東京大学
生産技術研究所
Institute of Industrial Science,
The University of Tokyo

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Impact of Drag Reduction Control on Energy Box of a Fully Developed Turbulent Channel Flow

Yosuke Hasegawa

Institute of Industrial Science, The University of Tokyo, Japan

Davide Gatti, **Bettina Frohnapfel**

Karlsruhe Institute of Technology, Germany

Andrea Cimarelli

Universita Plitecnica delle Marche, Italy

Maurizio Quadrio

Politecnico di Milano, Italy

Background

- A Fully Developed Channel Flow
  - ✓ Essential physics of near-wall turbulence
  - ✓ Flow control (**drag reduction**, mixing enhancement, etc.)
- Global Energy Budget

$$\textit{Total kinetic energy} = \underbrace{\frac{1}{2}\bar{u}^2}_{\text{Mean}} + \underbrace{\frac{1}{2}\overline{u'_i u'_i}}_{\text{Turbulent}}$$

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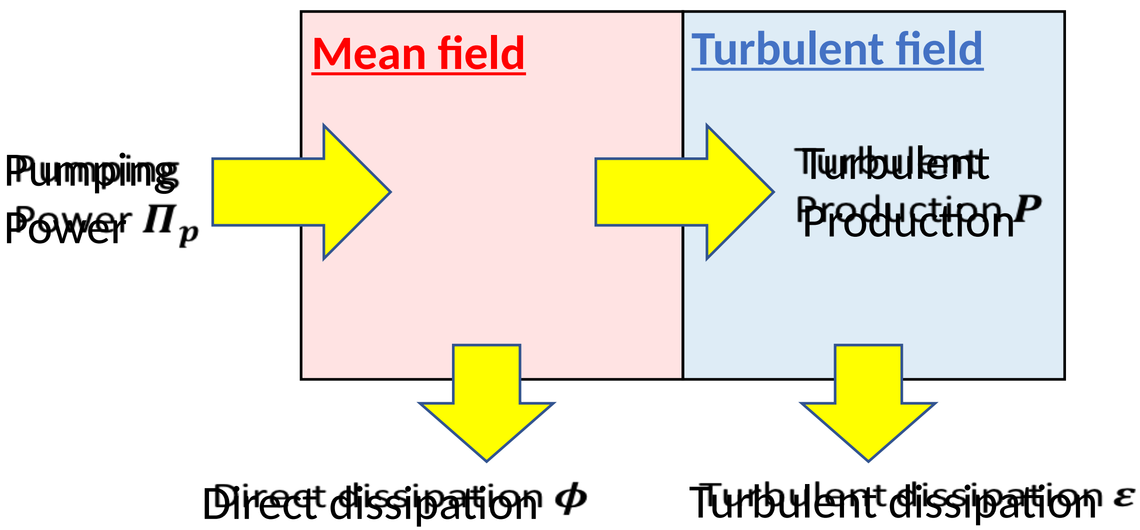
Mean — Turbulent

Energy Box



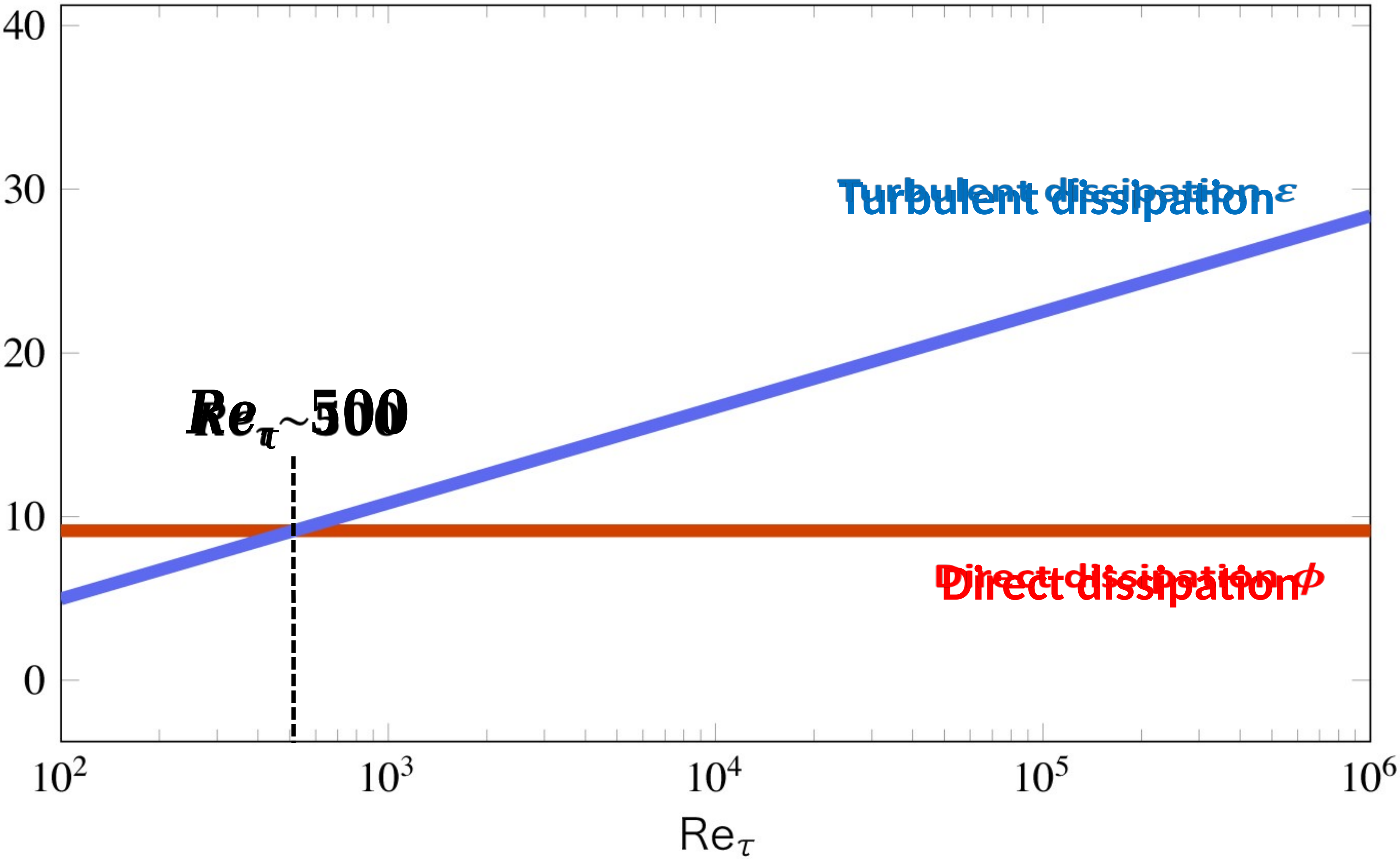
Direct dissipation (diss. of mean field)

$$\phi = \frac{1}{Re}\left(\frac{d\bar{u}}{dy}\right)^2$$

Turbulent dissipation

$$\varepsilon = \frac{1}{Re}\left(\overline{\frac{du'_i}{dx_j}\frac{du'_i}{dx_j}}\right)^2$$

Direct and Turbulent Dissipation in Uncontrolle d Flow



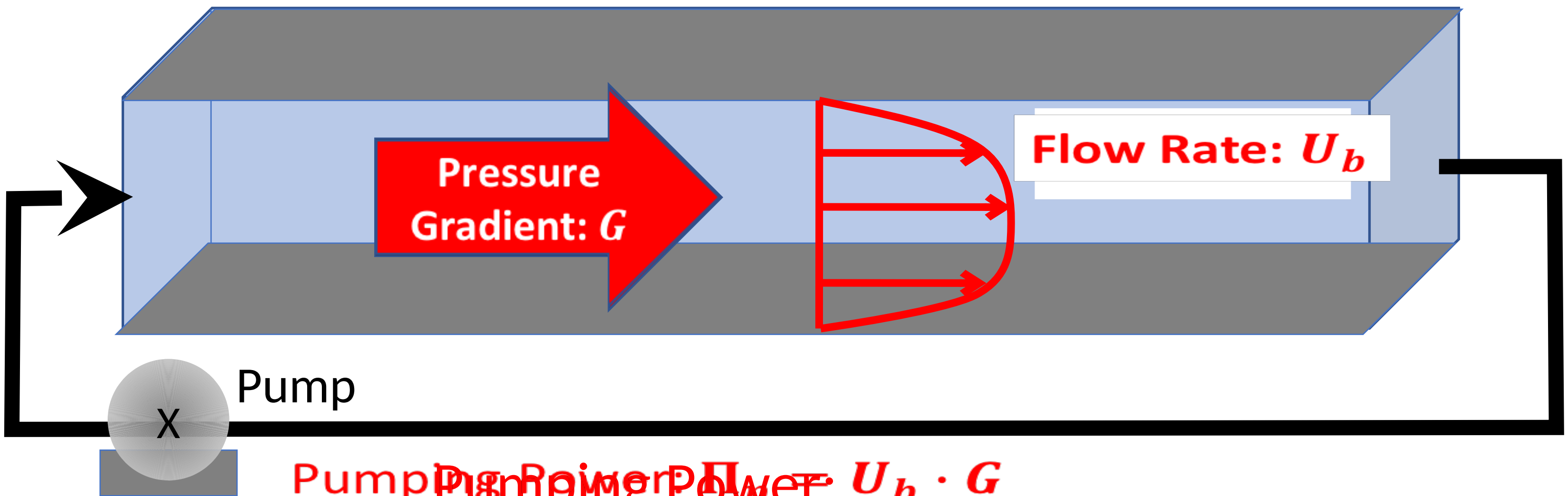
Objectives

- Drag reduction control is somewhat similar to make the “effective” Re lower
  - ➢ Then, the direct dissipation increases, while the turbulent dissipation decreases ?
- Ultimate control: complete relaminarization
  - ➢ All input energy should be dissipated by the direct dissipation only.

<u>Questions</u>

✓ Is there an unique relationship between the changes in direct/turbulent dissipation and a drag reduction effect ?

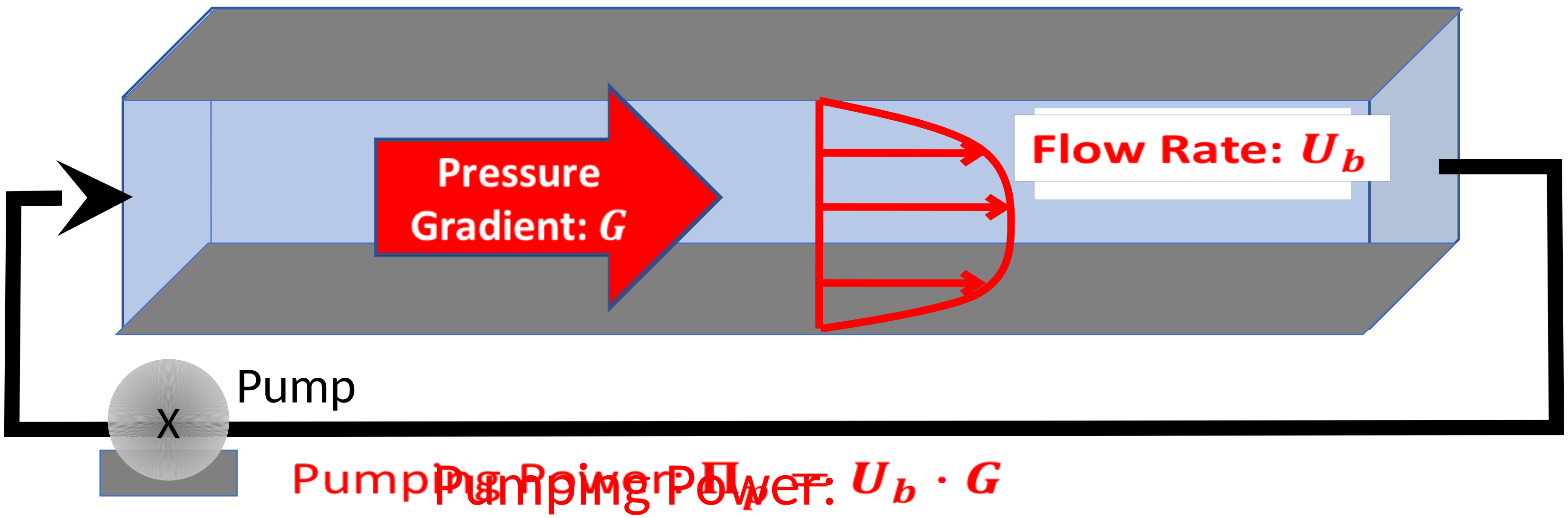
Flow Conditions

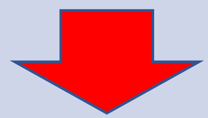
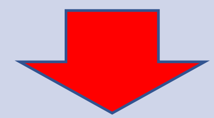
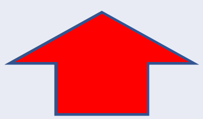
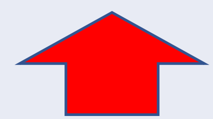


Pumping Power: $\Pi = U_b \cdot G$

Pumping Power:

Flow Conditions

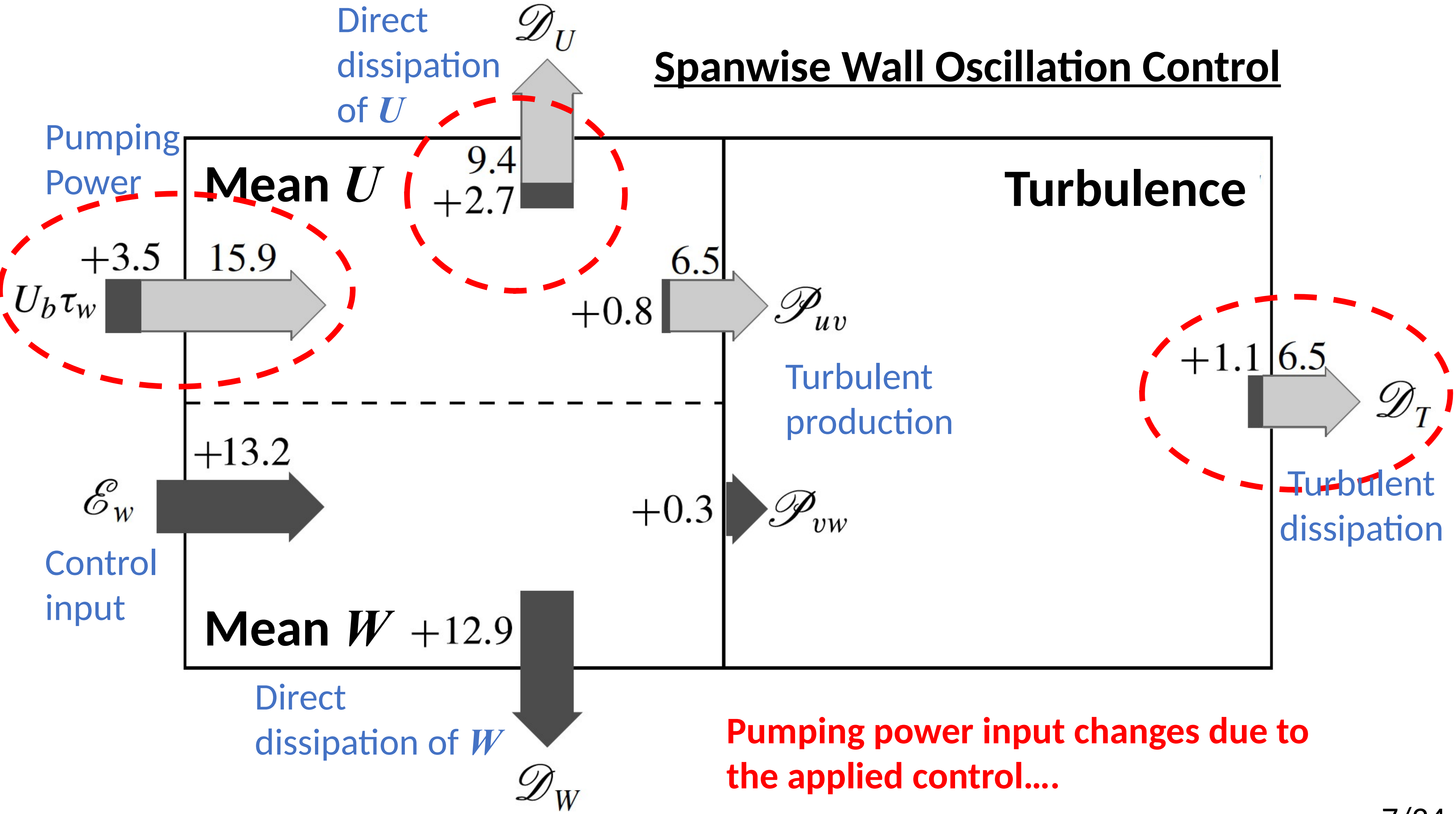


	Flow Rate: U_b	Pressure Gradient: G	Pumping Power: Π_p
Constant Flow Rate (CFR)	Constant		
Constant Pressure Gradient (CPG)		Constant	

Energy Box Under CPG

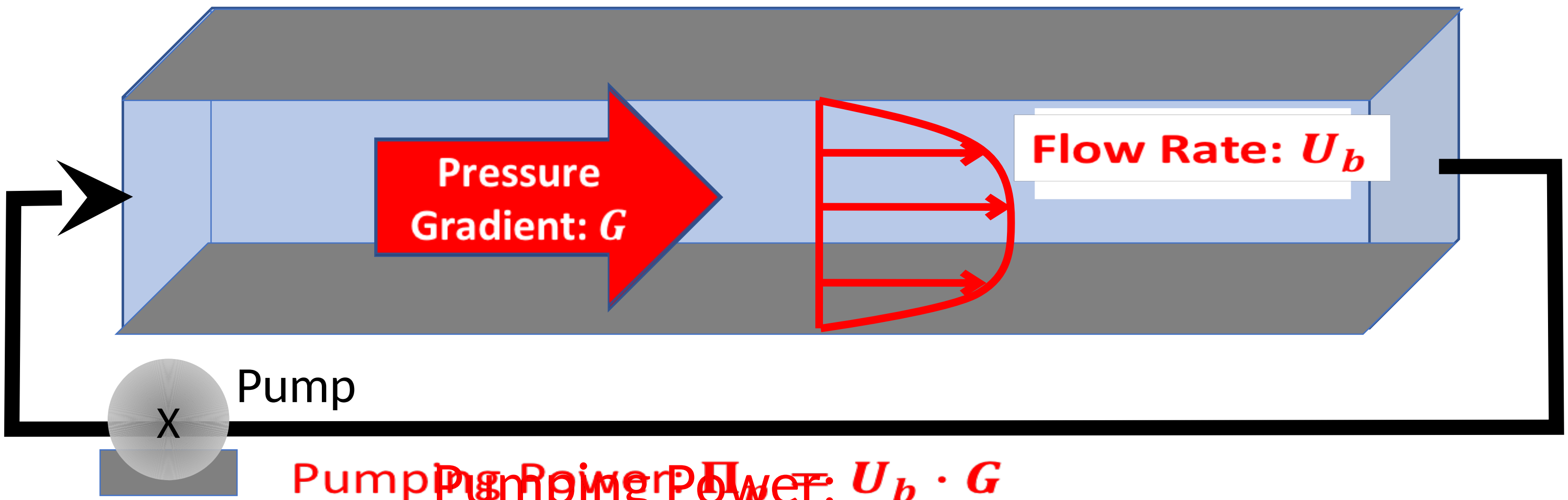
Ricco et al. JFM (2011)

Spanwise Wall Oscillation Control



Pumping power input changes due to the applied control….

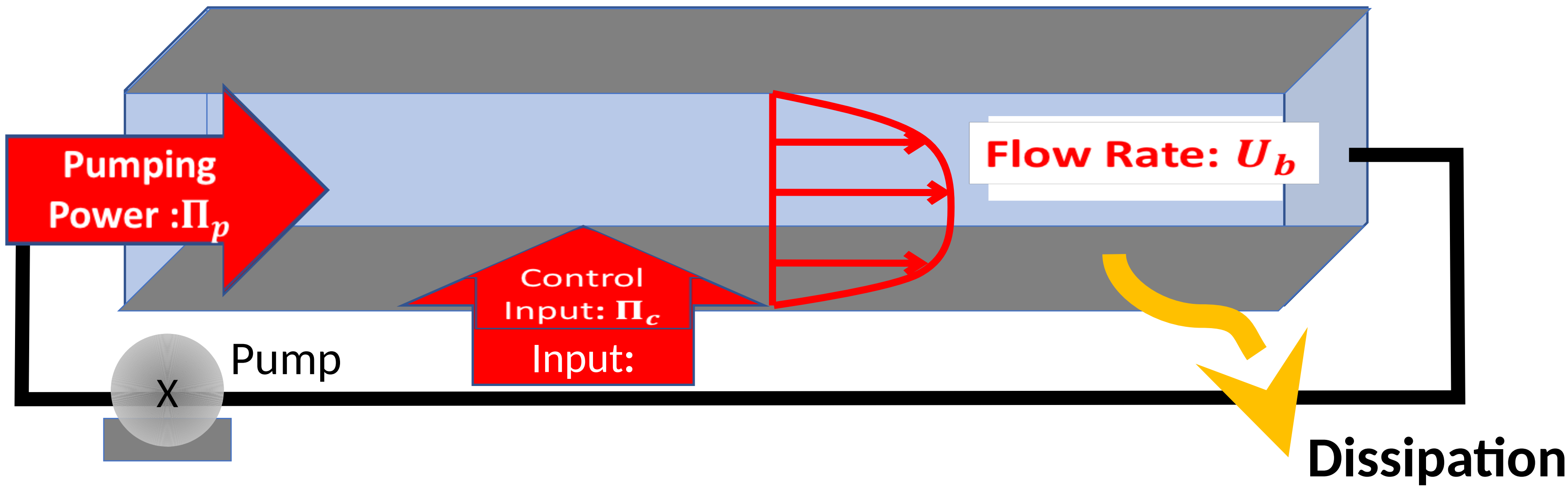
Flow Conditions



	Flow Rate: U_b	Pressure Gradient: G	Pumping Power: Π_p
Constant Flow Rate (CFR)	Constant	↓	↓
Constant Pressure Gradient (CPG)	↑	Constant	↑
Constant Power Input (CPI)	↑	↓	Constant

Concept of Constant Power Input (CPI)

(Frohnapfel et al. JFM 2012, Hasegawa et al. JFM 2014)



- Total Power Input

$$\Pi_t^* = \Pi_p^* + \Pi_c^* = const.$$

- Fraction of Control Power Input

$$\gamma = \Pi_c^* / \Pi_t^*$$

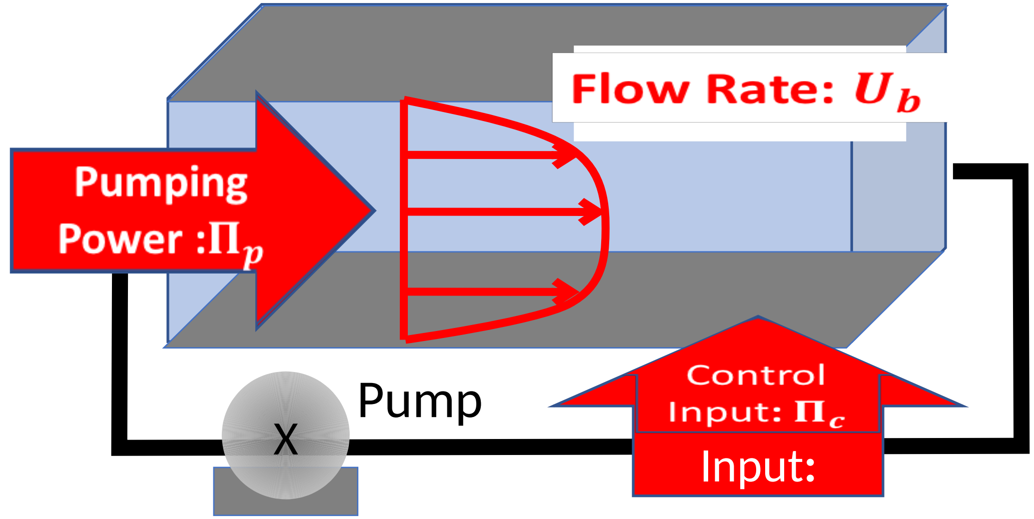
- Max. Achievable Flow Rate

$$U_\Pi^* = \sqrt{\frac{\Pi_t^* \delta^*}{3\mu^*}}$$

- Power-based Reynolds Number

$$Re_\Pi = \frac{U_\Pi^* \delta^*}{\nu^*}$$

Example



- $Re_\Pi = 6500$
  - $Re_\tau \cong 200$ (CPG)
  - $Re_\tau \cong 3176$ (CFR)
- Control Schemes
  - Opposition Control (Choi et al. JFM 1998)
  - Spanwise Wall Oscillation (Jung et al. PoF 1992)

	$U_b = U_b^*/U_\Pi^*$	$\gamma = \Pi_c^*/\Pi_t^*$	$U_b/U_{b,0}$
Reference (NC)	0.4887	0	1.0

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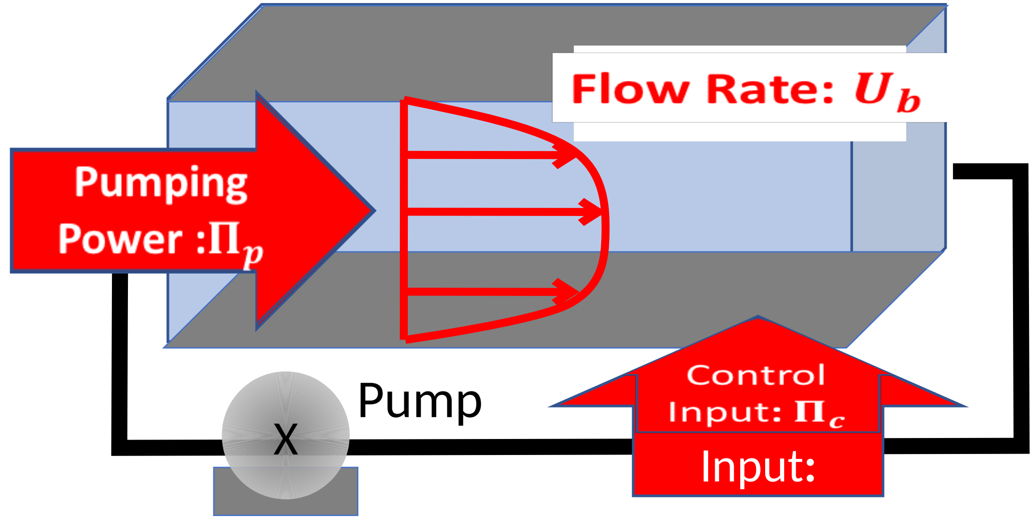

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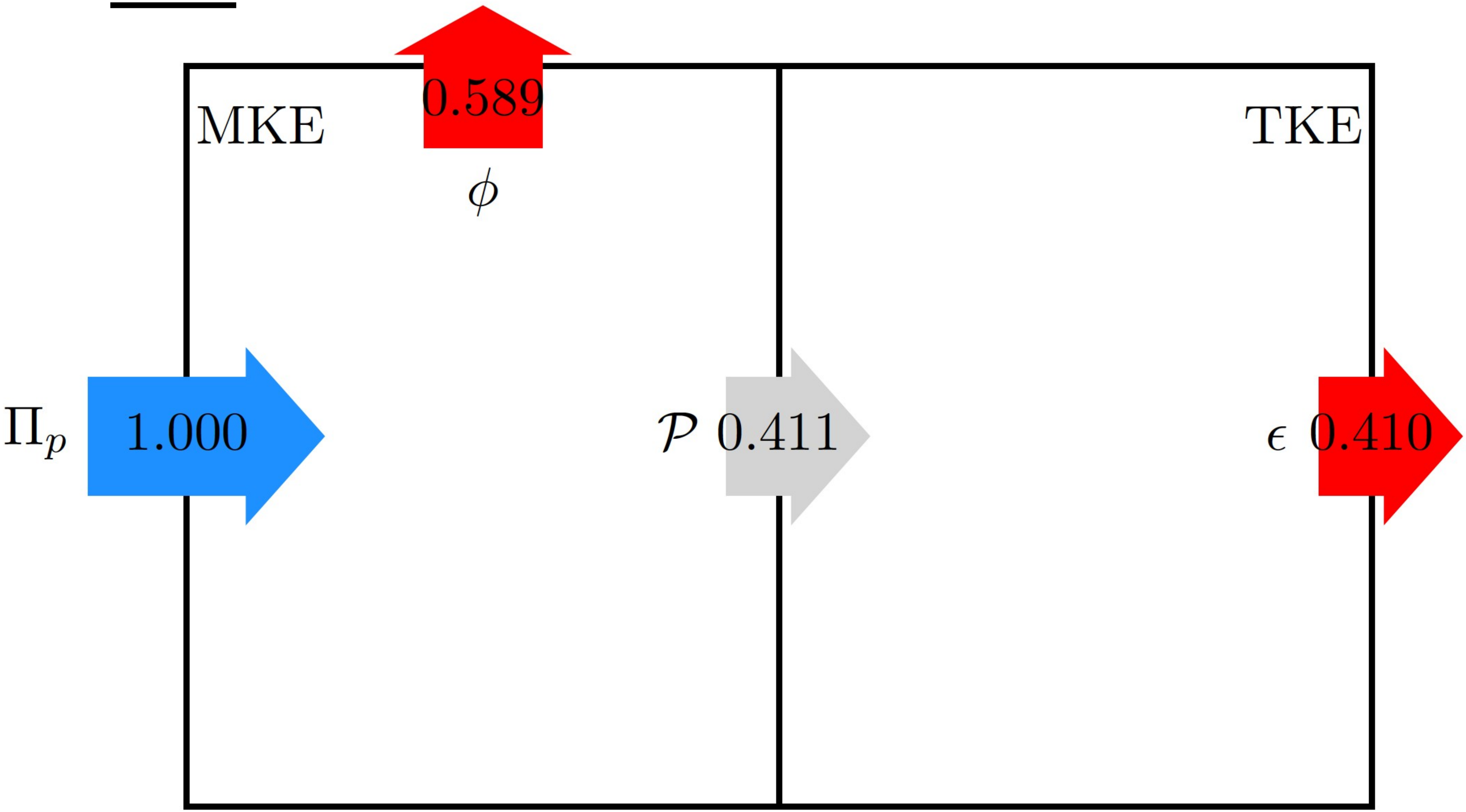
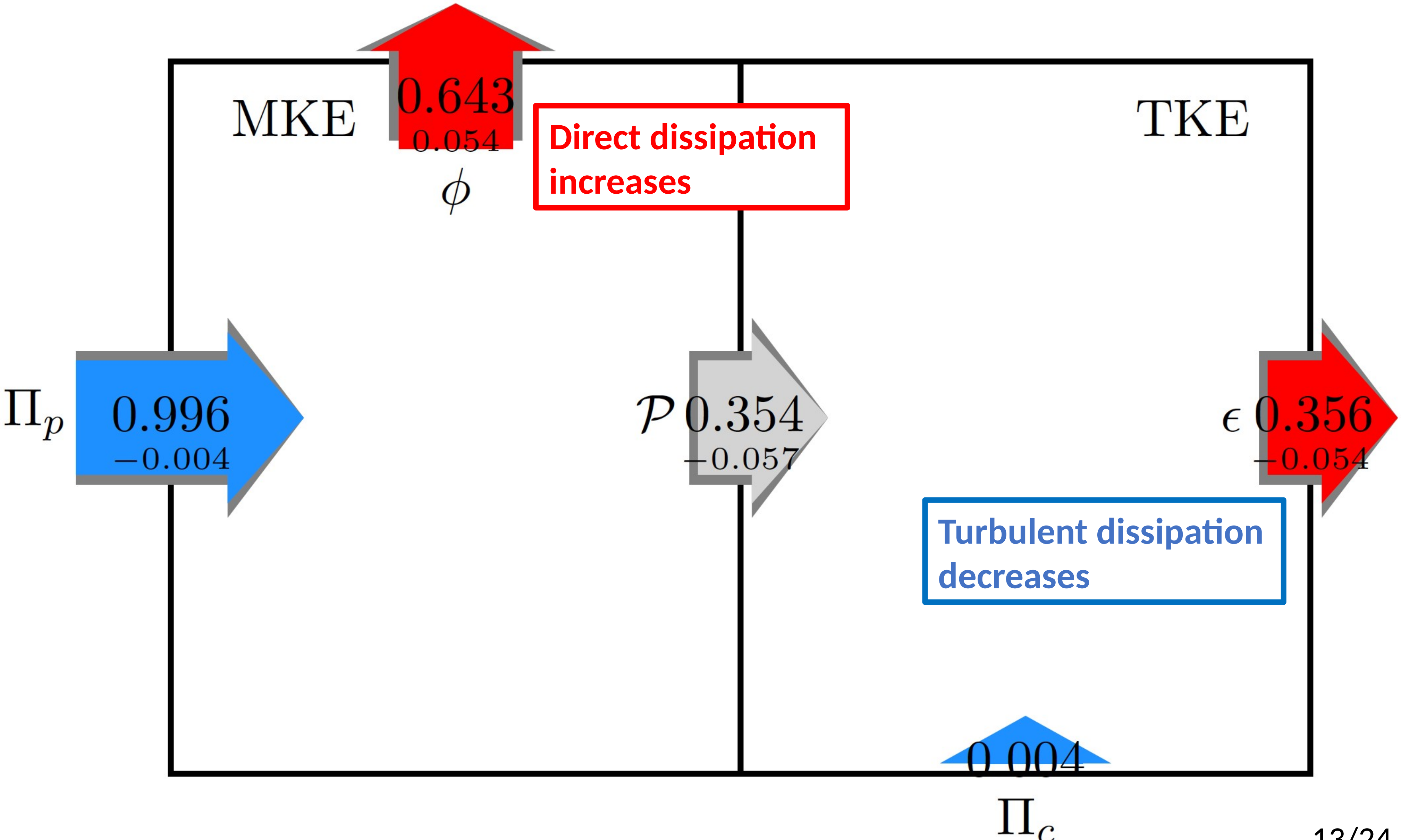
	$U_b = U_b^*/U_\Pi^*$	$\gamma = \Pi_c^*/\Pi_t^*$	$U_b/U_{b,0}$
Reference (NC)	0.4887	0	1.0
Wall Oscillation	0.5026	0.0978	1.028
Opposition Control	0.5345	0.0035	1.094

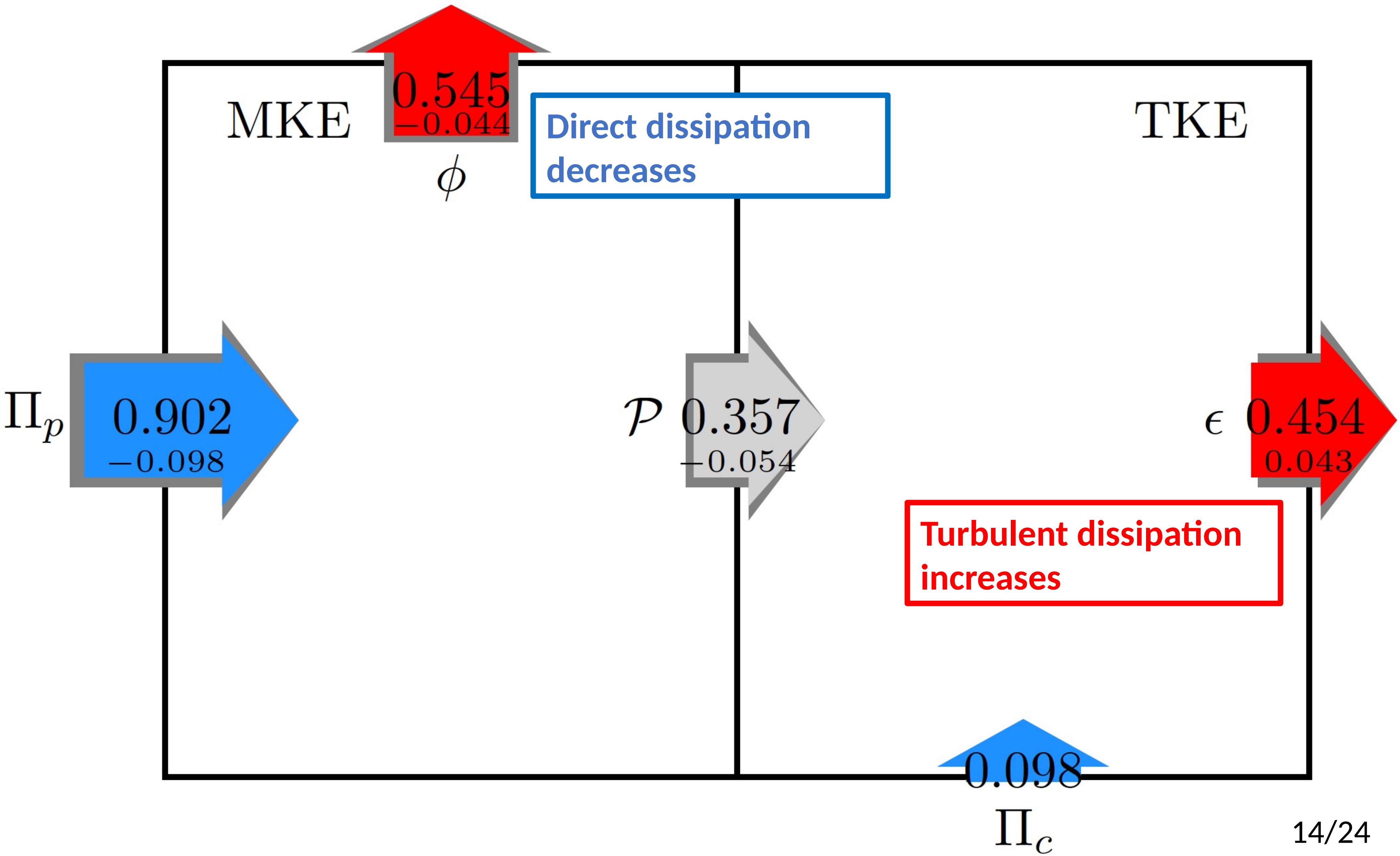
Energy Box of Uncontrolled Flow



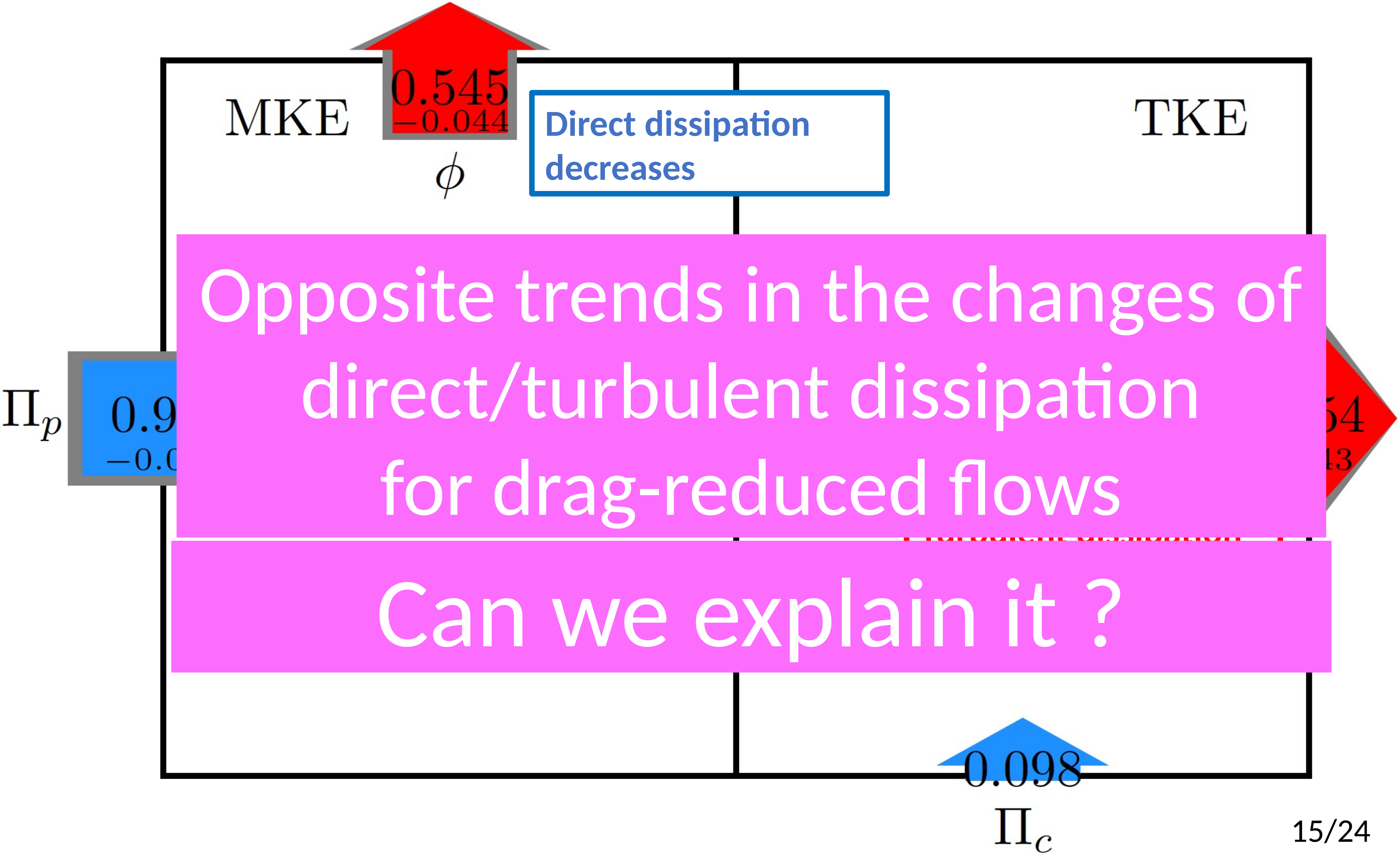
Energy Box under Opposition Control



Energy Box under Wall Oscillation Control



Energy Box under Wall Oscillation Control



Opposite trends in the changes of direct/turbulent dissipation for drag-reduced flows

Can we explain it ?

Flow Rate Under CPI

- FIK Identity (Fukagata et al. PoF 2002)

$$U_b = \frac{\alpha Re_\Pi}{2}\left(-1+\sqrt{1+\frac{4(1-\gamma)}{(\alpha Re_\Pi)^2}}\right)$$

(Hasegawa et al. JFM 2014)

The flow rate is determined by α and γ only.

- Fraction of Control Power Input

$$\gamma = \Pi_c^* / \Pi_t^*$$

- Weighted Reynolds Shear Stress

$$\alpha = \int_0^1 (1-y)\left(-\overline{u'v'}\right) dy$$

Two Limiting Cases

$$\begin{cases}\alpha \to 0 \\ \gamma \to 0\end{cases} \quad U_b \to 1$$

$$\alpha \to \infty \quad U_b \to 0$$

Energy Flux Under CPI

- Triple Decomposition

$$\boldsymbol{u} = U + \boldsymbol{u}'$$

Energy Flux Under CPI

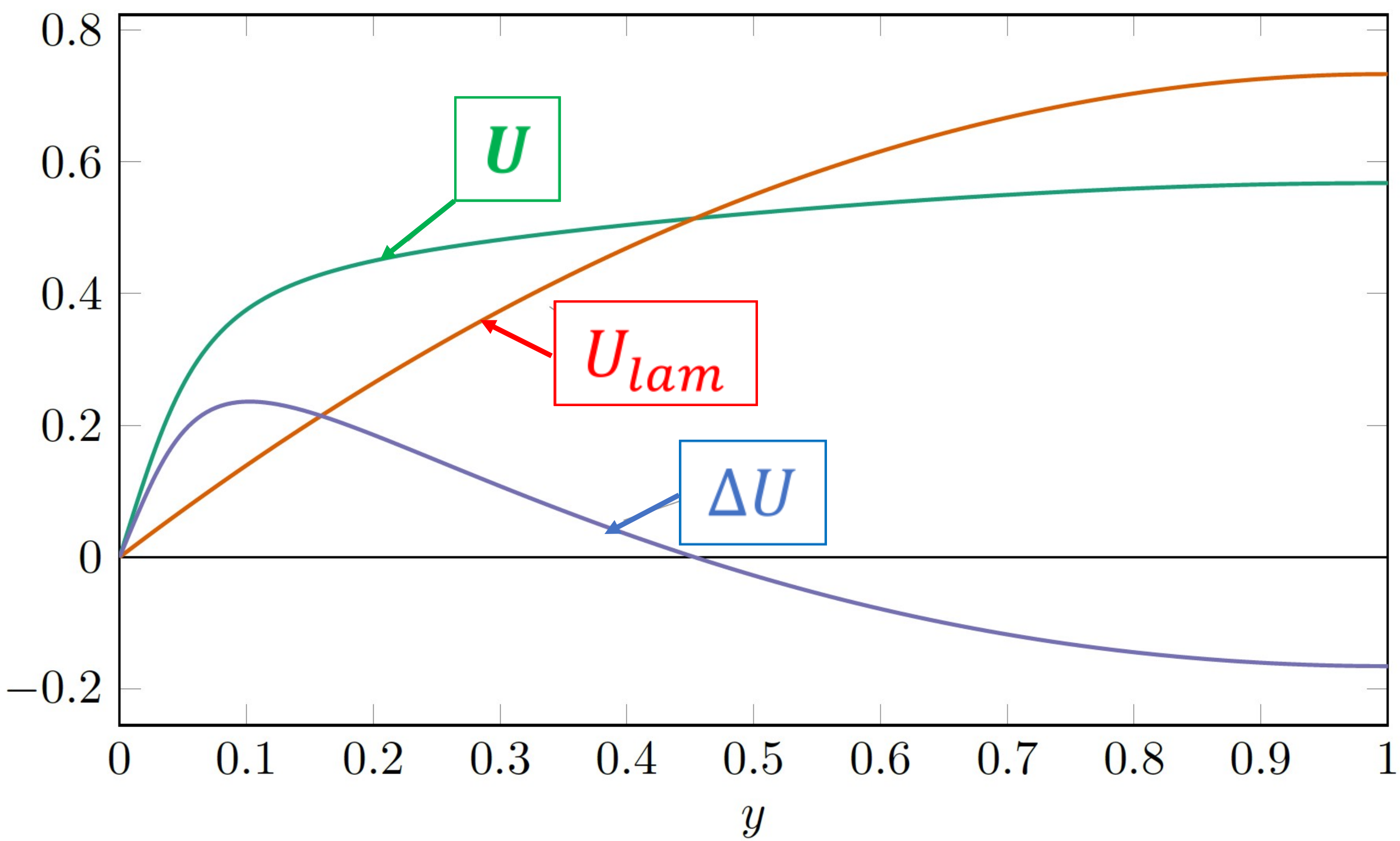
U_{lam} : parabolic profile with the same flow rate
ΔU : deviation from parabola

: parabolic profile with the same flow rate
: deviation from parabola

- Triple Decomposition

$$u = U + u' = U_{lam} + \Delta U + u'$$

(Echhardt et al., JFM 2007)



Energy Flux Under CPI

- Production

$$P \equiv P_{lam} + P_{\Delta} = \int_0^1 -\overline{u'v'}\frac{dU_{lam}}{dy}dy + \int_0^1 -\overline{u'v'}\frac{d\Delta U}{dy}dy$$

- Direct Dissipation

$$\phi \equiv \frac{1}{Re_\Pi}\int_0^1 \left(\frac{dU}{dy}\right)^2 dy = \frac{1}{Re_\Pi}\int_0^1 \left\{\frac{d}{dy}\left(U_{lam}+\Delta U\right)\right\}^2 dy$$

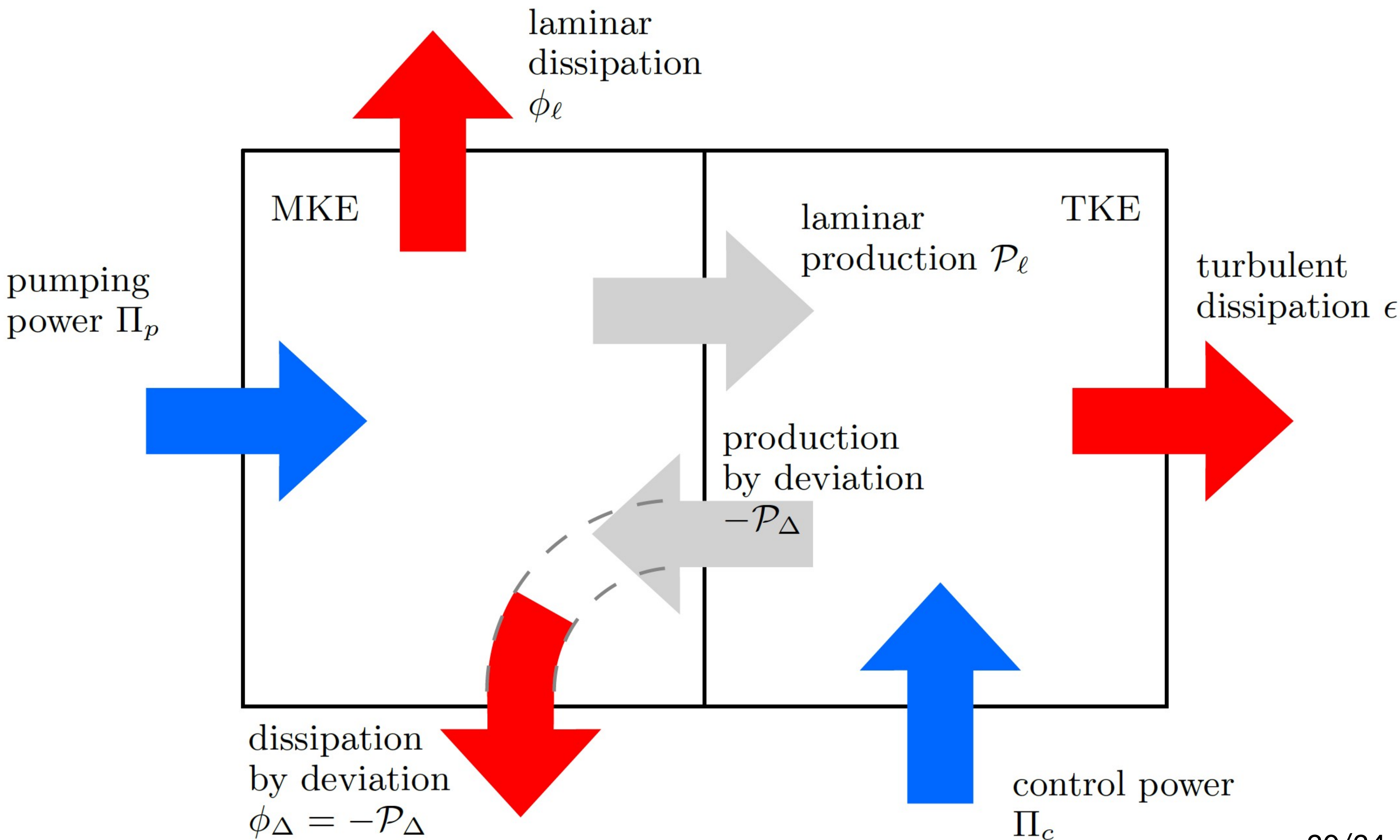
$$= \frac{1}{Re_\Pi}\int_0^1 \left\{\left(\frac{dU_{lam}}{dy}\right)^2 + \left(\frac{d\Delta U}{dy}\right)^2 + \left(\frac{dU_{lam}}{dy}\right)\left(\frac{d\Delta U}{dy}\right)\right\}dy$$

$$= \phi_{lam} + \phi_{\Delta}$$

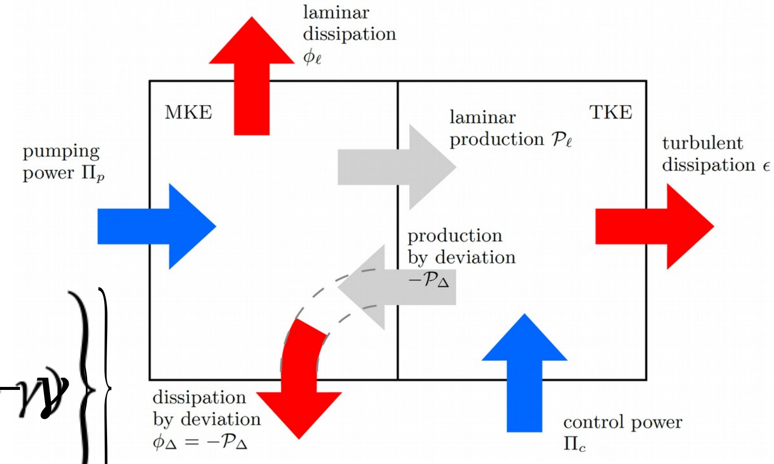
Only true in the present triple decomposition

In addition, it can be shown that $\phi_\Delta = -P_\Delta > 0$

Modified Energy Box



Modified Energy Box



- Direct Dissipation ($\phi = \phi_{lam} + \phi_\Delta$)

$$\phi_{lam} = \frac{3}{Re_\Pi}\left\{\left(\frac{\alpha Re_\Pi}{2}\right)^2\left(1 - \sqrt{1 + \frac{4(1-\gamma)}{\alpha Re_\Pi^2}}\right)^2 + (1-\gamma)\right\}$$

$$\phi_\Delta = Re_\Pi\left(\beta - 3\alpha^2\right)$$

- Turbulent Dissipation

$$\varepsilon = \frac{3}{Re_\Pi}\left\{\left(\frac{\alpha Re_\Pi}{2}\right)^2\left(1 + \sqrt{1 + \frac{4(1-\gamma)}{\alpha Re_\Pi^2}}\right)^2 - \frac{\beta Re_\Pi^2}{3} + \gamma\right\}$$

The following two quantities dictates all the fluxes in Energy Box !!!

$$\alpha \equiv \int_0^1 (1-y)\left(-\overline{u'v'}\right) dy \qquad \beta \equiv \int_0^1 \left(-\overline{u'v'}\right)^2 dy$$

Conclusions

- **Constant Power Input (CPI)** is beneficial to analyze global energy budgets of turbulent flows w/wo control
- There exists **no unique relationship** between the changes in direct/turbulent dissipation and DR effect
- DR effect under CPI is determined only by α : the integral of weighted RSS
- **Triple decomposition** of the velocity field reveals that global energy fluxes are expressed by two quantities: α and β.

$$\alpha = \int_0^1 (1-y)\left(-\overline{u'v'}\right)dy \qquad \beta = \int_0^1 \left(-\overline{u'v'}\right)^2 dy$$

- Total dissipation: $\phi + \varepsilon = \phi_{lam} + \phi_\Delta + \varepsilon$
- "**Wind" dissipation** $(\phi_\Delta + \varepsilon)$ can be considered to be a loss from energetic viewpoint.
  - ➢ A target quantity to be minimized

Thank you for your kind attention

Questions ?