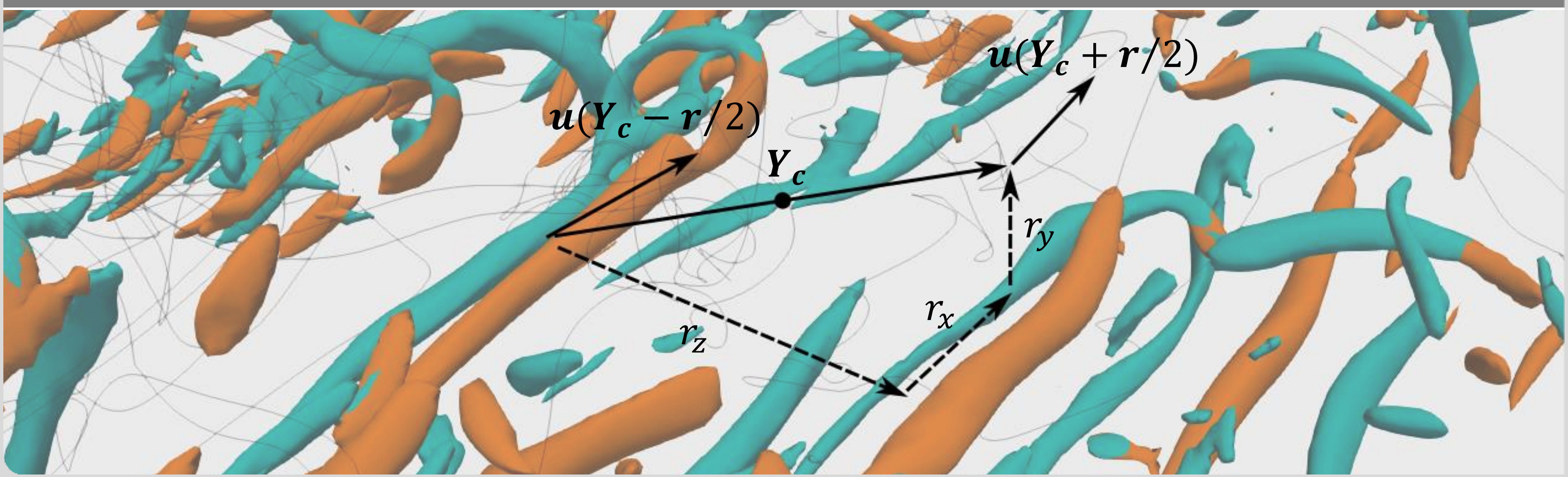
Karlsruhe Institute of Technology

Scale energy fluxes in turbulent channels with drag reduction at constant power input

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

Institute of Fluid Mechanics

16th EUROPEAN TURBULENCE CONFERENCE, Stockholm, Sweden



The question in drag reduction

“how do turbulent flows
with and without drag reduction
differ?”

- Comparison between different flows required
- Very different outcomes depending upon how flow is driven

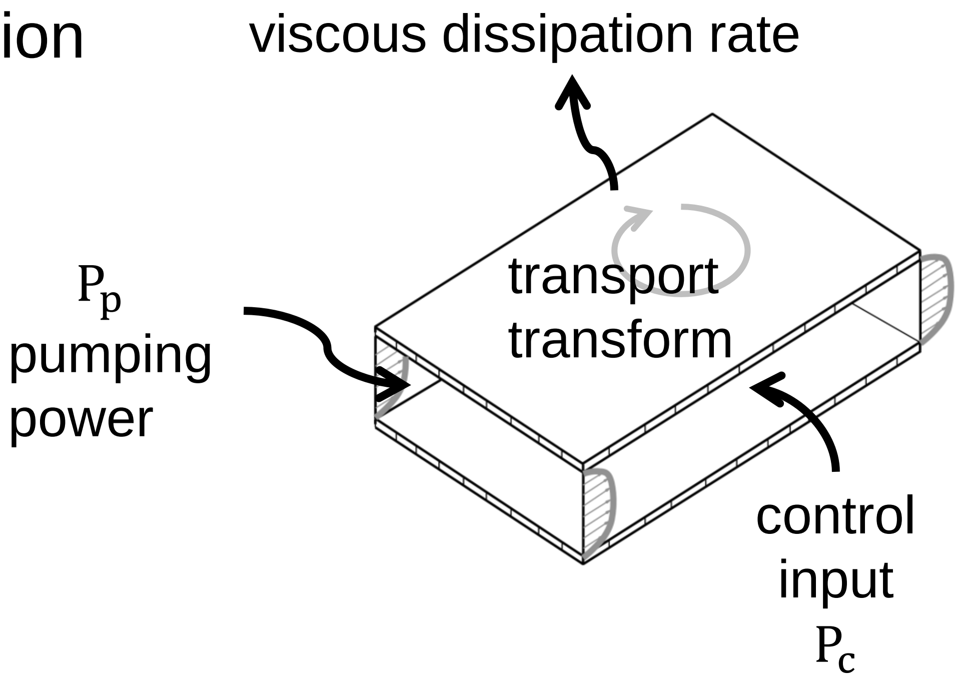
Our question in drag reduction

"how do turbulent flows
with and without drag reduction
differ **energetically**?"

- Comparison between different flows required
- Very different outcomes depending upon how flow is driven
- An example: enstrophy in drag reduced flows:
  - Ricco *et al.*, JFM12: at CPG increases
  - Agostini, *et al.*, JFM14: at CFR decreases
  - Gatti et al., submitted: …it depends!

Today's goal

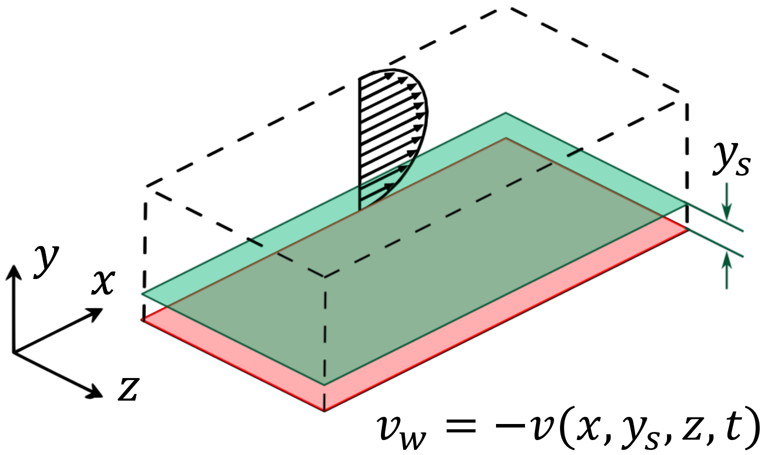
"how do turbulent flows
with and without drag reduction
differ **energetically**?"



Assess **changes of scale energy** fluxes
in turbulent channels
driven **at Constant Power Input** (Hasegawa et al., JFM14)

A model control strategy

Opposition Control (Choi, Moin & Kim, JFM94)



	reference	controlled
	$Re_\tau = \frac{u_\tau h}{\nu} = 200$	$Re_\tau = 190.5$
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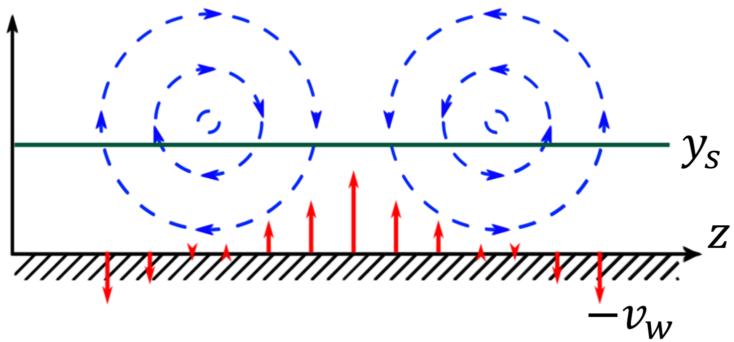


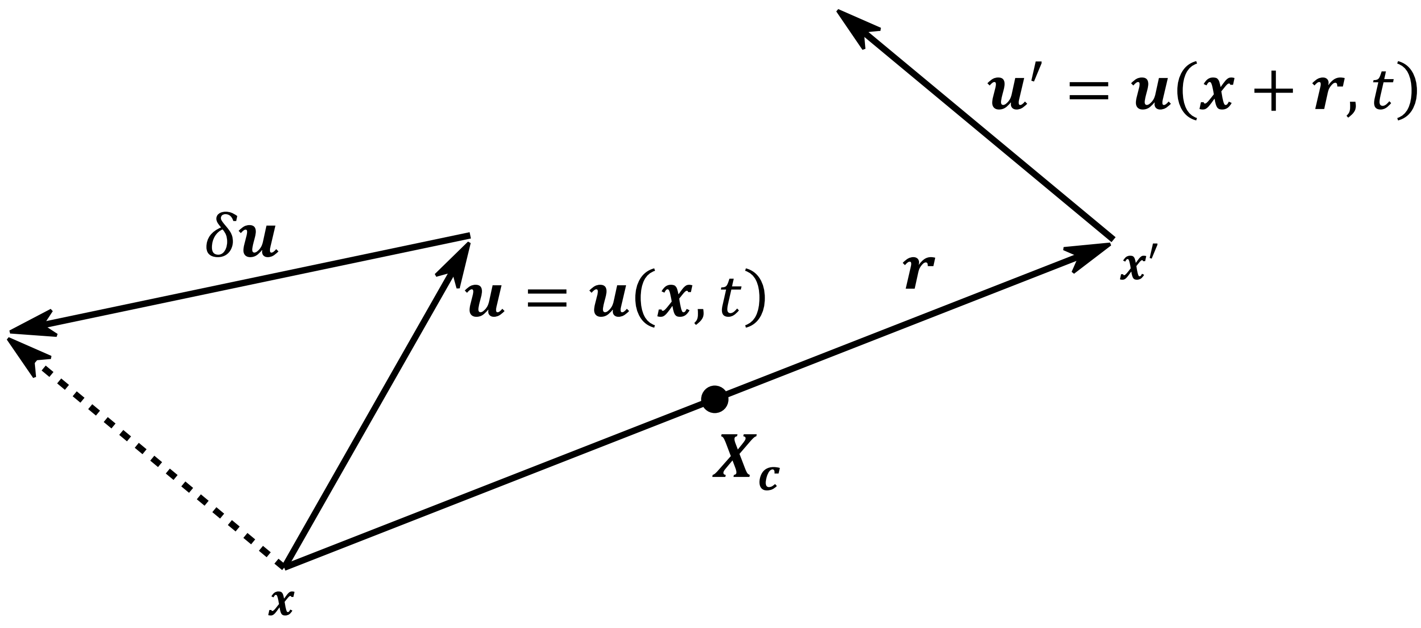
drag reduction $R = 1 - {C_f}/{C_{f,0}} = 23.9\%$

control power fraction $\gamma = {P_c}/{P_t} = 0.0035$

$$\frac{U_b}{U_{b,ref}} = 1.094$$

Second-order structure function (1)

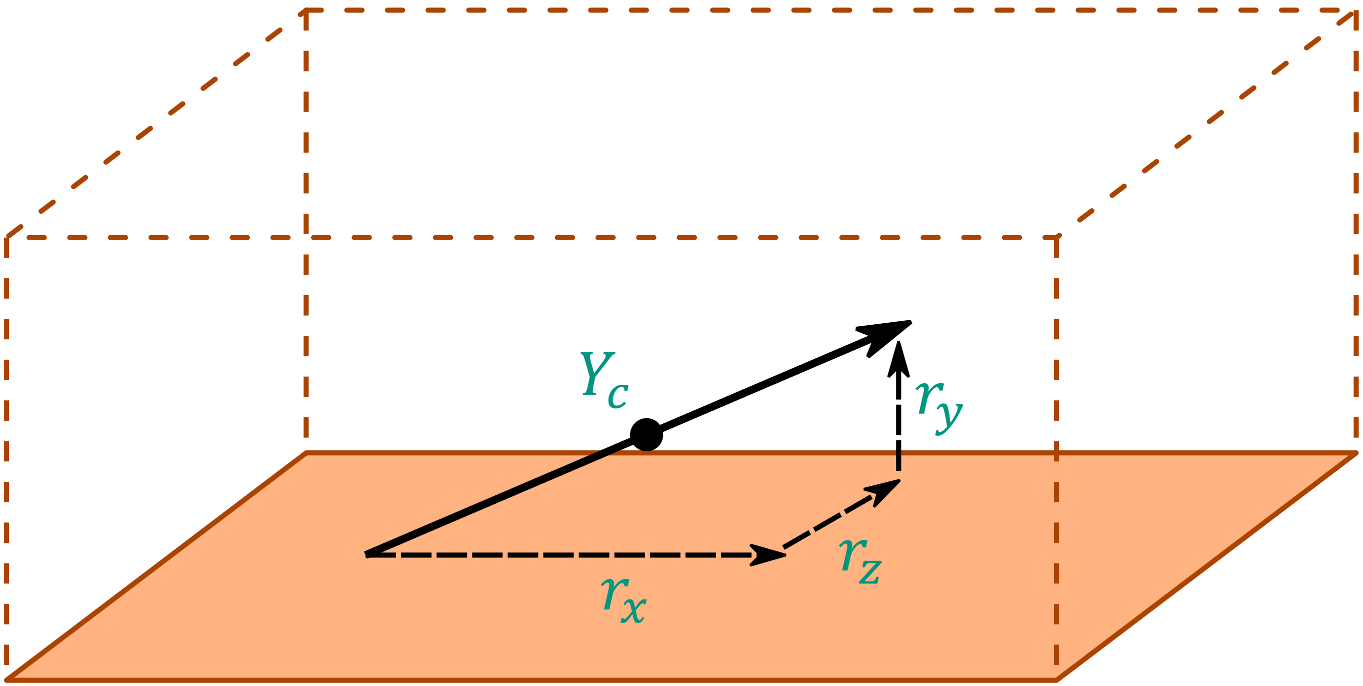
$$\langle \delta u^2 \rangle(\boldsymbol{r}, \boldsymbol{X}_c) = \left\langle [u(\boldsymbol{X_c} - \boldsymbol{r}/2) - u(\boldsymbol{X_c} + \boldsymbol{r}/2)]_i^2 \right\rangle$$



loosely speaking, amount of fluctuation **energy** at **scale** $||\boldsymbol{r}||$

Second-order structure function (2)

$$\langle \delta u^2 \rangle(\boldsymbol{r}, Y_c) = \left\langle [u(\boldsymbol{X_c} - \boldsymbol{r}/2) - u(\boldsymbol{X_c} + \boldsymbol{r}/2)]_i^2 \right\rangle$$

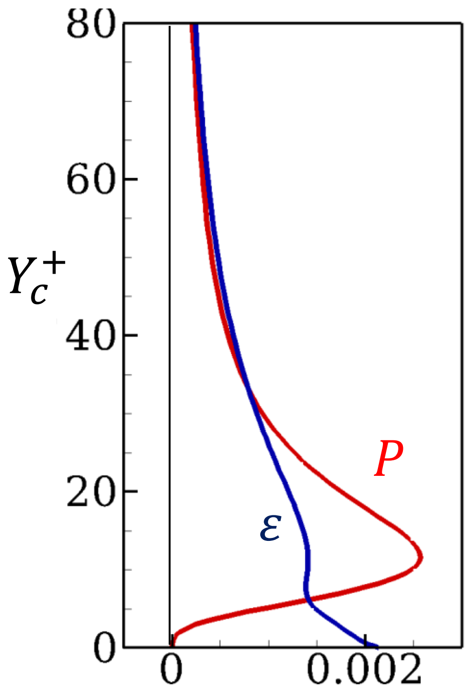


in channels function of wall-normal coordinate Y_c and vector $\boldsymbol{r}$

Kinetic energy budget

$k = \frac{1}{2}\langle u_i^2 \rangle$ budget

$$\frac{\mathrm{d}\Phi}{\mathrm{d}Y_c} = P - \epsilon = s(Y_c)$$



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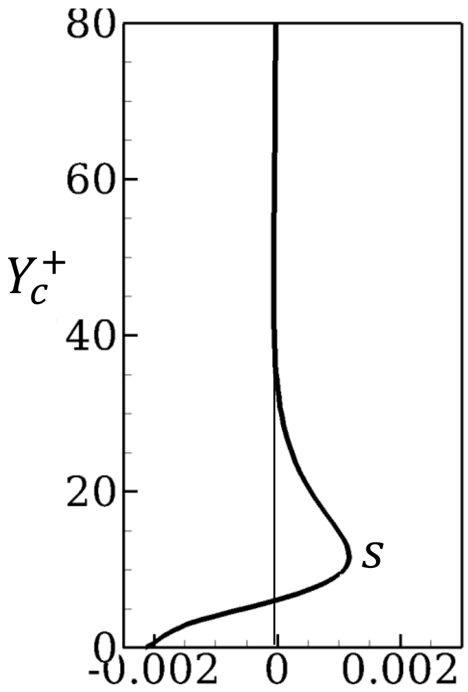

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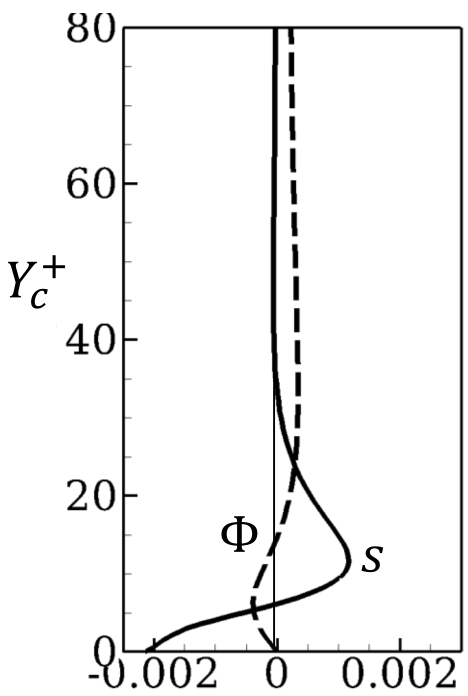

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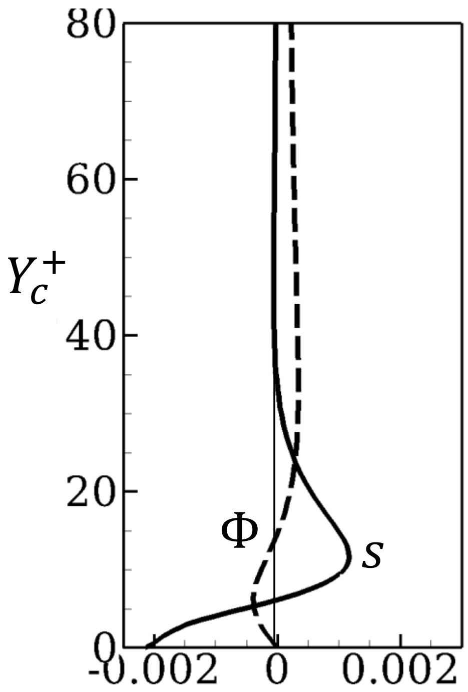
$$\boldsymbol{\nabla}_r \cdot \boldsymbol{\Phi}_r + \frac{\partial \Phi_c}{\partial Y_c} = s(\boldsymbol{r}, Y_c)$$



Scale energy budget: r_z, Y_c space

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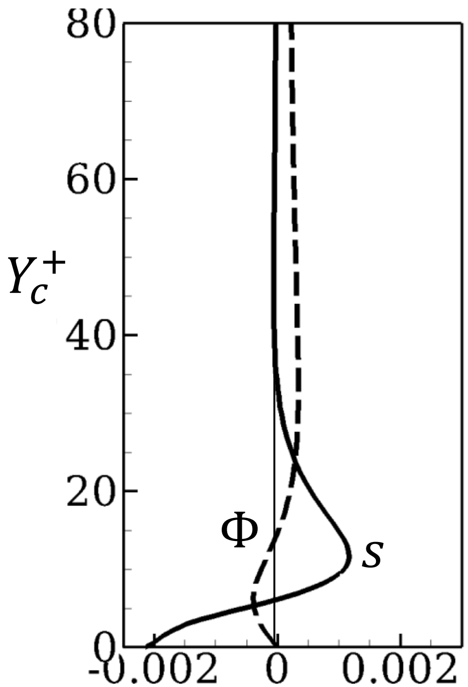

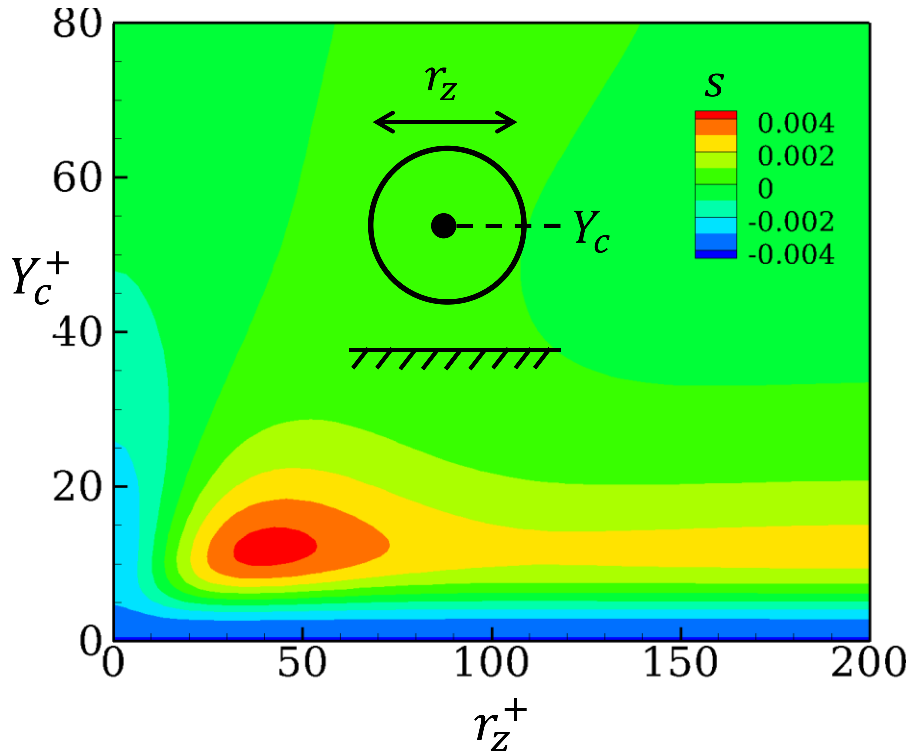

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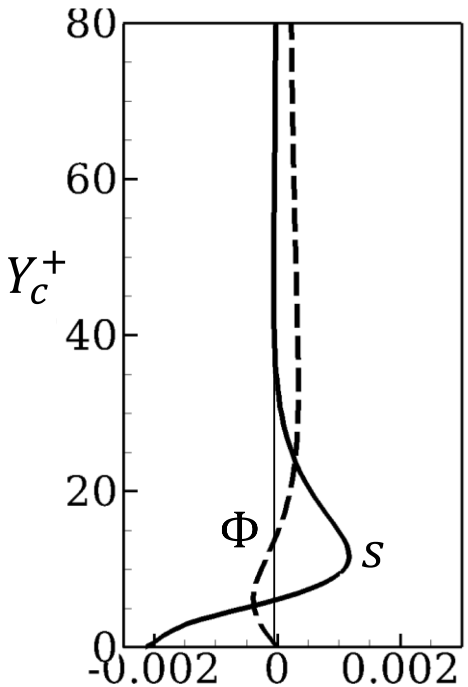

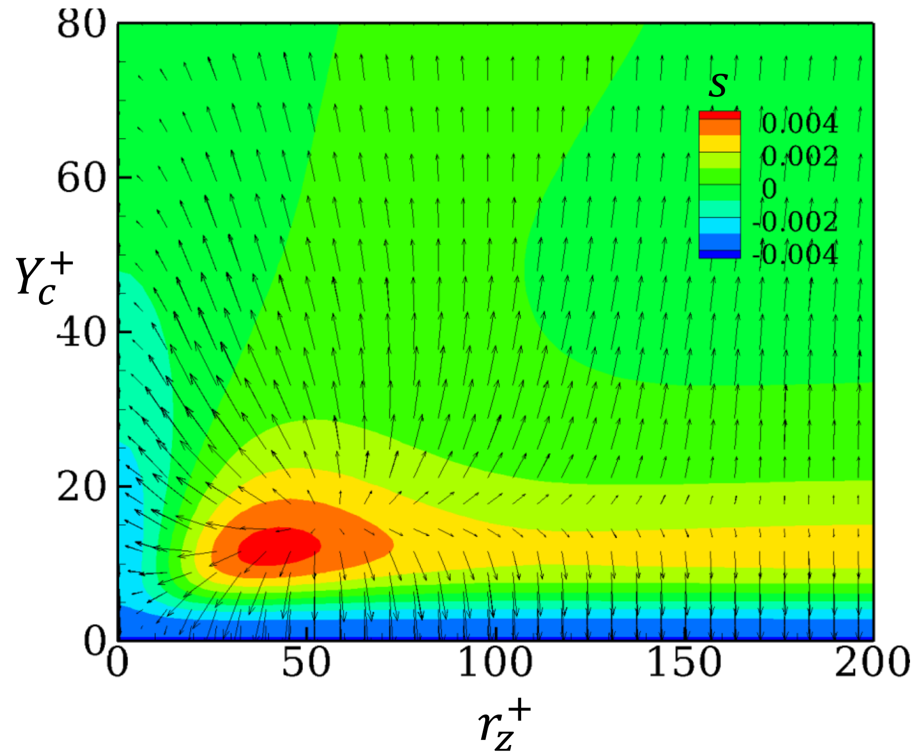

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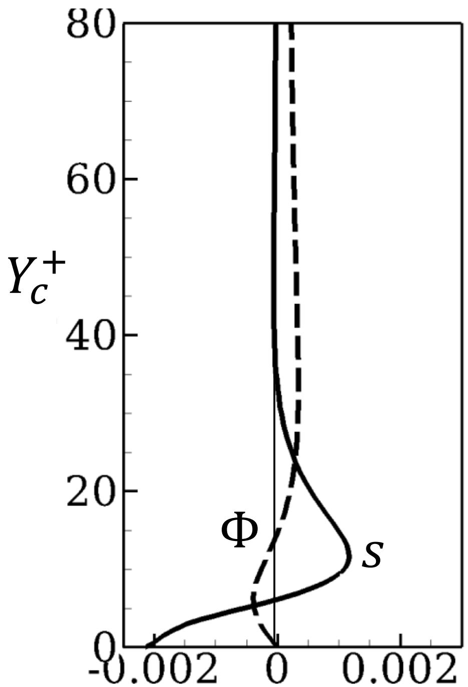

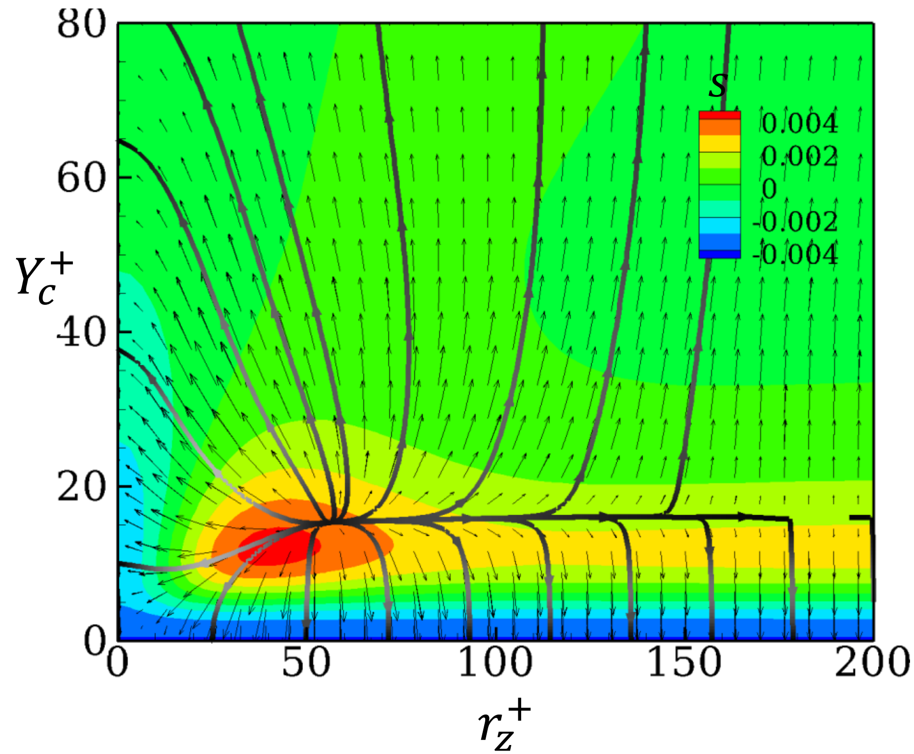

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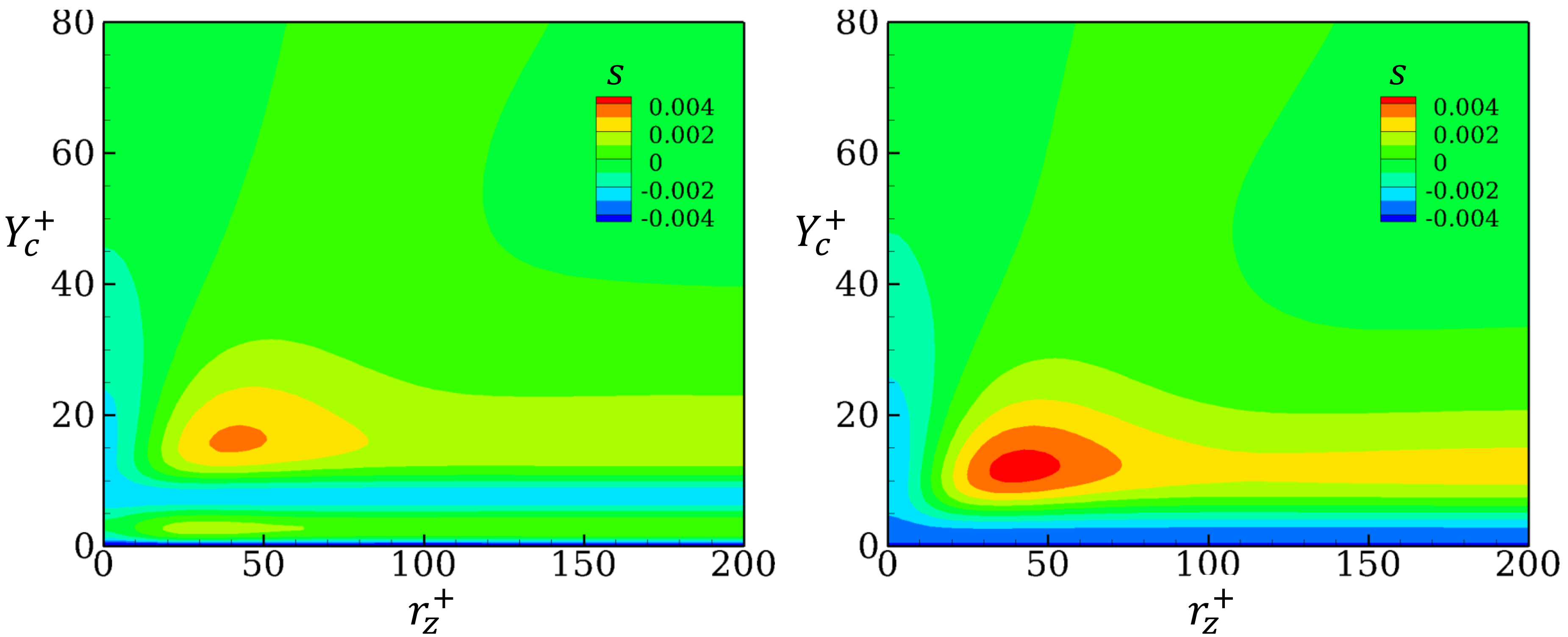
r_z, Y_c space with drag reduction

Opposition Control Reference



r_z, Y_c space with drag reduction

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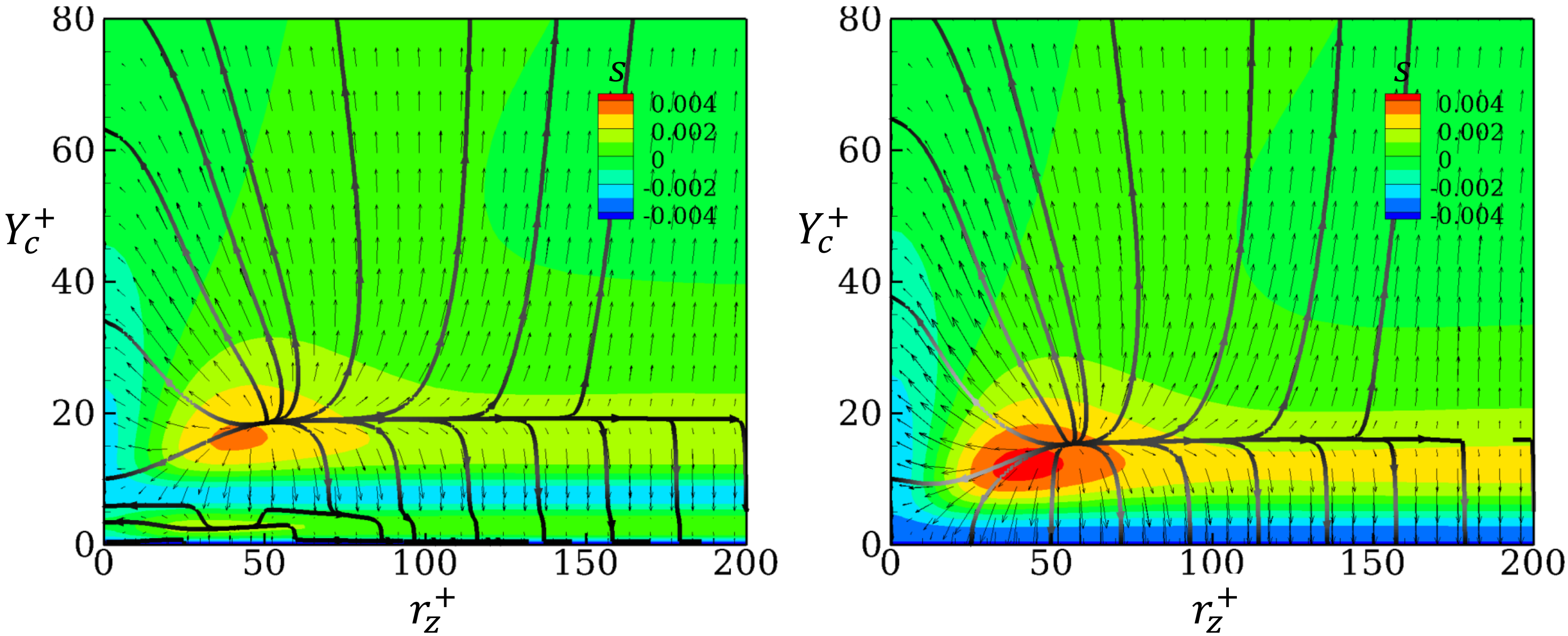
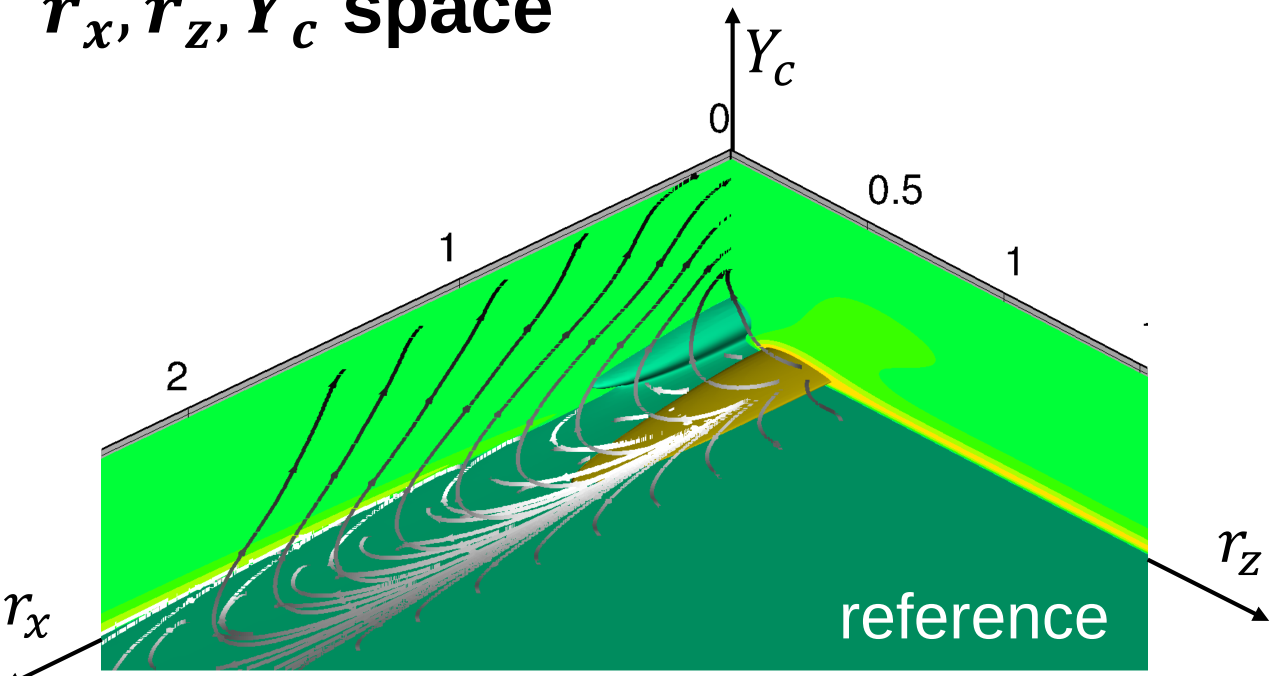
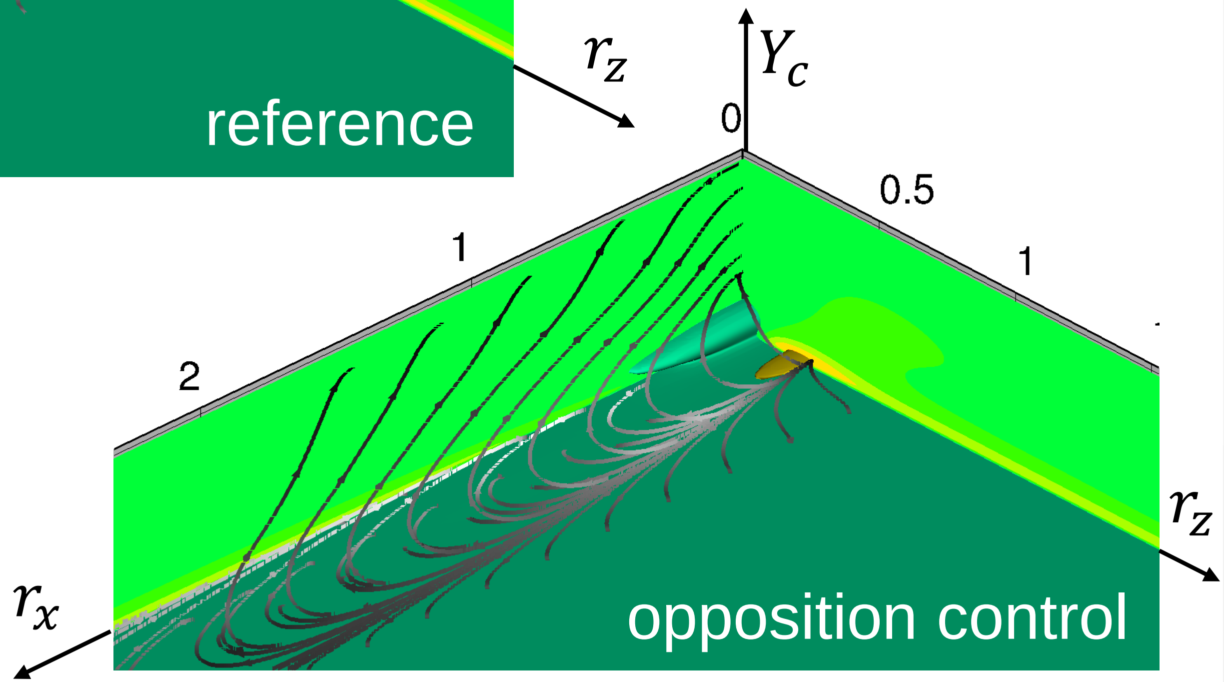


r_x, r_z, Y_c space





Conclusion

- Constant Power Input (CPI) approach
  - is essential to assess energy transfer rates in drag-reduced flows
- Scale energy budget
  - is modified by the control in the near-wall region
  - highlights some mechanisms of drag reduction
- Paths of energy
  - only **small differences** in drag reduced flow…
  - … when the comparison is fair! (CPI)
  - small differences **are important**!!

Outlook

- Quantitatively assess small control-induced changes
- Consider the whole 4D (r_x, r_y, r_z, Y_c)-space
- Consider the budget equation for $\langle \delta u \delta v \rangle$

THANKS

for your kind attention!

for questions, suggestions, complaints:

davide.gatti@kit.edu

Comparing energy transfer rates correctly

successful control $\boldsymbol{R} = 1 - \frac{C_f}{C_{f,0}} > 0$ in turbulent channels

	U_b	$-\frac{\mathrm{d}p}{\mathrm{d}x}$	$\mathbf{P_p} = -\frac{\mathrm{d}p}{\mathrm{d}x} hU_b$	$\mathbf{P_t} = \mathbf{P_p} + \mathbf{P_c}$	$\boldsymbol{C_f}$
CPG	↑	=	↑	↑	↓
CFR	=	↓	↓	?	↓

P_p and P_t change between controlled and natural flow!!

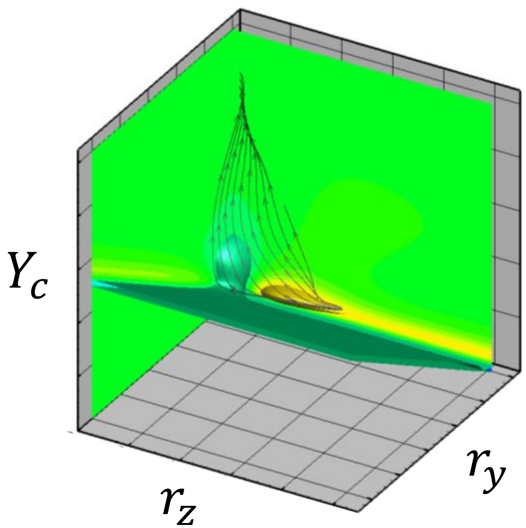
Hasegawa et al., JFM (2014) propose Constant Power Input:

CPI	↑	↓	↓	=	↓

Outlook

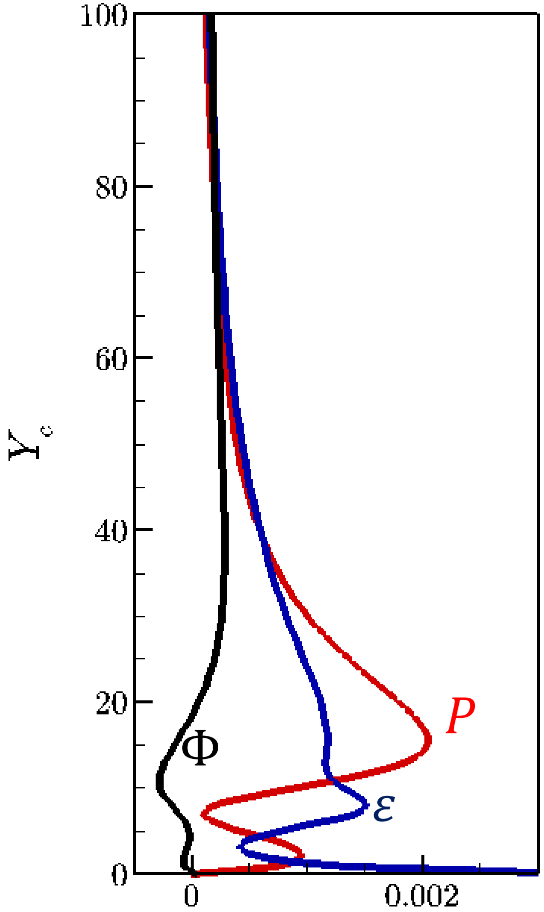
- Quantitatively assess small control-induced changes

- Consider the whole 4D (r_x, r_y, r_z, Y_c)-space

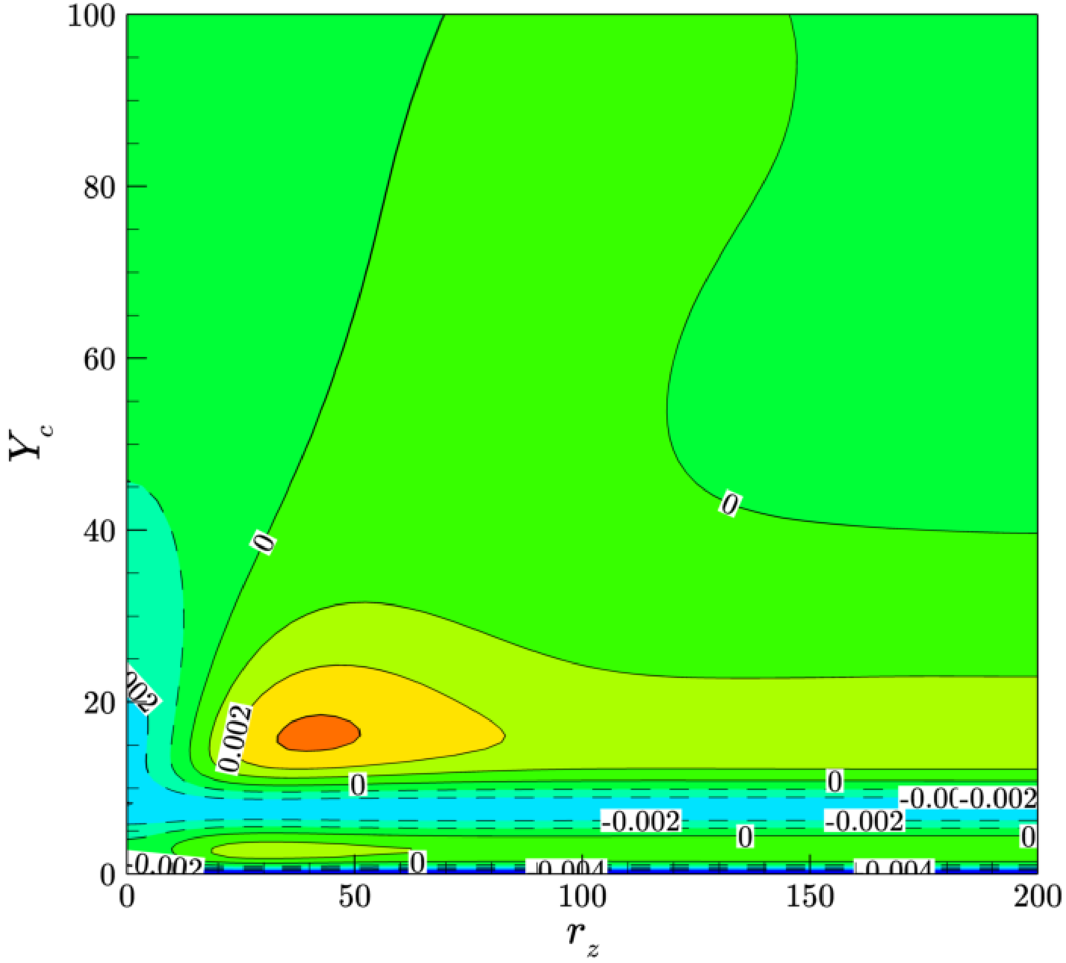


- Consider the budget equation for $\langle \delta u \delta v \rangle$

Results - vc

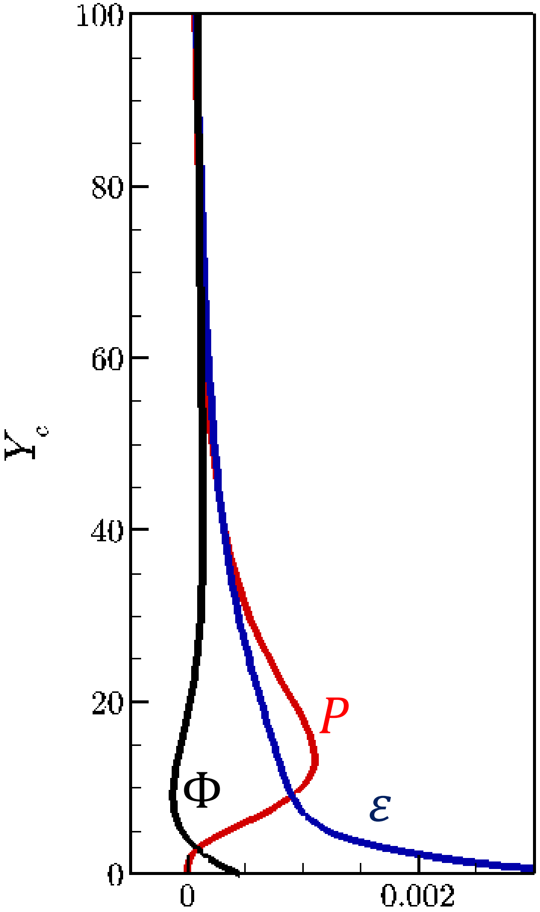


100
80
60
40
20
0
Y_c
0
0.002
Φ
P
ε



100
80
60
40
20
0
Y_c
0
50
100
150
200
r_z
0
0
0.002
0
0
-0.002
-0.002
0
-0.002
0

Results - ow



100
80
60
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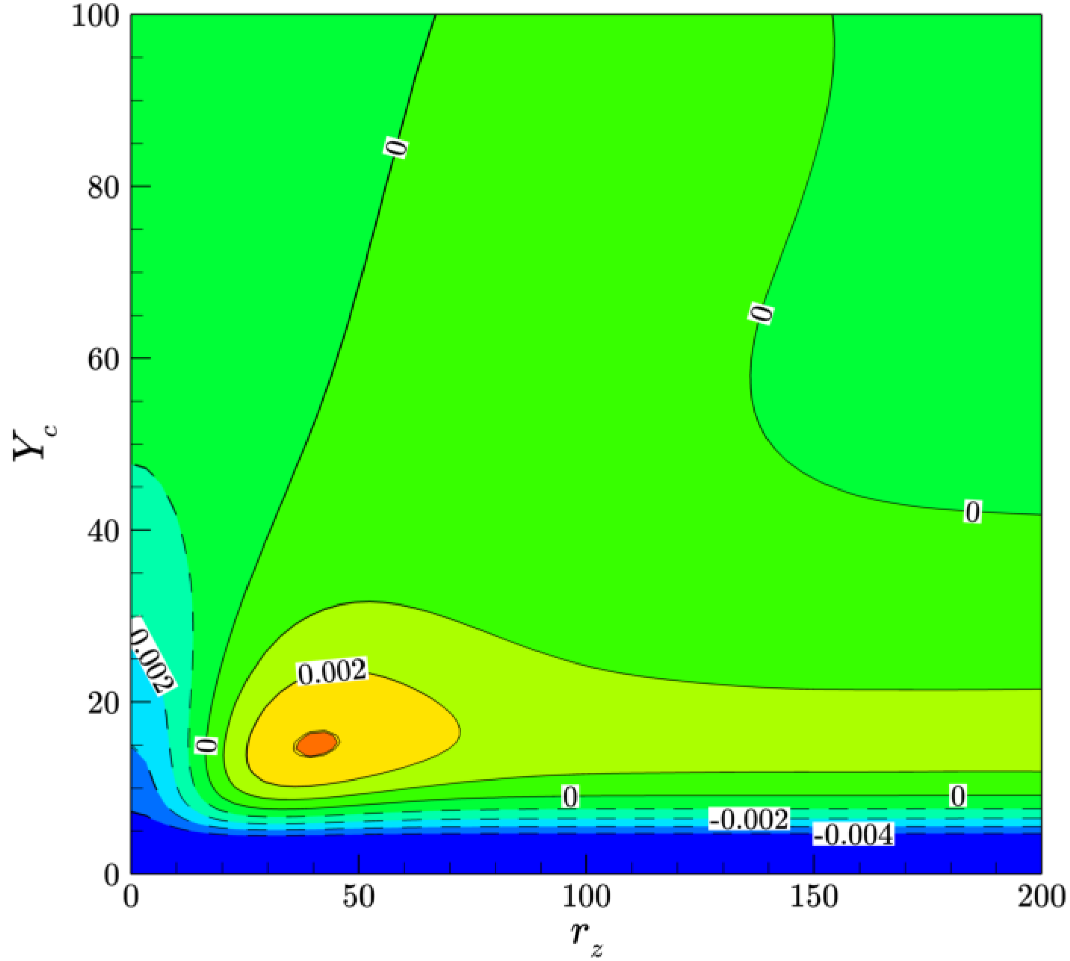
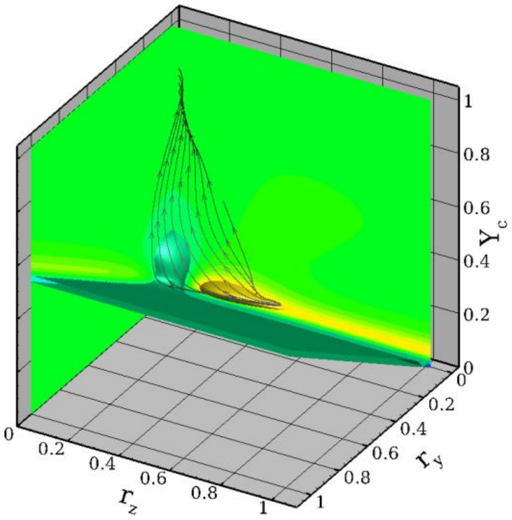
20
0
0
0.002
Y_c
P
Φ
ε

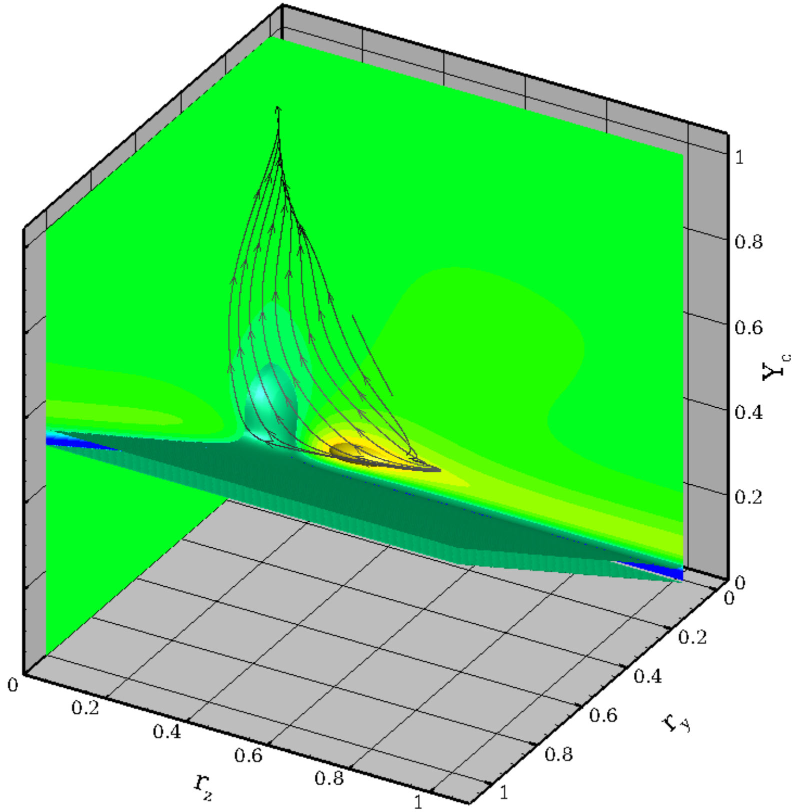


100
80
60
40
20
0
0
50
100
150
200
Y_c
r_z
0
0
0
0.002
0.002
0
0
0
-0.002
-0.004

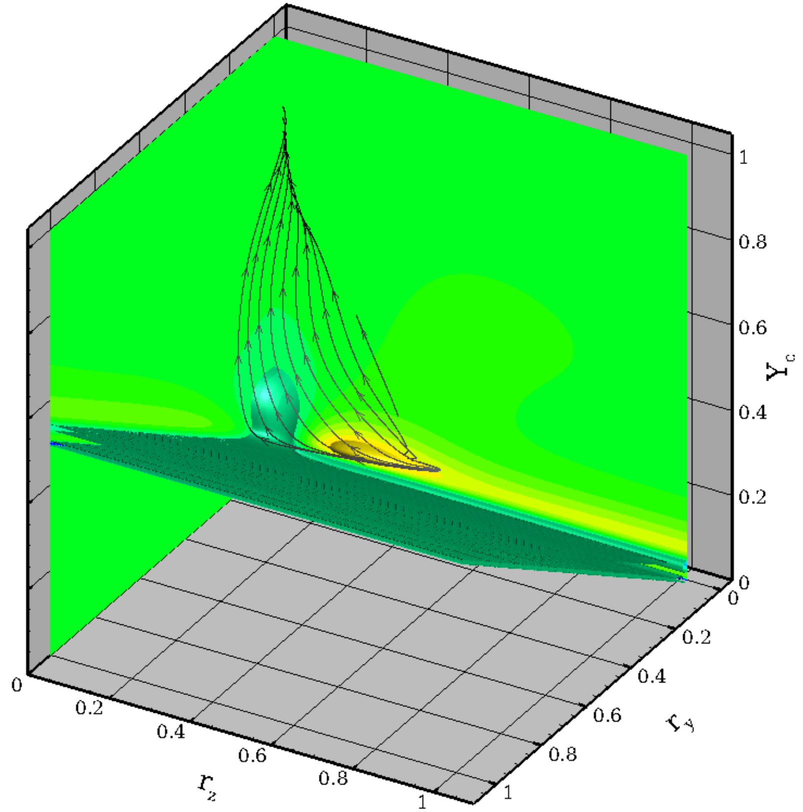
Results - ref



Results - ref



Results - ref



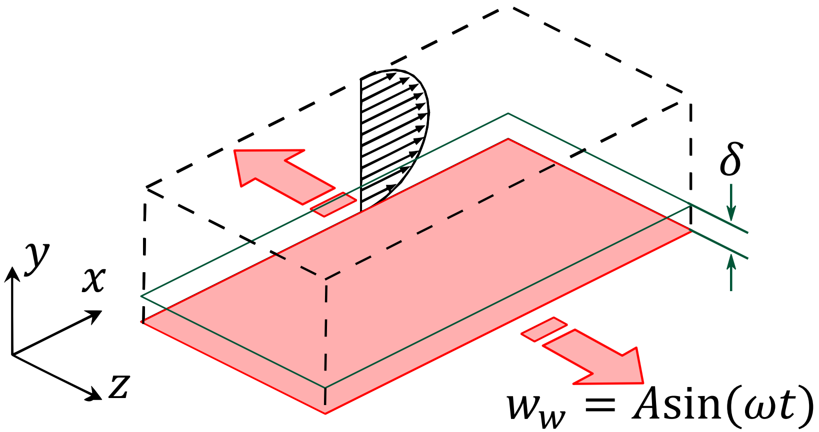
How to drive the flow?

successful control $\boldsymbol{R} = 1 - \frac{c_f}{c_{f,0}} > 0$

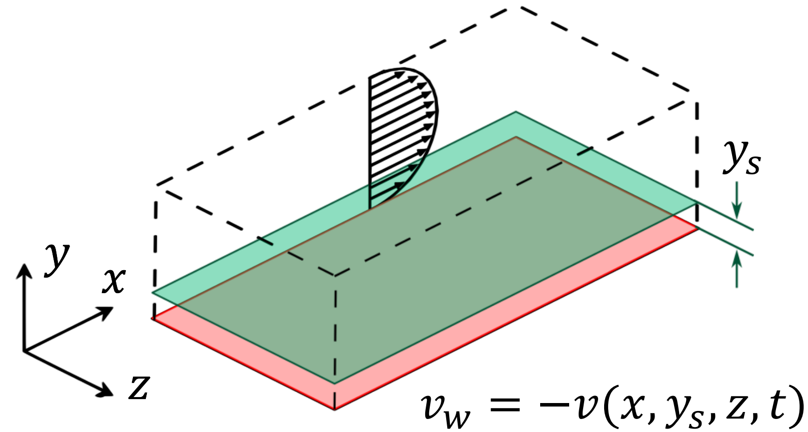
	U_b	$-\frac{\mathrm{d}p}{\mathrm{d}x}$	$\mathbf{P_p} = -\frac{\mathrm{d}p}{\mathrm{d}x} h U_b$	$\mathbf{P_t} = \mathbf{P_p} + \mathbf{P_c}$	$\boldsymbol{c_f}$
CPG	⇧	$=$	⇧	⇧	⇩
CFR	$=$	⇩	⇩	?	⇩

Control strategies

Spanwise wall oscillations



Opposition control



drag reduction $R = 1 - C_f / C_{f,0} = 17.1\%$ $\qquad R = 23.9\%$

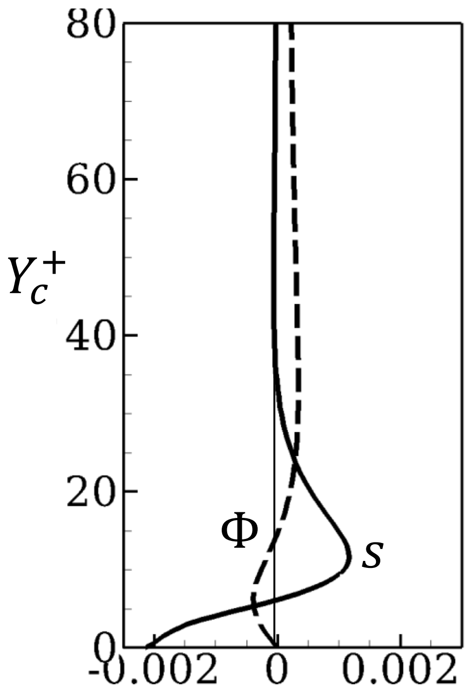
control power fraction $\gamma = P_c / P_t = 0.098$ $\qquad \gamma = 0.0035$

$$\frac{U_b}{U_{b,ref}} = 1.028 \qquad \frac{U_b}{U_{b,ref}} = 1.094$$

Scale energy budget

$k = \frac{1}{2}\langle u_i^2 \rangle$ budget

$$\frac{\mathrm{d}\Phi}{\mathrm{d}Y_c} = P - \epsilon = s(Y_c)$$



$\langle \delta u^2 \rangle$ budget

$$\nabla_{\boldsymbol{r}} \cdot \boldsymbol{\Phi}_{\boldsymbol{r}} + \frac{\partial \Phi_c}{\partial Y_c} = s(\boldsymbol{r}, Y_c)$$

divergence of fluxes

Scale energy budget

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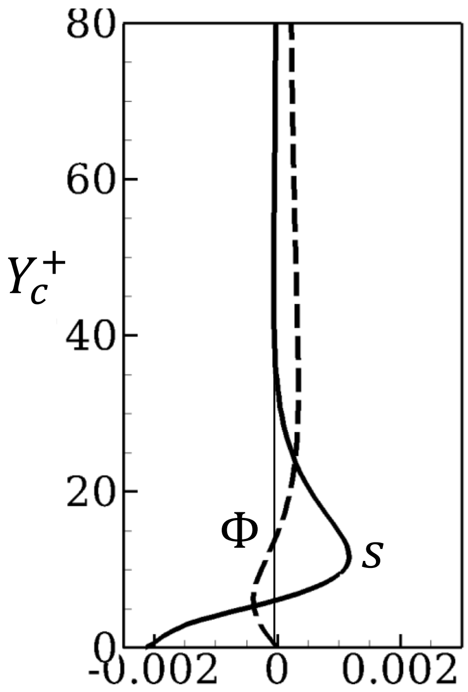

$\langle \delta u^2 \rangle$ budget

$$\boldsymbol{\nabla}_{\boldsymbol{r}} \cdot \boldsymbol{\Phi}_{\boldsymbol{r}} + \frac{\partial \Phi_c}{\partial Y_c} = s(\boldsymbol{r}, Y_c)$$

source term

$s(\boldsymbol{r}, Y_c)$

budget between P and dissipation ϵ

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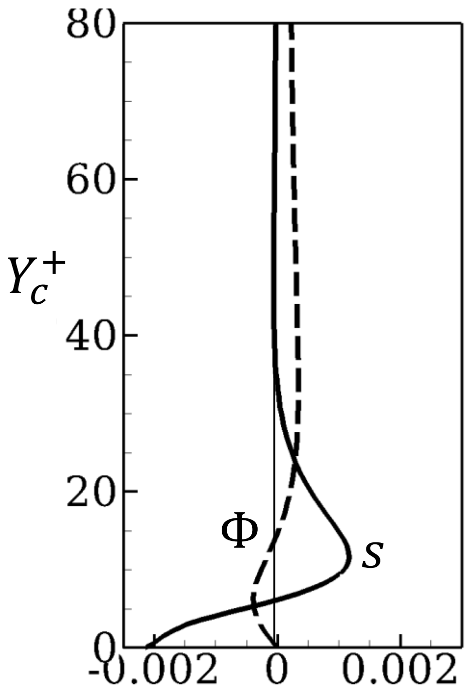

$\langle \delta u^2 \rangle$ budget

$$\boldsymbol{\nabla}_{\boldsymbol{r}} \cdot \boldsymbol{\Phi}_{\boldsymbol{r}} + \frac{\partial \Phi_c}{\partial Y_c} = s(\boldsymbol{r}, Y_c)$$

space flux

↓

$$\Phi_c(\boldsymbol{r}, Y_c)$$

transport of $\langle \delta u^2 \rangle$ in geometric space

in a channel flow, transfer of energy at scale $\boldsymbol{r}$ in Y_c-direction

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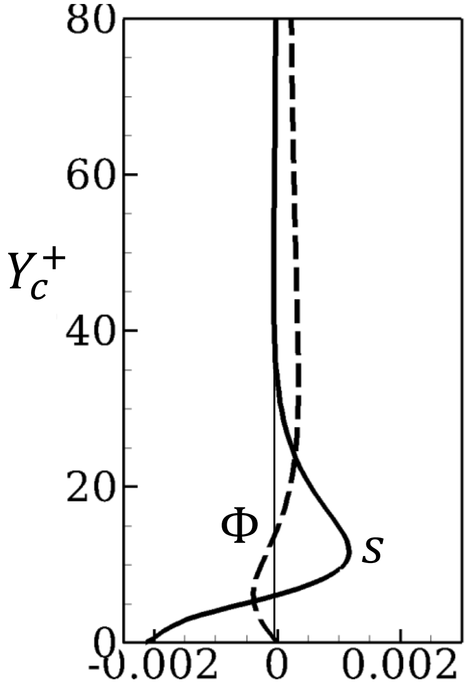

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scale flux

↓

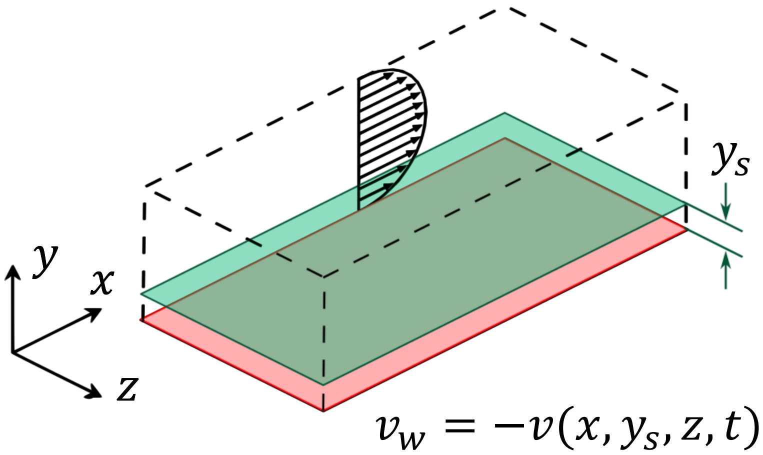
$$\boldsymbol{\Phi}_{\mathbf{r}}(\boldsymbol{r}, Y_c)$$

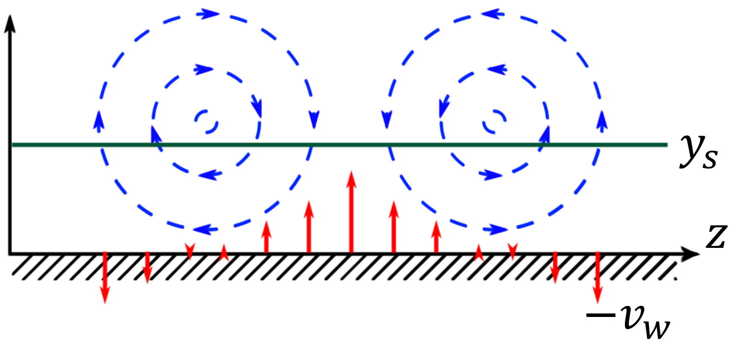
transport of $\langle \delta u^2 \rangle$ across scales $\boldsymbol{r}$

not visible in the TKE budget!

A model control strategy

Opposition Control (Choi, Moin, Kim, JFM94)





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