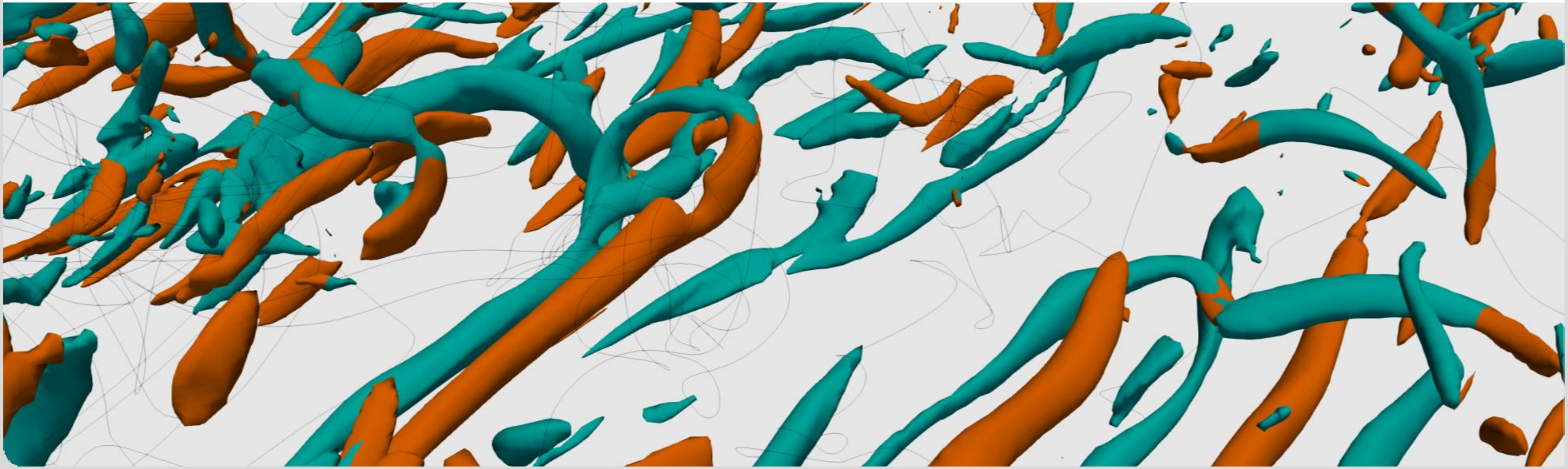
Integral energy budgets in turbulent channels with and without drag reduction

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

Institute of Fluid Mechanics

GAMM Meeting 2018, March 19—23, Munich, Germany



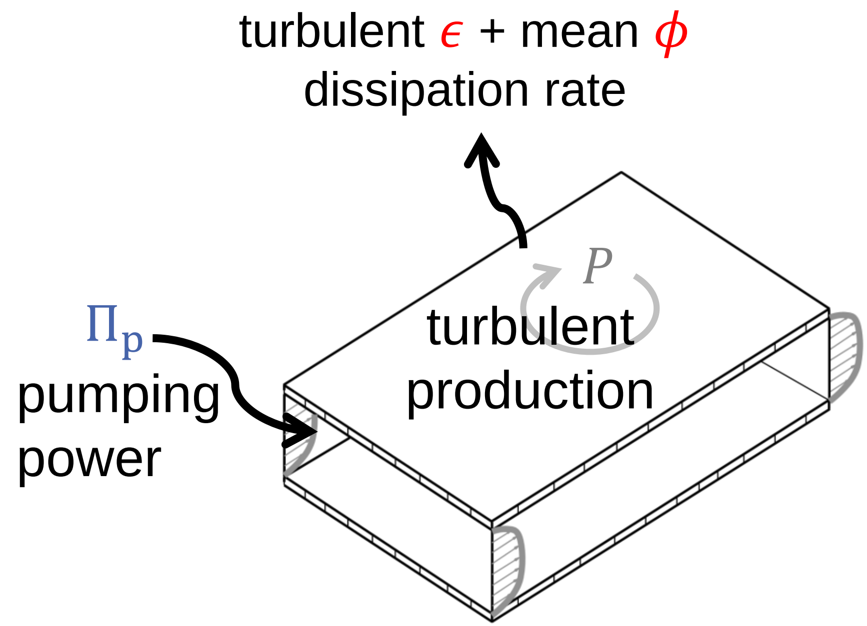
Today's goal

"how do dissipation and production
of turbulent kinetic energy relate
to turbulent friction drag?"

Today's goal

"how do dissipation and production of turbulent kinetic energy relate to turbulent friction drag?"

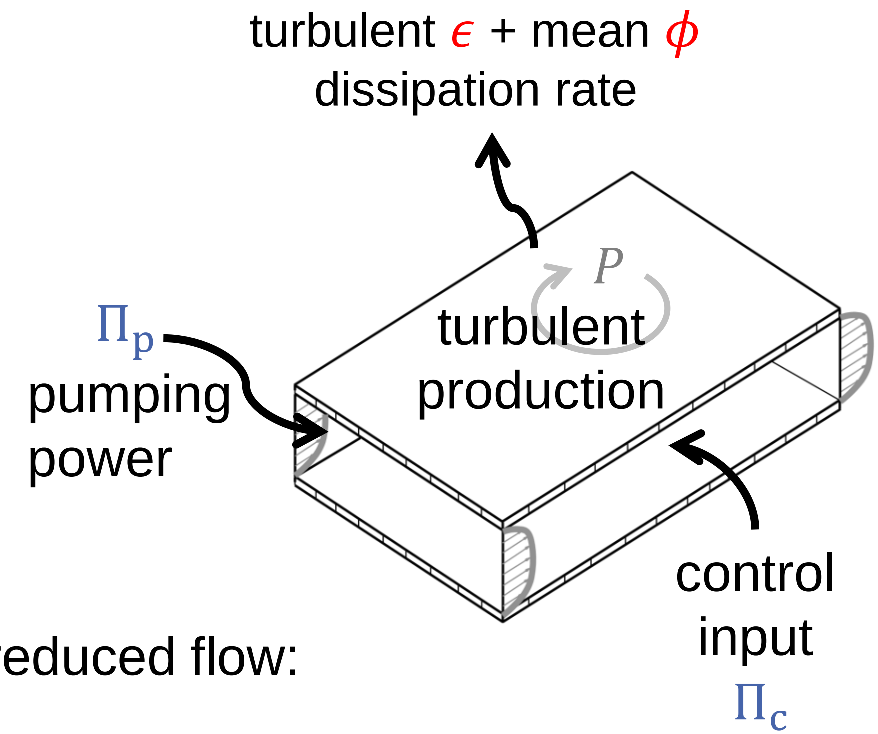
Reynolds decomposition
$$u = \langle u \rangle + u'$$



Today's goal

"how do dissipation and production of turbulent kinetic energy relate to turbulent friction drag in drag-reduced flows?"

Reynolds decomposition
$$u = \langle u \rangle + u'$$



Seemingly trivial, nontrivial problem!

Example turbulent dissipation in drag-reduced flow:

- Ricco *et al.*, JFM (2012): it increases
- Agostini, *et al.*, JFM14: it decreases

Constant Power Input (CPI)

Constant Power Input (CPI)

Definitions and characteristic quantities

- Total power Π_t is kept constant

$$\Pi_t = \Pi_p + \Pi_c$$

→ control power $\Pi_c = \gamma \Pi_t$

↓ pumping power $\Pi_p = (1-\gamma)\Pi_t$

- „Drag reduction“ increases flow rate $U_b / U_{b,0} > 1$

- A power-based velocity scale

$$U_\Pi = \sqrt{\frac{\Pi_t h}{3\mu}}$$

“The Stokes flow minimizes the power consumption for given flow rate”
Bewley (JFM, 2009), Fukagata et al. (Physica D, 2009)

- A power-based Reynolds number

$$Re_\Pi = \frac{U_\Pi h}{\nu}$$

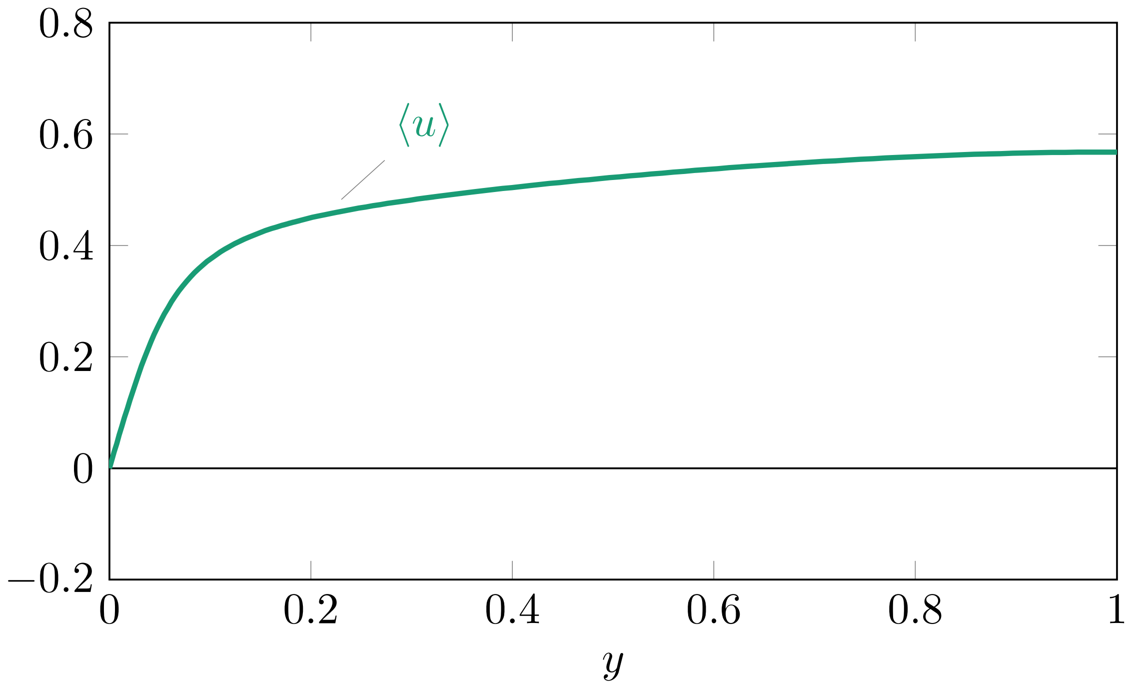
Hasegawa, Frohnapfel, Quadrio (JFM, 2009)

The wind of turbulence

The “wind decomposition” of turbulence

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

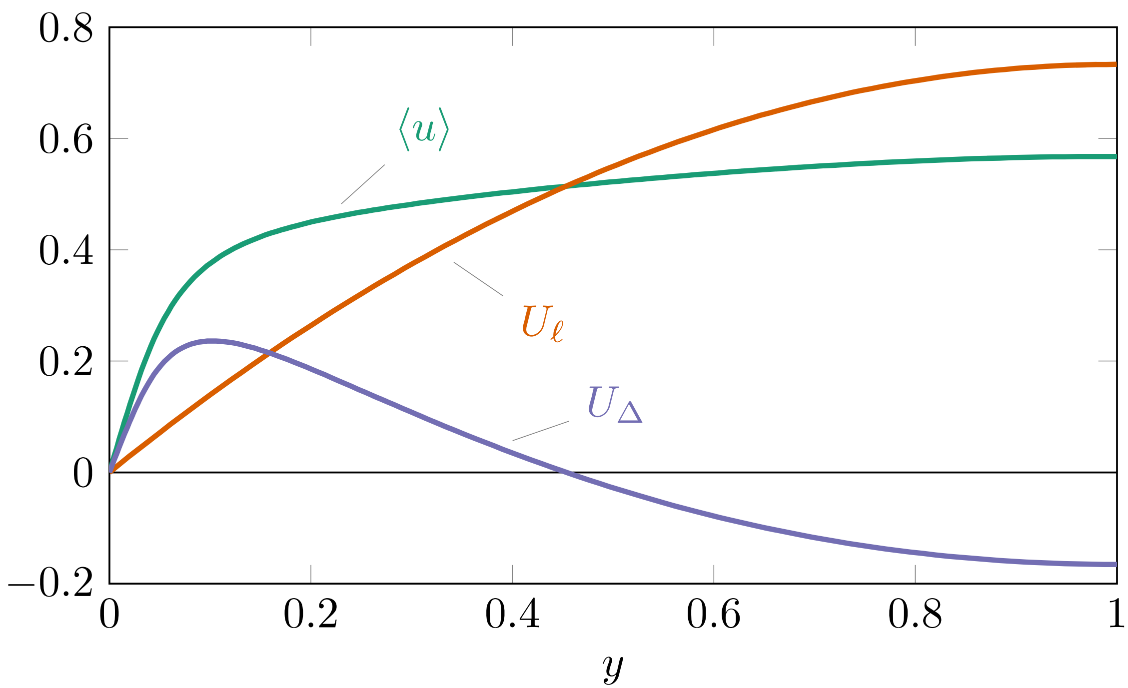
$$u = \langle u \rangle + u'$$



The "wind decomposition" of turbulence

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

$$u = \underbrace{U_\ell + U_\Delta}_{\langle u \rangle} + u'$$

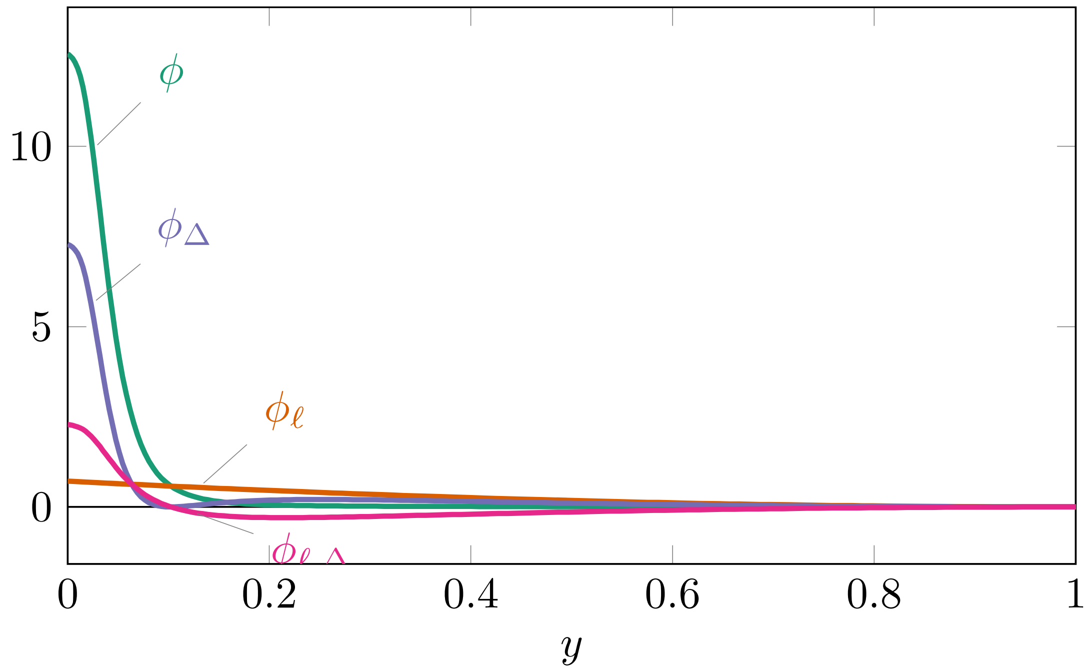


Production and mean dissipation

Mean dissipation decouples!

$$P = P_\ell + P_\Delta$$

$$\phi = \phi_\ell + \phi_\Delta + \phi_{\ell,\Delta} \to 0$$



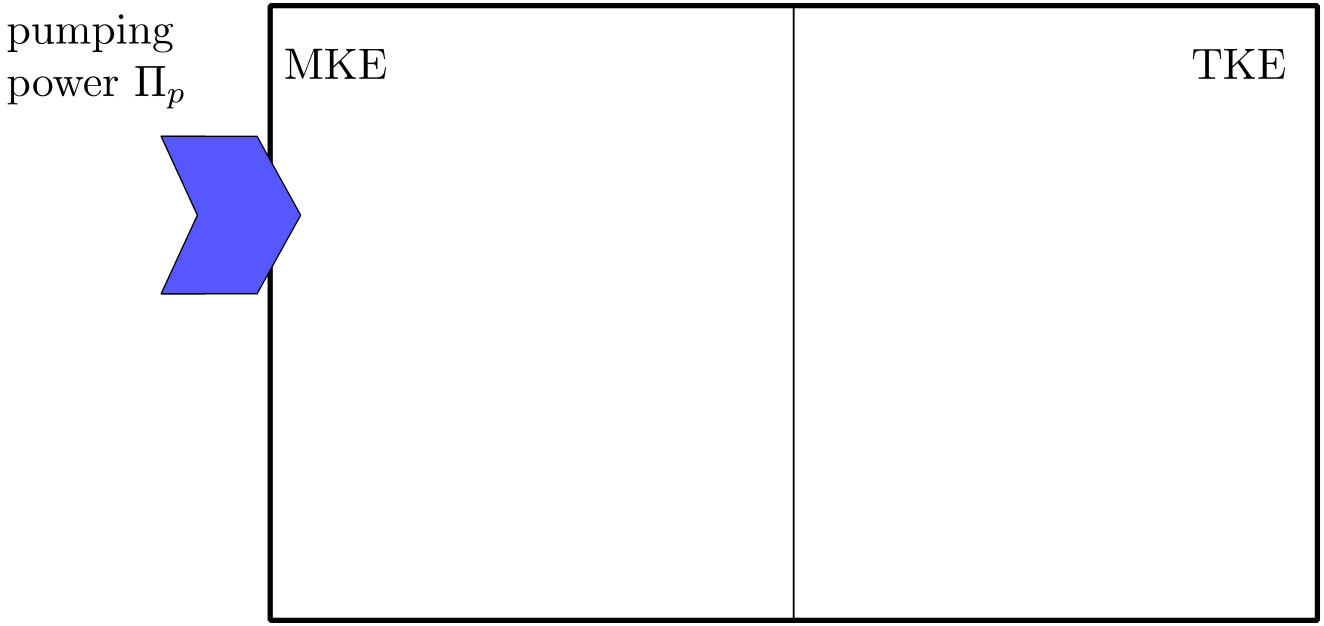
Analytical derivations

A fair amount of cumbersome algebra

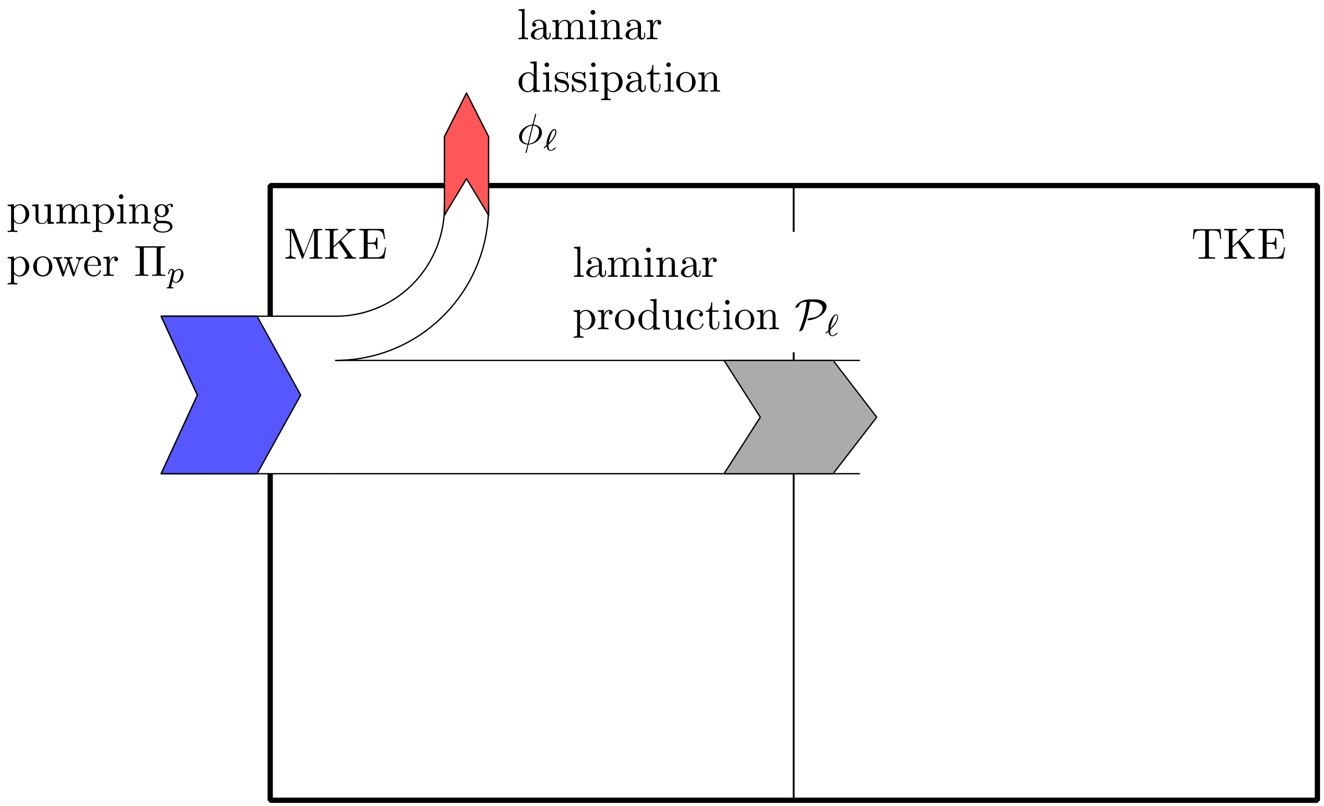
[This page intentionally left blank.]

D. Gatti *et al.*, J. Fluid Mech. (submitted)

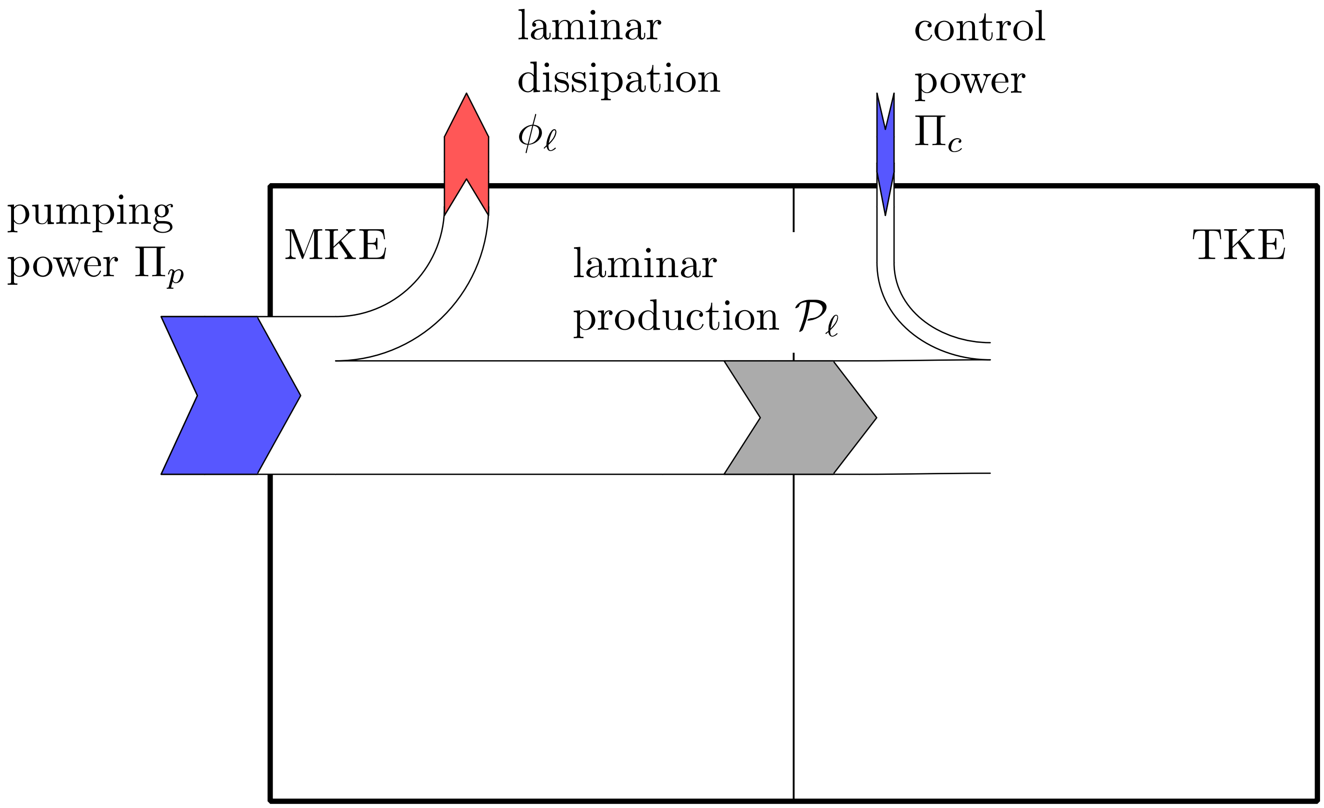
The new description



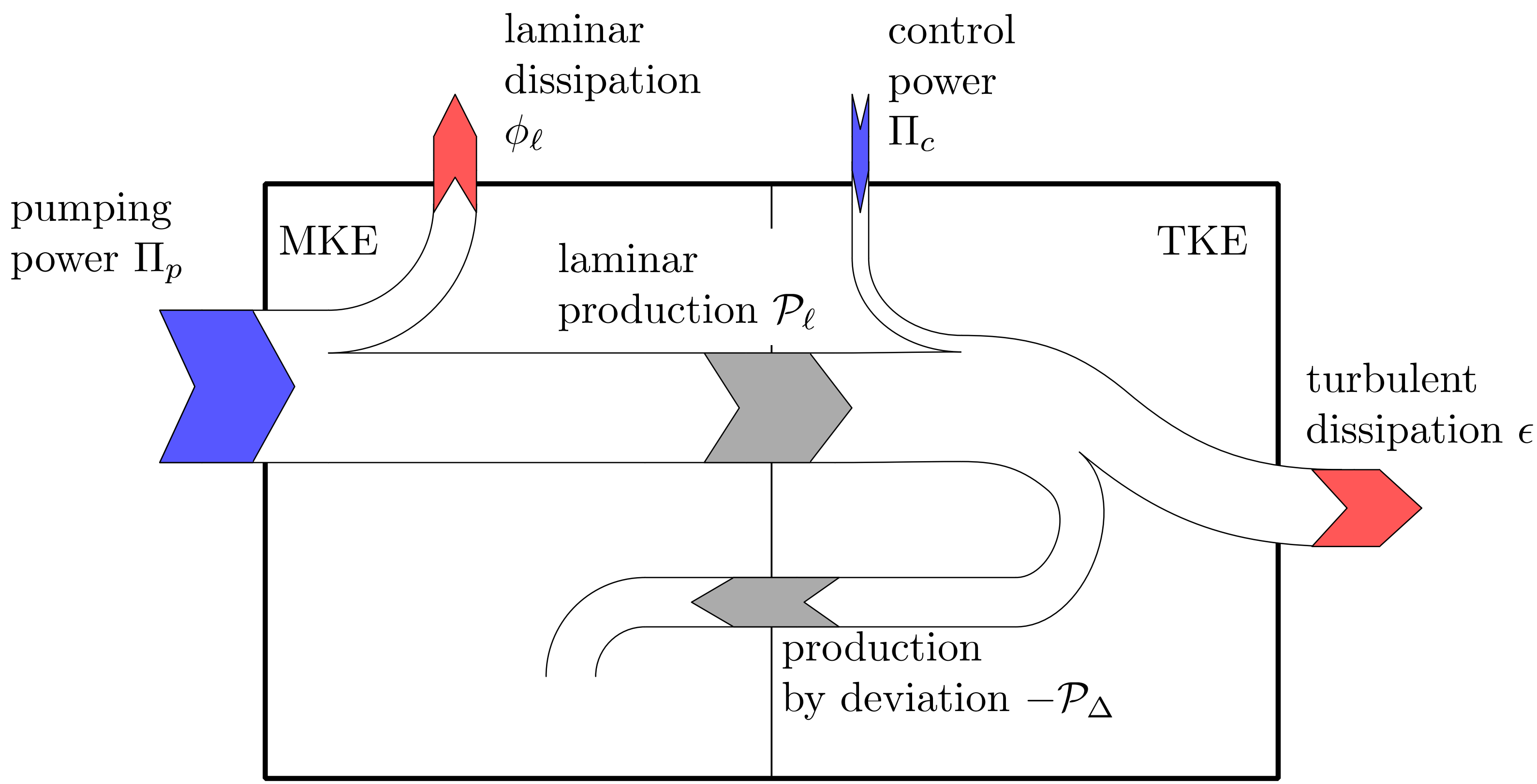
The new description



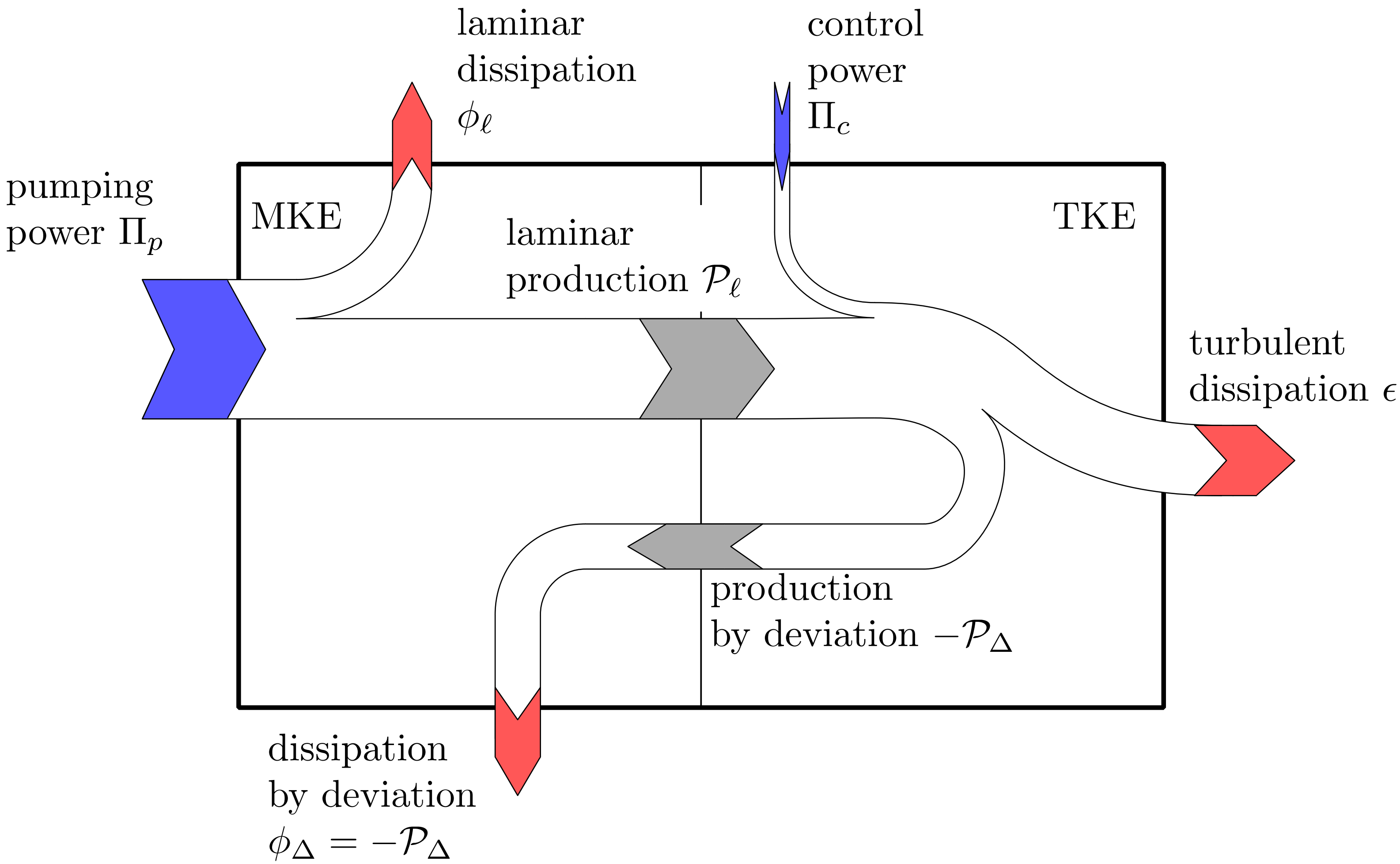
The new description



The new description



The new description



Two integrals of the turbulent shear stress

- Via FIK-like derivations, it is discovered that α and β parametrize all the fluxes

$$\alpha = \int_0^1 (1-y) r(y)\,\mathrm{d}y$$

$$\beta = \int_0^1 r^2(y)\,\mathrm{d}y \geq 3\alpha^2$$

- E.g.

$$P_\Delta = -\phi_\Delta = Re_\Pi (3\alpha^2 - \beta^2) \leq 0$$

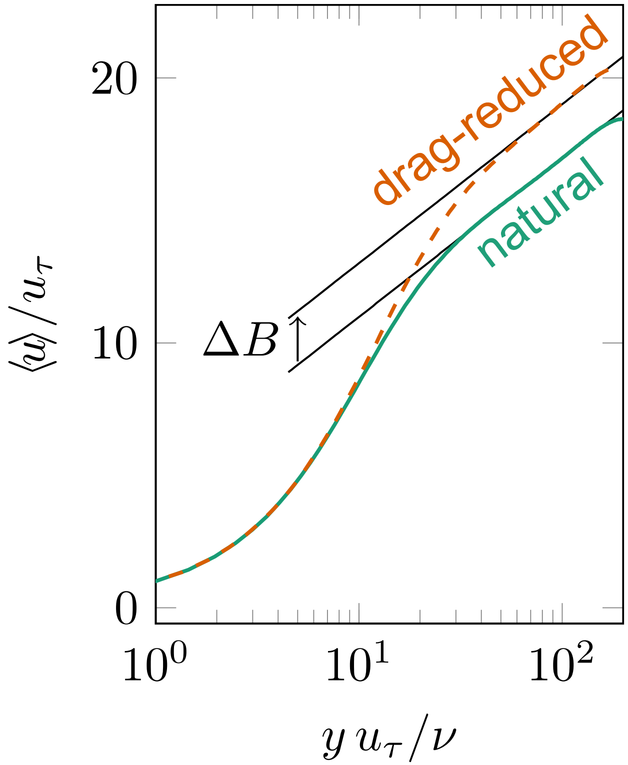
Key results

Every flux has a physical meaning

- ϕ_ℓ is the best way to dissipate pumping power
- P_ℓ is the fraction of pumping power wasted to produce turbulence
  - it decreases when control is successful
  - it can be negative as $P_\ell \sim \alpha$
- ϕ_Δ is the penalty for not being laminar
- $\phi_\Delta + \epsilon$ is the fraction of total power wasted by turbulence
  - it cannot be negative

A drag reduction model

- Control effect parametrized through ΔB

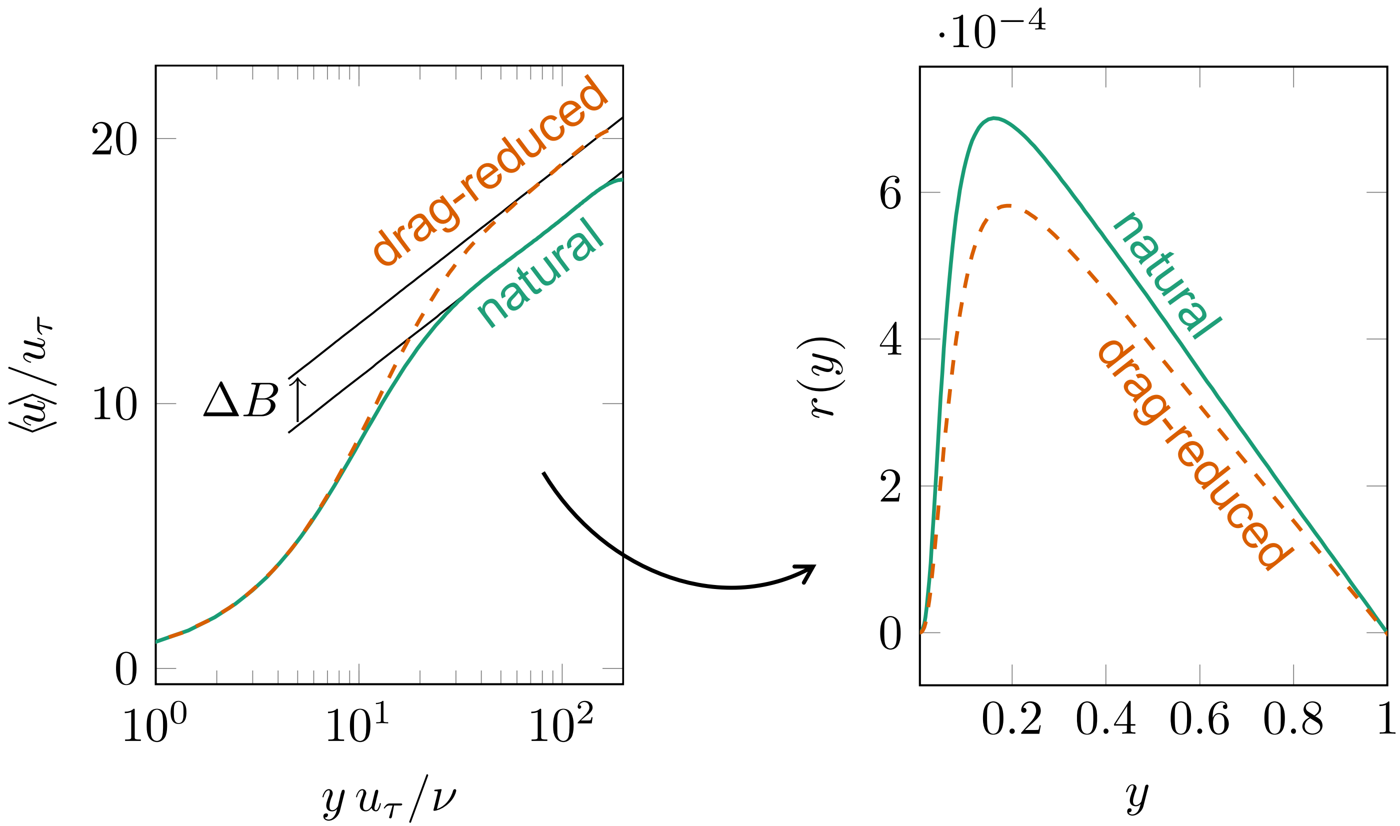


applicable to:

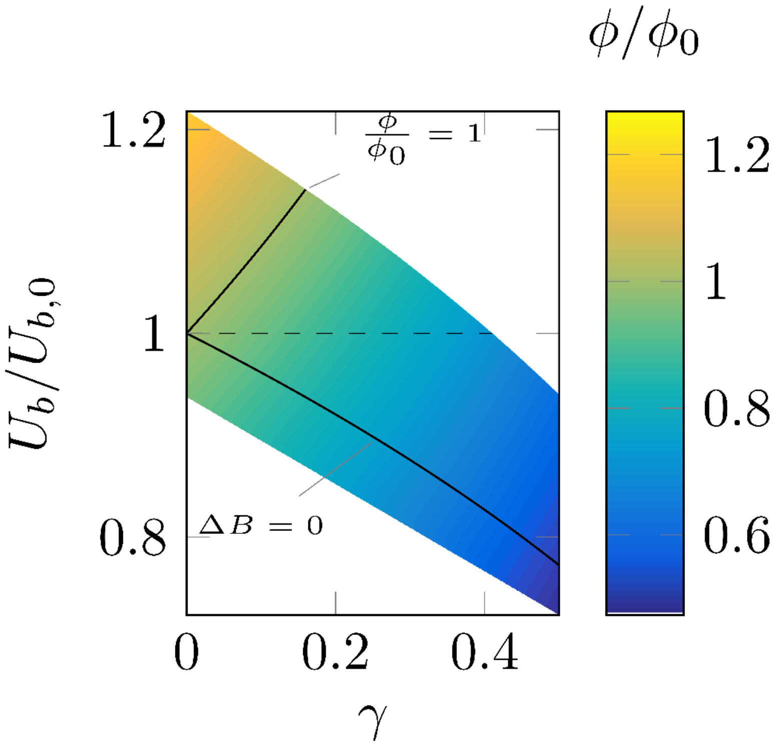
- riblets and roughness
- superhydrophobic surfaces
- spanwise wall forcing
- some feedback controls

A drag reduction model

- Control effect parametrized through ΔB
- Empirical description of velocity profile (Luchini, Phys. Rev. Letters, 2017)
- CPI contraint $3Re_{\Pi}^{2}(1-\gamma) = Re_{\tau}^{2}Re_{B}$



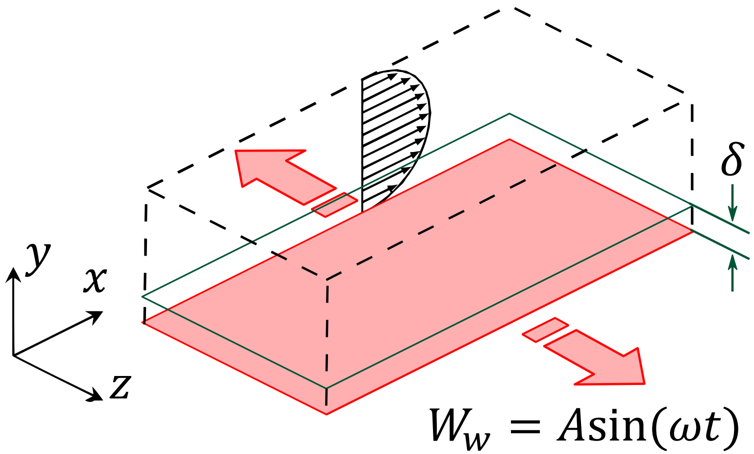
How do dissipations change with control?
Back to our initial question

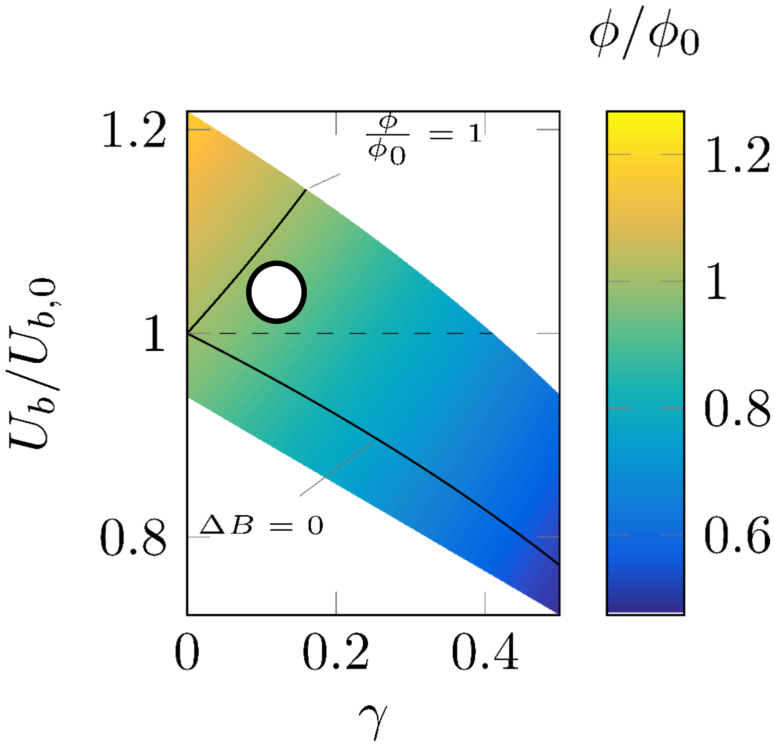


How do dissipations change with control?

Back to our initial question

spanwise wall oscillations

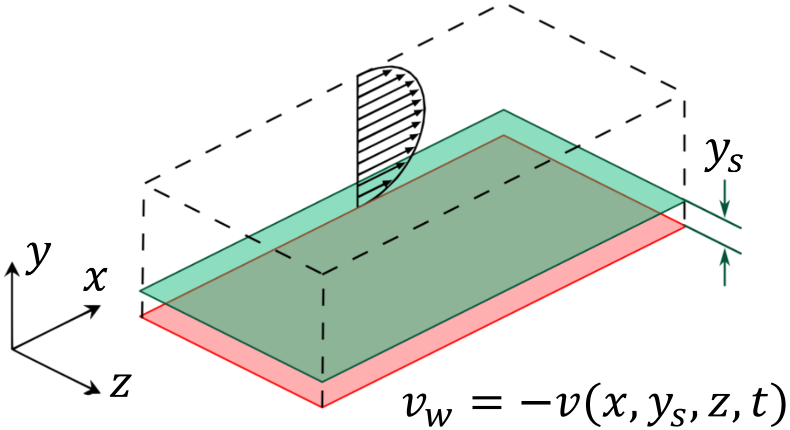


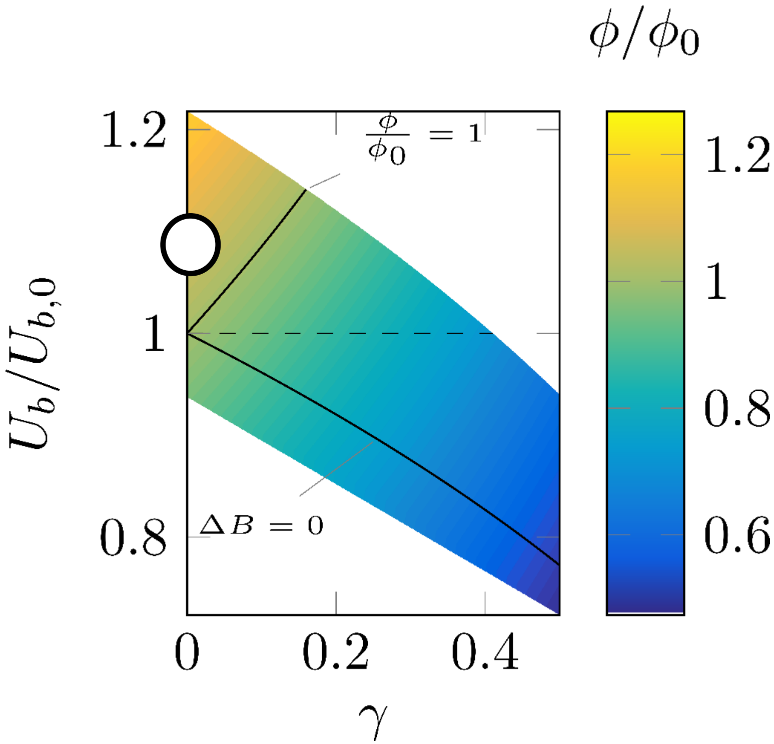


How do dissipations change with control?

Back to our initial question

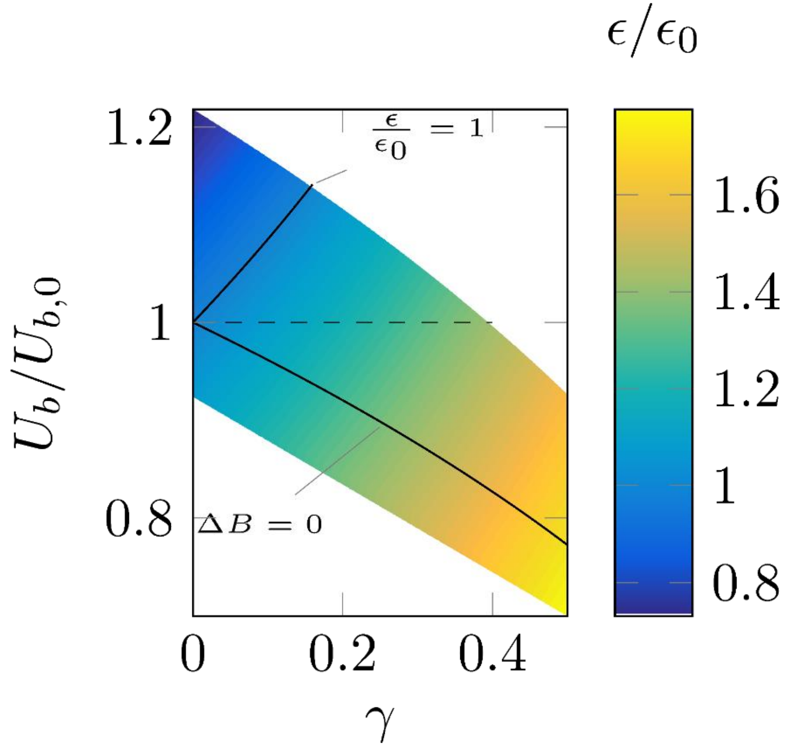
opposition control

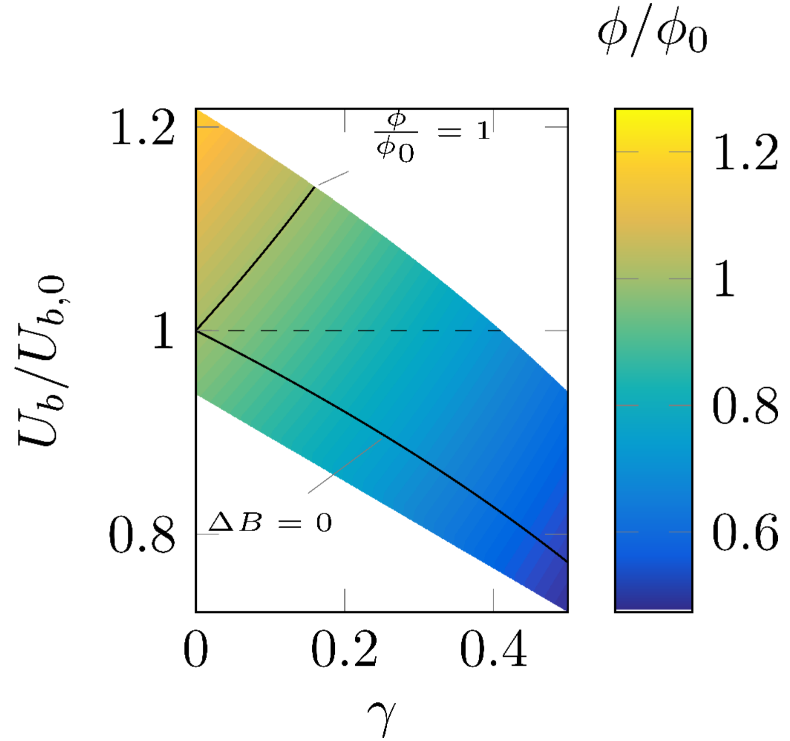




How do dissipations change with control?

Back to our initial question





Conclusion and outlook

- "Wind" decomposition and CPI introduced
- Theoretical framework for the flow control problem from energy perspective…
- …relevant also for uncontrolled flows: FIK-like identity for ϵ

- Optimal control theory: better choice of cost function
- Development of drag-reduction-aware RANS turbulence models

- CPI-enabled scale-energy analysis of drag reduced flows

European Drag Reduction and Flow Control Meeting

Bad Herrenalb (near Karlsruhe, Germany)

26—29 March 2019

THANKS

for your kind attention!

for questions, complaints, ideas:

davide.gatti@kit.edu

Institute of Fluid Mechanics istm