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Pole vaulting of long fibres in a turbulent wall-bounded flow

Christophe Brouzet, J Bec, Christophe Henry

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Pole-vaulting of long fibres in a turbulent wall-bounded flow

C. Brouzet

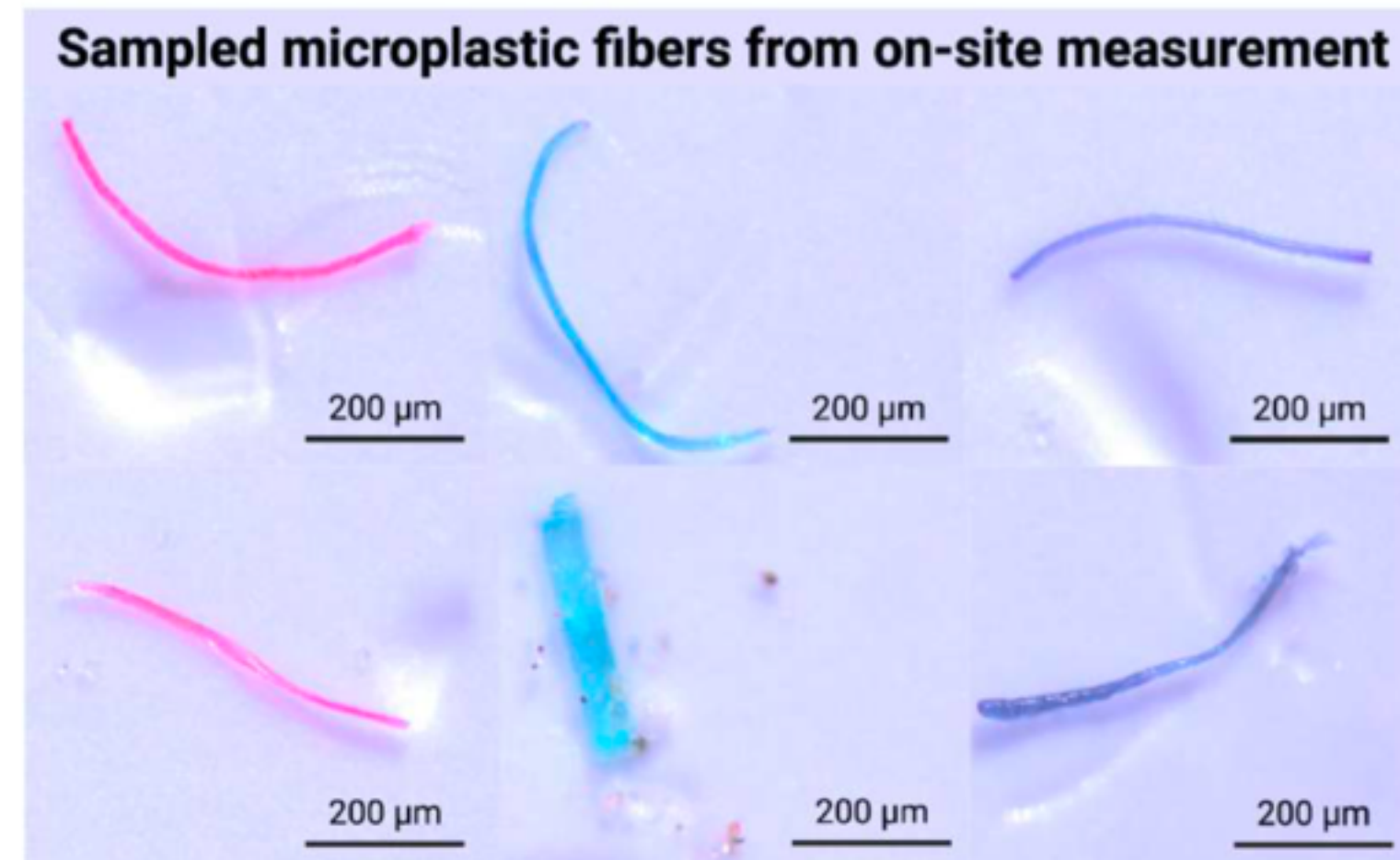
in collaboration with J. Bec & C. Henry

Motivations

- Fibres in turbulent flows:

- environmental applications:

* plastic pollution



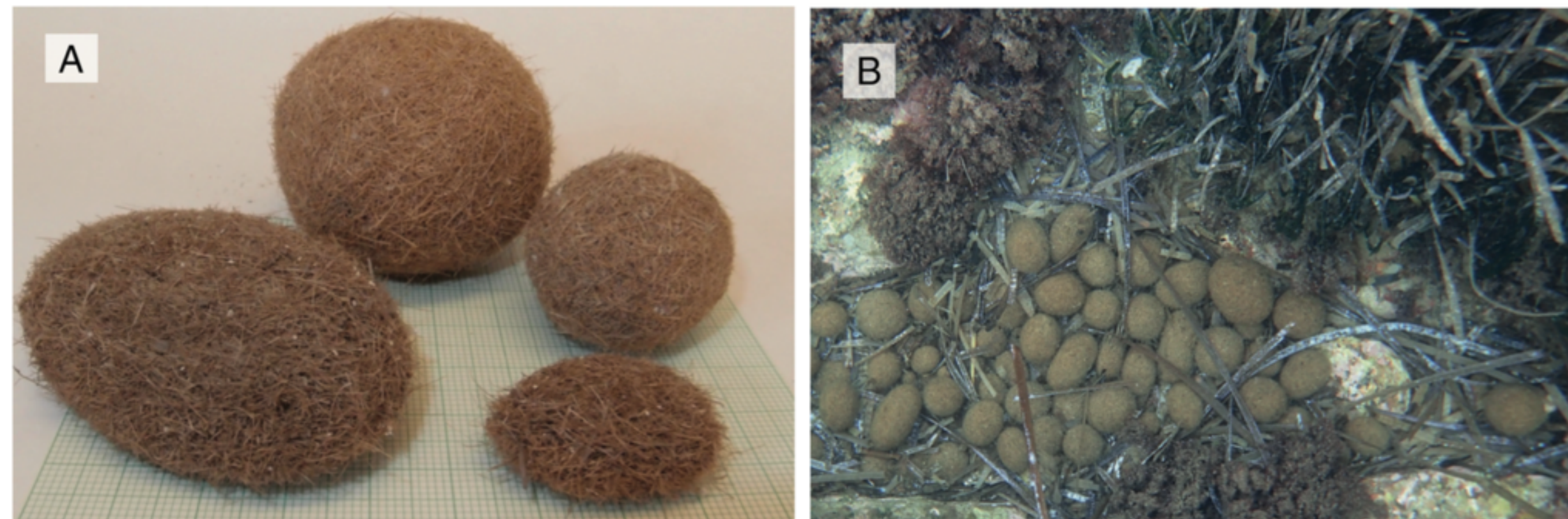
Allen *et al.* (2019)



Chubarenko *et al.* (2018)

transport ?
deposition ?
fragmentation ?

* natural fibre balls



Verhille *et al.* (2017)

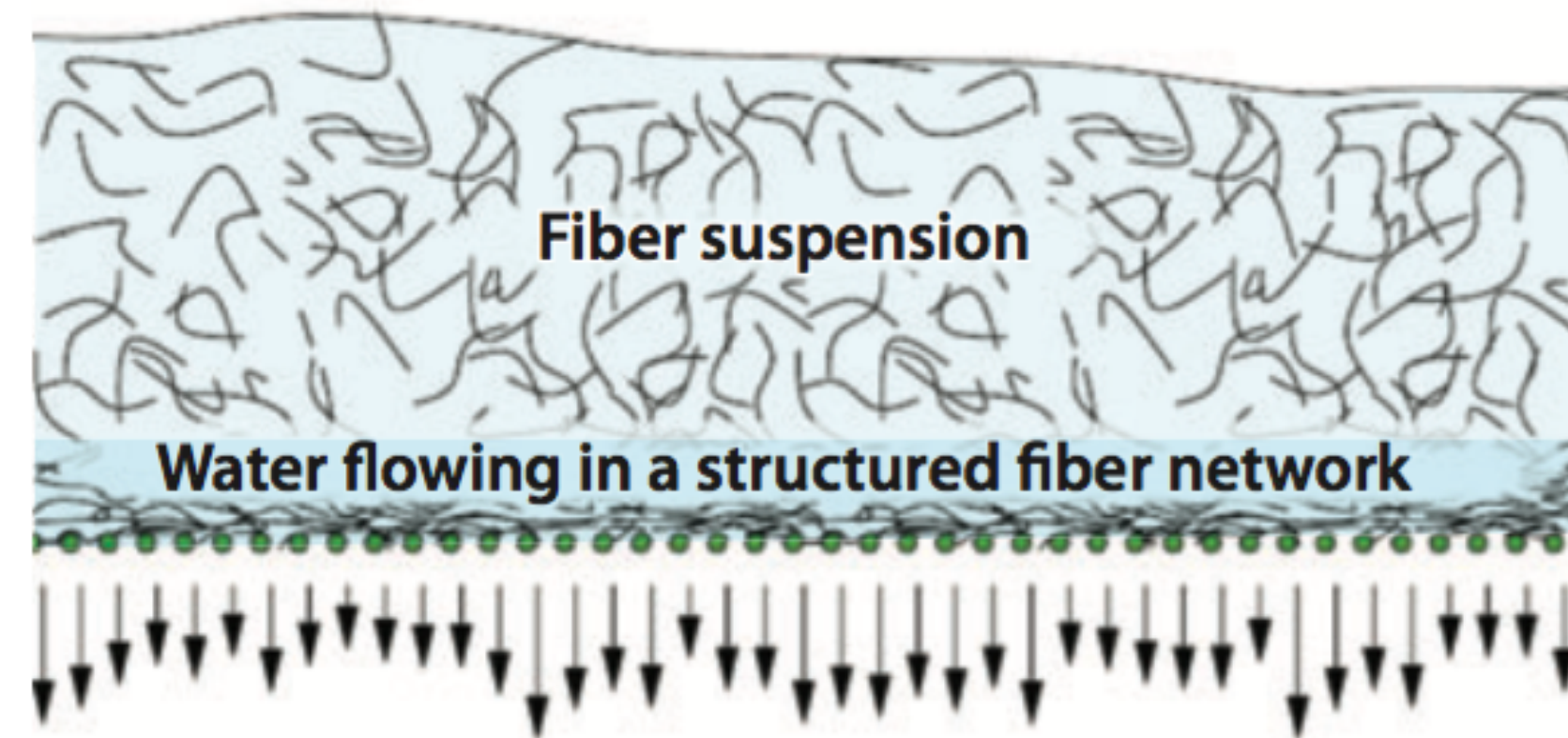
aggregation ?

Motivations

- Fibres in turbulent flows:

- industrial applications:

- * paper making & material fabrication



Lundell *et al.* (2011)

**orientation ?
aggregation ?**

- * water intakes



Credits: EDF



Redlinger-Pohn *et al.* (2020)

**deposition ?
clogging ?**

- Fibres in turbulent flows:
 - homogeneous & isotropic turbulence: “idealised case”
 - * rigid fibres (mainly)
 - * flexible fibres

- Fibres in turbulent flows:
 - homogeneous & isotropic turbulence: “idealised case”
 - * rigid fibres (mainly)
 - * flexible fibres
 - wall-bounded turbulent flows: inhomogeneous & anisotropic
 - * rigid & short fibres (only)

long flexible fibres in wall-bounded turbulence

=> experiments & simulations

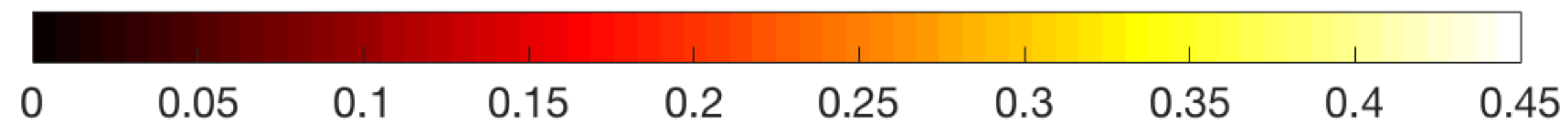
- Fluid flow:

- open-source spectral solver *Channelflow 2.0*

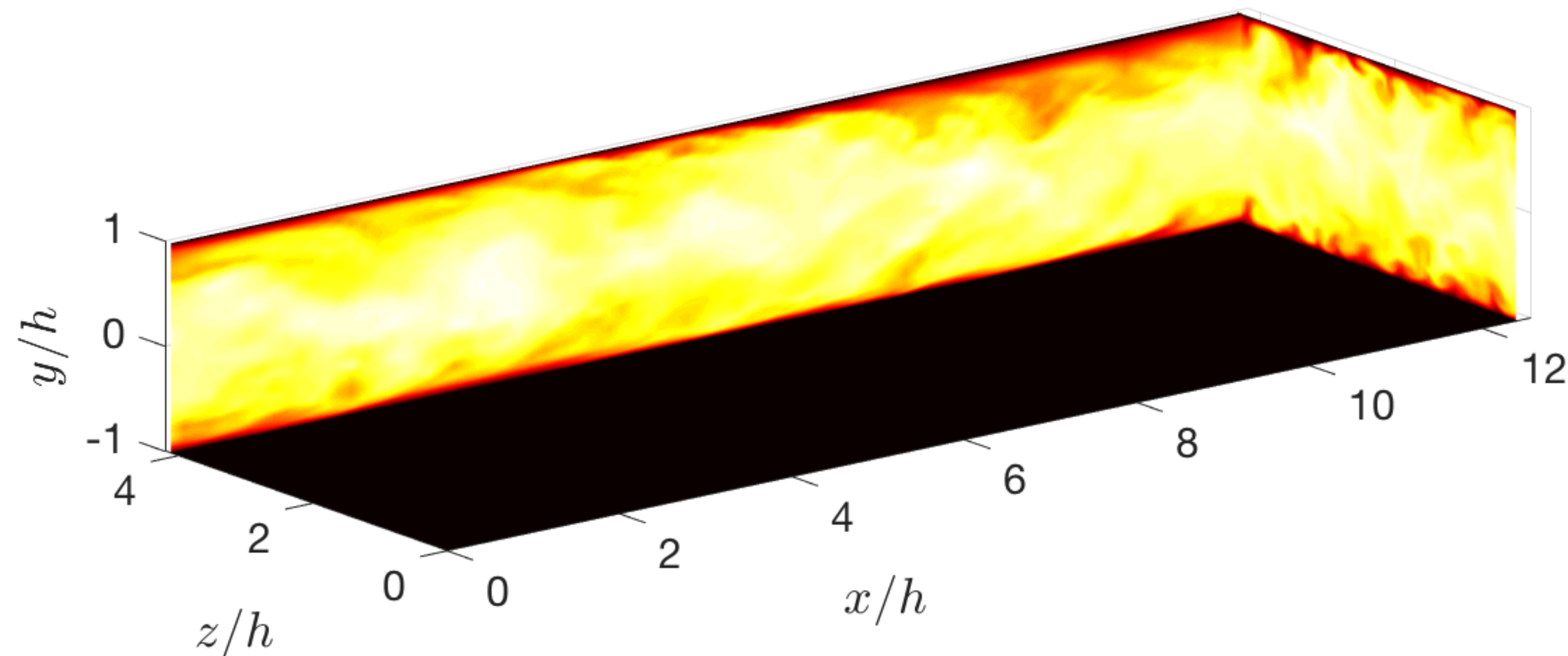
- * $L_x \times L_y \times L_z = 4\pi h \times 2h \times 4\pi h/3$

- * periodic boundary conditions in x and z

- * constant bulk velocity imposed



U



Numerical simulations

- Fluid flow:

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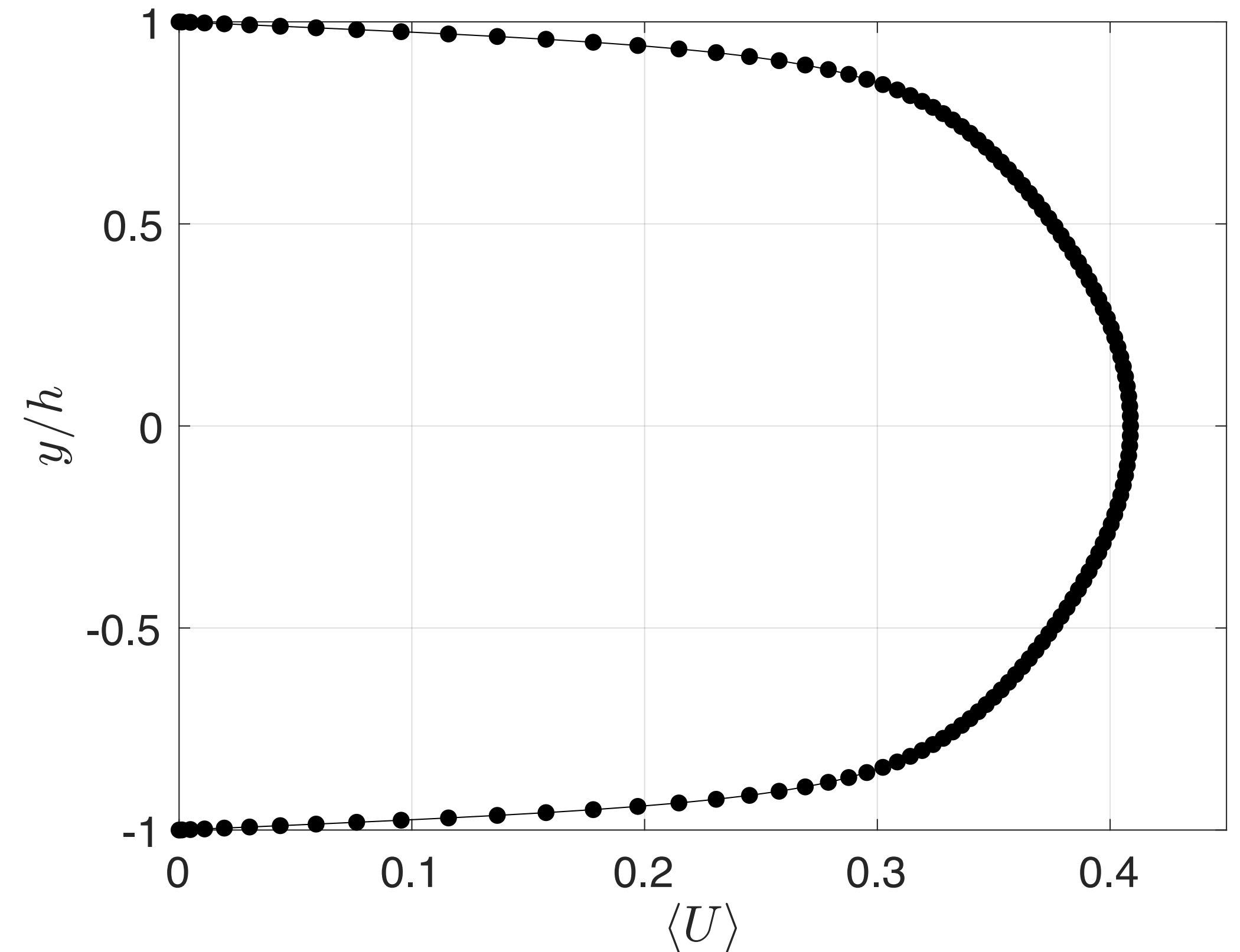
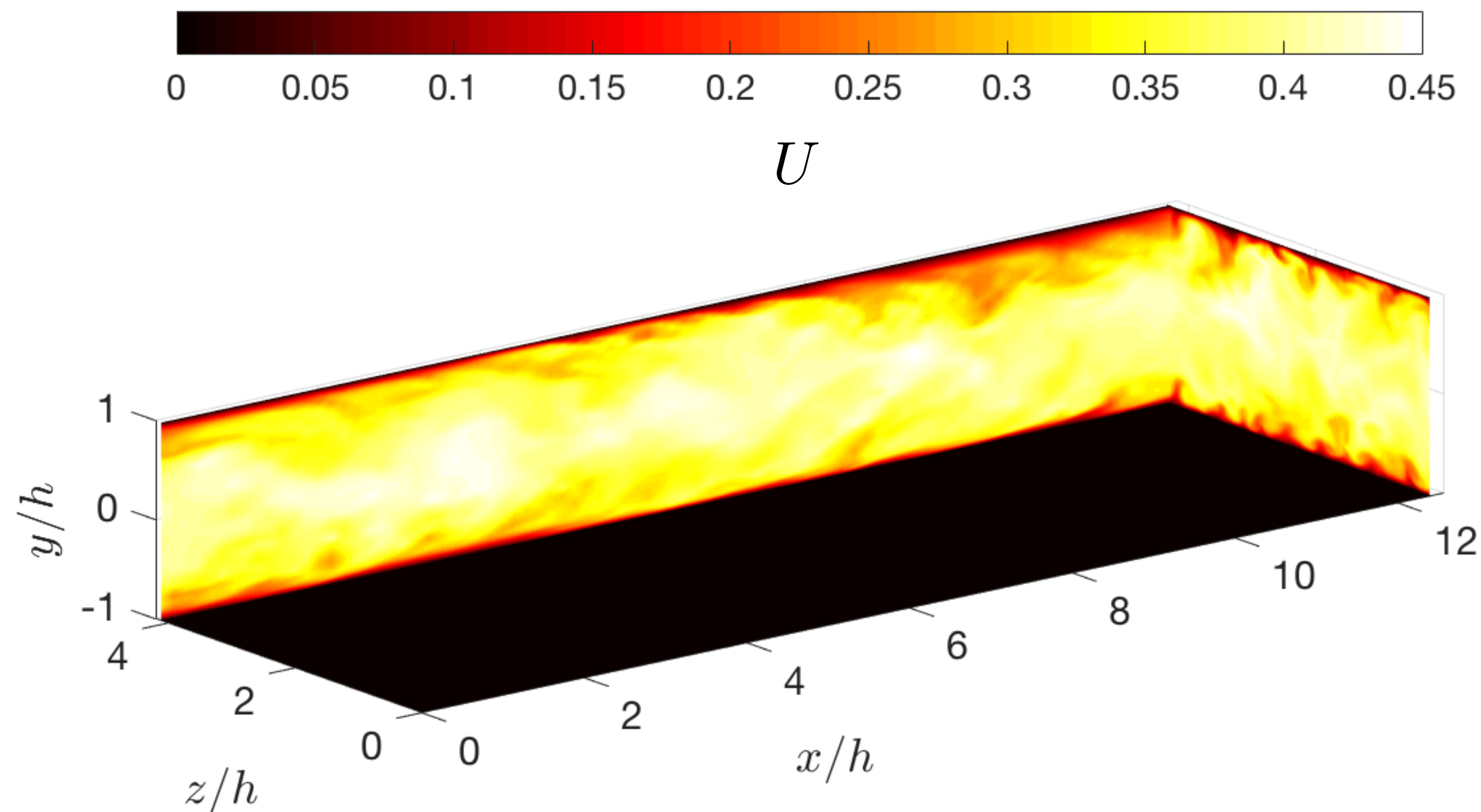
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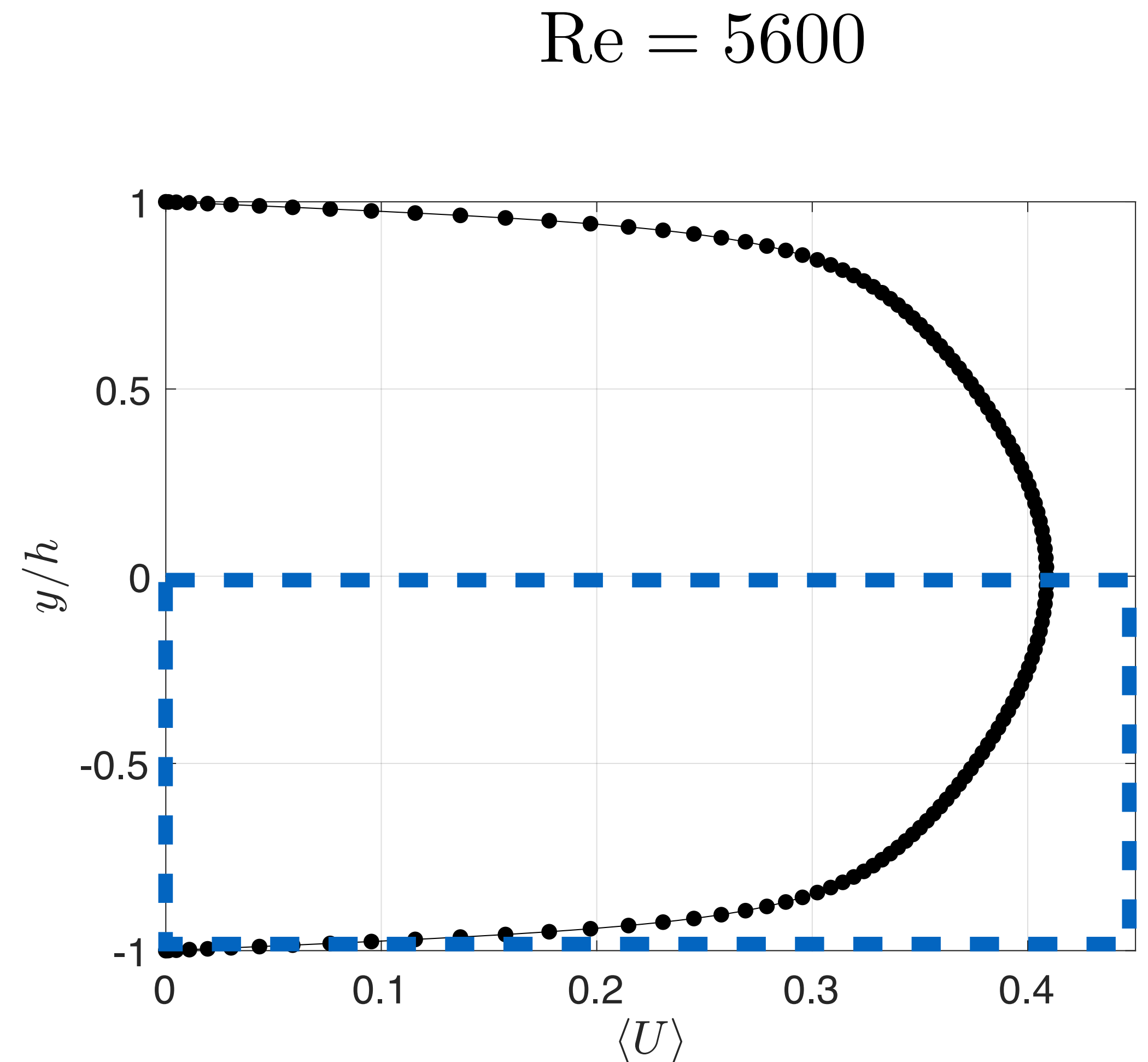
performed by Jérémie Bec

Re = 5600



performed by Jérémie Bec

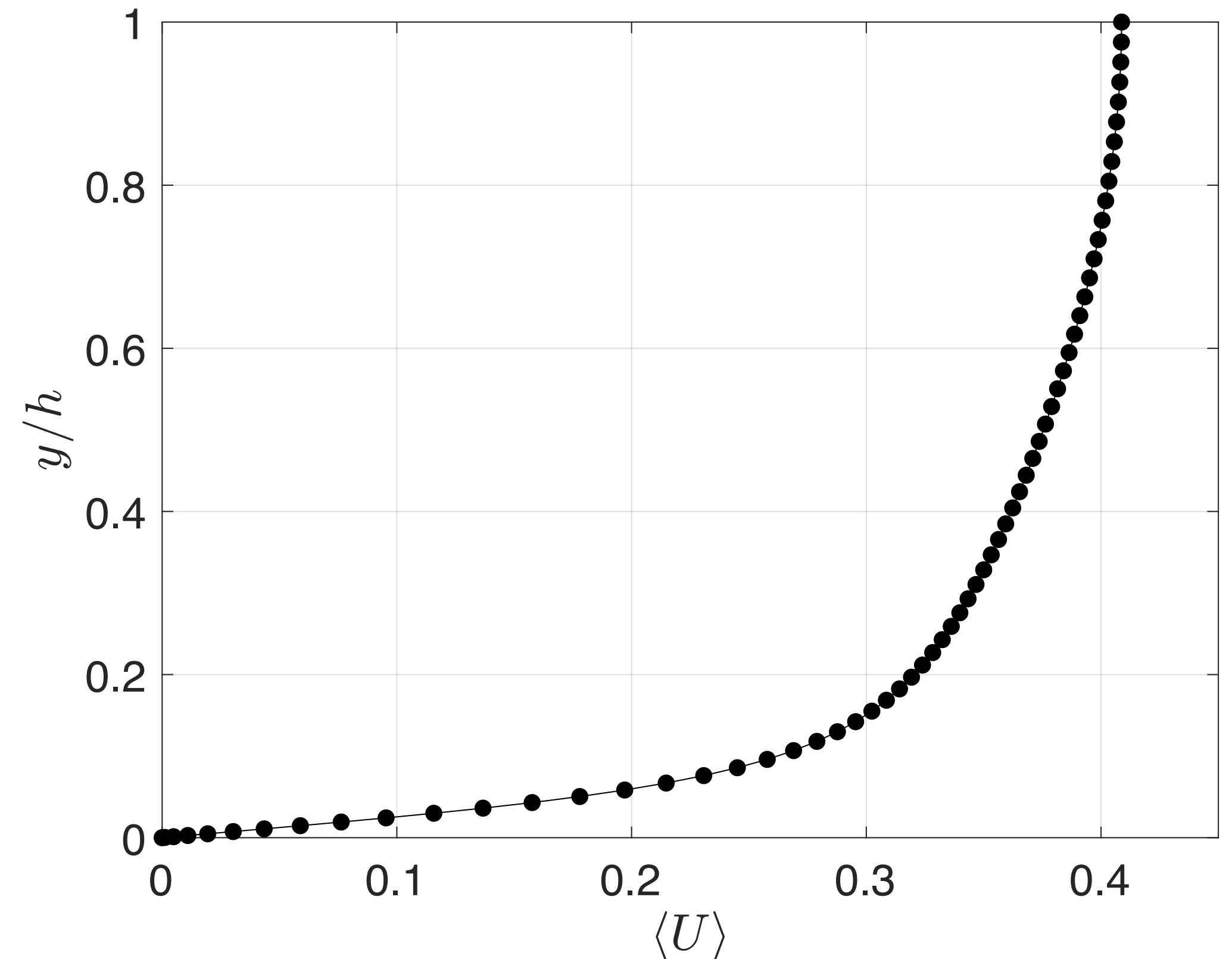
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 - mean velocity profile:



performed by Jérémie Bec

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 - * wall shear stress: τ_w

Re = 5600

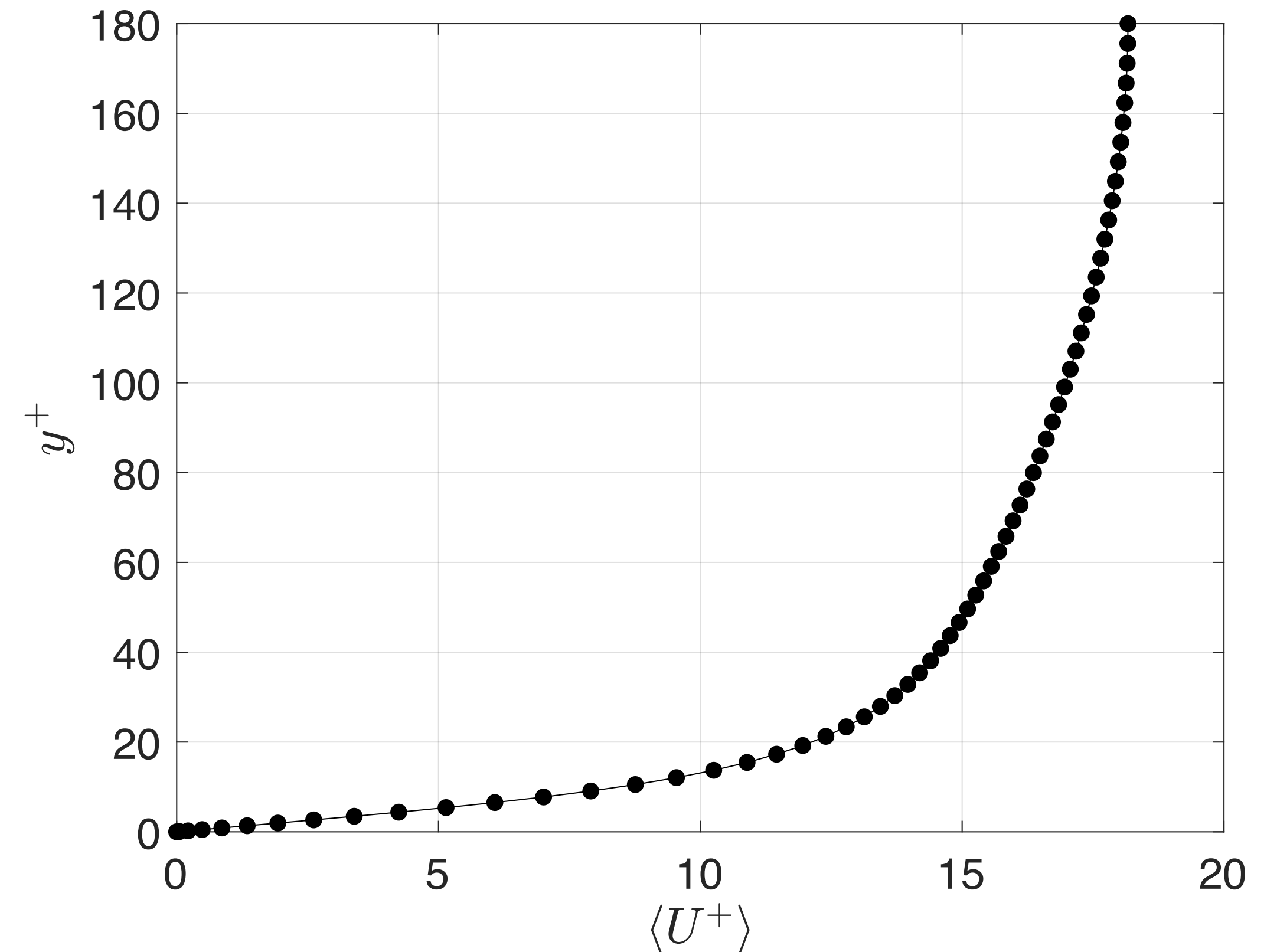


Numerical simulations

performed by Jérémie Bec

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$Re = 5600$

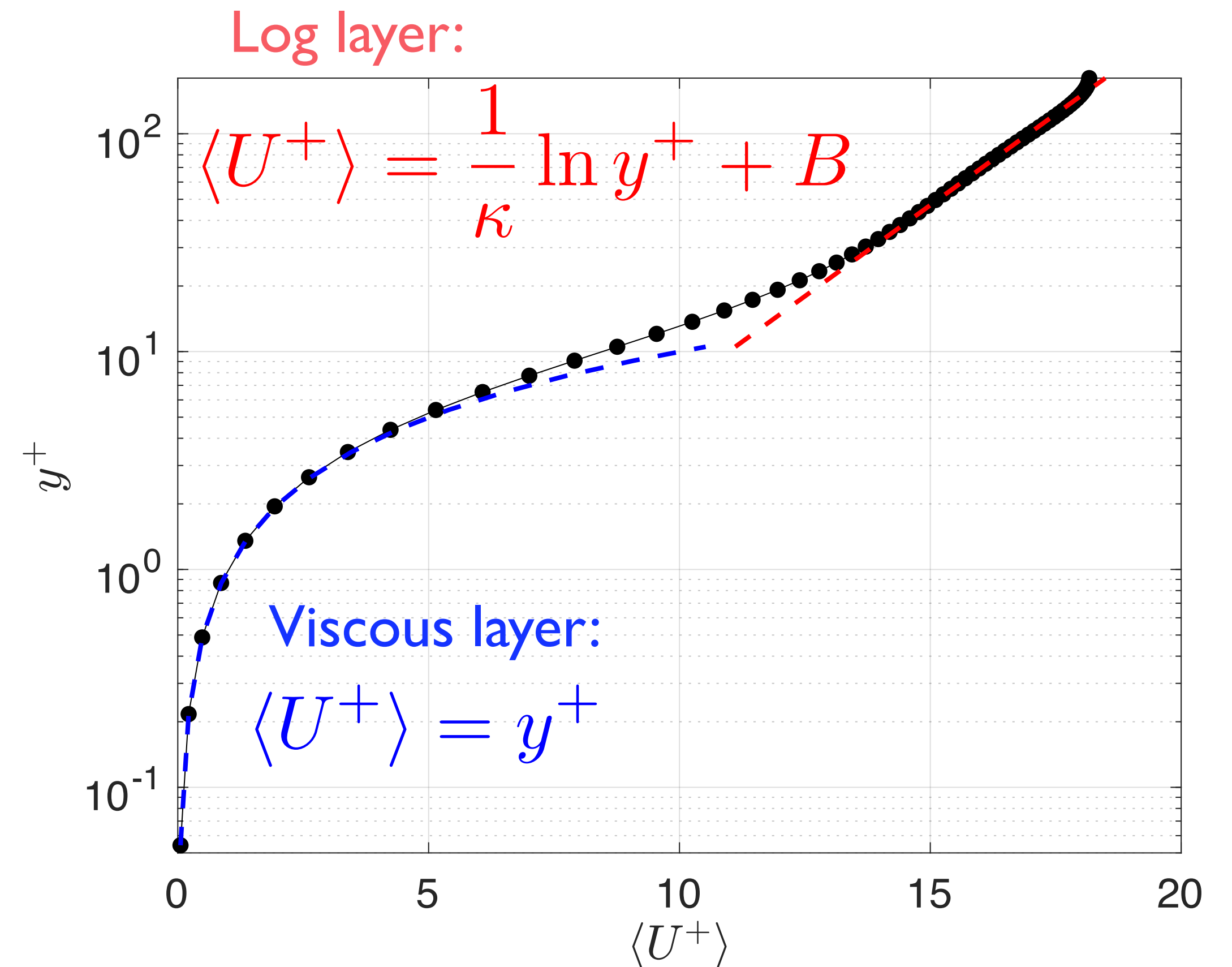


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 - * the law of the wall

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- Fibres:
 - inextensible and inertialess
 - one-way coupling

performed by Jérémie Bec

- Fibres:

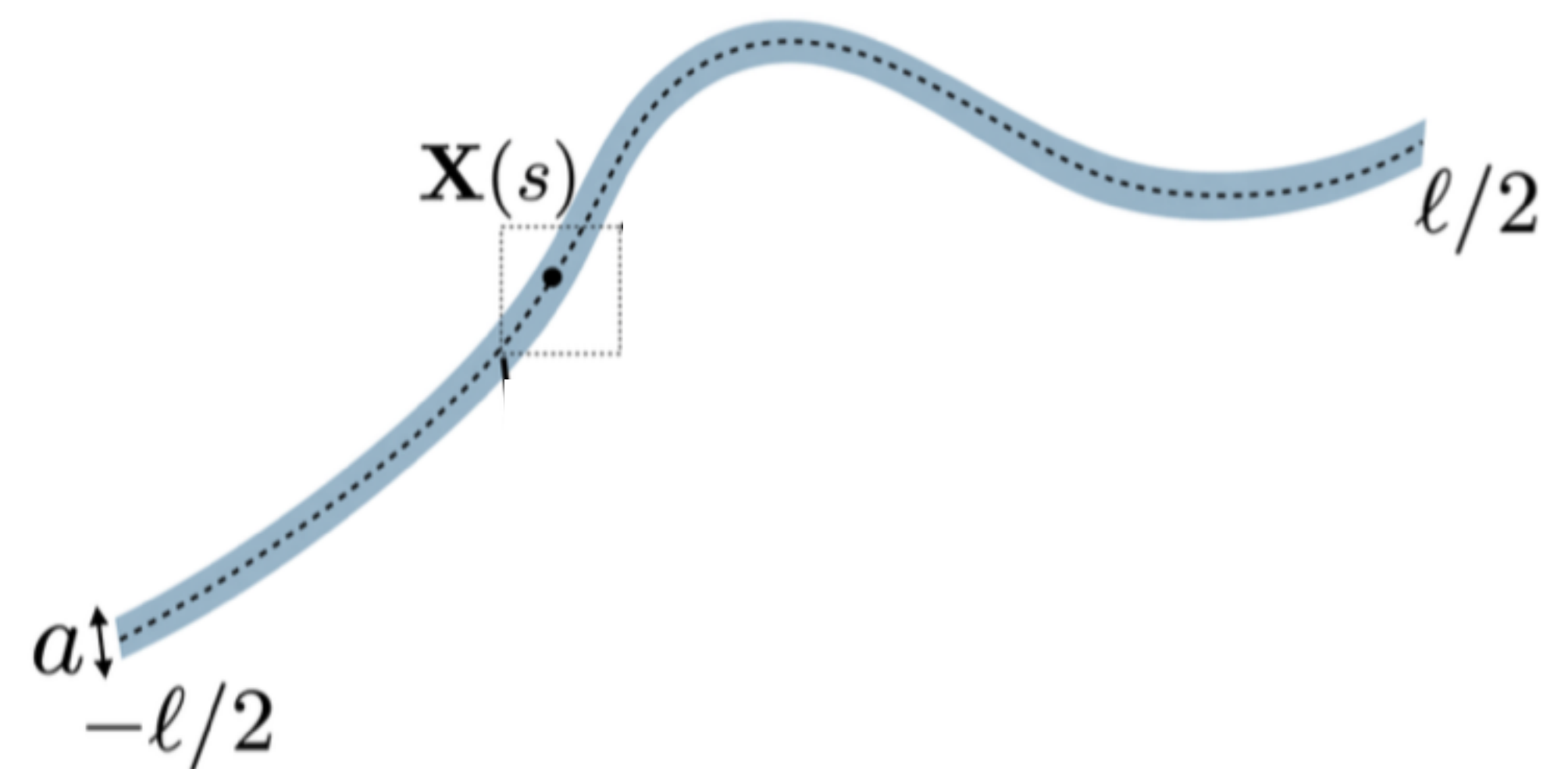
- inextensible and inertialess

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- over-damped slender-body theory: Cosserat equation for $\mathbf{X}(s, t)$

$$\partial_t \mathbf{X} = \mathbf{u}(\mathbf{X}, t) + \frac{c}{8\pi\eta} [\mathbb{I} + \partial_s \mathbf{X} \partial_s \mathbf{X}^\top] [\partial_s (T \partial_s \mathbf{X}) - EI \partial_s^4 \mathbf{X}]$$

with $|\partial_s \mathbf{X}|^2 = 1$



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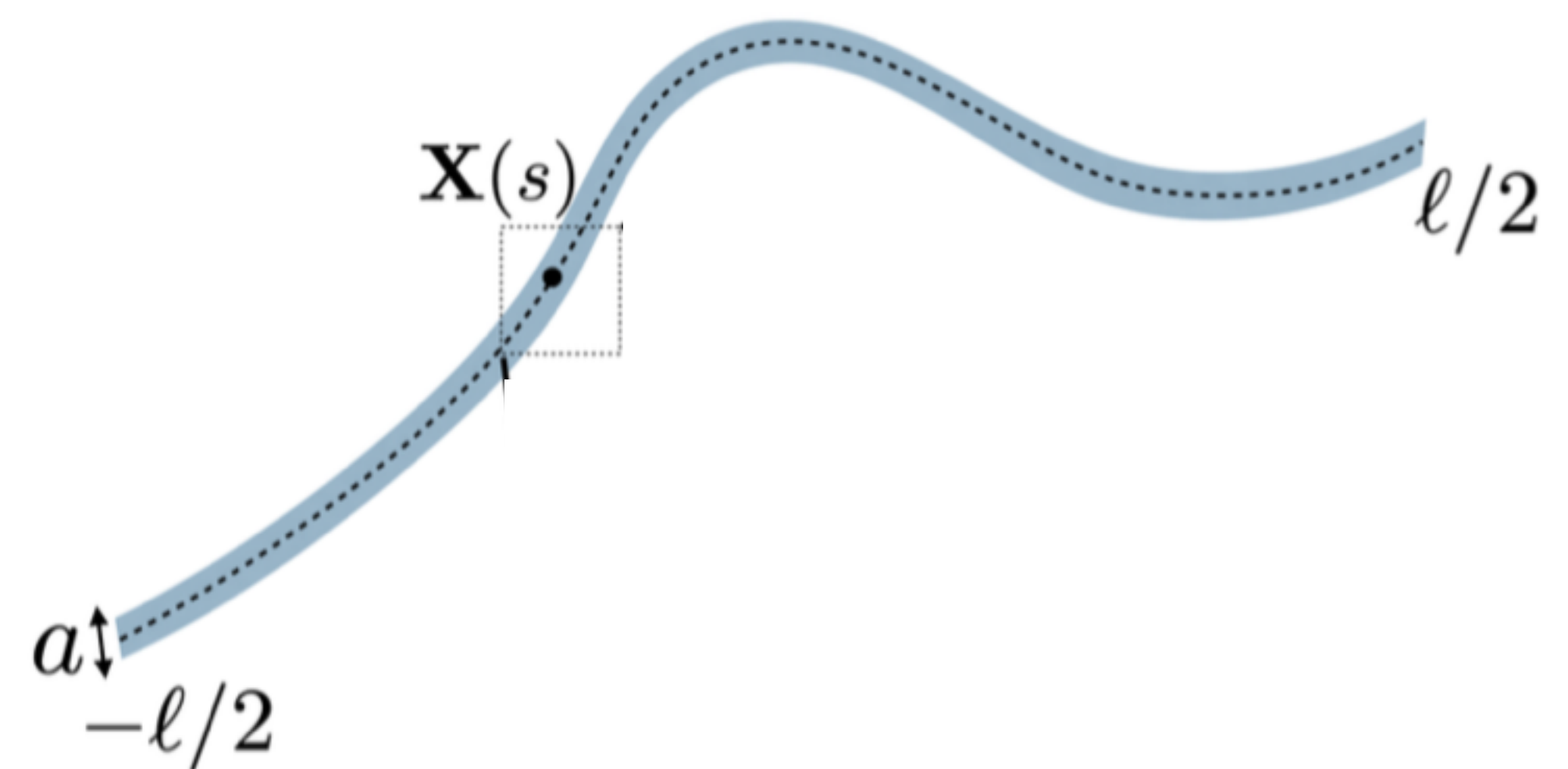
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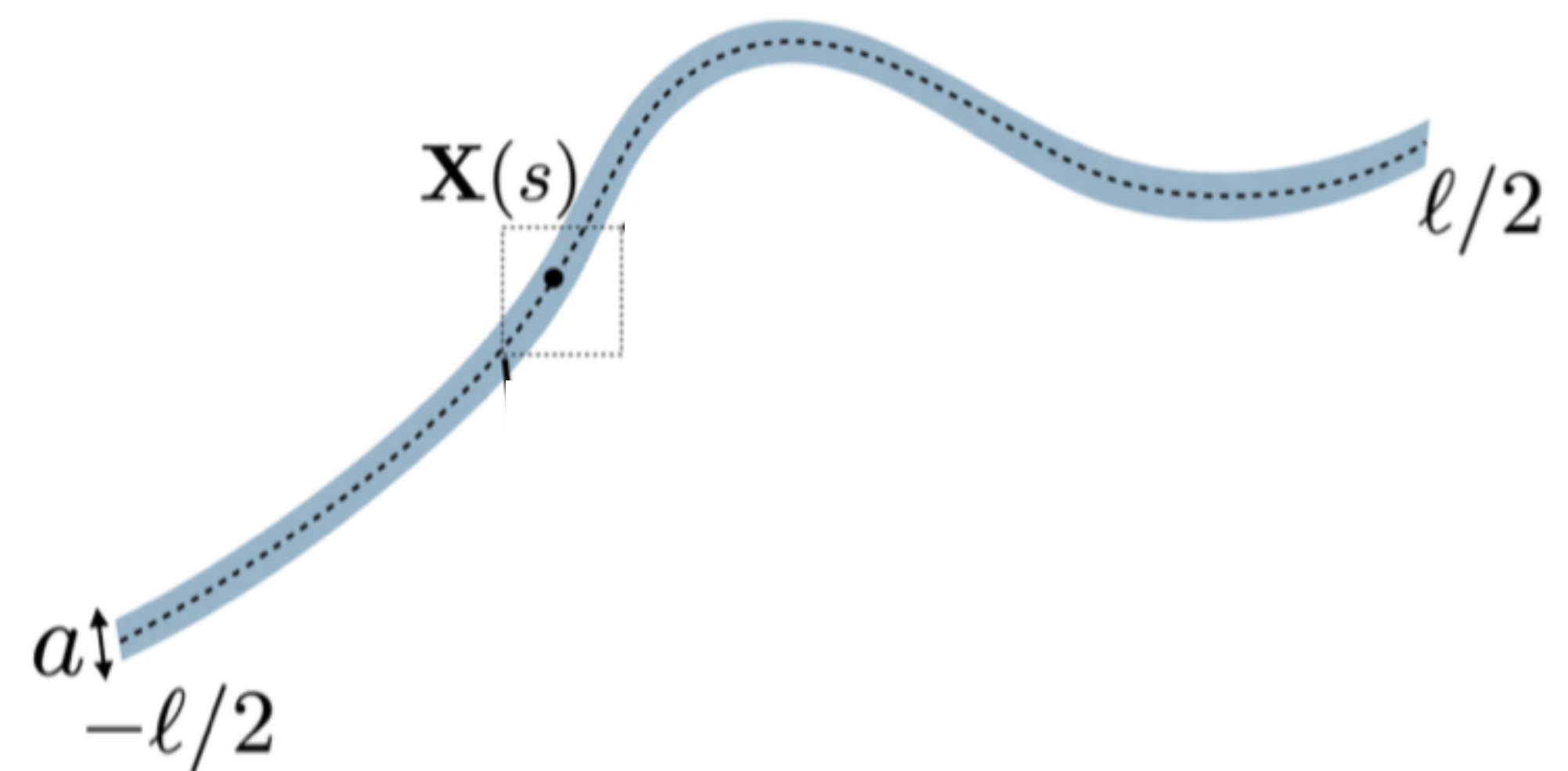
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Numerical simulations

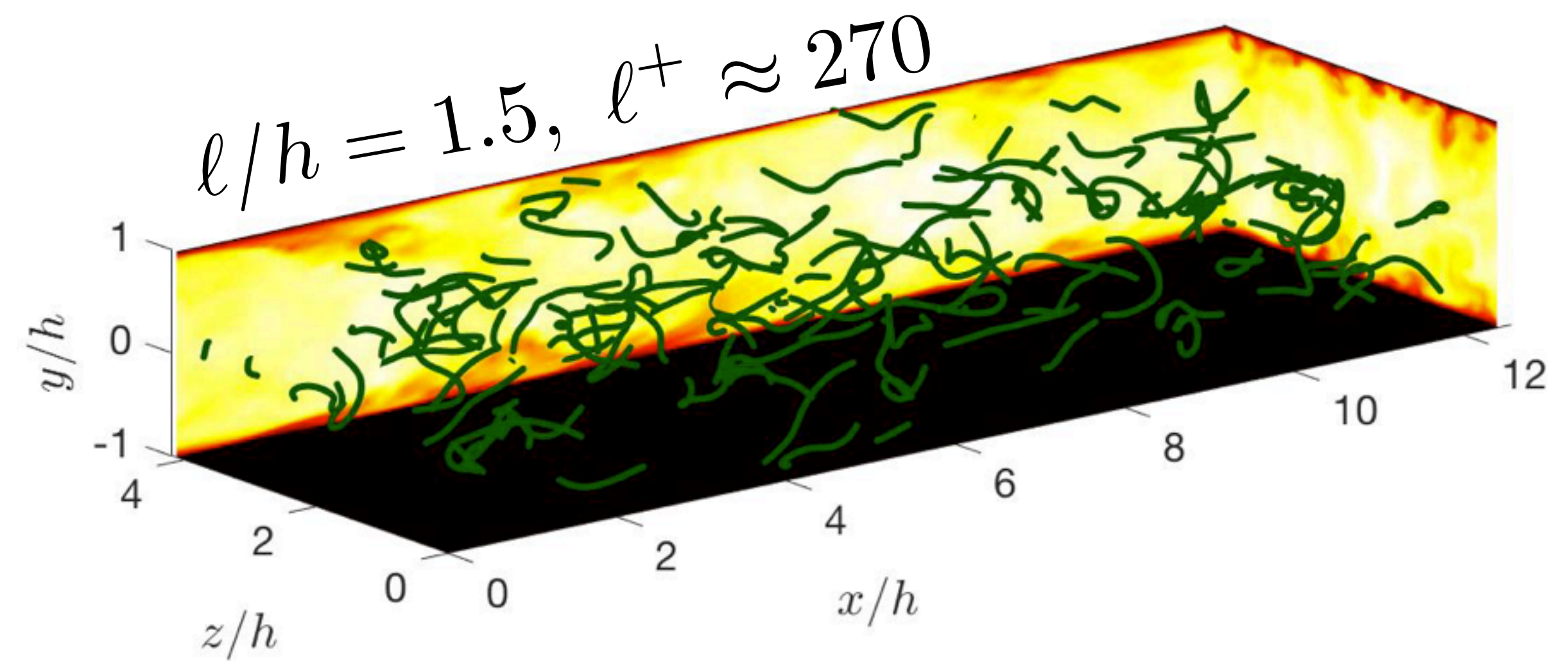
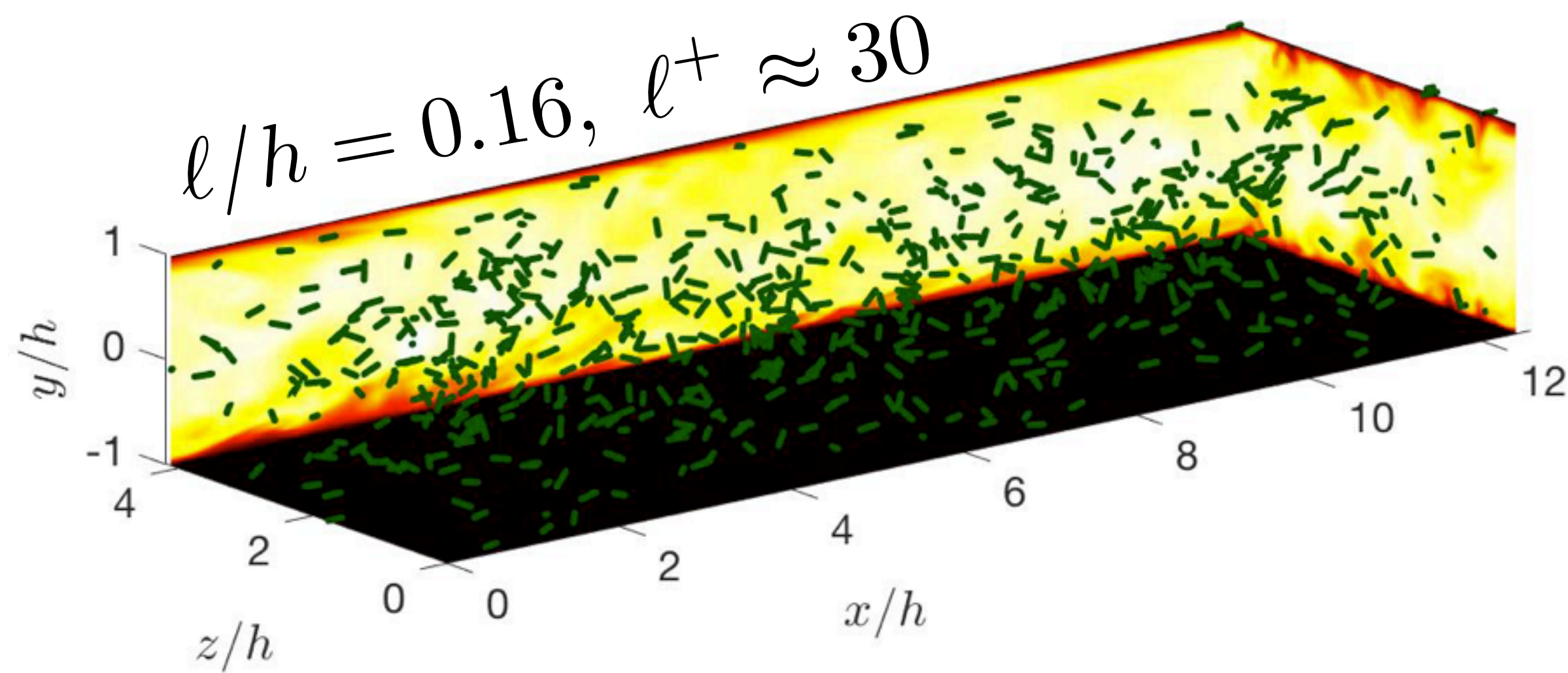
performed by Jérémie Bec

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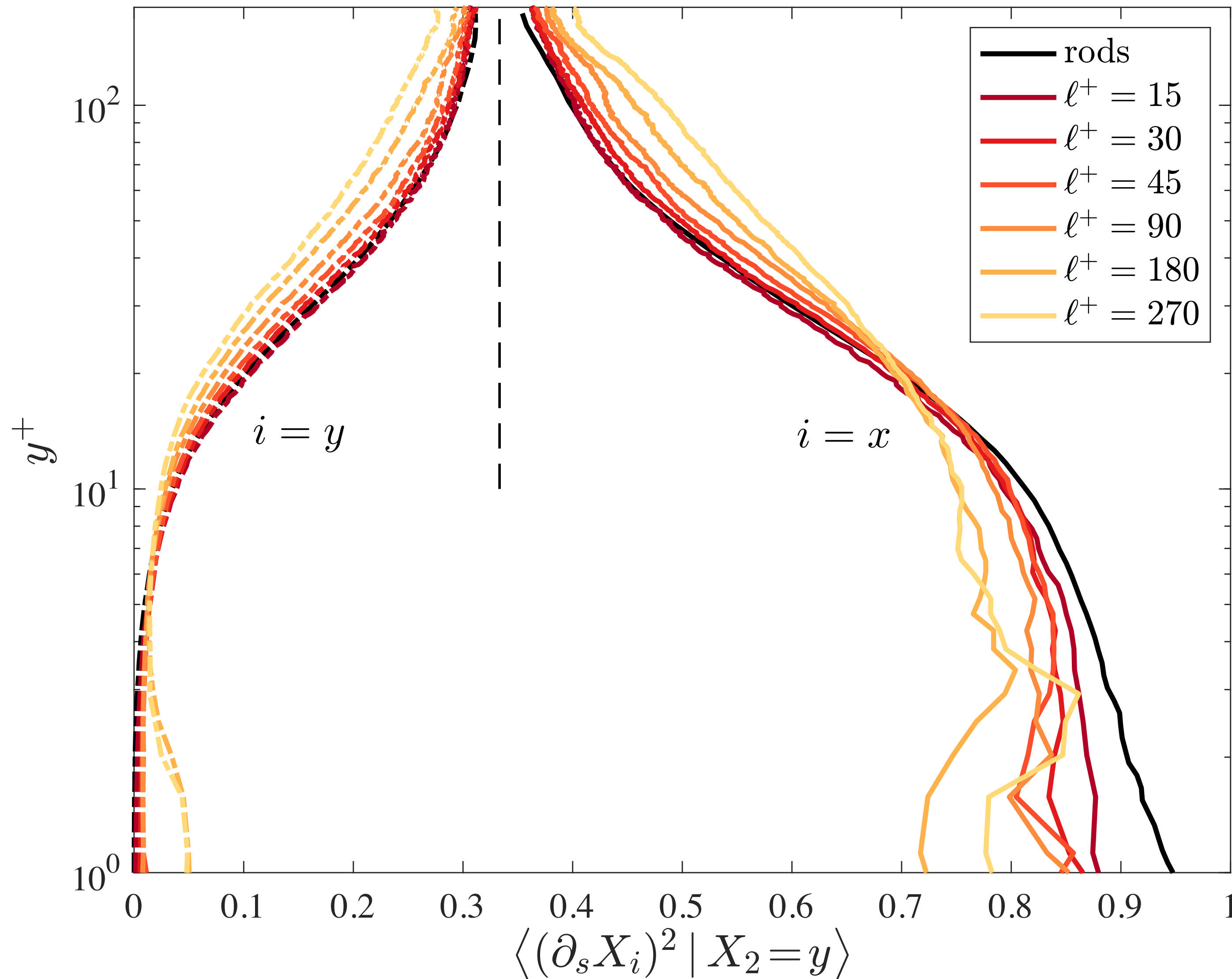
- parameter space:

- * fixed elastic length: $\ell_E^+ \approx 7.1$

- * 6 different lengths: $\ell/h \in [0.08 - 1.5]$, $\ell^+ \in [15 - 270]$ + rods

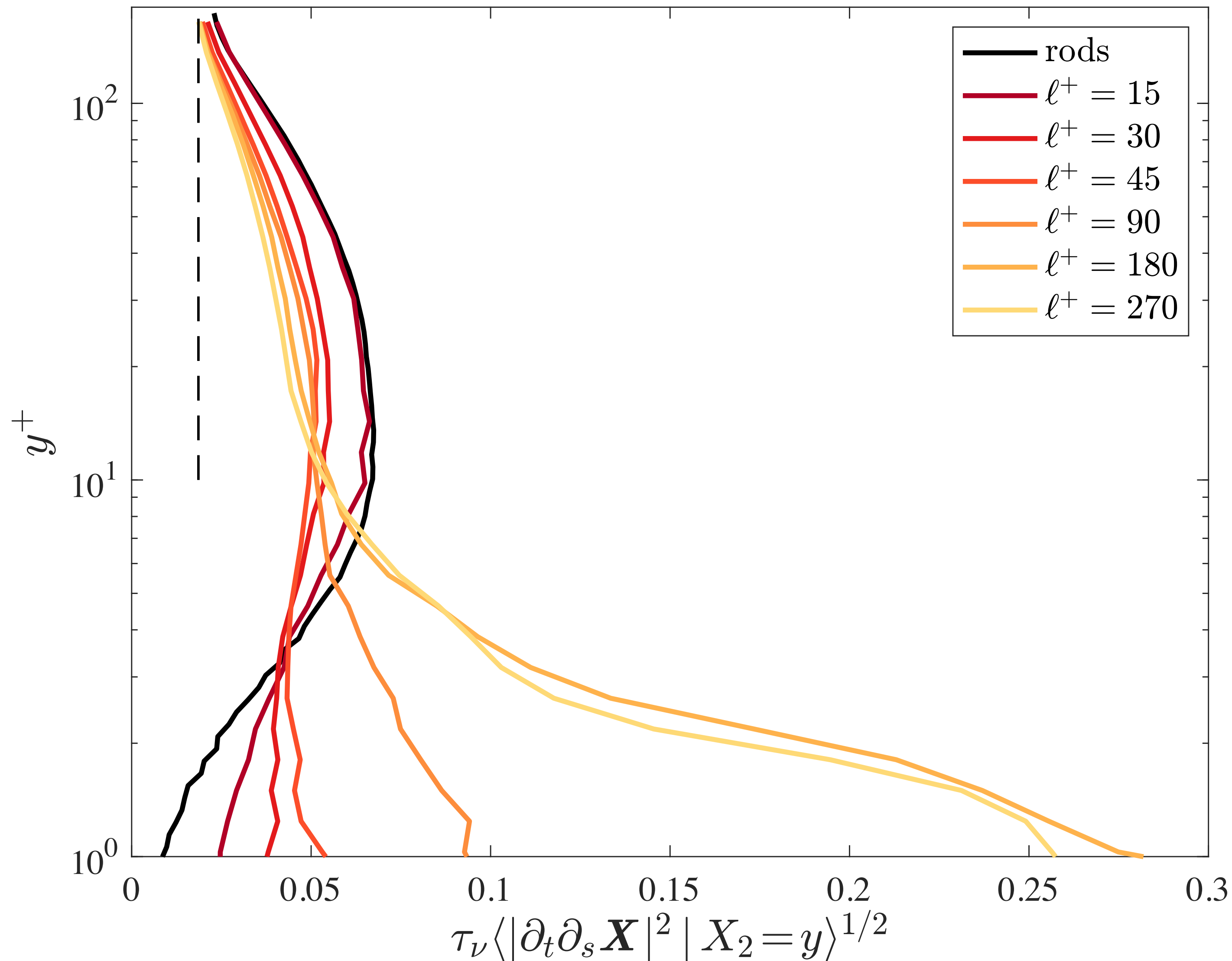


● Fibre orientation:



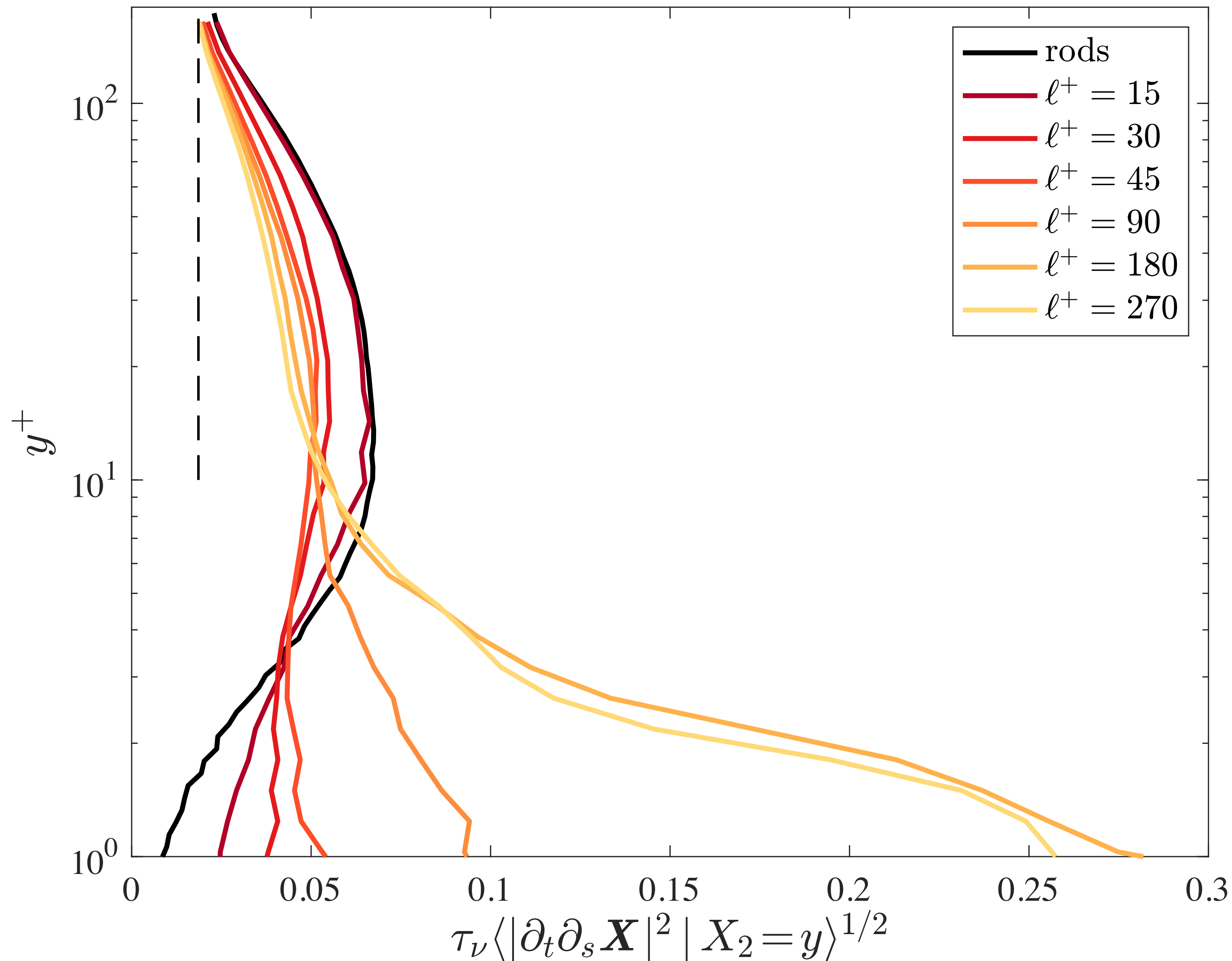
- in the centre: relatively isotropic
- close to the wall: aligned with the flow direction
- small variations with length

- Fibre tumbling rate:



- in the centre:
 - * mainly independent of length
 - * consistent with HIT
- close to the wall:
 - * strong variations with length
 - * the longer, the higher the rate

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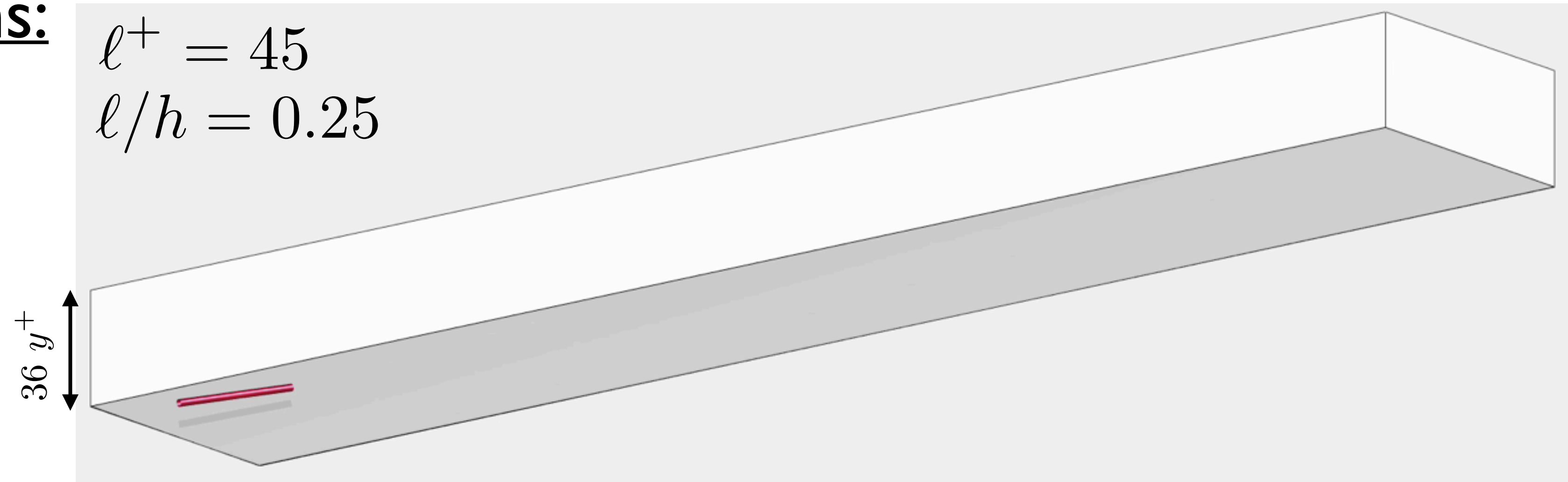
collisions ?
effects of the wall ?

Baker & Coletti (2022)

Results: pole vaulting

- Fibre-wall interactions:

- rebound on the wall
 - * high tumbling rate
 - * “pole vaulting”



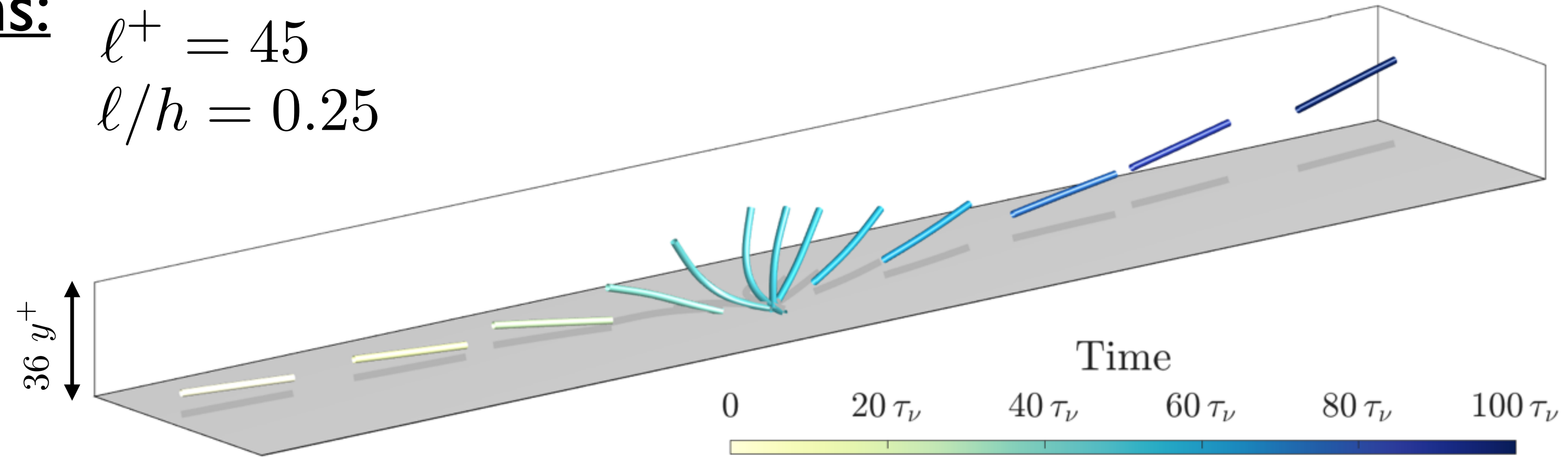
Results: pole vaulting

- Fibre-wall interactions:

$$\ell^+ = 45$$

$$\ell/h = 0.25$$

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- in the literature:

- * laminar case:

- Stover & Cohen (1990)

- Moses *et al.* (2001)



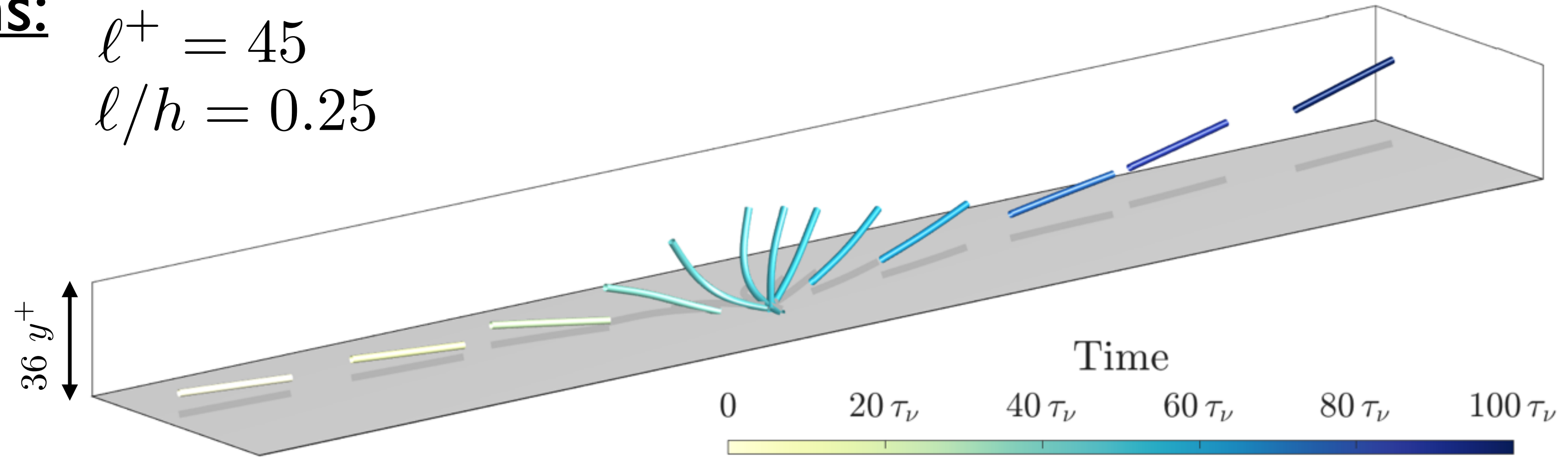
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Stover & Cohen (1990)

(a) $t^+ = 0$

(b) $t^+ = 1.6$

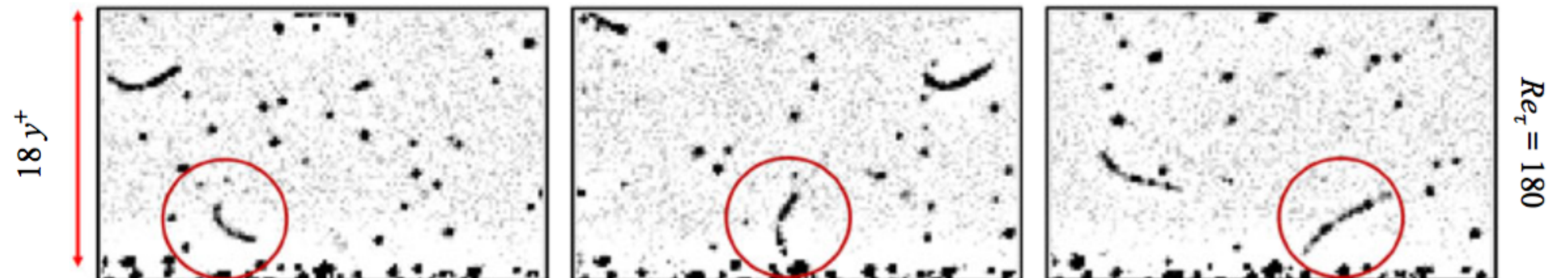
(c) $t^+ = 3.2$

- * turbulent case:

- Capone *et al.* (2017)

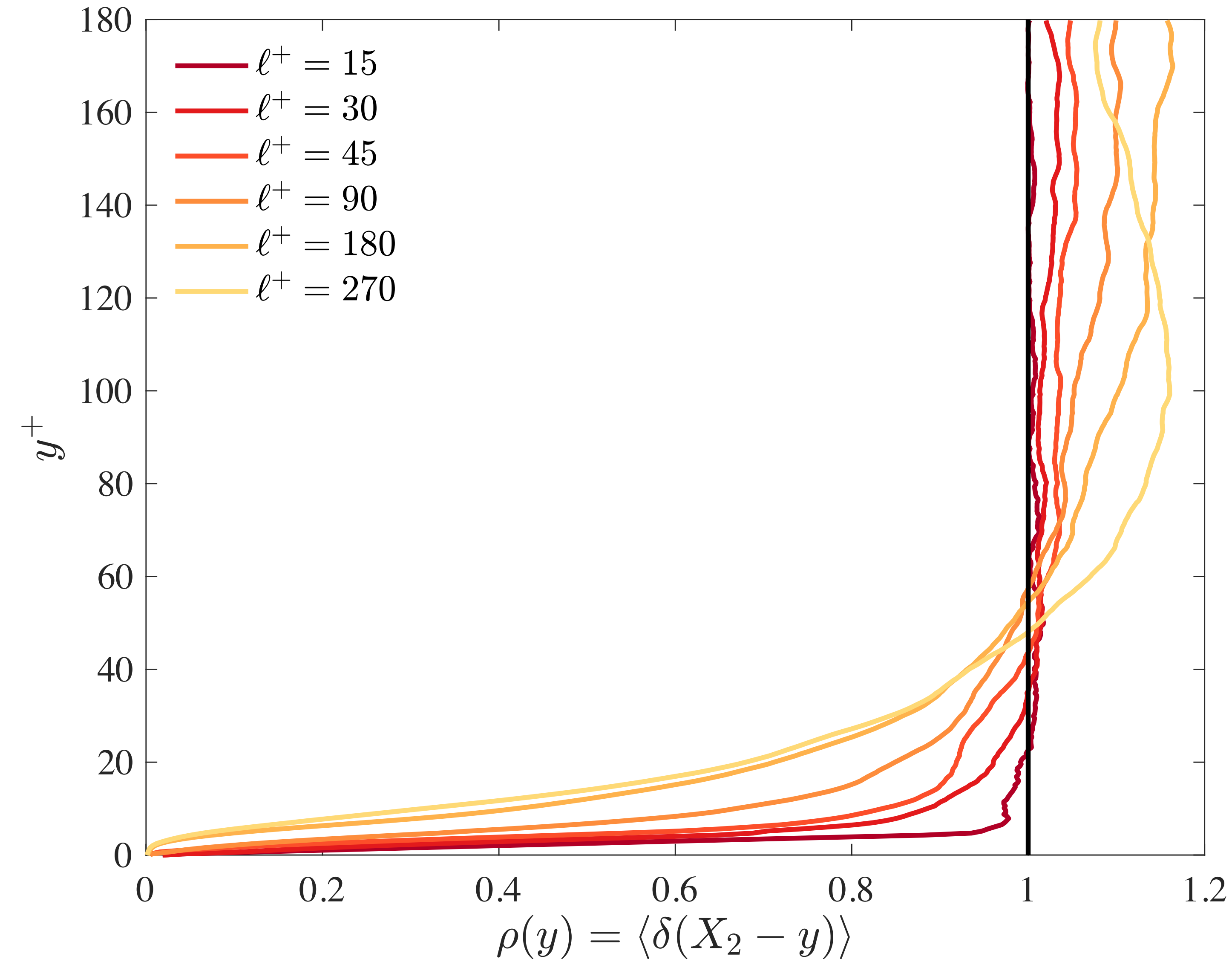
- Alipour *et al.* (2022)

- Baker & Coletti (2022)



Alipour *et al.* (2022)

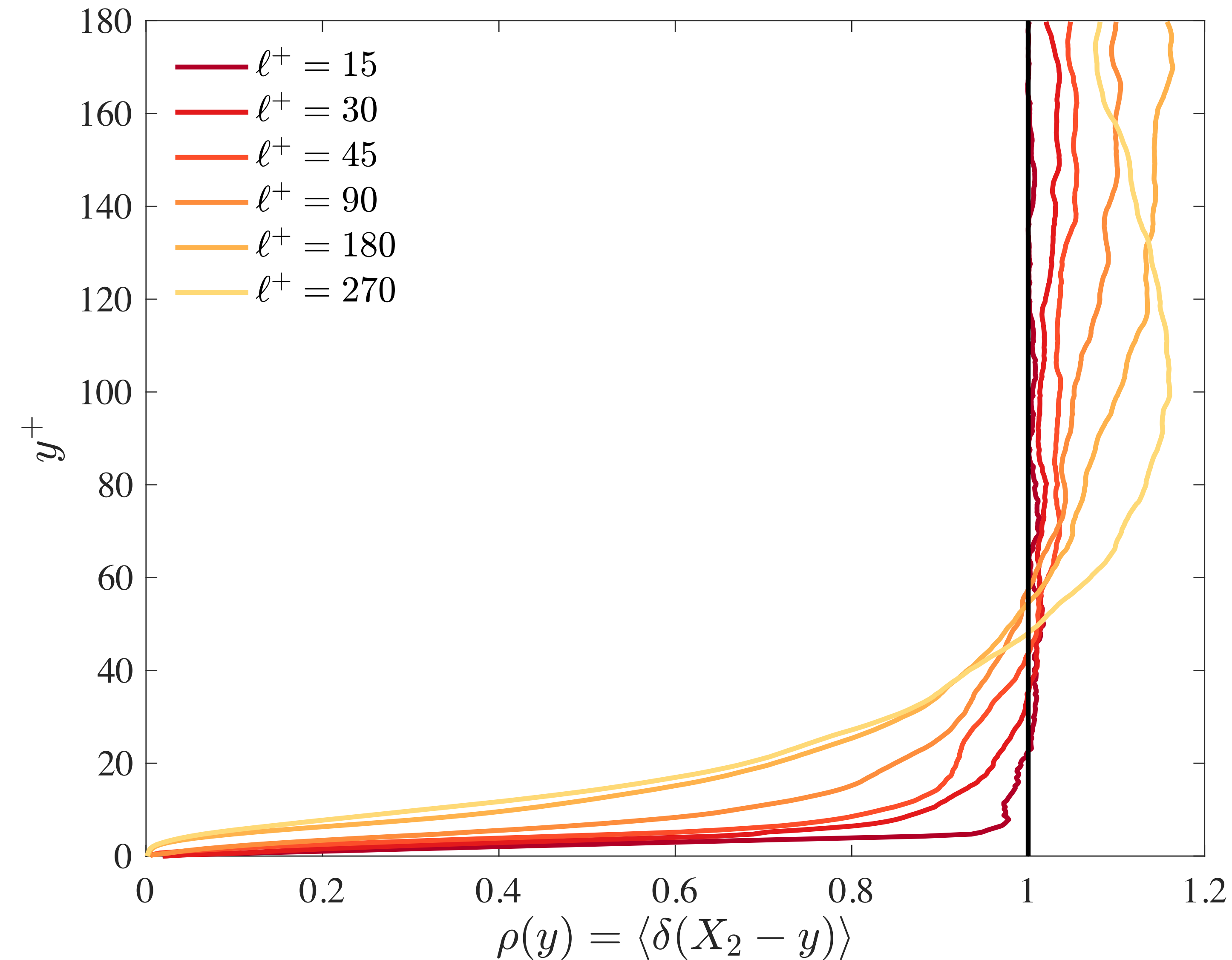
● Fibre density distribution:



- inhomogeneous distribution:
 - * higher concentration in the center
 - * depleted region close to the wall
 - * increases with fibre length

due to wall collisions ?

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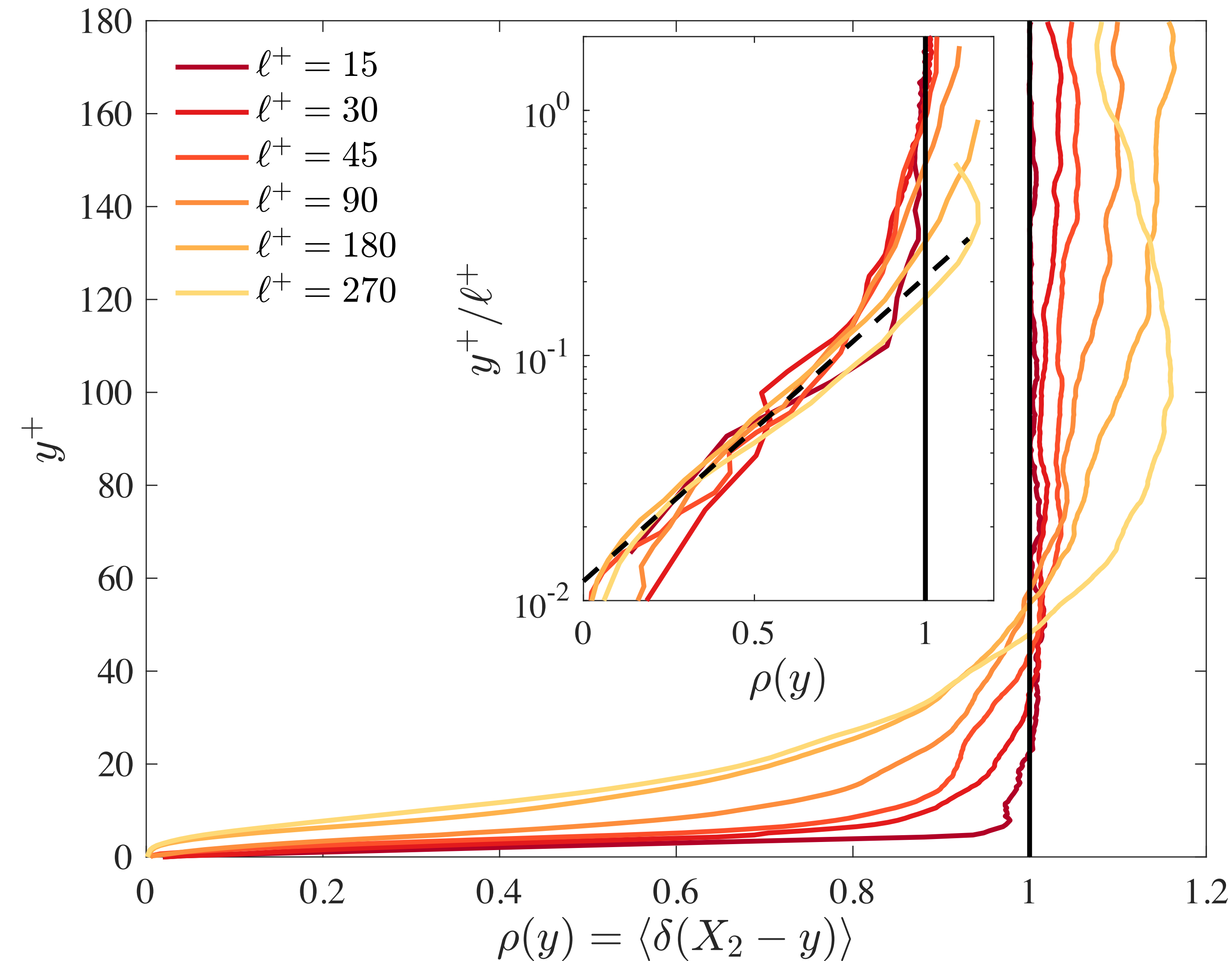


- inhomogeneous distribution:
 - * higher concentration in the center
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- high collision probability when tumbling if $y_{CoM}^+ < \ell^+ / 2$

due to wall collisions ?

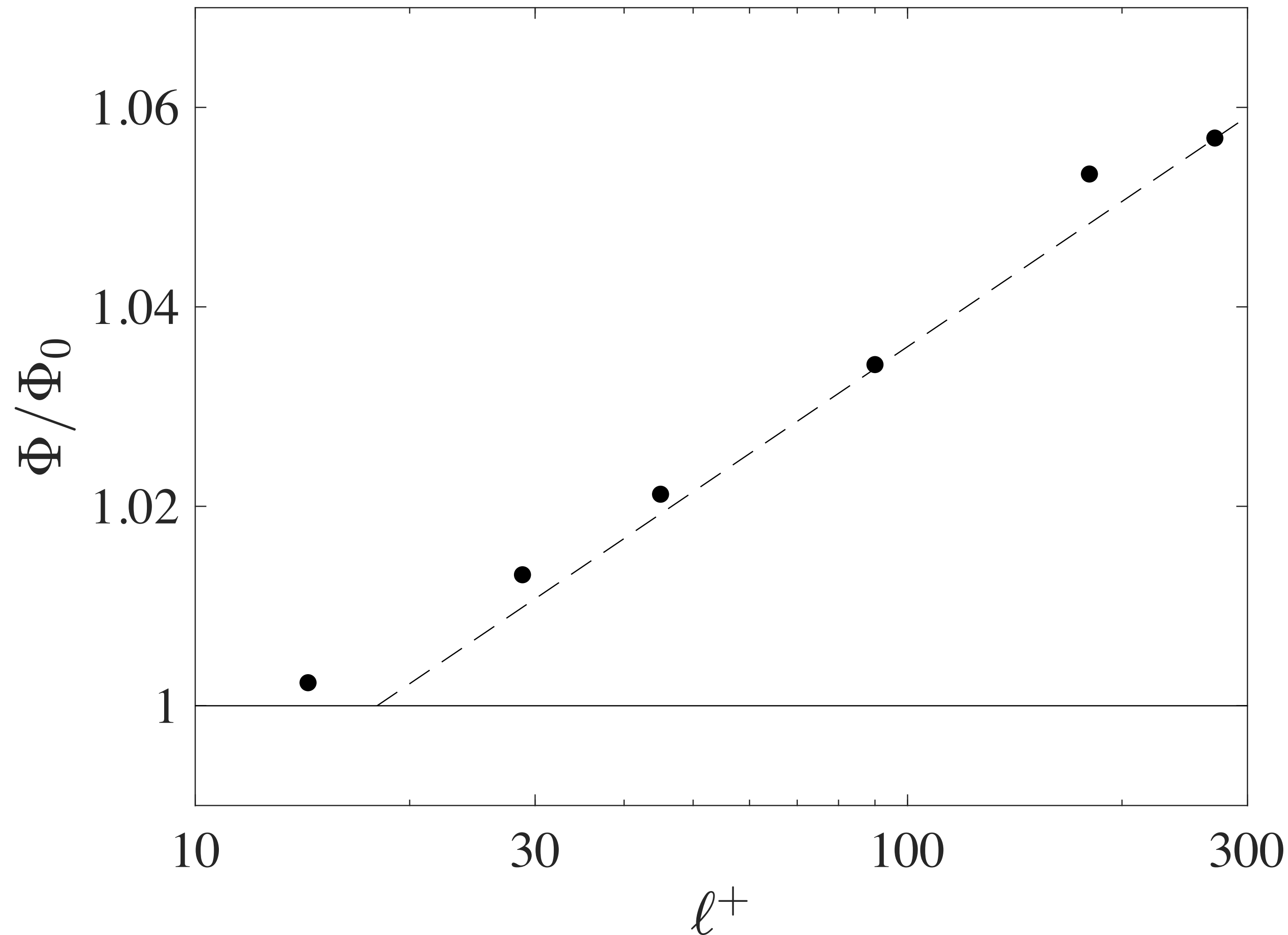
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due to wall collisions !

- Fibre net flux:



- fibres net flux Φ :
 - * velocity \times concentration
 - * compared to fluid flux Φ_0
 - * increases with fibre length
- enhancement:
 - * for fibre length within the log-layer
 - * log law scaling?

effect on the flux !

Conclusions

- Main results:

- first study on long flexible fibres in turbulent channel flow

- * numerical simulations

- * $\ell/h \in [0.08 - 1.5]$

- fibre-wall collisions: “pole vaulting”

- * high tumbling rates

- * depleted regions

increase with fibre length !

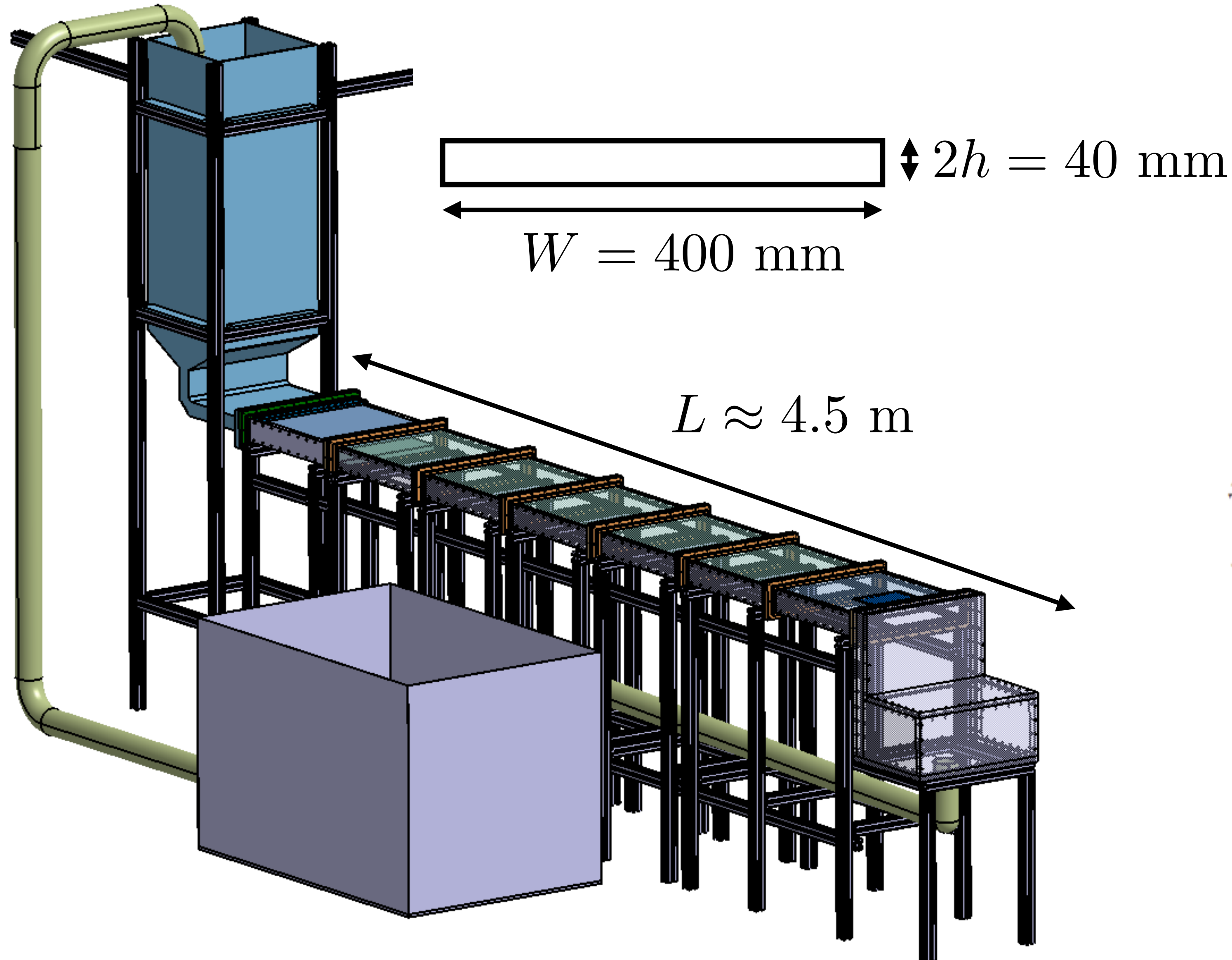
- effect on the fibre net flux:

- * higher fibre concentration in the centre

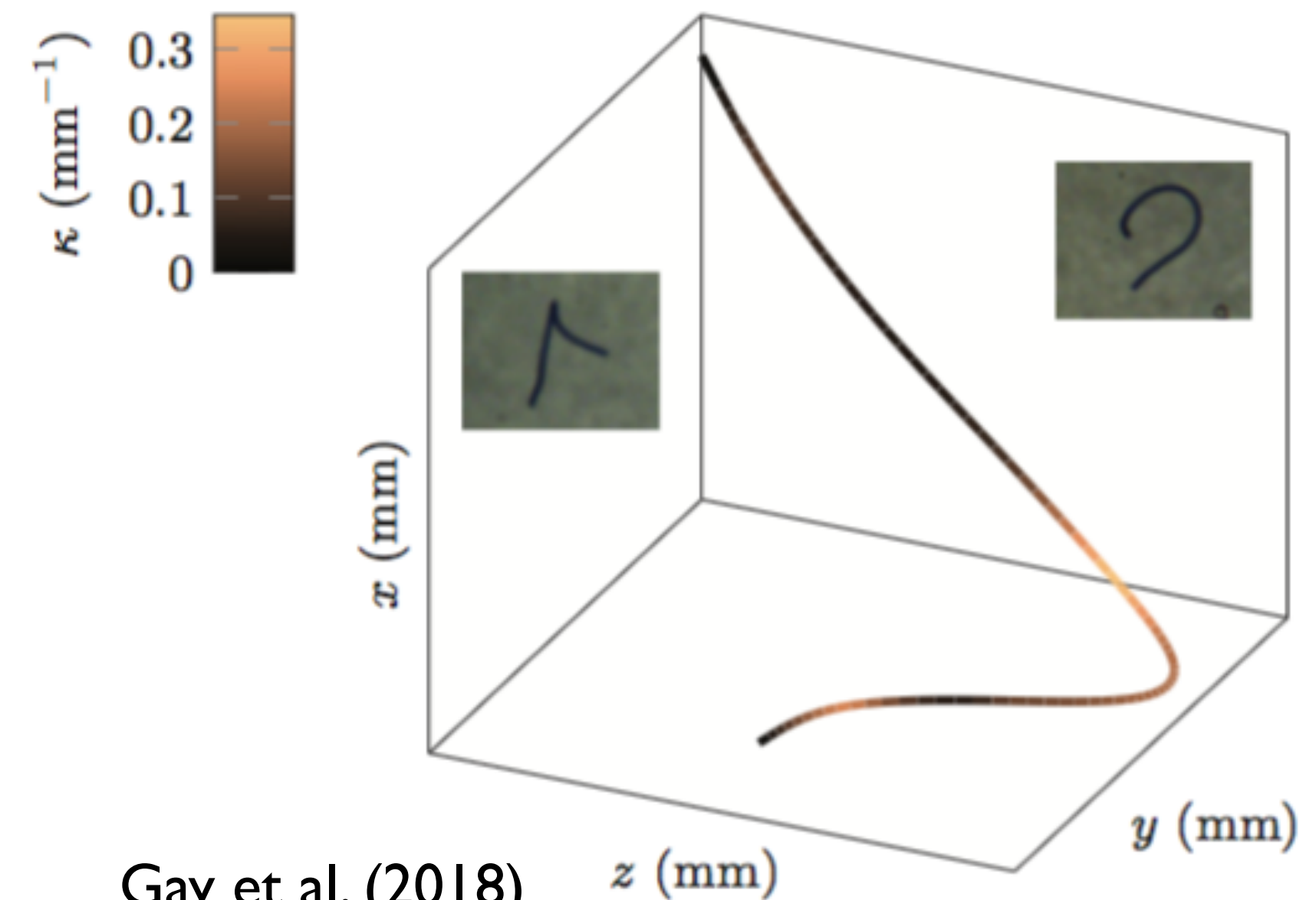
- * enhancement of the flux up to 6%

To go further

● Experiments at INPHYNI:

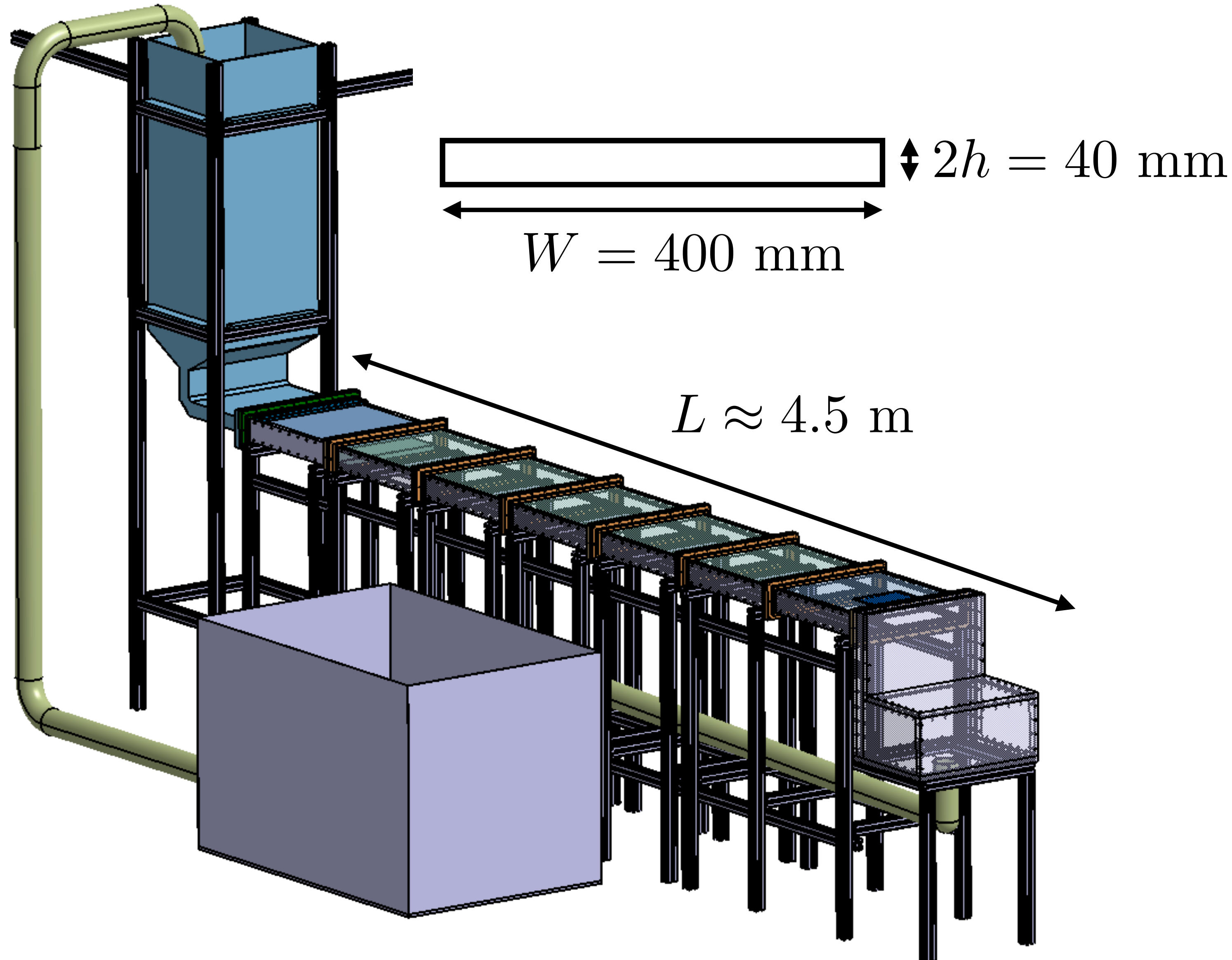


- turbulent channel flow:
 - * rectangular cross-section
 - * gravity driven
- 3D reconstruction:
 - * orientation / deformation
 - * 4 high-speed cameras (20 000 fps at 1 MPixels)



To go further

- Experiments at INPHYNI:



- turbulent channel flow:
 - * rectangular cross-section
 - * gravity driven
- 3D reconstruction:
 - * orientation / deformation
 - * 4 high-speed cameras (20 000 fps at 1 MPixels)
- Fundings:
 - * IDEX (Académie 2)
 - * CNRS
 - * INPHYNI
 - * Région Sud

To go further

- Experiments at INPHYNI:



- turbulent channel flow:
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- 3D reconstruction:
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 - * 4 high-speed cameras (20 000 fps at 1 MPixels)
- Design & manufacturing:
 - * Sandra Bosio
 - * Cyrille Claudet
 - * Christophe Pitiot
 - * Florian Zumbo
 - * Magali Varlet-Dusaucy

Questions ?

- Fibres:

- inextensible and inertialess

- one-way coupling

- over-damped slender-body theory:

- * discretisation in N_s points of length $\delta s^+ = l^+ / N_s \approx 0.9$

- * Cosserat equation for $\mathbf{X}(s, t)$

$$\partial_t \mathbf{X} = \mathbf{u}(\mathbf{X}, t) + \frac{c}{8\pi\eta} [\mathbb{I} + \partial_s \mathbf{X} \partial_s \mathbf{X}^\top] [\partial_s (T \partial_s \mathbf{X}) - EI \partial_s^4 \mathbf{X}]$$

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- wall contact: soft boundary approach

- Fibres:
 - wall contact: soft boundary approach
 - fibres are:
 - * allowed to penetrate the wall
 - * strongly repulsed by an effective force
 - fluid velocity outside the domain $\mathbf{u} = (0, v, 0)$

$$\text{bottom} \begin{cases} v = -\gamma(y + h) \\ \text{for } y < -h \end{cases}$$

$$\text{with } \gamma = 0.5/\Delta t$$

$$\text{top} \begin{cases} v = -\gamma(y - h) \\ \text{for } y > h \end{cases}$$