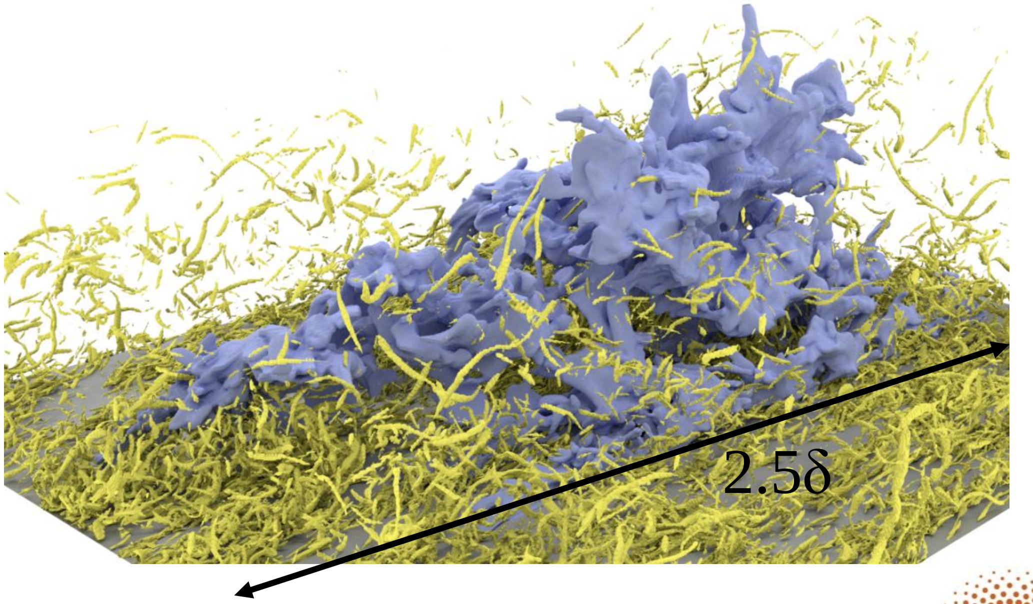
The Physics of Turbulent Boundary Layers

Javier Jiménez

School of Aeronautics, Madrid

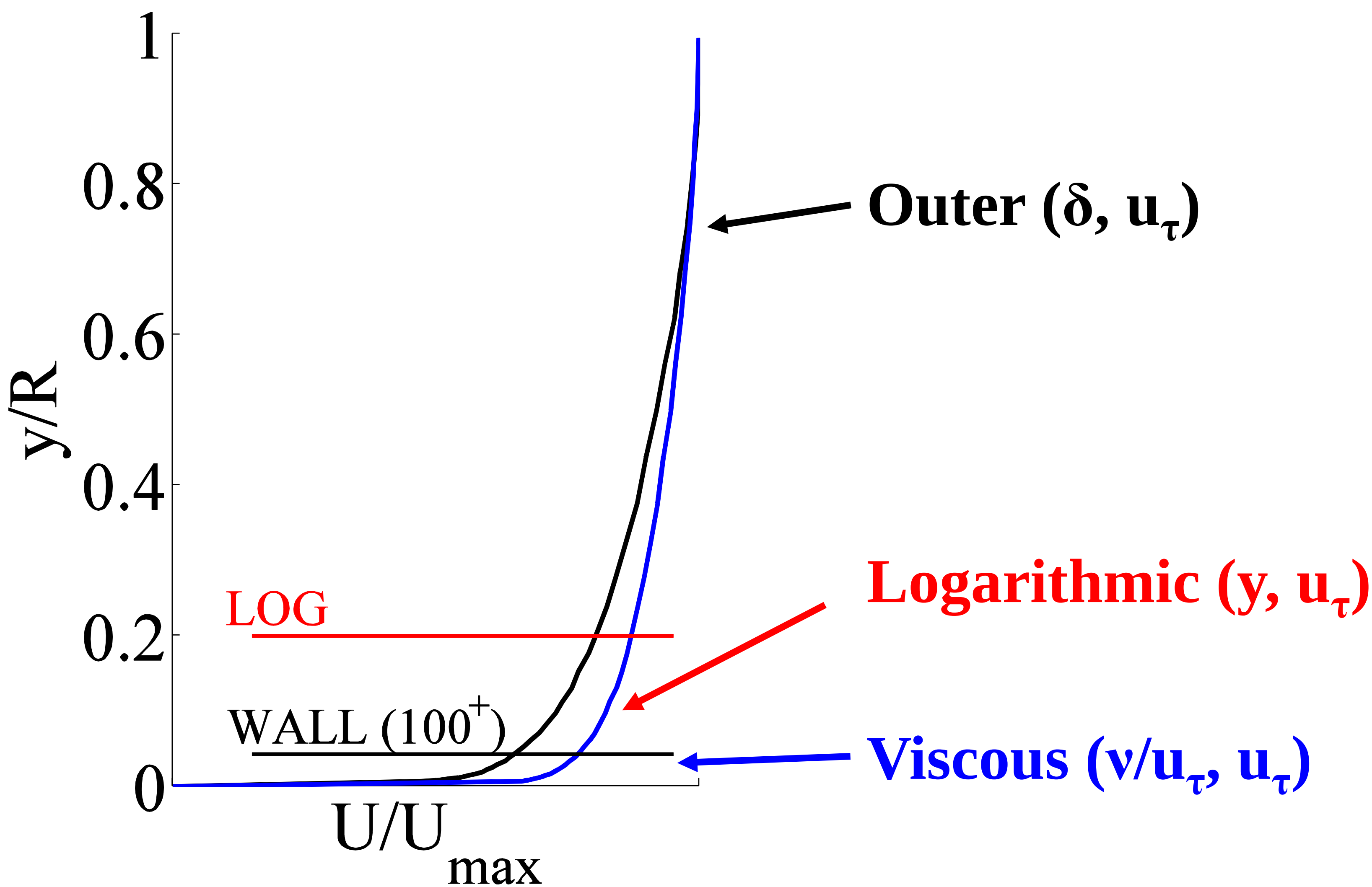


TBL
Re_τ=1800, u'^+=2

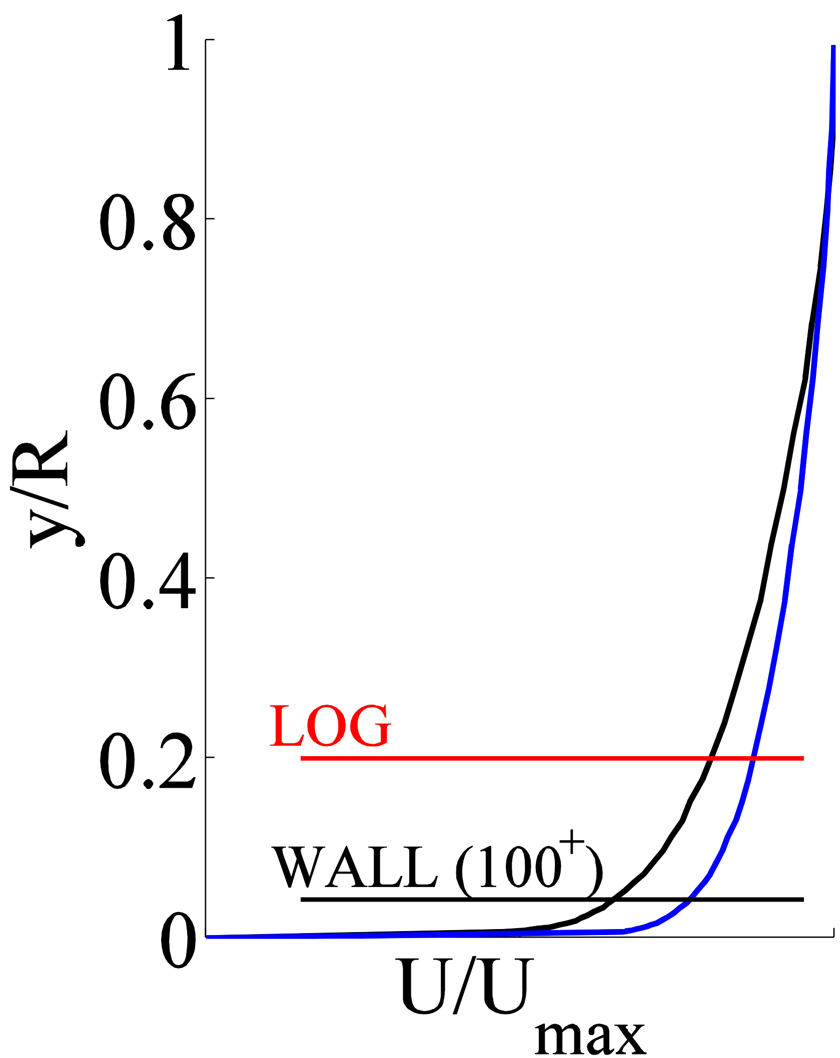
Outline

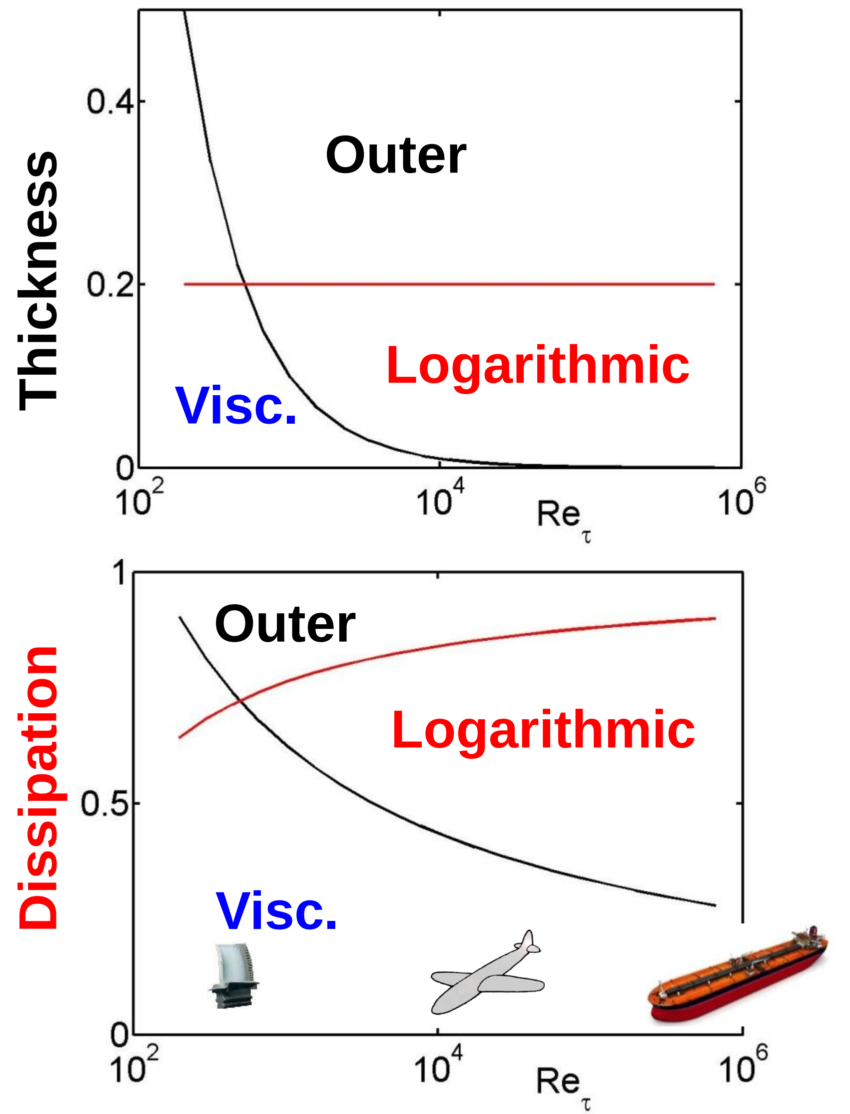
1. YOU REALLY WANT PHYSICS
2. YOU REALLY WANT DNS (LES)

ZPG Turbulent Boundary Layers



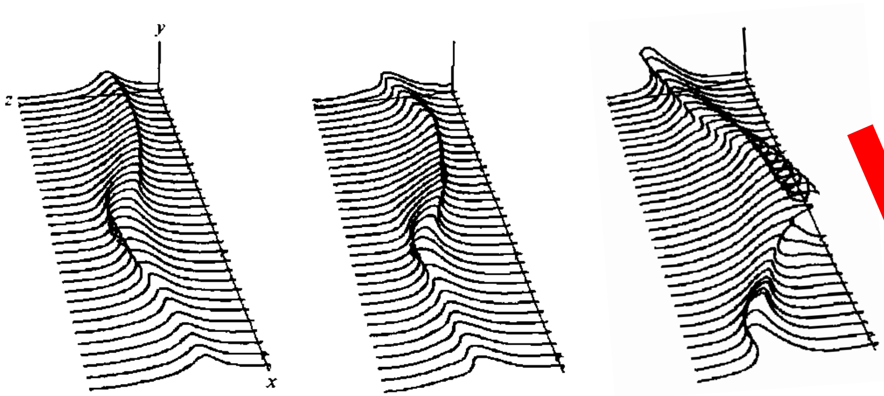
The wall "is not important"





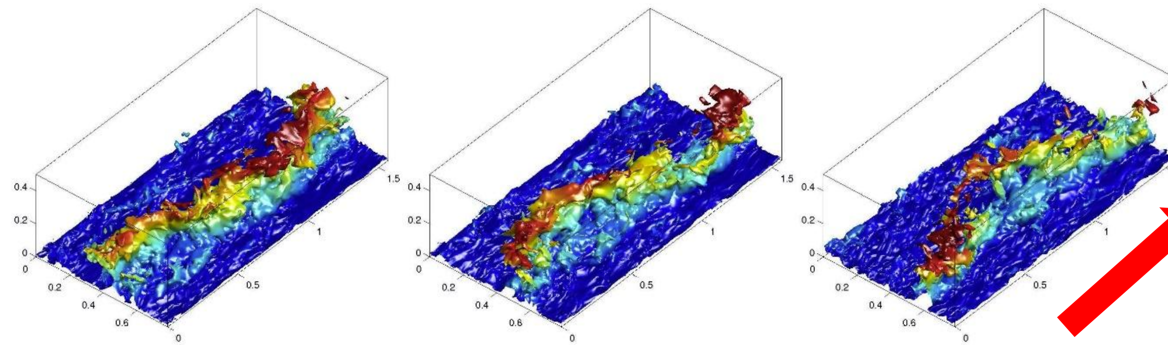
The wall "is not important"

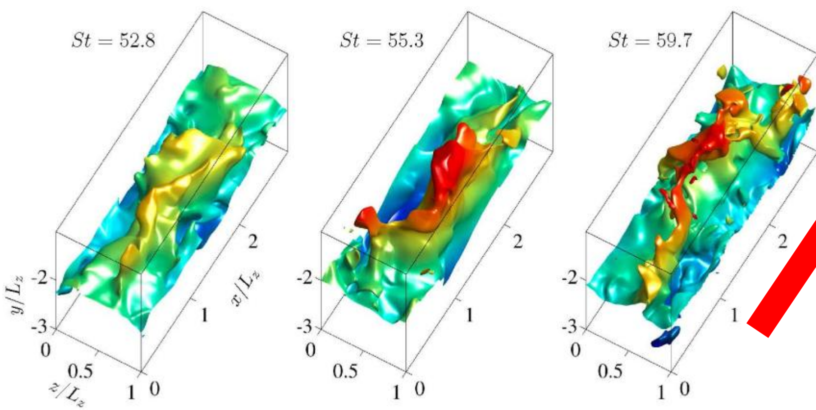
u-streaks



**viscous layer
near wall**

**logarithmic layer
far from wall**

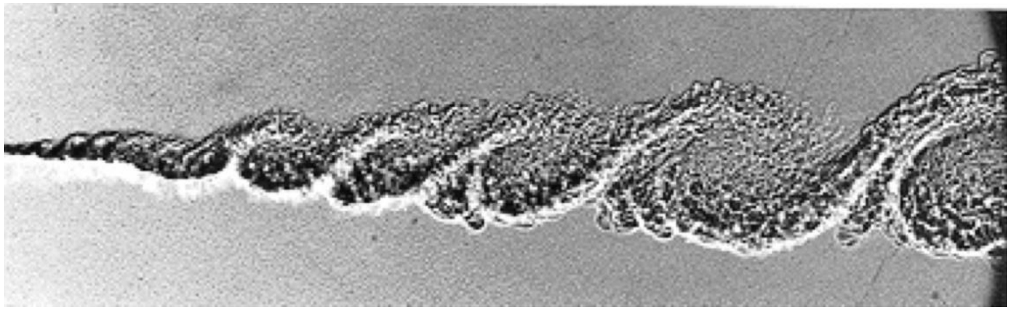


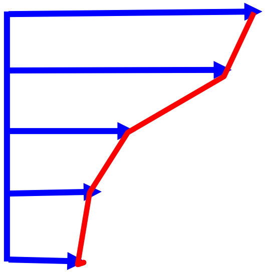


**homogeneous shear
no wall**

Turbulent Shear Flows

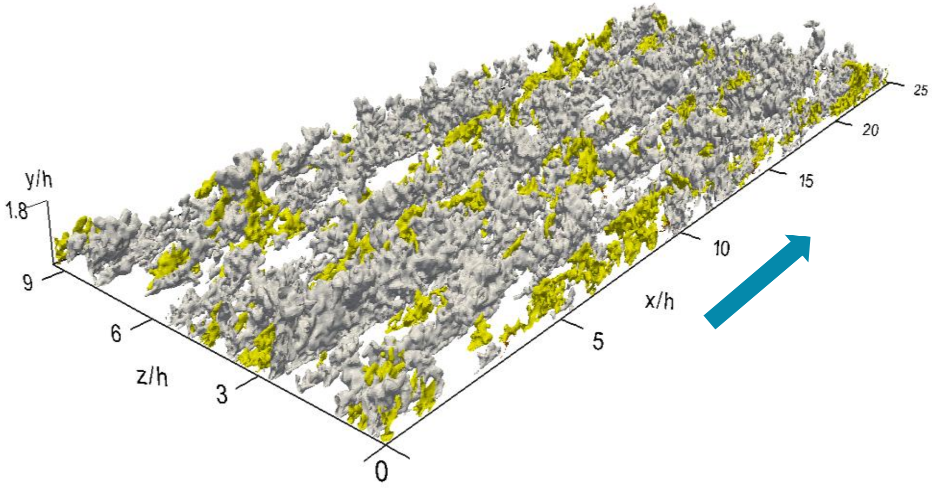
Free shear Flows

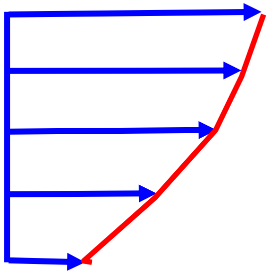




K-H Unstable

Wall-bounded Flows

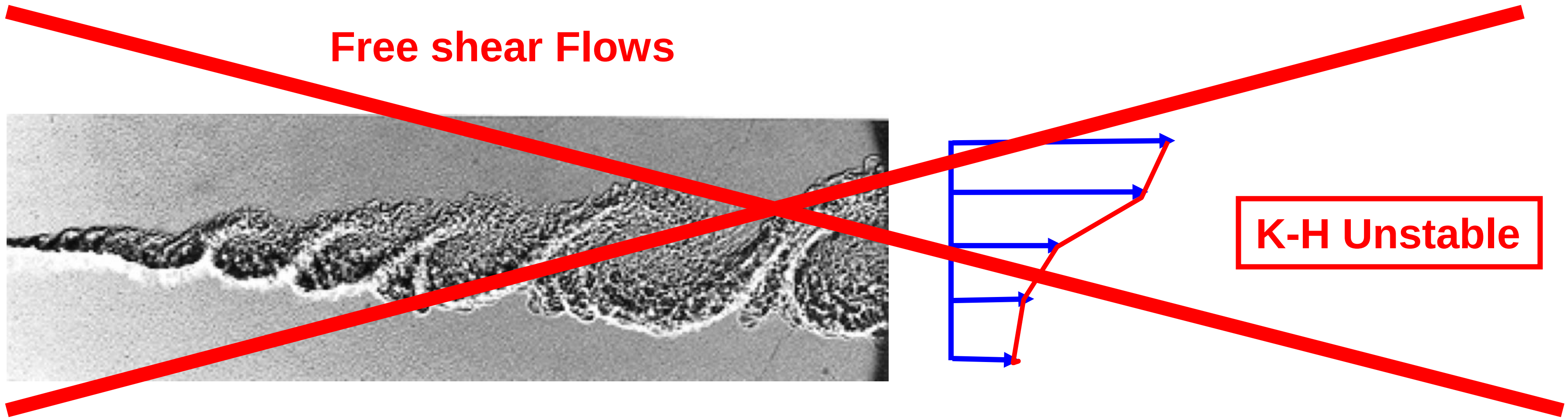




Stable

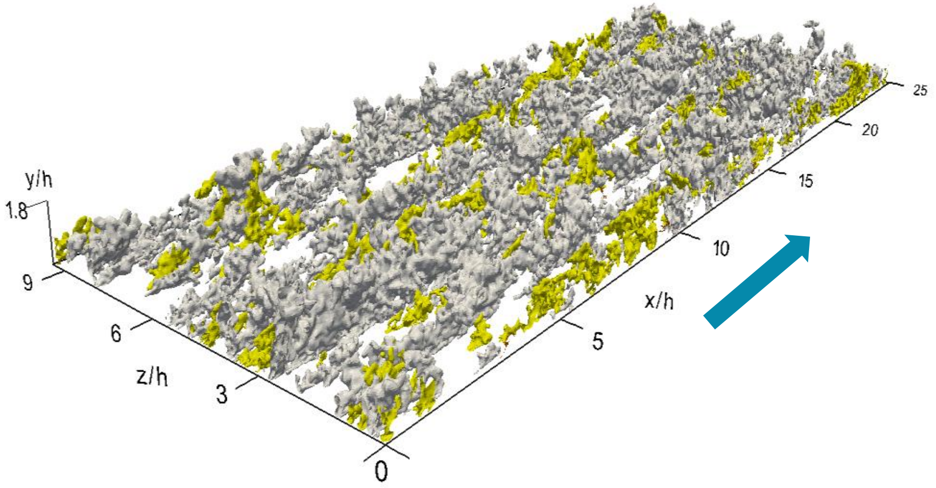
Turbulent Shear Flows

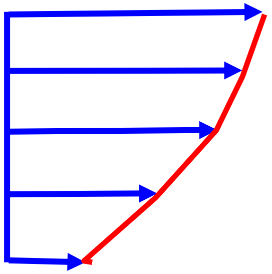
Free shear Flows



K-H Unstable

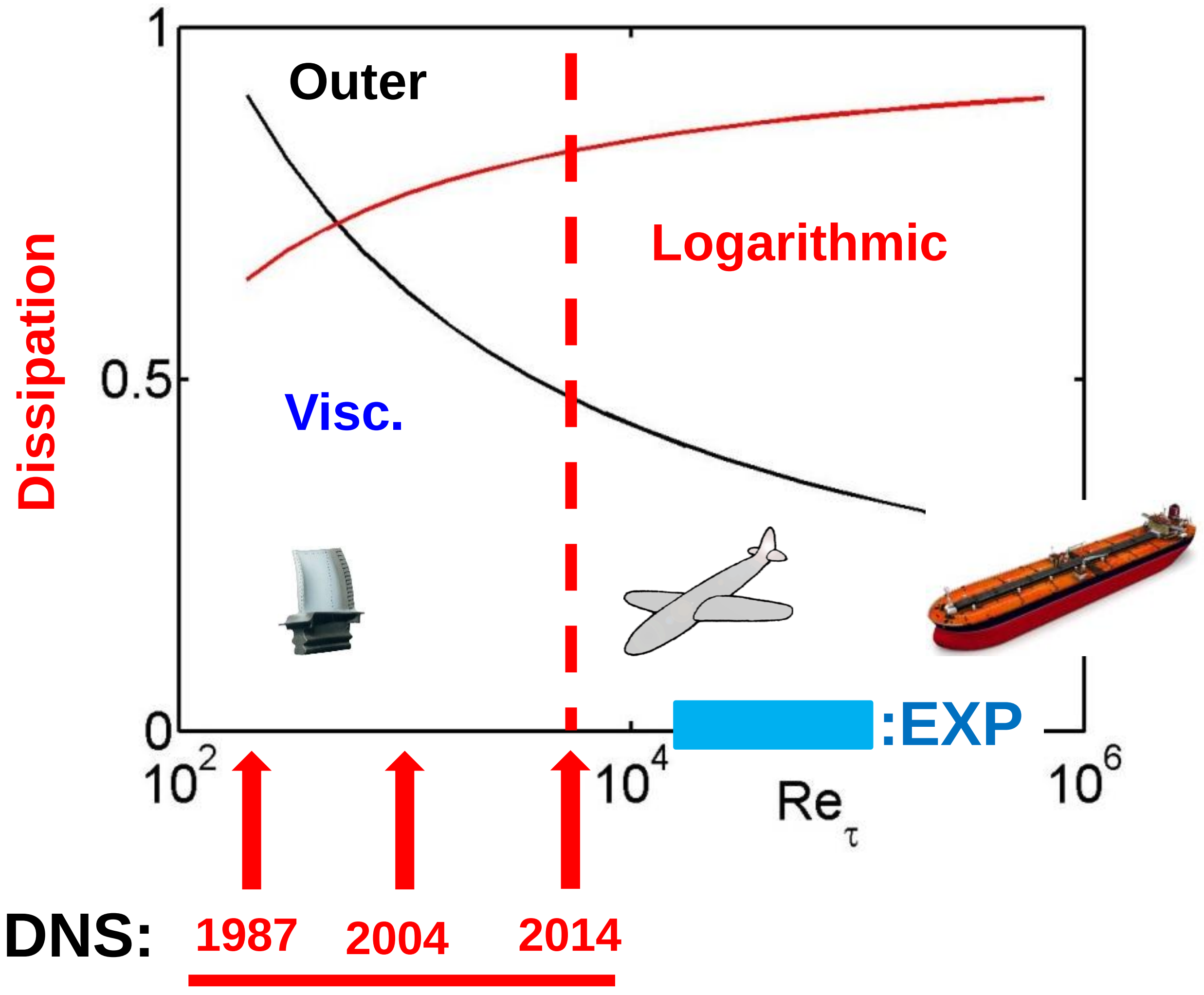
Wall-bounded Flows



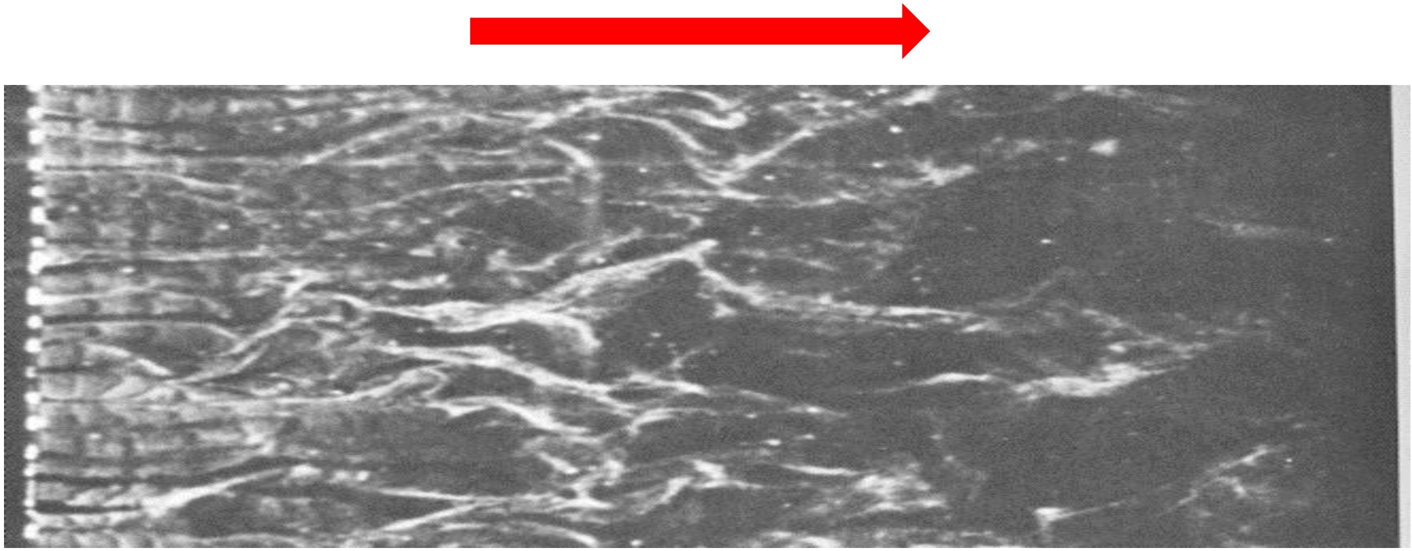


Stable

DNS of Wall-bounded Flows



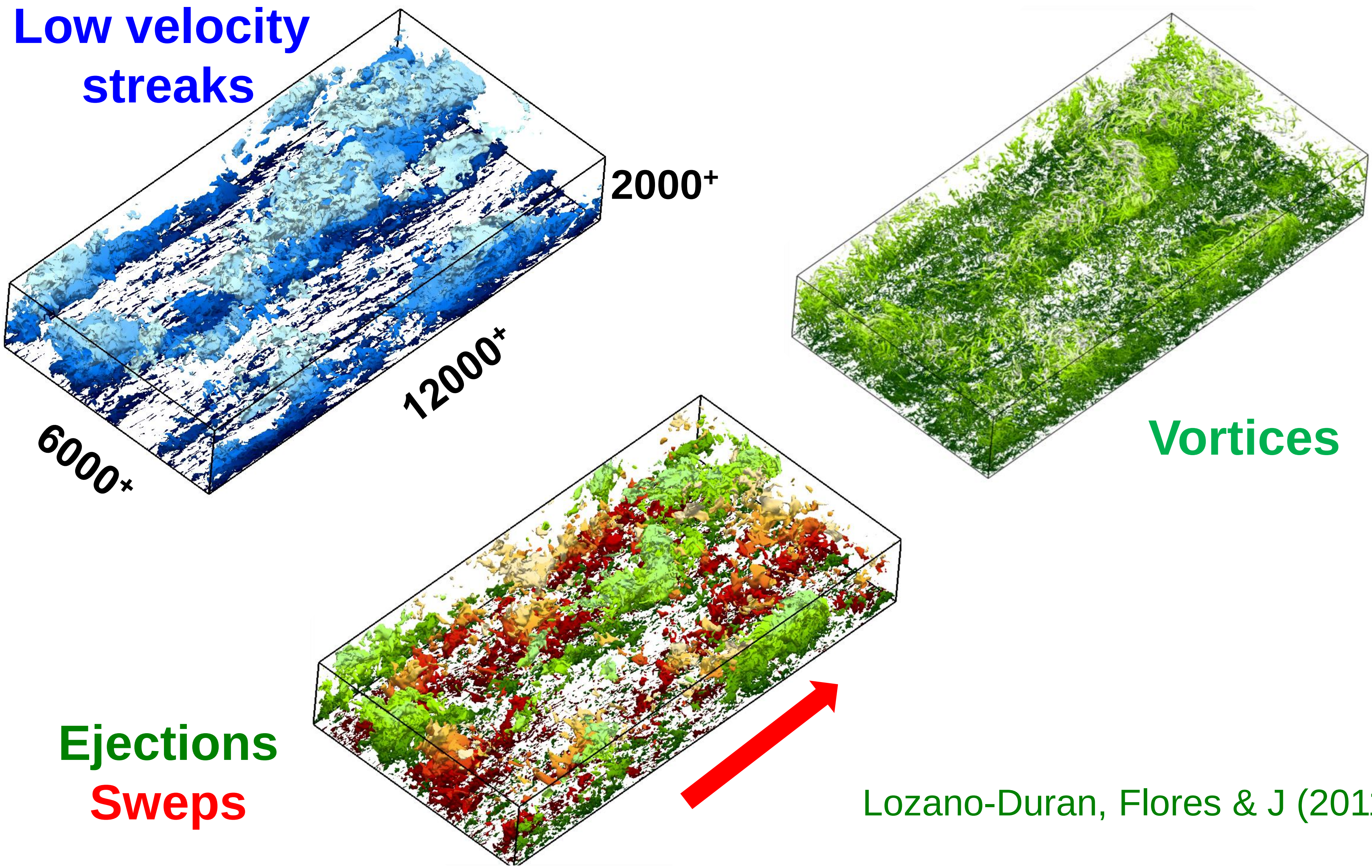
Wall Turbulence Before DNS



Streaks, Sweeps, Ejections ..

Kline et al. (1967)

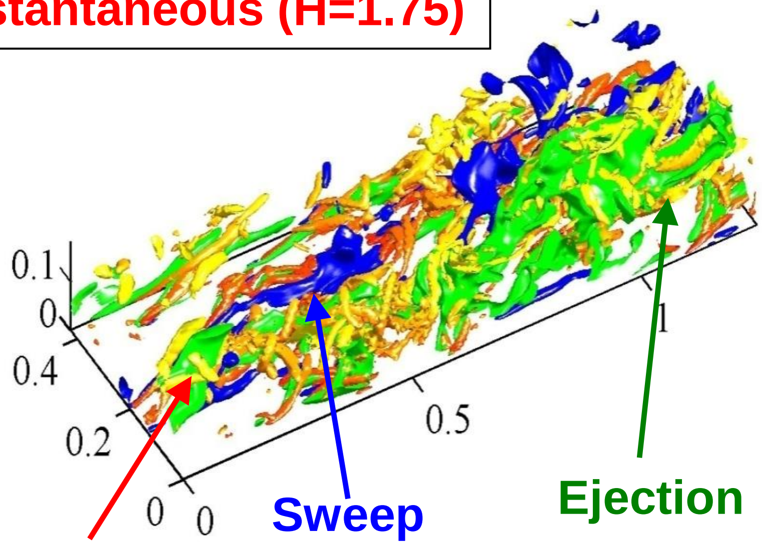
Wall Turbulence Now



Lozano-Duran, Flores & J (2011)

Sweeps and Ejections

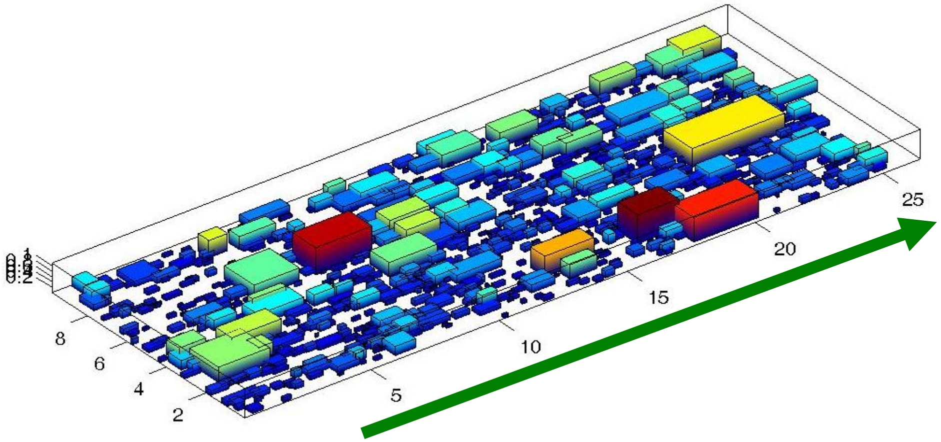
Instantaneous (H=1.75)



Vortex cluster

Sweep

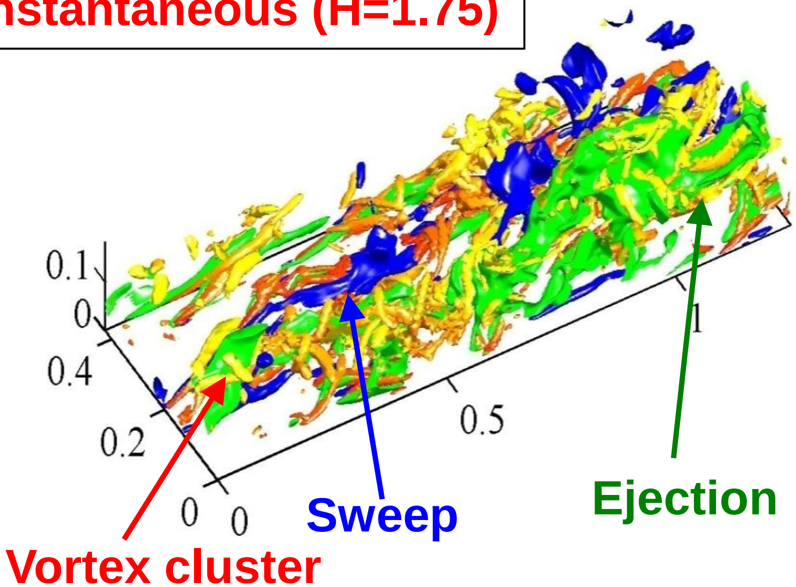
Ejection

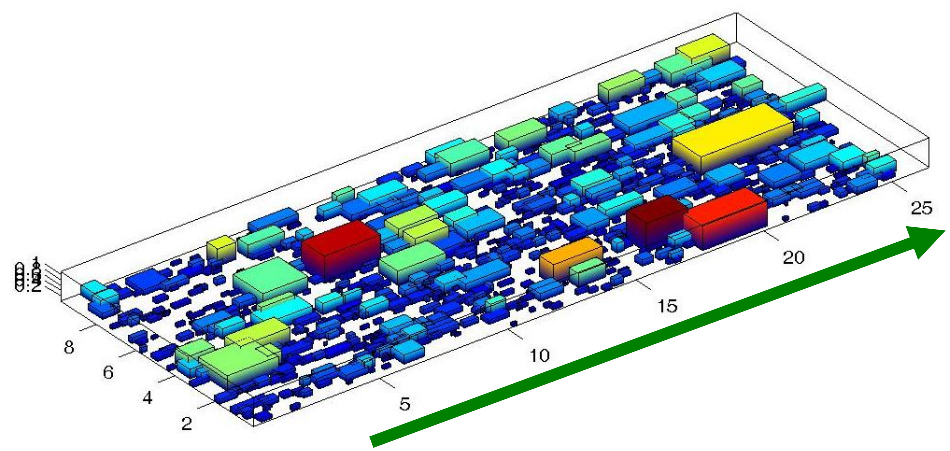


Lozano-Duran, Flores & J (2011)

Sweeps and Ejections

Instantaneous (H=1.75)



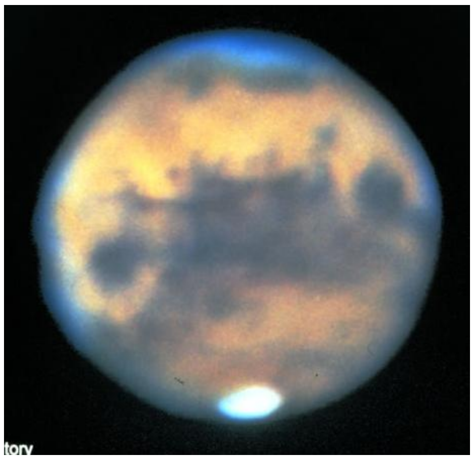


DNS HAS TO know everything

Lozano-Duran, Flores & J (2011)

Mars

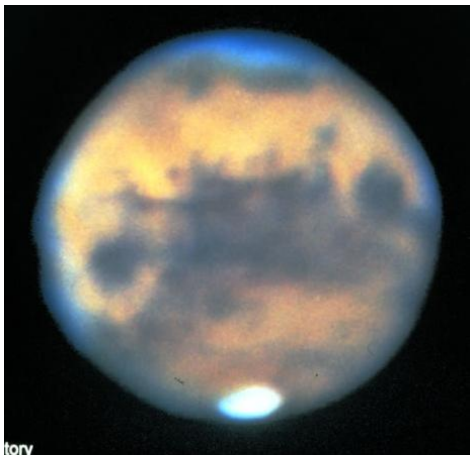
Pre -1960’s



Canals, Chlorophyll, Civilization

Mars

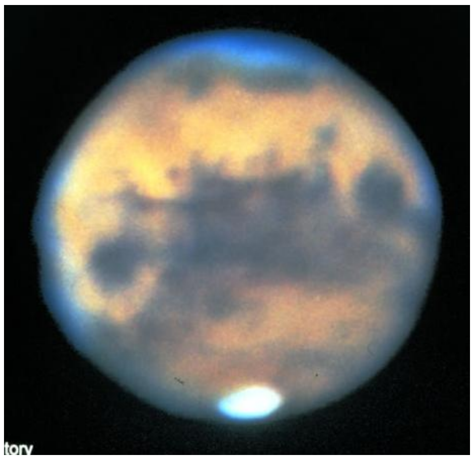
Pre -1960's



Post-2007

Mars

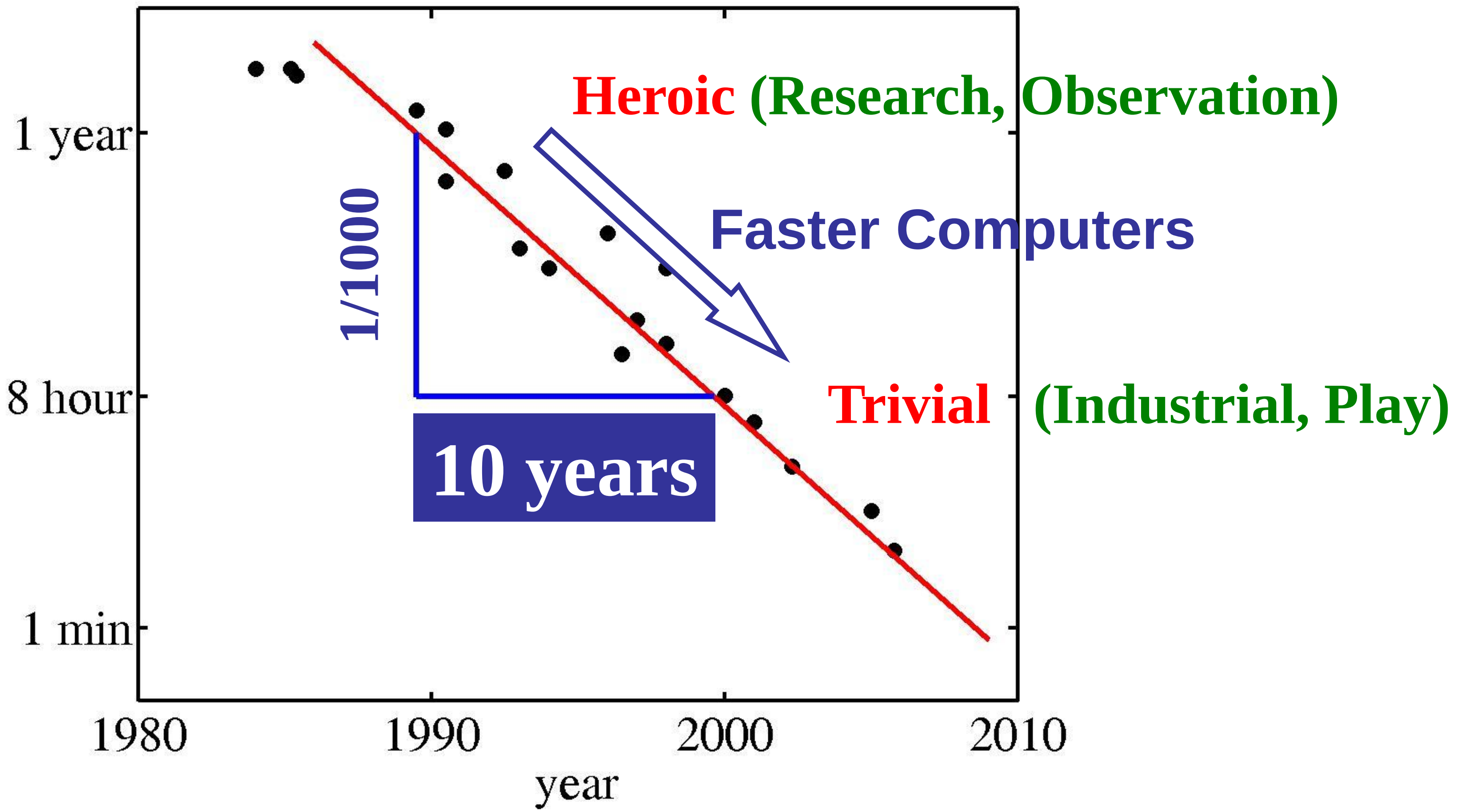
Pre -1960's



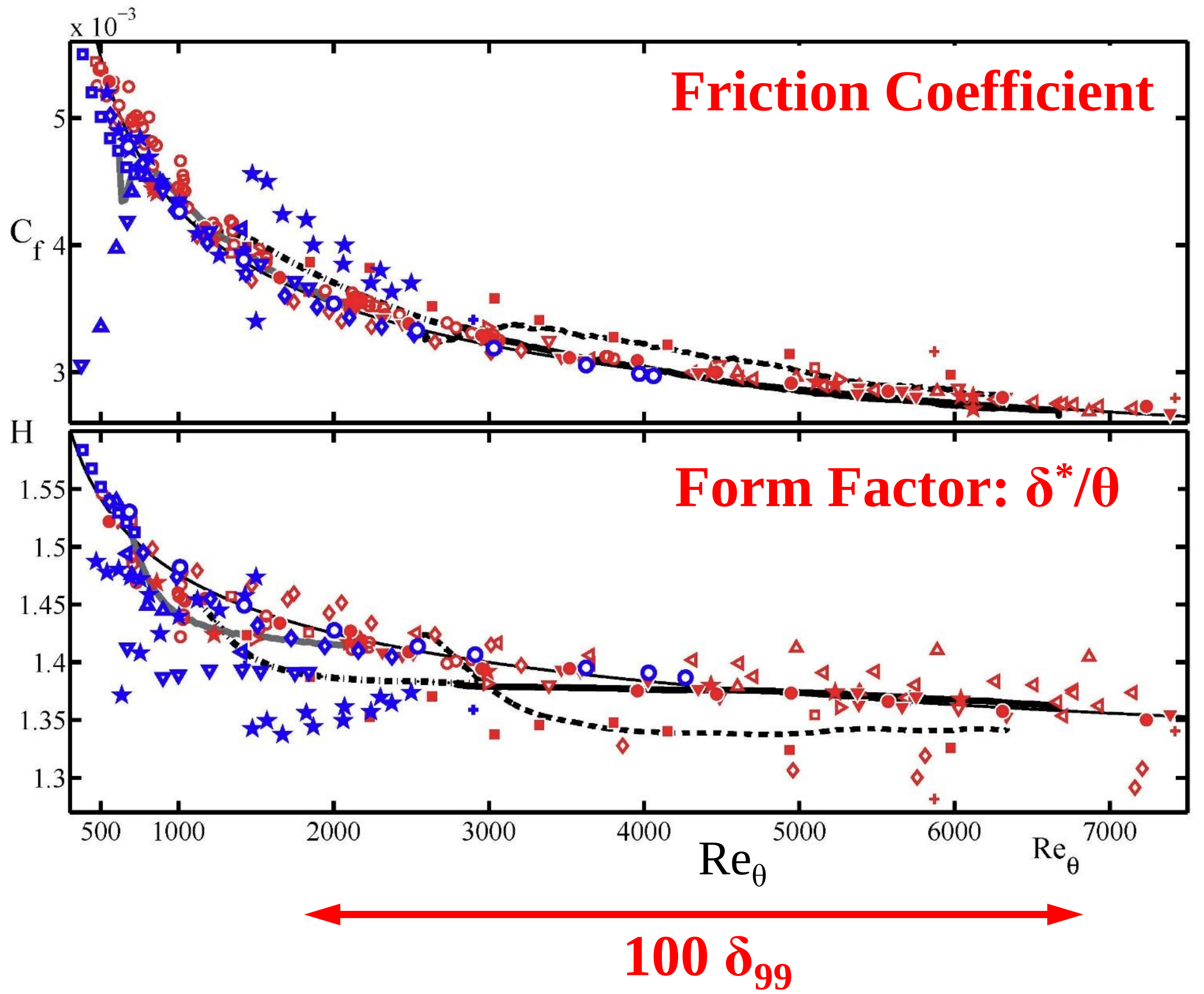
Post-2007

"No speculation"

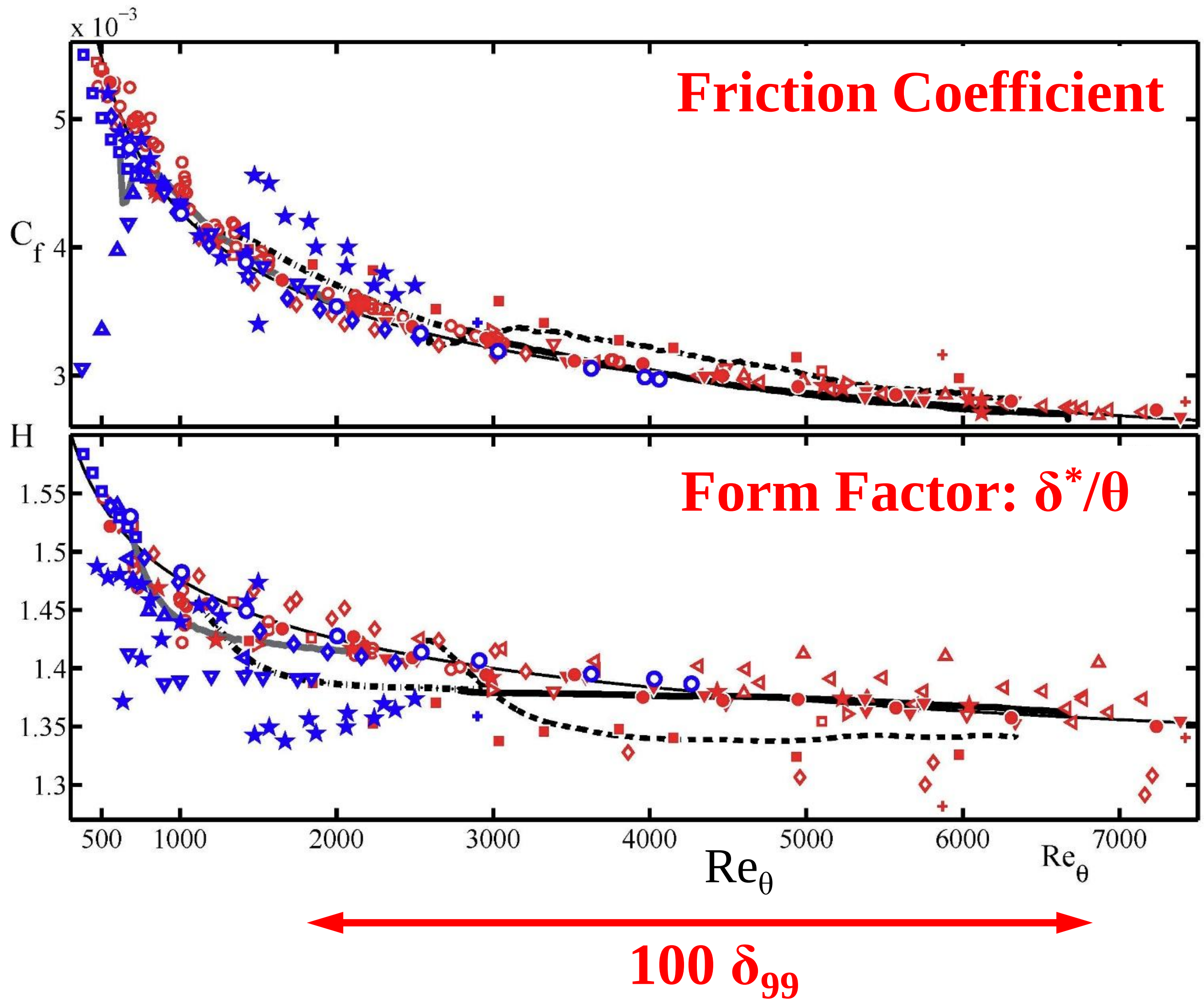
Computers get Faster



Zero-Pressure-Gradient BL



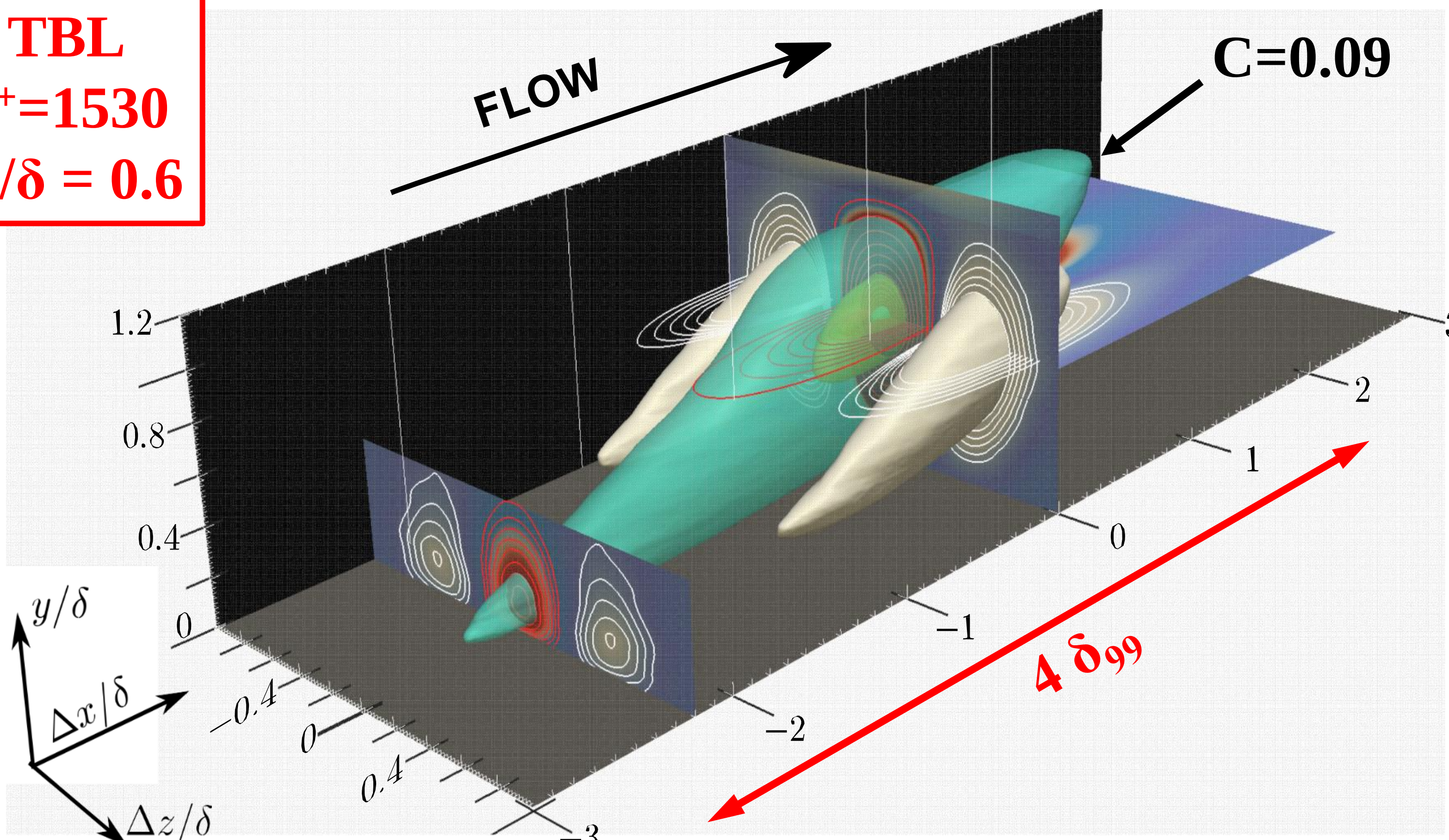
Boundary Layers have Long Memories



The C_{uu} Correlation

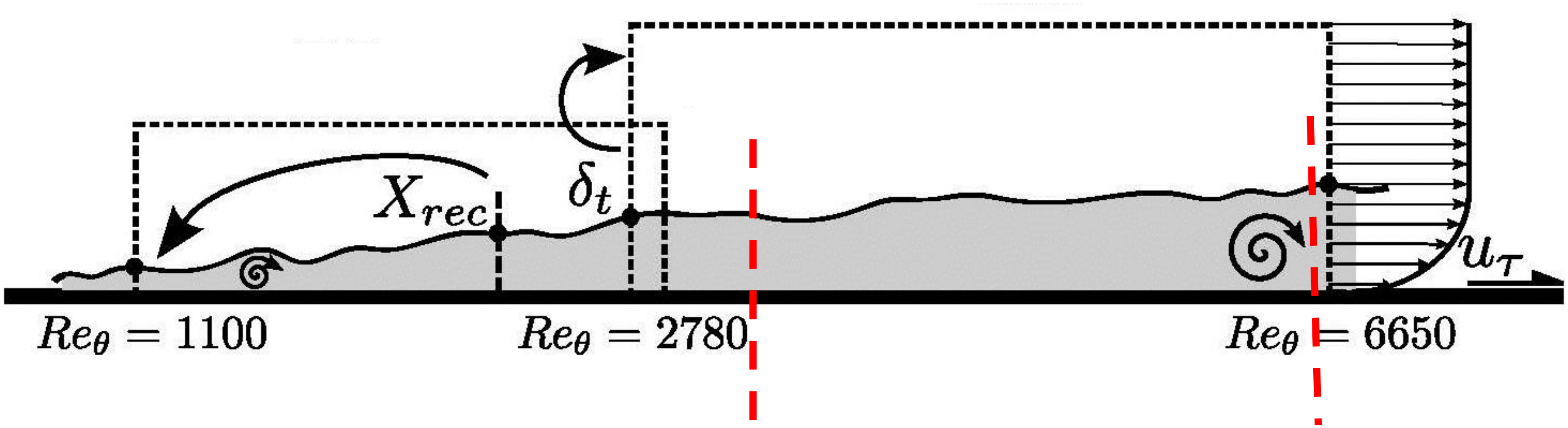
$$C_{uu} = \langle u(x)\, u(x')\rangle / (\langle u^2\rangle\langle u'^2\rangle)^{1/2}$$

TBL
δ^+=1530
y'/δ = 0.6



Sillero, J & Moser (PoF 2014)

ZPG Boundary Layers DNS

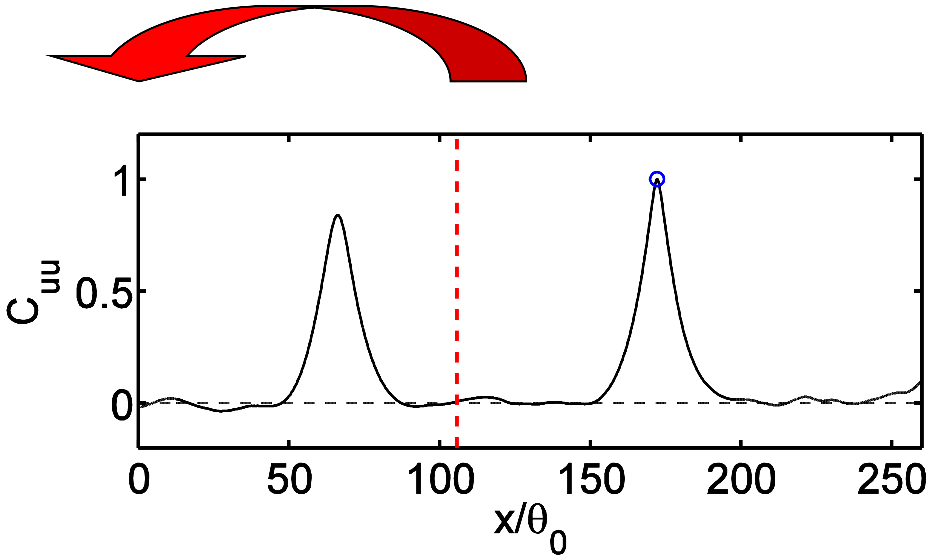


Re_θ	4025	6510
δ^+	1301	1990

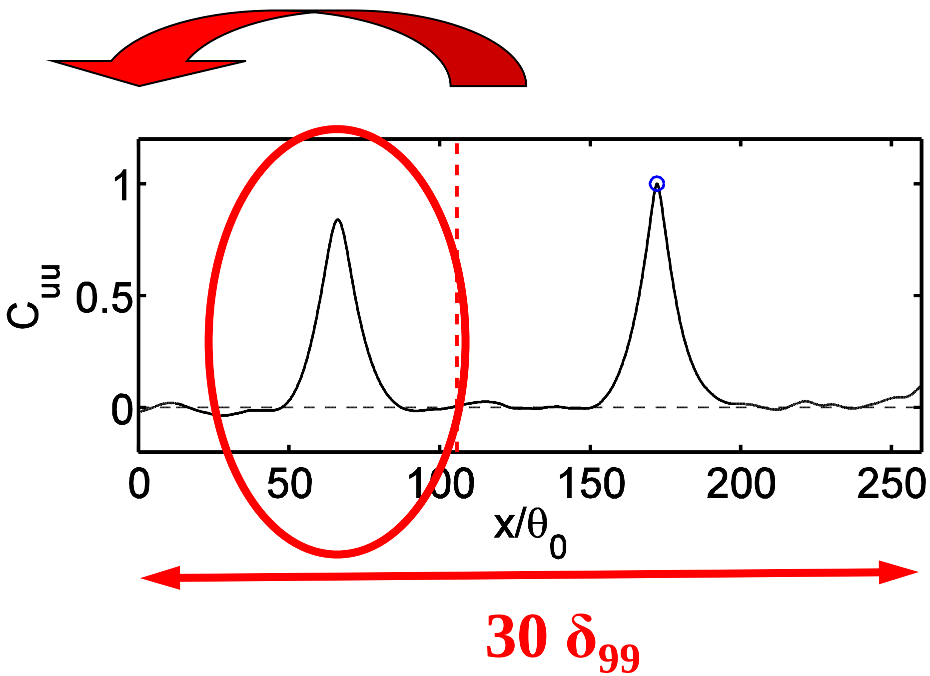
One-point statistics. Sillero, J & Moser (PoF 2013)

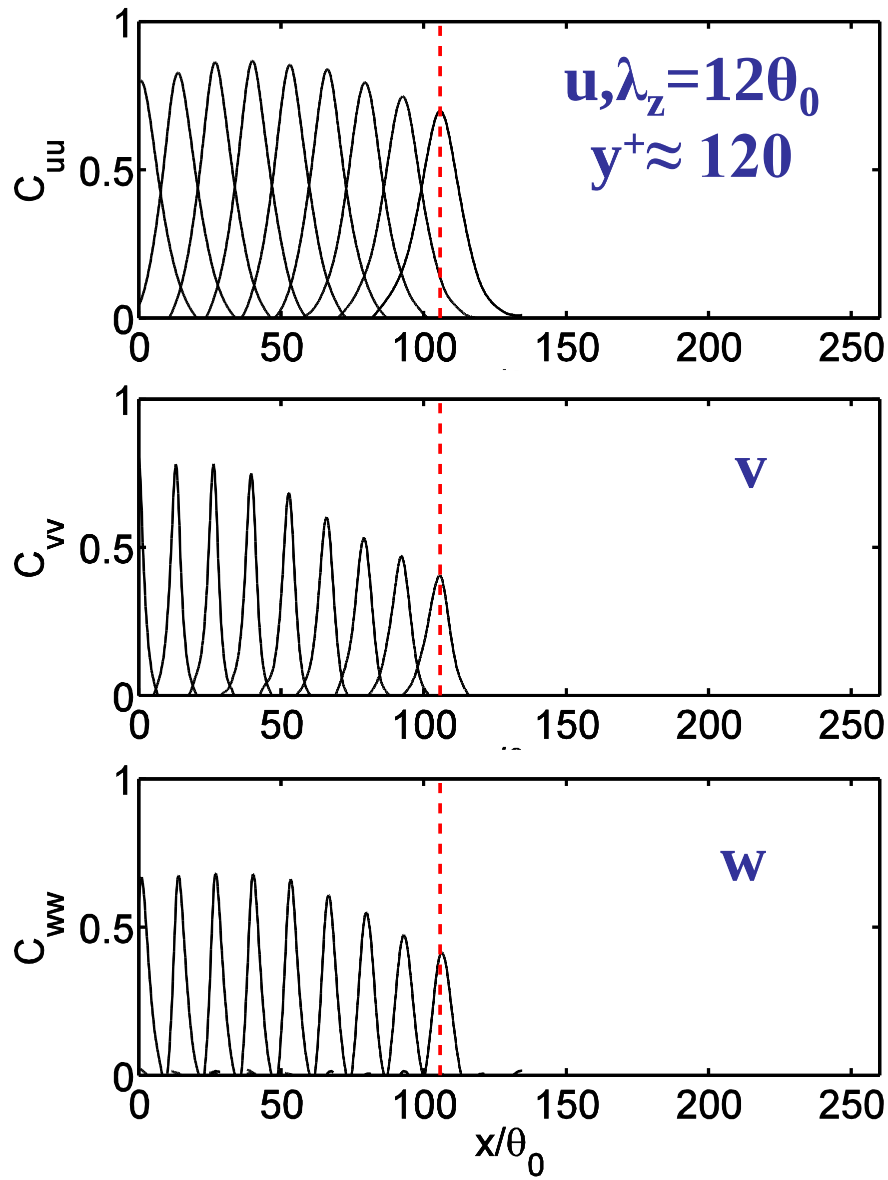
Correlations, spectra. Sillero, J & Moser (PoF 2014)

The True C_{uu} Correlation

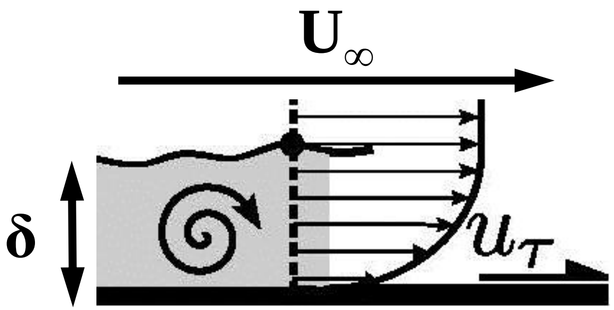


The Memory of the inlet

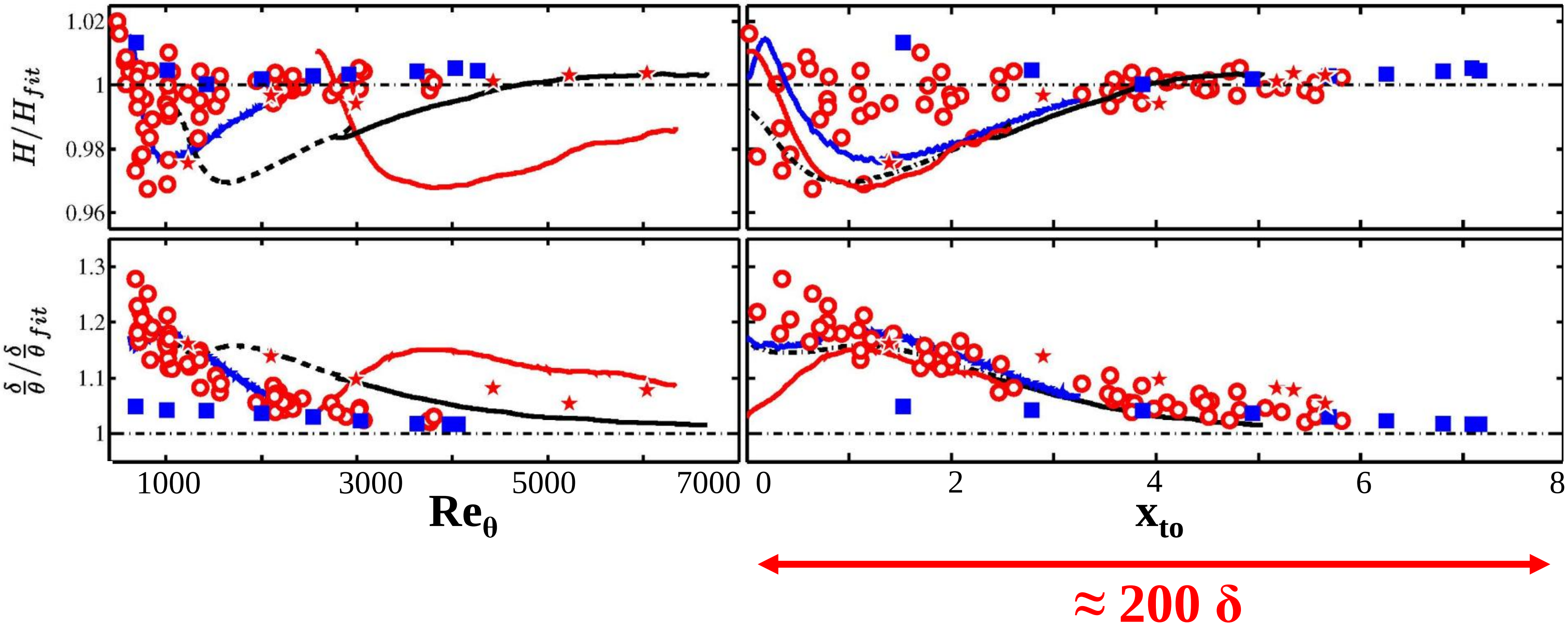




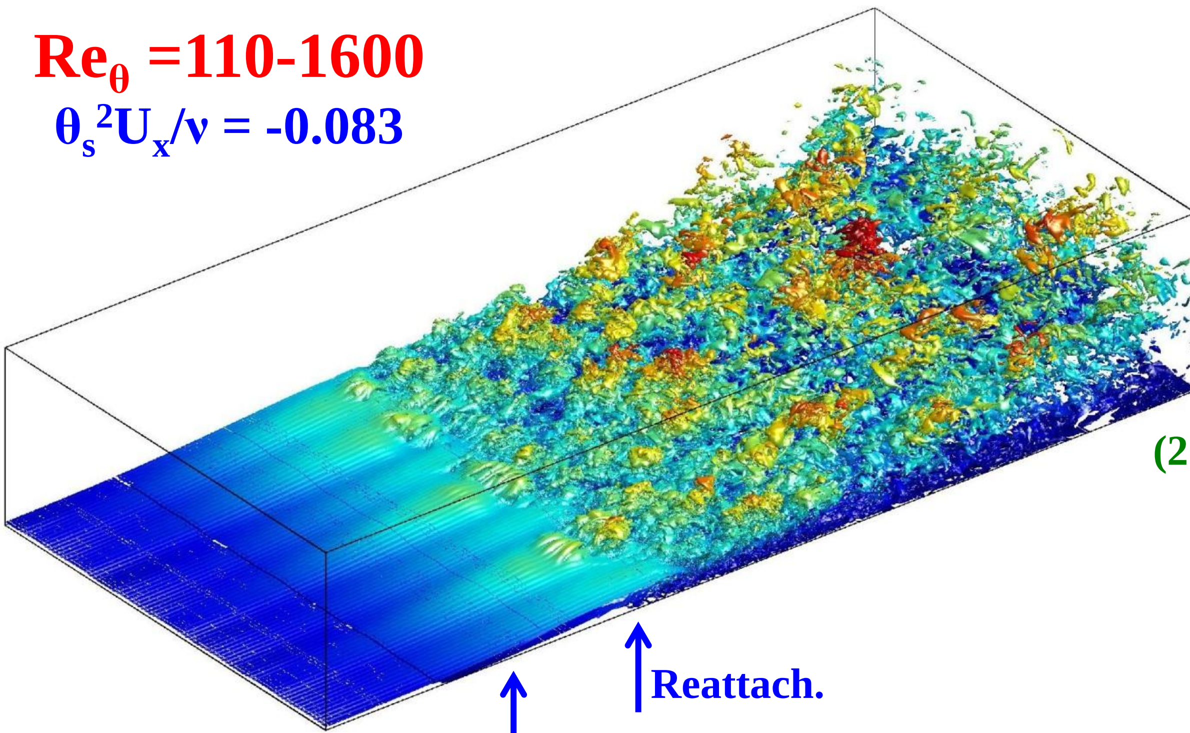
The Eddy-turnover Length



$$x_{to} = \int \frac{dx}{U_\infty} \frac{u_\tau}{\delta}$$



Adverse Pressure Gradient TBL

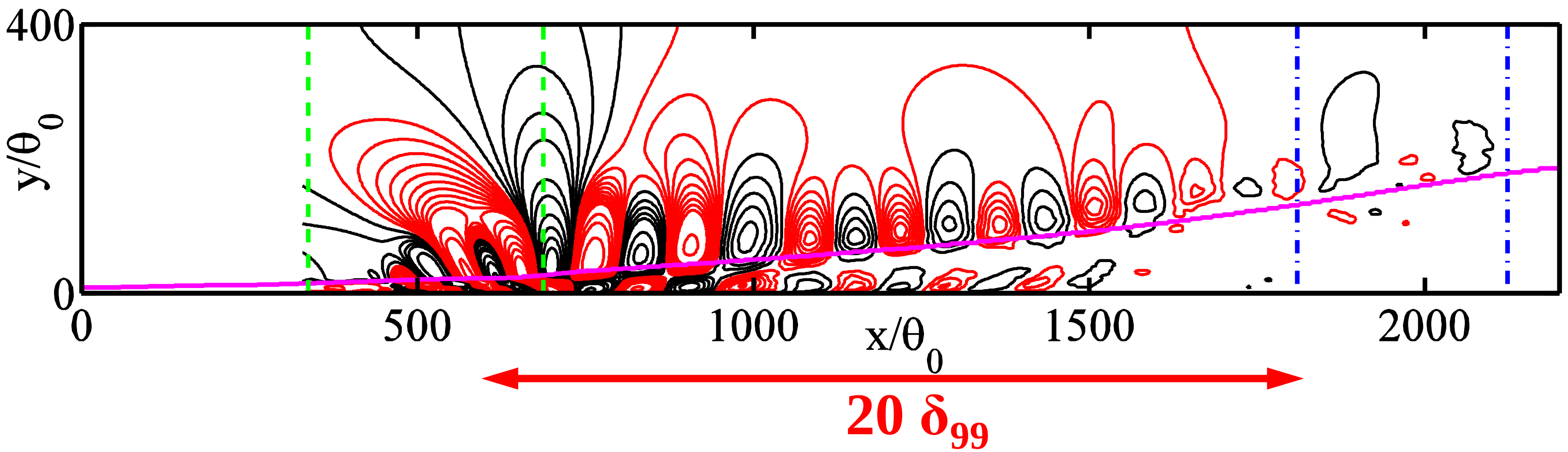


Model for low-pressure turbines (Exper. Zhang & Hodson, JoT 2005)

Simens *et al.*, JCP 2009

Long-range Correlations in Adverse Pressure Gradients BL

Re_θ =150-2200

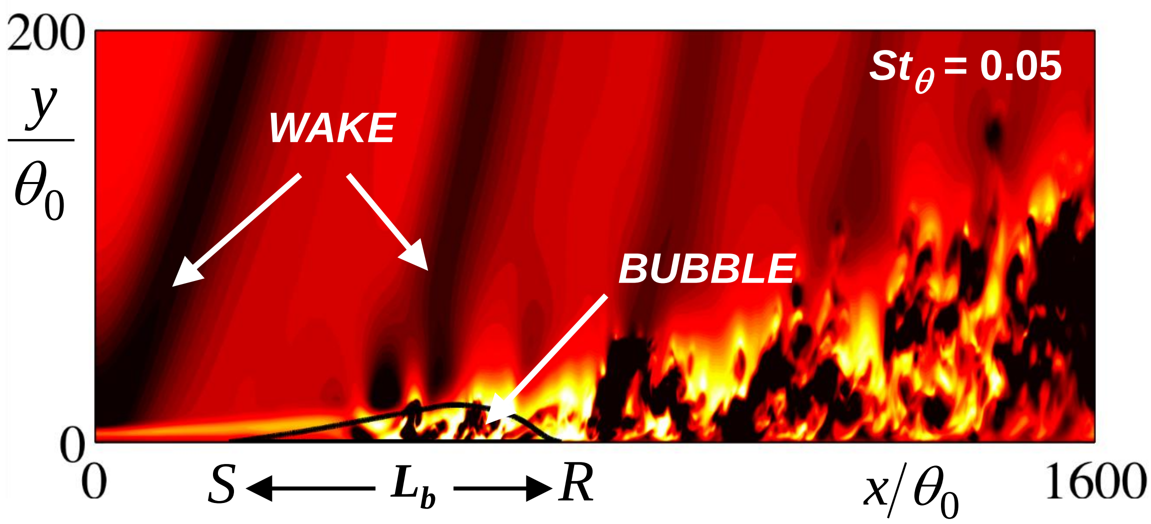


Gungor, Maciel, Simens, Soria (2013)

APG TBL + Wakes

"Laminar – Transition – Turbulence"

$Re_\theta = 110$

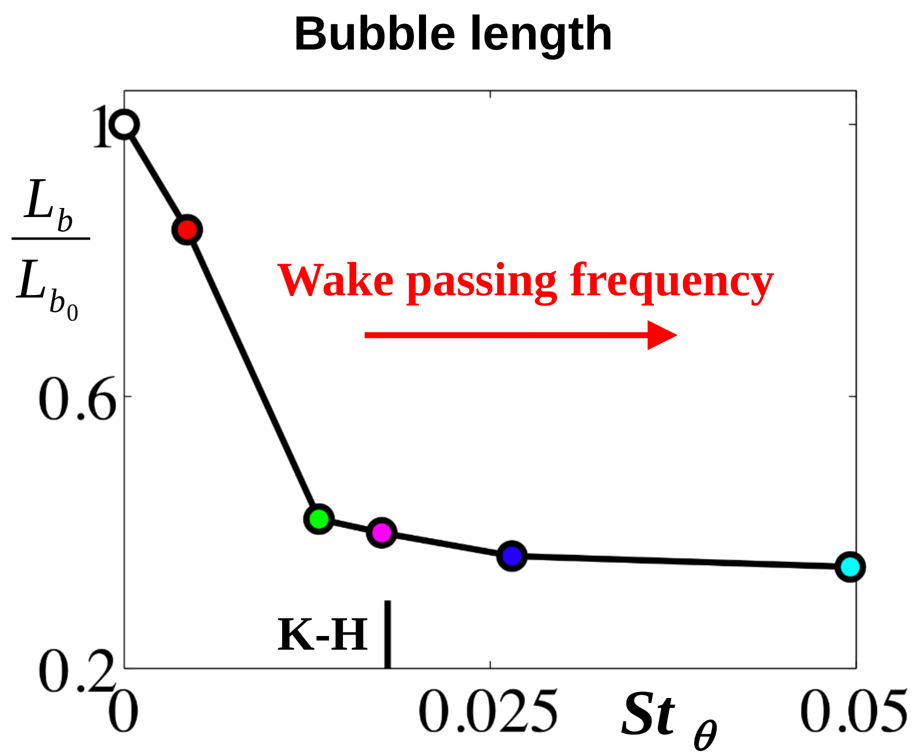


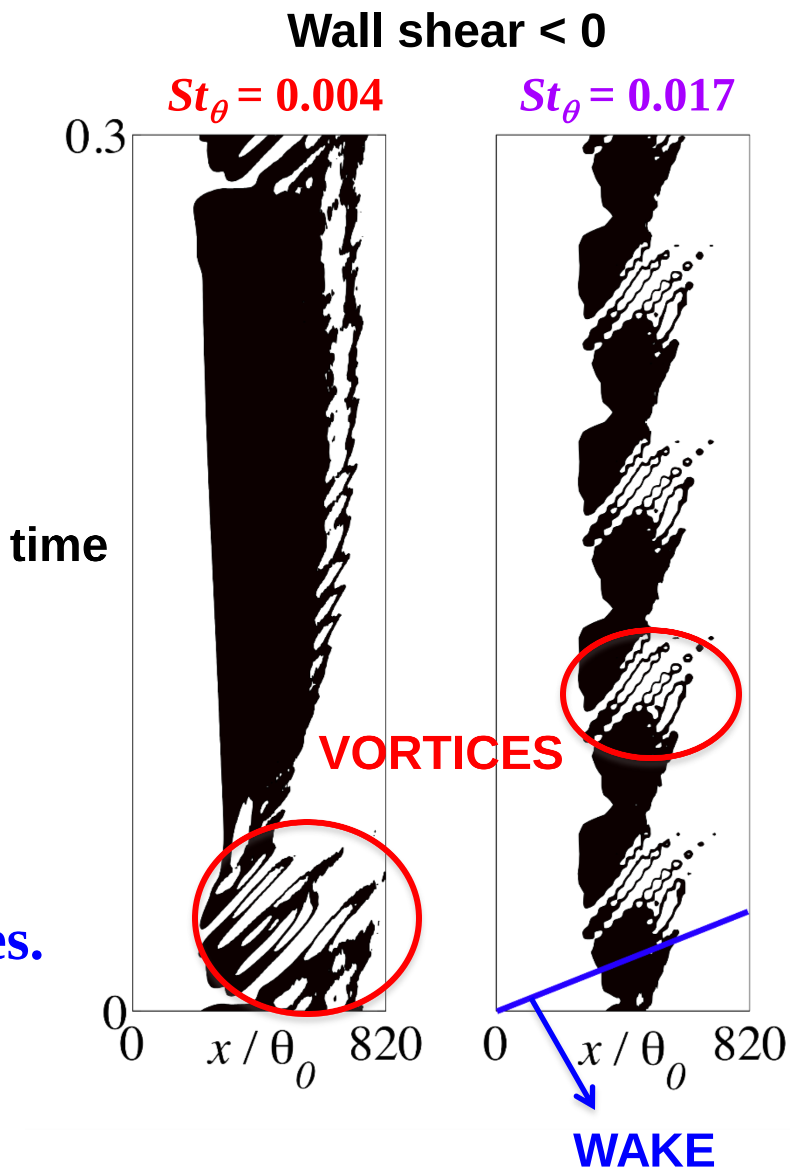
$Re_\theta = 1600$

- **Inflow:**
  - **Laminar** Hiemenz profile with steady 3D pert.
  - **Wake deficit** only, **turbulent fluctuations** neglected.
- **Wake passing frequency:**
  - St_θ = 0-0.05 (f θ_b/U_{ref})

Gungor, Simens & J, JoT 2012

Bubble Control with Wakes

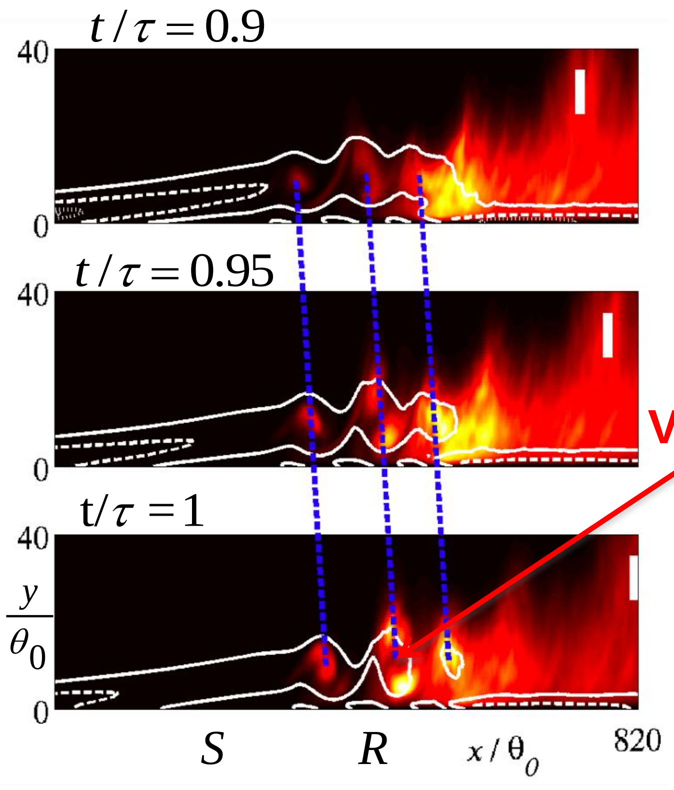




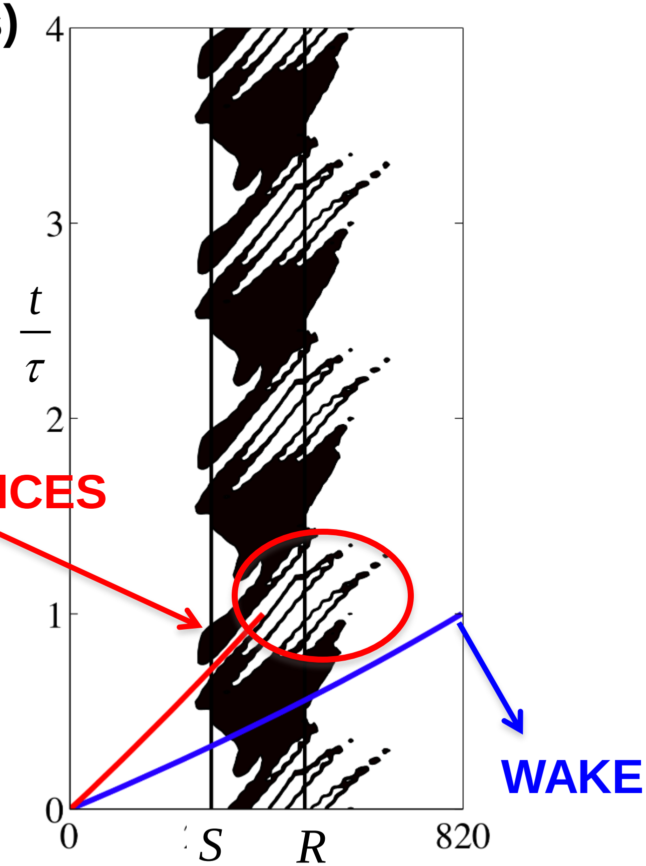
Separation moves **downstream** by the effect of **momentum** carried by the **wakes.**
Reattachment moves **upstream** by the **entrainment** due to **VORTICES.**

Precursor of the K-H vortices, $St_\theta = 0.026$

Vorticity (lines)
Spanwise fluctuations (contours)



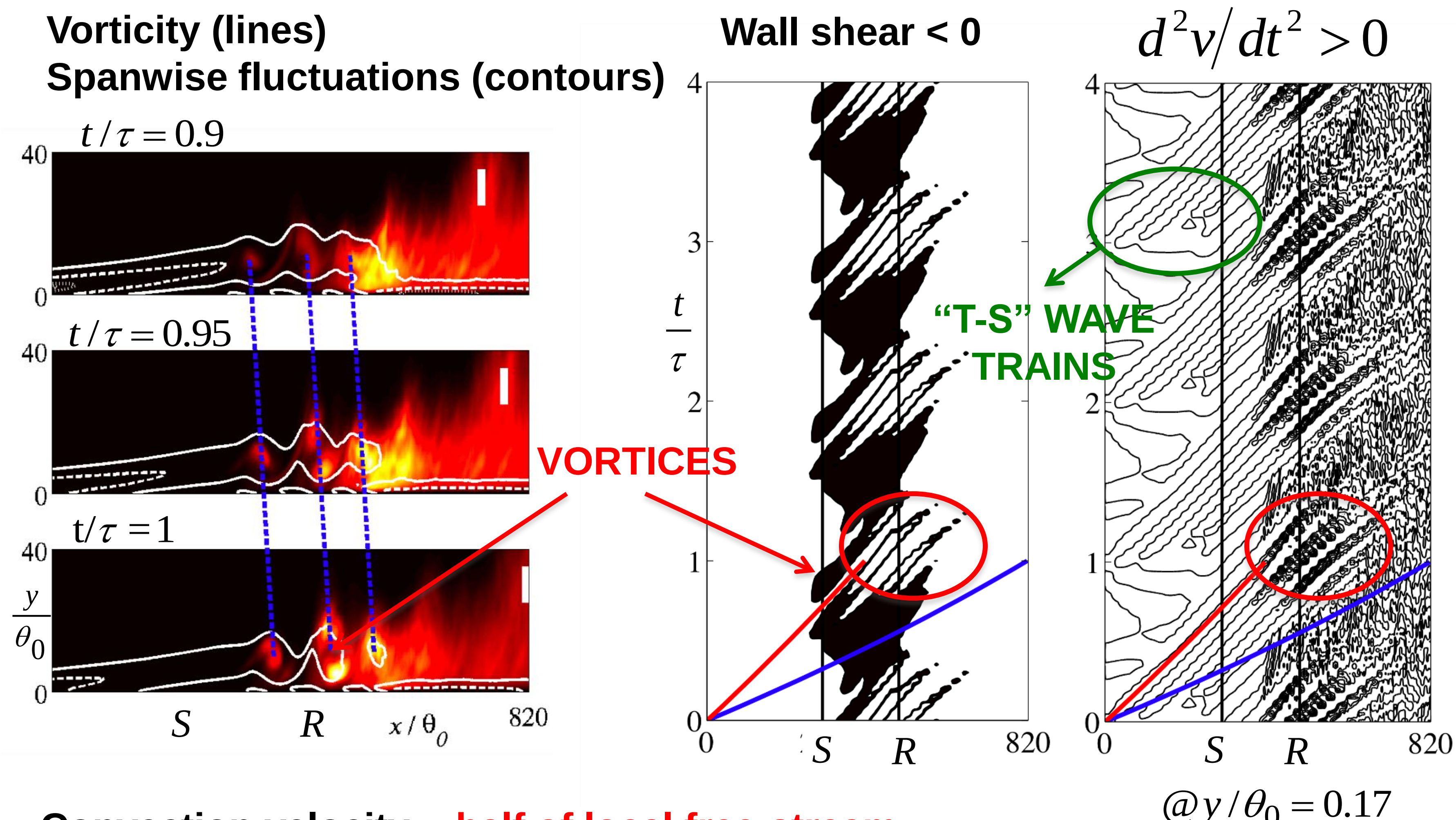
Wall shear < 0



Convection velocity ~ half of local free-stream

Gungor, Simens & J, JoT 2012

Precursor of the K-H vortices, $St_\theta = 0.026$

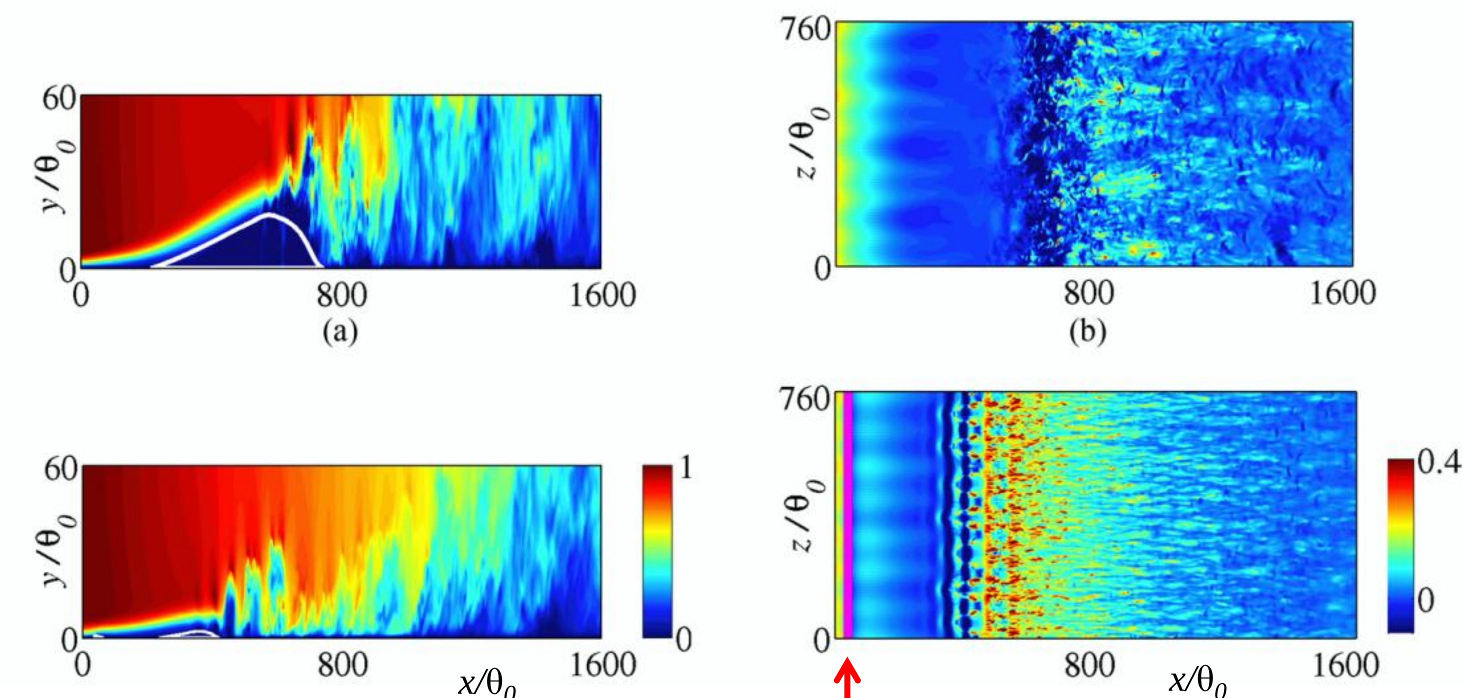


Convection velocity ~ half of local free-stream

Gungor, Simens & J, JoT 2012

Tripped Bubbles (Roughness)

Untripped

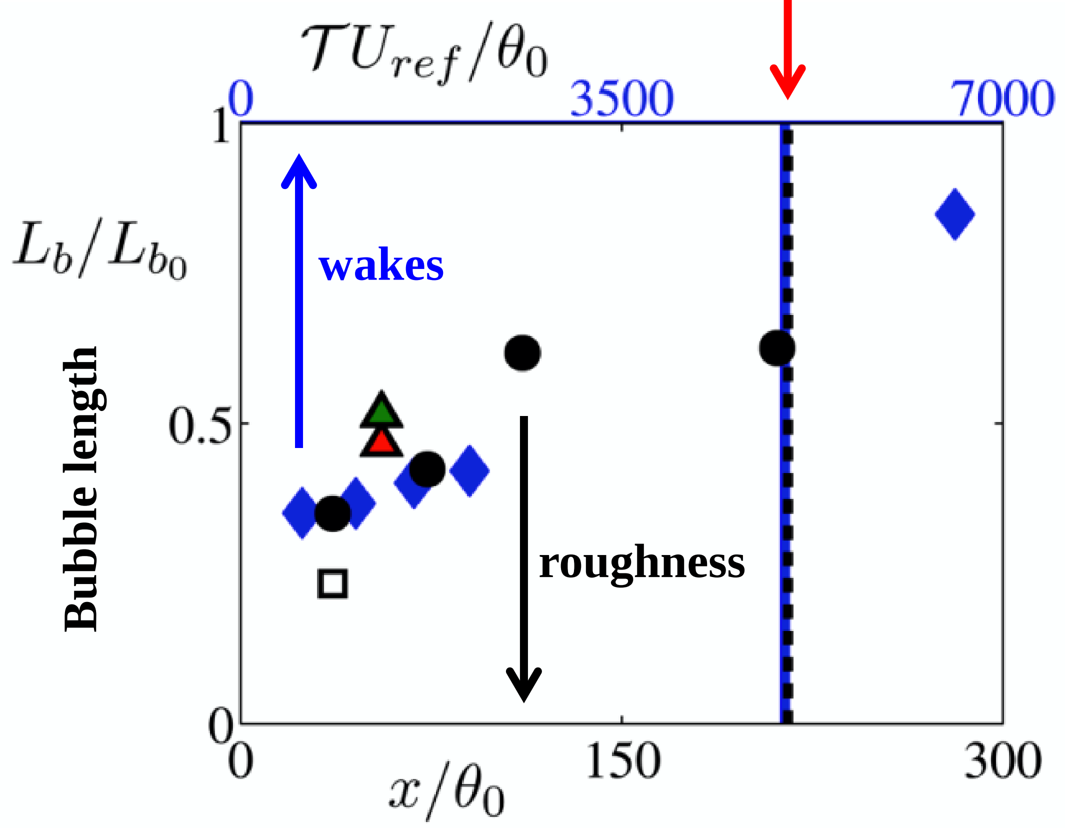


2D trip ($0.7\theta_0$)

Simens & Gungor, JoT 2014

Tripped Bubbles (Roughness)

Untripped bubble

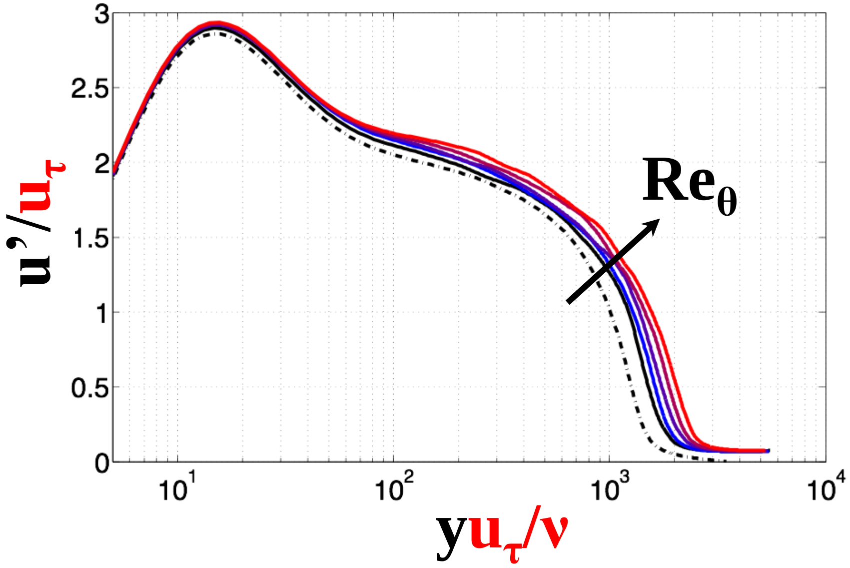


Trip location

Simens & Gungor, JoT 2014

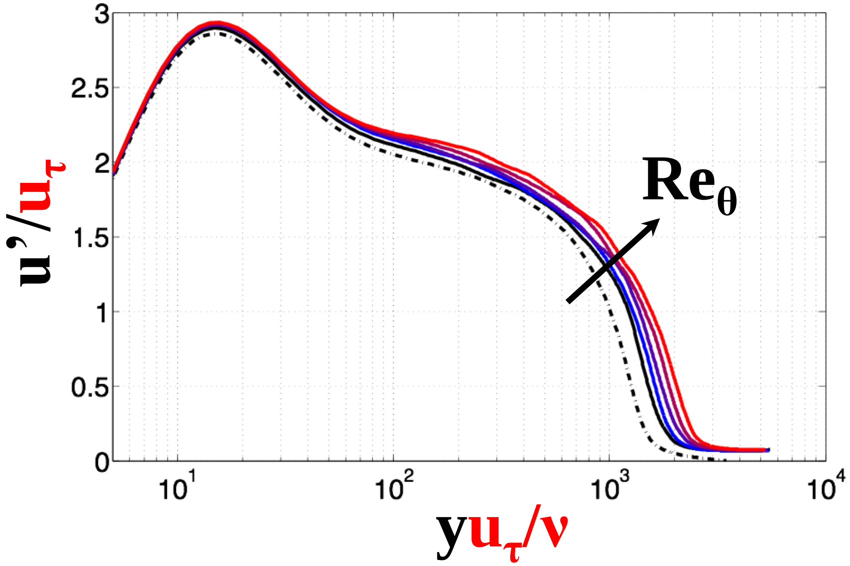
Scaling APG BL (????)

ZPG

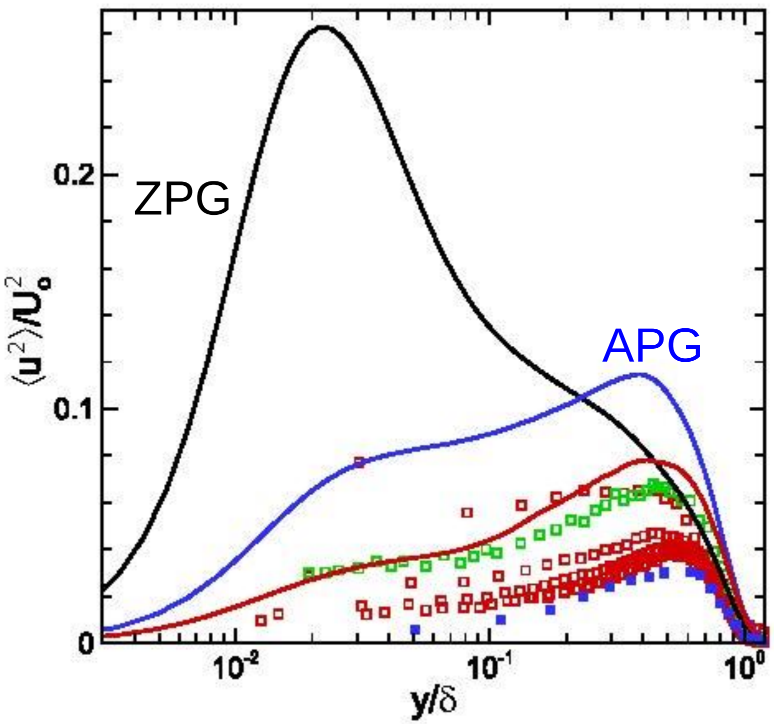


Scaling APG BL (????)

ZPG



APG



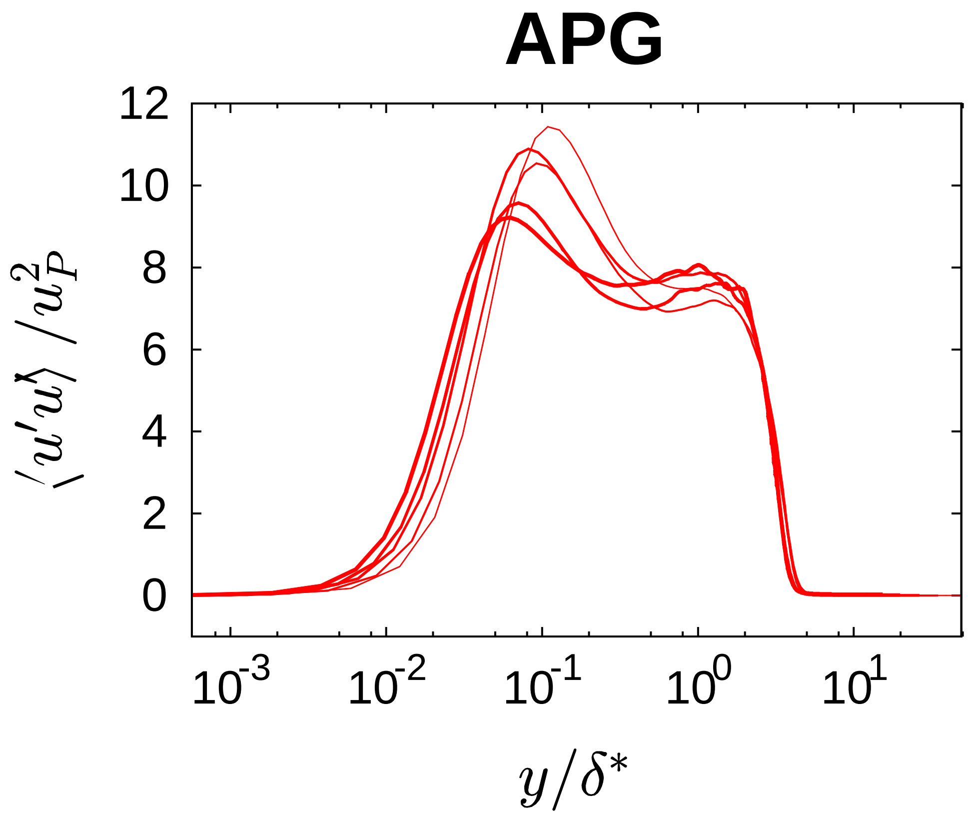
"Equilibrium" APG TBL

$U_\infty = A\, x^m$

$H \approx 2.5$

$u_p^2 = (\delta^*/\rho)dp/dx$

$u_p/U_\infty = \text{const.}$



Kitsios et al., IUTAM 2015

Summary

We know a lot about the ZPG Turb. BL

(in large part because of DNS)

Know something about the transitional APG BL

(in part because of DNS)

We know next to nothing about the APG TBL

(maybe because of lack of DNS)

Thank you