Viscous boundary layers in high Rayleigh number convection: A new insight from 3d velocity measurements

L.Li and R. du Puits,

Ilmenau University of Technology
Department of Mechanical Engineering
POB 100565, D-98693 Ilmenau, GERMANY

contact: *ronald.dupuits@tu-ilmenau.de*

André Thess
Christian Resagk
Elka Lobutova
Robert Kaiser
Vigimantas Mitschunas
Klaus Henschel
Joerg Schumacher
Mohammad Emran
Nan Shi

DFG DAAD Thüringer Ministerium für Bildung, Wissenschaft und Kultur NSF

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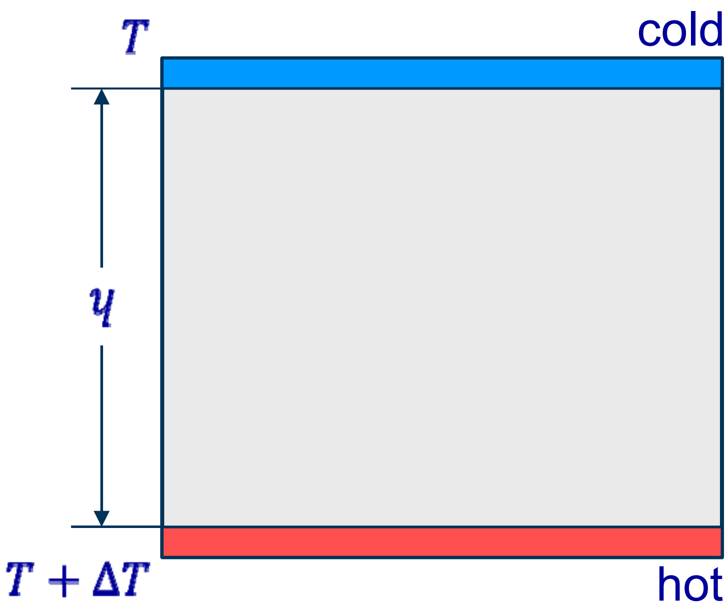
Outline

- **Technical news from the Barrel**
- **Present projects**
- **Viscous boundary layer measurements**

Sketch of the RB problem



Input:	Response:
$Ra = \frac{\beta g \Delta\vartheta h^3}{\upsilon\kappa}$	$Nu = \frac{\dot{q}}{\dot{q}_d}$
$\Gamma = D/h$	$Re = U_\infty h/\nu$
$Pr = \nu/\kappa$	

Technical news

Present projects

Measurements

BOI

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1. Technical News

Two different ways to study Rayleigh Bénard convection:

Global characteristics

- study of global quantities like heat flux, velocity, global flow structure, flow dynamics

↓

- aims to predict scaling laws like Nu,Re=f(Ra,Γ,Pr)

Local details

- local details like boundary layers, local transport, turbulent dissipation

↓

- looking for significant variations in the local flow fields, e.g transitions of the boundary layer structure

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Different philosophies to built up experiments:

to study global characteristics

- **maximum Ra numbers**
- **large parameter domains**
- **accurate measurements of the global quantities**

⇓

- **experiments in liquid Helium or compressed SF_6**
- **disadvantage: limitations of local measurements**

to study local details

- **large-scale experiments for high resolution**
- **small and (preferably) non-intrusive sensors**

⇓

- **experiments in air or water**
- **virtually unrestricted access for measurements**

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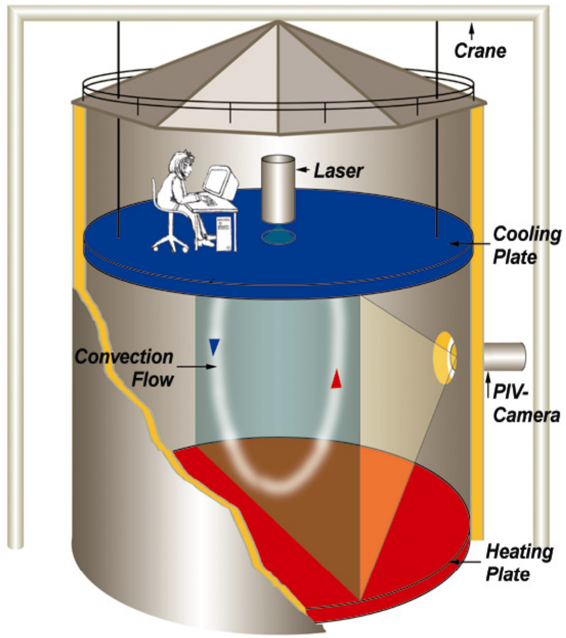
The „Barrel of Ilmenau“ (BOI)



Physical parameter:

$Ra = \dots 10^{12}$
$\Gamma = 1.13 \dots 143$
$Pr = 0.7$
$Nu = \dots 1000$
$Re = \dots 250{,}000$

Technical data:

$d = 7.15\ \mathrm{m}$
$h = 0.05 \dots 6.30\ \mathrm{m}$
$\Delta\vartheta = 2.5 \dots 60\ \mathrm{K}$
$\dot{Q}_h = 10\ \mathrm{kW}$
$\dot{Q}_c = 15\ \mathrm{kW}$

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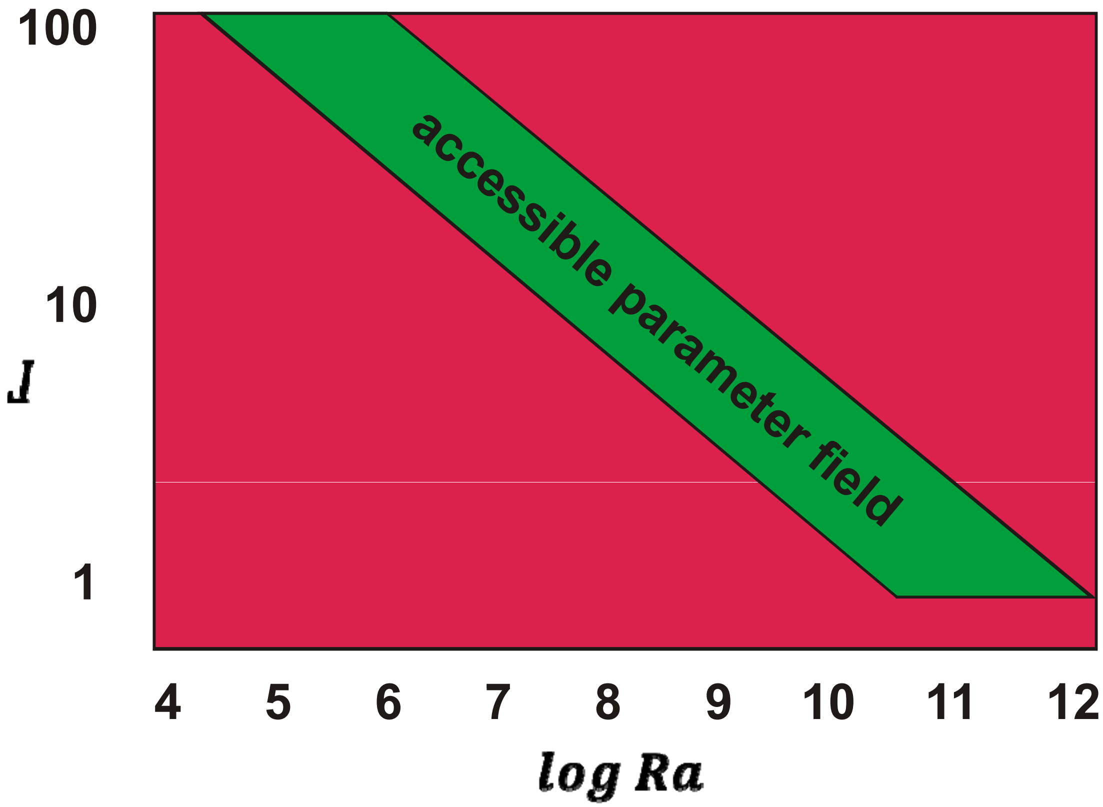
Even in the BOI it is of crucial interest to span a wide parameter range in Ra and Γ

Accessible parameter field of the D=7.15 m cell



$$Ra = \frac{\beta g \Delta\vartheta h^3}{\upsilon\kappa}$$

$$\Gamma = D/h$$

The domain in Ra for Γ=const. Is limited to 1.5 decades!
The variation in Γ for constant Ra is limited to a factor of 2.5!

Smaller inset of D=2.5 m in the big barrel

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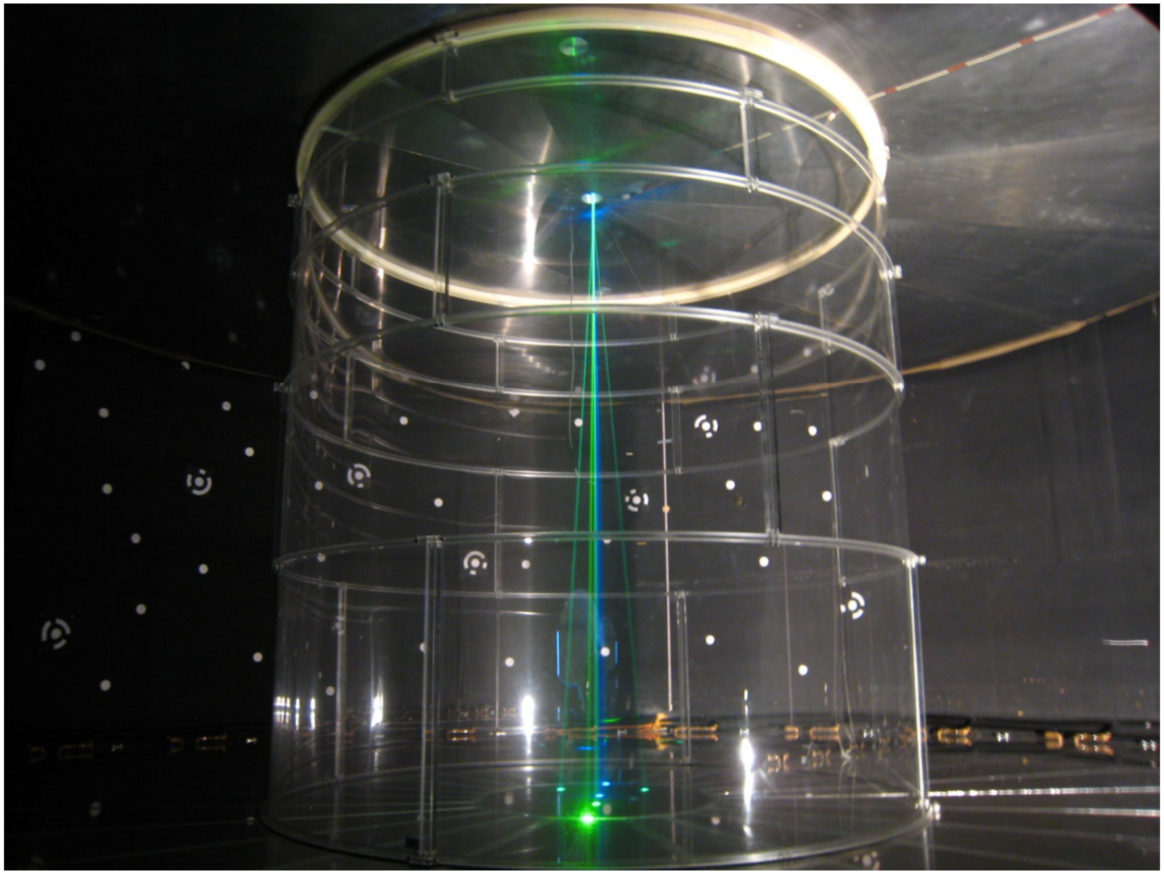

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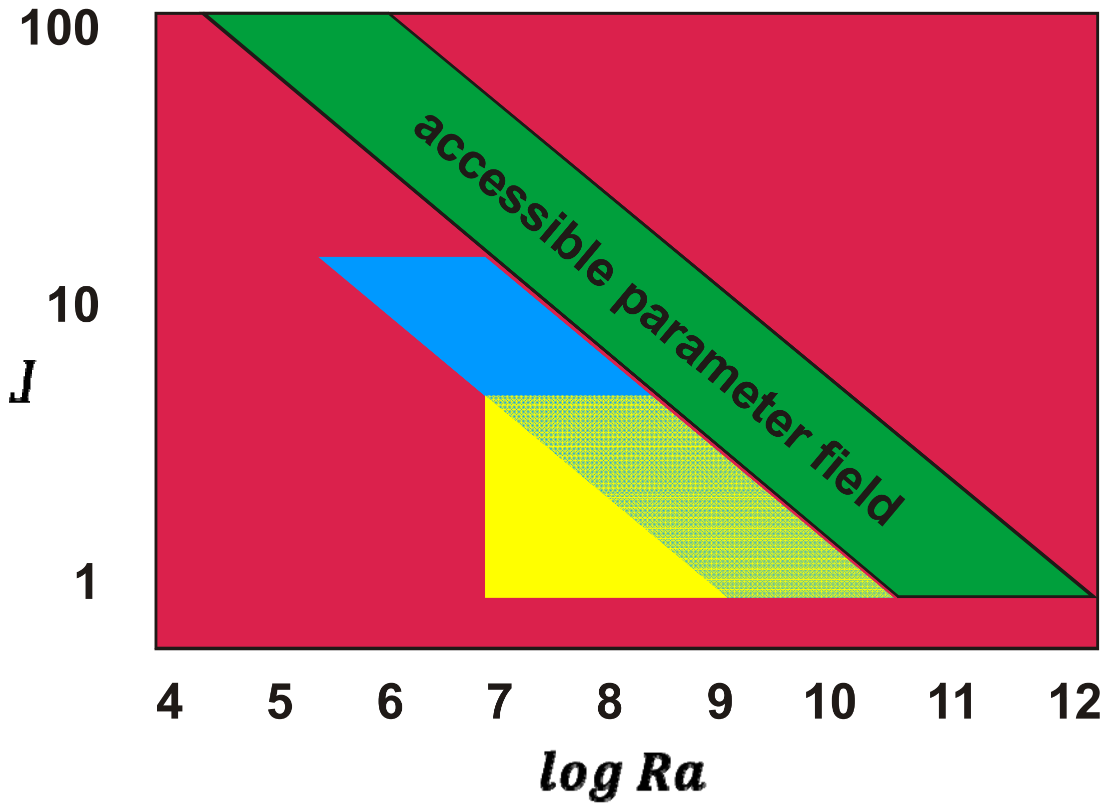

Accessible parameter field of:

- ✓ **D=7.15 m sample (green)**
- ✓ **D=2.50 m sample (blue)**
- ✓ **Numerics (yellow)**

2. Present projects

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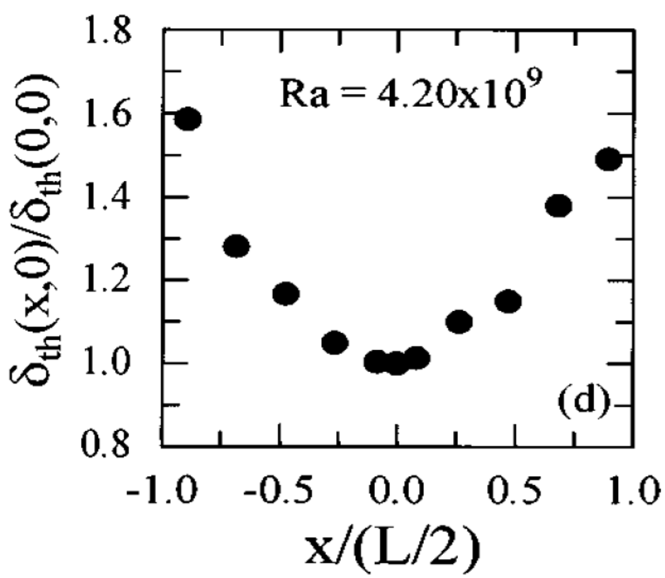
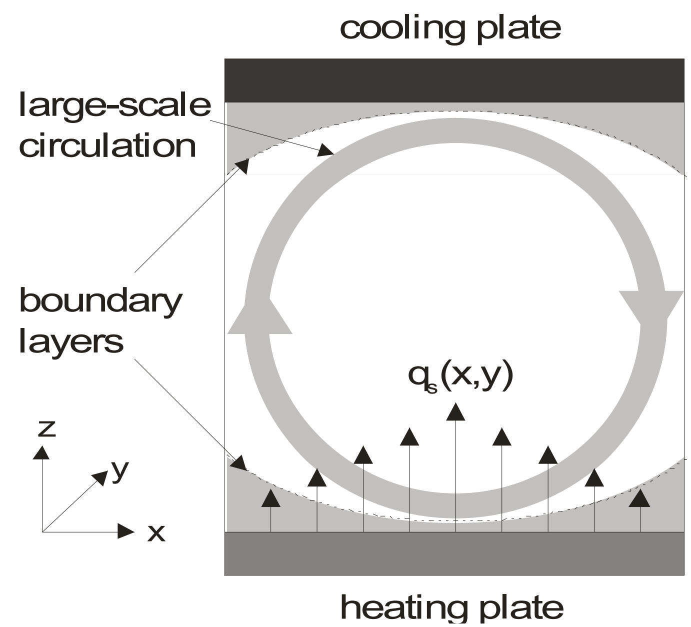
„Local wall heat flux measurements“

Relative thickness of the thermal boundary layer at Γ=1 along the large-scale circulation

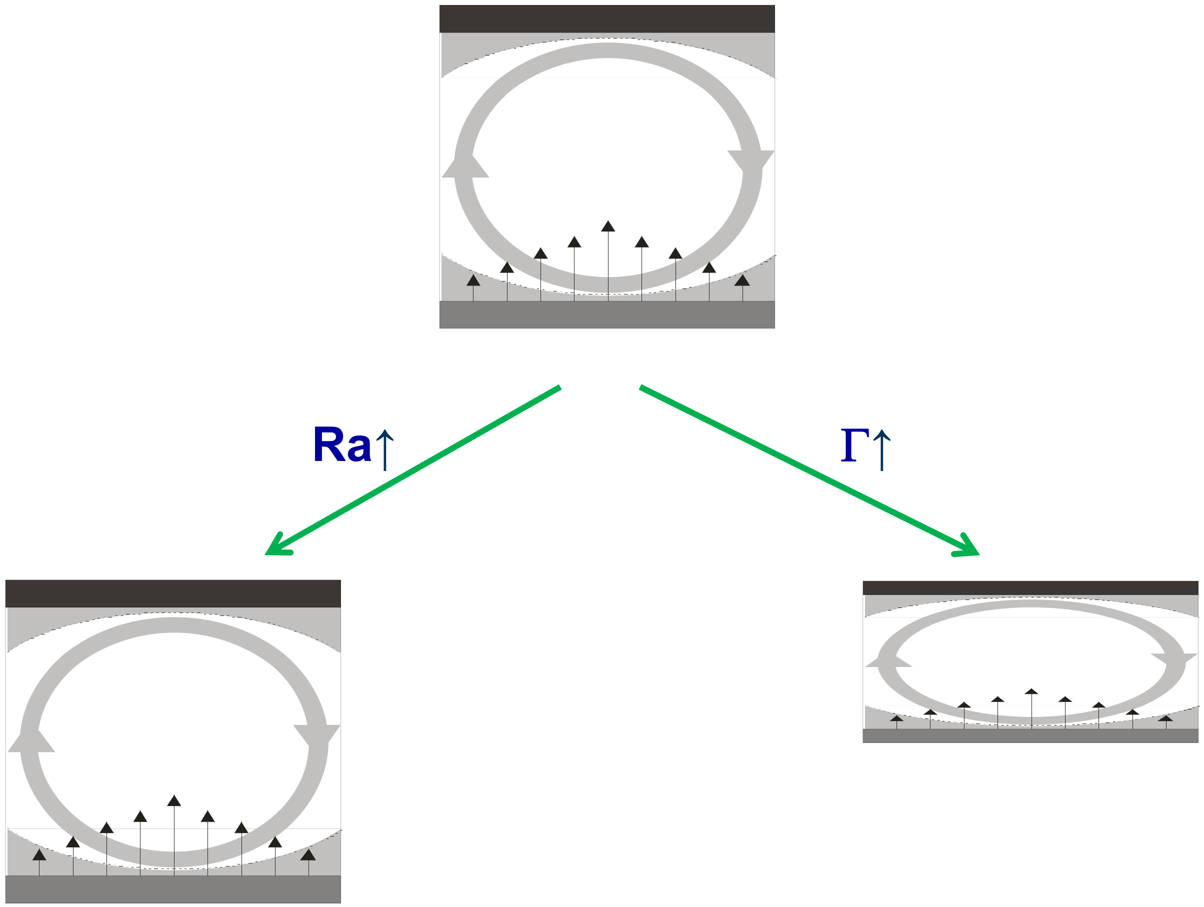


Lui and Xia, PRE 57 (1998)



du Puits etal., NJP ***12*** *(2010)*

To study the effect of Ra and Γ on the distribution of the local wall heat flux



Setup to measure the local wall heat flux distribution

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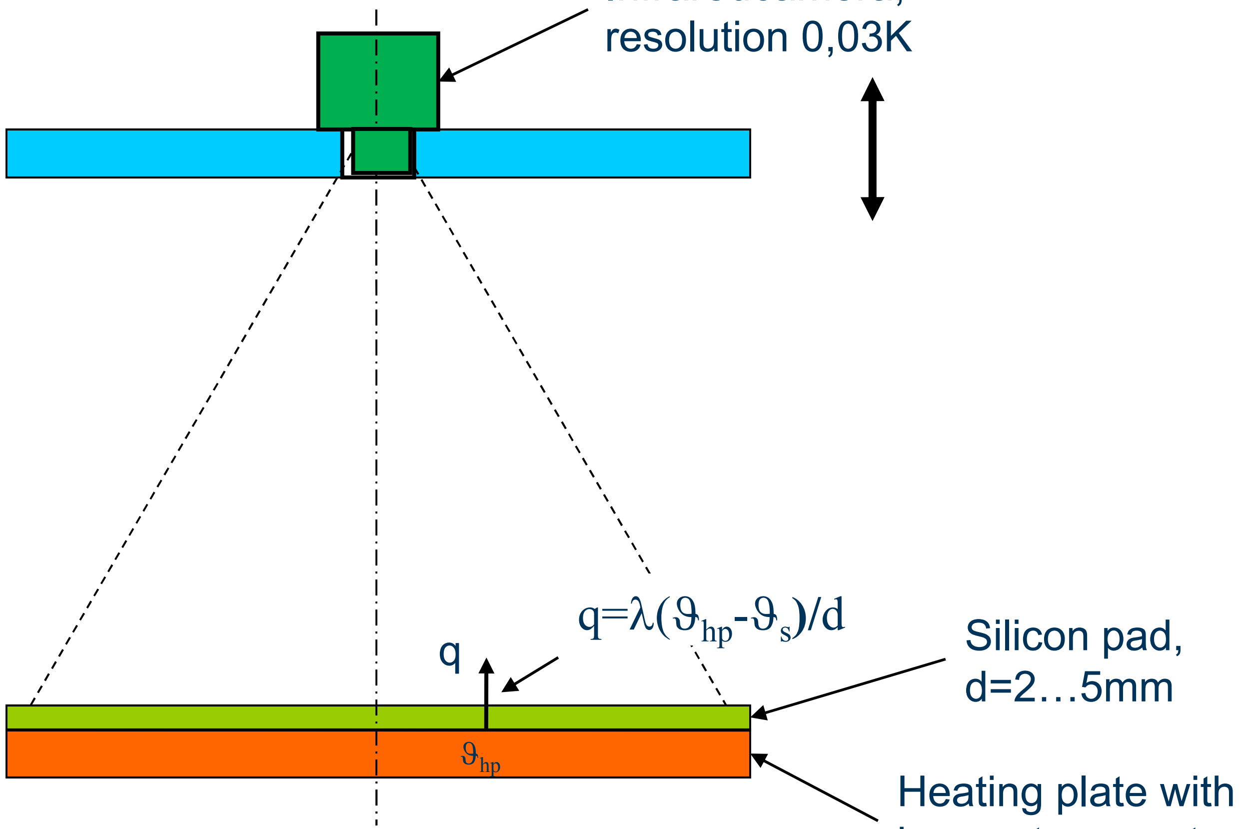

Some ideas to measure (more ideas are very welcome):

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Averaged quantities

- Distribution of the local heat flux at Γ=1 and variable Ra
- Distribution of the local heat flux at fixed Ra and variable Γ
- Global flow structure at variable Γ analyzing ist footprint at the plate
- Critical aspect ratios for transitions between different flow modes

Instantaneous quantities

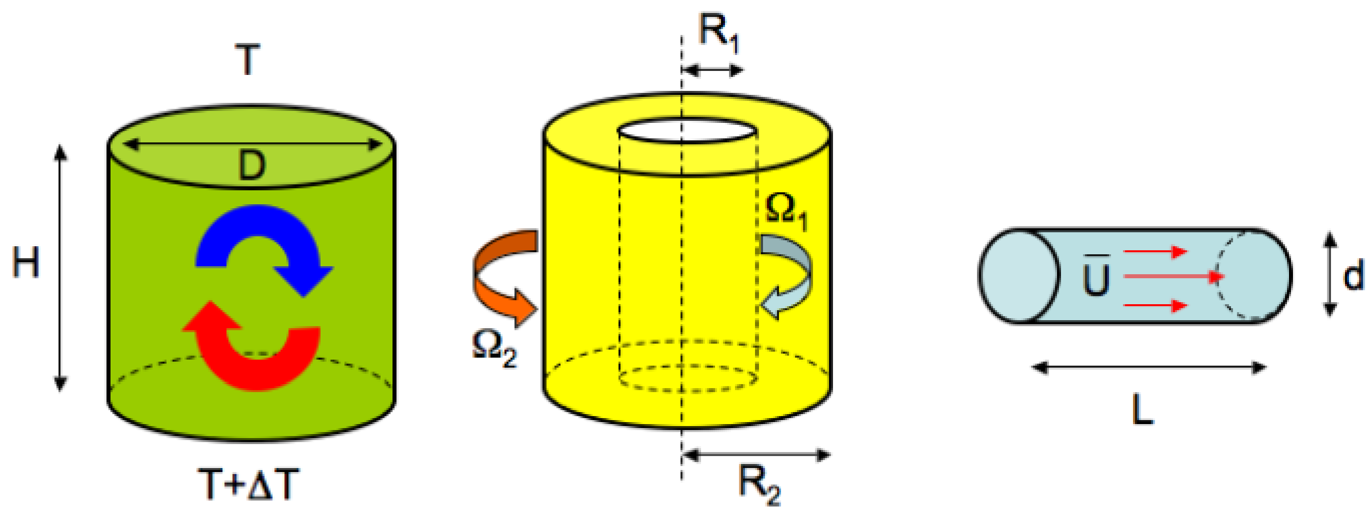
- Evolution of the mean flow orientation
- Probability of different flow modes at transitional aspect ratios

„Near wall transport and structures in turbulent RB-, TC- and pipe flow“

$$Ra = \frac{g\alpha\Delta T H^3}{\nu\kappa}$$

$$Re_{1,2} = \frac{\Omega_{1,2} R_{1,2} d}{\nu}$$

$$Re = \frac{\overline{U} d}{\nu}$$



Following the ideas of Eckhardt, Grossmann and Lohse [EPL 78 (2007)] the analogy in the turbulent transport between different systems will be studied.

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Our part in this project is the experimental study of the RB system and we will focus on the the flow field inside the boundary layers.

Parameter range

- **$Ra=10^9 \ldots 10^{12}$**
- **$\Gamma=1\ldots10$**
- **Various locations at the heating and the cooling plate**

Measurement tasks

- **Temperature profiles**
- **3d velocity profiles (all three velocity components)**
- **Simultaneous temperature and velocity measurements**
- **PIV, PTV measurements (which is hard since the orientation of the flow permanently varies)**

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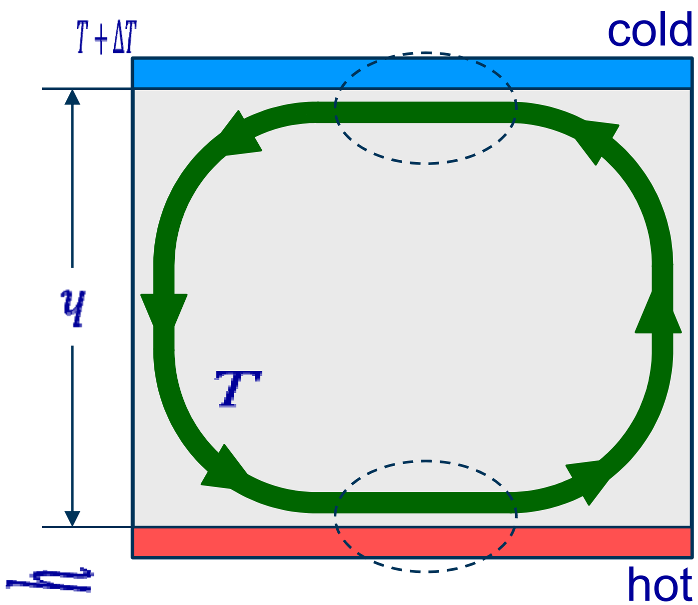
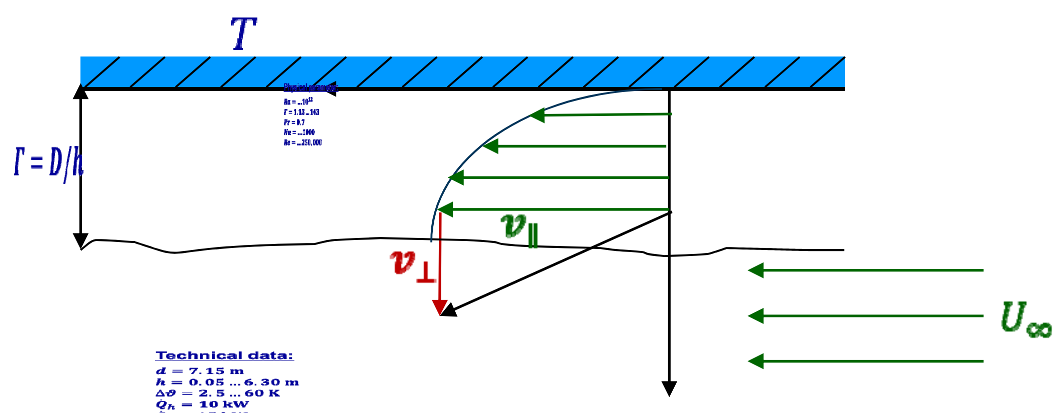
3. Viscous boundary layer measurements



- Finite lateral extent of the cell
- creates a mean flow
- Boundary layers develop
- Bl's determine the heat transport



„What is the nature of the heat transport troughout the boundary layers?“

$$q = -\lambda \frac{\;}{\partial z} + \rho c_p \langle w'T' \rangle$$

Diffusion **Advection**

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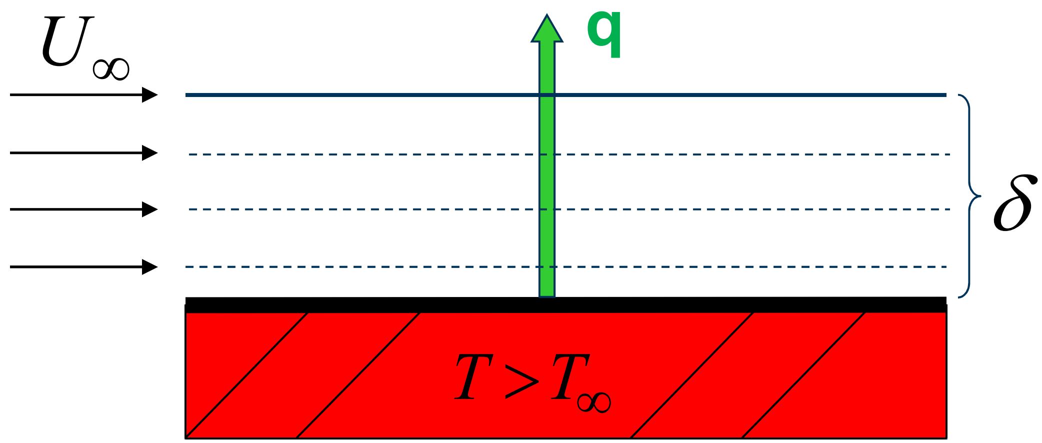
Scenario 1: Laminar boundary layer (acc. Prandtl/Blasius)



- **Stationary, two-dimensional flow, small fluctuations might be allowed**
- **Wall-normal velocity component small compared with that parallel to the wall**
- **Basically parallel stream lines (as shown in the sketch)**
- **Diffusive heat transport according Fourier's law**

$$q = -\lambda \frac{\partial T}{\partial z} \quad \Longrightarrow \quad T \sim -z$$

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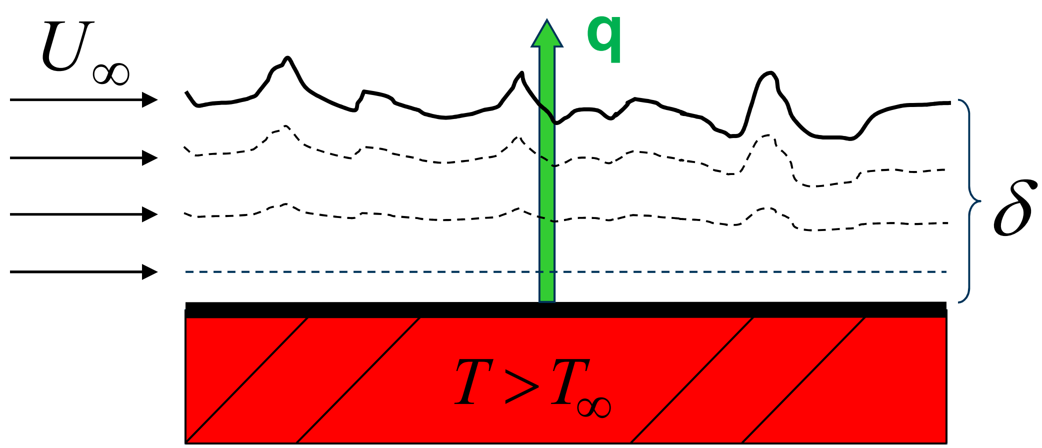
Scenario 2: Laminar boundary layer with fluctuations



- **Fluctuating but still two-dimensional flow, $u', v', w' < U_\infty$**
- **Basically parallel stream lines (as shown in the sketch)**
- **Diffusive + advective heat transport**

$$q = -\lambda \frac{\partial T}{\partial z} + \rho c_p \langle w'T' \rangle \quad \text{with} \quad \left| -\lambda \frac{\partial T}{\partial z} \right| \geq \left| \rho c_p \langle w'T' \rangle \right|$$

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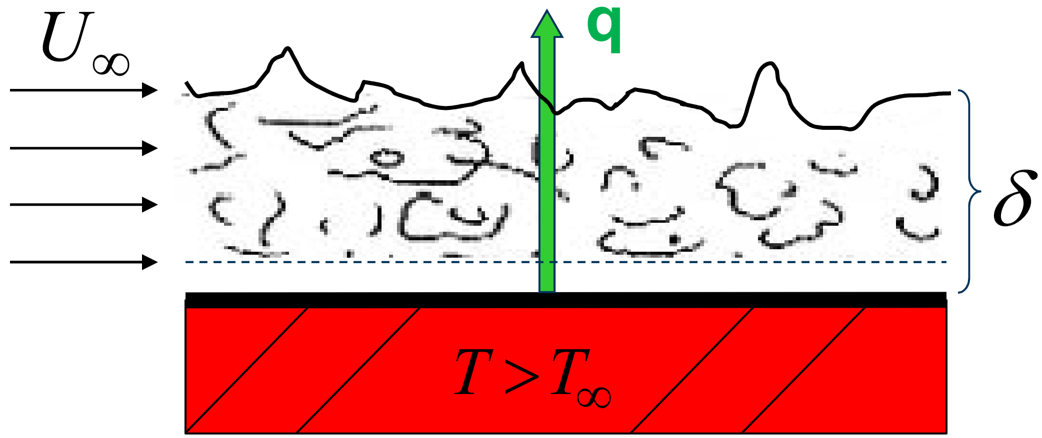
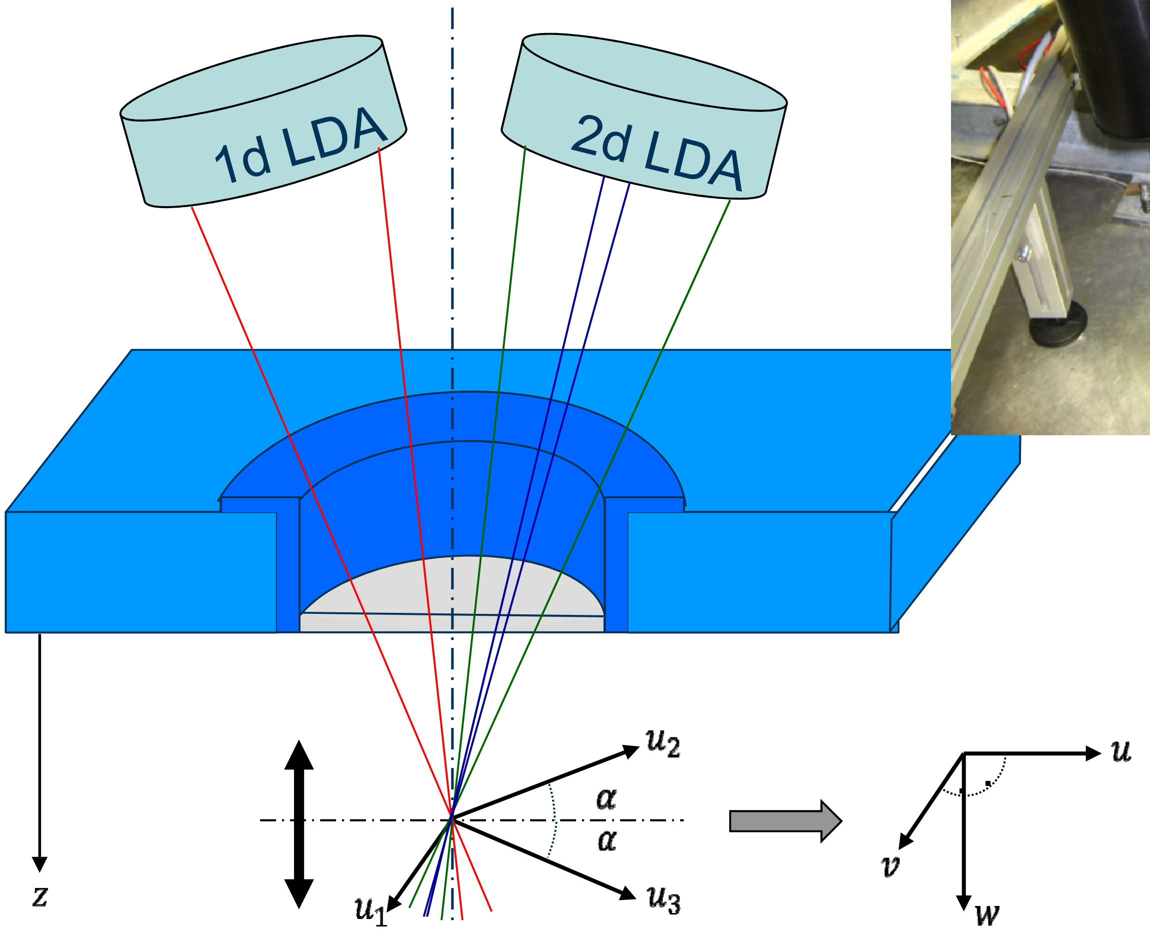
Scenario 3: Fully turbulent boundary layer



- **Fully turbulent boundary layer, $u', v', w' \approx U_\infty$**
- **Only a thin viscous sublayer survives**
- **Mainly advective heat transport**

$$q = -\lambda \frac{\partial T}{\partial z} + \rho c_p \langle w'T' \rangle \quad \text{with} \quad \left| -\lambda \frac{\partial T}{\partial z} \right| \ll \left| \rho c_p \langle w'T' \rangle \right|$$

Measurement setup



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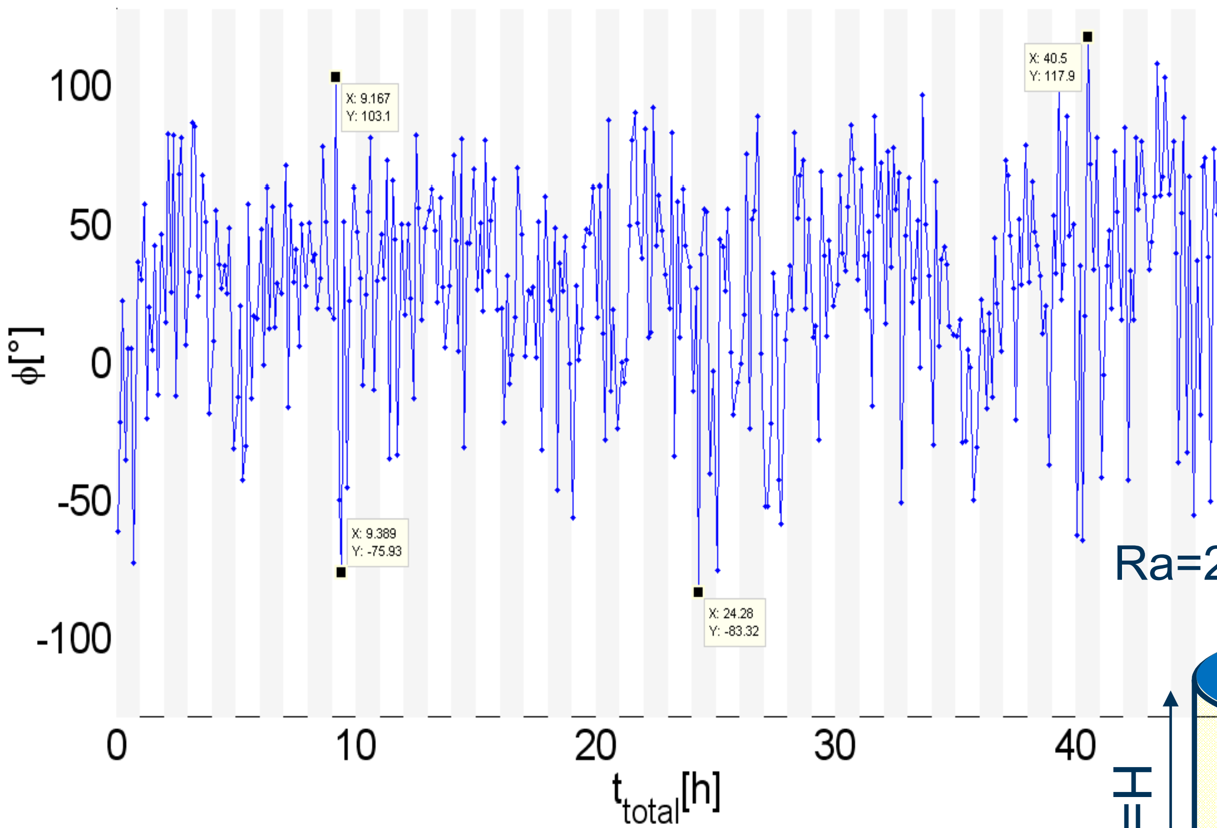
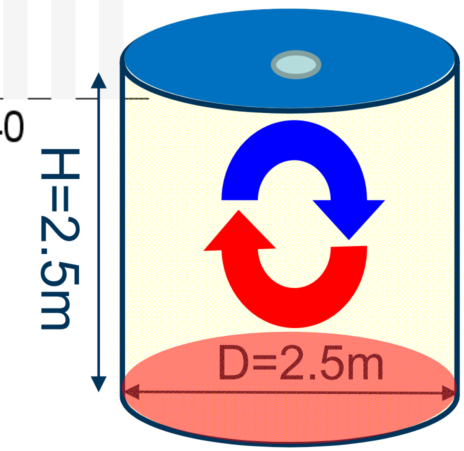
Orientation of the large-scale circulation



Ra=2.88 × 10^{10}, A=1



- **Plot the instantaneous angle of the LSC**
- **Oscillations by ±90° around the mean angle**

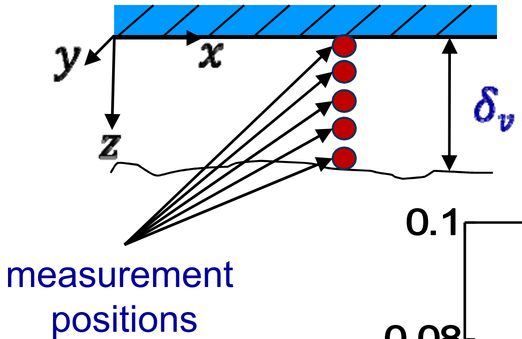
Mean horizontal velocity profile

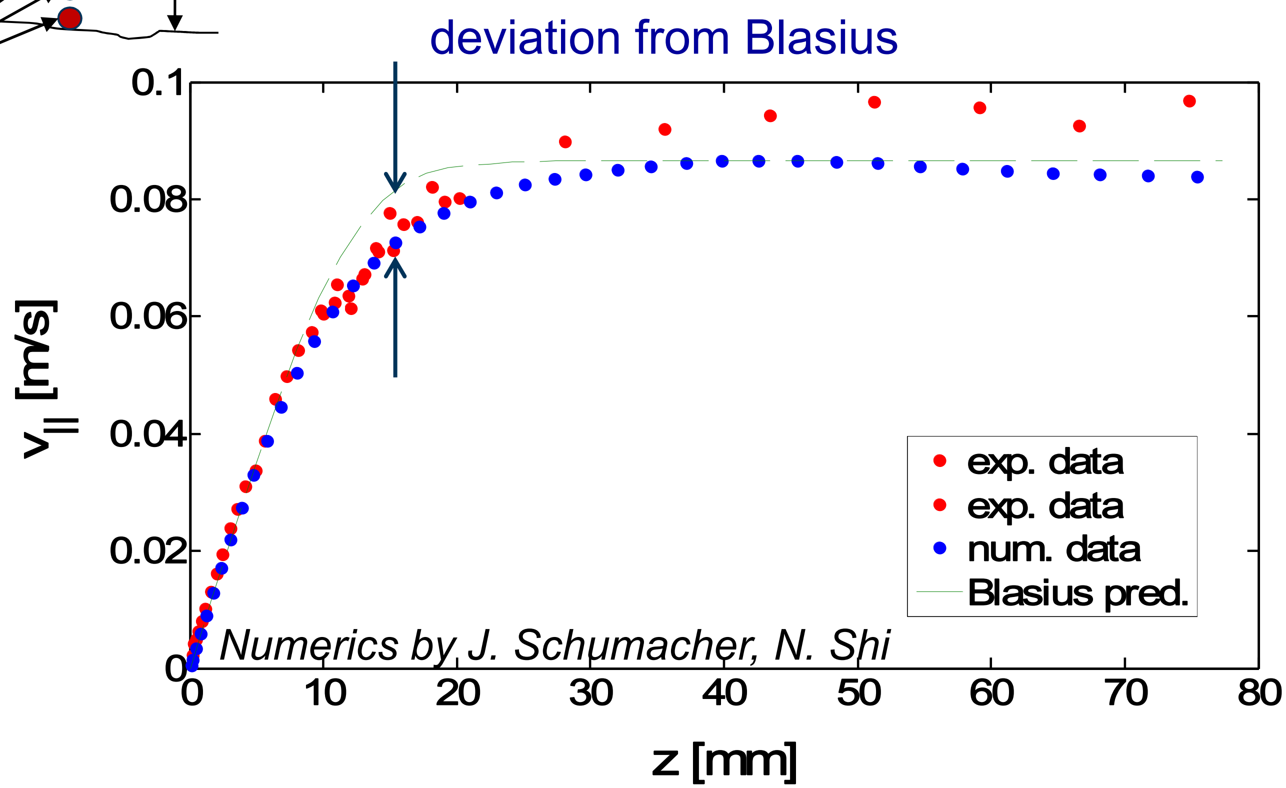
$Ra = 3.4 \times 10^9$

$\Gamma = 1, \quad Pr = 0.7$

$v_{\parallel} = \sqrt{u^2 + v^2}$ - wall-parallel velocity

w - wall-normal velocity



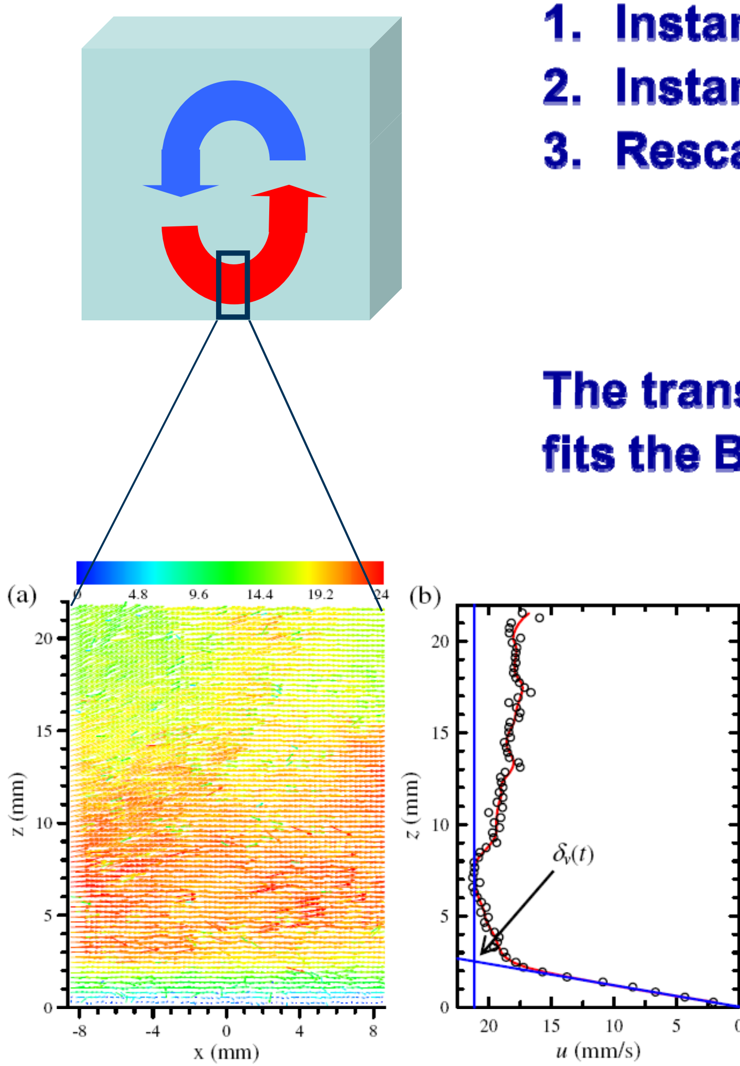


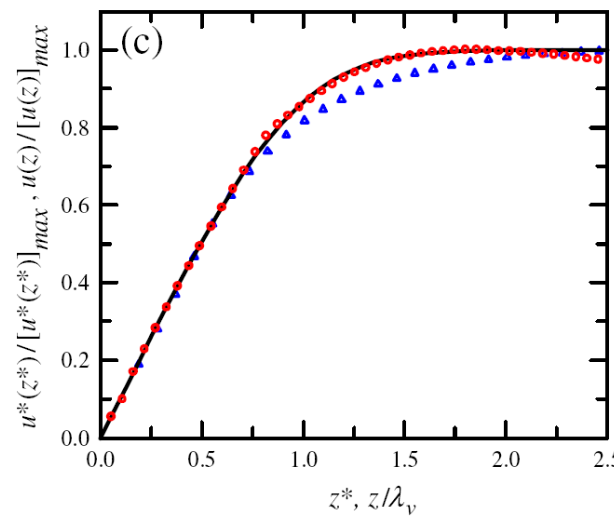
Dynamic space transformation of the profiles

Zhou and Xia, PRL 104 (2010)

1. **Instantaneaous velocity field**
2. **Instantaneous thickness $\delta_v(t)$ of the bl**
3. **Rescaling of z with respect to $\delta_v(t)$**

The transformed profile $u^*(z^*)$ perfectly fits the Blasius prediction





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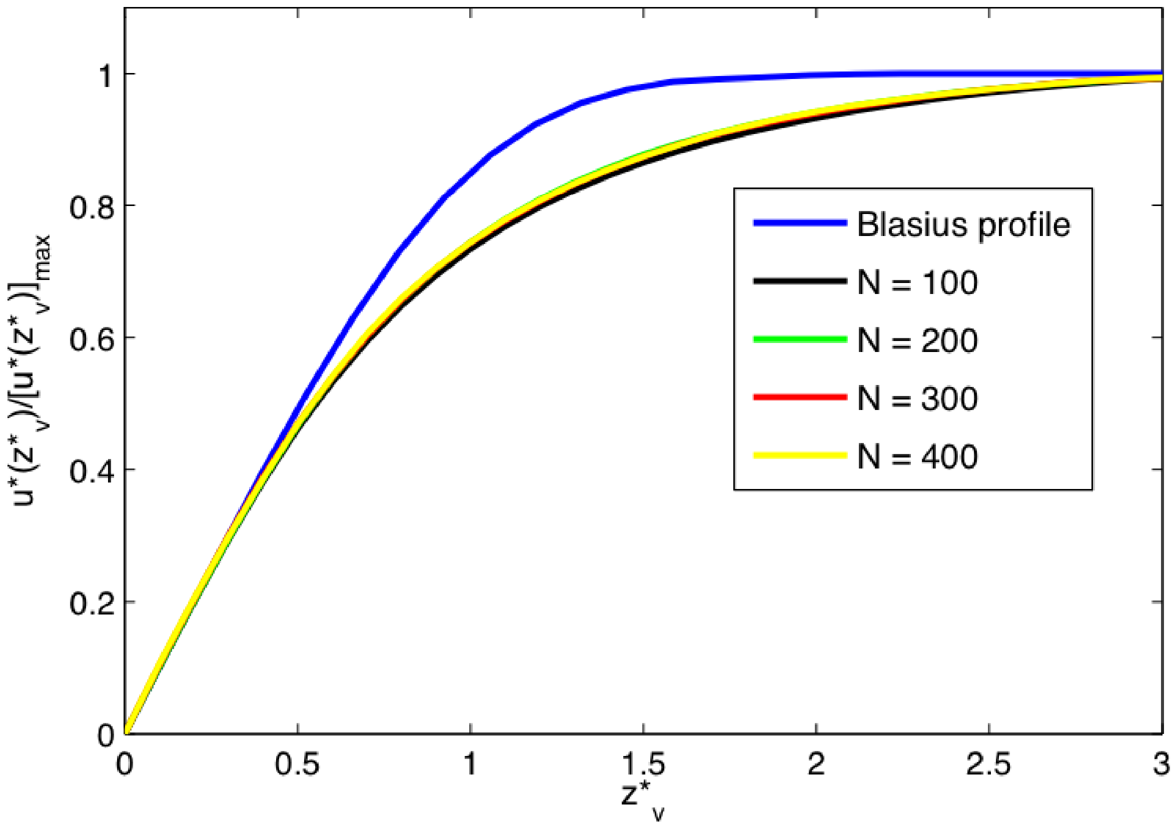
Dynamic space transformation of the profiles

Shi, Emran and Schumacher, APS meeting (2010)

$Ra = 3 \times 10^9$

$\Gamma = 1, \quad Pr = 0.7$



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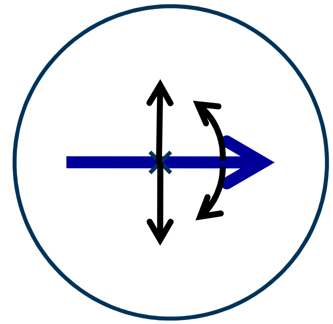
There are two fundamental differences:

Rectangular cell

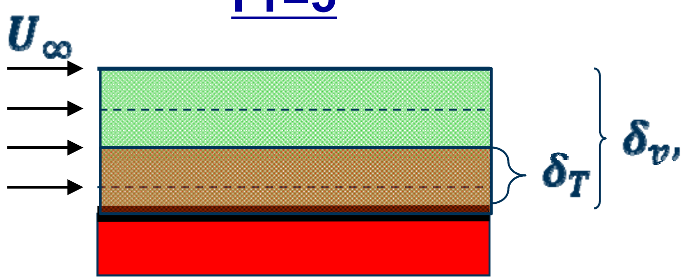
- Fixed orientation of the LSC

Cylindrical cell



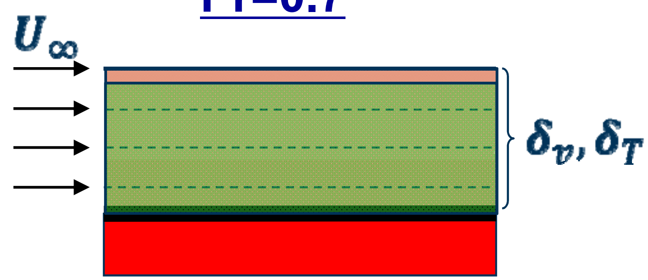
- One more degree of freedom for the LSC
- More dynamics!

Pr=5



- $\delta_T < \delta_v$

Pr=0.7



- δ_v and δ_T are of the same order

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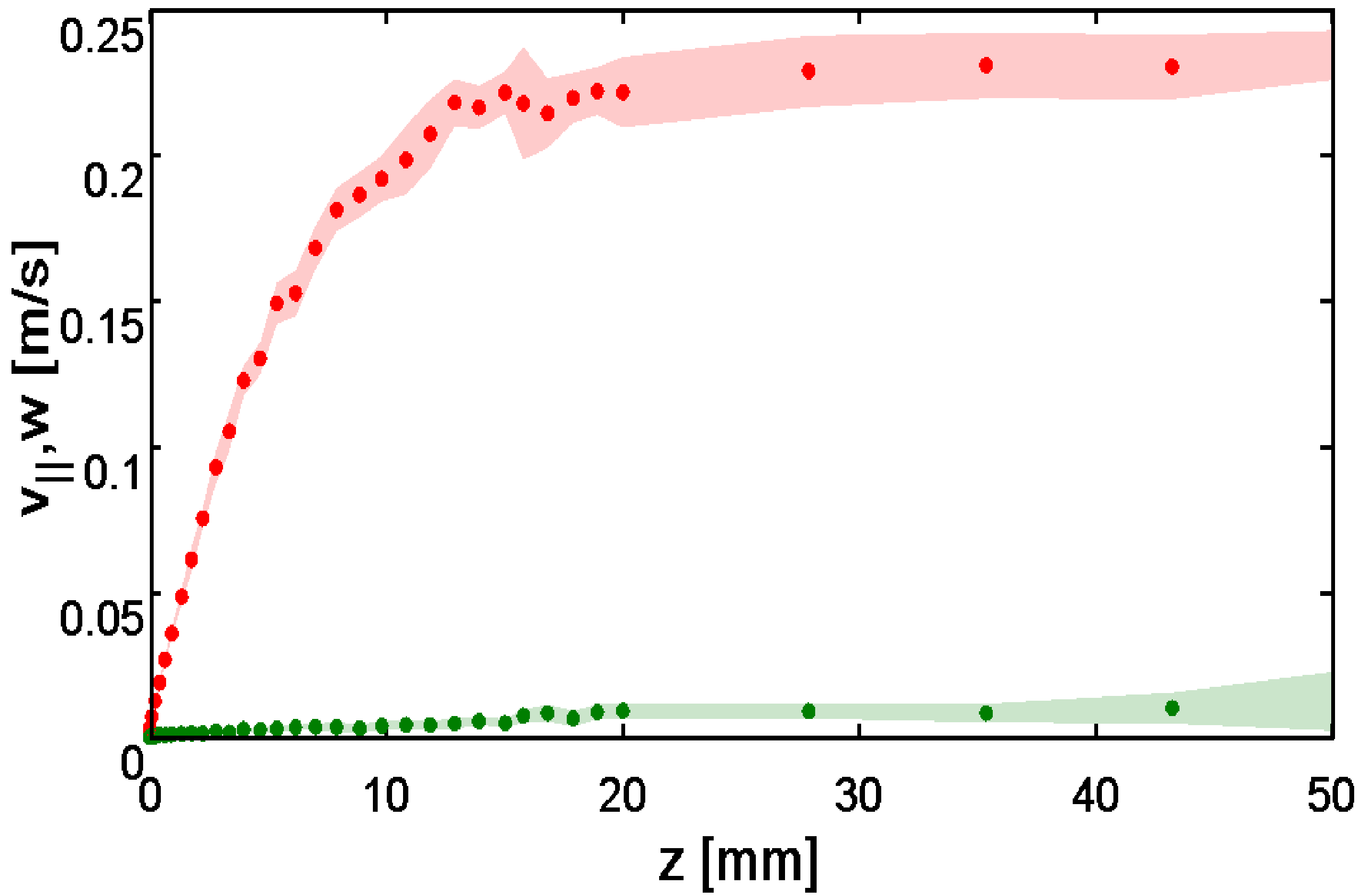
Mean velocity profiles

$Ra = 2.9 \times 10^{10}$ $\quad v_{\|} = \sqrt{u^2 + v^2}$ - wall-parallel velocity

$\Gamma = 1, \quad Pr = 0.7$ $\quad w$ - wall-normal velocity



KITP, "The nature of turbulence", Santa Barbara, California, 3/30/2011

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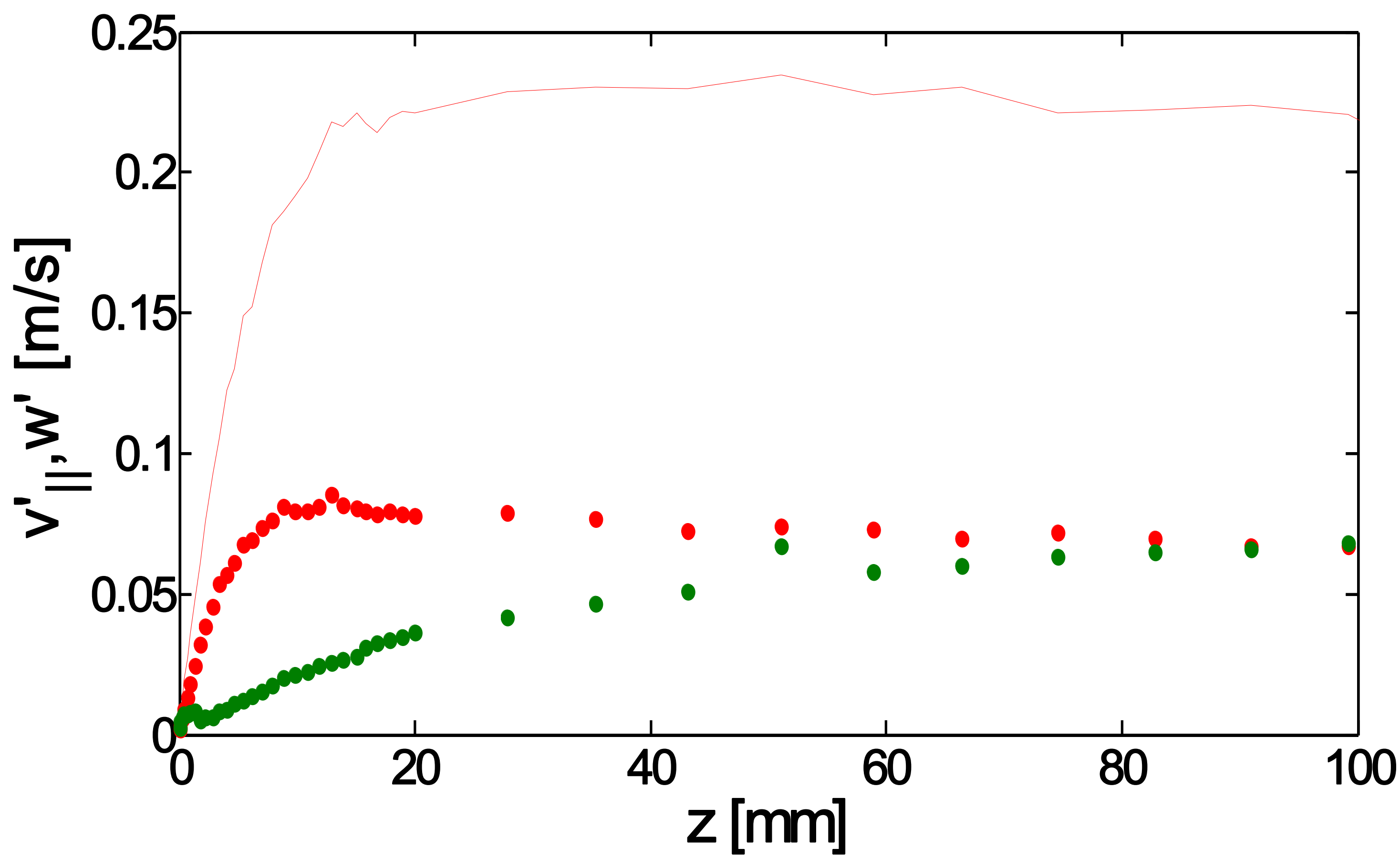
Fluctuations

$Ra = 2.9 \times 10^{10}$ $v'_{\parallel}$ - standard deviation of $v_{\parallel}$

$\Gamma = 1, \quad Pr = 0.7$ w' - standard deviation of w



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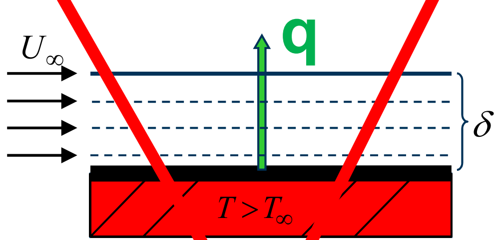
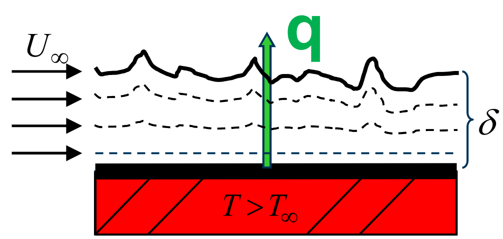
Which of the models for the boundary layer is the right one?

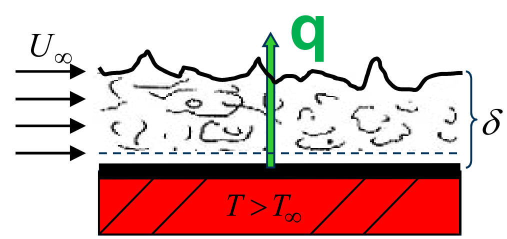


laminar bl

$$q = -\lambda \frac{\partial T}{\partial z}$$



laminar bl with fluctuations



turbulent bl

$$q = -\lambda \frac{\partial T}{\partial z} + \rho c_p \langle w' T' \rangle$$

$$\left| -\lambda \frac{\partial T}{\partial z} \right| \geq \left| \rho c_p \langle w' T' \rangle \right| \qquad \left| -\lambda \frac{\partial T}{\partial z} \right| \ll \left| \rho c_p \langle w' T' \rangle \right|$$

Have we already reached the ultimate state?

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THANK YOU!