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Turbulent dissipation in drag reduced flows

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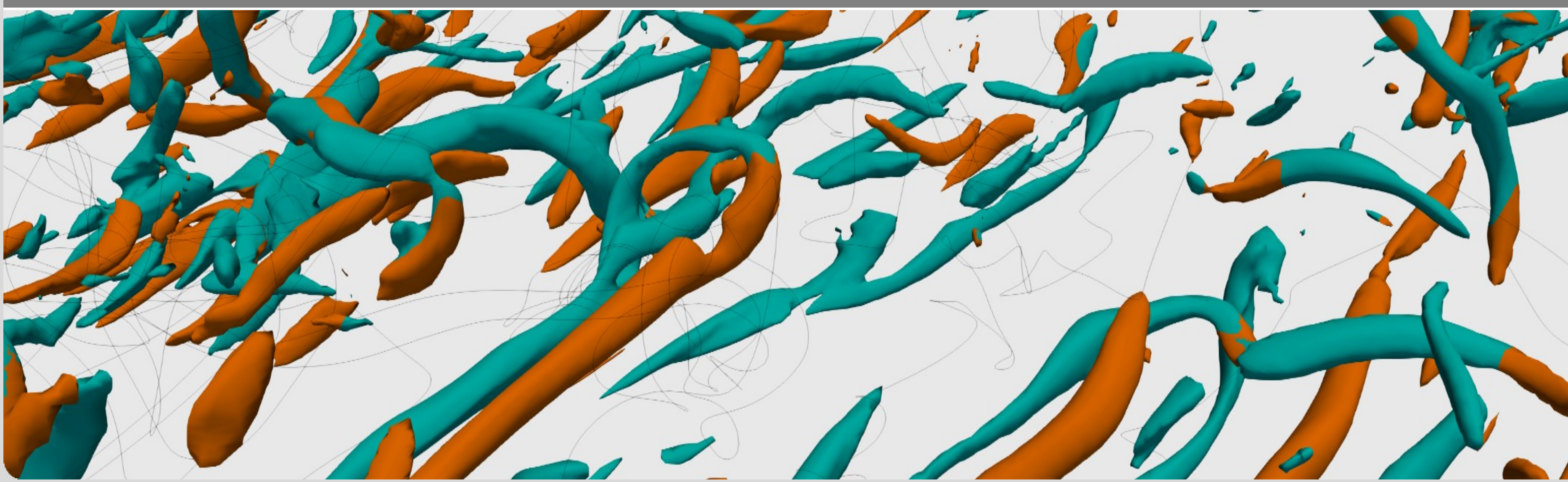


The question

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

do you need to

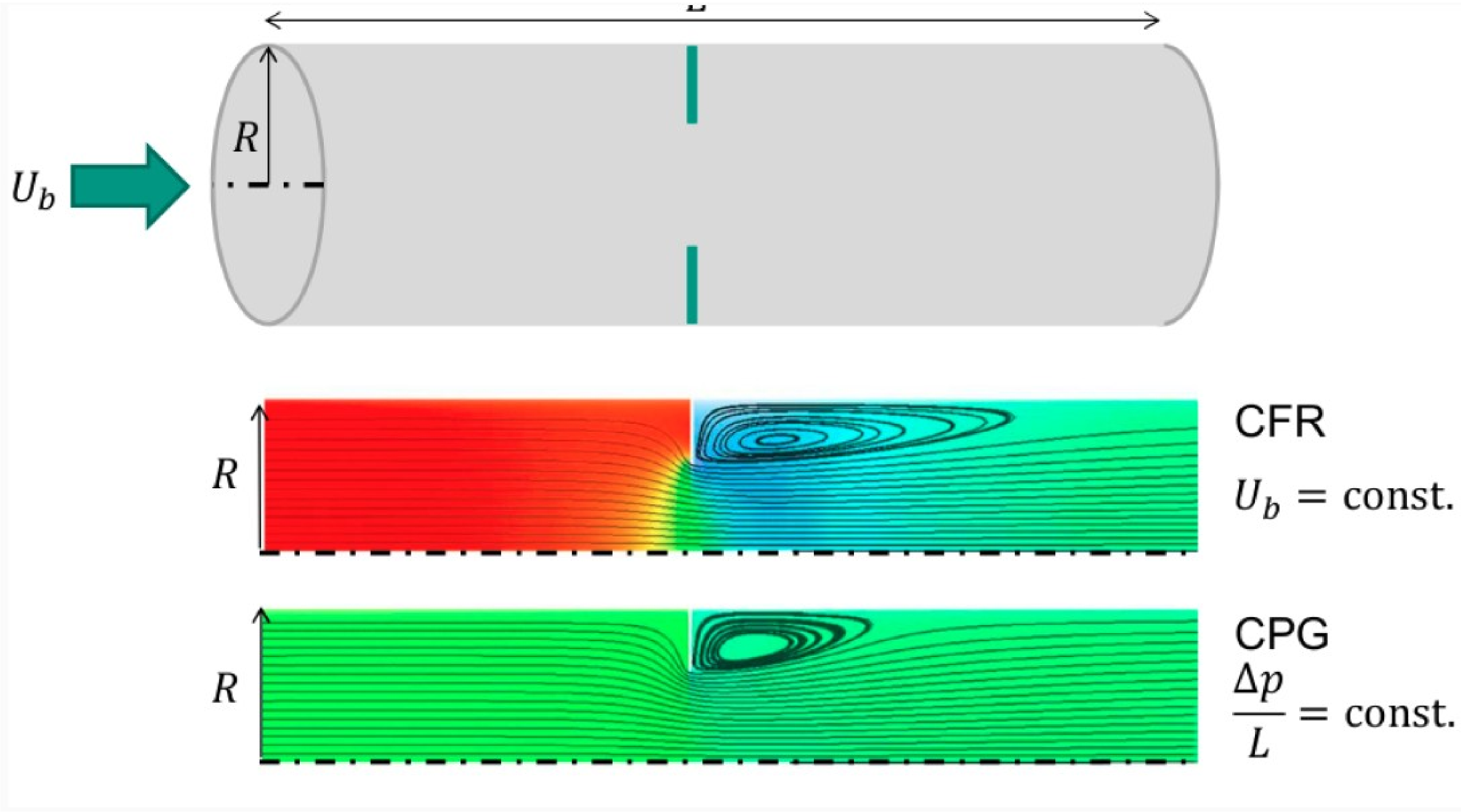
increase or decrease turbulent dissipation

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

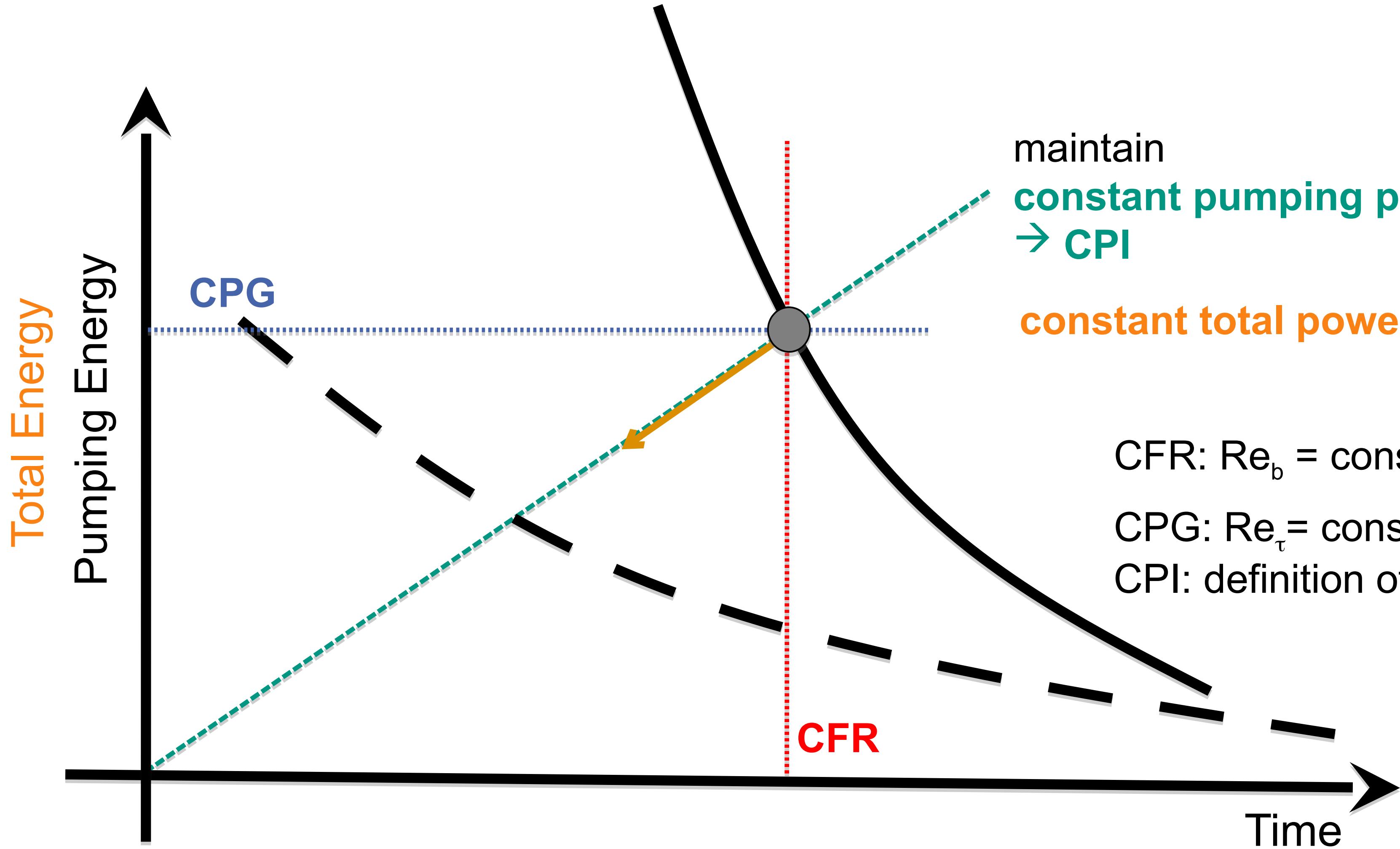
$$\Phi_{tot} = \Phi + \epsilon$$

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



CFR: Re_b = const

CPG: Re_τ = 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)

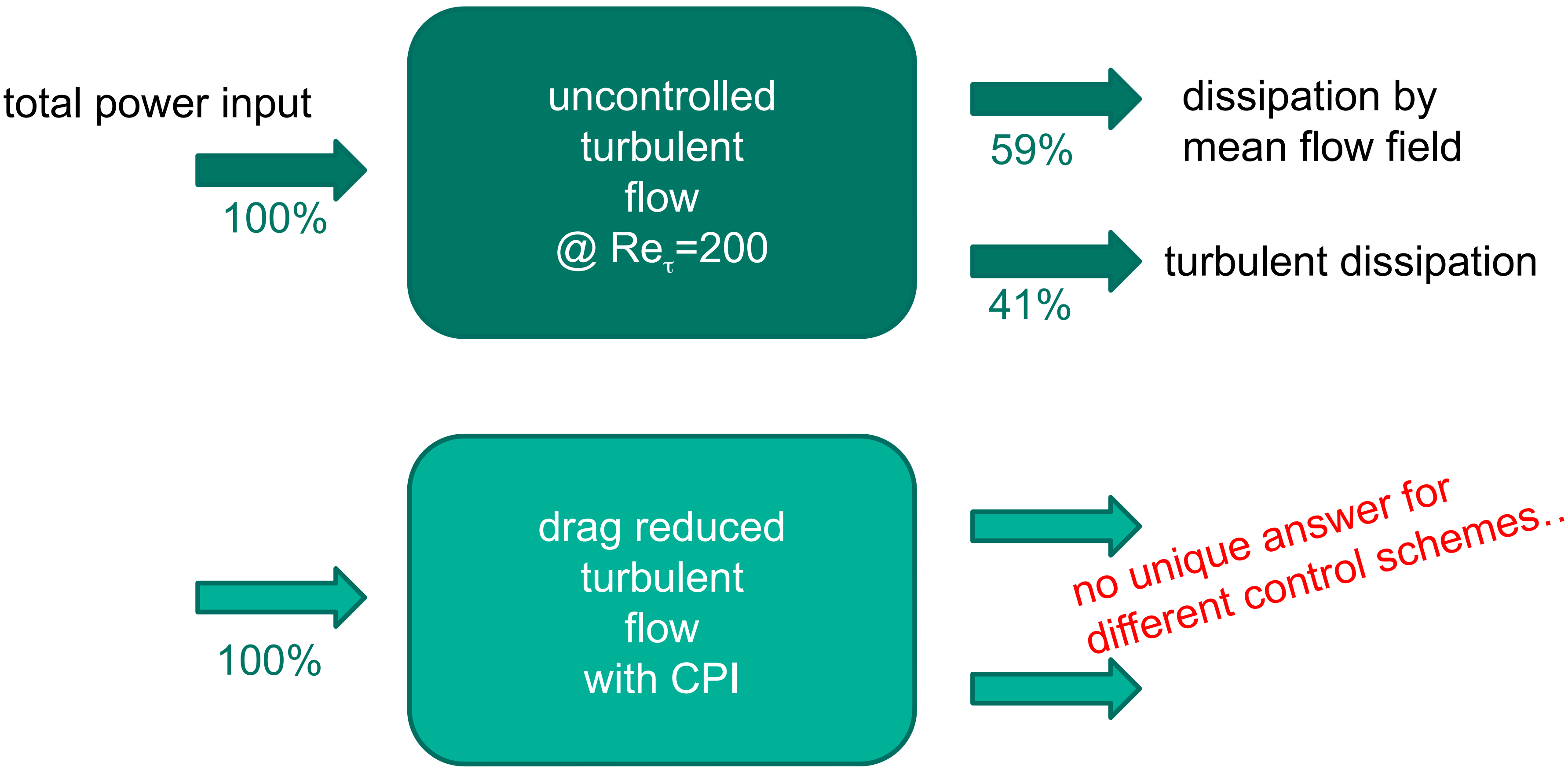
$$U_\pi = \sqrt{\frac{P_t \delta}{3\mu}} \qquad \mathrm{Re}_\pi = \frac{U_\pi \delta}{\nu}$$

Working at Re_π = *const* implies
keeping the input power
and thus total dissipation constant.

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

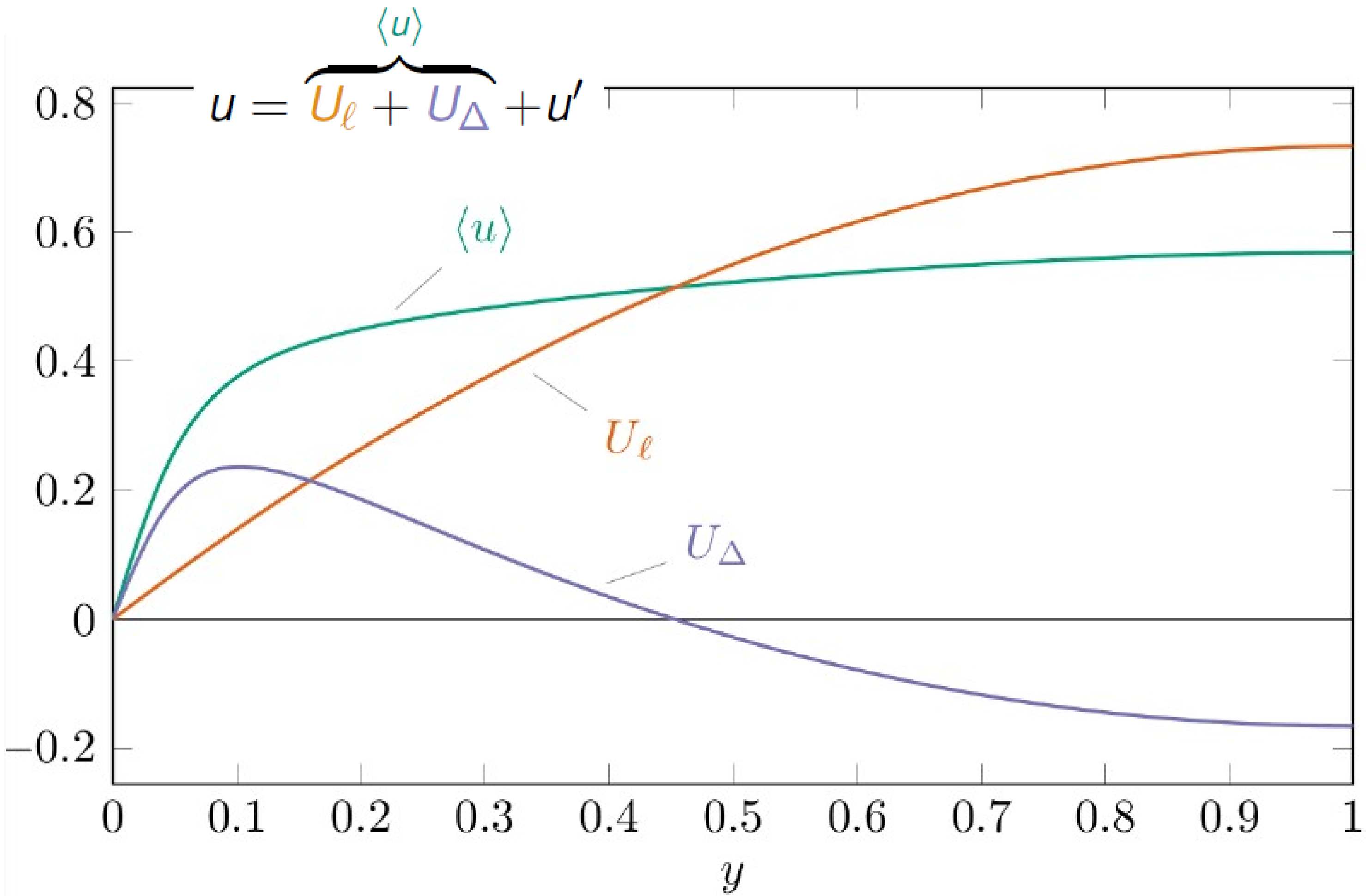
Hasegawa, Frohnapfel, Quadrio, JFM 2014

Energy Dissipation under CPI

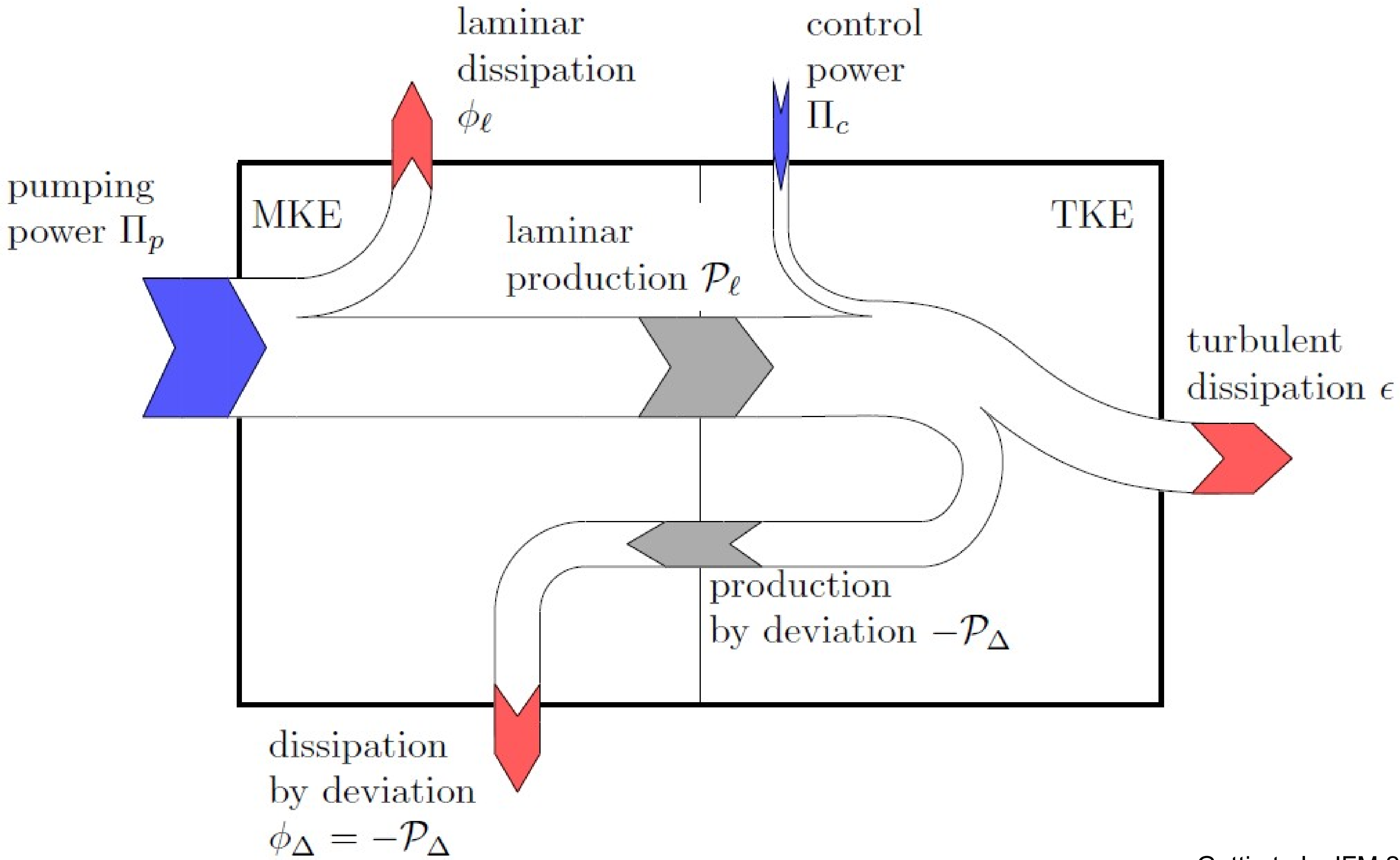


“Wind Decomposition”

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



Energy Box



Gatti et al., JFM 2018

Two integrals of the Reynolds shear stress

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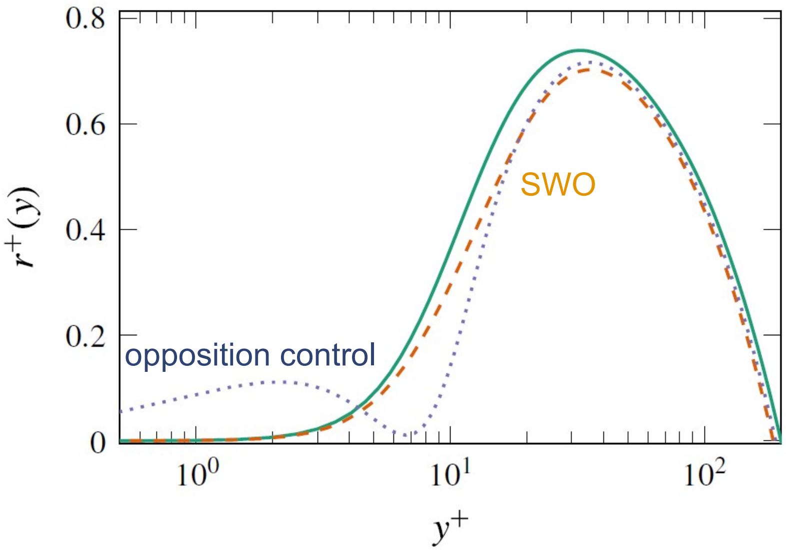
via FIK-like derivations at CPI, it is found that α and β parametrize all the fluxes

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

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

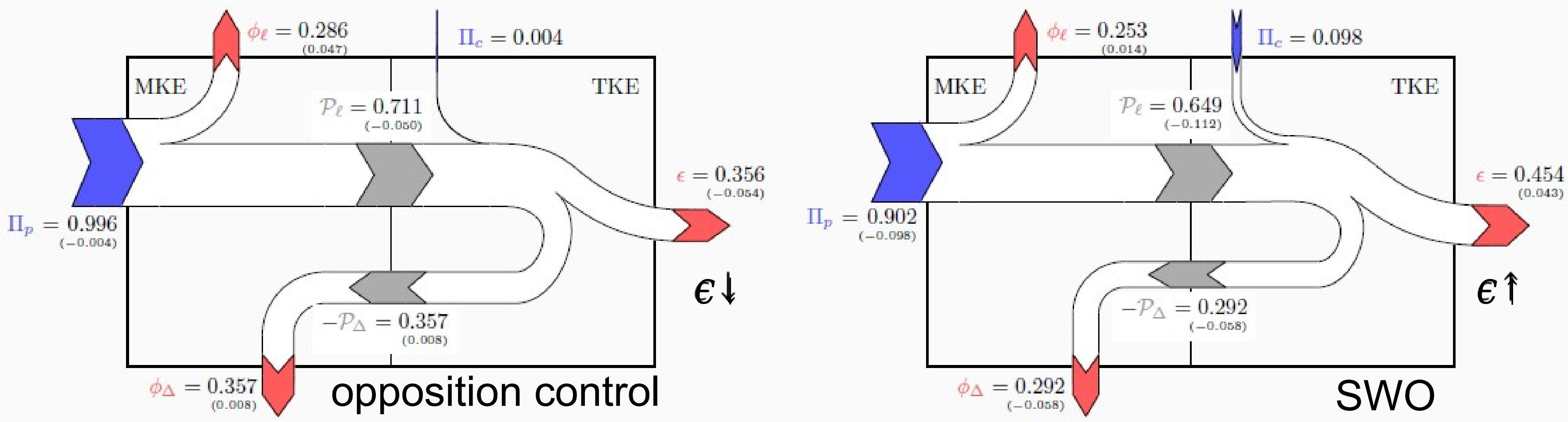


e.g. for turbulent dissipation:

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

γ – power ratio applied for control, passive/no control γ=0

Lessons Learned



1. ϕ_ℓ is the best way to dissipate pumping power
2. P_ℓ 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

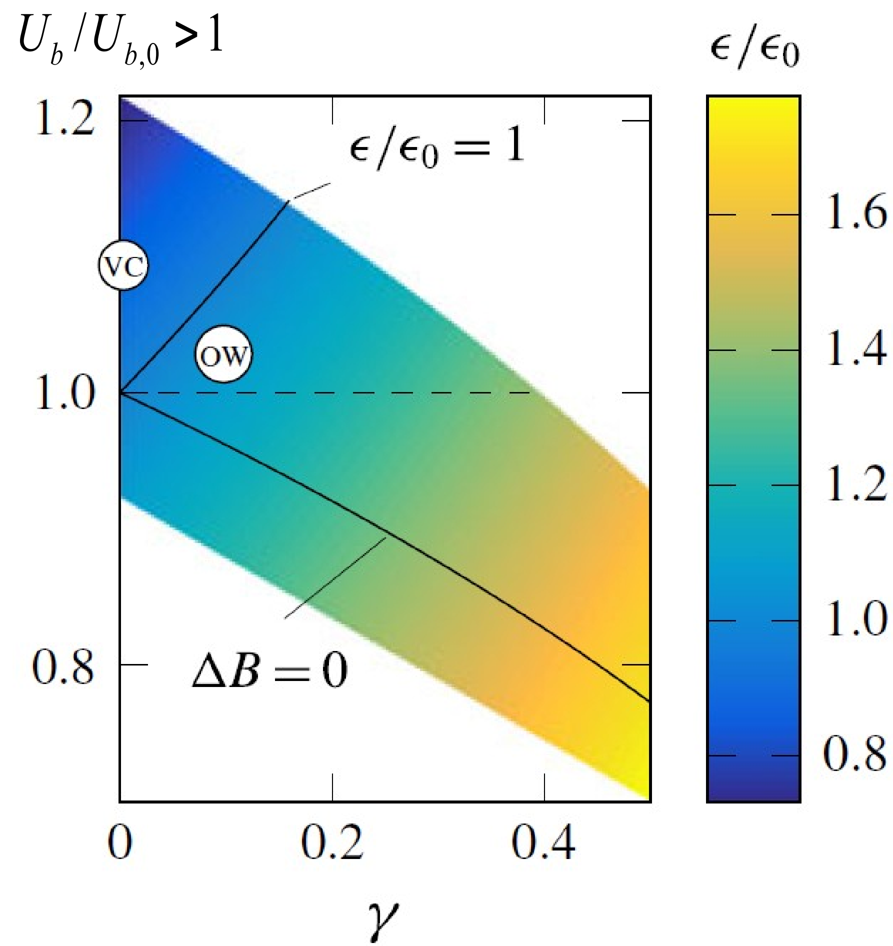
Gatti et al., JFM 2018

How does turbulent dissipation change with successful control?

a simple model system provides generality to conclusions:
drag reduction parametrized through ΔB (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