Very large scale streaks: non-normal growth, control & self-sustained processes

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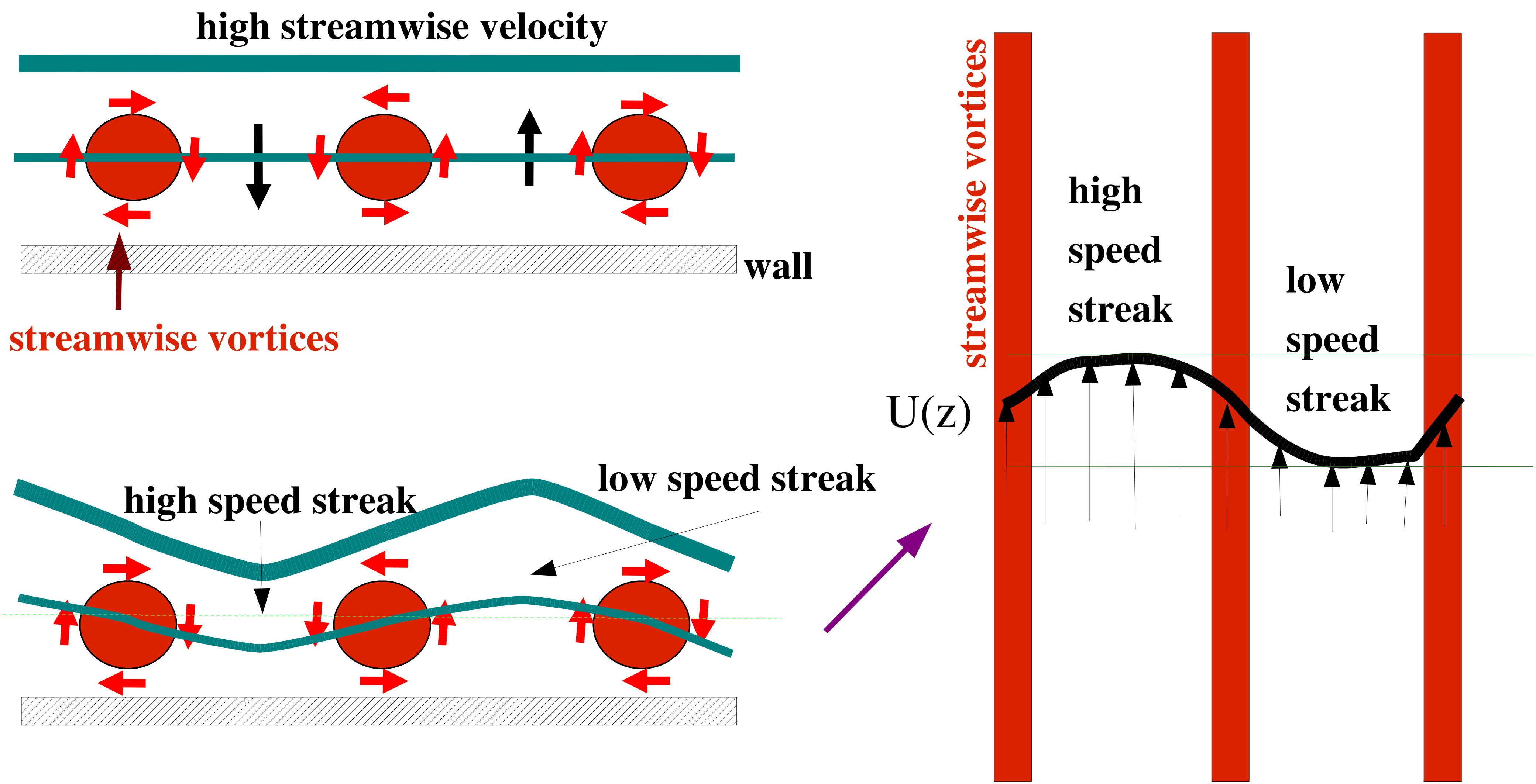
PROLOGUE: LIFT-UP IN LAMINAR FLOWS

Streaks formation: the lift-up effect

Streamwise vortices in a shear flow => streamwise streaks

Taylor 1939, Moffatt 1967,..., Landahl 1980, Ellingsen & Palm 1985...



Strongly related to non normality of the linearised operator

reviews in Trefethen et al 1993, Schmid & Hennigson 2001

Linearized system for parallel basic flows

$$\frac{\partial \mathbf{u}}{\partial t} + U\frac{\partial \mathbf{u}}{\partial x} + (v\,U',0,0) = -\nabla p + \nu\nabla^2\mathbf{u}$$

Linearized Navier-Stokes equations

$$\widehat{\mathbf{u}}(\alpha, y, \beta, t)\,\mathrm{e}^{i(\alpha x + \beta z)}$$

x-z Fourier modes

streamwise wavenumber (→ α) spanwise wavenumber (→ β)

Optimal growth

$$G(t,\alpha,\beta) = \max_{\hat{\mathbf{u}}_0 \neq 0} \frac{\|\hat{\mathbf{u}}\|}{\|\hat{\mathbf{u}}_0\|}$$

Kinetic energy ratio

Initial condition

Maximum growth

$$G_{max}(\alpha,\beta) = \max_t G(t)$$

Dependence of Gmax on wavenumbers & Re

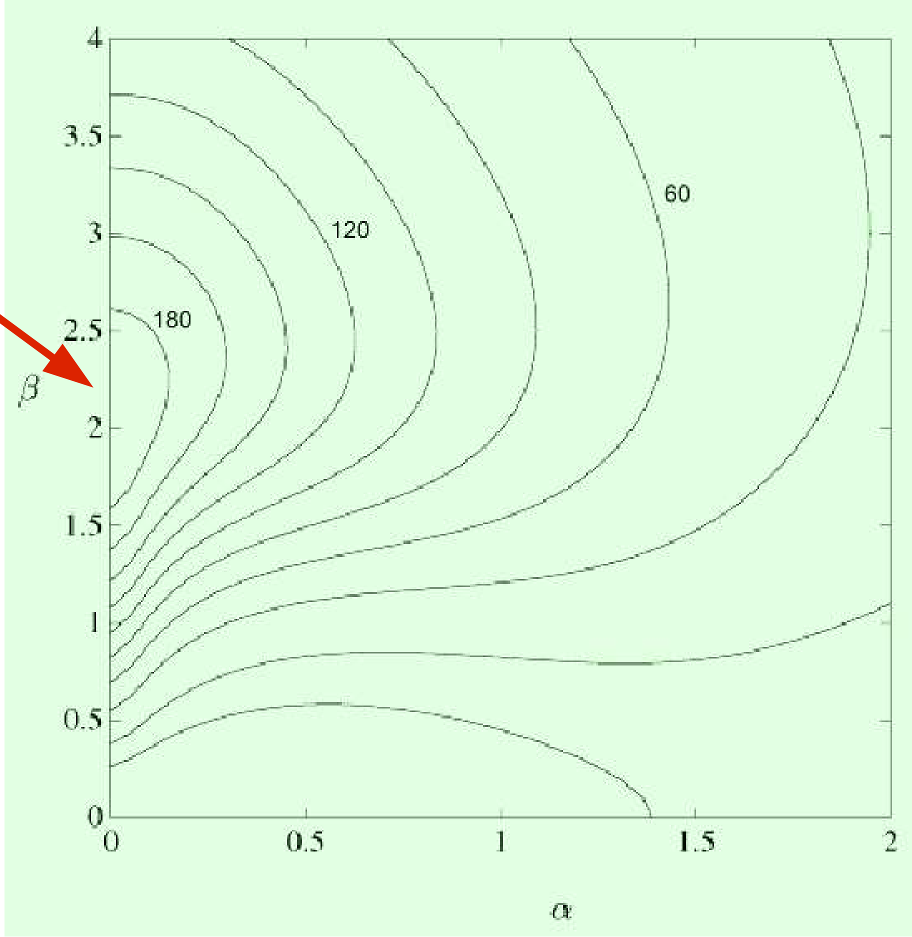
$G_{max}(\alpha,\beta)$: laminar Poiseuille, Re=1500

$\alpha = 0,\ \beta = 2/h$

$\lambda_x = \infty,\ \lambda_z = 3h$

Optimal λ_z in good agreement with scales of 'natural' streaks

Matsubara & Alfredsson, *JFM,* 2001



from Schmid & Henningson 2001

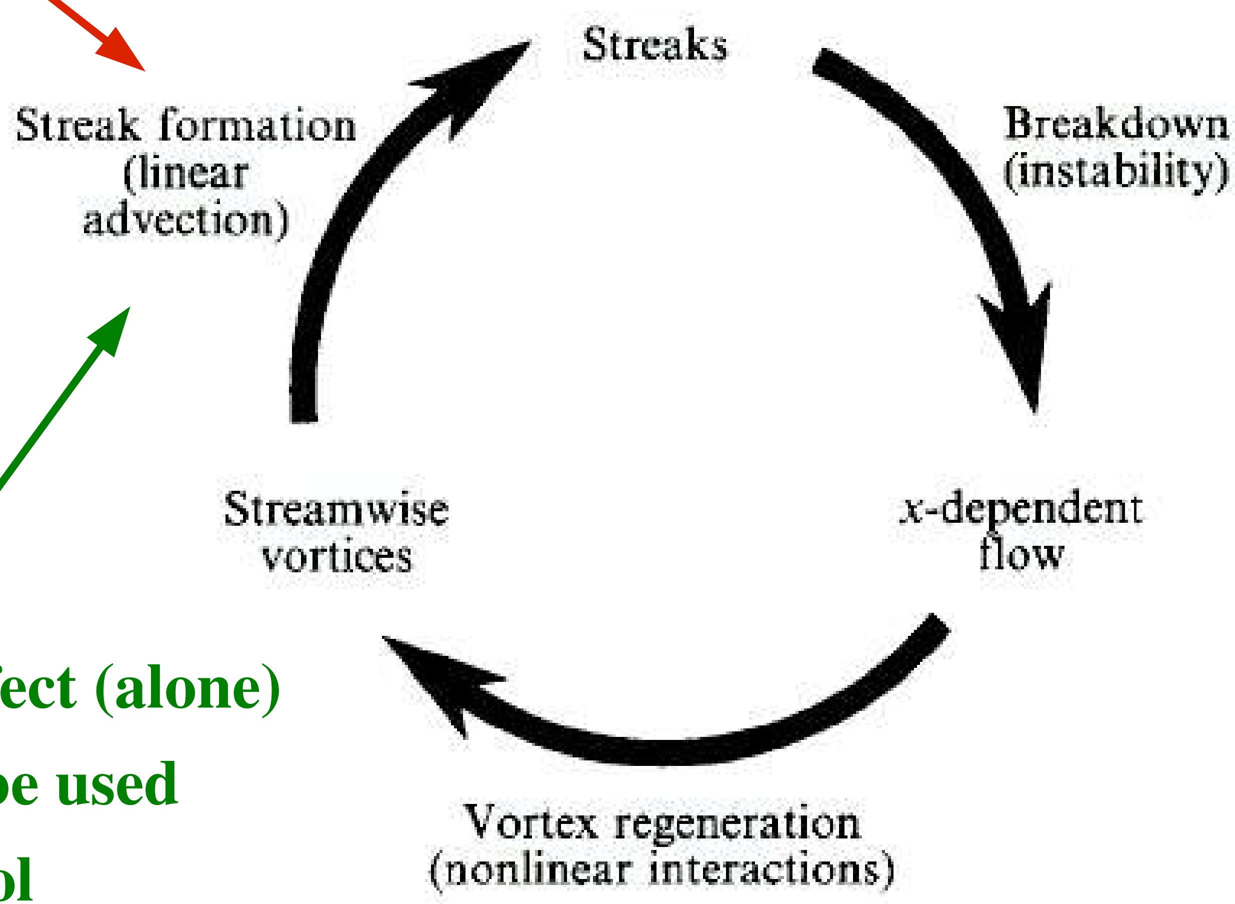
$$G_{max} \sim Re^2$$

Gustavsson 1991,...

Transition: self-sustained process

lift-up effect: selection of amplified spanwise scales λ_z (waveband β)

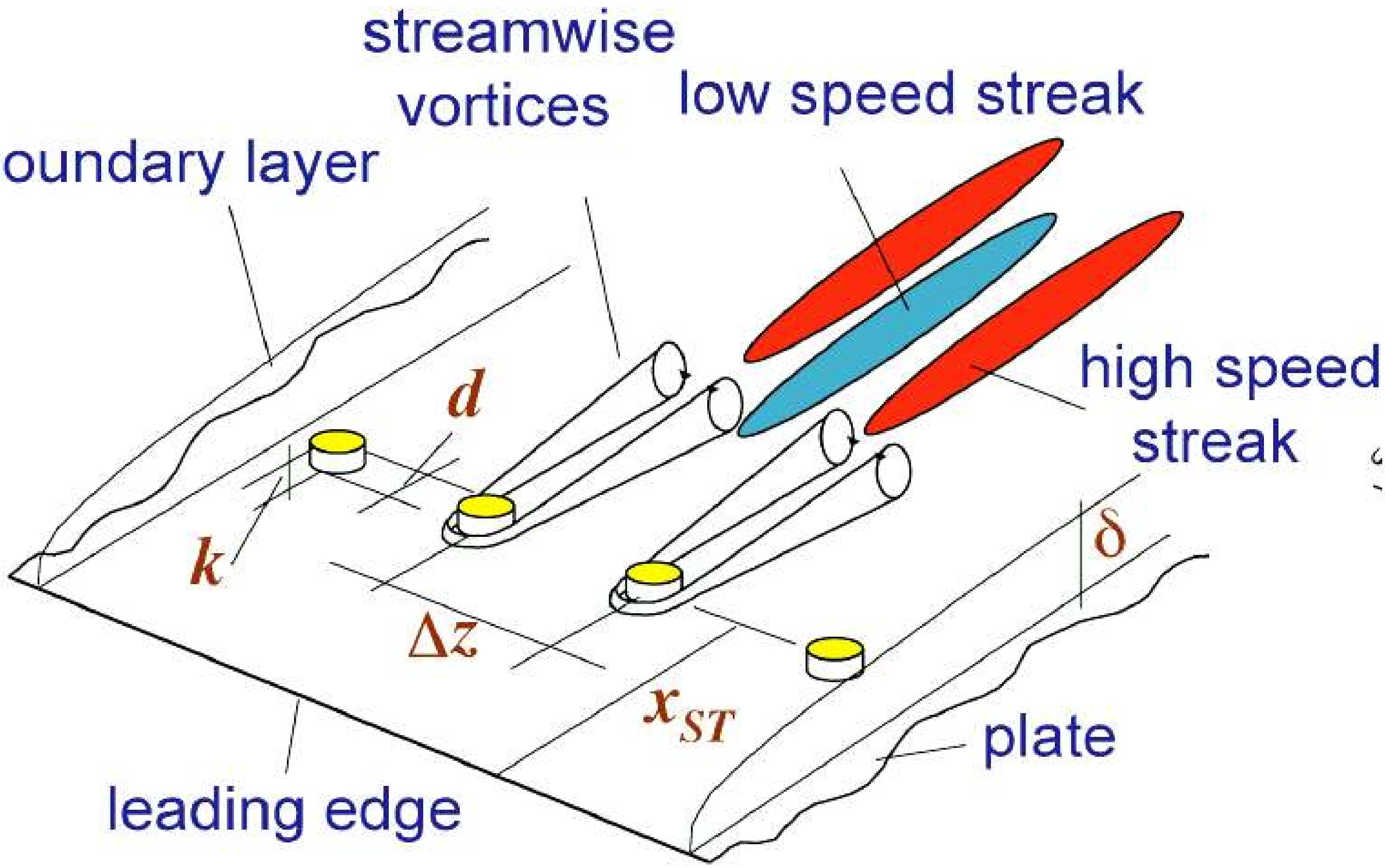
selection of unstable streamwise scales λ_x (waveband α)



lift-up effect (alone) can also be used for control

Figure from Hamilton et al.1995

Forcing streaks with roughness elements

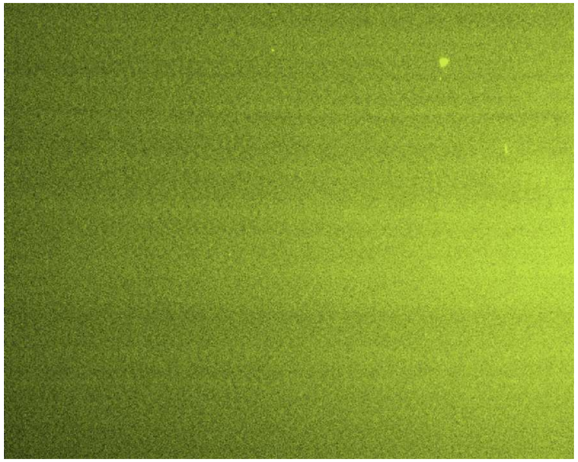


Fransson, Brandt, Talamelli, & Cossu, *Phys. Fluids* 2004 & 2005

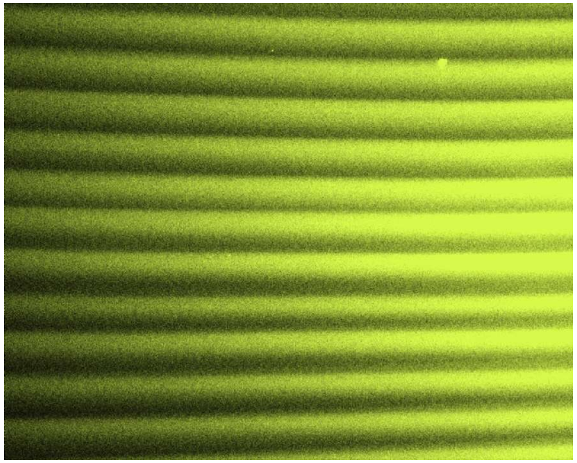
Transition delay by forced streaks

No streaks forced | **Streaks forced**

Base flow

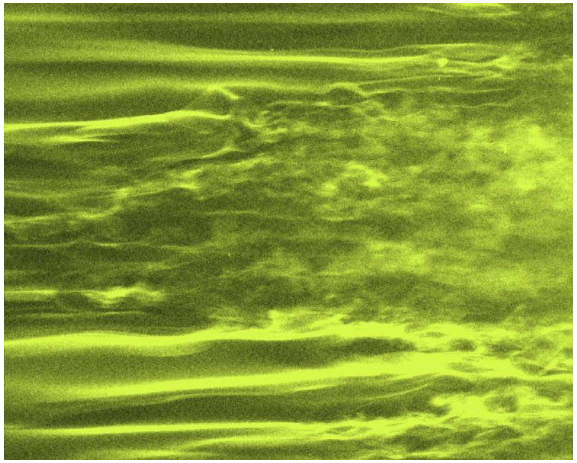


0 mV

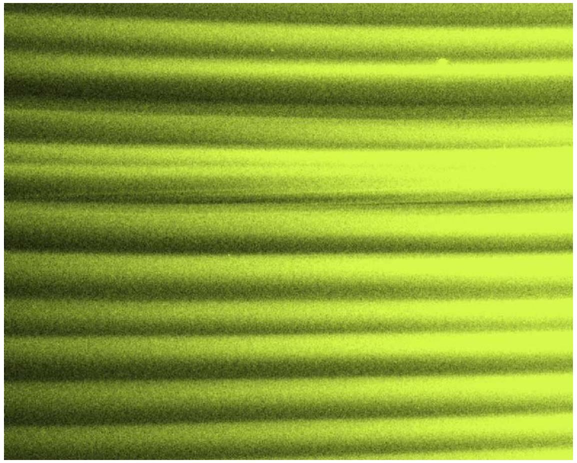


0 mV

Base flow + tripping (unsteady) forcing



205 mV



450 mV

Fransson, Talamelli, Brandt & Cossu, *Phys. Rev. Lett.* 2006

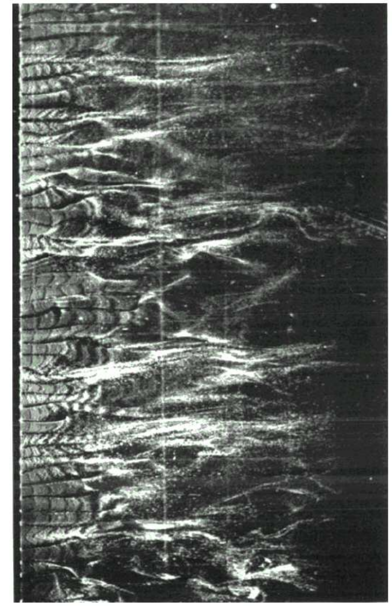
STREAKS IN FULLY TURBULENT FLOWS

Streaky structures in turbulent flows

Near wall streaks in a turbulent boundary layer

mean spanwise spacing $\lambda^+ \approx 100$

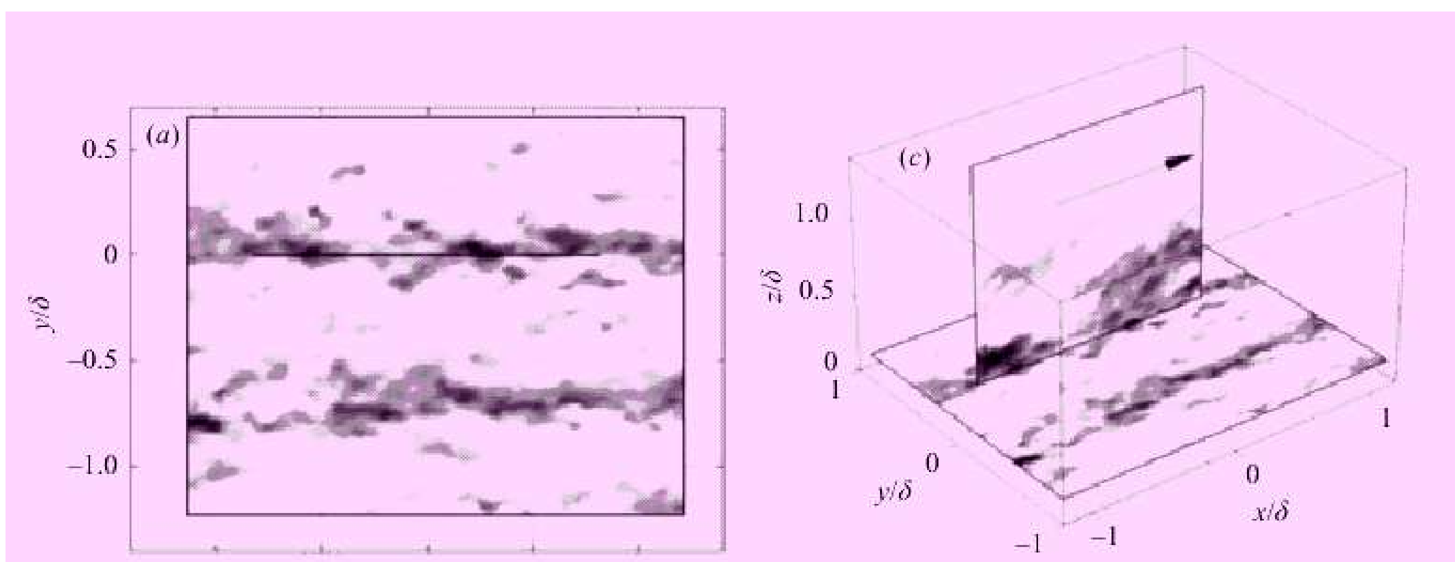
most probable spacing $\lambda^+ \approx 80$



Kline et al. JFM 1967

Large scale streaks in a turbulent boundary layer

Streks spacing
$\lambda \approx \delta$



Hutchins & Marusic JFM 2007

Some questions

Is a 'coherent' lift-up effect at work in fully developed turbulent flows?

Does it select the spanwise scales of the 'natural' streaks?

Are the optimal amplifications large?

Can we force those streaks for control purposes?

Does a self-sustained process exist at large scale?

Linearization near the mean flow

$$\mathbf{u} = \overline{\mathbf{u}} + \mathbf{u}' \quad ; \quad \overline{\mathbf{u}} = \langle \mathbf{u} \rangle$$

ensemble average

coherent field

decorrelated fluctuations

$$\overline{\mathbf{u}}(x,y,z,t) = \mathbf{U}(y) + \widetilde{\mathbf{u}}(x,y,z,t)$$

base mean flow

(no coherent perturbations)

(small) coherent perturbations to U (with coherent forcing or IC)

Linearized RANS equations:

Reynolds stresses due to u'

$$\frac{\partial \widetilde{\mathbf{u}}}{\partial t} + \nabla \widetilde{\mathbf{u}} \cdot \mathbf{U} + \nabla \mathbf{U} \cdot \widetilde{\mathbf{u}} = -\nabla p + \nabla \cdot \left[\nu_T(y) \left(\nabla \widetilde{\mathbf{u}} + \nabla \widetilde{\mathbf{u}}^T \right) \right] + \mathbf{f}$$

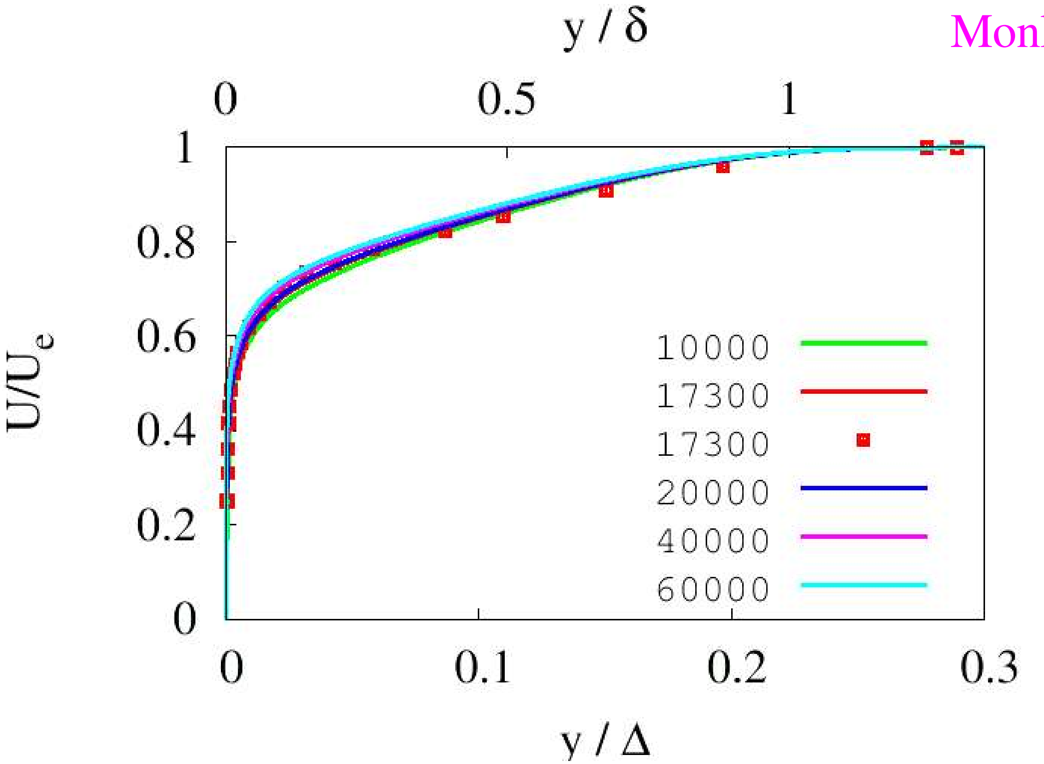
eddy viscosity in equilibrium with U

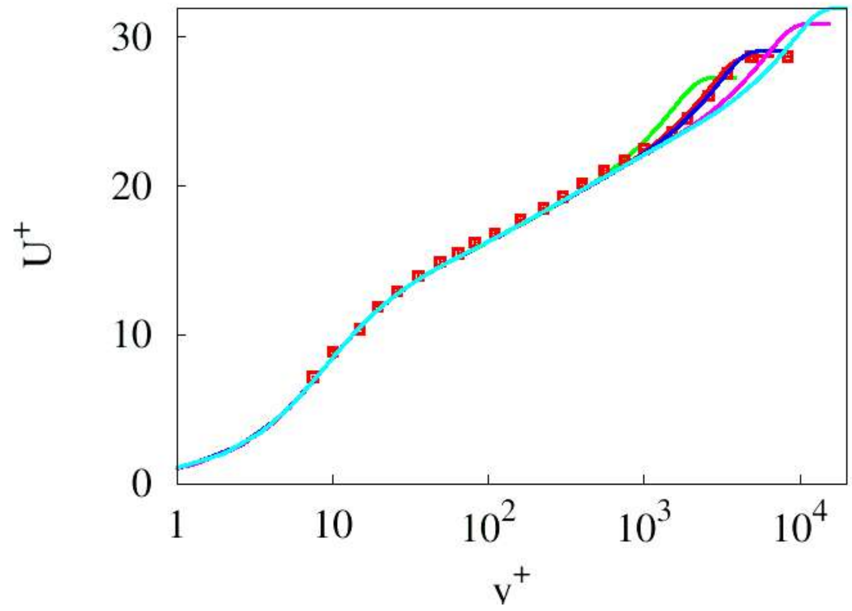
Reynolds & Hussain *JFM* 1972
del Alamo & Jiménez *JFM* 2006
Pujals, Garcia-Villalba, Depardon & Cossu, *Phys. Fluids* 2009
Cossu, Pujals & Depardon, *JFM* 2009
Hwang & Cossu *JFM* 2010

Base mean flow for the ZPGTBL

$$U = u_\tau \left[U_i^+(y^+) - U_{log}^+(y^+) + U_e{}^+(Re_{\delta_*}) - U_w^+(\eta) \right]$$

Monkewitz, Chauhan & Nagib *Phys. Fluids* 2007





Velocity profiles at different Reδ* in outer & inner units.

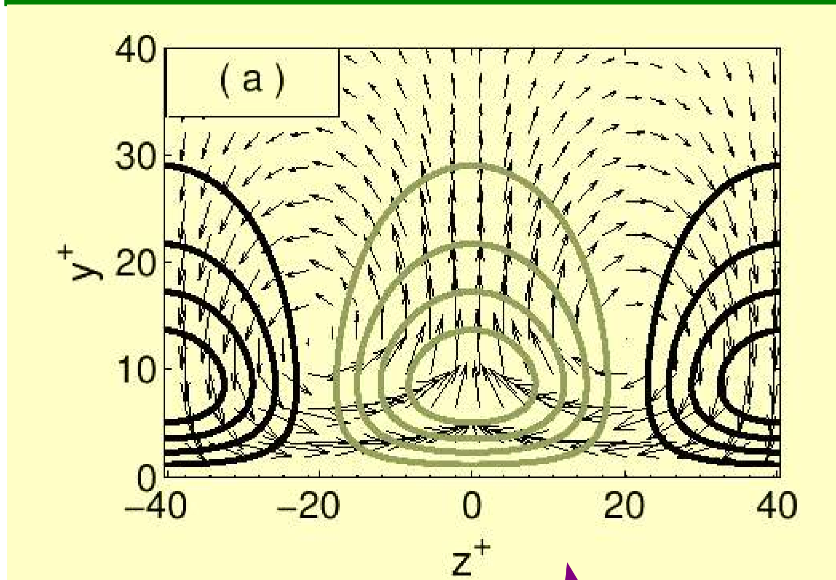
Comparison with data of de Graaf & Eaton (JFM 2000)

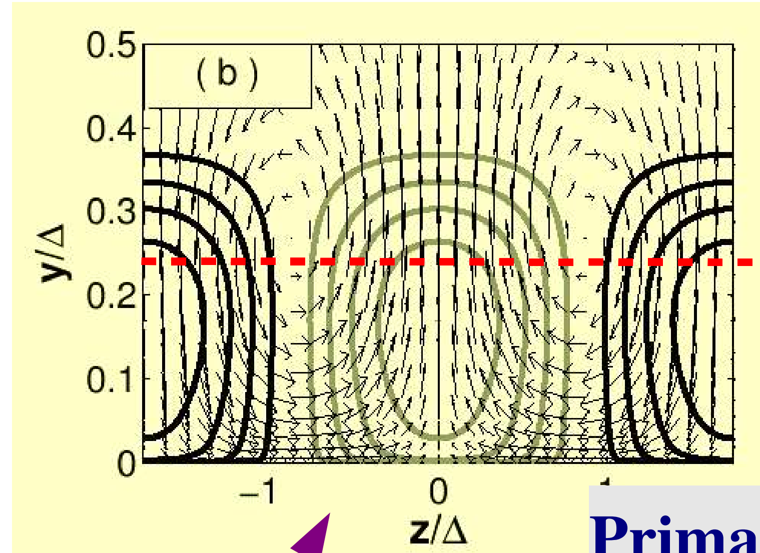
$$U_{log}^+(y^+) = \frac{1}{\kappa}\ln(y^+) + B$$

$$U_e{}^+(Re_{\delta_*}) = \frac{1}{\kappa}\ln(Re_{\delta_*}) + C$$

$$\kappa = 0.384,\ B = 4.17,\ C = 3.30$$

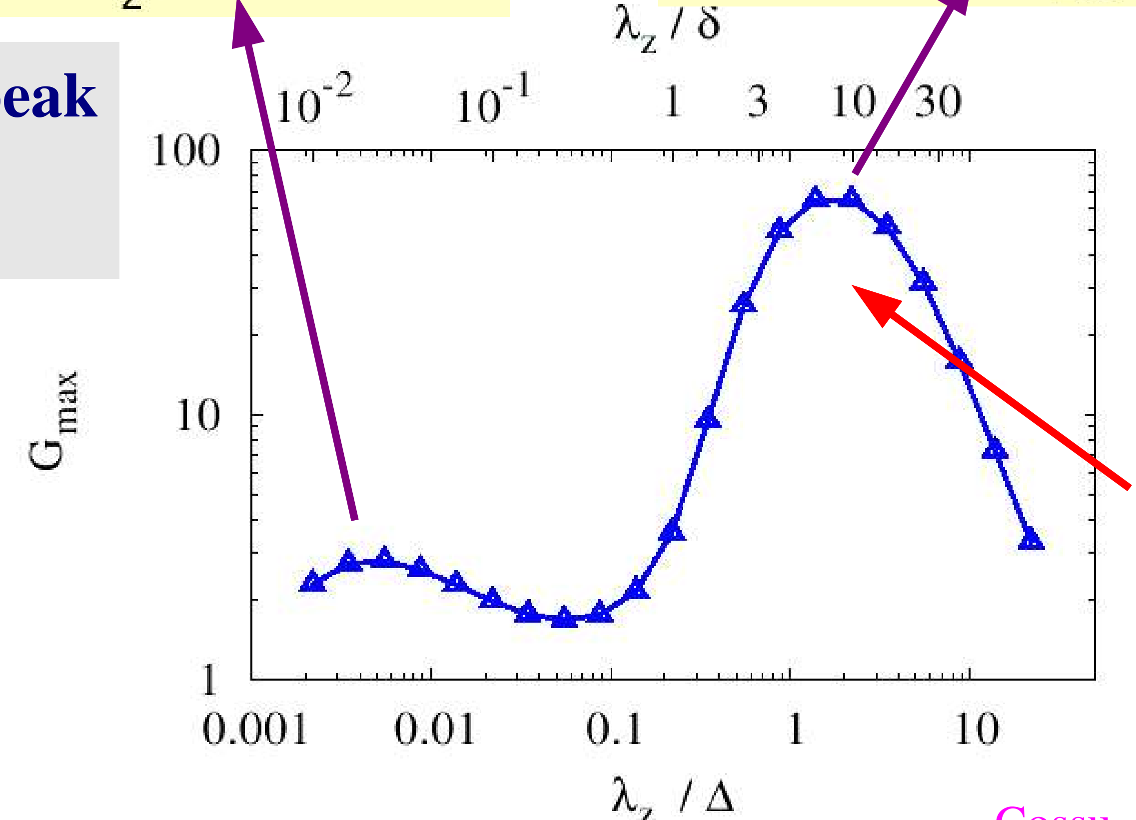
Optimal α=0 growth & perturbations at Reδ*=17300





Secondary peak at λ+ = 81.5

Primary peak at $\lambda_z = 7.6\ \delta_{99}$



Structures with $\delta_{99} < \lambda_z < 30\ \delta_{99}$ strongly amplified

Amplifications increase with Re

Cossu, Pujals & Depardon *JFM* 2009

Most amplified large scales for Gmax

Plane channel ($Re_\tau > \approx 500$): $\lambda_z \approx 4h$

del Alamo & Jiménez *JFM* 2006, Pujals et al. *Phis. Fluids* 2009

Pipe flow ($Re_\tau > \approx 500$): m=1 ($\lambda_z = 2\pi R/m \approx 6R$)

Willis et al. Subm. *PRE* 2010

Couette flow ($Re_\tau \approx 50$): $\lambda_z = 4.5h$

Hwang & Cossu *JFM* 2010

Boundary layer (ZPG) ($Re_{\delta*} > \approx 5000$): $\lambda_z \approx 6\text{–}8\delta$

Cossu et al. *JFM* 2009

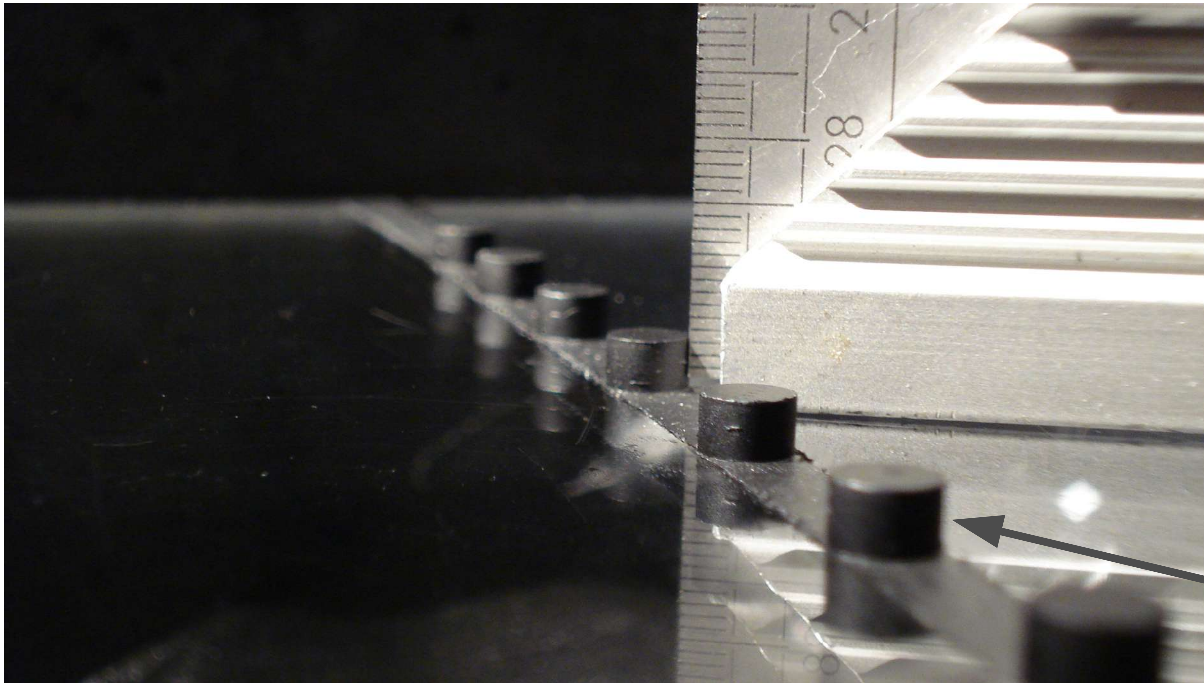
Results of optimal temporal growth (Gmax) analysis.

Similar scales obtained for stochastic forcing

Larger scales obtained for optimal harmonic forcing

REALITY CHECK IN THE TBL

Experimental results



Turbulent boundary layer
Ue=20m/s, δ ~ 4mm,
Reδ* ~ 1000 at x=0

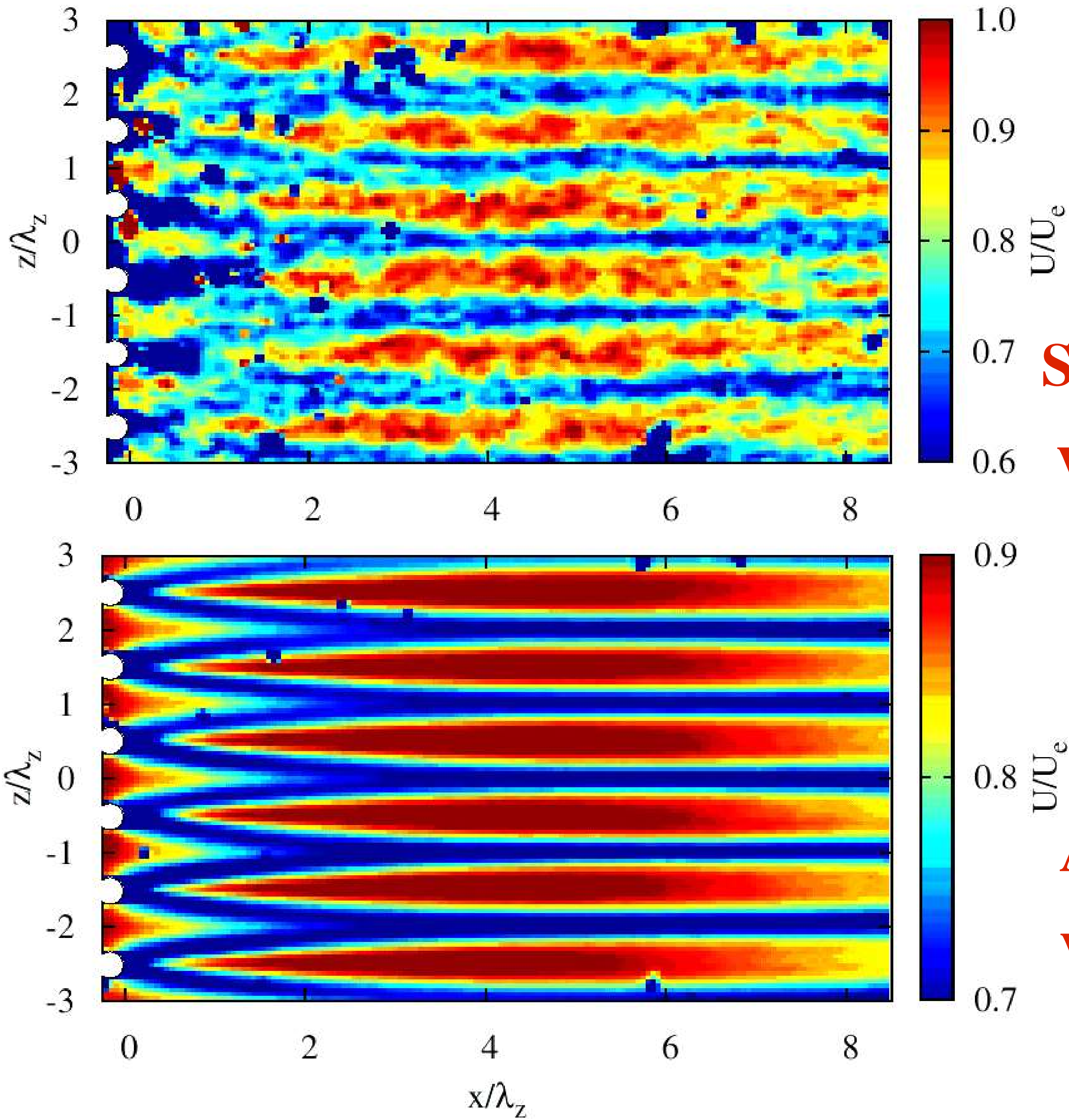
Spanwise array of *streaks generators*

Config.	λ_z (mm)	d (mm)	λ_z/d	λ_z/δ_0	k/δ_0
A	15.8	3.94	4	3	0.8
B	26.8	6.7	4	5	0.8
C	33	8.25	4	6	0.8
D	40.	10.	4	7.5	0.8
E	50.8	12.7	4	10	0.8
F	65.6	16.4	4	12	0.8

← Several spanwise wavelengths tested

Peugeot-Citroën Aerodynamics
Dept. Windtunnel in Velizy

Turbulent streaks large scale streaks



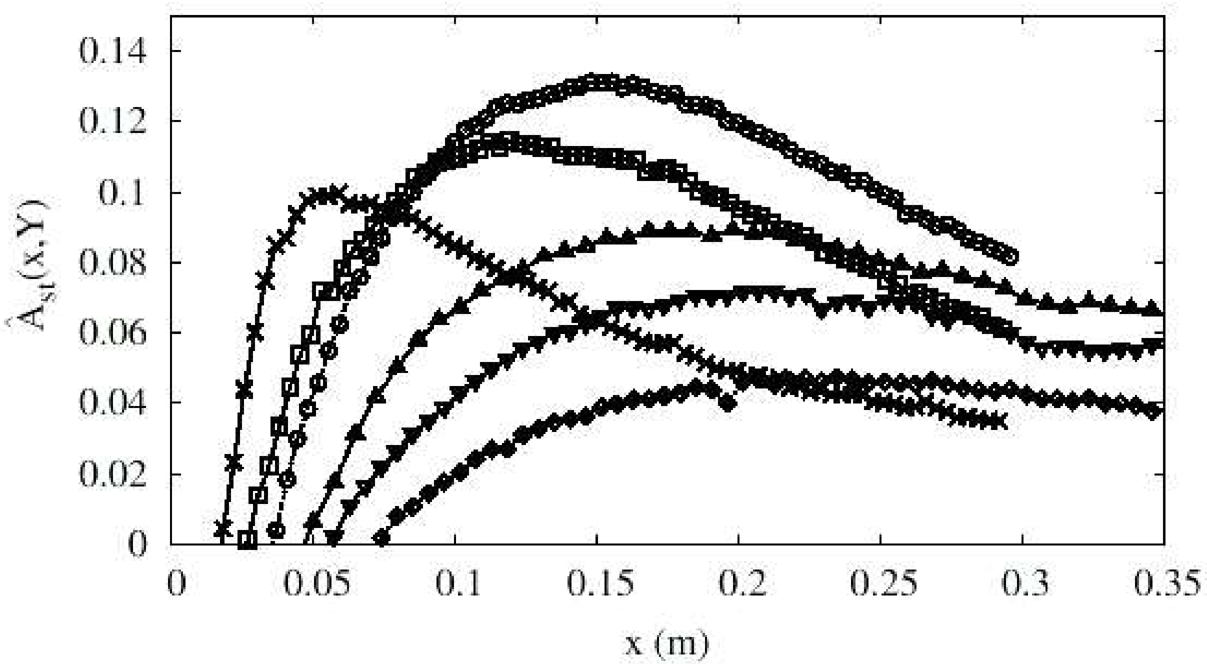
PIV data: horizontal plane Y=k (roughness height)

Snapshot streamwise velocity field

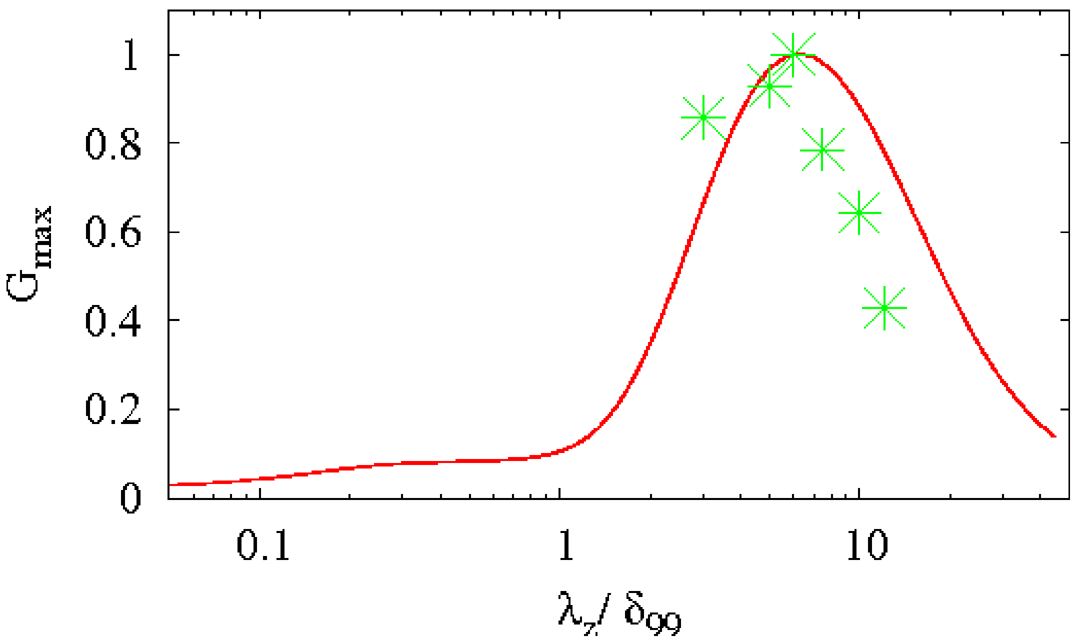
Averaged streamwise velocity field

Pujals, Depardon & Cossu, submitted to *J. Turb.*

TBL: Streaks amplitude and Gmax for different λ_z



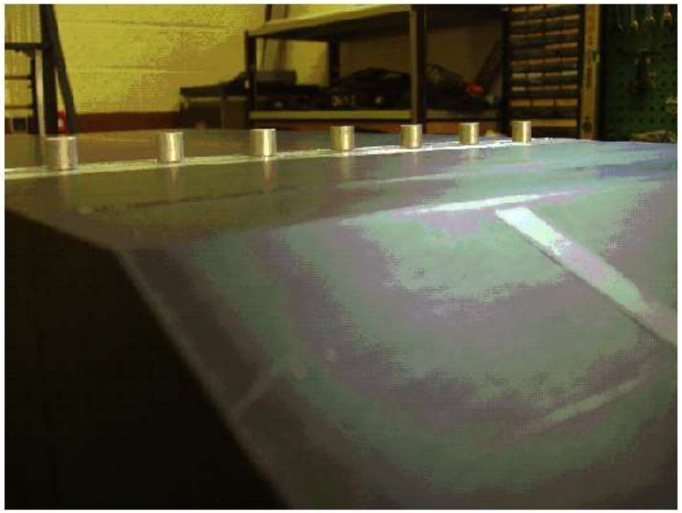
Ast(x) for selected λ_z



Experimental $A_{max}(\lambda_z)$ vs. theoretical $G_{max}(\lambda_z)$ at same Re

PASSIVE CONTROL WITH LARGE SCALE STREAKS

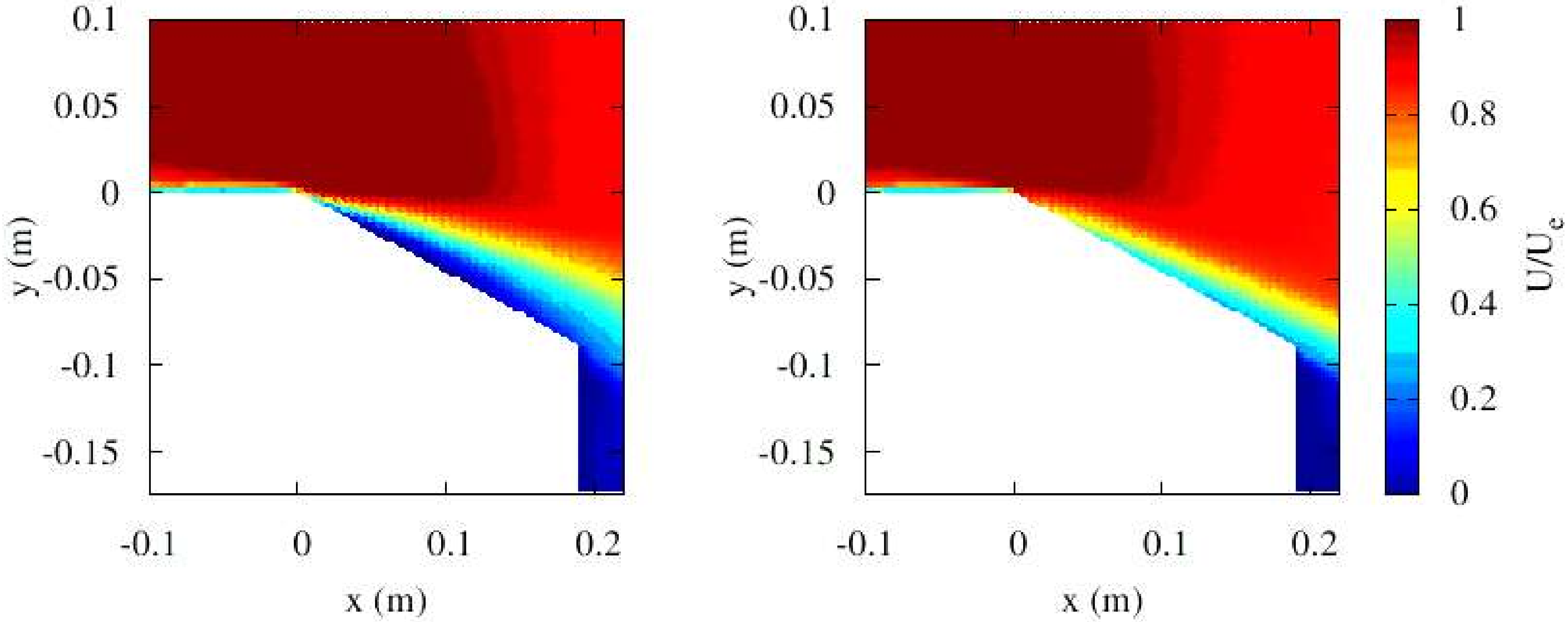
Separation control on the Ahmed body



Large scale streaks forced on the roof of the Ahmed body.

Total drag reduced by 10%

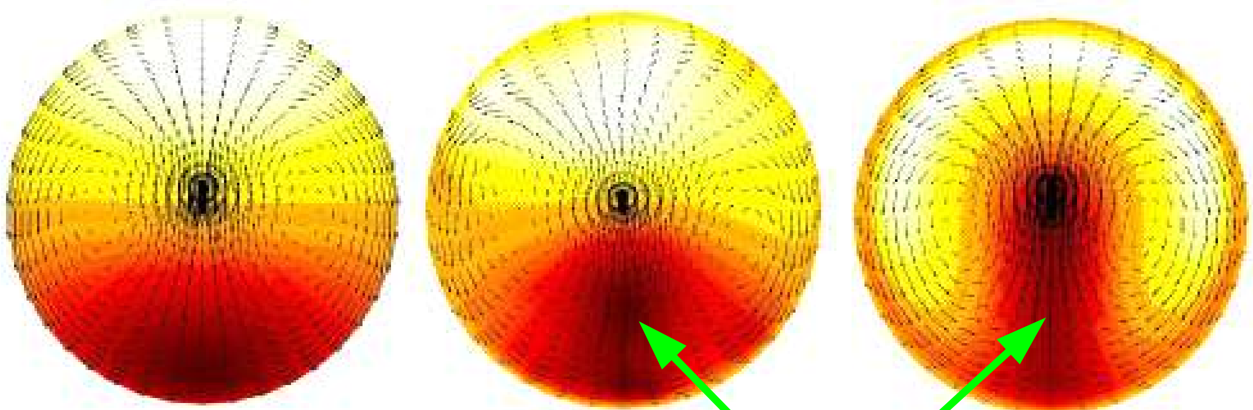
without streaks **with streaks**



PSA large wind tunnel

Pujals, Depardon & Cossu, *Exp. Fluids*, in press

Artificially forced m=1 streaks in the turbulent pipe



linear optimal DNS DNS

low speed streak

streamwise velocity

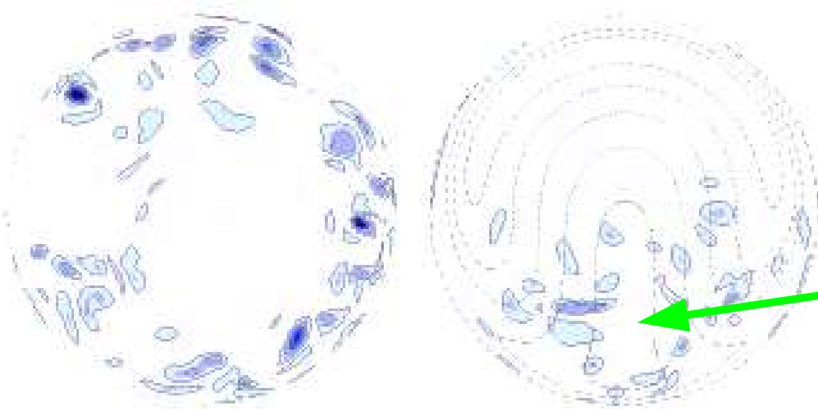
mean $u_z(r,\theta)$

Fully resolved DNS

Re=5300 (Reτ=180)

axial vorticity

istantaneous $\omega_z(r,\theta)$



small scale streamwise vortices pushed in the low speed streak

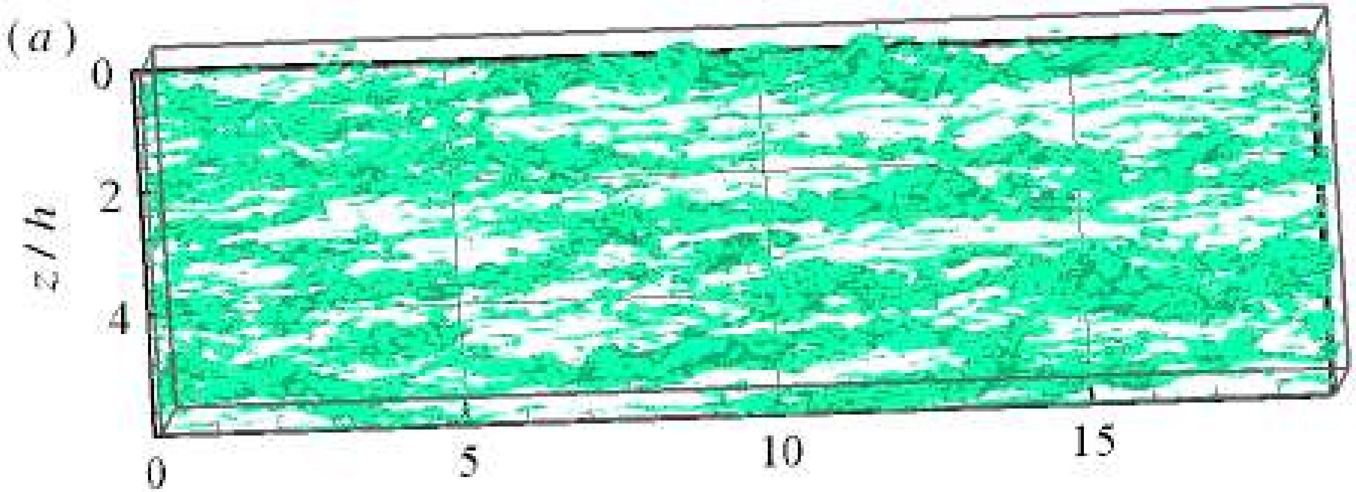
no control m=1control

Net power consumption reduced by 10% forcing the m=1 or m=2 modes

Willis, Hwang & Cossu *PRE* submitted (2010)

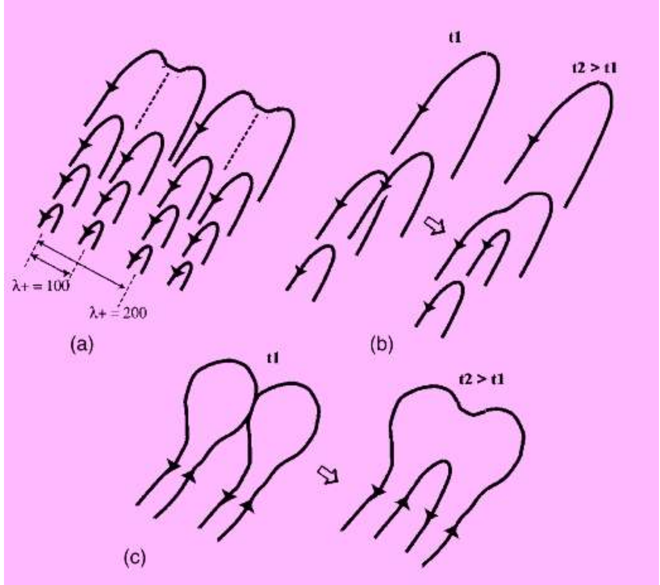
A SELF-SUSTAINED PROCESS AT LARGE & VERY LARGE SCALE

LES of a turbulent plane channel $Re_{\tau}=550$

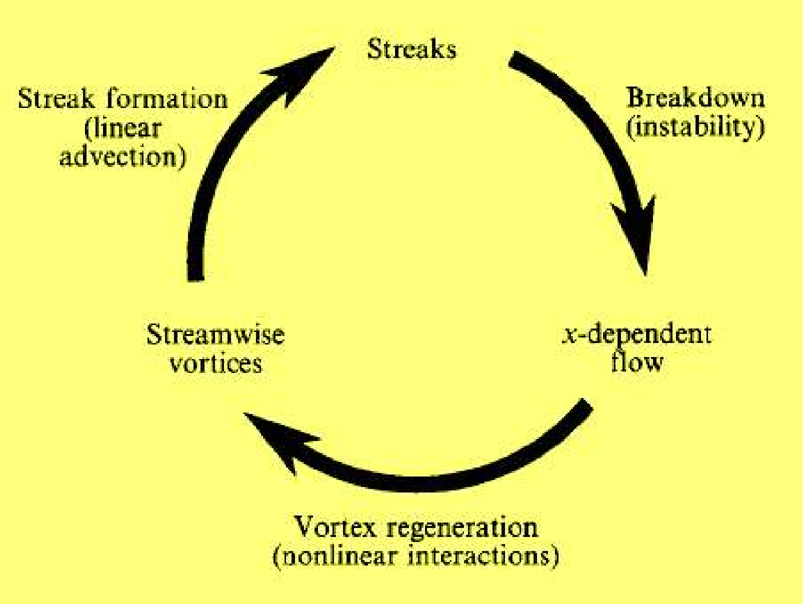


large and very large scale structures are due to:

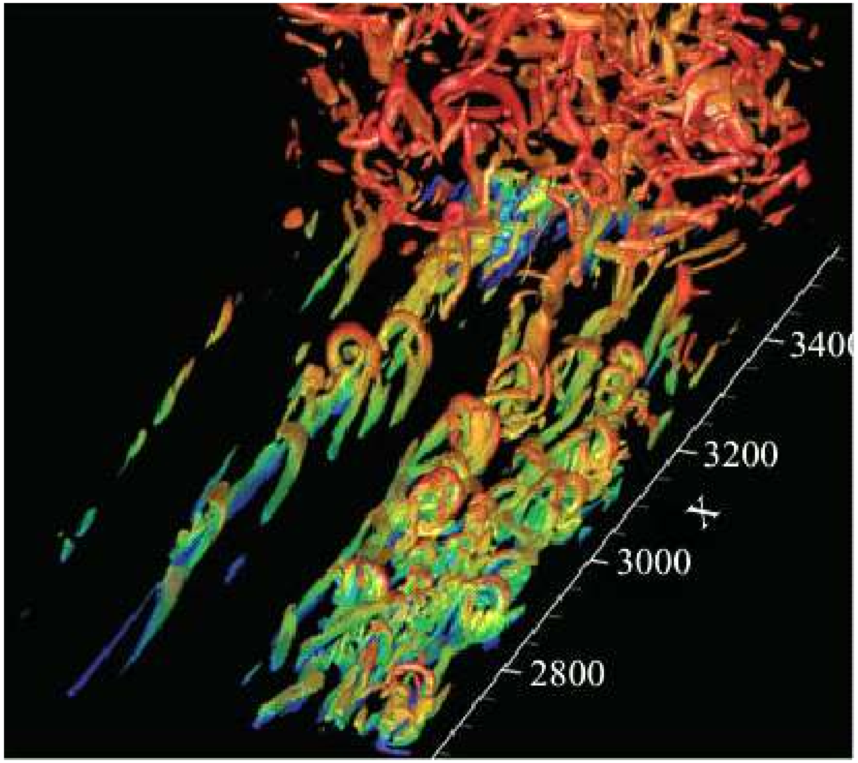
vortex aggregation... or **...SSP**



?



A question



Current belief is that smaller scale Λ vortices are necessary to create larger scales streaks

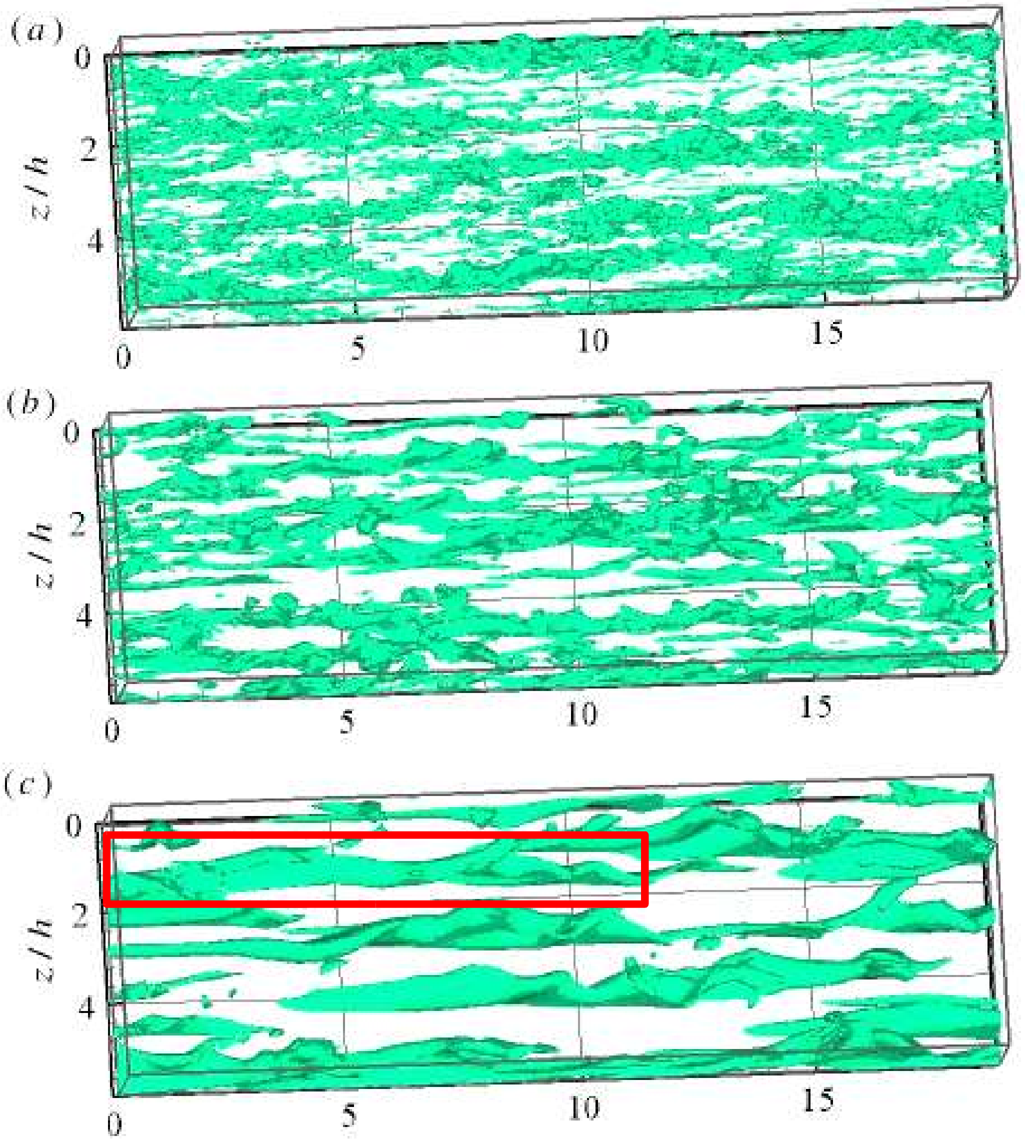
Wu & Moin *JFM.* 2009
Marusic *JFM - Focus on Fluids* 2009

QUESTION: Can the large scale structures survive in the absence of small scales?

...actually, how can the small scales be quenched while still preserving their turbulent dissipation?

LES plane channel at Re_τ=550 & large box Lx=55h, Lz=6h

streamwise velocity levels at u_τ^+=-2



Reference case = good dissipation

(same U, u_{rms}, v_{rms}, w_{rms}, premultiplied spectra as DNS)

Increasing artificial dissipation on the small scales at Re=cst.

Small & intermediate scales are increasingly quenched

(confirmed by premultiplied spectra).

Surviving structures:

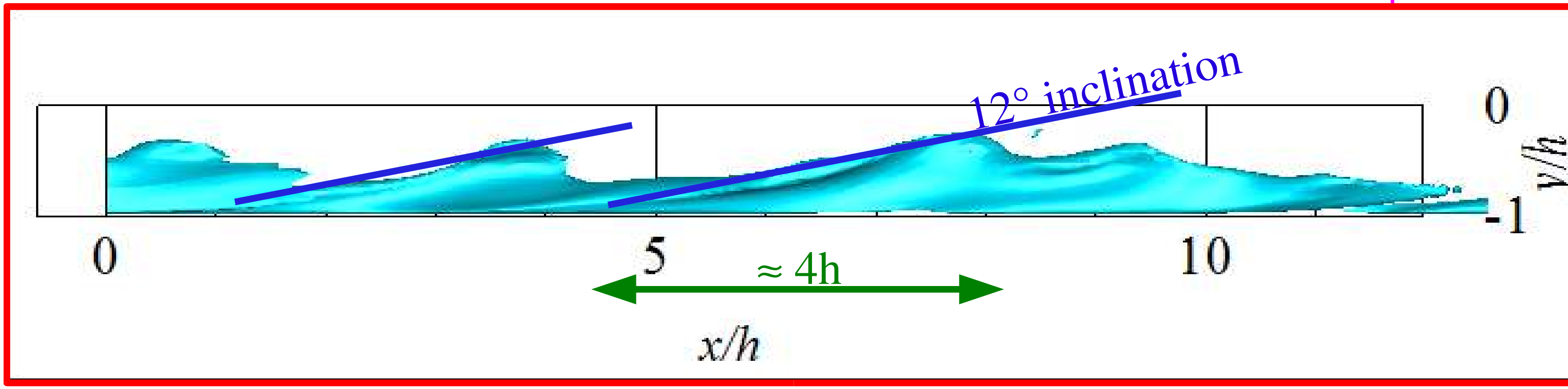
$\lambda z \approx 1.5h$, $\lambda x \approx 3–4h$ (peaks)

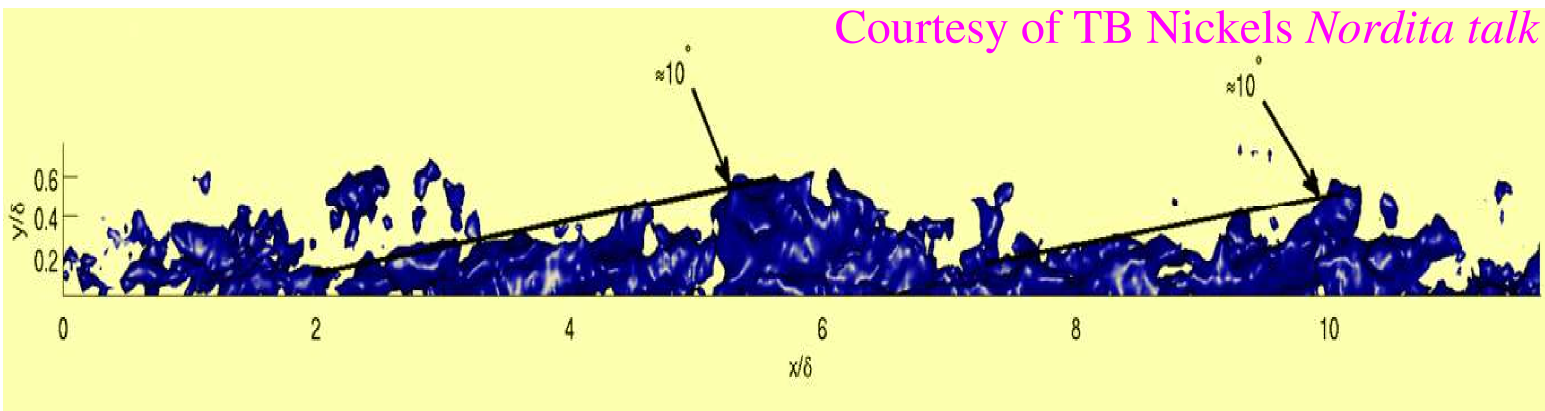
+ longer x-length near the wall

Hwang & Cossu *Phis. Rev. Lett..* submitted

The elementary mechanism

Zoomed side-view from extra dissipative LES





Structures very similar to large scale experimental ones!

MINIMAL BOX: The SSP at large scale with quenched small scales does not survive if $Lx < 3h$ or/and $Lz < 1.5h$

QUESTION: Can the large scale structures survive in the absence of small scales?

ANSWER: Yes they can!

Interested? see the talk by Yongyun Hwang on APR 29-30

THANK YOU FOR YOUR ATTENTION

http://yakari.polytechnique.fr/people/carlo/

http://www.imft.fr/page_perso/ccossu/