Numerical Simulation of Turbulent Boundary-Layer Flows… …using Ekman

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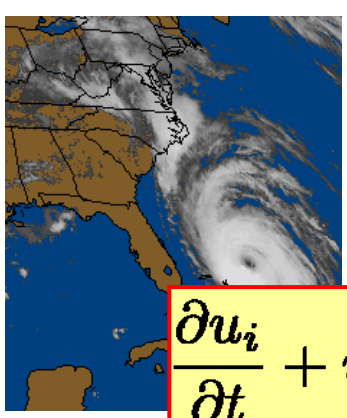
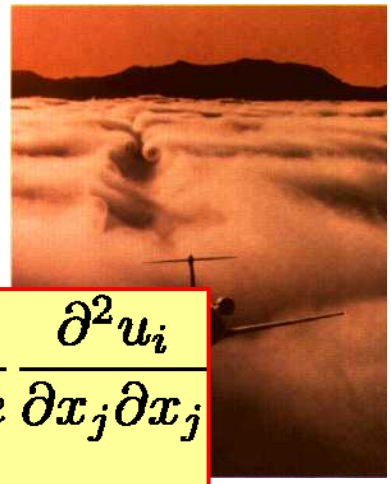
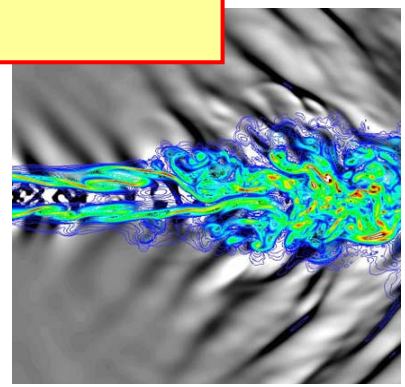
Turbulent flows are everywhere, and they can be described by …





$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re} \frac{\partial^2 u_i}{\partial x_j \partial x_j}$$

$$\frac{\partial u_i}{\partial x_i} = 0$$



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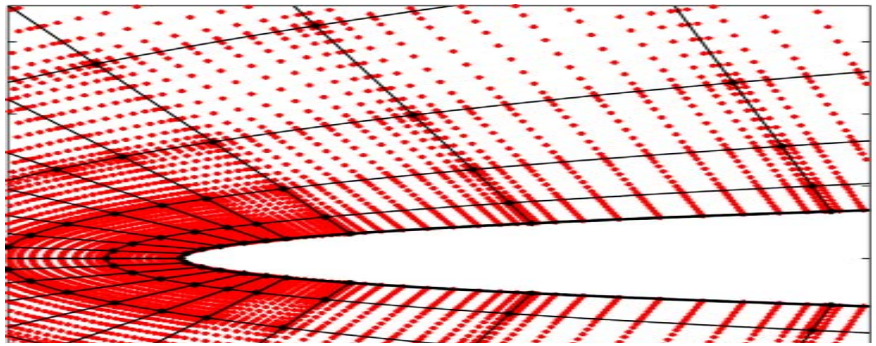
How do we perform numerical experiments?

- Solve the Navier-Stokes equations for the velocity on grid points using super computers



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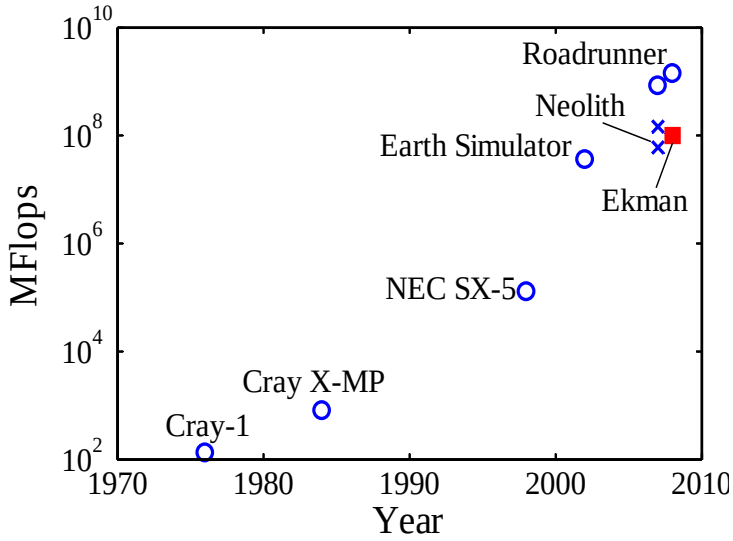
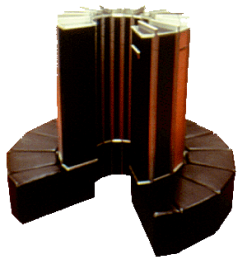
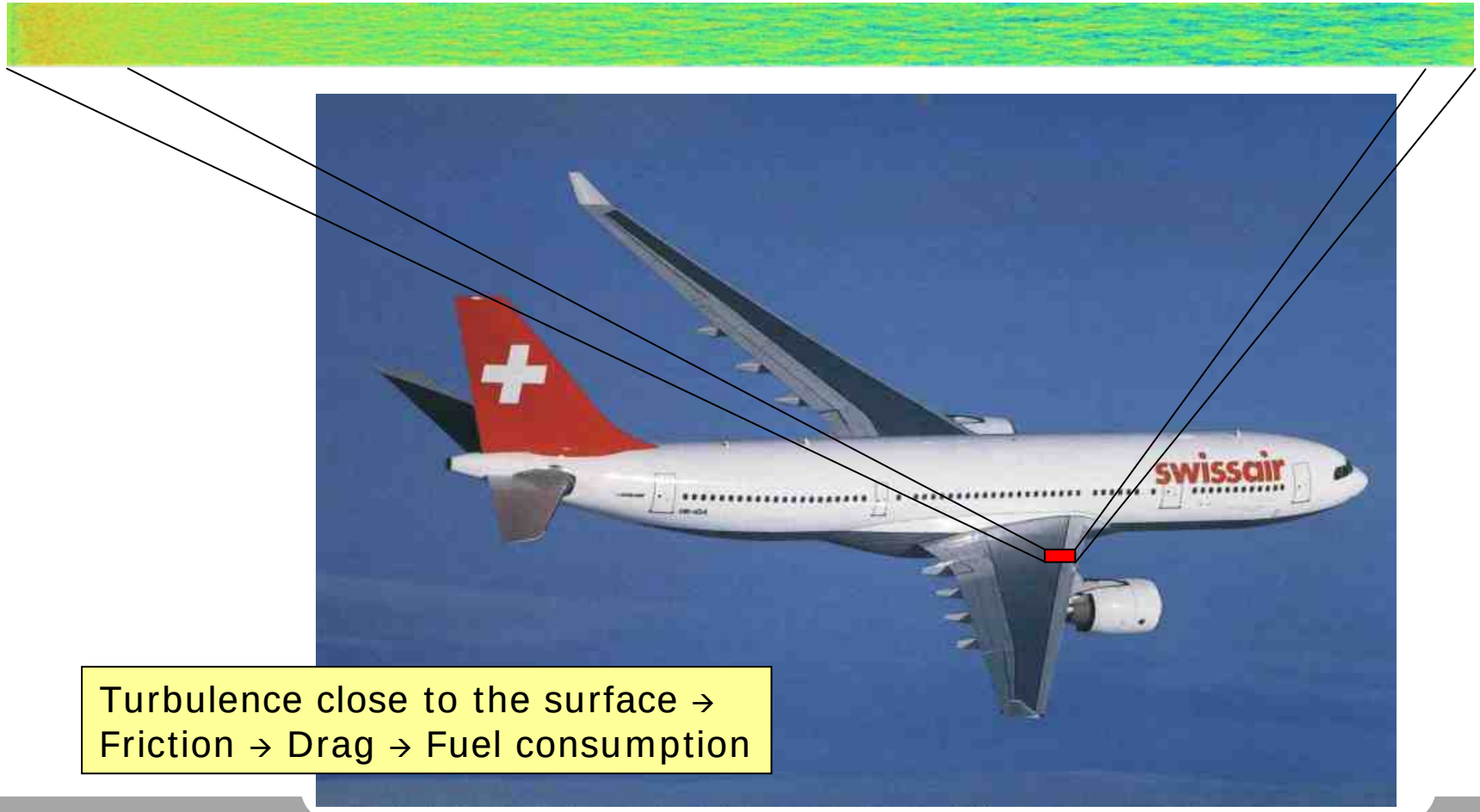




Cray-1 (1976)
100 Mflops
1 processor

Ekman Dell cluster
(2008) 70 Tflops
10000 processors

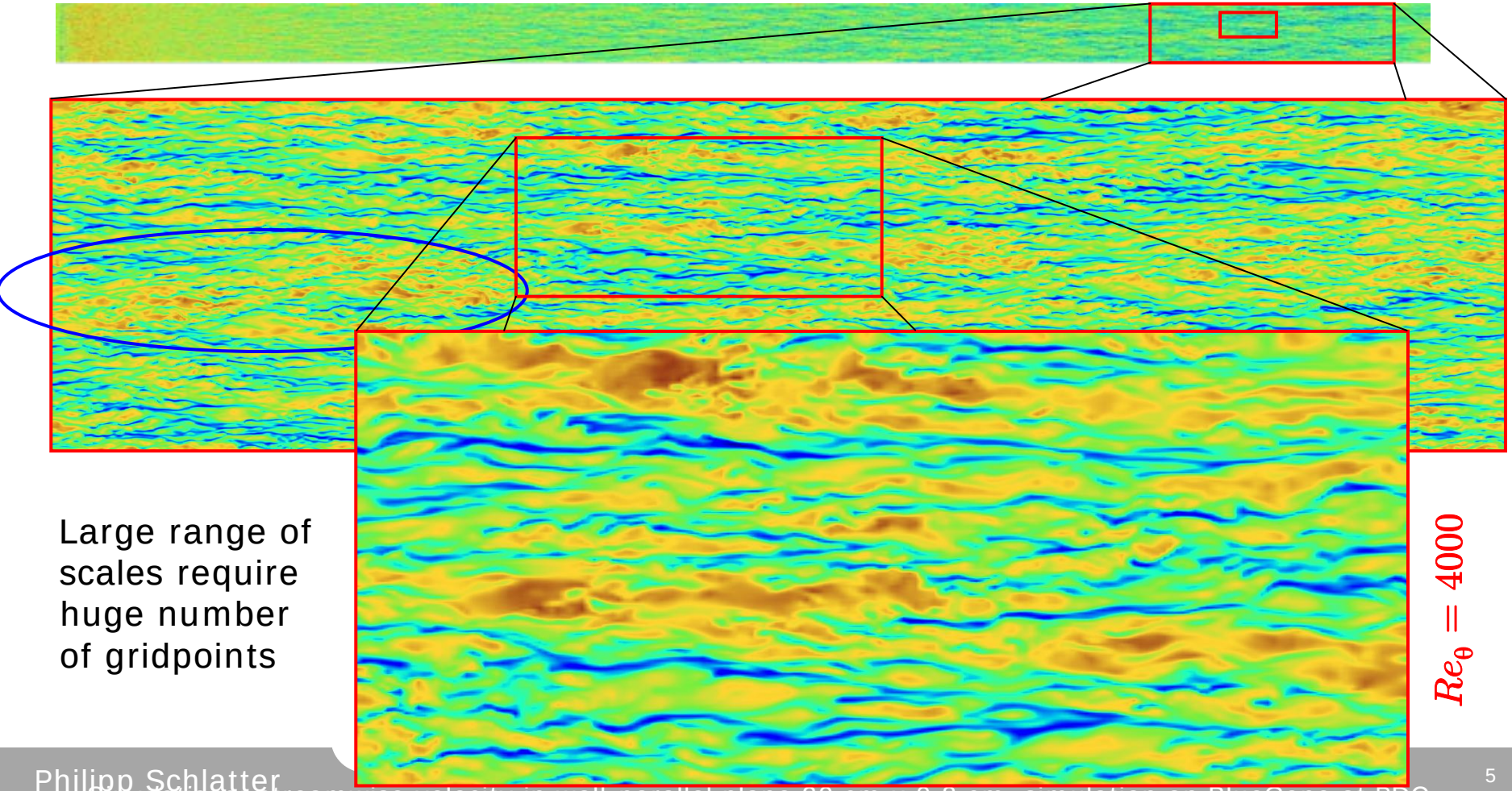
Numerical simulations turbulent flow close to solid walls...



Turbulence close to the surface → Friction → Drag → Fuel consumption

Numerical simulations of turbulent flow

- DNS with 8192 x 513 x 768 = 7.5 billion grid points running on 4096 cores



Large range of scales require huge number of gridpoints

$Re_\theta = 4000$

Simulations: streamwise velocity in wall-parallel plane 20 cm x 0.8 cm, simulation on BlueGene at PDC

How can simulations help make modern aircraft more environmentally friendly?

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- Suppressing turbulence on the wings (laminar flow control) improve fuel efficiency
- Better models of turbulence on wing surfaces improve engineering design
- Example: Airbus green aircraft concept

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

What can we learn from even larger simulations?

- 8192 x 513 x 768 = 7.5 billion grid points
- Overlap with large-scale experiments

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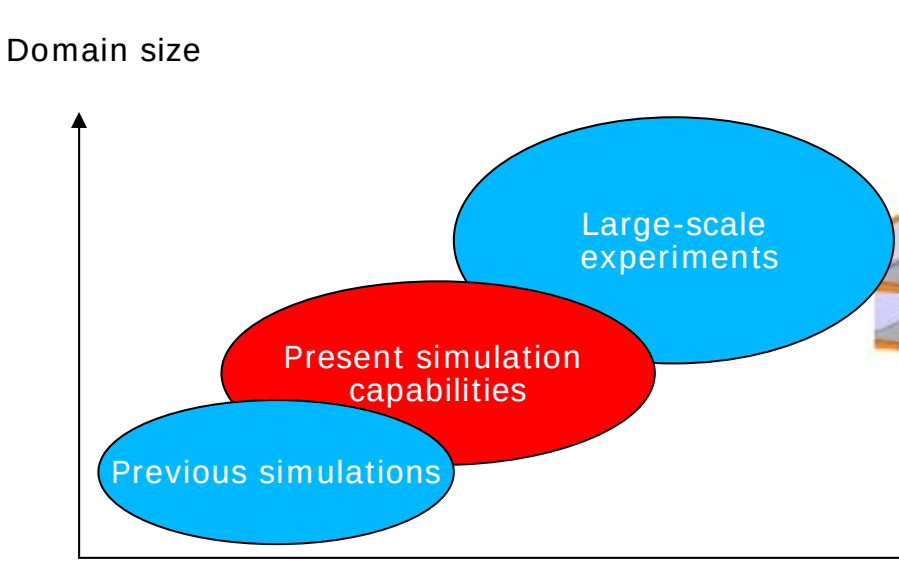
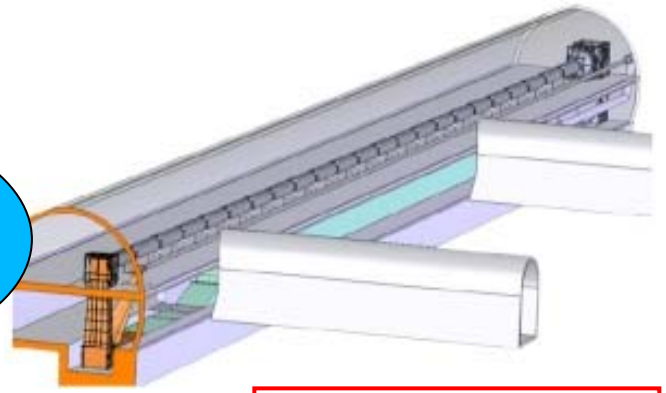
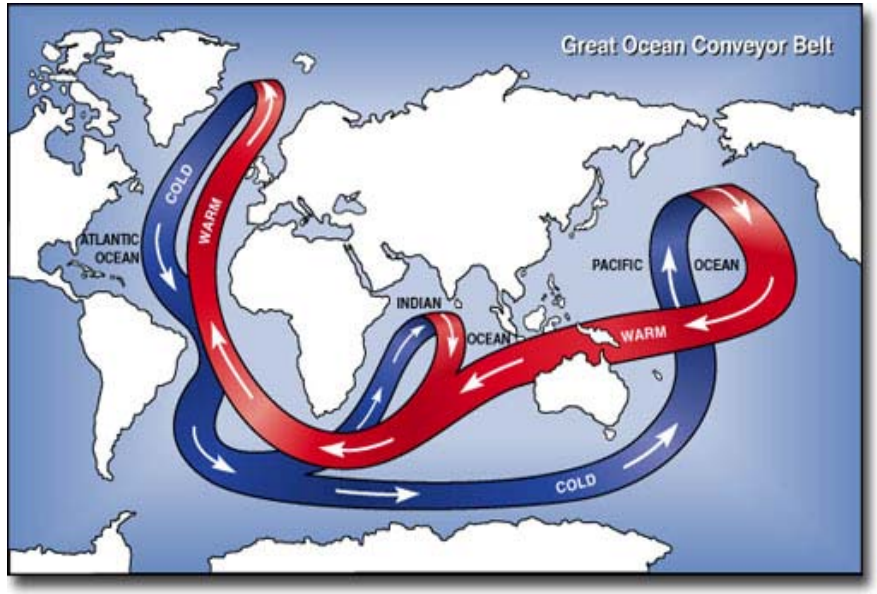




Ciclope project: large pipe flow facility in 130 m Italian tunnel

Measurement jamboree
(Marusic, Nagib, Smits, Alfredsson...)

How will the ocean circulation respond to global warming?



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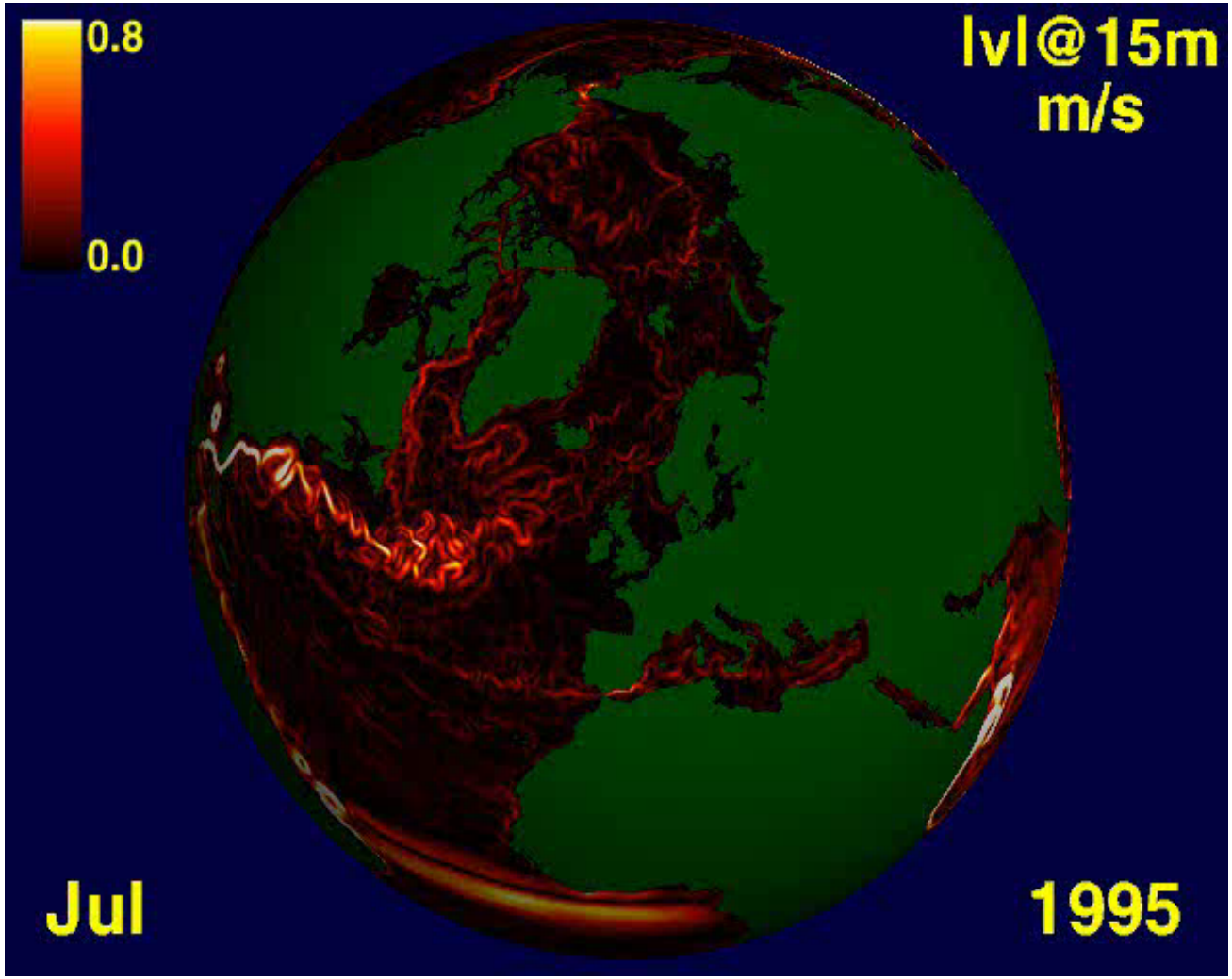
- Ocean large heat regulator of climate
- Great conveyor belt transport warm surface water to north pole and cold water back along bottom
- Circulation affected by global warming?

The ocean is turbulent!



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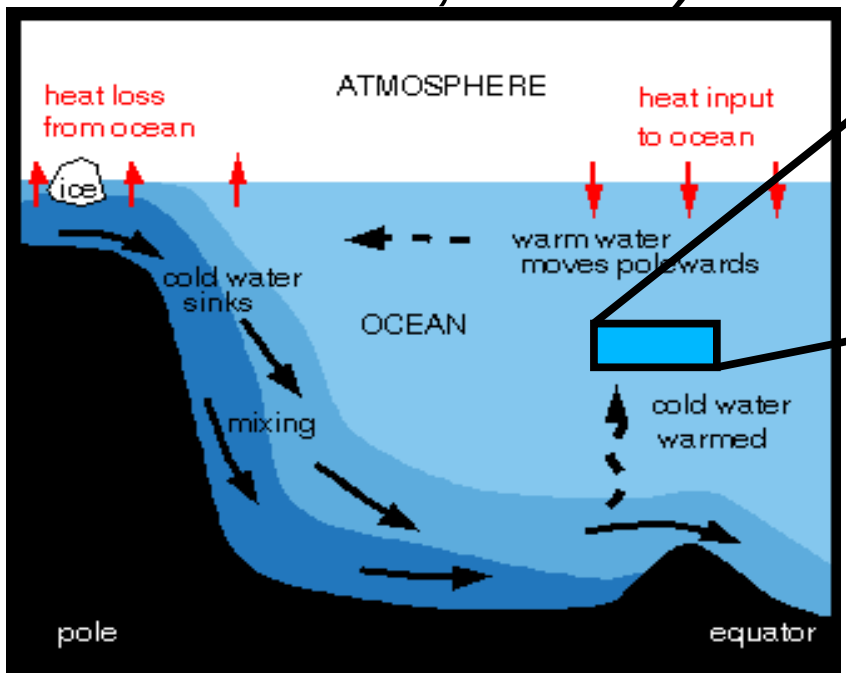
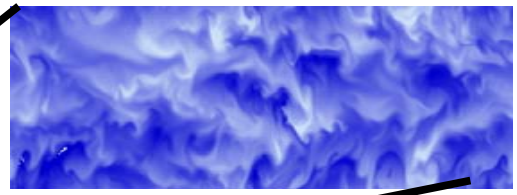
Simulation: ECCO code using MITgcm. JPL. NASA Ames

The global circulation is very sensitive to the turbulent diffusivity

(Nilsson *et al., MISU*)





There is even turbulence at centimeter scale!

Smaller scales determine turbulent diffusivity, how fast is the cold water cooling the warmer water above ?

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Efficient simulations on many processors

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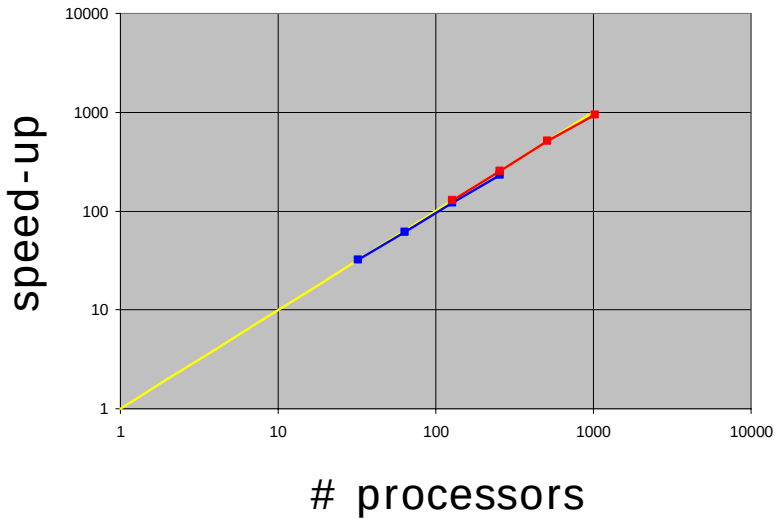
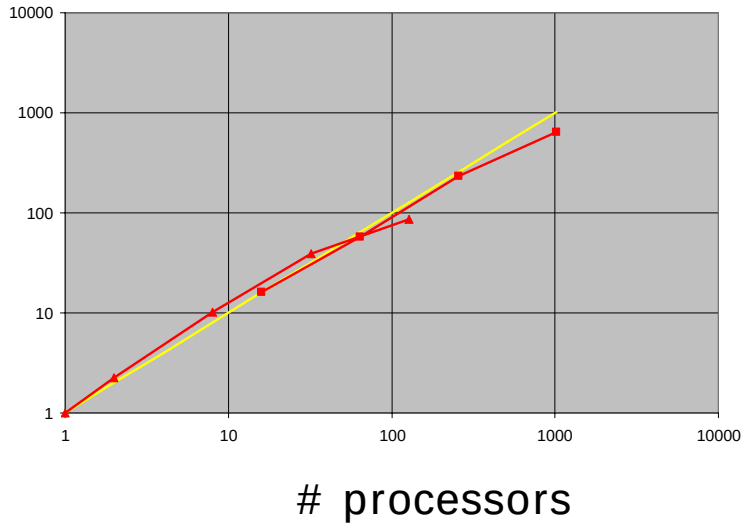
Nek5000 (spectral element)



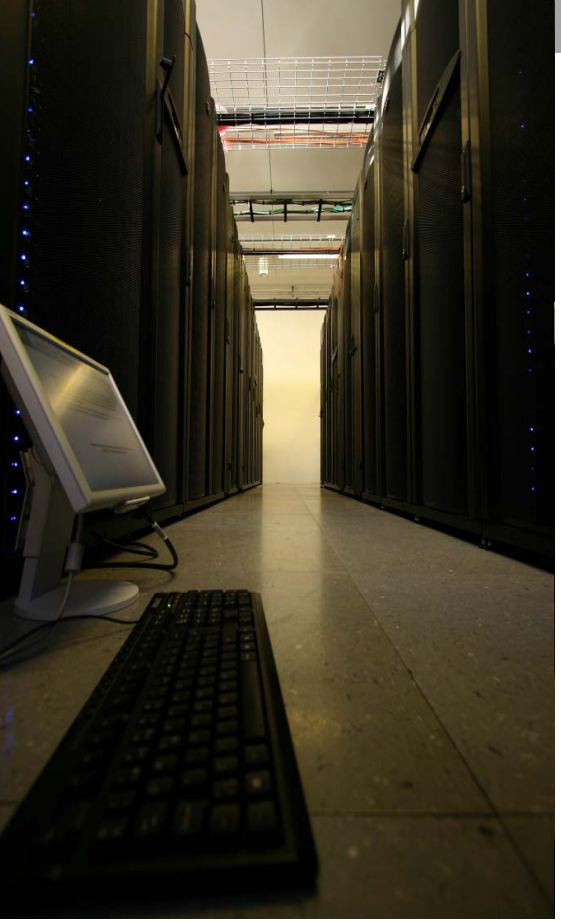
SIMSON (fully spectral)



How much faster does the simulation run on many processors?

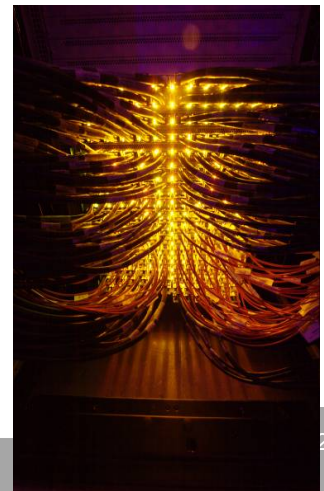
linear scaling — measurements (IBM BG/L)

from 256 to 4096 cores: 85% parallel efficiency!



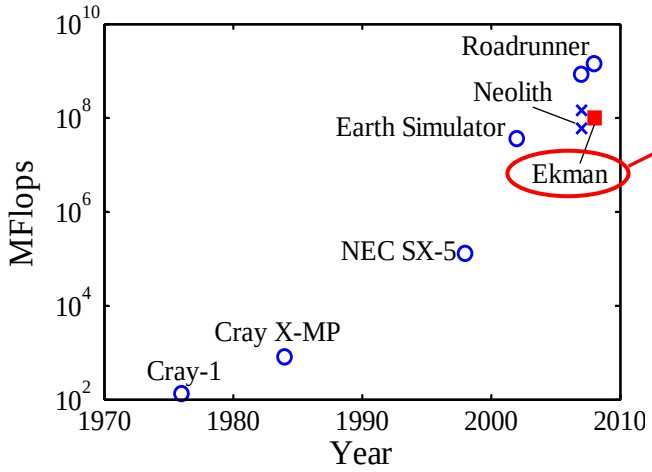
Ekman / Vagn

- **New supercomputer entirely dedicated for research on turbulence and climate!**
  Sponsors: Wallenberg foundation and SNIC
- **Status**: **Ekman**/PDC (1268 nodes → 10144 cores → 70TFlops) and **Vagn**/NSC in production use by groups at KTH Mechanics, MISU, and SMHI.
- **Ekman**: Compilers, MPI, queue system and file system (~100TB) installed and in full usage.
- **Vagn**: 6 analysis nodes, GPFS ready, final size ~500TB with tape robot, acquiring in phases.
- **Policy**:
  Large jobs/projects are prioritised.
  "Ekman group" is deciding on priorities
  Code performance shall be monitored



Fotograf: Harald Barth, PDC

Where does that put us...?



~100 times smaller than largest systems (about place 75 in top500)

→ possibility to run much larger jobs than previously possible!

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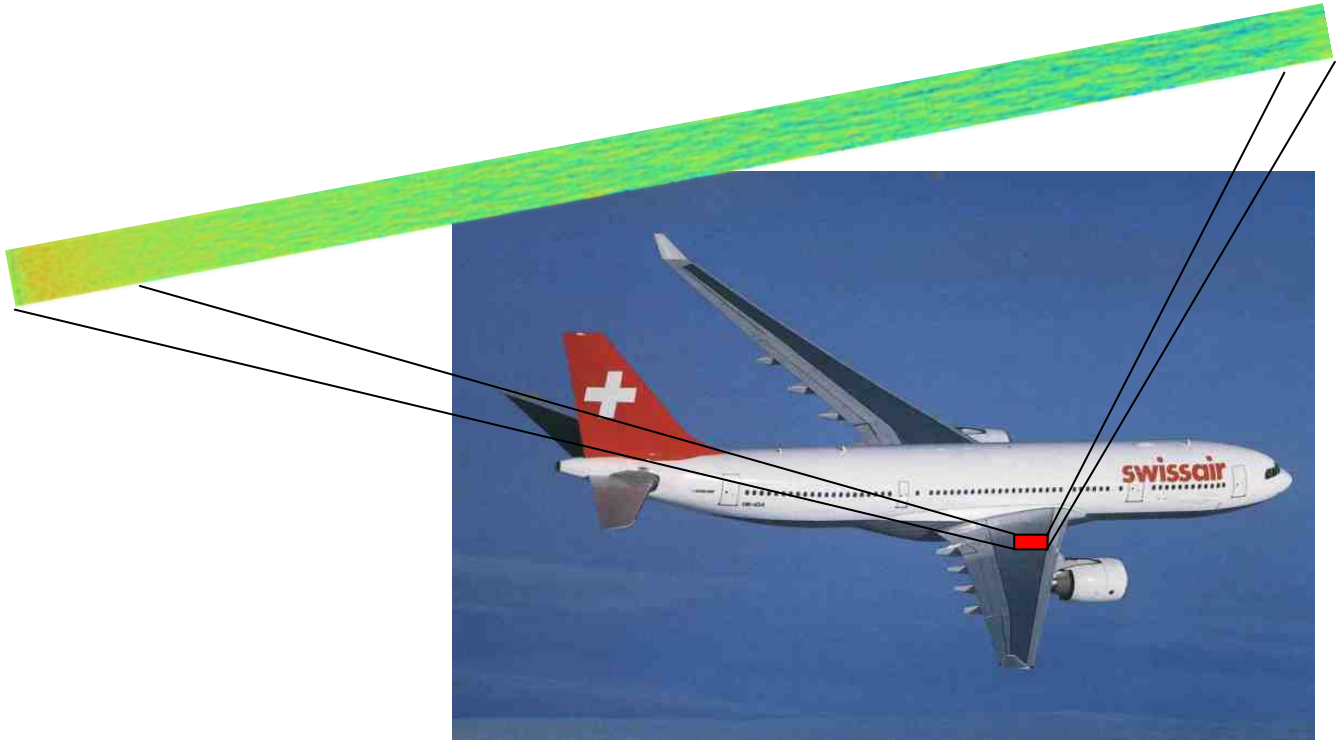
HOWEVER:

- Other groups (*e.g.* USA, Japan, Germany) are also heavily investing. Routine usage of e.g. large BG/P with *O*(50'000) cores.
- Ekman is a complement to enable very large jobs featuring a special mix of jobs (width and length), and not a "normal" SNIC machine.

FOCUS:
Turbulent Boundary Layer



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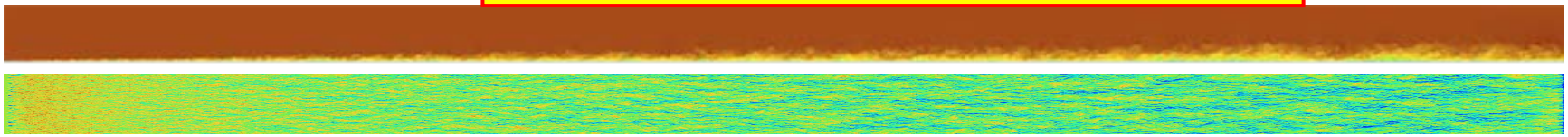
WHY?

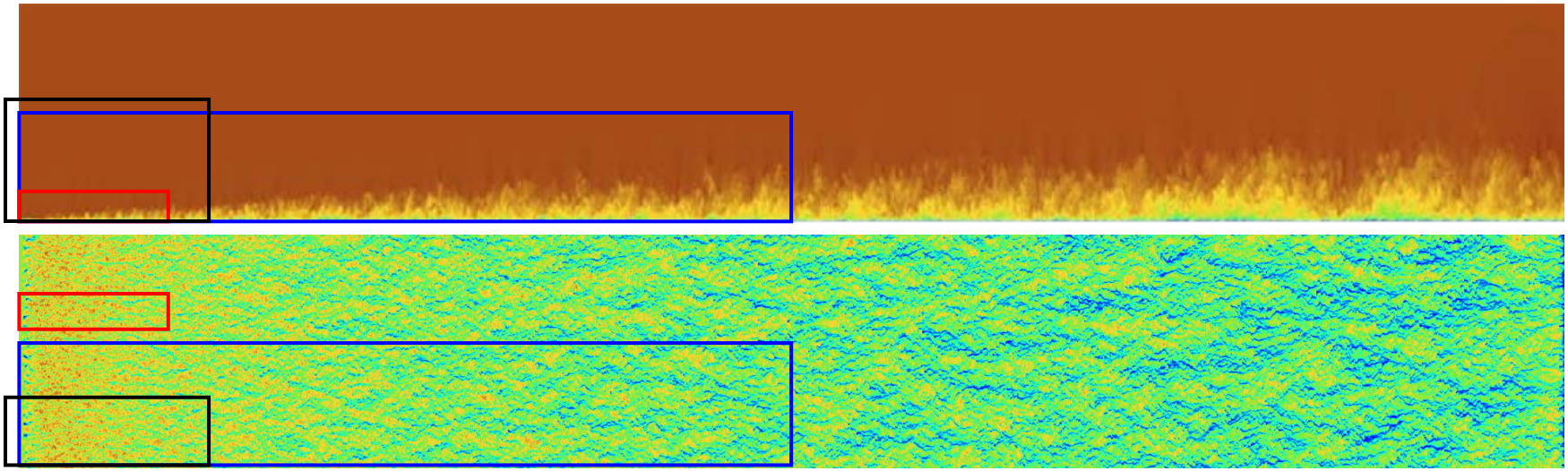
- many (fundamental) open questions
- engineering importance (drag!)
- very timely, both experiments and simulations

TBL up to $Re_\theta = 4000$

real aspect ratio: $O(10^{10})$ grid points, 4096 processors



aspect ratio 4:1 :



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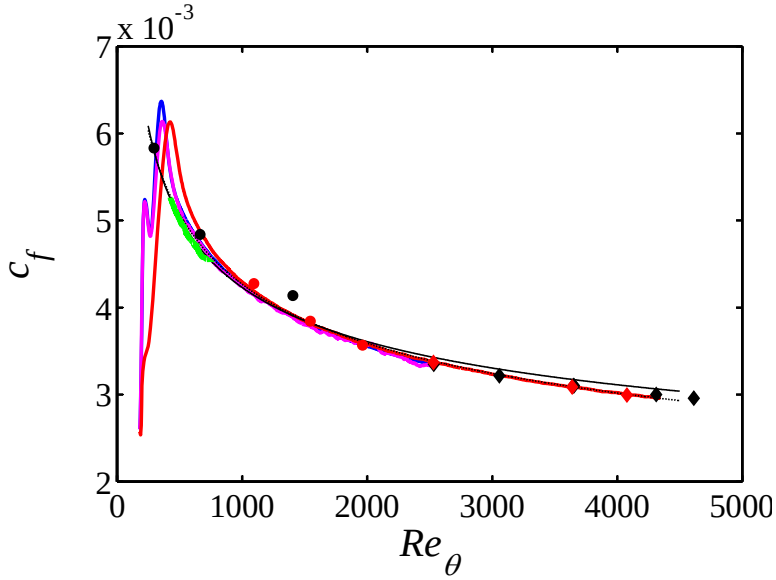
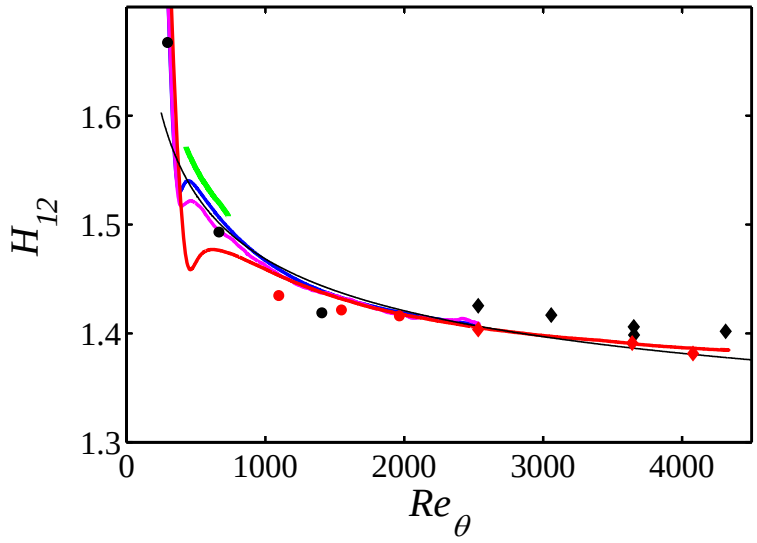
Statistical Data

Integral Quantities up to Re_θ=4300

- Skin friction c_f and shape factor H_{12}

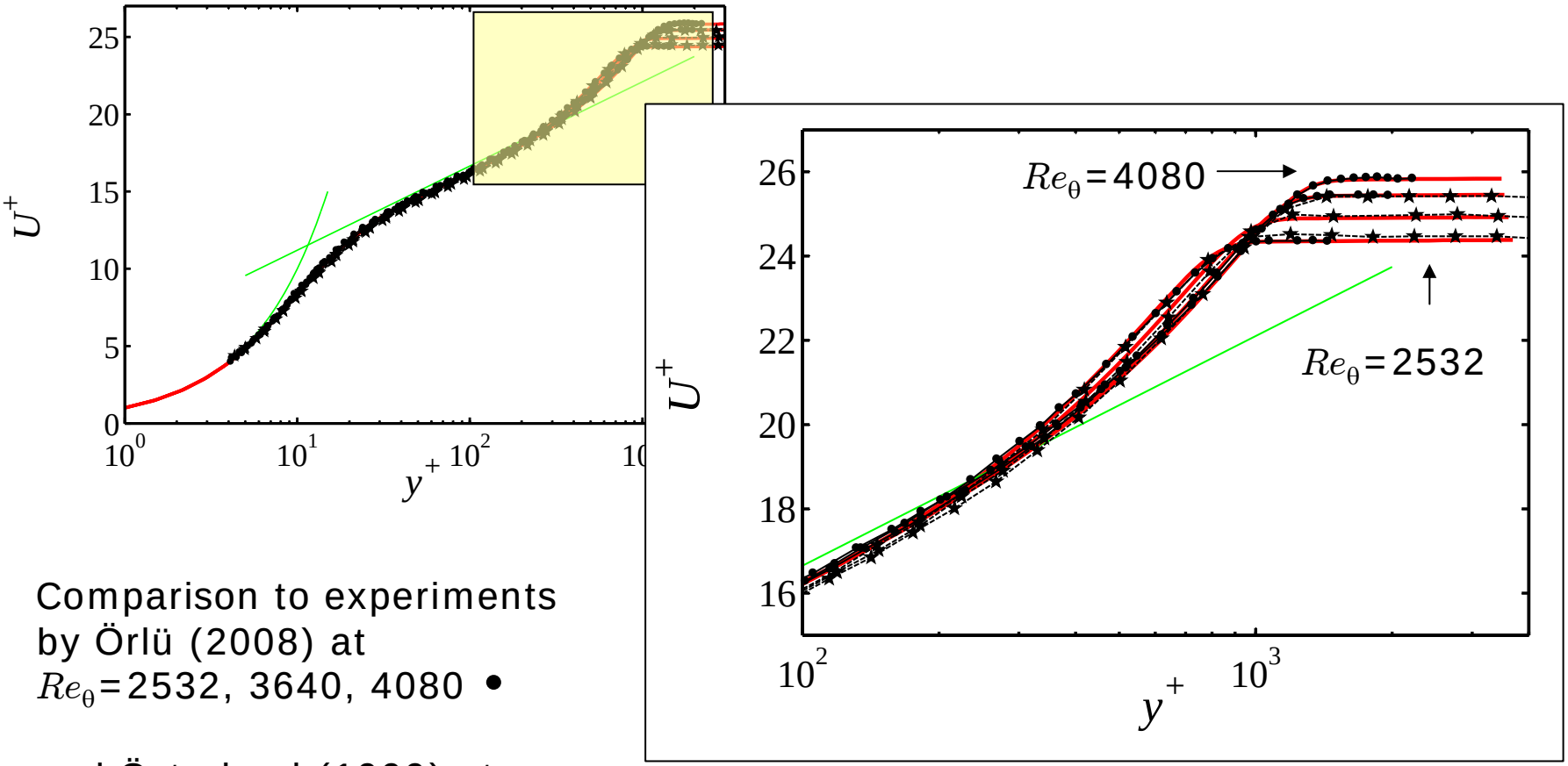




- DNS Spalart (1988) Re_θ=300, 670, 1410
- DNS Jiménez et al. (2009) Re_θ=1100, 1550, 2000
- EXP Österlund (1999) Re_θ=2500, 3000 ...
- EXP Örlü (2008) Re_θ=2500, 3000 ...
- Correlations (Monkewitz et al. 2007, Österlund (1999))
- DNS Skote (2001)

Medium DNS — Fine LES — Fine DNS

Comparison to Experiments



Comparison to experiments by Örlü (2008) at $Re_\theta = 2532, 3640, 4080$ •

and Österlund (1999) at $Re_\theta = 2532, 3060, 3651$ ★

present LES at matching Re_θ

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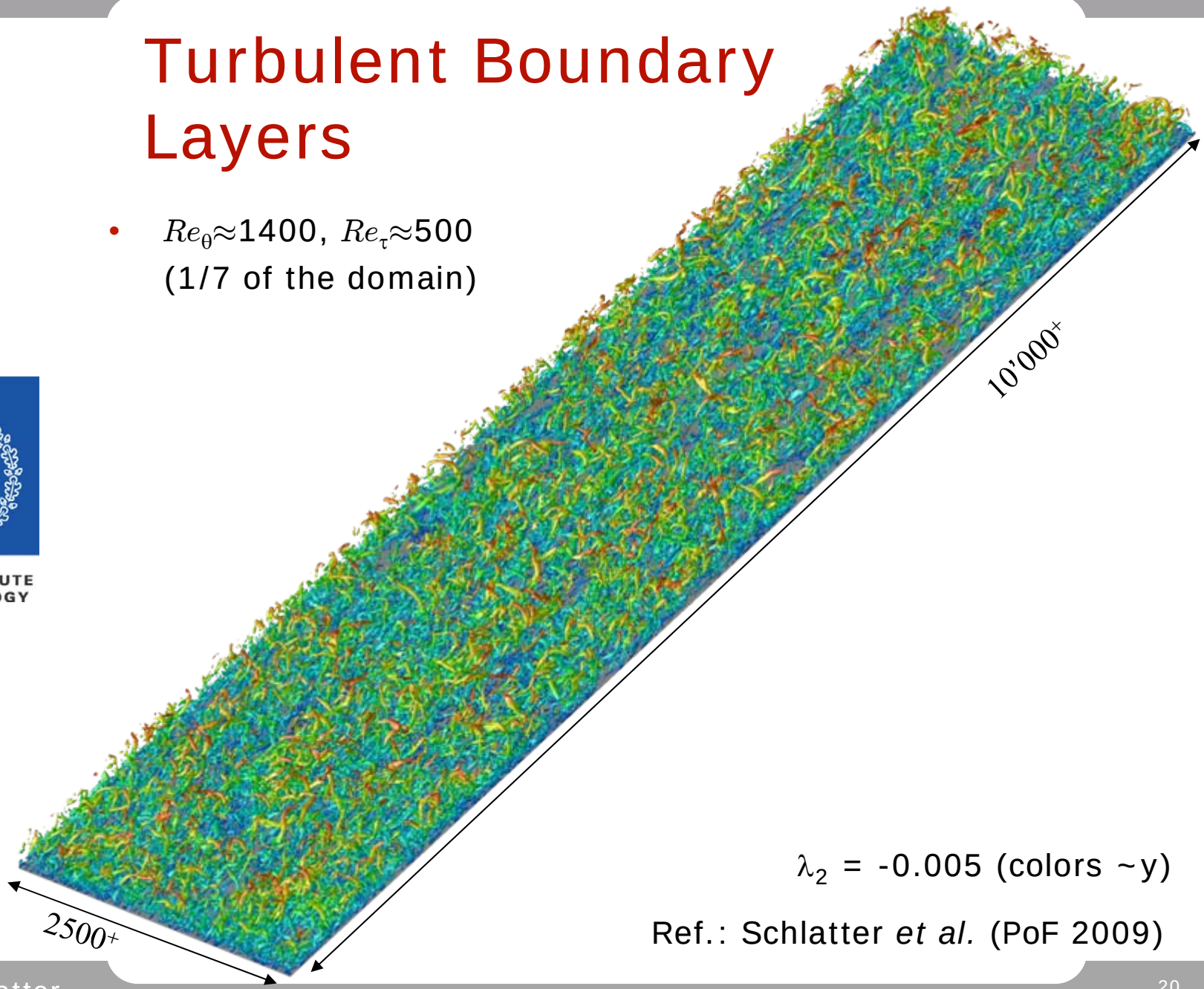
Visualisation – "Large-Scale" Structures

Turbulent Boundary Layers

- $Re_\theta \approx 1400$, $Re_\tau \approx 500$ (1/7 of the domain)



λ_2 = -0.005 (colors ~y)

Ref.: Schlatter *et al.* (PoF 2009)

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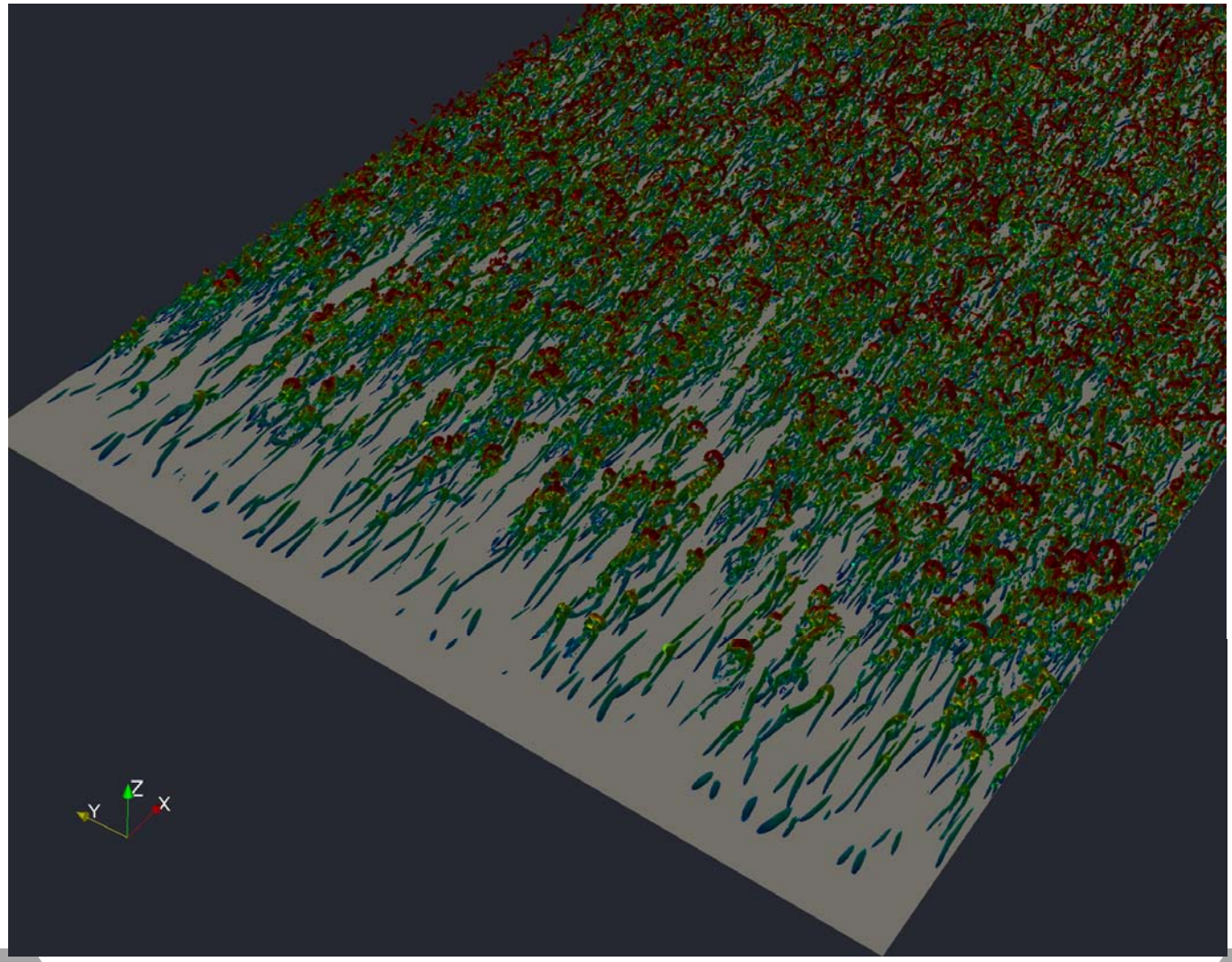
Up to Re_θ=700... (DNS)



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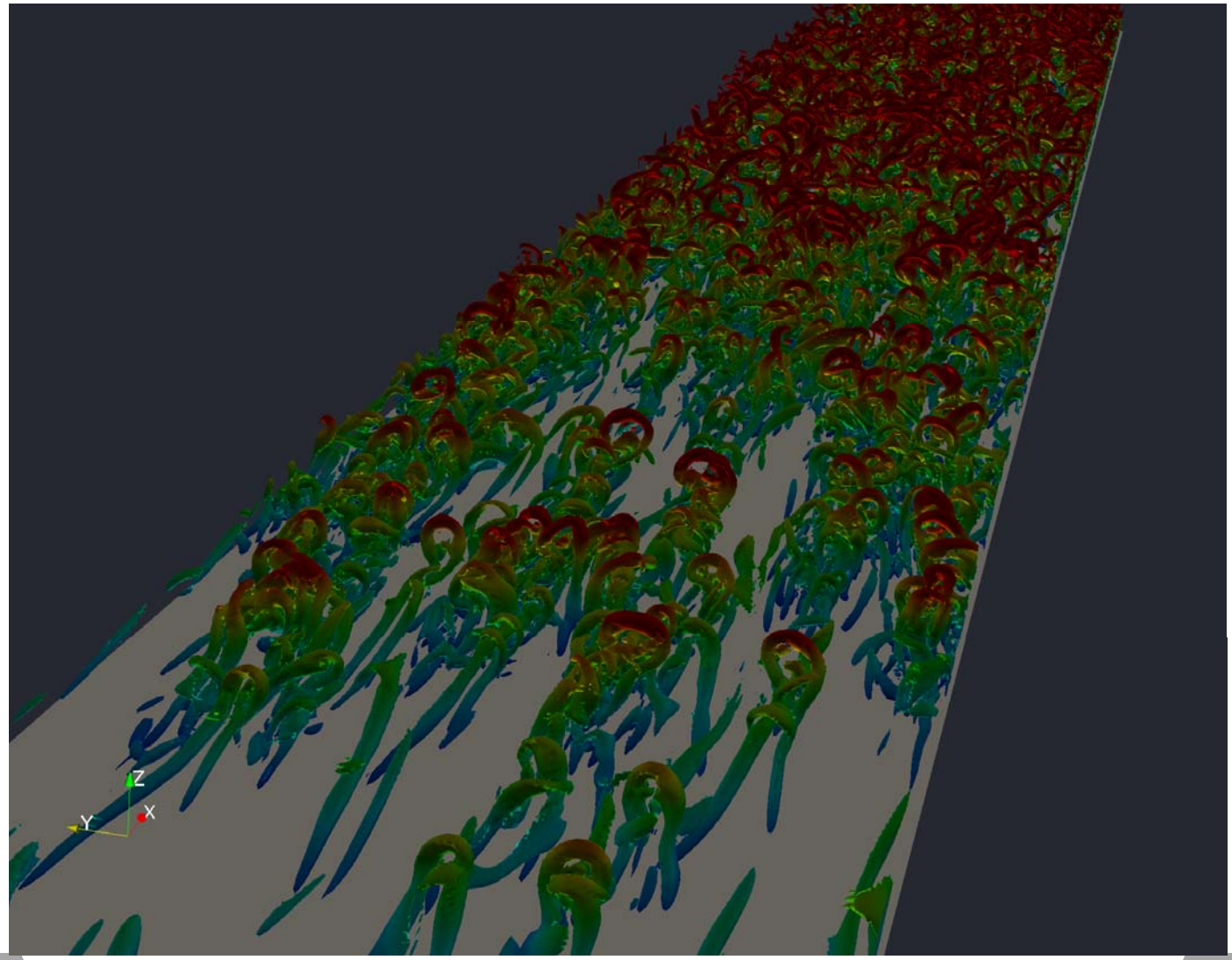
Q=0.015

Up to Re_θ=700... (DNS)



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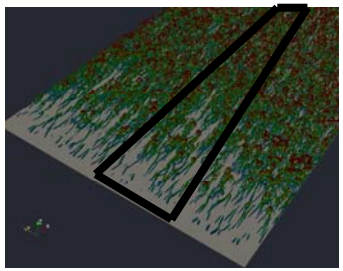
Q=0.015



25% of domain width, 5% of domain length, 10% of domain height

Visualisation High-Re

- Visualisation of:
  - streamwise velocity u=0.8
  - λ_2 = -0.002, -0.005 and -0.008

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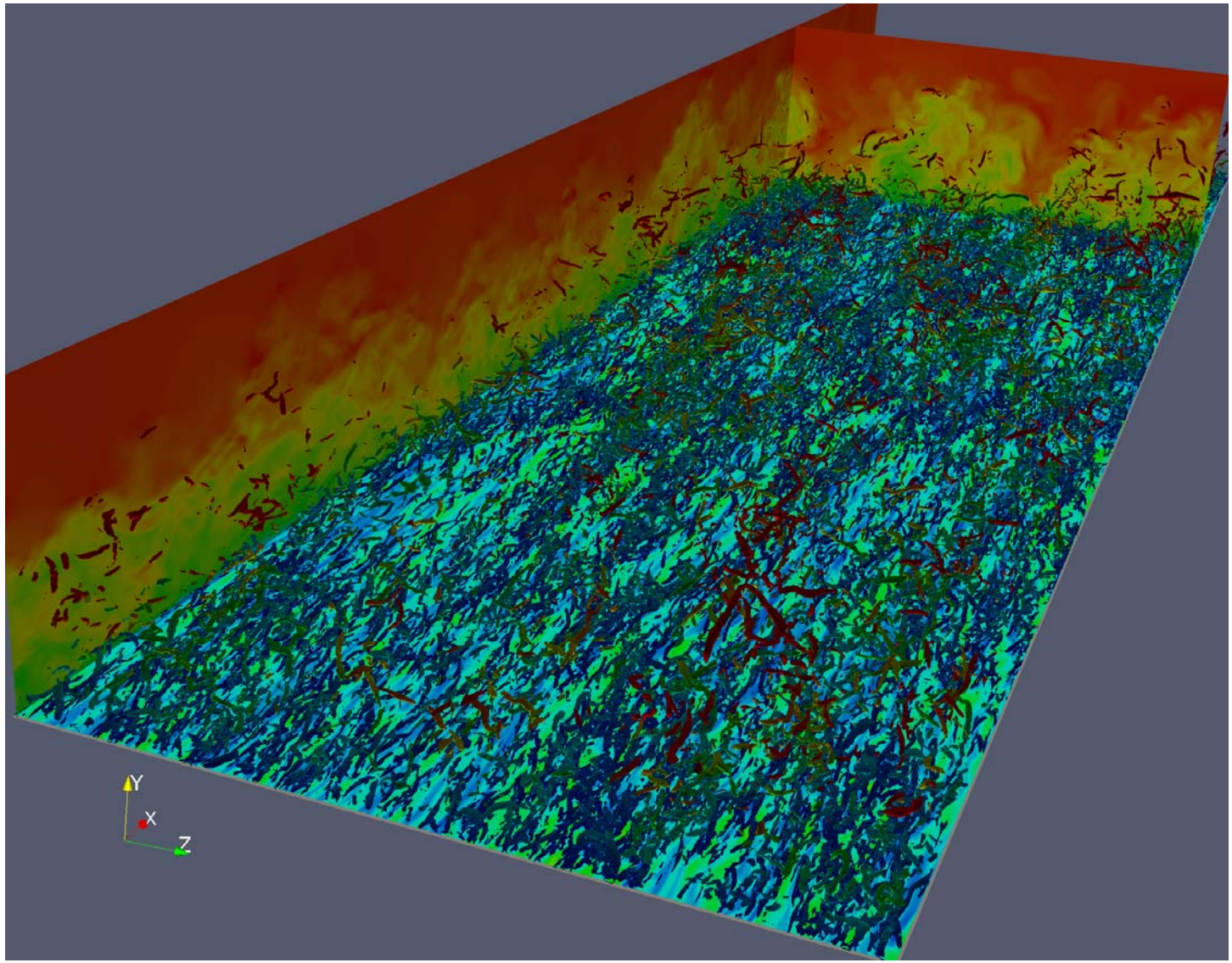
- $Re_\theta = 4000$
- real aspect ratio
- **visualised domain**:
  - 1/7 in streamwise direction
  - 1/2 in wall-normal direction
  - total 200· 10^6 grid points

→ 7% of the computational domain

Paraview (VTK) running at PDC on *O*(16 nodes)

$Re_\theta = 4000$



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flow direction

λ_2 = -0.005, colour ~ y

Conclusions and Outlook

- Simulation of turbulent flows is a computationally expensive endeveaur
- Turbulence close to walls and in climate (ocean etc.) main aspects of research on **Ekman**: basic open questions, practical relevance
- DNS/LES of a spatial turbulent zero pressure gradient turbulent boundary layer up to Re_θ=4300 (data: www.mech.kth.se).
  → Largest simulations to date for this geometry.
- Ekman (and similar machines) are a welcome and necessary complement (but not replacement) to SNIC resources.
- Visualisation of high-Re turbulent boundary layers: No clear hairpin vortices detected except for low-Re region.
- Outlook:
  → **Numerical/Computational Methods** as a focal area with new Swedish eScience strategy; KTH/LiU/SU/KI

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