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Turbulent skin-friction drag reduction in the Constant Power Input framework

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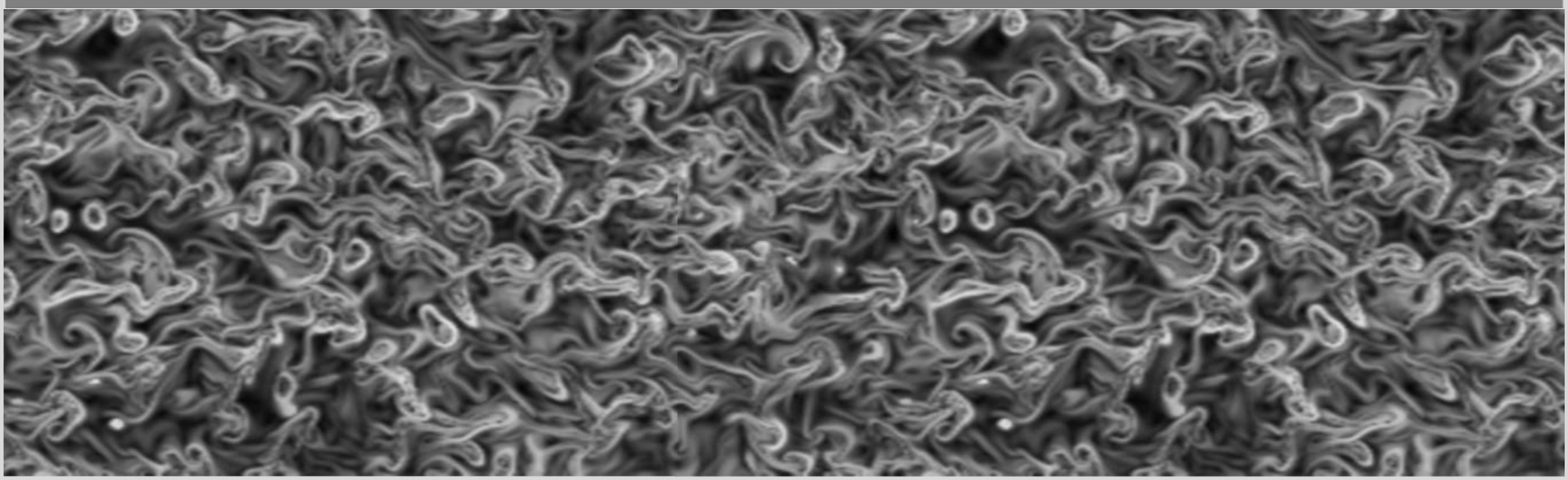
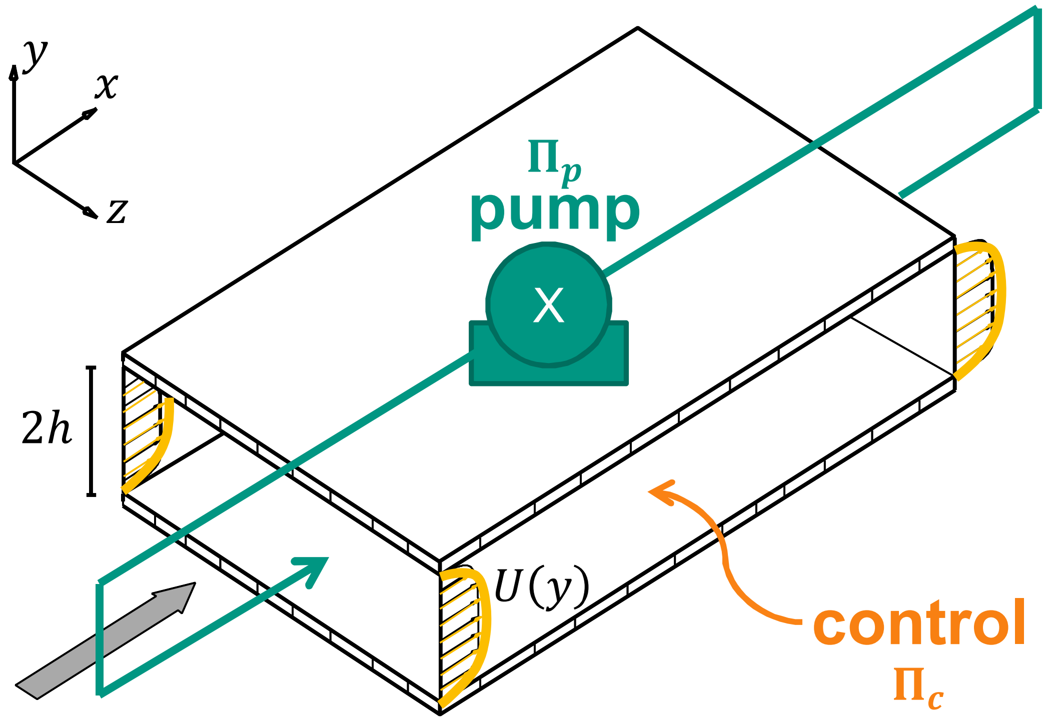
Institute of Fluid Mechanics istm

JOINT ANNUAL MEETING OF GAMM AND DMV, Braunschweig, Germany



The Drag Reduction Experiment



bulk velocity: U_b

pressure gradient:

$$-\frac{\mathrm{d}p}{\mathrm{d}x} = \frac{\tau_w}{h}$$

skin-friction coefficient:

$$C_f = \frac{2\tau_w}{\rho U_b^2}$$

pumping power (per unit area):

$$\Pi_p = -\frac{\mathrm{d}p}{\mathrm{d}x} h U_b$$

drag reduction rate: $R = 1 - \frac{C_f}{C_{f,0}}$

The choice of flow condition (1)

- Navier-Stokes equations alone do not pump fluid through the duct
- **Forcing term needed** to mimic pump

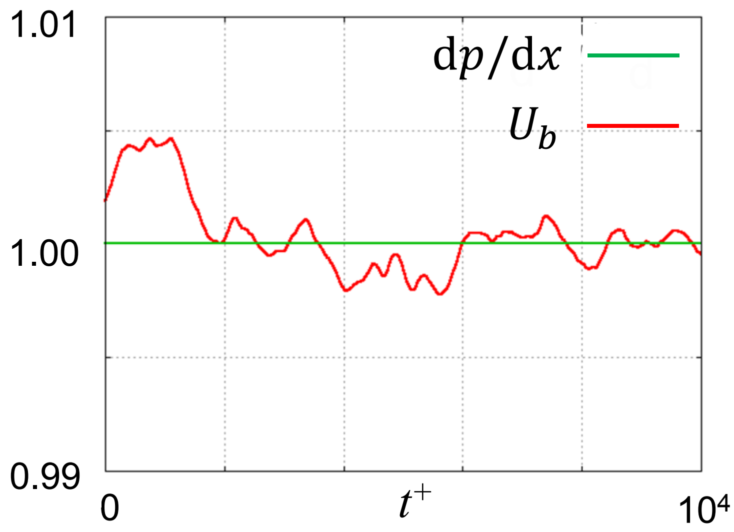
- Many **arbitrary choices** possible
- Often equivalent on physical grounds
- Different on practical grounds
- Different realizations, same statistics

The choice of flow condition (2)

Constant Pressure Gradient (CPG)

↓

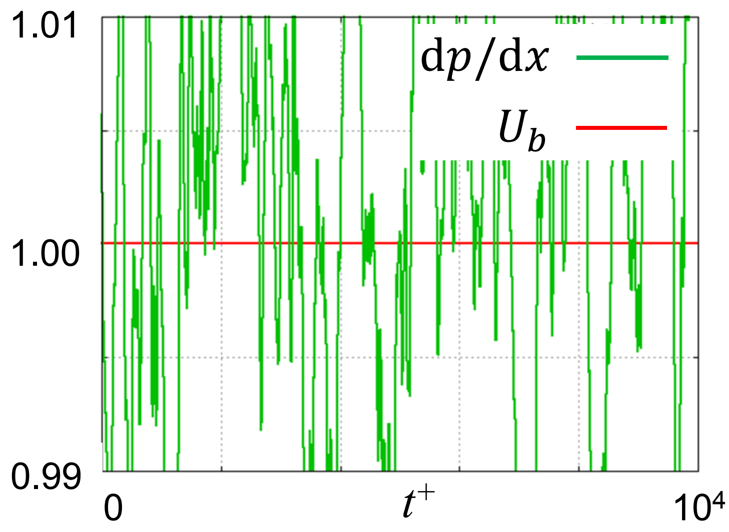
Flow rate fluctuates in time



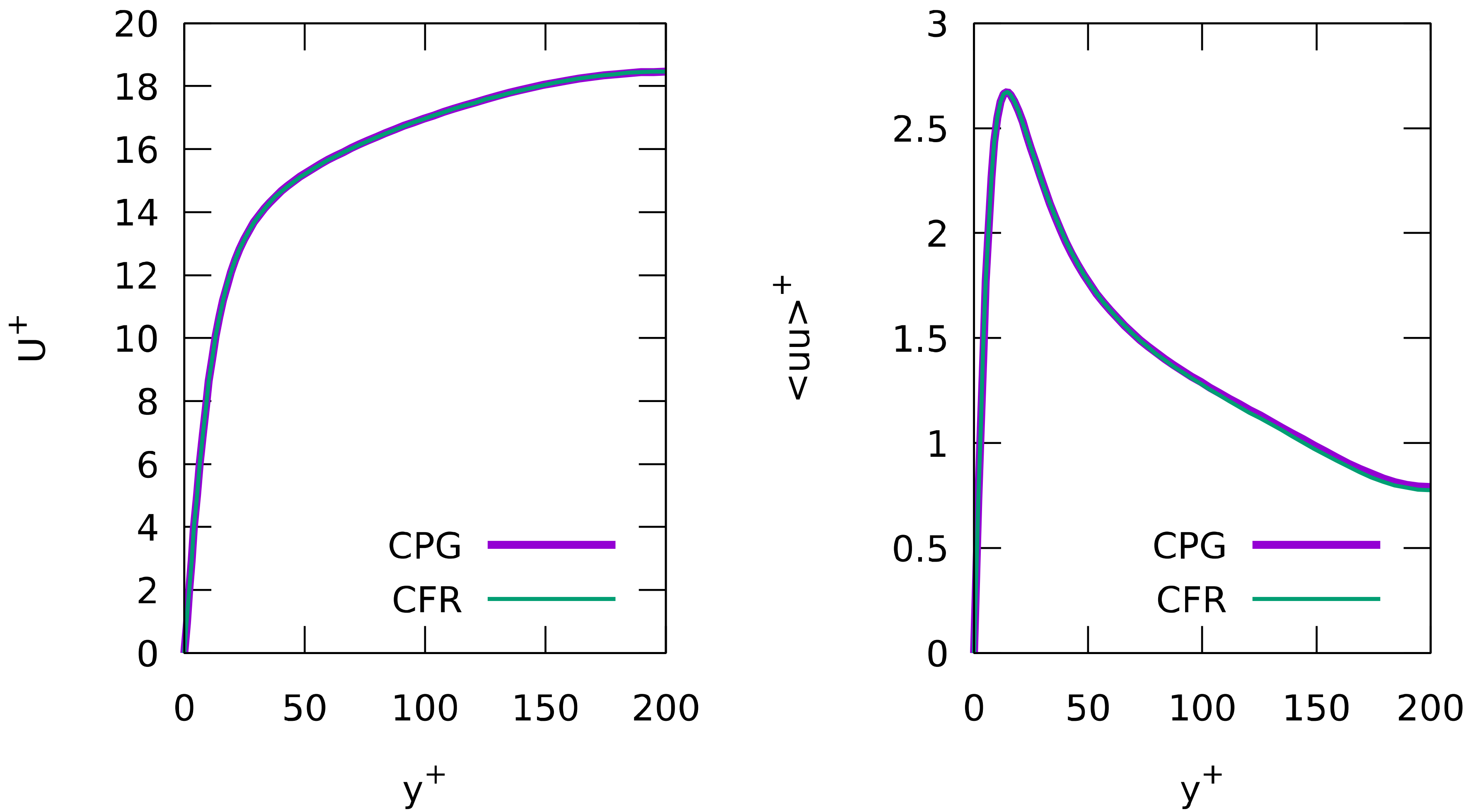
Constant Flow Rate (CFR)

↓

Pressure gradient fluctuates in time

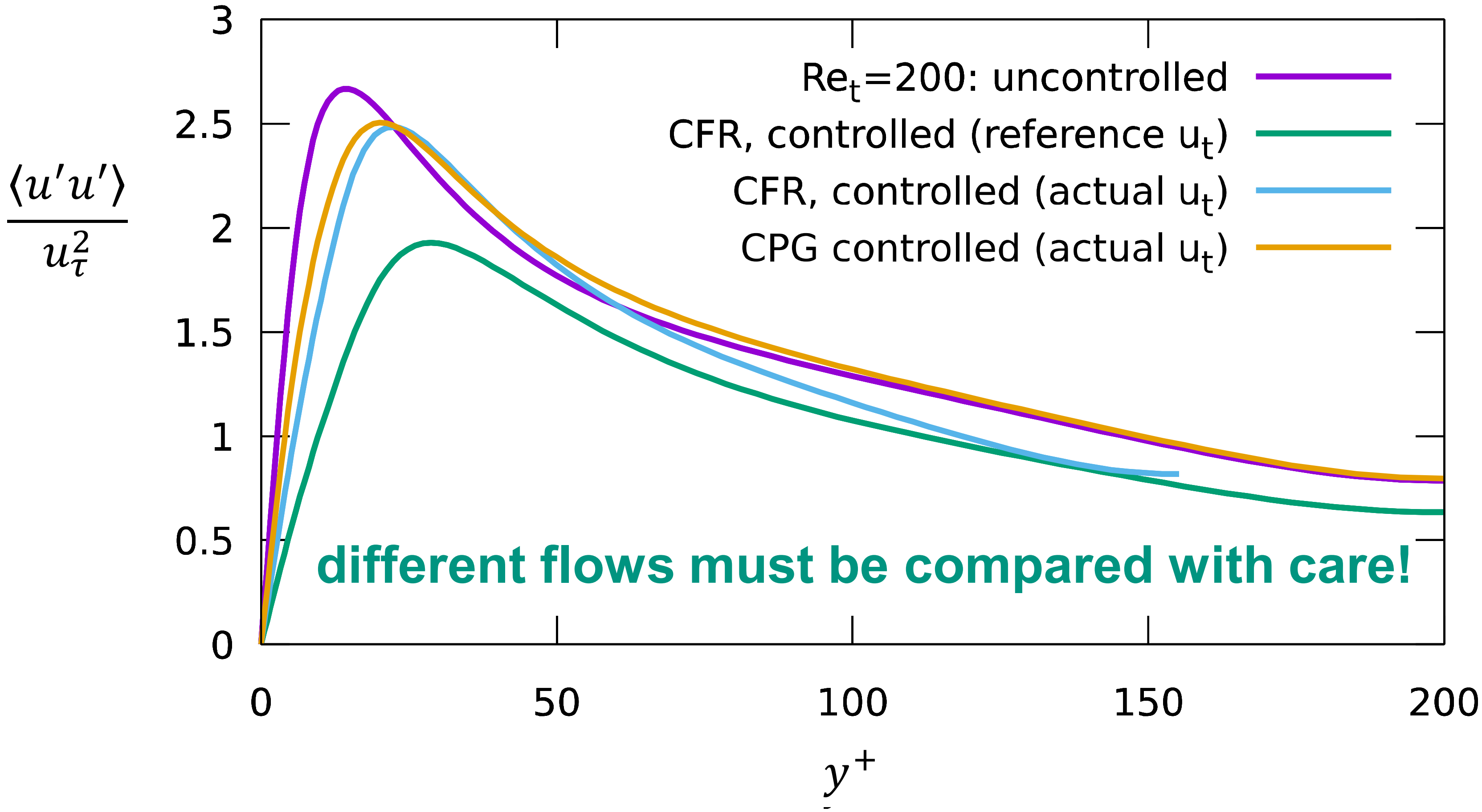


Unimportant choice for uncontrolled flows



Important choice in flow control!

"Turbulent fluctuations are destroyed" ?



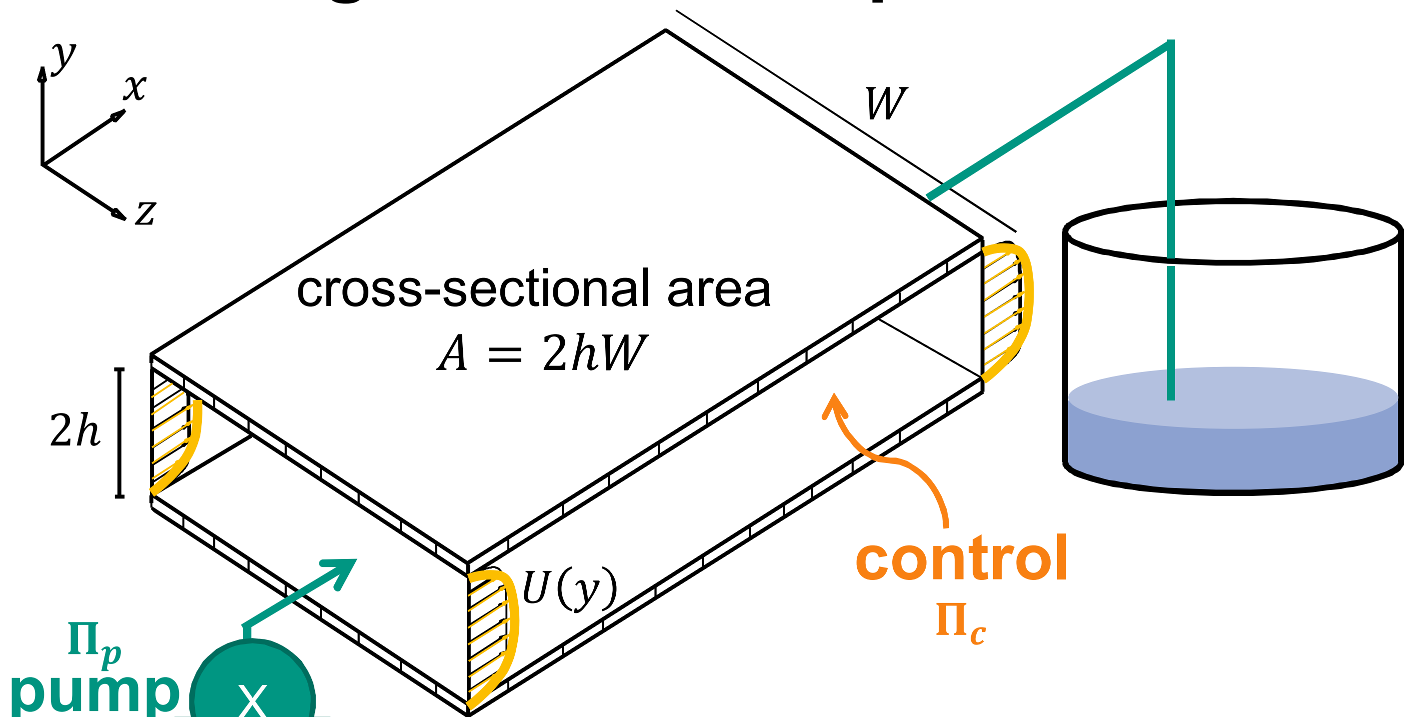
Important choice in flow control!

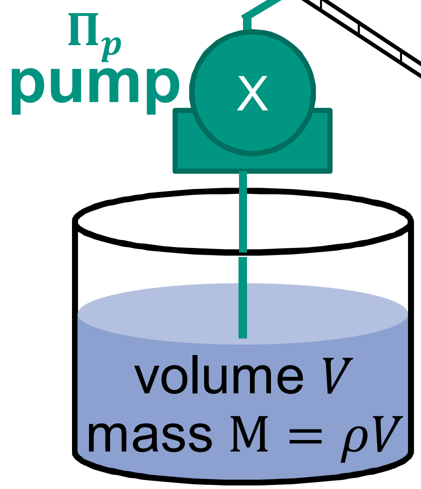
successful control $\boldsymbol{R} = 1 - \frac{C_f}{C_{f,0}} > 0$ manifests differently

	U_b	$-\frac{\mathrm{d}p}{\mathrm{d}x}$	$\Pi_\mathrm{p} = -\frac{\mathrm{d}p}{\mathrm{d}x} h U_b$	$\boldsymbol{C_f}$
CPG	↑	=	↑	↓
CFR	=	↓	↓	↓

- With control: either different Re_τ or different Re_B
- $\boldsymbol{C_f \neq \Pi_p}$: successful control can increase pumping power!

The Drag Reduction Experiment





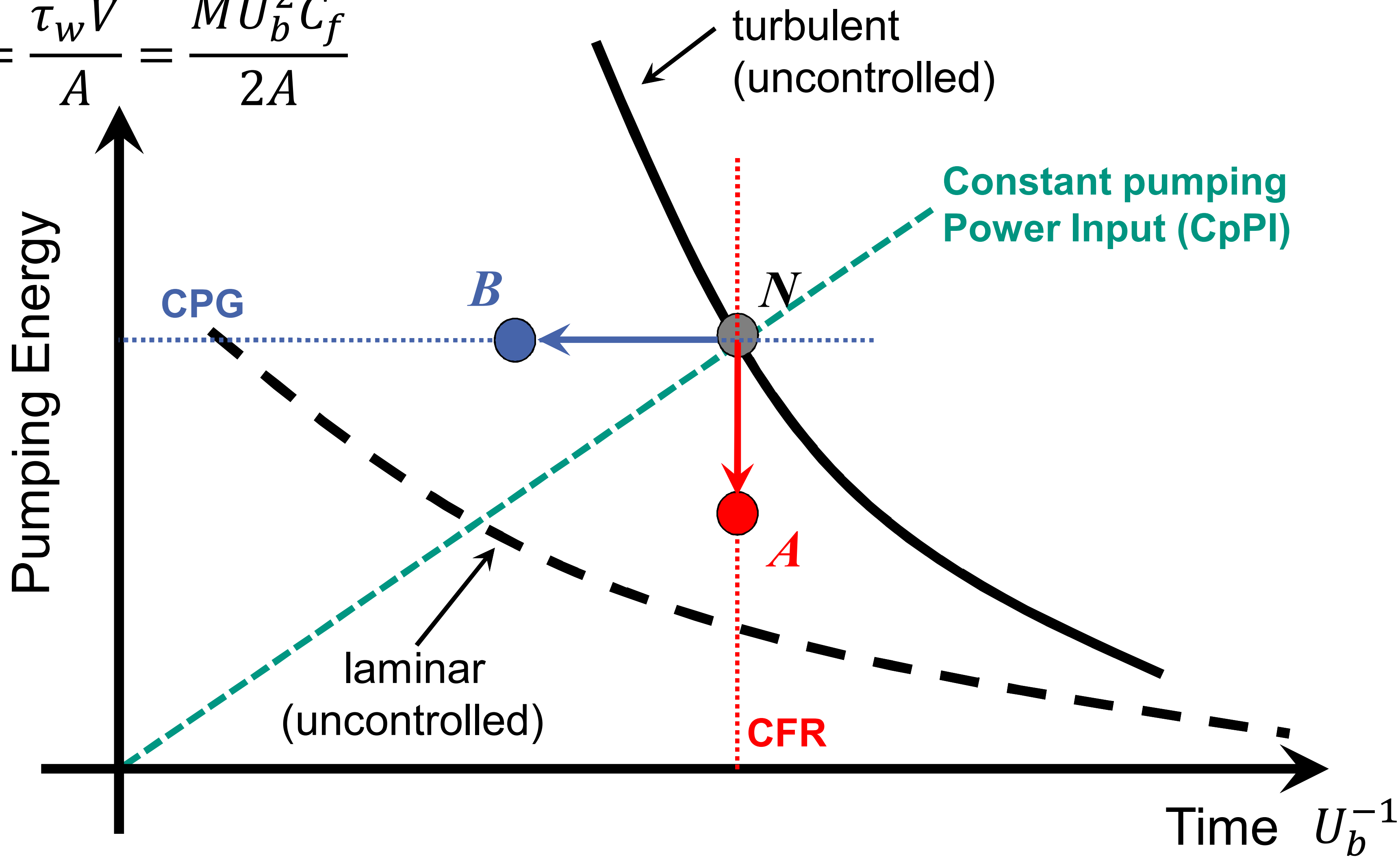
Pumping energy (per unit wetted area) : $E_p = \frac{\tau_w V}{A} = \frac{M U_b^2 C_f}{2A}$

Fluid travel time (per unit length) : $1/U_b$

Total energy : $E_{tot} = E_p + E_c$

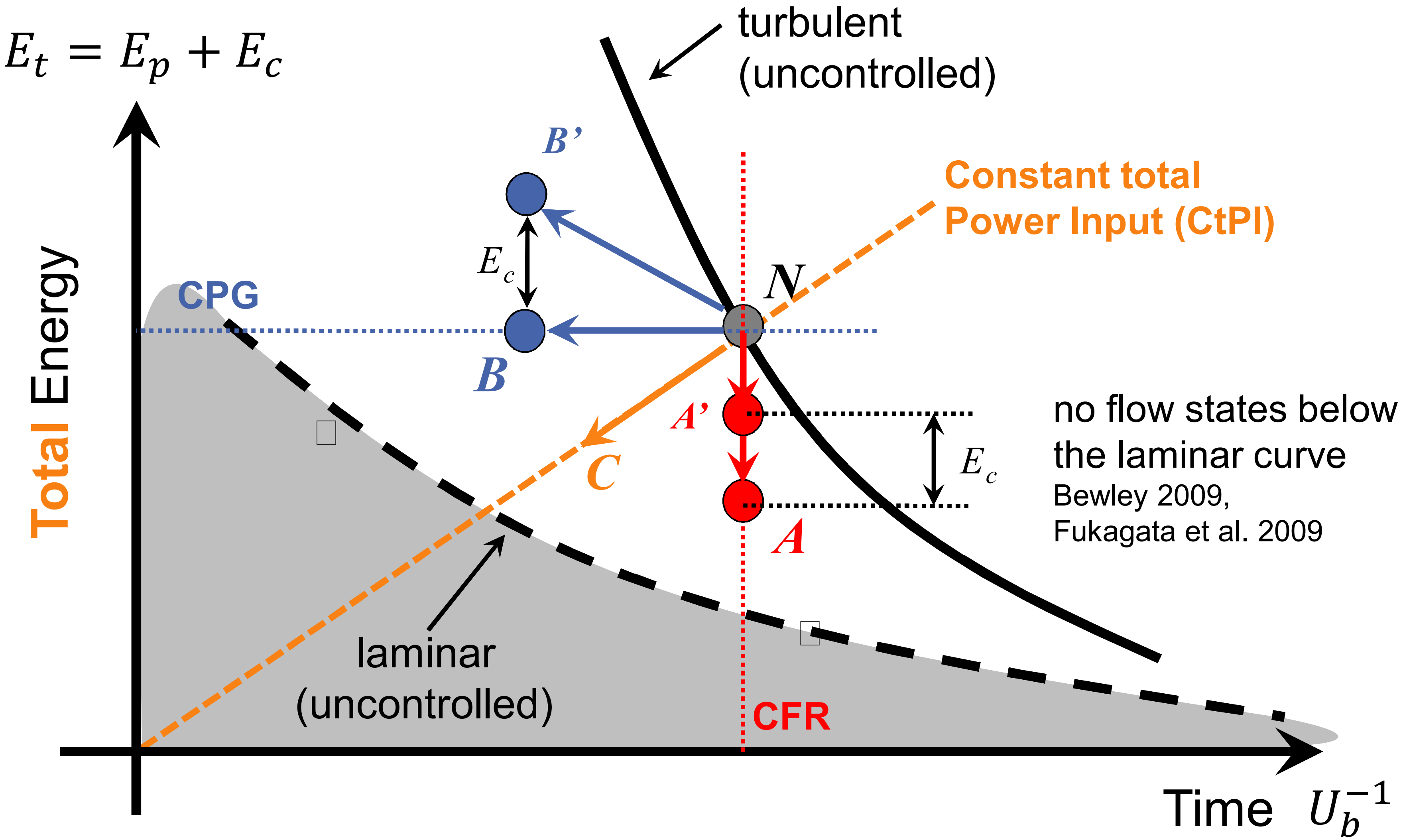
Energy (cost) vs. Time

$$E_p = \frac{\tau_w V}{A} = \frac{M U_b^2 C_f}{2A}$$



Frohnapfel, Hasegawa, Quadrio, JFM 2012

Total Energy (cost) vs. Time



no flow states below the laminar curve
Bewley 2009,
Fukagata et al. 2009

Frohnapfel, Hasegawa, Quadrio, JFM 2012

Comparison of different flow condition

successful control $\boldsymbol{R} = 1 - \frac{C_f}{C_{f,0}} > 0$ manifests differently

	U_b	$-\frac{\mathrm{d}p}{\mathrm{d}x}$	$\boldsymbol{\Pi_p} = -\frac{\mathrm{d}p}{\mathrm{d}x} h U_b$	$\boldsymbol{C_f}$
CPG	⇧	=	⇧	⇩
CFR	=	⇩	⇩	⇩
CPI	⇧	⇩	=	⇩

Constant Power Input framework

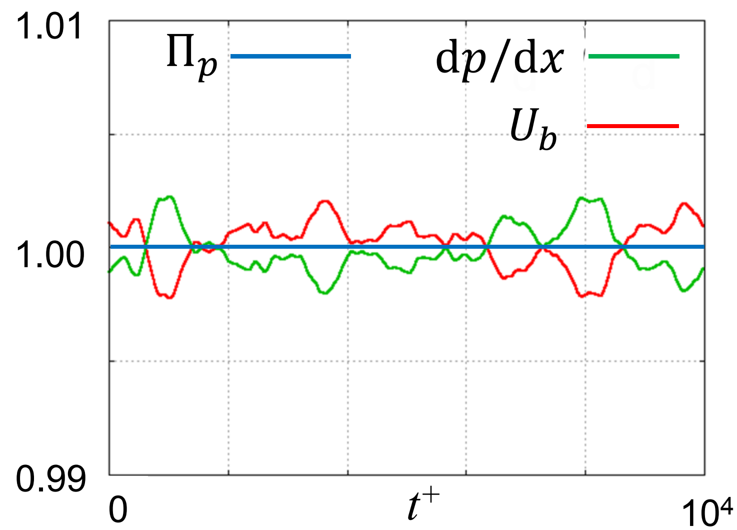
$$Re_\Pi = \frac{U_\Pi \delta}{\nu} \qquad U_\Pi = \sqrt{\frac{\Pi_t h}{3\mu}}$$

the velocity of a Poiseuille flow with the same total power Π_t

a Poiseuille flow maximizes the flow rate for a given total power Π_t

$$\Pi_t = \frac{3}{Re_\Pi} \qquad \gamma = \frac{\Pi_c}{\Pi_t}$$

$$\Pi_c = \gamma \Pi_t \qquad \Pi_p = (1-\gamma)\Pi_t$$



Checkpoint: what you should not forget

How to drive the flow (CFR, CPG, CPI)?

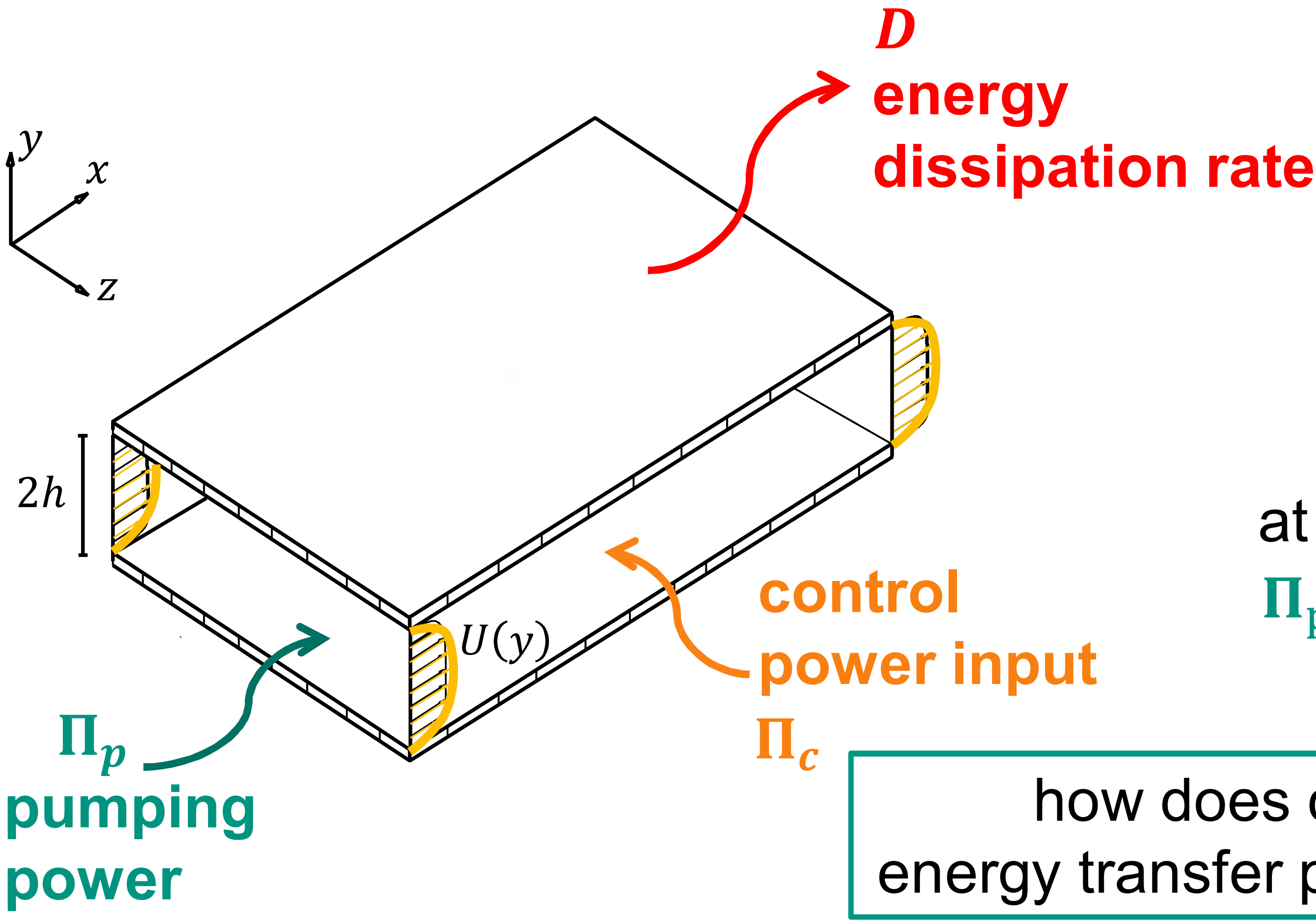
- necessary and important choice
- affects the results and their interpretations
- different manifestations of “drag reduction”

Constant Power Input

- possible choice close to real conditions (pump)
- power input (energy transfer rate) is kept constant

Control from the energetic viewpoint

CPI ideal framework to study energy transfer rates



at steady state:

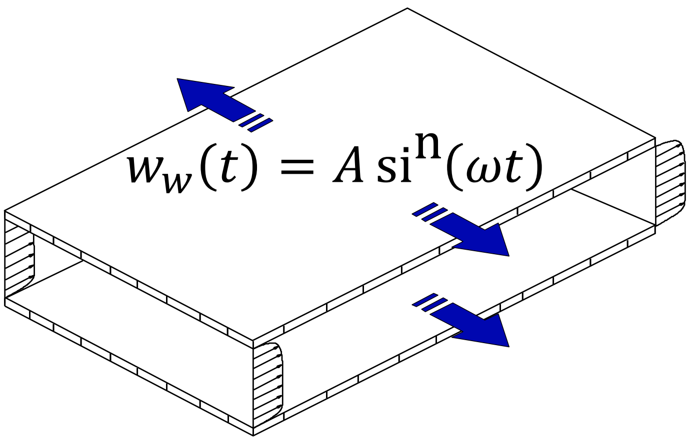
$$\Pi_\mathrm{p} + \Pi_c = \mathbf{D}$$

how does control affect energy transfer phenomena?

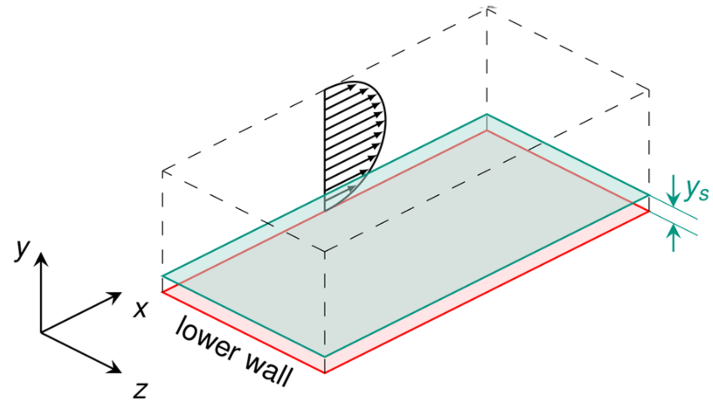
Model control strategies

$Re_{\pi} = 650^{0}$ $Re_{\tau,re}{}^{f} = 20^{0}$ Constant total Power Input (CtPI)

Spanwise wall oscillations



Opposition control



drag reduction $R = 17.2\%$ $R = 23.0\%$

control power fraction $\gamma = 0.11$ $\gamma = 0.01$

$$\frac{U_b}{U_{b,re}{}^{f}} = 1.02^{5} \qquad \frac{U_b}{U_{b,re}{}^{f}} = 1.08^{2}$$

One-point kinetic energy budgets (MKE)

Mean Kinetic Energy $\left(\frac{1}{2}U_i{}^2\right)$ budget:

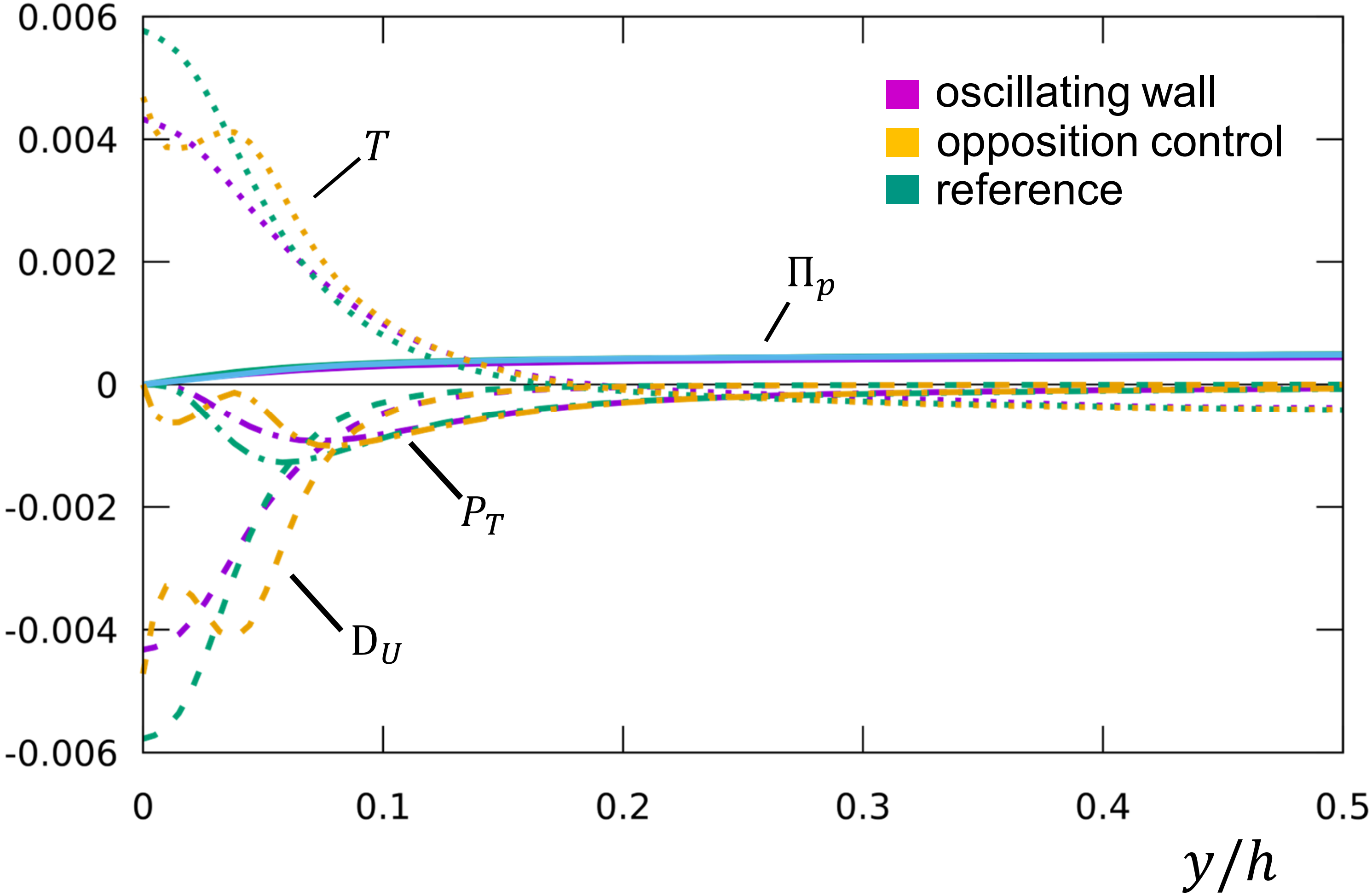
$$U\frac{\mathrm{d}p}{\mathrm{d}x} = \langle u'v'\rangle\frac{\partial U}{\partial y} - \frac{\partial(\langle u'v'\rangle U)}{\partial y} + \nu\frac{\partial}{\partial y}\left(U\frac{\partial U}{\partial y}\right) - \nu\left(\frac{\partial U}{\partial y}\right)^2$$

pumping power | turbulent production | turbulent and laminar transport | MKE dissipation rate

integrated in the whole channel:

$$\Pi_p = P_T - D_U$$

One-point kinetic energy budgets (MKE)



One-point kinetic energy budgets (TKE)

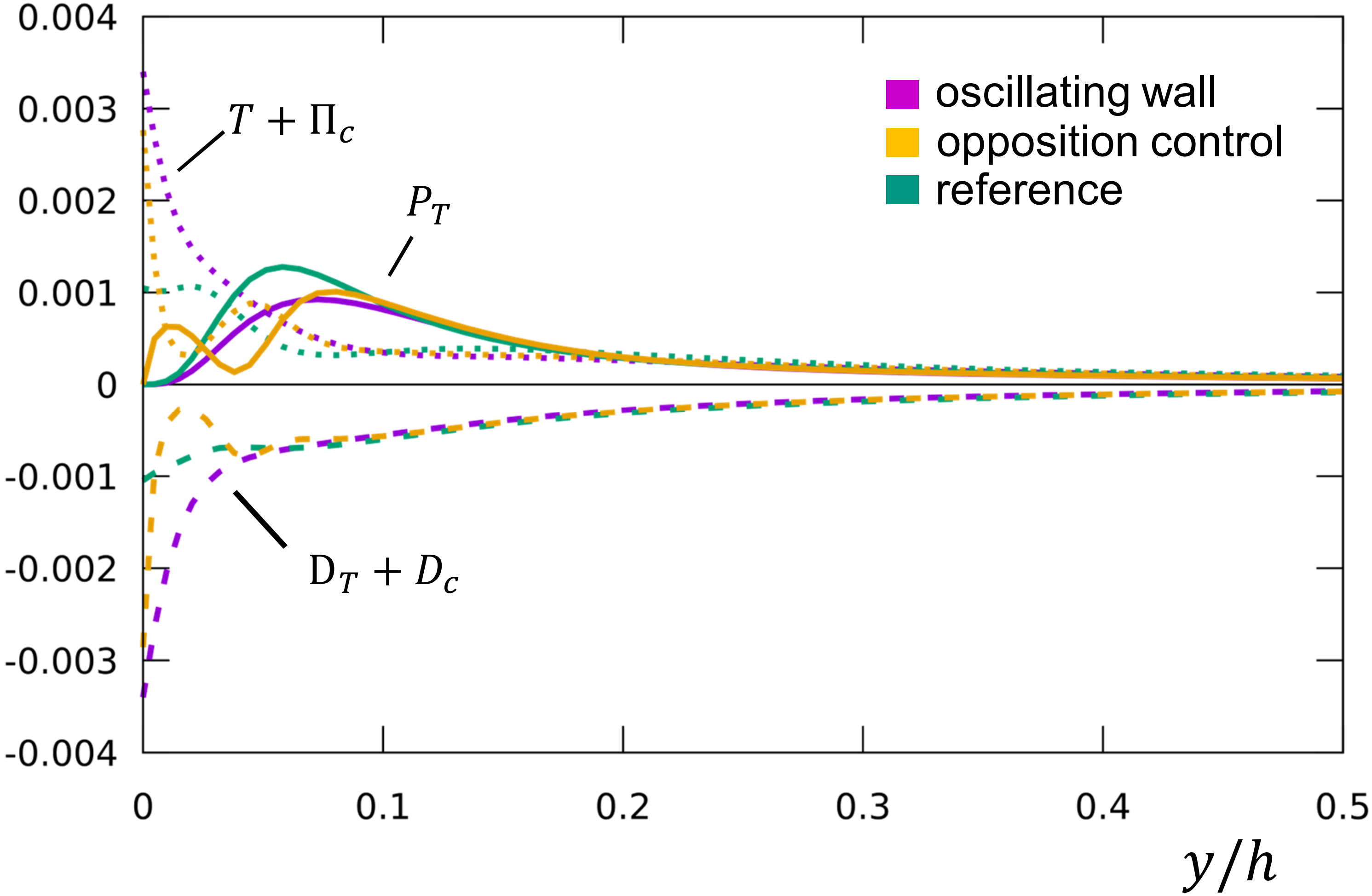
Turbulent Kinetic Energy $\left(k = \frac{1}{2} u_i'^2\right)$ budget:

$$\underbrace{\langle u'v' \rangle \frac{\partial U}{\partial y}}_{\text{turbulent production}} = -\nu \underbrace{\left\langle \frac{\partial u_i'}{\partial x_j} \frac{\partial u_i'}{\partial x_j} \right\rangle}_{\text{TKE dissipation rate}} + \frac{\partial}{\partial y} \underbrace{\left(\frac{\nu}{2} \frac{\partial \langle u_i'^2 \rangle}{\partial y} - \langle v'p' \rangle - \frac{1}{2} \langle v' u_i'^2 \rangle \right)}_{\text{transport (space fluxes)}}$$

integrated in the whole channel: with control

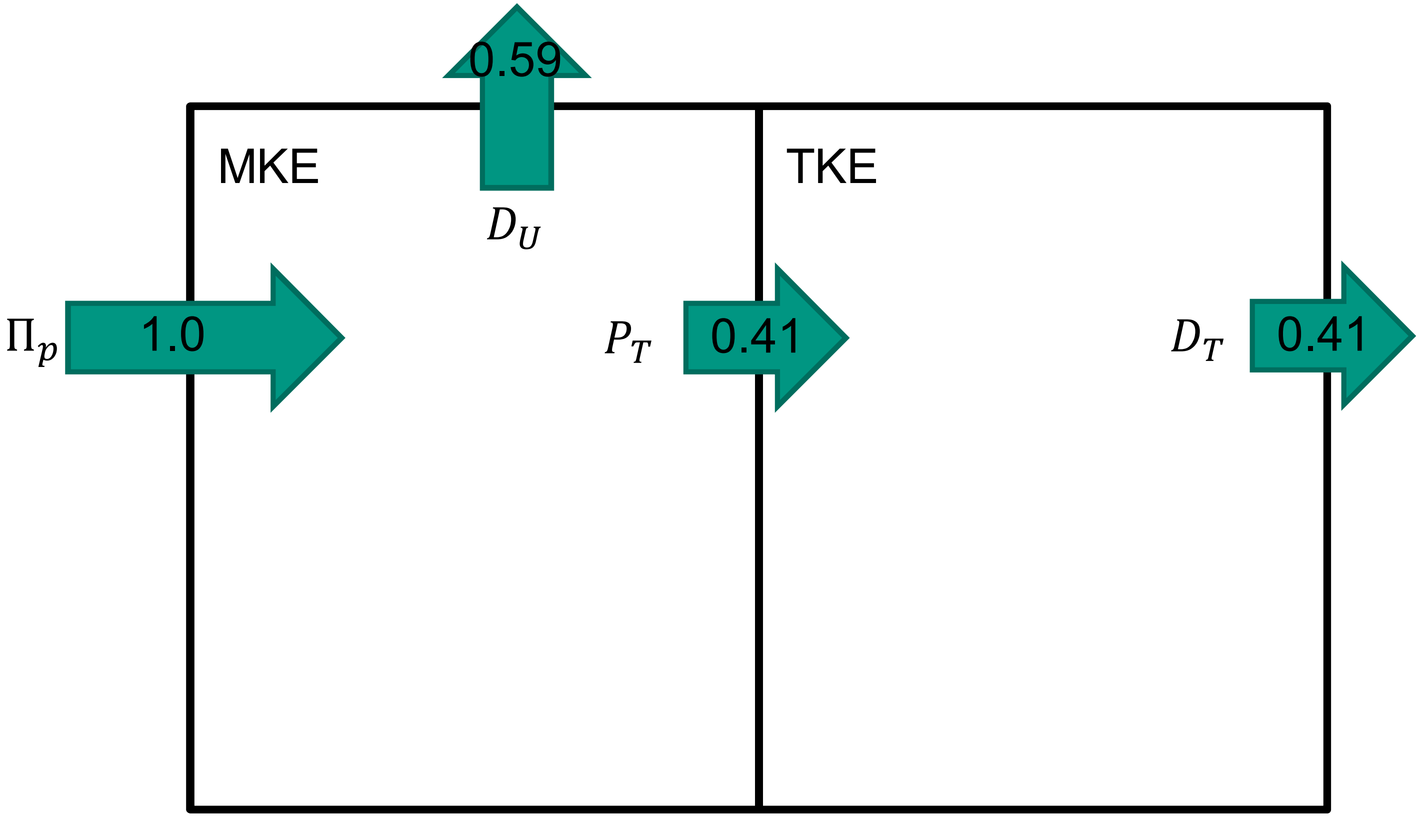
$$\Pi_c + P_T = D_T + D_C$$

One-point kinetic energy budgets (TKE)



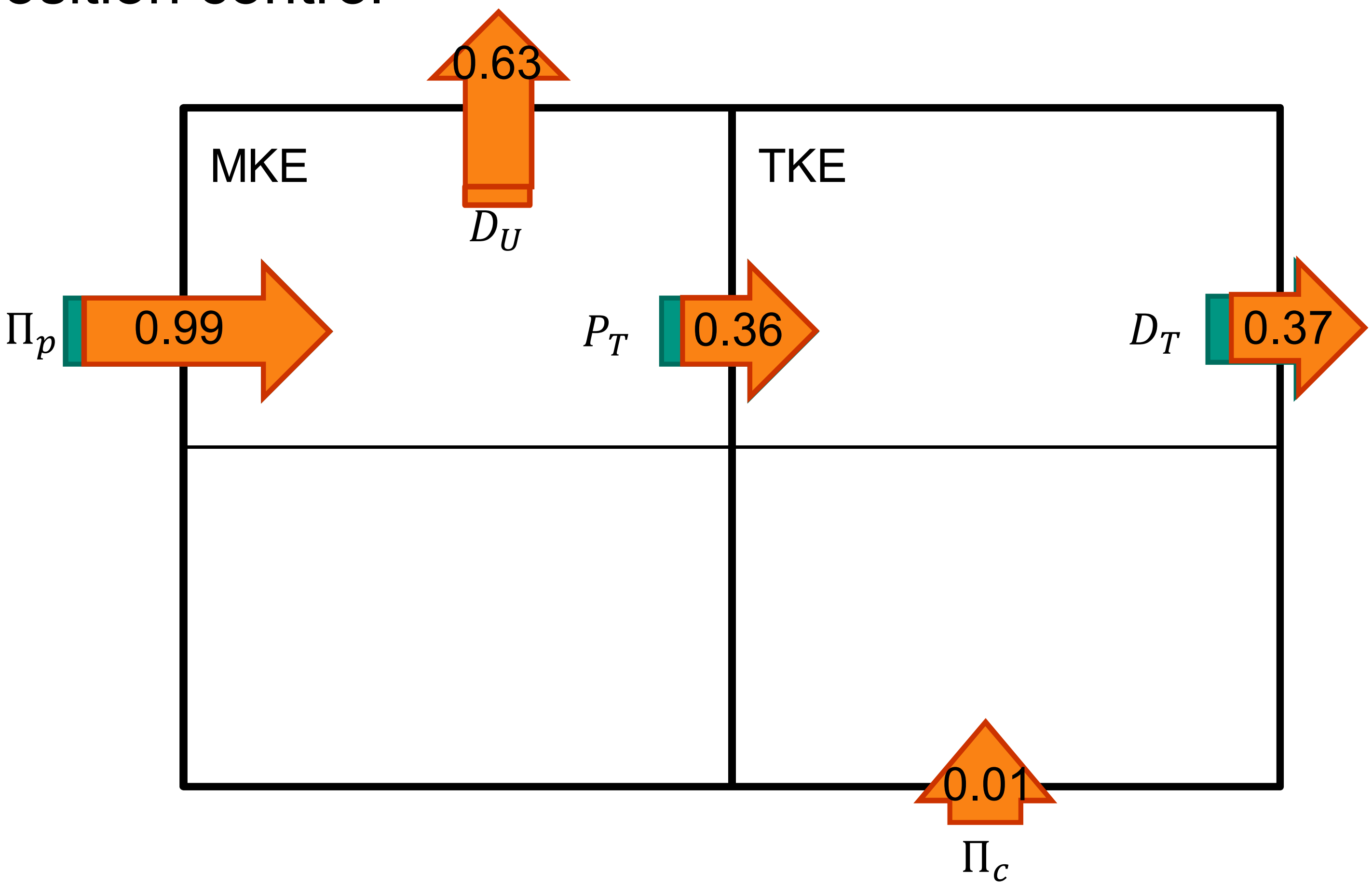
The Energy Box

uncontrolled flow



The Energy Box

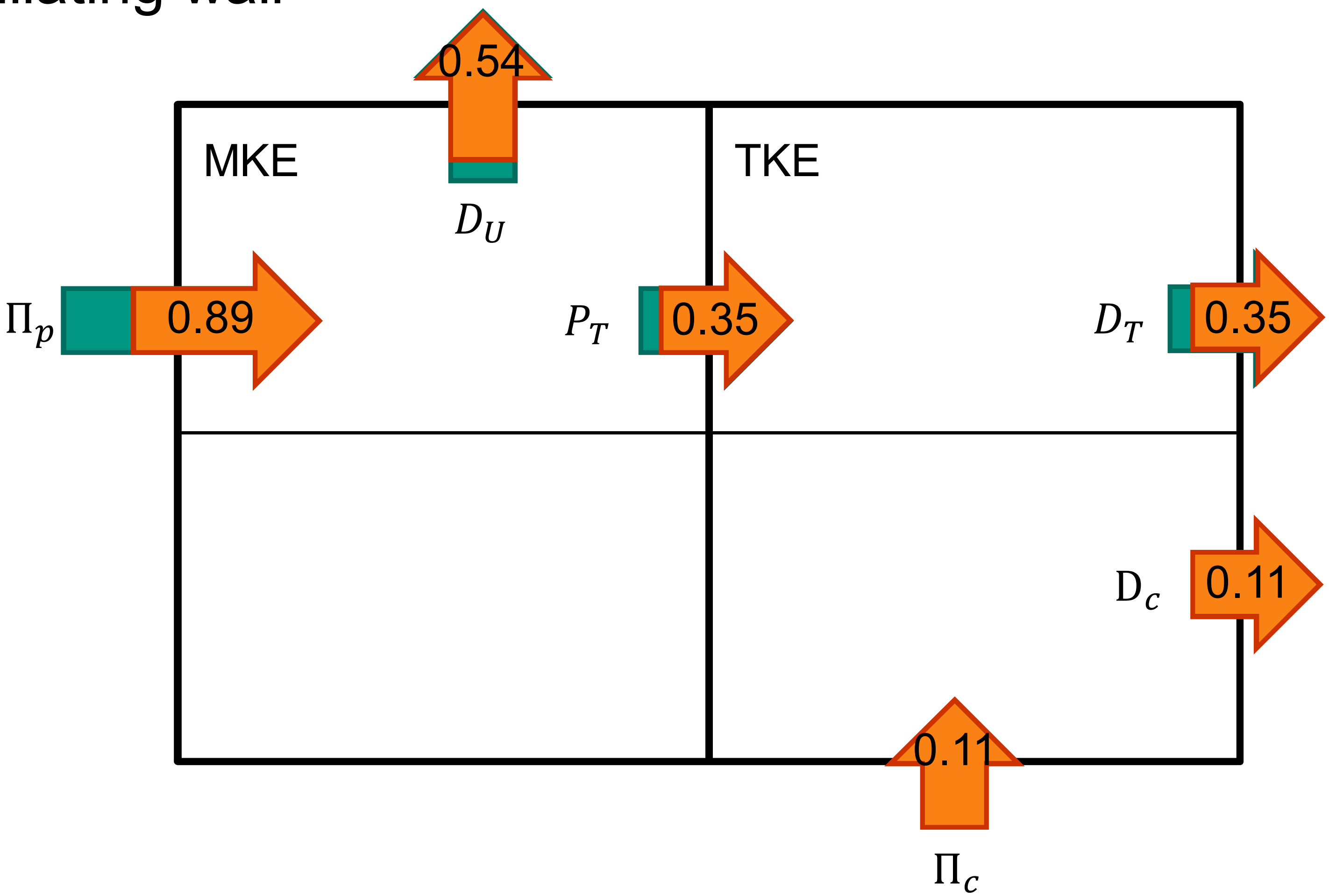
opposition control



MKE dissipation rate increases
TKE dissipation rate decreases

The Energy Box

oscillating wall



MKE and TKE dissipation rate decrease: U_b increases though!

The Energy Box: lesson

Drag reduction $\Leftrightarrow$ reduction of TKE dissipation rate

Drag reduction $\neq$ increase of MKE dissipation rate

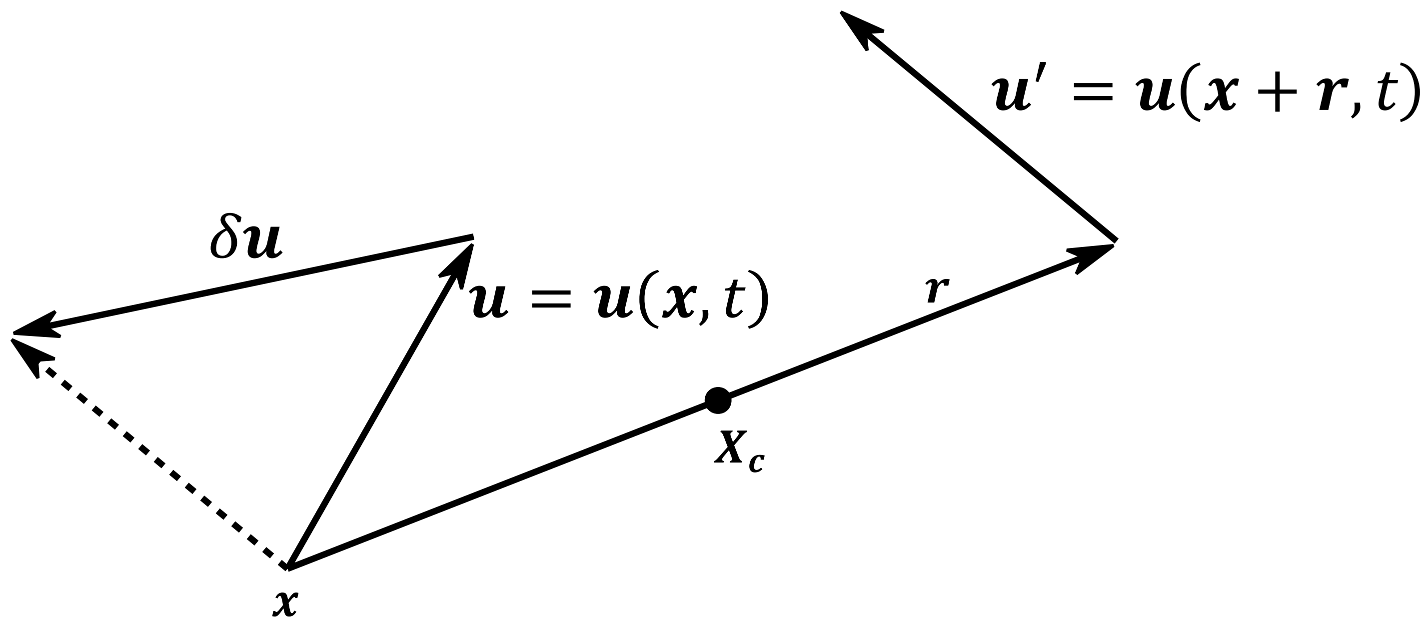
Effect of control on energy transfer rates unveiled!!

Sometimes Π_c is a good alternative to Π_p

How do we analyse the physics?

Second-order structure function

$$\langle \delta u^2 \rangle(\boldsymbol{r}, \boldsymbol{X}_c) = \left\langle [u(x+r) - u(x)]_i^2 \right\rangle$$



loosely speaking, amount of fluctuation **energy** at **scale** $\|\boldsymbol{r}\|$

Scale-energy budget equation (1)

$$\nabla_r \cdot \mathbf{\Phi_r}(\boldsymbol{r}, Y_c) + \frac{\mathrm{d}\Phi_c(\boldsymbol{r}, Y_c)}{\mathrm{d}Y_c} = s(\boldsymbol{r}, Y_c)$$

source term

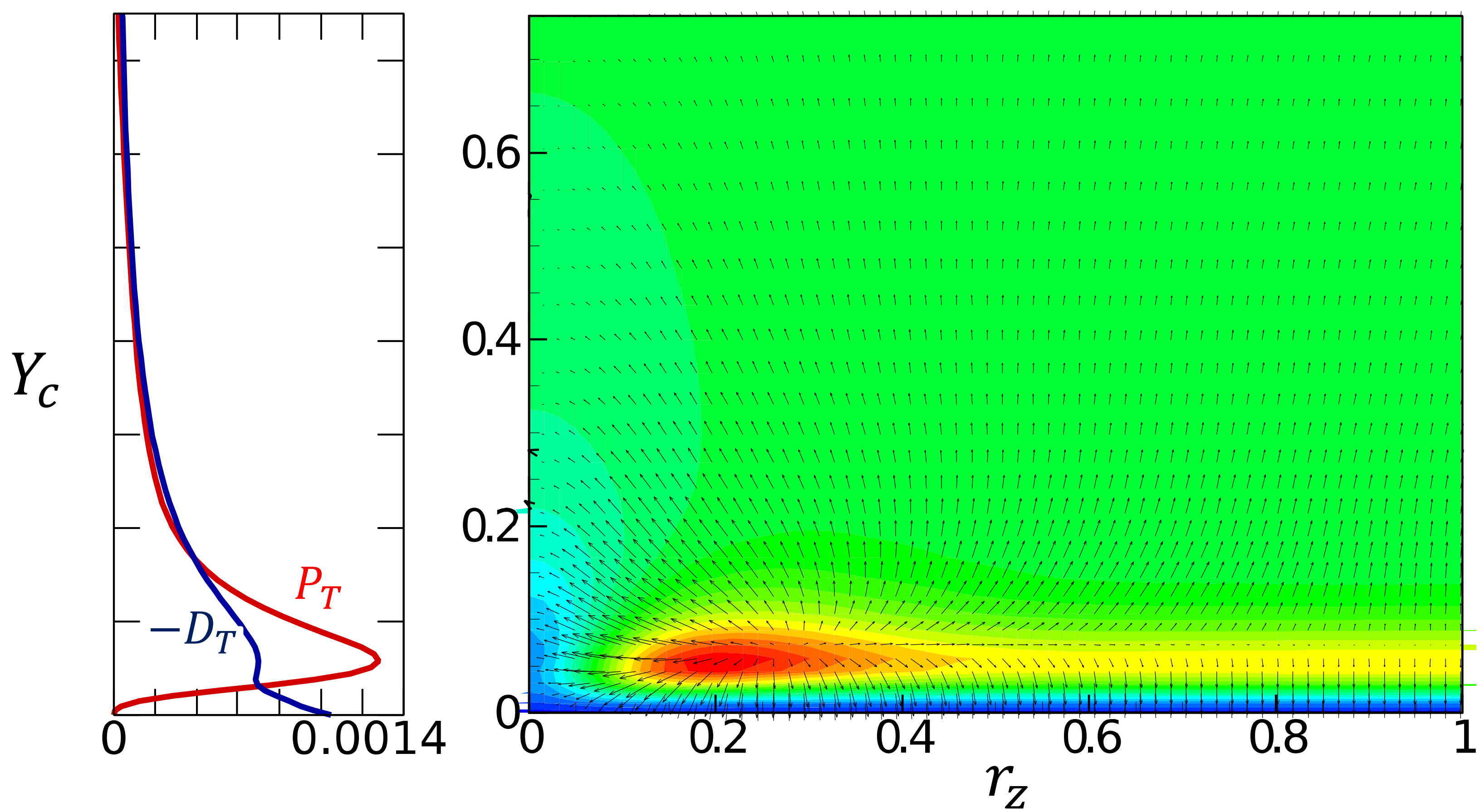
$$-2\langle \delta u \delta v \rangle (\mathrm{d}U/\mathrm{d}y)^* - 4\langle \varepsilon \rangle^* = s(\boldsymbol{r}, Y_c)$$

budget among **production** and **dissipation** of scale energy

Marati, Casciola, Piva, JFM 2004

Scale-energy budget equation (1)

$$-2\langle \delta u \delta v \rangle (\mathrm{d}U/\mathrm{d}y)^* - 4\langle \varepsilon \rangle^* = s(\boldsymbol{r}, Y_c)$$



Scale-energy budget equation (2)

$$\nabla_r \cdot \boldsymbol{\Phi}_{\mathbf{r}}(\boldsymbol{r}, Y_c) + \frac{\mathrm{d}\Phi_c(\boldsymbol{r}, Y_c)}{\mathrm{d}Y_c} = s(\boldsymbol{r}, Y_c)$$

space flux

turbulent pressure

$$\langle \delta u^2 \delta v^* \rangle + \frac{2}{\rho}\langle \delta p \delta v \rangle - \frac{\nu}{2}\frac{\mathrm{d}\langle \delta u^2 \rangle}{\mathrm{d}Y_c} = \Phi_c(\boldsymbol{r}, Y_c)$$

viscous

transport of scale energy in geometric space

in a channel flow, transfer of energy at scale r in y-direction

Scale-energy budget equation (3)

$$\nabla_r \cdot \boldsymbol{\Phi}_{\mathbf{r}}(\boldsymbol{r}, Y_c) + \frac{\mathrm{d}\Phi_c(\boldsymbol{r}, Y_c)}{\mathrm{d}Y_c} = s(\boldsymbol{r}, Y_c)$$

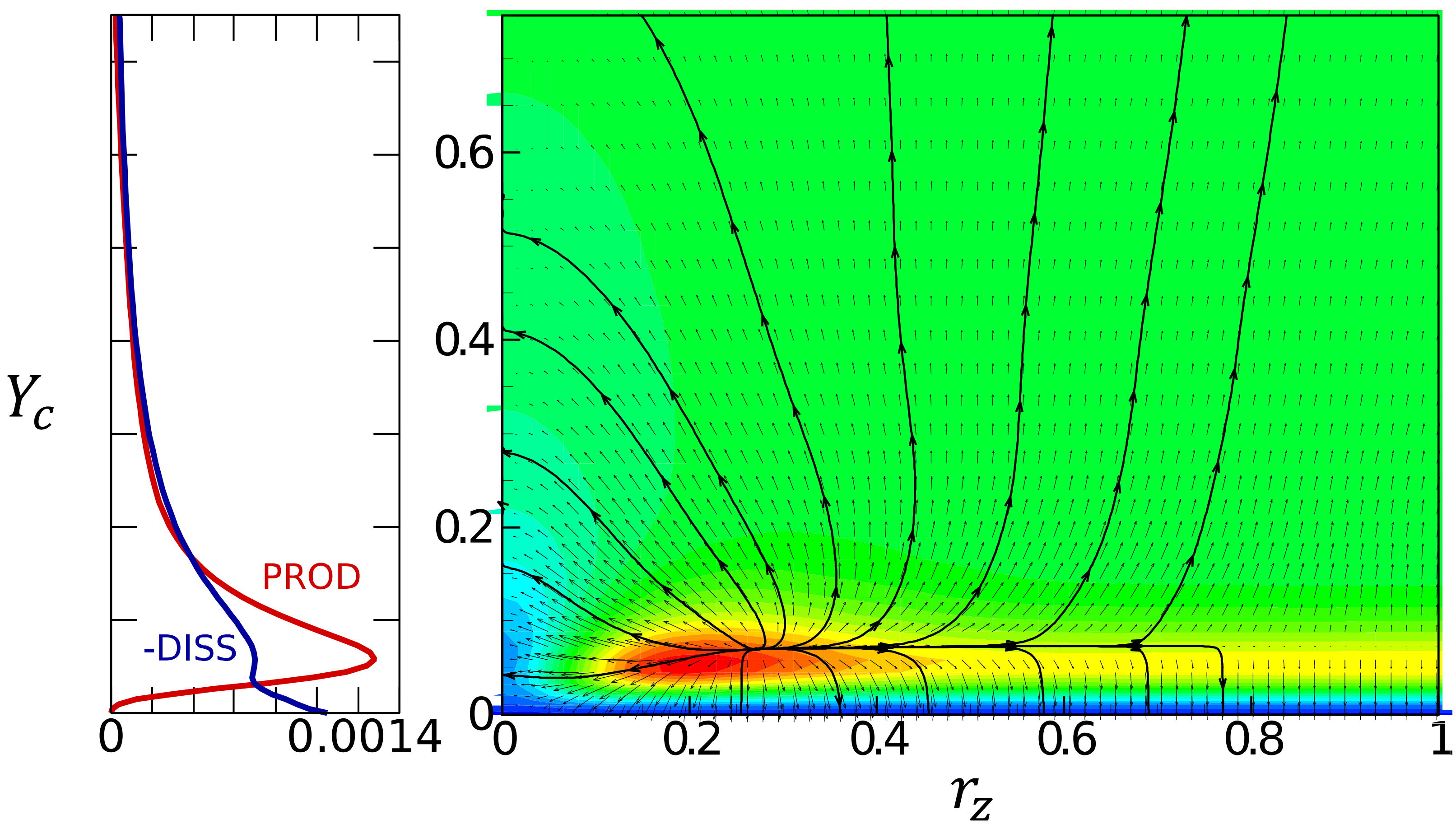
scale flux

$$\boldsymbol{\Phi}_{\mathbf{r}}(\boldsymbol{r}, Y_c) = \underbrace{\langle \delta u^2 \delta \boldsymbol{u} \rangle}_{\text{turbulent}} + \underbrace{\langle \delta u^2 \delta \boldsymbol{U} \rangle}_{\text{mean}} - \underbrace{2\nu \nabla_r (\delta u^2)}_{\text{viscous}}$$

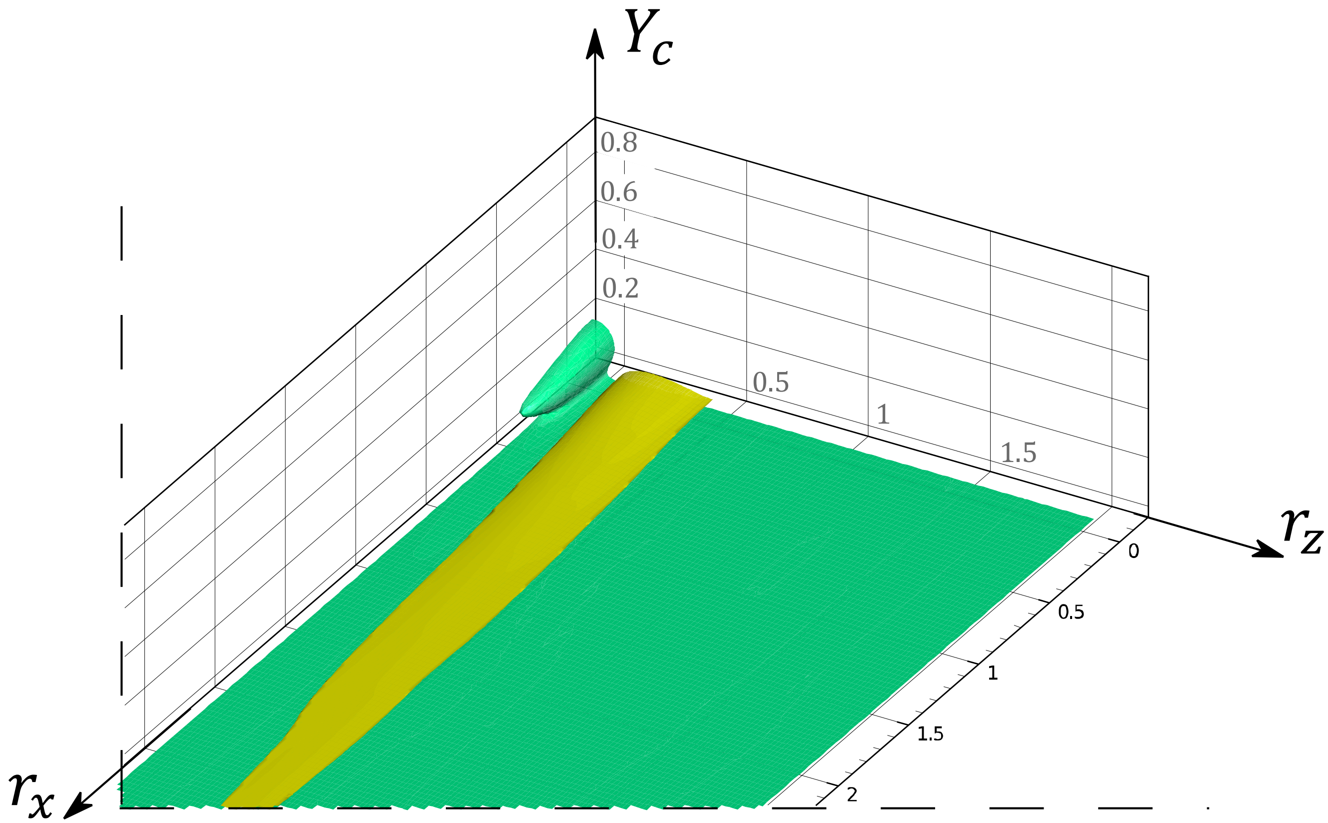
transport of scale energy across scales

not visible in the TKE budget!

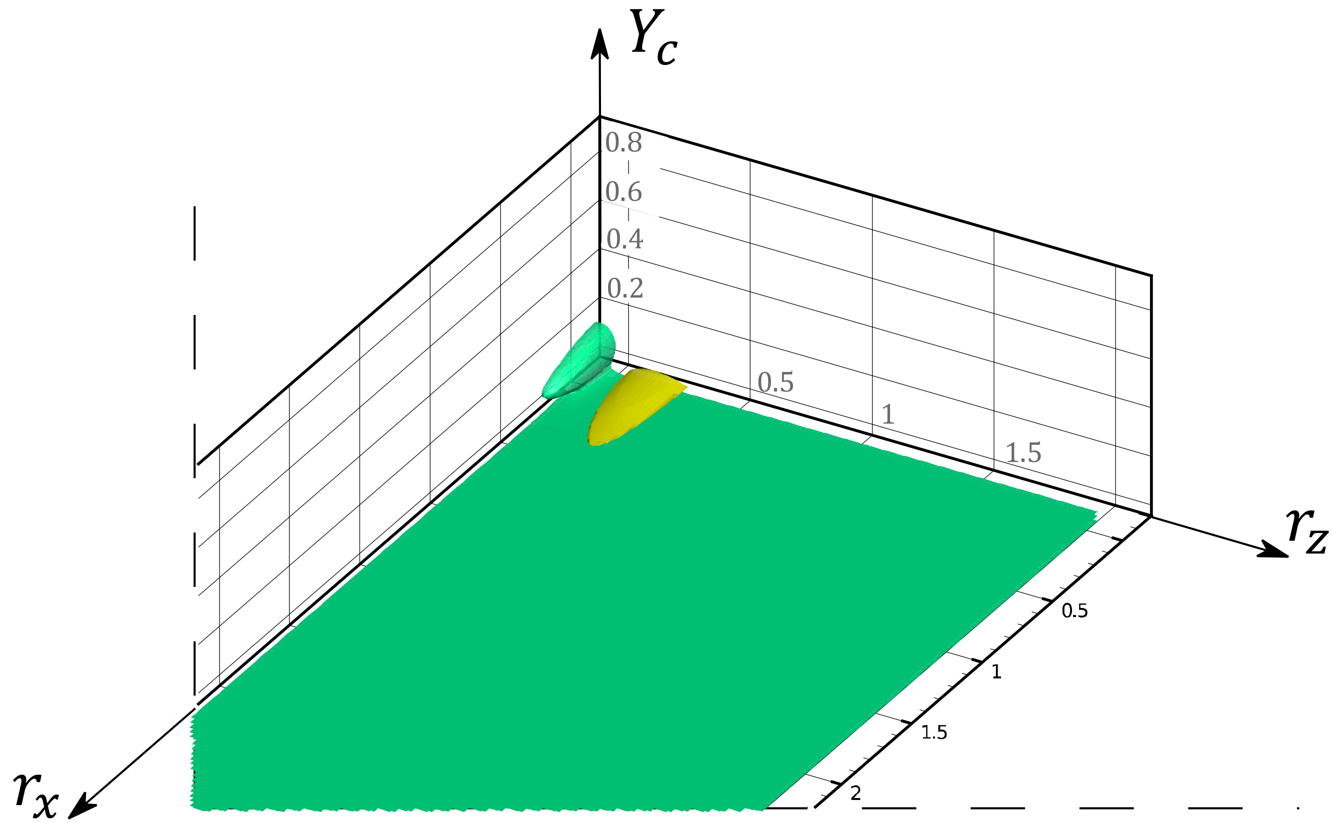
Paths of energy (uncontrolled)



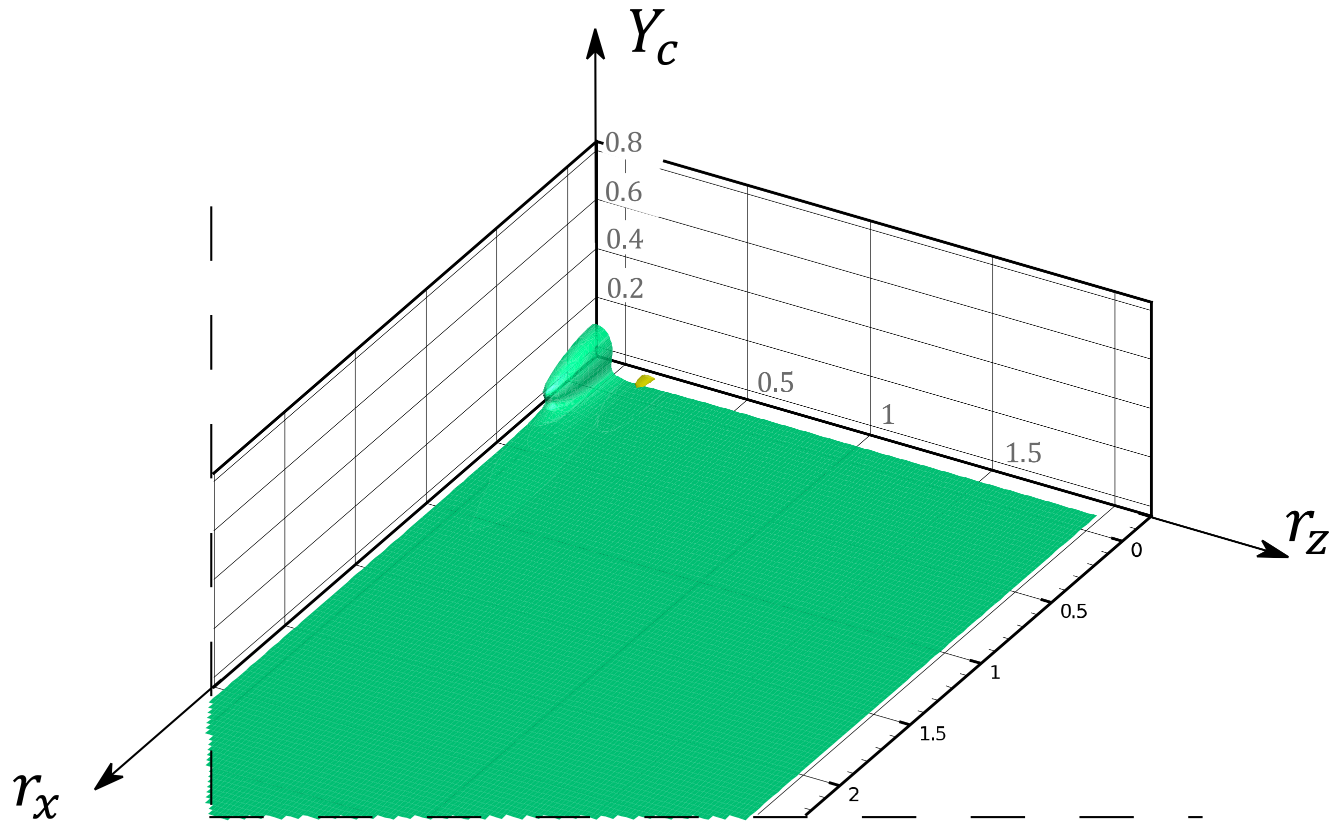
Source term (uncontrolled)



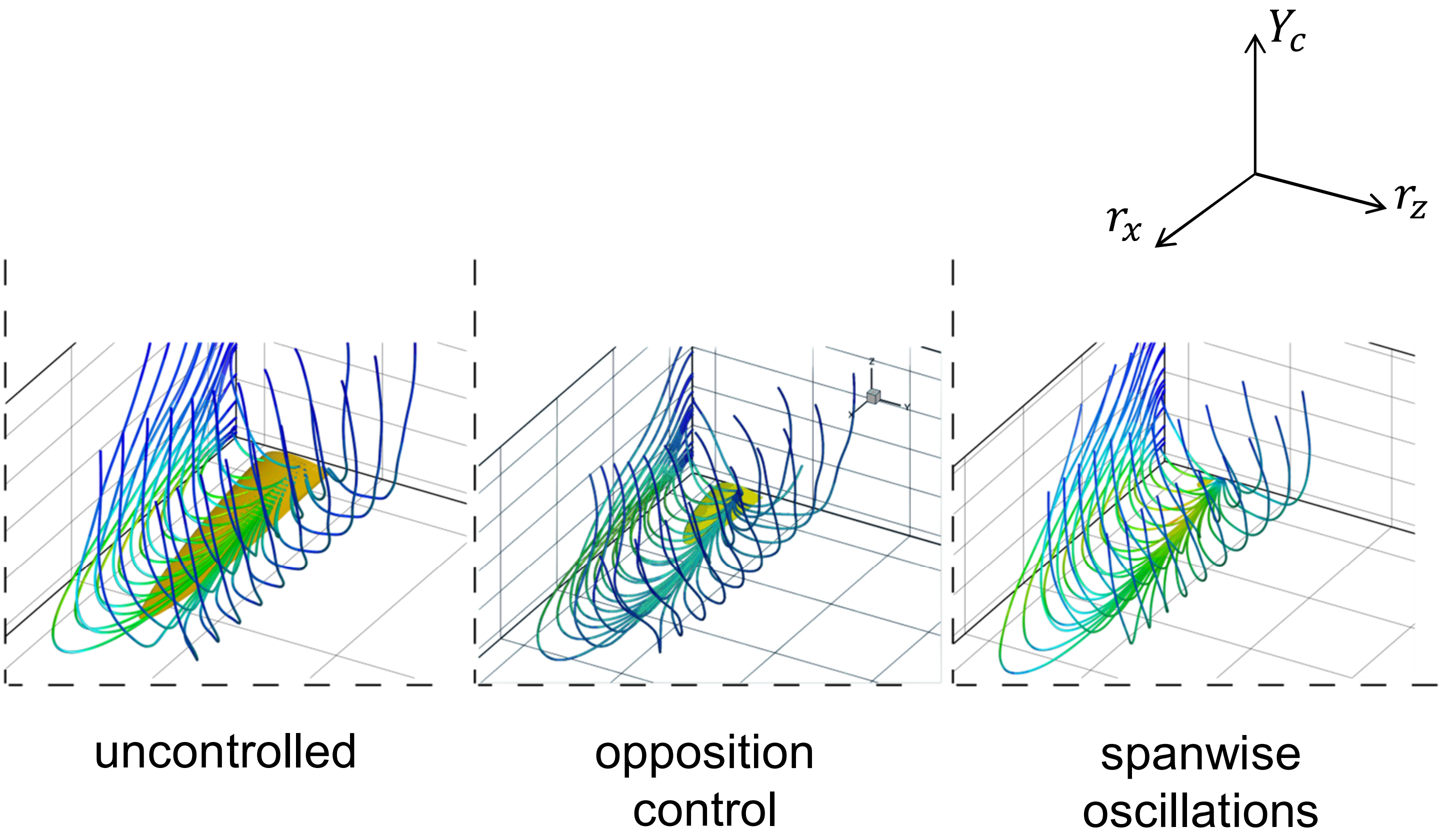
Source term (opposition control)



Source term (wall oscillations)

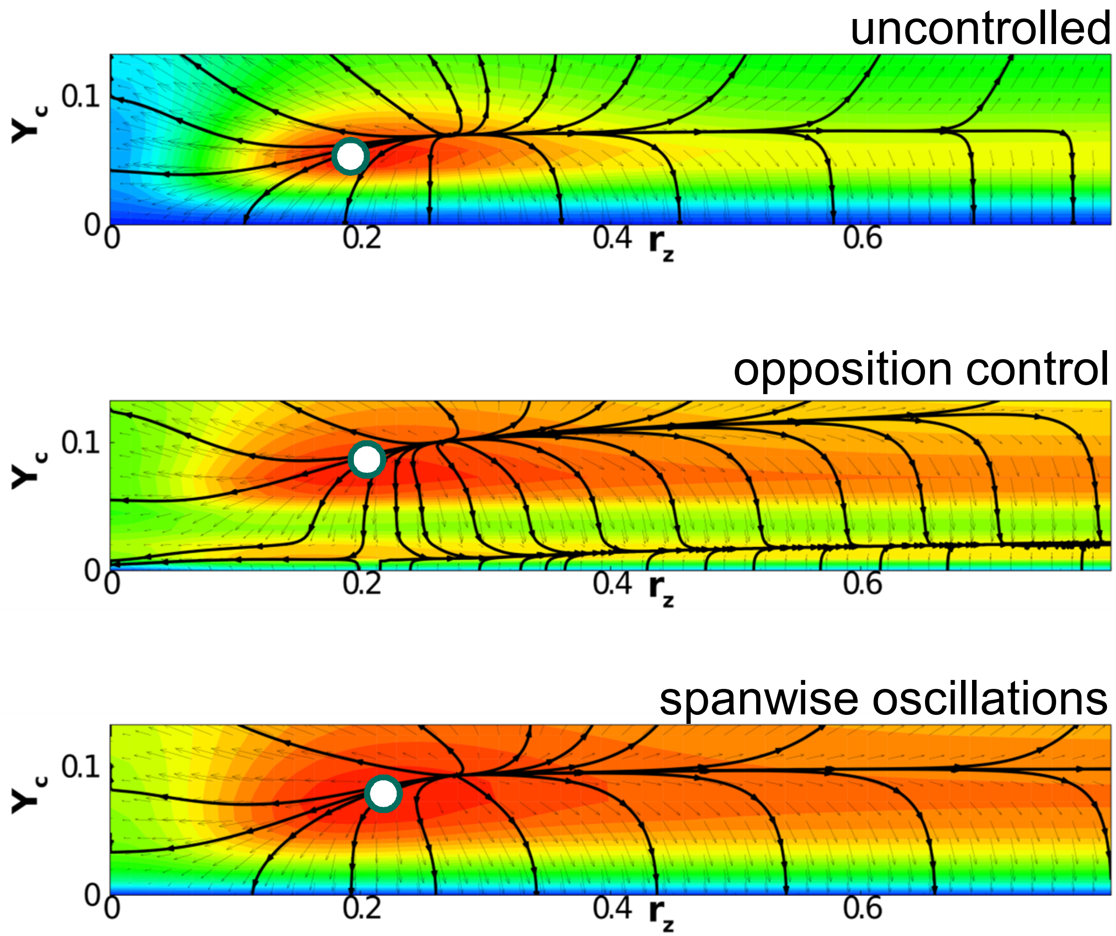


Paths of energy (outer topology)



No significant changes in the outer topology of the scale energy fluxes

Paths of energy (inner topology) $r_x = 0$



→ intermediate source region, shield wall dissipation

→ much lower production (and dissipation) of scale energy

Conclusions

- CPI natural framework to study control-induced changes of energy transfer rates

- Energy-box shows integral changes at a glance:
  drag reduction ⇔ **reduction of TKE dissipation** rate

- Scale-energy budgets show the changes in space at different scales
  drag reduction ⇔ upward **shift of peak production**
  reduction of wall prod. and diss.

Outlook

- Honestly… these are preliminary results!!!

from qualitative to quantitative

- Find universal phenomena related to drag reduction

which mechanisms should
successful control address?

- Large-scale energy production at high Re

is near-wall control affected
by large-scale energy production?

THANKS

for your kind attention!

for questions, complaints, ideas:

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