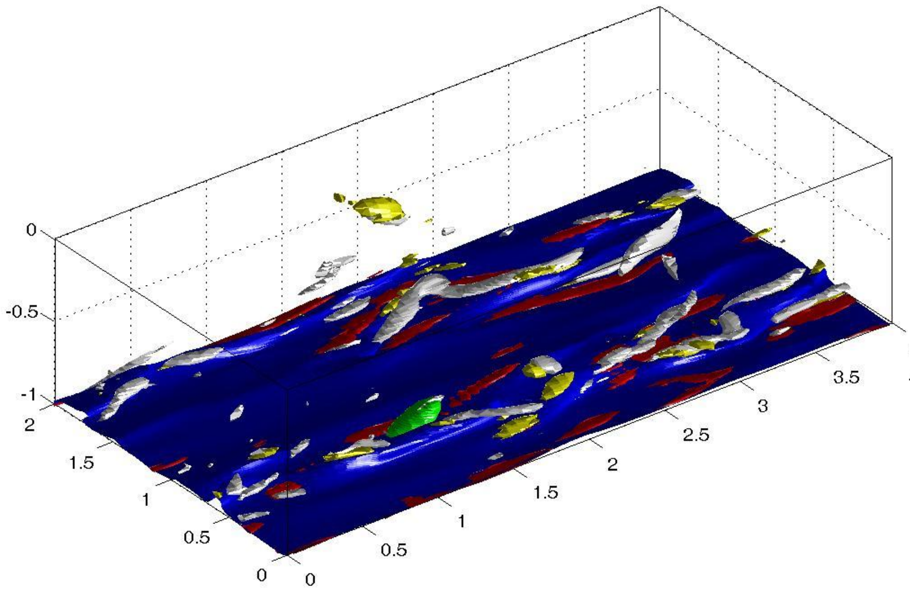
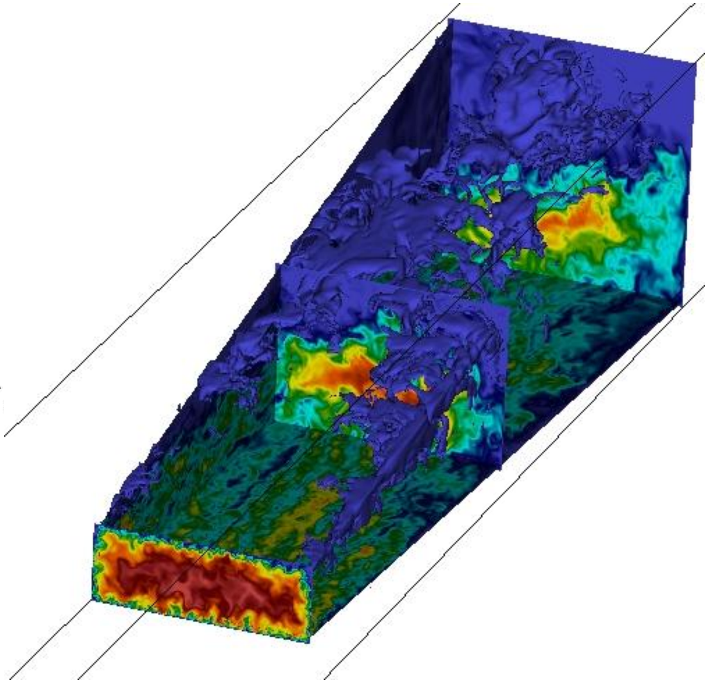
Testing a Vorticity Stretching Diagnostic for Turbulent Flows

Neil Sandham
University of Southampton

Johan Ohlsson
KTH

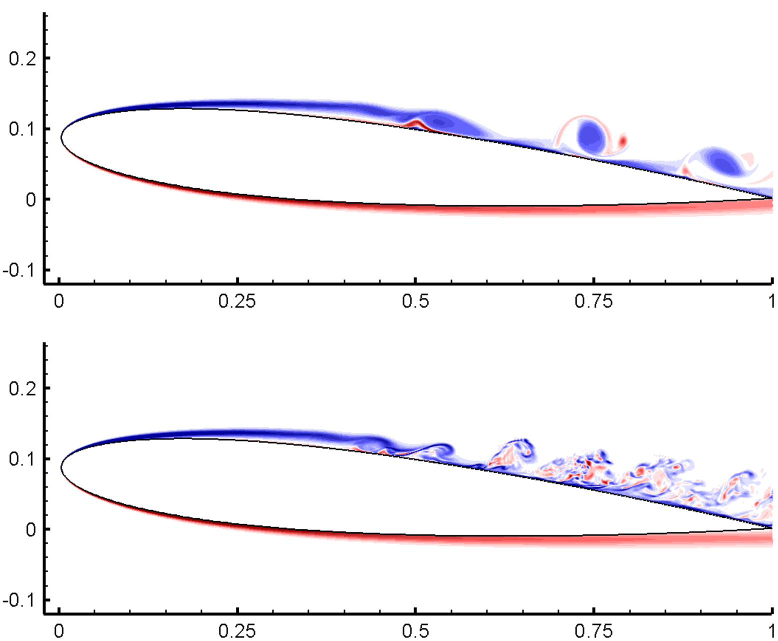


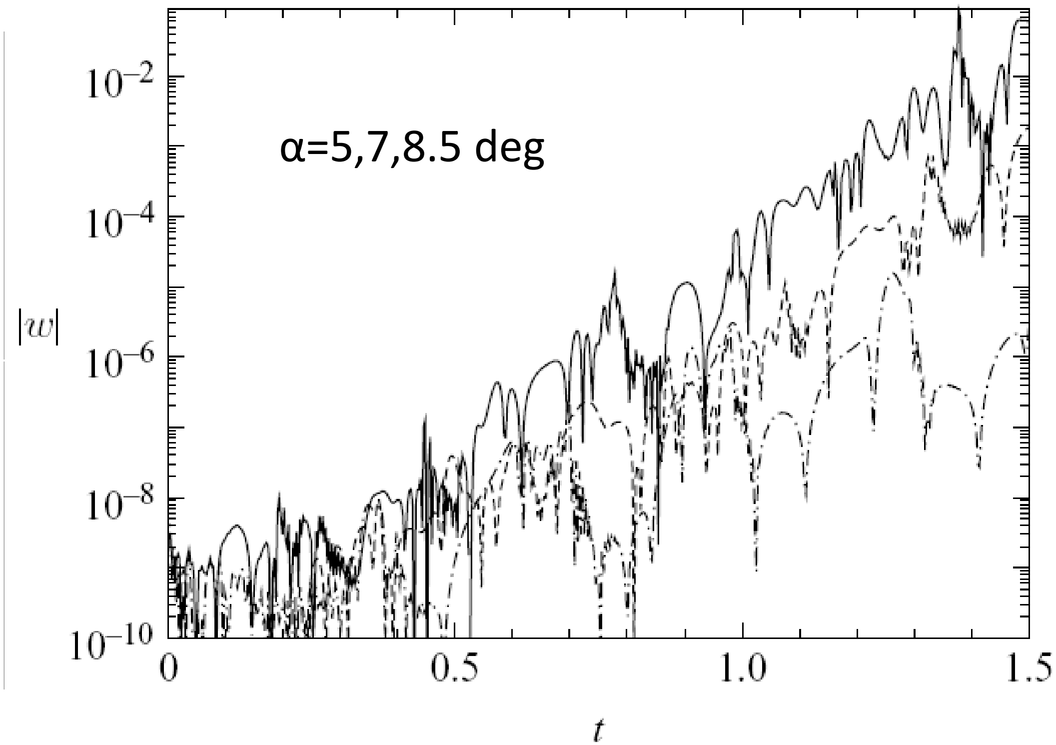


Outline

- Observations from transitional flows
  - Braid instability in a transitional separation bubble
  - Vorticity stretching during end stage transition
- Extensions to fully turbulent flow
  - Low-Re channel flow (this talk)
  - Asymmetric diffuser with separation (next talk)
- Conclusions

Airfoil DNS (Re=50,000) shows self-sustained transition process



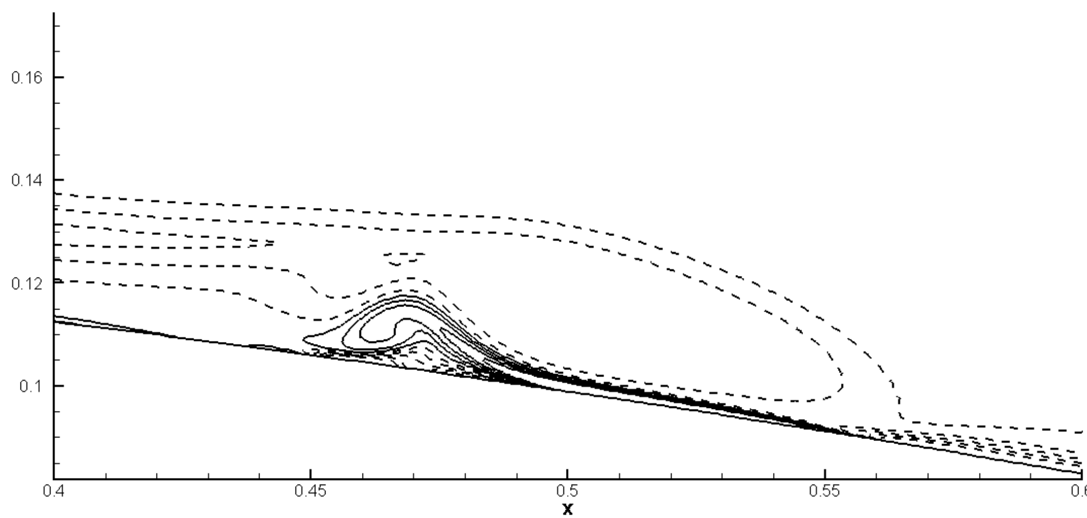


Rapid growth of 3D perturbations on 2D unsteady base flow until nonlinear amplitudes are reached

Too rapid to be caused by acoustic feedback mechanism

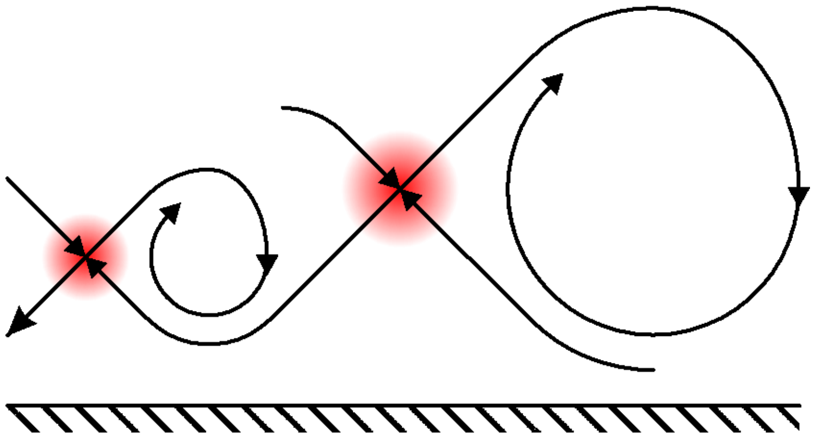
Self-sustaining transition mechanism: (a) upstream flow during shedding cycle

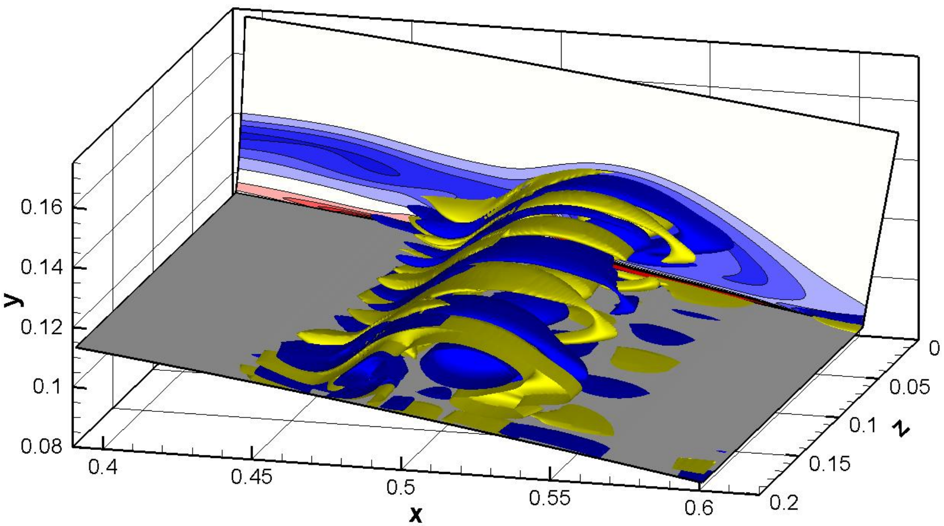
- Rapid upstream convection under growing vortices



Vorticity plus coloured scalar

Self-sustaining transition mechanism:
(b) rapid growth in braid region





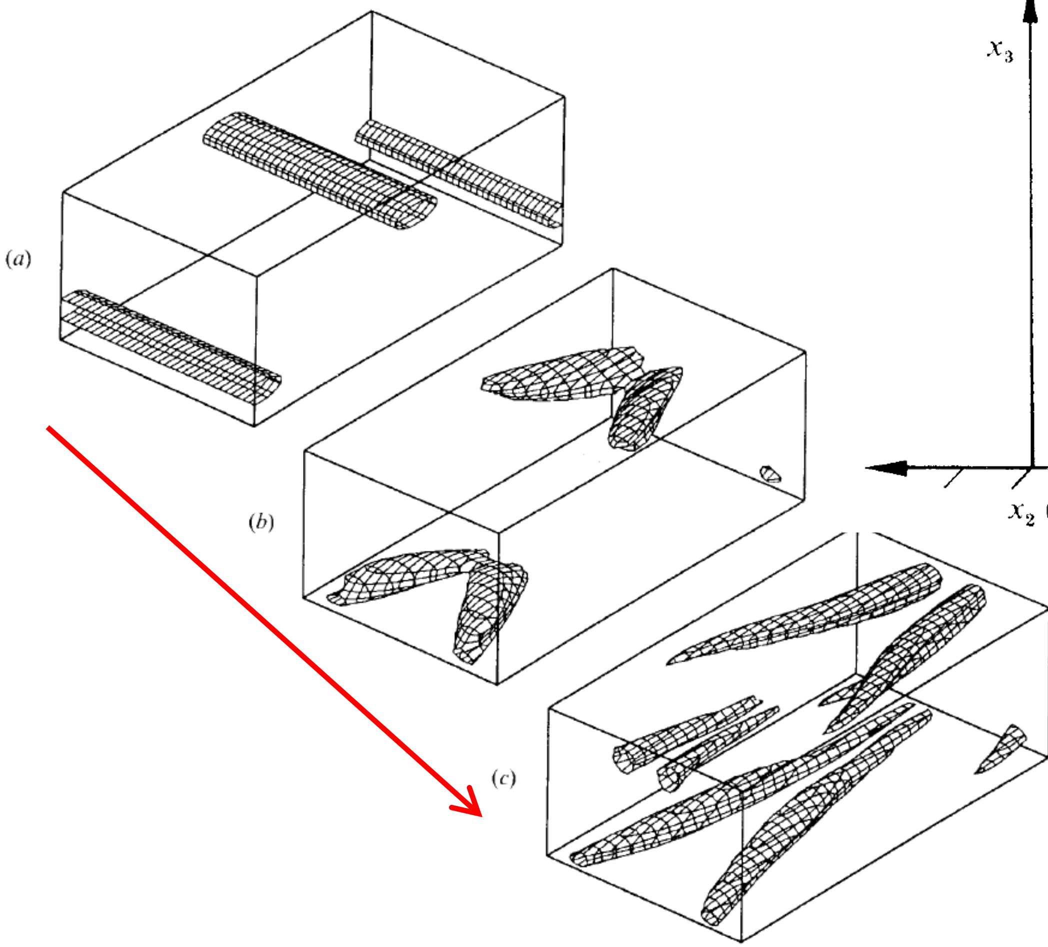
- Vorticity stretching in braid region provides a rapid growth mechanism

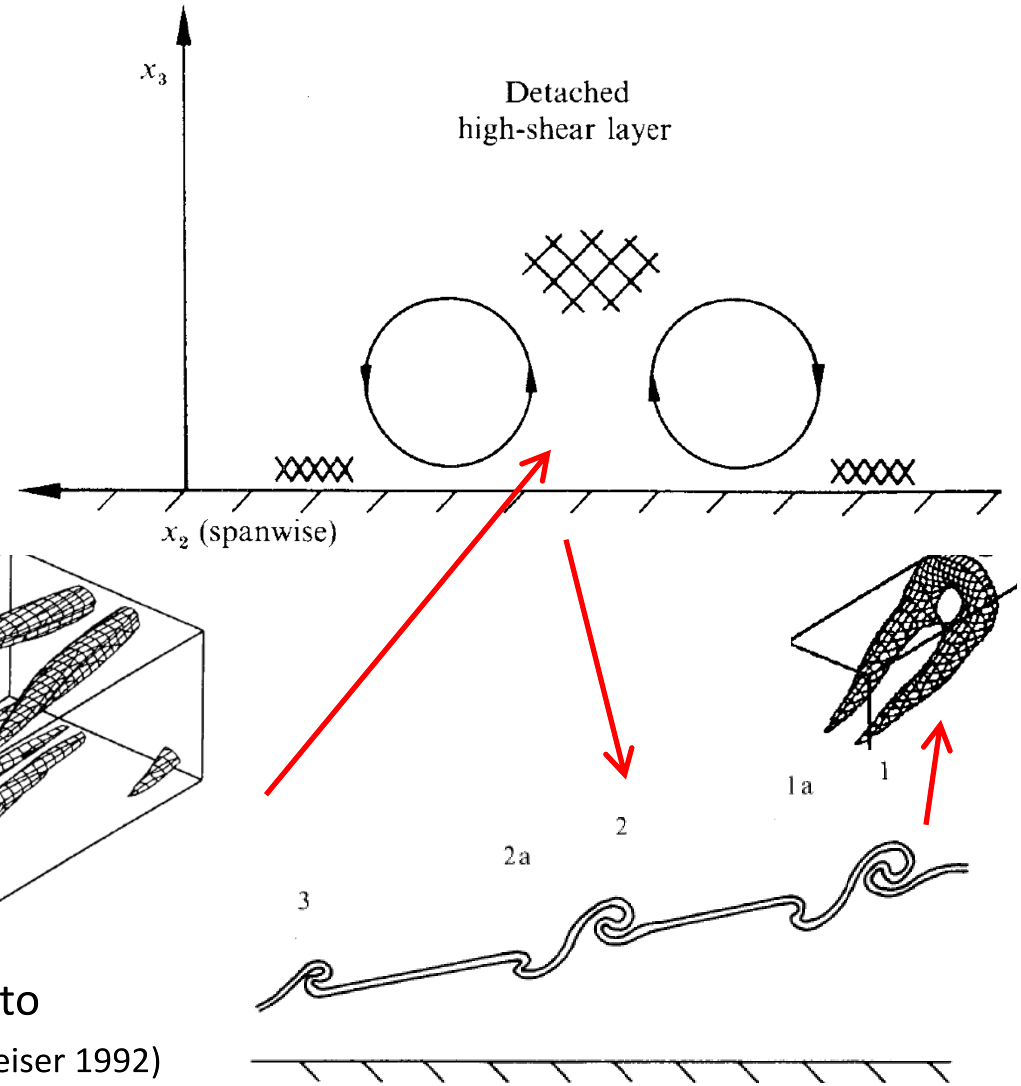
$$\frac{D\omega_s}{Dt} = \omega_s \frac{\partial q_s}{\partial s}$$

s = strain elongation axis

- Jones et al JFM 2008 (a weaker unstable acoustic feedback loop is covered in Jones et al JFM 2010)

Vorticity stretching in end-stage of K-type transition to turbulence





Roll-up of detached shear layers leading into turbulence regeneration cycle (Sandham & Kleiser 1992)

Vorticity transport equation

$$\frac{D\omega_x}{Dt} = \omega_x \frac{\partial u}{\partial x} + \omega_y \frac{\partial u}{\partial y} + \omega_z \frac{\partial u}{\partial z} + \nu \nabla^2 \omega_x$$

$$\frac{D\omega_y}{Dt} = \omega_x \frac{\partial v}{\partial x} + \omega_y \frac{\partial v}{\partial y} + \omega_z \frac{\partial v}{\partial z} + \nu \nabla^2 \omega_y$$

$$\frac{D\omega_z}{Dt} = \omega_x \frac{\partial w}{\partial x} + \omega_y \frac{\partial w}{\partial y} + \omega_z \frac{\partial w}{\partial z} + \nu \nabla^2 \omega_z$$

- Diagonal terms would lead to exponential blow-up of vorticity if tilting and diffusion terms are zero and strain rate is constant following the fluid element
- Role in real turbulent flow?

Scalar measure of vorticity stretching

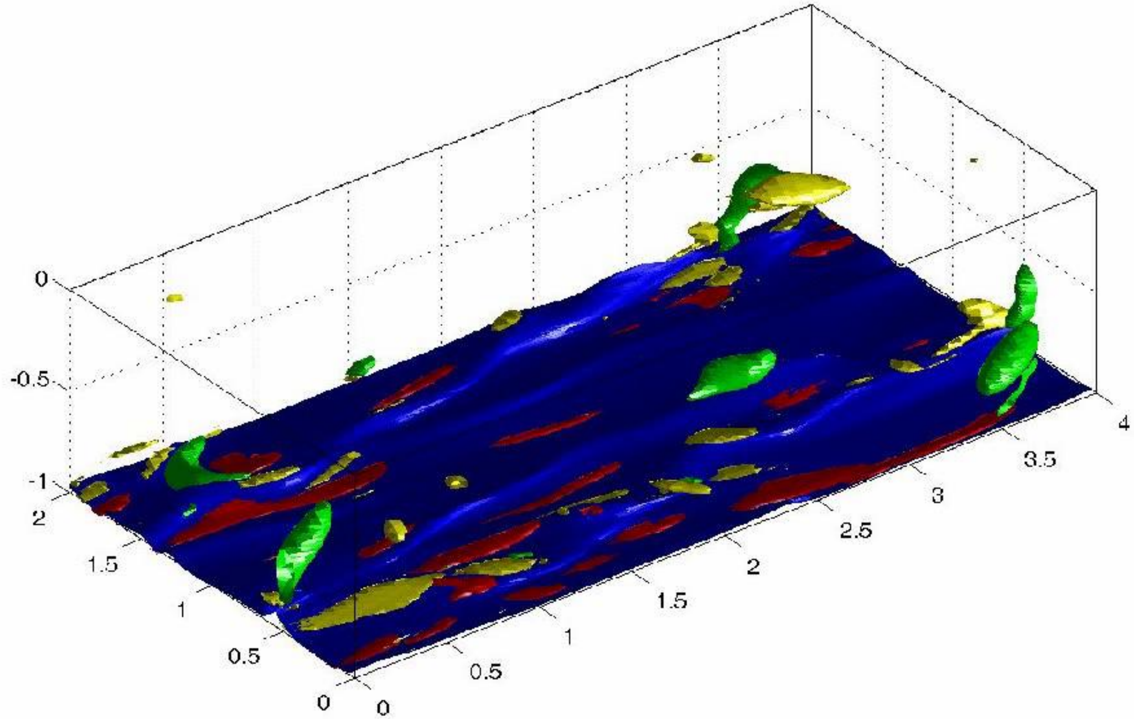
$$\Gamma = \max_{\alpha}\left(\left|\omega_{\alpha}\right| \frac{\partial u_{\alpha}}{\partial x_{\alpha}} \right)$$

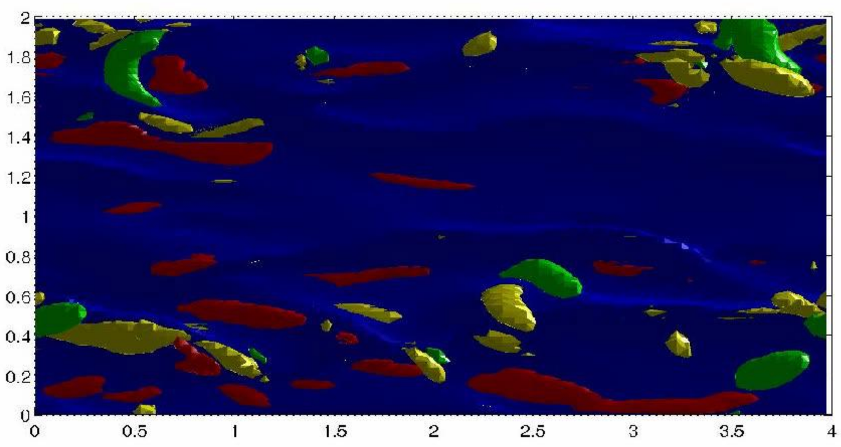
(No summation on α)

Test in turbulent flow to find which features are associated with high values of this measure

Channel flow animations

(Re_{τ}=180)





Blue = streamwise velocity, u

Red = vorticity stretching marker, Γ

Yellow = v(du/dy)

Green = low pressure, p

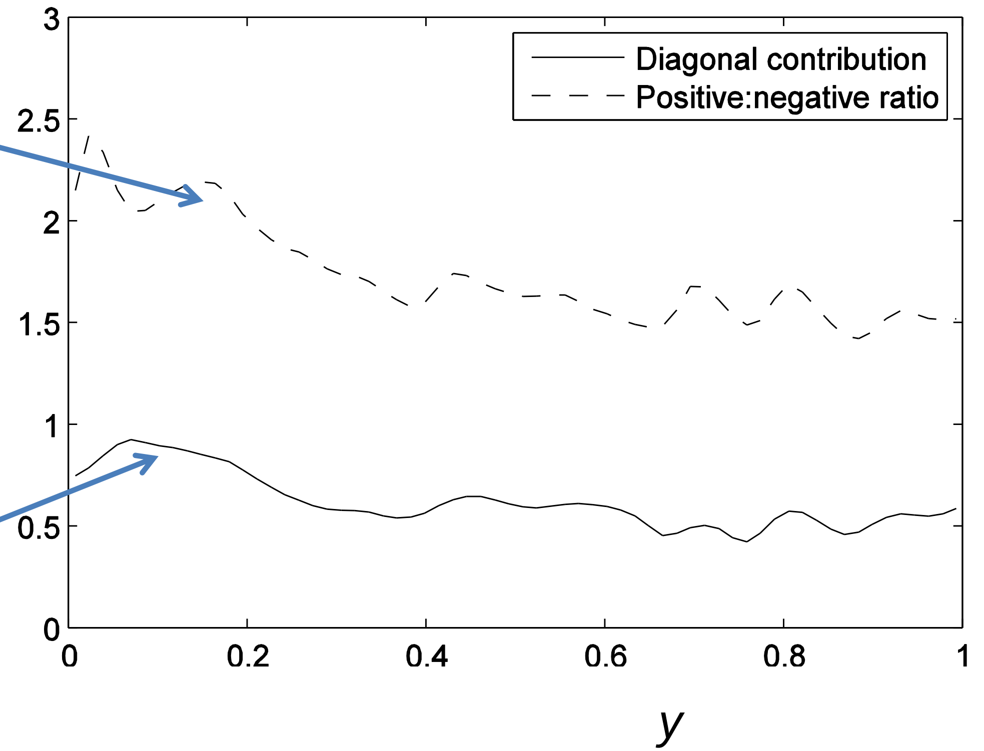
Observations of turbulence structure

- Yellow v(du/dy) correlates with low-speed blue (u)
  - Lift up of low speed streaks
- Yellow v(du/dy) and green (p) are often neighbours
  - Strong vortices lift up surrounding fluid
- Intermittent breakdown to smaller scales, often following large green (low p)
  - Bursting
- Red (Γ) mostly follows high-speed blue (u)
  - Drag creation by vorticity stretching and diffusion
  - Some activity also above low speed streaks

Statistical measures in channel flow

$$\frac{-<\sum_{\alpha}\omega_{\alpha}^{2}\max\left(0,\frac{\partial u_{\alpha}}{\partial x_{\alpha}}\right)>}{<\sum_{\alpha}\omega_{\alpha}^{2}\min\left(0,\frac{\partial u_{\alpha}}{\partial x_{\alpha}}\right)>}$$

$$\frac{<\sum_{\alpha}\omega_{\alpha}^{2}\frac{\partial u_{\alpha}}{\partial x_{\alpha}}>}{<\omega_i\omega_j\frac{\partial u_i}{\partial x_j}>}$$

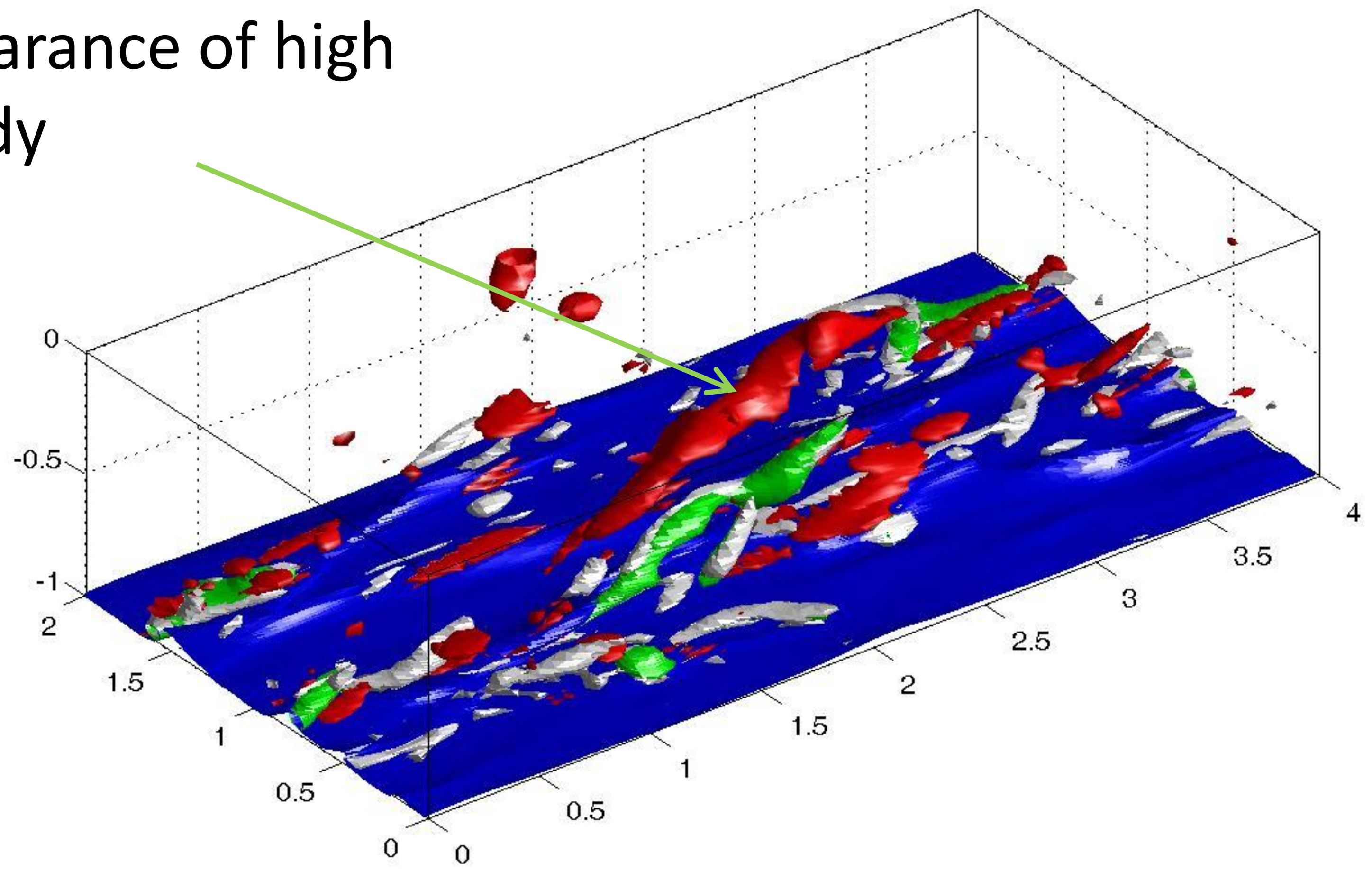


(limited sample size)

- Similarities with Ashurst et al (1987):
  - Preferential alignment of vorticity with intermediate eigenvector of stain rate in isotropic turbulence

yΓ (red) in relation to Q (white) and p (green)

Correlates with appearance of high vdu/dy



Conclusions

- Scalar measure of vorticity stretching Γ
  - Some statistical support for its relevance
  - Mainly locates strained regions in high-speed streaks associated with the production of spanwise vorticity
  - $y\Gamma$ shows formation of shear layers above low speed streaks and alongside low pressure regions
  - Intermediary role in turbulence dynamics between λ_2, p and $|\omega|$, sheets