Prediction of laminar-turbulent transition with DNS, LES and RANS methods

Wolfgang Rodi
University of Karlsruhe
Karlsruhe, Germany

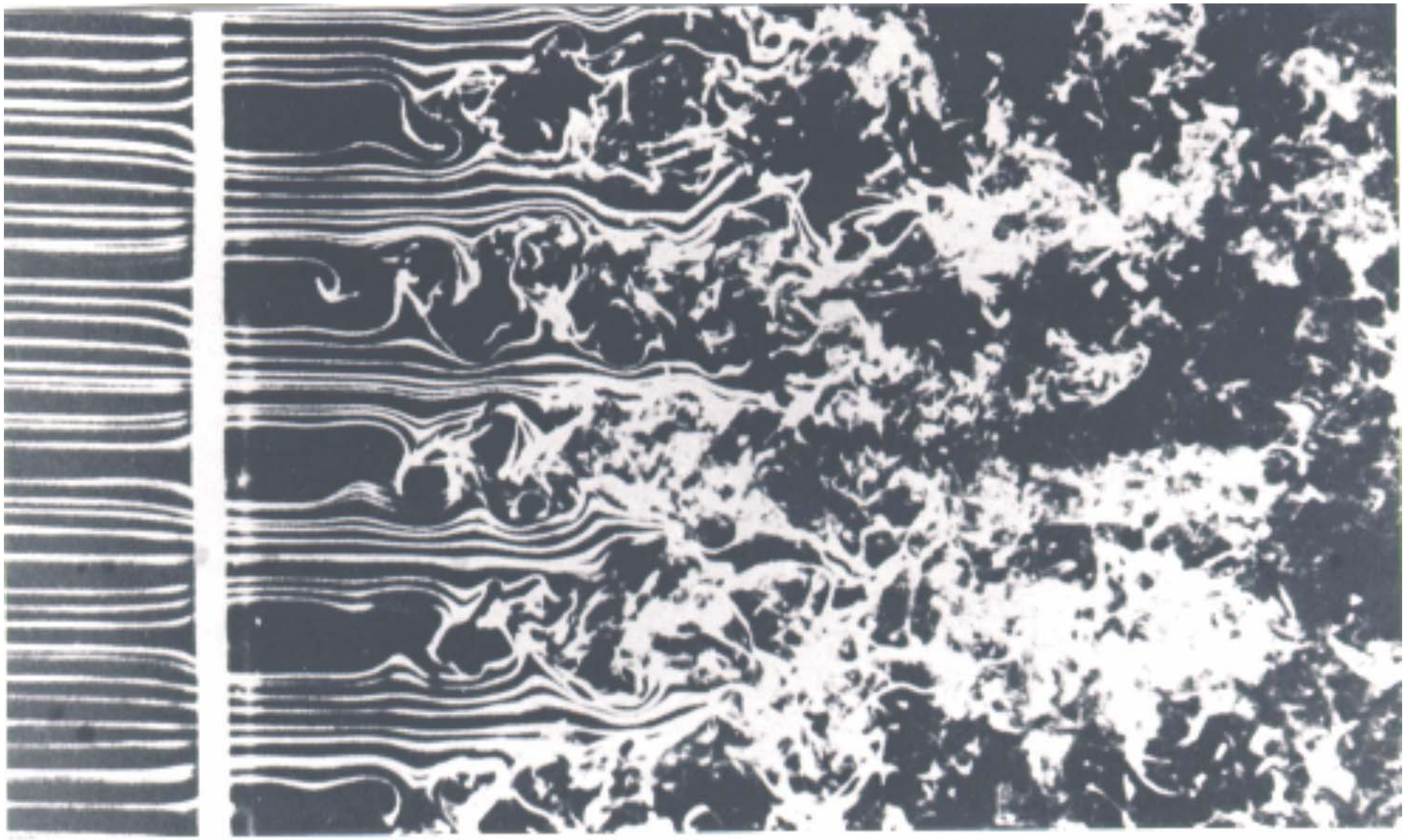
Introduction

- Transition of practical relevance in flows around
  - aircraft, space vehicles, ground vehicles
  - turbomachinery blades (compressor blades, turbine blades)
  - wind turbines and fixed structures exposed to wind
  - in conduits at low Re

- Transition can greatly influence the flow development, the losses, drag, heat transfer

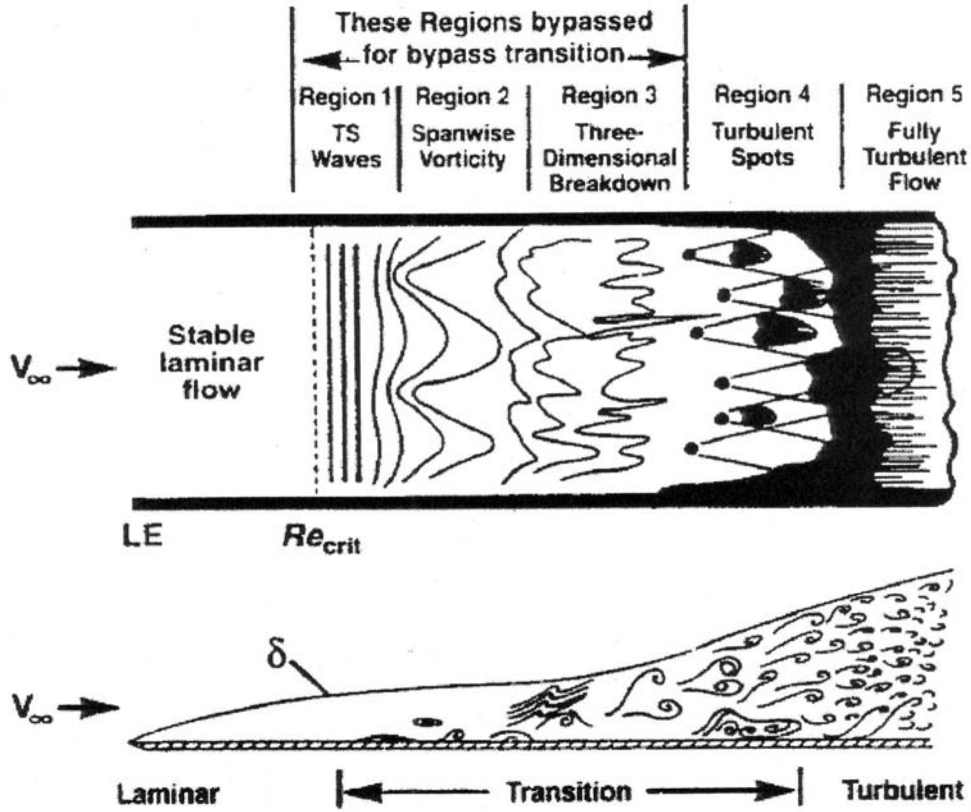
- Hence important to understand transition phenomena, have ability to predict transition processes

Illustration of difference laminar/turbulent flow



Modes of transition 1

1. **Natural transition**



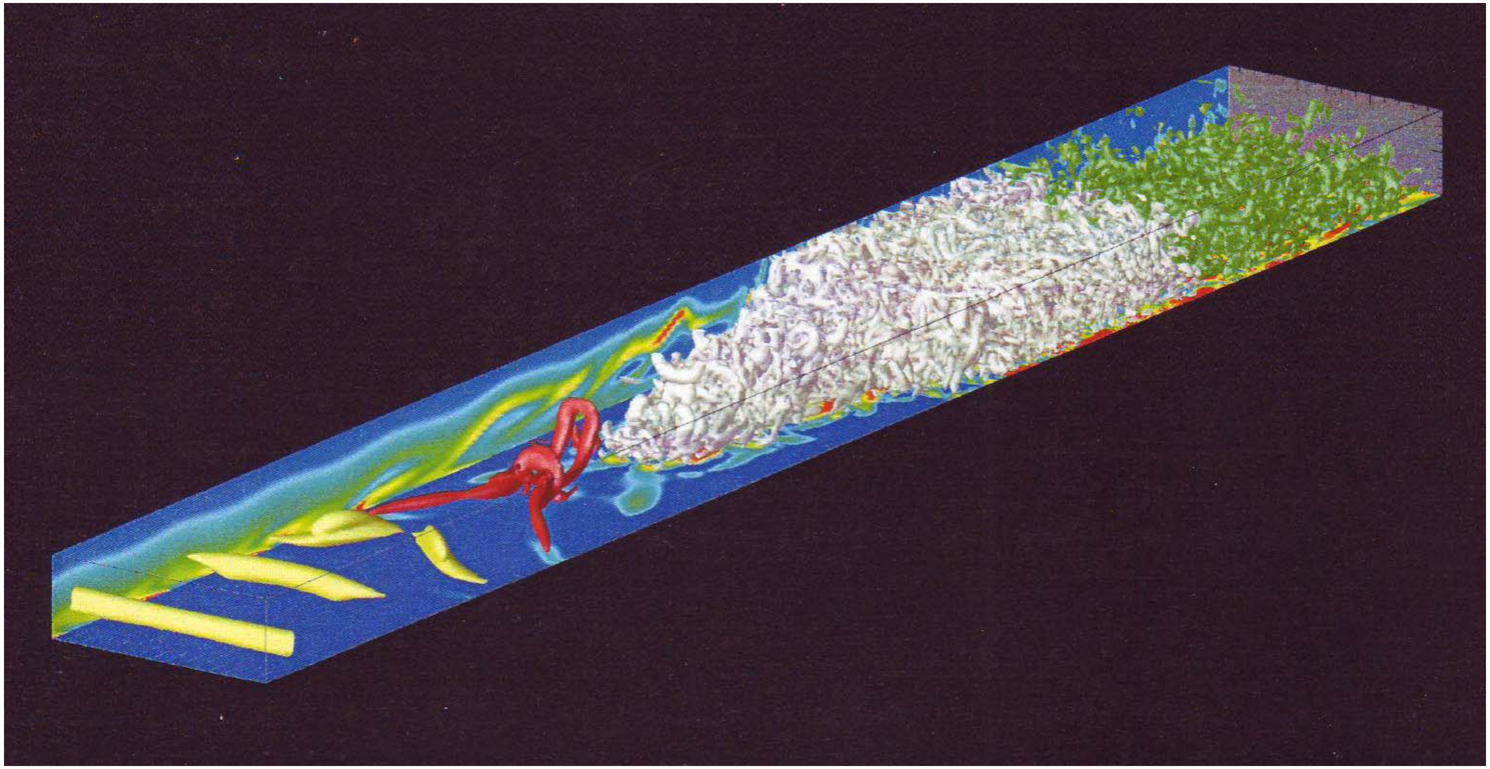
The natural transition process (from Schlichting, 1979)

2. **Bypass transition**

at larger disturbances (e.g. free-stream turbulence Tu > 1 %)

Natural transition – from LES

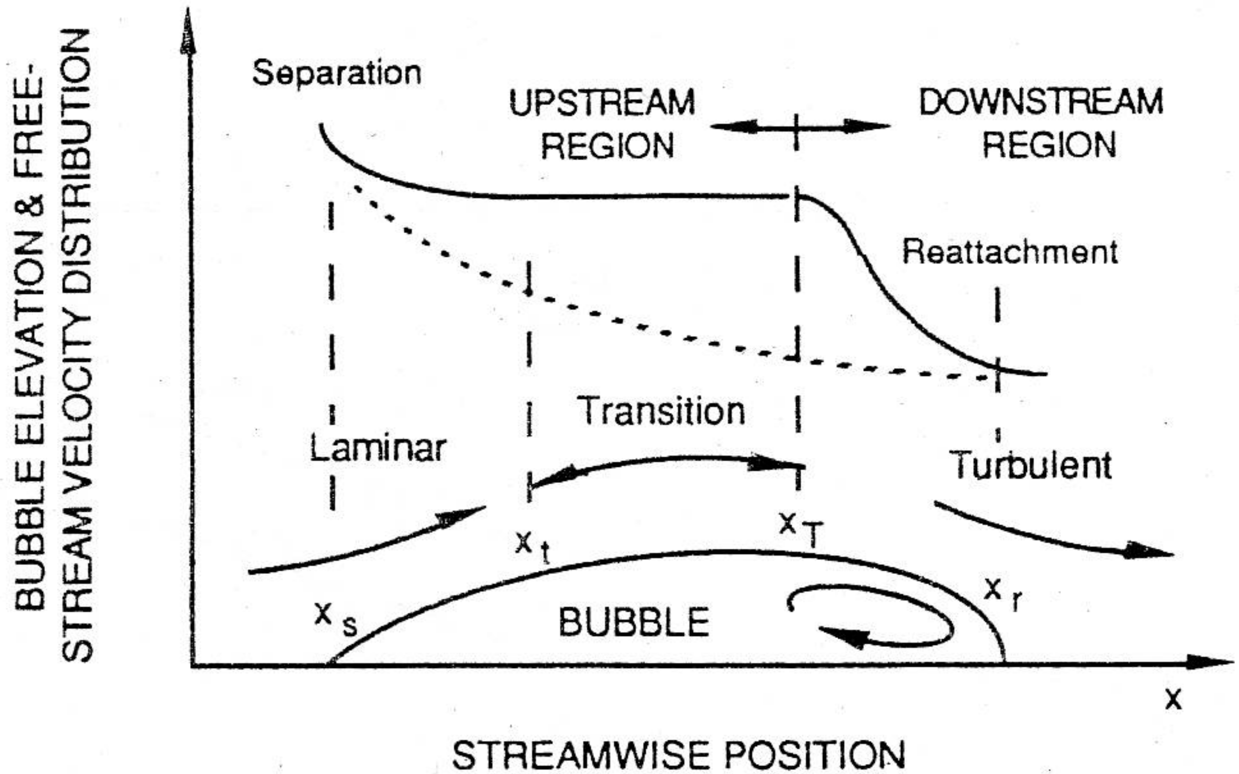
From P. Schlatter (2005), Ph.D. thesis, ETH Zurich



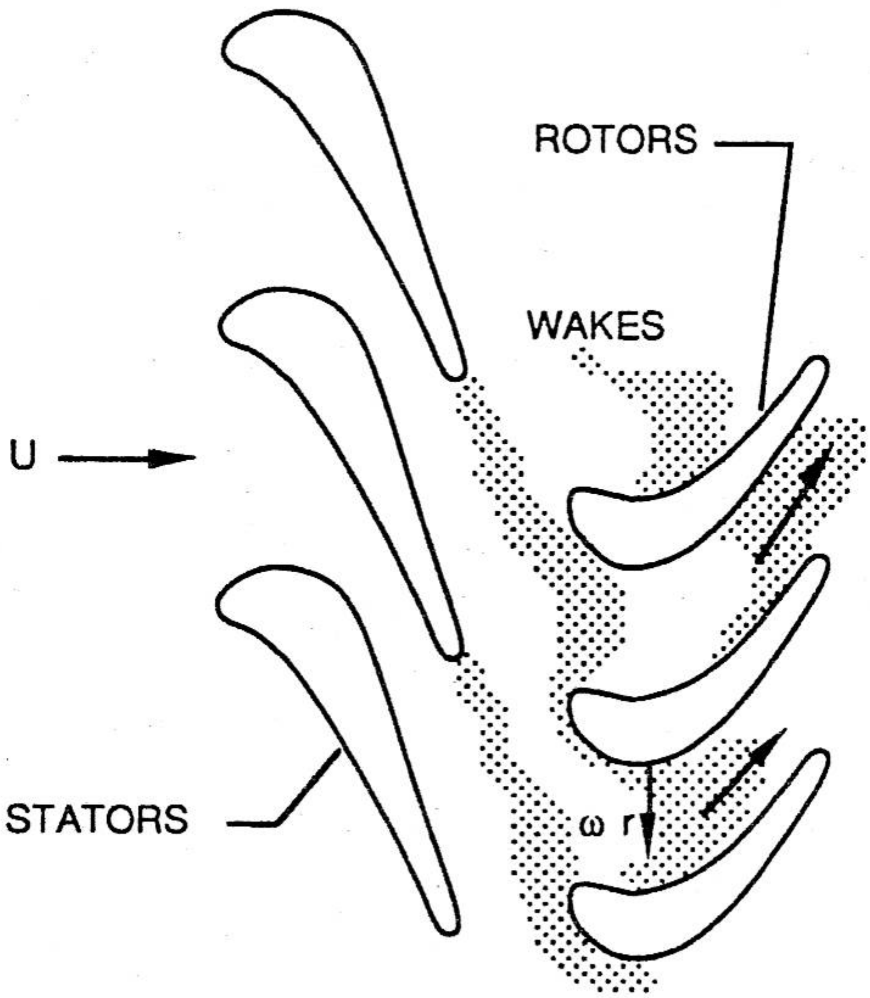
Modes of transition 2

3. Separated – flow transition

- transitional separation bubbles -



Periodic unsteady transition – due to passing wakes



- Periodic wakes cause intermittent bypass transition

  or

  influence strongly separated – flow transition

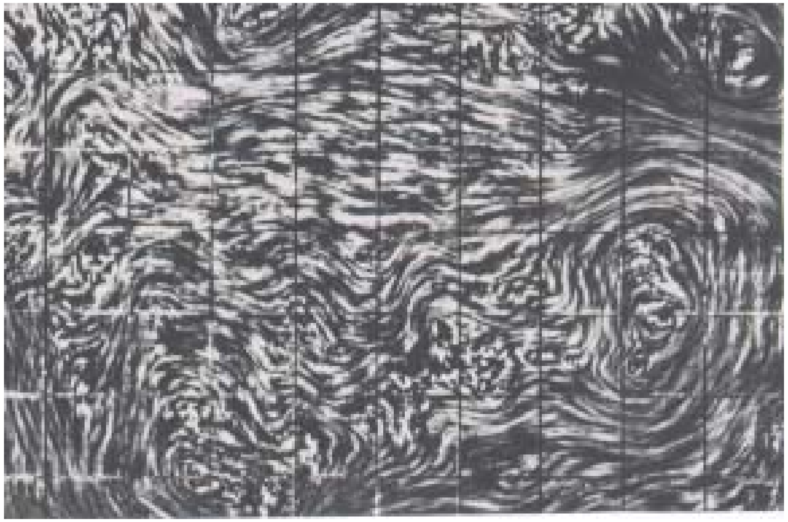
Prediction methods for transition

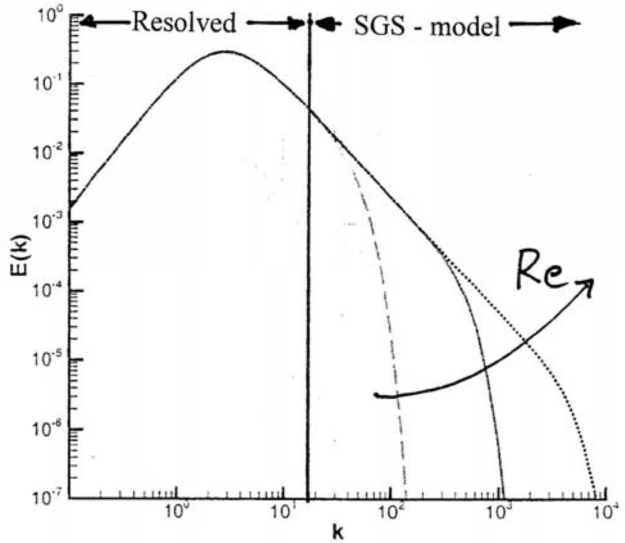
- Linear stability theory (e^n method) and parabolised stability equations (PSE)
  - mainly for predicting onset of natural tansition on airfoils
  - not for full transition process, bypass and separated-flow transition
- Direct Numerical Simulation (DNS)

- all processes involved, including turbulent fluctuations, governed by Navier-Stokes equations
- numerical solution of these equations, resolving all scales – no model involved
- very powerful tool, provides wealth of detailed information
- but very fine grid required, very expensive
- restricted to low Re and fairly simple geometries

Prediction methods for transition 2

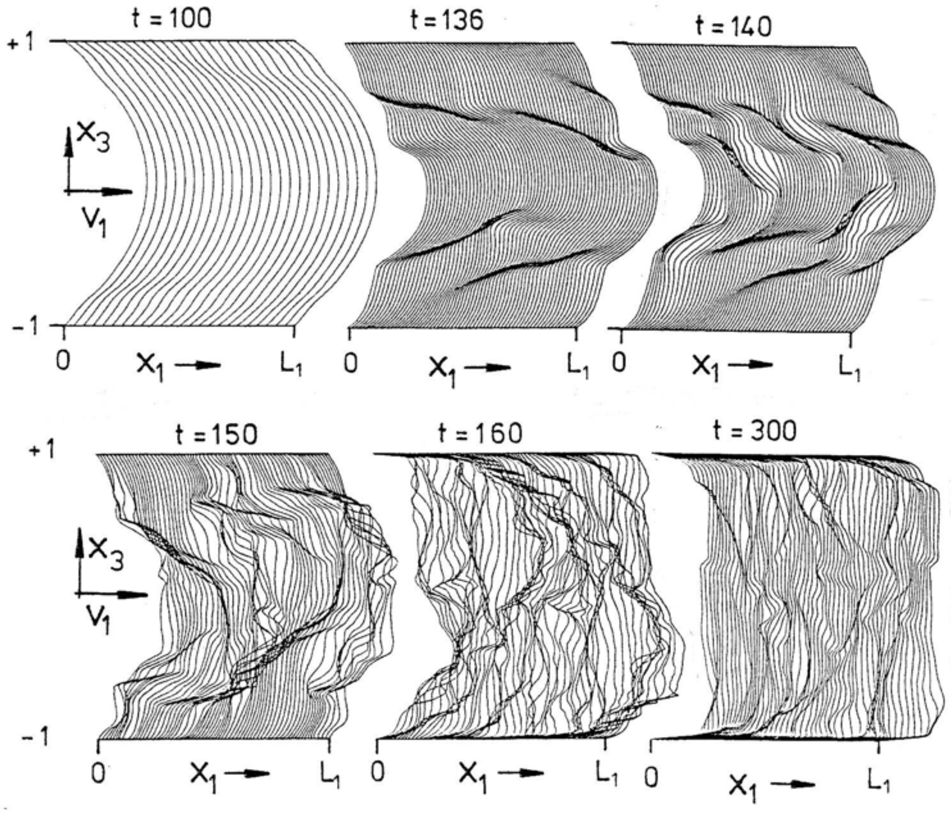
- <u>Large Eddy Simulation (LES)</u>
  - solves Navier-Stokes equations on coarser grids
  - does not resolve all scales
  - accounts for effect of unresolved small-scale motion (mainly dissipative) by subgrid-scale model
- <u>RANS methods</u>
  - solving Reynolds Averaged Navier-Stokes equations
  - model for Reynolds stresses – i.e. for entire spectrum of fluctuations
  - in general special transition model with empirical relations for onset and often length of transition





DNS of transition in channel flow 1

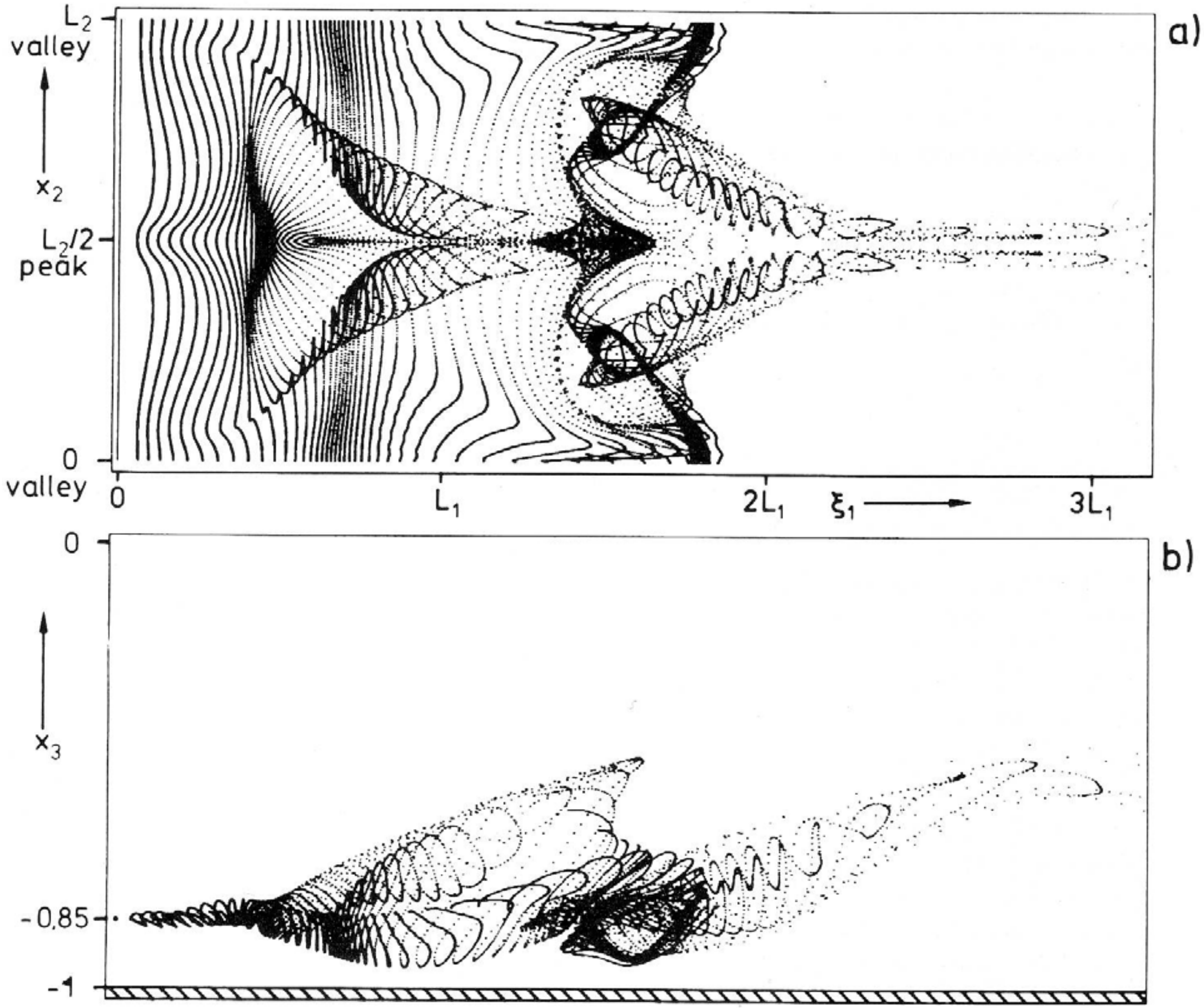
Gilbert (1988) & Gilbert & Kleiser (1990) - first DNS from laminar to fully turbulent state



temporal development of velocity profiles

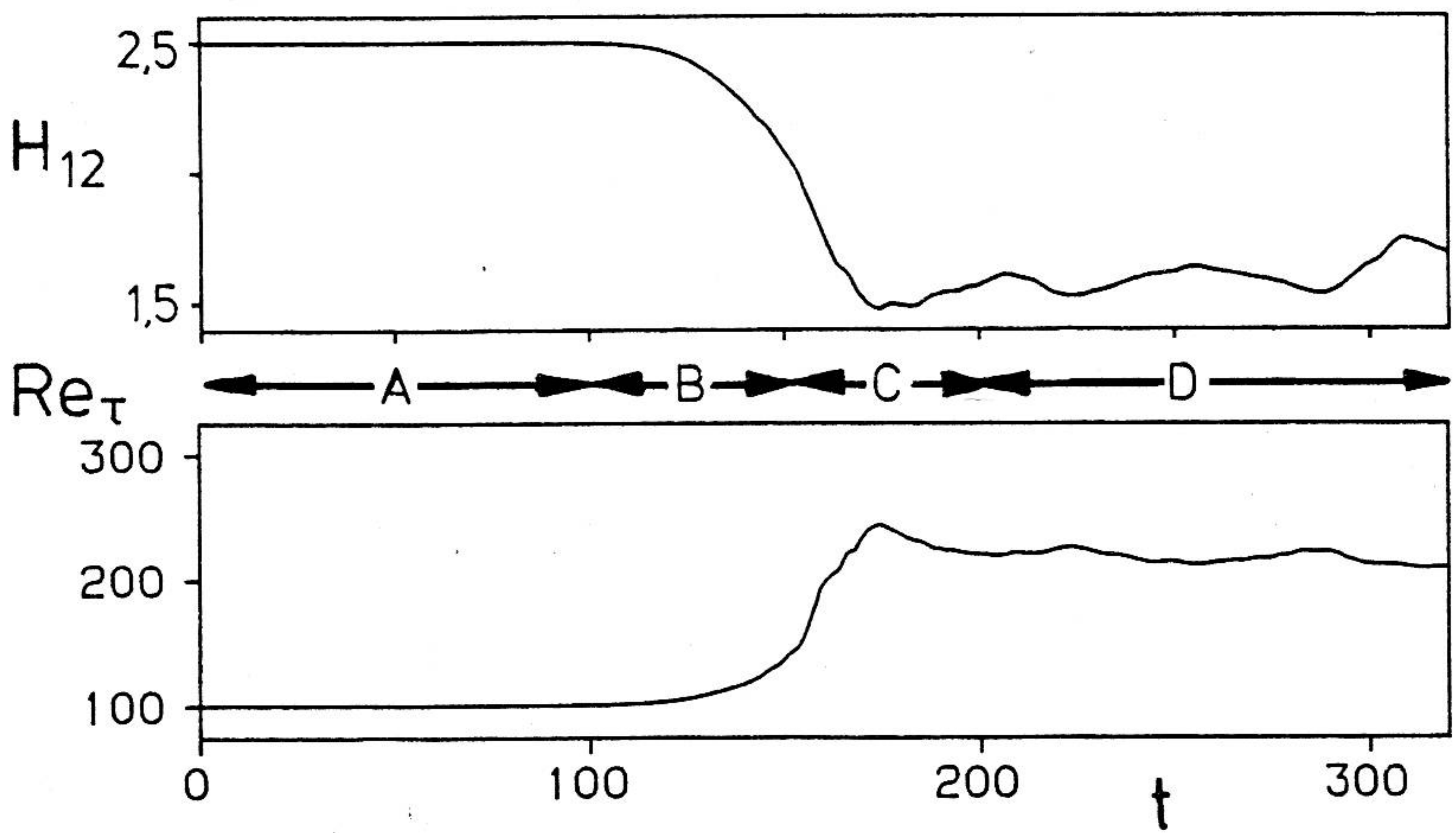
DNS of transition in channel flow 2

Pathlines showing Λ - vortices



DNS of transition in channel flow 3

Integral values



LES of transition in channel flow 1

- Smagorinsky model with

$$\nu_t = (C_s \Delta)^2 \left| \overline{S} \right| \quad , \quad \Delta = (\Delta x \Delta y \Delta z)^{1/3}$$

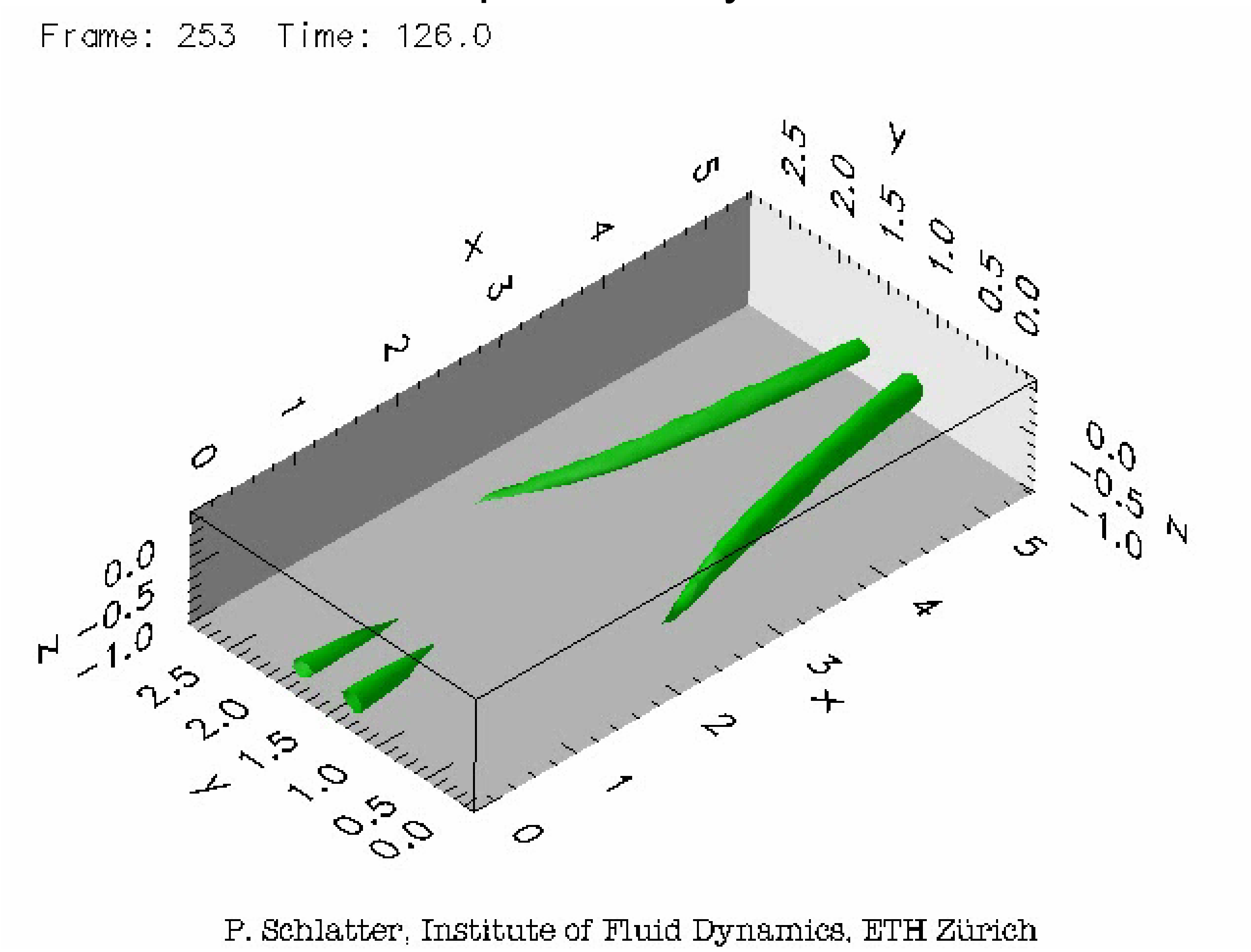
not suitable for transitional flow

- Dynamic model calculating C_s from smallest resolved motion is suitable
- Schlatter (2005) tested this and Approximate Deconvolution model (ADM) of Stolz & Adams (1999) for Gilbert's channel flow $(\mathrm{Re} = \overline{U} h / 2\nu = 3333)$
- He did DNS with 160^3 grid, LES with 32^3 grid
- Both SGS models o.k. for integral quantities, ADM model clearly better for transition structures – in this test case

	Δx^+	Δy^+	Δz^+
DNS	7.3	3.9	0.04
LES	37	20	1.0

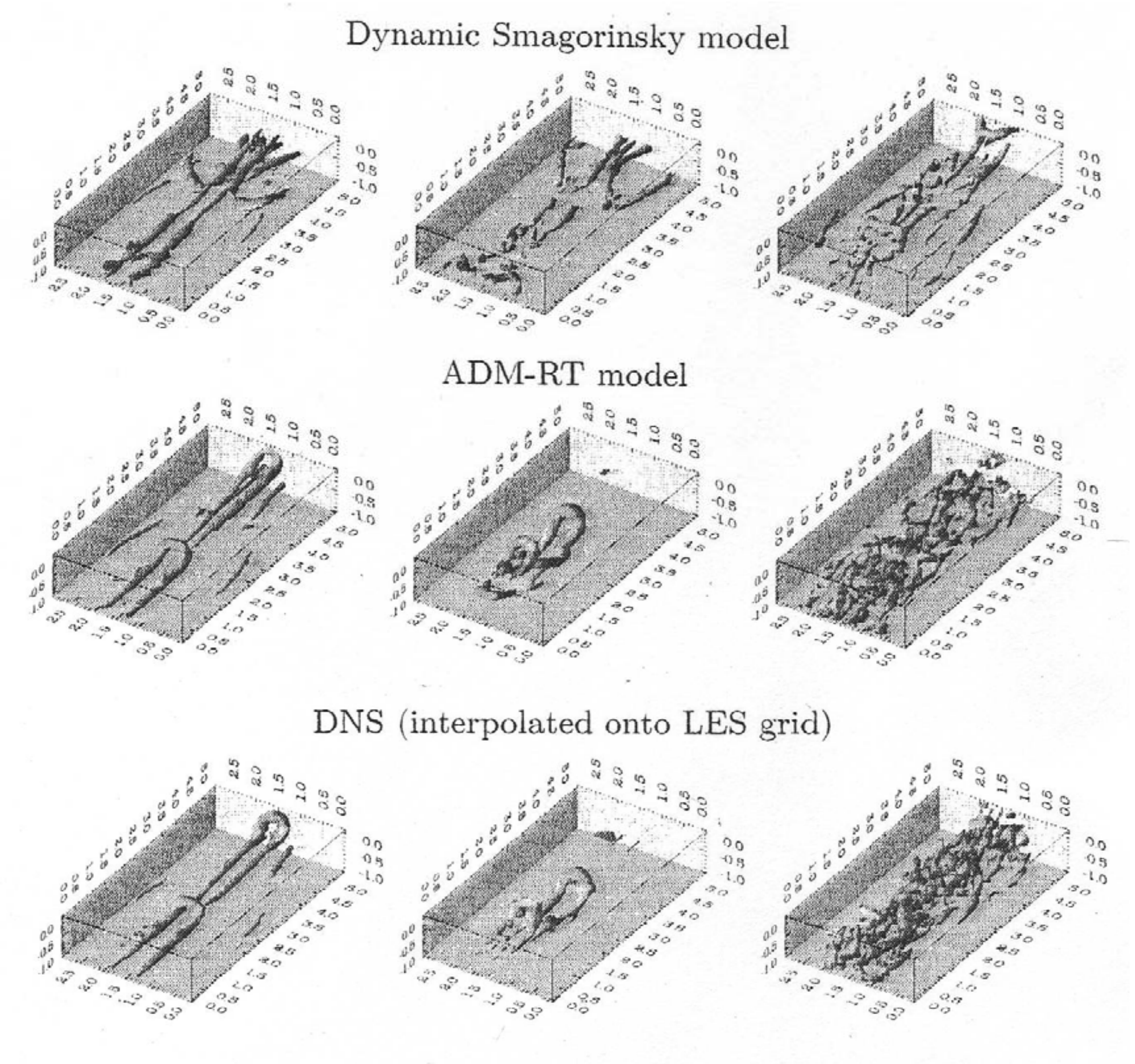
LES of transition in channel flow 2

Animation provided by P. Schlatter



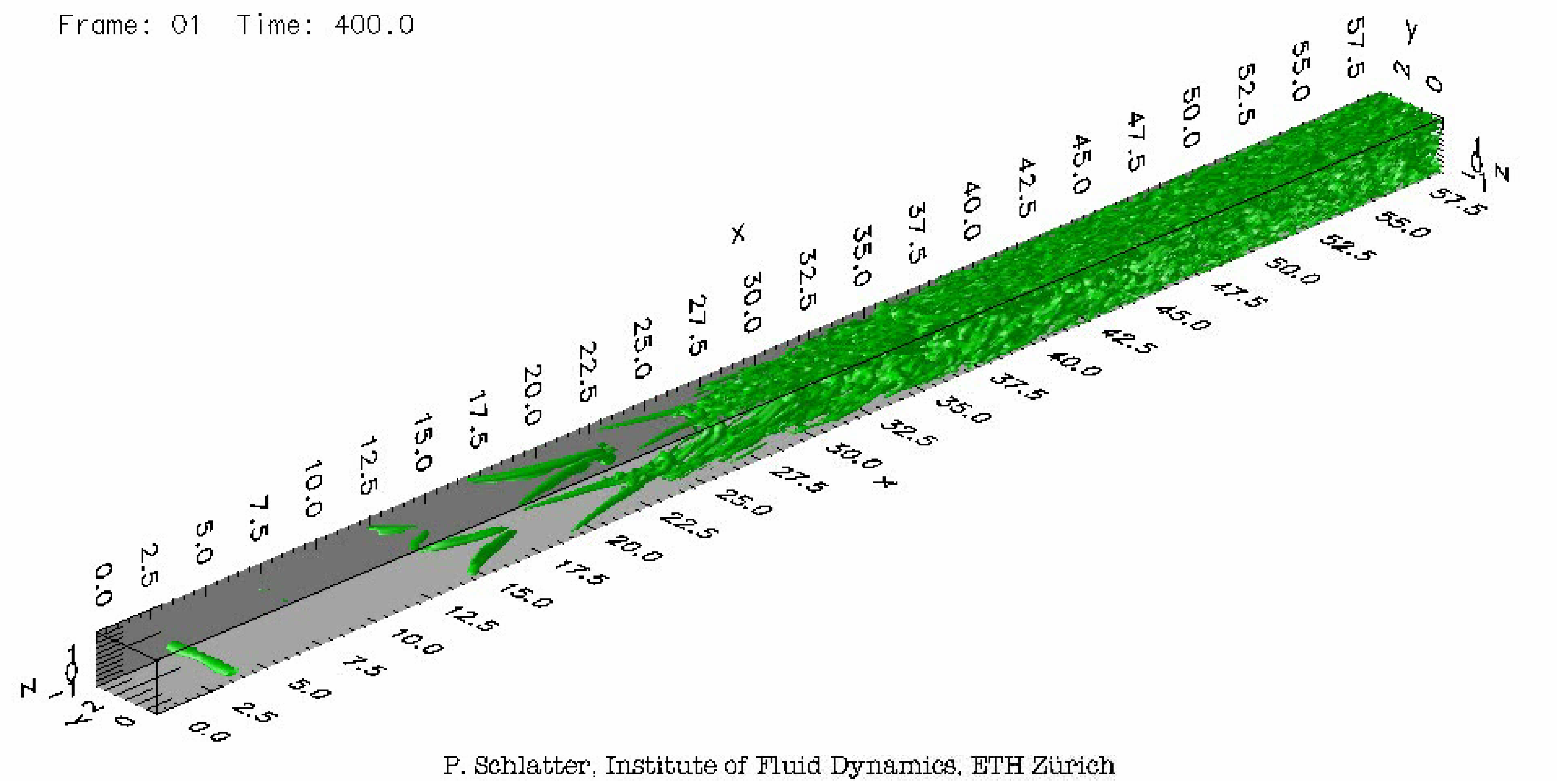
LES of transition in channel flow 3

Transitional structures visualized by λ_2 contours from Schlatter (2005)



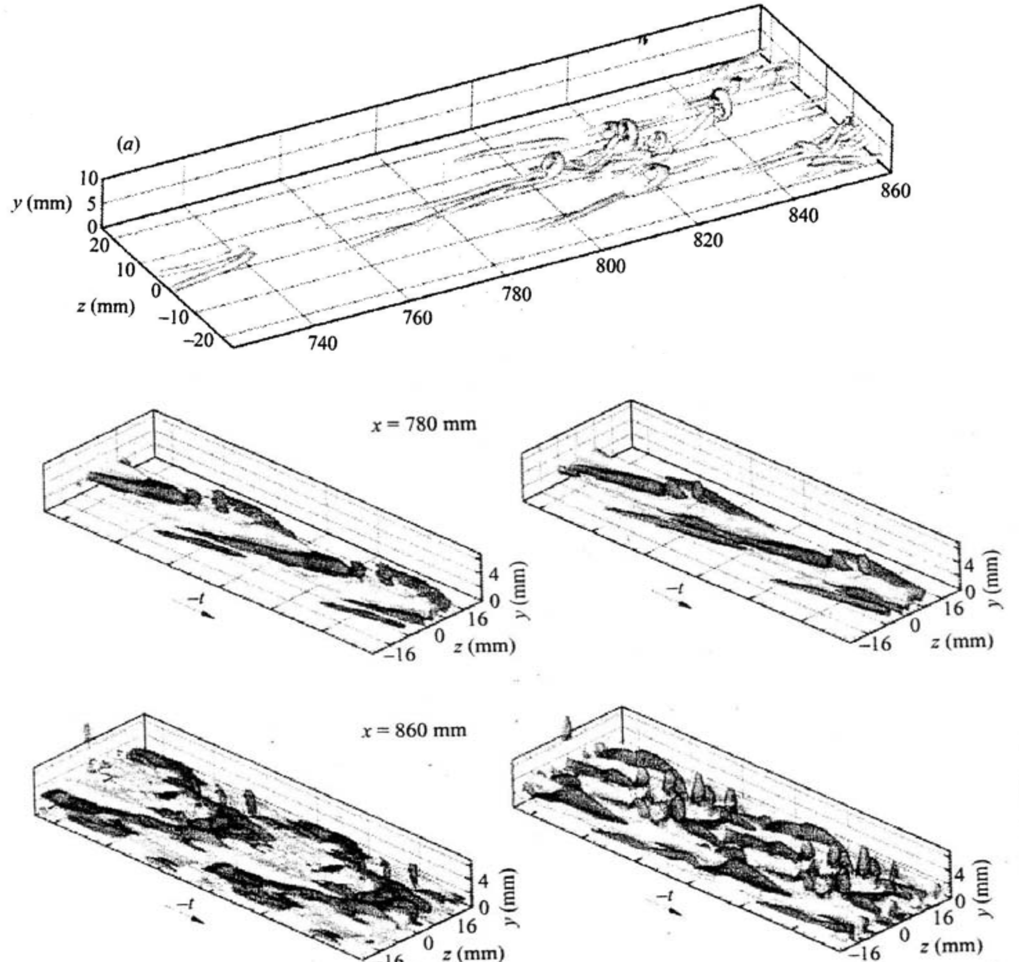
LES of transition in channel flow 4

LES of spatial development by P. Schlatter



DNS of natural transition in boundary layer

From Bake, Meyer, Rist (2002)



λ_2 isolevel

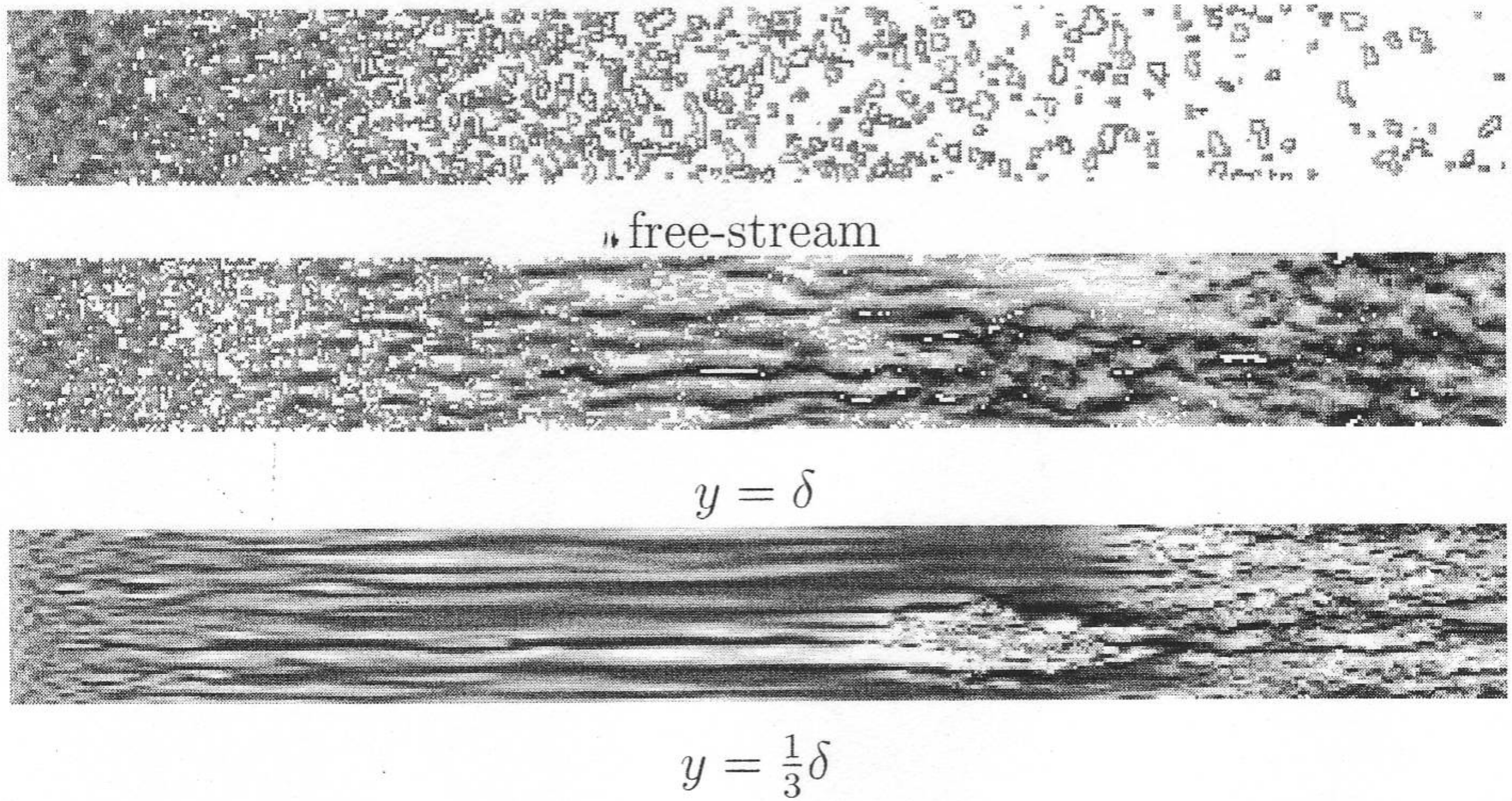
Iso-surfaces of u´

Experiment

DNS

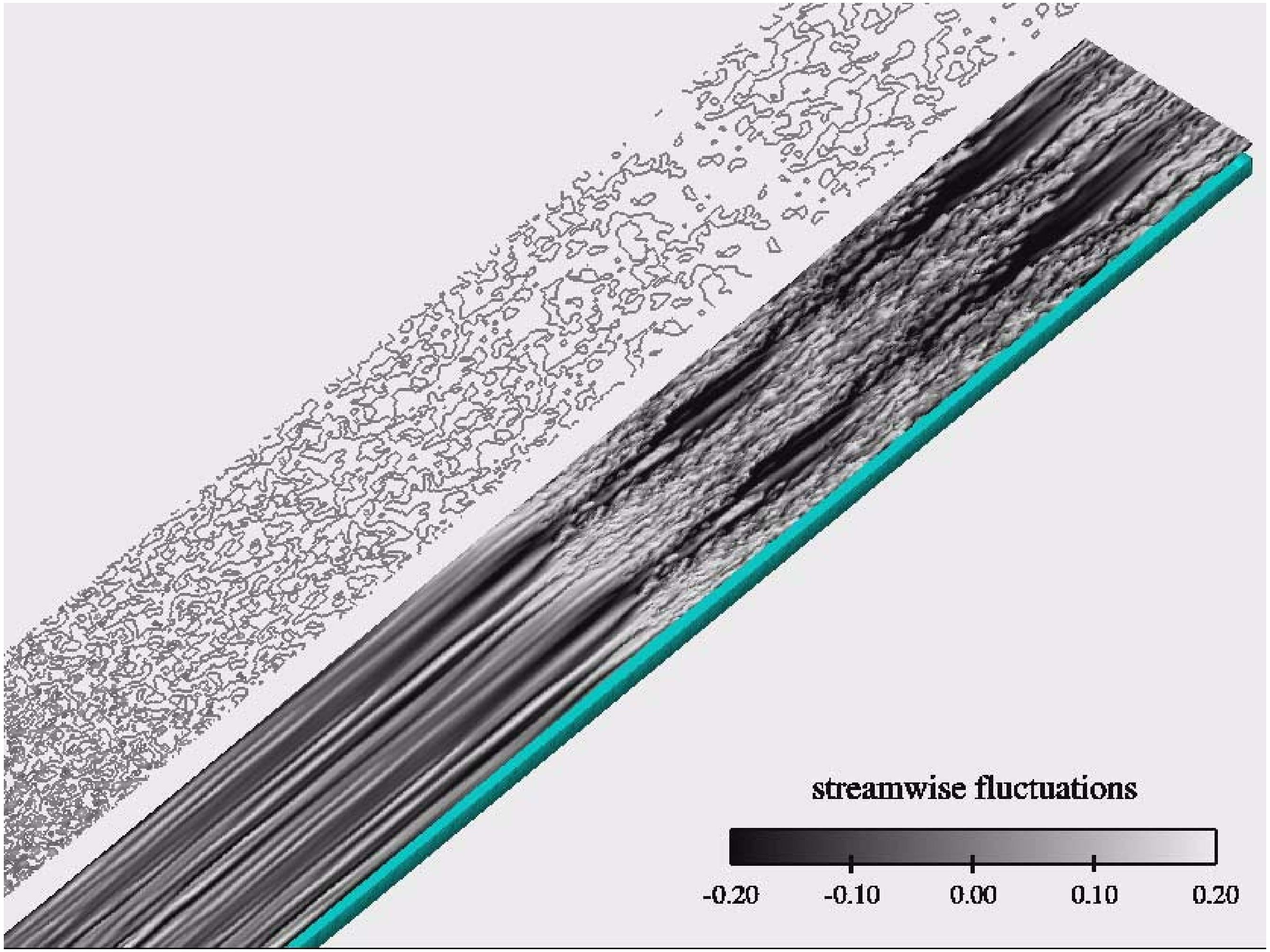
DNS of bypass transition in boundary layer 1

Velocity fluctuations in planes parallel to wall from Durbin et al (2002)

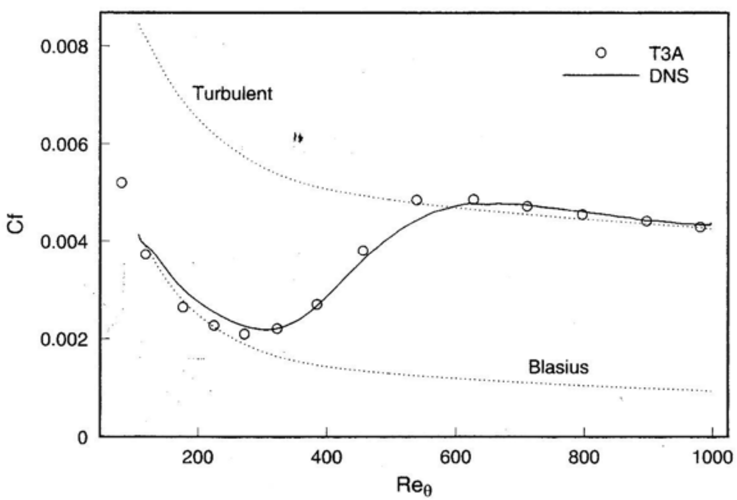


DNS of bypass transition in boundary layer 2

Animation provided by T. Zaki, Imperial College

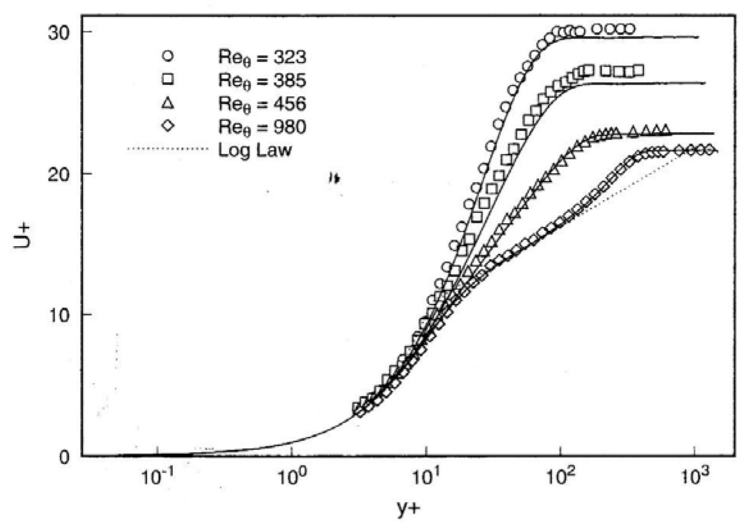


DNS of bypass transition in boundary layer 3

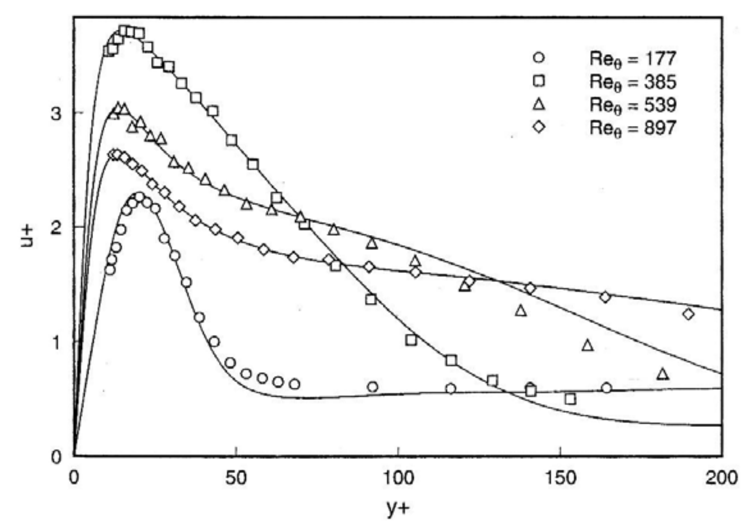


From Durbin et al (2002)

Experiments of Road and Brierly (1990)



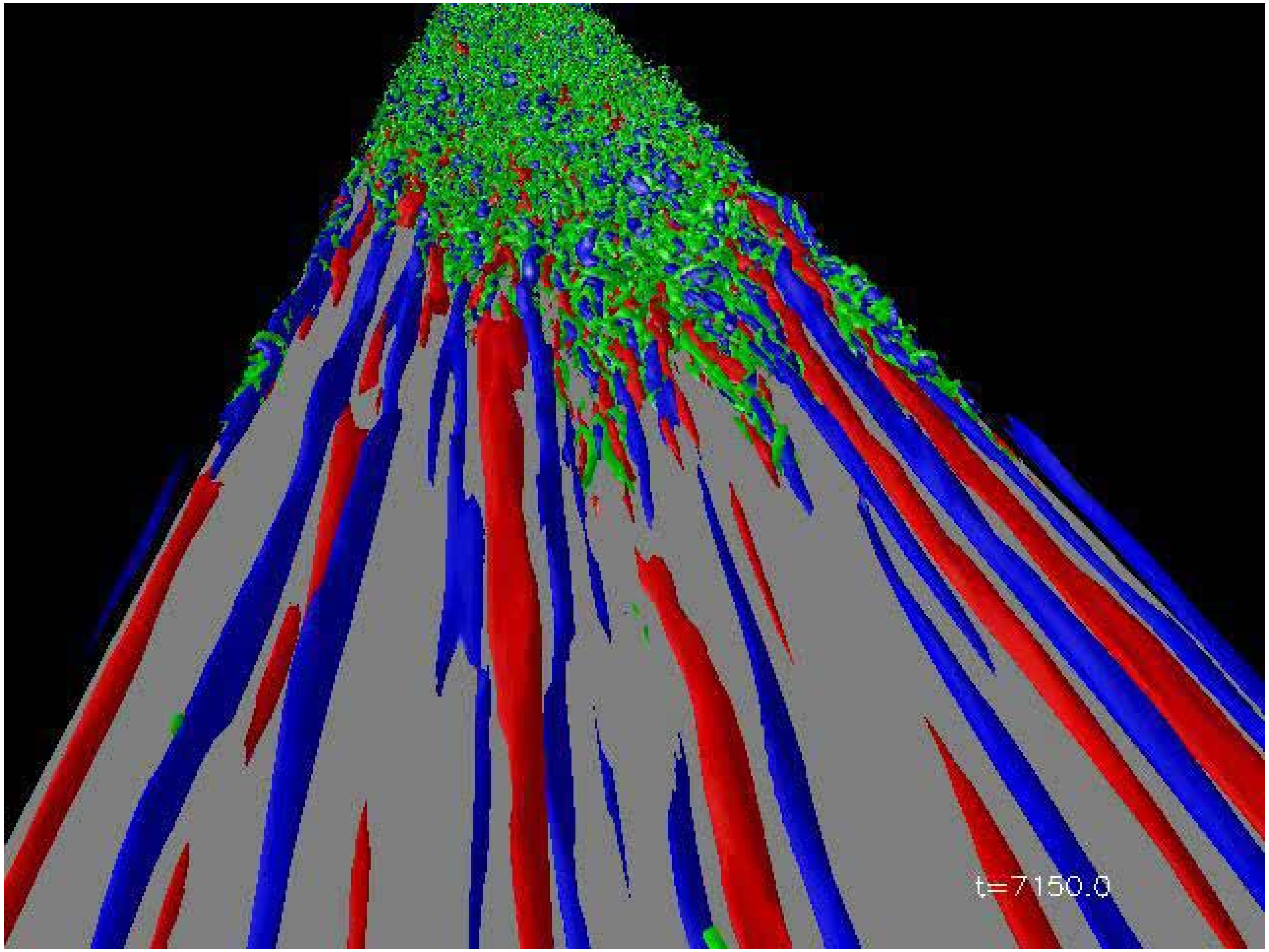
U profiles



u profiles

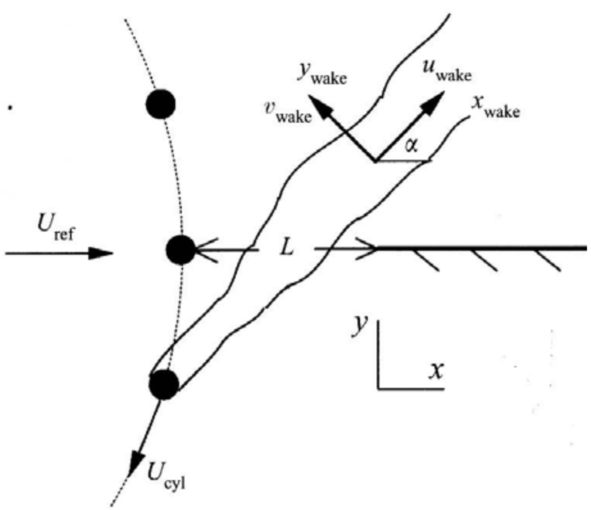
LES of bypass transition in boundary layer

Animation provided by P. Schlatter (KTH Stockholm)

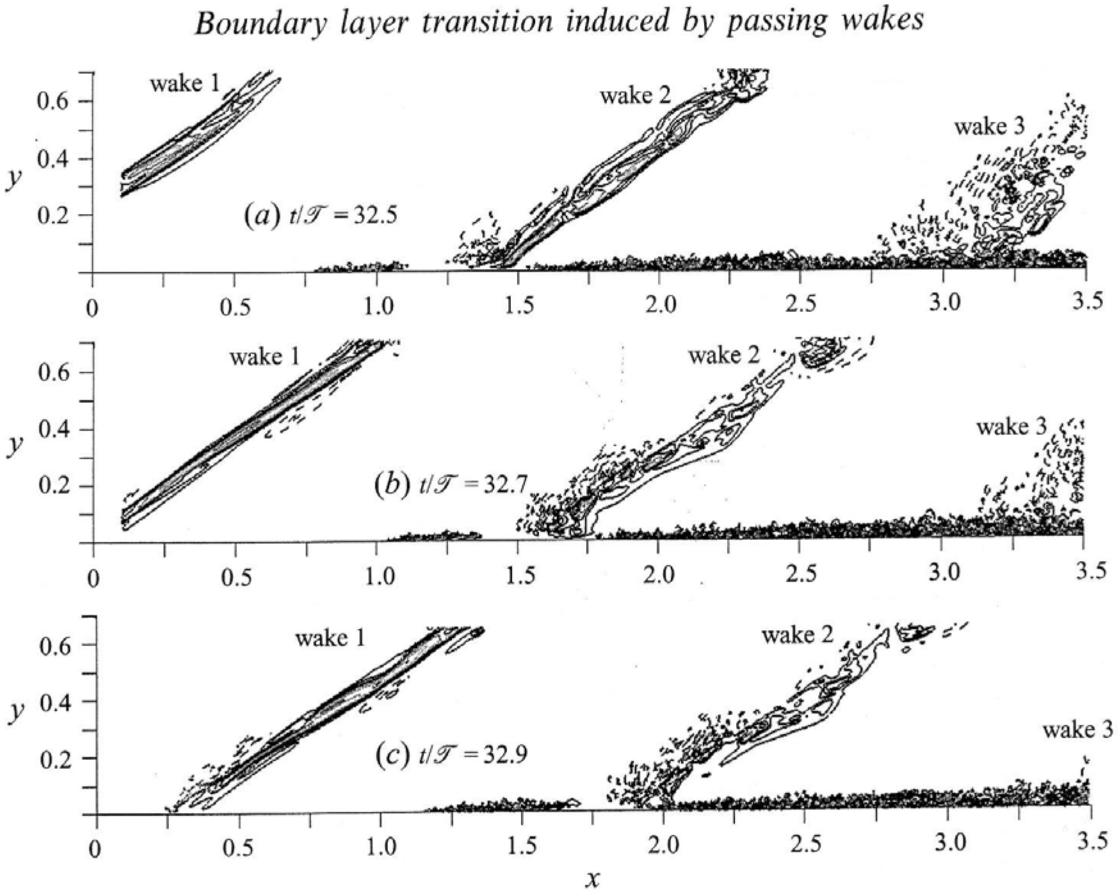


Transition induced by periodic wakes

DNS of Wu, Jacobs, Hunt, Durbin (1999)



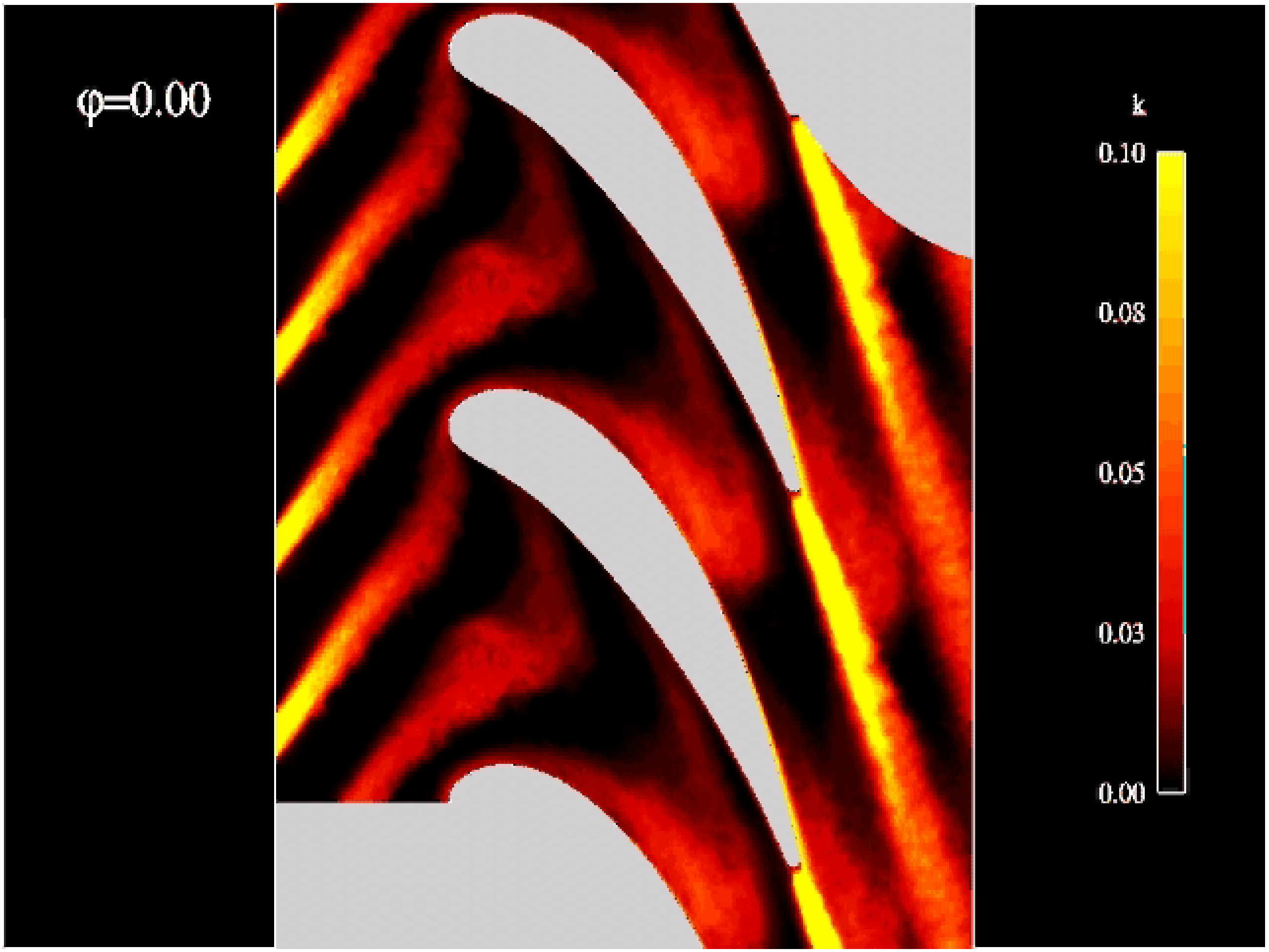
Idealization of experiment of Liu Rodi (1991)



Contours of v - fluctuations

Wakes passing through turbine cascade

Animation from Wissink, University of Karlsruhe



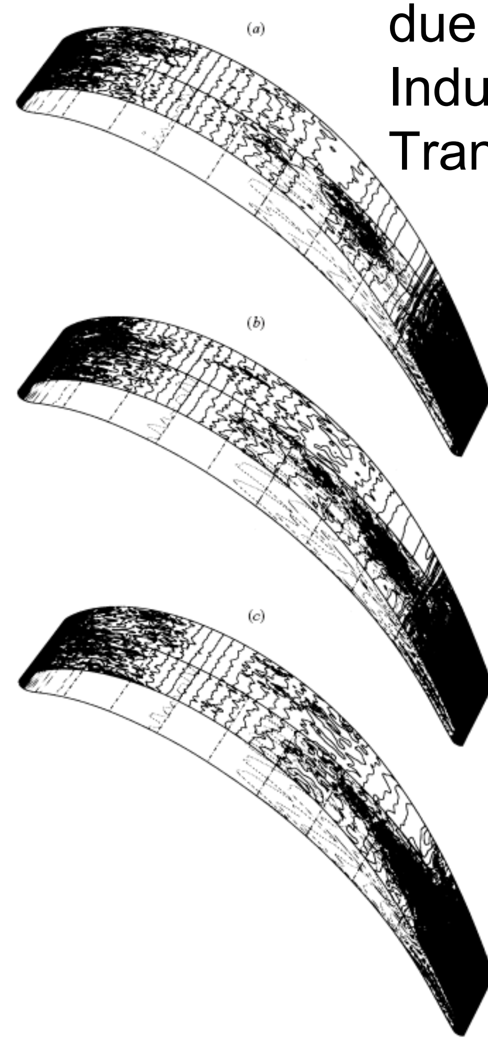
Transition on T106 LPT blade (Re = 148000)

DNS of Wu & Durbin – 50 mio grid points

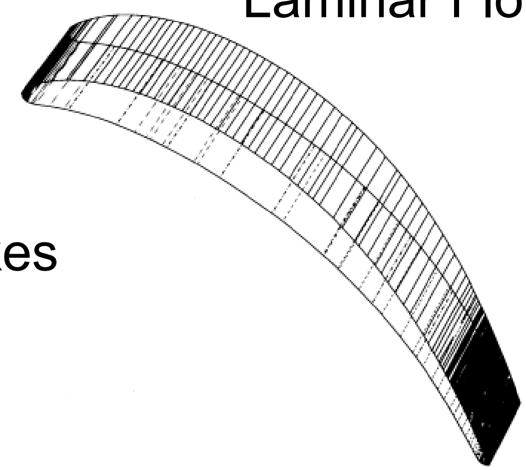
- contours of wall – normal velocity on suctionside

- straight lines indicate laminar flow

Turbulent Spot due to Wake-Induced Transition



Laminar Flow



No wakes

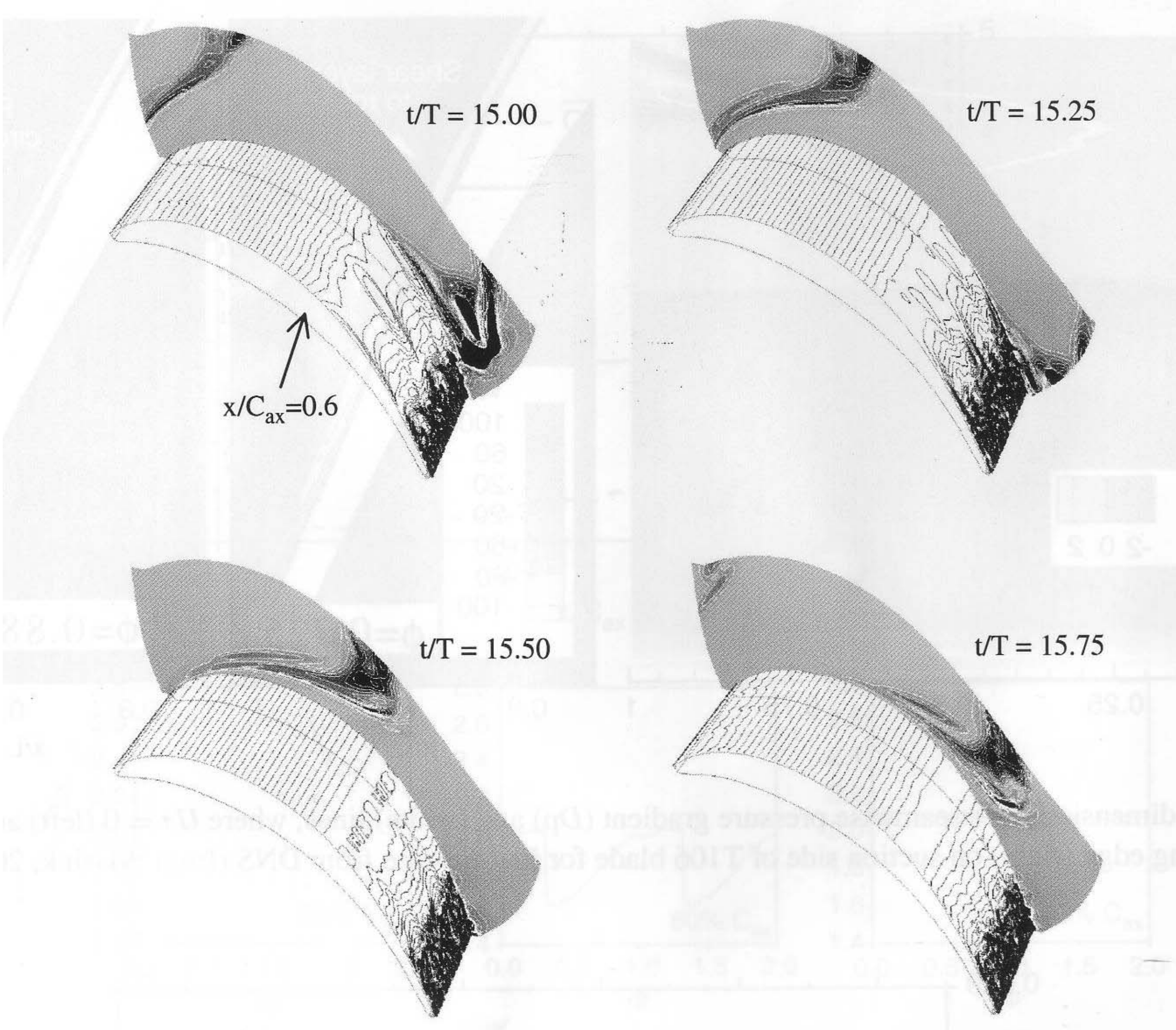
Turbulent Flow

Transition on T106 LPT blade (Re = 148000)

LES of
Michelassi et al (2003)

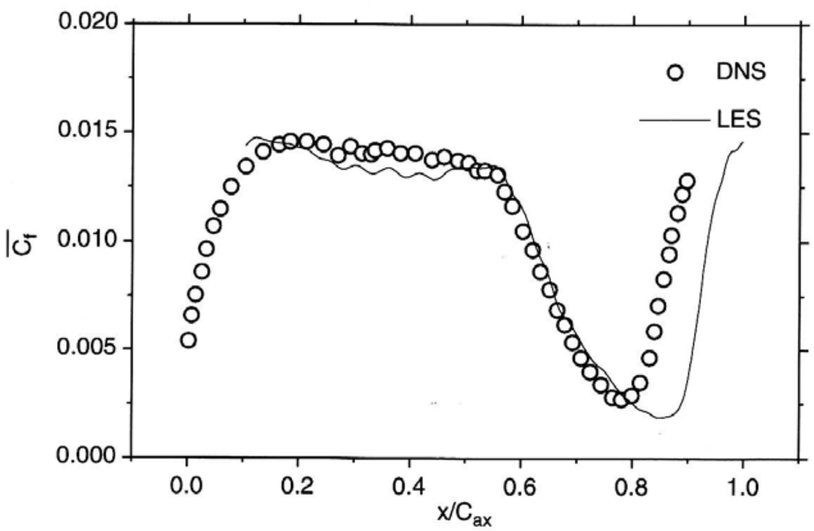
-10 mio grid points
Dynamic SGS model

- Isolines of vertical velocity

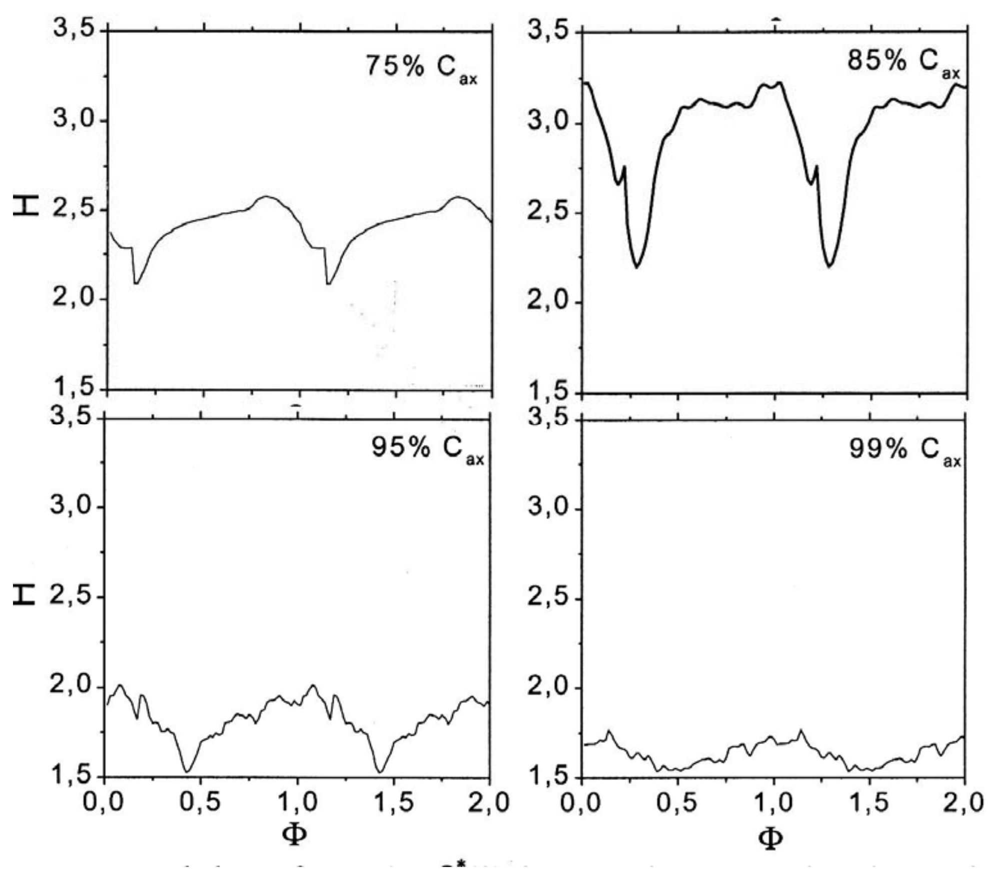


Transition on T106 LPT blade (Re = 148000)

From Michelassi et al (2003) – Suction side



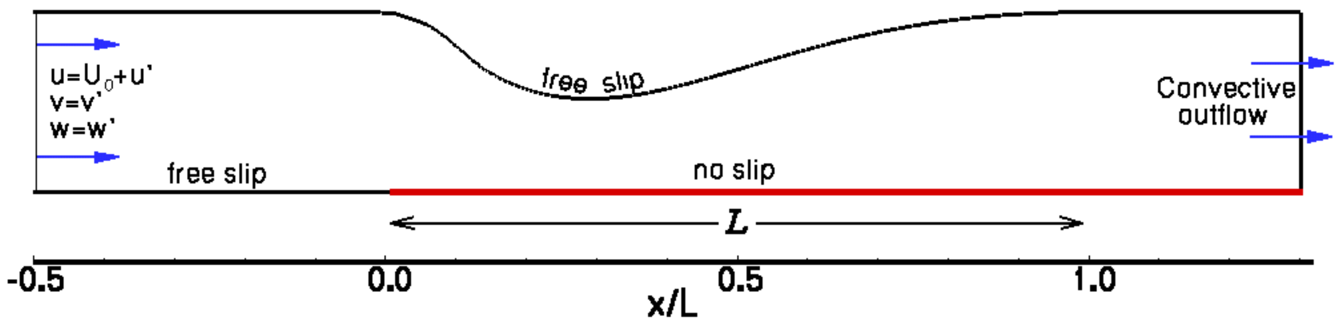
Time-averaged friction coefficient



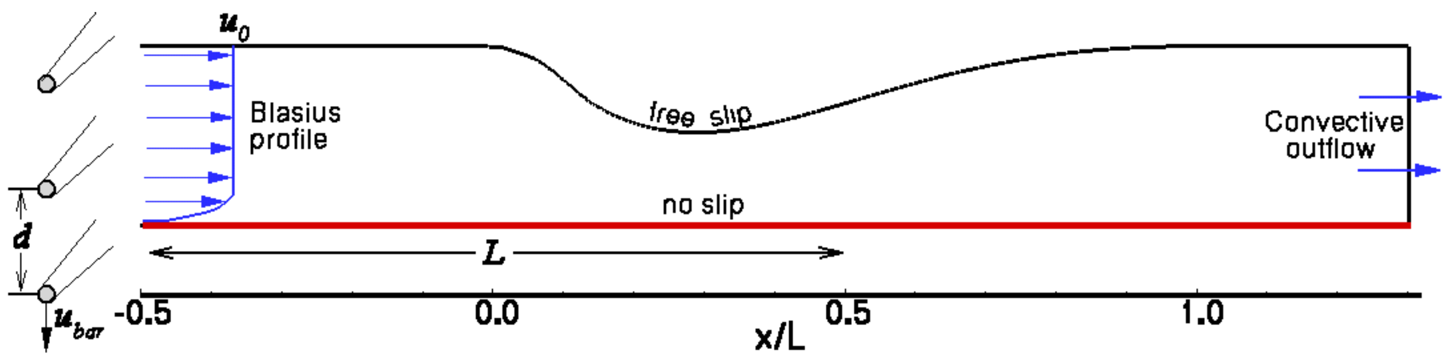
Phase-averaged shape factor

DNS of transitional separation bubbles

Simulations with and without uniformly distributed free-stream fluctuations:



Simulations with free-stream fluctuations concentrated in wakes
(wake data were kindly made available by Wu and Durbin from Stanford University):



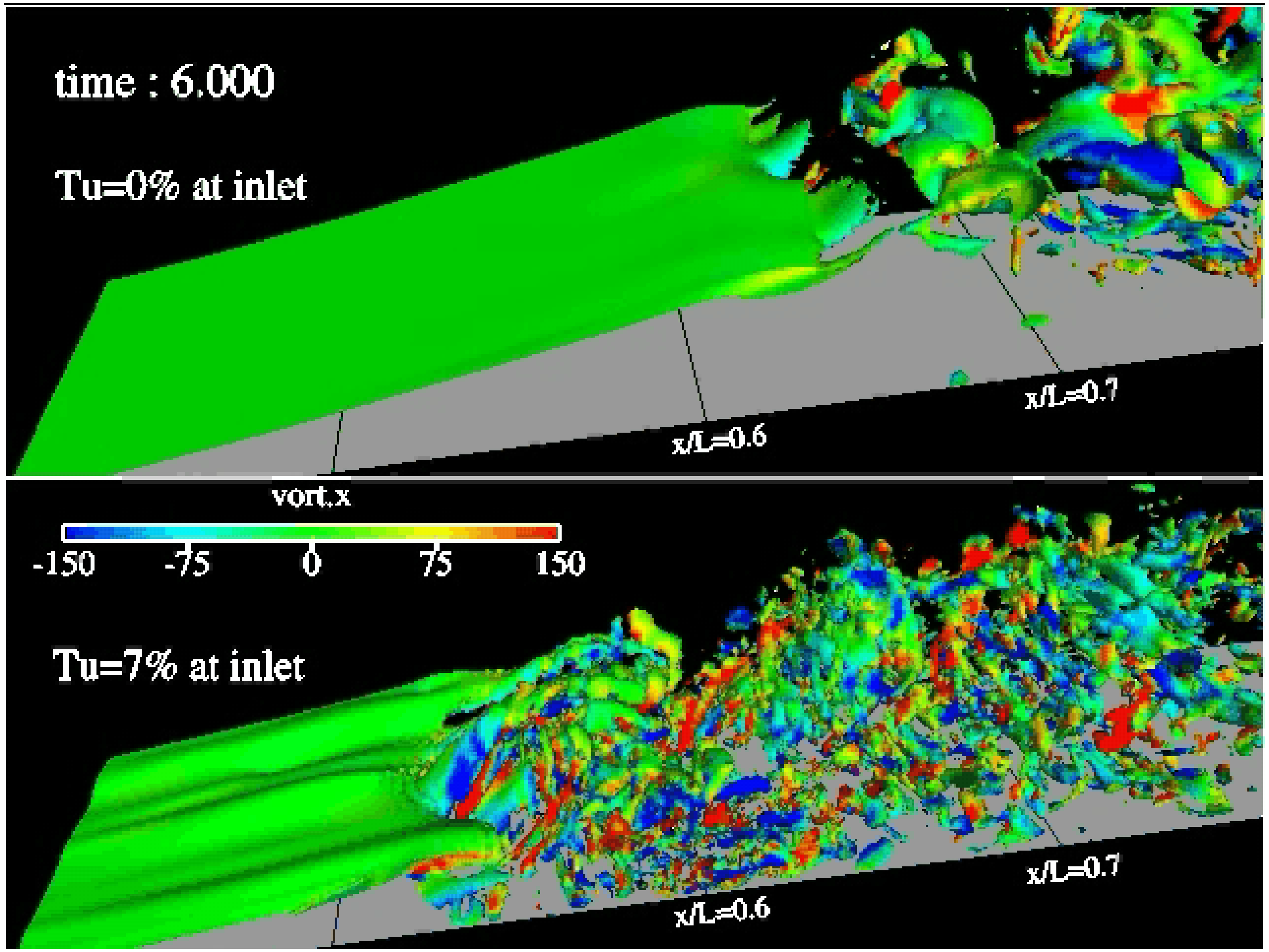
Periodic boundary conditions in spanwise direction,
Re=60000, is based on mean free-stream velocity U_0 and length-scale L (see figure)

Simulations performed

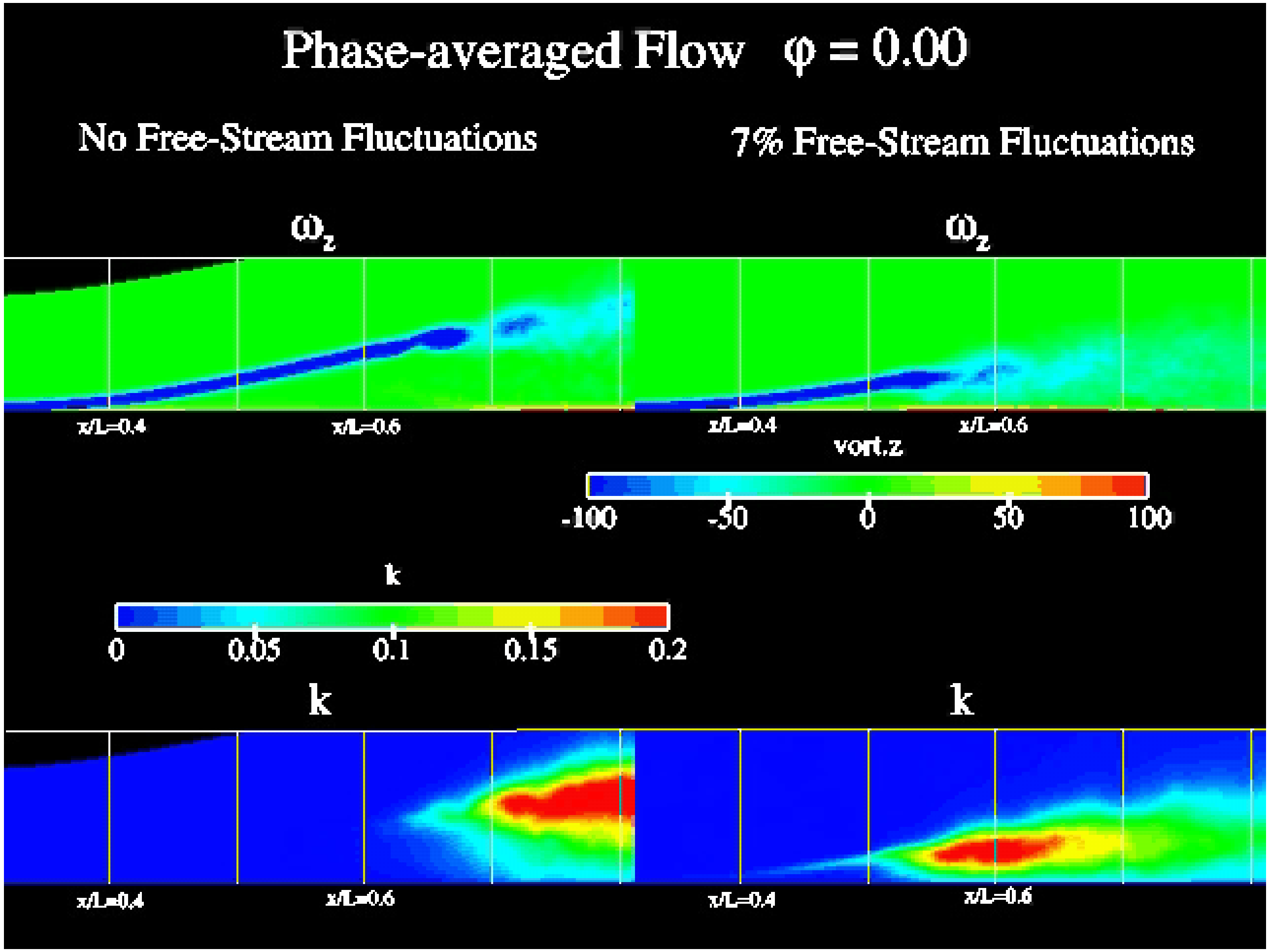
DNS was performed using a finite-volume method on a boundary-fitted curvi-linear grid.

Sim.	grid	Inlet disturbances	Period (T)	Streamw. size
1	*1038 x 226 x 128*	*none*	-	*2.1L*
2	*1926 x 230 x 128*	*7% free-stream fluctuations*	-	*3.5L*
3.1	*966 x 226 x 128*	*Oncoming wakes*	$0.6L/U_e$	*1.8L*
3.2	*1286 x 310 x 128*	*Oncoming wakes*	$0.3L/U_e$	*1.8L*

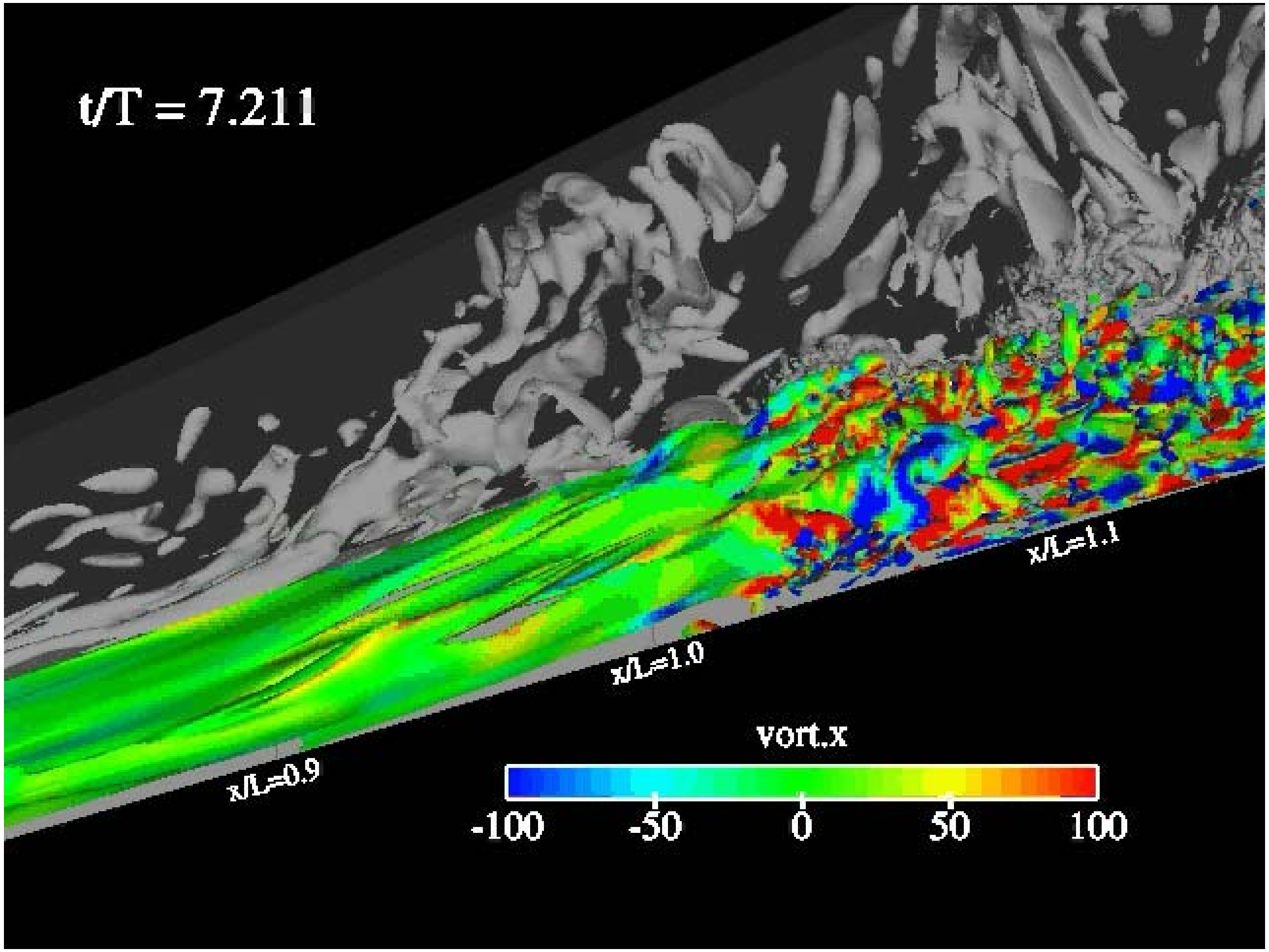
Spanwise vorticity iso-surfaces (Sims. 1,2)



Phase-averaged statistics (film)
Simulation 1 vs. Simulation 2

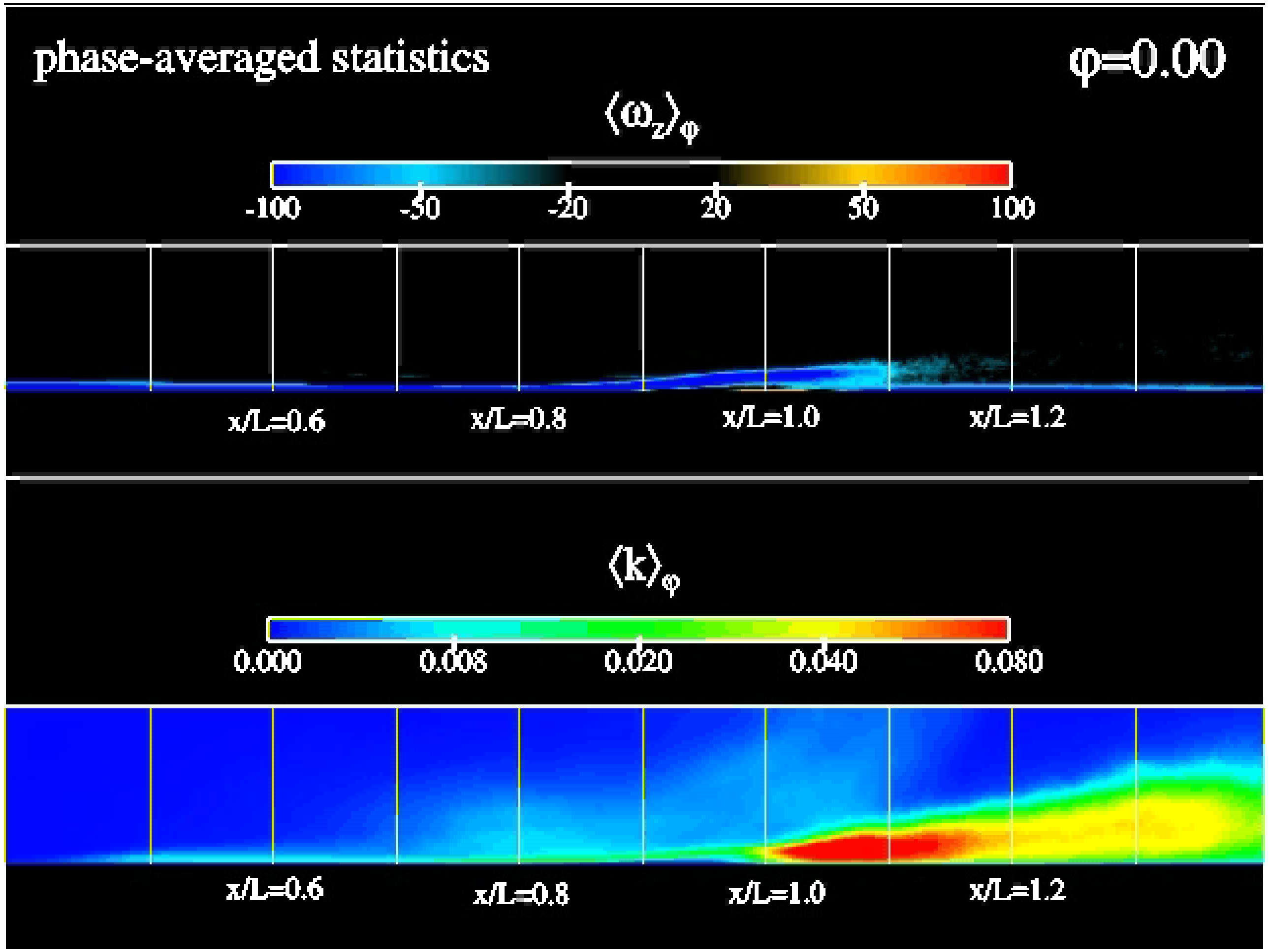


Boundary layer of Simulation 3.1
(made visible using an iso-surface of the spanwise vorticity)



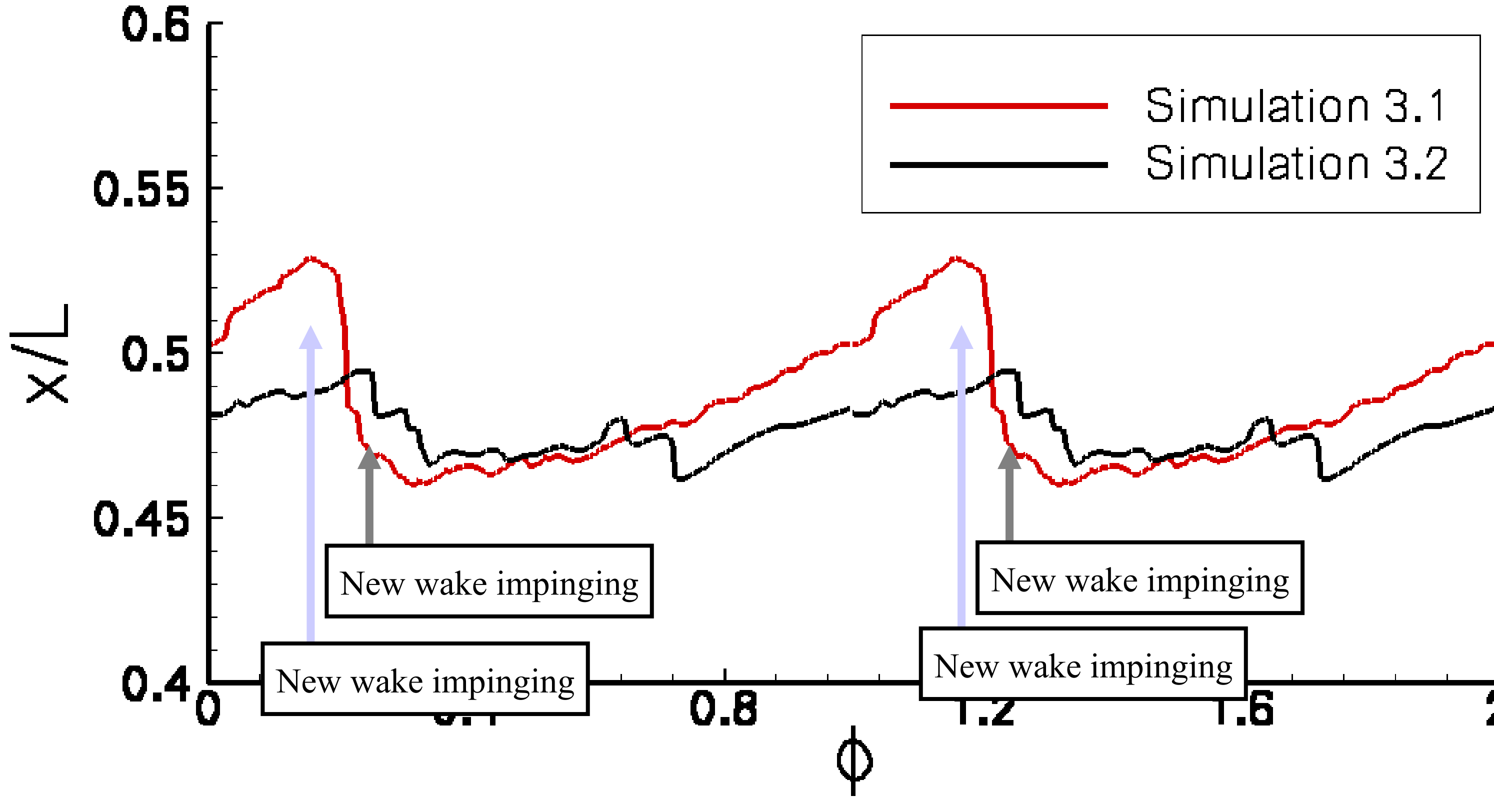
Vortical structures in translucent box at the back belong to impinging wakes and are made visible with the λ_2-criterion

Phase-averaged statistics of Simulation 3.1



Passing wakes induce elevated levels of $<k>_f$ in the free stream

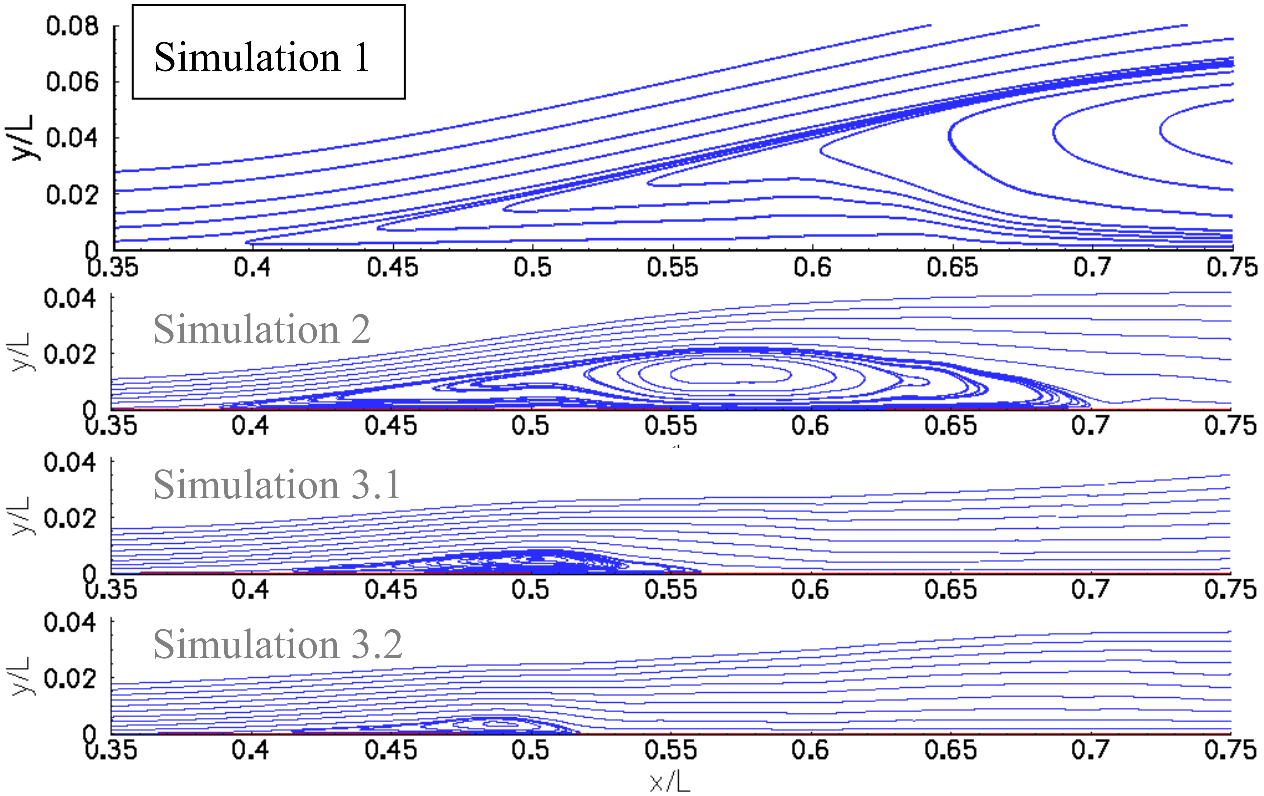
Transition location as function of phase ϕ of passing wake



Transition is identified with the most upstream location along the line $y/L=3.2\times10^{-4}$ where <ww> exceeds 20% of its maximum

Comparison of the size of the separation bubble

Simulations 1, 2, 3.1 and 3.2.



Transition prediction with RANS 1

- Turbulence is averaged out – effect of turbulent fluctuations on mean-flow quantities through Reynolds stresses $\overline{u_i u_j}$

- These need to be determined by a turbulence model
  - in transitional flows they go from zero in laminar flow to their values in the fully turbulent flow regions

- Wide variety of models developed basically for fully turbulent flows – ranging from mixing-length to Reynolds-stress models
  - in practice mostly eddy-visocity models used:
    2 - equation (k-ε, k-ω), 1 – equation (Spalart-Allmaras)

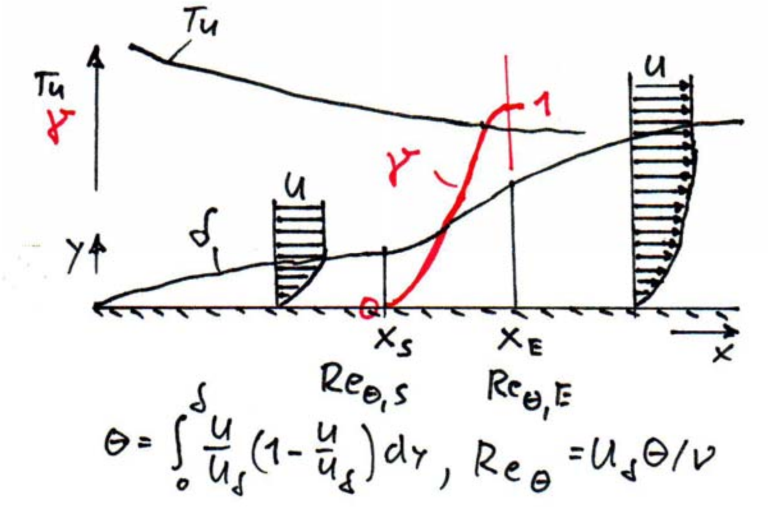
- **Can these models by themselves predict transition?**

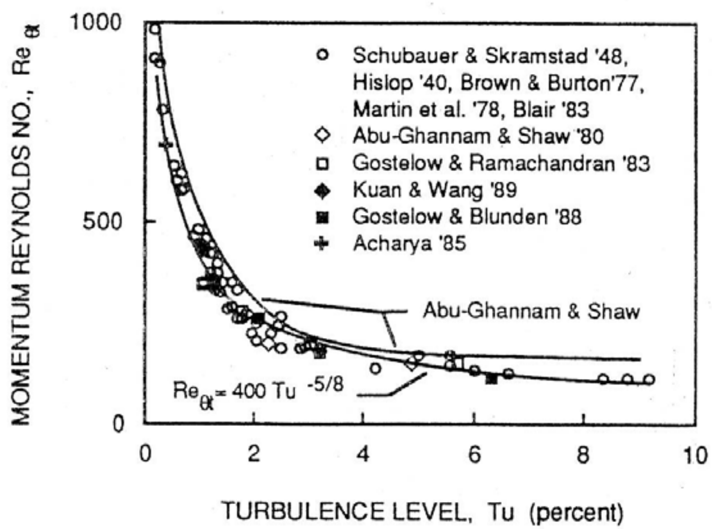
Transition prediction with RANS 2

- Natural transition owing to instability processes cannot be predicted by statistical RANS models
- Bypass transition (at Tu > 1%) is amenable to predictions by low Re versions of RANS models:
  - diffusion terms in transport equations for turbulence parameters (e.g. k) bring turbulence from free stream to near wall region, leading to production of more turbulence and then to transition
  - variety of models tested (Review by Savill 2002)
  - success more coincidental because predicted transition stronlgy dependent on distribution of turbulence parameters in laminar boundary layer
  - hence this approach considered unreliable

Transition prediction with RANS + empirical correlations 1

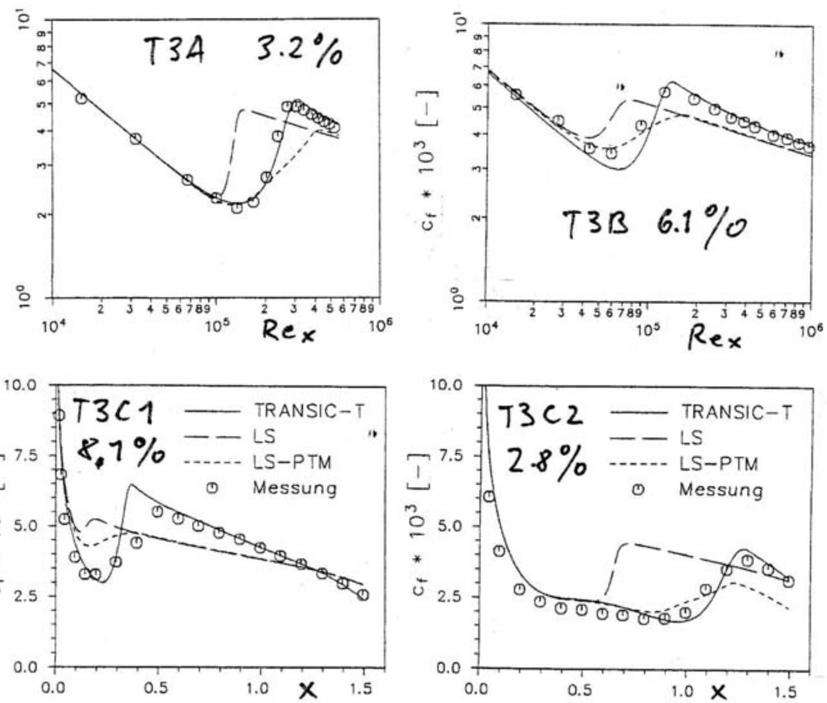
- More reliable to use empirical correlation for onset of transition
- μ_t from turbulence model multiplied by intermittency factor γ
- Transition starts where $Re_\Theta > Re_{\Theta, S}$
  Empirical correlation $Re_{\Theta, s} = f(Tu, \frac{dp}{dx})$
- γ through transition either
  - from empirical relation
    e.g. involving $Re_{\Theta, E}$ (with $Re_{\Theta, E} \approx 2\, Re_{\Theta, S}$)
  - or from transport equation for γ
- Many successful calculations
- But δ often not well defined
  - Re_Θ difficult to compute in modern CFD codes (unstructured grids, massive parallel execution)



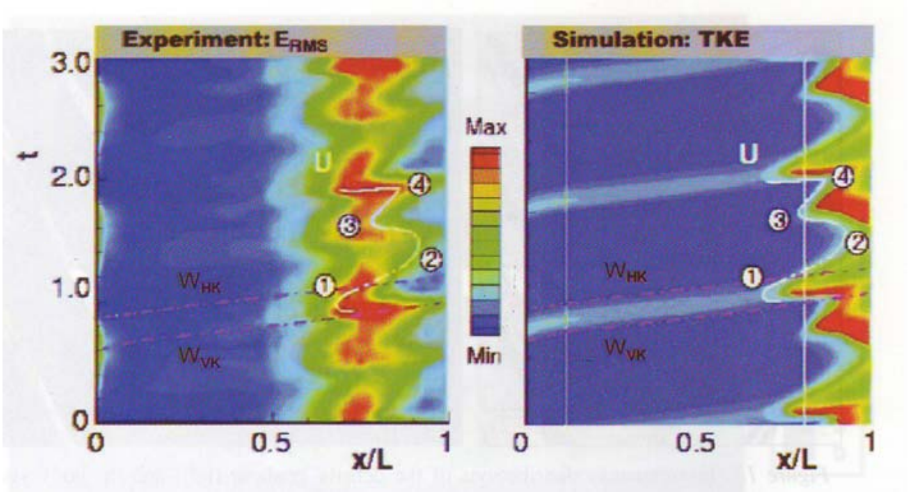


Transition prediction with RANS + empirical correlations 2

ERCOFTAC flat plate test cases from Schiele (2000)



From Nürnberger & Greza (2002)



Correlation based transition model using local variables

- Menter, Langtry et al (2004, 2006) model for use in modern CFD codes – correlations only based on local variables
- Instead of Re_Θ , use of local vorticity Reynolds number $Re_\nu = \frac{\rho y^2}{\mu} \frac{\partial u}{\partial y}$
- Transport equation for intermittency factor γ
- 2nd transport equation for transition momentum thickness Reynolds number $Re_{\Theta t}$

  - source terms such that outside boundary layer $Re_{\Theta t} = f\,(Tu, dp/ds)$ follows given empirical correlation

- When locally $Re_{\Theta t} > Re_v$, transition triggered by activating source term in γ-equation $\Rightarrow$ γ increases
- Basic turbulence model is Menter SST model

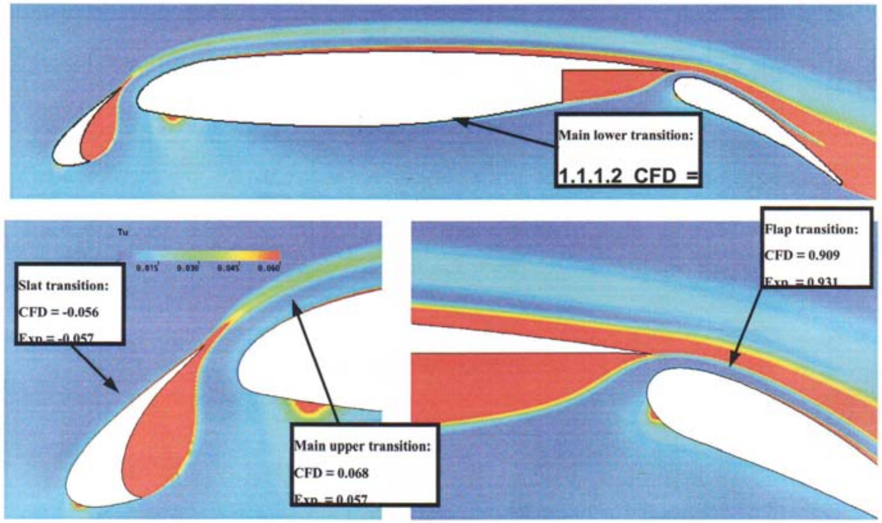
  - γ multiplies production term in k-equation (not μ_t)

- Modification for separation-induced transition

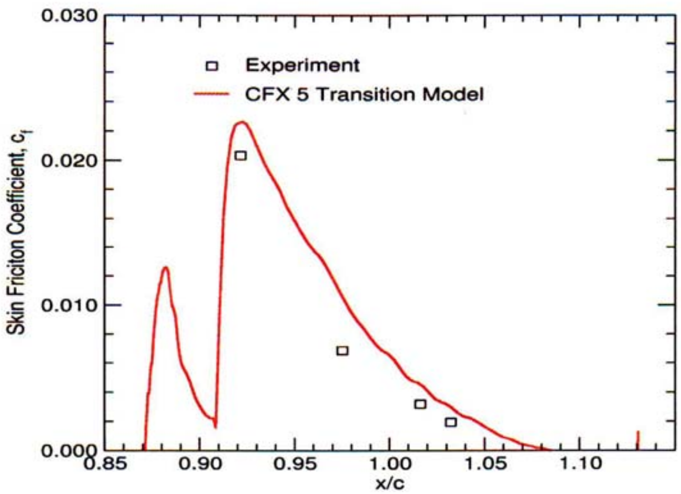
McDonald Douglas 30P-30N flap test case

From Menter /Langtry – Experiments performed at NASA Langley

Tu and transition location

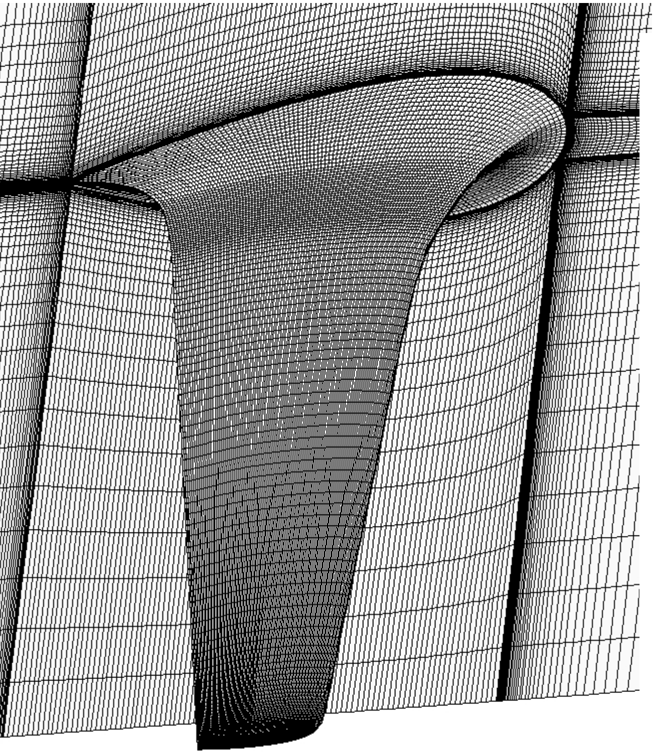


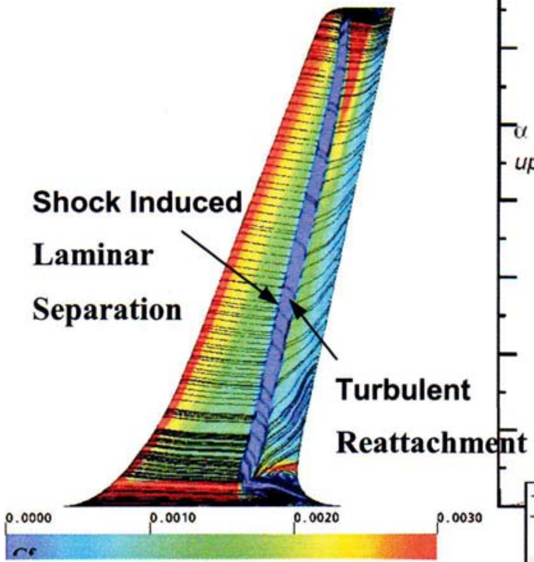
Skin fricion on upper surface of flap

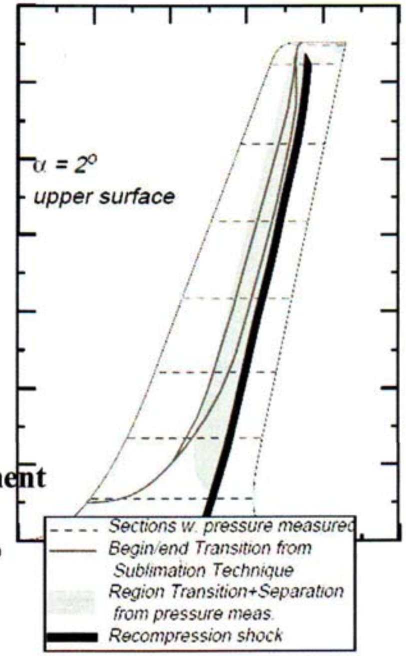


DLR F-5 Transonic Wing

From Menter/Langtry – Experiment of Sobieczky (1999)

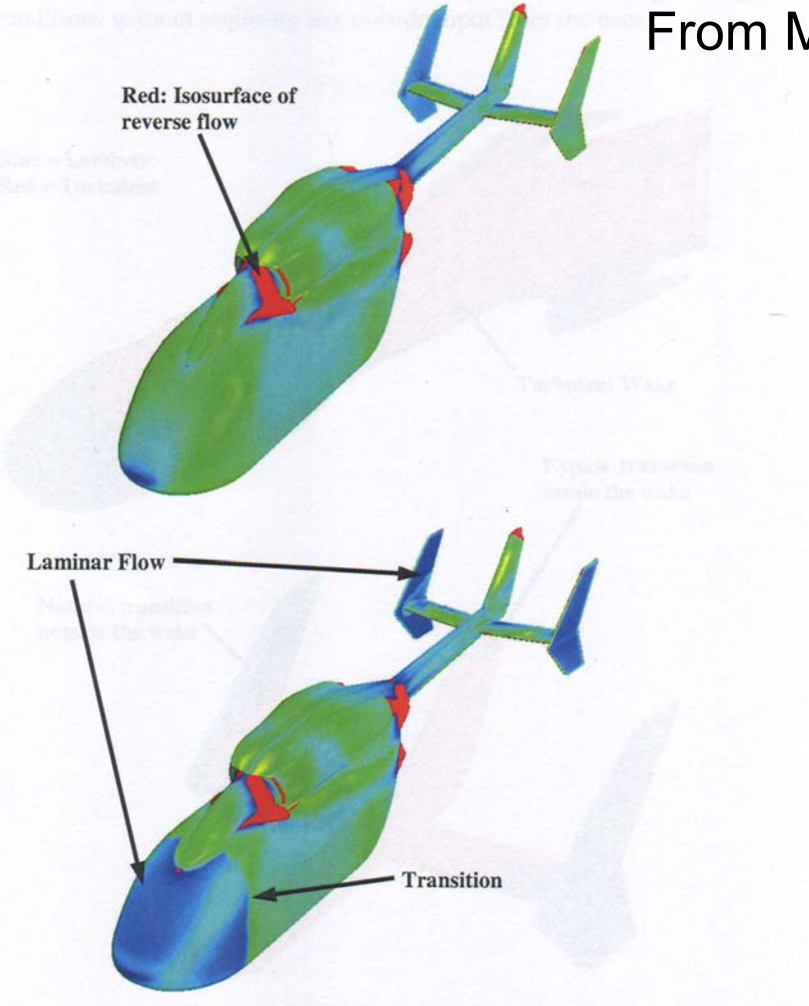




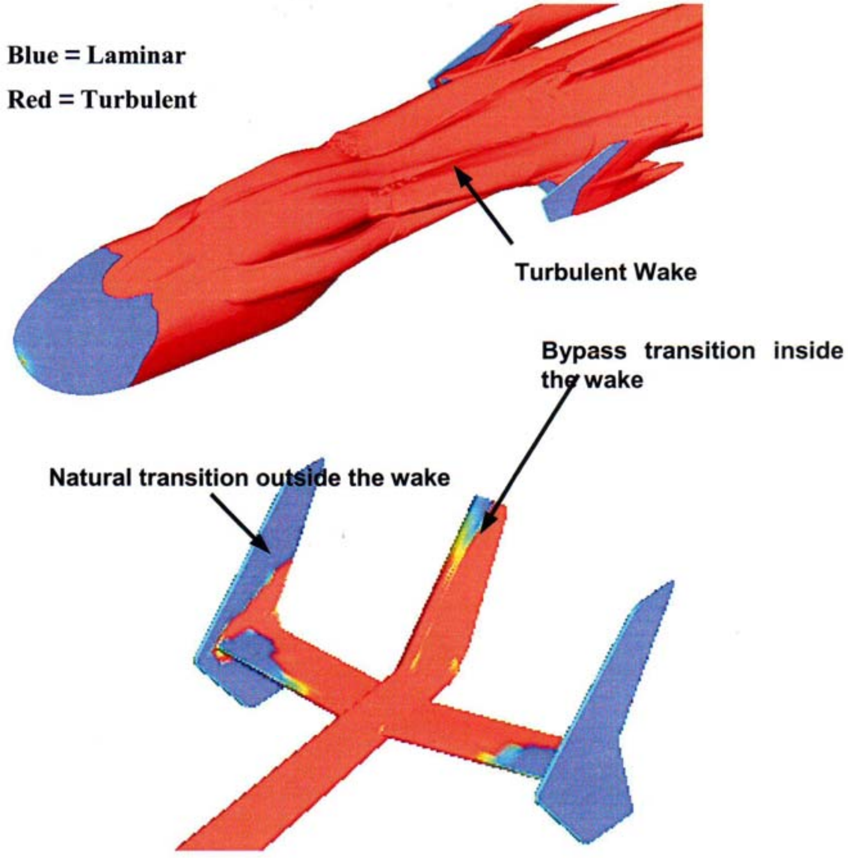


Eurocopter Airframe

From Menter/Langtry



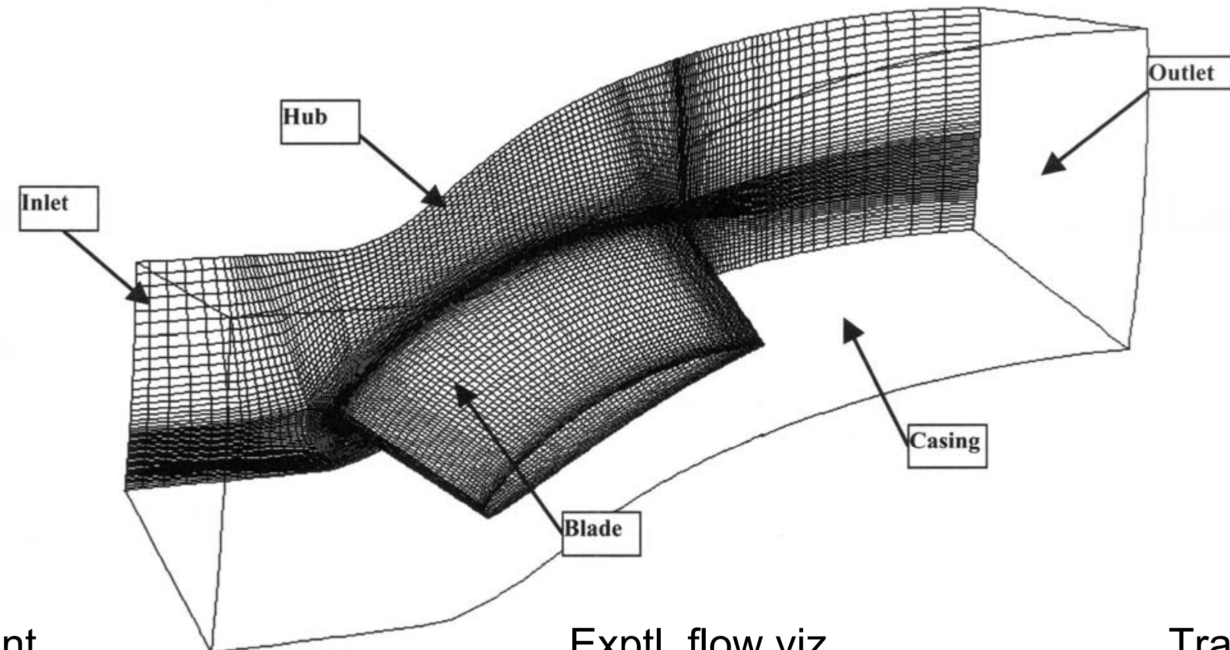
Contour plot of skin friction for a fully turbulent (top) and transitional (bottom) Eurocopter airframe.



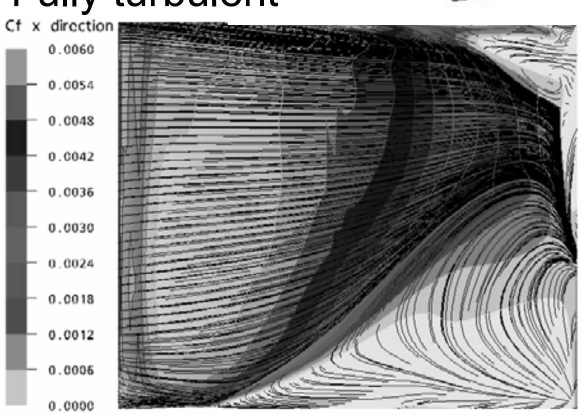
Iso-surface of turbulent flow (top) and surface value of intermittency (bottom) indicating the laminar (blue) and turbulent (red) regions on the Eurocopter airframe.

RGW Low Aspect Ratio Annular Compressor Cascade

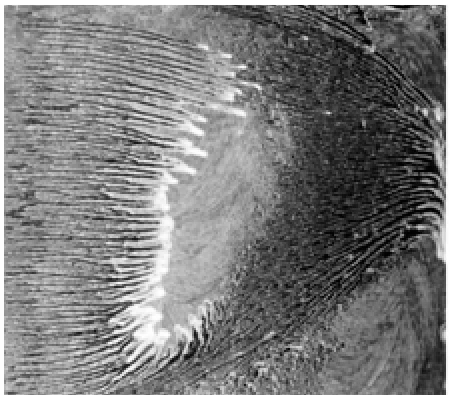
From Menter/Langtry – Expt. Schulz & Gallus (1988)



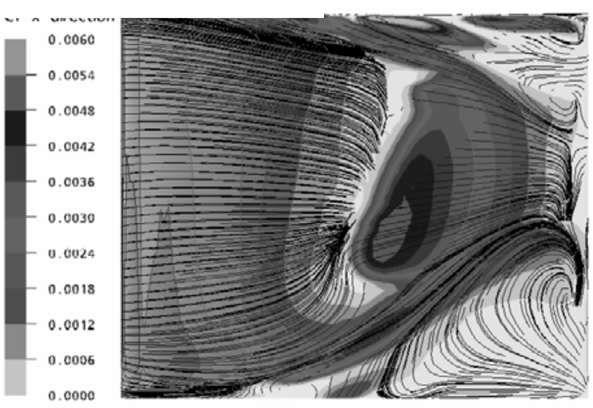
Fully turbulent



Exptl. flow viz.



Transitional



Conclusions

- DNS very powerful tool for studying all details of transition of all kinds
  - natural, bypass, separated flow
  - very expensive, requires large computing resources
  - so far restricted to low Re (of fully turbulent flow) and simple geometries
- LES less expensive – but still demanding
  - either near-DNS resolution near wall or suitable SGS model – more testing necessary
  - not yet used in practice
- RANS methods – approach used in practice
  - Without empirical transition correlations not sufficiently reliable
  - Methods using Re_{Θ} – based correlations quite successful but not suitable for use in modern general CFD codes
  - New model based on local variables encouraging, needs more testing