Direct numerical simulations of complex turbulent boundary layers

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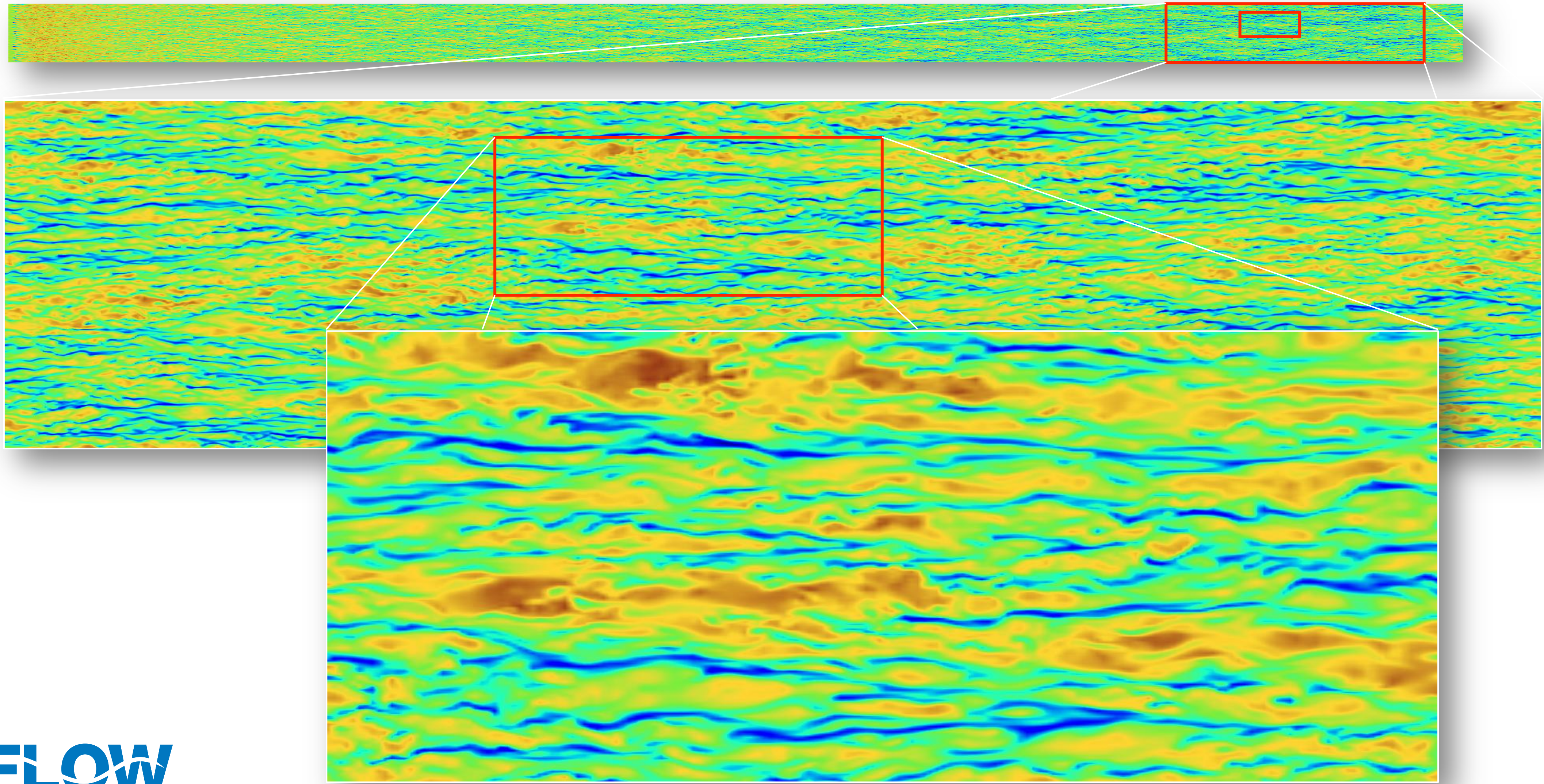
Outline – using DNS to complement experiments

- Analysis of high-Re DNS simulations –
  hairpin structures in turbulent boundary layers
- Toward simulations of complex turbulent flows –
  square cylinder in turbulent boundary layer
- Possibilities of numerical experiments of flows studied in typical university wind tunnels –
  calculating airfoils with turbulent boundary layers

DNS of wall bounded turbulent flow ...
where are we today? 40 cm on wing in cruise …

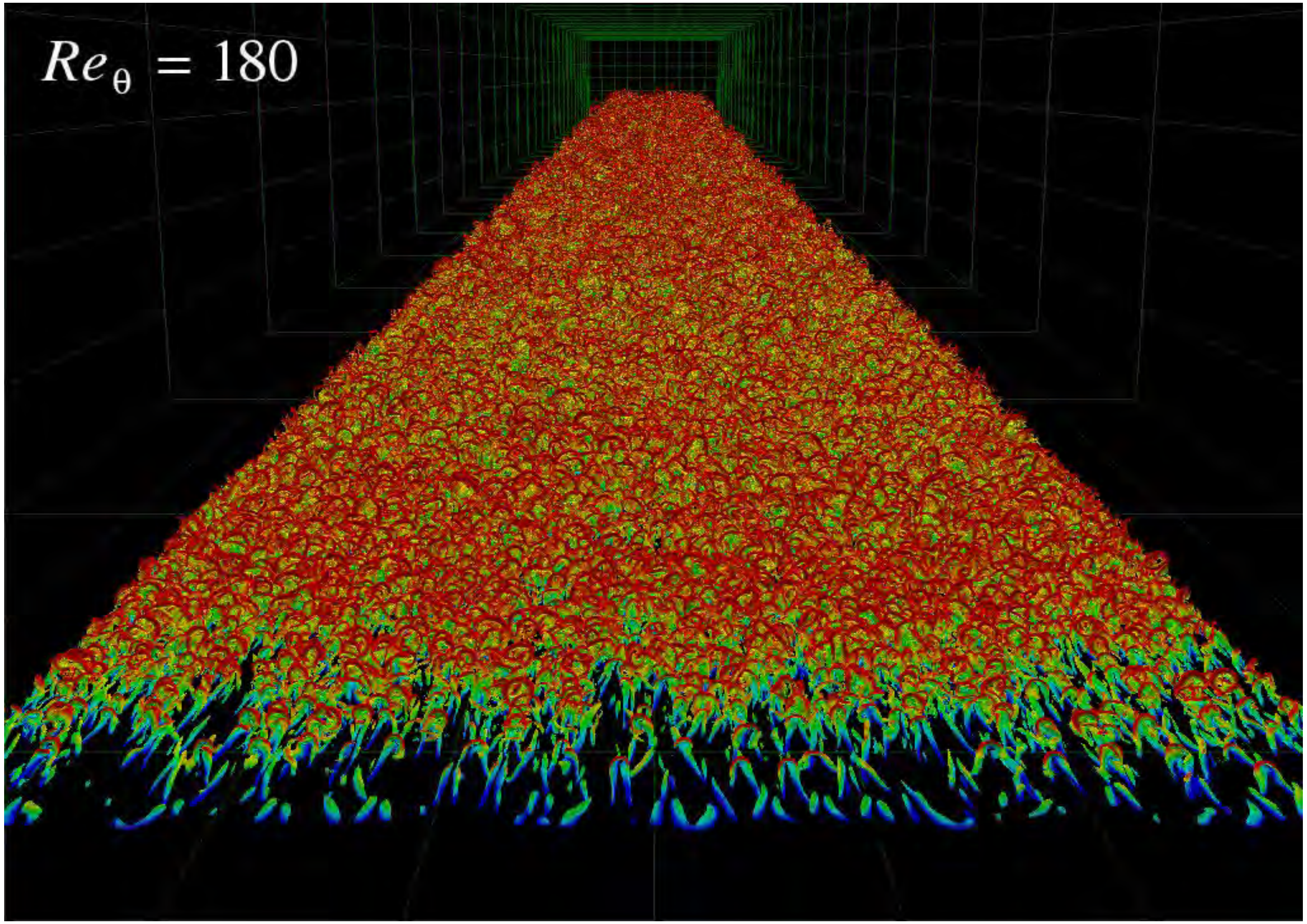
Turbulent flow close to solid walls...
reproduces measurements in detail (Schlatter, Örlu 2010)

simulation result: streamwise disturbance velocity



Turbulent flow close to solid walls...

no clear evidence of forest of hairpins at higher Re



P Schlatter, Q Li, R Örlü, F Hussain, DS Henningson

On the near-wall vortical structures at moderate Reynolds numbers

EJM-B/Fluids 48, 75-93, 2014

"Forest of hairpin vortices"

Journal of Fluid Mechanics

Focus on Fluids

Unravelling turbulence near walls

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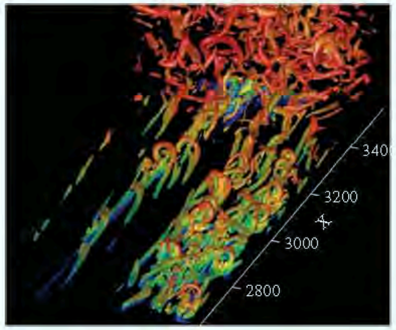


Turbulent flows near walls have been the focus of intense study since their first description by Ludwig Prandtl over 100 years ago. They are critical in determining the drag and lift of an aircraft wing for example. Key challenges are to understand the physical mechanisms causing the transition from smooth, laminar flow to turbulent flow and how the turbulence is then maintained. Recent direct numerical simulations have contributed significantly towards this understanding.

Keywords. Turbulent boundary layers, Transition

Wu & Moin (JFM 2009)

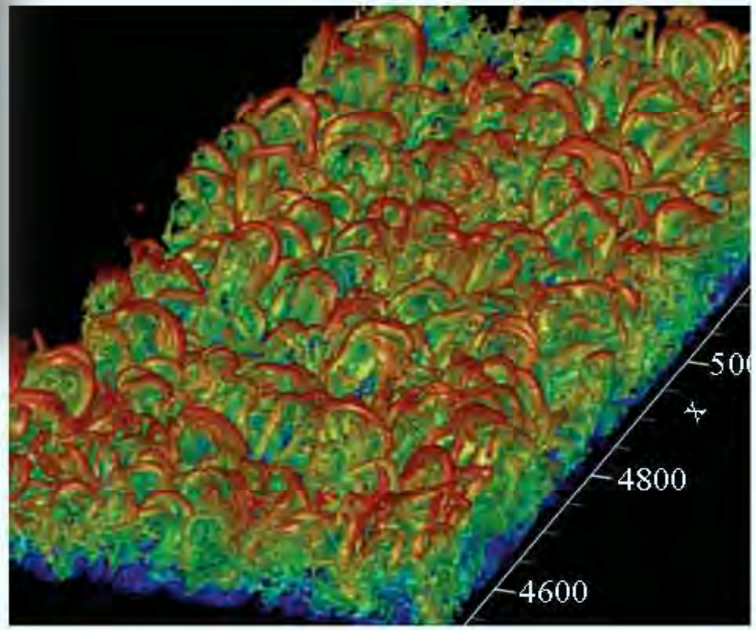
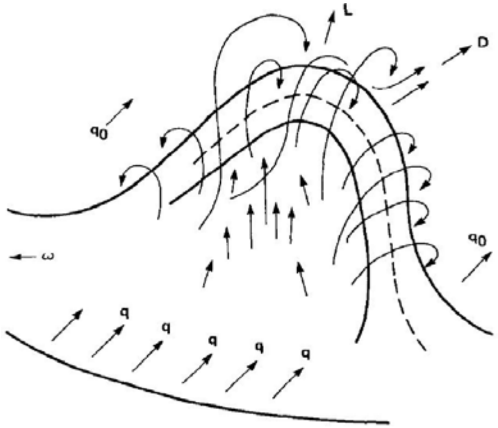


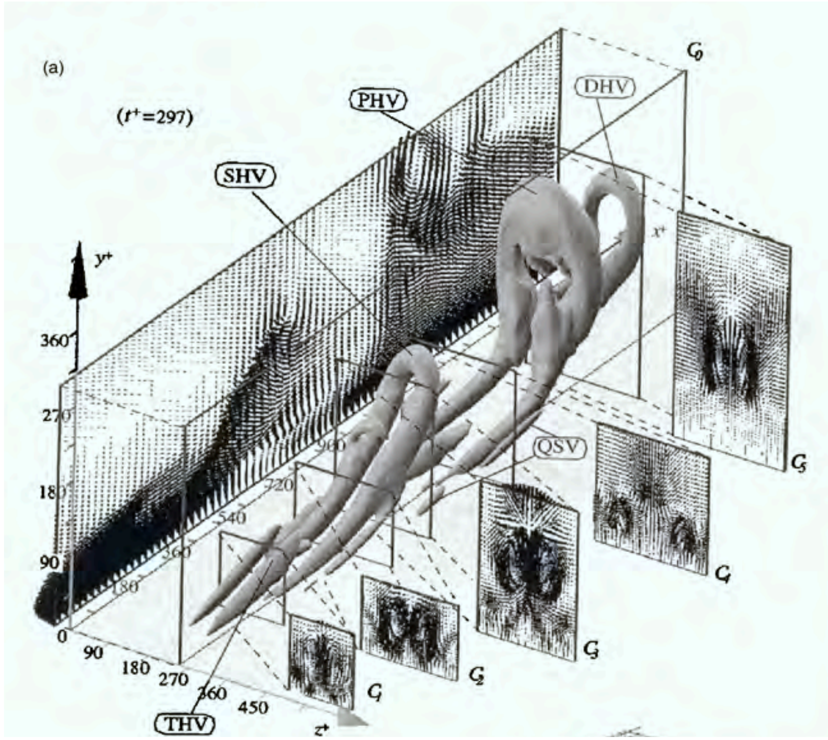
FIGURE 1. Instantaneous view of the coherent structures observed in the simulation of Wu & Moin in the fully turbulent region. The vivid appearance of hairpin-shaped structures is noted.

Hairpin Vortices

- What is a hairpin vortex...?

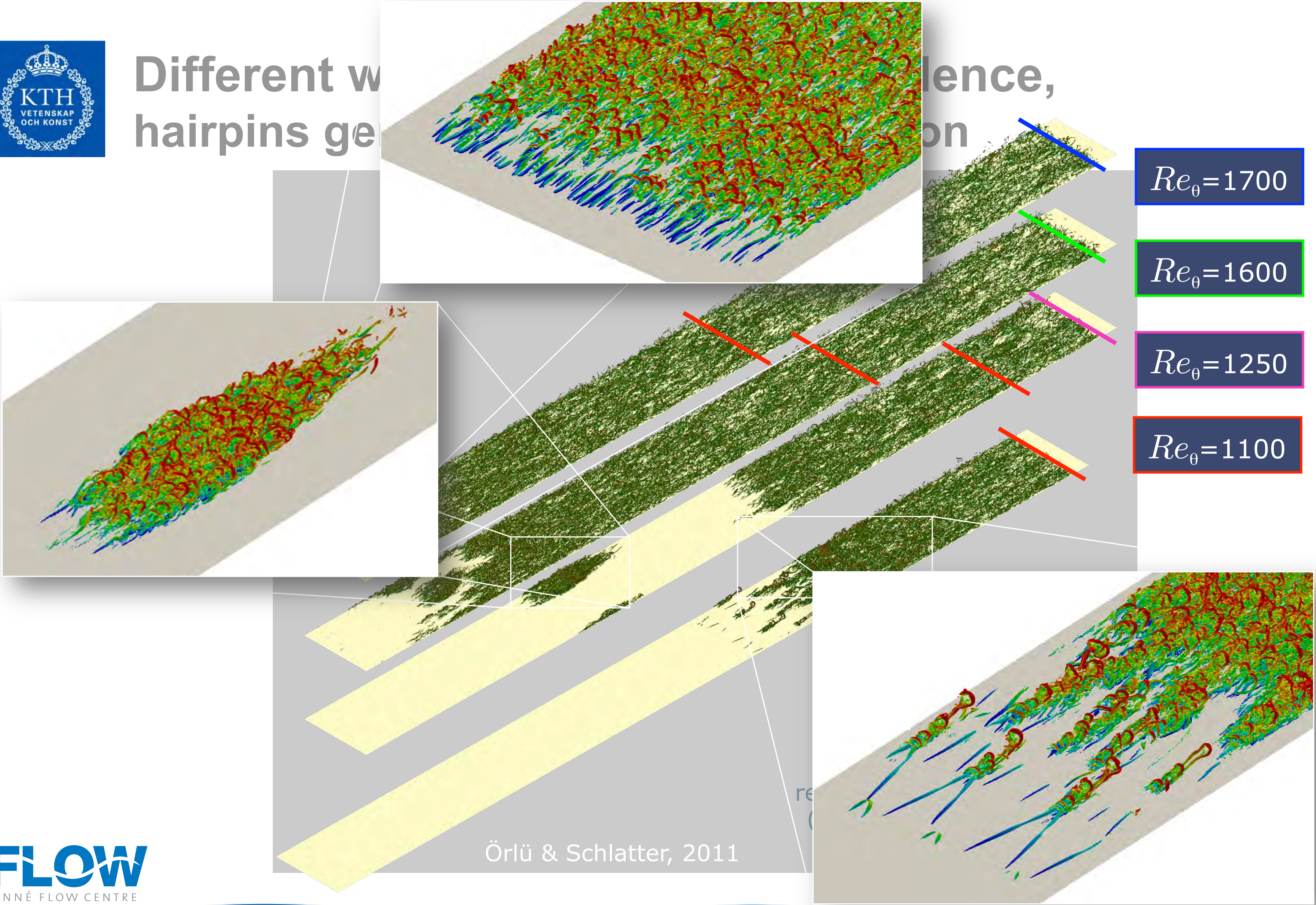


Theodorsen (1952)

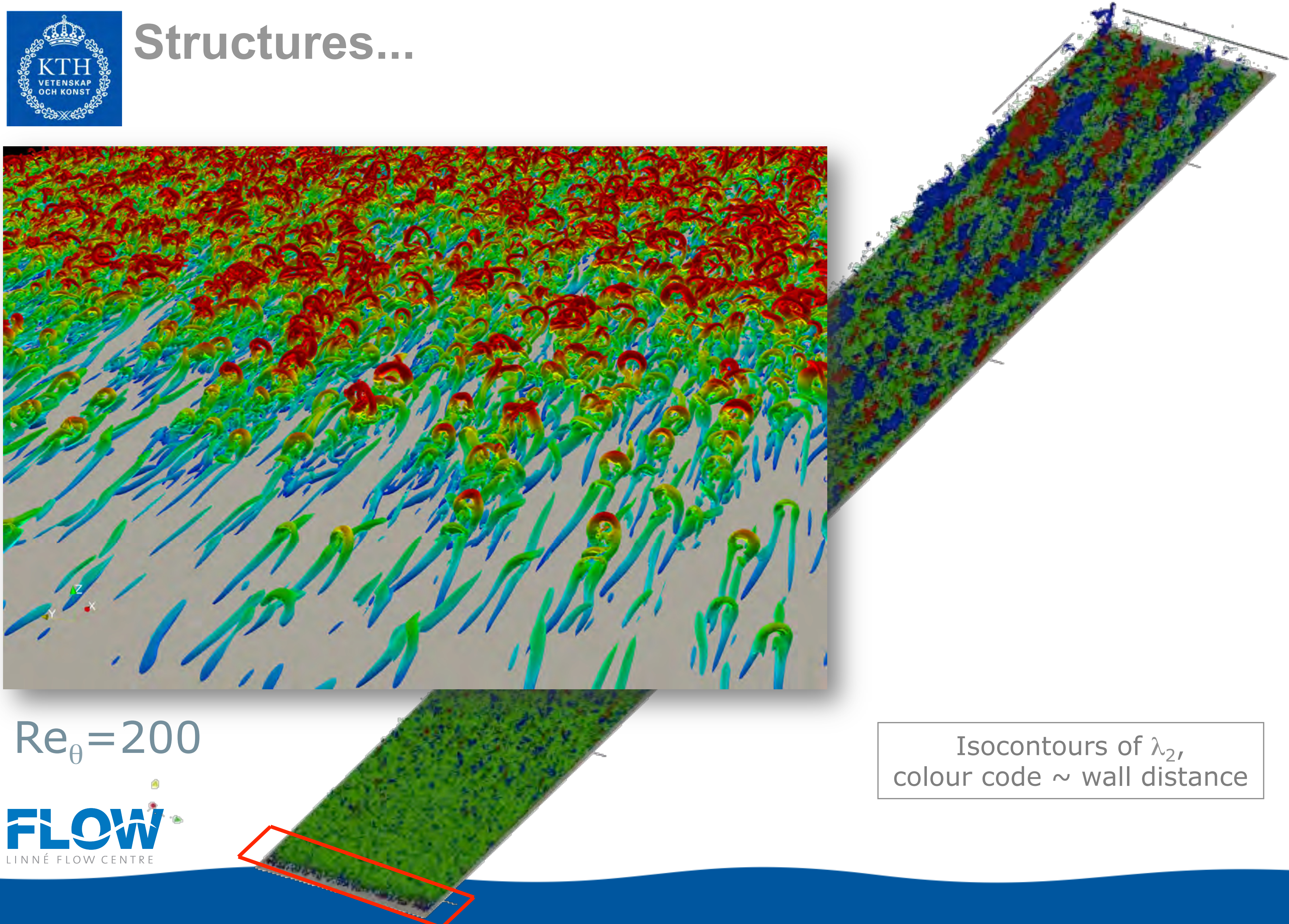


Adrian (*Phys. Fluids* 2007)

Different w… …lence,
hairpins ge… …on



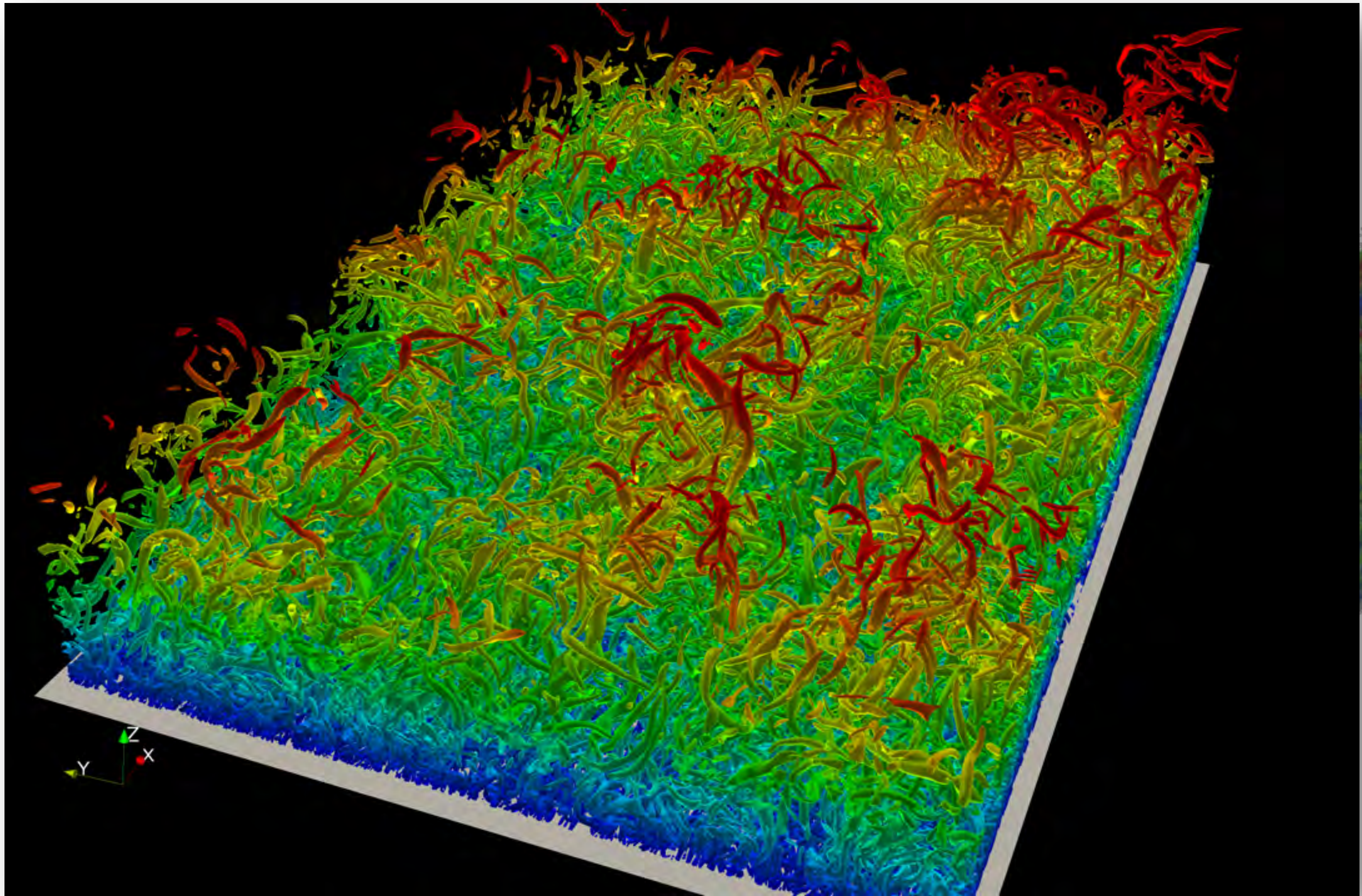
Structures...

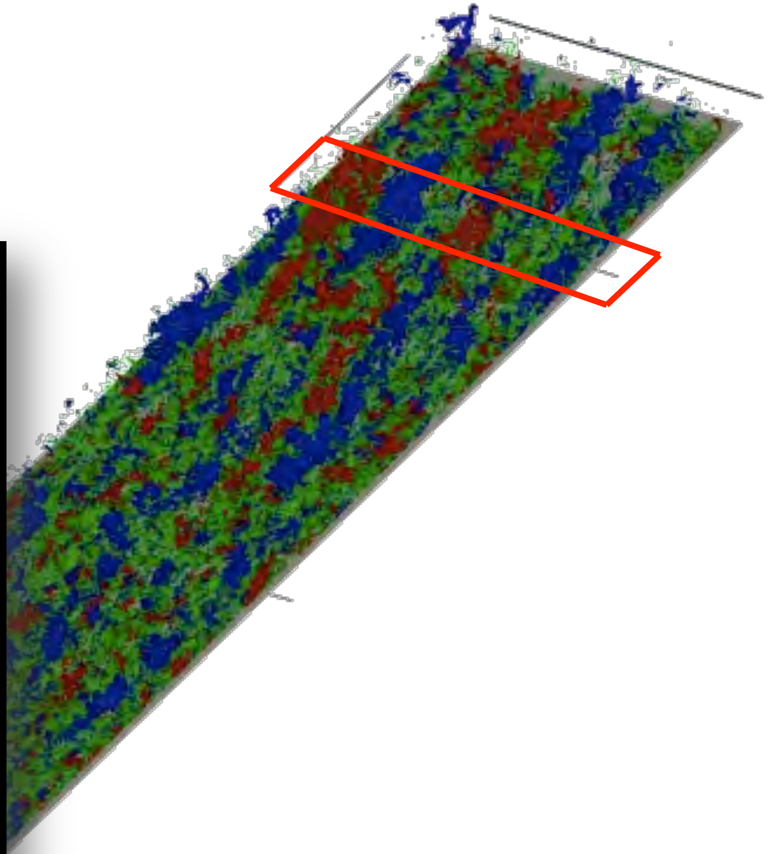


$Re_\theta = 200$

Isocontours of λ_2,
colour code ~ wall distance

Structures...





Re_θ=4300

Isocontours of λ_2,
colour code ~ wall distance

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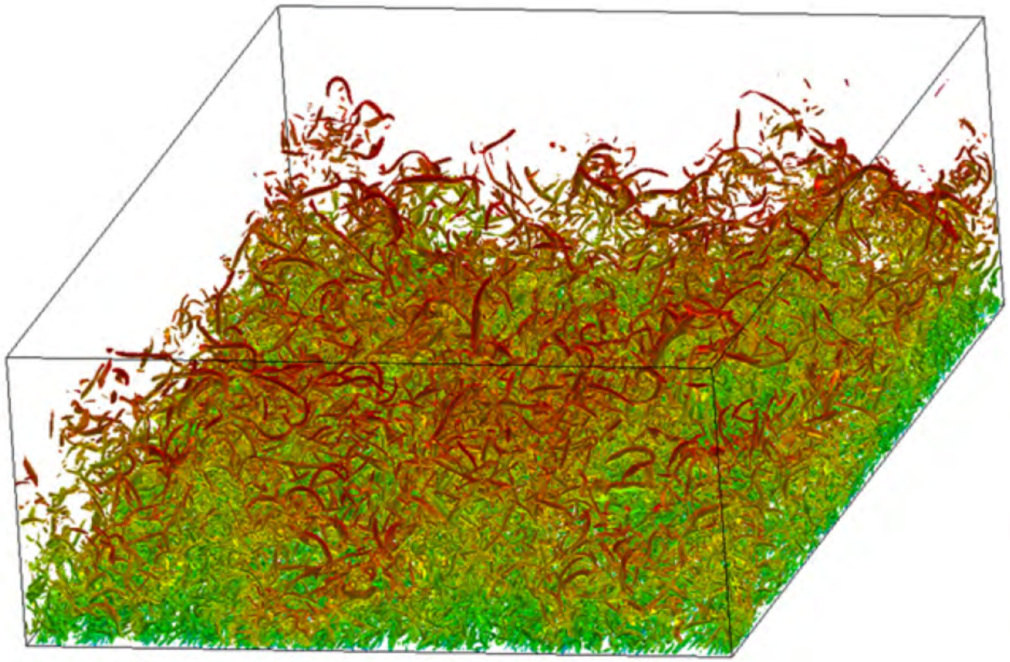
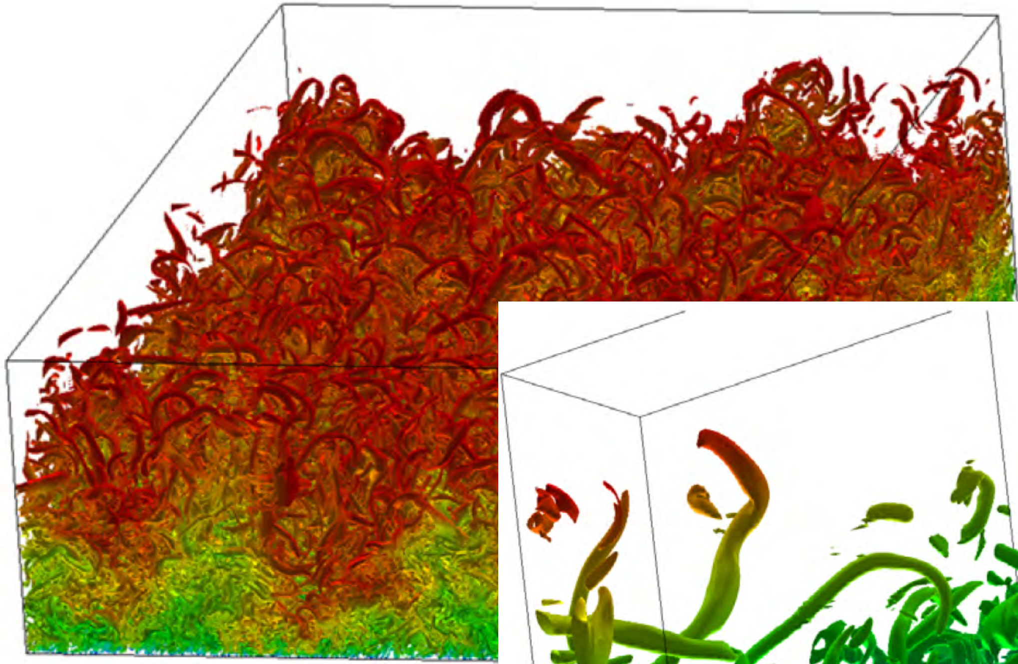
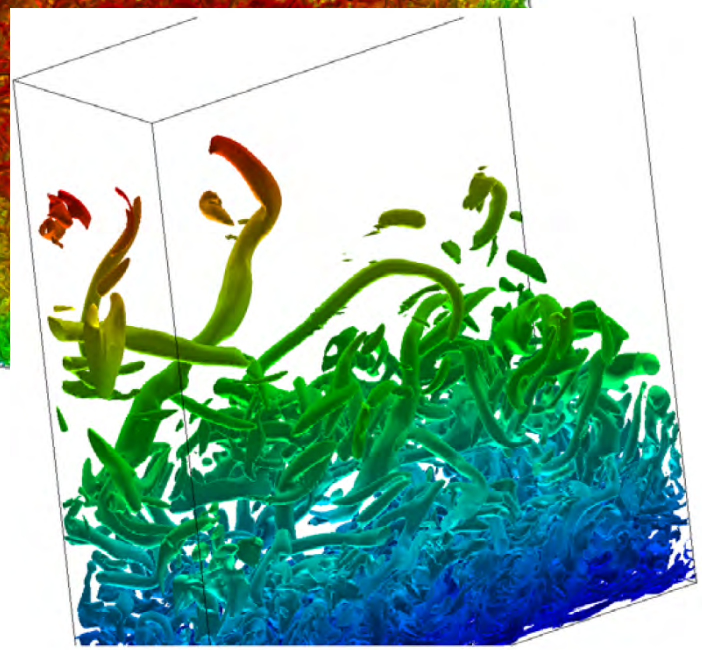
Counting the number of hairpin like structures …

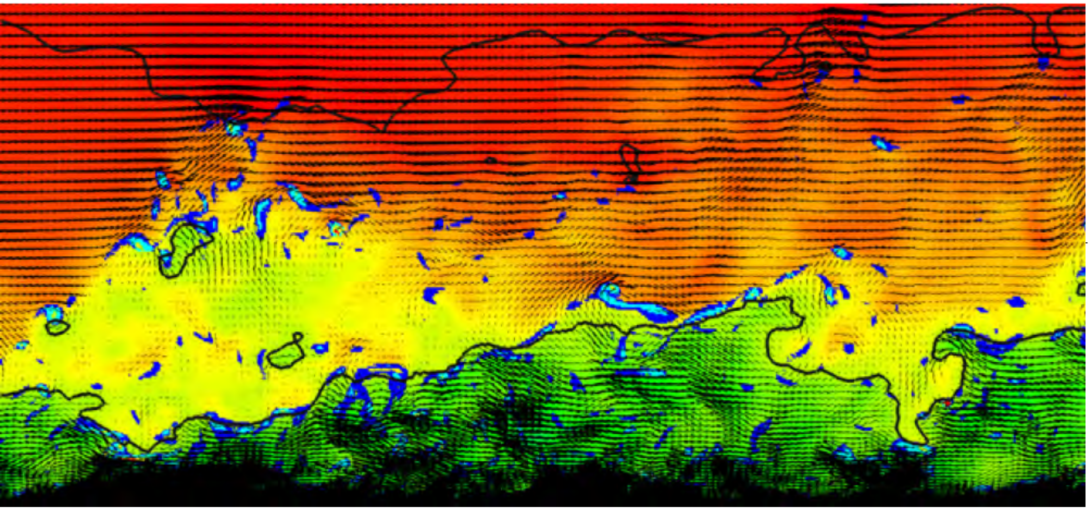


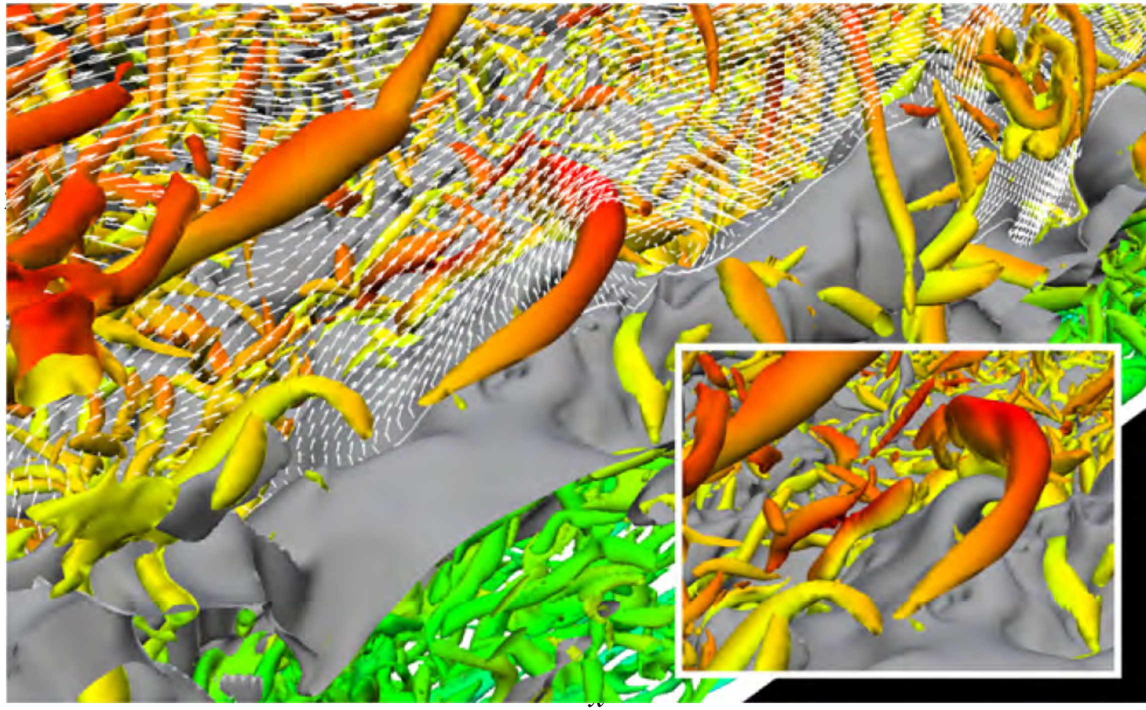




- **Counting**
  - o manually with different strengths of λ_2
  - o less than 2% resembles hairpins at Re_θ=4300
  - o some resemblance to arches at BL edge for low $-\lambda_2$

Vertical-streamwise cut (HVS Adrian 2007)





- **Streamwise velocity in x-y plane with velocity vectors**
  - ramp-like low speed structure as in PIV measurements
  - regions of strong swirl grouped along edge of ramps
  - 3D extrapolation of vortex structures do not show hairpin packets associated with swirl regions

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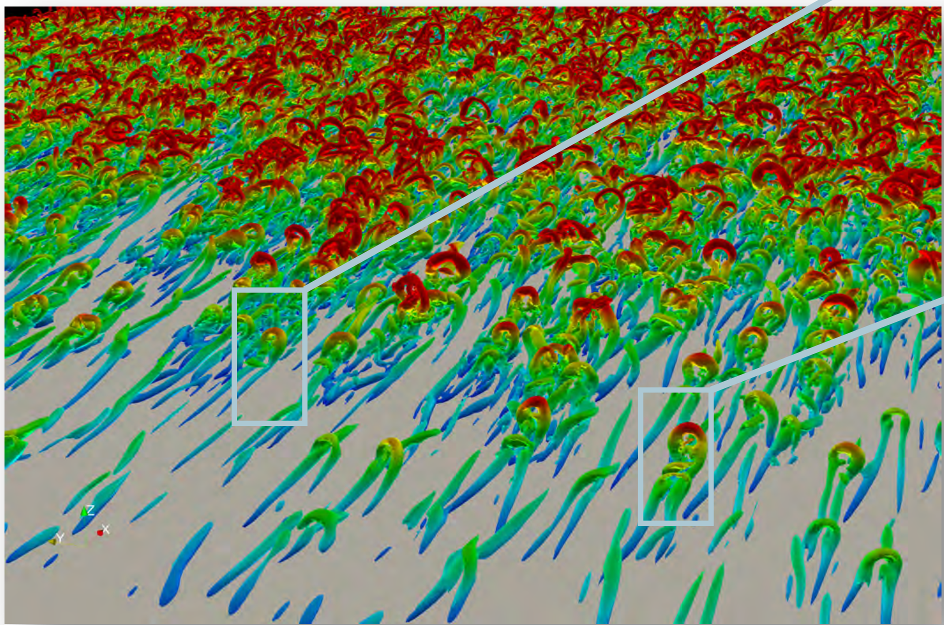
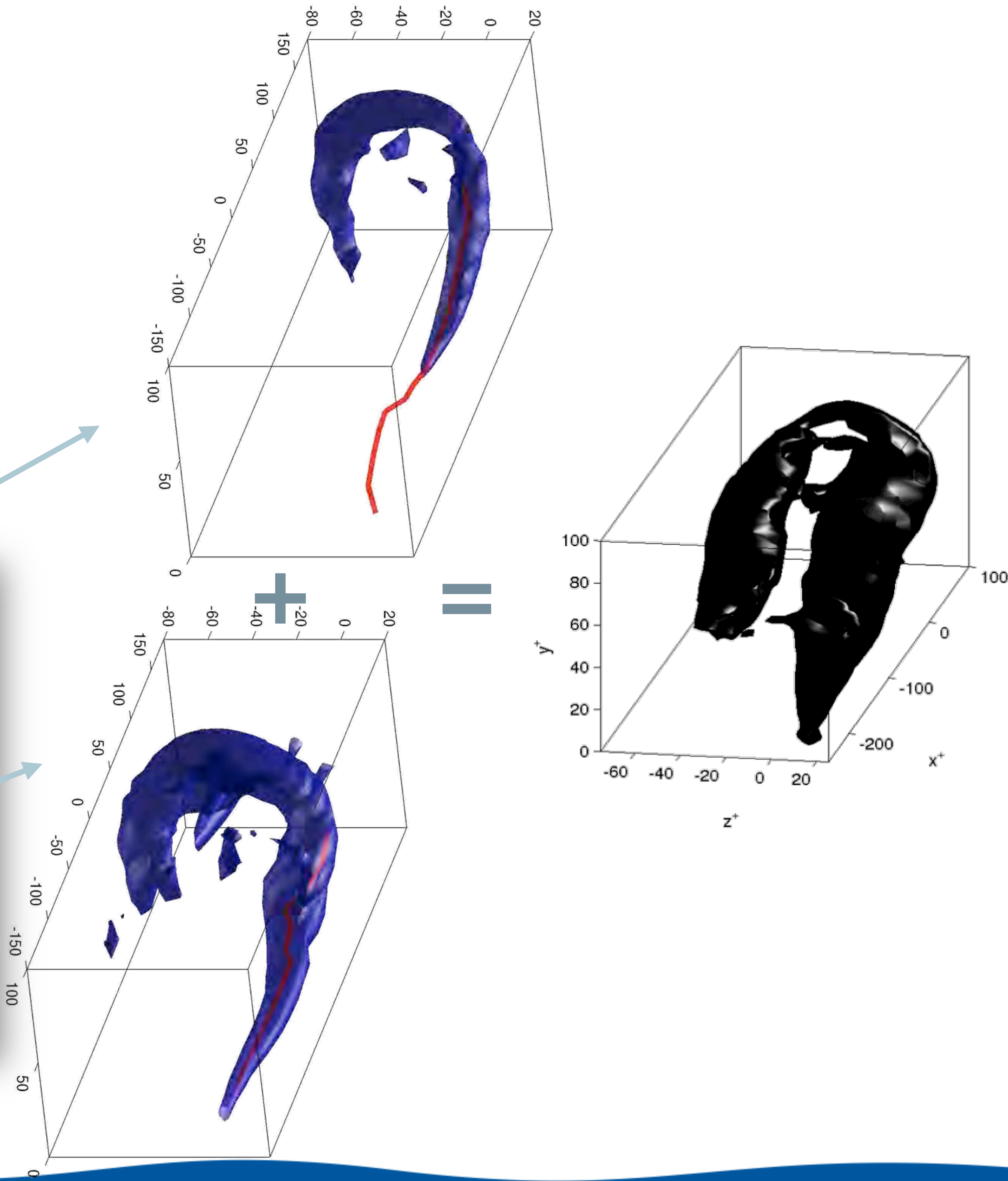
Vortex Eduction

- Jeong *et al.* (1998)

1. Identify axis of streamwise vortex
2. Apply selection criteria
3. Ensemble average





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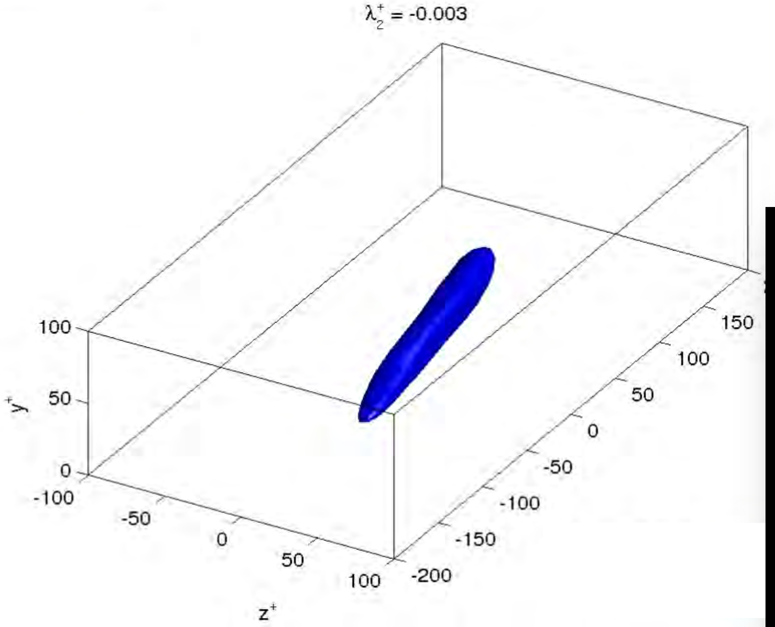
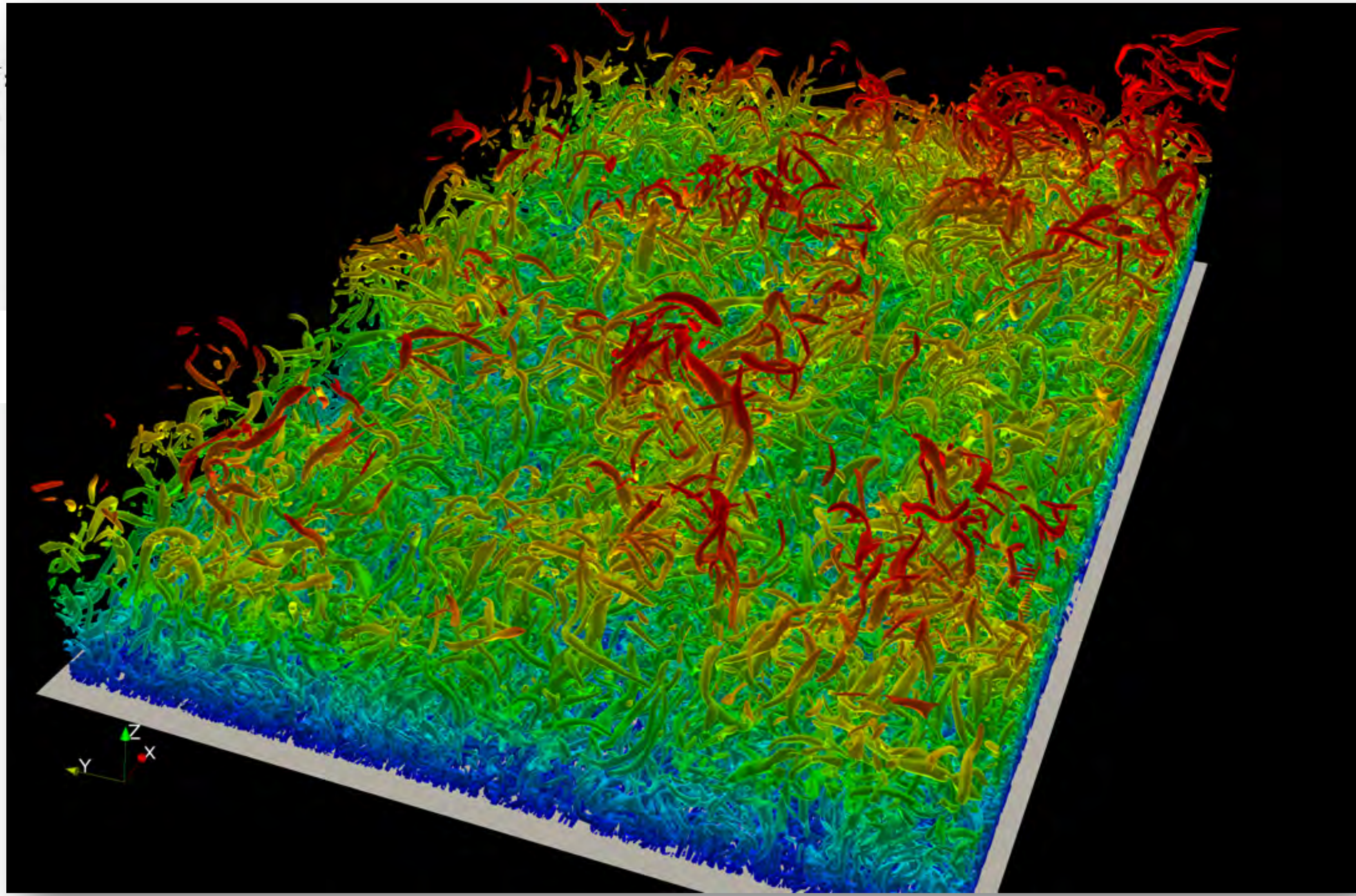
Eduction technique at high Reynolds numbers, finds streamwise vortices close to wall





Streamwise vortex

- about 10 inclination and tilting wrt x-axis
- average L^+=150-200

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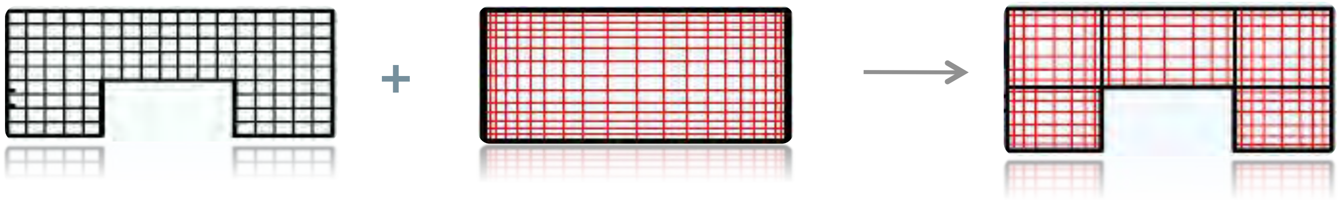
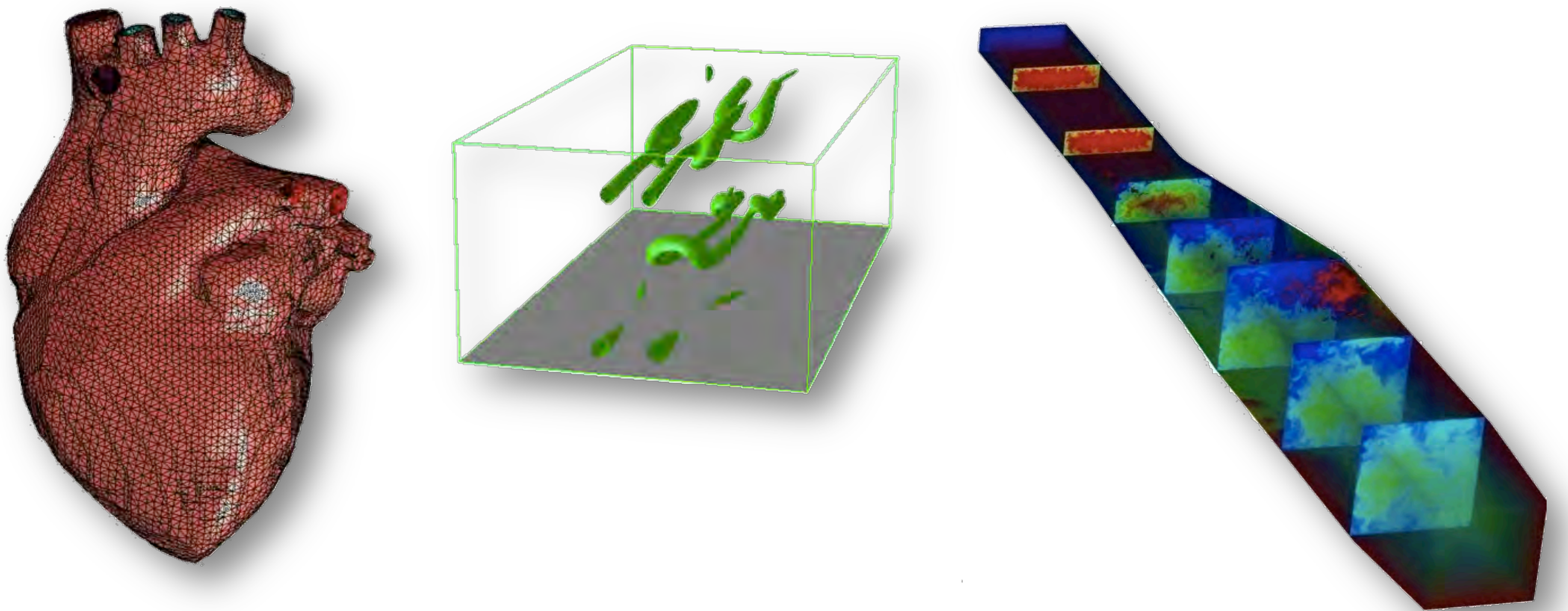
Hairpin structures in turbulent boundary layers

- Hairpin vortices not apparent in visualizations for high Reynolds number boundary layers (visual inspection)
- Counting vortex structures shows less than 2% hairpin-like at Re_θ=4300
- HVS signatures not associated with hairpins packets
- Vortex eduction techniques bring them out in transitional flow but not at higher Reynolds numbers

Towards complex geometries with spectral elements …

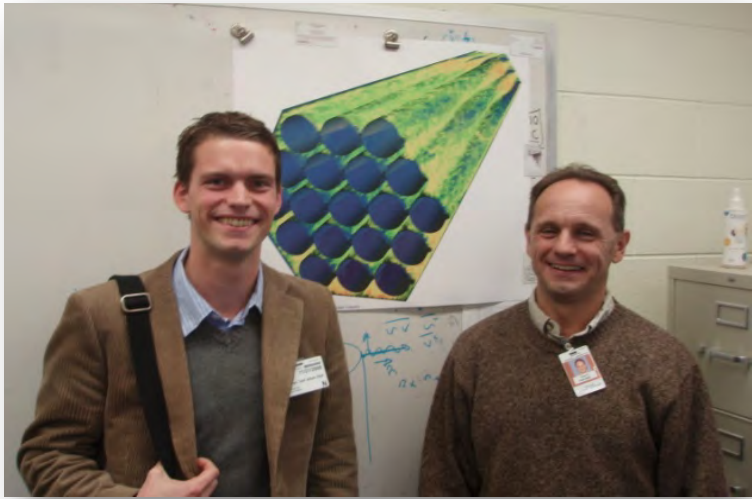
Finite element (FE) + Spectral → Spectral element (SE)





Infrastructure: Codes

- **SIMSON**
  - In-house spectral code for channel & boundary layers
  - Continuously improved, now running on up to 16384 cores
- **Nek5000**
  - SEM code by **Paul F. Fischer**, Argonne National Lab, USA
    Open source: `nek5000.mcs.anl.gov`
  - Good scaling up to 1,000,000 cores!



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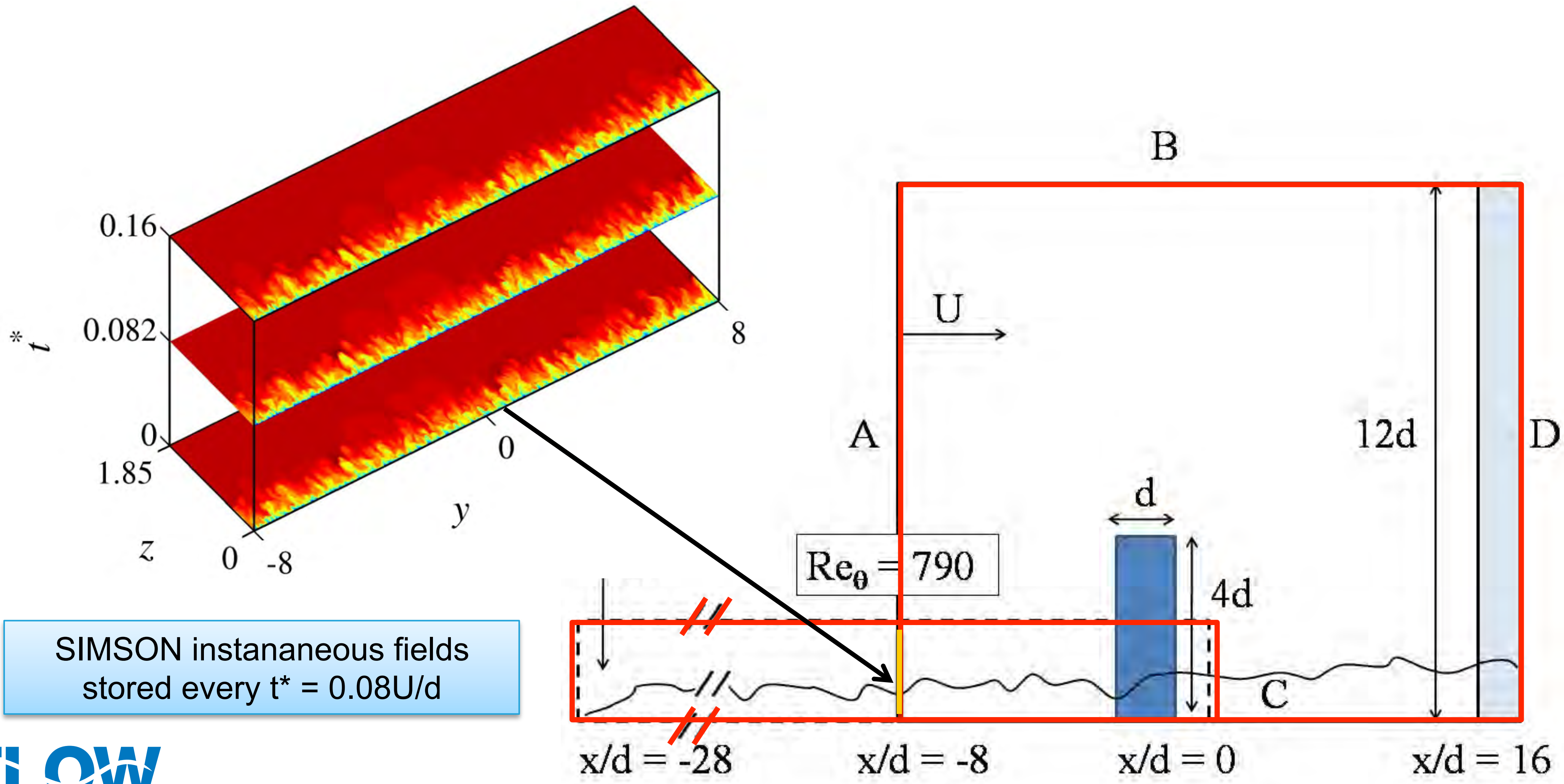
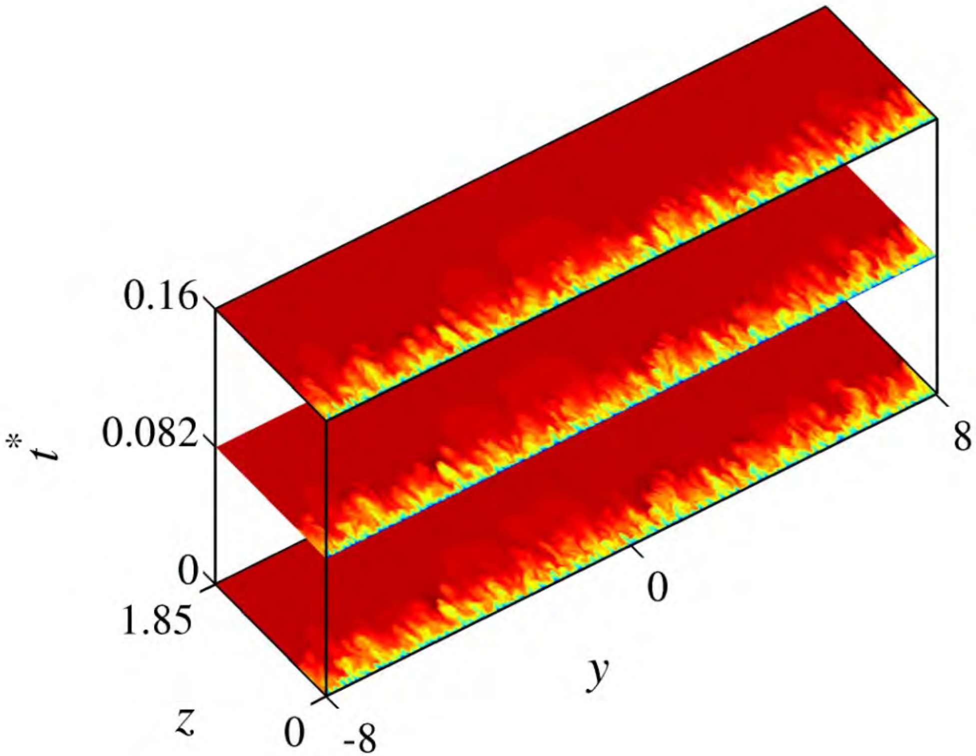
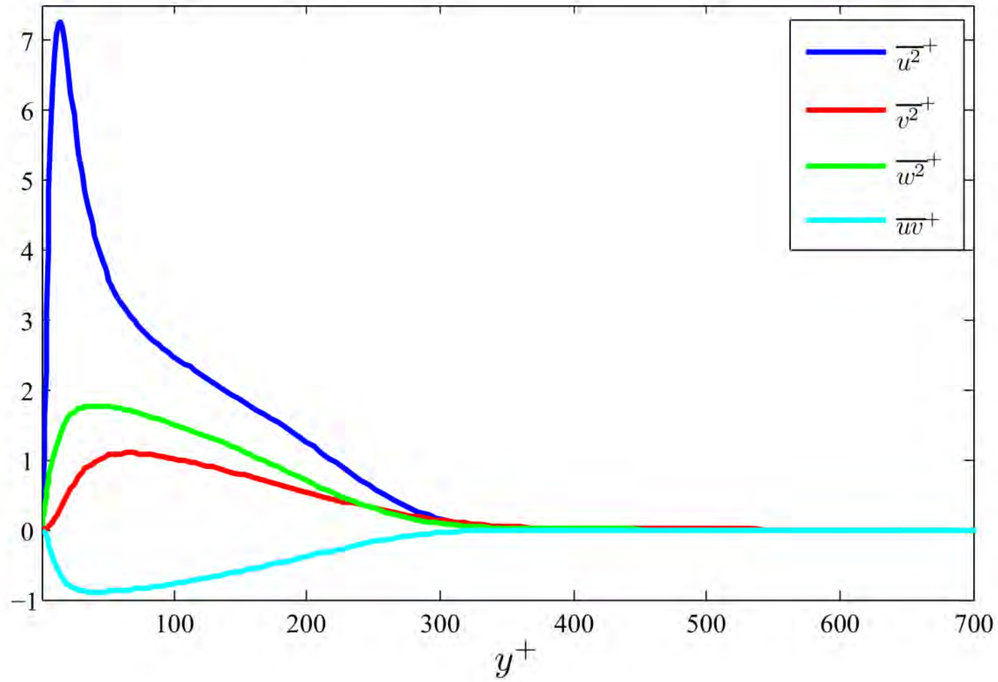
Obstacle in BL – 2012 Canadian CFD Challenge:
Calgary experiment by Robert Martinuzzi
Flow Configuration & Simulation Set-Up



SIMSON instananeous fields
stored every t* = 0.08U/d

Quality of inflow conditions





- Turbulent statistics from SIMSON simulation at x=-8d.
- **<u>Excellent agreement</u>** with reference databases (Schlatter and Örlü, 2010).

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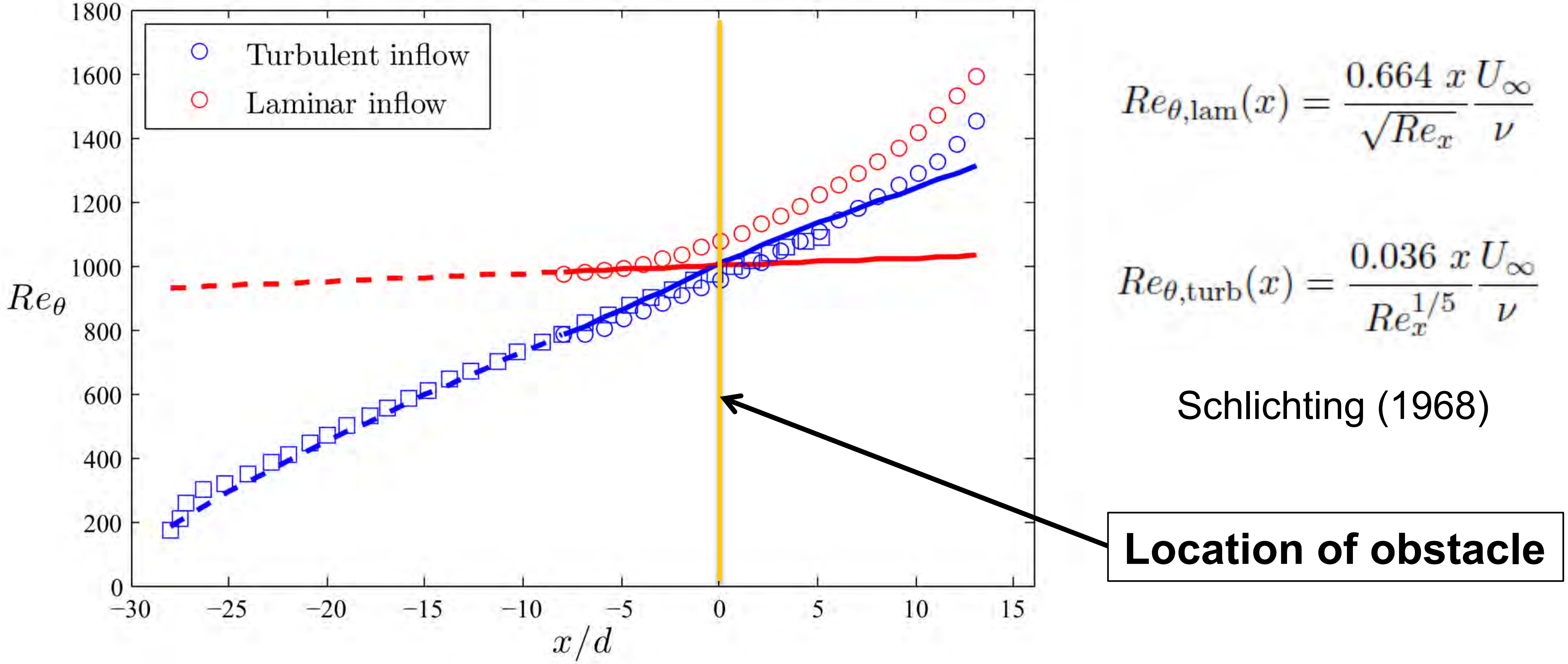
Streamwise development of incoming flow: simulations of both turbulent and laminar inflow



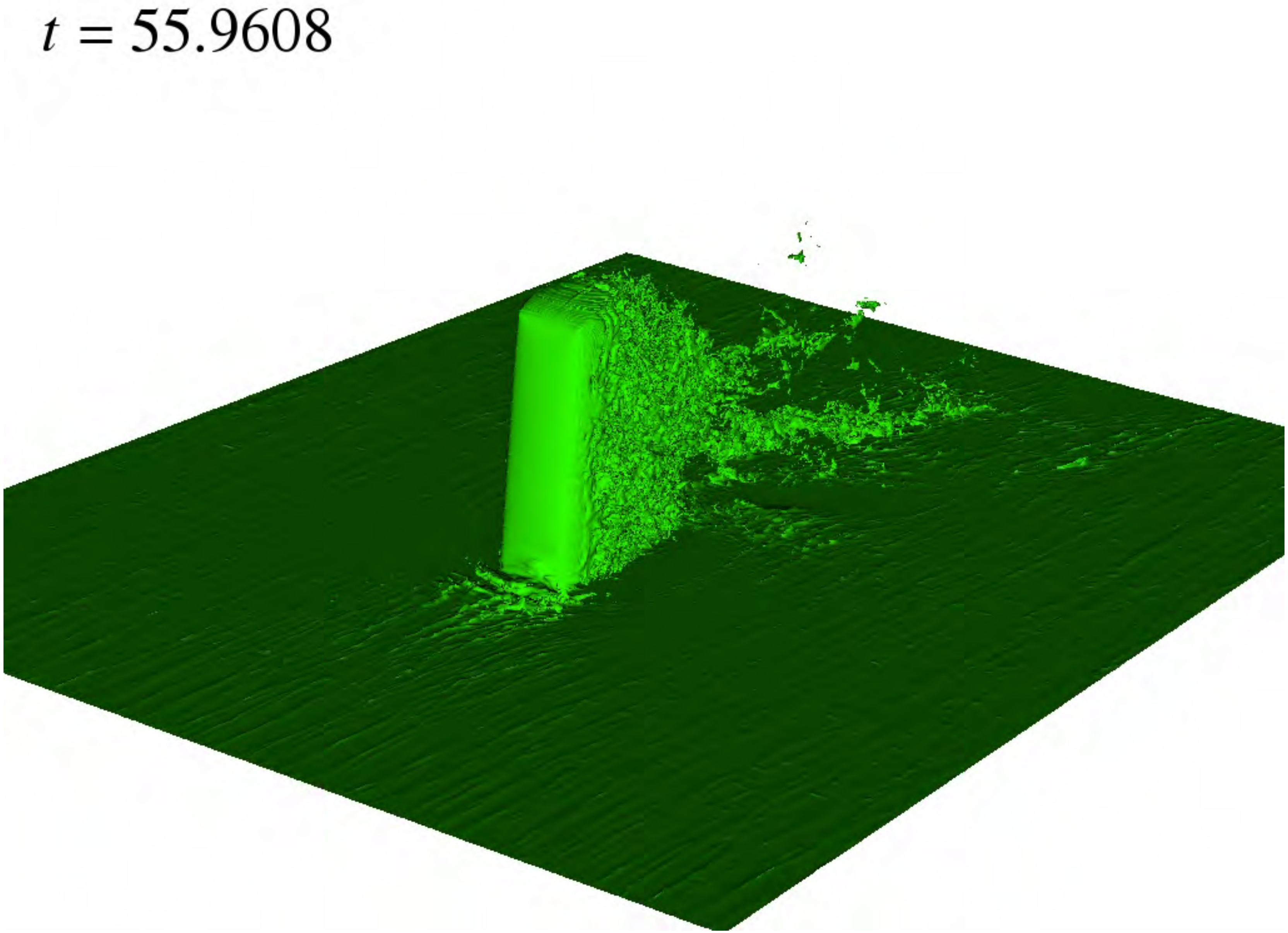
$$Re_{\theta,\mathrm{lam}}(x) = \frac{0.664\ x}{\sqrt{Re_x}} \frac{U_\infty}{\nu}$$

$$Re_{\theta,\mathrm{turb}}(x) = \frac{0.036\ x}{Re_x^{1/5}} \frac{U_\infty}{\nu}$$

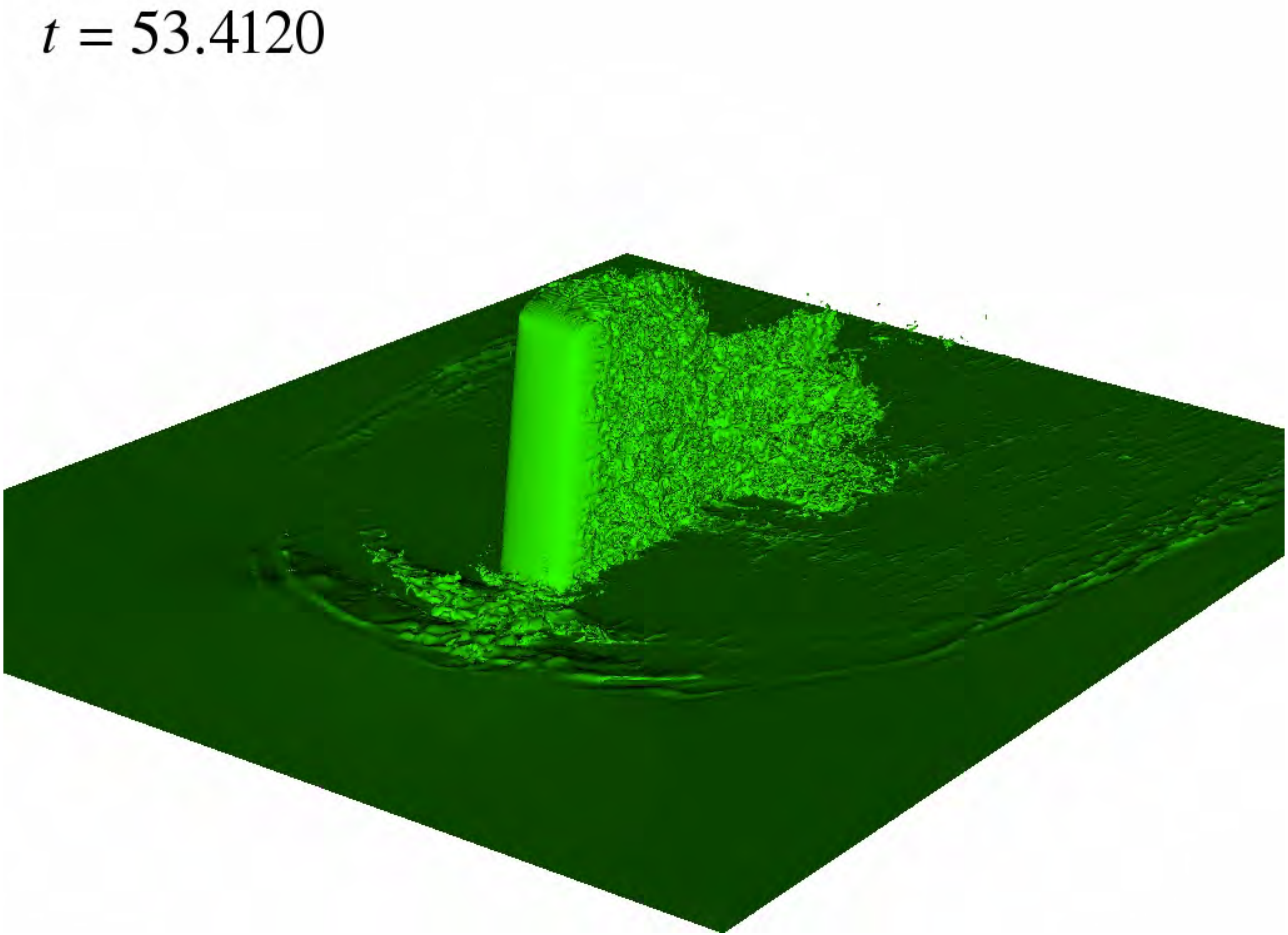
Schlichting (1968)

- Momentum thickness of undisturbed flow matched at obstacle
- Growth of turbulent BL much faster than laminar one

Flow visualization

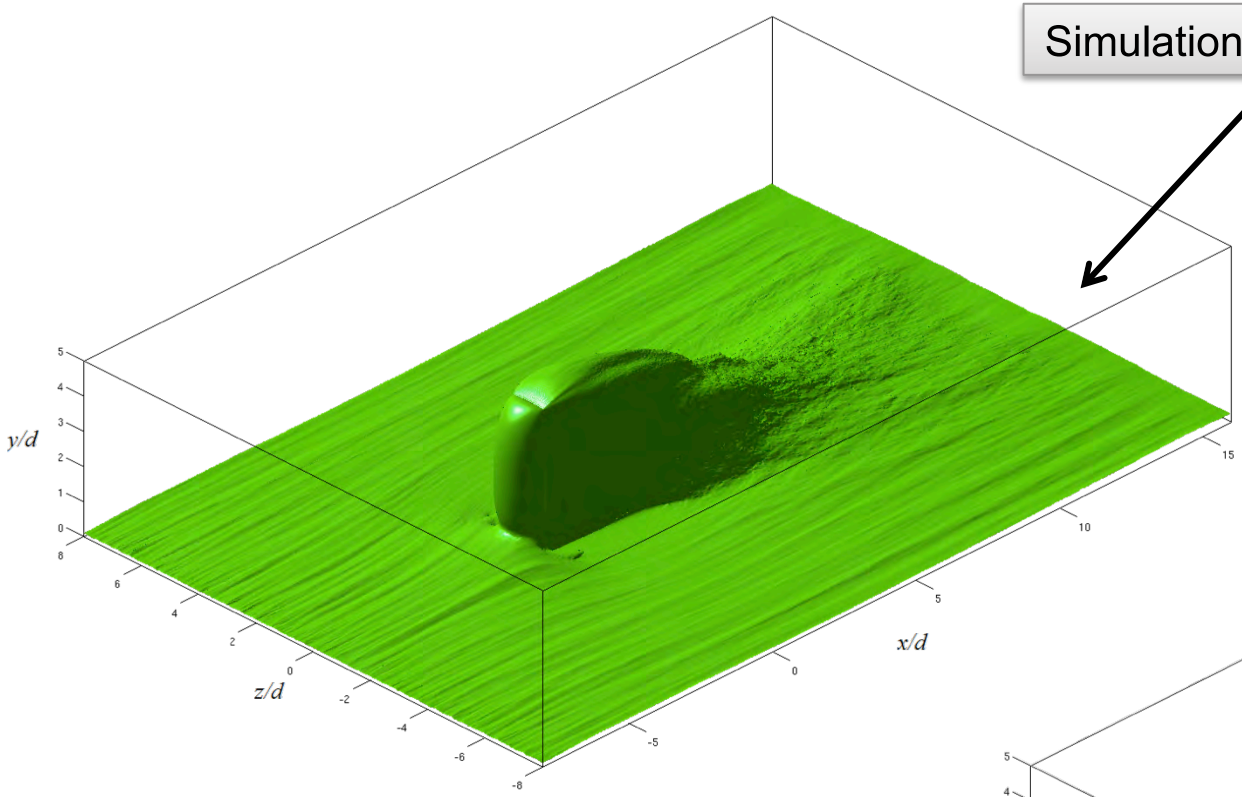


Simulation with laminar inflow

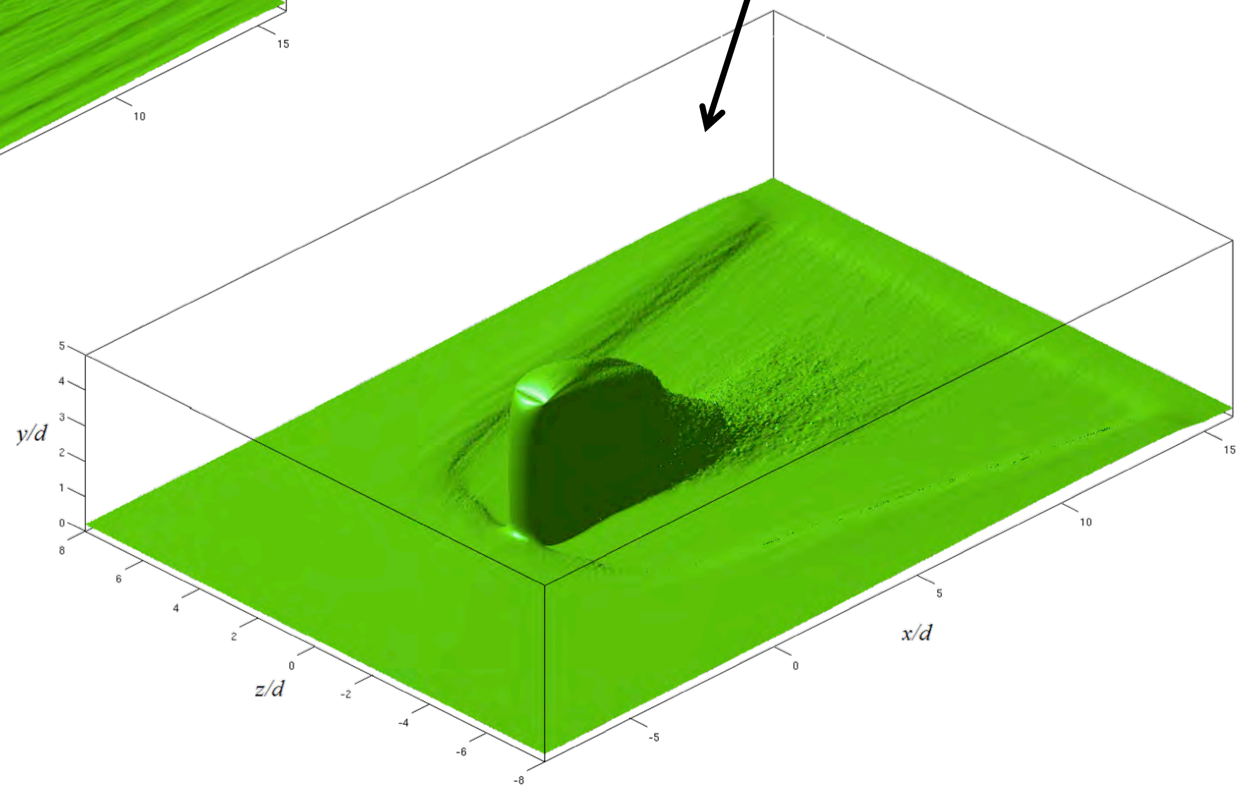


Time averaged streamwise velocity

Simulation with turbulent inflow



Simulation with laminar inflow



- Horseshoe vortex observed in the turbulent case after **<u>averaging in time.</u>**
- Also noticed in experiments.

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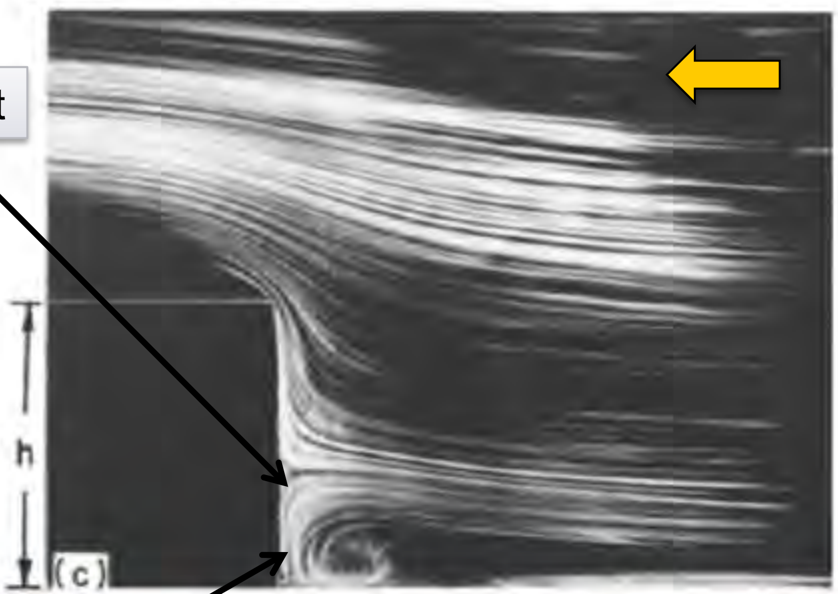
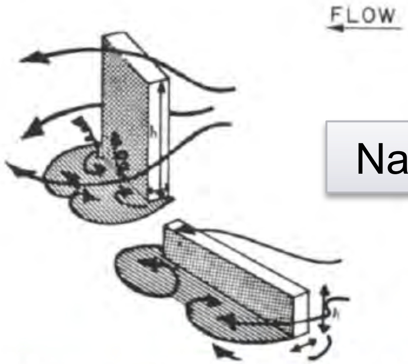
Comparison with experiments at IIT (Chicago)

- Long-time exposure (~1 s) smoke-wire visualizations.



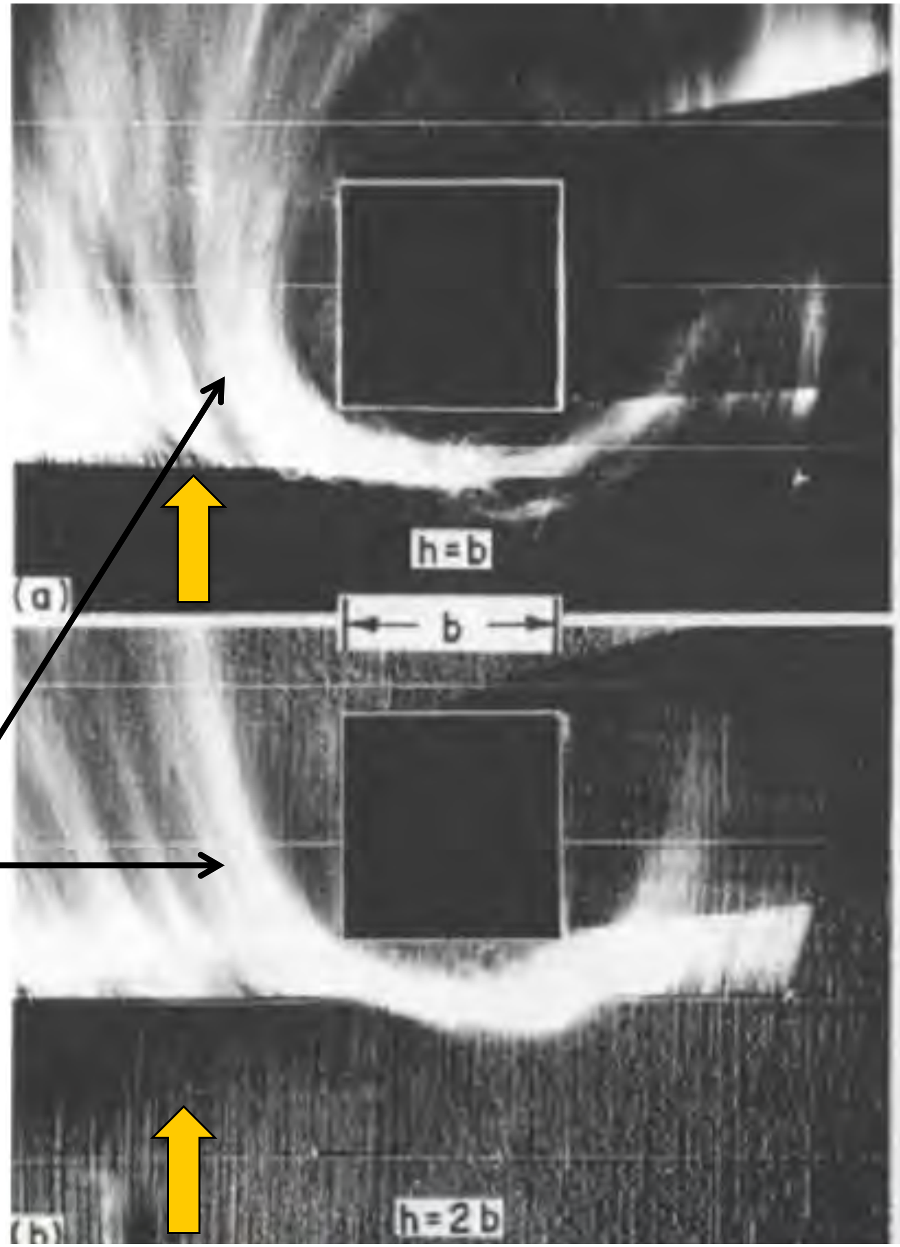
Stagnation point

Recirculation bubble



Horseshoe vortex

Nagib and Corke (1983)

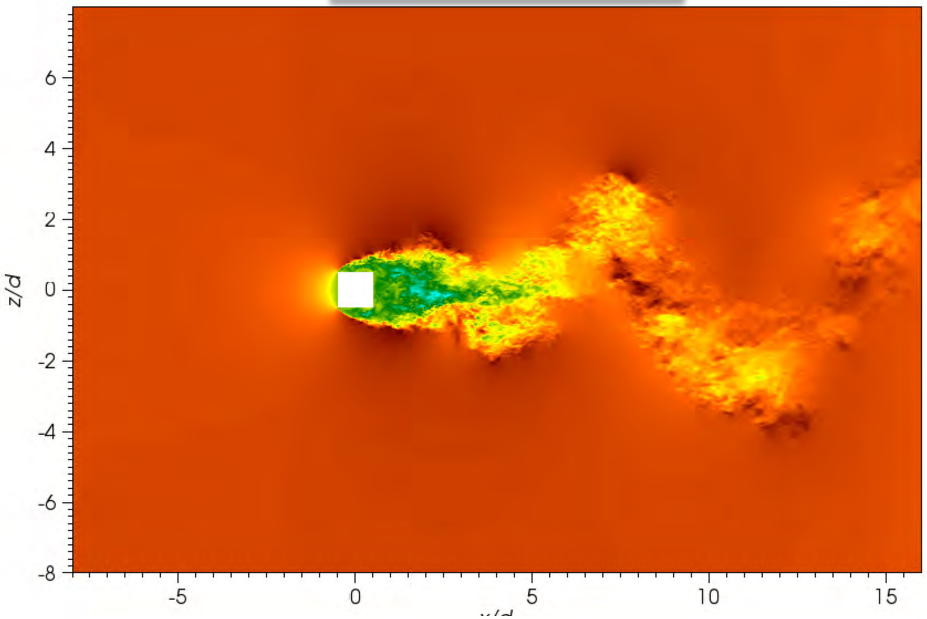


Wake comparison: turbulent vs laminar inflow

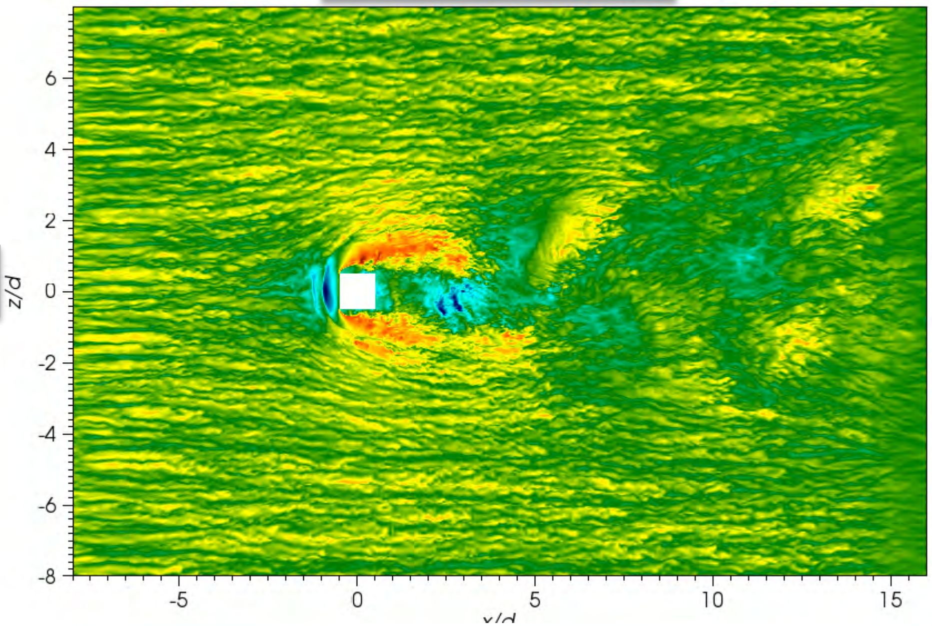
St = 0.1 ± 0.03 for both cases in agreement with exp

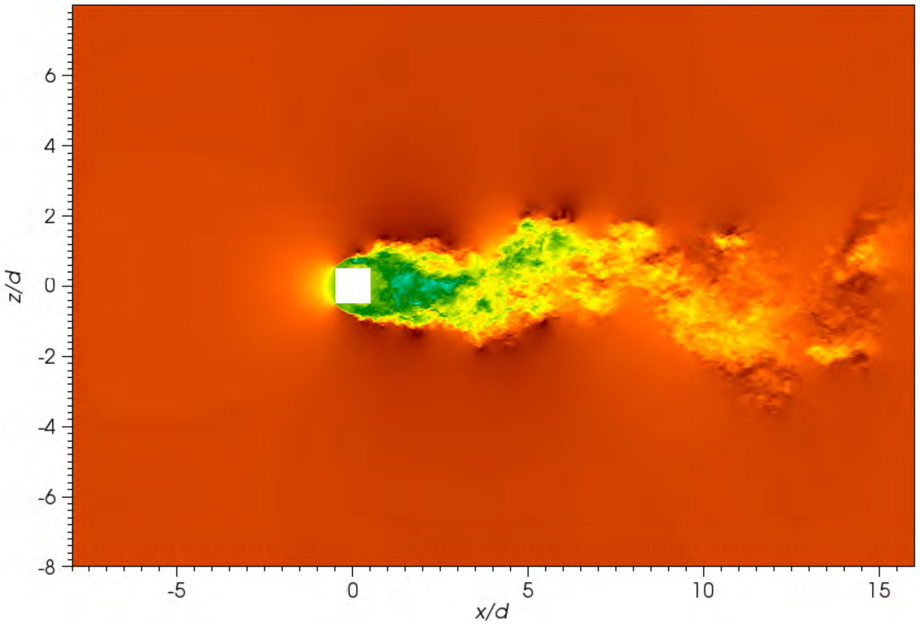
y = 2d

$y^+ \approx 15$

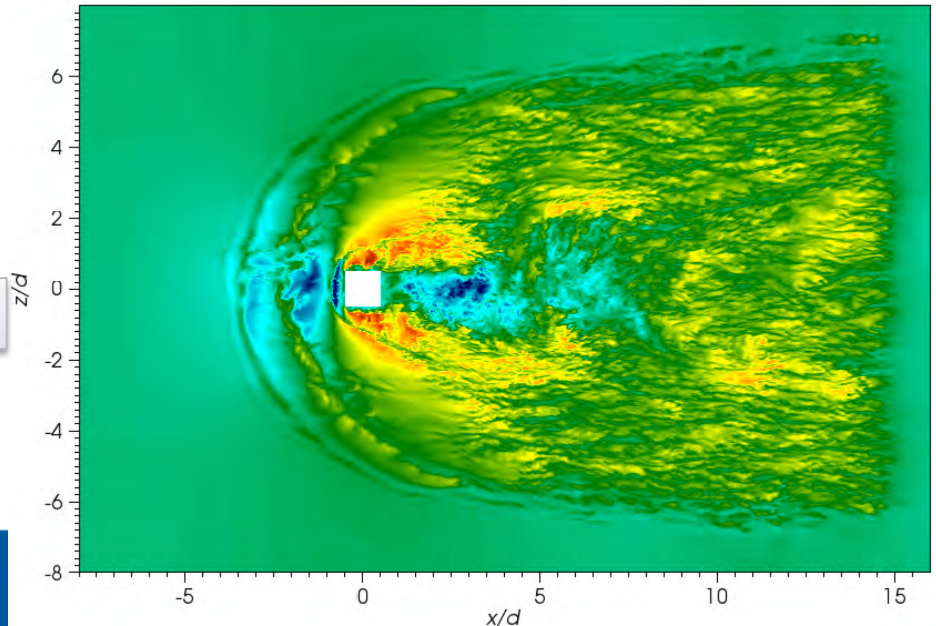


Turbulent inflow

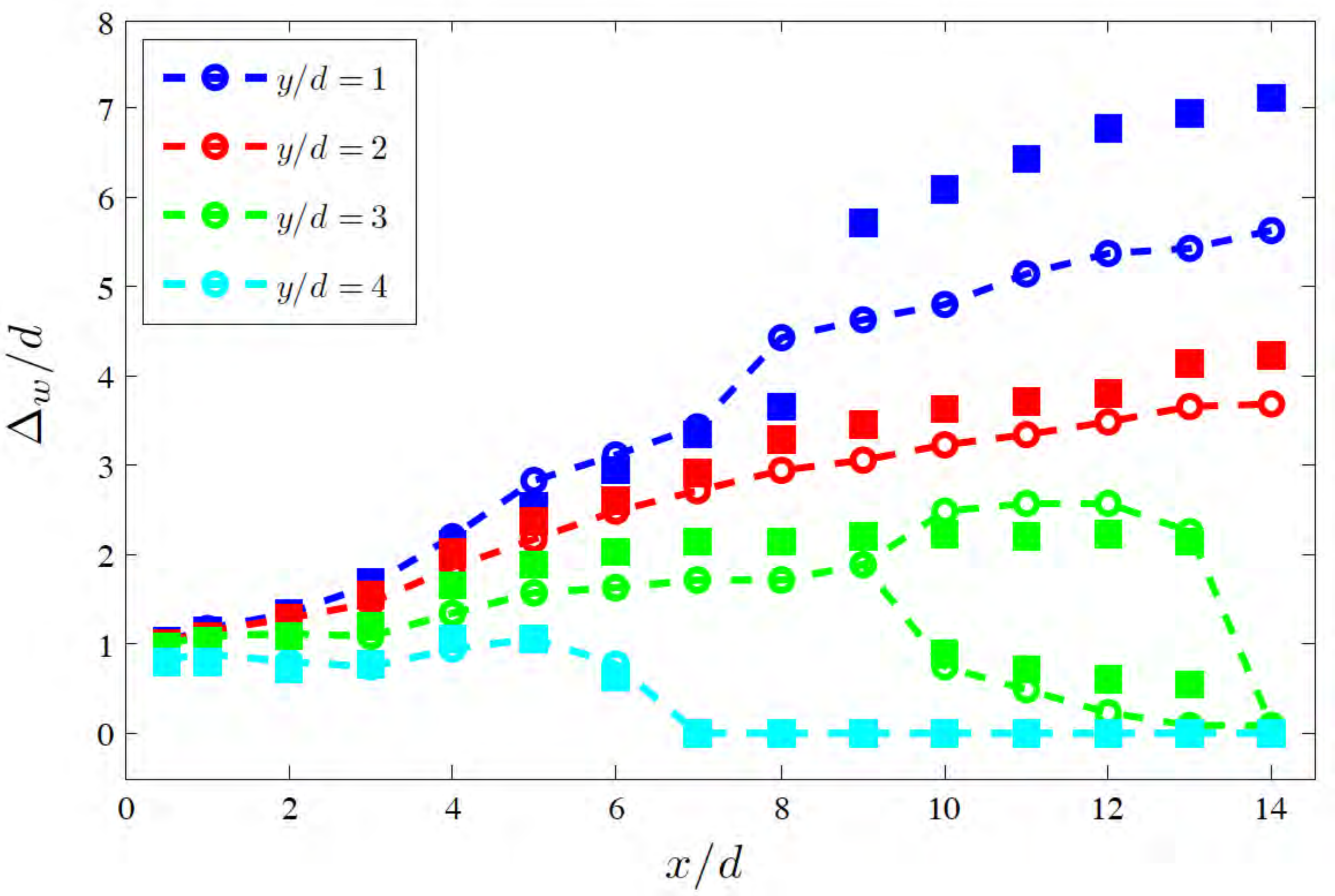




Laminar inflow

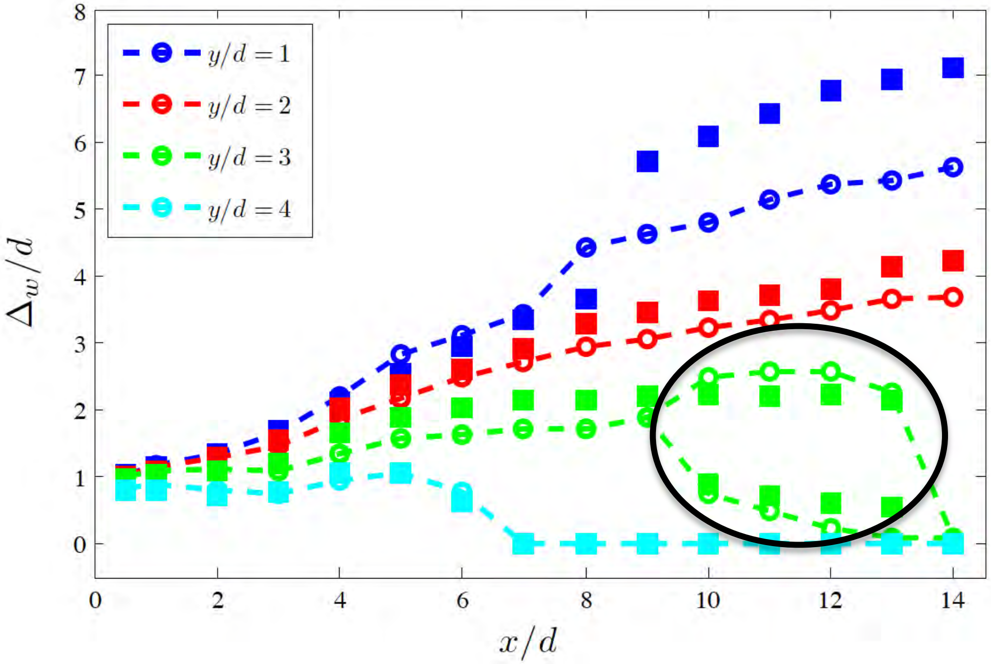


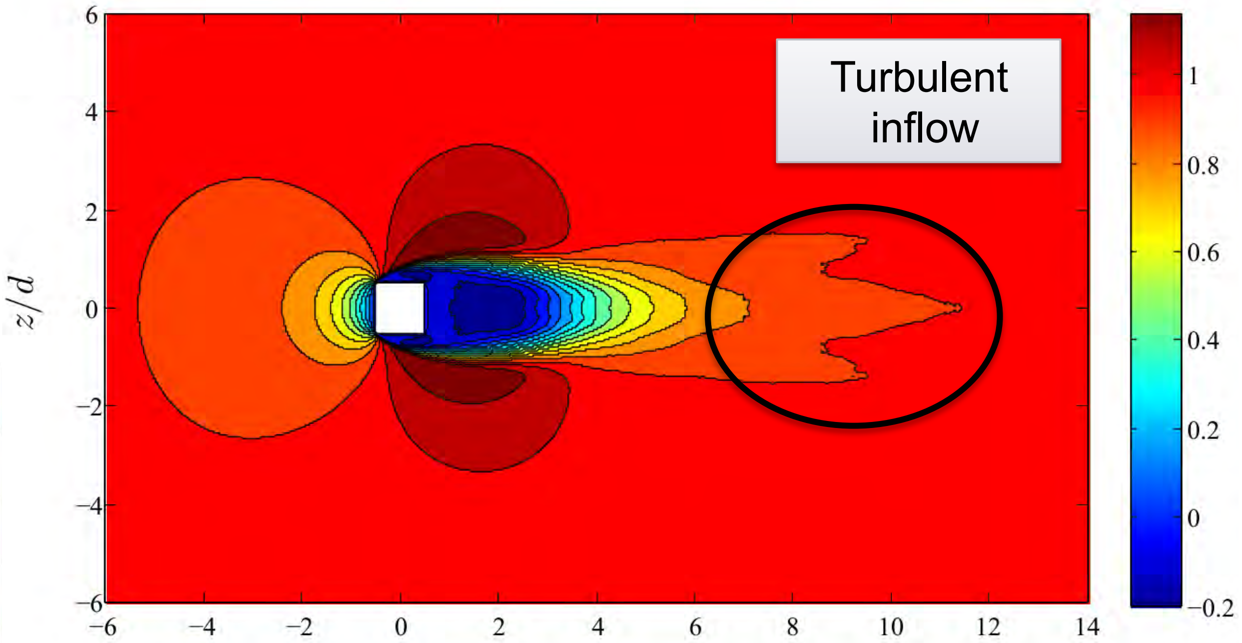
Wake half-width comparison

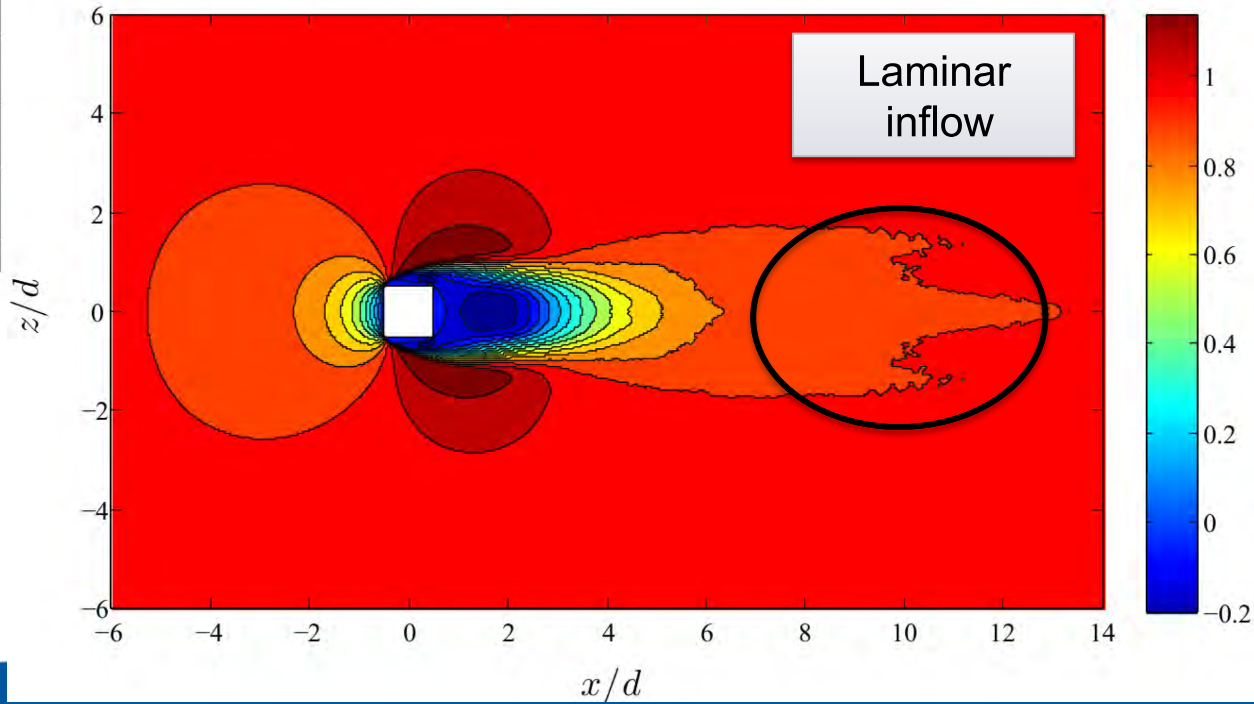


- **<u>Circles</u>**: Laminar; **<u>Squares</u>**: Turbulent
- Wake is wider close to wall
- Turbulent wake is wider than laminar one close to wall
- Both wakes similar for x<3d, differences decrease with y.

Wake half-width comparison at y=3d



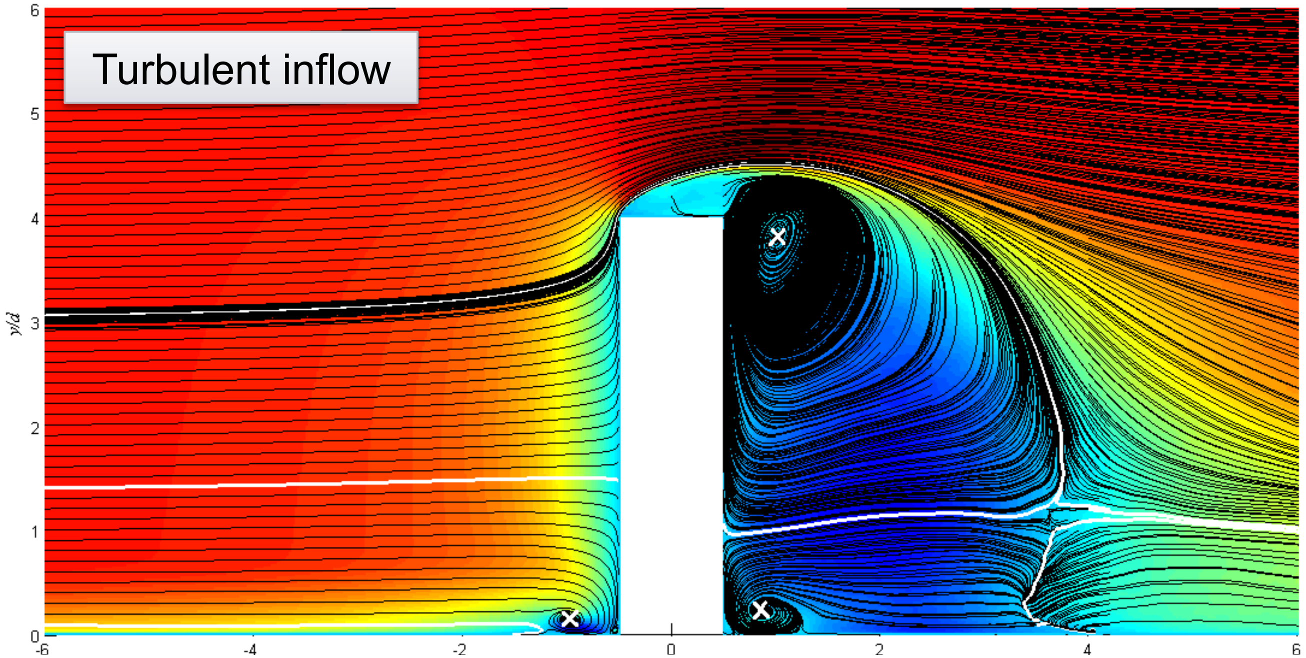




Comparison of mean streamlines

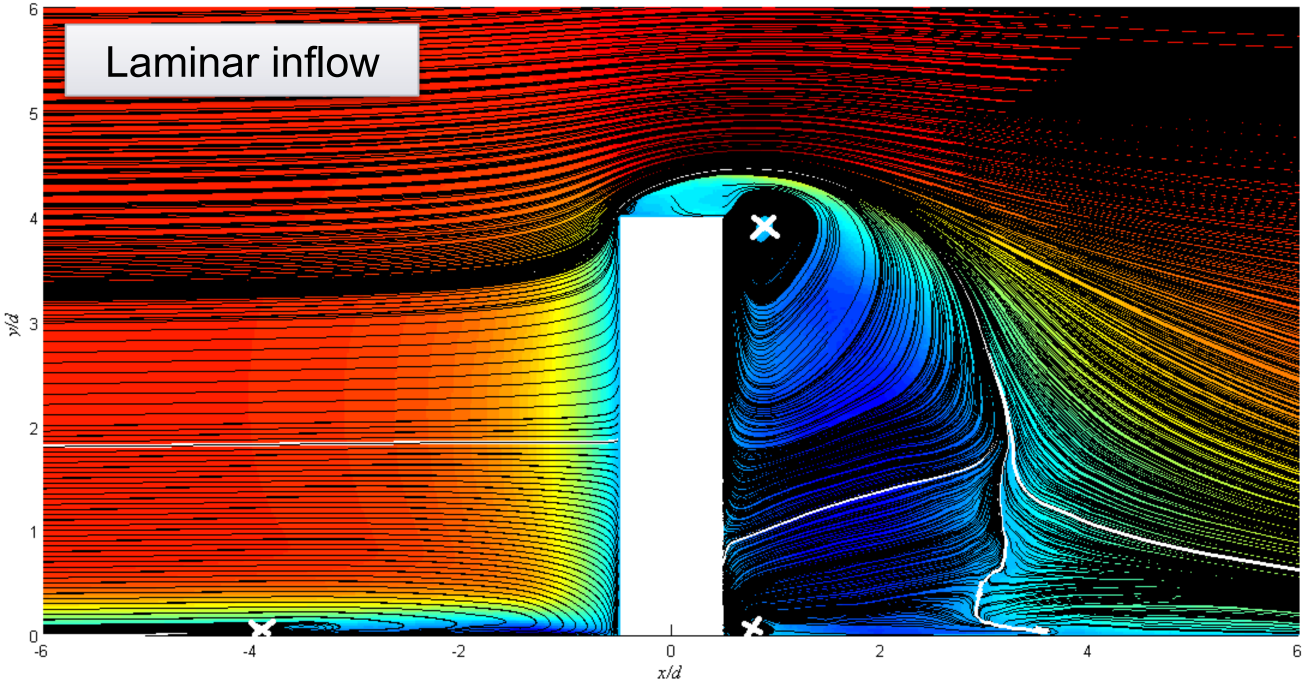
- **Windward side**:
- Stagnation point: y ≈ 1.5d
- Recirculation bubble: x ≈ -1.5d

- **Leeward side:**
- Stagnation point: y ≈ 1d
- Recirculation bubble: x ≈ 4d



- **Windward side:**
- Stagnation point: y ≈ 1.9d
- Recirculation bubble: x ≈ -5d

- **Leeward side:**
- Stagnation point: y ≈ 0.7d
- Recirculation bubble: x ≈ 3.6d



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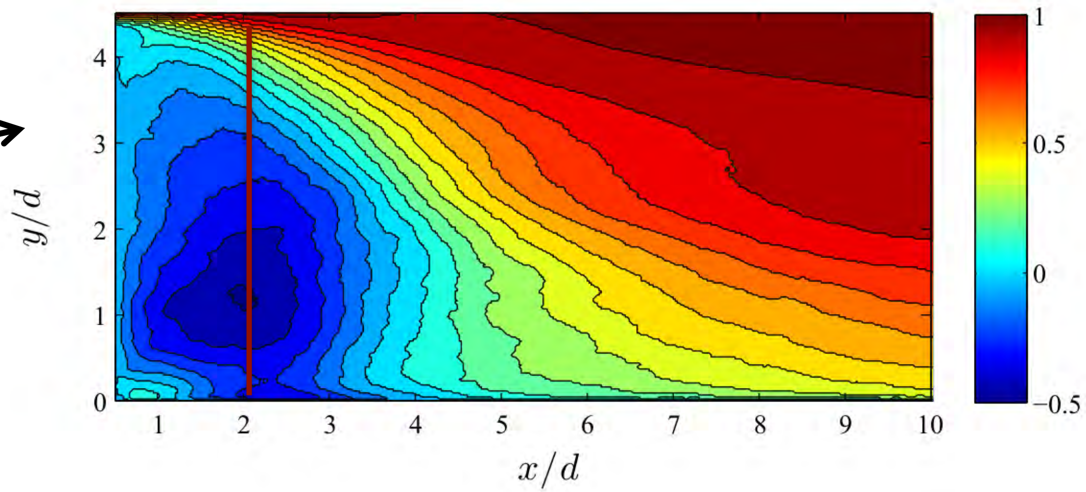
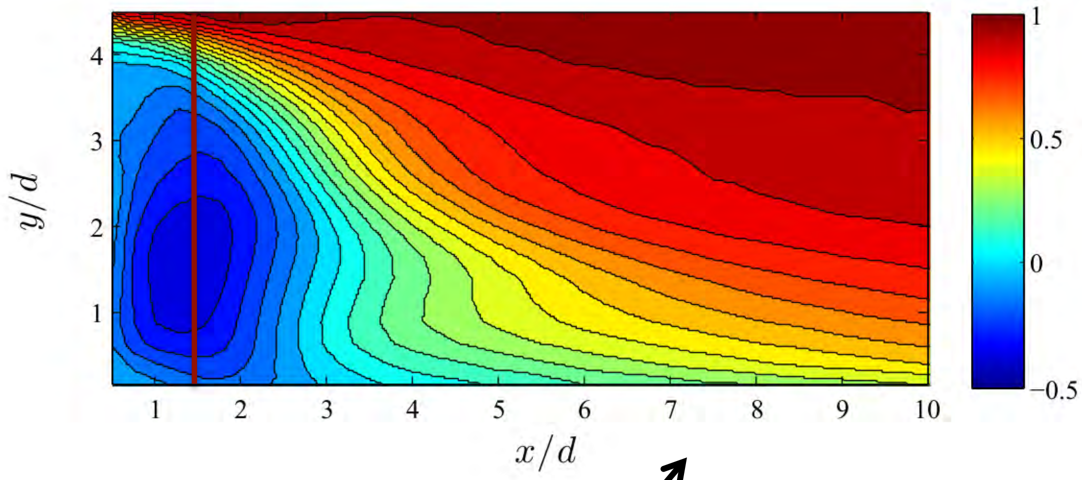
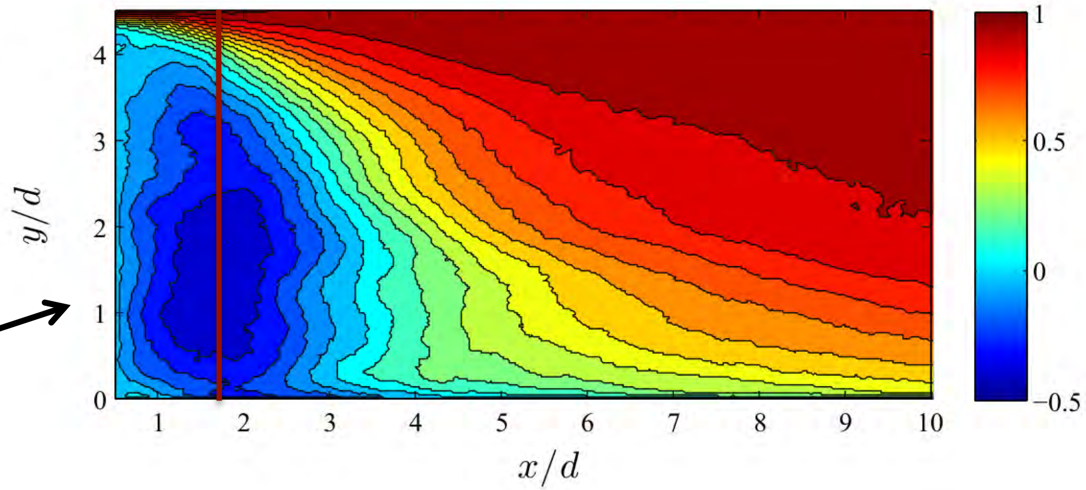
Comparison with experiment: Mean flow z/d=0

Simulation with turbulent inflow





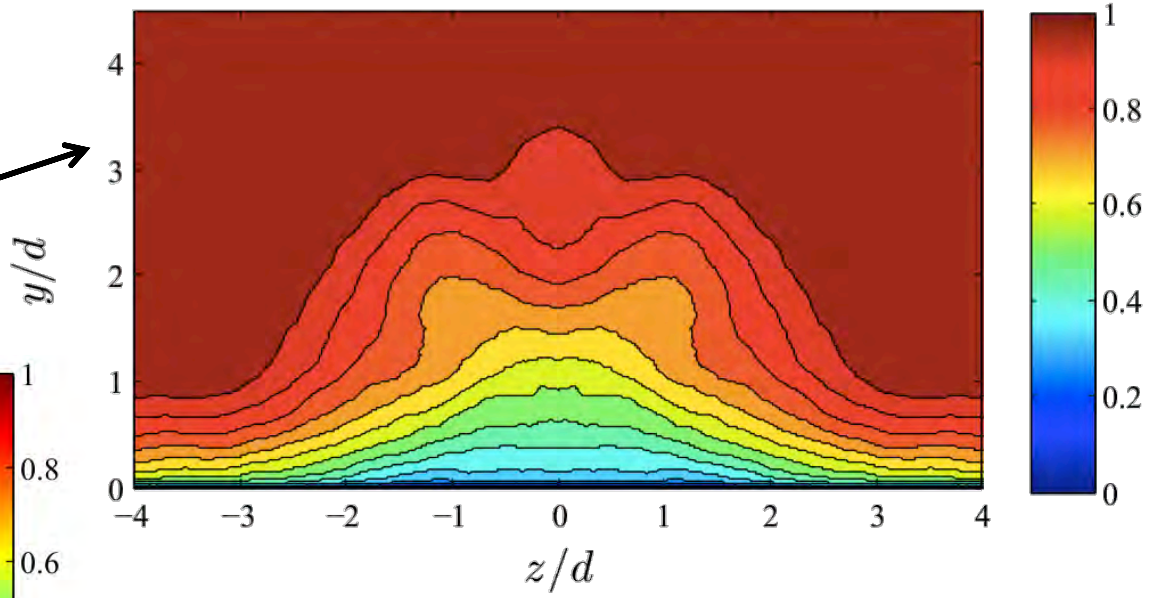
Experiment

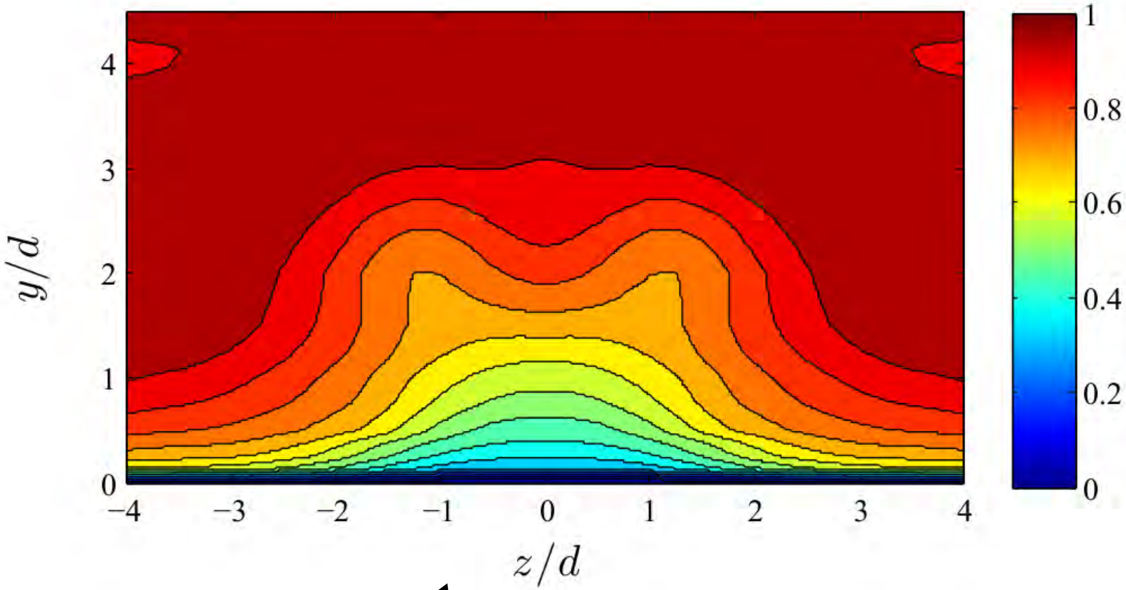


Simulation with laminar inflow

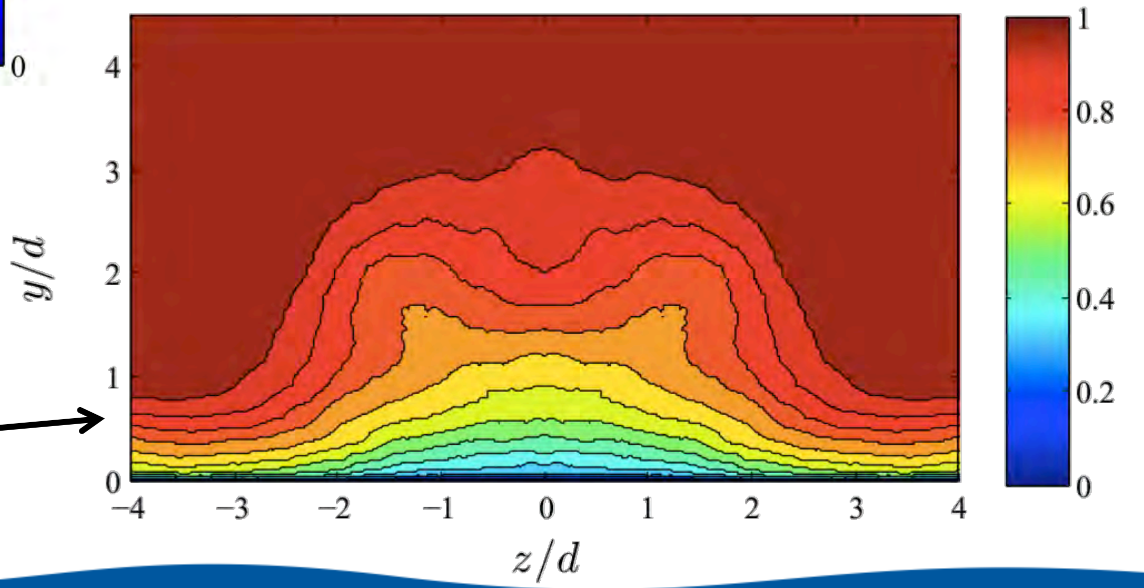
Mean flow x/d=8

Simulation with turbulent inflow





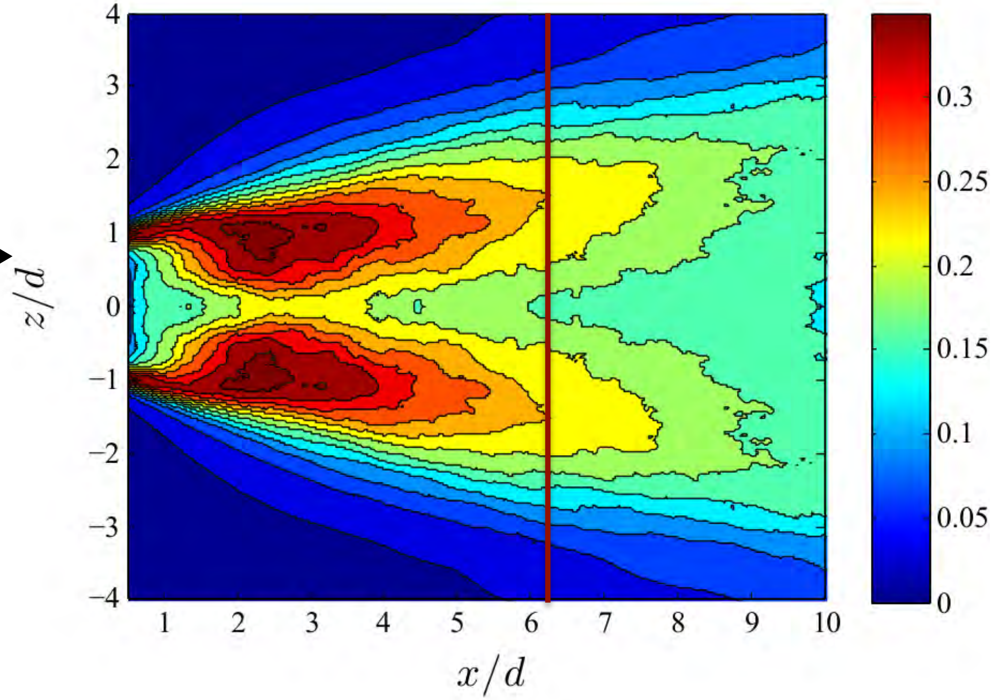
Experiment

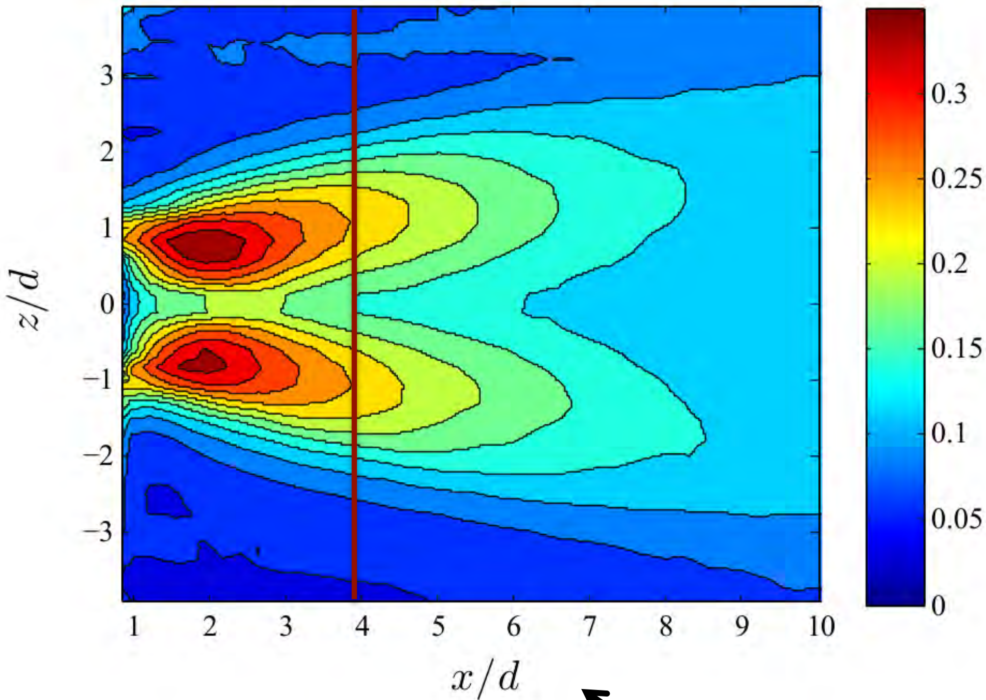


Simulation with laminar inflow

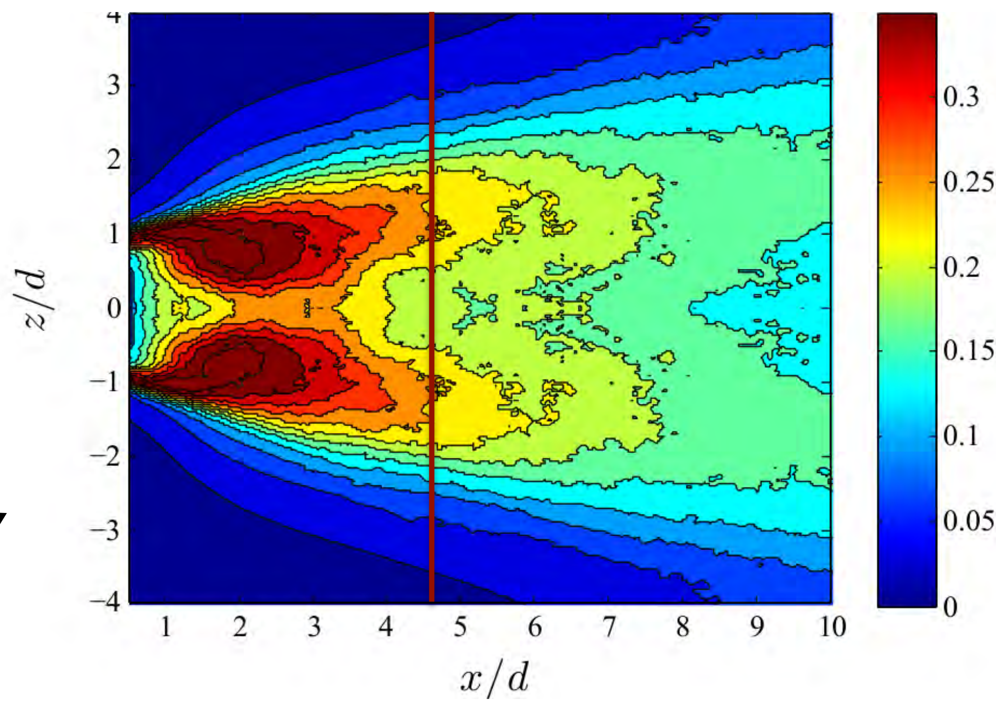
Turb. int. u_{rms} at $y/d=1$

Simulation with turbulent inflow





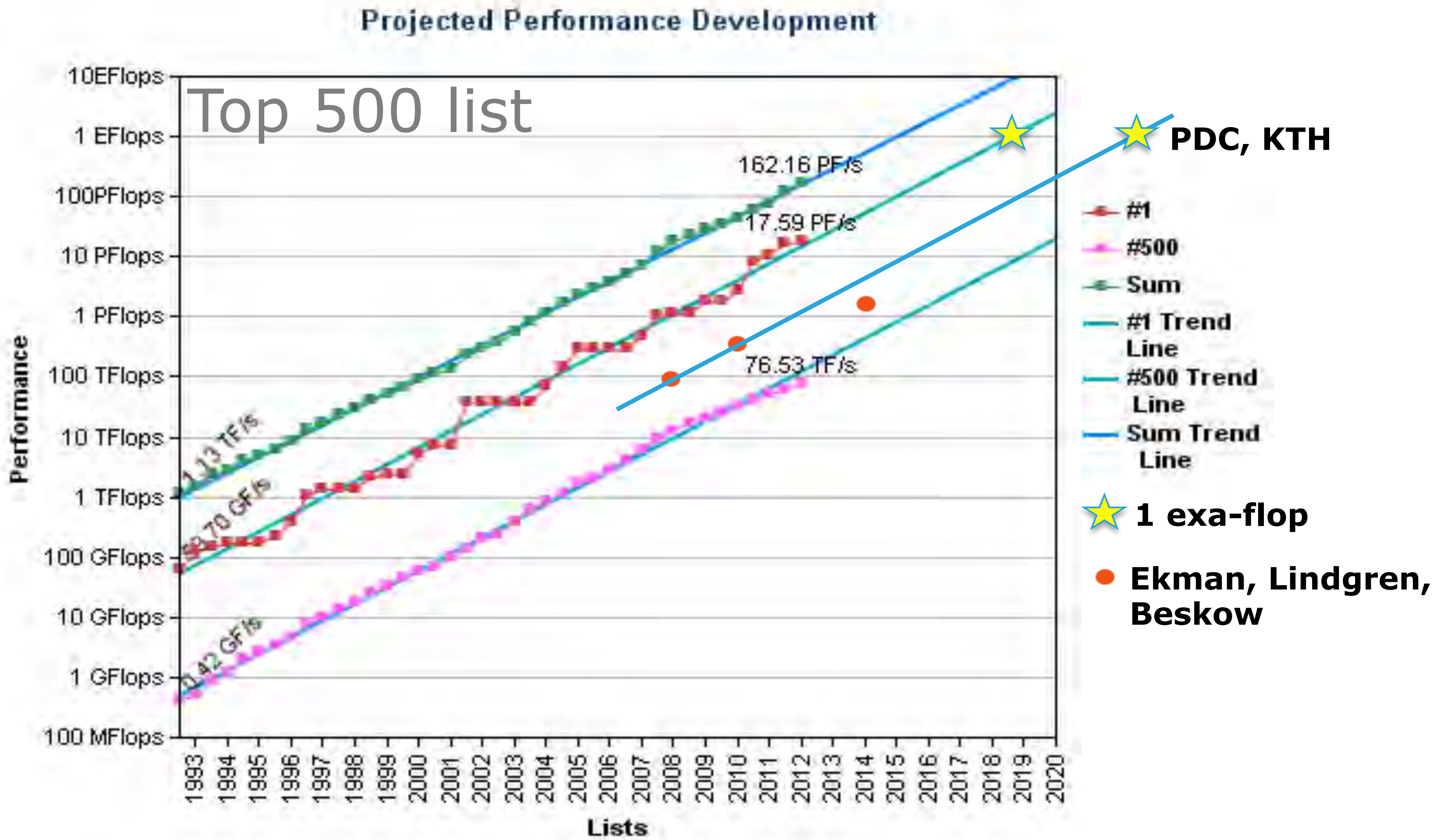
Experiment



Simulation with laminar inflow

Future possibilities with increasing computer speed, exa-flop 2018/19?

Slope faster than hardware development!



Can we go to exa-scale with Nek5000?

- Number of grid points N per processor P important, local work has to outweigh cost for communication

- For Nek5000 on BG/P: $(N/P) \sim$ 1000—10,000 sufficient

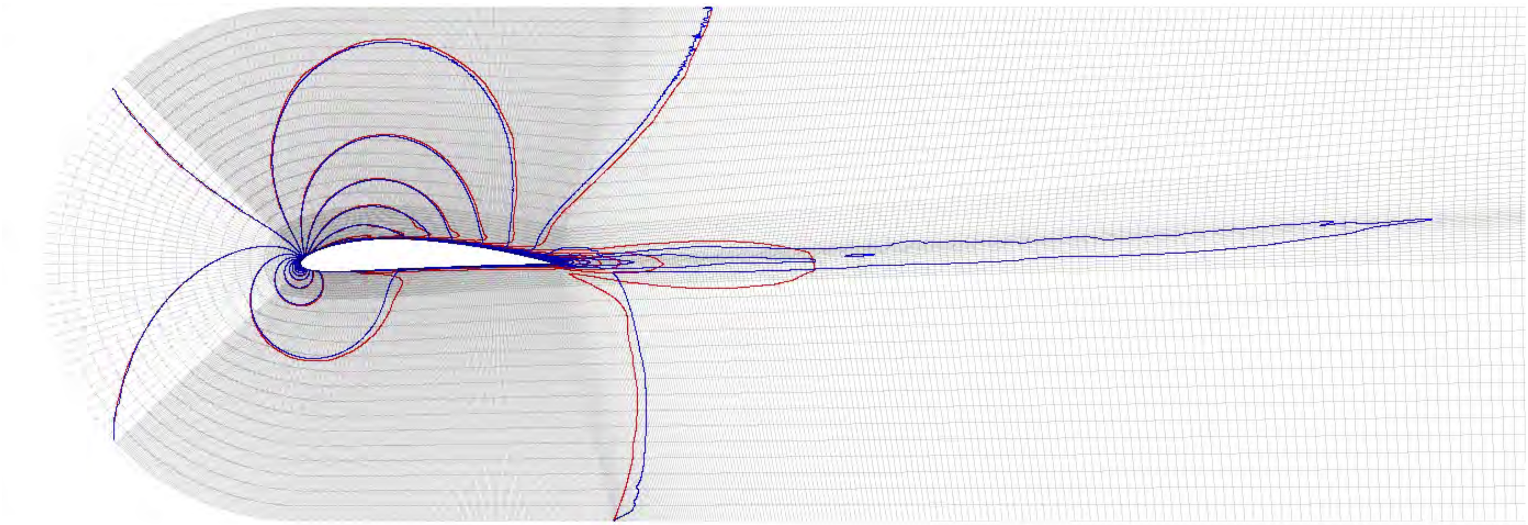
➔ **$N \sim 10^{11}$ is minimum number of points to scale to $P = 10^{8}$ (1 exa)**

- We must have large problem size for efficient usage of exa-scale, possible for higher Reynolds numbers

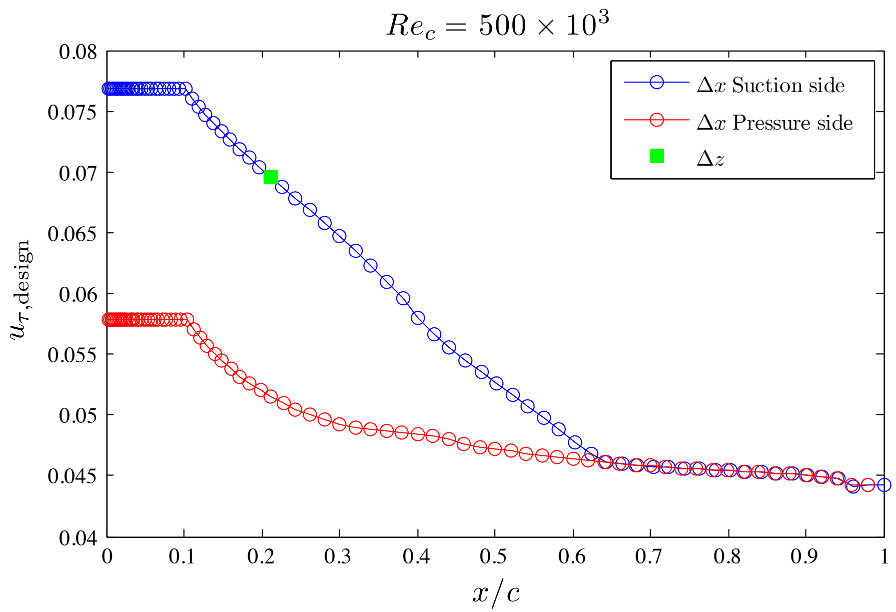
- More work per grid point advantage
  - HOM (Higher Order Methods) such as SEM
  - Multi-physics (magneto-hydrodynamics, combustion, heat transfer)
  - Accelerators (GPU) require more points per processor

Test case NACA 4412 Re = 500.000

Resolution and CPU requirements

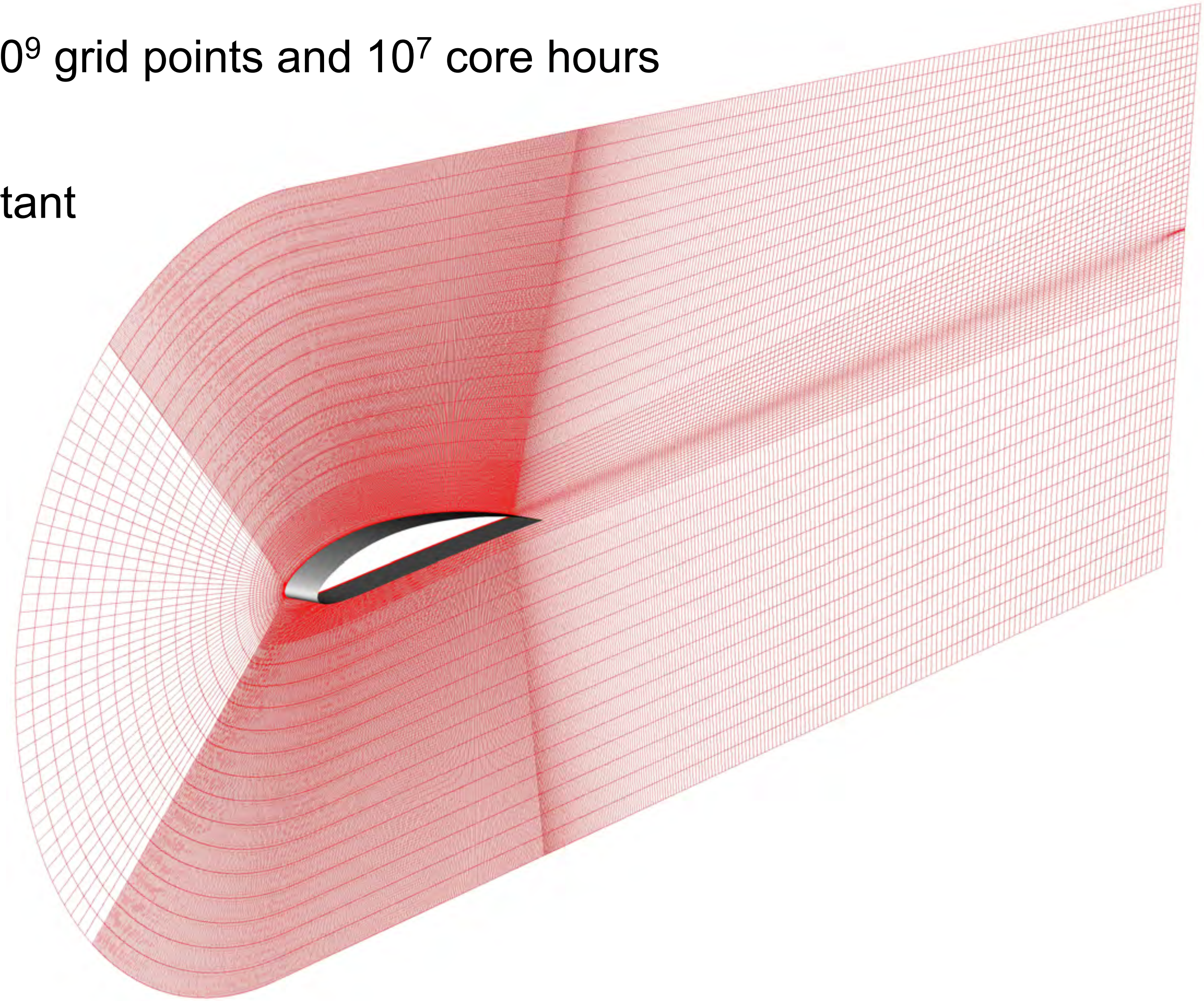


- RANS simulations used for external BC
  - o Possible to make grid smaller: embedded DNS
- RANS simulations give resolution estimates
  - o u_τ variation on wing surface

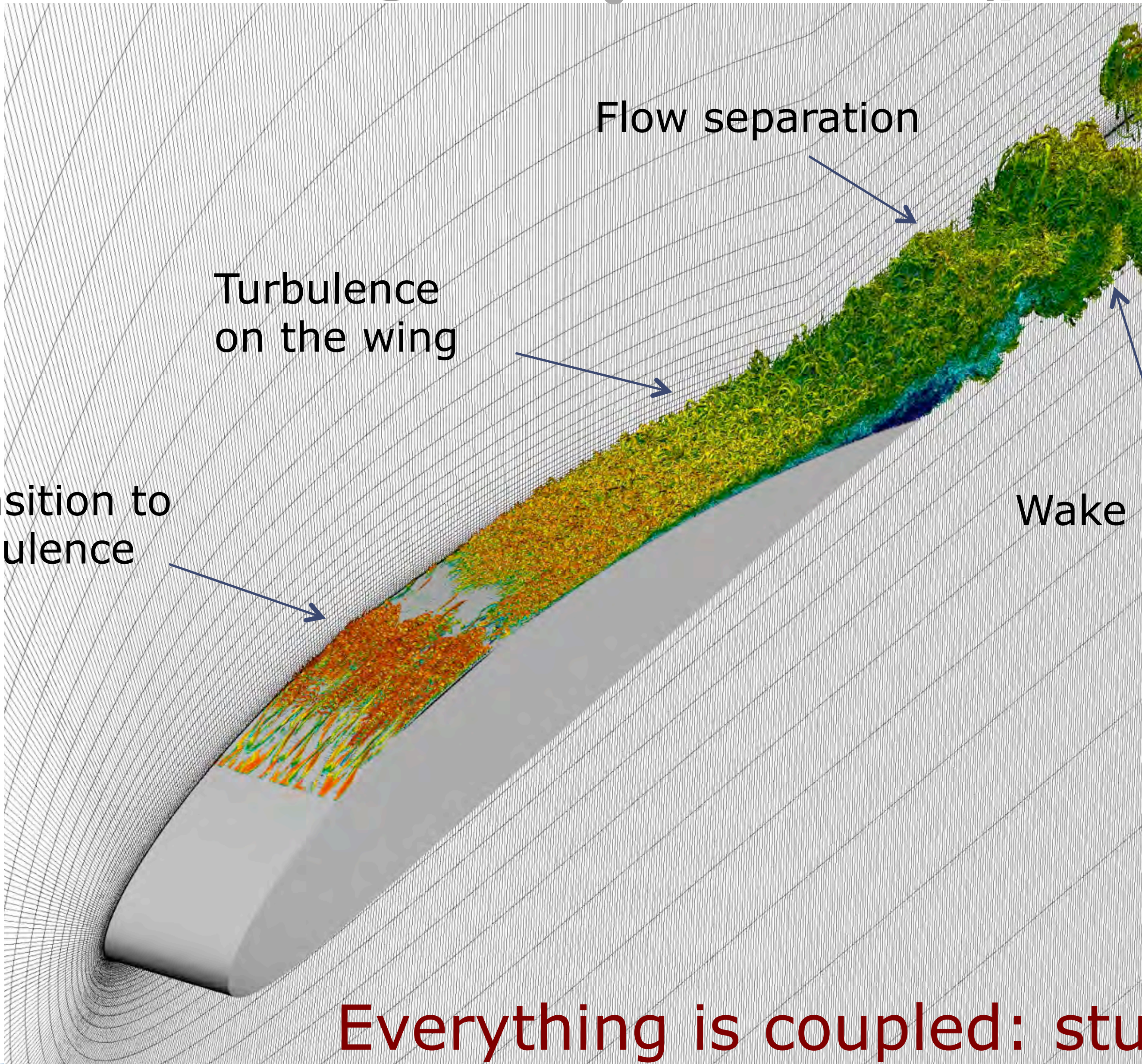


Resolution and CPU requirements

- Re_c= 500.000 requires $5x10^9$ grid points and 10^7 core hours
- 1 month on 10^4 cores
- Quality of mesh very important
  - aspect ratio influences pressure iterations



Direct numerical simulation of flow over a full NACA4412 wing at Re_c = 500.000 (preliminary cal.)



Everything is coupled: study interaction

LINNÉ FLOW CENTRE

Numerical wind tunnel: simulations of typical university wind tunnel experiments

Laminar Flow Control Experiment:
Re = 1*15/1.5*10^{-5} = 1x10^{6}

Turbulent boundary layer:
Re = 5*30/1.5*10^{-5} = 10x10^{6}

- DNS of wind tunnel experiment with Re = 1x10^{6}
  - 20 billion (2x10^{10}) grid points
  - 0.1 billion (10^{8}) core hours
  - 10 months on 10^{4} cores (0.1 peta)
- Exa-scale possibilities
  - 10^{11} grid point scale to 10^{8} cores (1 exa)
  - Re few million in one day

Conclusions

- DNS data Re_θ=4300 dataset from KTH extensively analyzed, no dominance of hairpin structure at high Reynolds numbers
- High-order DNS of surface-mounted square cylinder with laminar and turbulent inflow conditions show massively separated flow with distinct shedding at St = 0.10, in agreement with experiments.
- Simulations suggest the experimental conditions were closer to our laminar inflow simulation, possibly due to insufficient tripping and development length.
- Essential to fully match experimental conditions to perform high-accuracy comparisons.
- Possibilities with substantially larger simulations with coming exascale computers, Nek5000 good candidate for such calculations.
- Numerical wind tunnel, simulations can be performed of typical university wind tunnel experiments with exa-flop capabilities in 5-10 years.