Characterisation of Marginally Turbulent Square Duct Flow

M. Uhlmann, A. Pinelli

Numerical Simulation and Modeling Unit, CIEMAT

Madrid, Spain

A. Sekimoto, G. Kawahara

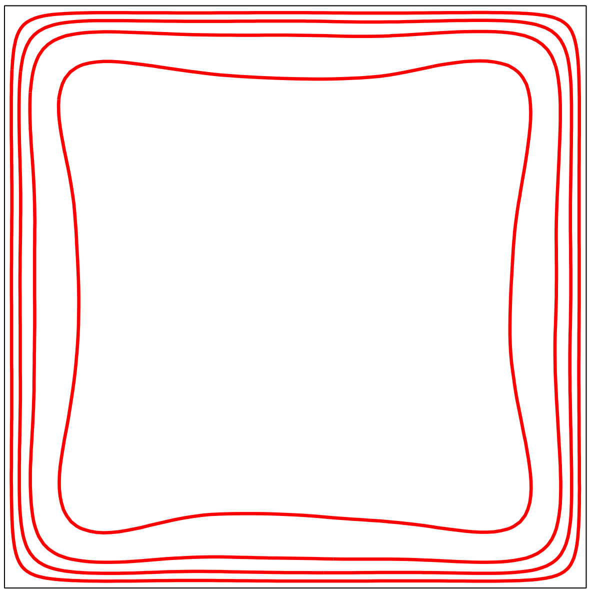
Department of Mechanical Science, Osaka University

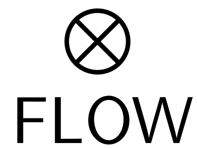
Osaka, Japan

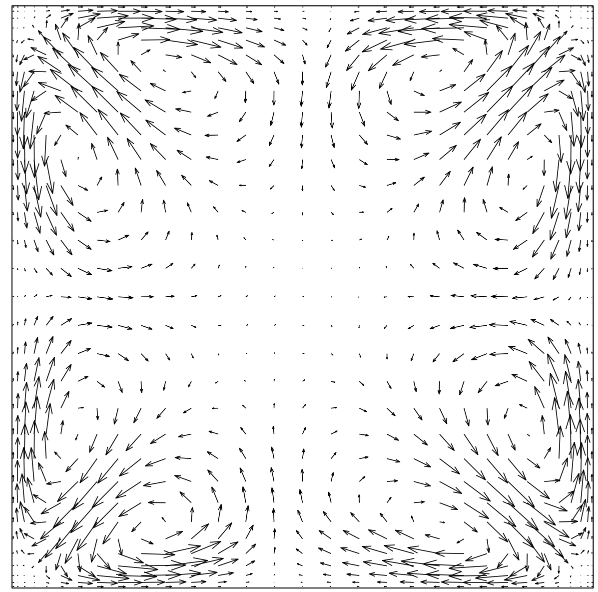
ETC11

Motivation

turbulence-induced secondary flow in a square duct:







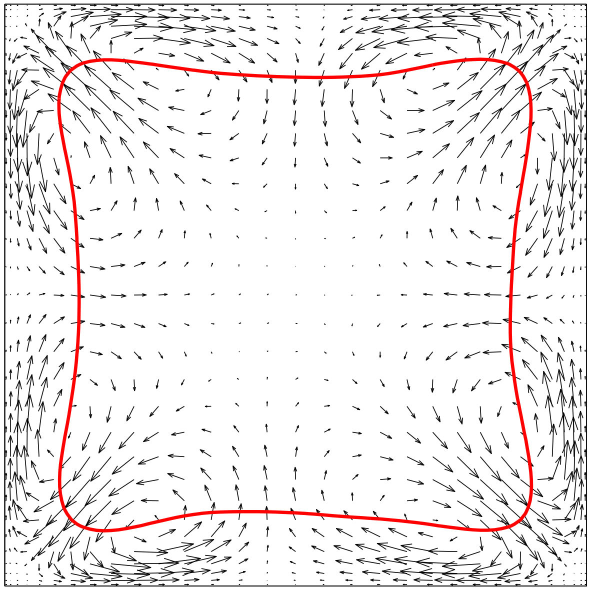
primary mean flow

secondary mean flow

⇝ how does it arise?

Turbulence-Induced Secondary Flow

- 8-vortex pattern
- weak intensity
- significant deformation of primary flow
- previous investigations: focus on Reynolds-averaged budgets



$\rightsquigarrow$ underlying mechanism unclear

Present Scope

1. investigate: coherent structures $\leftrightarrow$ secondary flow
   - choose marginal Reynolds number

   $\Rightarrow$ scales of CS comparable to duct width

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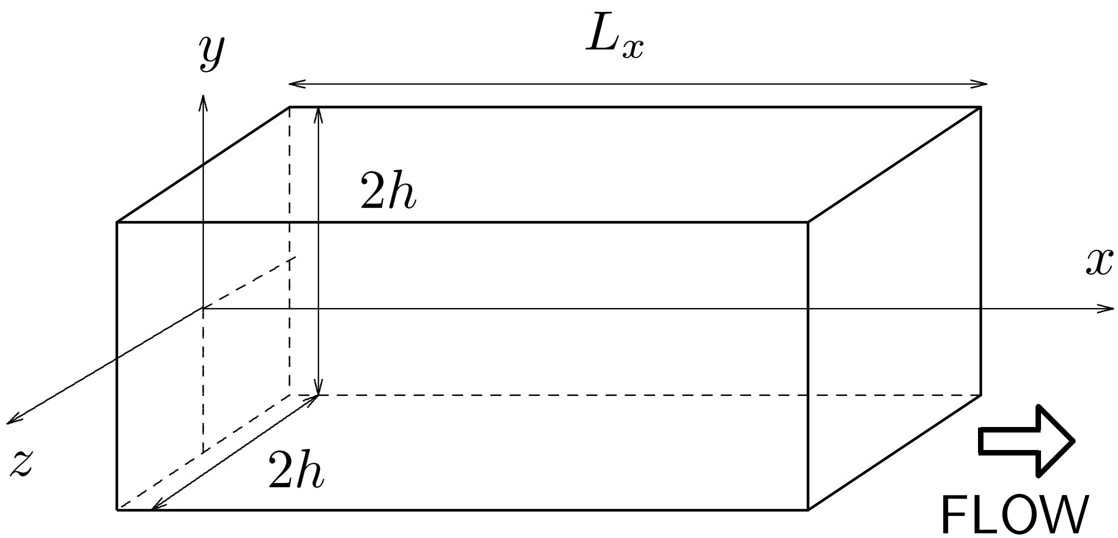
   $\Rightarrow$ scales of CS comparable to duct width

2. need to establish 'marginal' regime:
   - determine bounds for sustained turbulence

Configuration



- period L_x/h
- $Re_b = \dfrac{u_b\,h}{\nu}$

  $Re_\tau = \dfrac{u_\tau\,h}{\nu}$

  (u_τ: average)

- constant flow rate is imposed

Direct Numerical Simulation Method

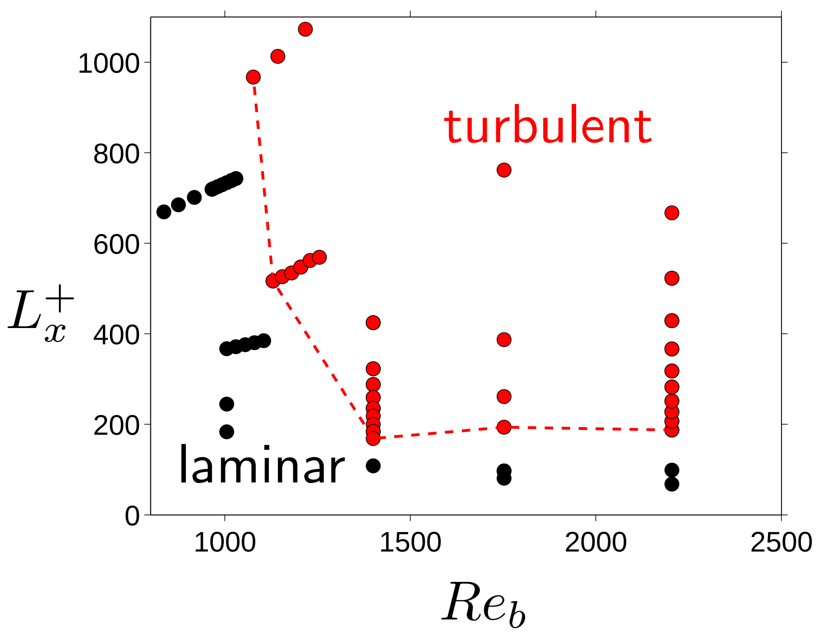
- “primitive” variable formulation, projection method
- Runge-Kutta-3, Crank-Nicholson
- Fourier-Chebyshev-Chebyshev pseudo-spectral
- resolution:

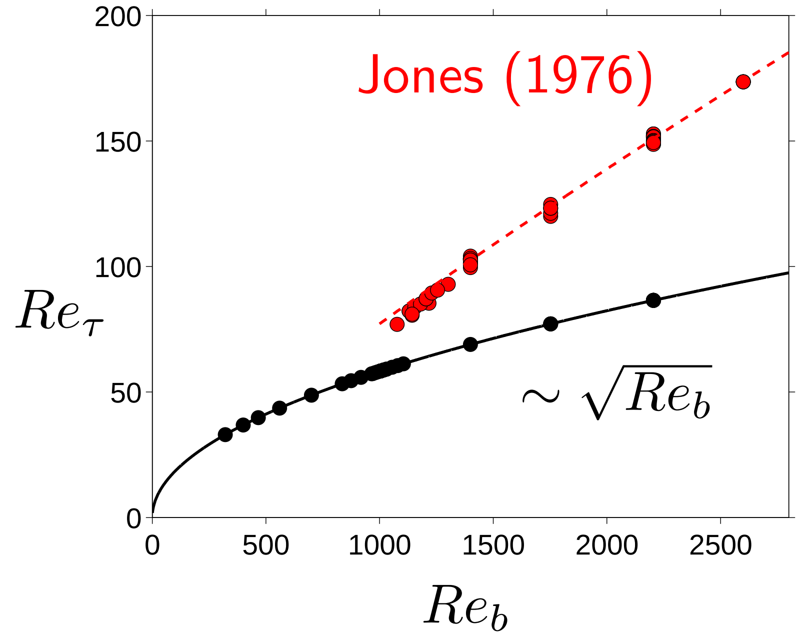
$$CFL \leq 0.3;\ \Delta x^{+} \leq 15;\ y^{+}_{min}, z^{+}_{min} \leq 0.1$$

$\Rightarrow$ validated against previous DNS & experiments

Requirements for Sustained Turbulence

integration time: $2000h/u_b$

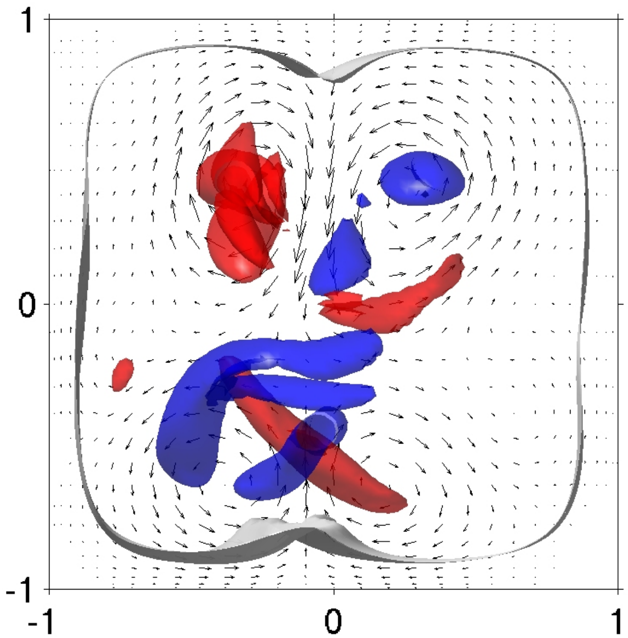


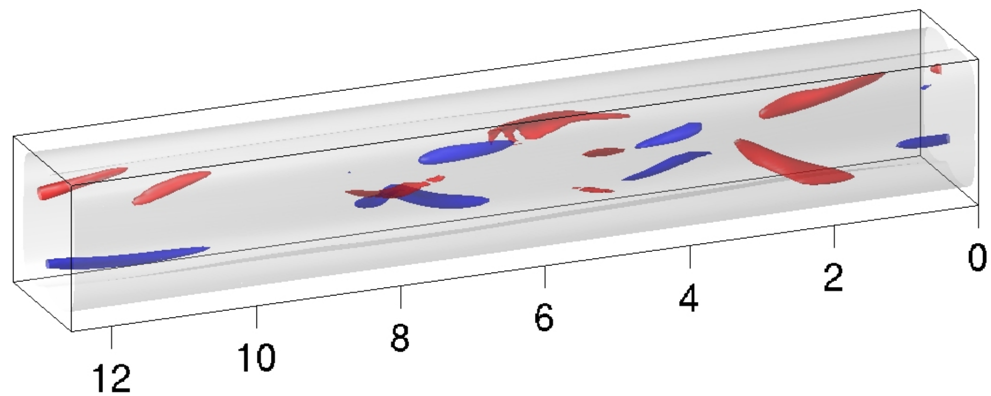


- critical Reynolds: $Re_{b,min} \approx 1100 \longrightarrow Re_{\tau,min} \approx 80$
- minimum length: $L_x^+ \approx 200$

Marginal Reynolds: Instantaneous Flow Field

$$Re_b = 1100,\ L_x/h = 4\pi$$



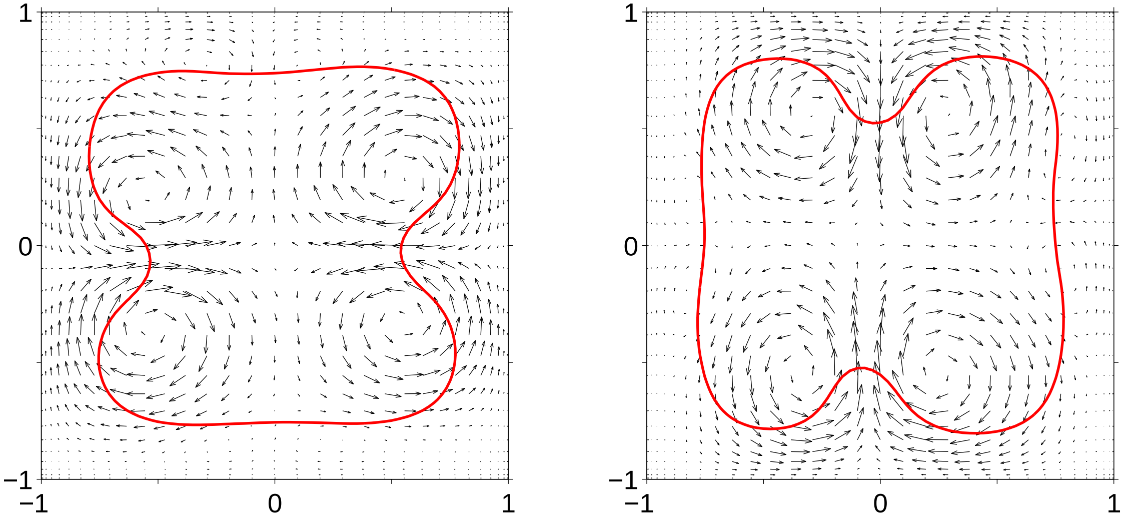


- $u/u_b = 0.62$, ●● $\omega_x \nu / u_\tau^2 = \pm 0.25$

Marginal Reynolds Number: Mean Flow

$$Re_b = 1205,\ L_x/h = 2\pi$$

time-average over $\mathcal{O}(100)h/u_b$

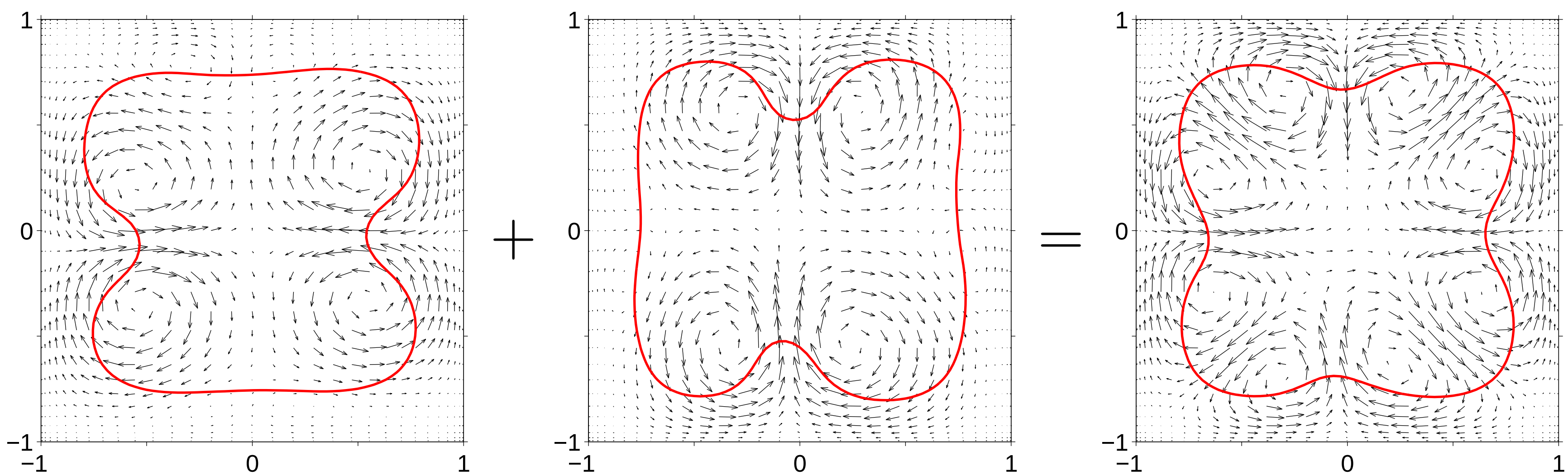


- flow exhibits <u>4-vortex pattern</u>

Marginal Reynolds Number: Mean Flow

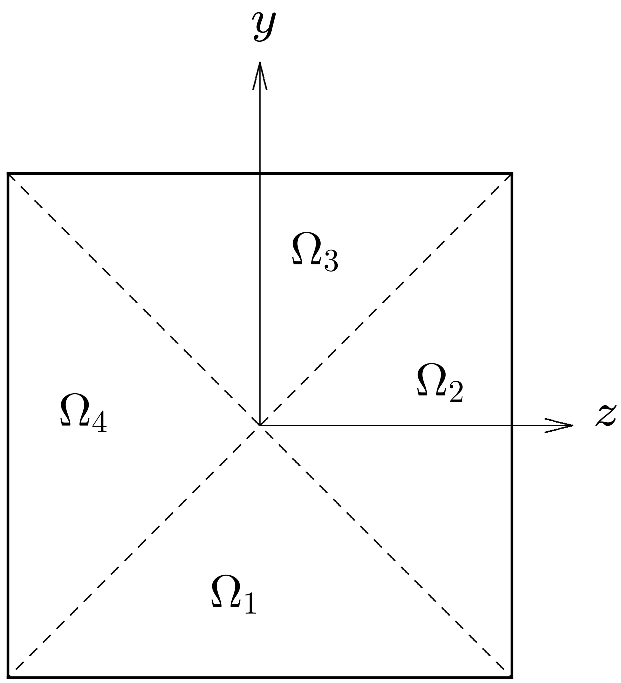
$$Re_b = 1205,\ L_x/h = 2\pi$$

time-average over $\mathcal{O}(100)h/u_b$ $\qquad$ $\mathcal{O}(1000)h/u_b$



• flow exhibits 4-vortex pattern $\Rightarrow$ 8-vortex pattern

Quantification of Vortex Pattern



- define indicator I:

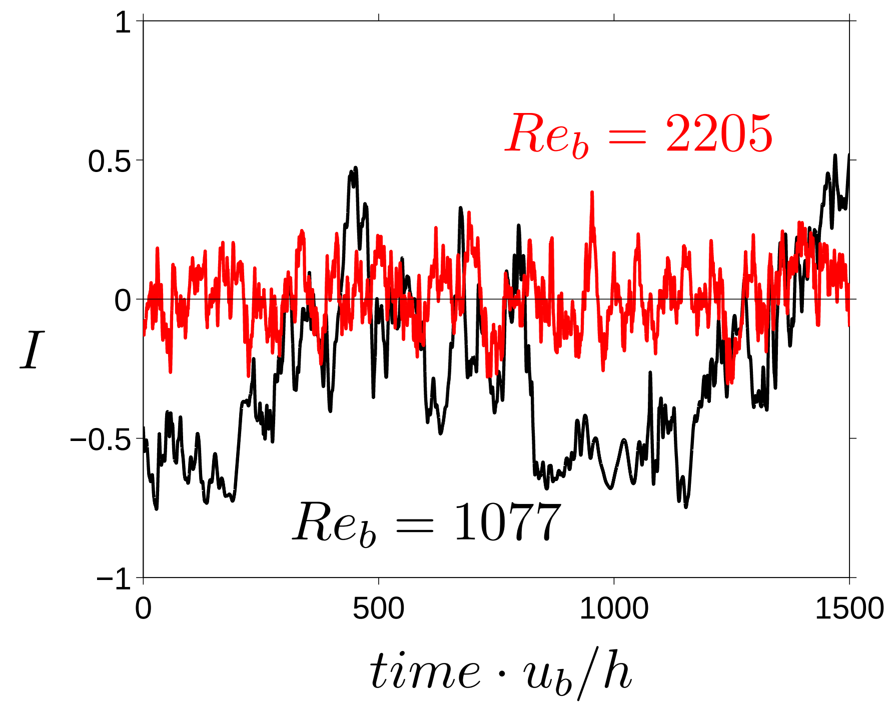
$$I(t) = \frac{(S_1 + S_3) - (S_2 + S_4)}{S_1 + S_2 + S_3 + S_4}$$

$$S_i(t) = \int_{\Omega_i} \langle \omega_x \rangle_x^2 \, \mathrm{d}y \, \mathrm{d}z$$

$\Rightarrow$ reflects how $\langle \omega_x \rangle_x$ is partitioned

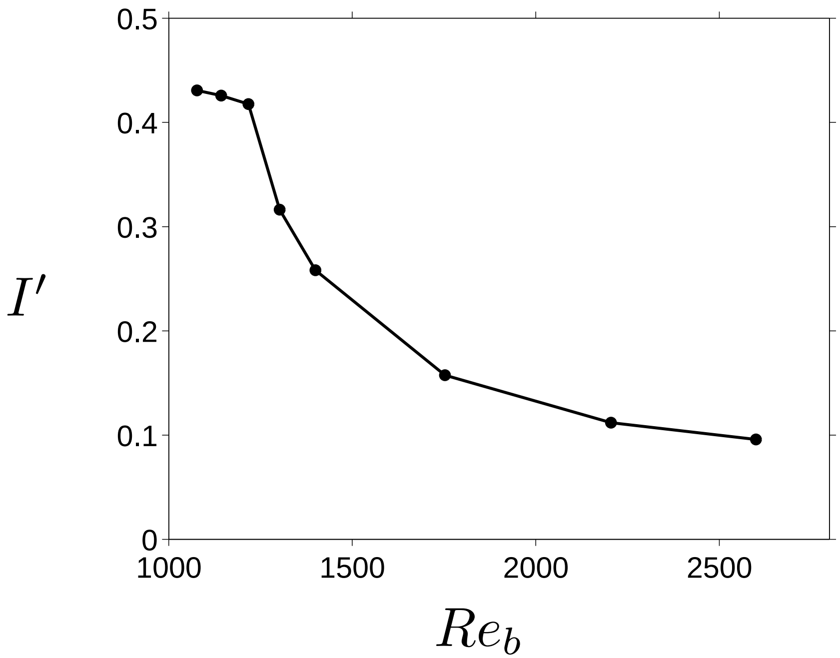
Temporal Evolution of Indicator I

- amplitude & frequency: Reynolds-dependent



Reynolds-Dependency

r.m.s. intensity of I



$\Rightarrow$ gradual transition to usual 8-vortex pattern

Reynolds-Dependency

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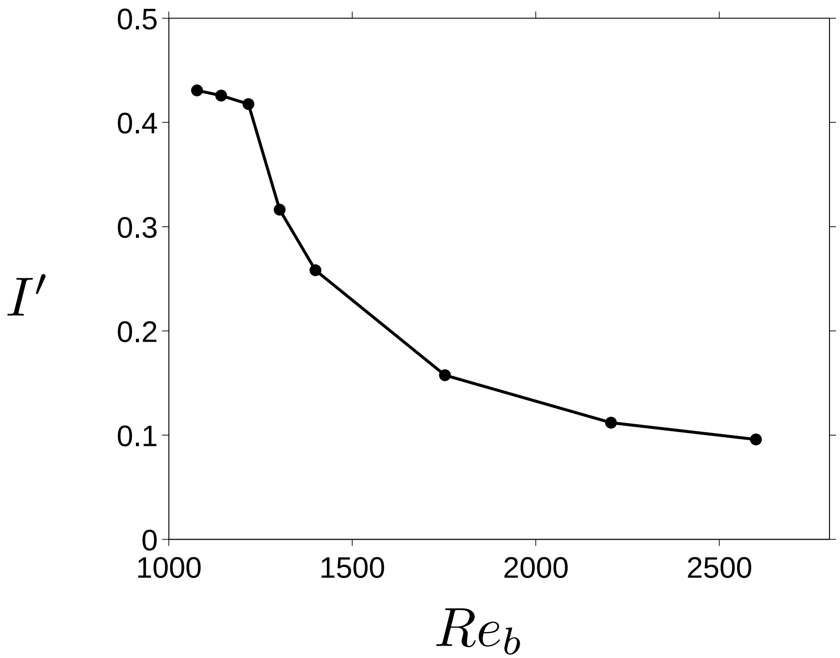
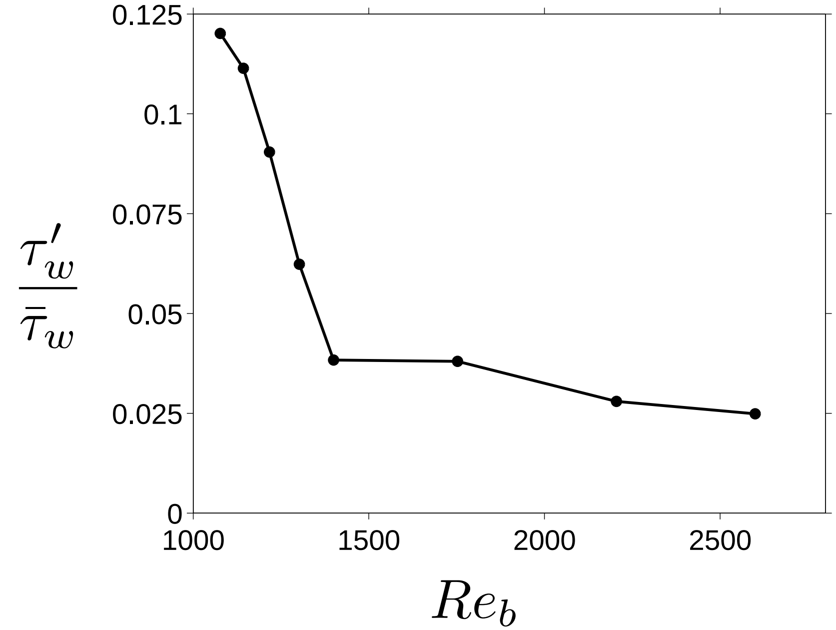


fluctuation of wall shear



$\Rightarrow$ gradual transition to usual 8-vortex pattern

Coherent Structure Eduction

Streamwise vortices

- criterion of Kida & Miura (1998):
  local pressure minima + swirl condition

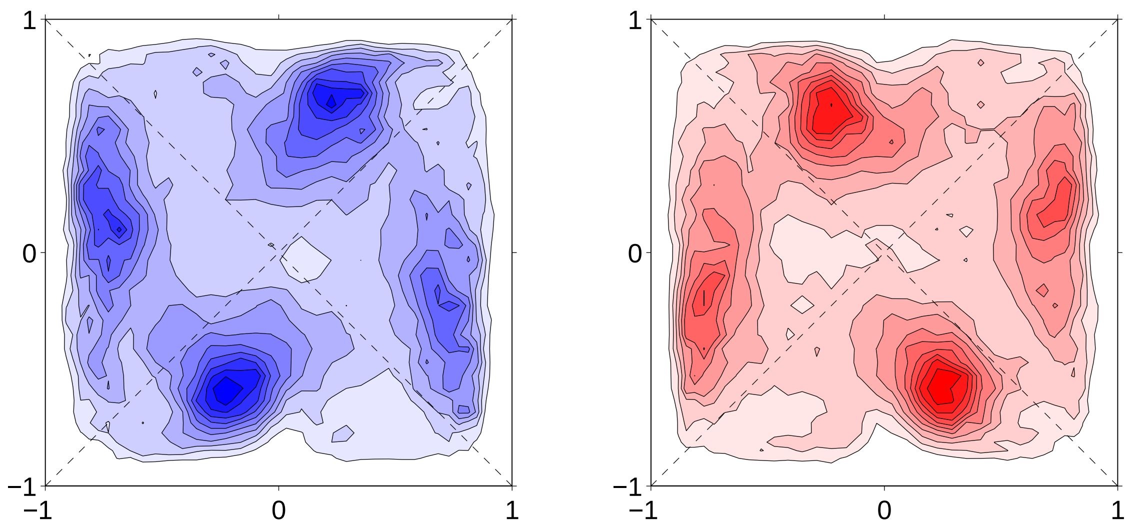
⇒ center coordinates of streamwise vortices

- accumulate statistics over 960 snapshots $(1000h/u_b)$

PDF of Streamwise Vortex Centers

$$Re_b = 1143,\ L_x/h = 4\pi$$

pdf: $\omega_x < 0$ pdf: $\omega_x > 0$



⇒ preferential location of CS

PDF of Streamwise Vortex Centers

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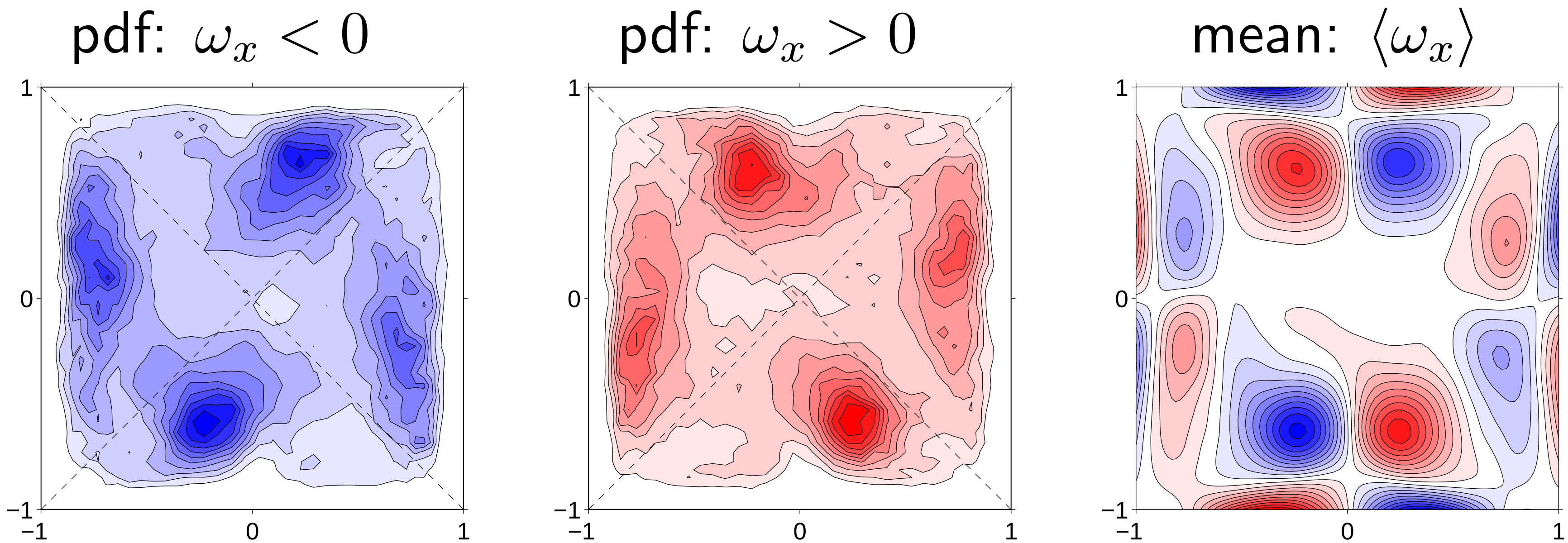


$\Rightarrow$ preferential location of CS: consistent with $\langle \omega_x \rangle$

Conclusions

DNS of turbulent flow in a square duct

- sustained turbulence: $Re_b \gtrsim 1100$, $L_x^+ \gtrsim 200$
- regime of marginal Reynolds numbers ($Re_b \lesssim 1400$):

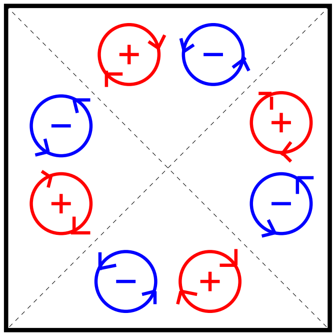
  mean 4-vortex pattern over $\mathcal{O}(100)$ intervals

  $\longrightarrow$ consistent with long-time average
- preferential location of streamwise vortices

  $\Rightarrow$ collapses with mean secondary vorticity

Perspectives

- sign selection mechanism?



- generation of secondary flow at higher Reynolds numbers