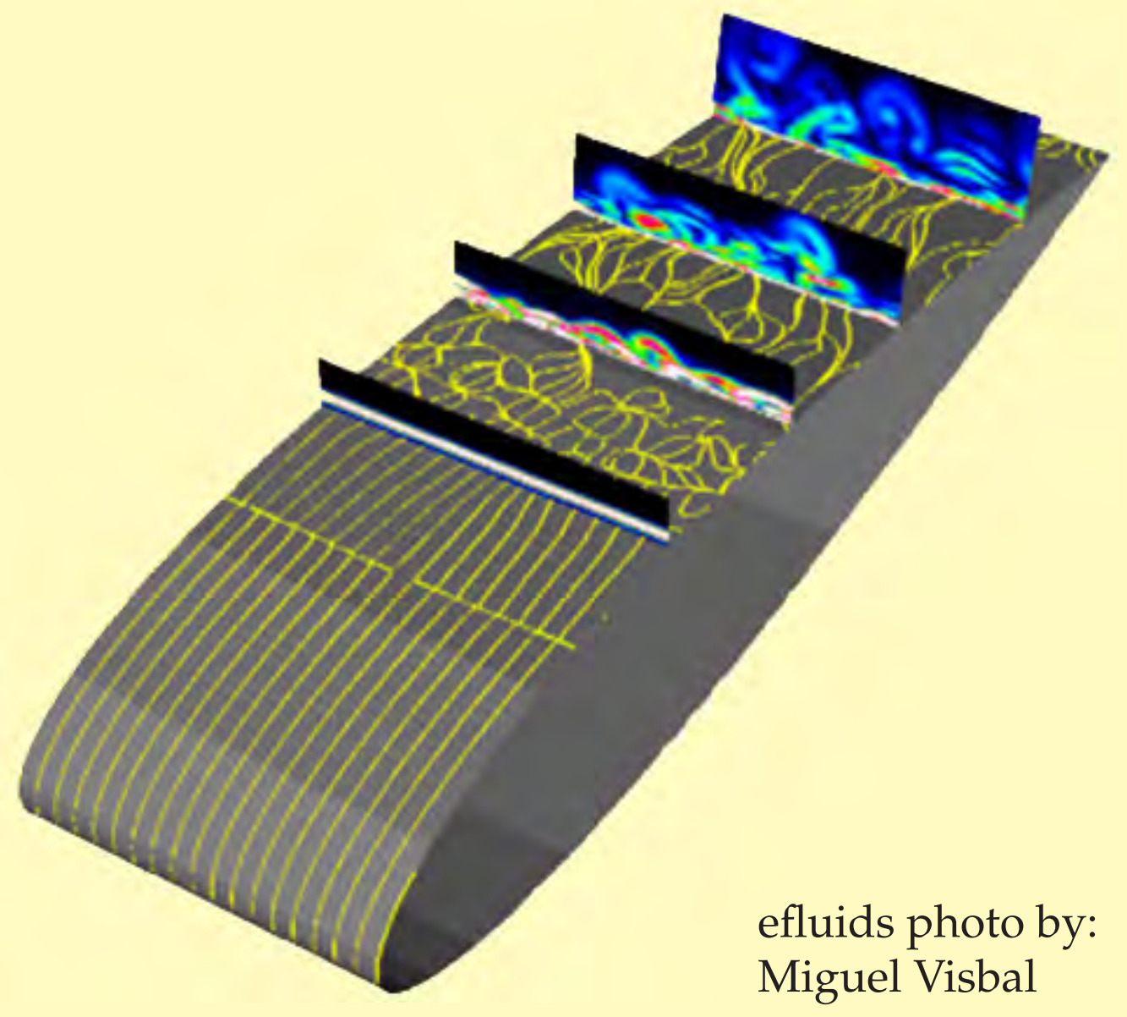
Controlling the onset of turbulence by streamwise traveling waves

Rashad Moarref Binh K. Lieu Mihailo R. Jovanović (PI, CAREER Award CMMI-06-44793, Control Systems)

Motivation

- **Transition to turbulence:** increases fuel consumption

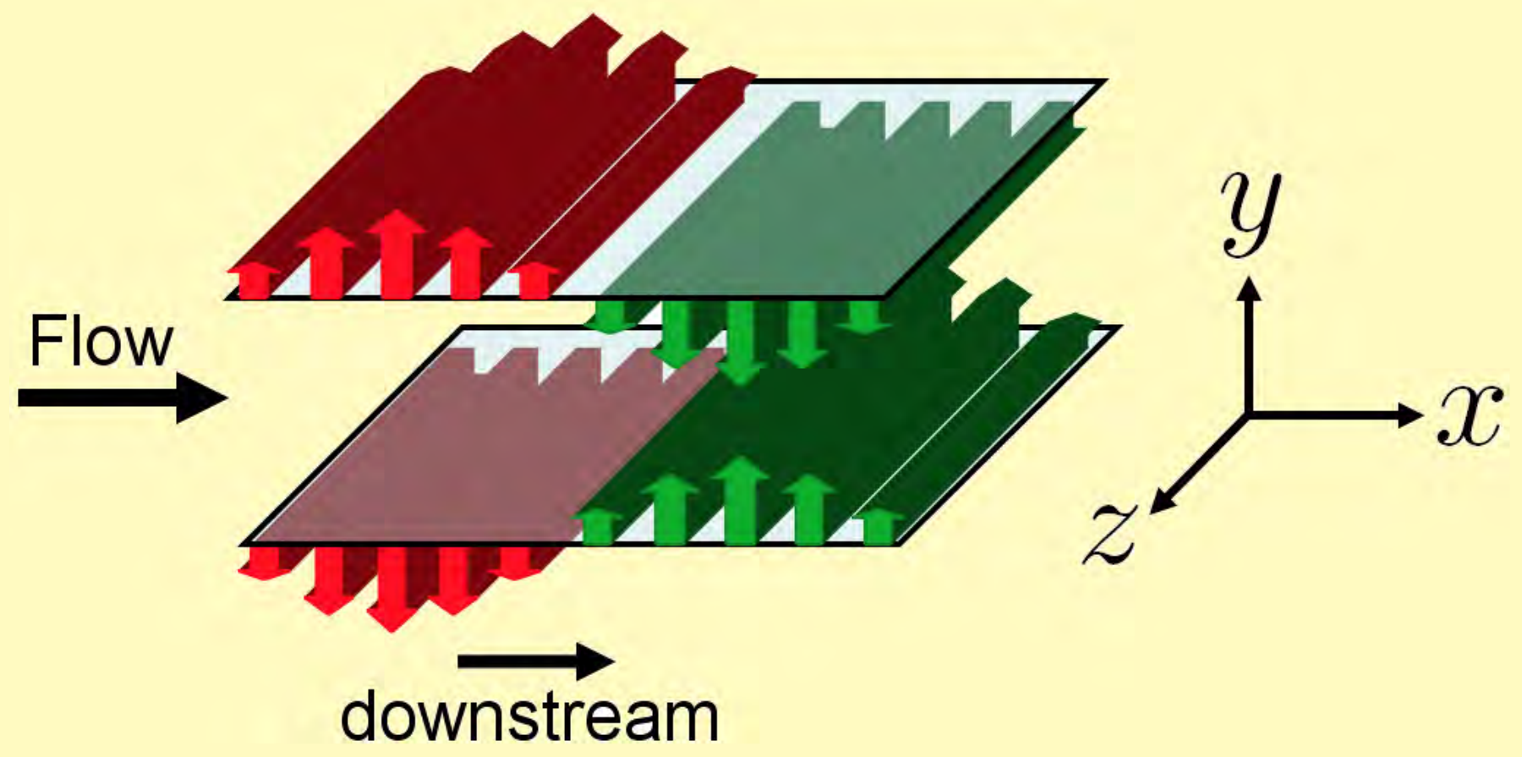
- **Objective:** delay/prevent transition



efluids photo by: Miguel Visbal

Problem formulation

- Pressure driven channel flow



actuation: surface blowing and suction

- Governing equations

$$\begin{aligned} \mathbf{u}_t &= -(\mathbf{u}\cdot\nabla)\,\mathbf{u} - \nabla p + (1/R)\,\Delta\mathbf{u} \\ 0 &= \nabla\cdot\mathbf{u} \end{aligned}$$

- Vertical velocity along the walls

$$\begin{aligned} V\,(y = \pm 1) &= \mp 2\,\alpha\,\cos\left(\omega_x\,(x - c\,t)\right) \\ &= \mp 2\,\alpha\,\cos\left(\omega_x \bar{x}\right) \end{aligned}$$

- $\mathbf{u}$ - velocity
- p - pressure
- **Key parameters:**

$$R = \frac{\text{inertial forces}}{\text{viscous forces}}$$

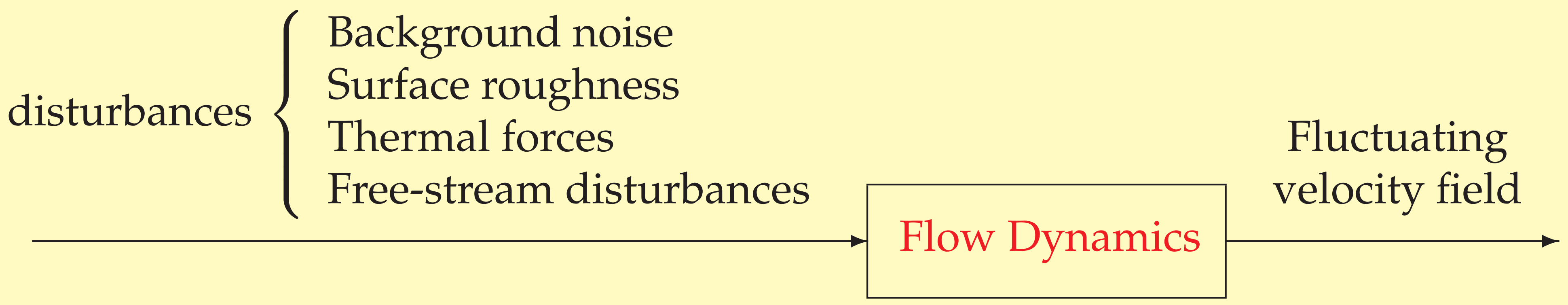
α = wave amplitude

c = wave speed

ω_x = wave frequency

Perturbation analysis: traveling wave design

- **Objective:** controlling the onset of turbulence
- **Turbulence initiated by:** large flow sensitivity
- **Approach:** design traveling waves to reduce flow sensitivity



disturbances
Background noise
Surface roughness
Thermal forces
Free-stream disturbances

Flow Dynamics

Fluctuating velocity field

- Perturbation analysis of energy density (α small)

EXPLICIT FORMULA:

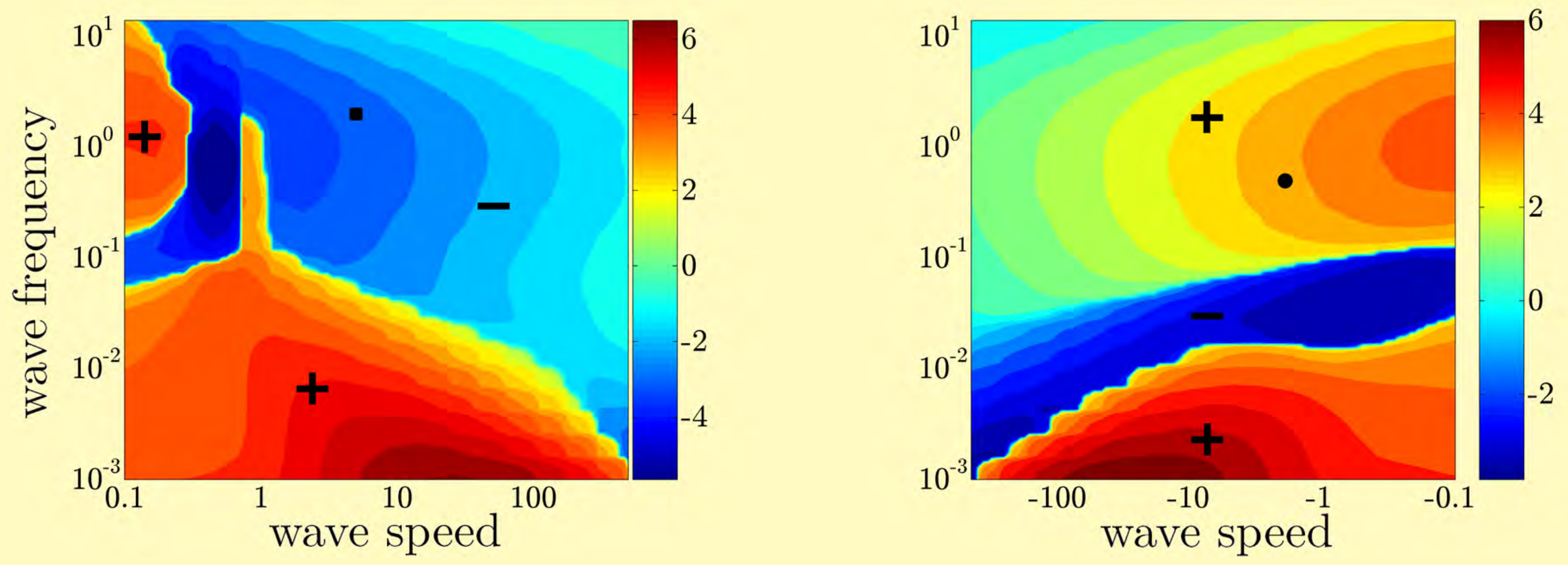
$$\boxed{\frac{\text{Energy density with control}}{\text{Energy density w/o control}} \approx 1 + \alpha^2\, g_2(\theta, k_z; \omega_x, c)}$$

$(\theta, k_z) \rightsquigarrow$ spatial wavenumbers

- Energy amplification in controlled flow with $R = 2000$

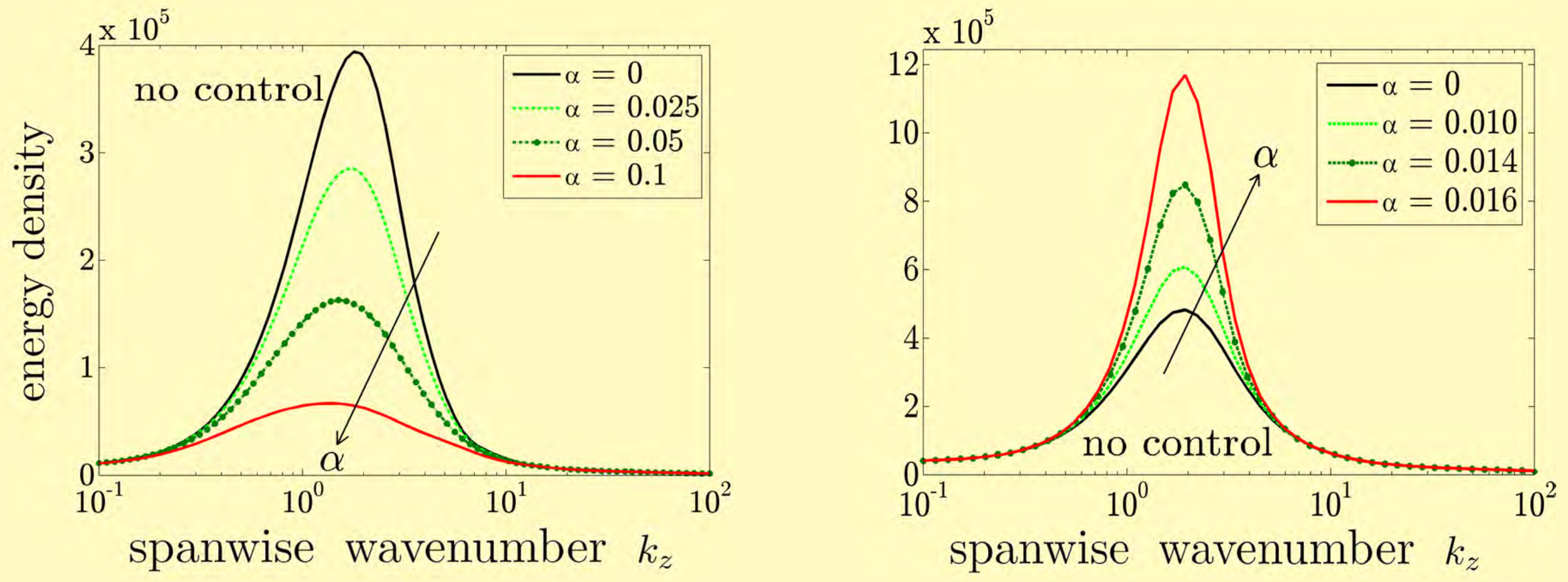
$(\theta = 0, k_z = 1.78)$: most energy w/o control

g_2, downstream: g_2, upstream:



- Perturbation analysis captures the essential trends

downstream ($c = 5, \omega_x = 2$): upstream ($c = -2, \omega_x = 0.5$):



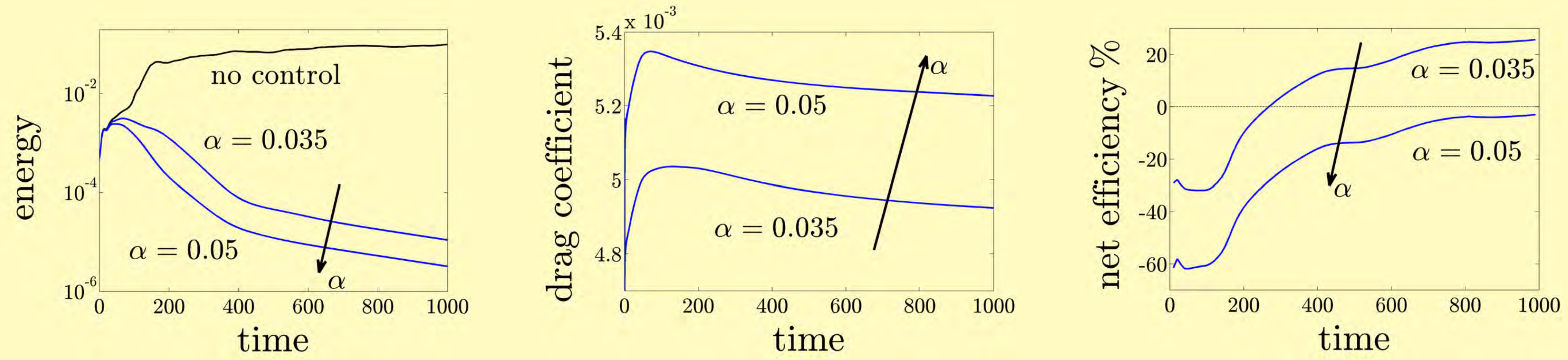
- Downstream ($c = 5, \omega_x = 2$): reduce energy amplification
  good candidate for controlling the onset of turbulence

PEAK TO PEAK: $\approx \begin{cases} 60\,\%\ \text{reduction}, & \alpha = 0.05 \\ 80\,\%\ \text{reduction}, & \alpha = 0.1 \end{cases}$

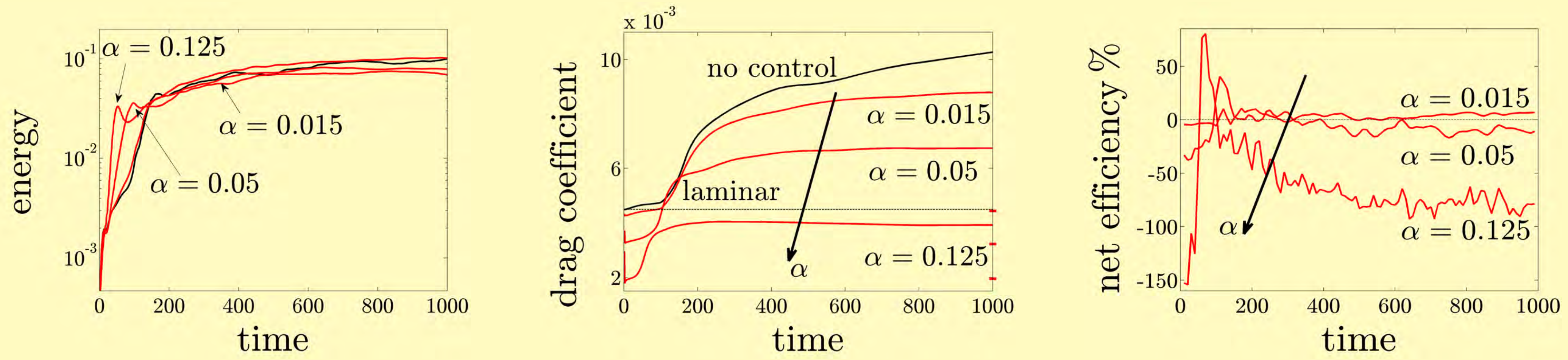
Simulations of nonlinear flow dynamics: verification

- Net efficiency $= \dfrac{\text{(produced power)} - \text{(required power for wall actuation)}}{\text{(required power to drive uncontrolled flow)}}$

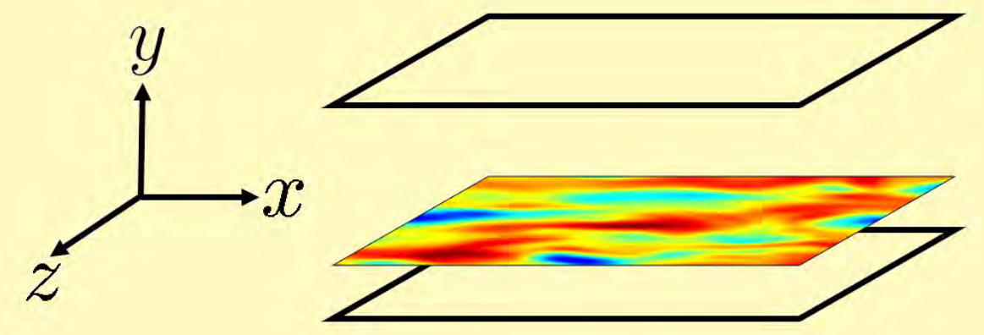
downstream ($c = 5, \omega_x = 2$): **avoidance of turbulence**



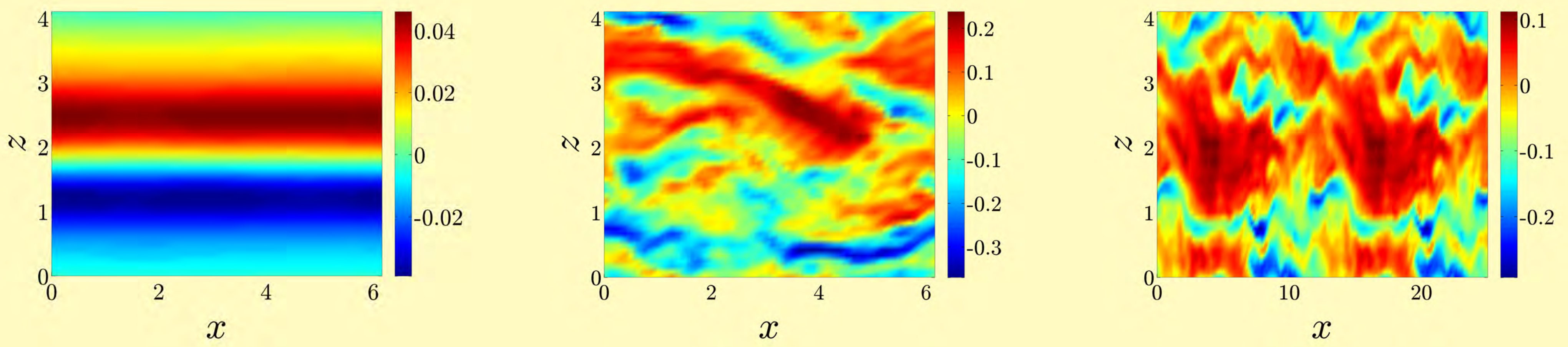
upstream ($c = -2, \omega_x = 0.5$): **promotion of turbulence**



streamwise velocity at $t = 150$:



downstream ($\alpha = 0.05$): uncontrolled: upstream ($\alpha = 0.05$):



Remarks

- Control-oriented model: linearized Navier-Stokes equations with uncertainty
  - powerful simulation-free approach to predicting full-scale results
- Facts revealed by perturbation analysis
  - downstream: reduce amplification $\rightsquigarrow$ avoidance of turbulence
  - upstream: increase amplification $\rightsquigarrow$ promotion of turbulence
- High-fidelity numerical simulations
  - verification of theoretical predictions

Publications

[1] R. Moarref and M. R. Jovanović, "Controlling the onset of turbulence by streamwise traveling waves. Part 1: Receptivity analysis", *J. Fluid Mech.*, vol. 663, pp. 70 - 99, (2010).

[2] B. K. Lieu, R. Moarref, and M. R. Jovanović, "Controlling the onset of turbulence by streamwise traveling waves. Part 2: Direct numerical simulations", *J. Fluid Mech.*, vol. 663, pp. 100 - 119, (2010).