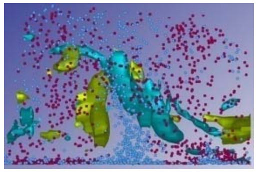

Euromech Colloquium 513 on

Dynamics of Non-Spherical Particles in Fluid Turbulence

Orientation, Distribution and Deposition of Inertial Fibers in Turbulent Channel Flow

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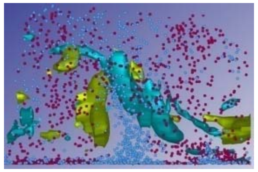
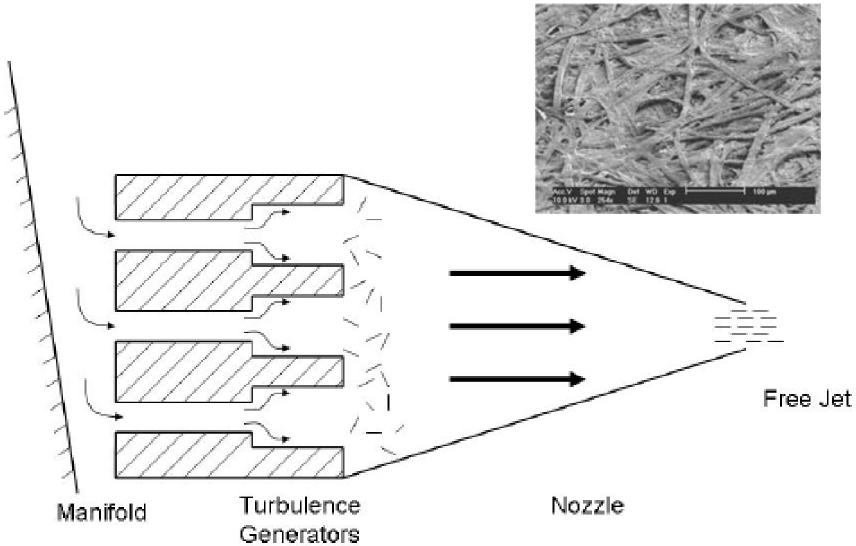
Udine, April 6-8, 2011



Motivation of this Study:
Examples of Practical Applications with Fibers



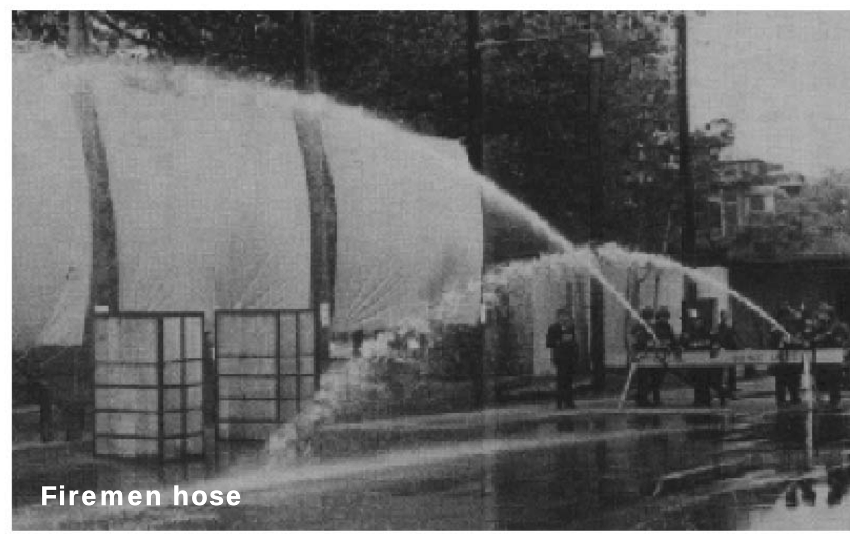
Schematic of industrial headbox for papermaking
(From: Krochak, Olson & Martinez, IJMF, 2009)

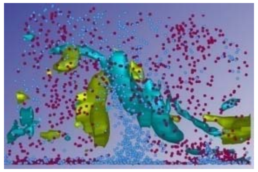
1. Pulp and paper making

Controlling the rheological behavior and the orientation distribution of fibers is crucial to optimize production operations

2. Fluid transport systems

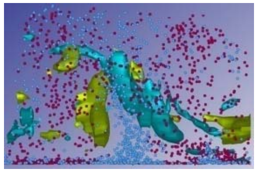
Pressure drops can be reduced by adding small fibers to the conveyed fluid (due to fiber-induced drag reduction!)





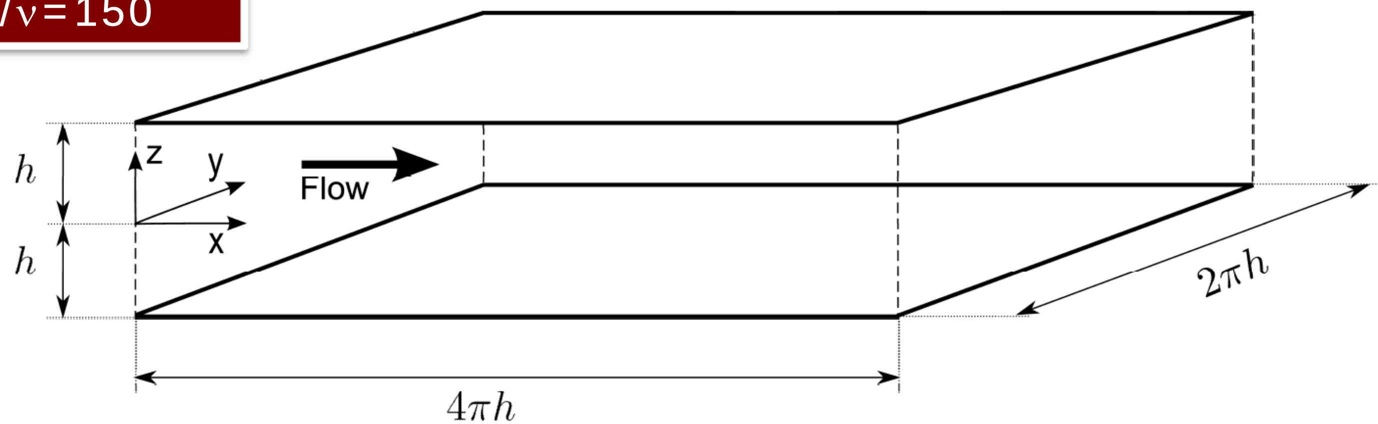
Aim of this Study

- In all of these applications, fibers are dispersed in a **turbulent flow** field within confined geometries.
- A thorough **physical understanding** of fiber dispersion in internal flows is **still missing** (few studies available, lack of systematic investigations).
- Our study aims at providing **quantitative results** on fiber distribution, orientation, translation and rotation to fill up the physical picture of the problem.
- The focus is on the **influence of wall turbulence** on the processes which govern fiber dispersion.
- This influence is investigated for fibers with different **elongation** and **inertia** dispersed in channel flow.



Methodology - Carrier Fluid

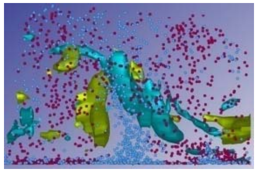
DNS of turbulent channel flow @ $Re_\tau = u_\tau h/\nu = 150$



$$
\begin{cases}
\dfrac{\partial u_j}{\partial x_j} = 0 \\
\rho \left[\dfrac{\partial u_i}{\partial t} + u_j \dfrac{\partial (u_i)}{\partial x_j} \right] = -\dfrac{\partial P}{\partial x_i} + \mu \dfrac{\partial^2 u_i}{\partial x_j \partial x_j}
\end{cases}
$$

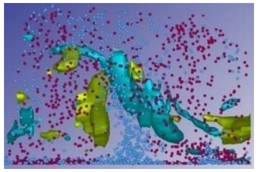
Pseudo-Spectral method: 128x128 Fourier modes in *x and y*, 129 Chebyshev modes in *z.*

- **Examples: flow of air at 1.8 m/s in a 4 cm high channel**
  flow of water at 3.8 m/s in a 0.5 cm high channel



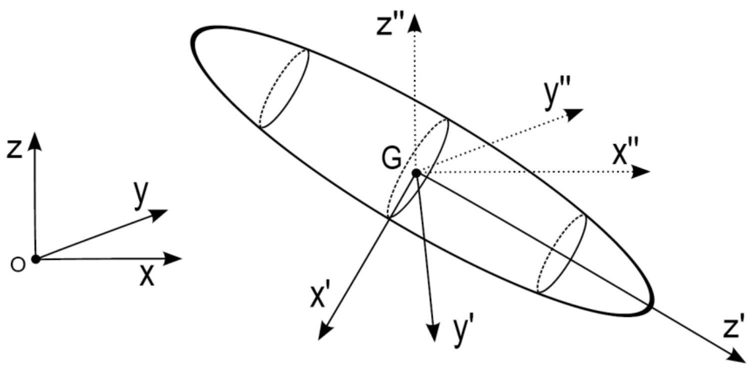
Methodology - Fibers

- Fibers are modelled as **prolate ellipsoidal particles**.
- **Lagrangian** particle tracking.
- Simplifying assumptions: dilute flow, **one-way coupling**, Stokes flow ($Re_P < 1$), pointwise particles (particle size is smaller than the smallest flow scale).
- Periodicity in *x* ed *y*, elastic rebound at the wall and **conservation of angular momentum**.
- **200,000 fibers** tracked, *random* initial position and orientation, linear and angular velocities equal to those of the fluid at fiber's location.

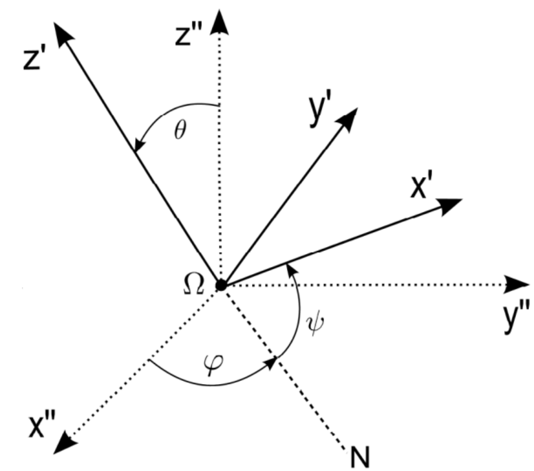


Methodology – Fiber Kinematics

<u>Kinematics</u>: described by (1) position of the fiber center of mass and (2) fiber orientation.



- x_G, y_G, z_G
- **3 frames of reference (to define orientation)**
- **Euler angles: φ, ψ, θ (singularity problems)**

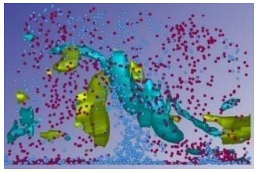


- **Euler parameters:** e_0, e_1, e_2, e_3

$$e_0 = \cos\left[\frac{1}{2}(\psi + \varphi)\right]\cos\left(\frac{\theta}{2}\right) \quad , \ldots$$

- **Rotation matrix:** $\mathbf{x}' = R_{Eul}\mathbf{x}''$

$$R_{eul} = \begin{bmatrix} e_0^2 + e_1^2 - e_2^2 - e_3^2 & 2(e_1e_2 + e_0e_3) & 2(e_1e_3 - e_0e_2) \\ 2(e_1e_2 - e_0e_3) & e_0^2 - e_1^2 + e_2^2 - e_3^2 & 2(e_2e_3 + e_0e_1) \\ 2(e_1e_3 + e_0e_2) & 2(e_2e_3 - e_0e_1) & e_0^2 - e_1^2 - e_2^2 + e_3^2 \end{bmatrix}$$



Methodology – Fiber Dynamics

Rotational dynamics: Euler equations with Jeffery moments.

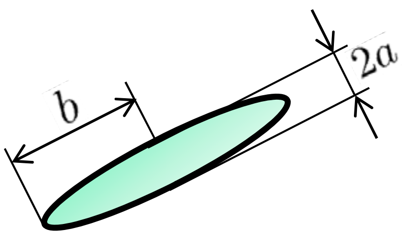
- **Euler Equations:** **(2nd cardinal law)**

$$\begin{cases} I_{x'x'}\dot{\omega}_{x'} + \omega_{y'}\omega_{z'}(I_{z'z'} - I_{y'y'}) = M_{x'}^{est} \\ I_{y'y'}\dot{\omega}_{y'} + \omega_{x'}\omega_{z'}(I_{z'z'} - I_{x'x'}) = M_{y'}^{est} \\ I_{z'z'}\dot{\omega}_{z'} + \omega_{x'}\omega_{y'}(I_{y'y'} - I_{x'x'}) = M_{z'}^{est} \end{cases}$$

(in the particle frame)

- **Jeffery moments:** ***(Jeffery, 1922)***

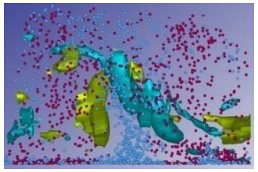
$$M_{x'}^{Jeff} = \frac{16\pi\mu a^3\lambda}{3(\beta_0 + \lambda^2\gamma_0)}\left[(1-\lambda^2)f' + (1+\lambda^2)(\xi' - \omega_{x'})\right]$$



Aspect Ratio $\lambda = \frac{b}{a}$

- **Hence:** **Euler equations with Jeffery couples** → $\int\int(\ldots)dtdt$ → **e_0, e_1, e_2, e_3 (Euler parameters)**

$$R_{eul} = R_{eul}(e_0, e_1, e_2, e_3)$$



Methodology – Fiber Dynamics

Translational Dynamics: hydrodynamic resistance (Brenner, 1963).

- **First cardinal law:** $m_P \frac{d\mathbf{v}}{dt} = \sum_i \mathbf{F}_i = \mathbf{F}_{drag}$ **(inertia and drag only!!)**
- **Brenner's law: (form drag and skin drag)** $\mathbf{F}'_{drag} = \mu \pi a \bar{\bar{\mathbf{K}}}'(\mathbf{u}' - \mathbf{v}')$ **(in the fiber frame)**

Resistance Tensor (that is, $\bar{\bar{\mathbf{K}}}'$)

- **In the inertial (Eulerian) frame:**

$$\mathbf{u}' = R_{eul}\mathbf{u}$$

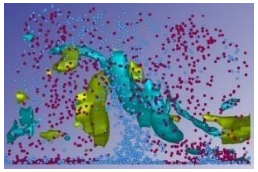
$$\bar{\bar{\mathbf{K}}}_{(\varphi,\theta,\psi)} = R_{eul}^T \bar{\bar{\mathbf{K}}}' R_{eul}$$

$$\Longrightarrow \mathbf{F}_{drag} = \mu \pi a \bar{\bar{\mathbf{K}}}_{(\varphi,\theta,\psi)}(\mathbf{u} - \mathbf{v})$$

$$\begin{cases} m_P \frac{d\mathbf{v}}{dt} = \mu \pi a \bar{\bar{\mathbf{K}}}_{(\varphi,\theta,\psi)}(\mathbf{u} - \mathbf{v}) \\ \frac{d\mathbf{x}_{(G)}}{dt} = \mathbf{v} \end{cases}$$

$\Rightarrow$ $\mathbf{v}(t)$ $\mathbf{x}_G(t)$ **(via numerical integration)**

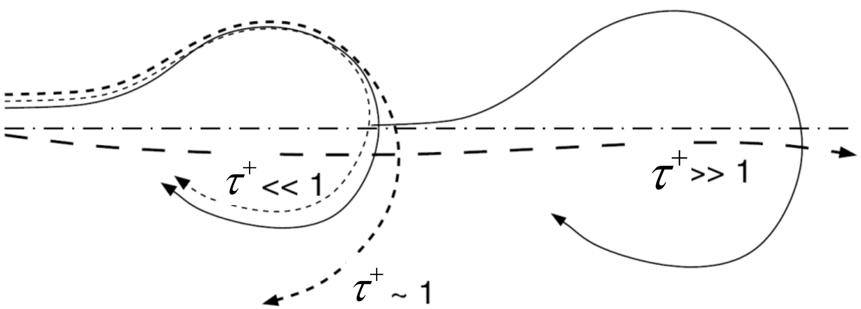
Once fiber orientation is known, fiber translational motion can be computed!



Relevant Parameters and Summary of the Simulations

> The physics of turbulent fiber dispersdion is determined by a small set of parameters

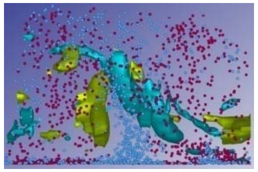
- **Aspect ratio:** $\lambda = \frac{b}{a}$ **(chosen values: <u>λ=1.001, 3, 10, 50</u>)**
- **Stokes number:** $\tau^{+} = \frac{\tau_P}{\tau_F}$ **(chosen values: <u>τ^{+}=1, 5, 30, 100</u>)**



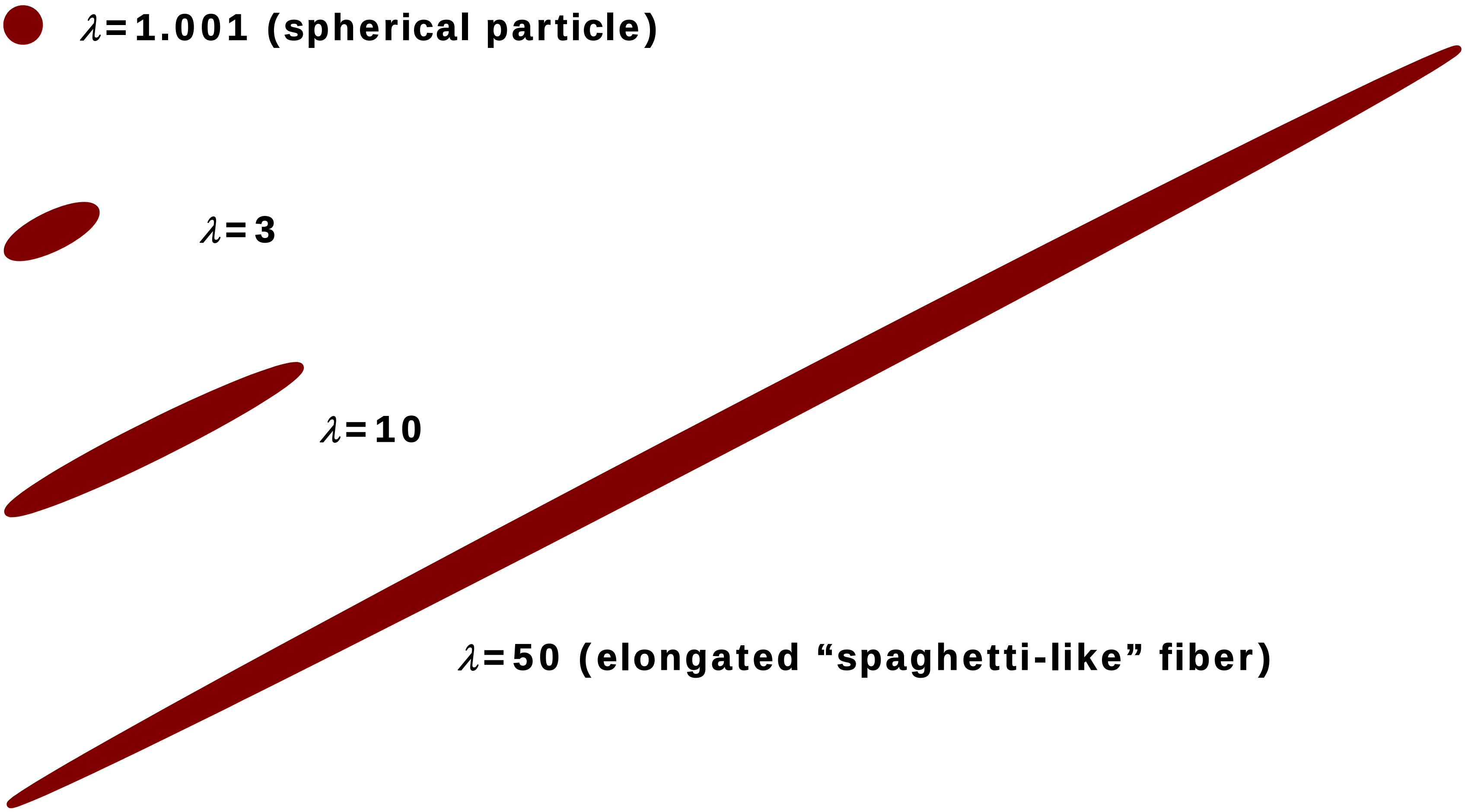
- $\tau^{+} >> 1$: **large inertia ("stones")**
- $\tau^{+} << 1$: **small inertia (tracers)**
- $\tau^{+} \sim 1$: **preferential (selective) response to flow structures**

- **Specific density:** $S = \frac{\rho_P}{\rho_F}$

> Input parameters: S, τ^{+}, λ

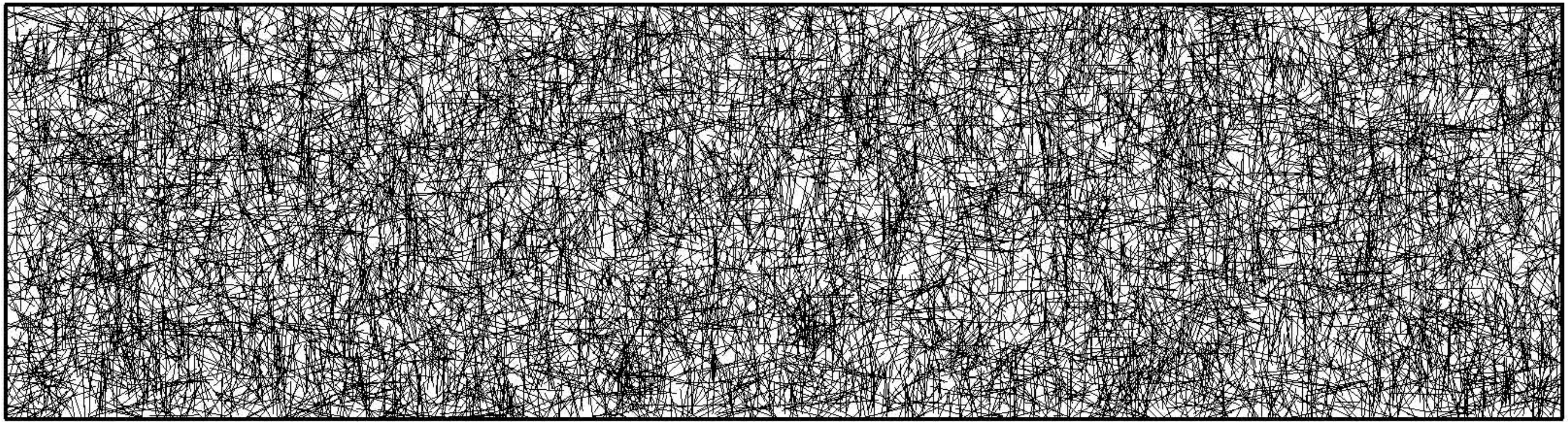


"Cartoon" of fiber's elongation

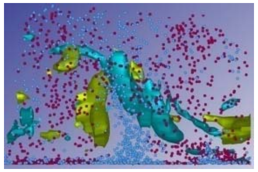


Results - Non-Homogeneity of Fiber Preferential Distribution

Front view: fibers accumulate in the near-wall region due to t*urbophoresis*

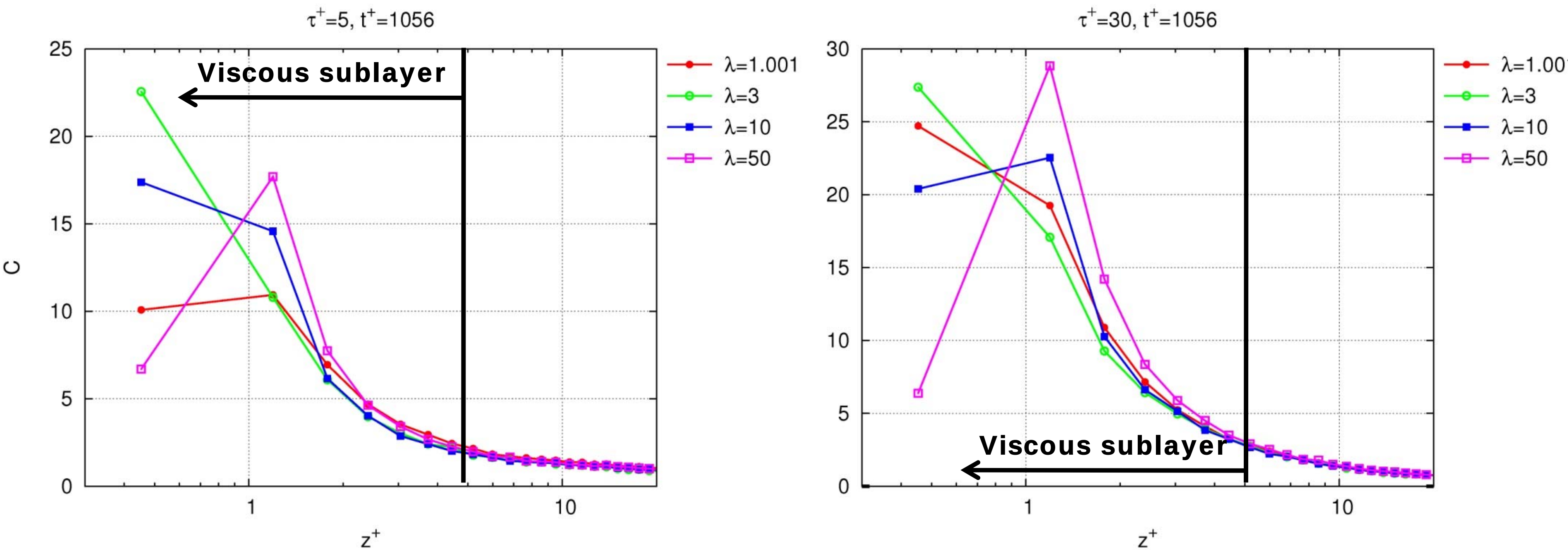


Sample animation for τ^{+}=30, λ=50 fibers (cross-section)

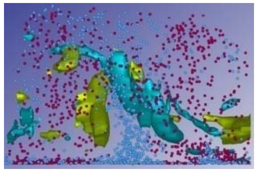


Results - Fiber Accumulation in the Near-Wall Region

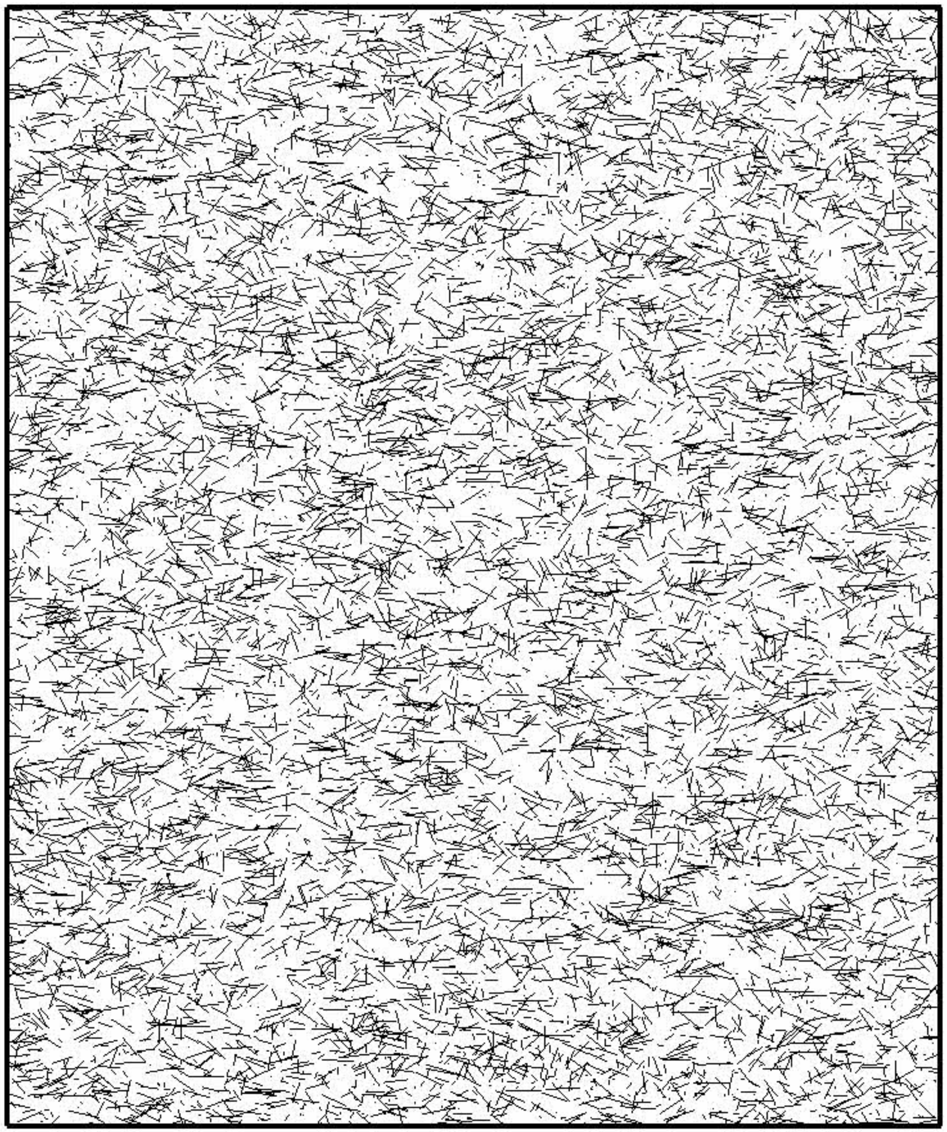
Instantaneous wall-normal fiber number density distribution



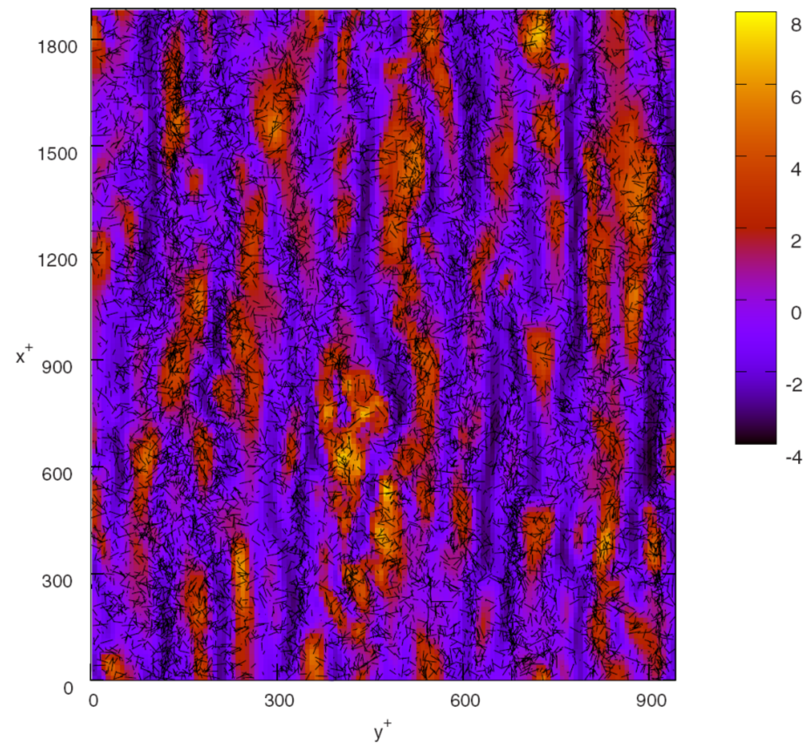
- The near-wall behavior of particle concentration is **strongly influenced by *λ*.**
- The influence of *λ* is not monotonic and depends on the Stokes number.



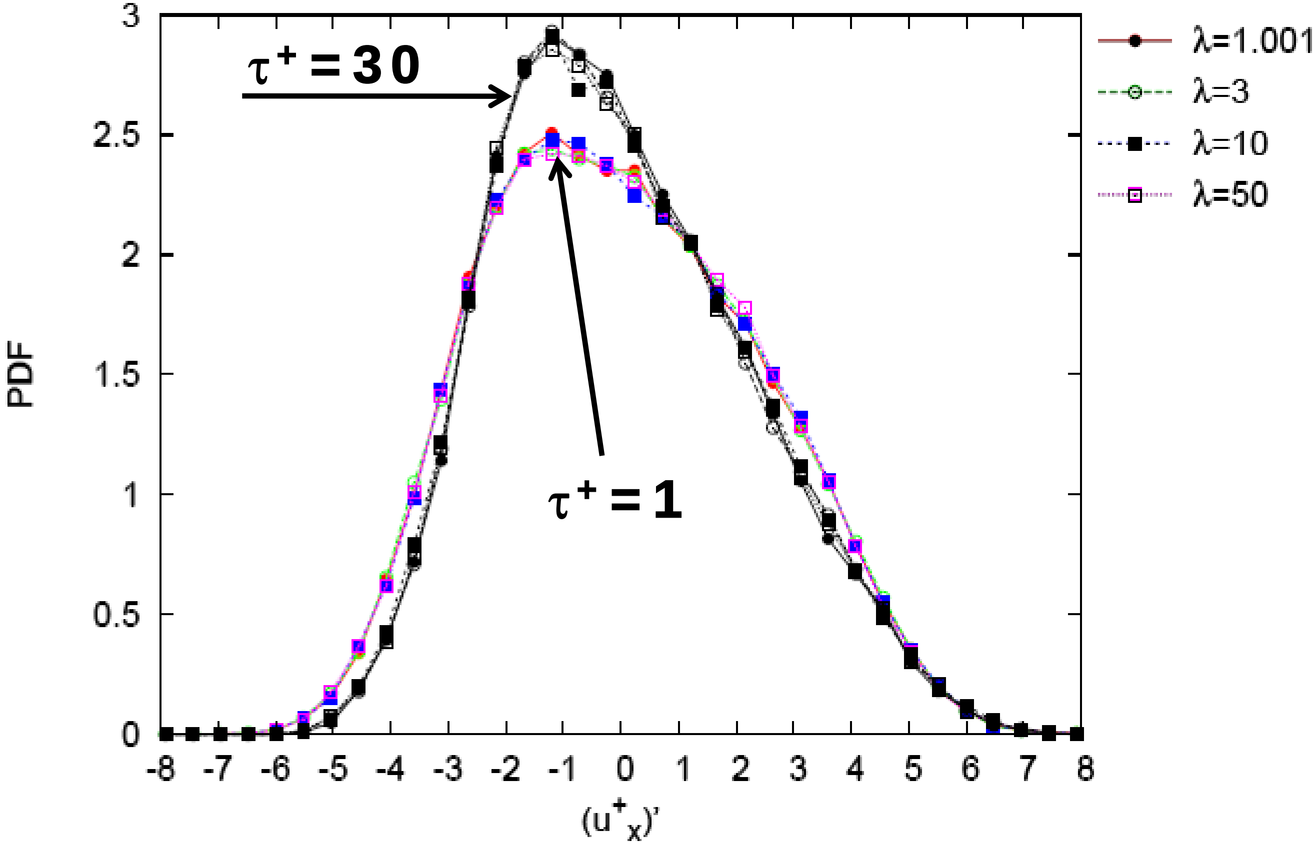
Results - Non-Homogeneity of Fiber Preferential Distribution



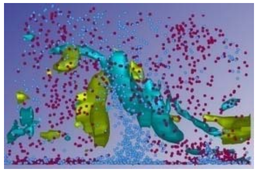
Top view: fibers segregate in streaks which superpose to fluid low-speed streaks



Results - Once in the Near-Wall Region…

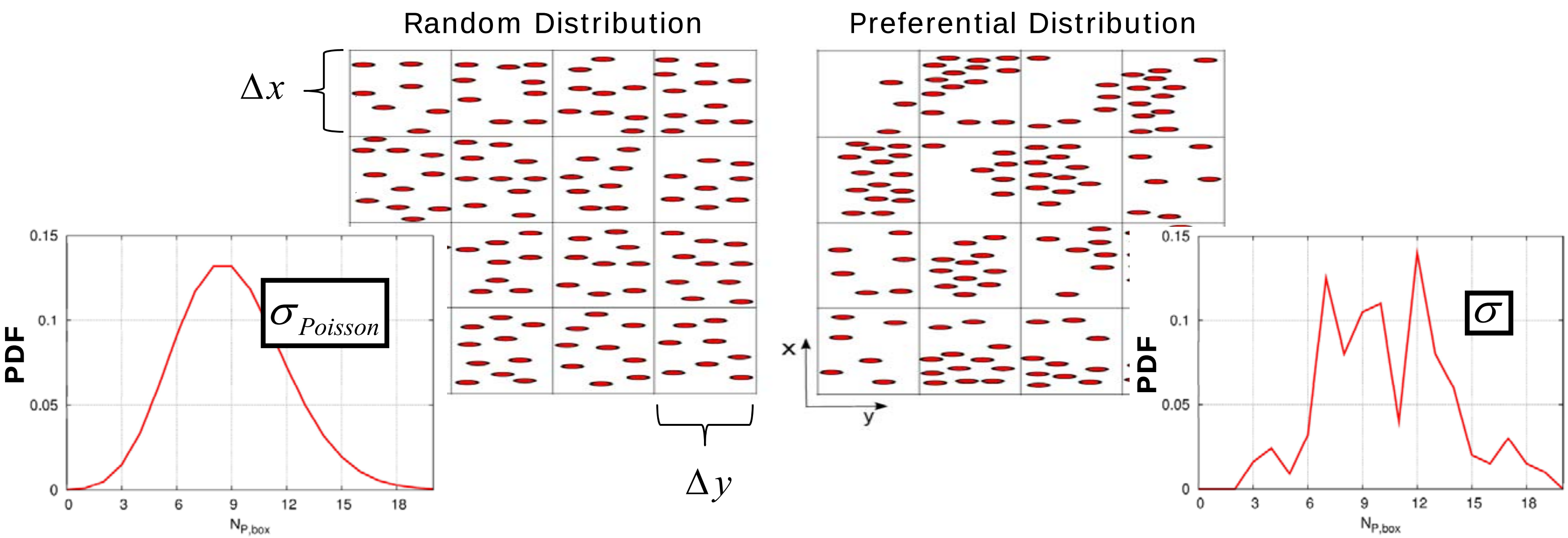


- **Fibers segregate into streaks which superpose to the fluid low-speed velocity streaks**
- **The degree of segregation does not depend on λ**



Results - Quantification of Local Fiber Segregation

- **Turbulence segregates fibers**
- **Higher-inertia fibers appear more segregated**
- **How to quantify segregation? As deviation from a random distribution ***

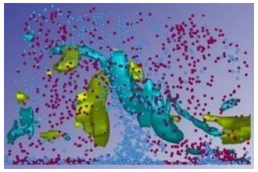


σ: standard deviation

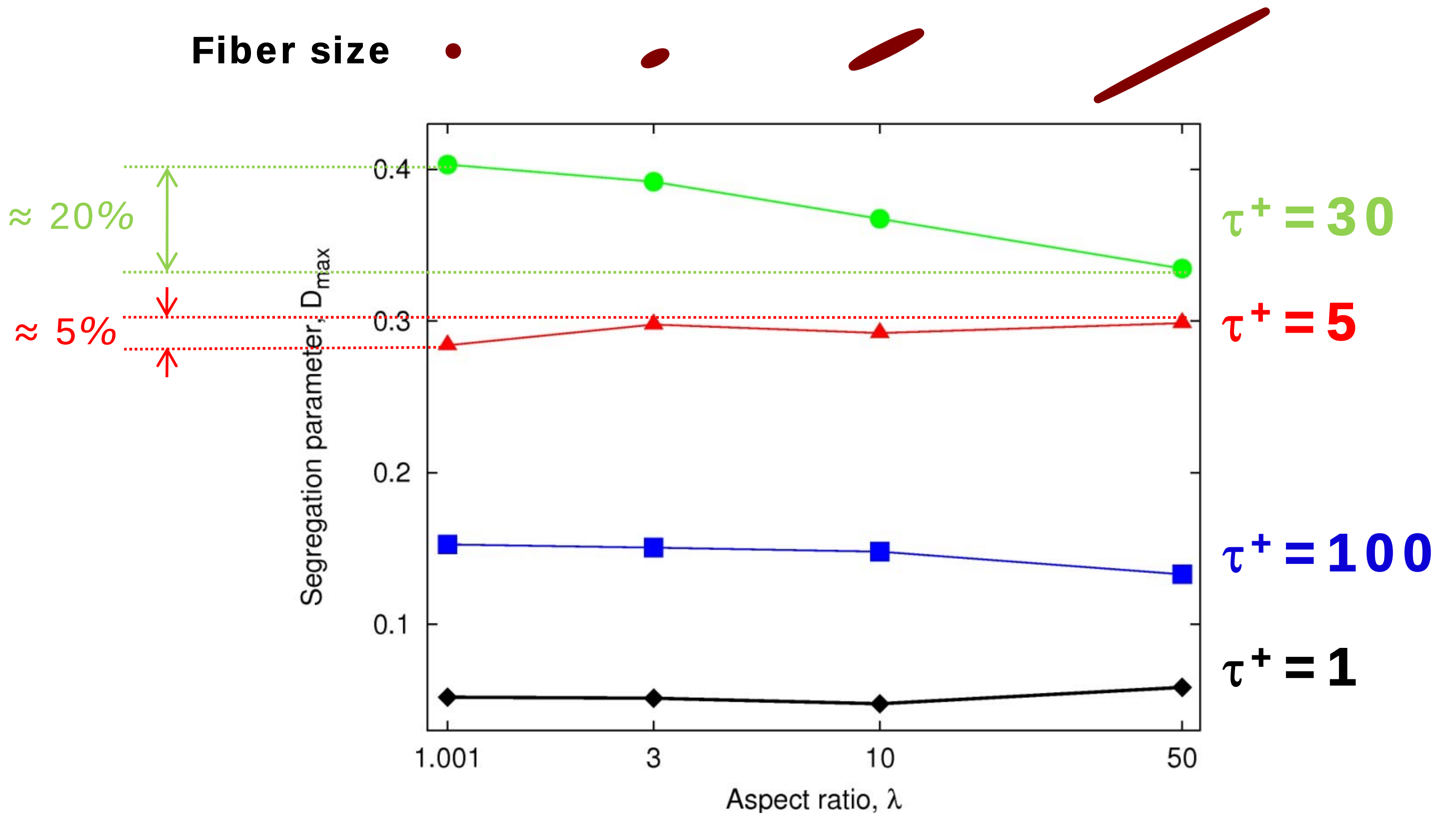
m: mean number of particles per cell

$$\Longrightarrow \quad D = \frac{\sigma - \sigma_{Poisson}}{m} = D_{(\Delta x, \Delta y)} \quad \Longrightarrow \quad D_{\max}$$

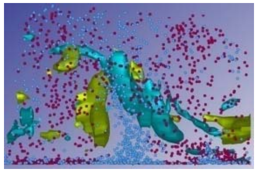
**** Ref. Fessler, Phys. Fluids (1994)***



Results – Quantification of Local Fiber Segregation



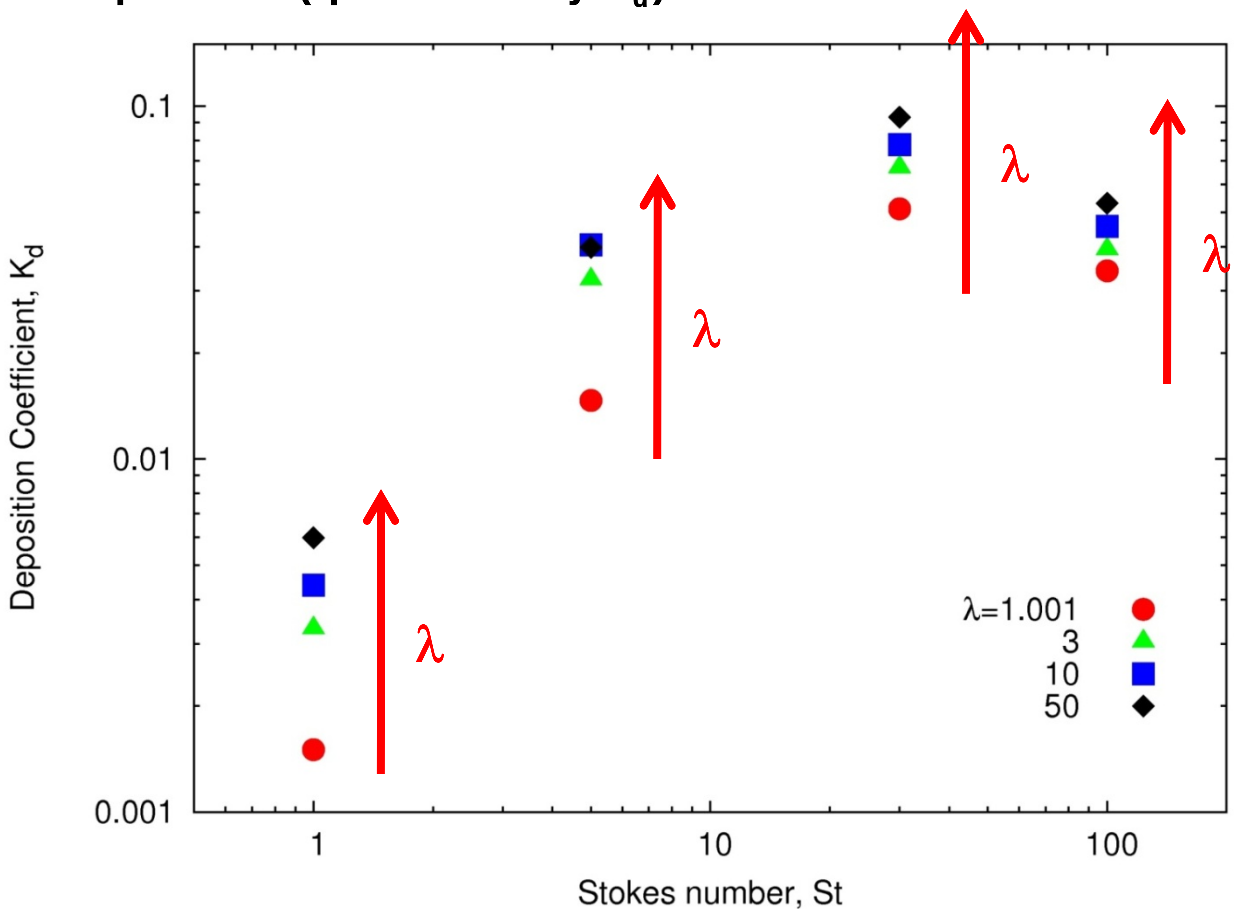
- The degree of segregation in the near-wall region depends also on λ (not only on τ^+)
- The influence of λ on segregation changes sensibly for different τ^+ (different inertia)



Results - Fiber Deposition Rate

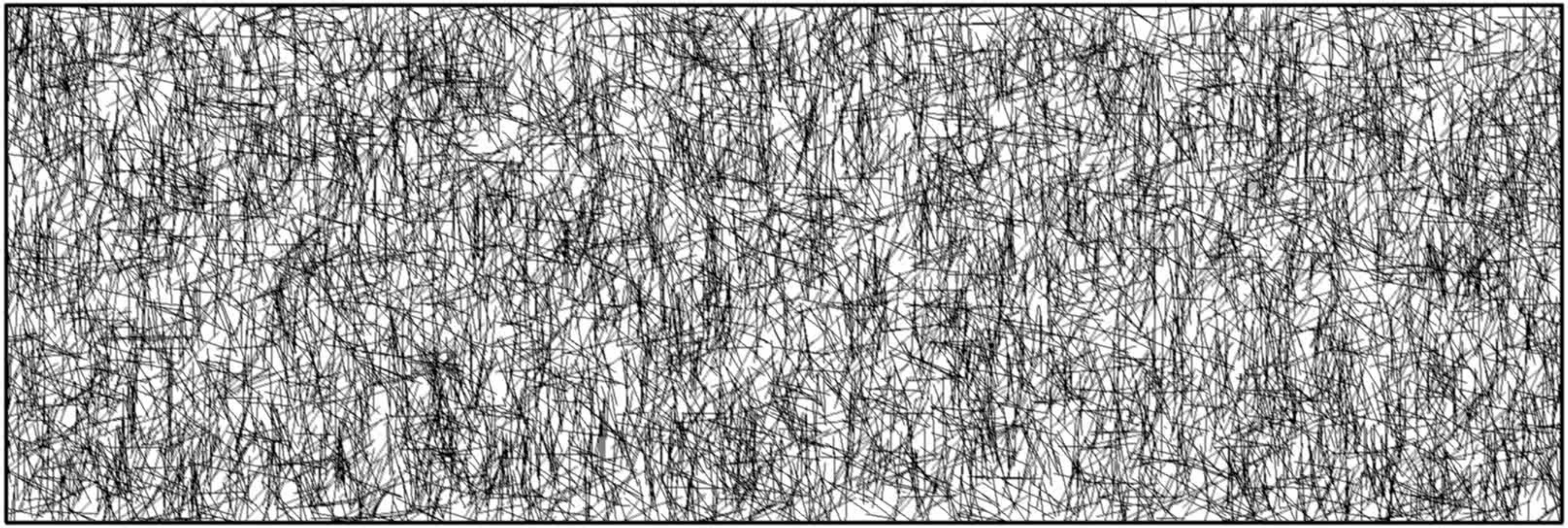
- **Longer fibers tend to segregate less (not always true, though…)**
- **From Eulerian-Lagrangian studies of spherical particle dispersion in TBL, we know that segregation controls deposition**
- **Let's look at fiber deposition (quantified by K_d)**

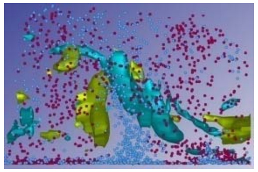
$$K_d = \frac{J \quad [kg/m^2 s]}{C \quad [kg/m^3]}$$



Results - Fiber Orientation
Look at fibers near the wall…

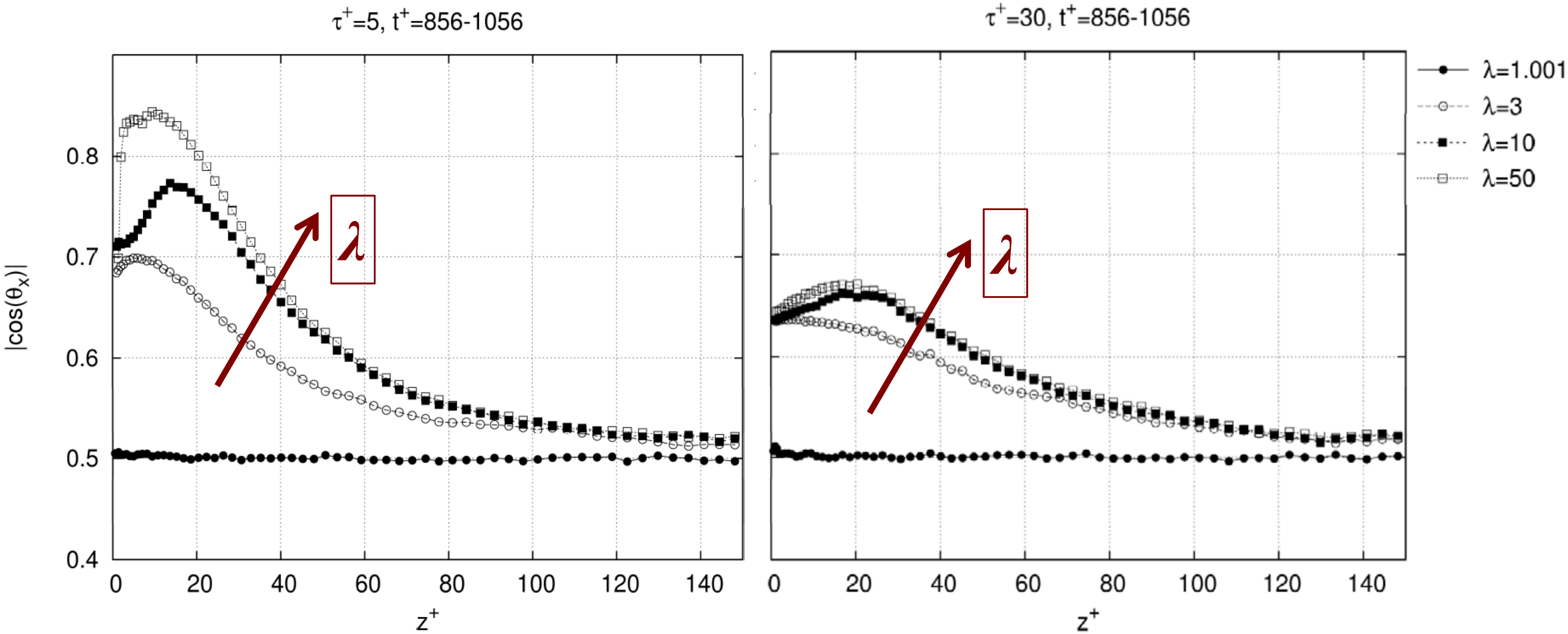
Side view: fibers in the near-wall region rotate preferentially in the longitudinal plane



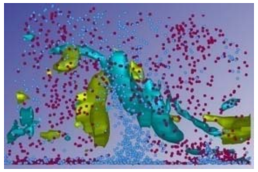


Results – Fiber Orientation

- **Fiber orientation with respect to the co-moving frame (given by the mean value of the direction cosines).**



- **Orientation <u>strongly depends on *λ*</u> and on the Stokes number as well.**
- **Fibers preferentially align in the streamwise (mean flow) direction.**
- **Fiber orientation becomes isotropic in the center of the channel.**
- **Results in agreement with Literature (e.g. *Mortensen, Phys. Fluids, 2008*).**



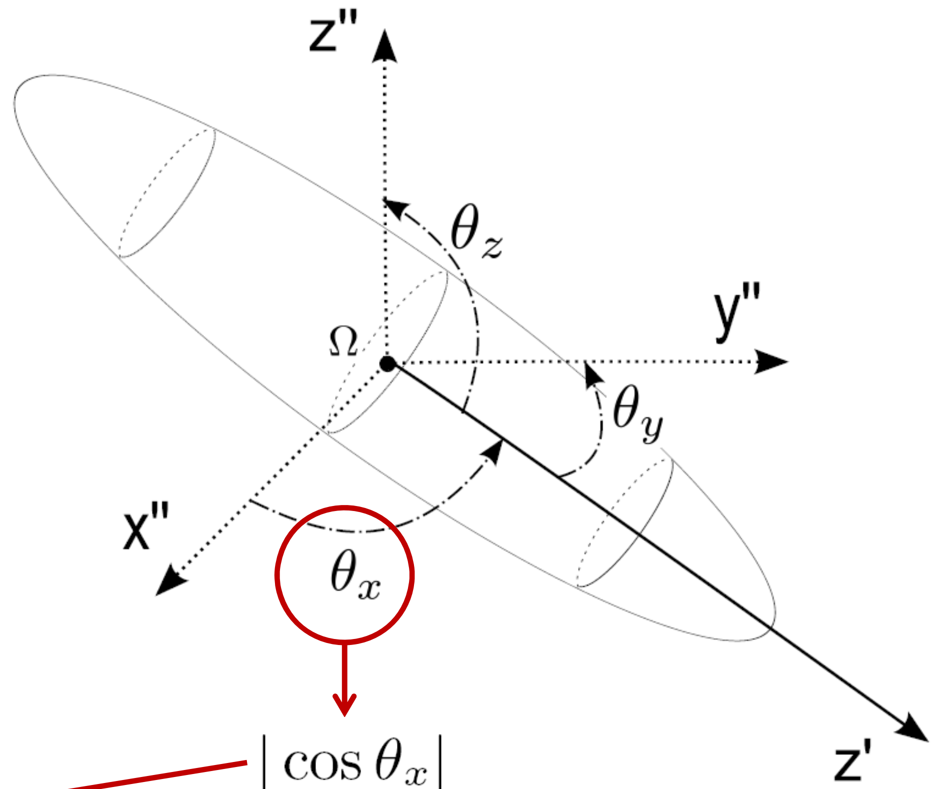
Results – Fiber Orientation Alignment Frequency

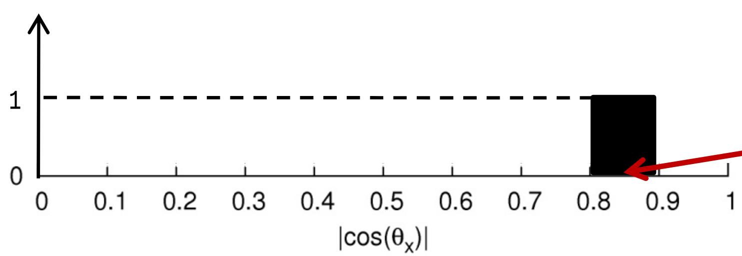
How long do fibers in the near-wall region remain aligned with the mean flow?

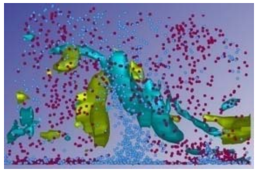
Is this alignment a "stable condition"?

Calculate <u>Alignment Frequency:</u>

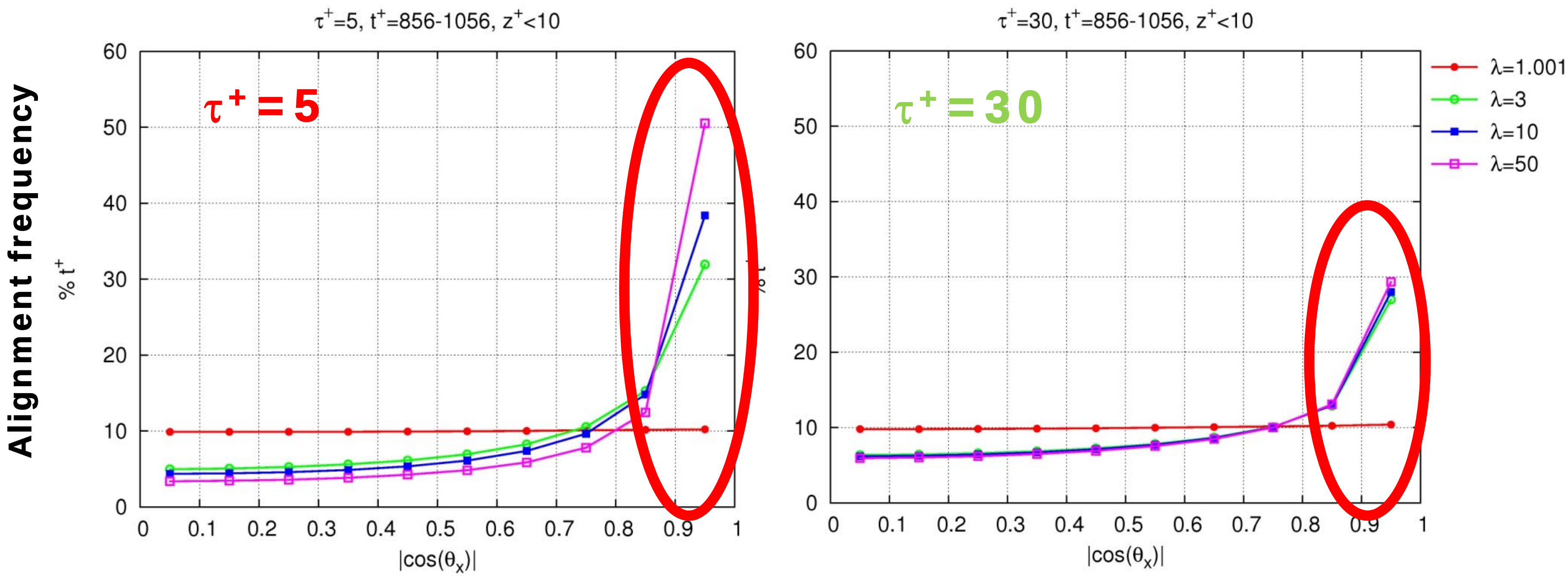
- **Divide the interval [0,1] into 10 orientation classes**
- **At each time step:**
  - **Compute $|\cos(\theta_i)|$ for each fiber**
  - **Identify the orientation class sampled**
  - **Increment the time step counter for that class**
- **Compute percent values**





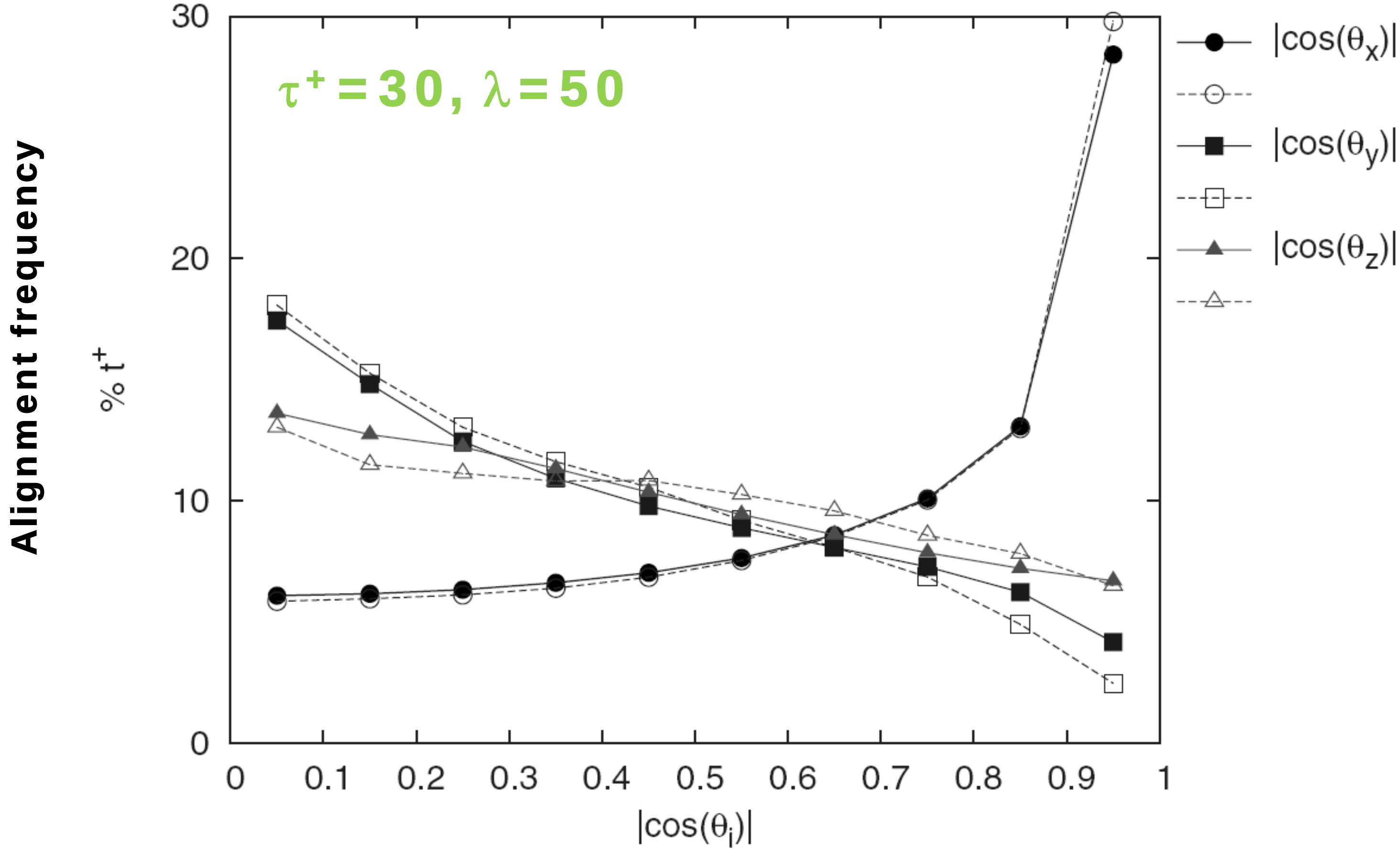


Results – Fiber Orientation
Alignment Frequency

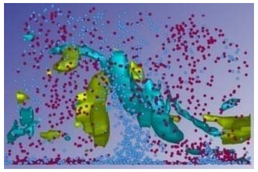


Fibers are aligned with the mean flow for just 50% of the time in the most favourable case (τ^+=5, λ = 50). Much less in the other cases.

Results – Fiber Orientation
Alignment Frequency



Alignment frequency statistics do not change if computed accounting only for fibers segregated into near-wall streaks



Conclusions …

…and Future Developments

The coupling between rotation and translation is non negligible: it affects accumulation rates at the wall, concentration and segregation.

This influence quantitatively depends on both fiber inertia and elongation.

Fiber alignment with the mean flow is highly unstable.

REF: C. Marchioli, M. Fantoni & A. Soldati *Phys. Fluids*, Vol. 22, 033301 (2010)

Include more values of *St*, λ and *Re* in the DNS+LPT database.

Collision models for particle-particle interactions (non-dilute flows).

Two-way coupling : parametric study to analyse fiber feedback on the fluid. Possible improvement in the physical understanding of *drag-reduction.*