Karlsruhe Institute of Technology

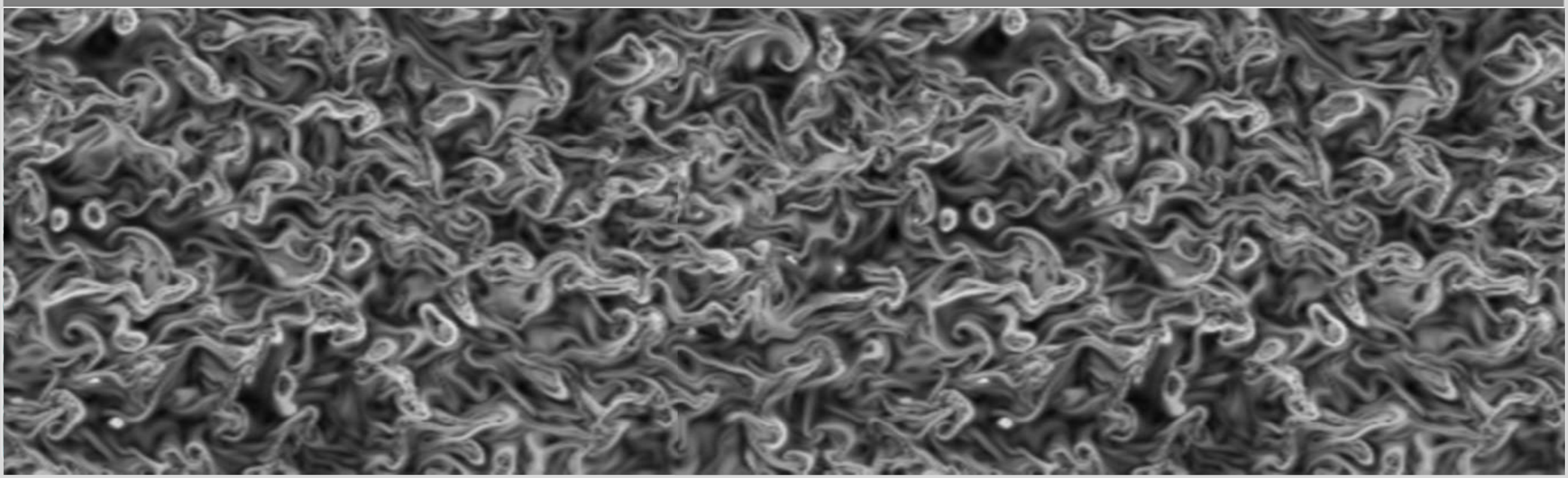
Study of energetics in drag-reduced turbulent channels

Davide Gatti, B. Frohnapfel,
A. Cimarelli, M. Quadrio, Y. Hasegawa

7.9.2016

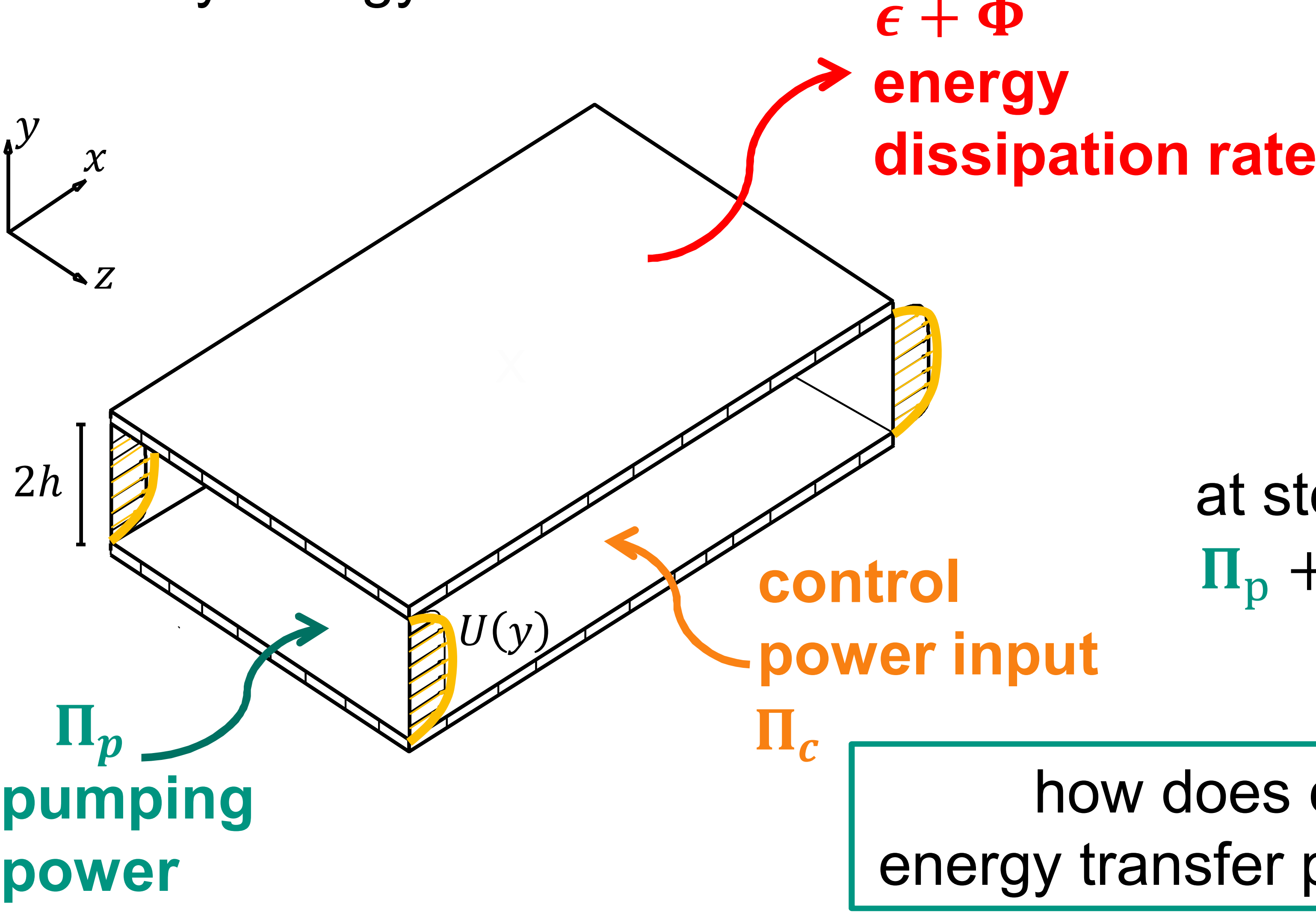
Institute of Fluid Mechanics istm

International Turbulence Initiative, Bertinoro, Italy



Control from the energetic viewpoint

Constant Power Input ideal framework
to study energy transfer rates



at steady state:

$$\Pi_p + \Pi_c = \epsilon + \Phi$$

how does control affect energy transfer phenomena?

Constant Power Input framework

We perform Direct Numerical Simulations of turbulent channel flows driven at Constant total Power Input (CtPI)

$$Re_\Pi = \frac{U_\Pi \delta}{\nu} = 6500 \qquad \text{corresponding to } Re_\tau \approx 200 \qquad U_\Pi = \sqrt{\frac{\Pi_t h}{3\mu}}$$

$$\Pi_t = \frac{3}{Re_\Pi} = \Pi_p + \Pi_c \quad \text{is kept constant}$$

Π_p → pumping

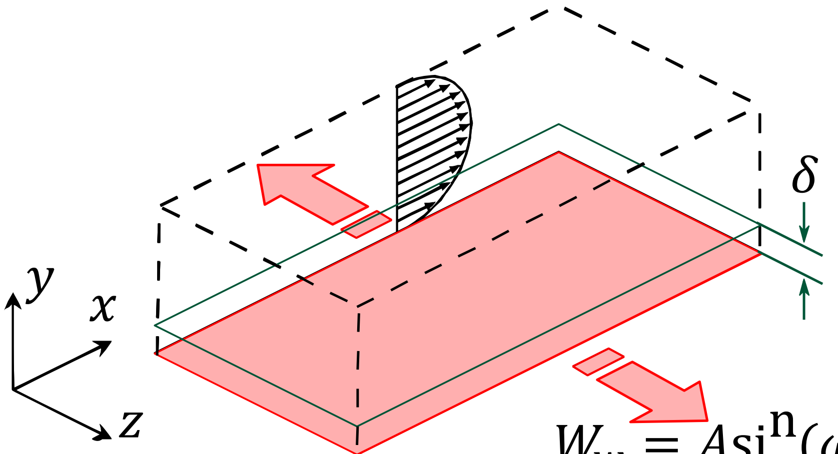
Π_c → control

Successful control yield $U_b > U_{b,\mathrm{ref}}$ $\qquad Re_\tau < Re_{\tau,\mathrm{ref}}$

Model control strategies

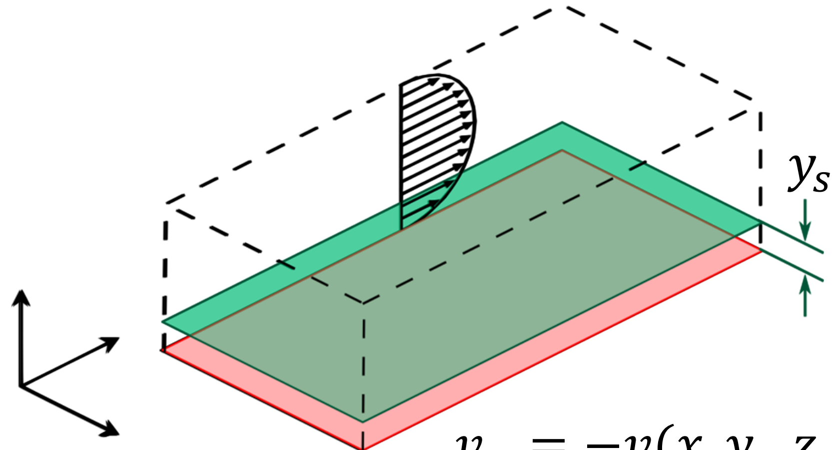
Karlsruhe Institute of Technology

Spanwise wall oscillations



$$W_w = Asi^{\mathrm{n}}(\omega t)$$

Opposition control



$$v_w = -v(x, y_s, z, t)$$

	Spanwise wall oscillations	Opposition control
drag reduction	$R = 1 - {C_f}/{C_{f,0}} = 17.1\%$	$R = 23.8\%$
control power fraction	$\gamma = {\Pi_c}/{\Pi_t} = 0.09^8$	$\gamma = 0.003^5$
	$\frac{U_b}{U_{b,re^f}} = 1.02^8$	$\frac{U_b}{U_{b,re^f}} = 1.09^3$

Institute of Fluid Mechanics istm

Global kinetic energy budgets

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

$$\Pi_p = P_{uv} - \Phi \qquad \Phi = \int_0^1 \frac{1}{Re_\Pi}\left(\frac{\mathrm{d}\overline{u}}{\mathrm{d}y}\right)^2 \mathrm{d}y$$

TKE: Turbulent Kinetic Energy $\left(\frac{1}{2}u'^2\right)$ budget:

$$P_{uv} = \epsilon \qquad P_{uv} = \int_0^1 \overline{-u'v'}\left(\frac{\mathrm{d}\overline{u}}{\mathrm{d}y}\right)\mathrm{d}y$$

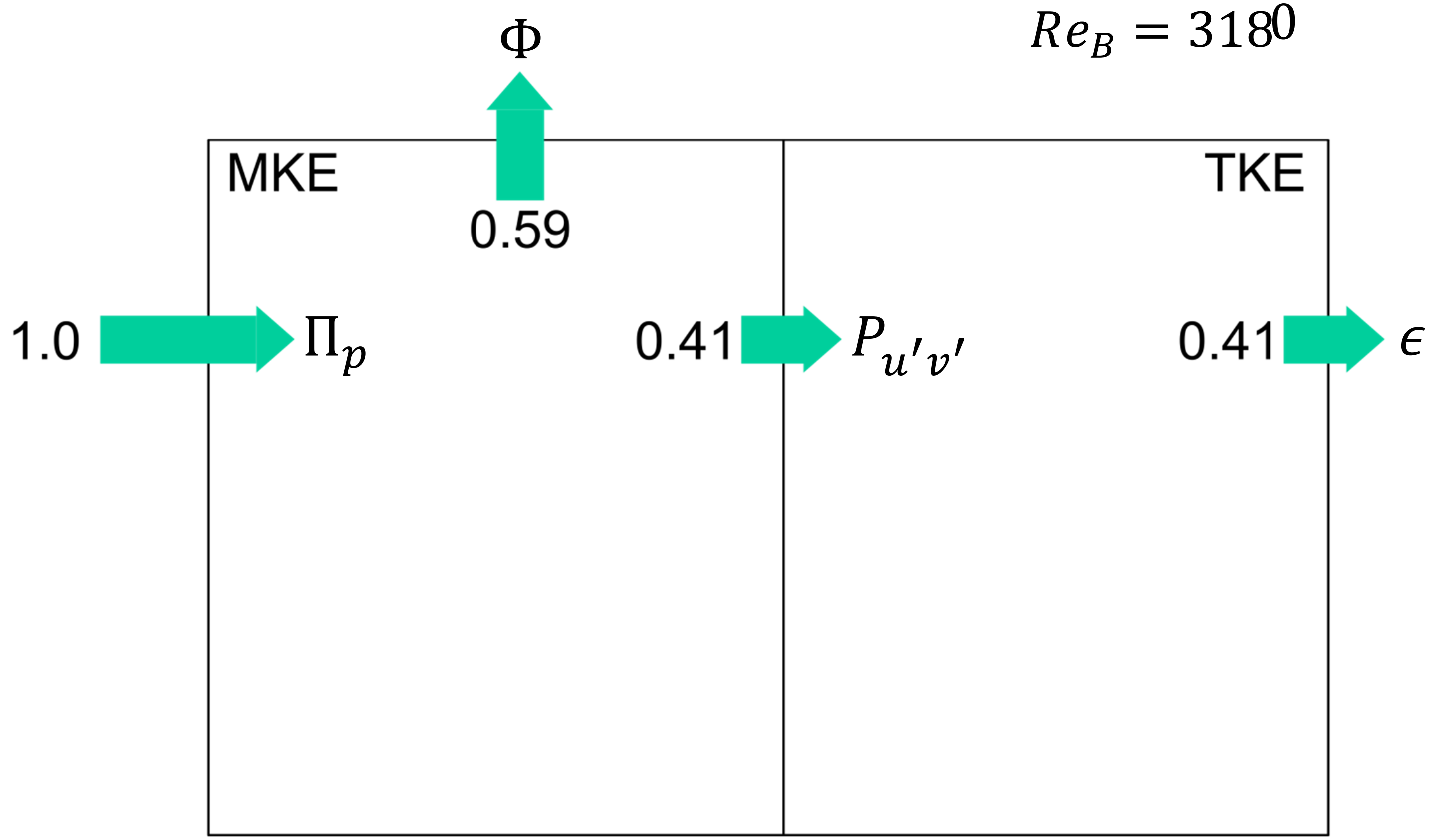
$$\epsilon = \int_0^1 \frac{1}{Re_\Pi}\overline{\frac{\partial u_i'}{\partial x_j'}\frac{\partial u_i'}{\partial x_j'}}\,\mathrm{d}y$$

The Energy Box

uncontrolled flow

$Re_{\tau} = 200$

$Re_{B} = 3180$

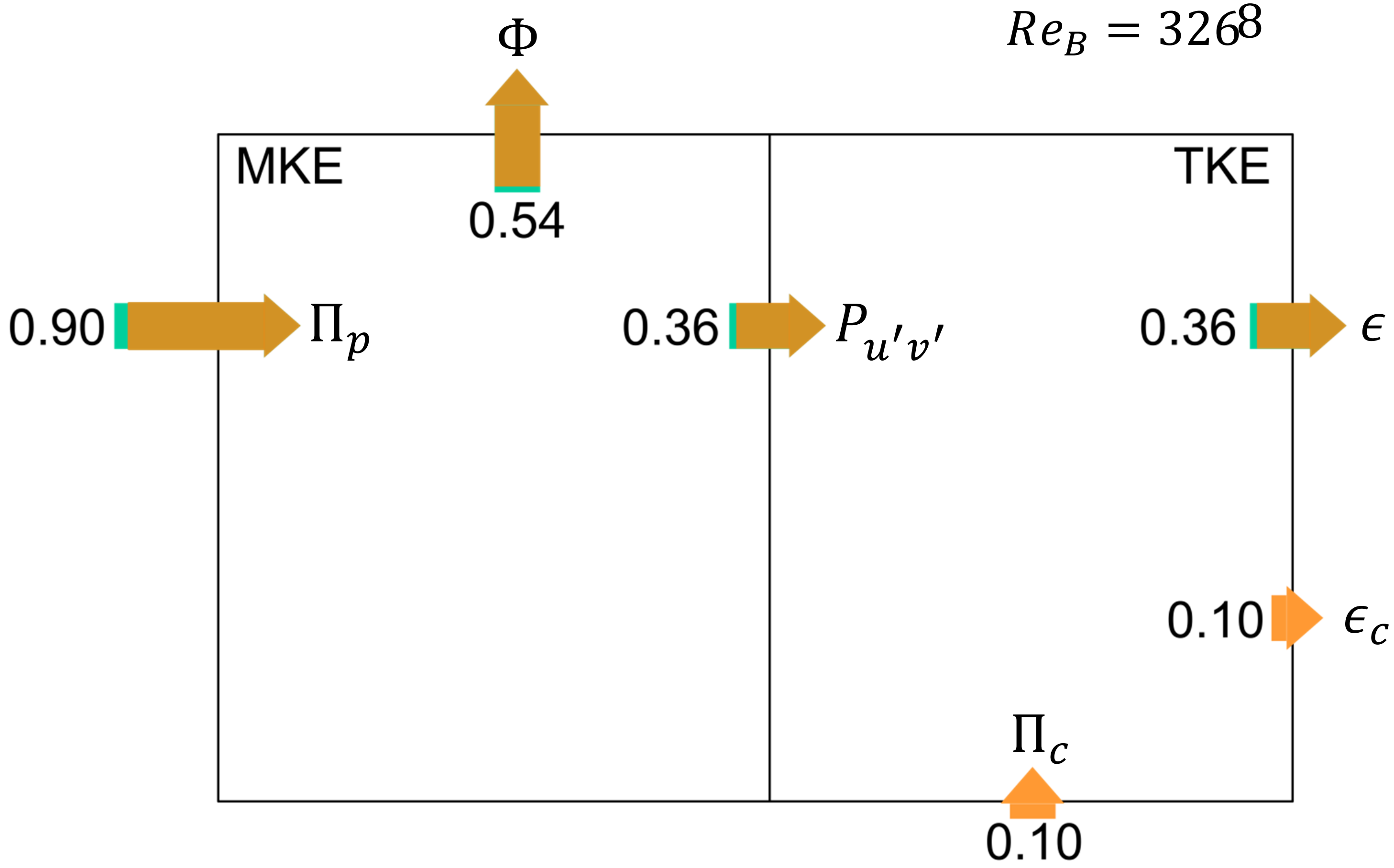


The Energy Box

oscillating wall

$Re_\tau = 187$

$Re_B = 3268$

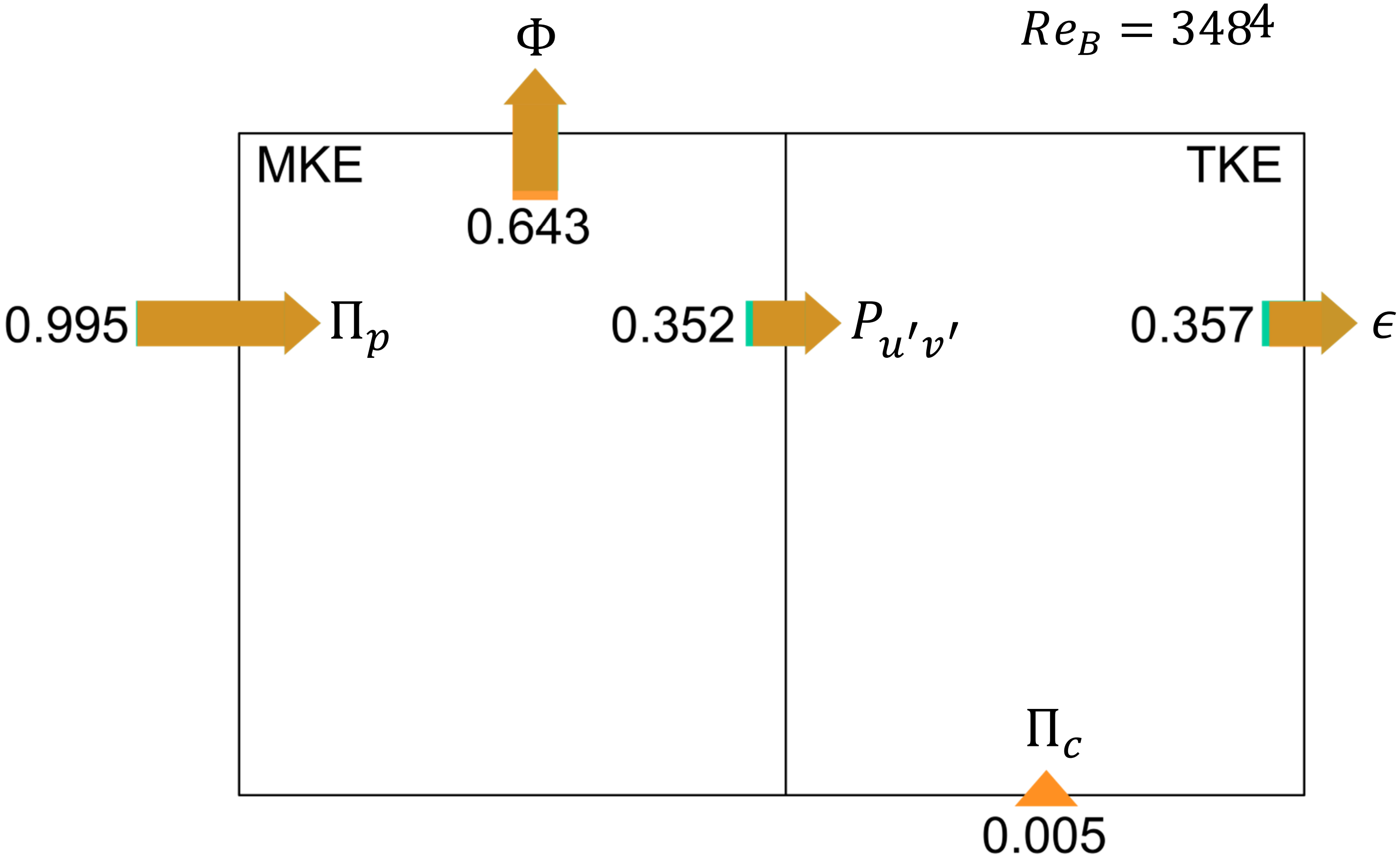


The Energy Box

opposition control

$Re_{\tau} = 19^{1}$

$Re_{B} = 348^{4}$



The Energy Box: lesson

Drag reduction $\Leftrightarrow$ reduction of TKE dissipation rate

Drag reduction $\neq$ increase of MKE dissipation rate

For successful control $U_b > U_{b,\mathrm{re}}{}^{\mathrm{f}}$ one can only say:

P_{uv} relative to the pumping power decreases

Φ relative to the pumping power increases

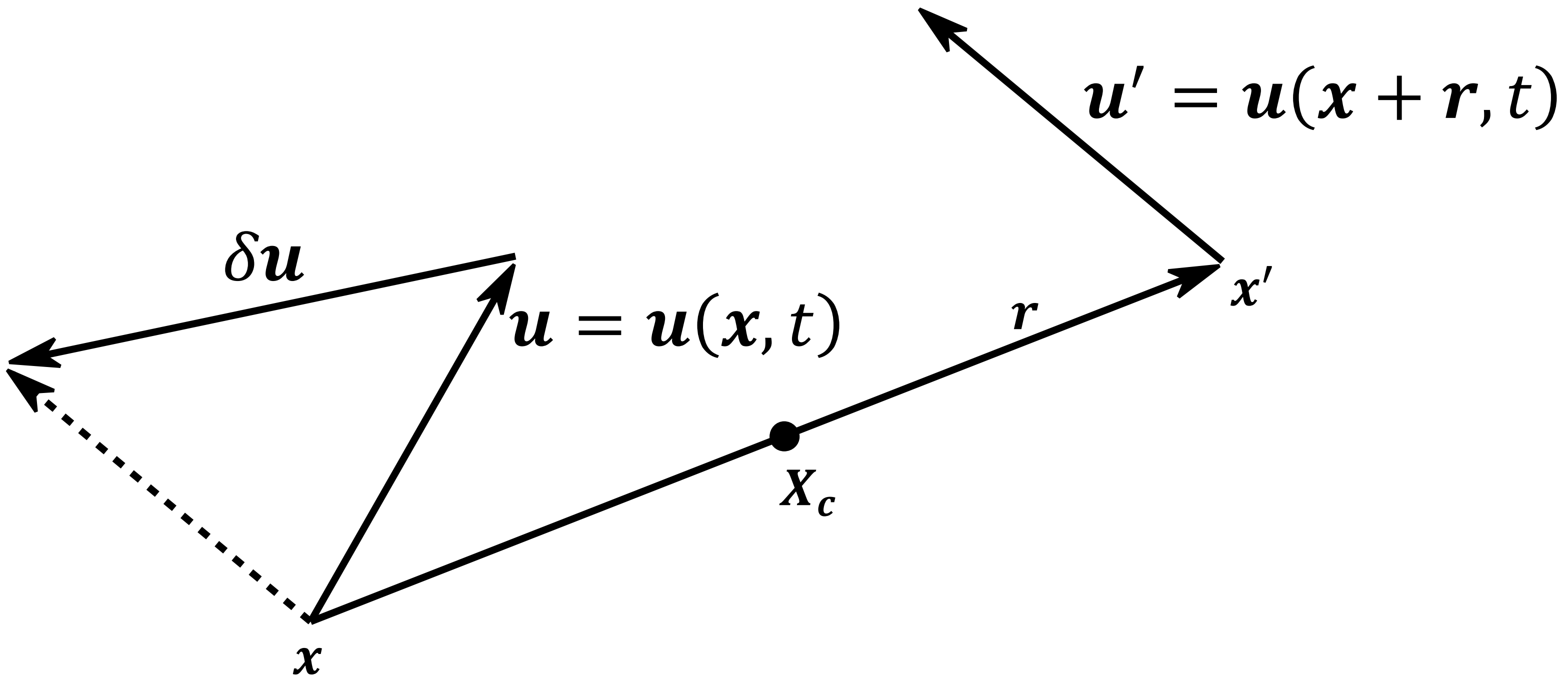
Φ and ϵ is not the only possible decomposition

decomposition à la Eckhardt “wind” interesting: ask

How do we address the physics?

Second-order structure function

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



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

Scale-energy budget equation (1)

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

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 (2)

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

space flux

turbulent — pressure — viscous

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

transport of scale energy in geometric space

in a channel flow, transfer of energy at scale $\boldsymbol{r}$ in y-direction

Scale-energy budget equation (3)

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

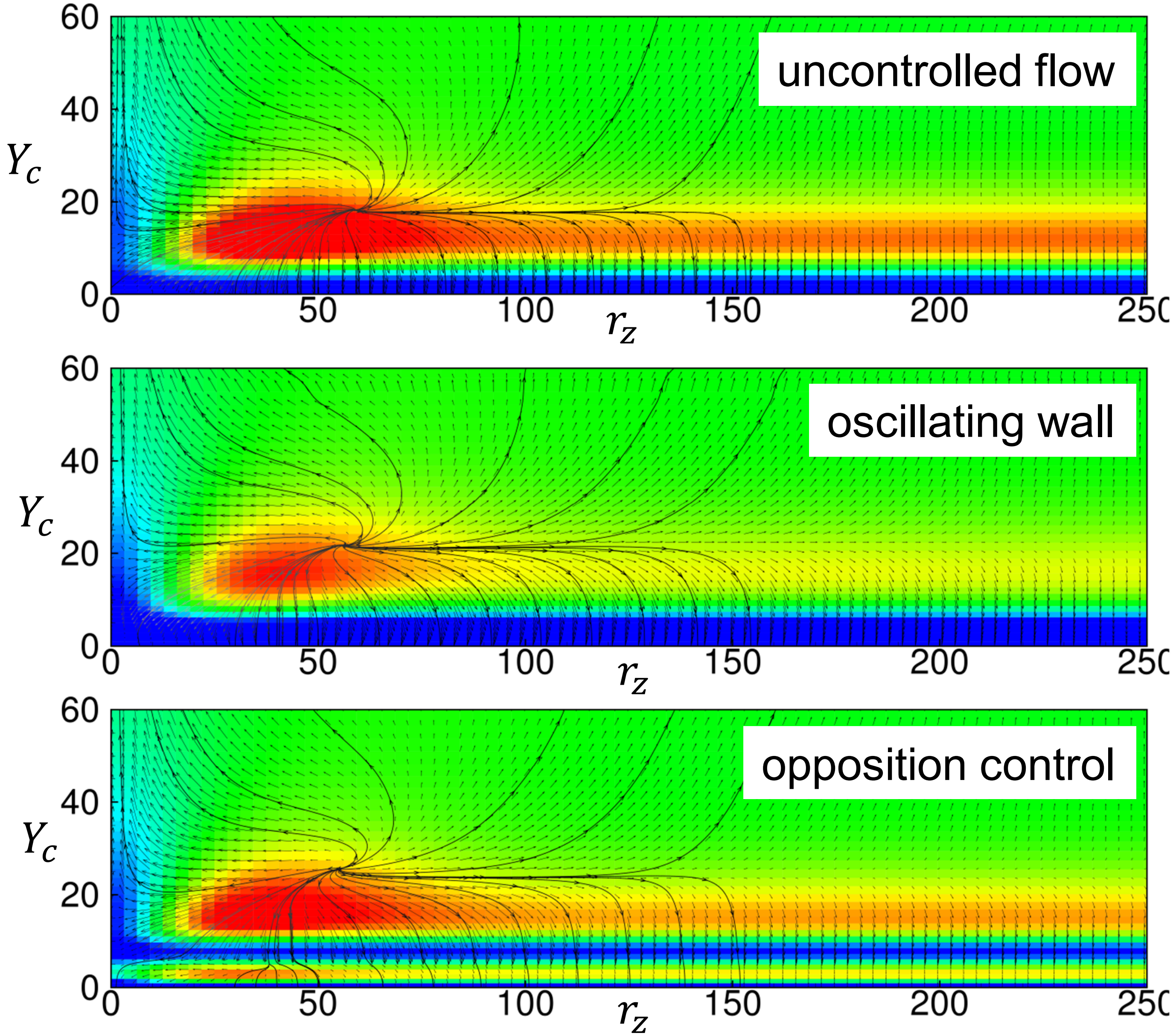
scale flux

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

transport of scale energy throughout scales

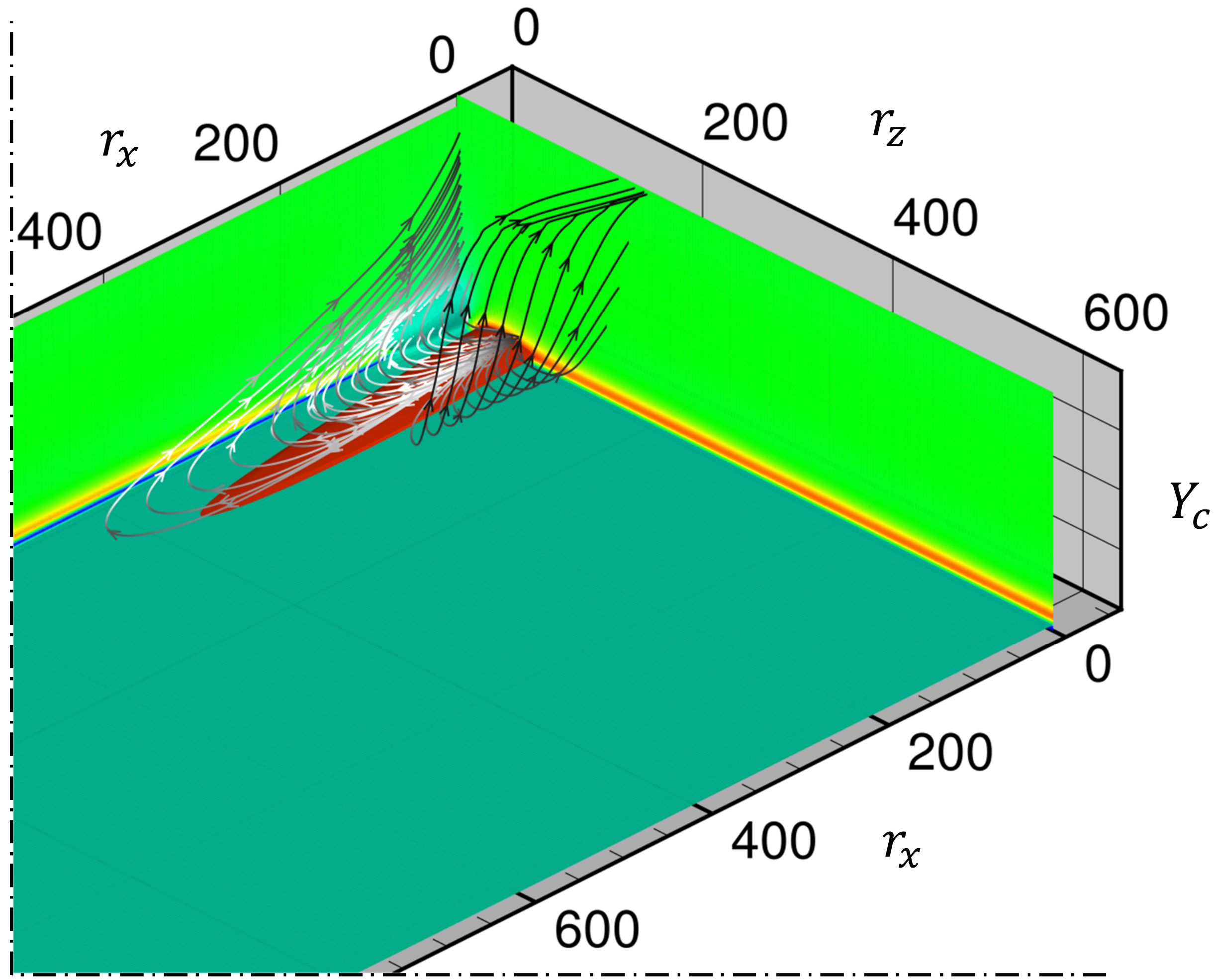
not visible in the TKE budget!

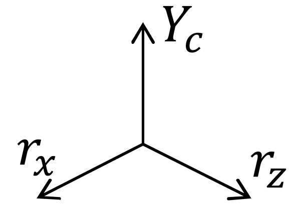
Inner topology $\left(r_x = 0, r_y = 0\right)$



Outer topology $(r_y = 0)$

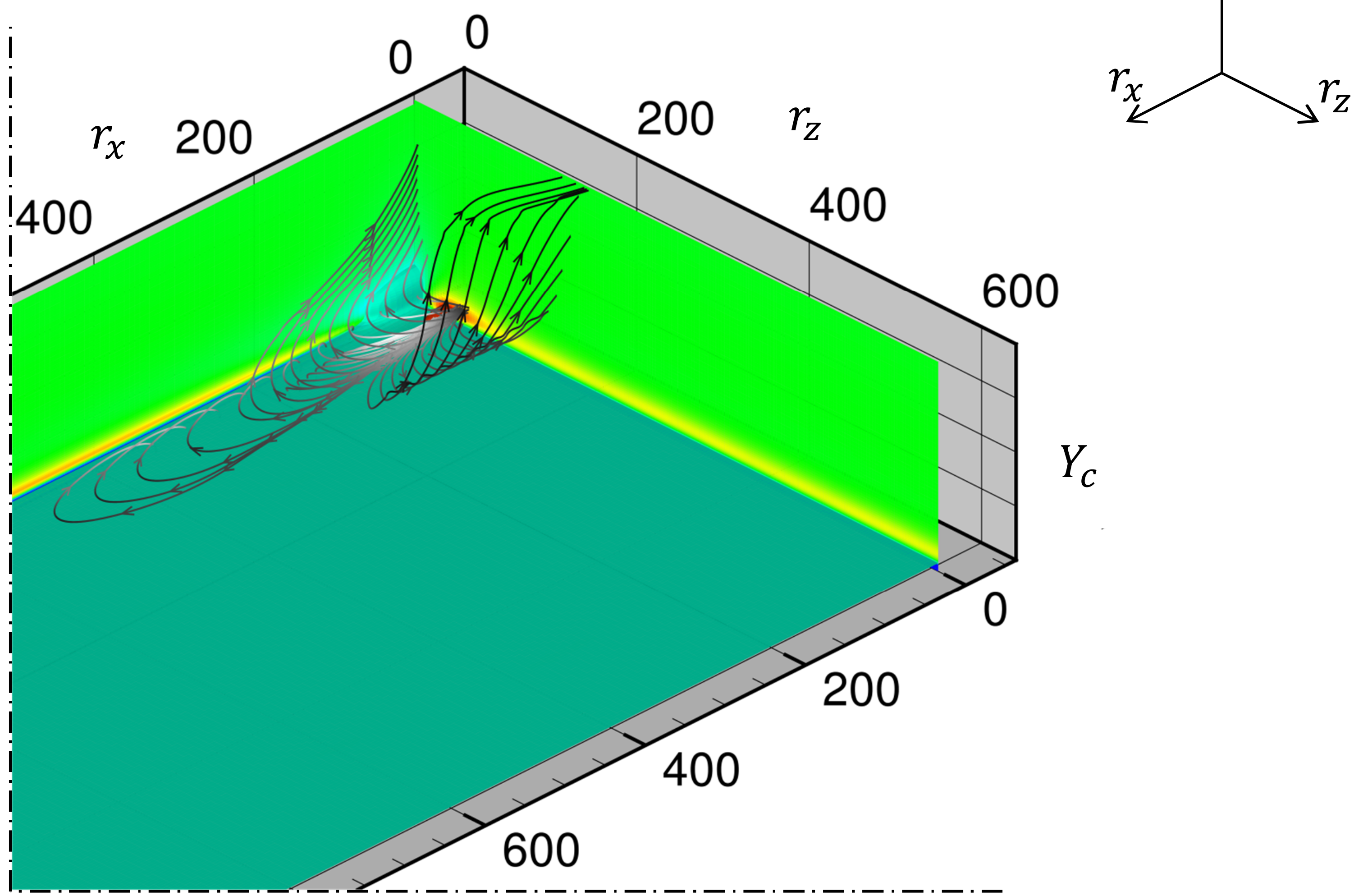
uncontrolled flow





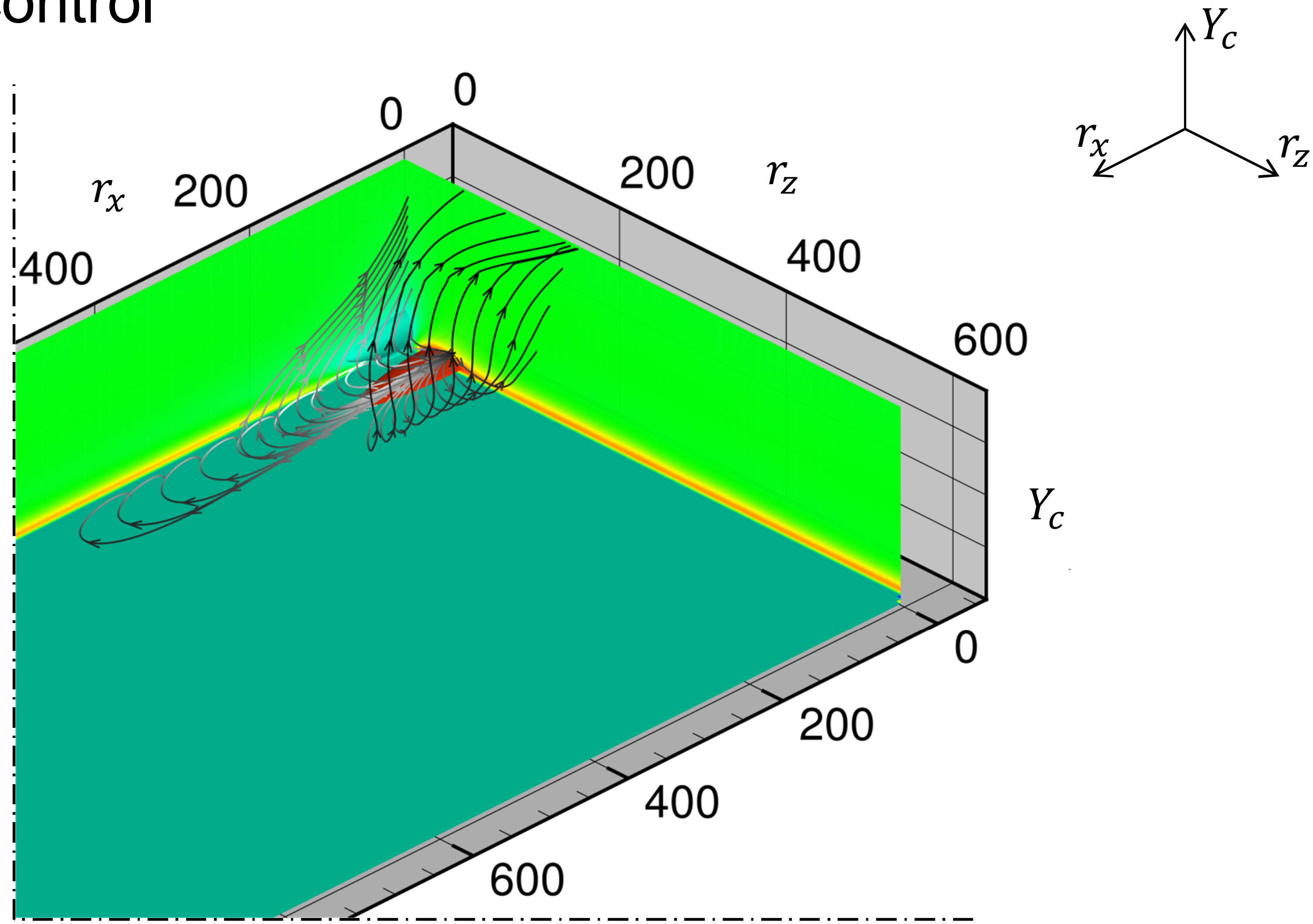
Outer topology $(r_y = 0)$

oscillating wall



Outer topology $(r_y = 0)$

opposition control



Institute of Fluid Mechanics

Conclusions

Karlsruhe Institute of Technology

- 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.

Institute of Fluid Mechanics

Outlook

- Honestly… these are preliminary results!!!

  from qualitative to quantitative

- Find universal behaviours related to drag reduction

  are changes in ϵ and Φ quantitatively predictable?

- Scale energy production at high Re

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

THANKS

for your kind attention!

for questions, complaints, ideas:

davide.gatti@kit.edu

Karlsruhe Institute of Technology

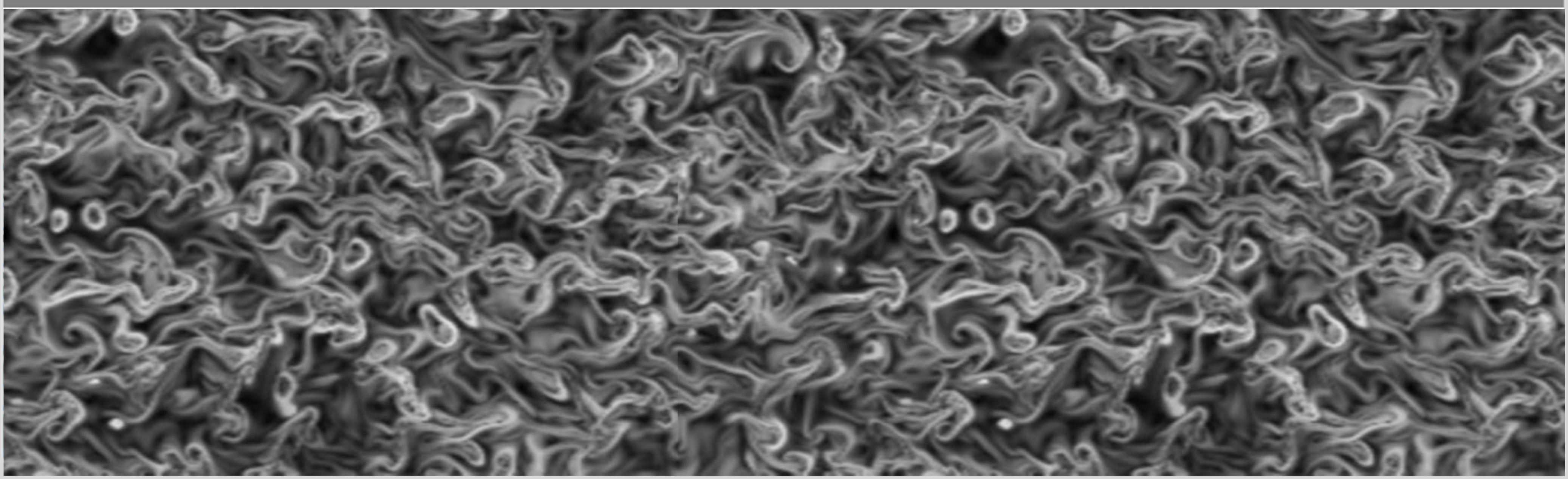
Study of energetics in drag-reduced turbulent channels

Davide Gatti, B. Frohnapfel,
A. Cimarelli, M. Quadrio, Y. Hasegawa

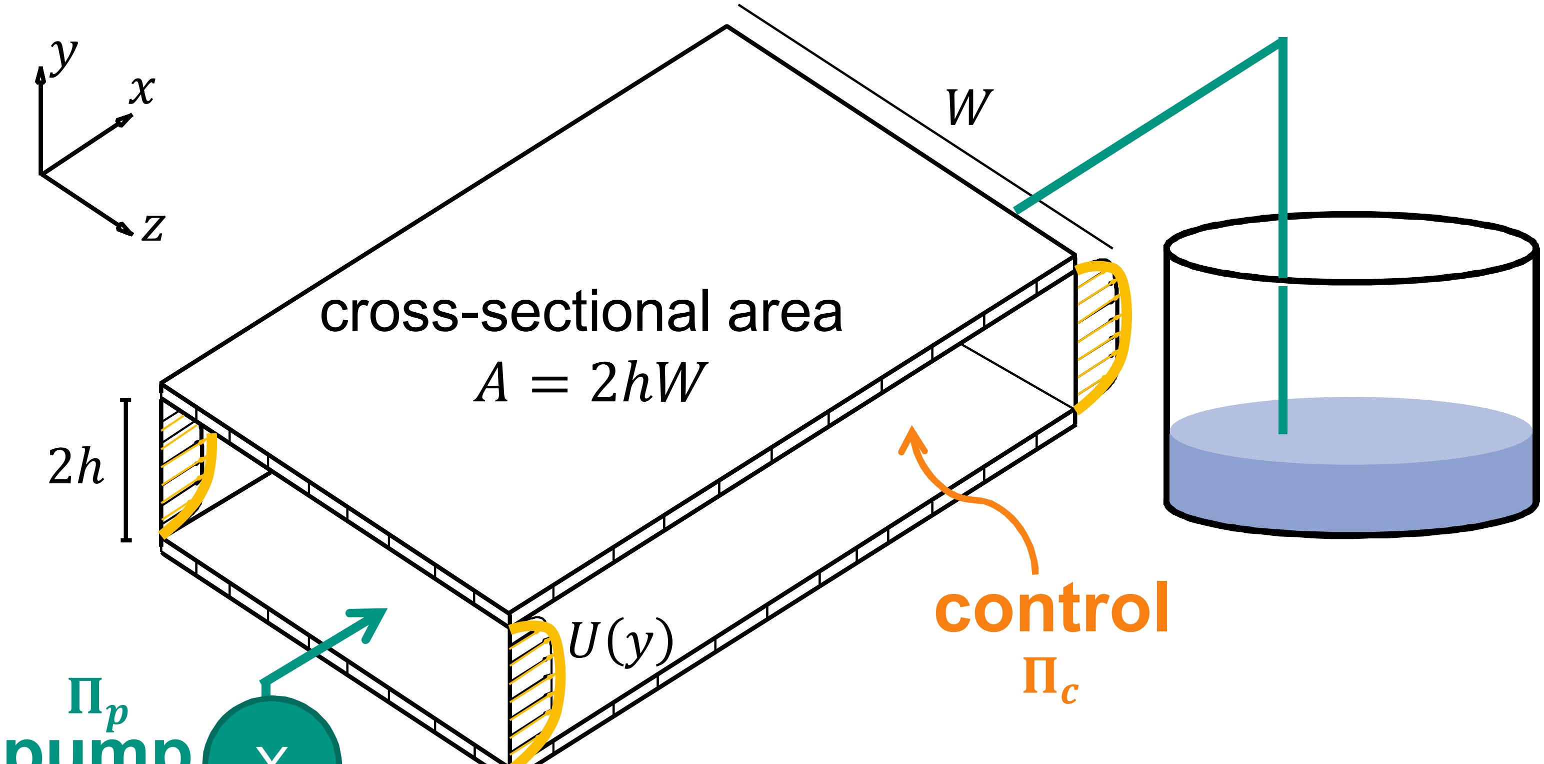
7.9.2016

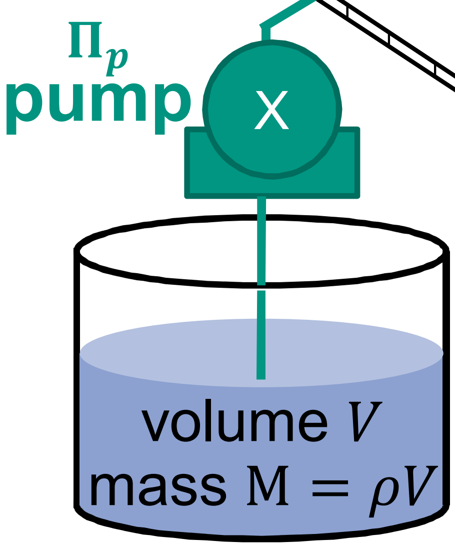
Institute of Fluid Mechanics istm

International Turbulence Initiative, Bertinoro, Italy



The Drag Reduction Experiment





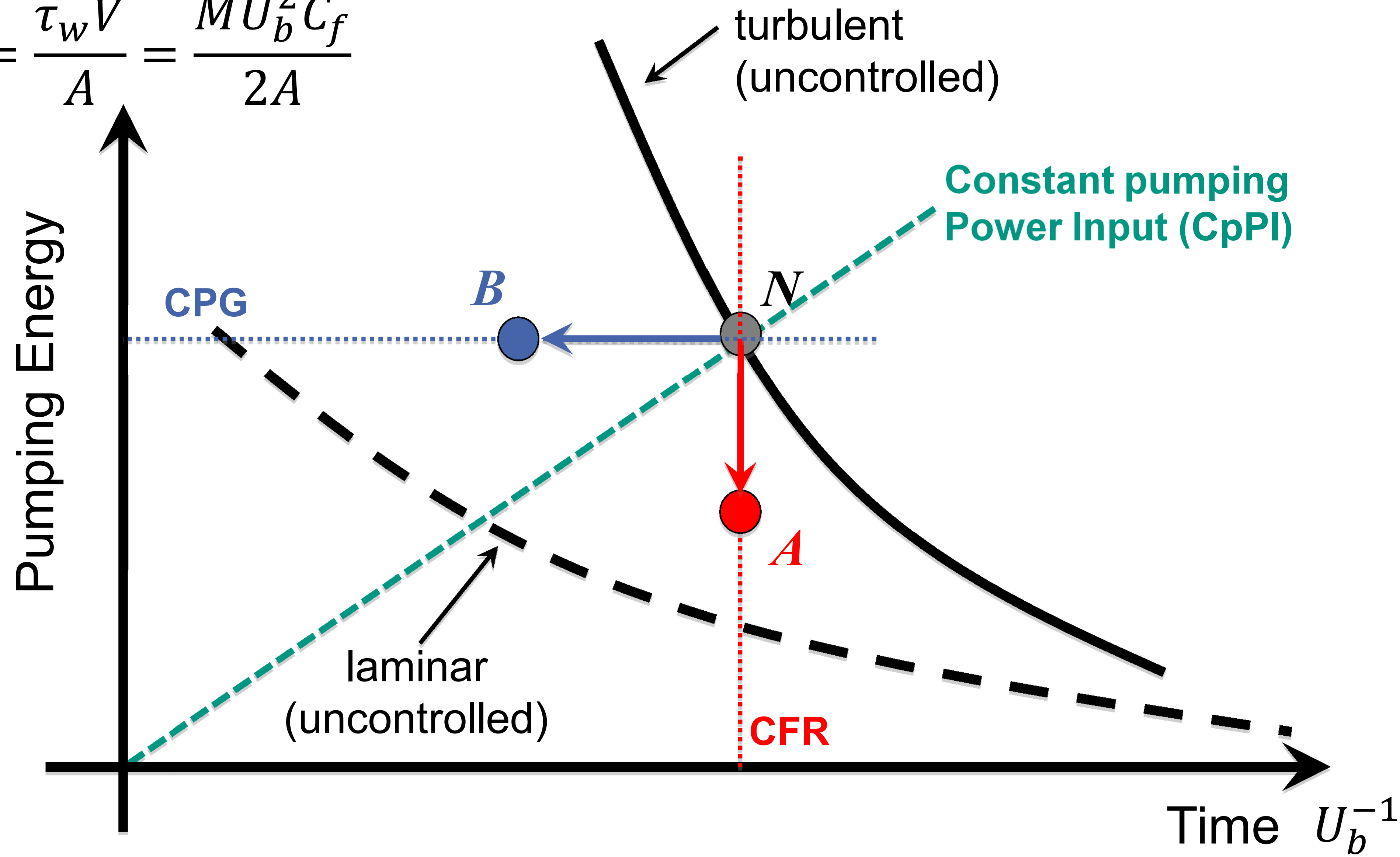
Pumping energy (per unit wetted area) : $E_p = \dfrac{\tau_w V}{A} = \dfrac{M U_b^2 C_f}{2A}$

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

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

Energy (cost) vs. Time

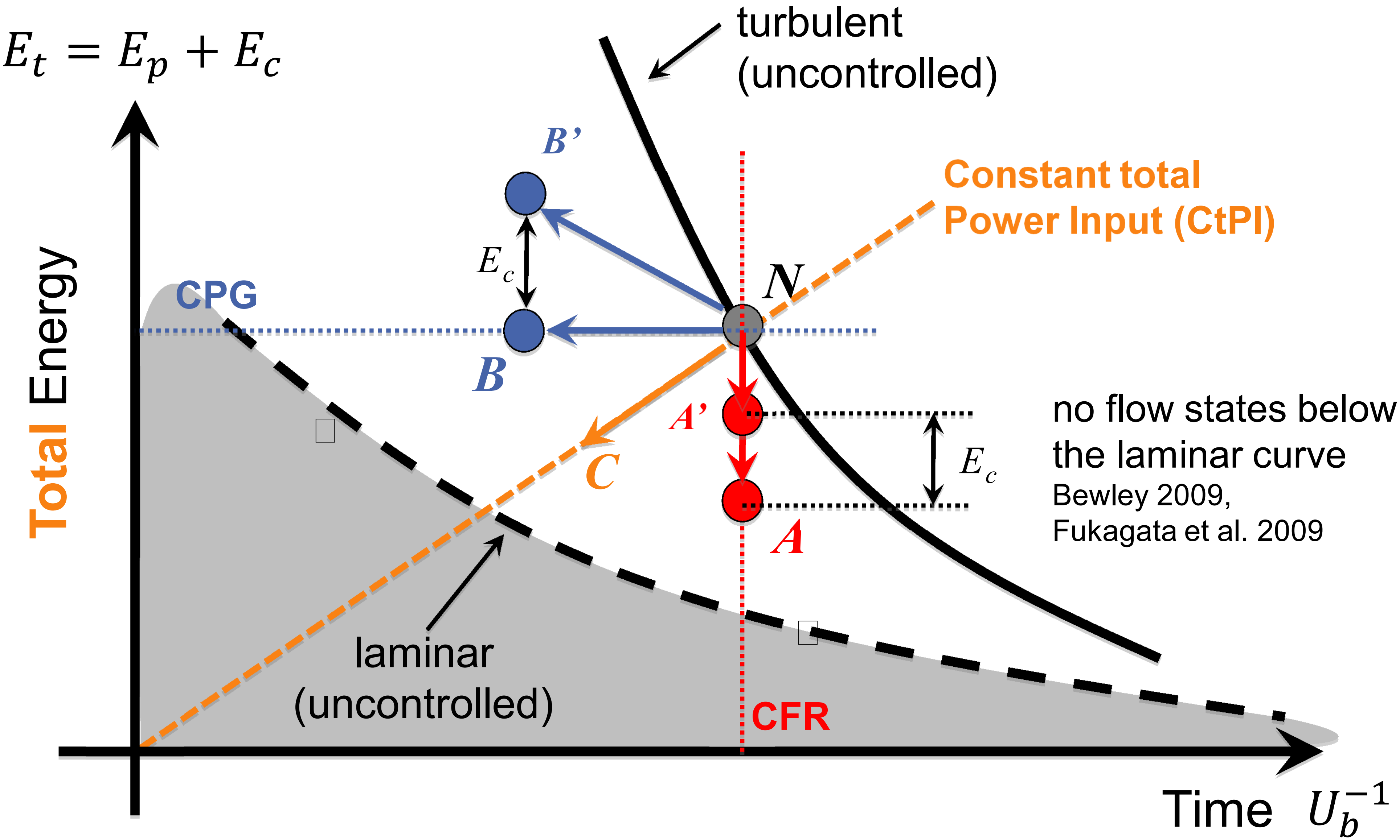
$$E_p = \frac{\tau_w V}{A} = \frac{M U_b^2 C_f}{2A}$$



Frohnapfel, Hasegawa, Quadrio, JFM 2012

Total Energy (cost) vs. Time

$$E_t = E_p + E_c$$



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

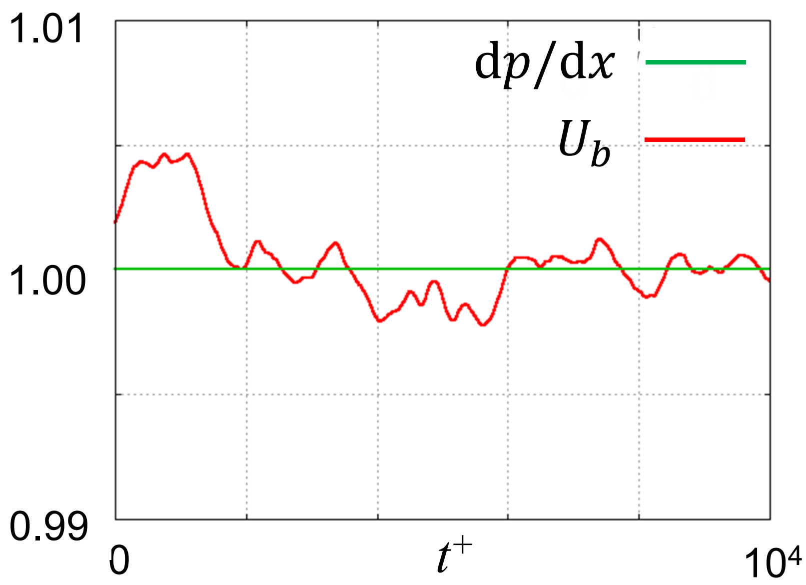
Frohnapfel, Hasegawa, Quadrio, JFM 2012

The choice of flow condition (2)

Constant Pressure Gradient (CPG)

↓

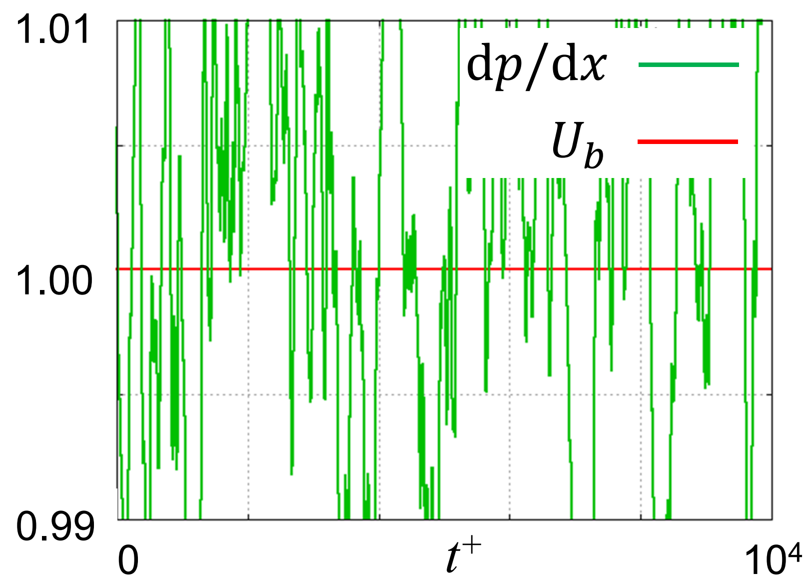
Flow rate fluctuates in time



Constant Flow Rate (CFR)

↓

Pressure gradient fluctuates in time

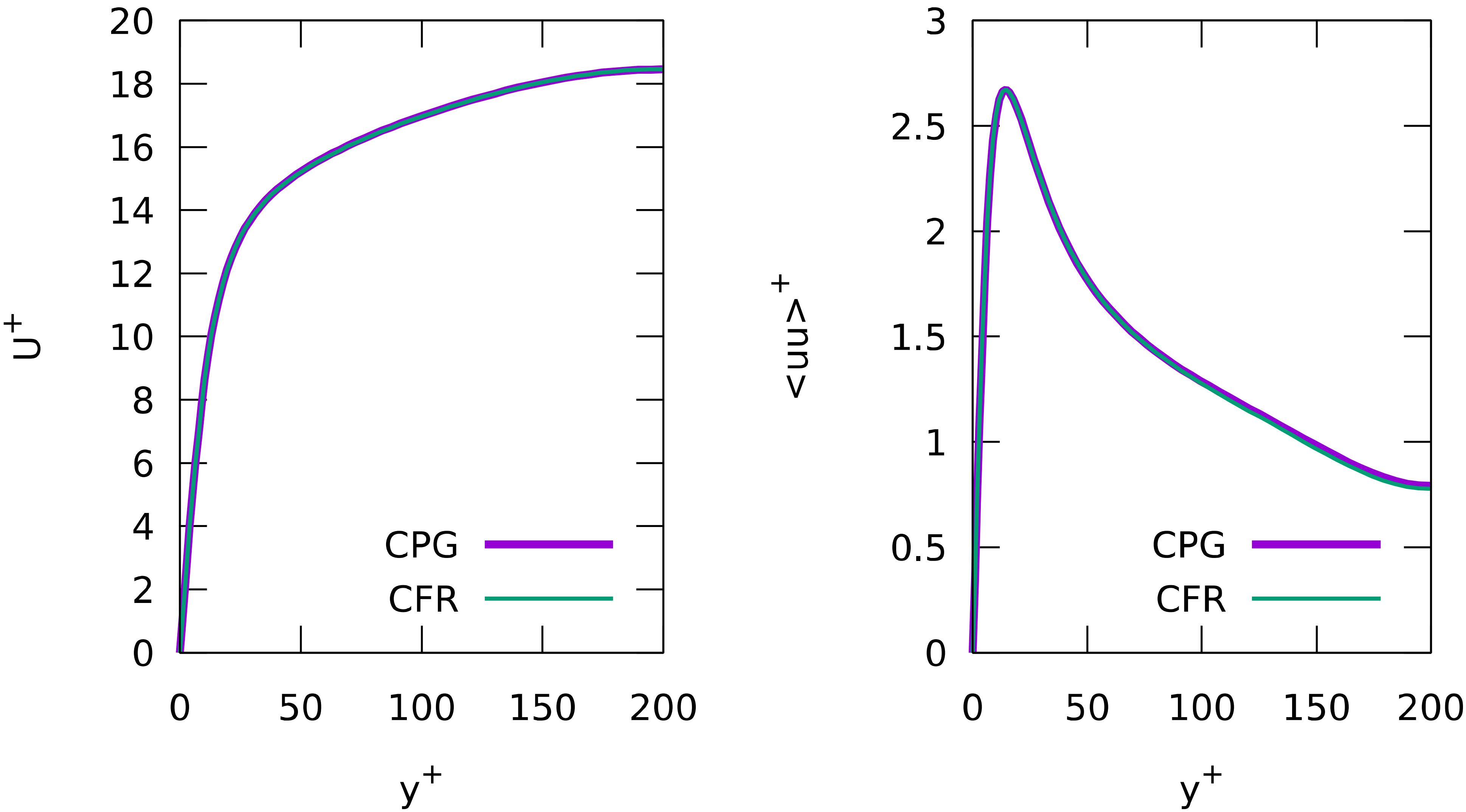


The choice of flow condition (1)

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

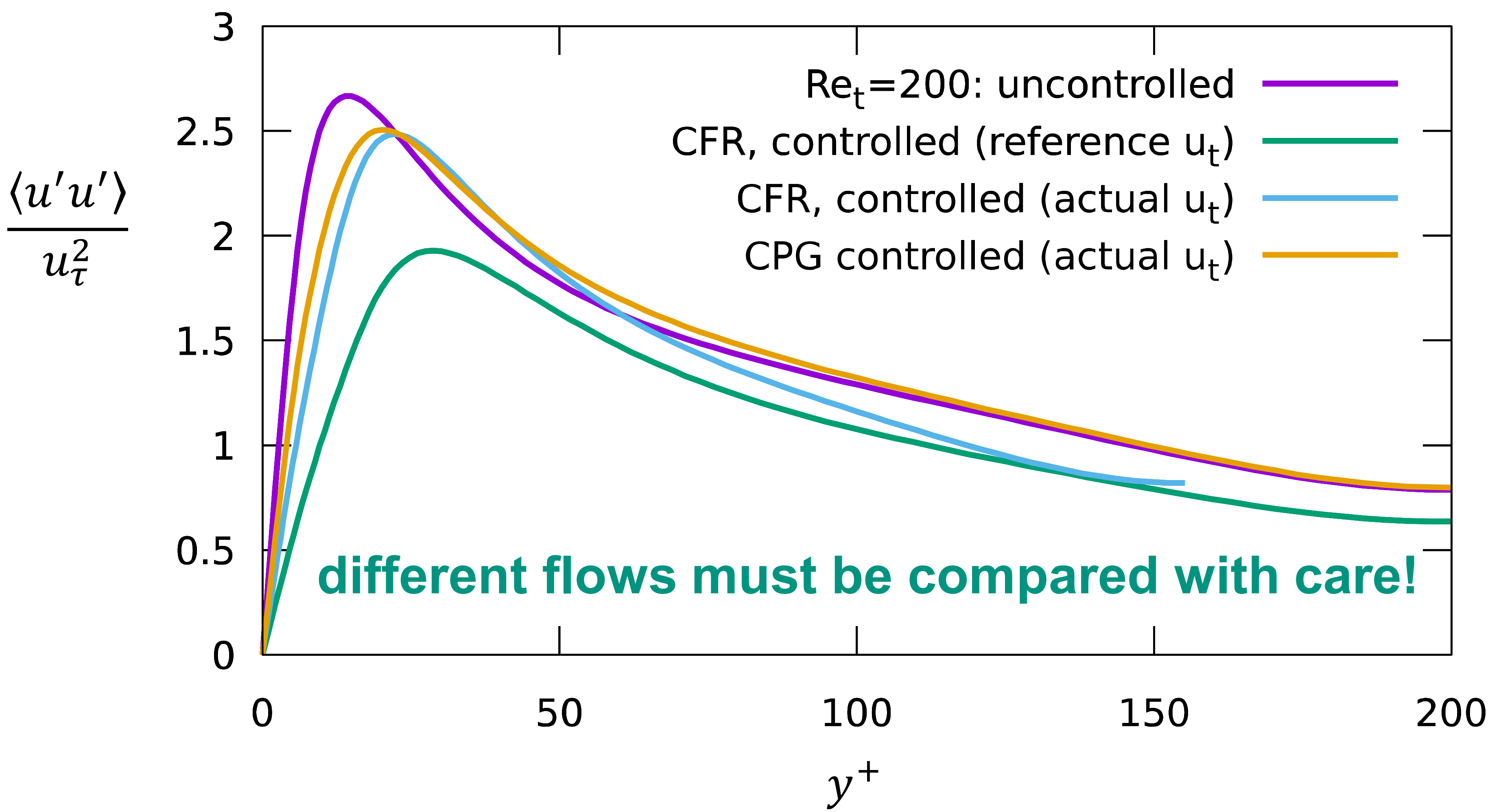
- Many **arbitrary choices** possible
- Often equivalent on physical grounds
- Different on practical grounds
- Different realizations, same statistics

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

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

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 (TKE)

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

$$\langle u'v' \rangle \frac{\partial U}{\partial y} = -\nu \left\langle \frac{\partial u_i'}{\partial x_j} \frac{\partial u_i'}{\partial x_j} \right\rangle + \frac{\partial}{\partial y} \left(\frac{\nu}{2} \frac{\partial \langle u_i'^2 \rangle}{\partial y} - \langle v'p' \rangle - \frac{1}{2} \langle v' u_i'^2 \rangle \right)$$

turbulent production — TKE dissipation rate — transport (space fluxes)

integrated in the whole channel: with control

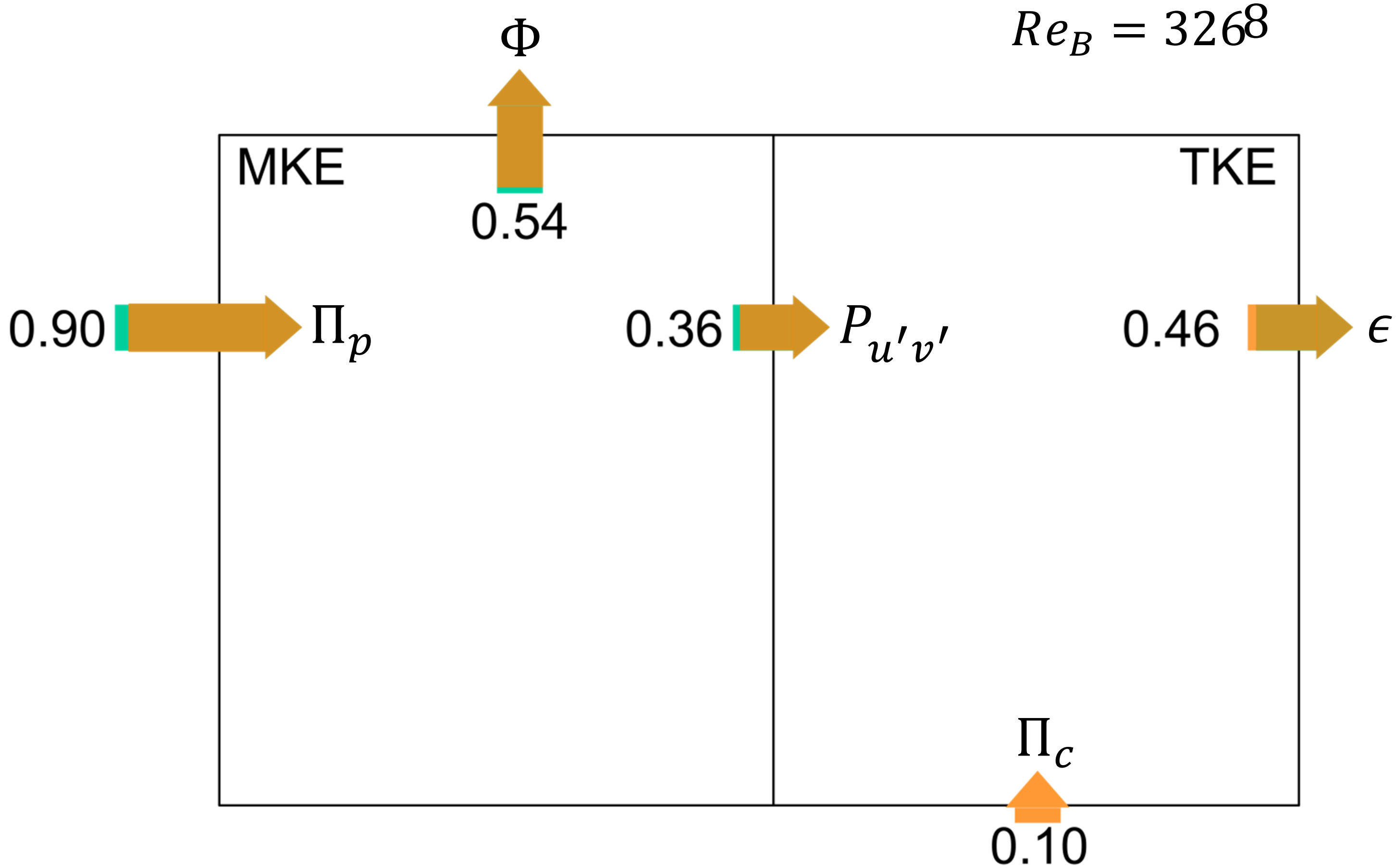
$$\Pi_c + P_T = D_T + D_C$$

The Energy Box

oscillating wall

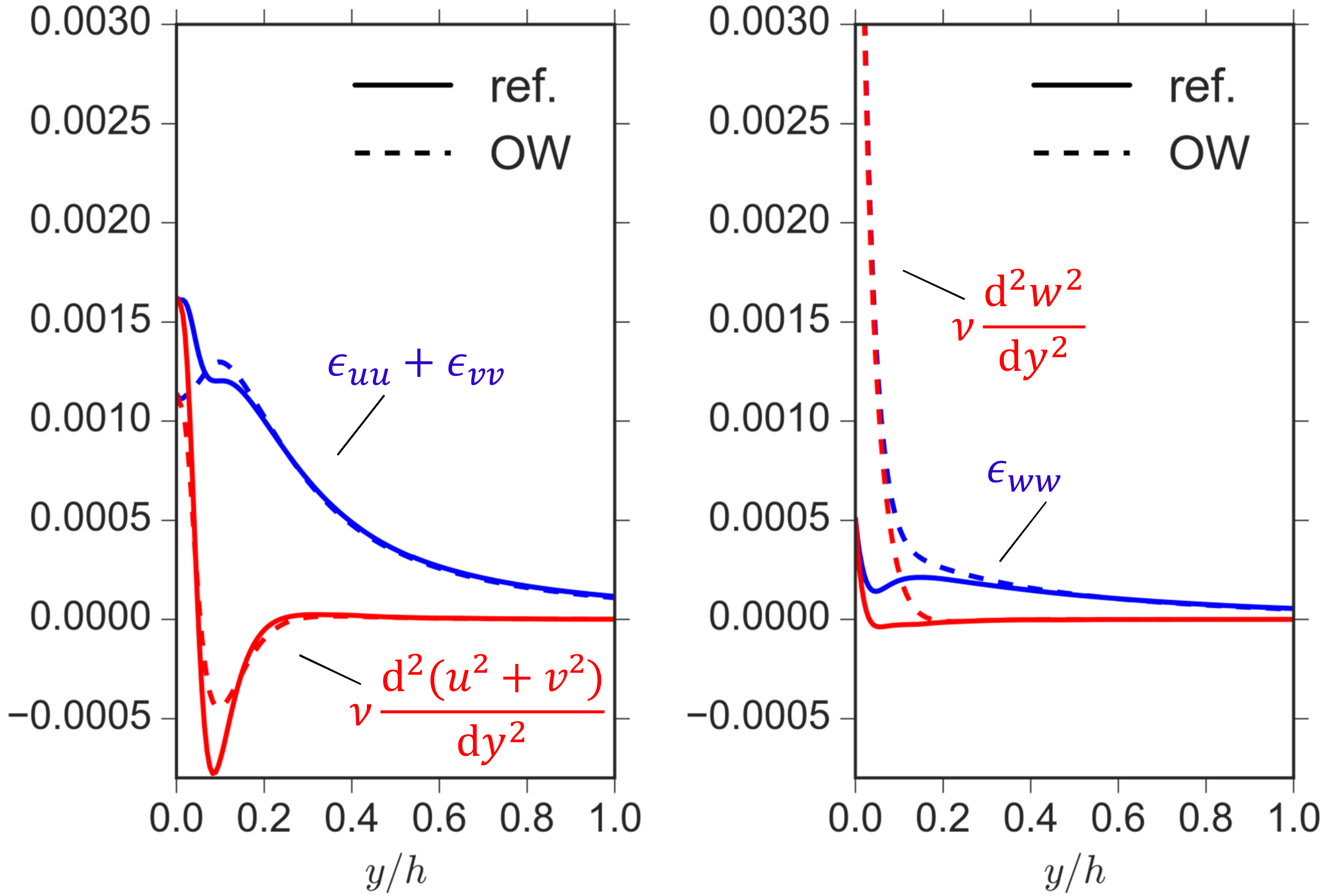
$Re_\tau = 187$

$Re_B = 3268$

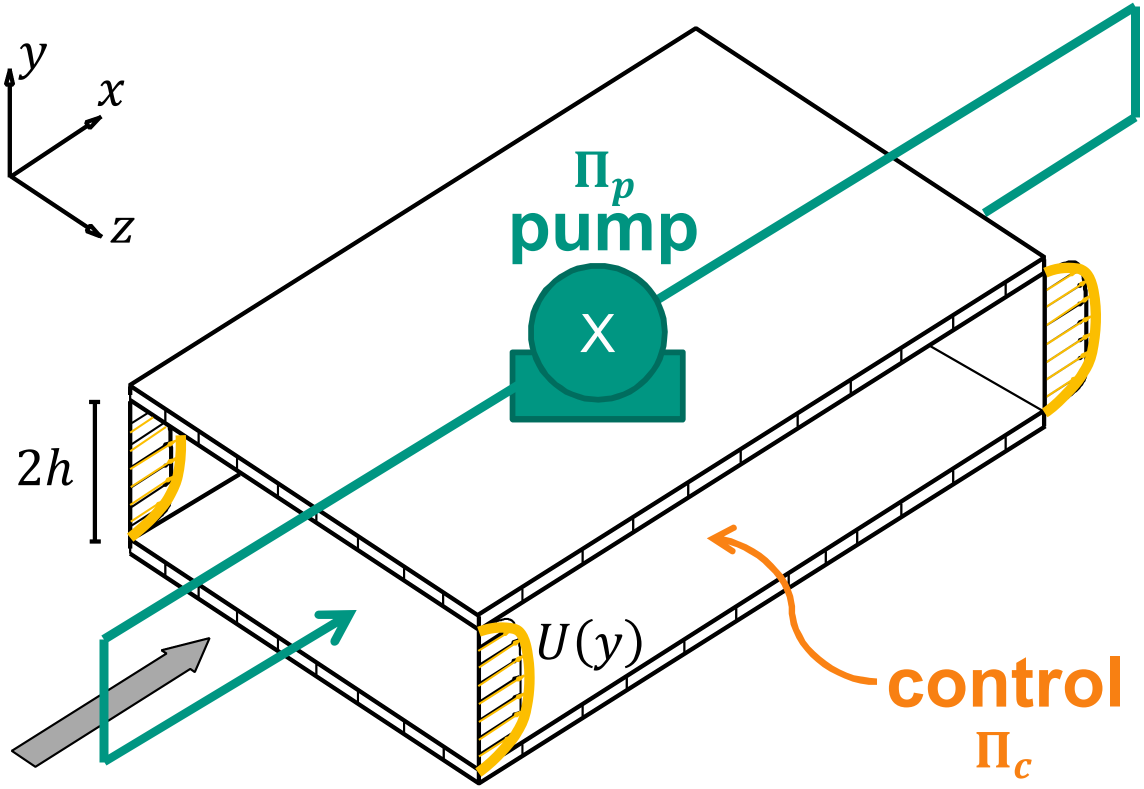


The Energy Box

oscillating wall



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: $\boldsymbol{R} = 1 - \frac{C_f}{C_{f,0}}$

How to drive the flow?

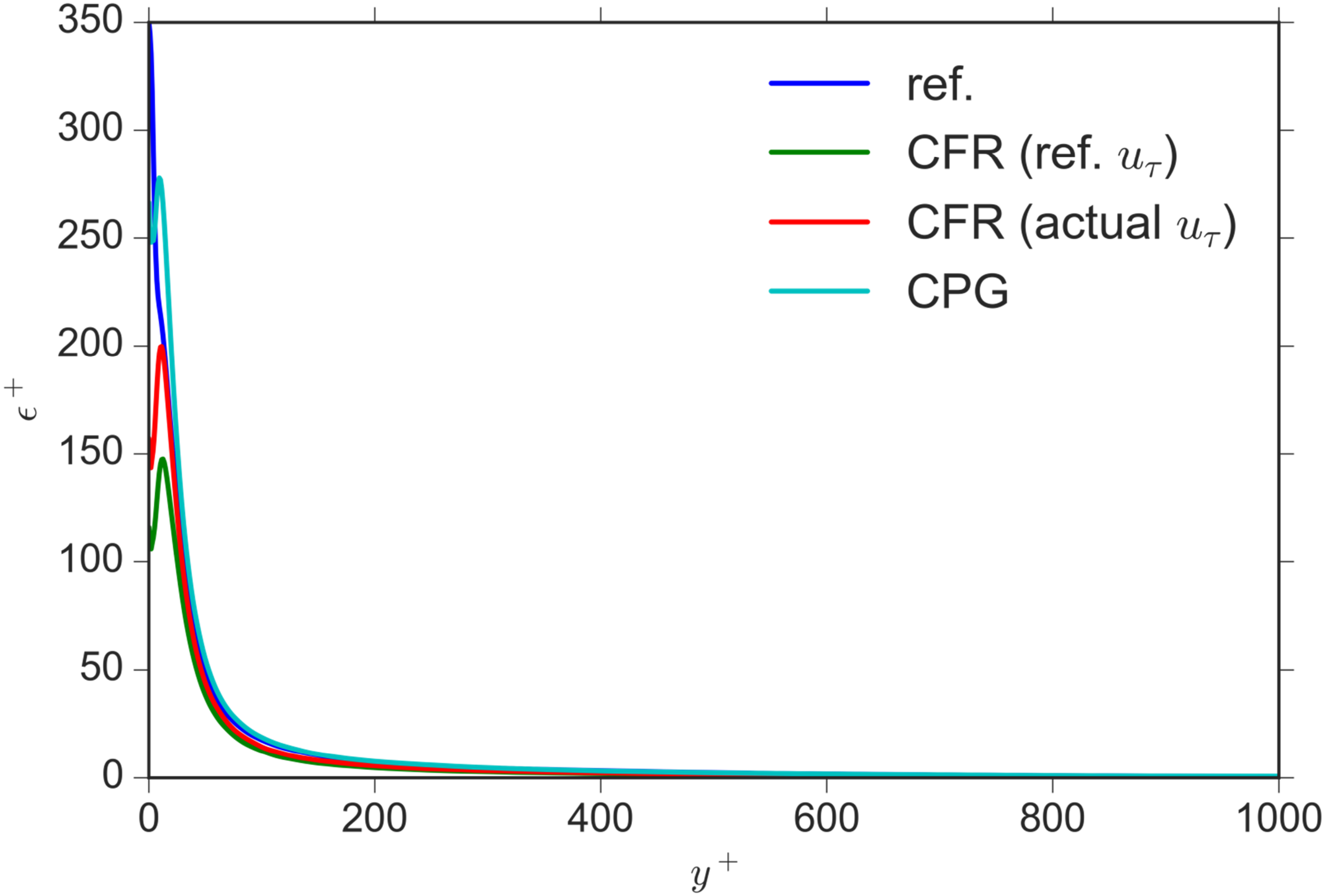
Karlsruhe Institute of Technology

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

	U_b	$-\frac{\mathrm{d}p}{\mathrm{d}x}$	$\boldsymbol{\Pi}_{\mathbf{p}} = -\frac{\mathrm{d}p}{\mathrm{d}x} h U_b$	$\boldsymbol{c_f}$
CPG	↑	=	↑	↓
CFR	=	↓	↓	↓

Important choice for drag-reduced flows!

"dissipation decreases with control"



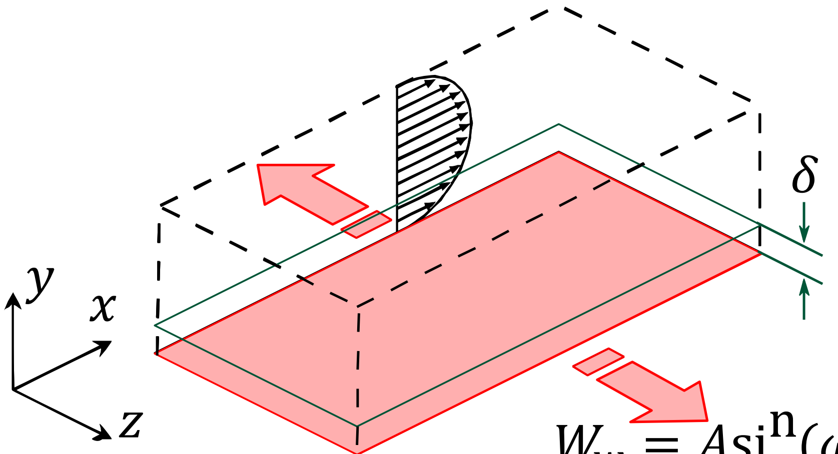
Another choice is possible!

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	↑	↓	=	↓

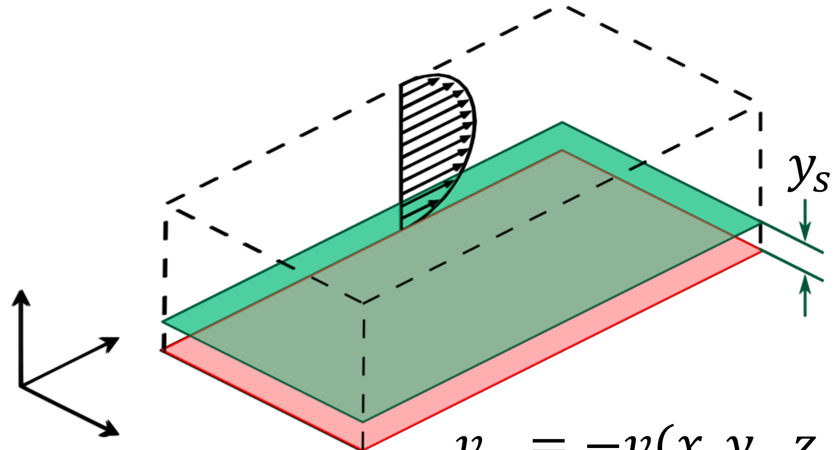
Model control strategies

Spanwise wall oscillations



$$W_w = A\sin(\omega t)$$

Opposition control



$$v_w = -v(x, y_s, z, t)$$

	Spanwise wall oscillations	Opposition control
drag reduction	$R = 1 - {C_f}/{C_{f,0}} = 17.1\%$	$R = 23.8\%$
control power fraction	$\gamma = {\Pi_c}/{\Pi_t} = 0.098$	$\gamma = 0.0035$
	$\dfrac{U_b}{U_{b,ref}} = 1.028$	$\dfrac{U_b}{U_{b,ref}} = 1.093$

Alternative decomposition

into “useful” and “wasted” power

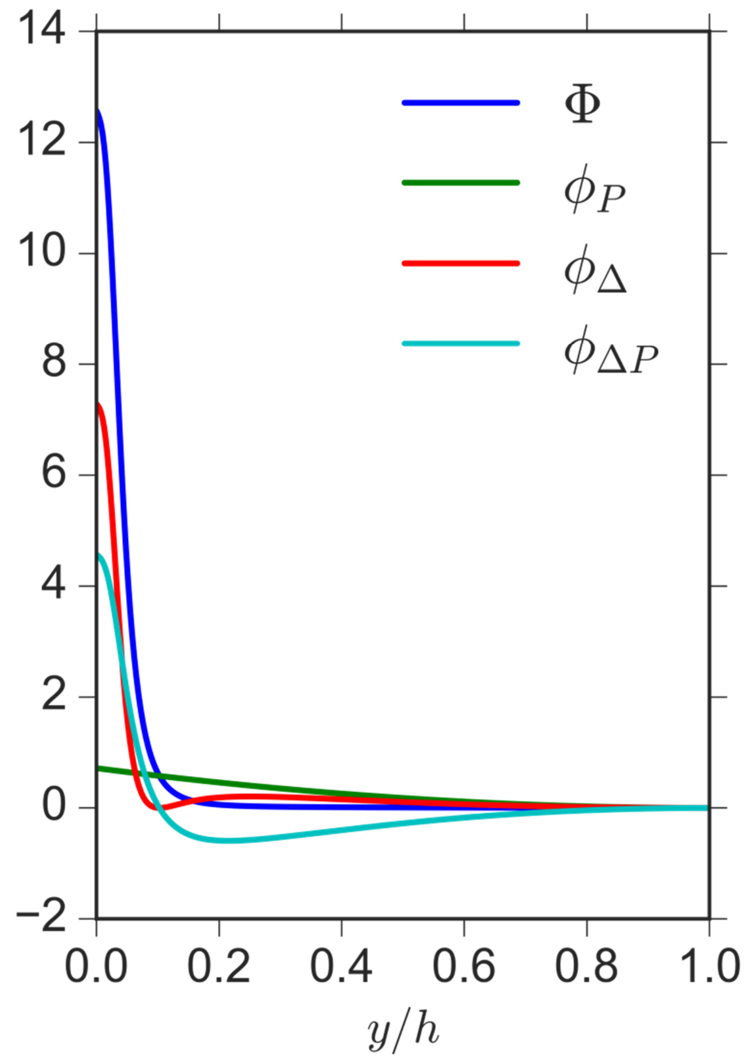
$$\Phi = \phi_P + \phi_\Delta + \phi_{\Delta P}$$

=0

$$P_{uv} = P_{uv,P} + P_{uv,\Delta}$$

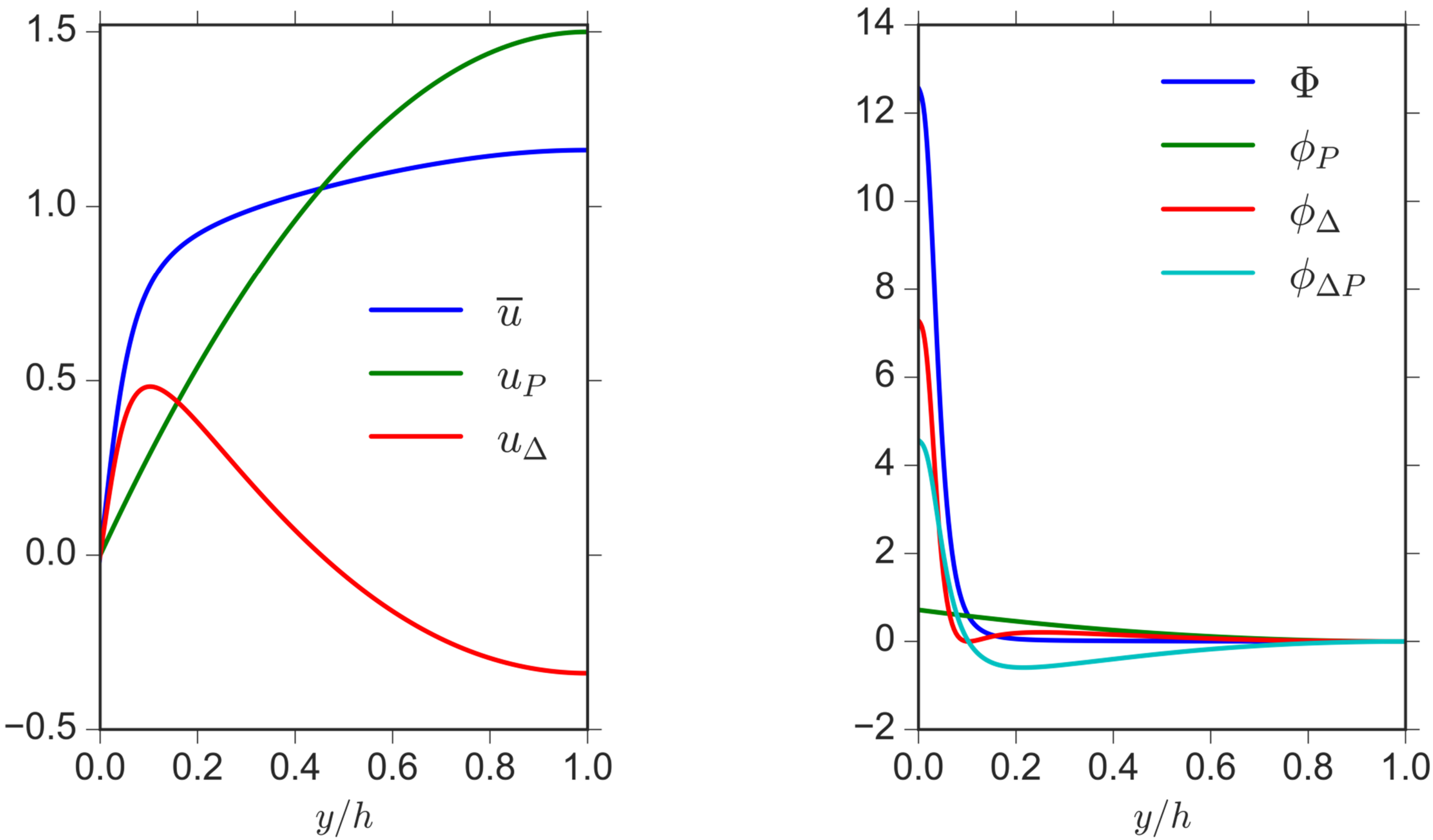
$$3U_b \int_0^h \left(1 - \frac{y}{h}\right) \overline{-u'v'}\, \mathrm{d}y$$

interpretation of FIK weighting?



Alternative decomposition

into “useful” and “wasted” power

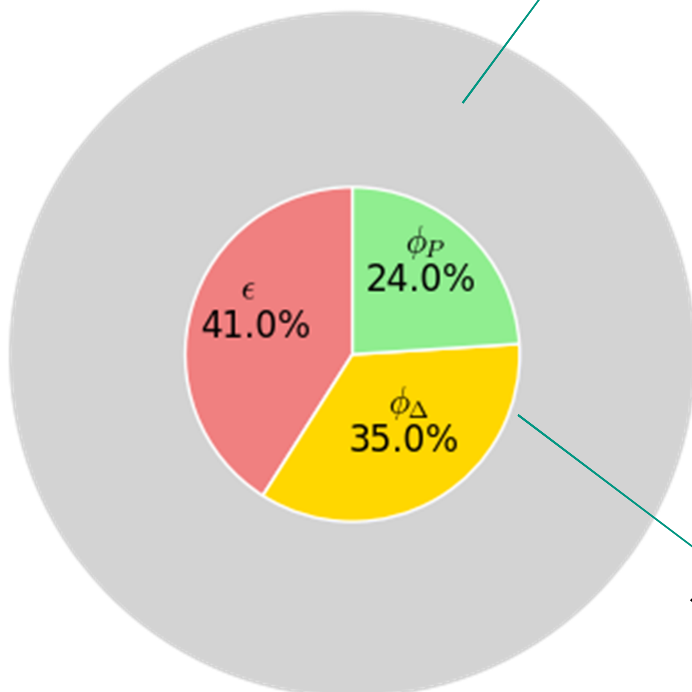


The Energy Pie

$Re_\tau = 200$

$Re_B = 3179$

$R \sim U_\Pi$



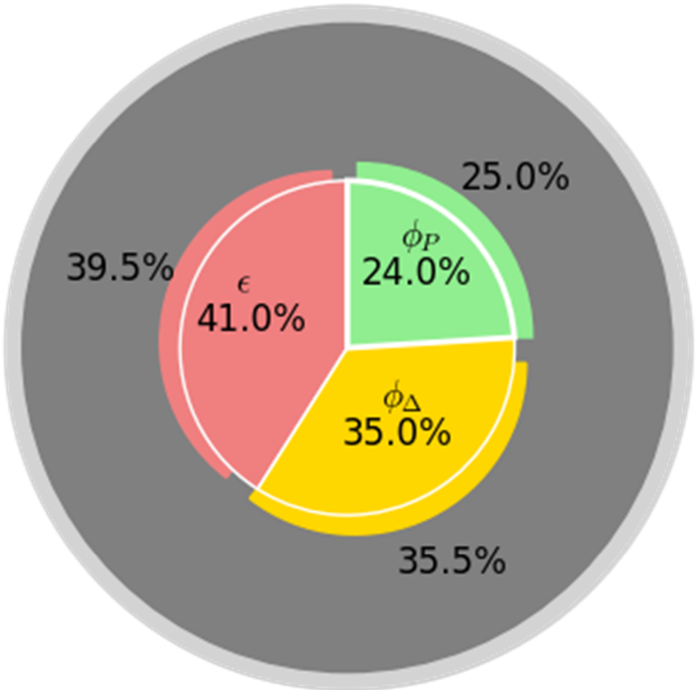
$r \sim U_b$ $\quad$ $\pi r^2 \sim \frac{3}{Re_\Pi}$

reference case

The Energy Pie

$Re_\tau = 187$

$Re_B = 3268$

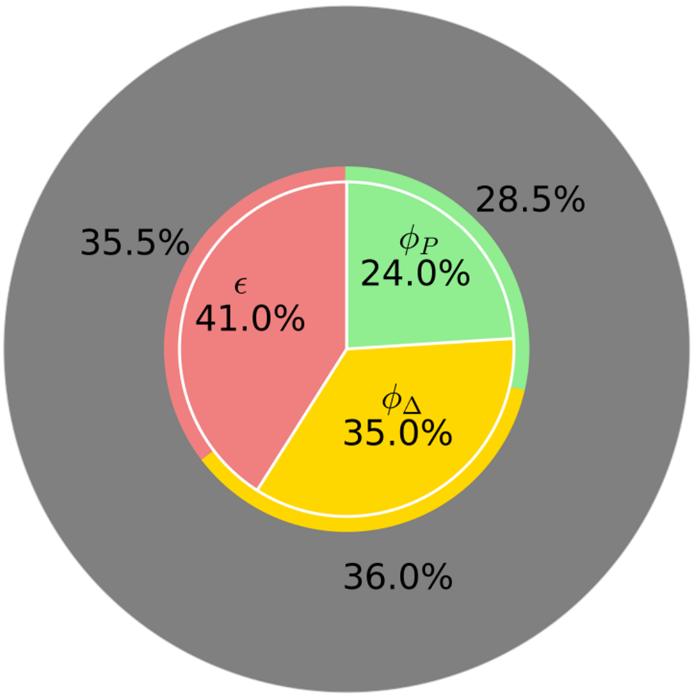


oscillating wall

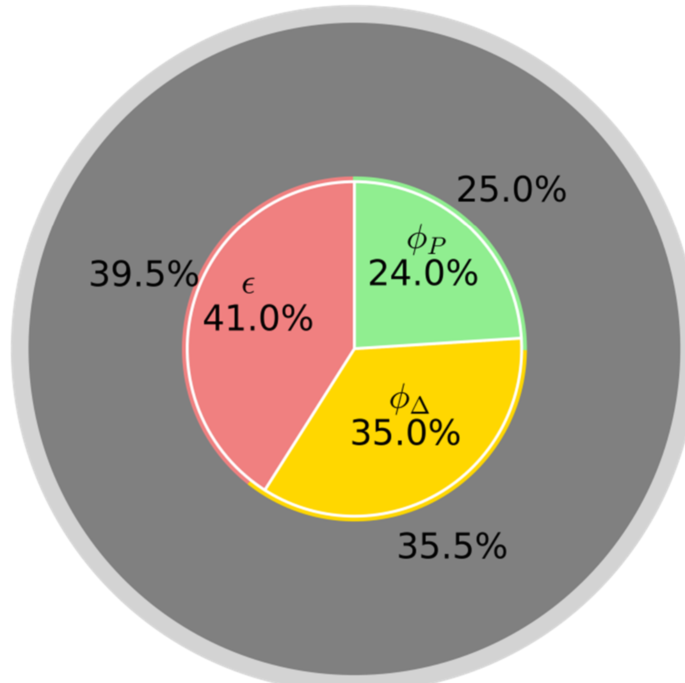
The Energy Pie

$Re_\tau = 191$ $Re_\tau = 187$

$Re_B = 3484$ $Re_B = 3268$



opposition control



oscillating wall