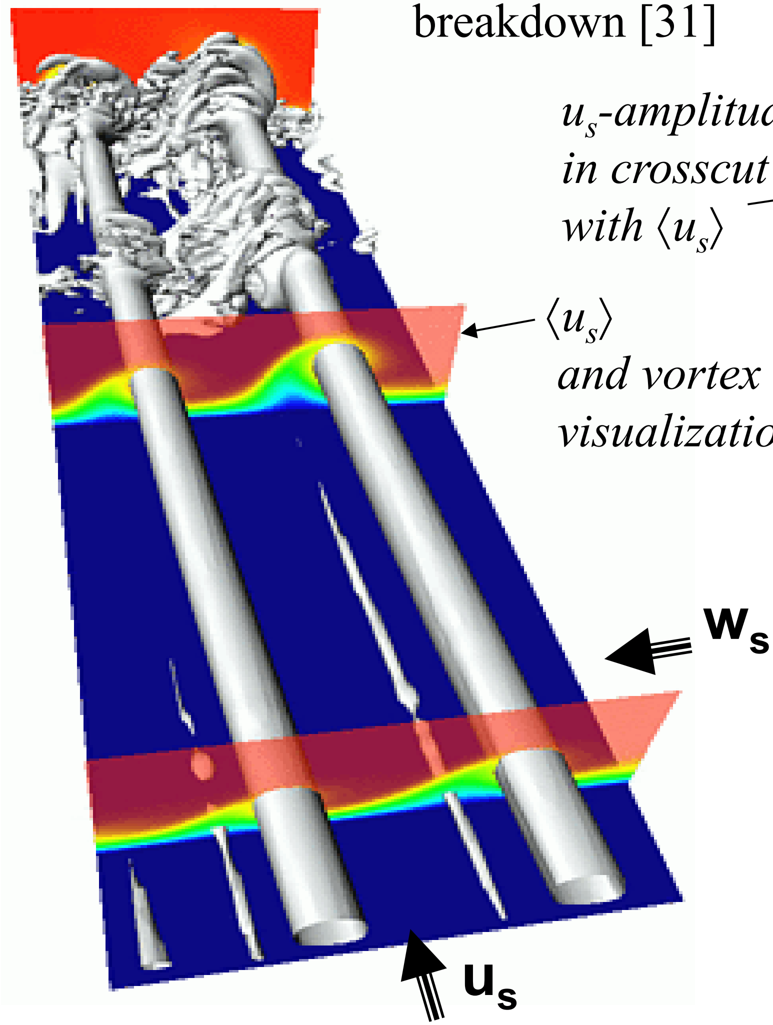
*with downstream rolling separation zone due to large-amplitude 2-d TS wave in the decelerated Falkner-Skan-layer. Does **not** appear with Blasius flow, falsifying fig. 16.14 in [2].*

5.2 LSI/Crossflow breakdown, 5

- Steady-crossflow-vortex induced breakdown in a *3-d* boundary layer on a swept wing
- The subsequent DNS results are for the base flow introduced in §4.3, 3-6, [31]

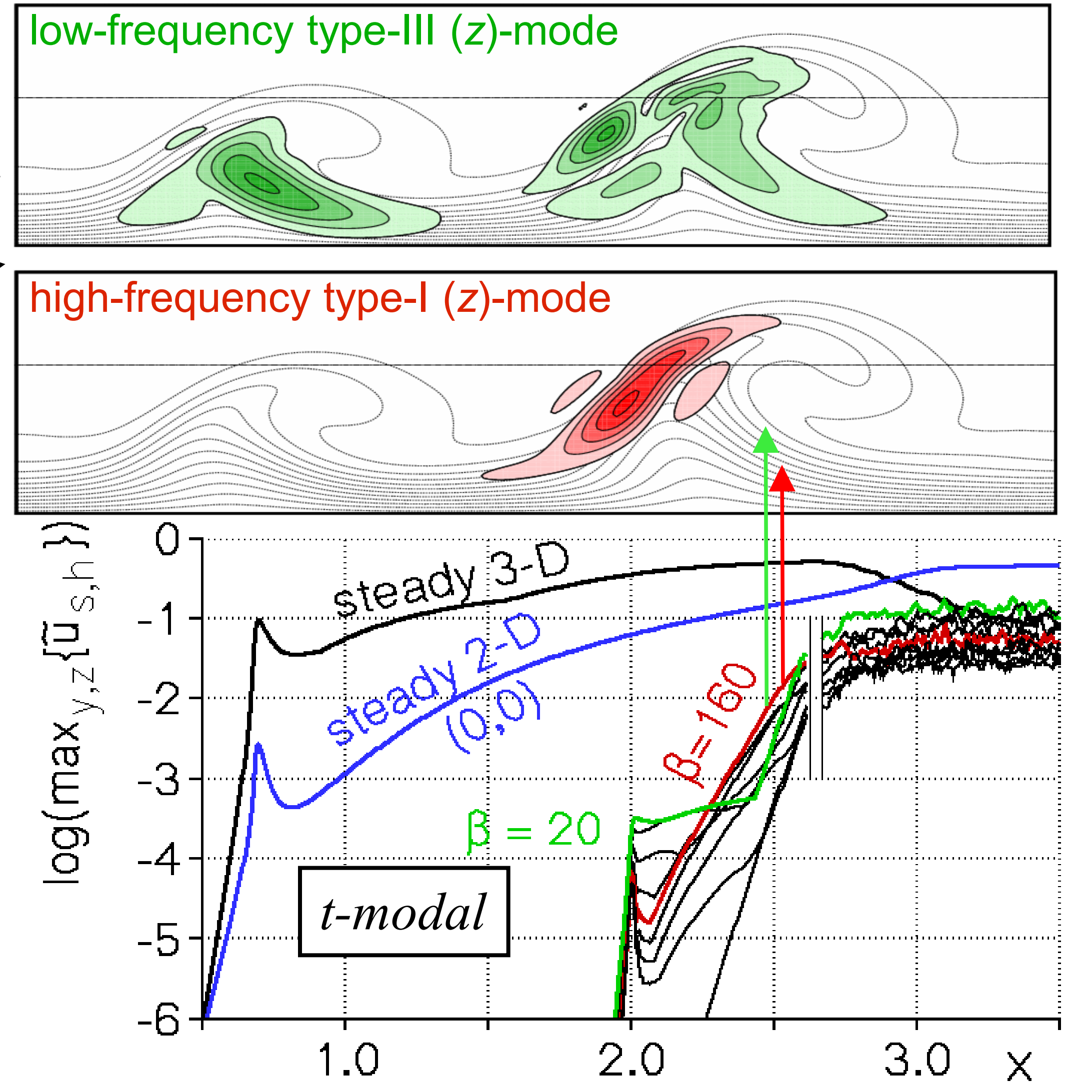


- Steady-crossflow-vortex induced breakdown [31]



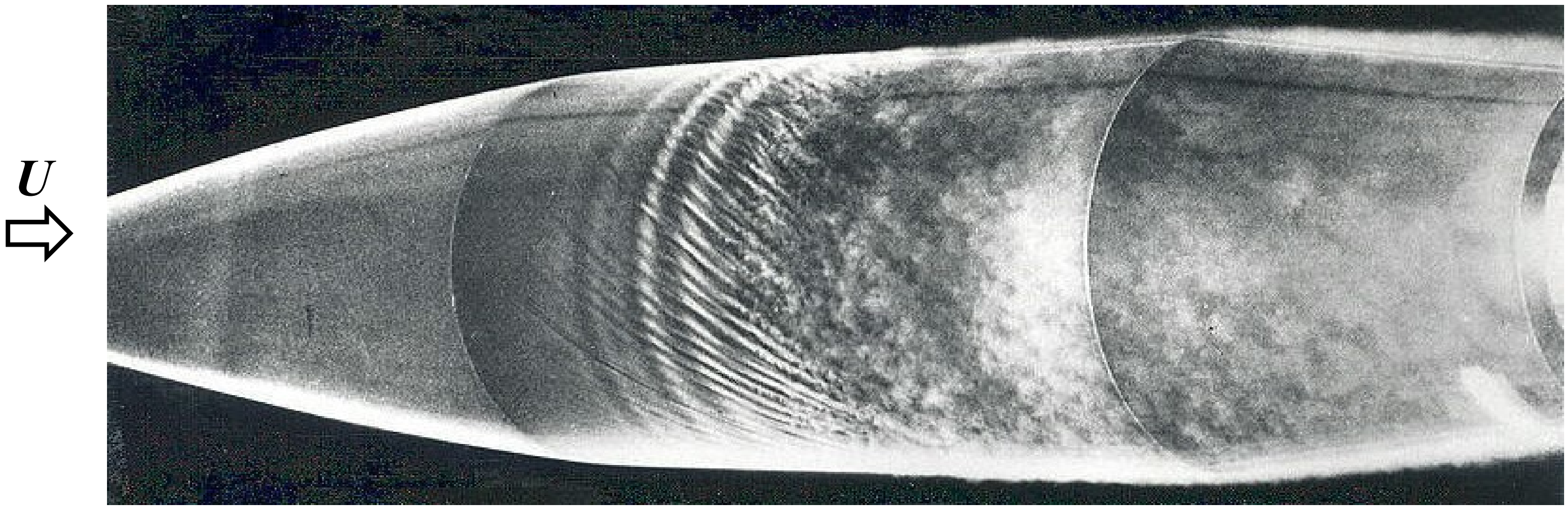
u_s-amplitudes in crosscut with $\langle u_s \rangle$

$\langle u_s \rangle$ and vortex visualization



5.2 LSI/Crossflow breakdown, 10

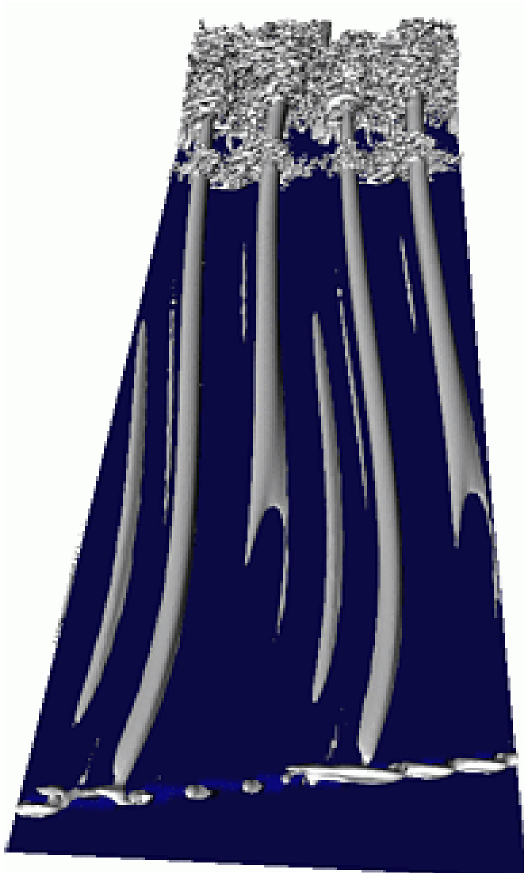
• Experimental visualization of (slow) crossflow-vortex induced breakdown on a spinning body of revolution by smoke



specialty: in the beginning also TS waves can be seen.
(Mueller, Nelson, Kegelmann, Morkovin 1981, see [38])

6.1 Laminar Flow Control, DNS, 5

- Example to method B: Passive suppression / delay of crossflow-vortex induced transition in a *3-d* boundary layer by forcing of narrow-spaced vortices (UFD/DRE method) with $2/3\lambda_z$ of the naturally most amplified mode. Note that the $2/3\ \lambda_z$ control mode needs to be more amplified initially, and then be damped, i.e. the stability diagram over the *x-γ*-plane must have a thumb shape, see §4.3, 5. The control mode is sometimes called 'subcritical' referring to its λ_z being smaller than the one of the turbulence triggering mode (DNS [31]).



U *„Natural" scenario*

With forcing of closer-spaced control vortices upstream (Upstream Flow Deformation, UFD)

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6.4 Literature for §5-§6, 1 (see also §4.5) *Transition*

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6.4 Literature for §5-§6, 2 (see also §4.5)

[32] **Kloker, M.** 2002 *Direct numerical simulation of transitional boundary-layer flows at sub- and hypersonic speeds*. *DGLR-JT2002-017*.

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