The effect of free-stream turbulence on growth and breakdown of TS-waves

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ETC-11, Porto, June 25-28, 2007

Outline

- Introduction & Background
  - Laminar-turbulent transition
  - Control by boundary-layer streaks
  - Bypass transition
- Simulation Approach
  - Large-eddy simulation (LES) and numerical method
  - Disturbance generation and validation
- Simulation Results
  - Statistical results
  - Modal results
  - Instantaneous visualisations
- Conclusions

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Introduction:
Transition to Turbulence

Classical Transition

Low levels of free-stream turbulence (FST) (<1%)

→ exponential growth of TS and secondary instability

$$E \propto \exp(2|\alpha_i|x)$$

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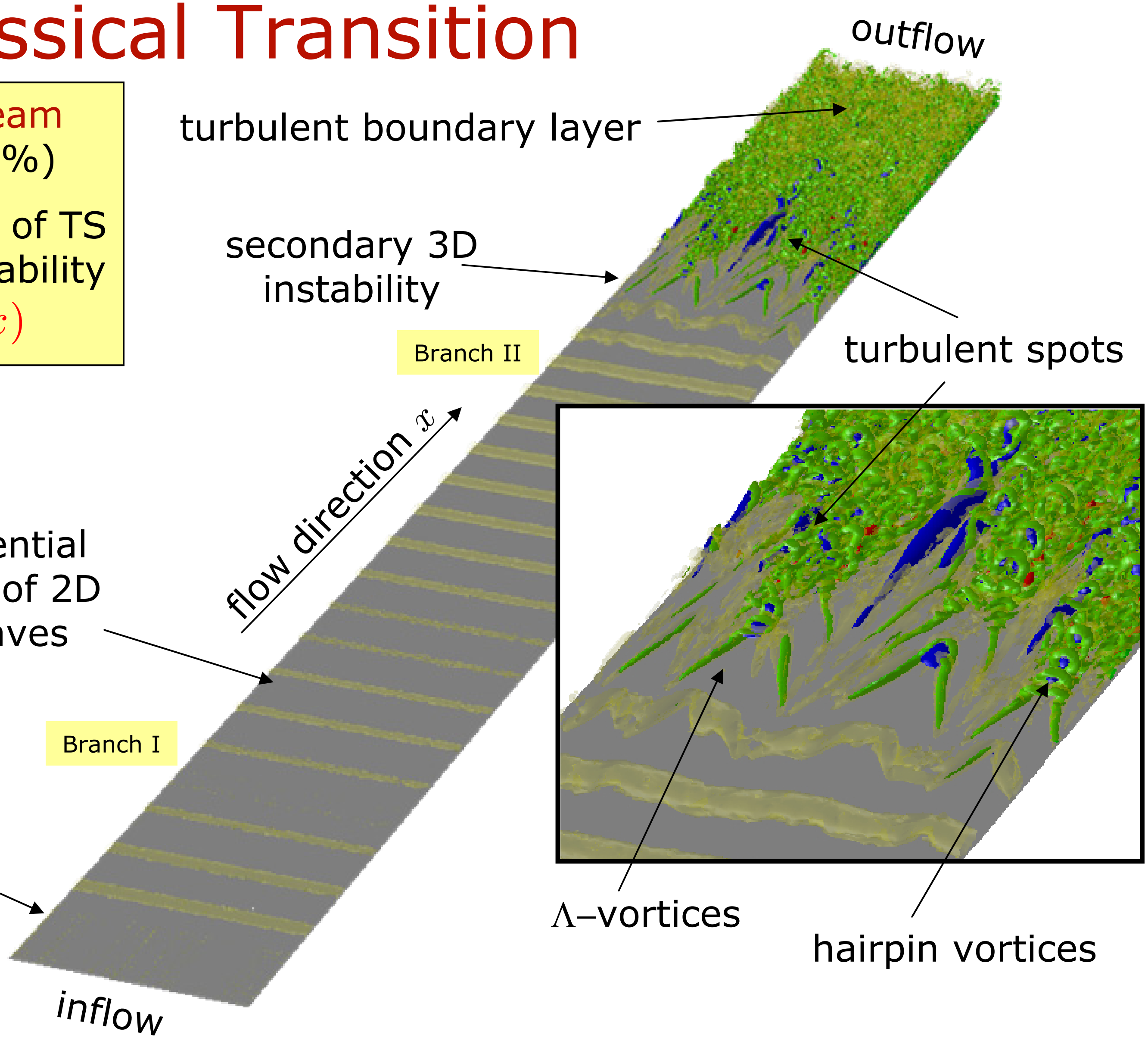

high velocity
low velocity
contours of λ_2

Bypass Transition

High levels of free-stream turbulence (>1%)

→ exponential growth of TS waves is "bypassed"

$$E \propto Tu^2 Re_x$$

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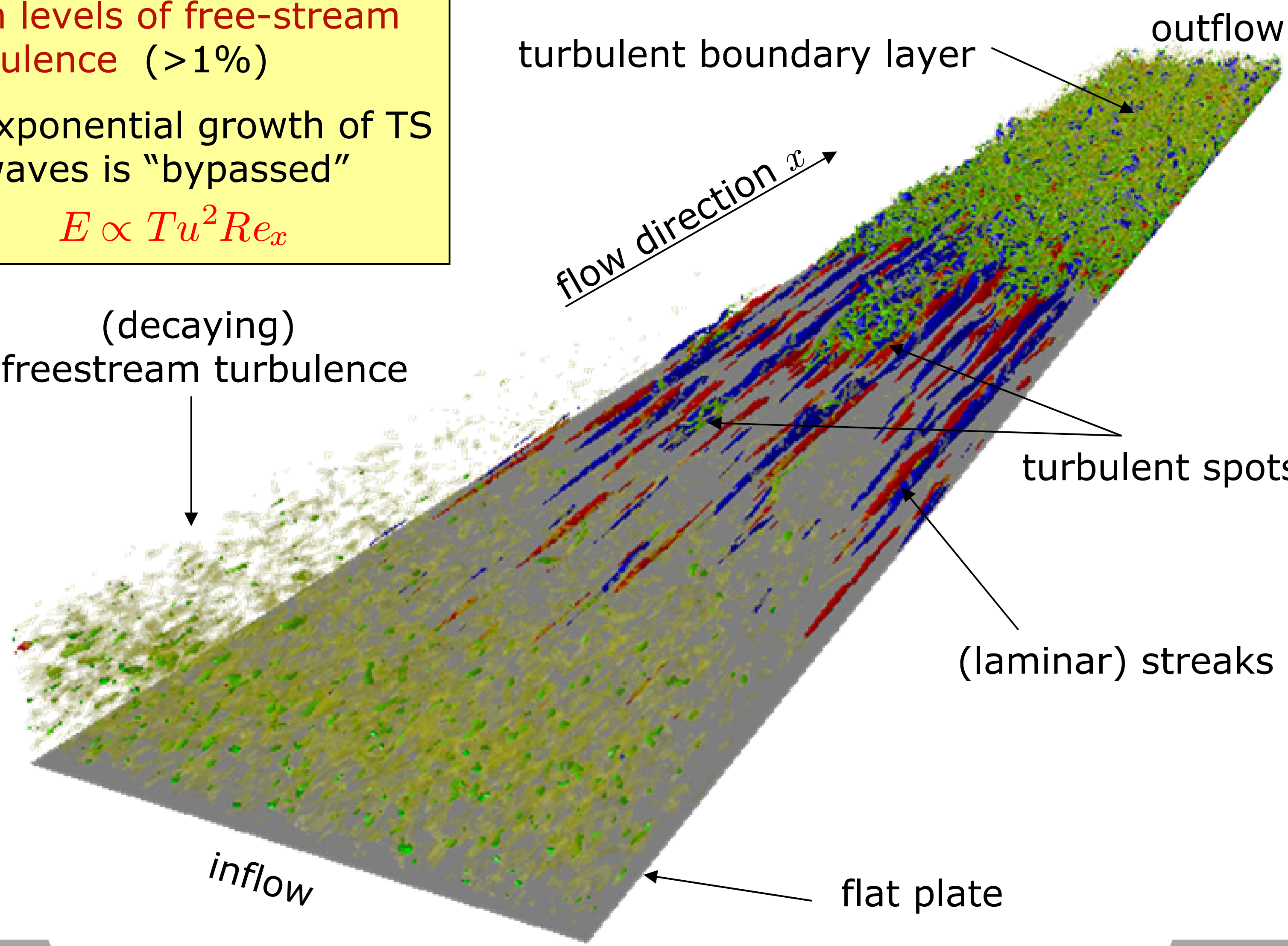
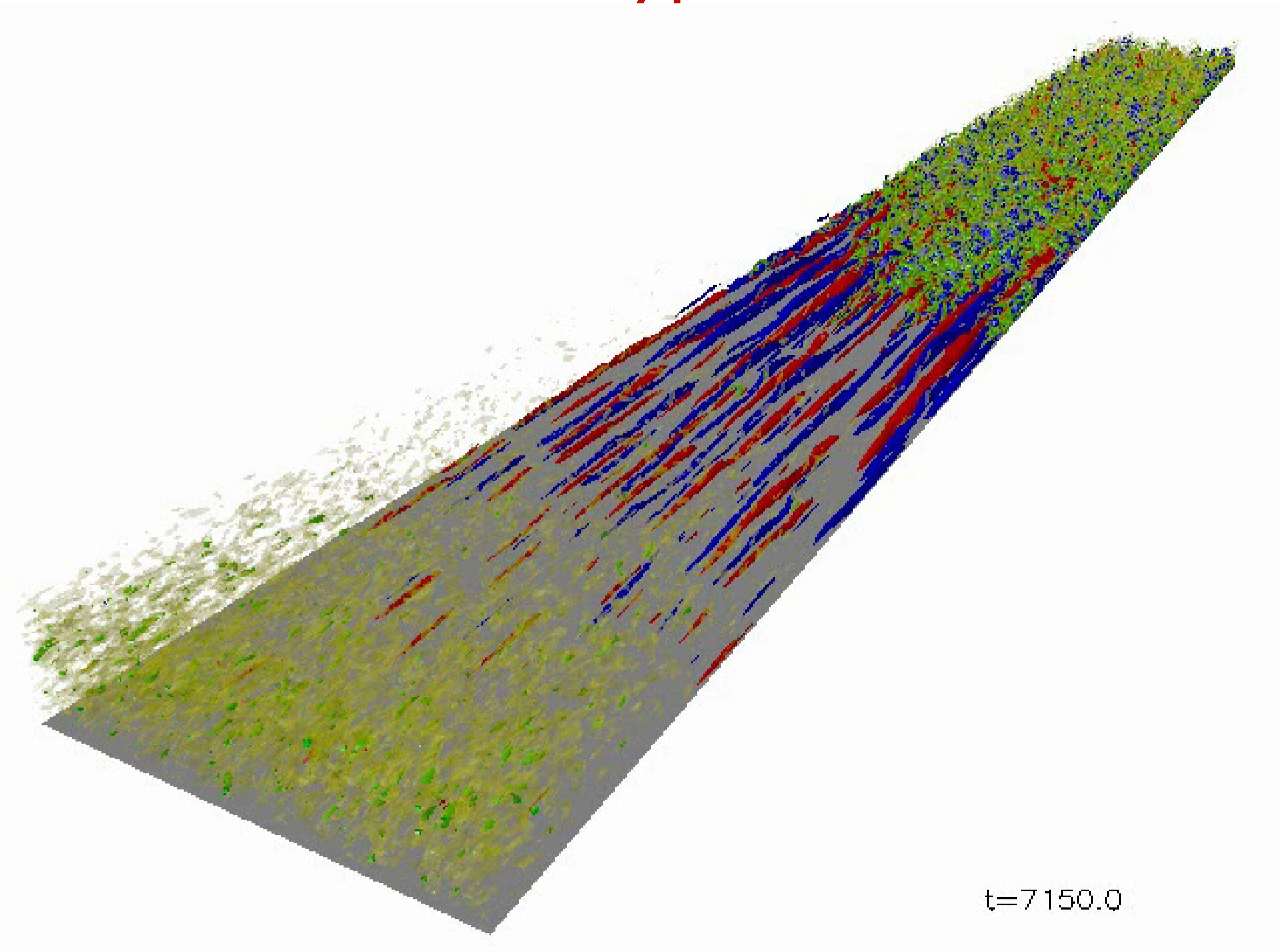


high velocity
low velocity
contours of λ_2

Visualisation of Bypass Transition



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λ_2 criterion
high dist. velocity
low dist. velocity

Previous Results

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- (Artificial, steady) streaks are shown to stabilise TS-waves:
  - Experimentally: Kachanov & Tararykin (1987), Fransson *et al.* (2004-2006)
  - Theoretically/numerically: Cossu & Brandt (2002), Schlatter *et al.* (2007)
- Streaks induced by low levels of FST:
  - Experimental:
    - Transition sometimes delayed (Arnal & Juillen 1978)
    - Stabilising mean action on low amplitude TS-waves (Boiko *et al.* 1994)
    - Destabilising interaction with large amplitude TS-waves (Boiko *et al.* 1994, Westin *et al.* 1994)
- Aims of the present study:
  - Combine FST and TS-waves → Influence on transition?
  - Conduct a simulation with realistic computational setup
  - Confirm experimental findings
  - Extend experimental/theoretical studies

Animation

A_{st} at the inflow plane varies from 0% at t=15000 to 10% at t=18000.

steady noise

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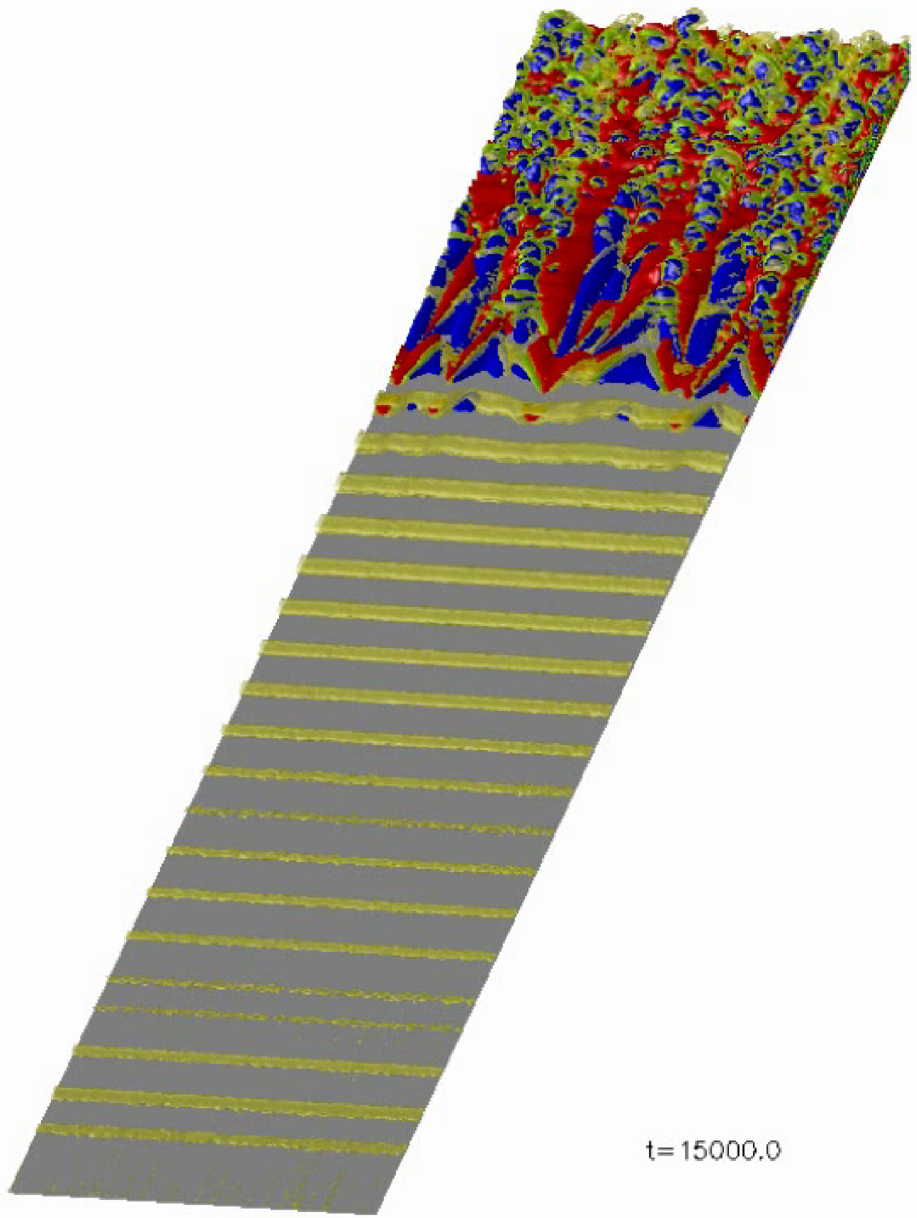

λ_2 criterion
high dist. velocity
low dist. velocity

Schlatter *et al.* (2007)

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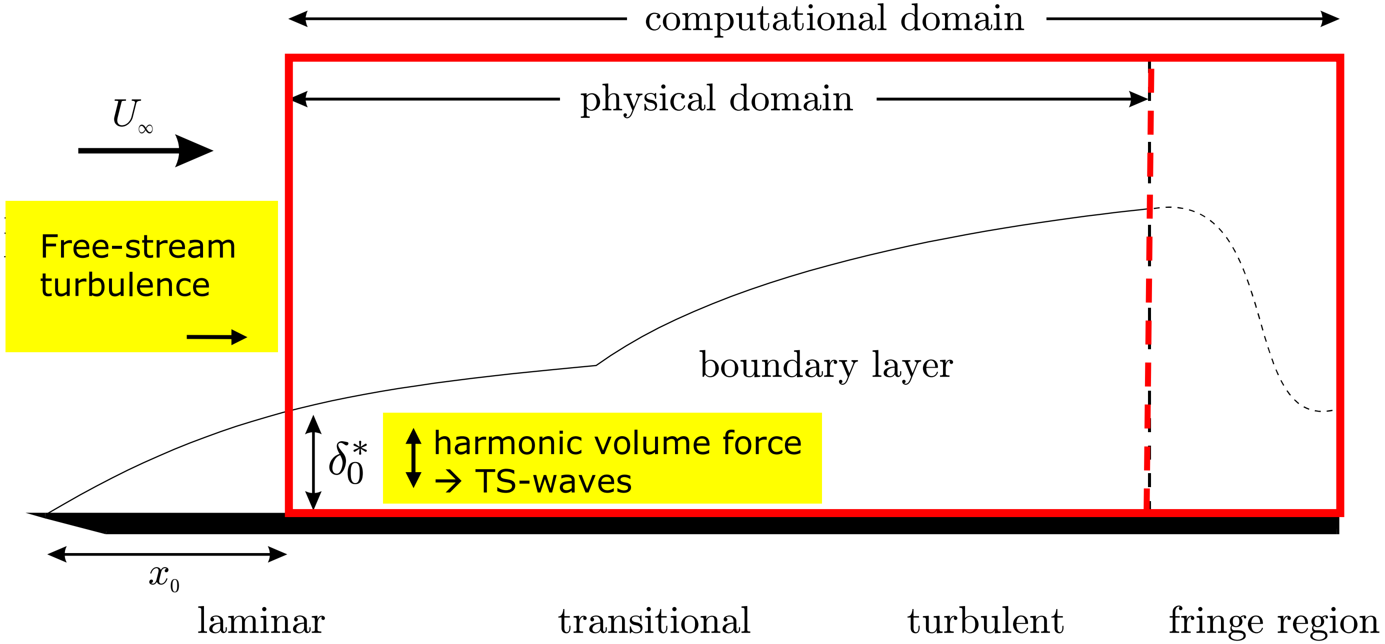
Simulation Approach

Numerical Setup

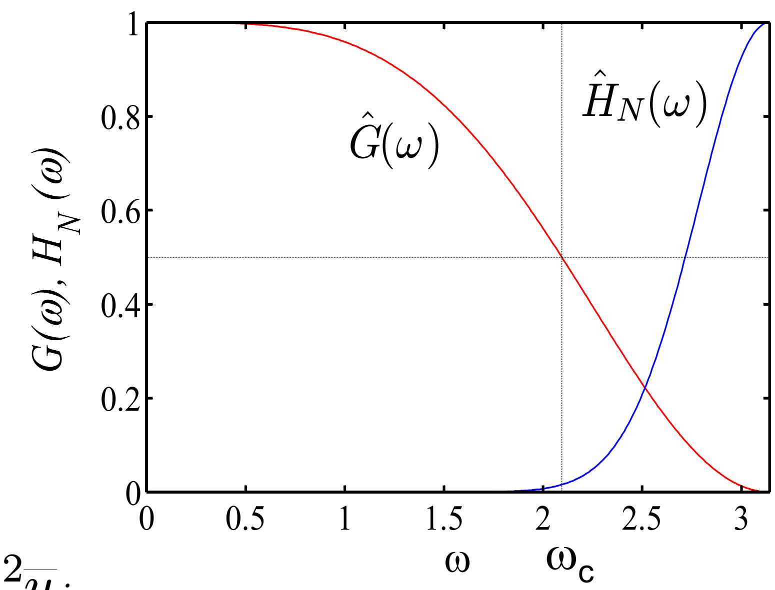


- Fully spectral method: Fourier/Chebyshev tau method
- Periodic boundary condition in the wall-parallel directions, no-slip at lower wall, Neumann conditions at upper boundary.
- Fringe region (volume force) to enforce laminar Blasius inflow condition with superimposed free-stream turbulence (FST)
- FST modelled as superposition of Orr-Sommerfeld/Squire modes

Relaxation Term Model: ADM-RT

- High-order low-pass filter: G
- High-pass filter: $H_N = (I - G)^{N+1}$

here: $N = 5$ and $\omega_c = 2\pi/3$



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$$\frac{\partial \overline{u}_i}{\partial x_i} = 0$$

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial \overline{u}_i \overline{u}_j}{\partial x_j} + \frac{\partial \overline{p}}{\partial x_i} - \frac{1}{Re} \frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} = -\chi H_N * \overline{u}_i$$

No Filtering
Grid-filtered quantities no modification of nonlinear term

Model Coefficient χ
Dynamic or non-dynamic determination possible

Relaxation Term
Necessary drain of energy (SGS dissipation), acting on the small scales only.

Reference: Schlatter, Stolz & Kleiser, *Int. J. Heat Fluid Flow* (2004)

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Validation:

TS-Waves
Bypass Transition

Validation: TS-Waves

- Large-eddy simulation using ADM-RT (*i.e.* Relaxation term → high-order filtering)

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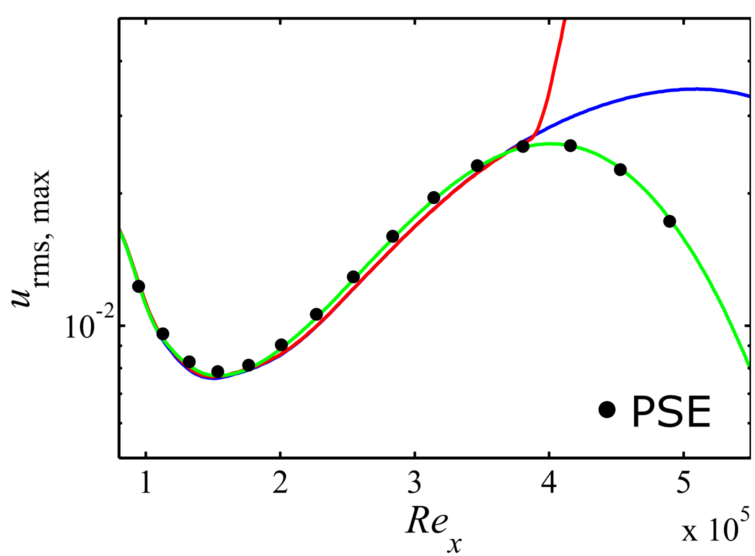

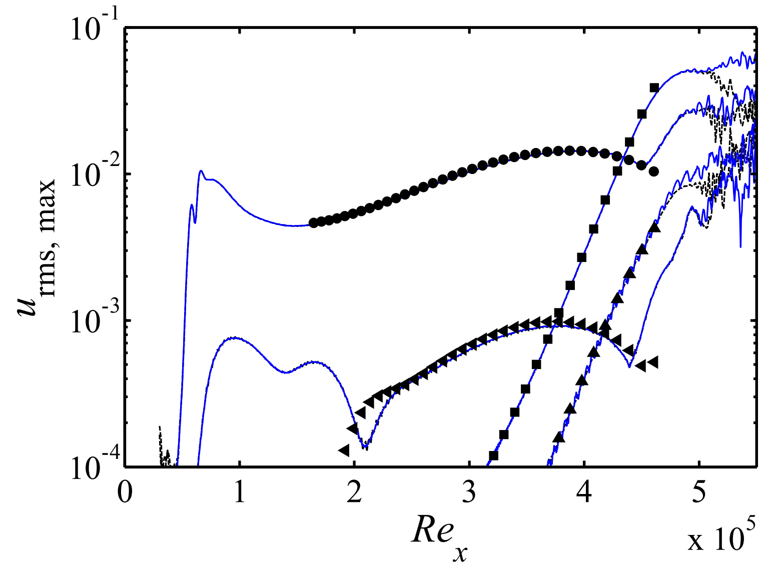

Growth of TS-waves from LES compared to PSE:

- low-amplitude TS-wave (rescaled) (green line)
- saturated (nonlinear) TS-wave (blue line)
- TS-wave plus random disturbances (red line)

H-type transition (Herbert 1993)

(symbols): PSE
(lines): LES

2D TS-Waves + steady streaks

- Damping of 2D TS-waves
- Function of streak amplitude
- → Comparable to experiments

- Streaky TS-wave

$$(\omega_{\mathrm{TS}}, n \cdot \beta_{\mathrm{st}})$$

- → Typical M shape

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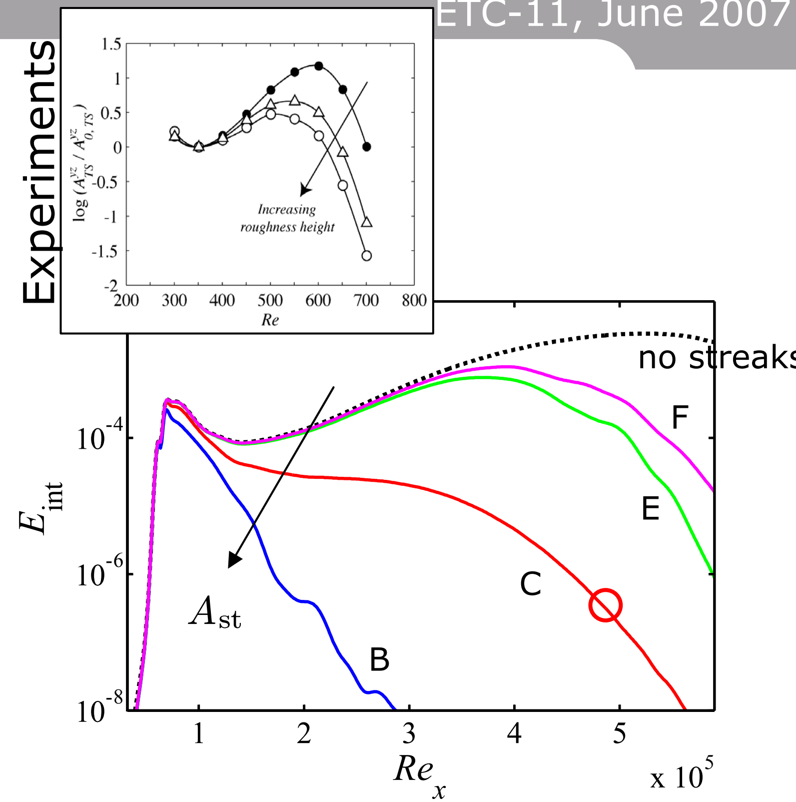

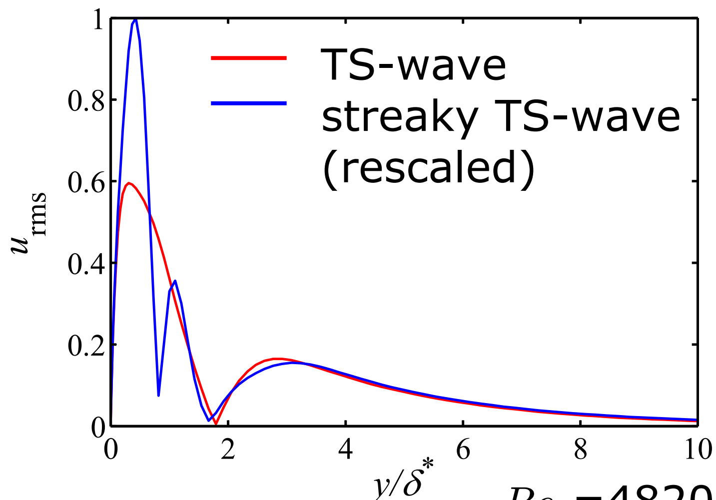

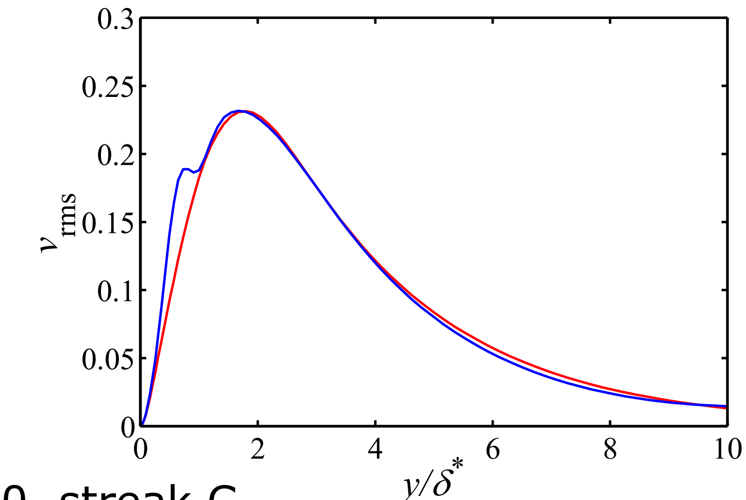

Re_x=482000, streak C

Bypass Transition

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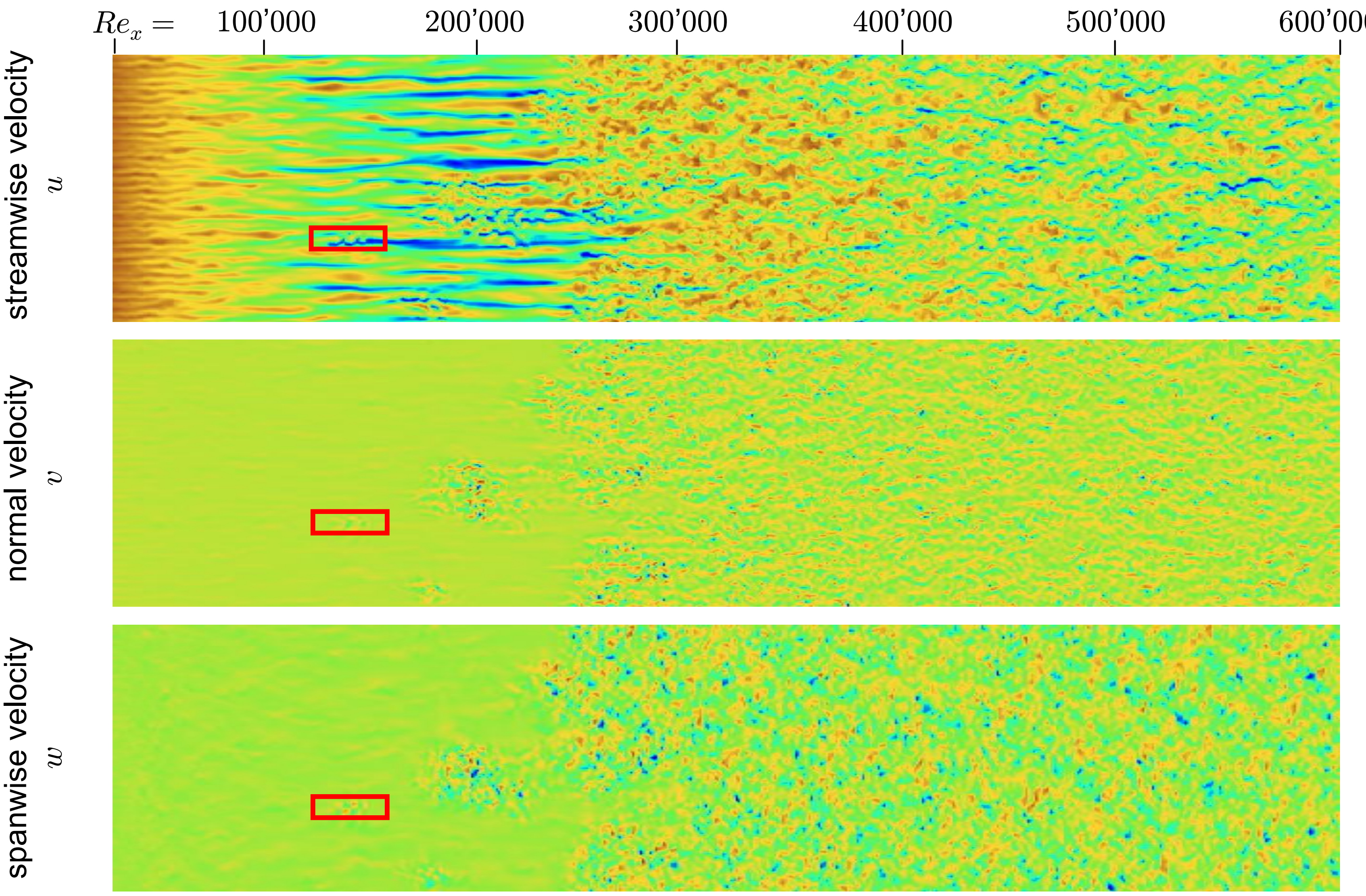
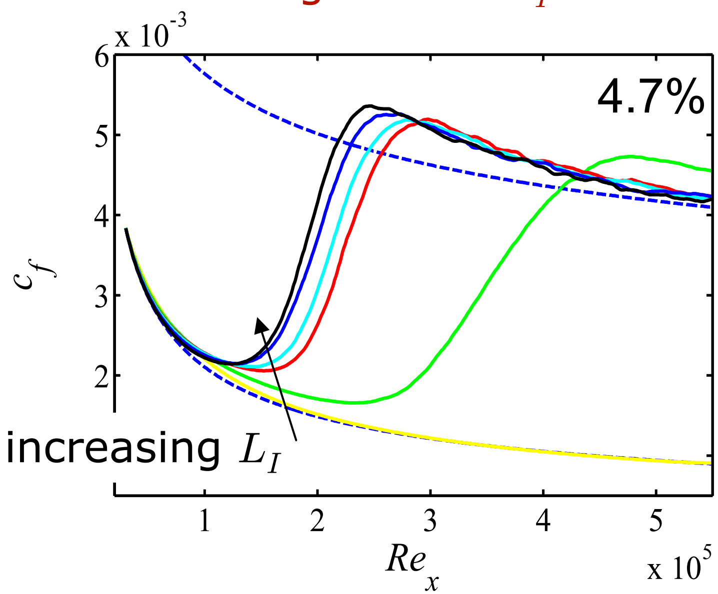


Resolution: 512x121x128 grid points ~ 15 Mio.

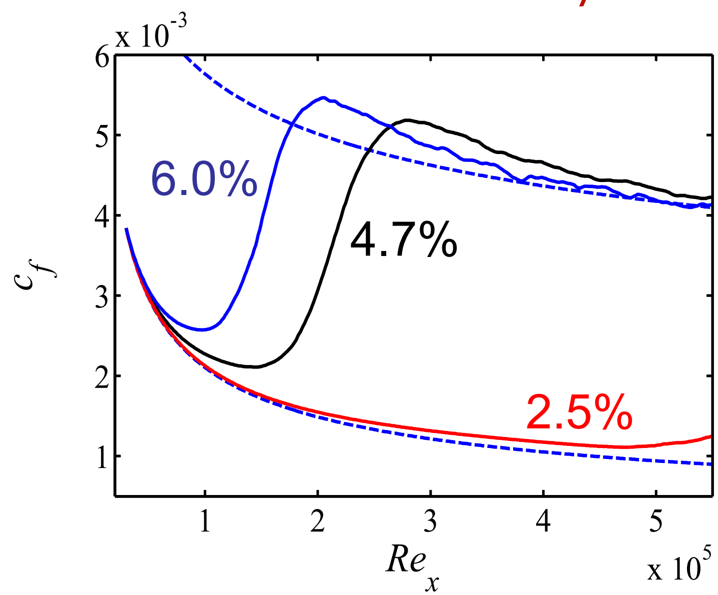
Bypass Transition: Influences

- Skin friction coefficient c_f as function of (LES with ADM-RT)

Length scale L_I of FST



Turbulence intensity



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Findings from DNS (Brandt *et al.* 2004) are qualitatively and quantitatively confirmed by LES (Schlatter *et al.* 2006)

Results

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Interaction FST/TS-Waves (1)

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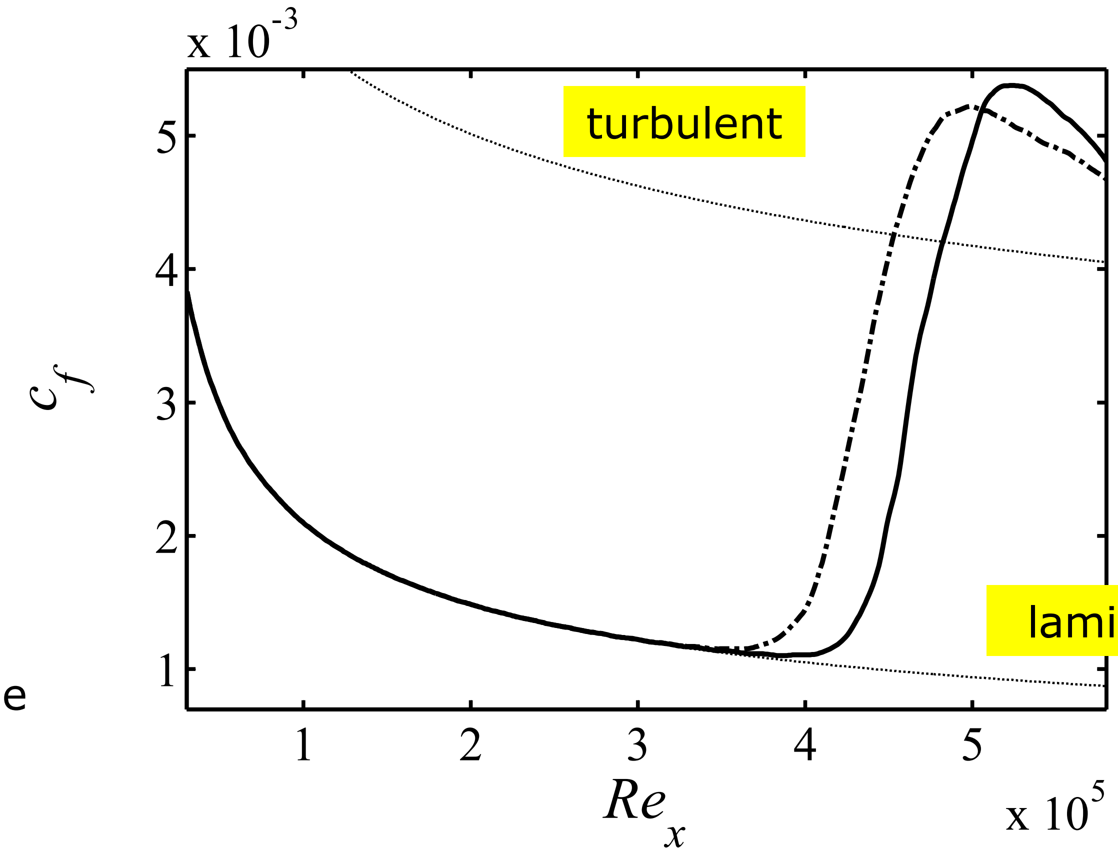
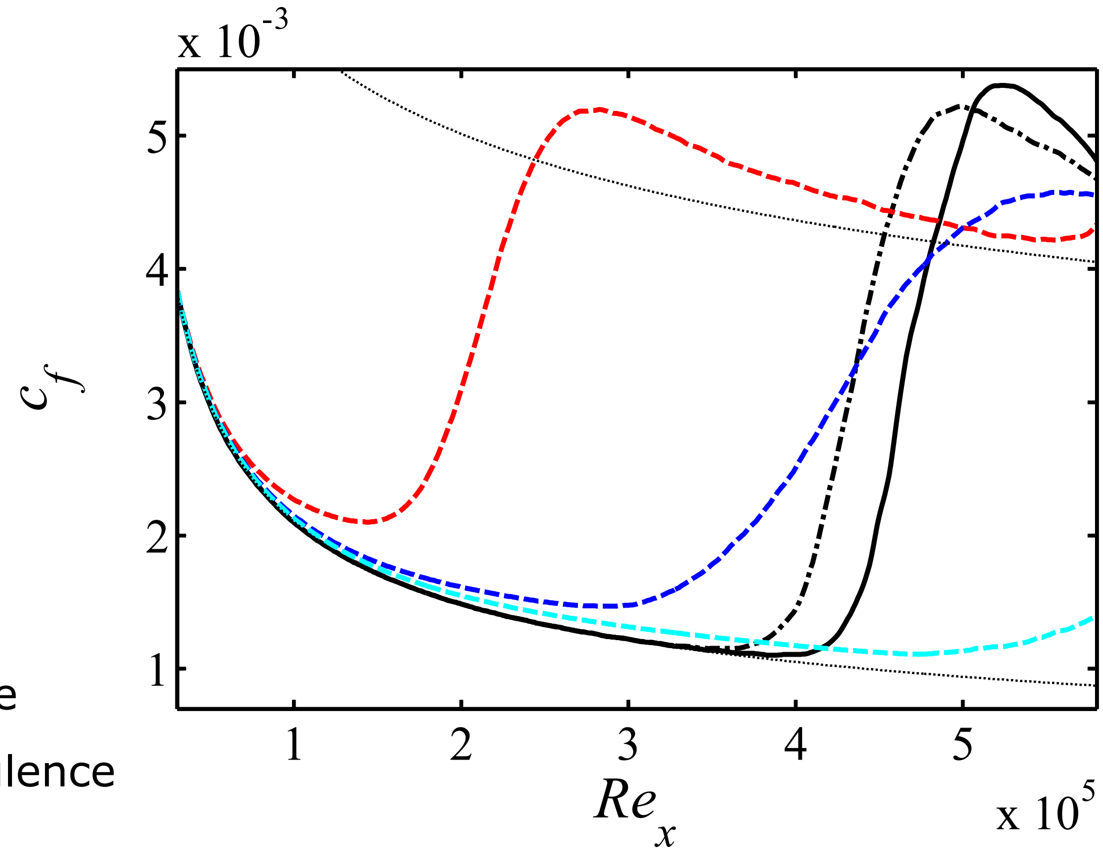


only TS-waves
—— steady → K-type
- · - unsteady → H-type

Amplitude of TS-wave at branch I: 0.76%

Interaction FST/TS-Waves (2)



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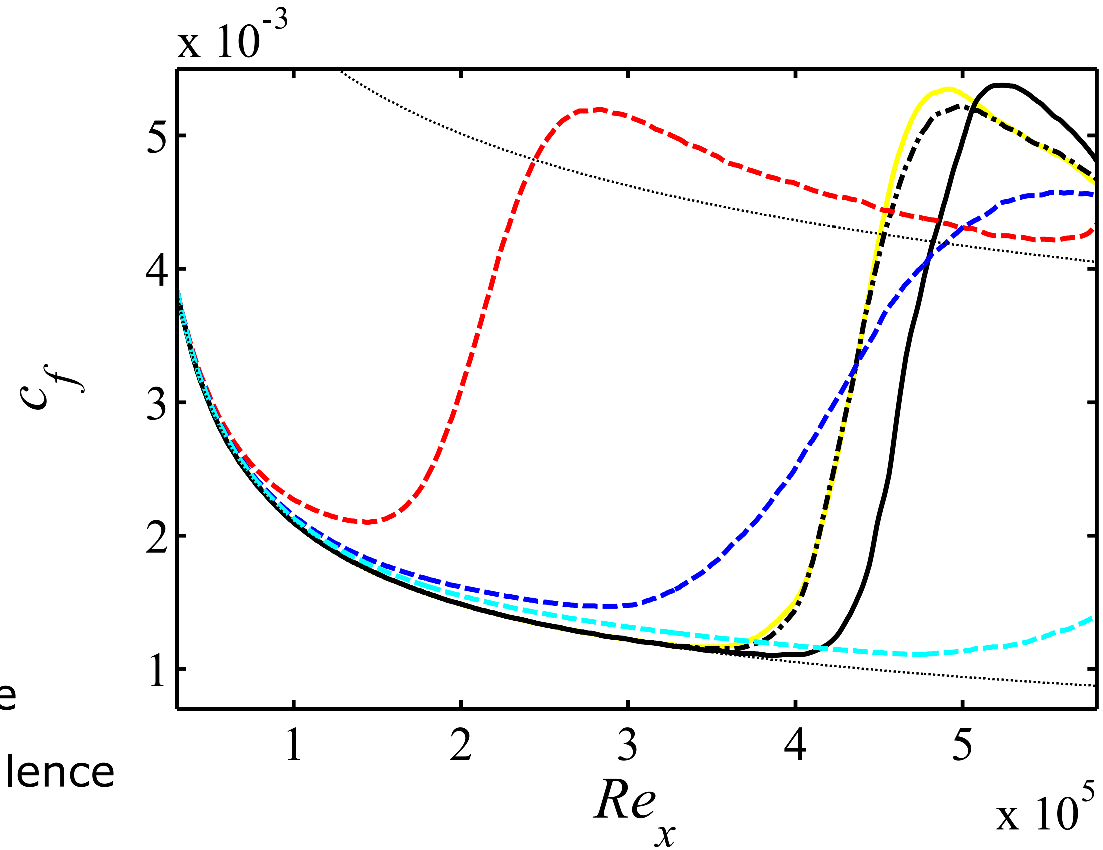
only TS-waves
- steady → K-type
- unsteady → H-type

only free-stream turbulence
- Tu=3%
- Tu=3.5%
- Tu=4.7%

Interaction FST/TS-Waves (3)



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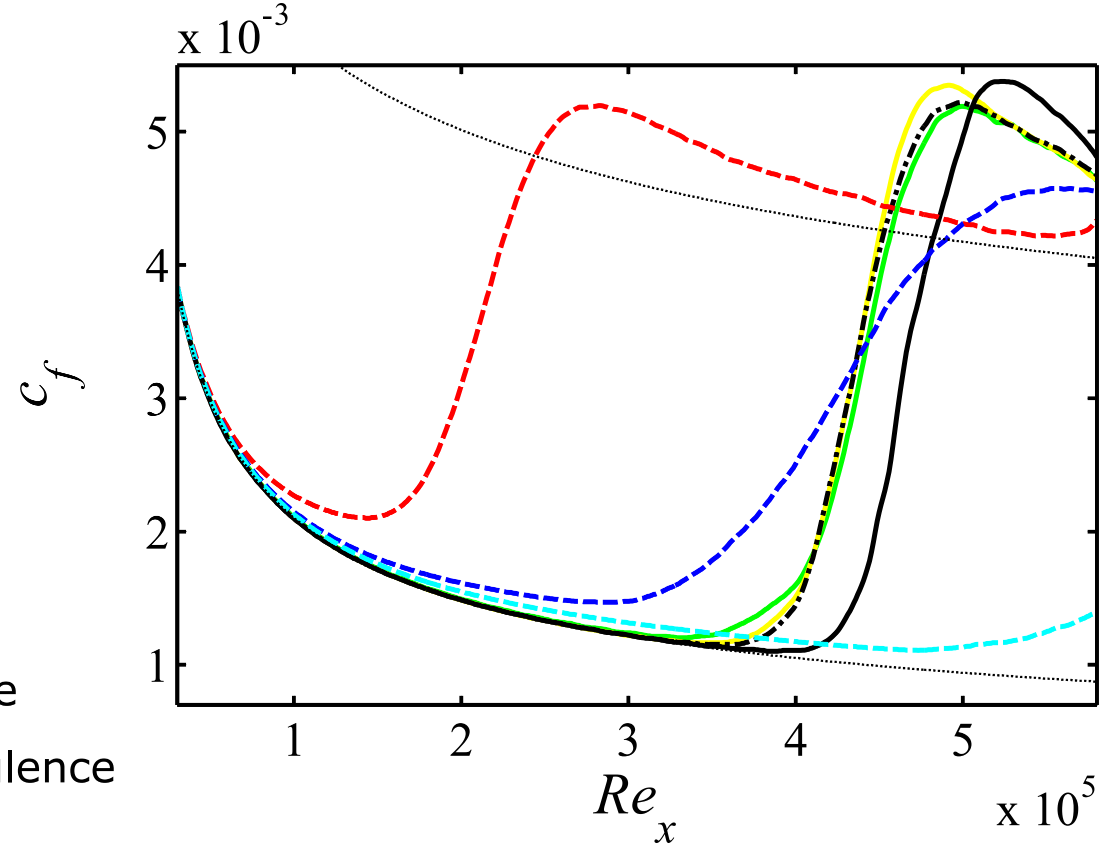
only TS-waves
- steady → K-type
- unsteady → H-type

only free-stream turbulence
- Tu=3%
- Tu=3.5%
- Tu=4.7%
- Tu=1%

Interaction FST/TS-Waves (4)



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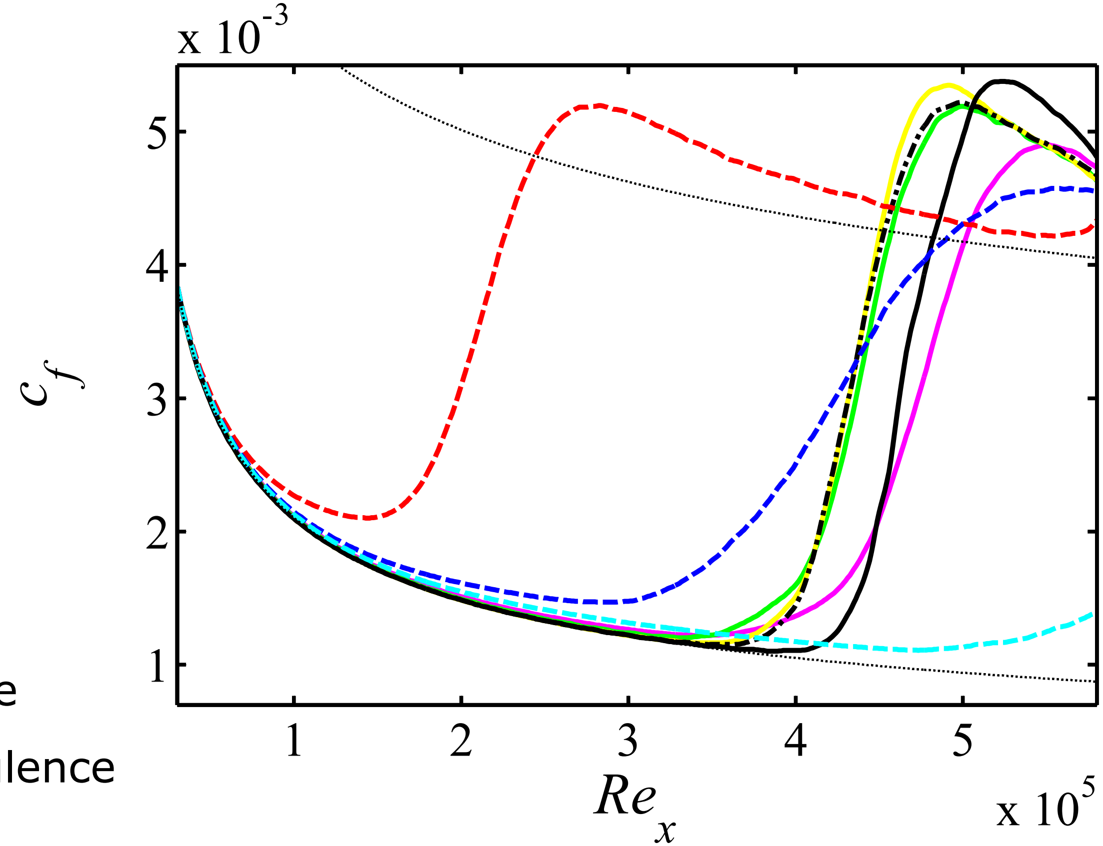
only TS-waves
- steady → K-type
- unsteady → H-type

only free-stream turbulence
- Tu=3%
- Tu=3.5%
- Tu=4.7%
- Tu=1%
- Tu=2%

Interaction FST/TS-Waves (5)



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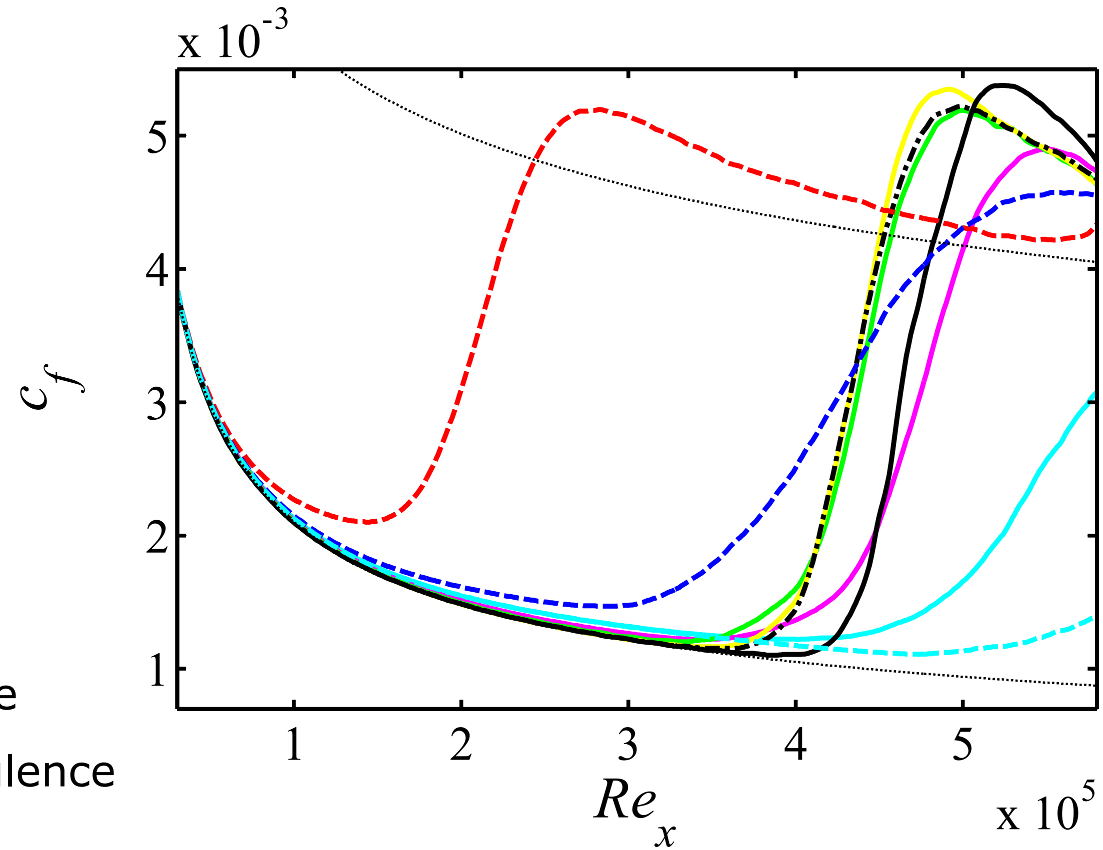
only TS-waves
- steady → K-type
- unsteady → H-type

only free-stream turbulence
- Tu=3%
- Tu=3.5%
- Tu=4.7%
- Tu=1%
- Tu=2%
- Tu=2.5%

Interaction FST/TS-Waves (6)



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only TS-waves

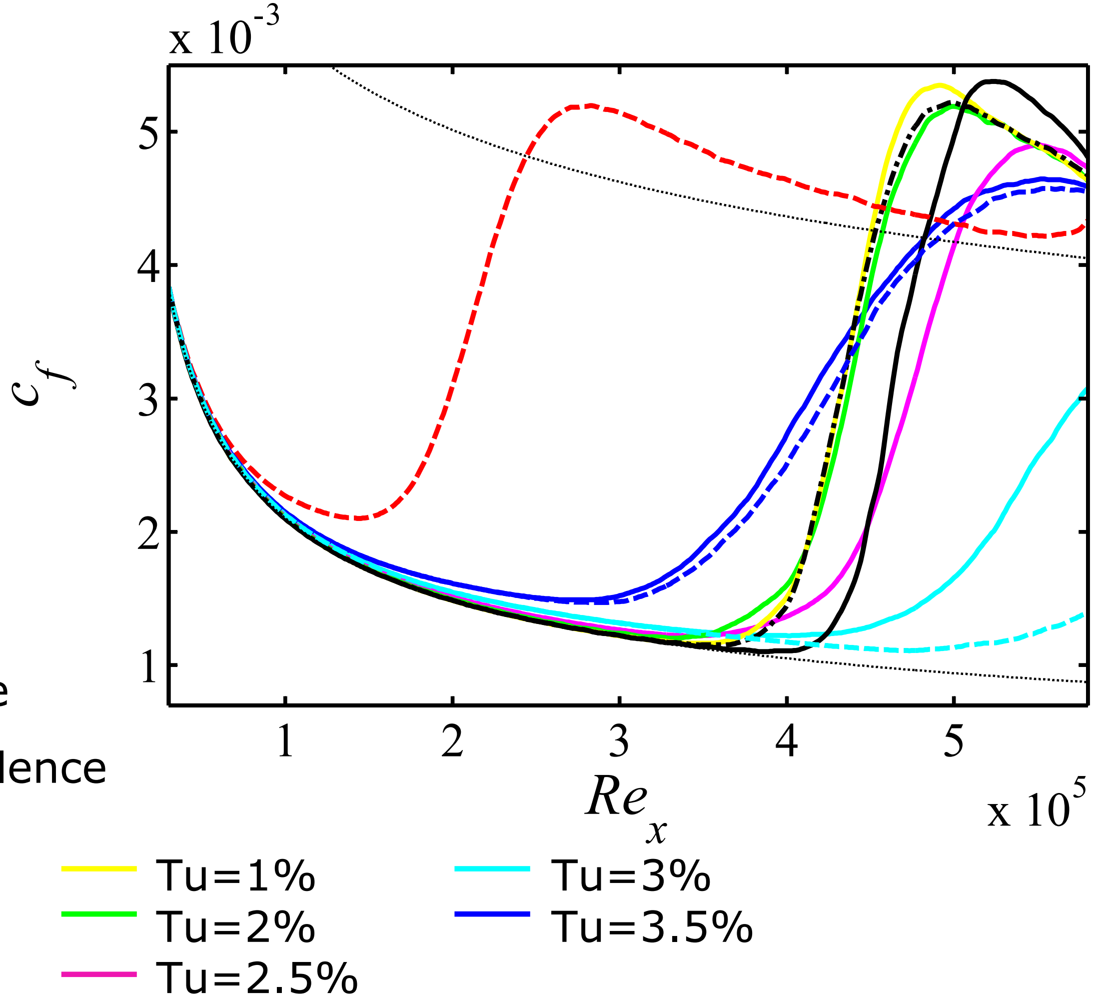
- steady → K-type
- unsteady → H-type

only free-stream turbulence

- Tu=3%
- Tu=3.5%
- Tu=4.7%

- Tu=1%
- Tu=2%
- Tu=2.5%
- Tu=3%

Interaction FST/TS-Waves (7)



only TS-waves
- steady → K-type
- unsteady → H-type

only free-stream turbulence
- Tu=3%
- Tu=3.5%
- Tu=4.7%

Interaction FST/TS-Waves (8)

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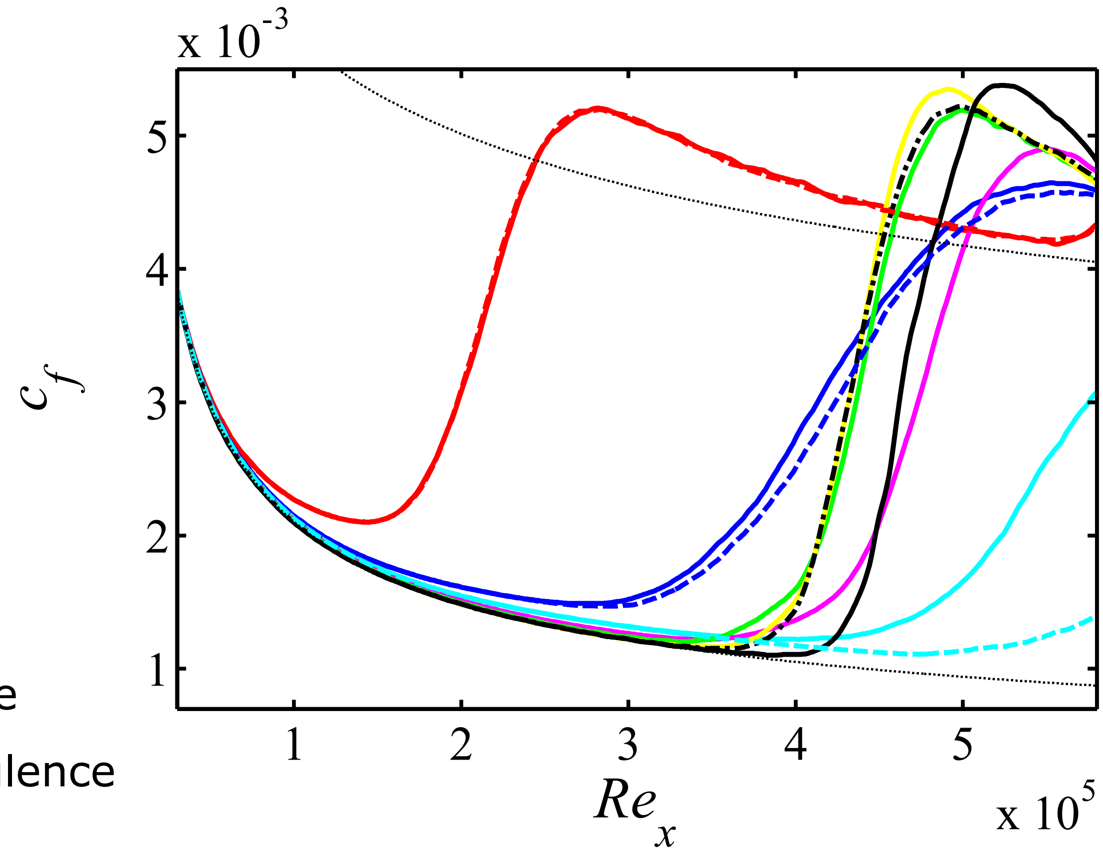

only TS-waves
- steady → K-type
- unsteady → H-type

only free-stream turbulence
- Tu=3%
- Tu=3.5%
- Tu=4.7%

- Tu=1%
- Tu=2%
- Tu=2.5%
- Tu=3%
- Tu=3.5%
- Tu=4.7%

FST & TS-Waves

- Shape factor and streak growth (u_{rms})
  Amplitude of TS-wave at branch I: 0.76%

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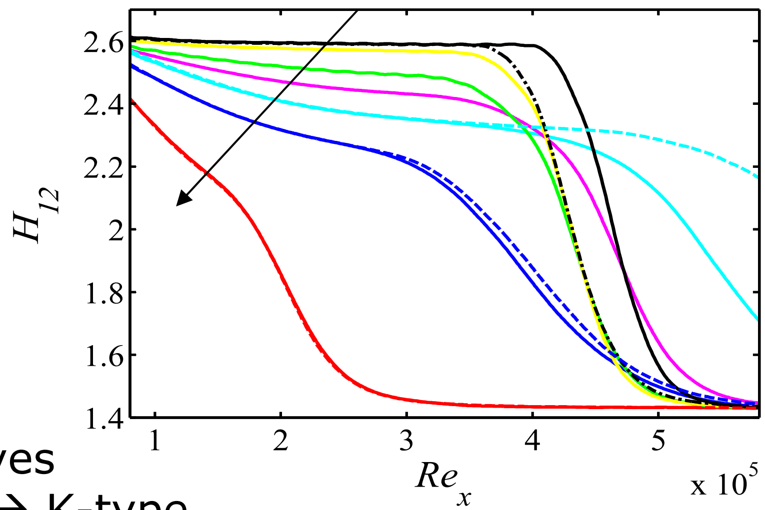

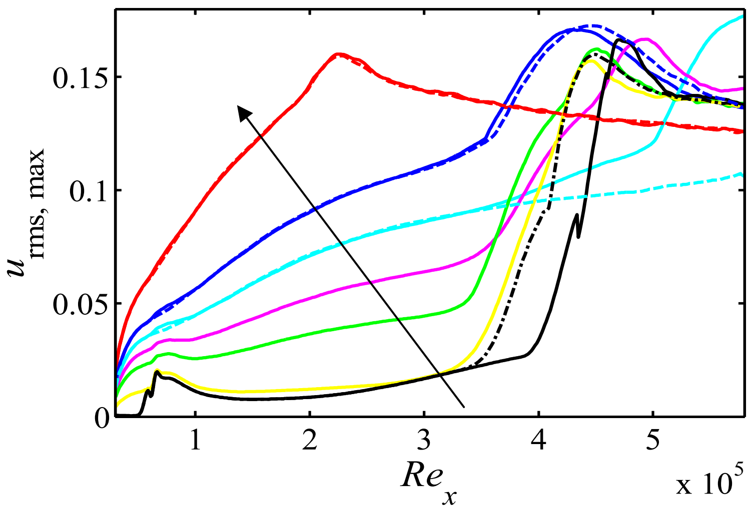

only TS-waves
- steady → K-type
- unsteady → H-type

only free-stream turbulence
- Tu=3%
- Tu=3.5%
- Tu=4.7%

- Tu=1%
- Tu=2%
- Tu=2.5%
- Tu=3%
- Tu=3.5%
- Tu=4.7%

FST & TS-Waves

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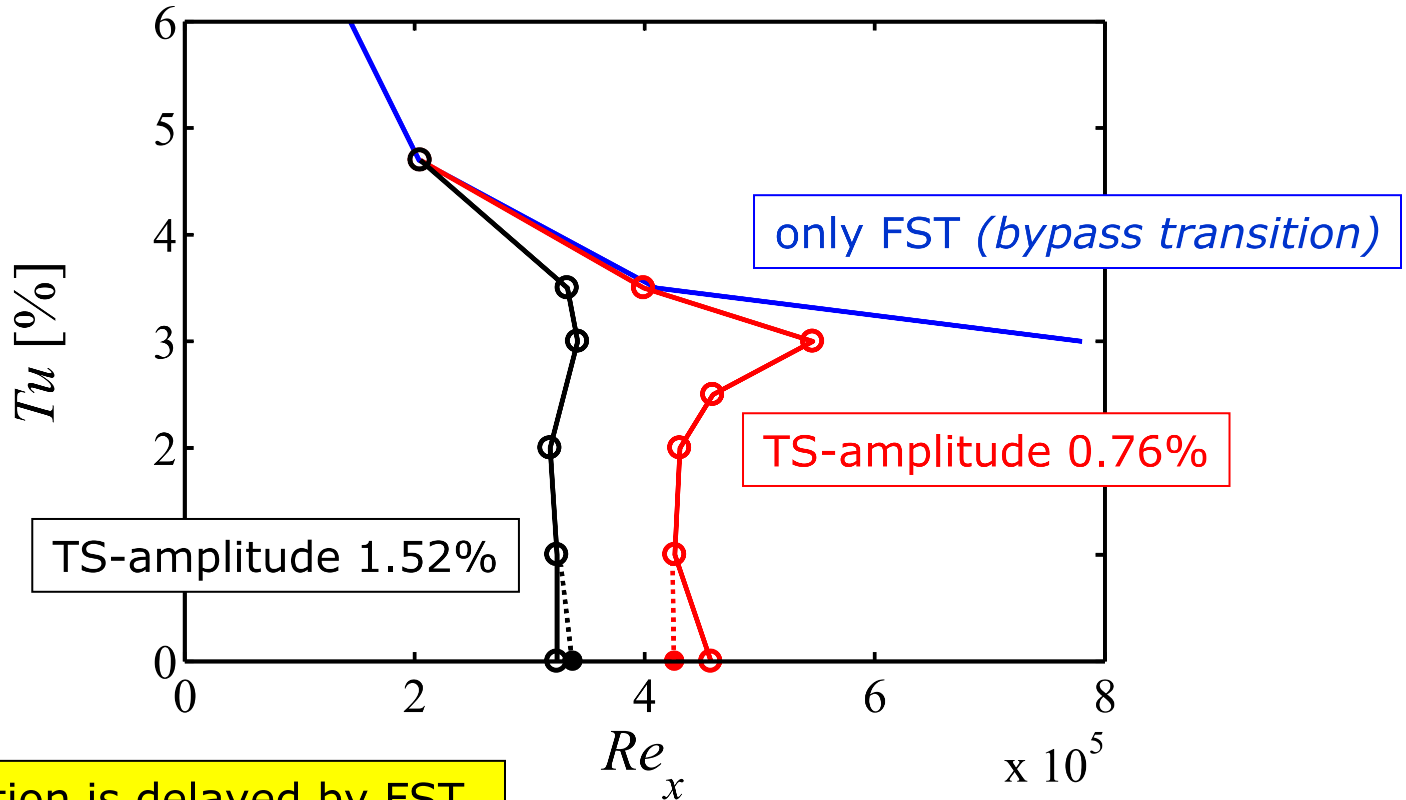
- Transition location *vs.* turbulence intensity



- Classical transition is delayed by FST
- Bypass transition is not influenced by TS-waves

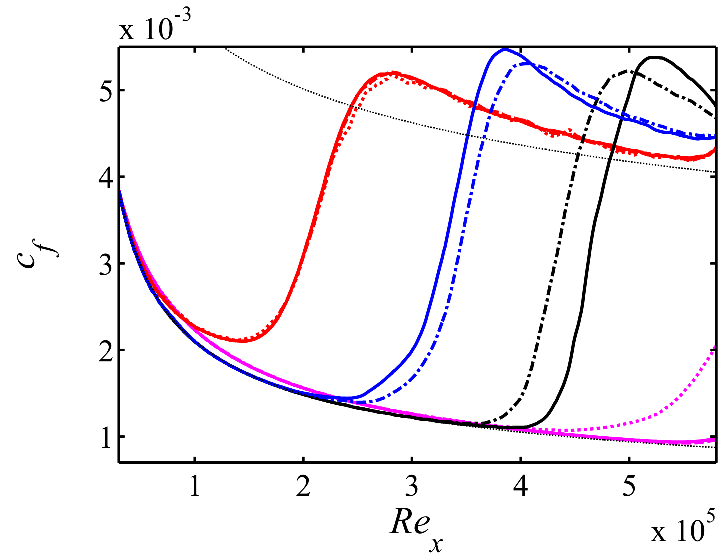
○ steady forcing → K-type
● unstead forcing → H-type

FST Length Scale Tu=4.7%

<u>Influence of FST length scale</u>:

- Streaks are generated and decay
- Streak breakdown is prevented due to faster decay of the FST

→ Efficient stabilisation of TS-waves!



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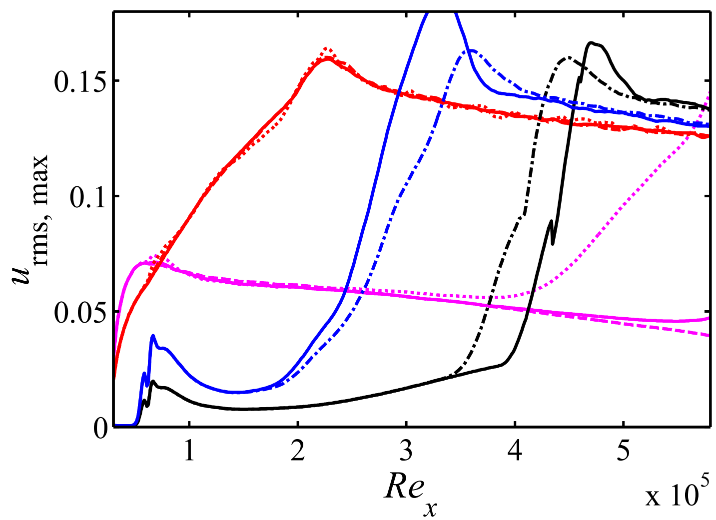
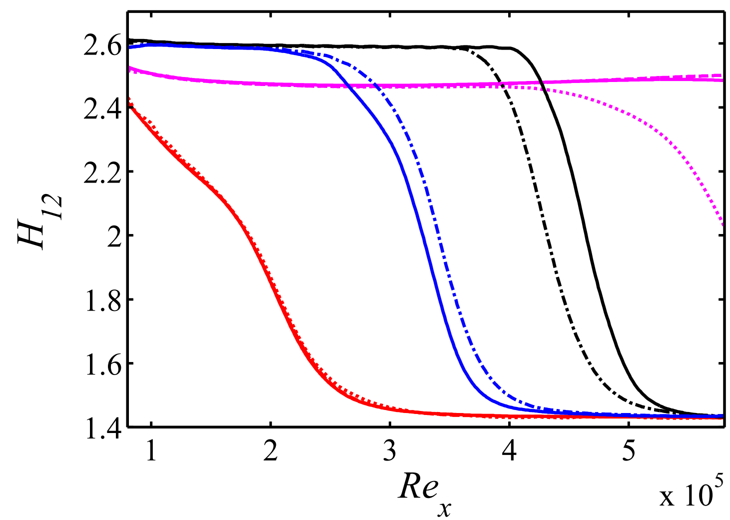


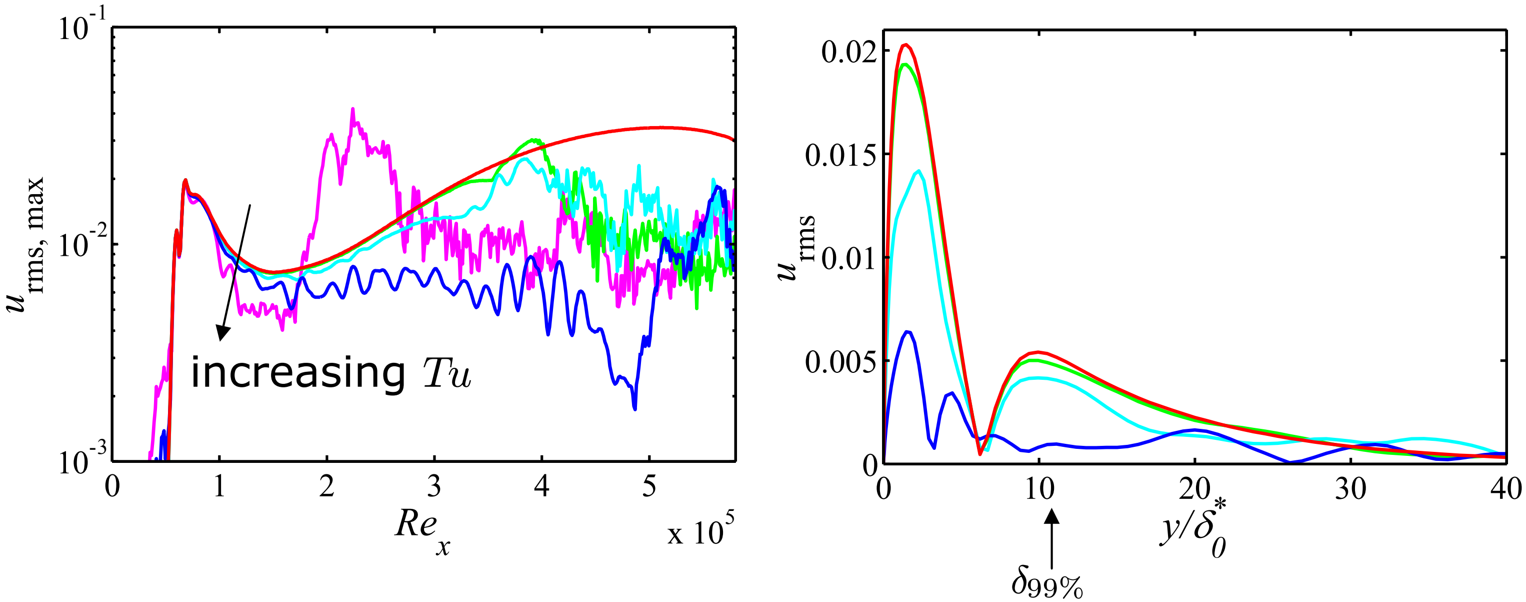


L_I=1.5
L_I=5

TS amplitude 0.76%
TS amplitude 1.52%

Modal Analysis

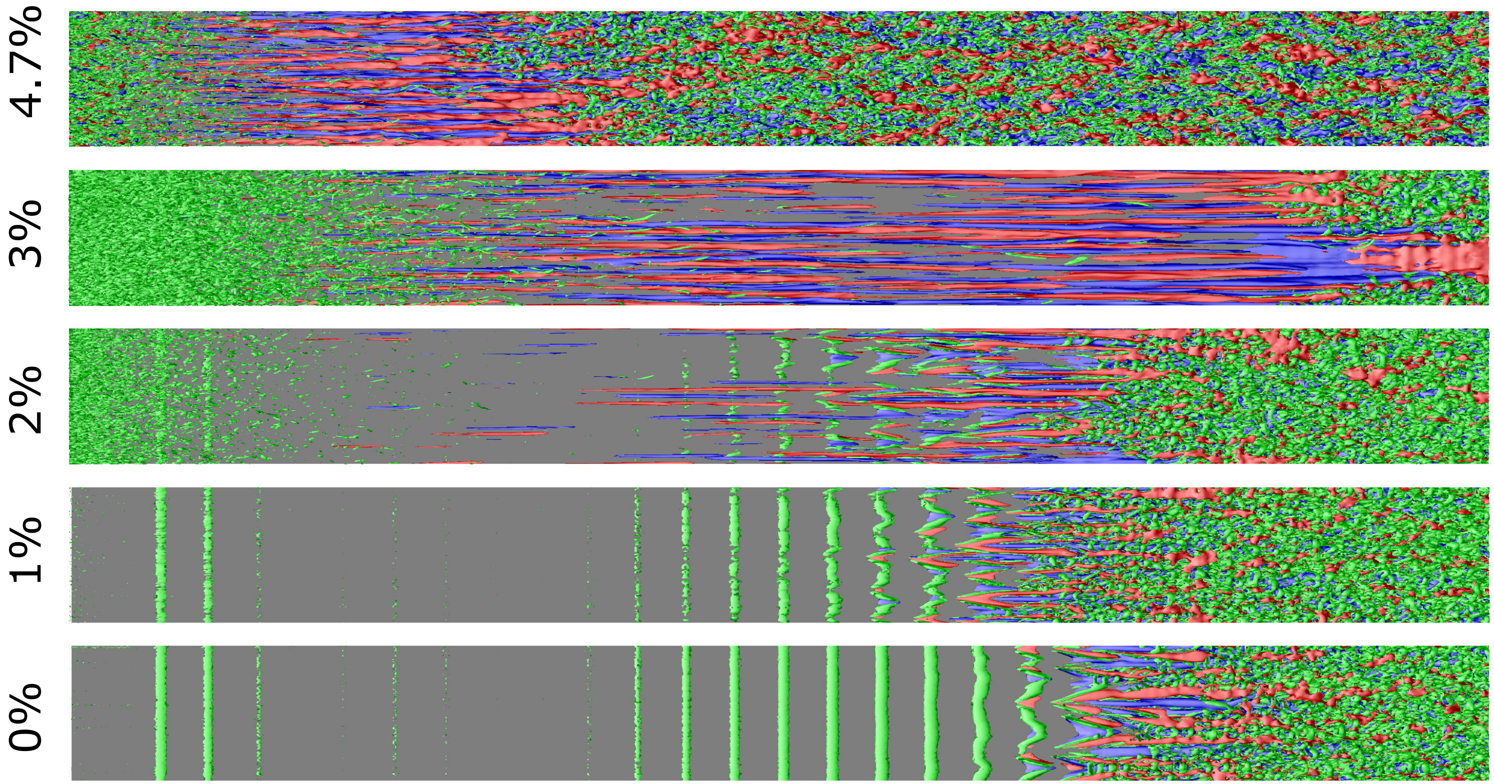
- Evolution of TS-wave mode (ω_0, 0) *(left)*
- Waveform of TS-wave at Re_x=300000 *(right)*



- Growth of TS-wave is damped with increasing Tu
- Typical “M”-shaped wave form for the so-called “streaky TS-wave”

Flow Fields: FST and TS-Waves

- Interaction of FST and TS-waves
  (Note, for 4.7% slightly adapted λ_2 isocontour levels)



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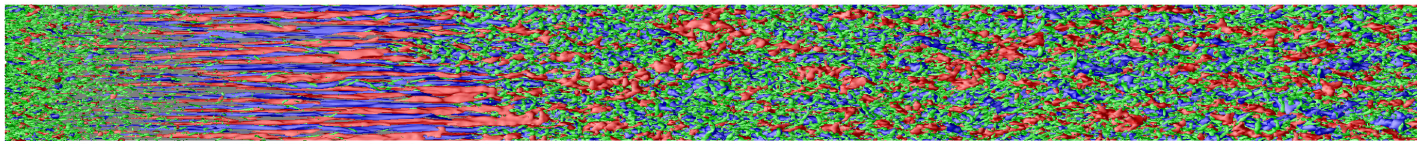
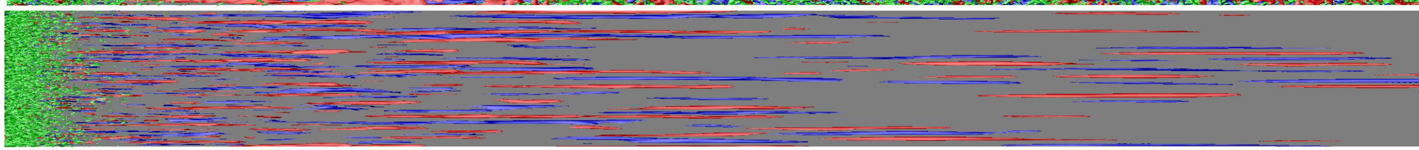
λ_2 criterion
high dist. velocity
low dist. velocity

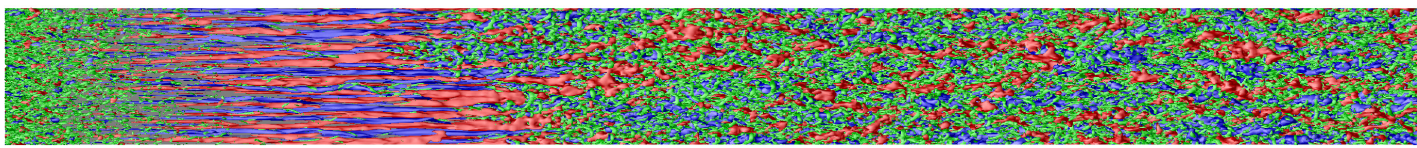
Flow Fields: Influence of FST Length scale

- FST level 4.7% (for all cases)
- only FST; $L_I=5\delta_0^*$ and $L_I=1.5\delta_0^*$ (*i.e.* no TS-waves)

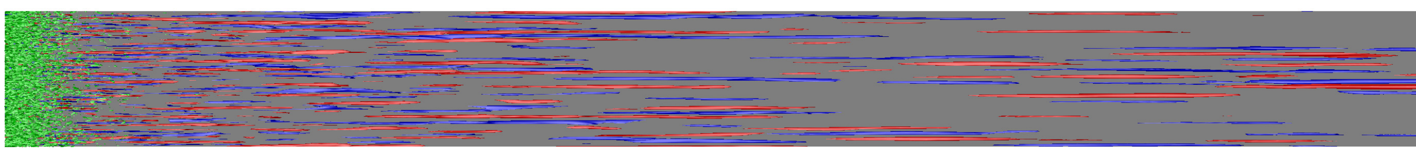




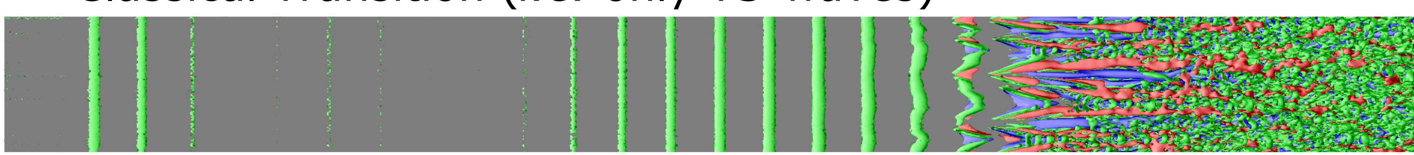
- Length scale $L_I=5\delta_0^*$ with TS-waves



- Length scale $L_I=1.5\delta_0^*$ with TS-waves



- Classical Transition (*i.e.* only TS-waves)



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Conclusions

Conclusions

- Large-eddy simulation using high-order relaxation (ADM-RT model) with realistic setup. Accurate prediction of:
  - Bypass and classical transition scenario
  - Combination of both FST and harmonic forcing
- Experimental/theoretical findings confirmed (mainly work by Boiko *et al.* 1994, Westin *et al.* 1994)
  - Low FST produces boundary-layer streaks
  - Streaks stabilise TS-waves
  - Breakdown related to intermittent appearance of spots
- FST at sufficiently low amplitude delays transition induced by TS-waves. However, TS-waves do not stabilise transition due to FST (*i.e.* streak instability, bypass transition)
- Influence of FST length scale: Lower length scales more effective since "bypass-related" breakdown is later

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Thank you!