Numerical experiments of turbulent flows on supercomputers

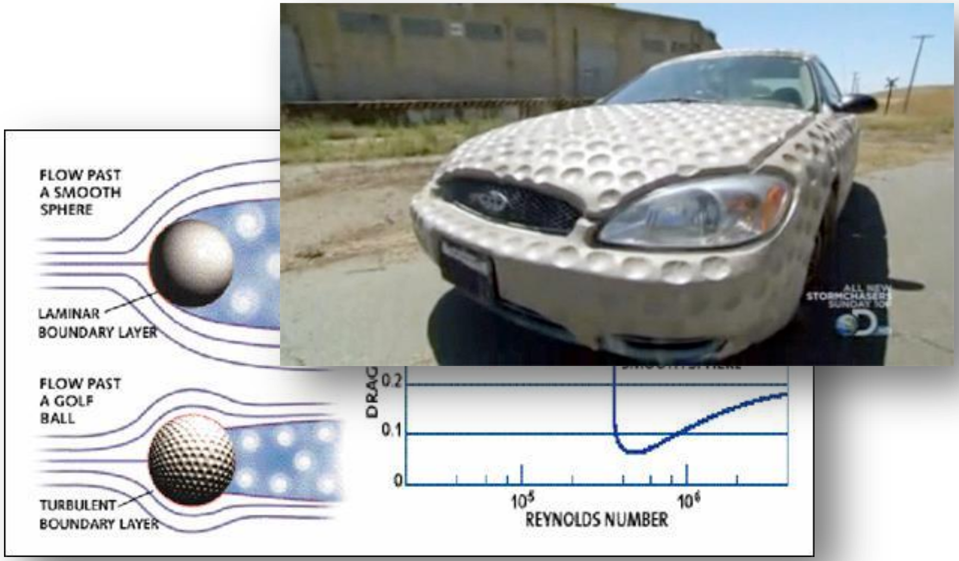
Philipp Schlatter & Dan Henningson

Linné FLOW Centre – KTH Mechanics

Collaborators: Paul Fischer, Johan Malm

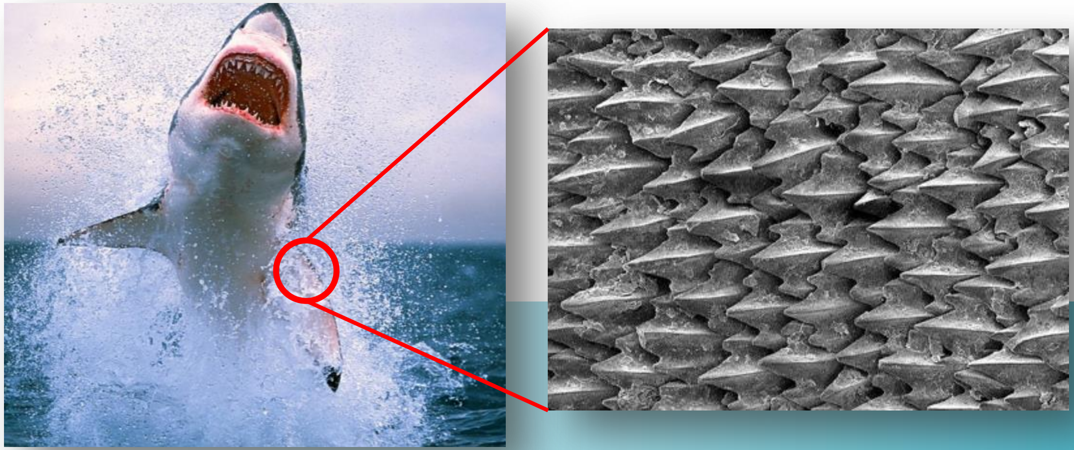
Why care about turbulence...

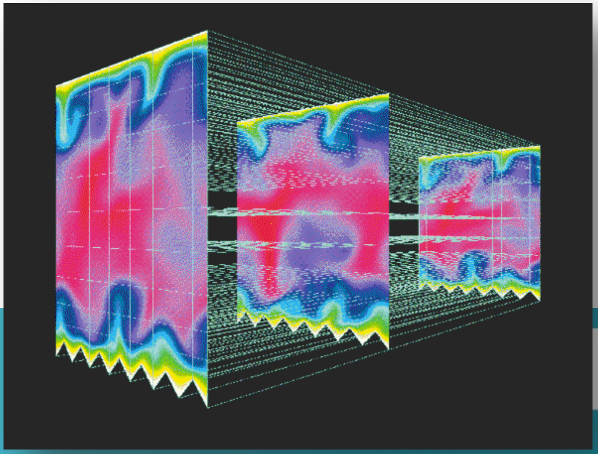
- Playing golf...



- Shark skin (riblets)...

10% drag reduction!



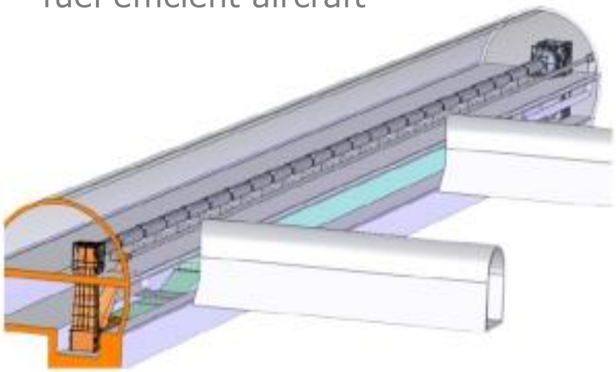


Why care about turbulence...

- Suppressing turbulence on the wings (laminar flow control) to improve fuel efficiency
- Better turbulence models on wing surfaces helps engineering design
- **Airplane**: 15% reduction of fuel consumption if the flow was laminar
- **Large experimental interest**:
  - **CICLoPE project** (autumn 2013)
  - **ICET** (Int. Collab. Exp. Turb.) with KTH, IIT, Melbourne, Princeton

$$$$

EU NACRE project: Concept for quiet, light fuel efficient aircraft

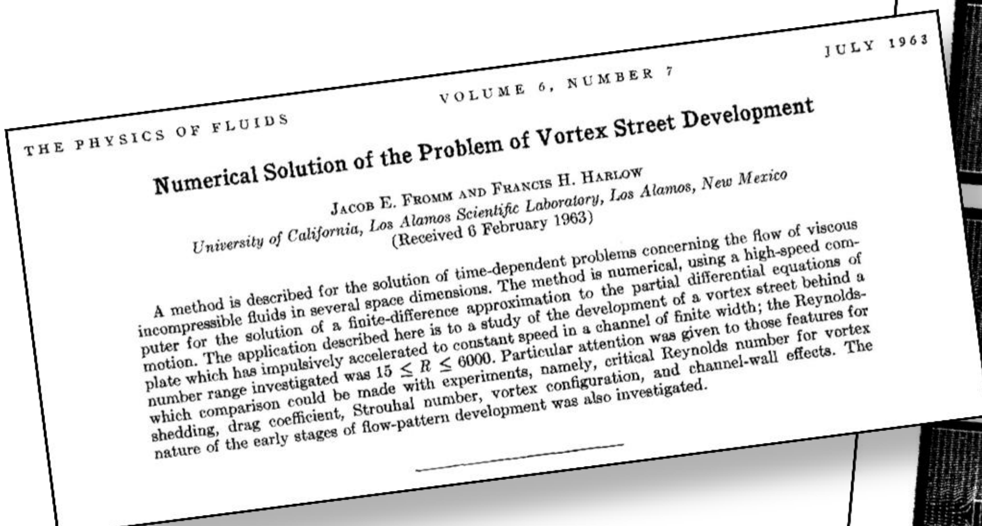


130m long pipe facility near Bologna, Italy

SeRC Swedish e-Science Research Centre

Brief History (1/4): - 1960's

- "First simulations" (NWP) by Lewis Fry Richardson 1920: Eight hours weather prediction in 6 weeks, using **2000 "human" computers**
- Low-*Re* cylinder wakes by Thom (1933), Kawaguti (1953) and Fromm & Harlow (1963), Los Alomos



THE PHYSICS OF FLUIDS VOLUME 6, NUMBER 7 JULY 1963

Numerical Solution of the Problem of Vortex Street Development

JACOB E. FROMM AND FRANCIS H. HARLOW
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
(Received 6 February 1963)

A method is described for the solution of time-dependent problems concerning the flow of viscous incompressible fluids in several space dimensions. The method is numerical, using a high-speed computer for the solution of a finite-difference approximation to the partial differential equations of motion. The application described here is to a study of the development of a vortex street behind a plate which has impulsively accelerated to constant speed in a channel of finite width; the Reynolds-number range investigated was $15 \leq R \leq 6000$. Particular attention was given to those features for which comparison could be made with experiments, namely, critical Reynolds number for vortex shedding, drag coefficient, Strouhal number, vortex configuration, and channel-wall effects. The nature of the early stages of flow-pattern development was also investigated.

1440 grid points!

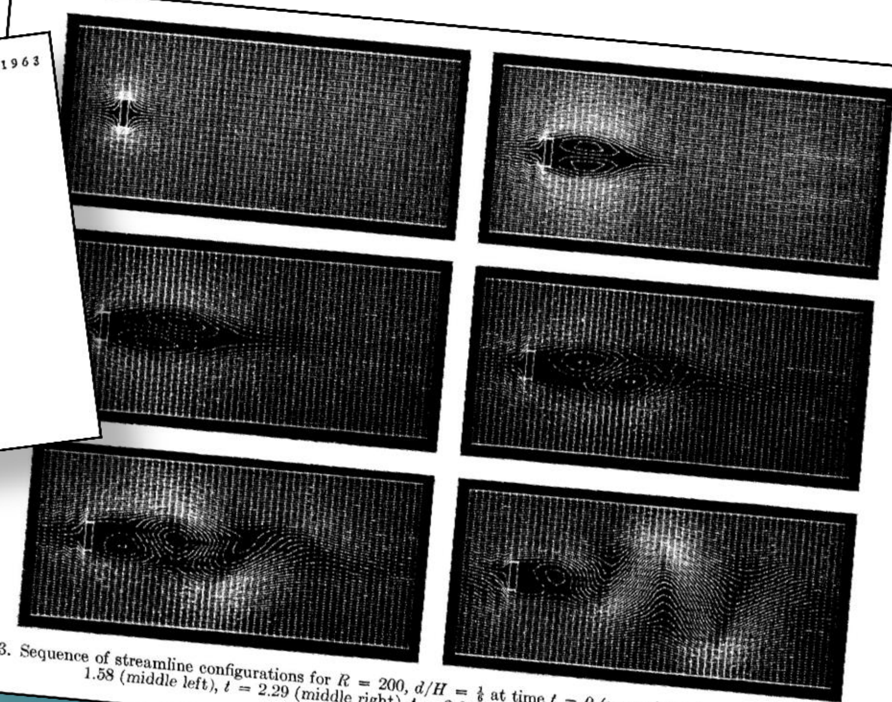
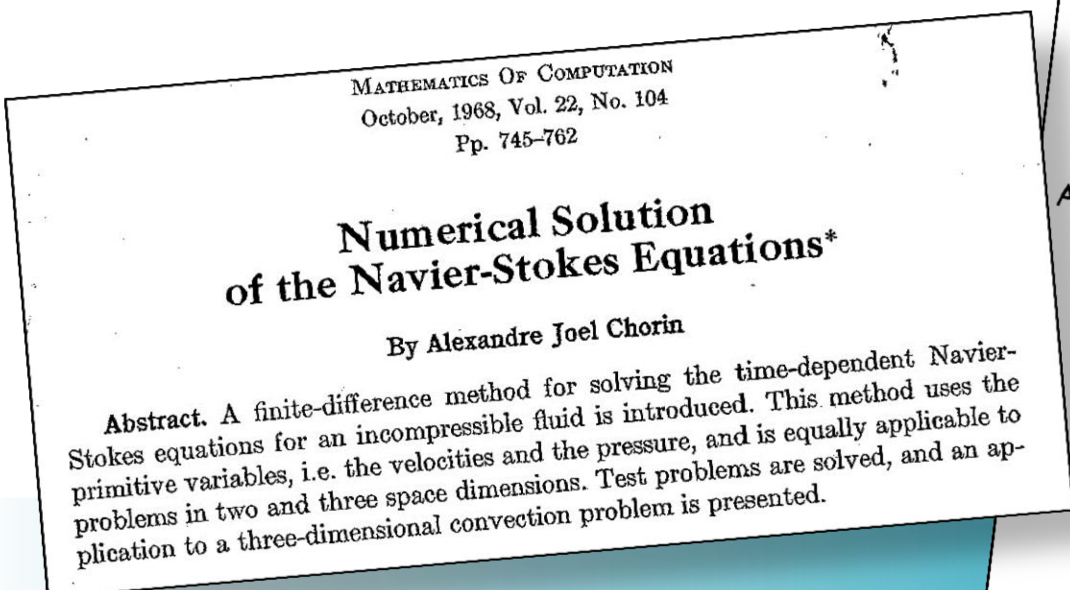


FIG. 3. Sequence of streamline configurations for $R = 200$, $d/H = \frac{1}{8}$ at time $t = 0$ (upper left), $t = 0.70$ (upper right), $t = 1.58$ (middle left), $t = 2.29$ (middle right), $t = 2.64$ (lower left), and $t = 3.16$ (lower right).

Brief History (2/4): 1960's

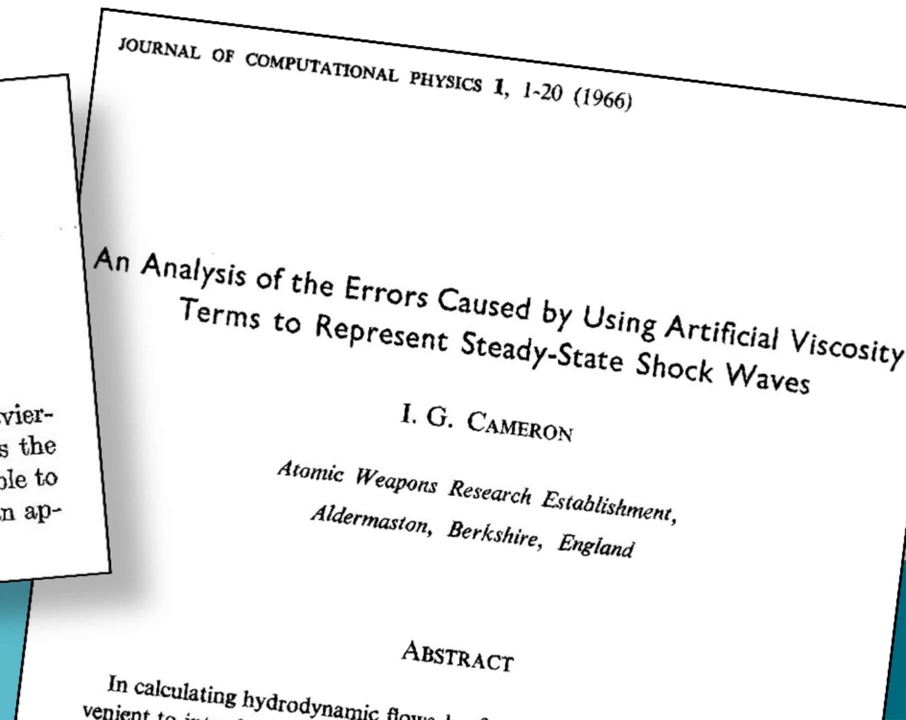
- 1965: **MAC** (Marker&Cell) method (Harlow&Welch): staggered grid
- 1966: Journal of Computational Physics founded
- 1968/1969: **Numerical methods for NS with pressure projection**: Chorin and Temam.


MATHEMATICS OF COMPUTATION
October, 1968, Vol. 22, No. 104
Pp. 745–762

Numerical Solution of the Navier-Stokes Equations*

By Alexandre Joel Chorin

Abstract. A finite-difference method for solving the time-dependent Navier-Stokes equations for an incompressible fluid is introduced. This method uses the primitive variables, i.e. the velocities and the pressure, and is equally applicable to problems in two and three space dimensions. Test problems are solved, and an application to a three-dimensional convection problem is presented.


JOURNAL OF COMPUTATIONAL PHYSICS 1, 1-20 (1966)

An Analysis of the Errors Caused by Using Artificial Viscosity Terms to Represent Steady-State Shock Waves

I. G. CAMERON

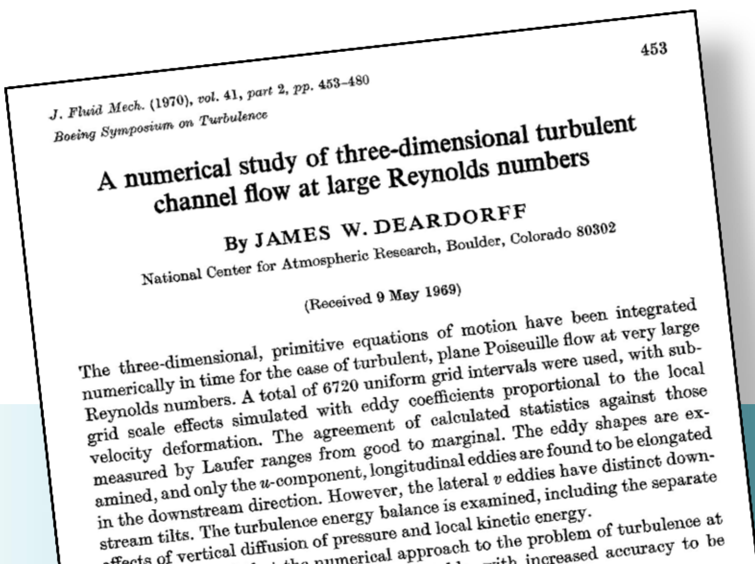
Atomic Weapons Research Establishment, Aldermaston, Berkshire, England

ABSTRACT

In calculating hydrodynamic flows ...

Brief History (3/4): 1970's

- 1970: first channel-flow **large-eddy simulation**: Deardorff (6720 grid points), based on Smagorinsky model (1963)
- 1972: *k*-ε **turbulence model** (RANS): Spalding & Launder
- 1972: SIMPLE (semi-implicit method for pressure-linked equations): Patankar & Spalding
- 1973: The abbrevation **CFD** (**Computational Fluid Dynamics**, not "Colours for Directors"...) is coined


453

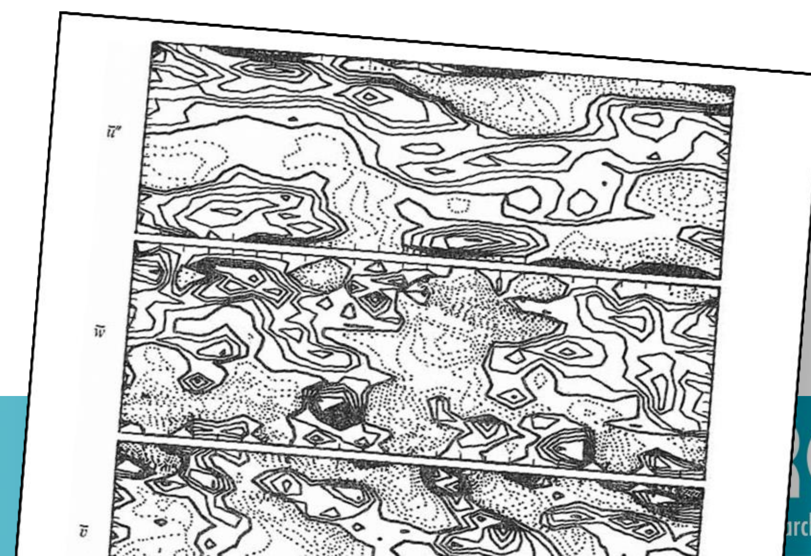
J. Fluid Mech. (1970), vol. 41, part 2, pp. 453–480
Boeing Symposium on Turbulence

A numerical study of three-dimensional turbulent channel flow at large Reynolds numbers

By JAMES W. DEARDORFF
National Center for Atmospheric Research, Boulder, Colorado 80302

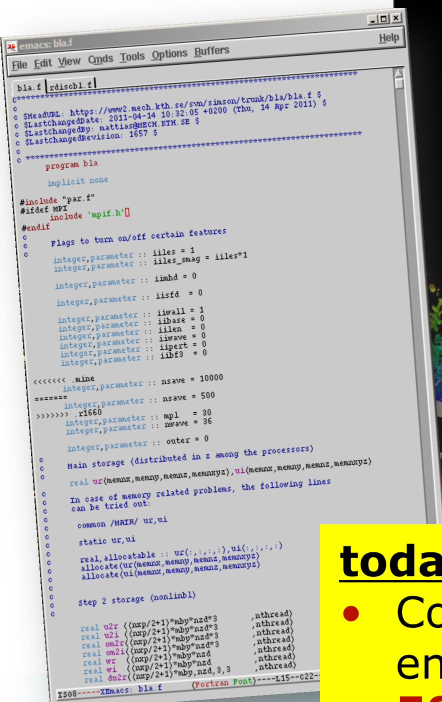
(Received 9 May 1969)

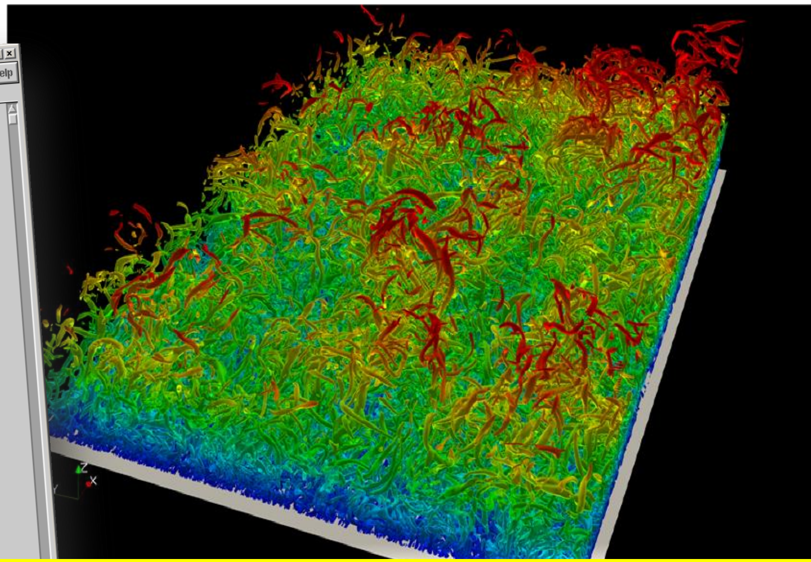
The three-dimensional, primitive equations of motion have been integrated numerically in time for the case of turbulent, plane Poiseuille flow at very large Reynolds numbers. A total of 6720 uniform grid intervals were used, with sub-grid scale effects simulated with eddy coefficients proportional to the local velocity deformation. The agreement of calculated statistics against those measured by Laufer ranges from good to marginal. The eddy shapes are examined, and only the *u*-component, longitudinal eddies are found to be elongated in the downstream direction. However, the lateral *v* eddies have distinct down-stream tilts. The turbulence energy balance is examined, including the separate effects of vertical diffusion of pressure and local kinetic energy.
... the numerical approach to the problem of turbulence at ... with increased accuracy to be

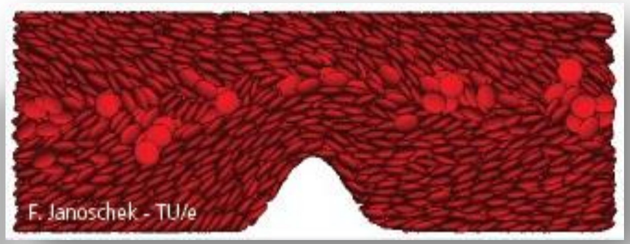


Brief History (4/4): 1980's -

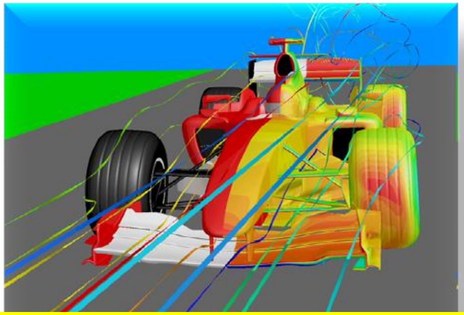
- 1980 - : CFD codes used in engineering (e.g. Fluent, ANSYS, *etc.*); first for aircrafts, then also automotive *etc.*
- 1987: **First fully resolved simulation (DNS) of channel flow (4·10^6 grid points):** Kim, Moin & Moser







TU Eindhoven

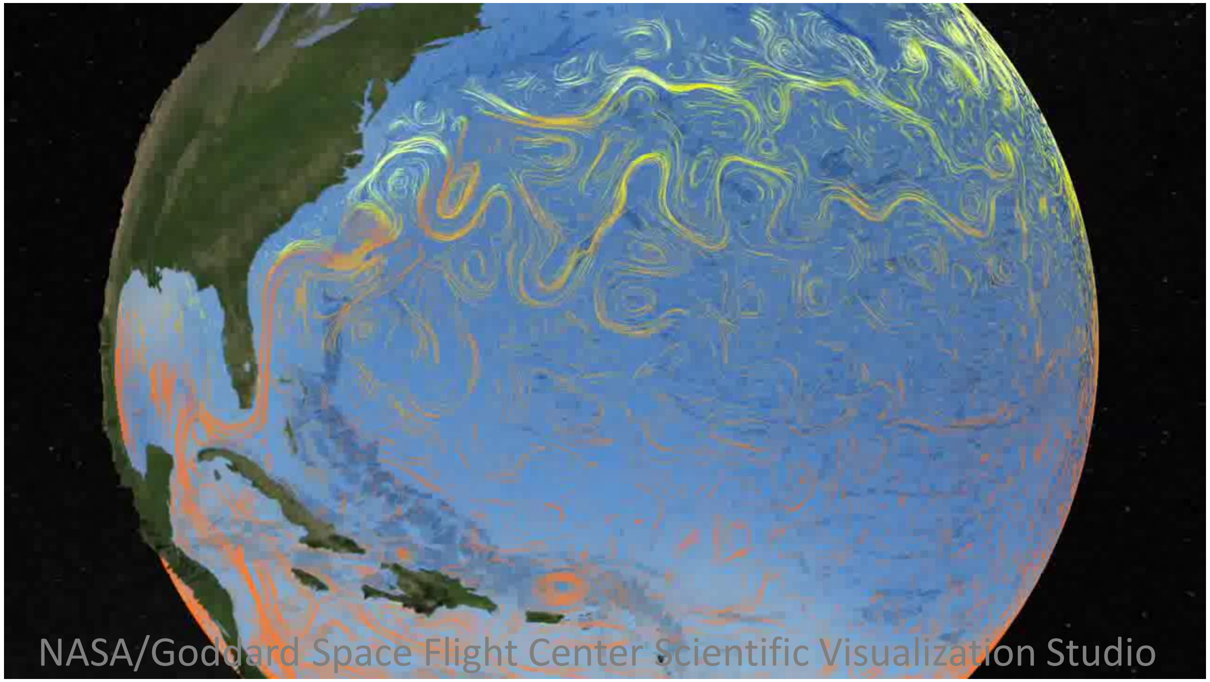


Fluent

today:
- Computational fluid dynamics is integral part of both engineering and research, calculations up to **50·10^9 grid points** and **1'000'000 cores** "easily" possible
- Data post processing! Storage! Visualisation!

Swedish e-Science Research Centre

The ocean and atmosphere are turbulent



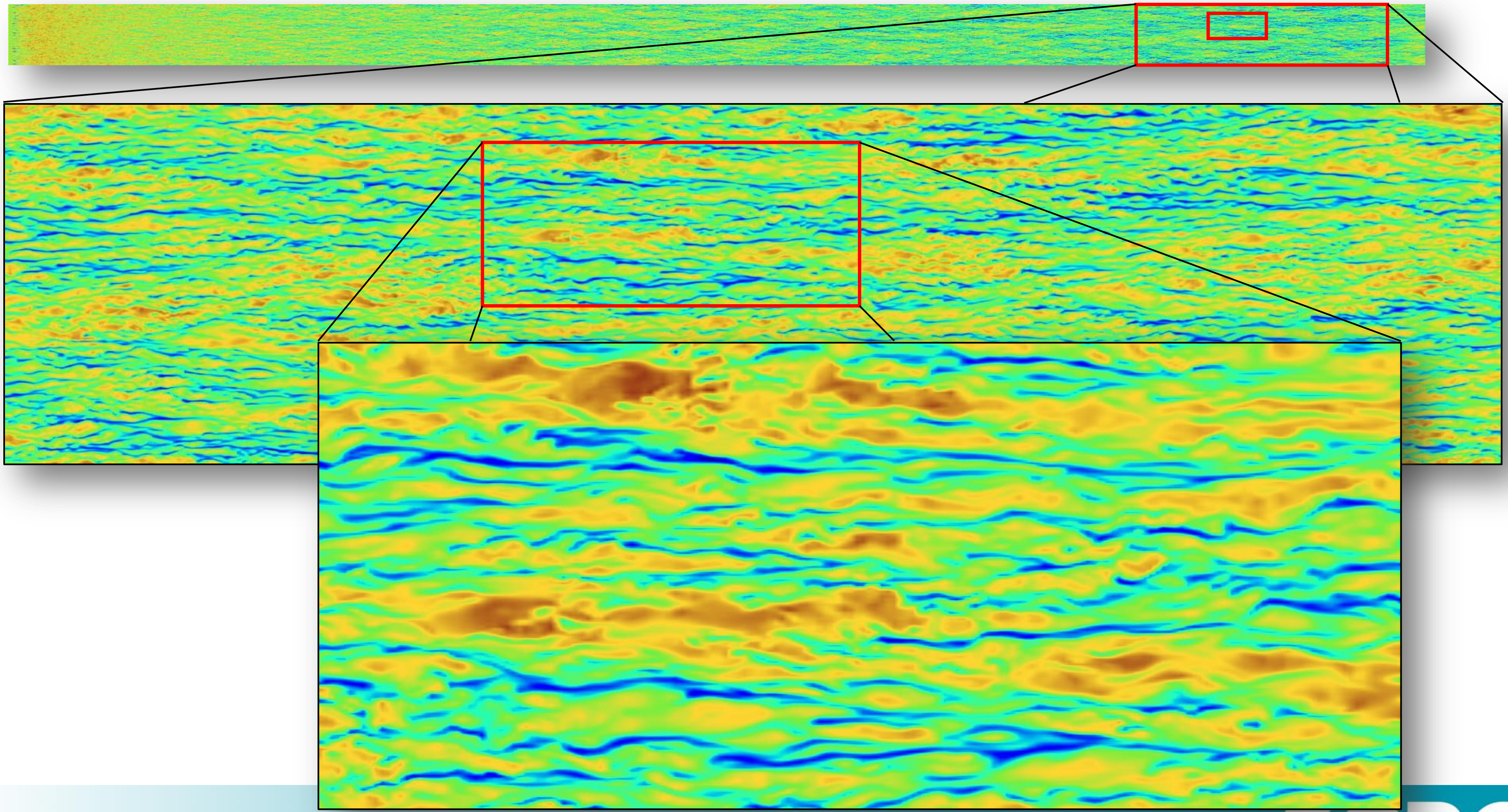
Global circulation very sensitive to turbulence properties

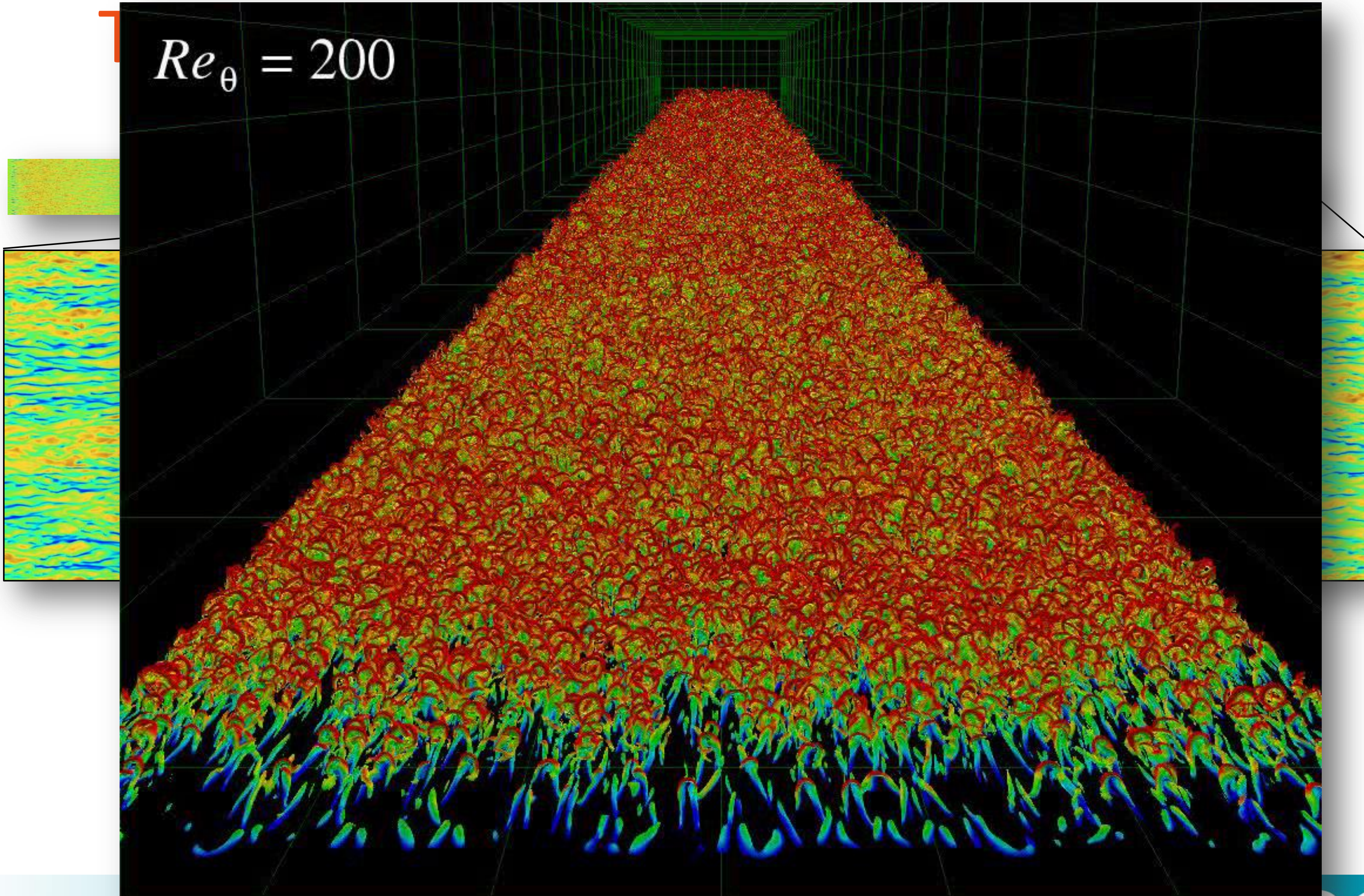
- Supercomputer simulations predict how turbulence properties influences heat transfer in oceans.
- Climate simulations need to parameterize effects of turbulence, down to centimetre scale!

Turbulent flow close to solid walls...

Turbulent flow close to solid walls...

simulation result





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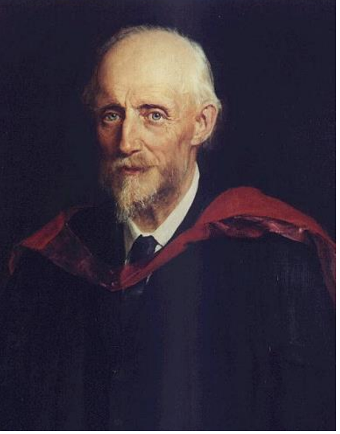


Osborne Reynolds
1842-1912

Governing Equations

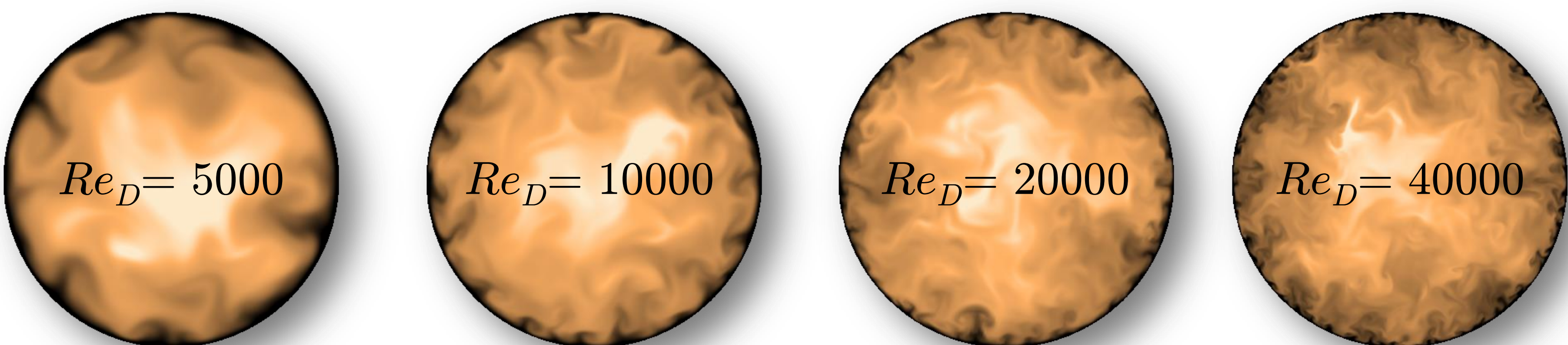
- Incompressible Navier-Stokes equation → conservation of momemtum

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \;=\; -\nabla p + \frac{1}{Re} \nabla^2 \mathbf{u}$$

- Continuity equation → conservation of mass

$$\nabla \cdot \mathbf{u} \;=\; 0$$

The Reynolds number Re is defined with $Re = \frac{UL}{\nu}$
velocity U, length L and viscosity



up to 2.5 billion grid points!

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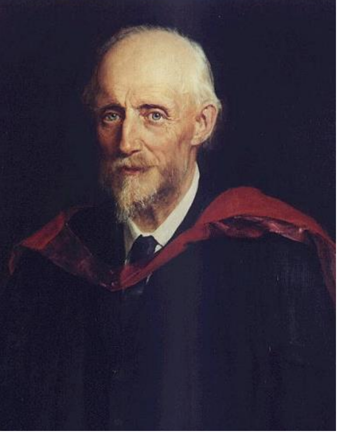
Governing Equations



Osborne Reynolds
1842-1912

- Incom … on of momemtum

$$\frac{\partial \mathbf{u}}{\partial t} + \ldots$$

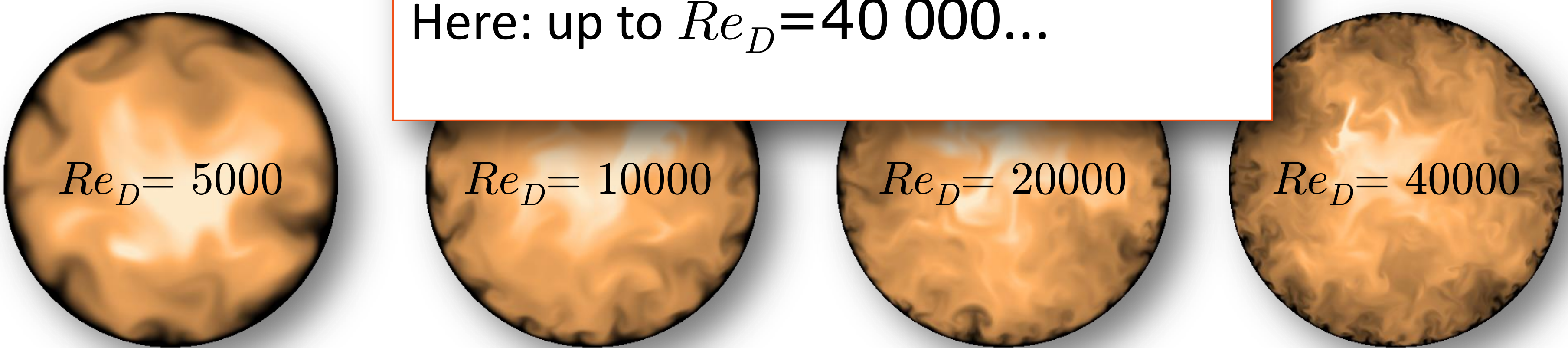
- Contin …

The Reyn …
velocity U …

Meaning of the **Reynolds number**:

Re_D	$<$ 2500	laminar
Re_D	= 1000	blood in veins
Re_D	= 3000	soda with a straw
Re_D	= 100 000	oil pipelines
Re_D	= 10^7	gas pipelines

Here: up to Re_D=40 000...



up to 2.5 billion grid points!

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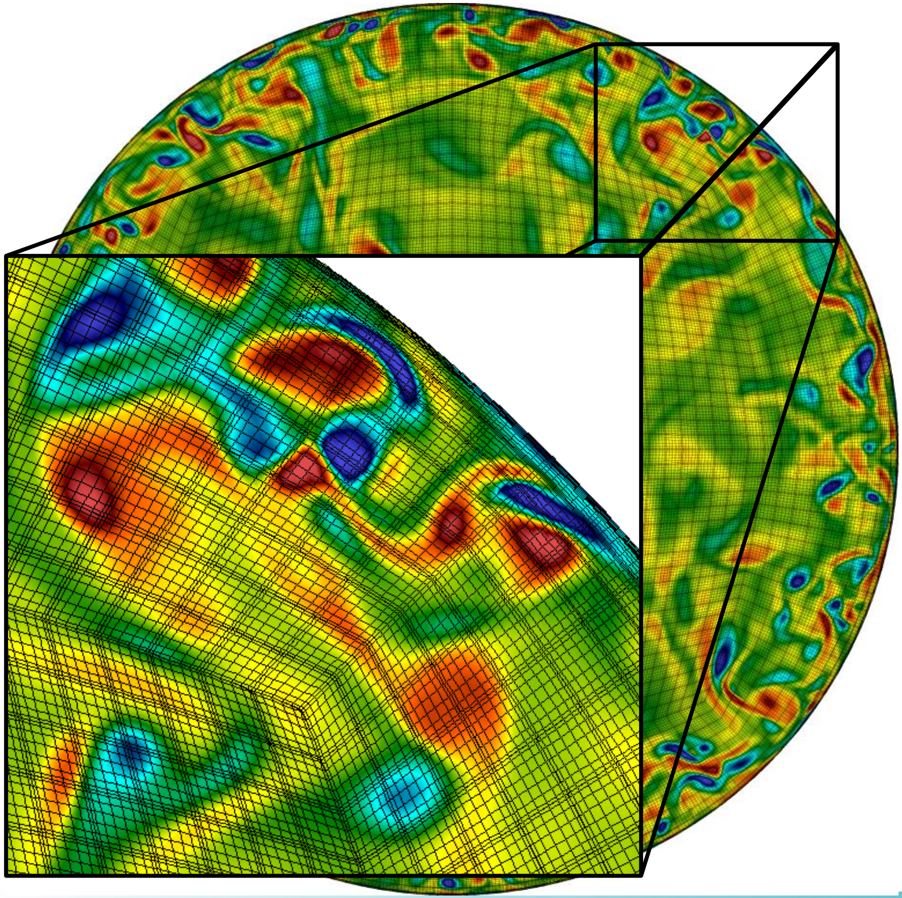
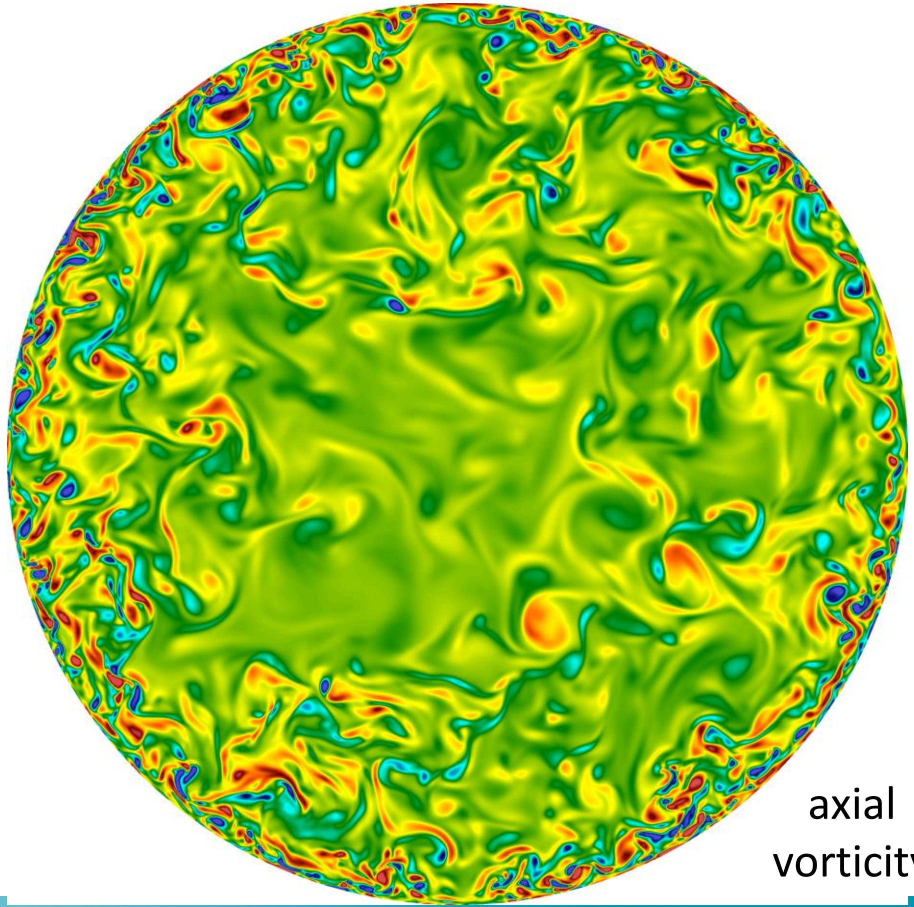
Direct Numerical Simulation – DNS → numerical experiment

$Re_\tau = 550$



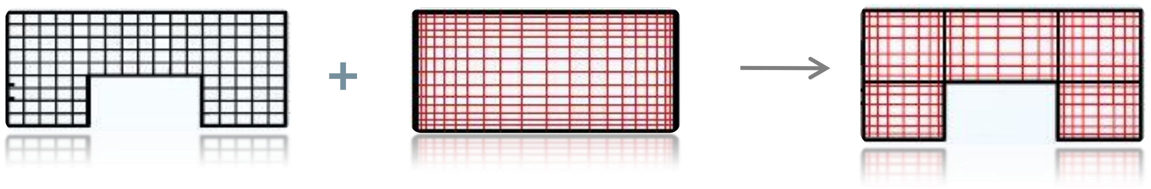
$Re_\tau = 1000$

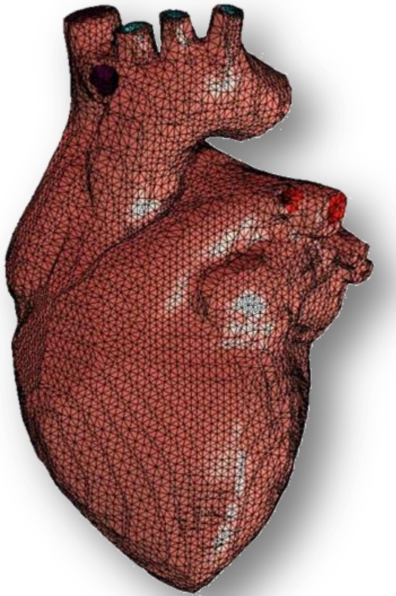


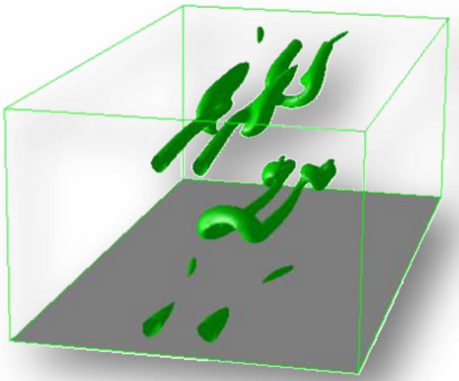
Very high resolution close to walls needed!

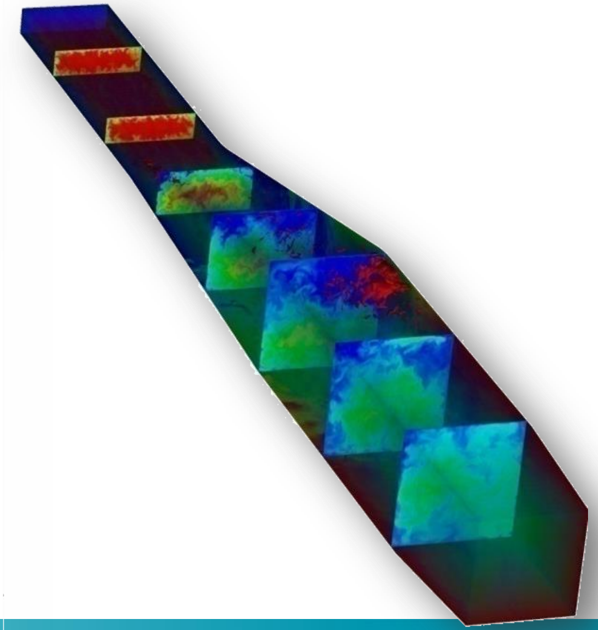
Discretisation methods
Order of the schemes

Finite element (FEM) Spectral Spectral element (SEM), Patera 1984









Typically low order "infinite" order Locally "infinite" order

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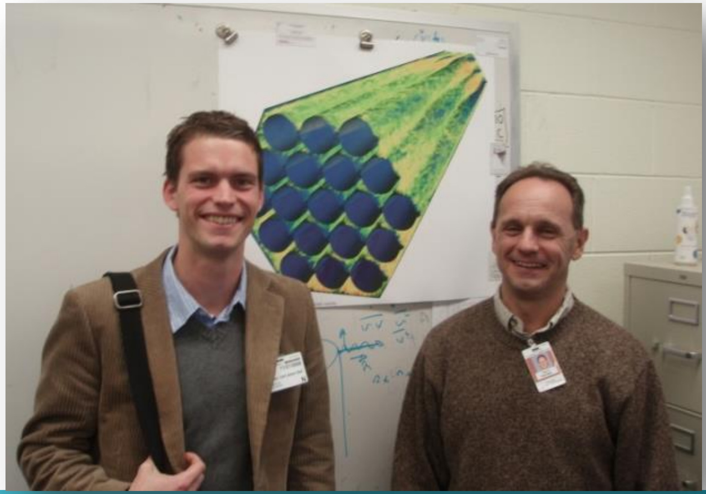
Infrastructure: Codes

- **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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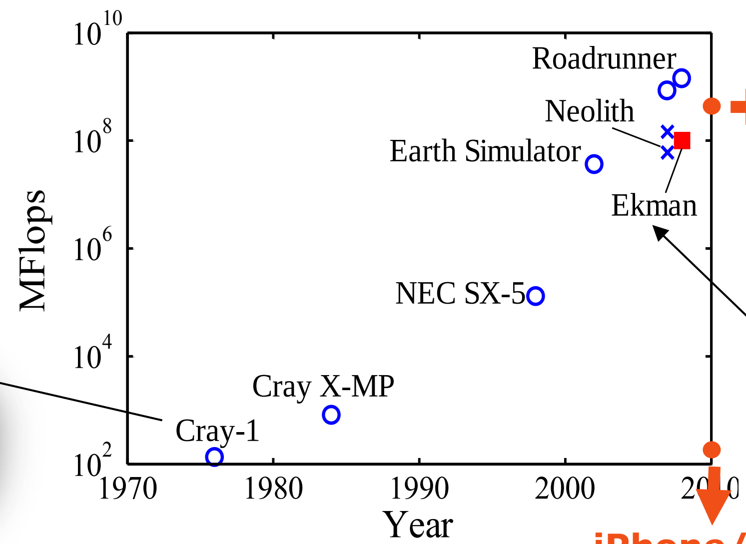
Main computational resources

- About 100 million core h/year last couple of years
  - Ekman: 43 milj core h/year (2008-2012)
  - Lindgren (PDC) 24 milj core h/year (2010-2014)
  - PRACE > 30 milj core h/year (2011-2012)
  - Triolith (NSC) 12 Milj core h/year (2013-2016)

Cray-1 (1976)
100 MFlops
1 core



Lindgren

Ekman (2008)
100 TFlops
10000 cores

iPhone/iPad

Main computational resources

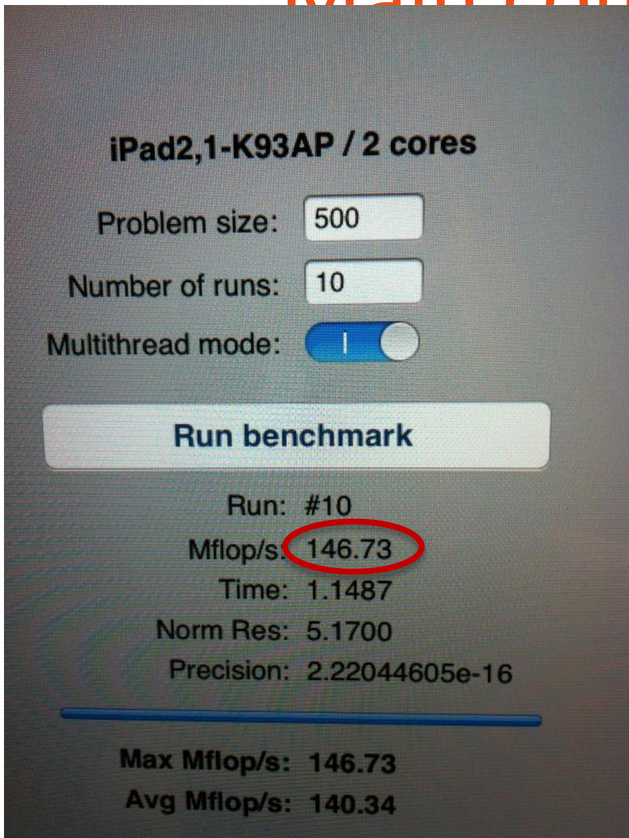
/year last couple of years

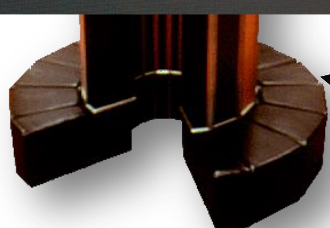
ar (2008-2012)

re h/year (2010-2014)

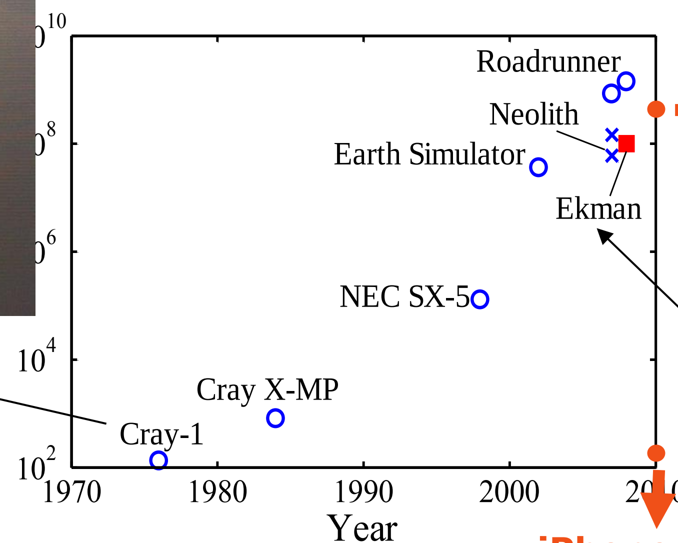
ar (2011-2012)

h/year (2013-2016)





Cray-1 (1976)
100 MFlops
1 core

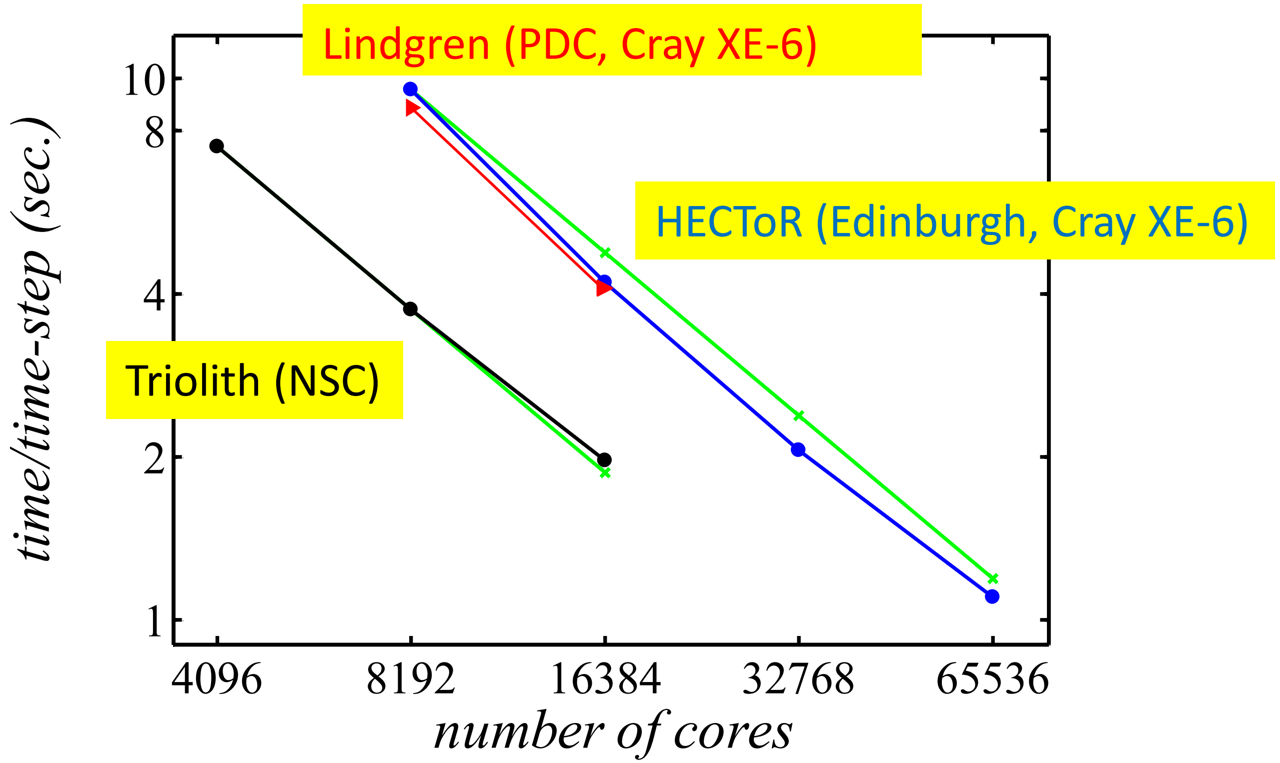


iPhone/iPad

Lindgren

Ekman (2008)
100 TFlops
10000 cores

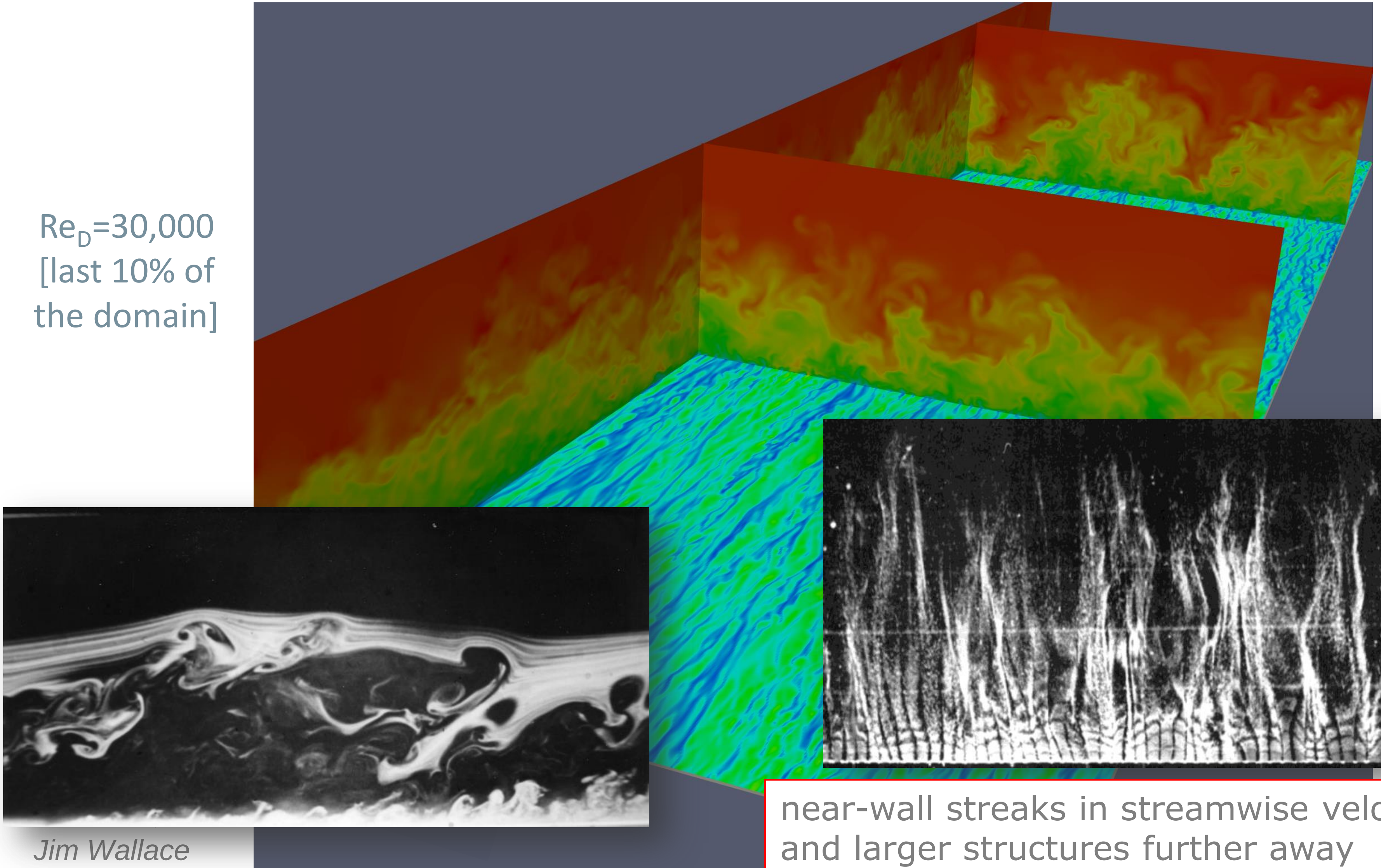
Scaling of Nek5000 on Cray and clusters



Strong scaling on production case
(turbulent pipe flow, 2 billion grid points)

What does turbulence look like?

Re_D=30,000
[last 10% of
the domain]

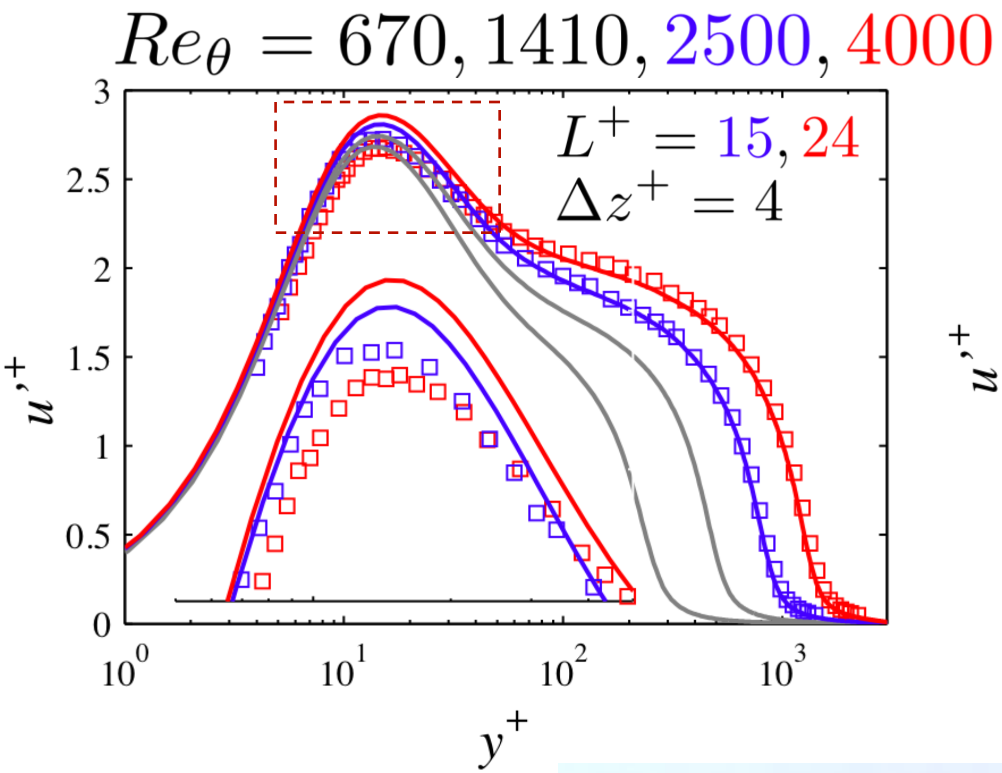


Jim Wallace

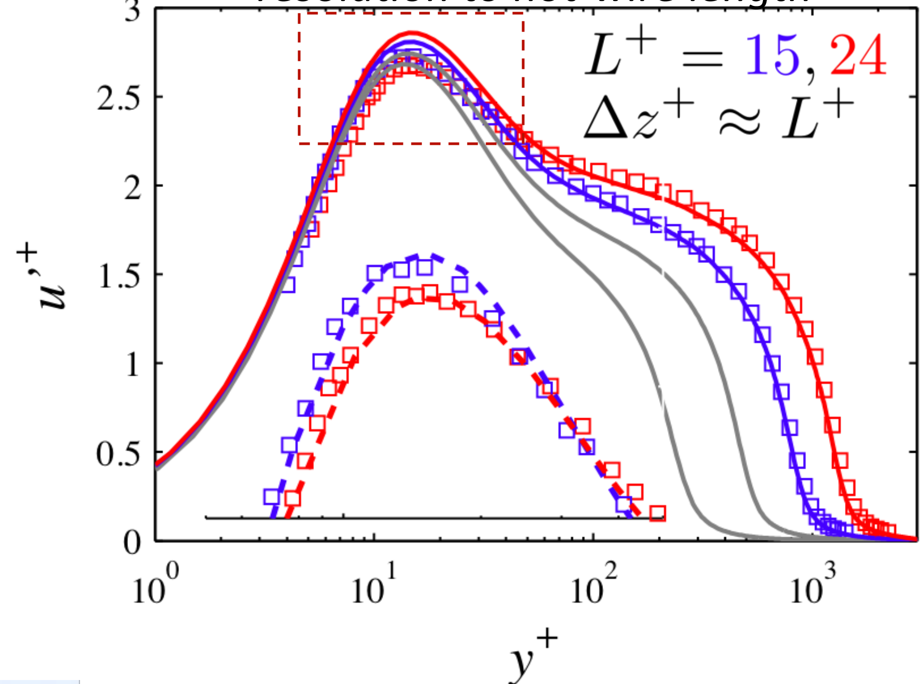
Kline et al. (1968)

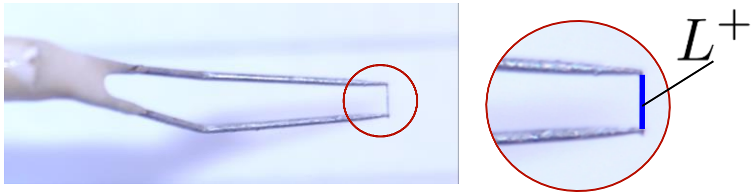
near-wall streaks in streamwise velocity
and larger structures further away

Turbulence intensity profiles (u_{rms})



--- *DNS with matched spatial resolution to hot-wire length*





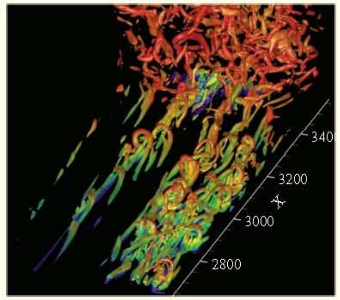
Schlatter & Örlü, Exp. Fluids, 2013

Swedish e-Science Research Centre

”Forest of hairpin vortices”

Journal of Fluid Mechanics
Focus on Fluids

Unravelling turbulence near walls



IVAN MARUSIC[1]

[1]Department of Mechanical Engineering,
University of Melbourne, Victoria, 3010, Australia

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)

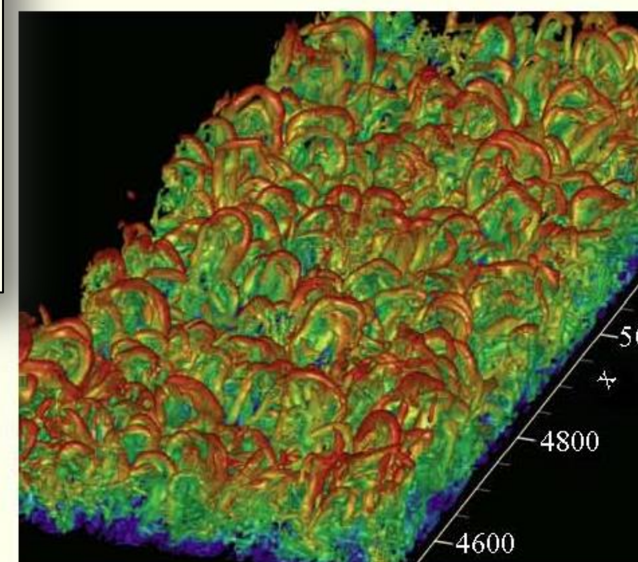
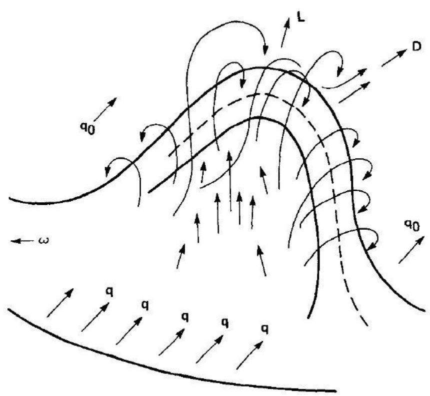


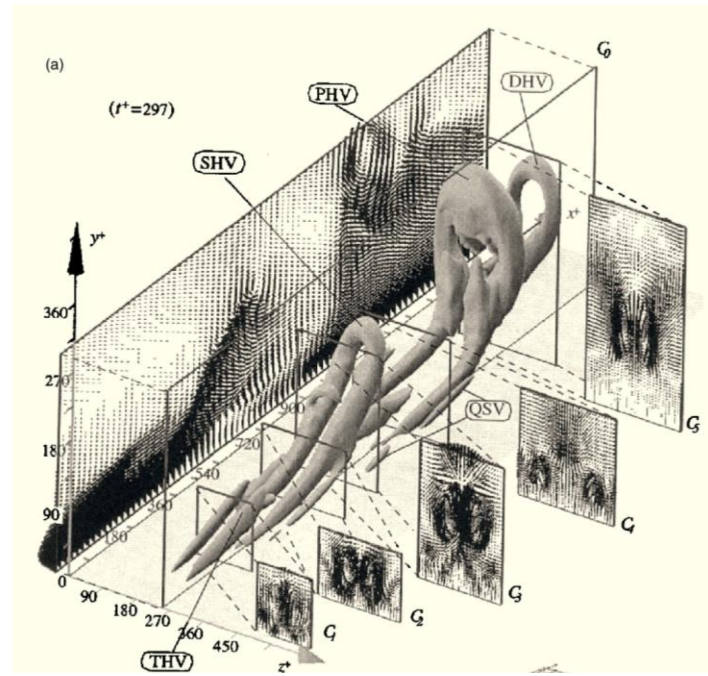
FIGURE 1. Instantaneous view of the coherent structures observed in the simulation of Wu & Moin in the fully turbulent region. The vivid appearance of hairpin-shaped structures is noted.

Hairpin Vortices

- What is a hairpin vortex…?

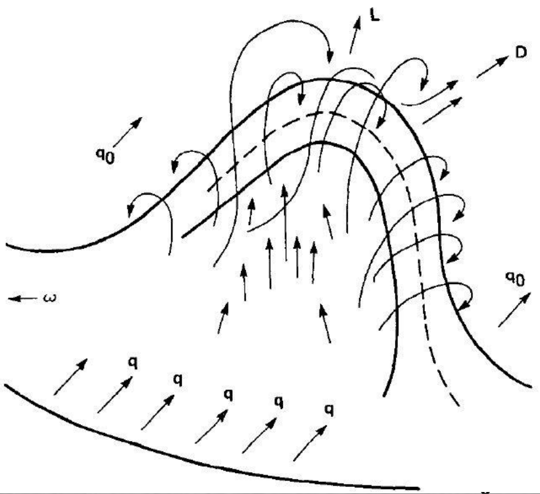


Theodorsen (1952)

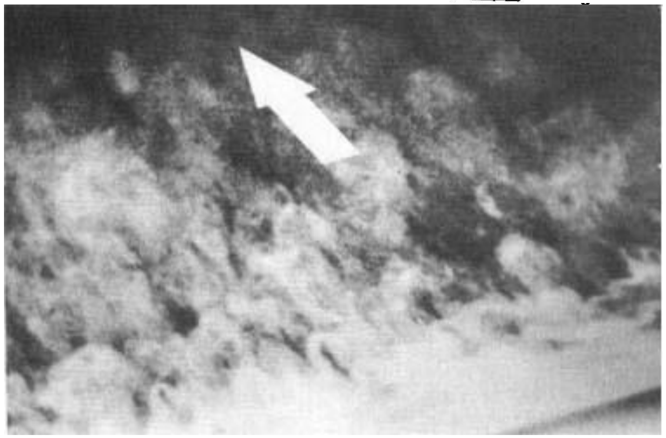


Adrian (*Phys. Fluids* 2007)
Zhou et al., JFM 1999

Hairpins *et al.*



- Theodorsen (1952):
  - Concept of `horseshoe vortex´:
  - *`The horseshoe represents the universal element of the structure of turbulent flow.´*

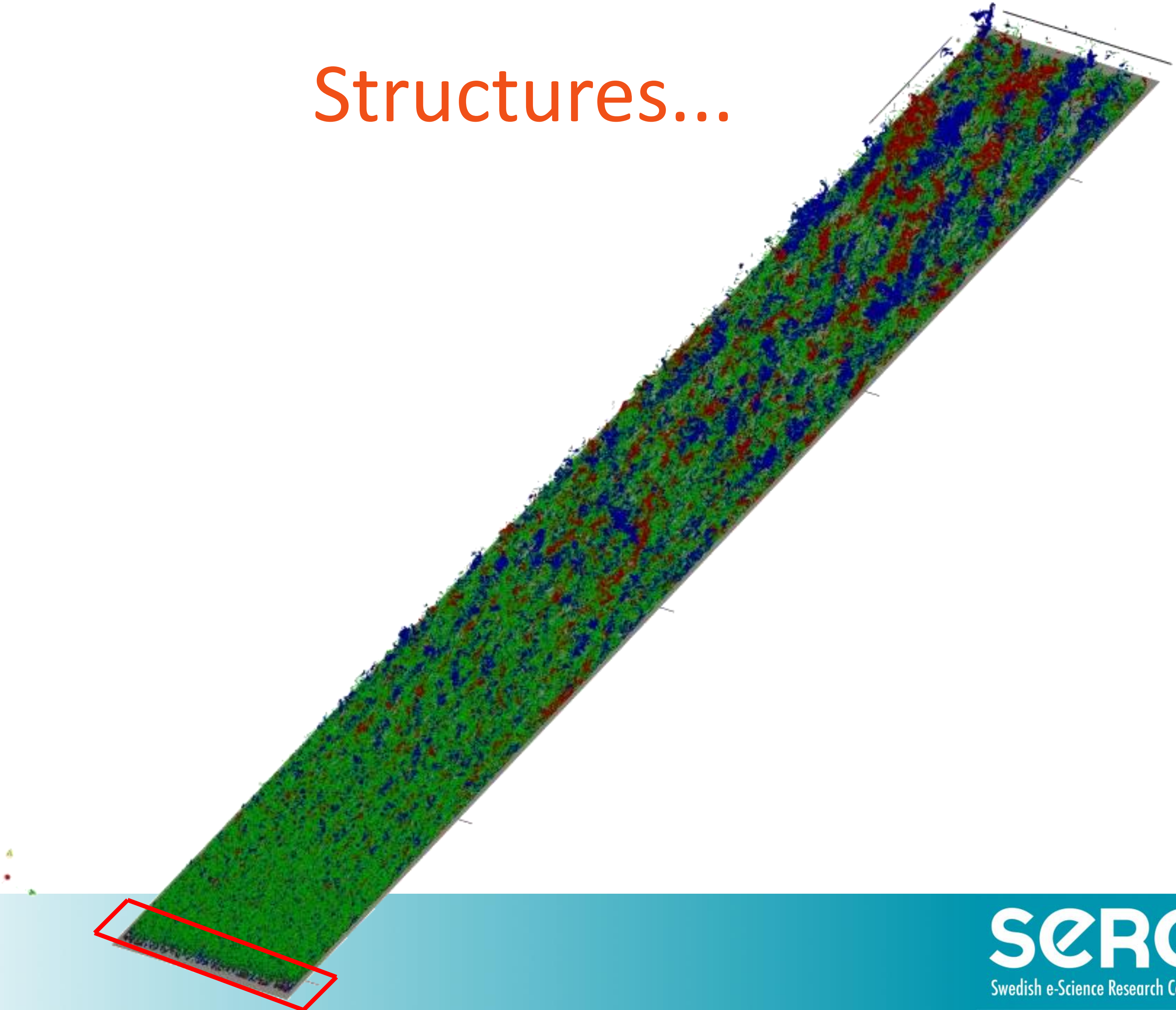


- Head & Bandyopadhyay (1981):
  - Experimental evidence:
  - *`hairpin vortices […] are a major constituent of the turbulent boundary layer at all Reynolds numbers´*

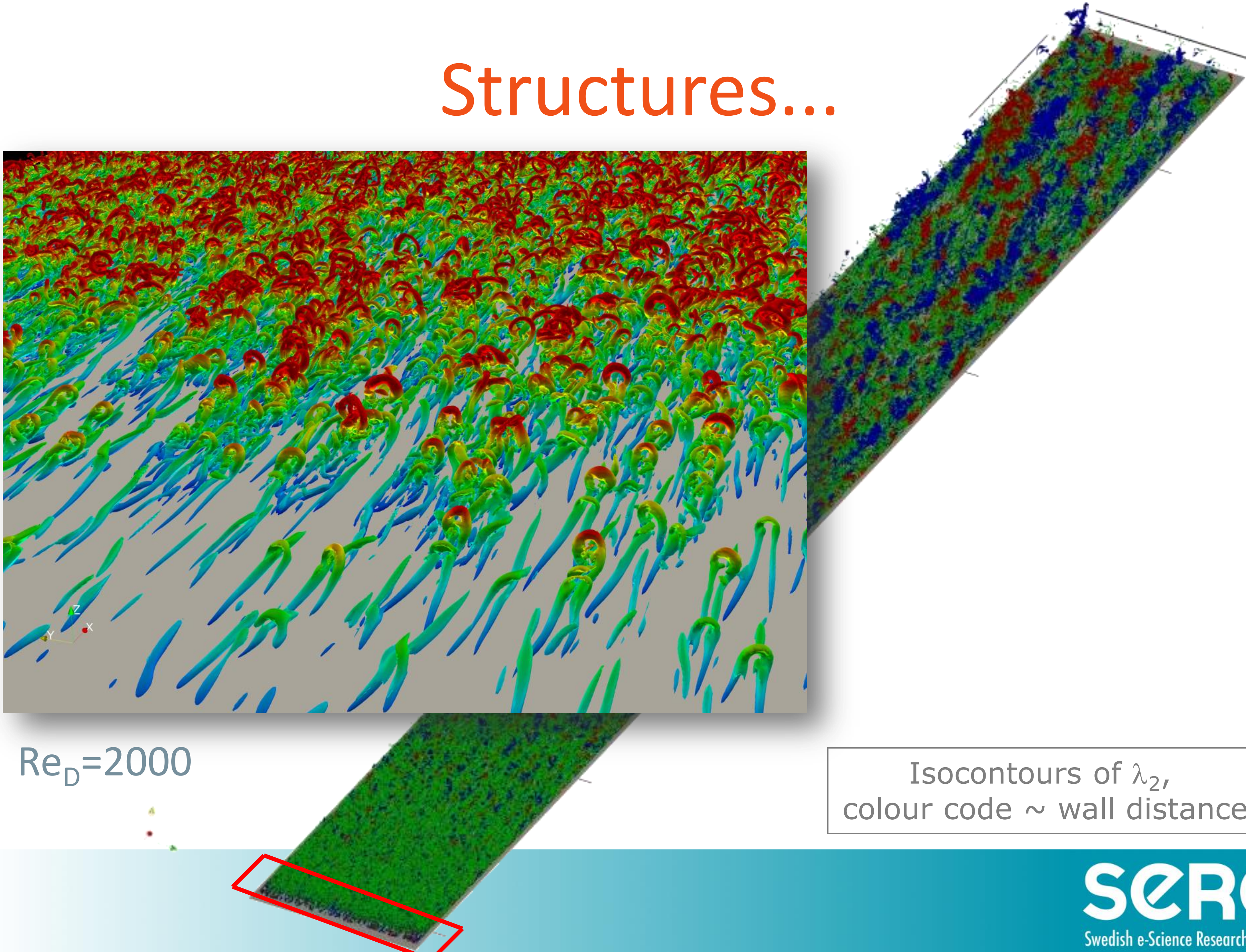
Adrian & Marusic (2012): *`the* ***strongest experimental support*** *for the existence of hairpin vortices´*

Wu & Moin (2009): `relatively ***large trips used in their tunnel*** *may lead one to speculate that hairpins were actually put in their flow, and did* ***not evolve naturally****´*

Structures...



Structures...



Re_D=2000

Isocontours of λ_2,
colour code ~ wall distance

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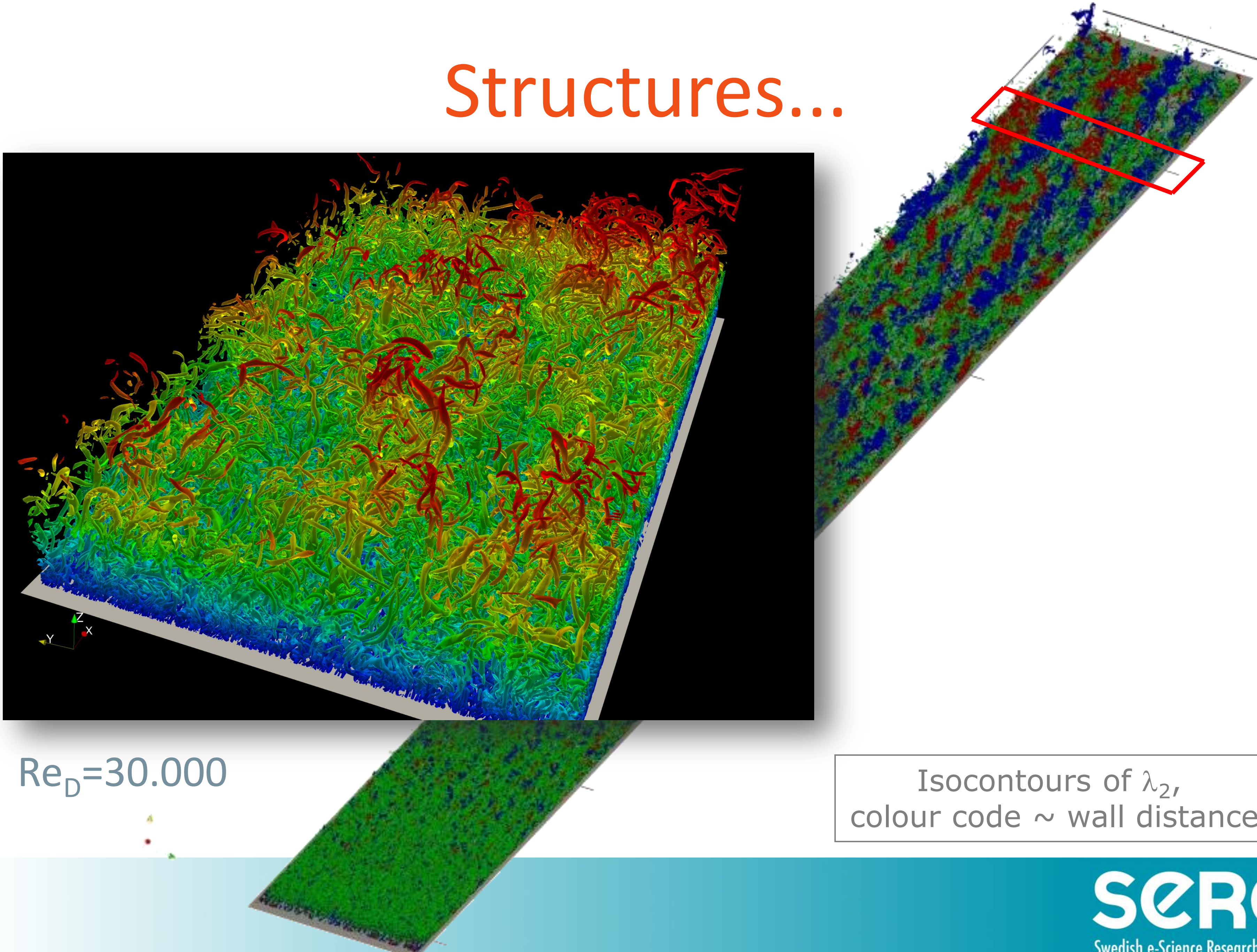
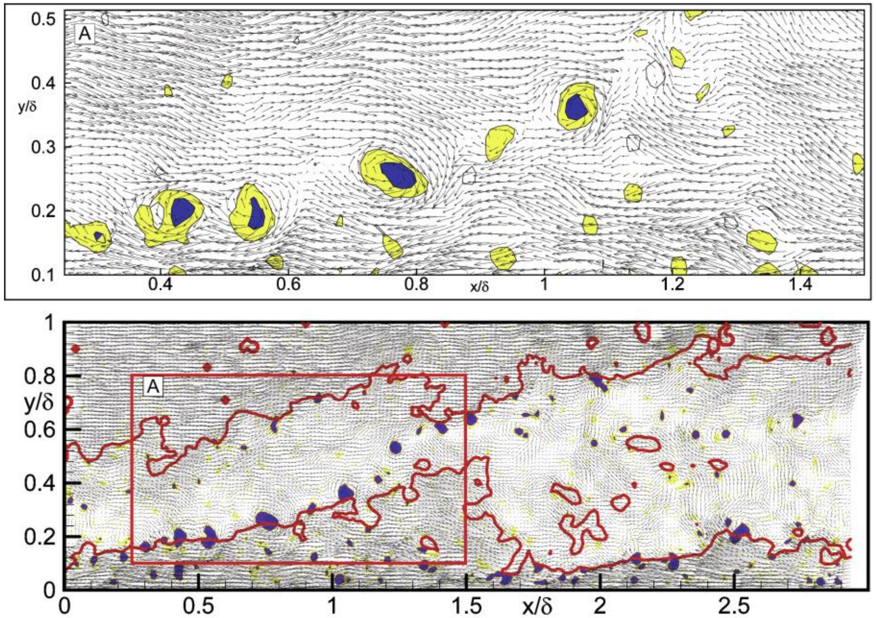
Structures...



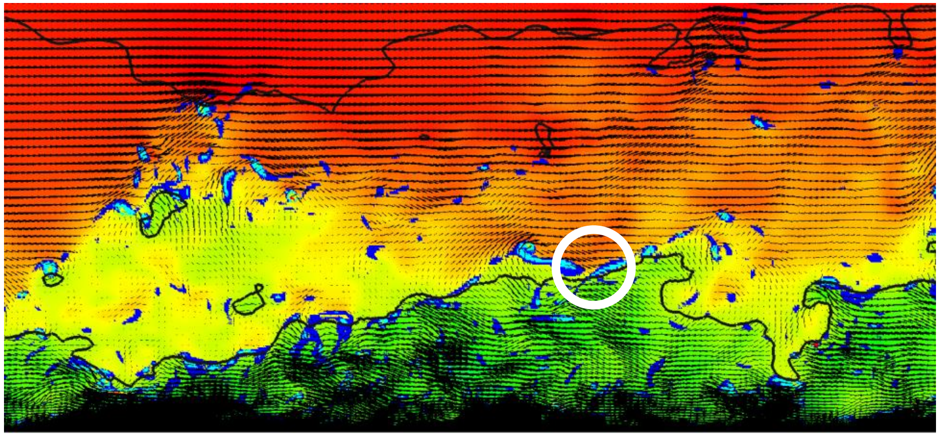
Re_D=30.000

Isocontours of λ_2,
colour code ~ wall distance

HVS – Hairpin Vortex Signatures



Adrian (2007): Experiments



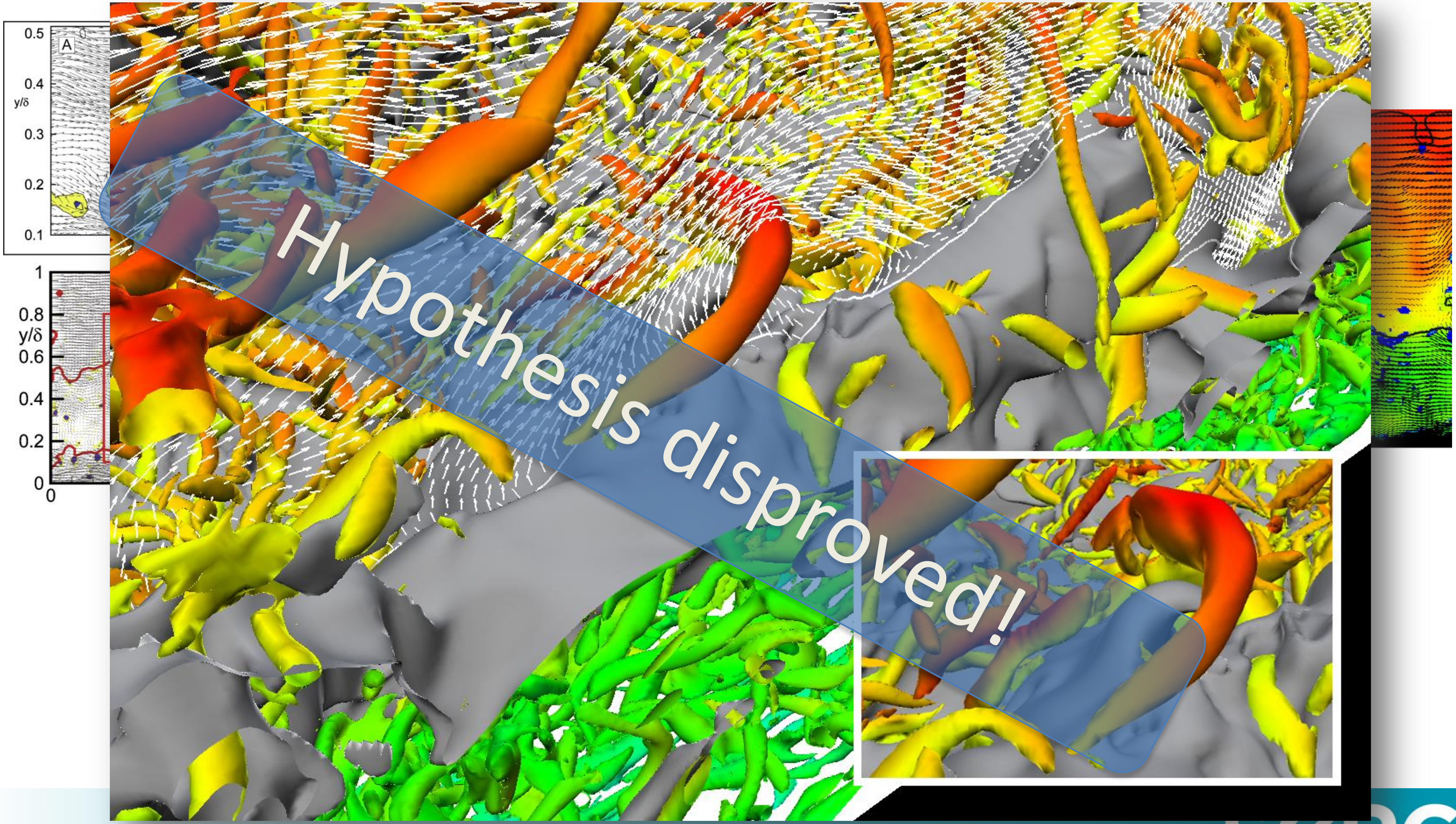
Our simulation

Sideview with velocity vectors

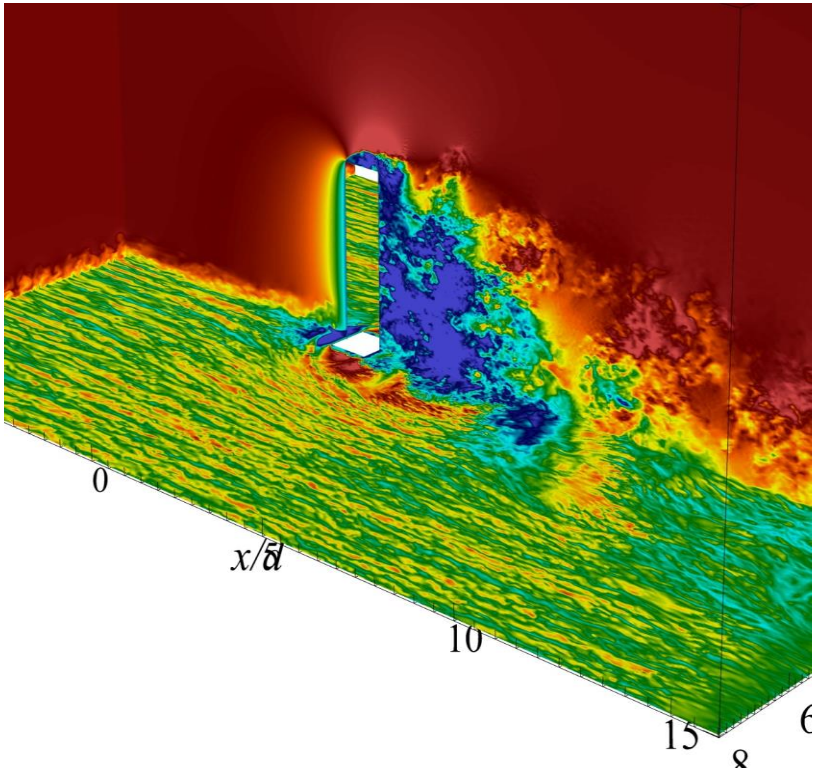
U_∞=0.3 and 0.9

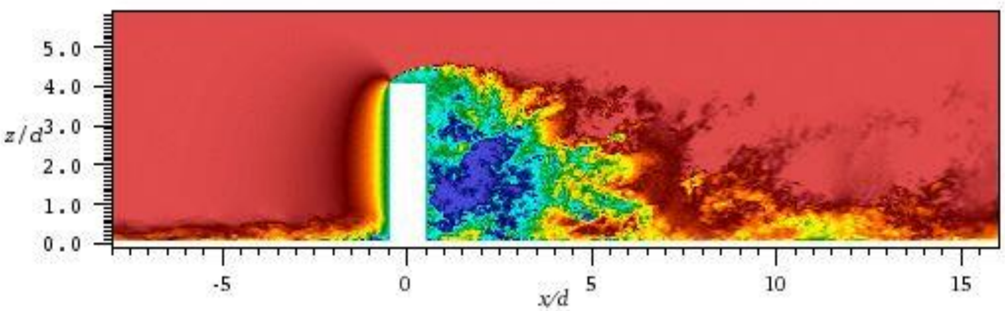
regions of high swirl

HVS – Hairpin Vortex Signatures



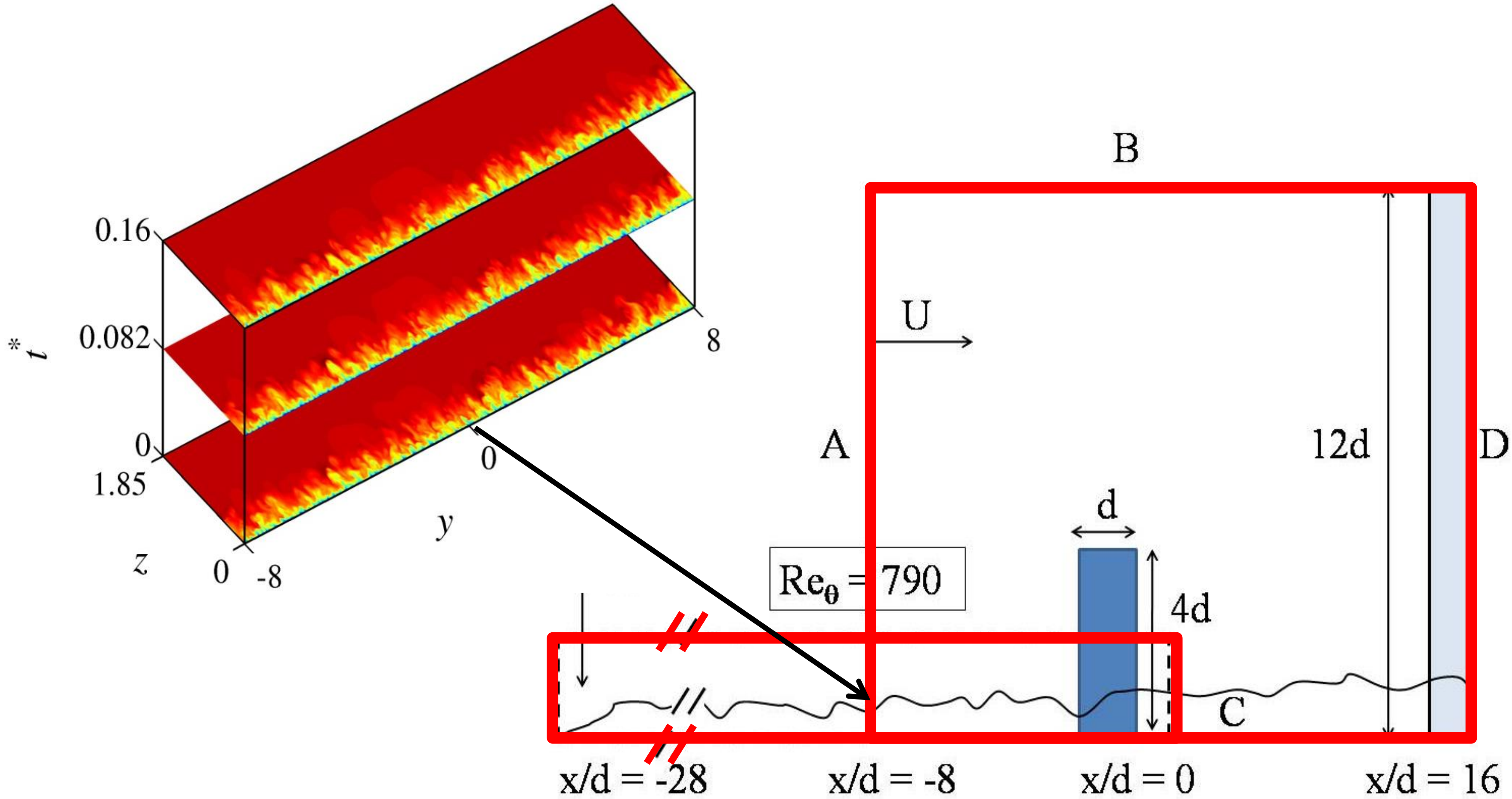
Complex flow with Nek5000: square cylinder ("sky scraper") in boundary layer



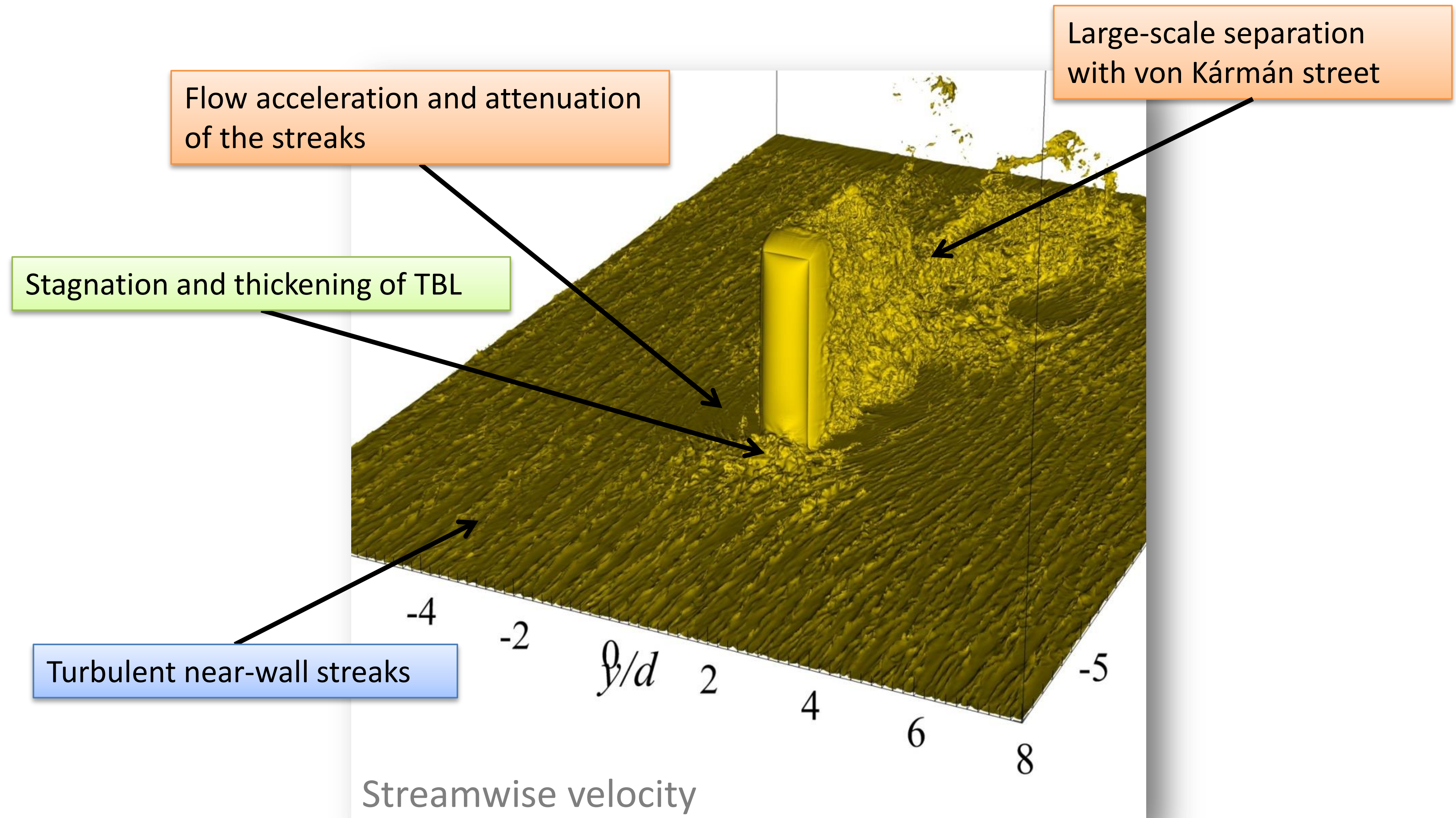


Swedish e-Science Research Centre

Flow Configuration & Simulation Set-Up

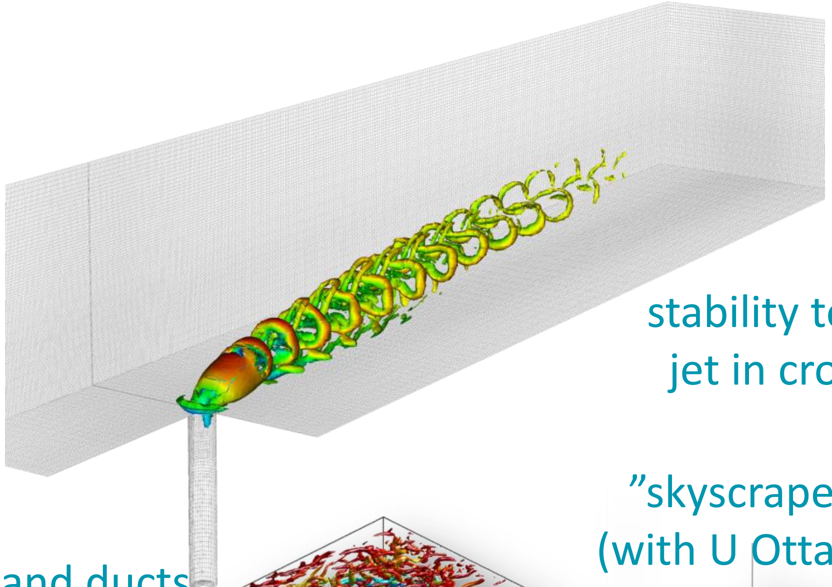


Instantaneous Flow



Some Nek5000 projects at FLOW

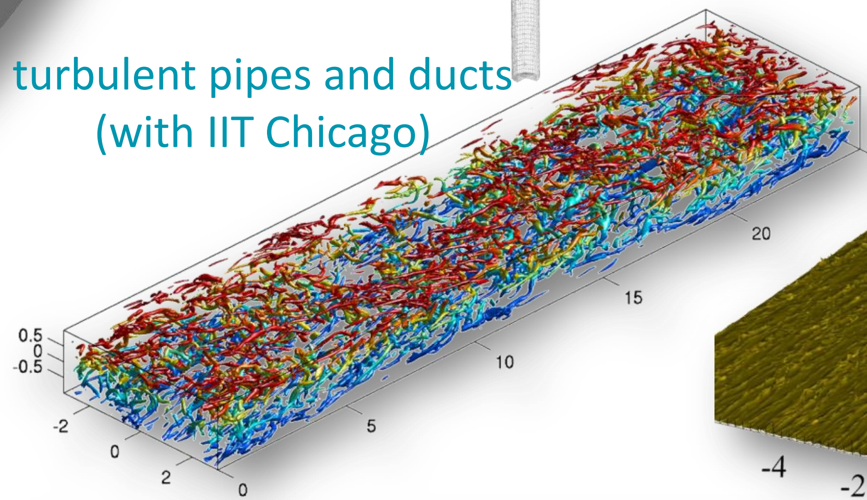
transition to turbulence
on airplane wings

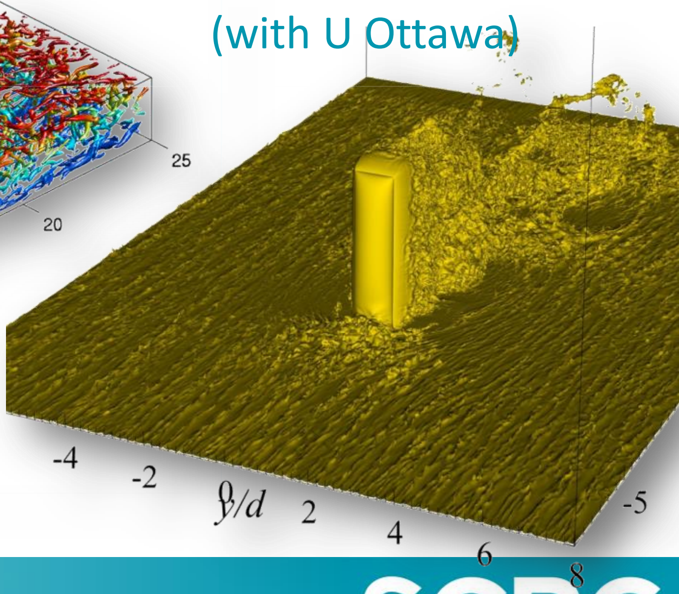


stability tools for
jet in crossflow

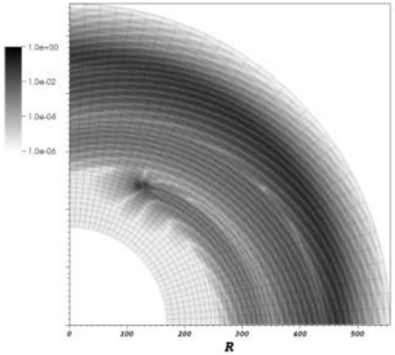
"skyscraper"
(with U Ottawa)

turbulent pipes and ducts
(with IIT Chicago)





rotating disk
(Kármán flow)



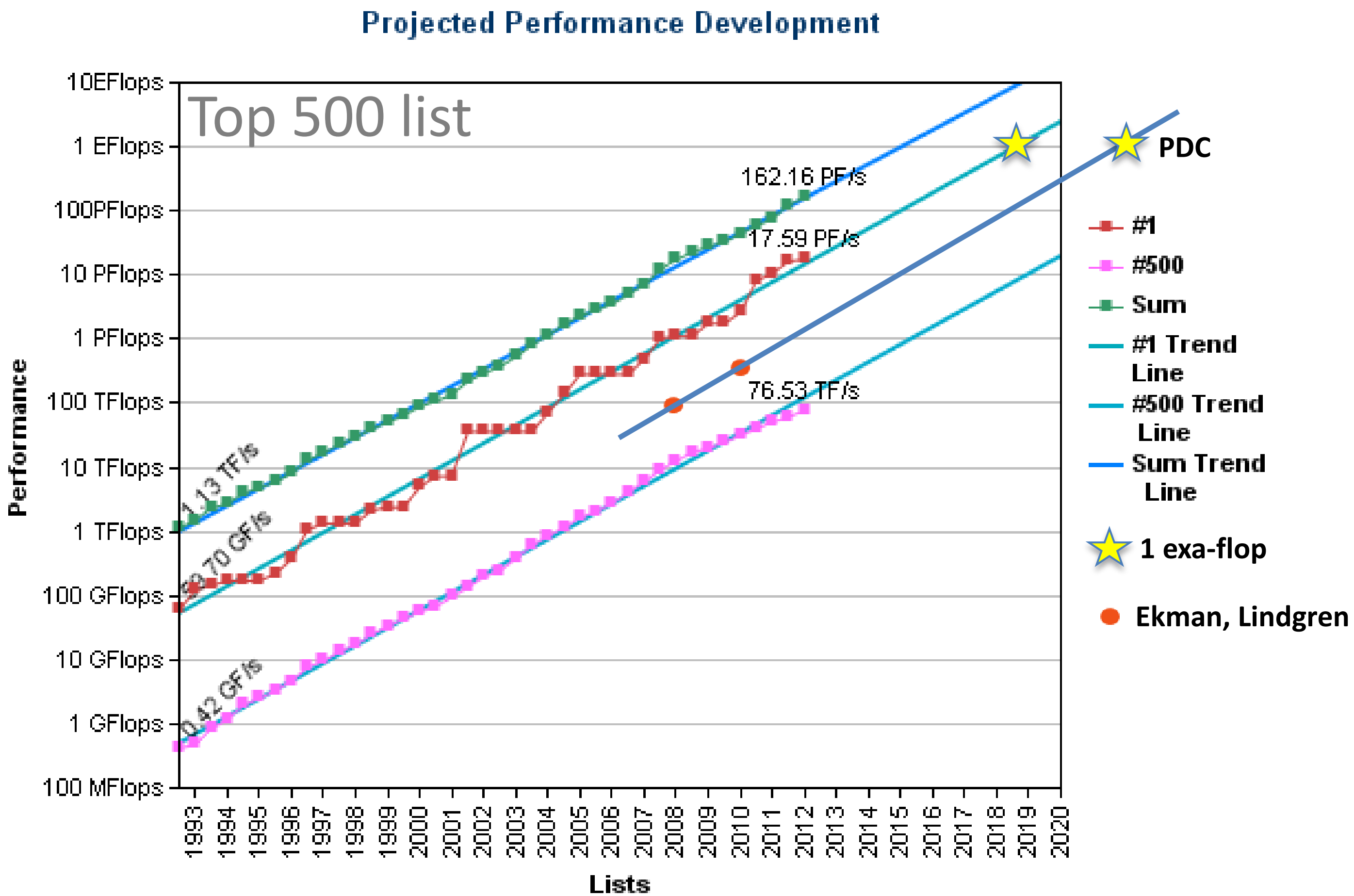
Numerical wind tunnel

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

Turbulent boundary layer:
$Re = 5*30/1.5*10^{-5} = 10x10^6$
(Re_D = 200 000)

- DNS of typical wind tunnel experiment
  - ~ 100 billion grid points
  - ~ 10 billion core hours
  - ~ 1 peta byte of data
  - ~ 10 months on 1 million cores (peta-scale sufficient)
- DNS of Saab 2000 commuter aircraft wing section
  - ~ 1000 times larger computation (exa-scale needed)

1 exa-flop 2018/2019



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

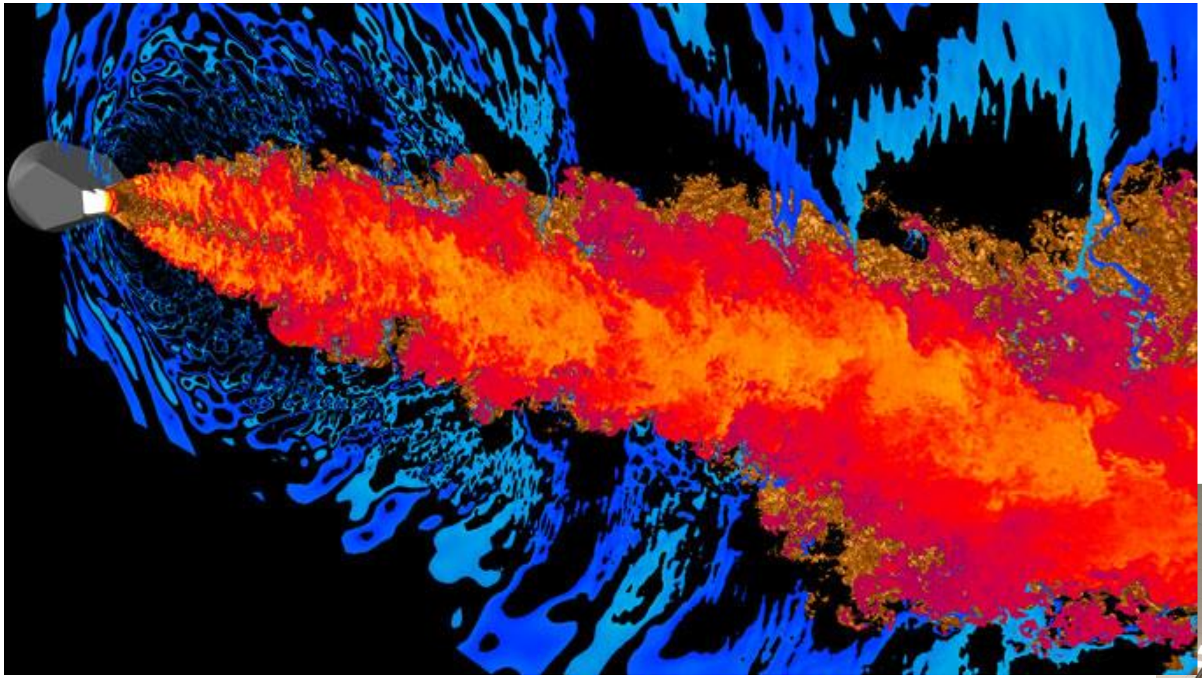
  ➔ **$\sim 10^{12}$ = minimum number of points to scale to $P = 10^8$**

- We must increase problem size for efficient usage of exa-scale, no problem 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
- EU-project CRESTA

Conclusions

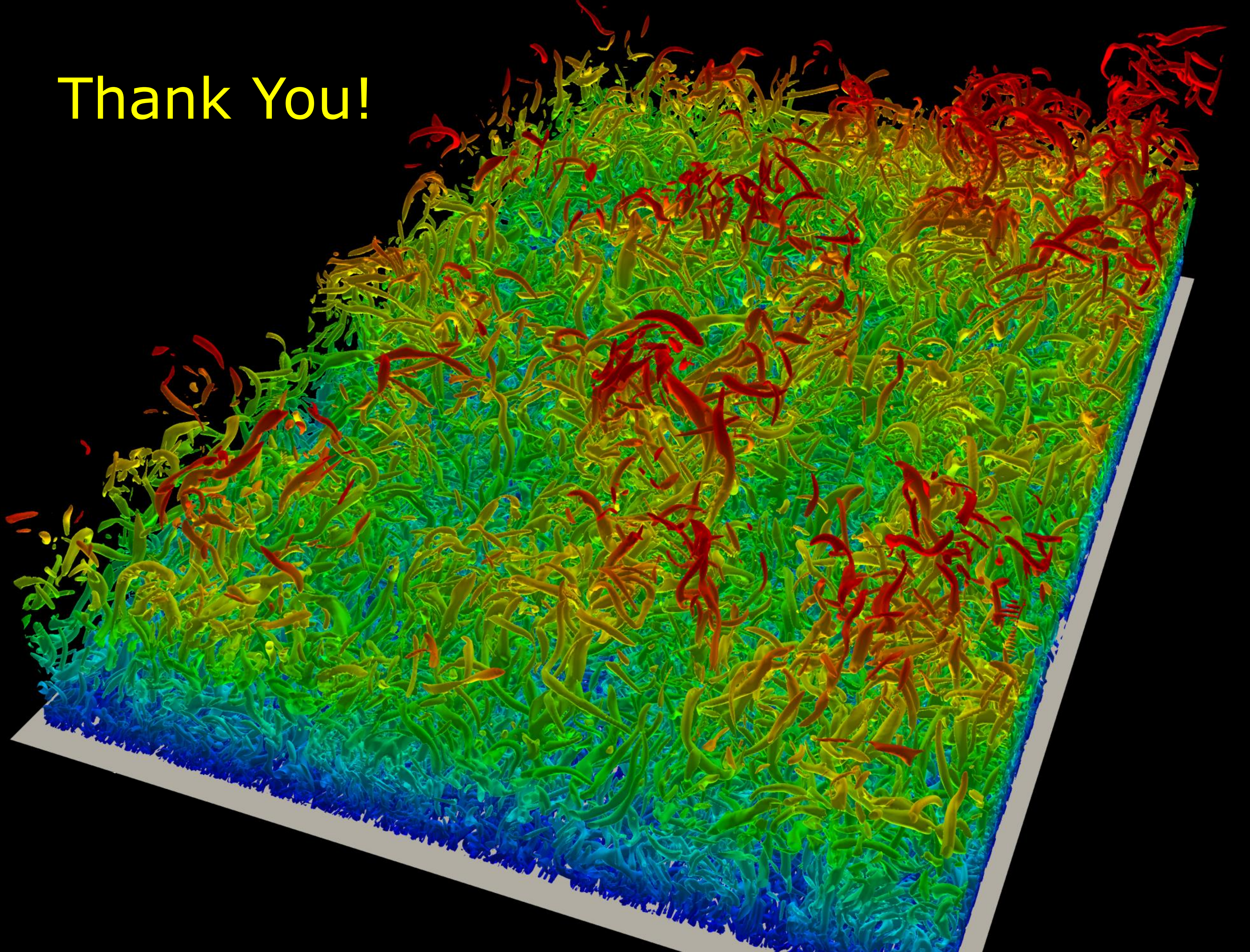
- e-Science: research carried out by systematically using advanced computer based tools
  - example “numerical wind tunnel”
  - e-Science tools such at visualization and parallelization very important
- Turbulence simulations at ”the edge of computing”
  - Turbulence at high Reynolds number multi-scale phenomena
  - Numerical experiments can replace physical experiments for typical university wind tunnel use with sustained peta-scale computations
  - Nek5000 will scale to exa-scale for sufficiently large problem size
  - Complex geometries requires handling of huge amounts of data
- Large scale simulations can give new insight into turbulence
  - ordered “hairpin” vortices lost for high Reynolds numbers, settled 60-year old controversy

“Jet noise simulation break million-core supercomputer barrier” (2013)



- Center for Turbulence Research, Stanford, CA
- Sequoia IBM Bluegene/Q at Lawrence Livermore

Thank You!



Acknowledgments:

VisIt

ParaView

KTH VETENSKAP OCH KONST
ROYAL INSTITUTE OF TECHNOLOGY

SeRC
Swedish e-Science Research Centre

FLOW
LINNÉ FLOW CENTRE

PDC HPC

NSC
National Supercomputer Centre at Linköpings universitet

PRACE

Knut och Alice Wallenbergs Stiftelse

Vetenskapsrådet

SNIC
Swedish National Infrastructure for Computing