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# Turbulent dissipation in drag reduced flows

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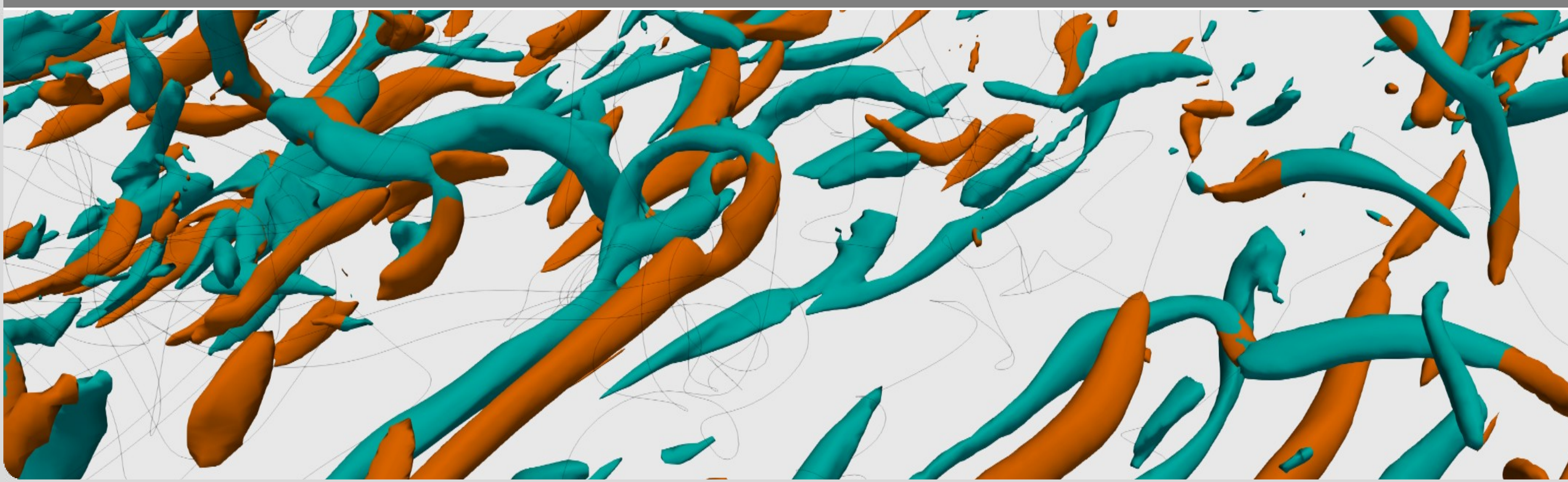


# The question

In order to achieve energy savings with drag reducing flow control,

do you need to

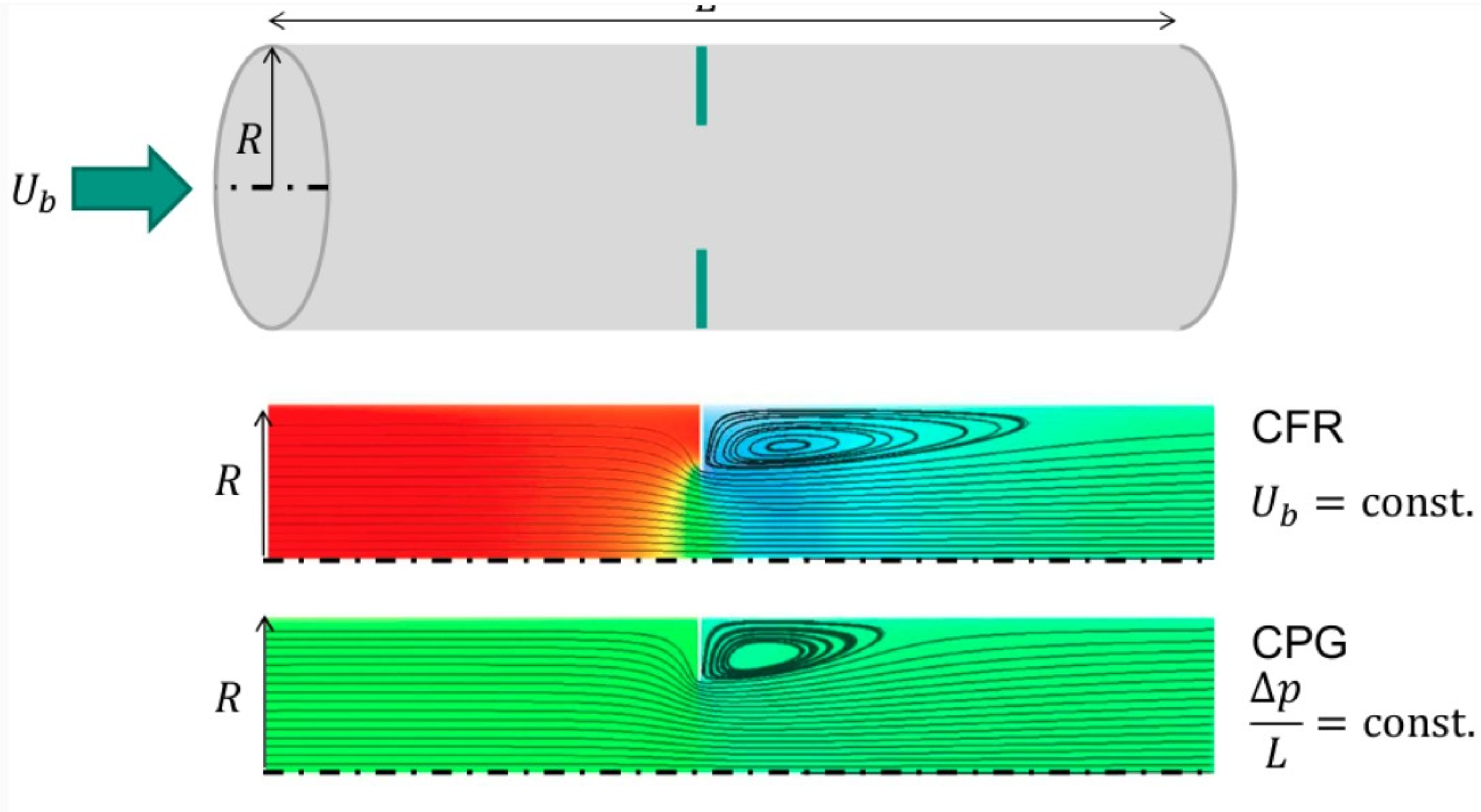
**increase or decrease turbulent dissipation**

compared to the uncontrolled reference flow?

# but before…

What is a suitable definition of a reference flow?

# The art of comparison



# Energy Dissipation

total energy dissipation = direct dissipation + turbulent dissipation

$$\Phi_{tot} = \Phi + \epsilon$$

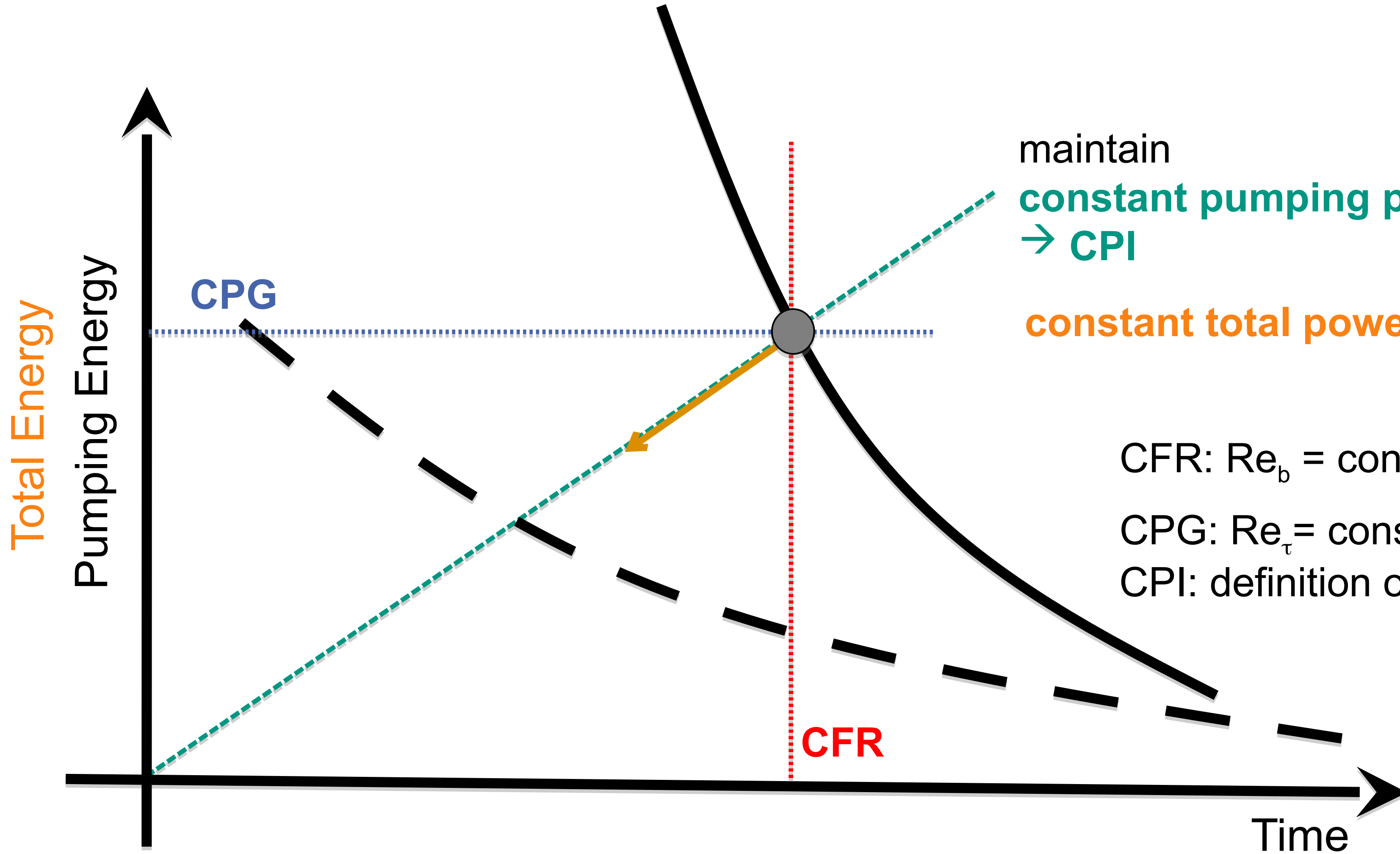
total energy dissipation rate = pumping power input

$$\Phi_{tot} = P = \dot{V}\,\Delta p$$

DR in CFR ✉ power input ↓ ✉ energy dissipation ↓

DR in CPG ✉ power input ↑ ✉ energy dissipation ↑

# Energy vs. Time ✉ Constant Power Input




maintain
**constant pumping power**
→ **CPI**

**constant total power**

CFR: $Re_b$ = const

CPG: $Re_\tau$ = const

CPI: definition of Re?

Frohnapfel, Quadrio, Hasegawa, JFM 2012

# Velocity Scale based on Power Input

Stokes flow yields minimum energy dissipation and therefore requires minimum power input Bewley (JFM, 2009), Fukagata et al. (Physica D, 2009)

→ power based velocity scale for CPI
(laminar bulk velocity in channel flow)

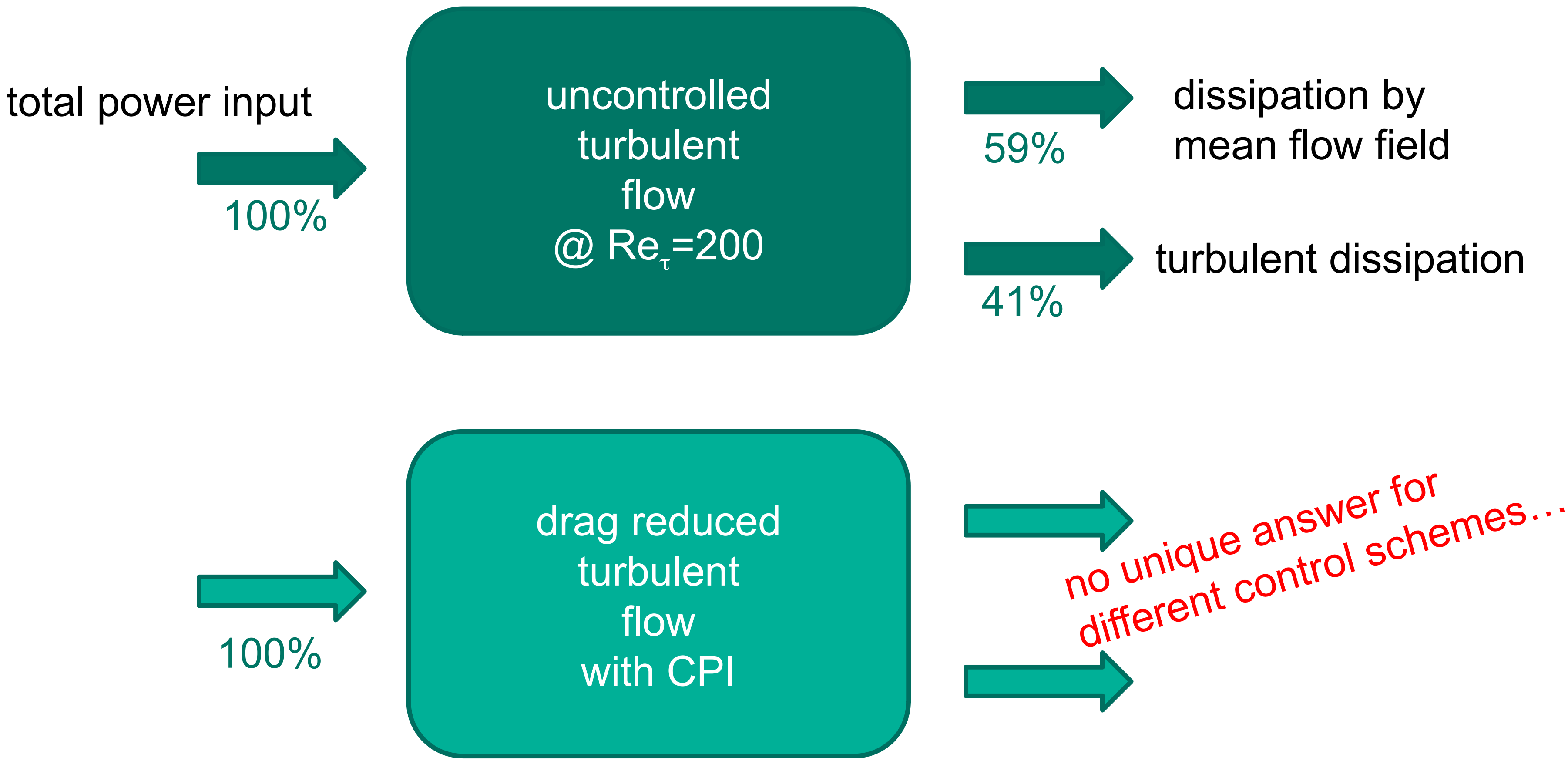
$$U_\pi = \sqrt{\frac{P_t \delta}{3\mu}} \qquad \mathrm{Re}_\pi = \frac{U_\pi \delta}{\nu}$$

Working at $Re_\pi$ = *const* implies
keeping the input power
and thus total dissipation constant.

in general: $U_b / U_\pi \leq 1$
successful control under CPI: $U_b / U_{b,0} > 1$

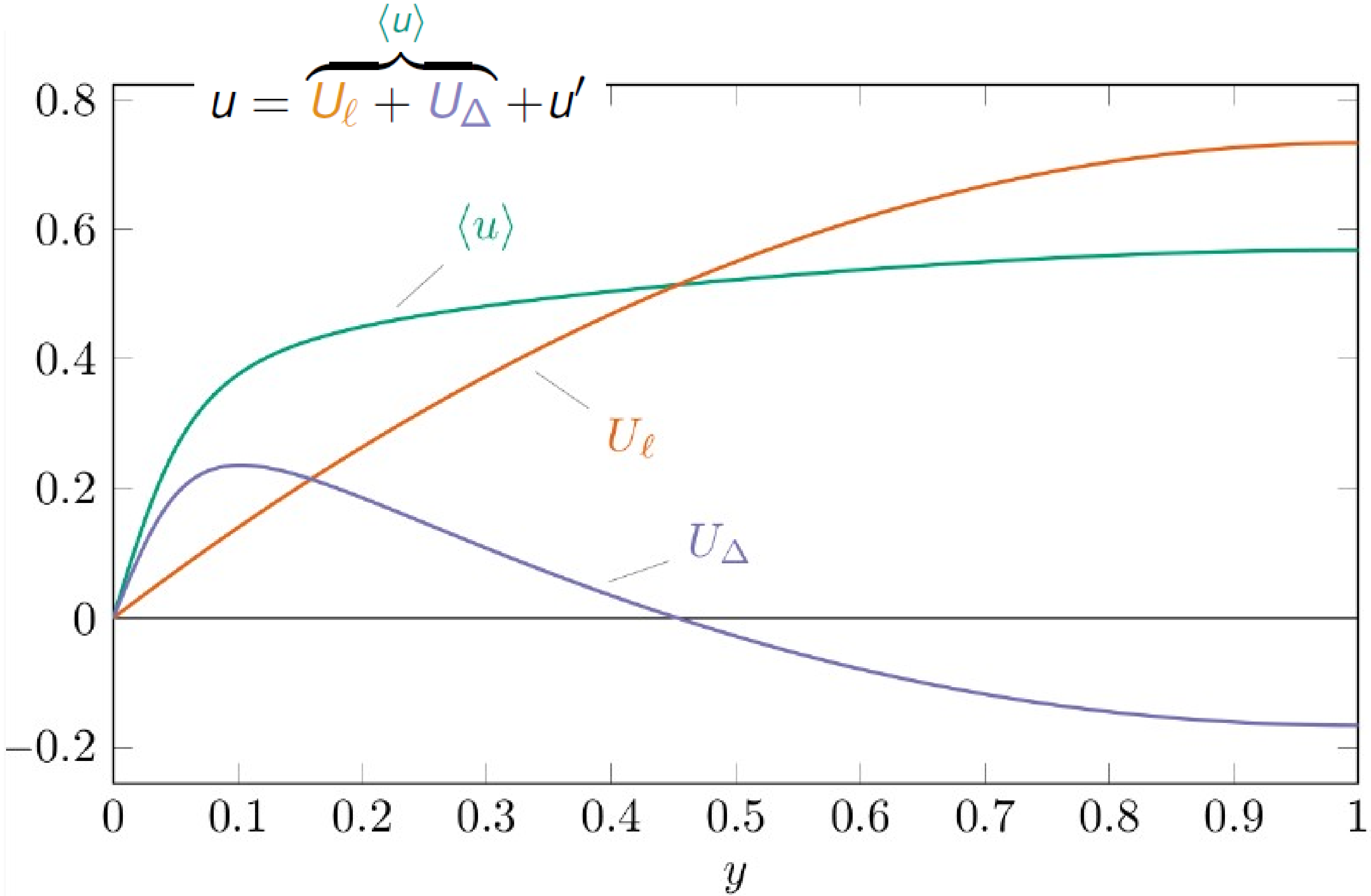
Hasegawa, Frohnapfel, Quadrio, JFM 2014

# Energy Dissipation under CPI



# “Wind Decomposition”

A triple decomposition with analytical advantages   Eckhardt et al., JFM 2007



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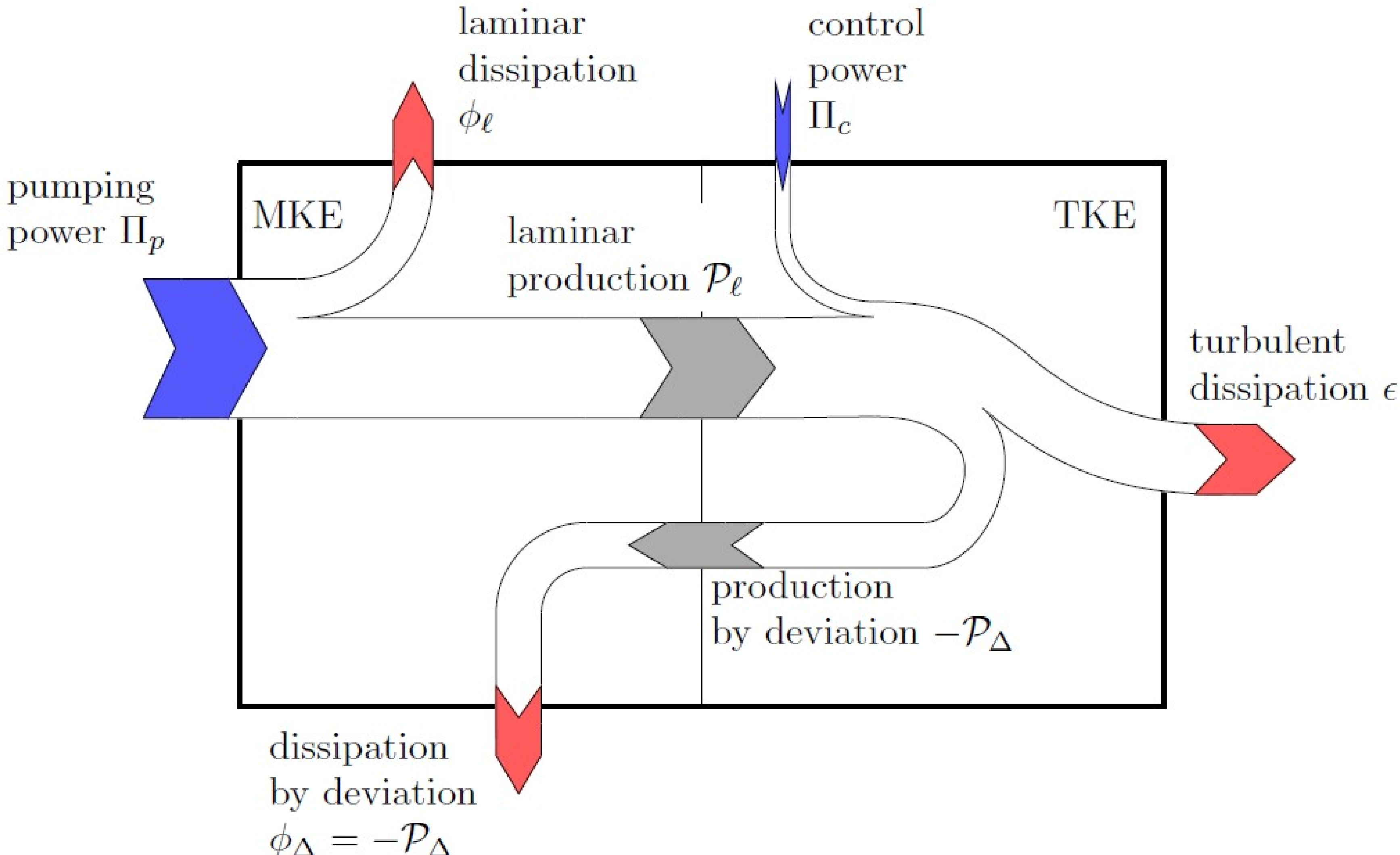
# Energy Box



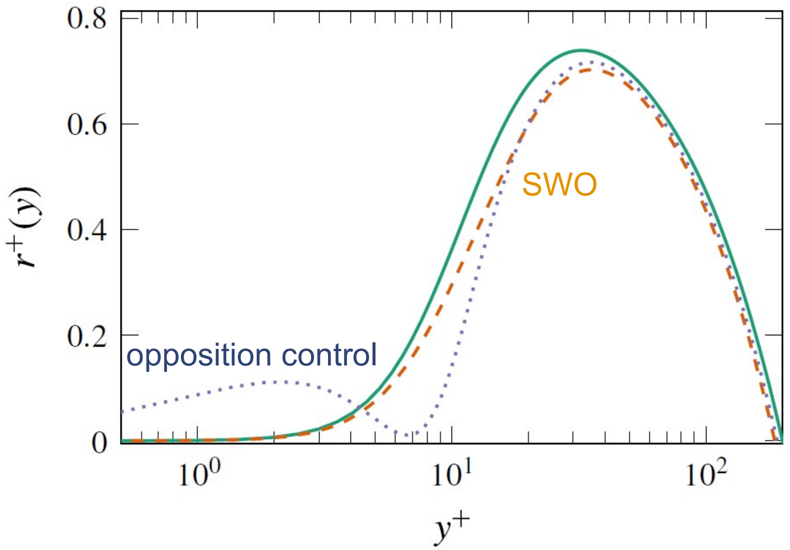

Gatti et al., JFM 2018

# Two integrals of the Reynolds shear stress

via FIK-like derivations at CPI, it is found that $\alpha$ and $\beta$ parametrize all the fluxes

$$\alpha = \int_0^1 (1-y)\, r(y) dy$$

$$\beta = \int_0^2 r(y)^2 dy \geq 3\alpha^2$$

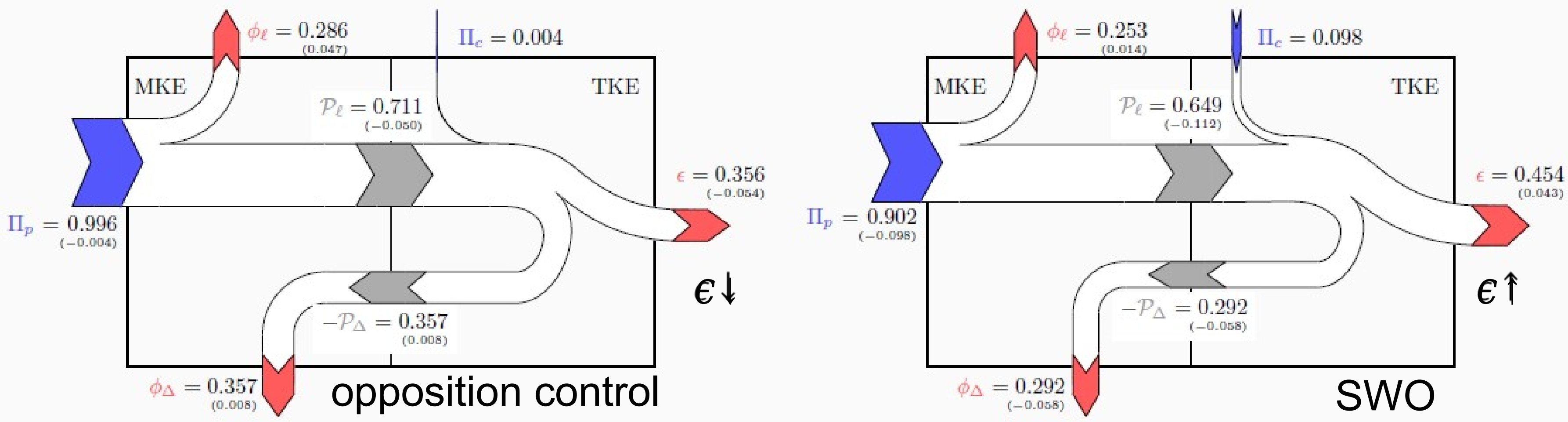



e.g. for turbulent dissipation:

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

$\gamma$ – power ratio applied for control, passive/no control $\gamma$=0

# Lessons Learned




1. $\phi_\ell$ is the best way to dissipate pumping power
2. $P_\ell$ is the fraction of the pumping power wasted to produce turbulence. It decreases when control is successful. It can become negative as $P_\ell \propto \alpha$
3. $\phi_\Delta \geq 0$ is the penalty for not being laminar.
4. $\phi_\Delta + \epsilon$ is the fraction of the total power wasted by turbulence

Gatti et al., JFM 2018

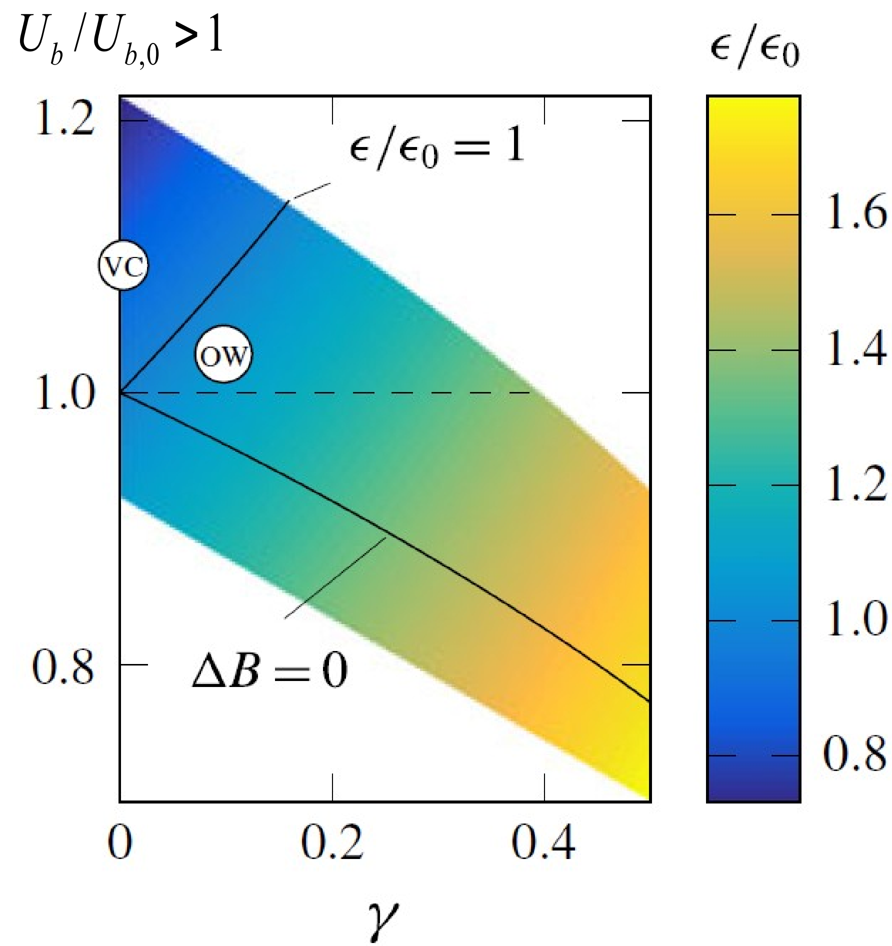
# How does turbulent dissipation change with successful control?



a simple model system provides generality to conclusions:
drag reduction parametrized through $\Delta B$ (shift in log region of mean profile)

**passive control:**
turbulent dissipation is decreased

**active control:**
can yield flow rate increase with increased turbulent dissipation




turbulent dissipation is not a suitable objective for active flow control

# Conclusions

- combination of CPI + „wind decomposition" provides theoretical framework for energy consideration in controlled flows

- all energy fluxes can be parametrized by two integrals of the Reynolds shear stress

$$\alpha = \int_0^1 (1-y)\, r(y)\, dy$$

$$\beta = \int_0^2 r(y)^2 dy \geq 3\alpha^2$$

- energy saving flow control needs to minimize: $\Phi_\Delta + \varepsilon$

fraction of total power wasted by turbulence

# European Drag Reduction and Flow Control Meeting

26–29 March 2019

Bad Herrenalb (near Karlsruhe), Germany
www.edrfcm.science