Flow Control and Turbulence Modeling

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Goals in Turbulence Research

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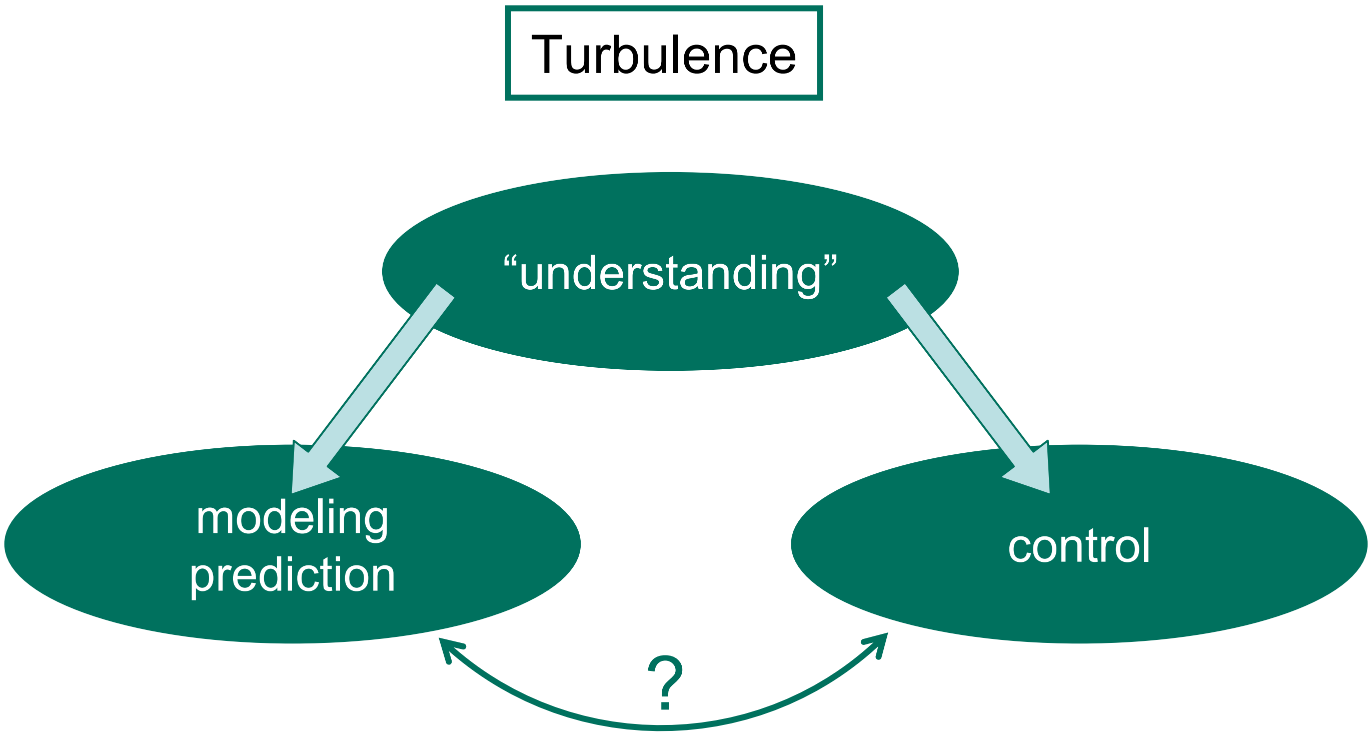

S.B. Pope (PoF 2011, based on APS Otto Laporte Lecture 2009):
The objective of developing theories and models is of particular importance as the methodologies developed often can be used to achieve other objectives such as control of turbulent flows.

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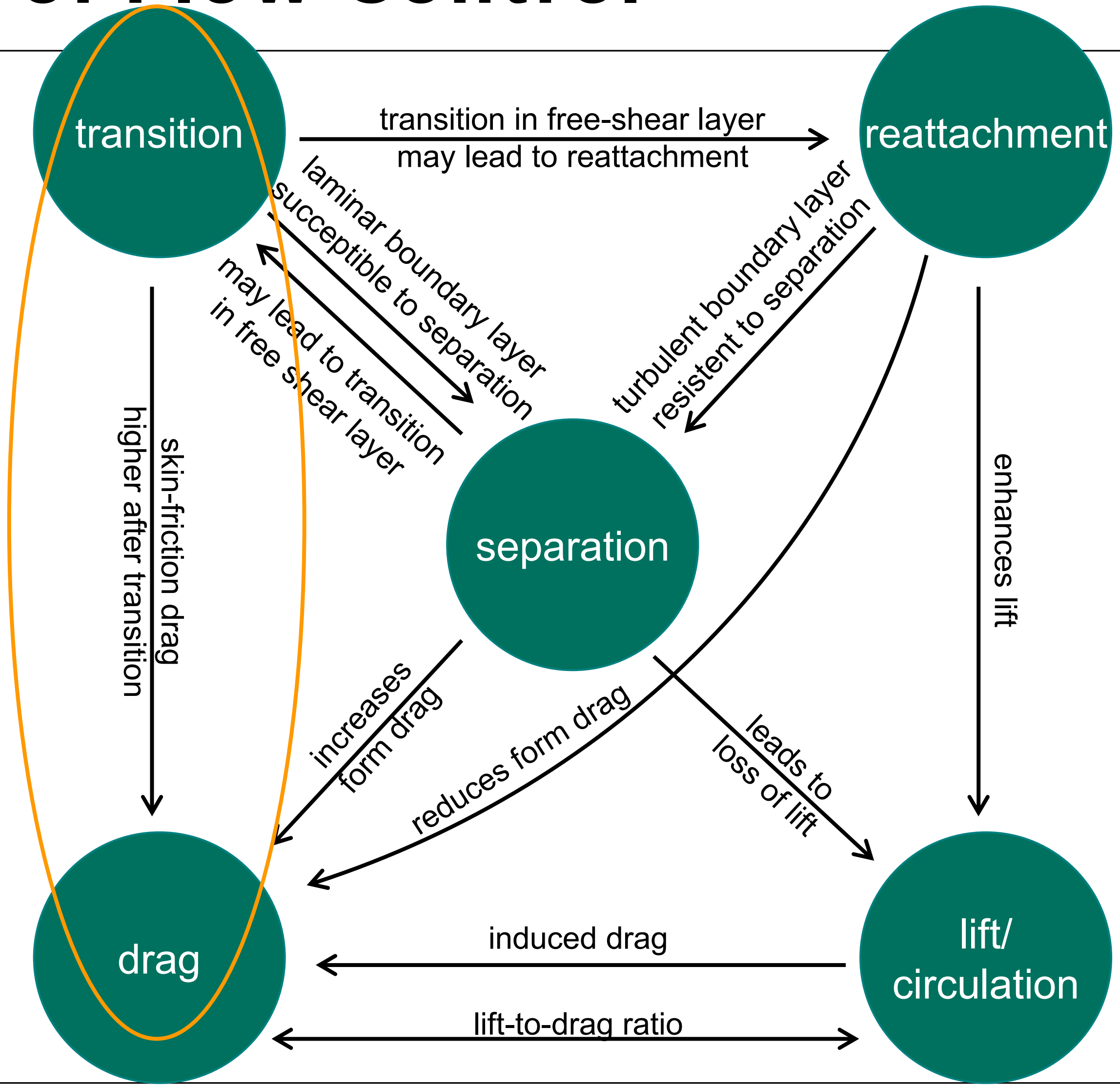
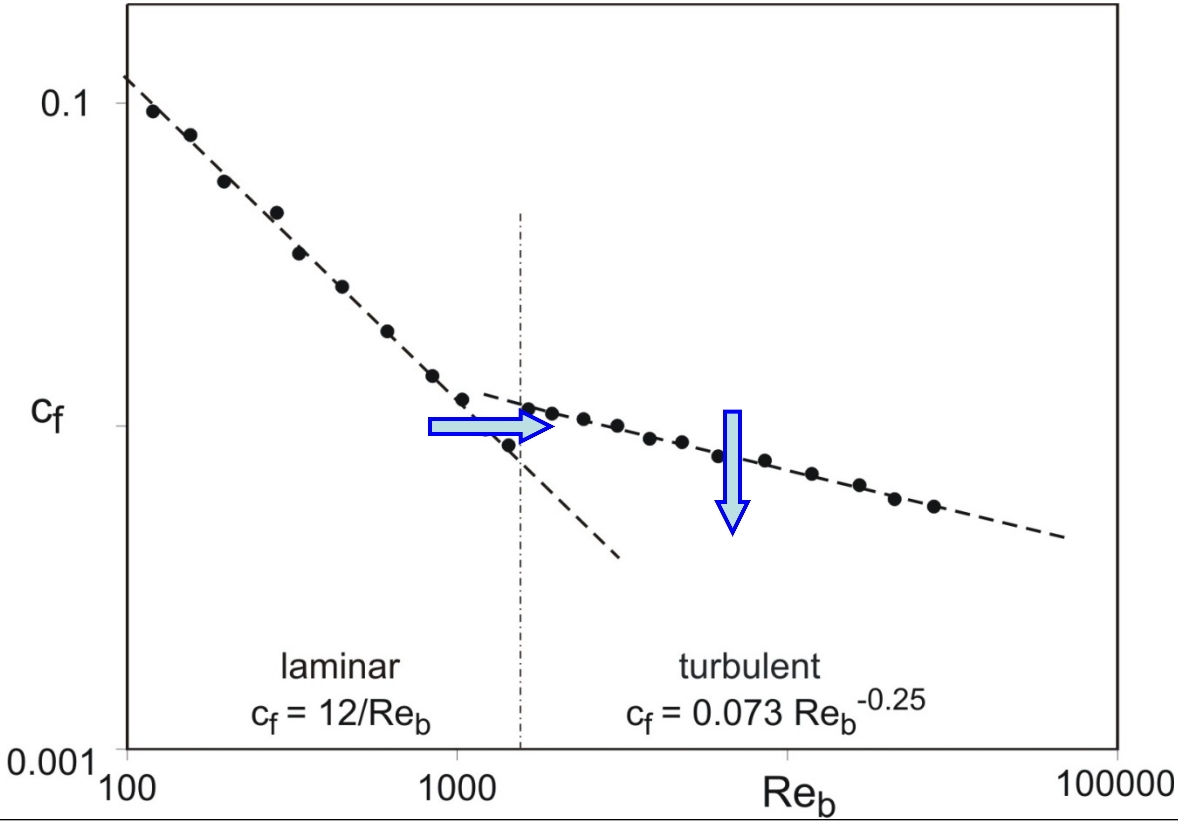
Goals of Flow Control



Gad-el-Hak, 2000

Skin Friction Reduction

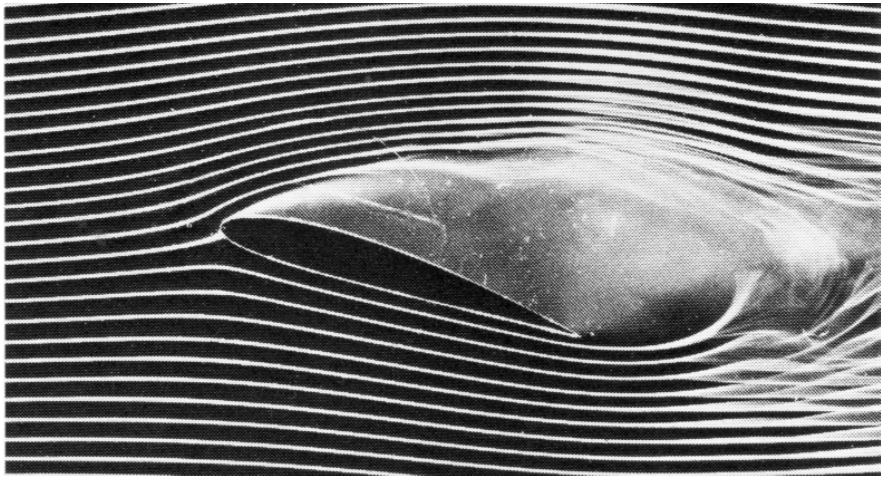
Friction coefficient $c_f = \frac{\tau_w}{\frac{1}{2}\rho \overline{U}^2}$ $\qquad \tau_w = \mu \left(\frac{d\overline{U}_1}{dx_2} \right)_{Wall}$ $\qquad DR = 1 - \frac{\tau_{w,\text{new}}}{\tau_{w,\text{old}}}$



Postpone laminar to turbulent transition to higher Reynolds numbers

Drag reduction in turbulent flows

Drag in a Flow Field



Fantasy of Flow, 1993

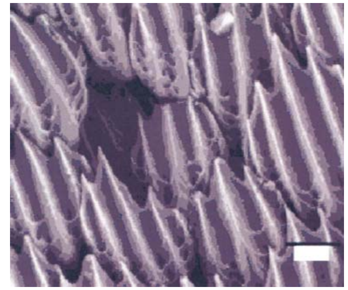
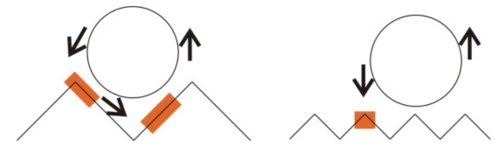
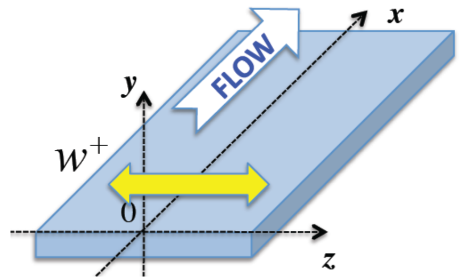
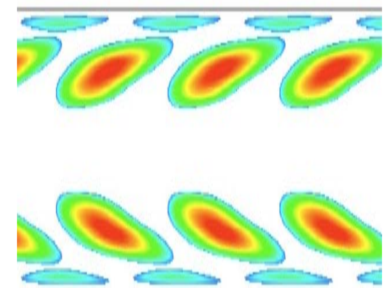
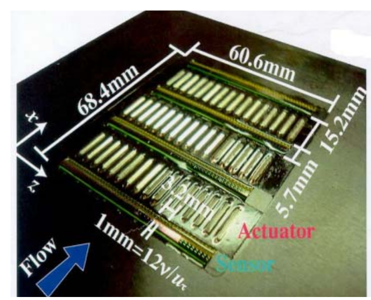
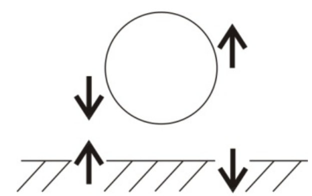
Skin friction drag constitutes

- 40 - 50% of the total drag on airplanes
- 50 - 90% of the total drag on (under)water vehicles
- up to 100% of the total drag in pipelines

Possible savings

- 20% drag reduction on airplanes
  1 Billion Dollar/Year (Gad el Hak, 2000)
- 10% drag reduction on surface ships
  5 Billion Dollar/Year (Gollup, 2006)
- 7 instead of 10 pumpstations in
  Transalaska Pipeline (www.alyeska-pipe.com)

Flow Control Methods

Passive	Additives Morphology Physical Chemistry		 high friction low friction
Active (predetermined)	Actuators: Wall movement Wall fluxes Body Forces		
Reactive (closed loop)	Actuators & Sensors: Wall movement Wall fluxes Body Forces		 Attenuation of QSV

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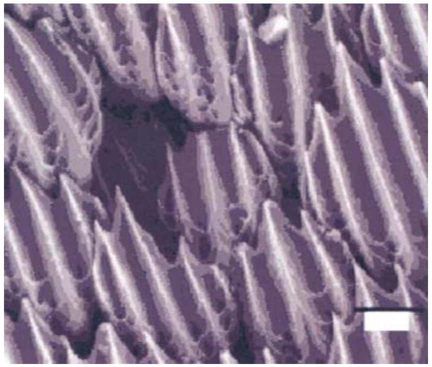
Flow Control with Additives

www.wikipedia.de

- additives (especially long-chain polymers) are used in practical applications
- research: experimental & DNS
- in DNS: model of polymer-flow interaction
- some remaining discrepancies between experiment and DNS and different “opinions” in respect to the underlying physical mechanism
- additives cannot be used in all situations, but the engineering dream would be to reproduce this DR effect by other means!
- RANS prediction?

current DR world record: 96.5% at Re=200.000,
flow with polymeric and fibrous additives in pipe with Ø 2.4cm (Lee et al. 1974)

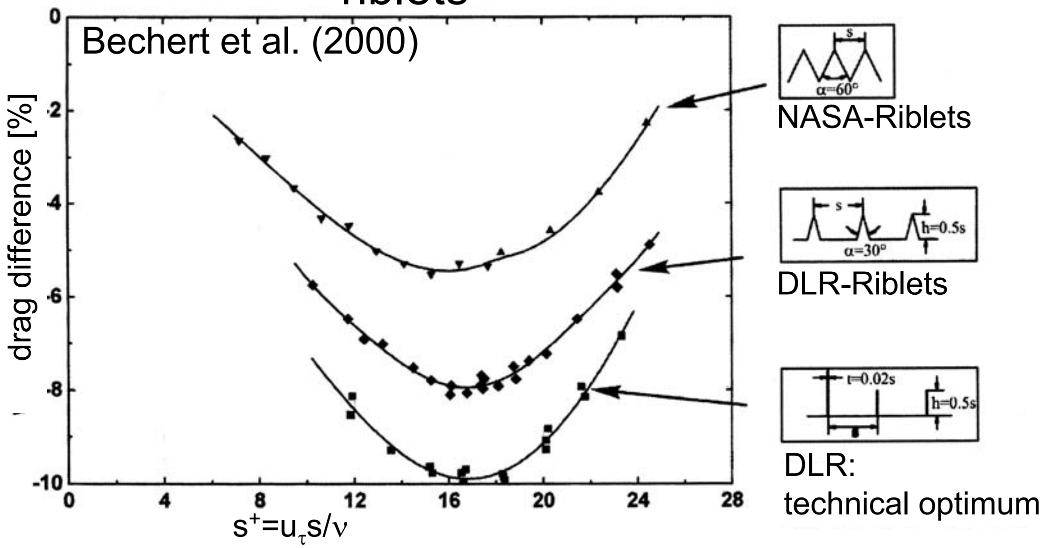
Flow Control with Riblets



Riblets
experiments: broad parameter study
analytical work for viscous regime
DNS

high Re-number testing on airplanes (1-2% fuel saving), application on yacht for America's cup

riblets



goal: increase drag reducing potential to reach break even point for applications

Using LES for flow control - wavy riblets

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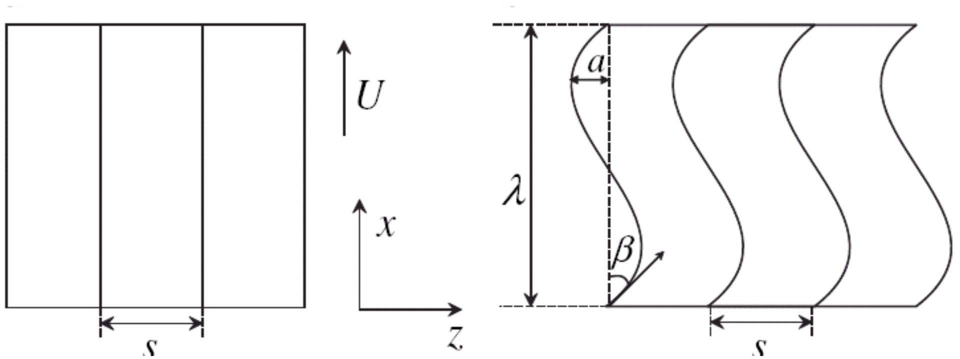
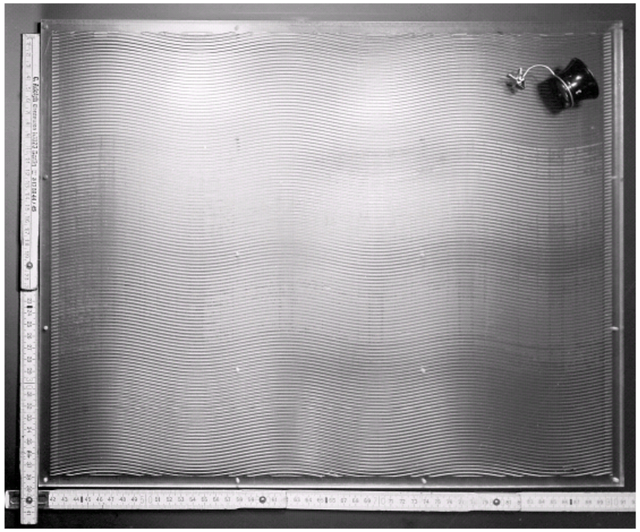
sinusoidal riblets / 3D riblets



Peet & Sagaut (2009)

LES Results
$DR_{max} \approx 14\%$

DNS & Experiments (Berlin group, 2010):
no positive effects of sinusoidal shape



Kramer et al. (2010)

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(Re-)Active Control

Net energy savings are difficult to realize!

Net energy budget

- Pumping power: P
- Power saving: P'
- Control input: P_{in}

Definitions

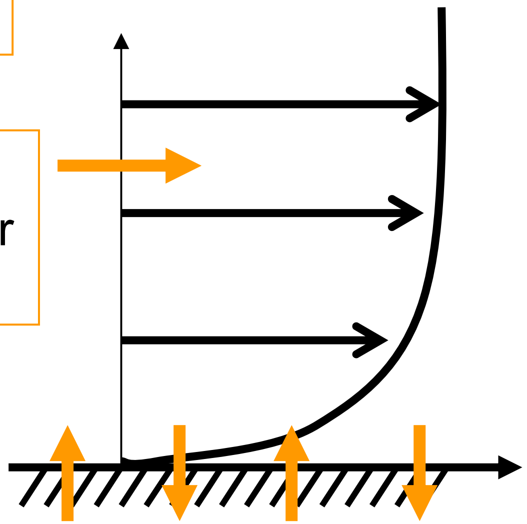
- Net energy saving

$$E_{net} = (P - P') - P_{in}$$

- energy gain

$$G = \frac{E_{net}}{P_{in}}$$

Reduced pumping power $P - P'$

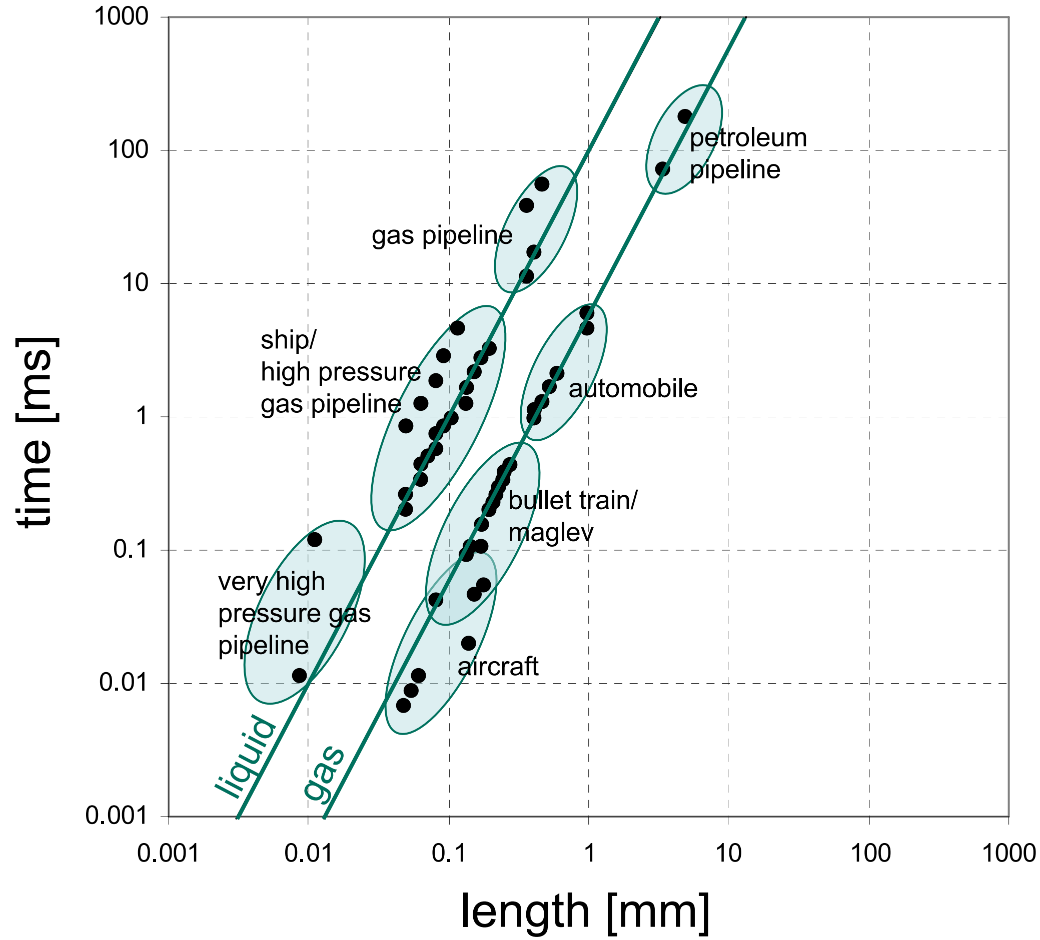


Control input

Reactive control: G = 100 ~ 300

Active control: G ~ 1.7

Challenges for Reactive Control



typical length scale of near-wall vortices

10µm – 1mm

→ MEMS

typical time scale of near-wall vortices

10µs – 10ms

→ real time control

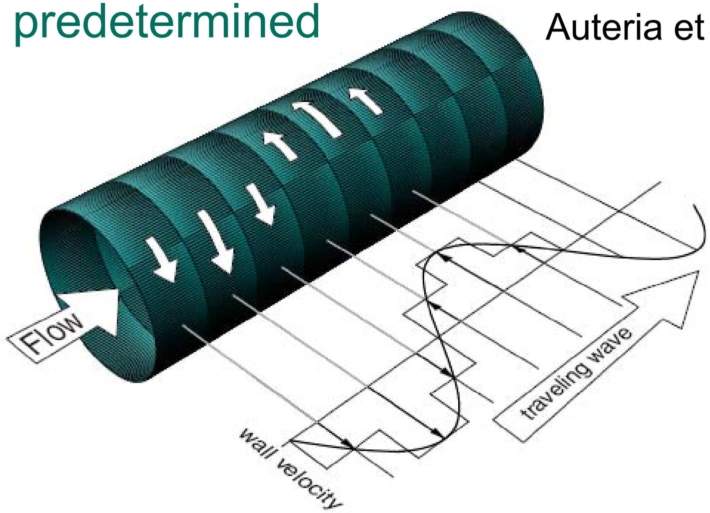
Kasagi et al., 2009

Present Challenges

active and reactive control is mostly done in DNS (low Reynolds number)
very few experiments (also at low Re) – proof of principle

predetermined

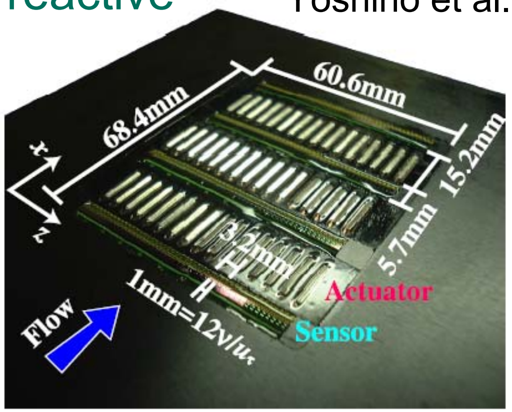
Auteria et al., 2010



travelling wave in pipe
$DR_{max} \approx 30\%$, $G_{opt} \approx 1.5$
$G_{real} \approx 2.4 * 10^{-5}$ (huge net losses)

reactive

Yoshino et al., 2008



arrayed hot-film sensor and wall deformation actuators
GA optimization, 10hour optimization, about 6% DR

Reynolds Number Dependency

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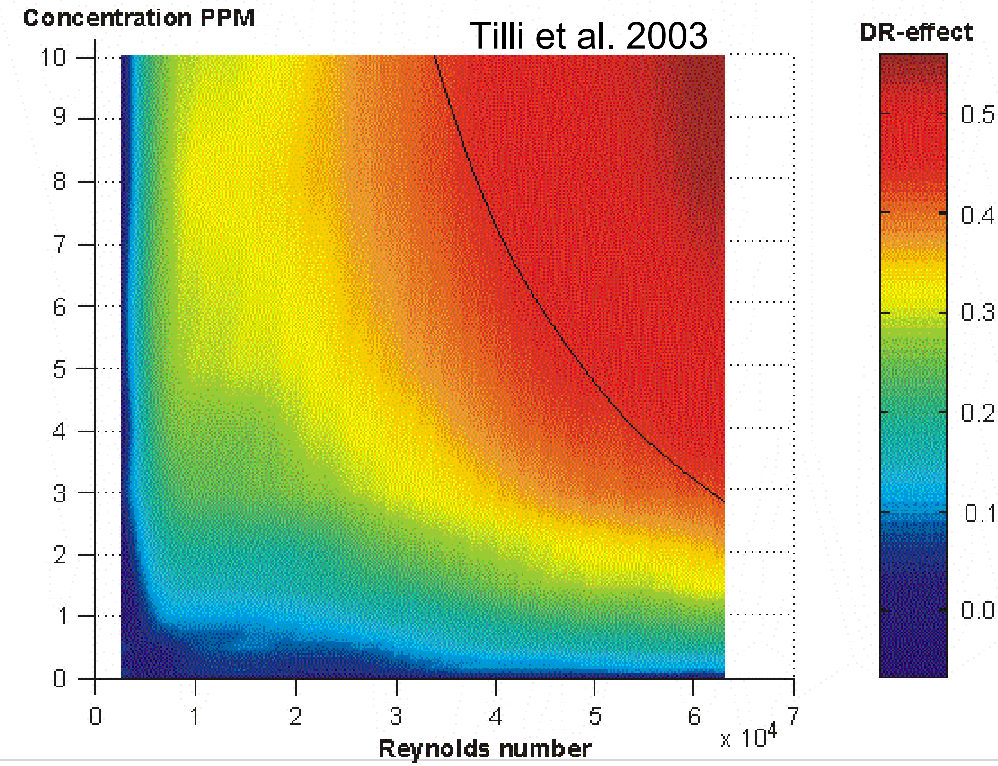
- **polymer drag reduction**



- **streamwise travelling waves** of spanwise wall velocity, **DR decreases weakly with Reynolds number** (up to Re_b=10000), similar for spanwise wall oscillation; further tests with LES did not produce comparable results to DNS so far

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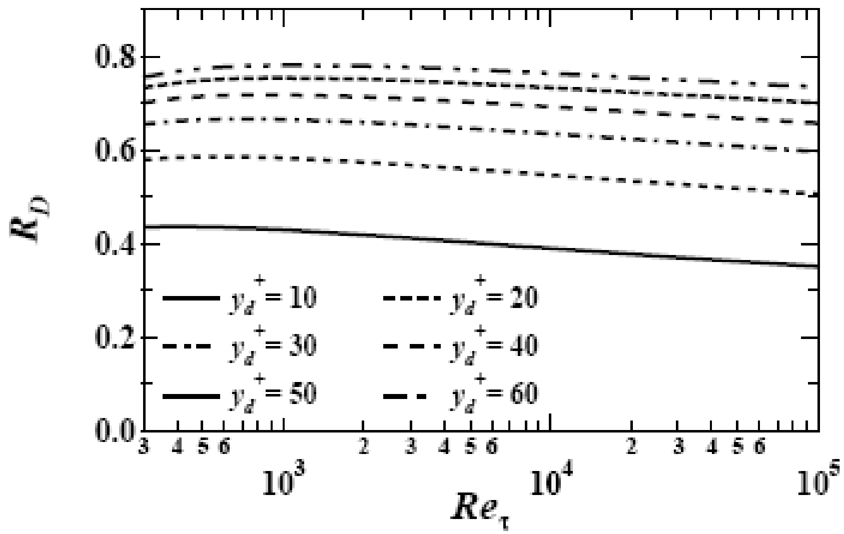
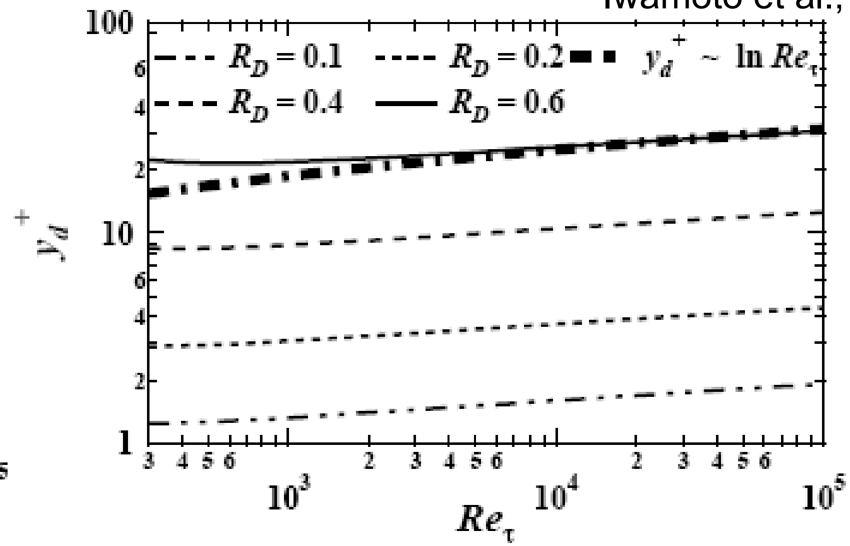
Reynolds Number Dependency

Iwamoto et al., 2005

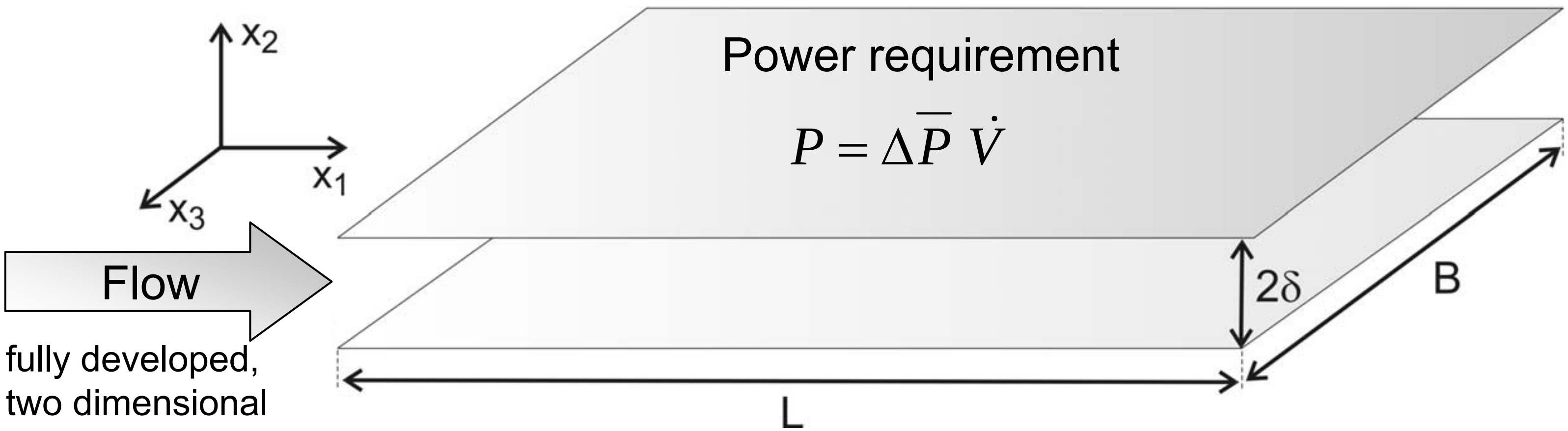




ideal damping of turbulence near the wall, weak Reynolds number dependence
(damping of large scale structures is less effective)

If it were possible to capture viscous drag reduction with turbulence models important insight in respect to the Re-number dependency could be gained…

Turbulent Channel Flow



fully developed,
two dimensional

momentum balance (RANS)

$$-\frac{\partial \overline{P}}{\partial x_1} = \frac{\rho U_b^2}{2\delta} c_f \qquad c_f = \frac{12}{Re_b} + 12 \int_0^1 2\,(1 - x_2)\,(-\overline{u_1 u_2})\,dx_2$$

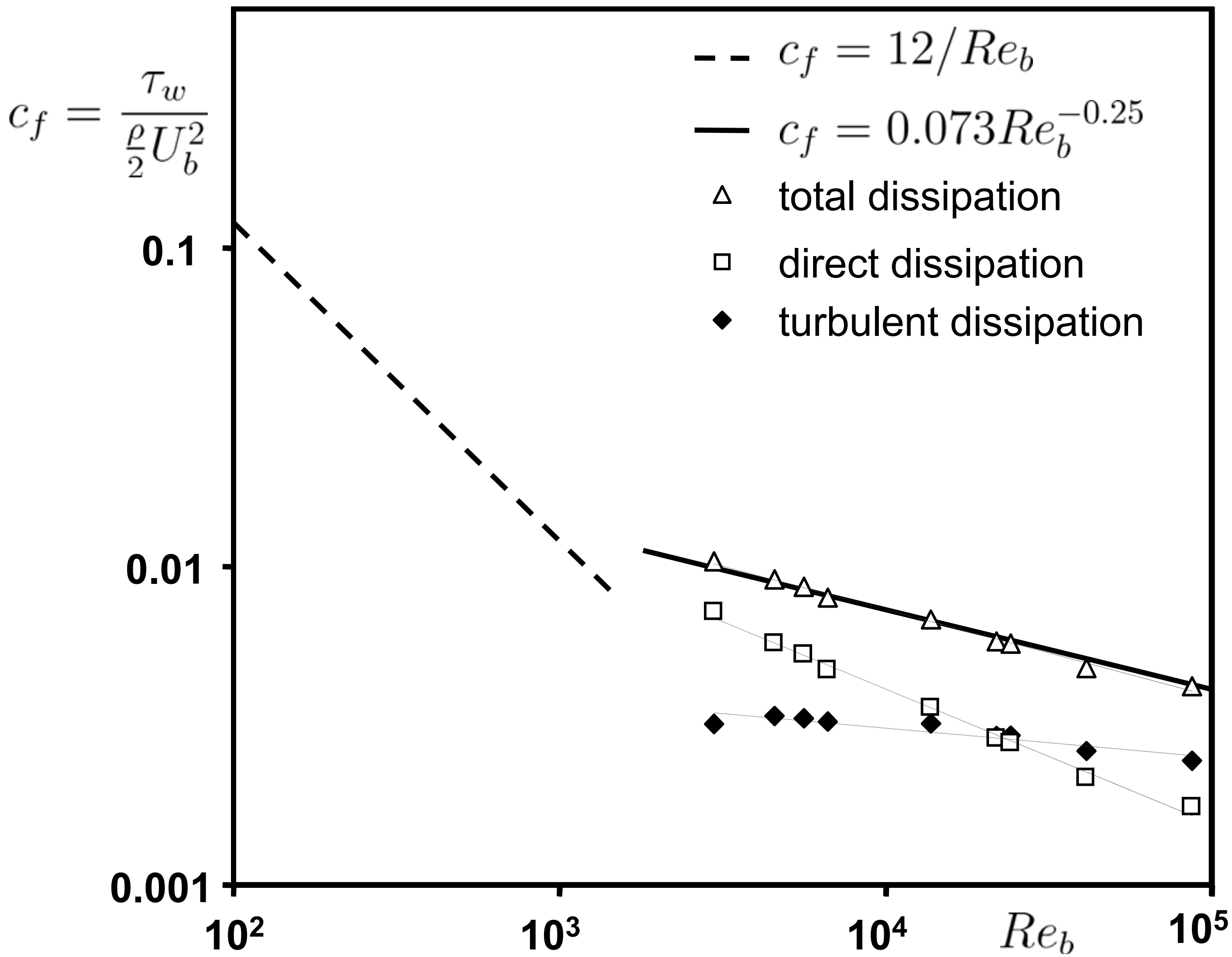
Fukagata et al., 2002

energy balance

$$-\frac{\partial \overline{P}}{\partial x_1} = \frac{\rho}{U_b} \Phi \qquad \Phi = \frac{1}{V} \int_V (\epsilon_{dir} + \epsilon)\,dV$$

$$\epsilon_{dir} = \nu \left(\frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i} \right) \frac{\partial \overline{U}_i}{\partial x_j} \qquad \epsilon = \nu \overline{\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j}}$$

Skin Friction and Energy Dissipation Rate



Total Energy Dissipation Rate

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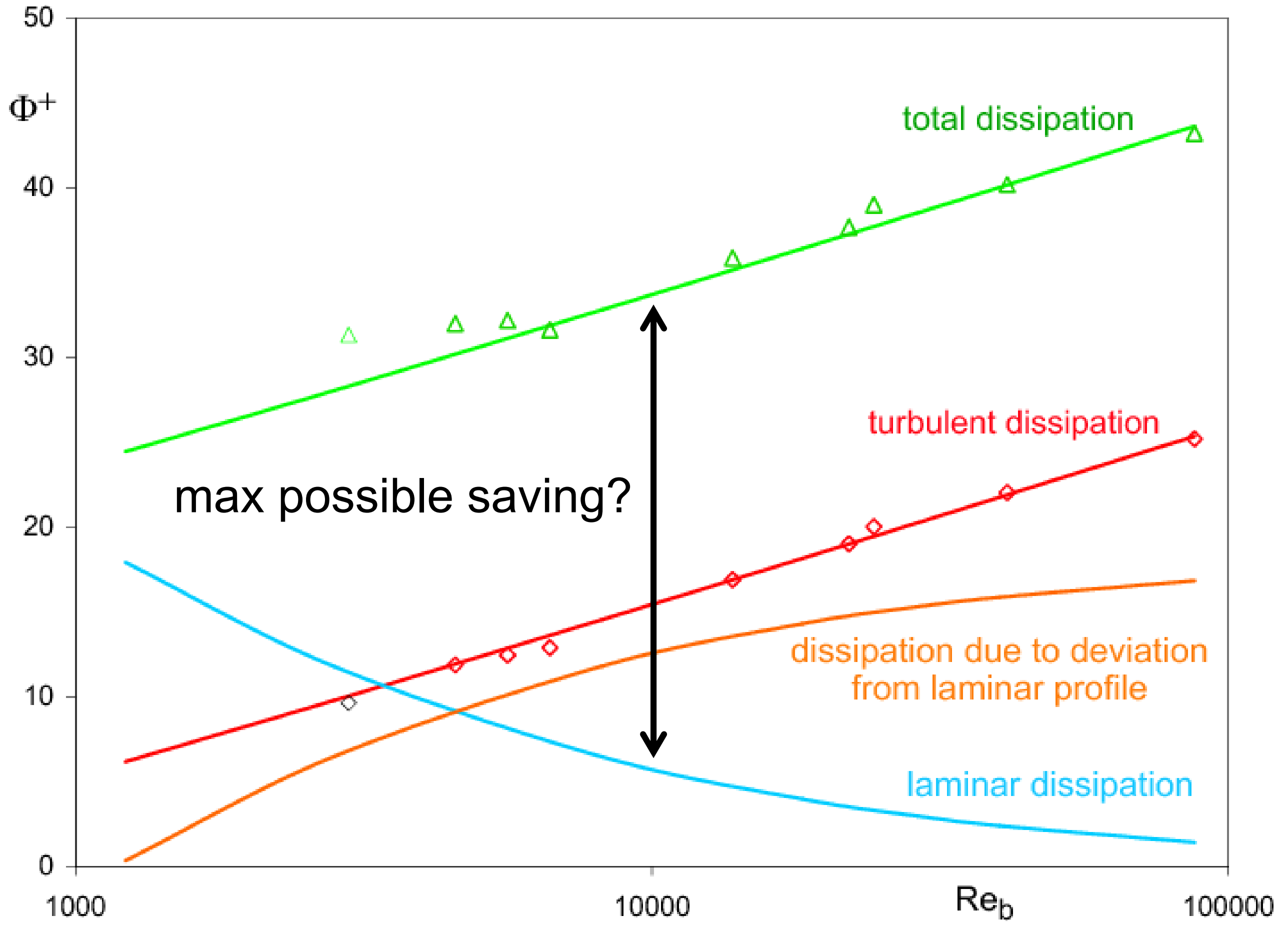

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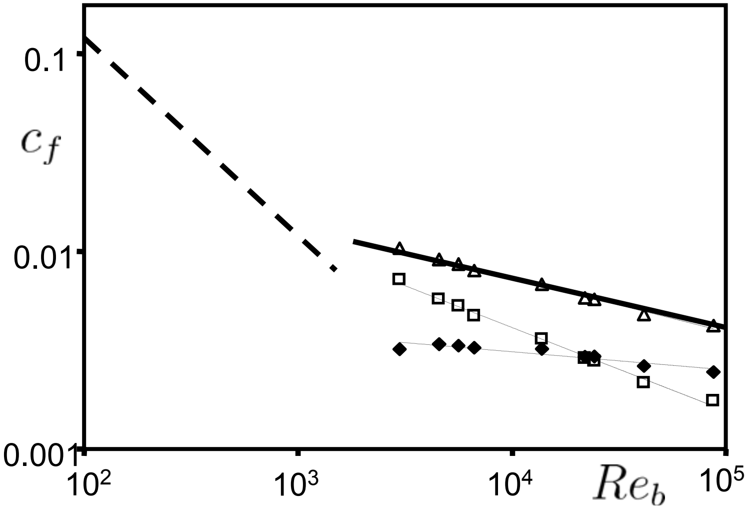
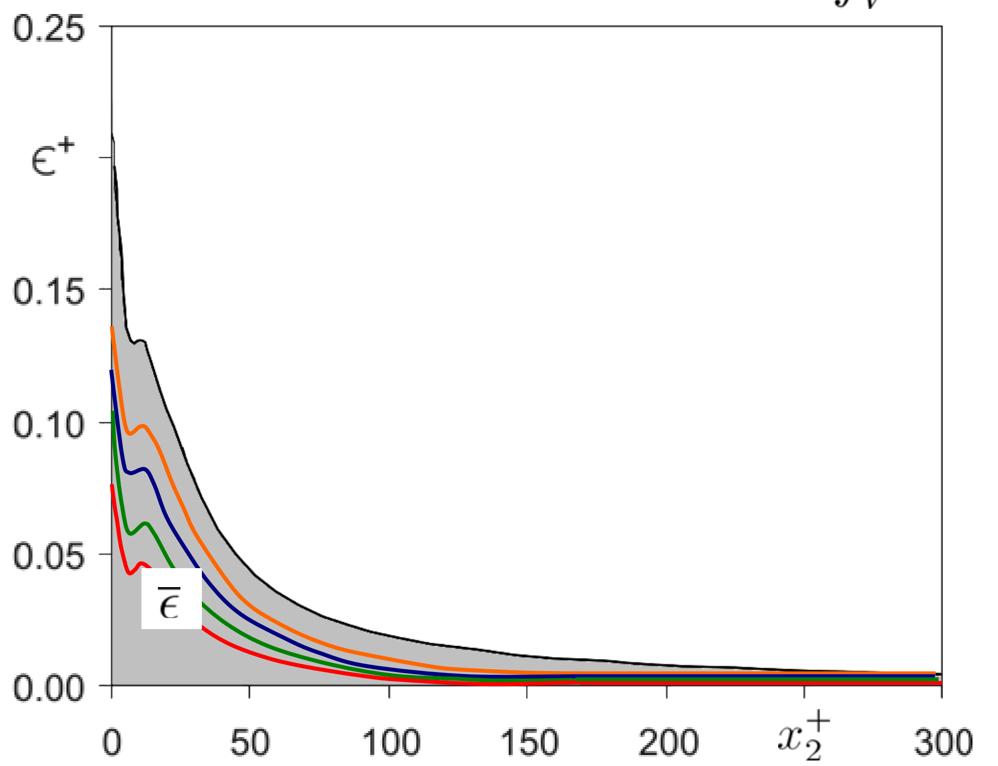
Turbulent Dissipation



turbulent dissipation $\epsilon = \nu \overline{\frac{\partial u_i}{\partial x_k} \frac{\partial u_i}{\partial x_k}}$

turbulent dissipation rate $\overline{\epsilon} = \frac{1}{V} \int_V \epsilon dV$



drag reduction

$$min\left(\epsilon_{Wand}\right) \leftrightarrow min\left(\overline{\epsilon}\right)$$

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Anisotropy-Invariant Map

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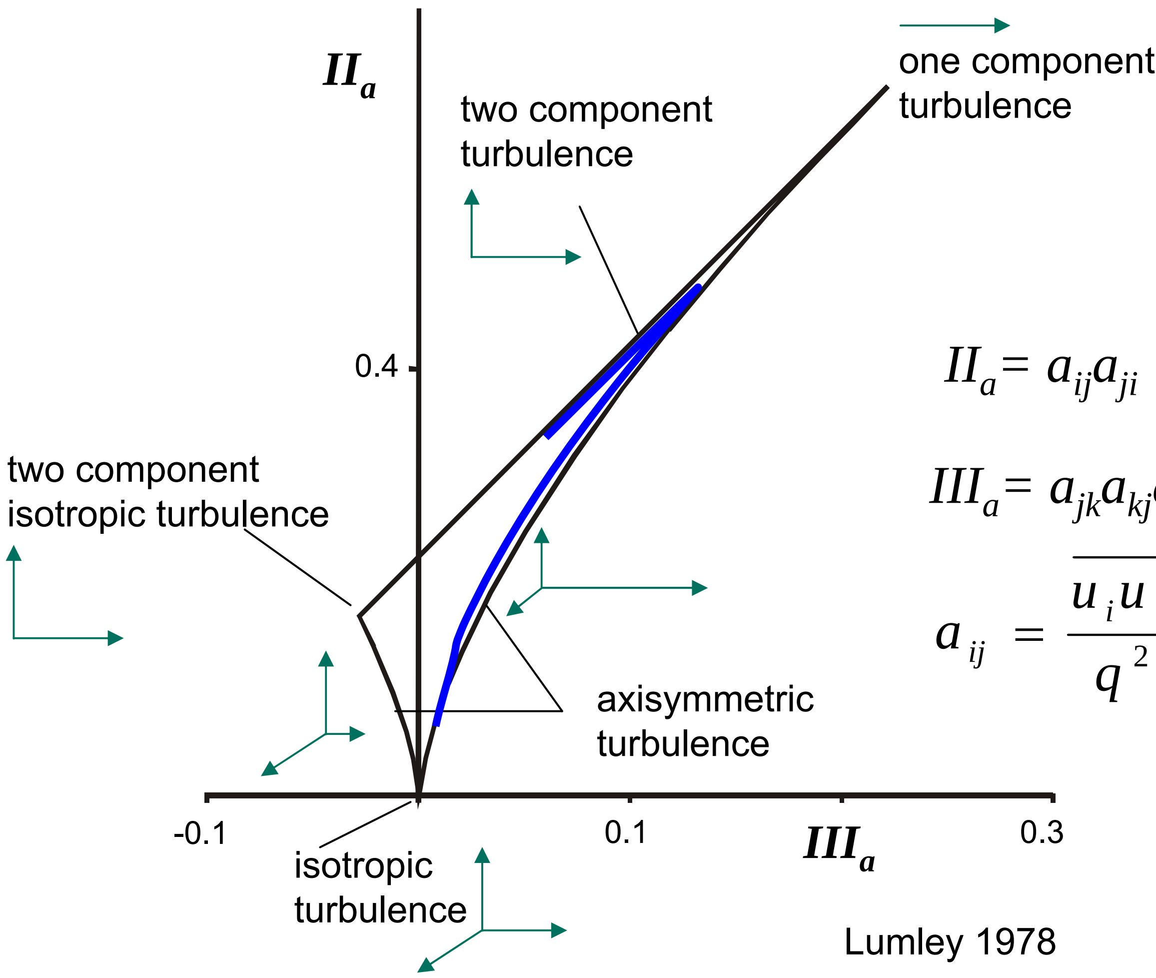

$$II_a = a_{ij}a_{ji}$$

$$III_a = a_{jk}a_{kj}a_{ij}$$

$$a_{ij} = \frac{\overline{u_i u_j}}{q^2} - \frac{1}{3}\delta_{ij}$$

Lumley 1978

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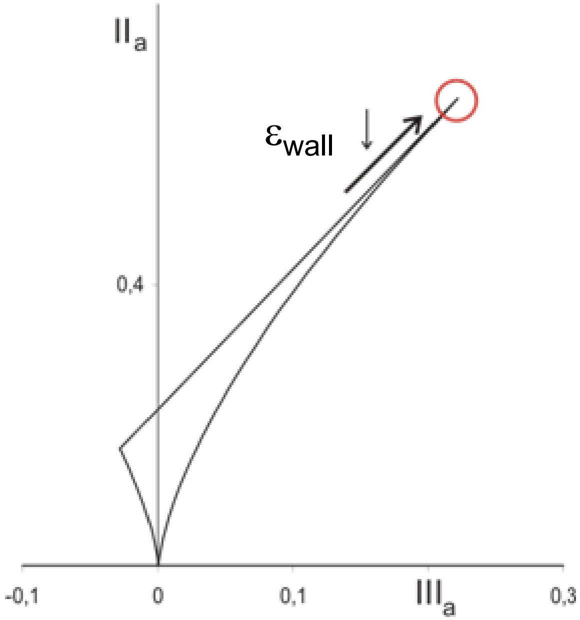
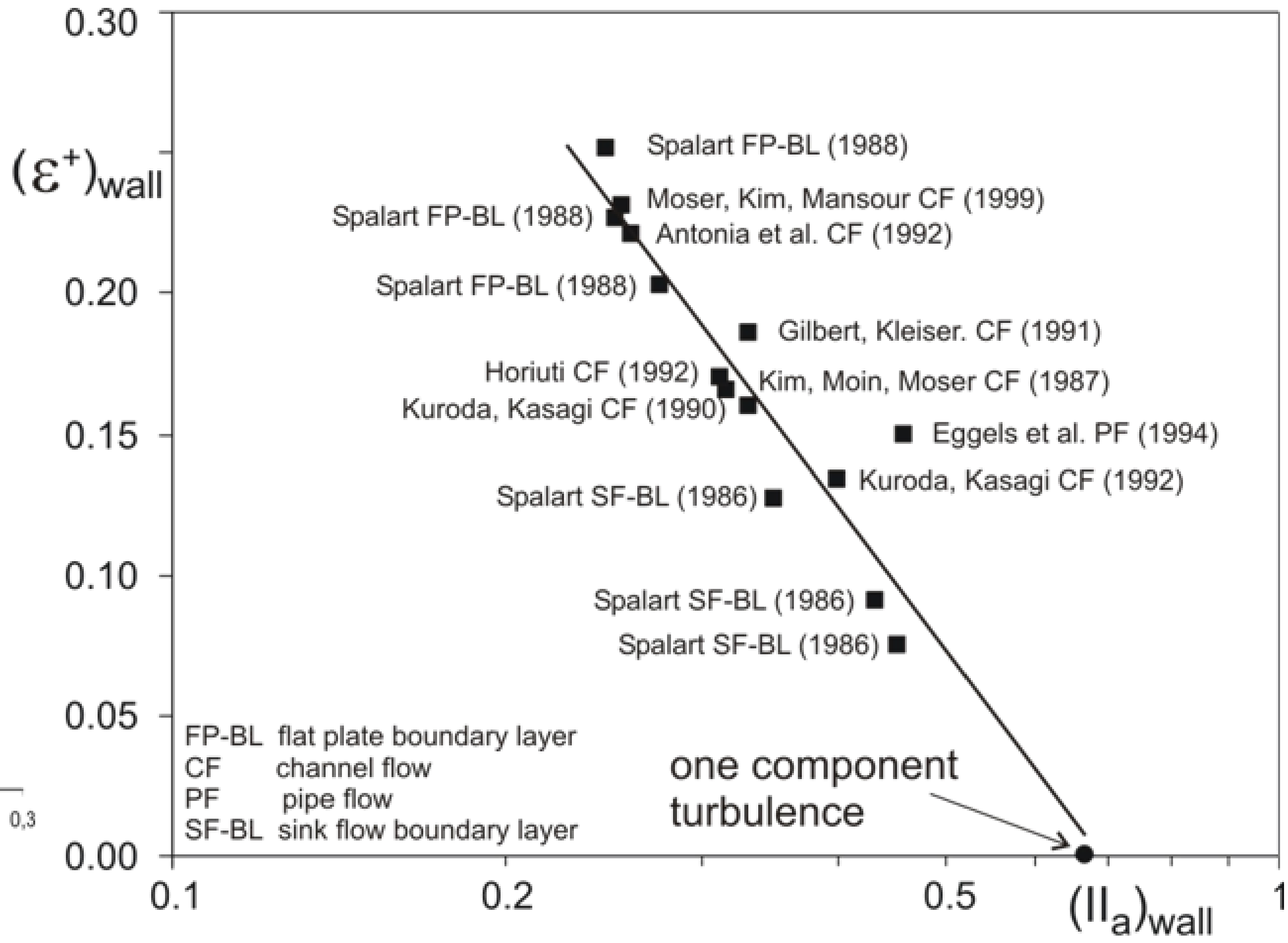
Turbulent Dissipation at the Wall





The Limiting State at the Wall

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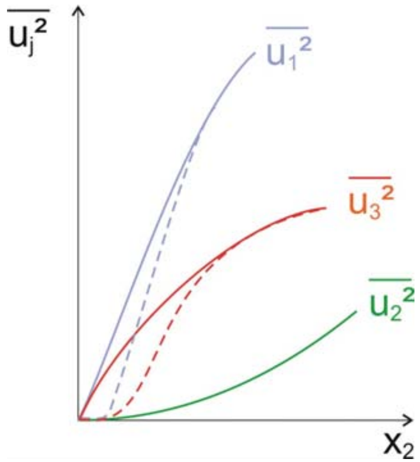
series expansion for u_j around the wall
Monin and Yaglom (1987)

$$\left.\begin{aligned} u_1 &= a_1 x_2 + a_2 x_2{}^2 + \ldots \\ u_2 &= \qquad\quad b_2 x_2{}^2 + \ldots \\ u_3 &= c_1 x_2 + c_2 x_2{}^2 + \ldots \end{aligned}\right\} \quad for \quad x_2 \to 0$$



local axisymmetry (around x_1-axis)
George and Hussein (1991)

$$\overline{\left(\frac{\partial^n u_1}{\partial x_2{}^n}\right)^2} = \overline{\left(\frac{\partial^n u_1}{\partial x_3{}^n}\right)^2}$$

$$\overline{\left(\frac{\partial^n u_2}{\partial x_2{}^n}\right)^2} = \overline{\left(\frac{\partial^n u_3}{\partial x_3{}^n}\right)^2}$$

$$\overline{\left(\frac{\partial^n u_2}{\partial x_3{}^n}\right)^2} = \overline{\left(\frac{\partial^n u_3}{\partial x_2{}^n}\right)^2}$$

all coefficients have to vanish

$$\varepsilon_w = \nu \left.\overline{\left(\frac{\partial u_j}{\partial x_i}\frac{\partial u_j}{\partial x_i}\right)}\right|_{x_2=0} \approx \upsilon\left(\overline{a_1^2} + \overline{c_1^2}\right) \to 0$$

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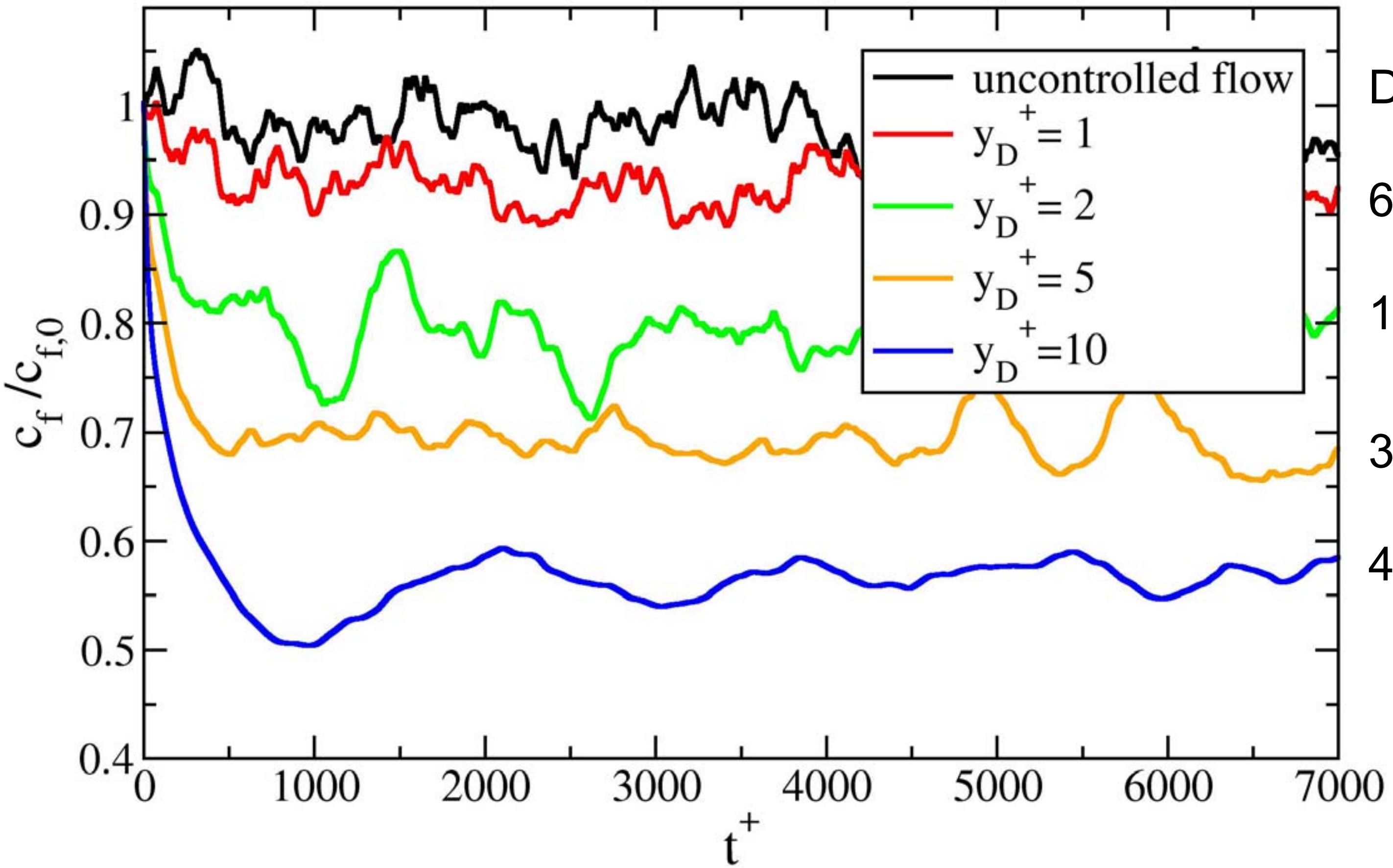
Numerical Experiments



DR

6%

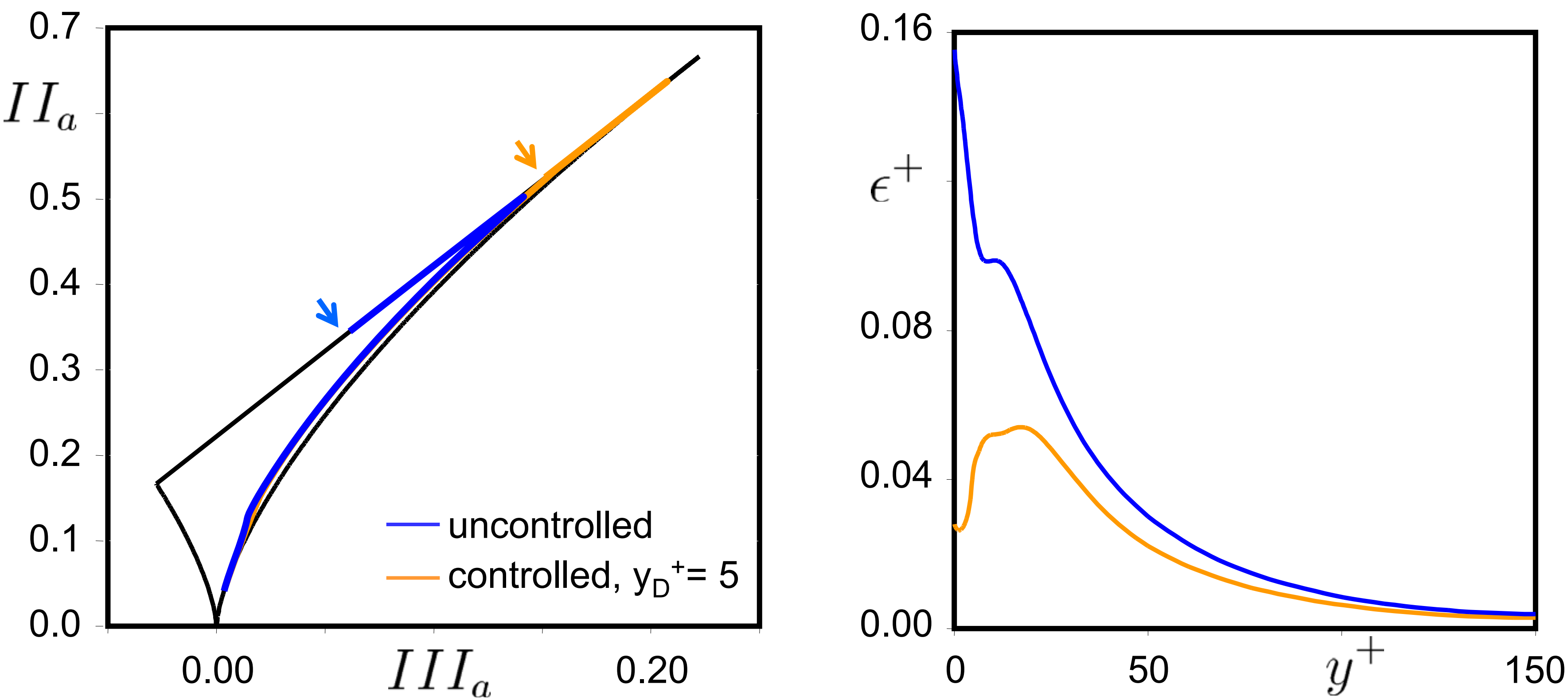
19%

30%

42%

suppression of the spanwise velocity fluctuations

Numerical Experiments

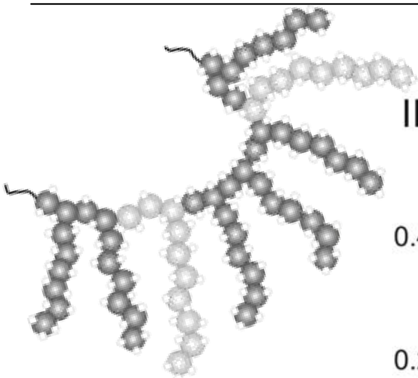


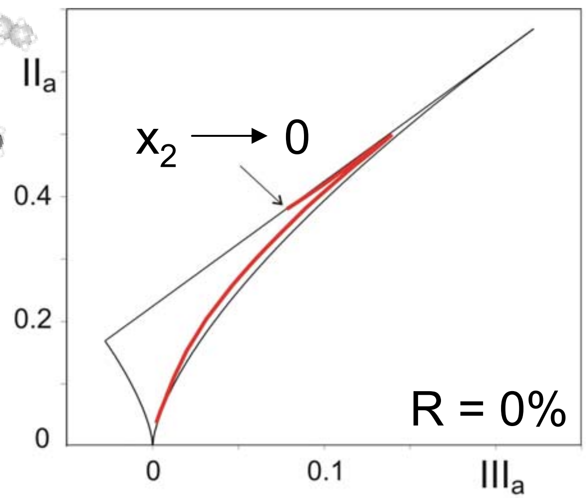
suggested drag reduction mechanism can be reproduced in DNS

→ effects within viscous sublayer – probably impossible with any RANS approach

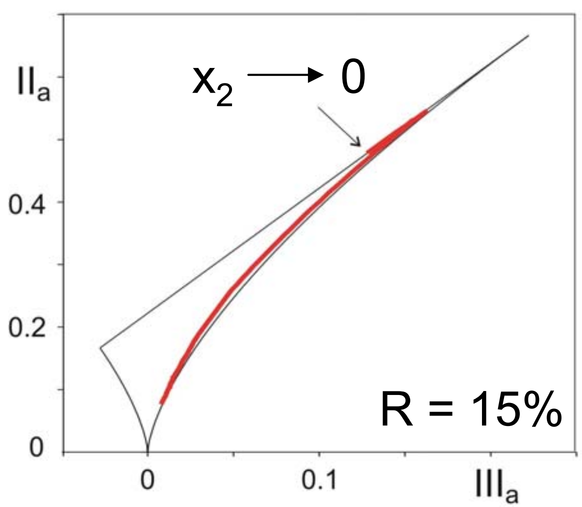
„need to put a model near the wall"

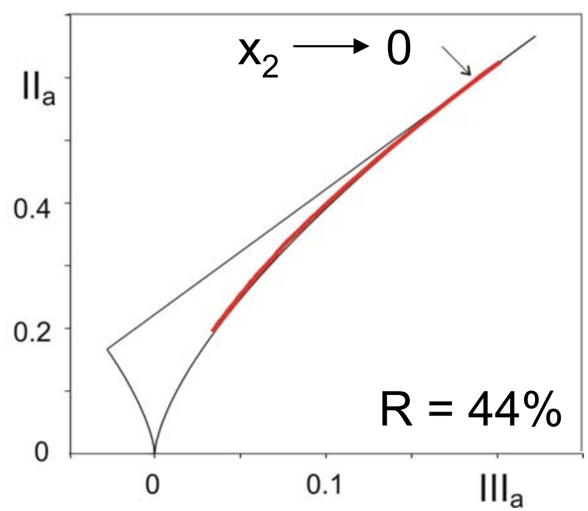
Polymer Drag Reduction





near wall fluctuations:
statistically axisymmetric &
invariant under rotation about the
axis aligned with the mean flow





DNS Data:
Dimitropoulos
et al. (1998)

Quantitative Relation

FIK Identity: $c_f = \frac{12}{Re_b} + 12 \int_0^1 2\,(1 - x_2)\,(-\overline{uv})\,dy$ Fukagata et al.,2002

$$\begin{pmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \overline{uu} & \overline{uv} & 0 \\ \overline{uv} & \overline{vv} & 0 \\ 0 & 0 & \overline{ww} \end{pmatrix} \begin{pmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} EV1 & 0 & 0 \\ 0 & EV2 & 0 \\ 0 & 0 & EV3 \end{pmatrix}$$

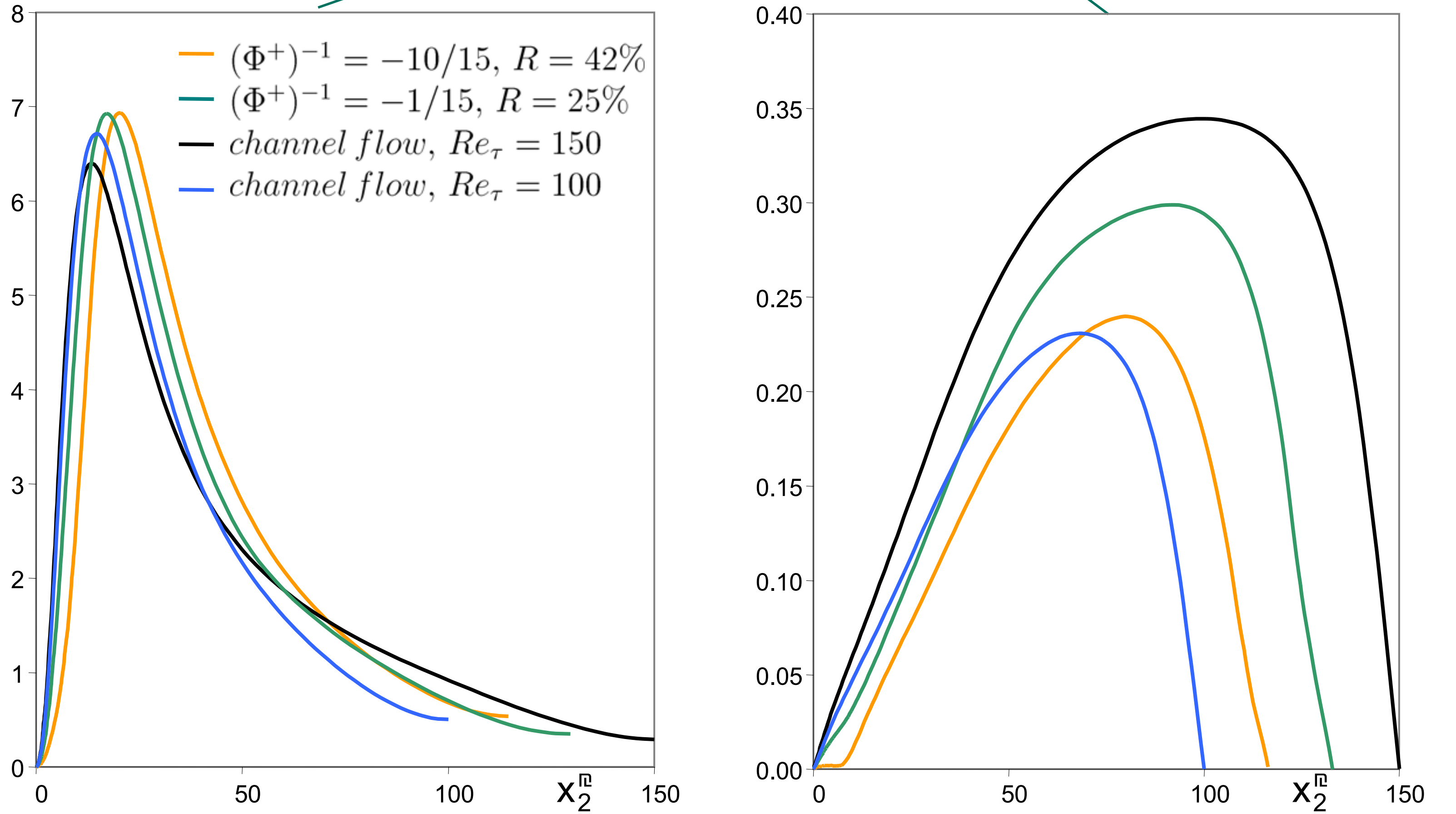
$$-\overline{uv} = -(EV2 - EV1)\frac{sin2\alpha}{2}$$

$$a_{ij} = \frac{\overline{u_i u_j}}{q^2} - \frac{1}{3}\delta_{ij} \qquad -\overline{uv} = -q^2(EV2(a_{ij}) - EV1(a_{ij}))\frac{sin2\alpha}{2}$$

$$q^2 = \overline{u_s u_s} = 2k$$

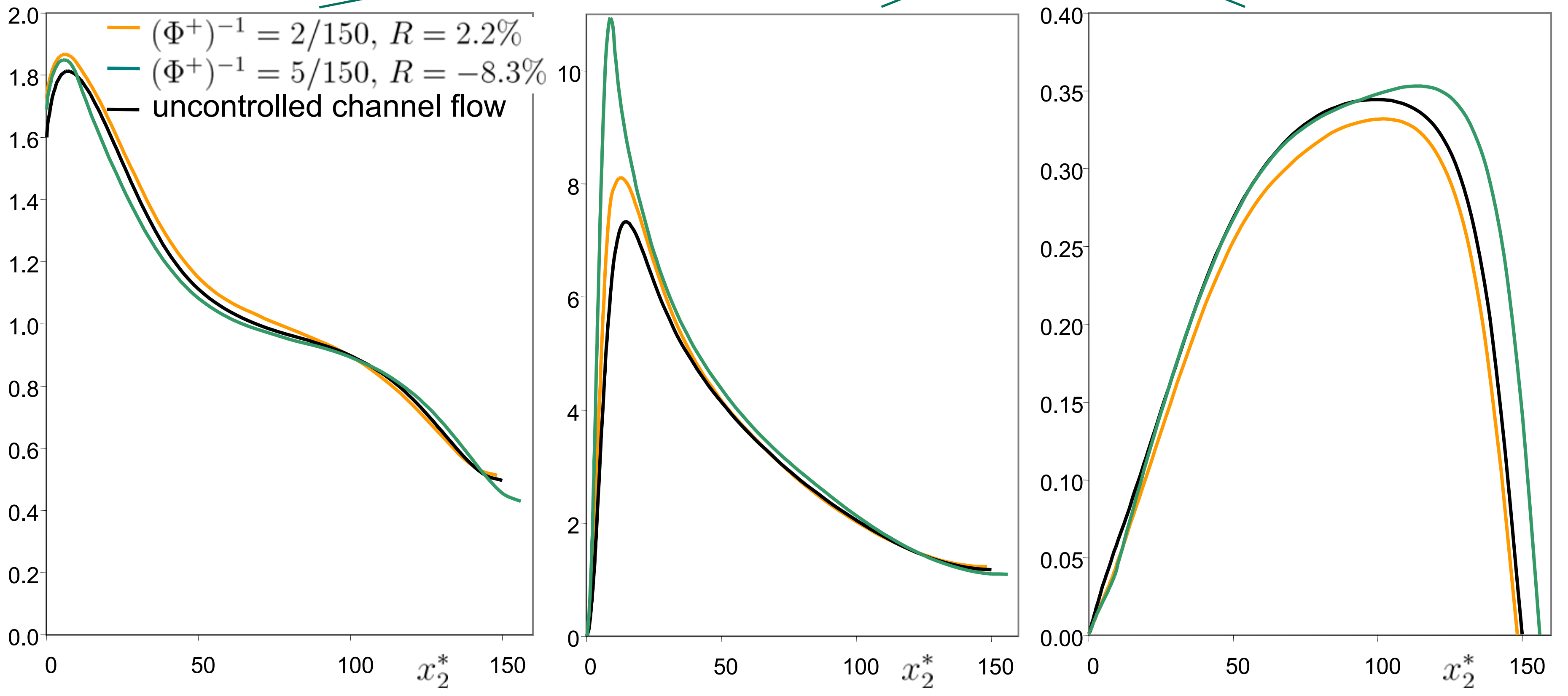
Shear Stress Contribution: w'-damping

$$-\overline{uv} = -(EV2 - EV1)\,\frac{sin2\alpha}{2}$$



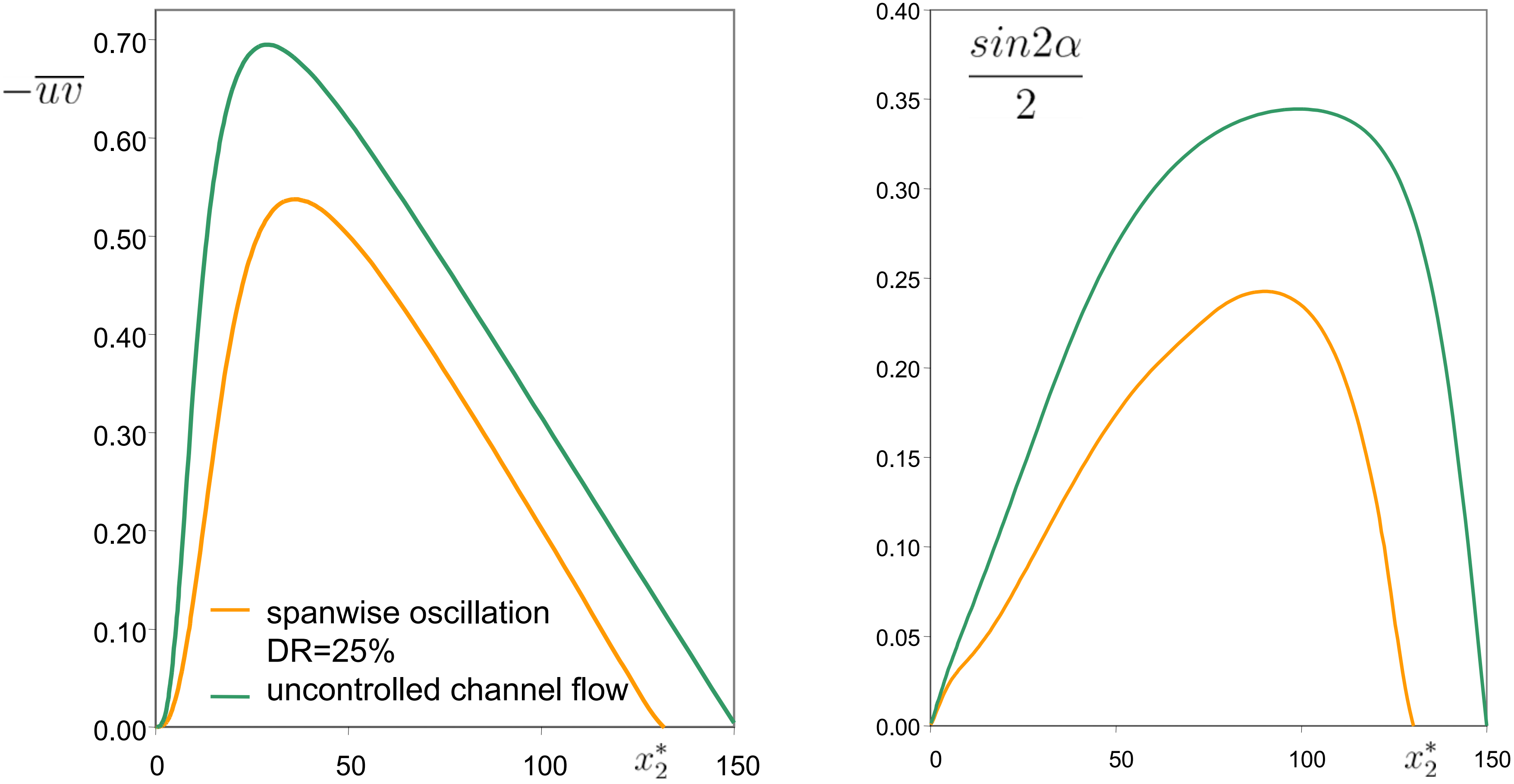
Shear Stress Contribution: u'-enhancement

$$-\overline{uv} = \boxed{-(EV2(a_{ij}) - EV1(a_{ij}))}\ \boxed{q^2}\ \boxed{\frac{sin2\alpha}{2}}$$

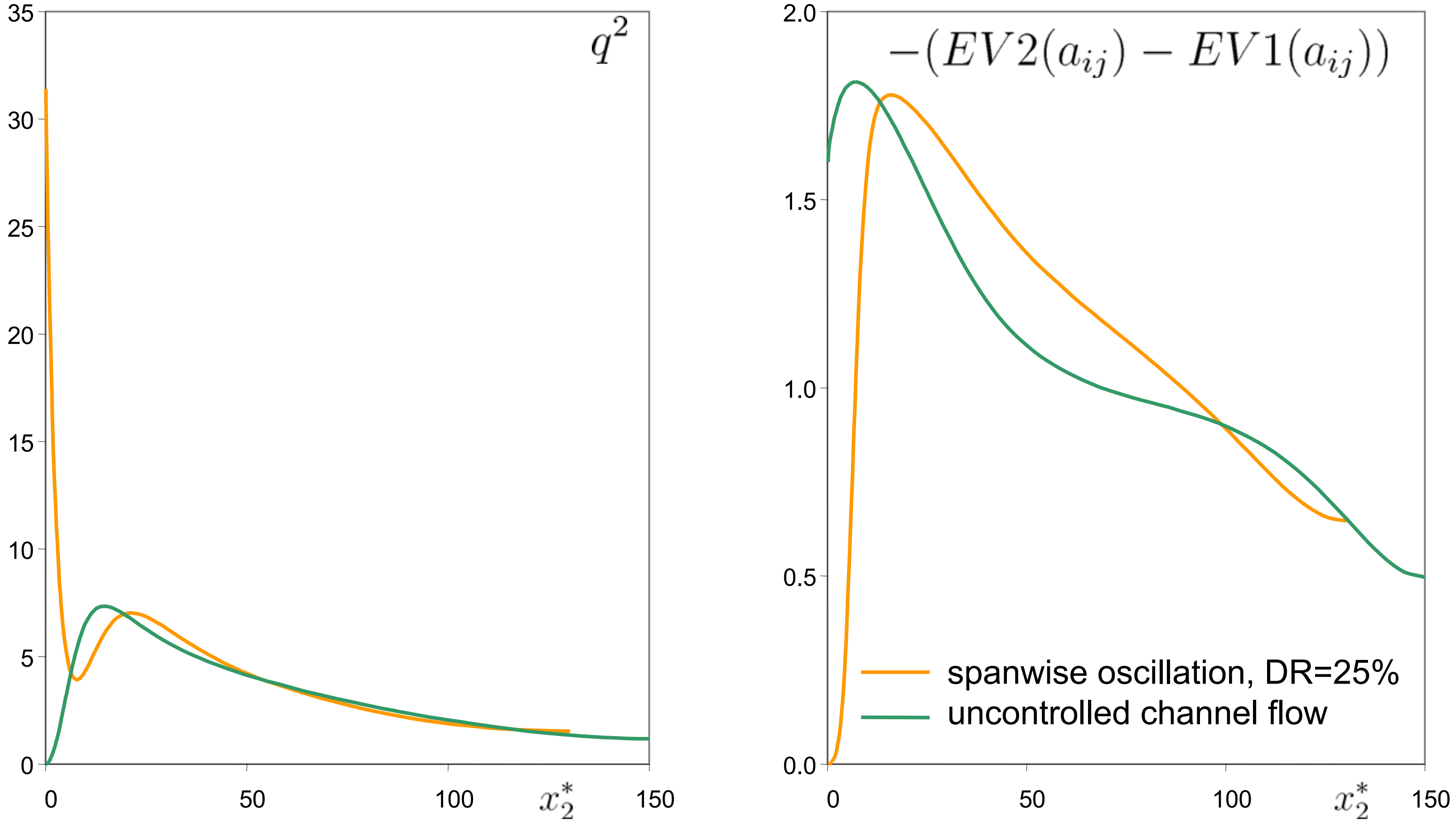


Spanwise Wall Oscillation

$$-\overline{uv} = -(EV2(a_{ij}) - EV1(a_{ij}))\, q^2\, \frac{sin2\alpha}{2}$$

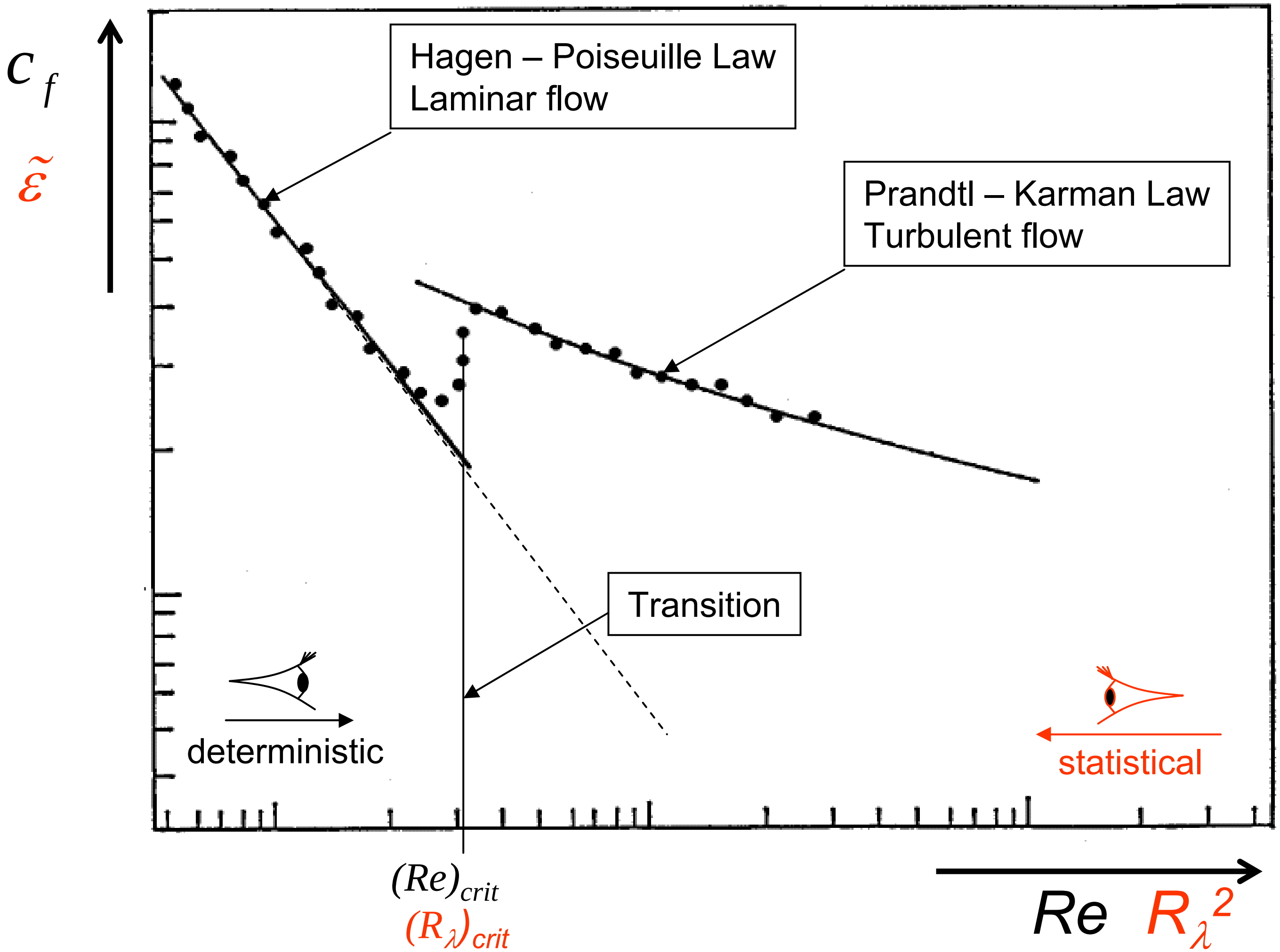


Spanwise Wall Oscillation



source of drag reduction: reduced eigenvalue difference → physical meaning?

Learn Something about Transition?

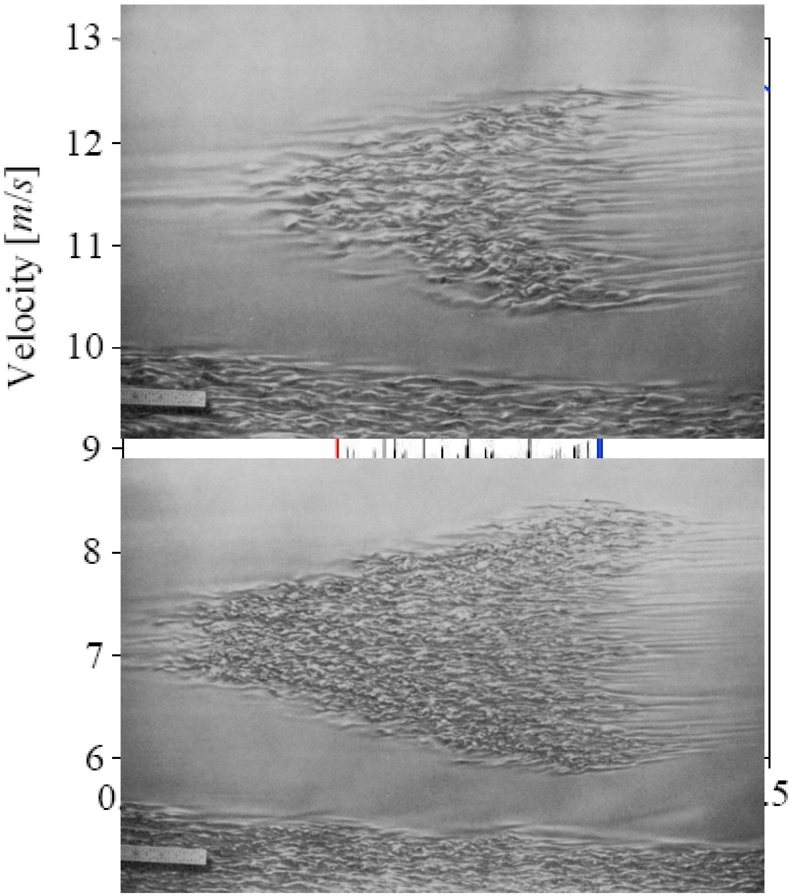


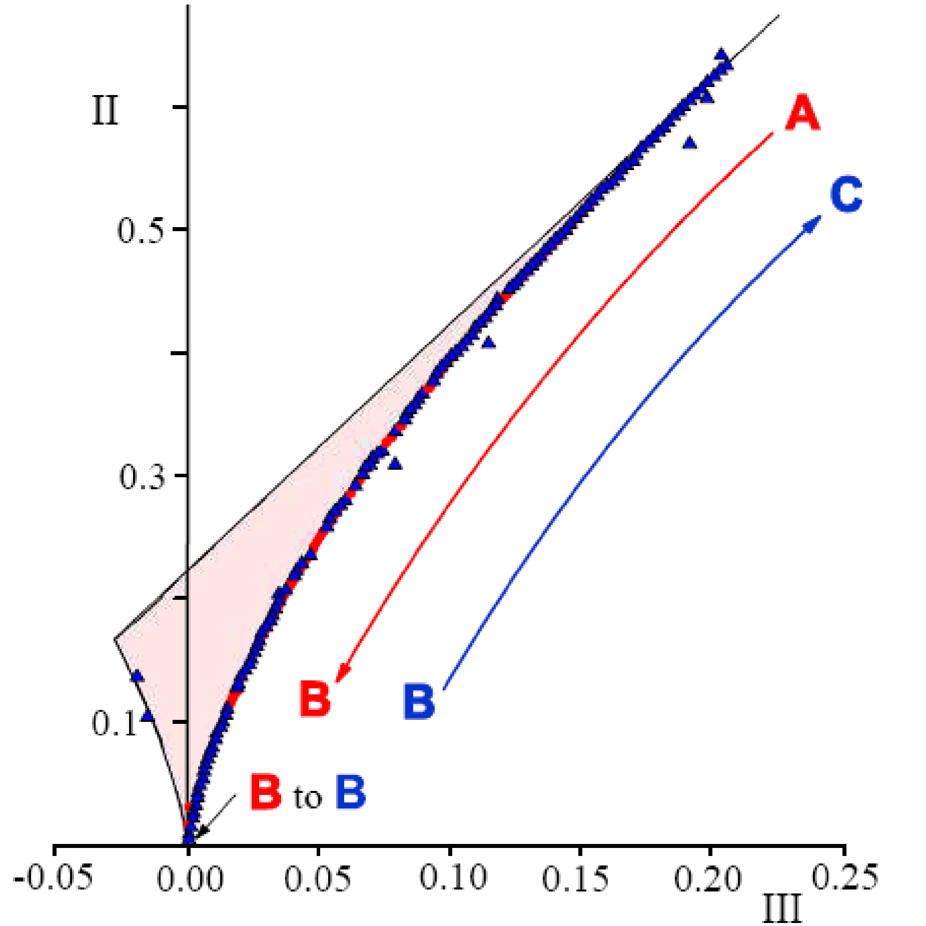
$$\tilde{\varepsilon} = \frac{\varepsilon D}{u_\tau^2 U_B}$$

$$\mathrm{Re} \propto R_\lambda^2$$

Turbulent Spots

Cantwell, Coles, Dimotakis 1978





Nishi 2009

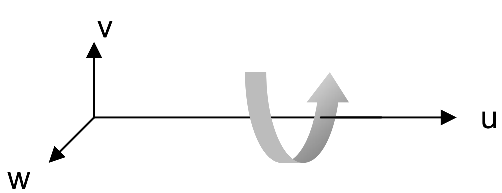
Apparent Stresses

disturbances $u_i' << U_i$ **mean flow velocity**

transport equation for apparent stresses:

$$\frac{D\overline{u_i'u_j'}}{Dt} = \underbrace{-\overline{u_j'u_k'}\frac{\partial U_i}{\partial x_k} - \overline{u_i'u_k'}\frac{\partial U_j}{\partial x_k}}_{P_{ij}} \underbrace{- \frac{1}{\rho}\left[\overline{u_j'\frac{\partial p'}{\partial x_i}} + \overline{u_i'\frac{\partial p'}{\partial x_j}}\right]}_{\Pi_{ij}} \underbrace{- 2\upsilon\overline{\frac{\partial u_i'}{\partial x_k}\frac{\partial u_j'}{\partial x_k}}}_{\varepsilon_{ij}} \underbrace{+ \upsilon\frac{\partial^2\overline{u_i'u_j'}}{\partial x_k \partial x_k}}_{D_{ij}}$$

closure for axisymmetric disturbances



$$\Pi_{ij} = f\left(U_i, \overline{u_i'u_j'}\right)$$

$$\varepsilon_{ij} = f\left(U_i, \overline{u_i'u_j'}\right)$$

Modeled Equations

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Transport equations for the evolution of statistically axisymmetric disturbances:

$$\frac{D\overline{u_i'u_j'}}{Dt} \cong P_{ij} + a_{ij}P_{ss} + F\left(\frac{1}{3}P_{ss}\delta_{ij} - P_{ij}\right) - 2A\varepsilon_h a_{ij} - \frac{2}{3}\varepsilon_h\delta_{ij} + \frac{1}{2}\upsilon\frac{\partial^2\overline{u_i'u_j'}}{\partial x_k\partial x_k}$$

$$\frac{D\varepsilon_h}{Dt} \cong -2A\frac{\varepsilon_h\overline{u_i'u_k'}}{k} - \psi\frac{\varepsilon_h^{\;2}}{k} + \frac{1}{2}\upsilon\frac{\partial^2\varepsilon_h}{\partial x_k\partial x_k}$$

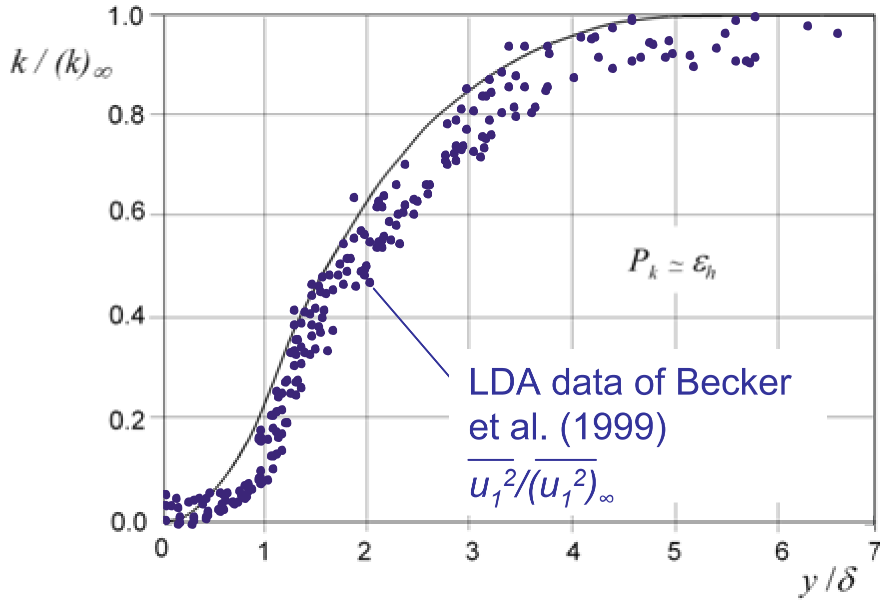
$$A,\psi = f\left(II_a, III_a, R_\lambda\right)$$

$$F = f\left(II_a, III_a\right)$$

Energy equation for the disturbances:

$$\frac{Dk}{Dt} \cong P_k - \varepsilon_h + \frac{1}{2}\nu\frac{\partial^2 k}{\partial x_k\partial x_k}$$

$$k = \frac{1}{2}\left(\overline{u_s'u_s'}\right)$$



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Dissipation Equation

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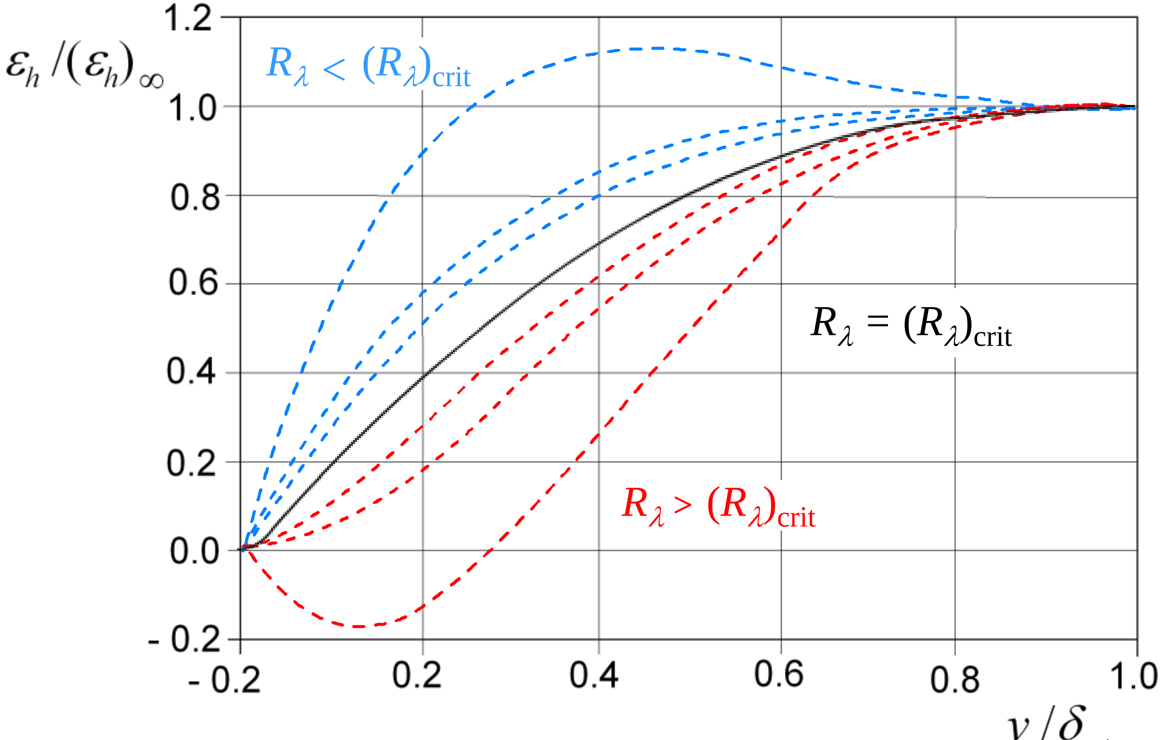
Dissipation equation for the disturbances:

$$\frac{D\varepsilon_h}{Dt} \cong (2A-\psi)\frac{\varepsilon_h^2}{k} + \frac{1}{2}\nu\frac{\partial^2\varepsilon_h}{\partial x_k \partial x_k} \qquad \text{with} \qquad P_k \cong \varepsilon_h$$



transition criterion: $2A-\psi \geq 0$ where $A,\psi = f(II_a, III_a, R_\lambda)$

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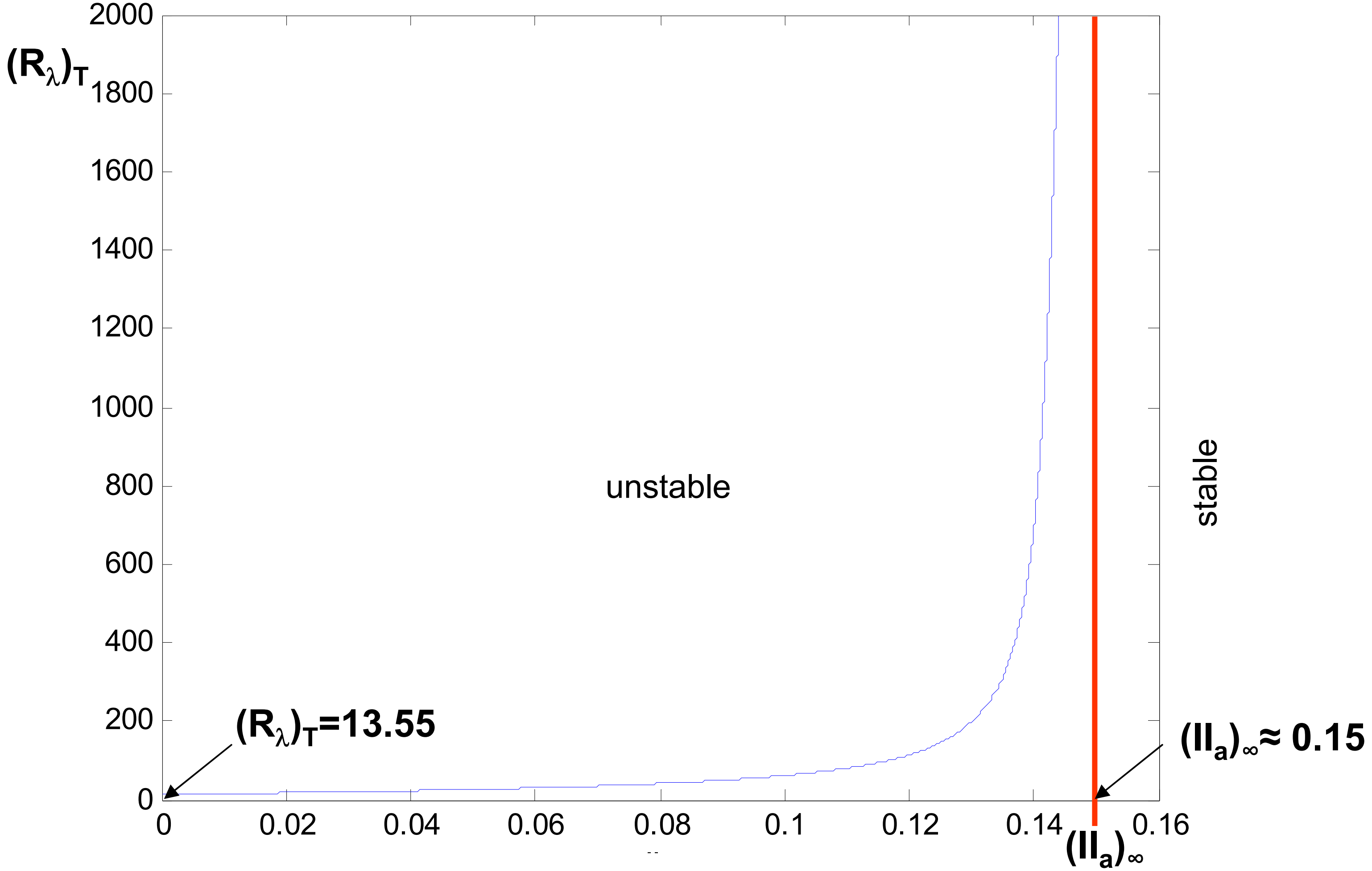
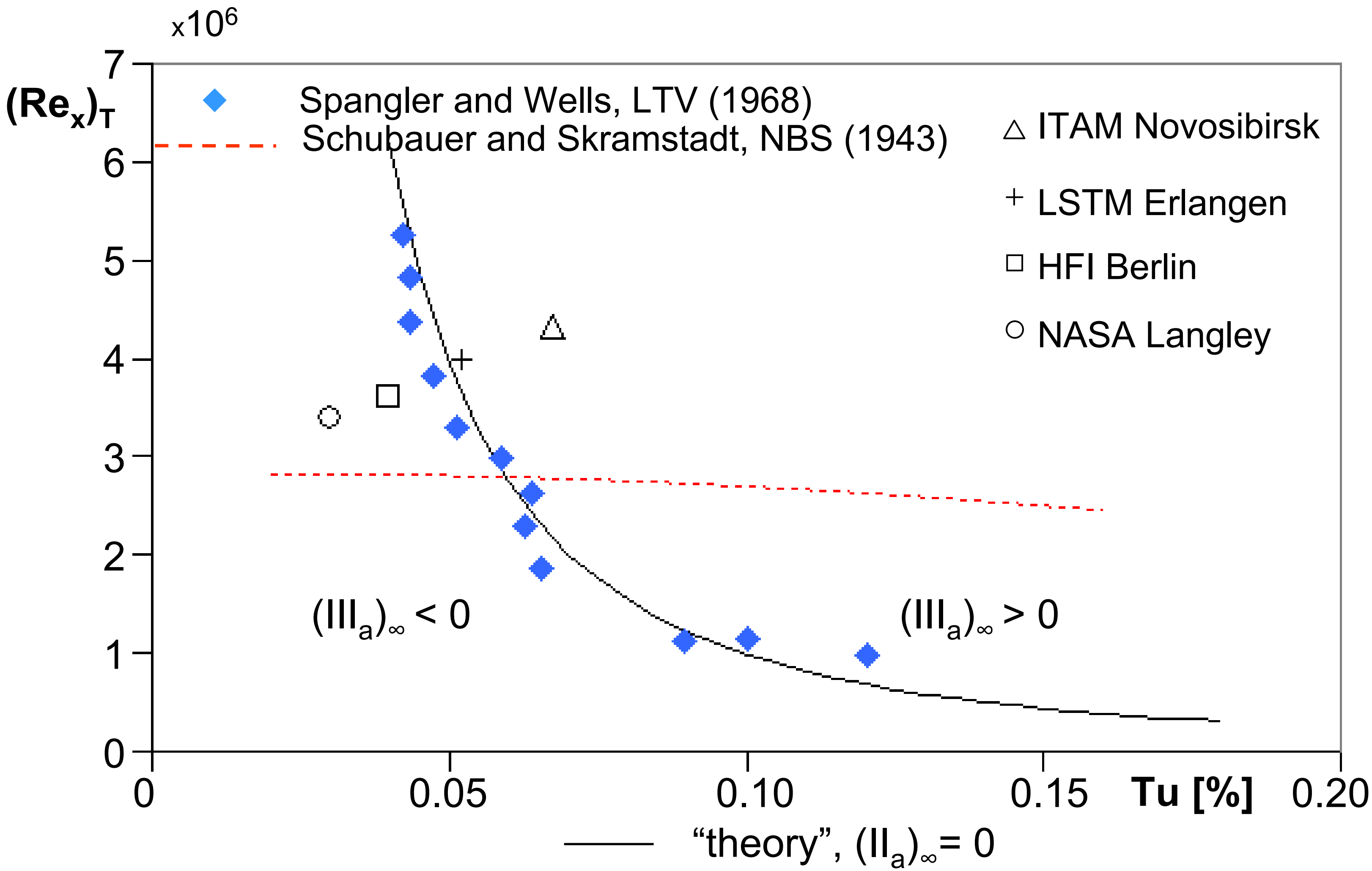
Transition Criterion

transform transition criterion in terms of $(R_\lambda)_T = f(II_a)$



Overview: Transition Experiments



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Conclusions/ Open Questions

- Enhanced communication between turbulence modeling/ turbulence theory and flow control community might provide valuable insight

- Understanding/ models that were obtained for prediction purposes can provide insight into flow control options/ limitations

- Can modifications of skin friction drag be captured with RANS or LES?

  - Reynolds number scaling
  - application to “real” problems