Integral energy budgets in turbulent channels with and without drag reduction

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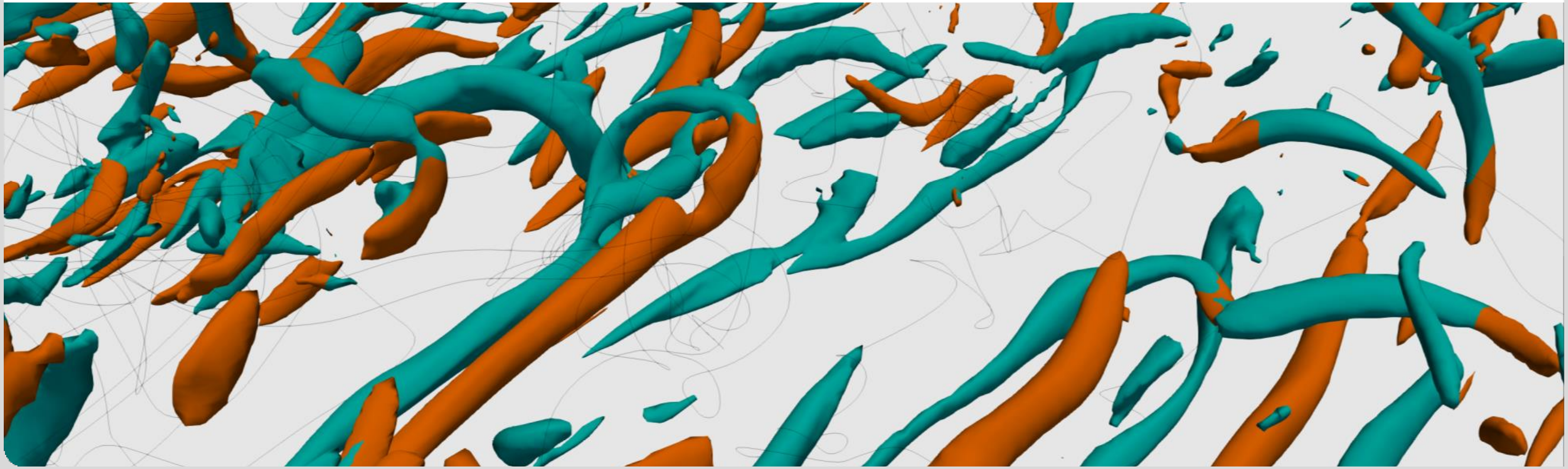

Today’s goal

“how do dissipation and production
of turbulent kinetic energy relate
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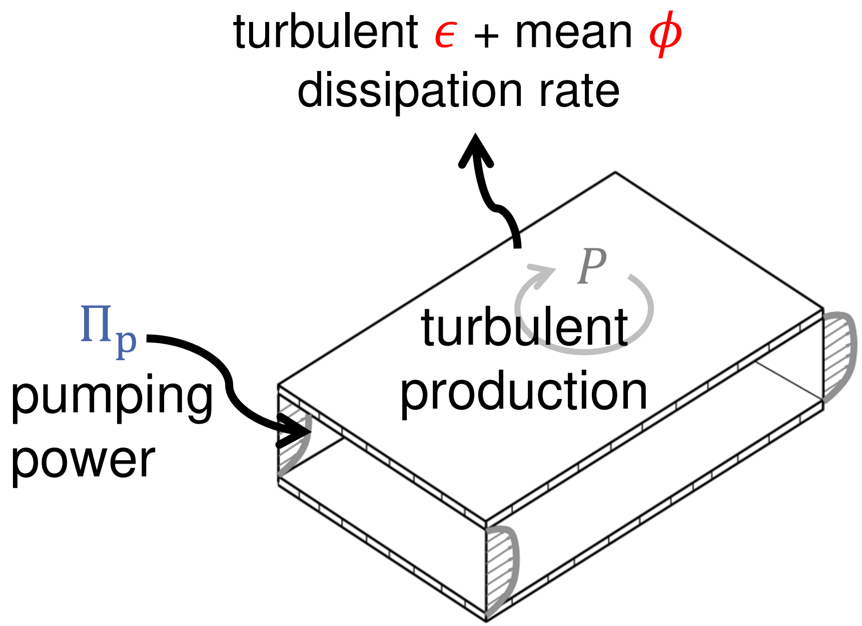
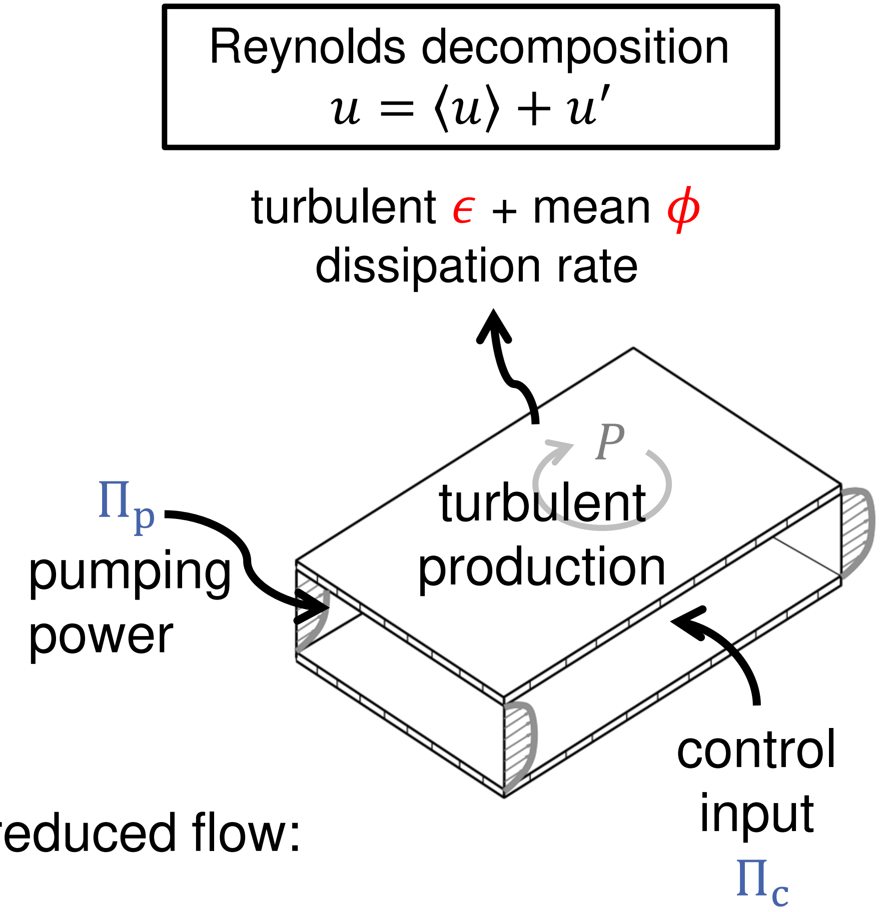
Reynolds decomposition
$$u = \langle u \rangle + u'$$



Today's goal

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



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)

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Definitions and characteristic quantities

- Total power Π_t is kept constant

$$\Pi_t = \Pi_p + \Pi_c \longrightarrow \text{control power } \Pi_c = \gamma \Pi_t$$

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)

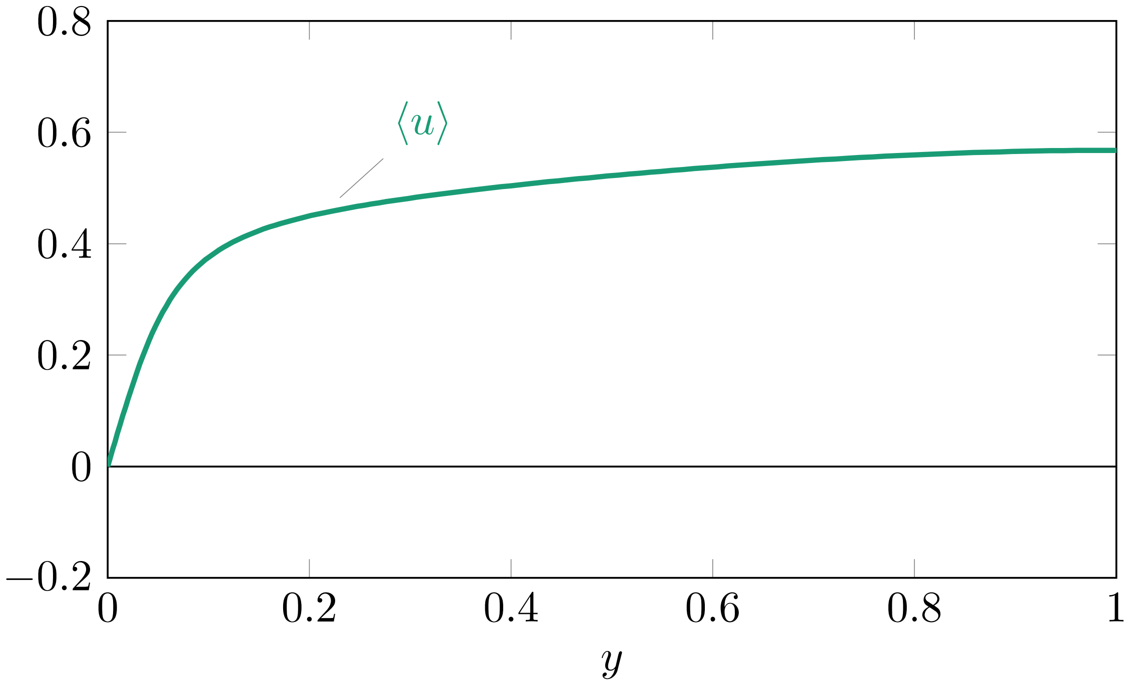
The wind of turbulence

The “wind decomposition” of turbulence

A triple decomposition with analytical advantages

Eckhardt et al, JFM 2007

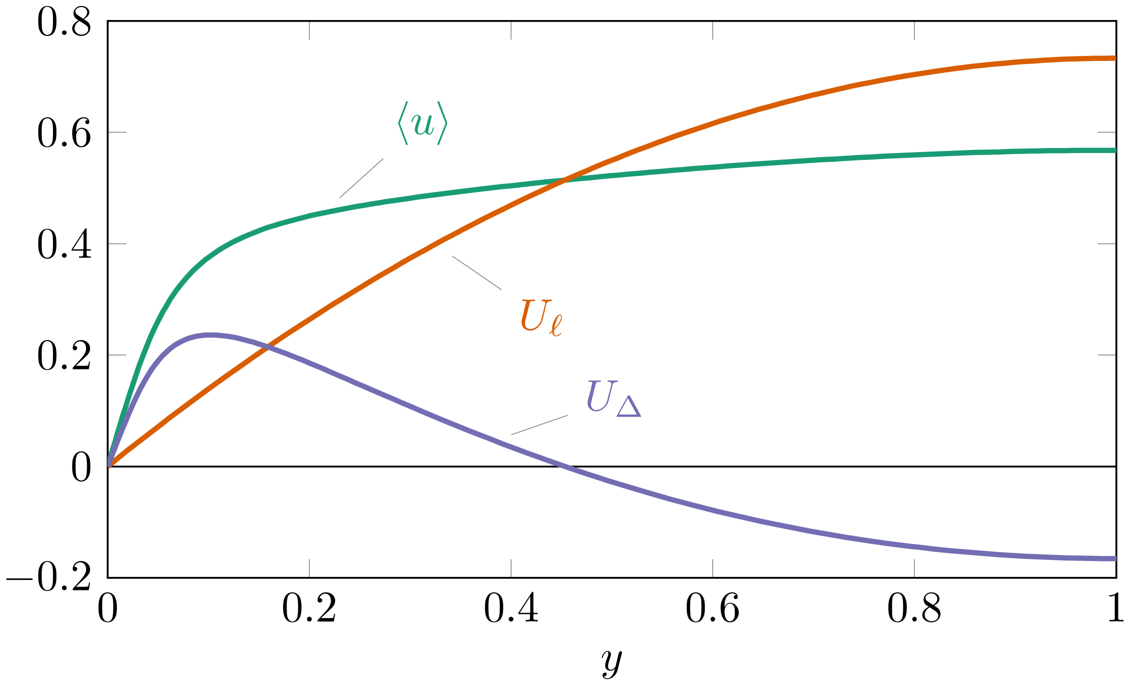
$$u = \langle u \rangle + u'$$



The “wind decomposition” of turbulence

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

$$u = \overbrace{U_\ell + U_\Delta}^{\langle u \rangle} + u'$$

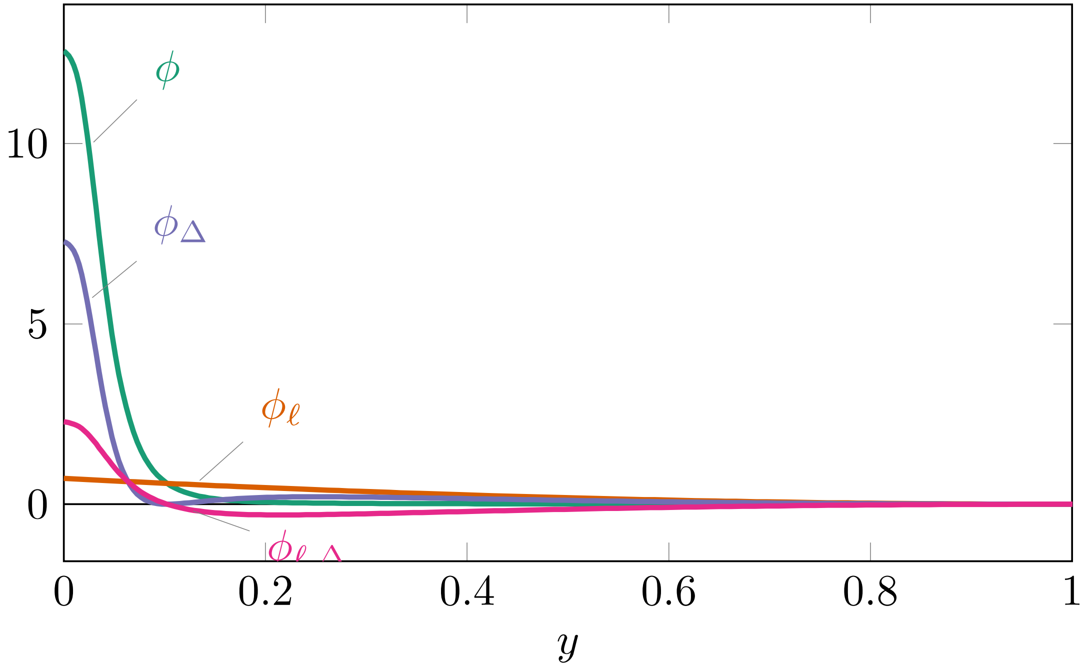


Production and mean dissipation

Mean dissipation decouples!

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

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



Analytical derivations

A fair amount of cumbersome algebra

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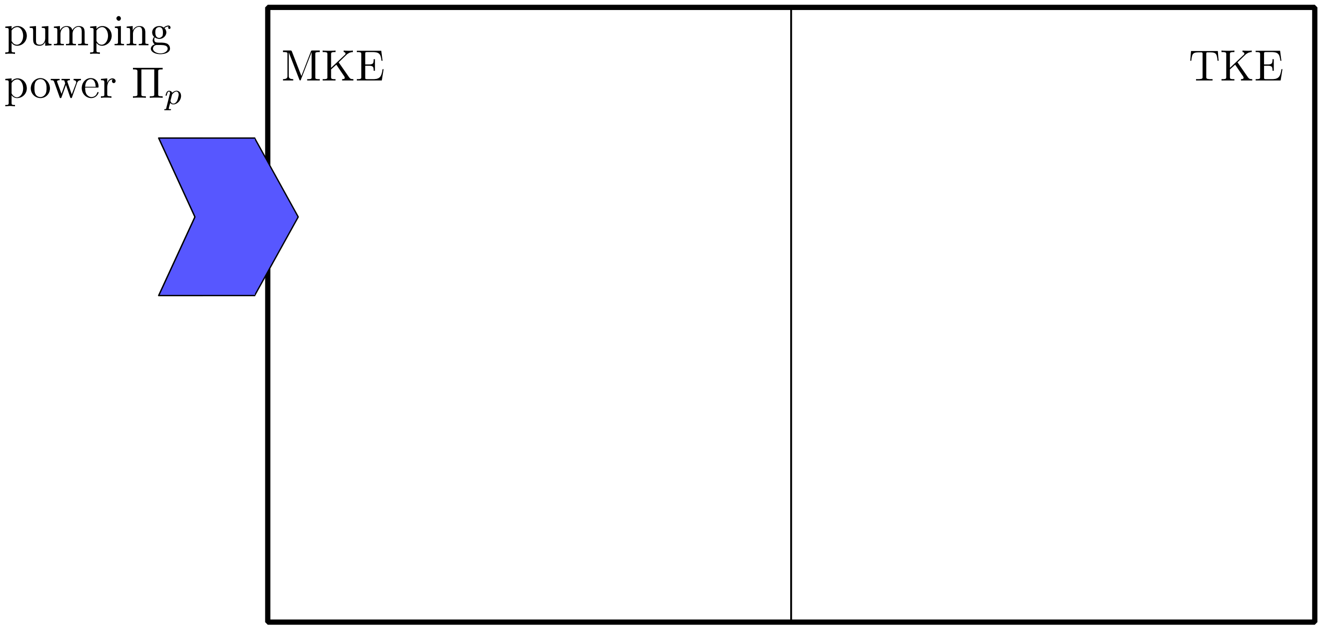
D. Gatti *et al.*, J. Fluid Mech. (submitted)

The new description



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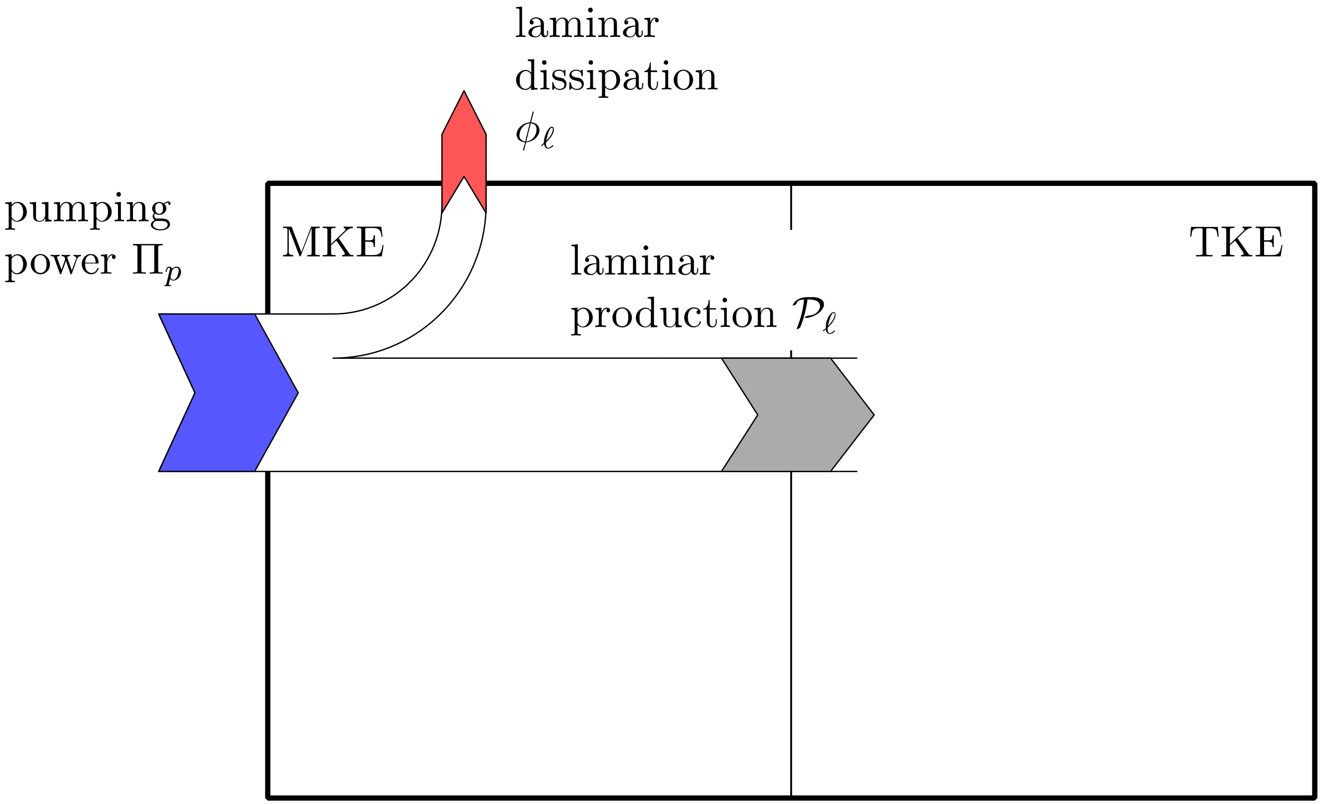

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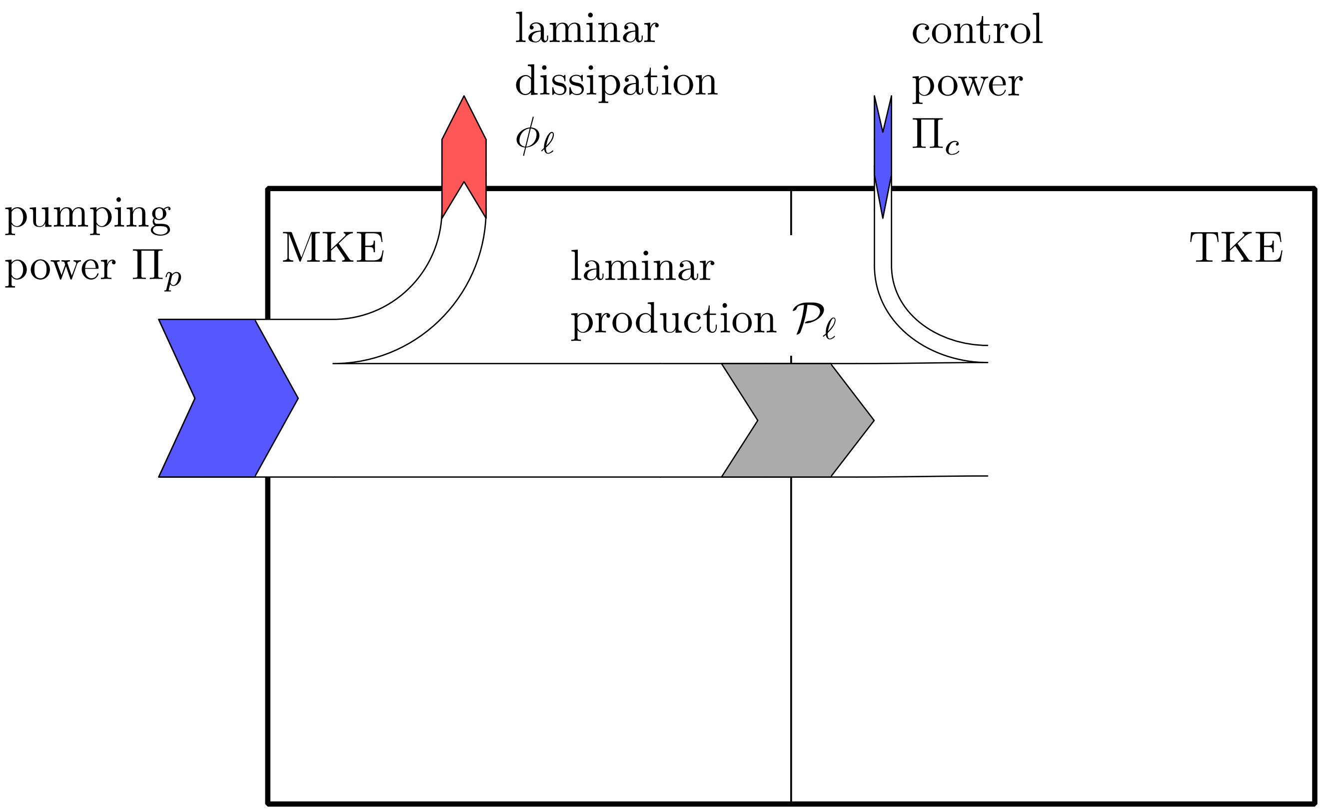

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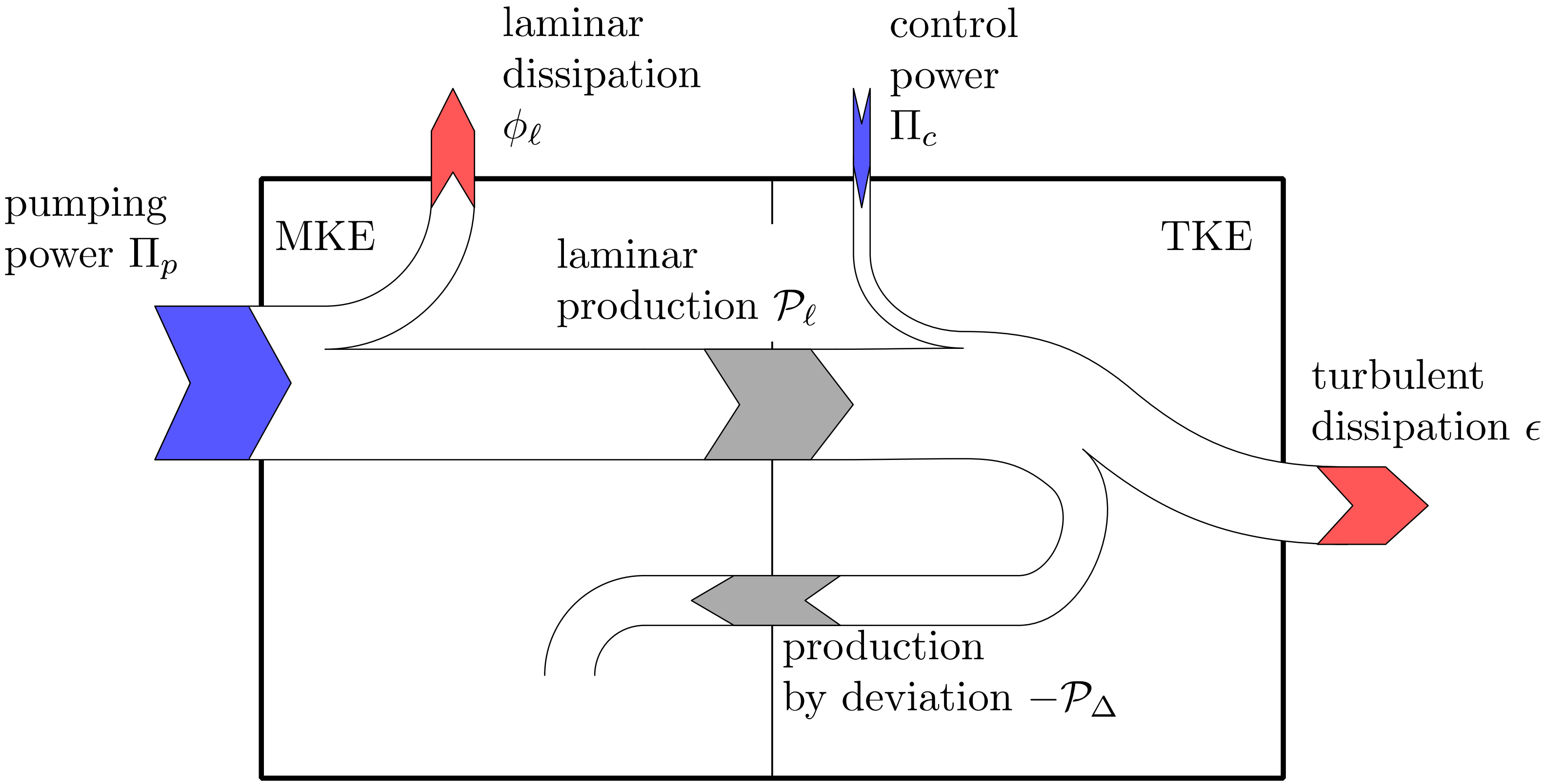

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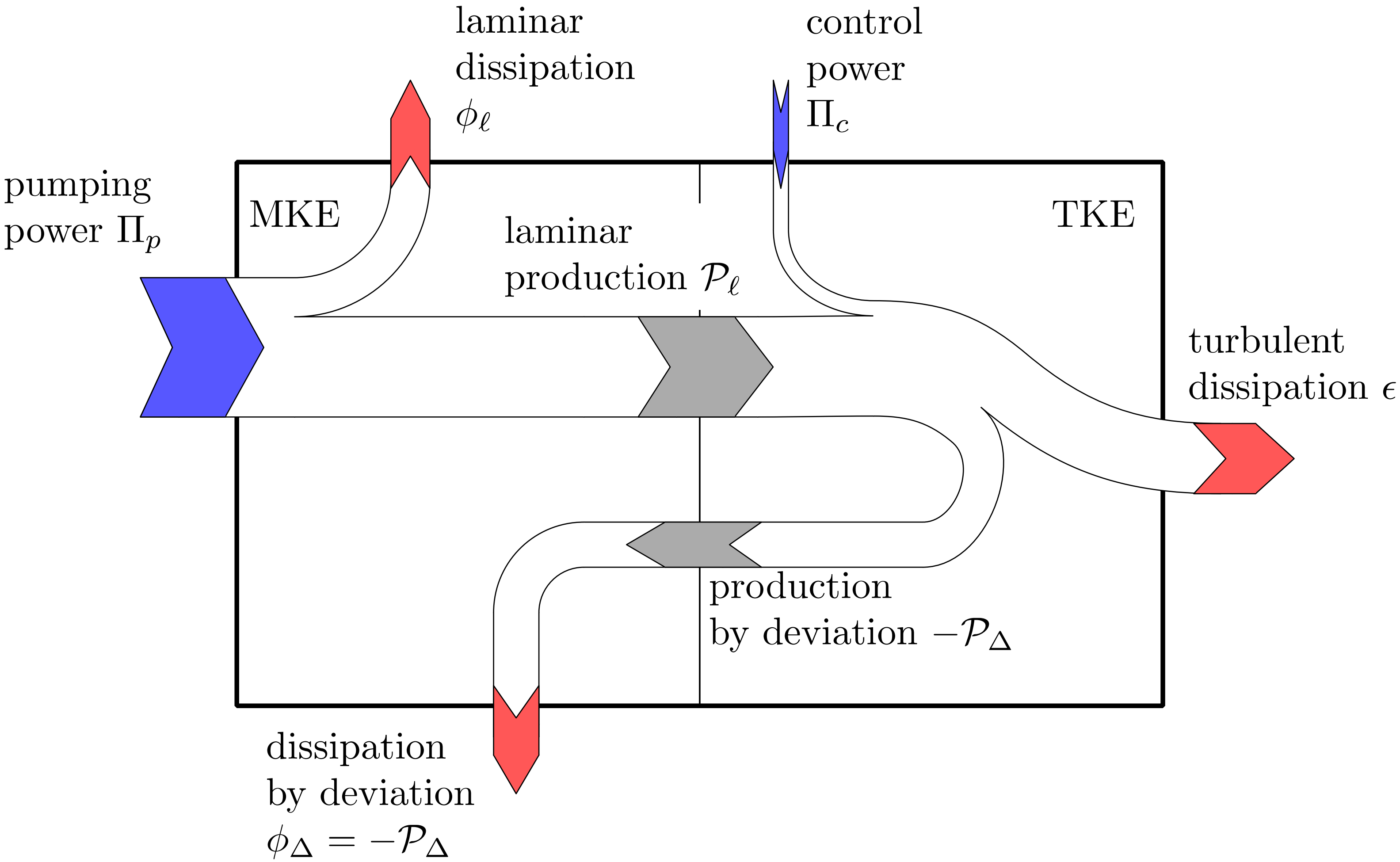


Two integrals of the turbulent shear stress

- 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.

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

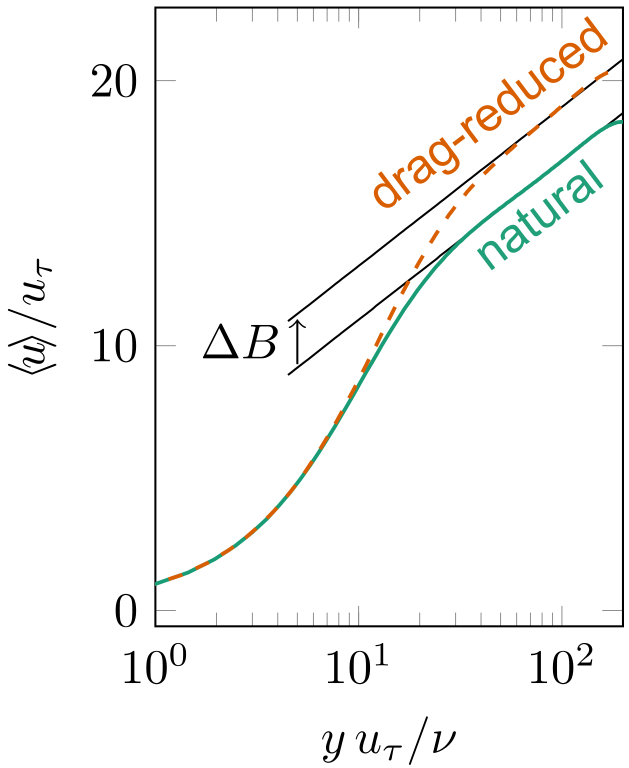
Key results

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

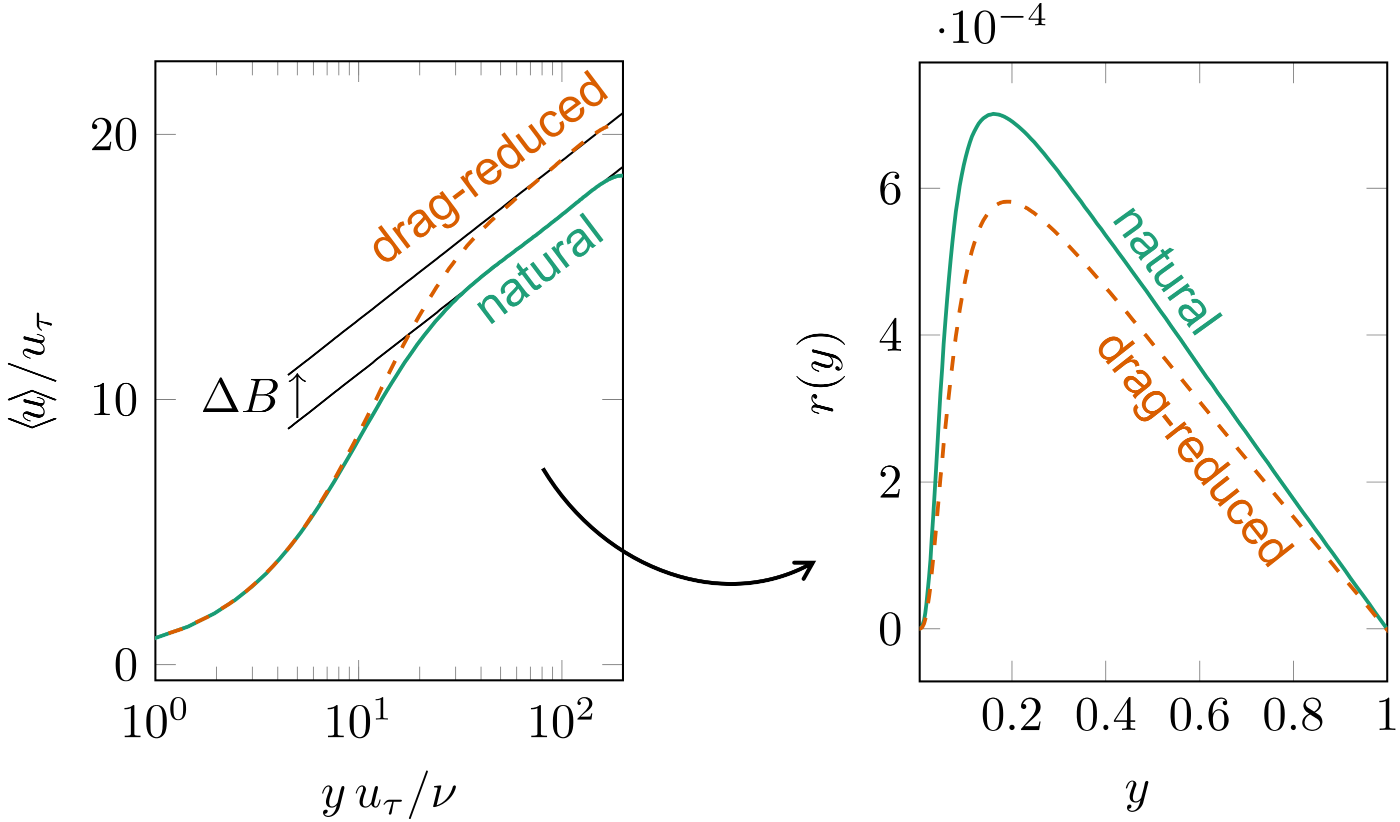


applicable to:

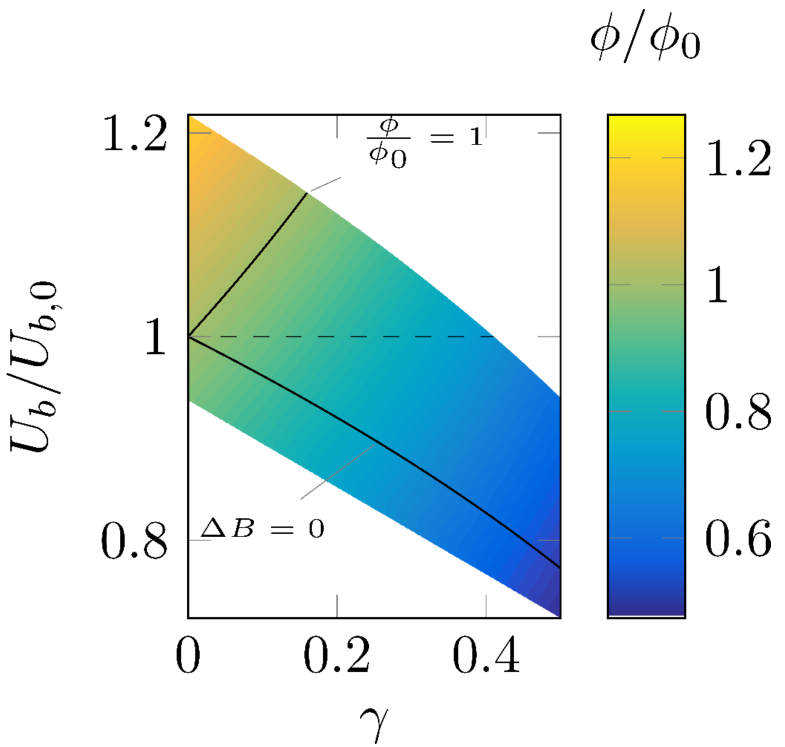
- riblets and roughness
- superhydrophobic surfaces
- spanwise wall forcing
- some feedback controls

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



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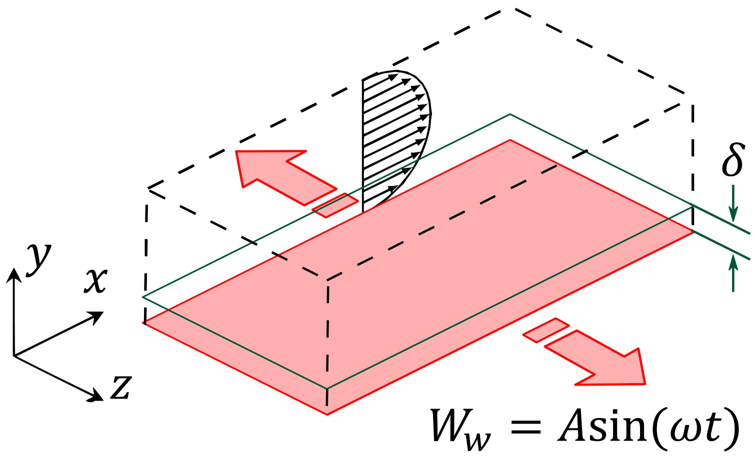
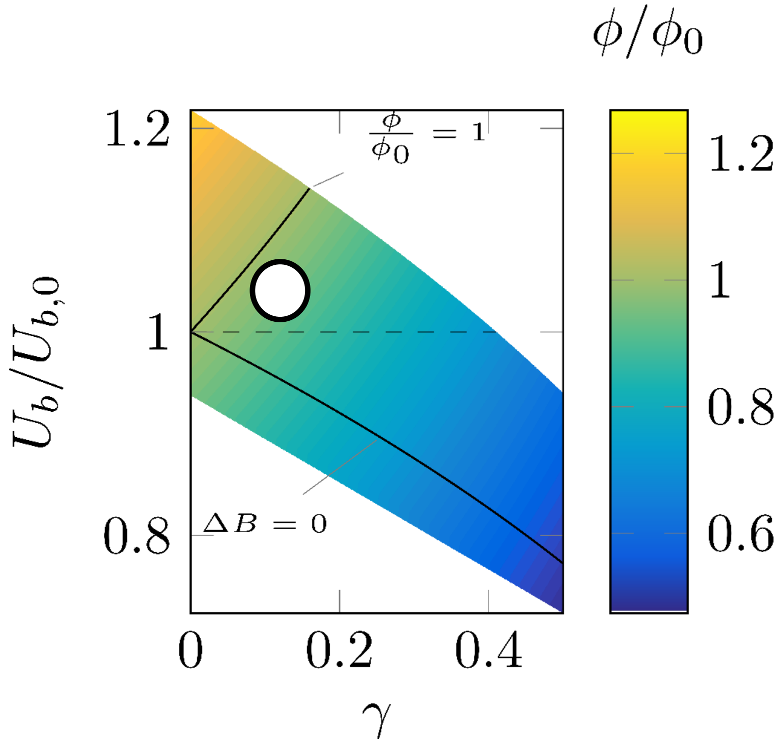
spanwise wall oscillations





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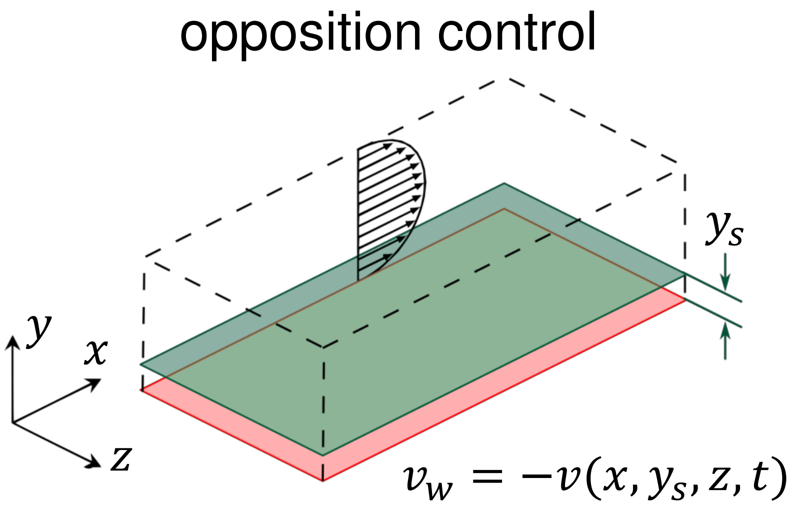

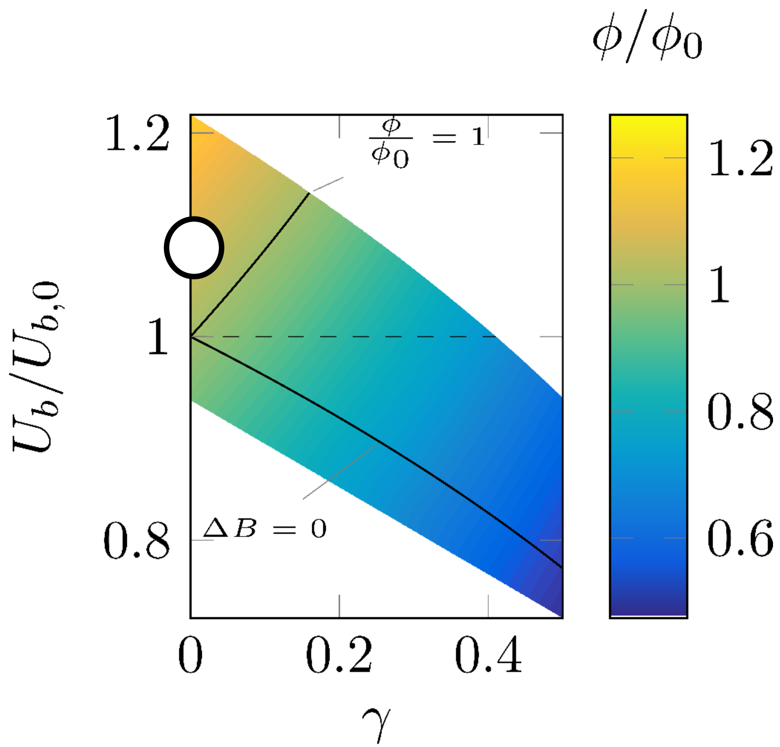

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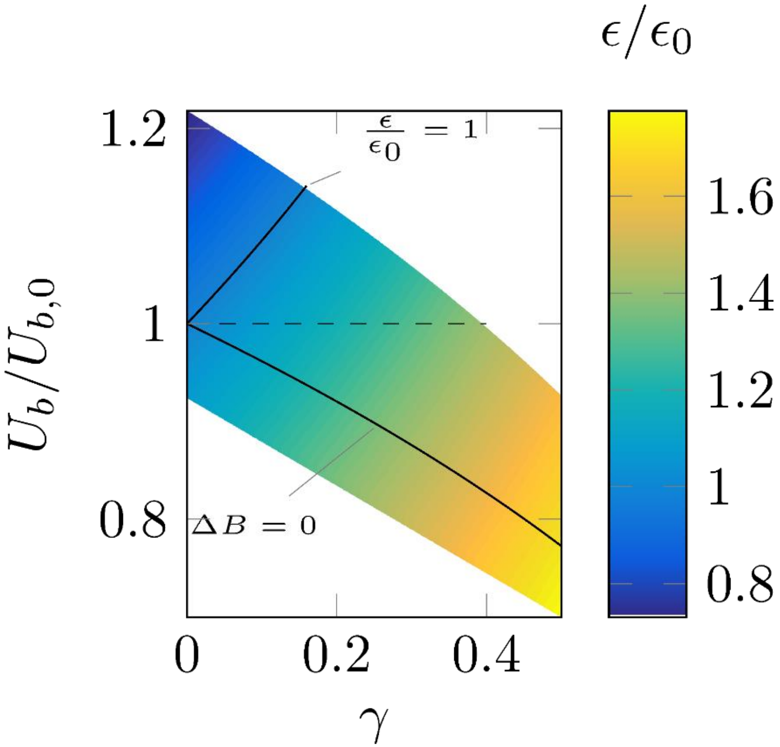

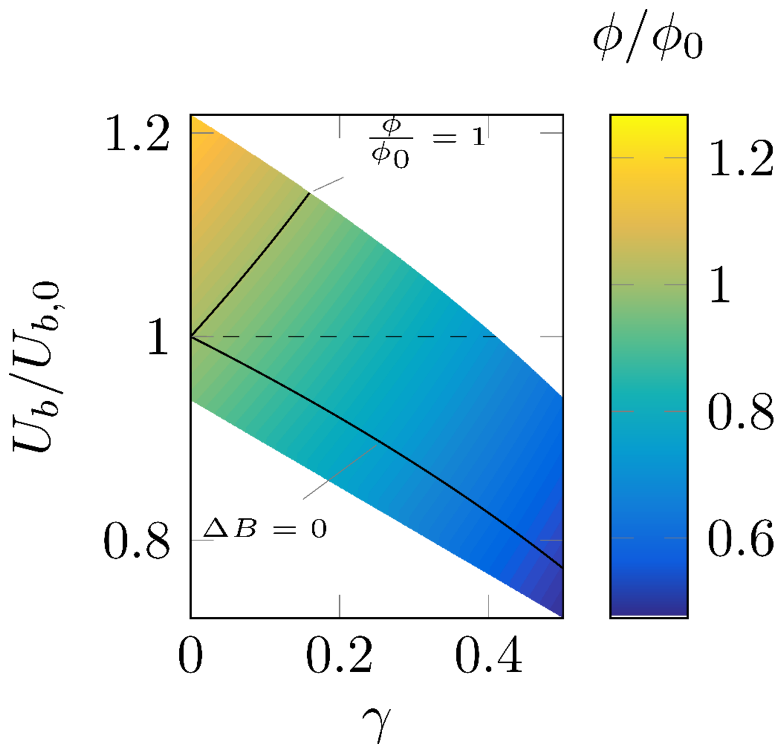

Conclusion and outlook

- "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

European Drag Reduction and Flow Control Meeting

- Topics:
  - all laminar and turbulent drag reduction
  - flow & noise control studies
- Attended by all major scientists in the field
- Young contributors are invited to submit abstracts
- Conference fee ~ 400€ including accommodation!
- More info: www.edrfcm.science

THANKS

for your kind attention!

for questions, complaints, ideas:

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