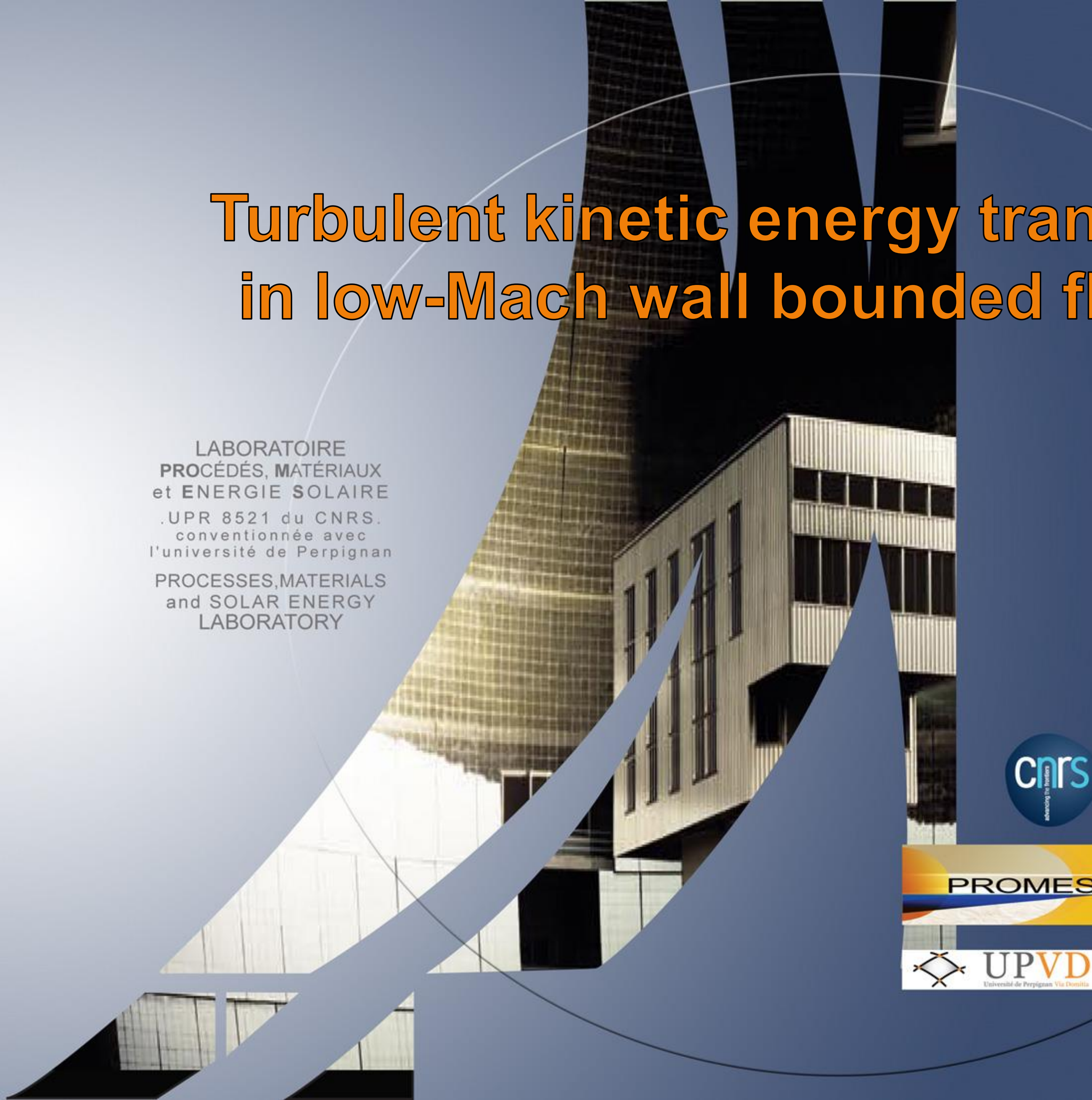
# Turbulent kinetic energy transfers in low-Mach wall bounded flows



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**PRO**CÉDÉS, **M**ATÉRIAUX
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conventionnée avec
l'université de Perpignan

PROCESSES,MATERIALS
and SOLAR ENERGY
LABORATORY


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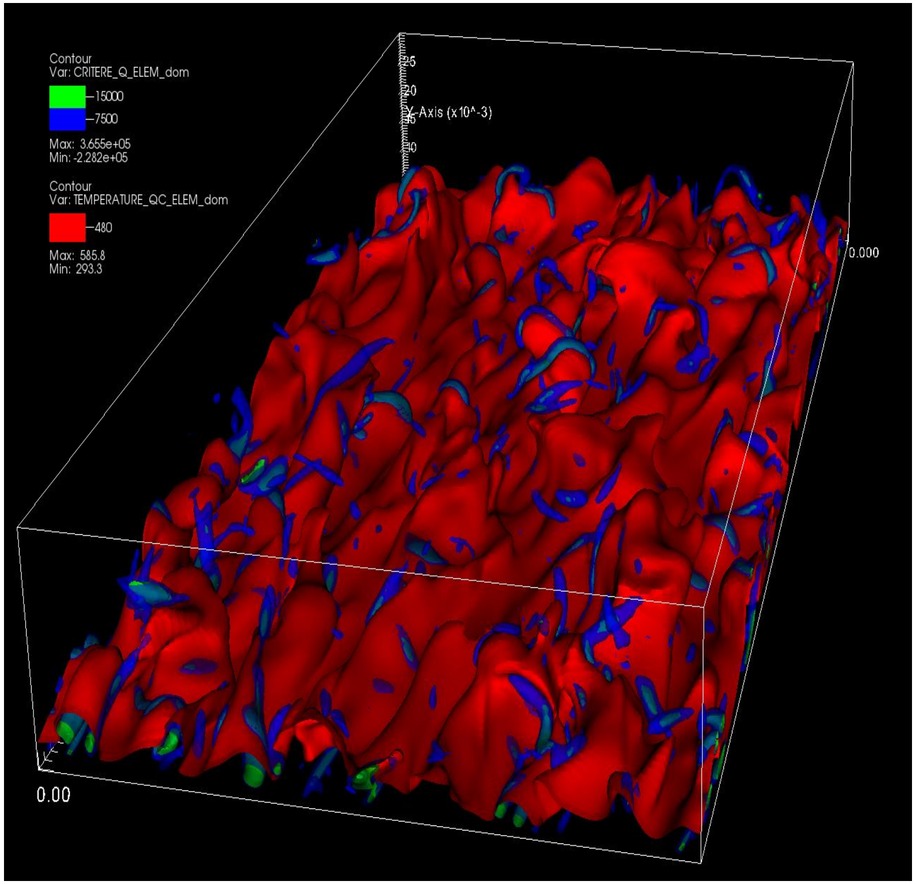
# Flows inside solar processes

- The vast majority of flows inside solar systems are very **anisothermal and turbulent**.

- The understanding of the **coupling between velocity and temperature** is a fruitful approach for the optimization of solar processes.

# Very anisothermal flow

A simple illustration of velocity and temperature coupling




Bi-periodic channel flow submitted to a high temperature gradient
Isosurfaces: Q-criterion (in blue and green)
Isotherm 480 K (in red)

# Global strategy

One of the difficulties:
Size difference between
small turbulent structures (~ µm) and
the solar receiver geometry (~ m)

➡ **Multi-scale approach**

- ❑ **Local scale: study of velocity/temperature coupling**
- ❑ Modular scale: heat transfer characterization
- ❑ Industrial scale: design and sizing

**Numerical and experimental tools dedicated to each scale**

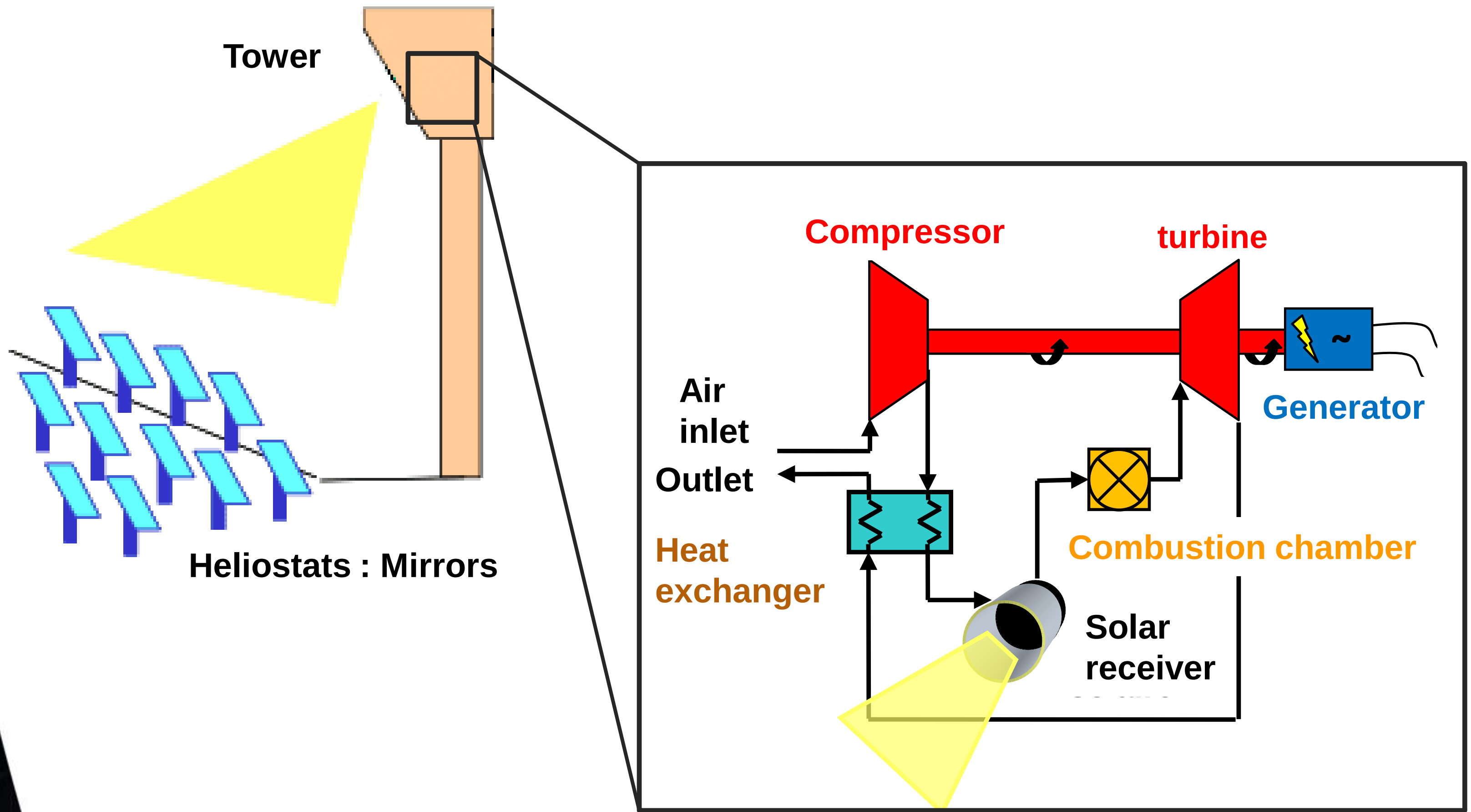
# Outline

1. Concentrated solar power plant
2. Resolution of low-Mach equations
3. Velocity/temperature coupling
4. Turbulent kinetic energy

Conclusions and outlook

# Concentrated solar tower plant

Choice of a high temperature thermodynamic cycle:
Brayton cycle at 1000°C




**Solar receiver**: a **key component** that transfers the concentrated solar energy to the working fluid

# Plate pressurized solar receiver

## Goal

Transfer of the concentrated solar energy to the working fluid

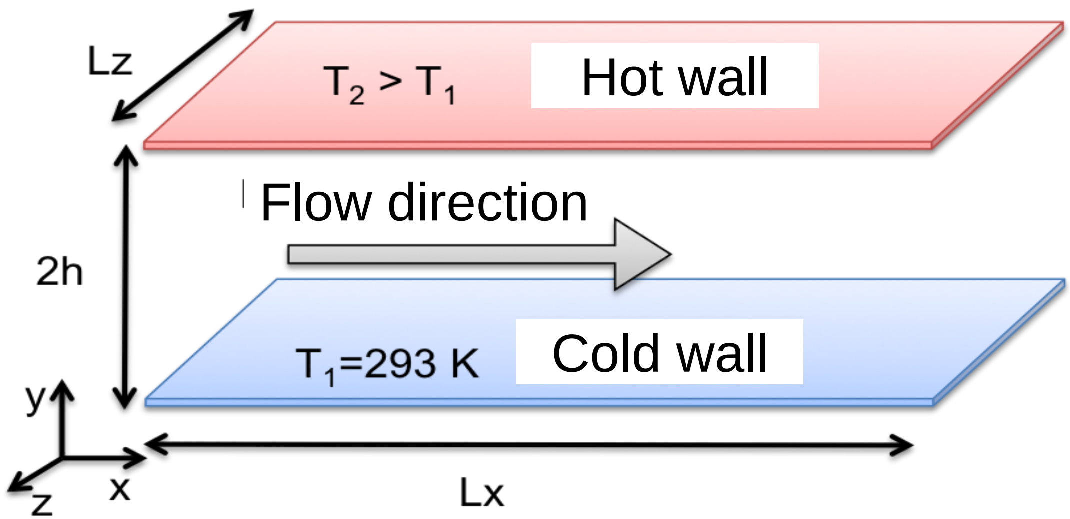
- Maximize the heat exchange between the gas and the wall,
- Minimize the pressure drop

## Characteristics

- High temperature 1000°C
- Turbulent flow
- Asymmetric heating
- Velocity/temperature coupling

# Resolution of Low-Mach equations: simplified geometry

- Main characteristics of HT SR:
  - Turbulent flow
  - Asymmetric heating
- Bi or mono periodic channel flow




- Study of the coupling between velocity and temperature

# Resolution of Low-Mach equations: numerical tools

- Trio_U software developed by CEA

- Realized improvement
  - Time and convection schemes
  - Parallel multigrid methods
  - Post processing for spectral analysis
  - **New algorithm for Low Mach number equations (incompressible):**
    - **Acoustic is not solve**
    - **Dilatation is taken into account**

# Resolution of Low-Mach equations: new algorithm

New algorithm advantages:

- Mass and energy conservation
- Coupling between temperature and velocity

Global conservation is achieved by finite volume method

Density
(Mass conservation)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0$$

- Thermodynamic pressure
  (Global energy conservation)
- Temperature
  (Ideal gas law)

$$\frac{\partial P_{th}}{\partial t} = \frac{\gamma - 1}{V} \int_S \lambda(T) \nabla T dS$$

$$T = \frac{P_{thermo}}{\rho \; r}$$

Fixed-point iteration

- Velocity
  (Navier-Stokes equation)
- Dynamic pressure
  (Local energy conservation)

$$\nabla \cdot (U) = \frac{1}{\gamma P_{th}} \left( (\gamma - 1) \nabla \cdot (\lambda(T) \nabla T) - \frac{\partial P_{th}}{\partial t} \right)$$

# Resolution of Low-Mach equations:

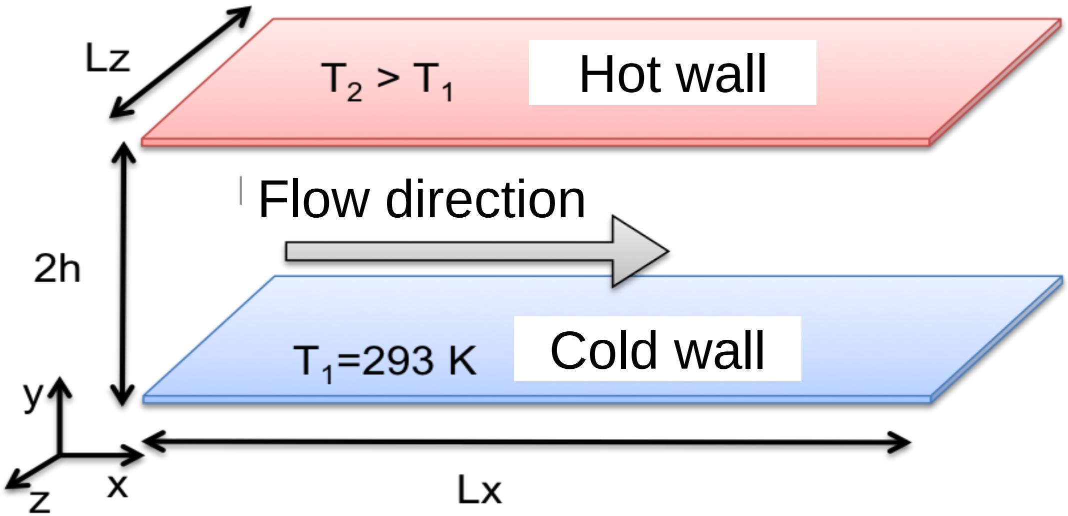
- Accurate numerical tools:
  - Conservation properties
  - Channel flow in agreement with literature
- Fine Simulations: DNS and LES
- Reference data for the study of
  the coupling between temperature and velocity

# Velocity/temperature coupling

- Goal: Model development for RANS
- Contribution: understanding of velocity/temperature coupling
- Effect of the temperature gradient on turbulence properties:
  - Mean and fluctuation velocities
  - Mean and fluctuation temperatures
  - Study in the space and frequency domains
- DNS $Re_\tau=395$ and T2/T1=2
  $L_x=4\pi h$, $L_y=2h$, and $L_z=2\pi h$
  1536x896x1536 (2.1 billion) cells and $y^+=0.125$

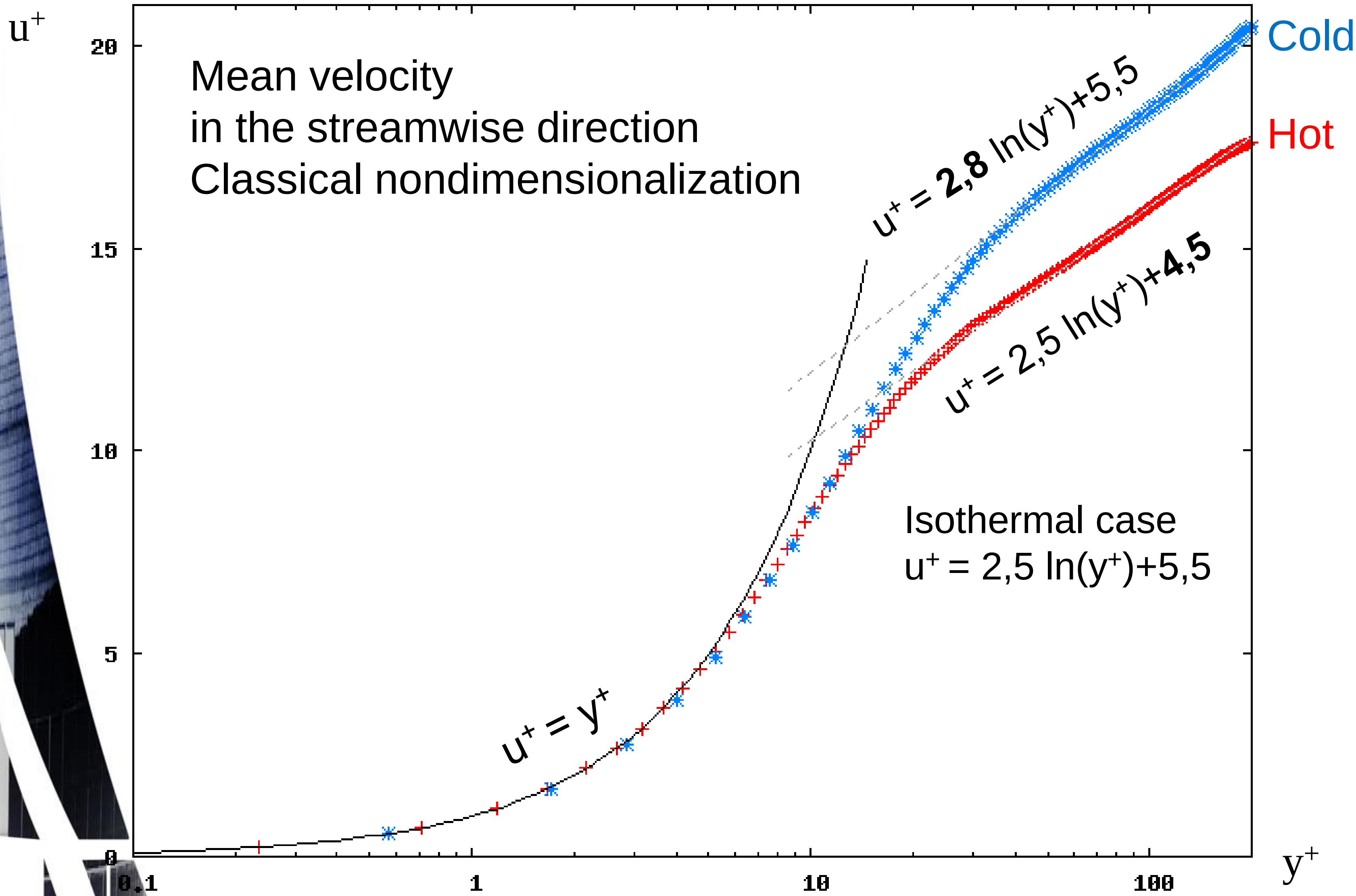
# Velocity/temperature coupling

- Simplified geometry: bi-periodic channel flow




- Statistics:
  - Average in the homogeneous directions (x and z),
  - Average in time,
  - Functions of the distance to the wall (y).

# Local scale: DNS $Re_\tau$=395 and T2/T1=2



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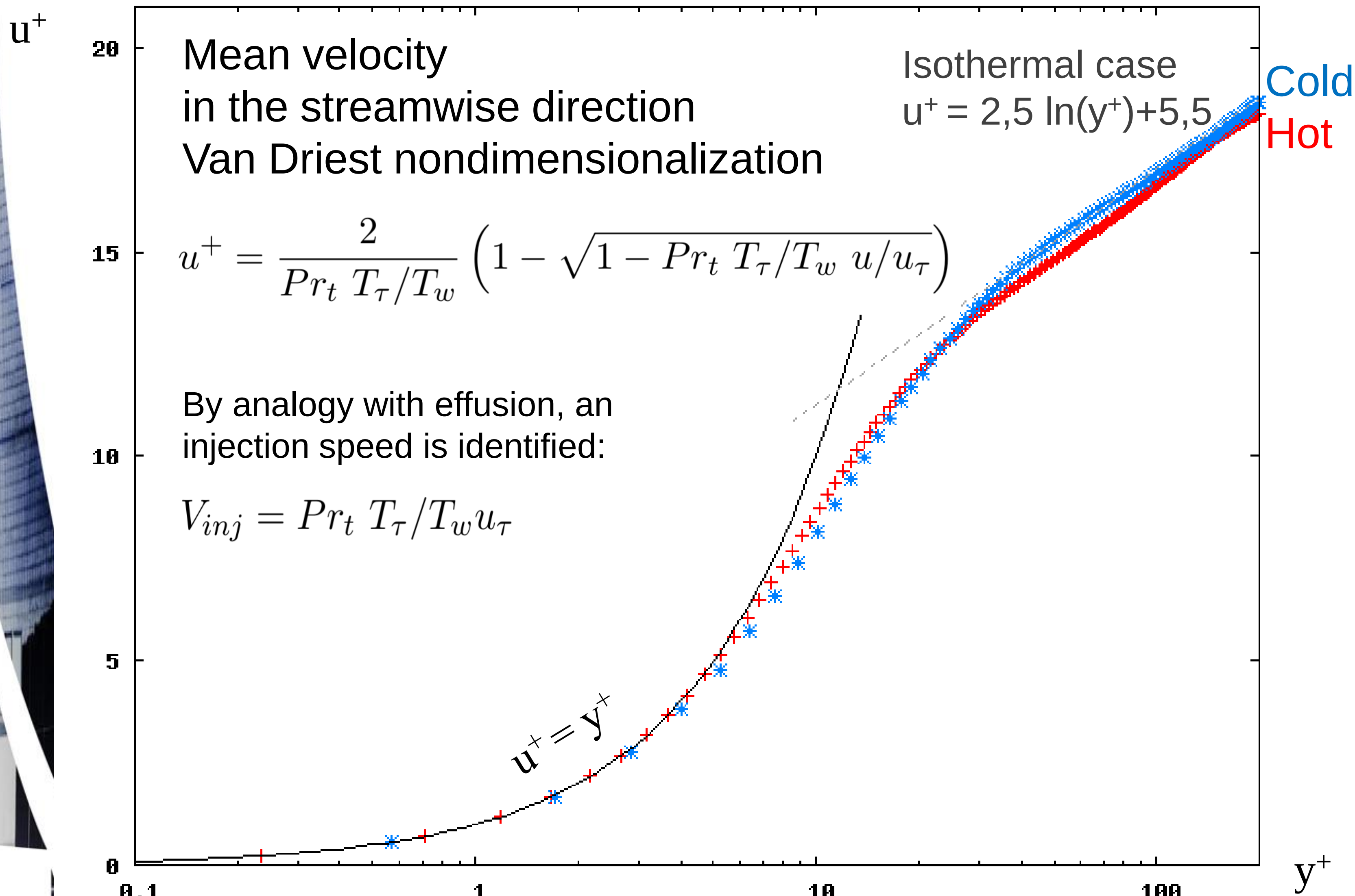

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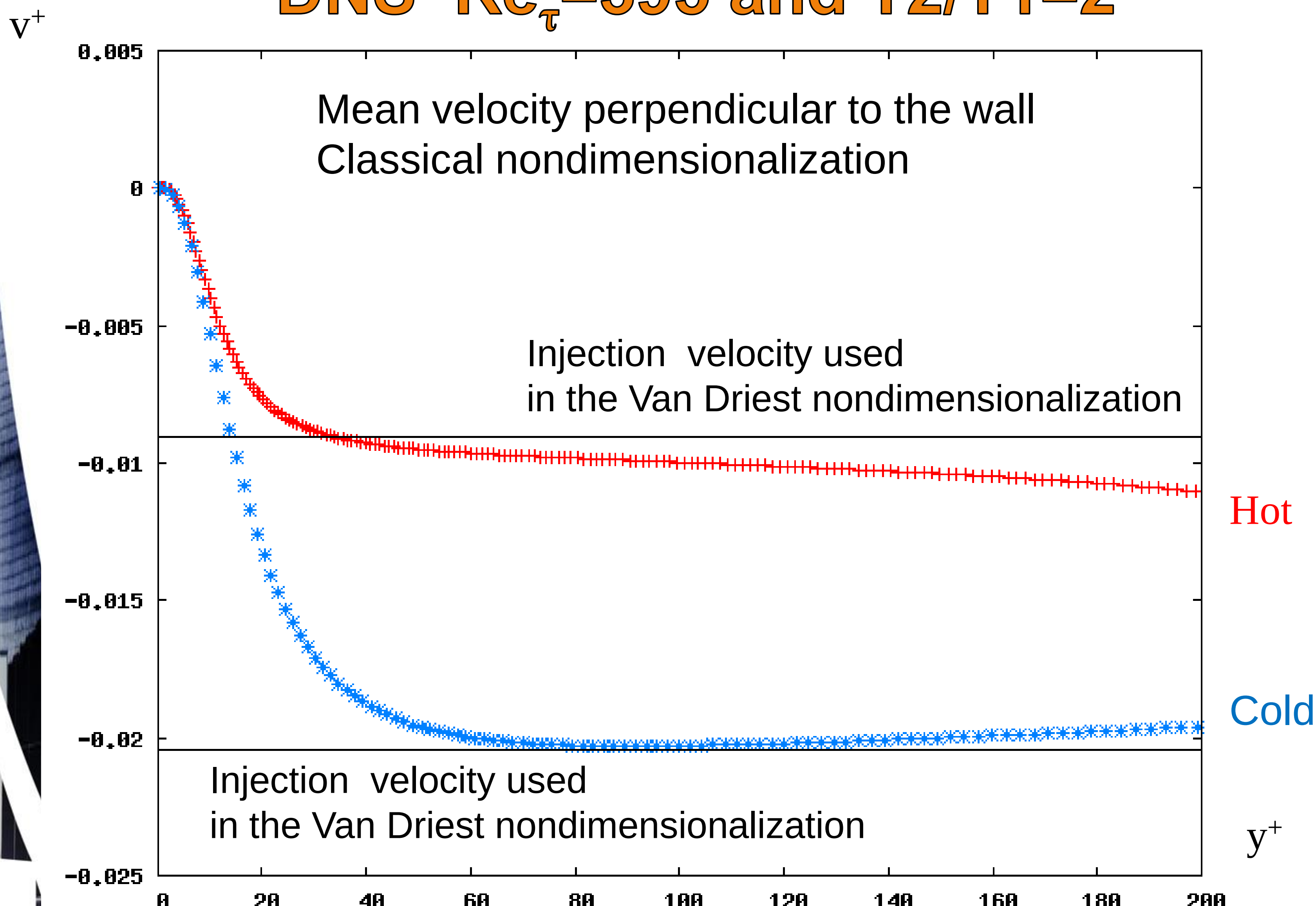


# Velocity/temperature coupling

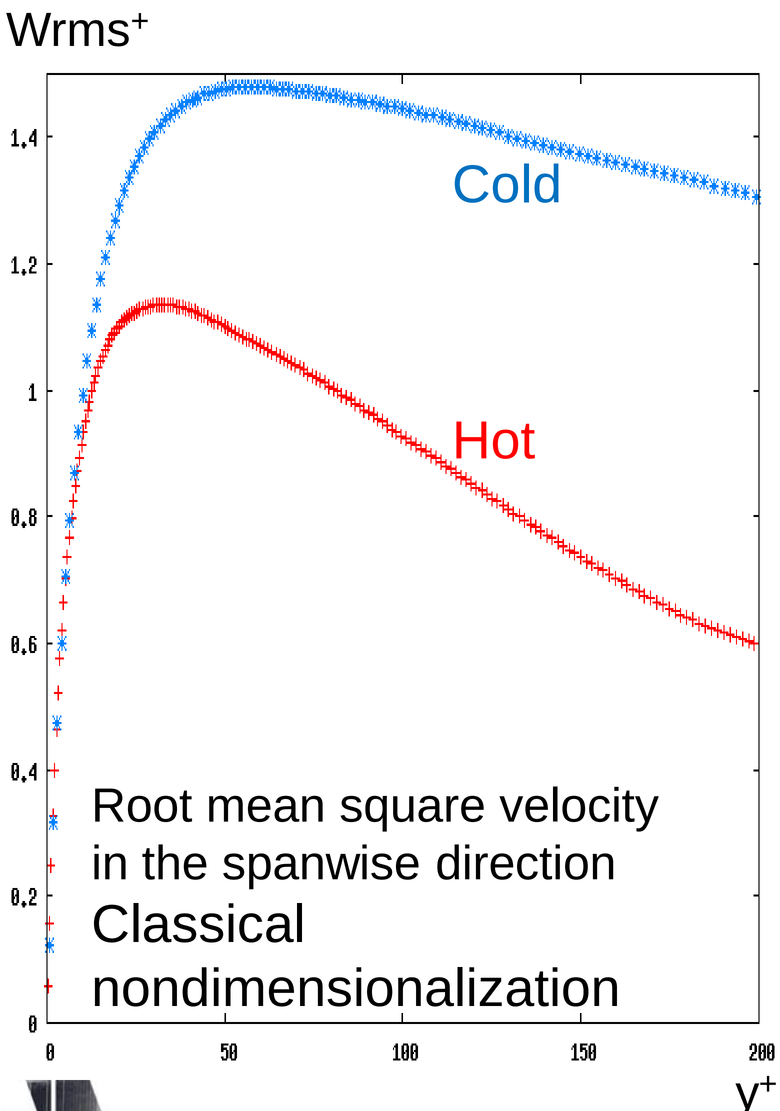
- **Mean velocity** perpendicular to the wall = 0 in the **isothermal case.**

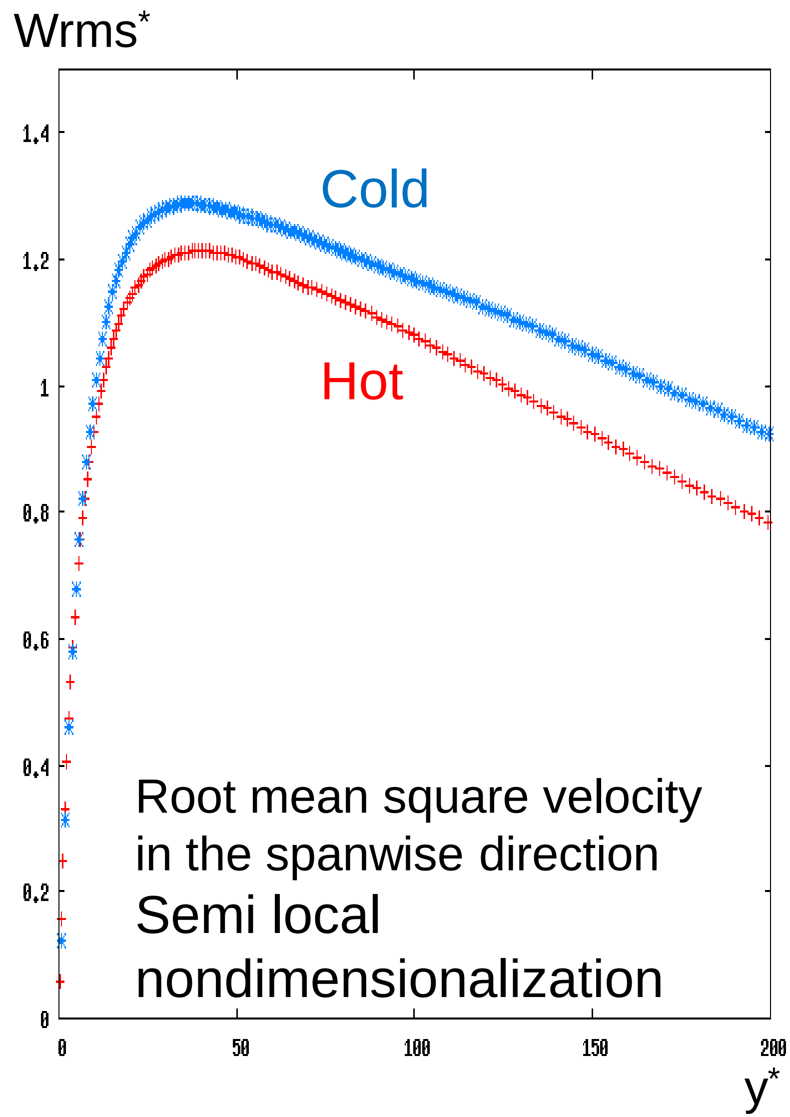
- This velocity is **due to the temperature gradient** that creates a density gradient that generates the mean velocity perpendicular to the wall.

- The **Van Driest nondimensionalization** can be understood as the **taking into account of the mean velocity** perpendicular to the wall created by the temperature gradient.

- This velocity **modifies the turbulence properties**. Because it is negative (from the hot side to the cold one):
  - it pushes back the turbulent structures from the hot side
  - it brings the turbulent structures closer to the cold side

# Velocity/temperature coupling: DNS $Re_\tau$=395 and T2/T1=2



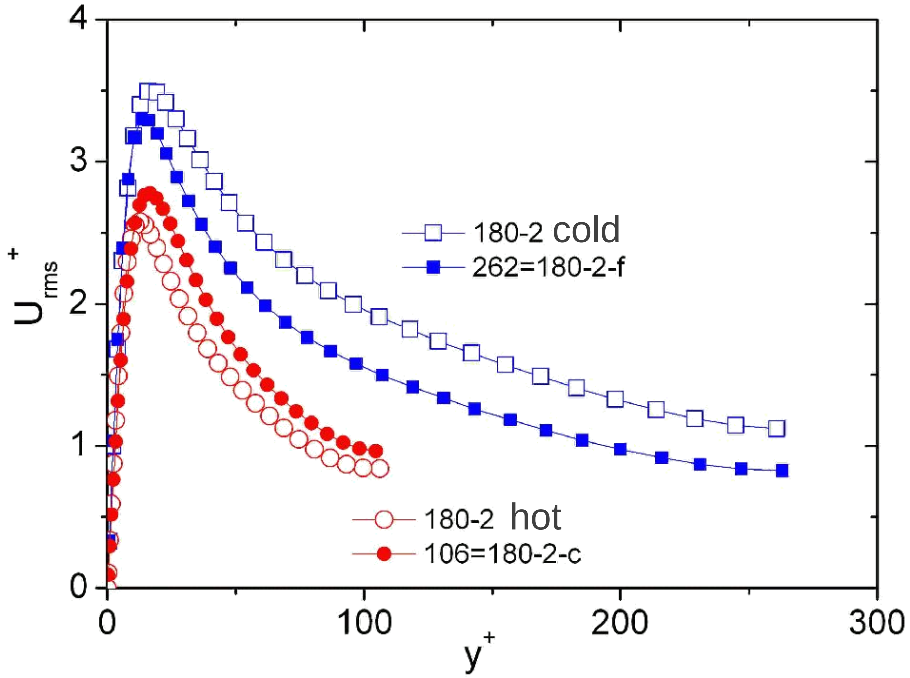



# Velocity/temperature coupling

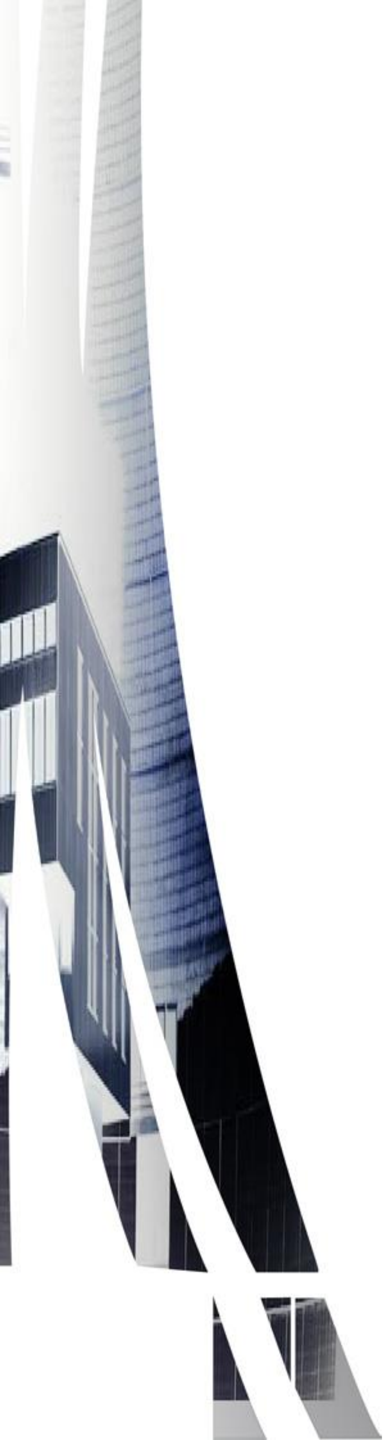
- Taking into account the mean variations of fluid properties (semi local nondimensionalization) does not remove the dissymmetry.
- The velocity/temperature coupling is more complex.
- It is the first time that it is shown by DNS in a fully turbulent case (without low Reynolds effect).
- Is the dissymmetry due to the turbulence levels of the hot and cold sides?

# Velocity/temperature coupling

- Viscous effect: comparisons of anisothermal profiles with isothermal profiles at equivalent Reynolds number.




- The temperature gradient effect is bigger than the viscous effect.
- Study in the frequency domain.



# Turbulent kinetic energy: Study in the frequency domain

- ❑ Evolution equation
- ❑ Spectral model

# Turbulent kinetic energy: Evolution equation

$$\frac{\partial E_c(k,y)}{\partial t} = \Pi(k,y) + \sum T_n(k,y) + D(k,y)$$

Production | Transfer | Dissipation

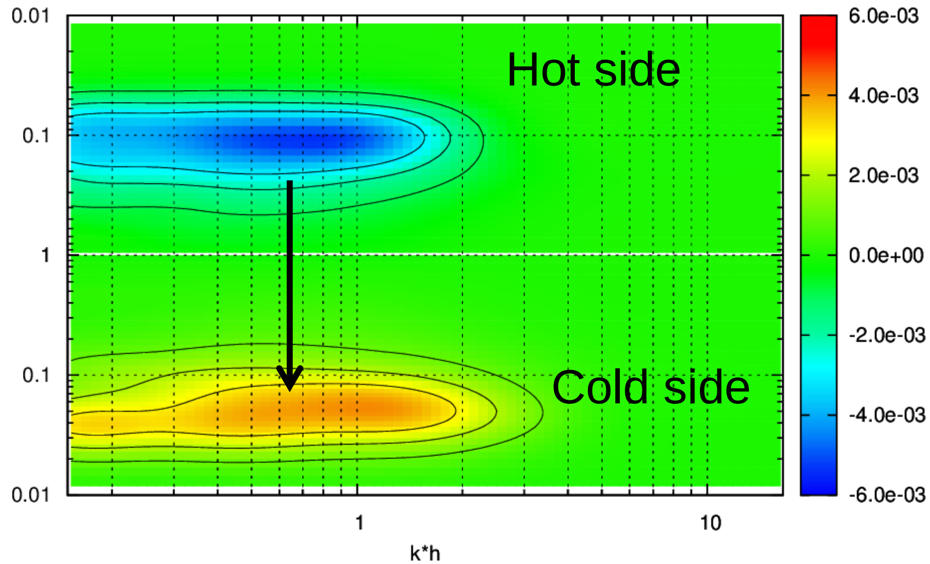
Terms specific to anisothermal case

$$\int_k -2\Re\left[\sum_i \left[\widehat{v_i^*}'\,\overline{U_y}\,\widehat{\frac{\partial v_i'}{\partial y}} + \frac{1}{2}\widehat{v_i^*}'\,\widehat{v_i'}\,\frac{\partial \overline{U_y}}{\partial y} - \sum_j \frac{1}{2}\widehat{v_i^*}'\left(\widehat{v_i'\frac{\partial u_j'}{\partial x_j}}\right) + \sum_j \widehat{v_i^*}'\,\overline{V_i}\,\widehat{\frac{\partial u_j'}{\partial x_j}}\right]\right] dk$$

Non zero velocity normal to the wall

Non zero velocity divergence

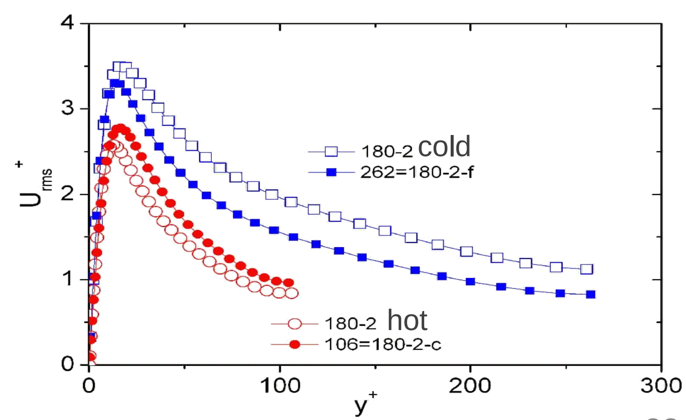
# Turbulent kinetic energy: terms specific to anisothermal case




Turbulent kinetic energy transfer from the hot side to the cold side

➡ **Explanation of the turbulent fluctuation levels**

**Real geometry should avoid this transfer**



# Turbulent kinetic energy: spectral model

Simulation results show that, according to the Reynolds number, the temperature gradient and the side of the channel, the slope of the inertial range of turbulent kinetic energy spectra is equal to -5/3 or -7/3.

| | $Re_{\tau m} = 180$ | | $Re_{\tau m} = 395$ | |
|---|---|---|---|---|
| | $T_R = 2$ | $T_R = 5$ | $T_R = 2$ | $T_R = 5$ |
| Probe | Slope $k^{-\sigma}$ | Slope $k^{-\sigma}$ | Slope $k^{-\sigma}$ | Slope $k^{-\sigma}$ |
| $S_H$ | N/A | N/A | $\sigma \approx 7/3$ | N/A |
| $S_C$ | $\sigma \approx 7/3$ | $\sigma \approx 7/3$ | $\sigma \approx 5/3$ | $\sigma = 7/3$ |

# Turbulent kinetic energy: spectral model

Introduction of a time scale that depends of temperature gradient

→ generalisation of the Kolmogorov model

Kolmogorov model

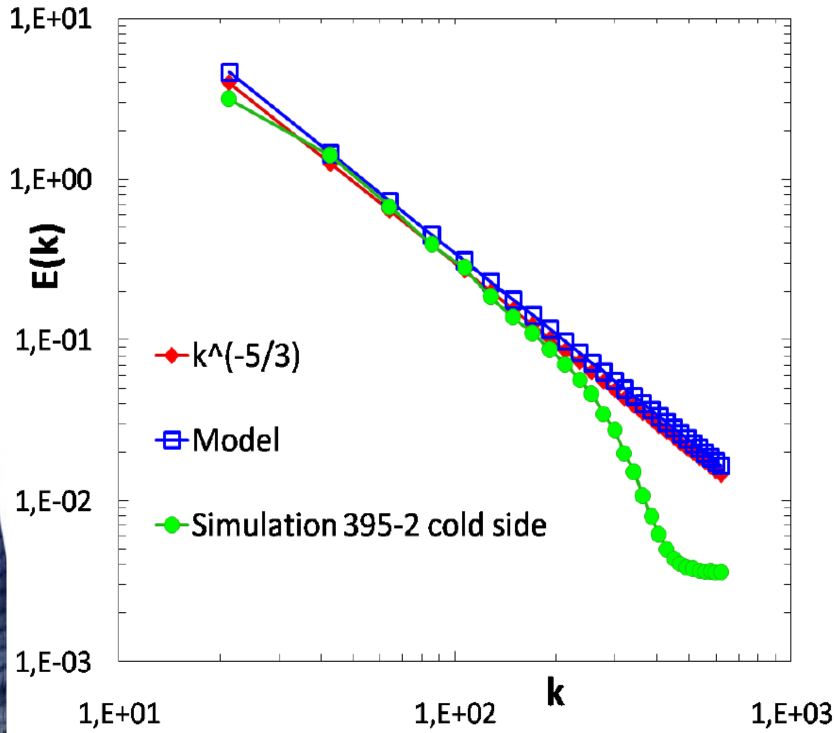
$$E(k) = \boxed{C_K \epsilon^{2/3} k^{-5/3}} \boxed{\left(1 + \frac{1}{fkh}\right)^{2/3}}$$

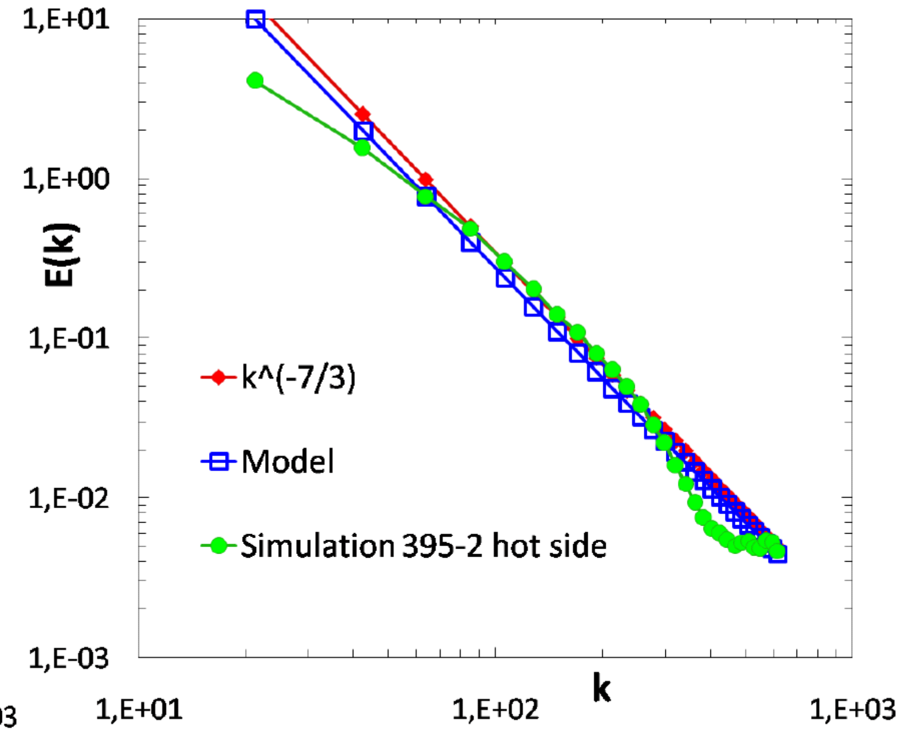
Correction for very anisothermal case

No temperature gradients, $f \to \infty$, $E \sim k^{-5/3}$

Big temperature gradients, $f \to 0$, $E \sim k^{-7/3}$

# Turbulent kinetic energy: spectral model



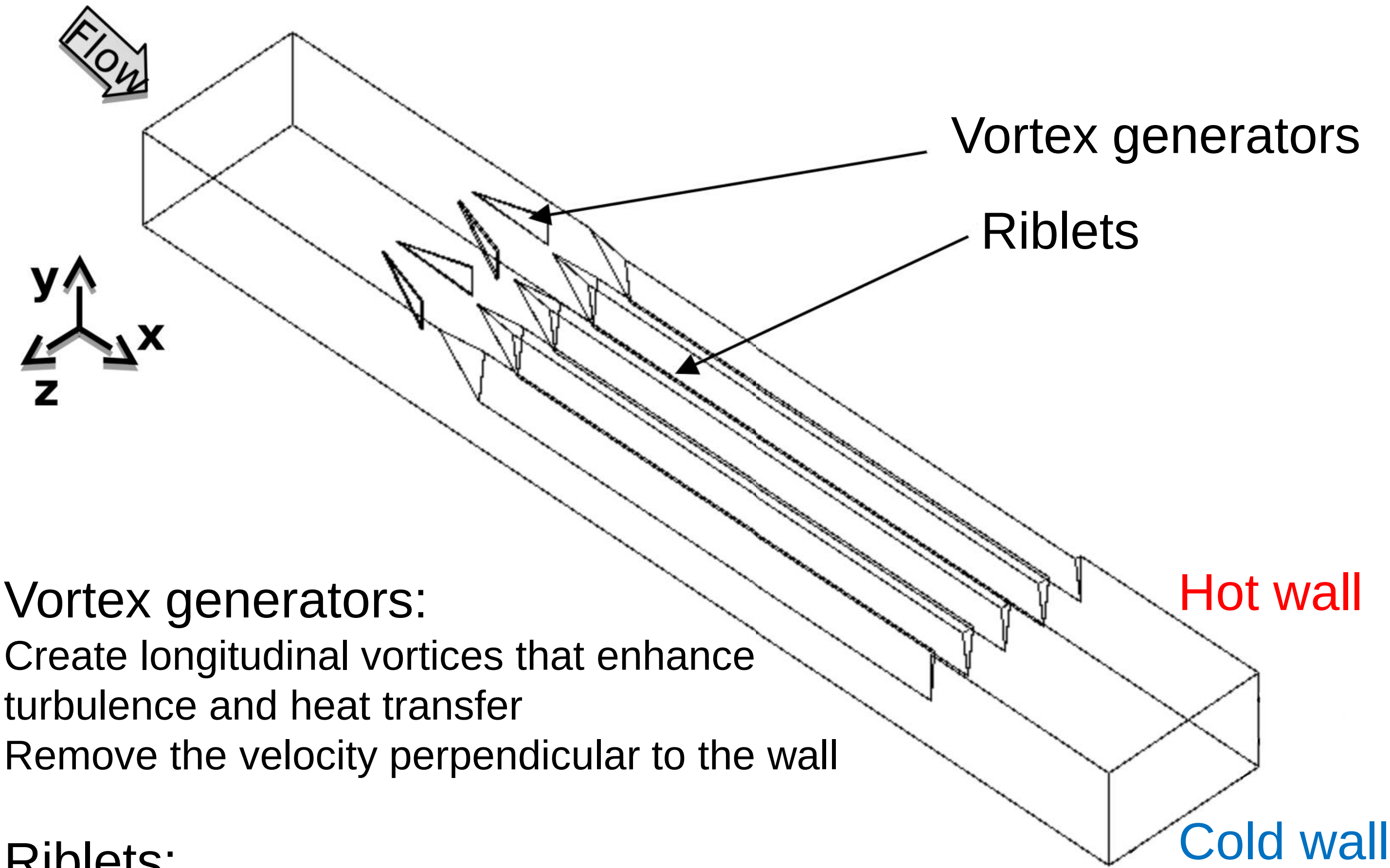




The model finds again the good behaviour.

The best situation corresponds to 5/3 slope at the hot side.

# Heat transfer enhancement

- Innovative geometry of real solar receivers




## Vortex generators:

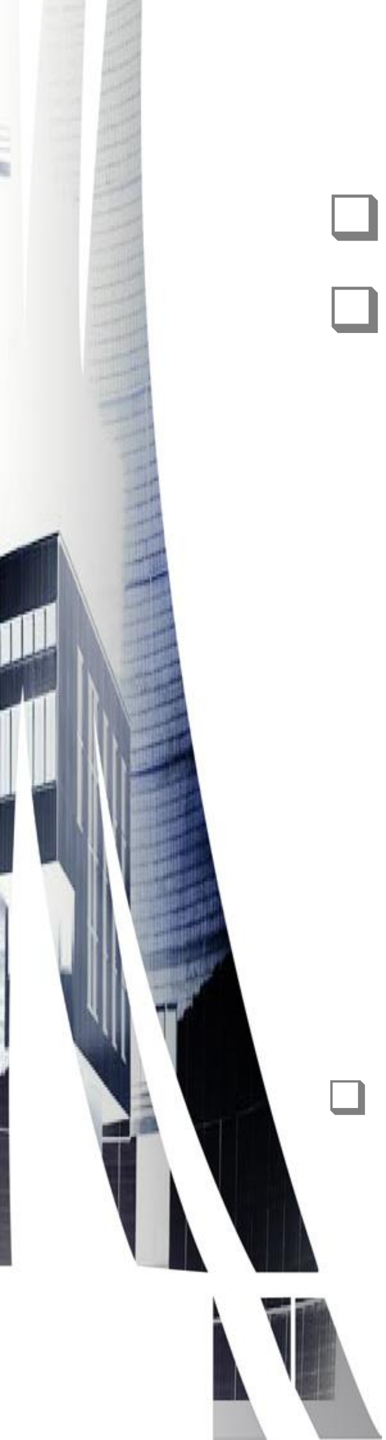
Create longitudinal vortices that enhance turbulence and heat transfer

Remove the velocity perpendicular to the wall

## Riblets:

Increase surface exchange

Lead vortices



# Conclusions

- Development of numerical tools: new algorithm
- Velocity/temperature coupling
  - The temperature gradient modifies the turbulence characteristics
  - A dissymmetry between the hot and cold side appears
  - This dissymmetry is not only due to the mean variation of the fluid properties or to the turbulent intensity
  - A turbulent kinetic energy transfer from the hot side to the cold side exists
  - We propose a model of the inertial zone of the turbulent kinetic energy spectrum


- Acknowledgement:
  - Trio_U, open source developed by CEA
  - This work was performed using HPC resources from GENCI-CINES (Grants 20XX-c20152a5099, c20142a5099, c20132a5099)

# Outlook

- Development of numerical tools
  - Kinetic energy conservation
  - Large Eddy Simulation modelling
- Velocity/temperature coupling
  - Study of the turbulent kinetic energy equation
- High temperature solar receiver
  - Tests under high solar flux at the Themis power plant

# Thank you