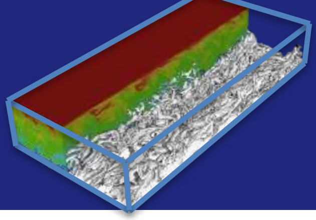


XIVth Multiphase Workshop and Summer School

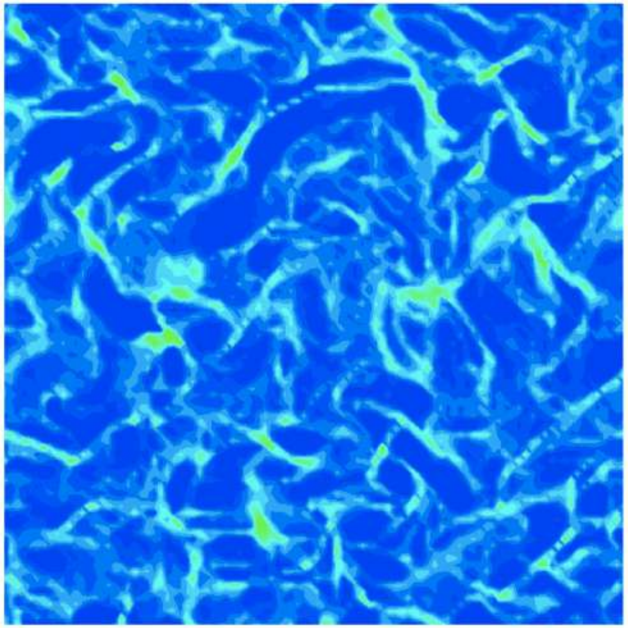
Multiphase Flow Laboratory
University of Udine

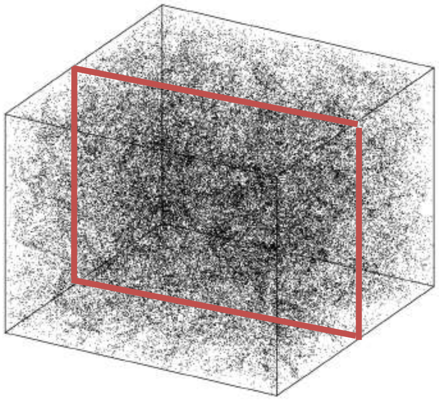
# Point-particle simulations of complex turbulent dispersed flows

Cristian Marchioli
University of Udine & CISM

Gdansk 2-4 September 2021

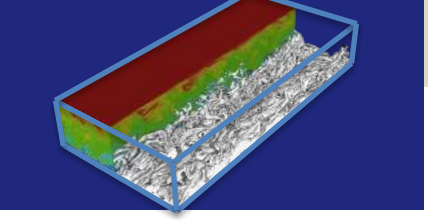
# What's common to (almost) all particle-laden turbulent flows?





Particle number density in homogeneous isotropic turbulence ($Re_\lambda$=51, St=1)

Particles concentrate preferentially in high-strain, low-vorticity regions due to their inertia

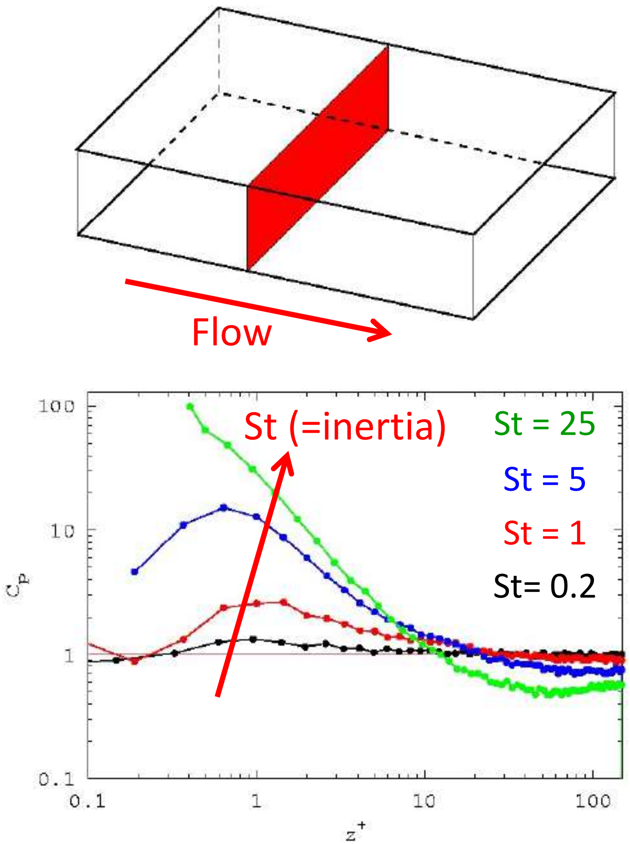


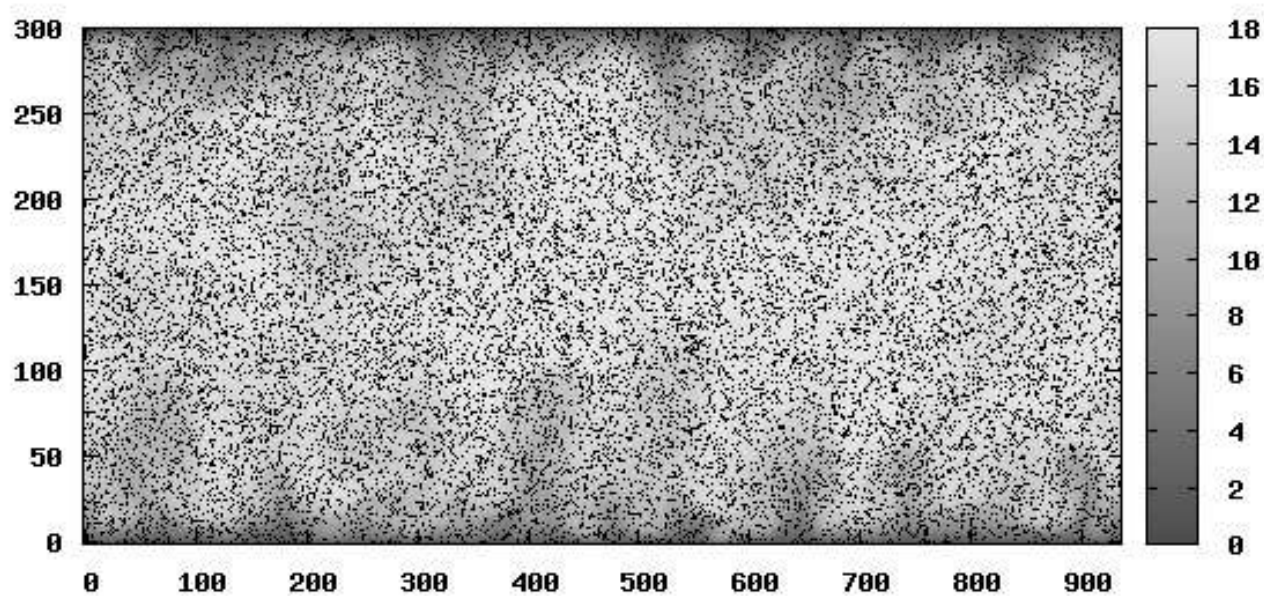


# What's common to (almost) all particle-laden turbulent flows?

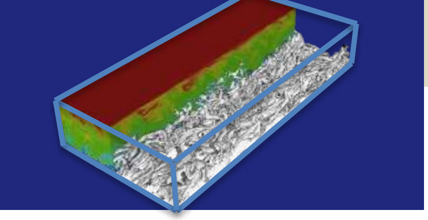


In wall-bounded flows inertial particles concentrate preferentially but also accumulate at the wall

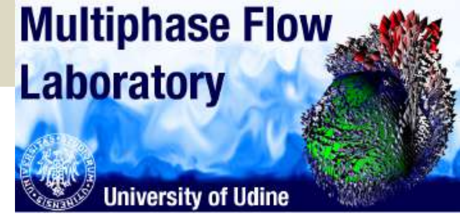



Time evolution of particle distribution in a turbulent channel ($Re_\tau$=150, St=25)

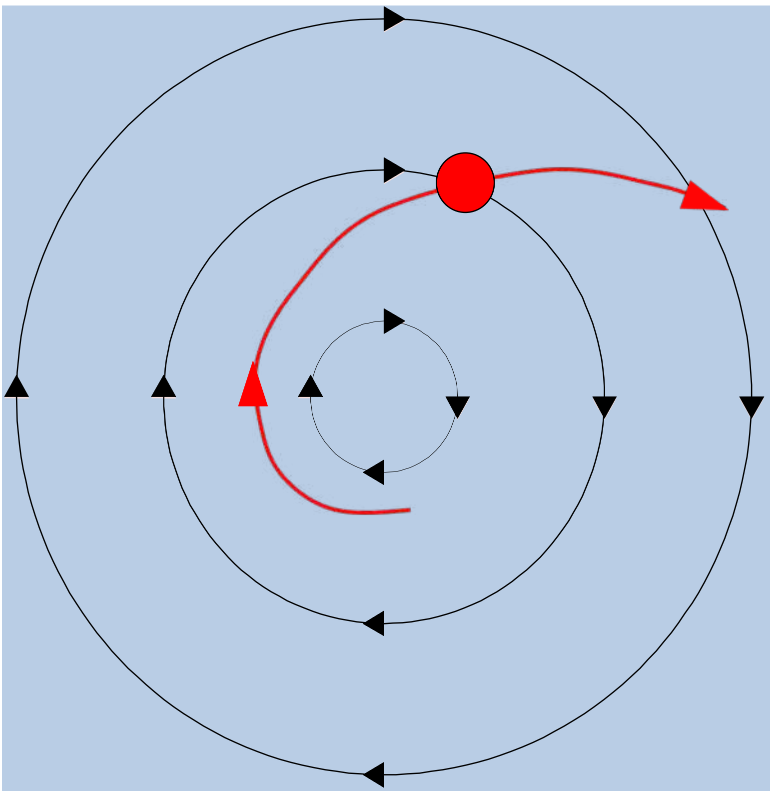







# What's common to (almost) all particle-laden turbulent flows?

**My answer is: in all flows, particles tend to deviate from fluid streamlines!**



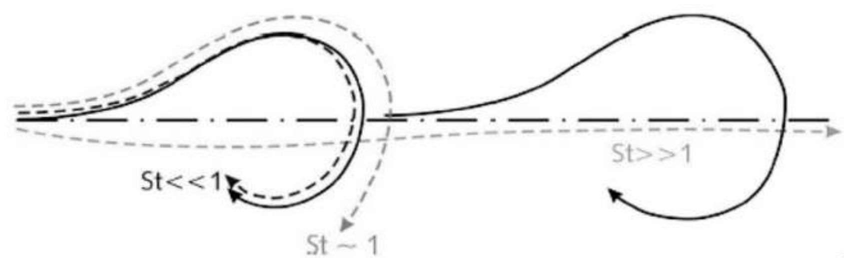
**Only source of bias: particle inertia!**

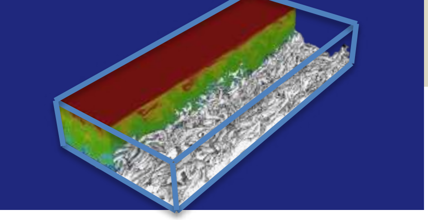
Deviations depend on the particle response time to the underlying flow field:

Particle Relaxation Time: $\tau_p = \dfrac{\rho_p d_p^2}{18\mu}$

Flow Time Scale: $\tau_f$

Particle Stokes number: $St = \dfrac{\tau_p}{\tau_f}$





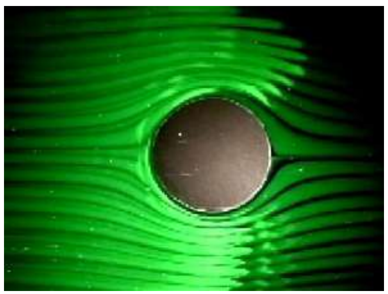




# A numerical approach to study preferential concentration

The simplest dynamical model to study "inertia-driven" preferential concentration considers small **pointwise** spherical particles (only source of bias is inertia!)

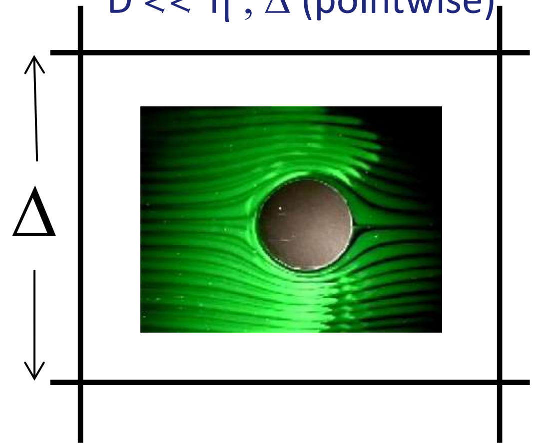
No wake (Stokes flow)



$$Re_p = \frac{u_{rel} L}{\nu} << 1$$

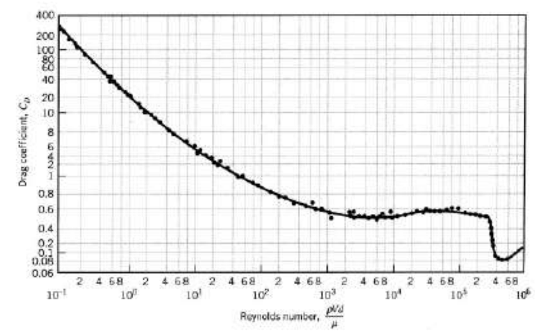
Enough to know $\mathbf{x}_p$ and $\mathbf{v}_p$!

$D << \eta$ , $\Delta$ (pointwise)

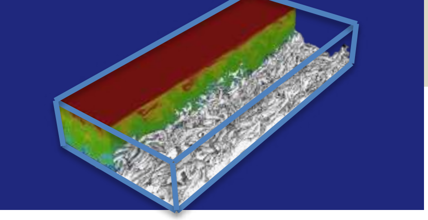



$$\frac{d\mathbf{x}_p}{dt} = \mathbf{v}_p, \quad m_p \frac{d\mathbf{v}_p}{dt} = \sum_i \mathbf{F}_i$$

Force model: Drag



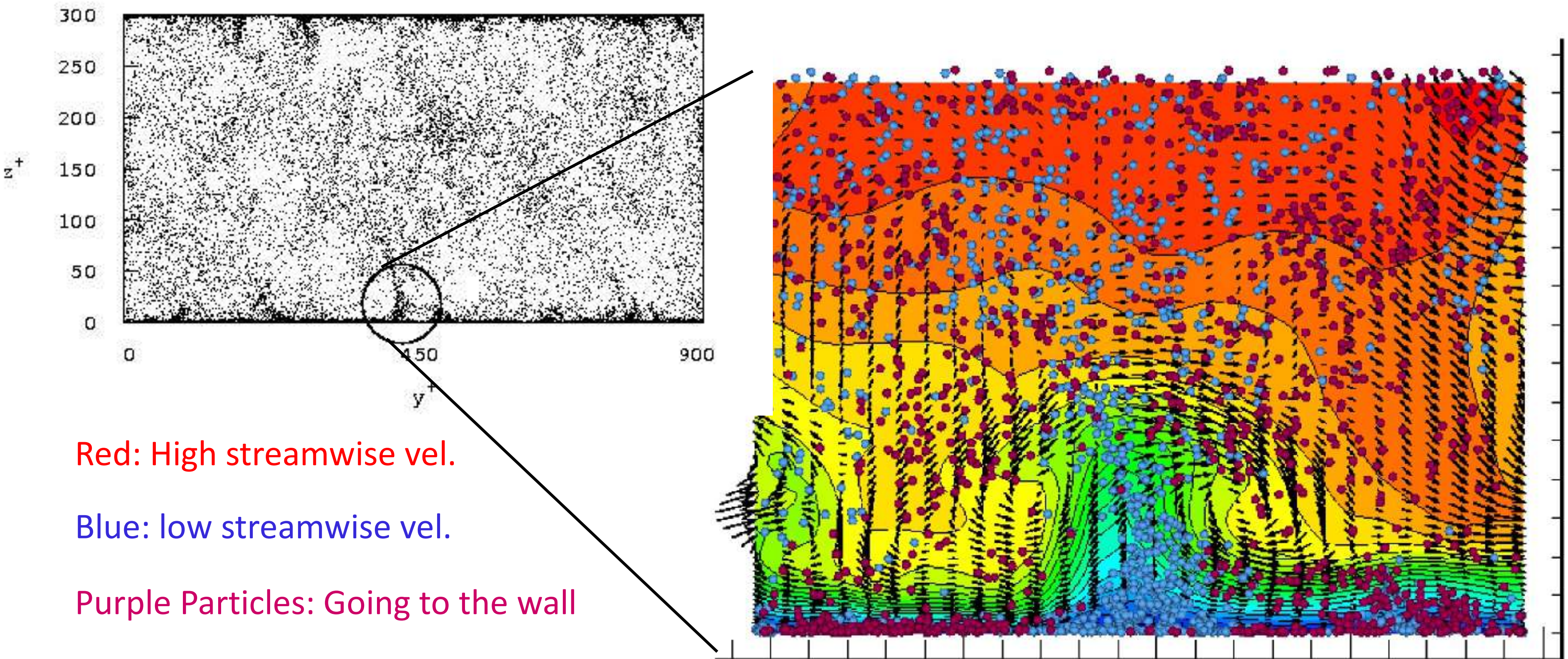

$$C_D(Re_p) = \frac{\mathbf{F}_D}{\frac{1}{2}\rho \mathbf{u}_{rel}^2 A_p}$$





# Phenomenology of preferential concentration

Physics learned from this simple model (in DNS):
Qualitative explanation of particle deposition and entrainment in turbulent boundary layers

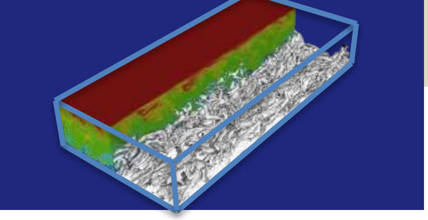



Red: High streamwise vel.

Blue: low streamwise vel.

Purple Particles: Going to the wall

Blue Particles: Going away from the wall

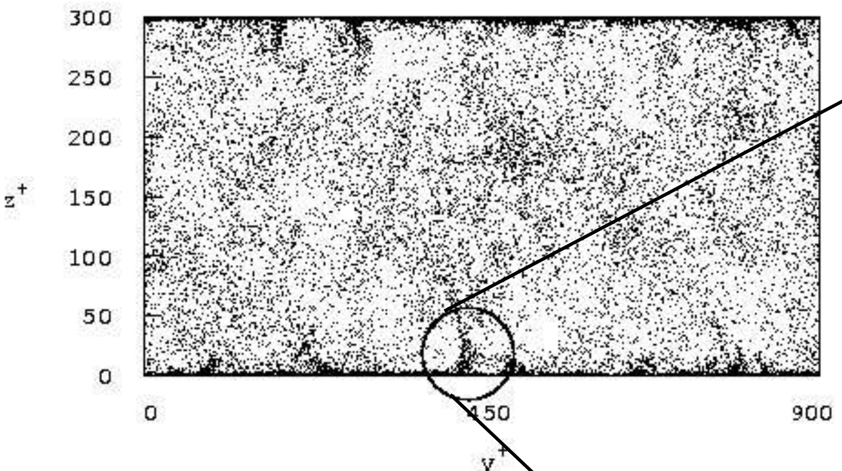




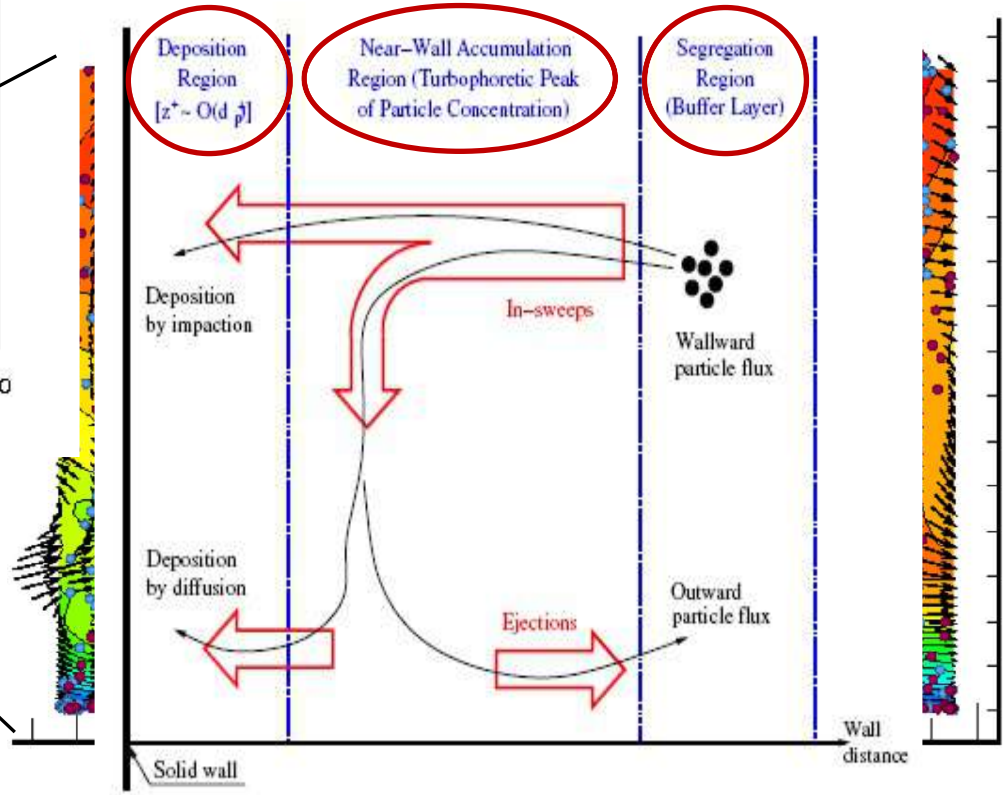


# Phenomenology of preferential concentration

Physics learned from this simple model (in DNS):
Qualitative explanation of particle deposition and entrainment in turbulent boundary layers




**STRUCTURES → SEGREGATION → ACCUMULATION → DEPOSITION**




Red: High streamwise vel.

Blue: low streamwise vel.

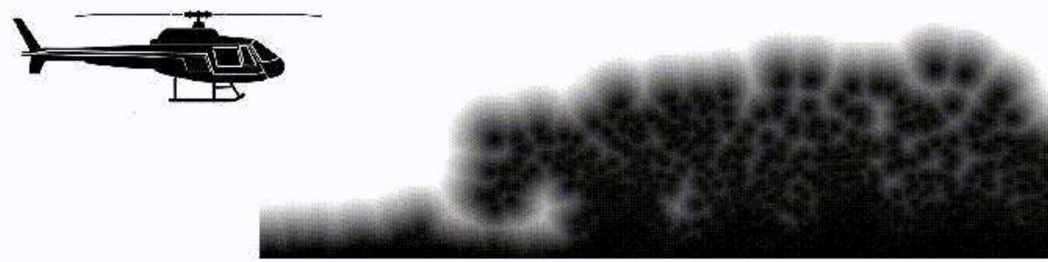
Purple Particles: Going to the wall

Blue Particles: Going away from the wall

# An interesting application:
# Rotor-wing brownout

Figure courtesy of Chinook landing in the desert. Retrieved 27 Oct., 2014, from http://www.defencetalk.com/dod-budget-cuts-stall-new-purchases-of-helicopters-44481/

During brownout sand and dust are resuspended from arid soil

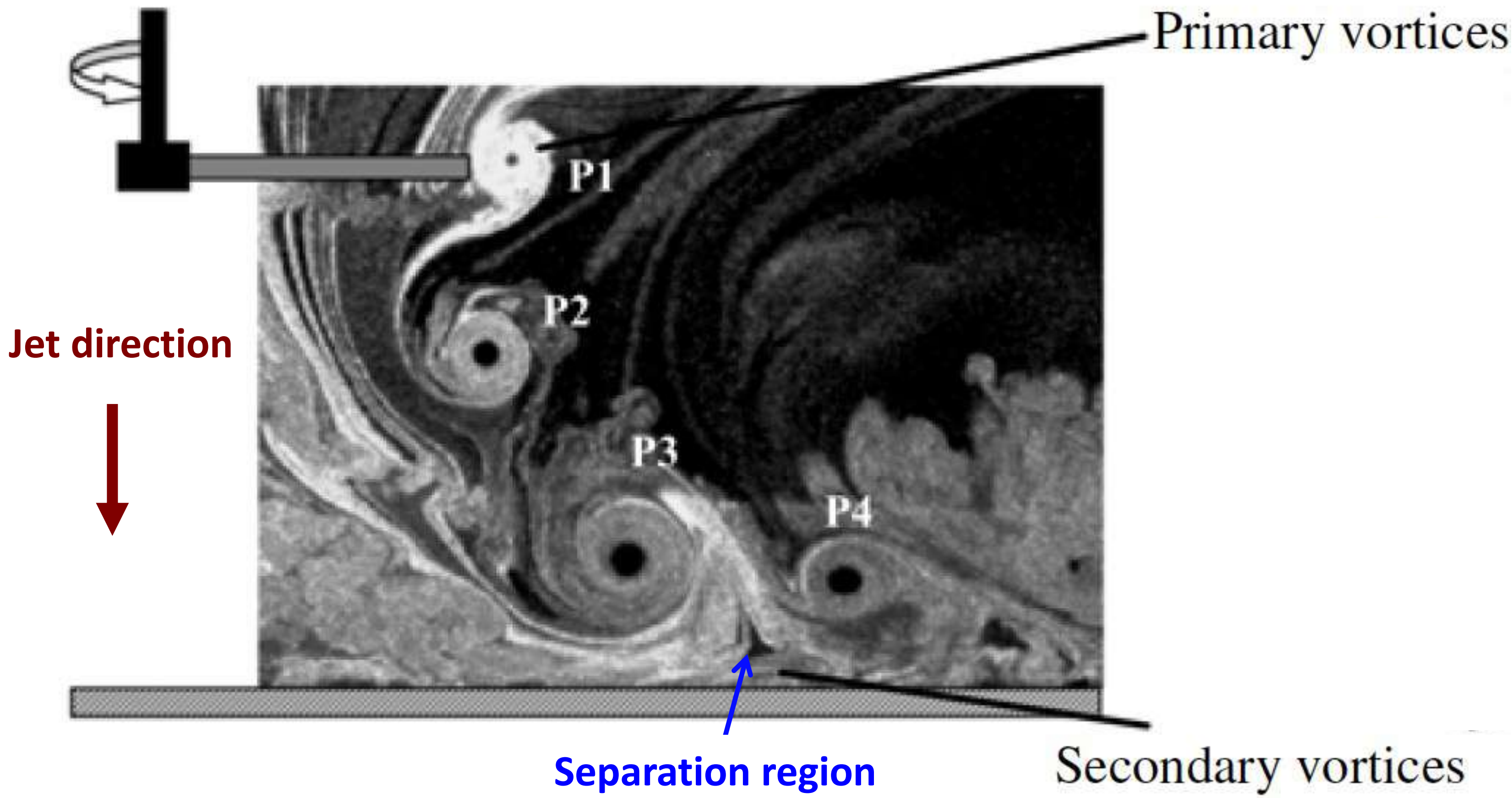


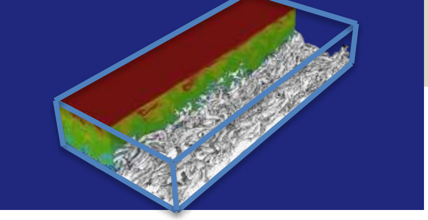
The downflow generated by the rotor-wing can be modelled as a periodically-forced turbulent jet impinging on a solid wall

# Resuspension by periodically-forced turbulent impinging jet

## Flow field: Forced round imping jet

(cfr. Wu & Piomelli, JoT 2014 2016, EJM-B/Fluid 2015)

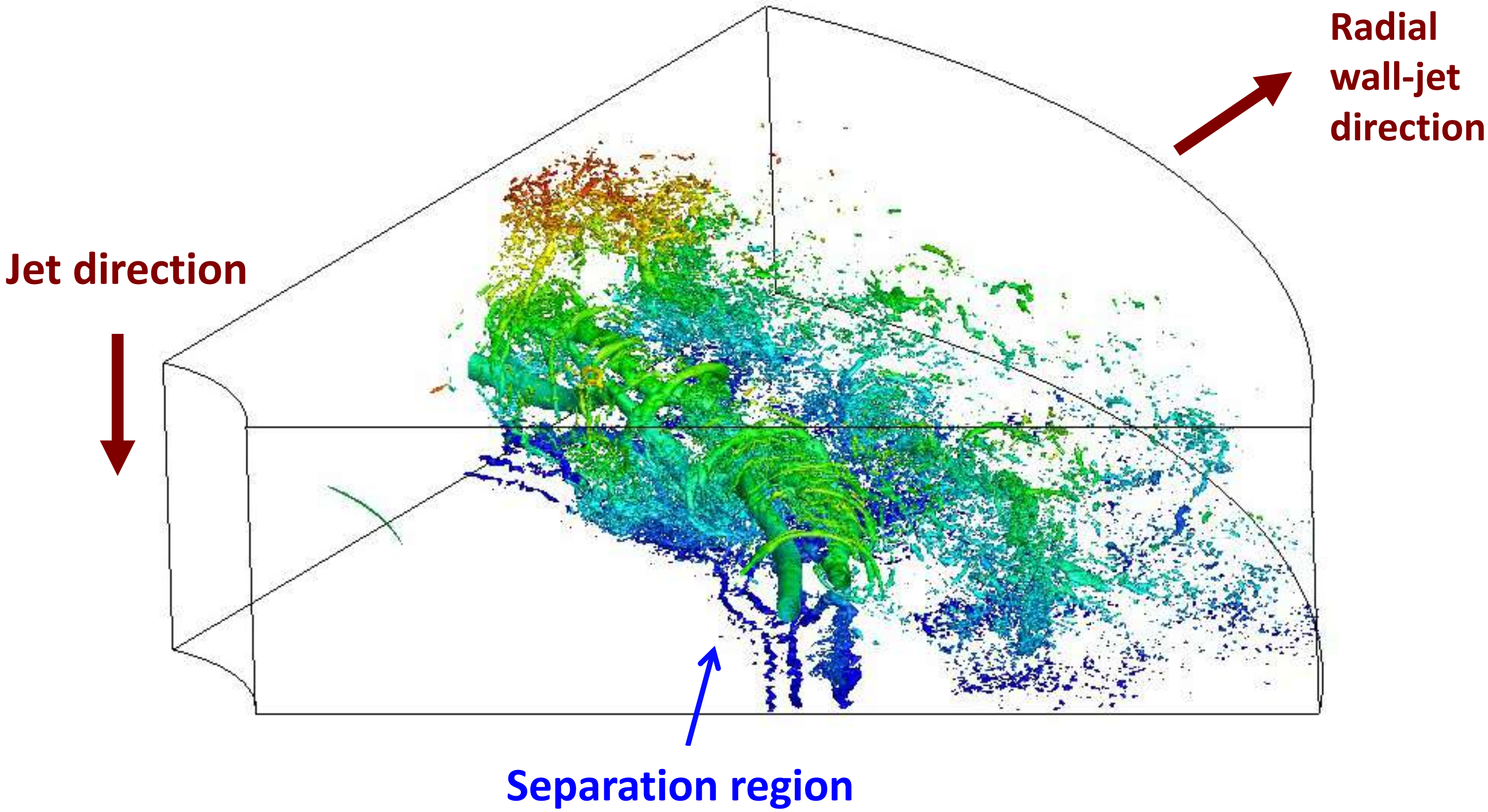




# Resuspension by periodically-forced turbulent impinging jet

## Flow field: Forced round imping jet

(cfr. Wu & Piomelli, JoT 2014 2016, EJM-B/Fluid 2015)



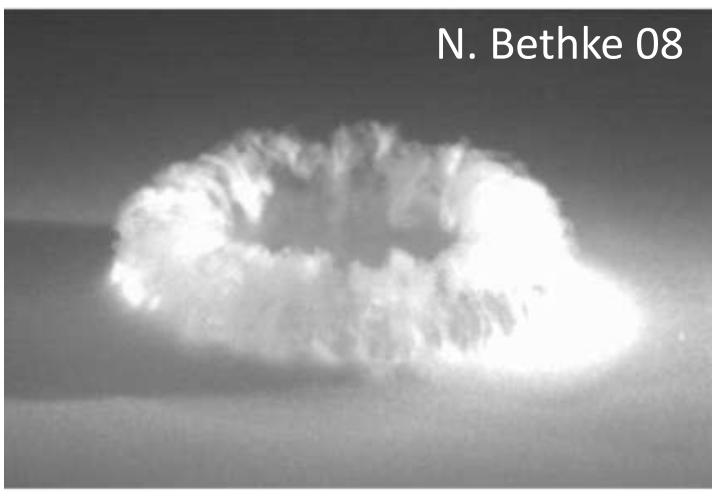
# Resuspension by periodically-forced turbulent impinging jet

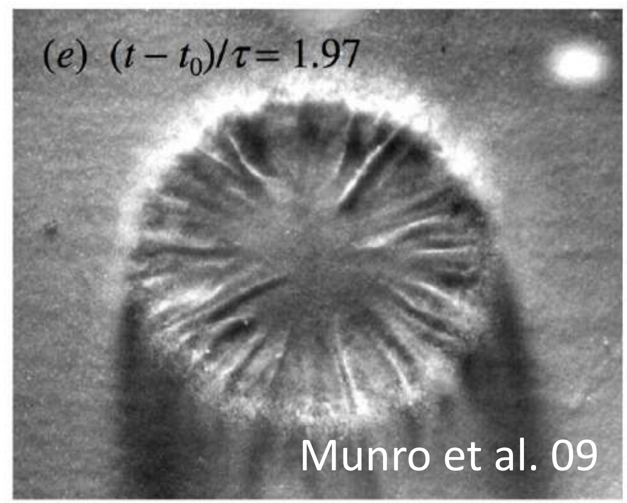
Question: What are the mechanisms governing particle resuspension ?

(cfr. Wu et al., JFM 2017)

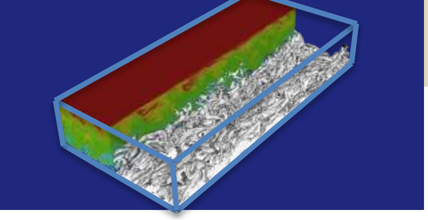
Any analogy with sediment bed erosion by vortex rings?

(cfr. Munro et al., 2009; Bethke & Dalziel, 2012; Mulinti & Kiger, 2012; ...)




“Spokelike” scar features formed on the crater





# Methodology

- Fluid
  - Filtered continuity and Navier-Stokes equations

$$\nabla \cdot \overline{\boldsymbol{u}} = 0,$$

$$\frac{\partial \overline{\boldsymbol{u}}}{\partial t} + \nabla \cdot \overline{\boldsymbol{u}}\,\overline{\boldsymbol{u}} = -\nabla \overline{P} - \nabla \cdot \boldsymbol{\tau} + \nu_f \nabla^2 \overline{\boldsymbol{u}},$$

  - $2^{nd}$–order accurate in space & time, staggered FD
  - Lagrangian-averaged dynamic eddy-viscosity model

$$\frac{\mathrm{d}\theta_p}{\mathrm{d}t} = \frac{v_{p,\theta}}{r}, \quad \frac{\mathrm{d}r_p}{\mathrm{d}t} = v_{p,r}, \quad \frac{\mathrm{d}z_p}{\mathrm{d}t} = v_{p,z},$$

- Particles
  - Lagrangian tracking
  - Point-particle approach
  - One-way coupling
  - Forces: Drag, lift, buoyancy, gravity

$$\frac{\mathrm{d}v_{p,\theta}}{\mathrm{d}t} = \frac{C_D}{\tau_p}(\overline{u}_{@p,\theta} - v_{p,\theta}) - \frac{v_{p,\theta} v_{p,r}}{r} + f_{S,\theta},$$

$$\frac{\mathrm{d}v_{p,r}}{\mathrm{d}t} = \frac{C_D}{\tau_p}(\overline{u}_{@p,r} - v_{p,r}) + \frac{v_{p,\theta}^2}{r} + f_{S,r},$$

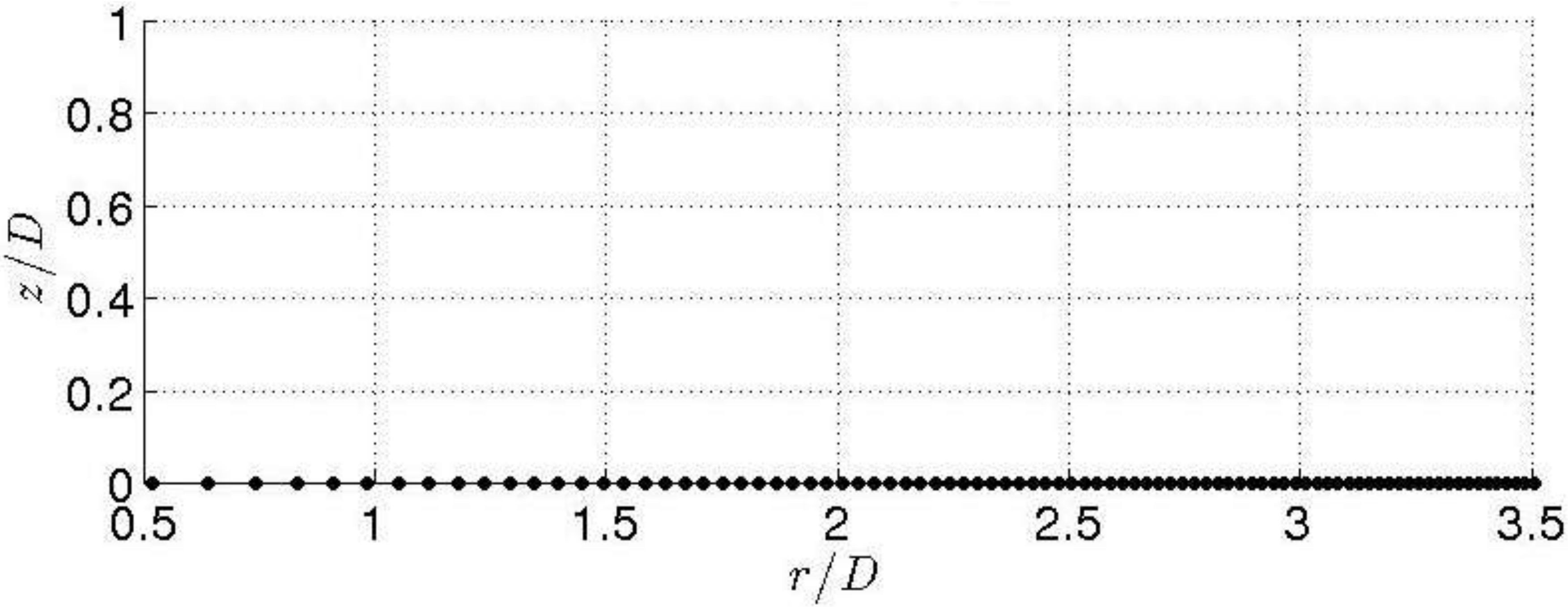
$$\frac{\mathrm{d}v_{p,z}}{\mathrm{d}t} = \frac{C_D}{\tau_p}(\overline{u}_{@p,z} - v_{p,z}) + \left(1 - \frac{\rho_f}{\rho_p}\right) g + f_{S,z},$$

Wu et al., Particle resuspension by periodically-forced impinging jet.
*Journal of Fluid Mechanics*, vol. 820 *(2017)*

# Jet-induced particle resuspension

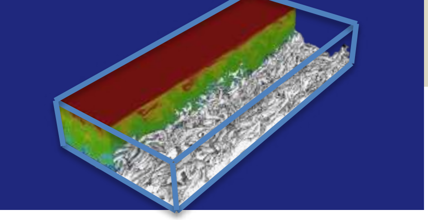


- Particle parameters
  - 20 micron; 50000 particles used; re-seed from inlet when exits






Wu et al., Particle resuspension by periodically-forced impinging jet.
*Journal of Fluid Mechanics*, vol. 820 *(2017)*







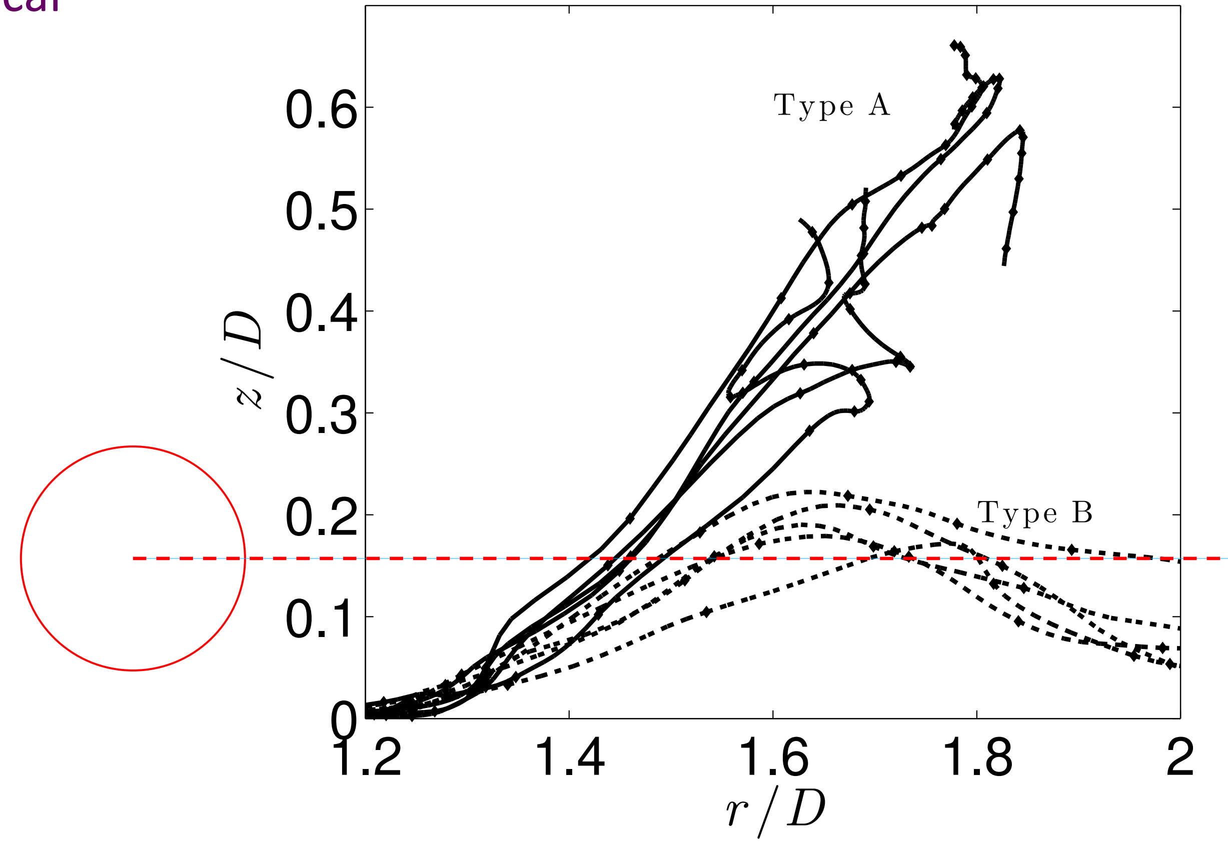
# Jet-induced particle resuspension

- Different behaviors for identical particles
  - Must be caused by local flow characteristics

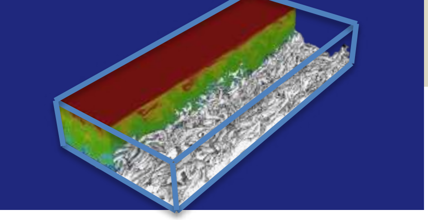
Type A: particles that reach 0.3D and higher

Type B: particles that stay below 0.3D

- Type B particles perform a small initial jump




Wu et al., Particle resuspension by periodically-forced impinging jet. *Journal of Fluid Mechanics*, vol. 820 *(2017)*





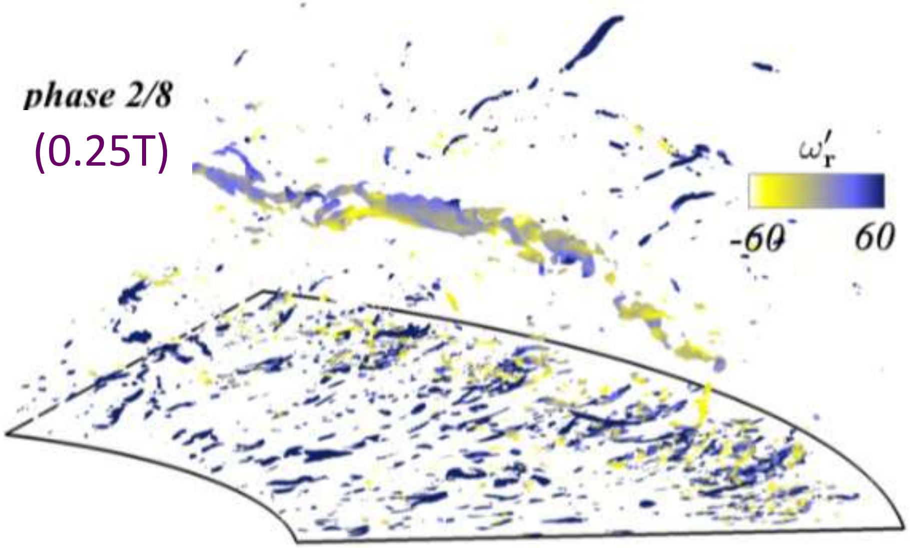
# Jet-induced particle resuspension

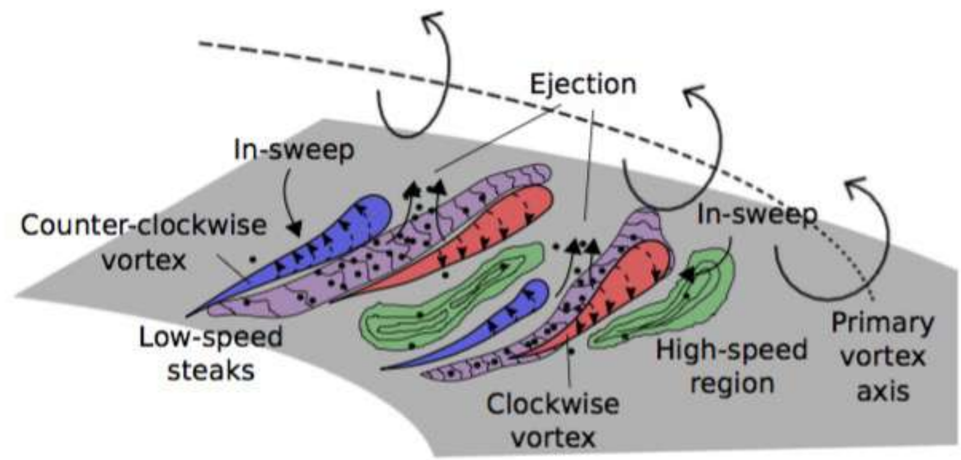
- Different behaviors for identical particles
  - Local flow characteristics: rib-like vortices, streaks, sweeps and ejections are observed in-between primary vortices

$$Q = (\Omega_{ij}\Omega_{ij} - S_{ij}S_{ij})/2$$

T = forcing period

(0.25T)



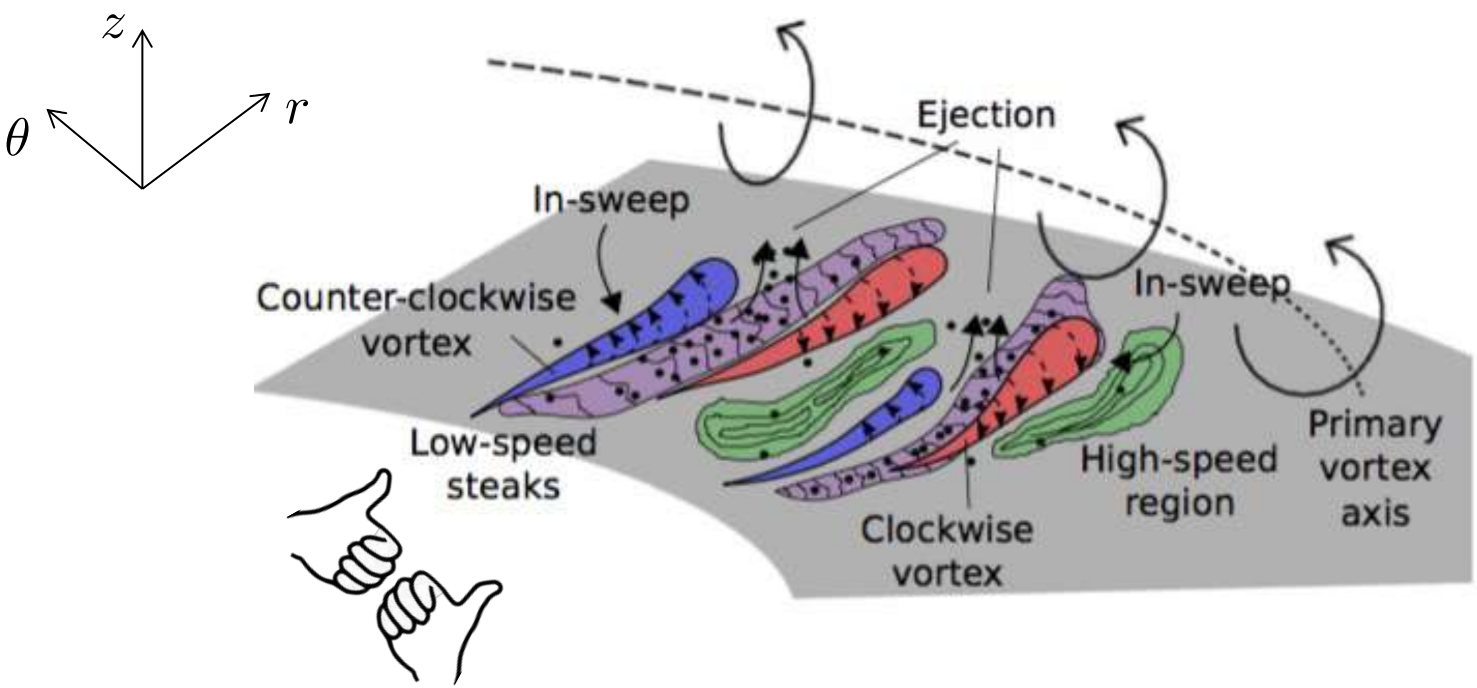





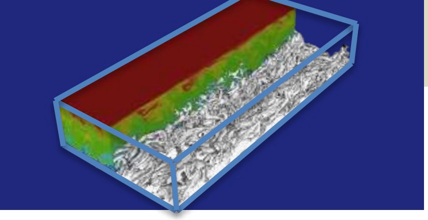

Wu et al., Particle resuspension by periodically-forced impinging jet. *Journal of Fluid Mechanics*, vol. 820 *(2017)*

# Jet-induced particle resuspension

- Different behaviors for identical particles
  - Particles can be entrained by ejections (where $u'_{r,f} < 0,\ u'_{z,f} > 0$)

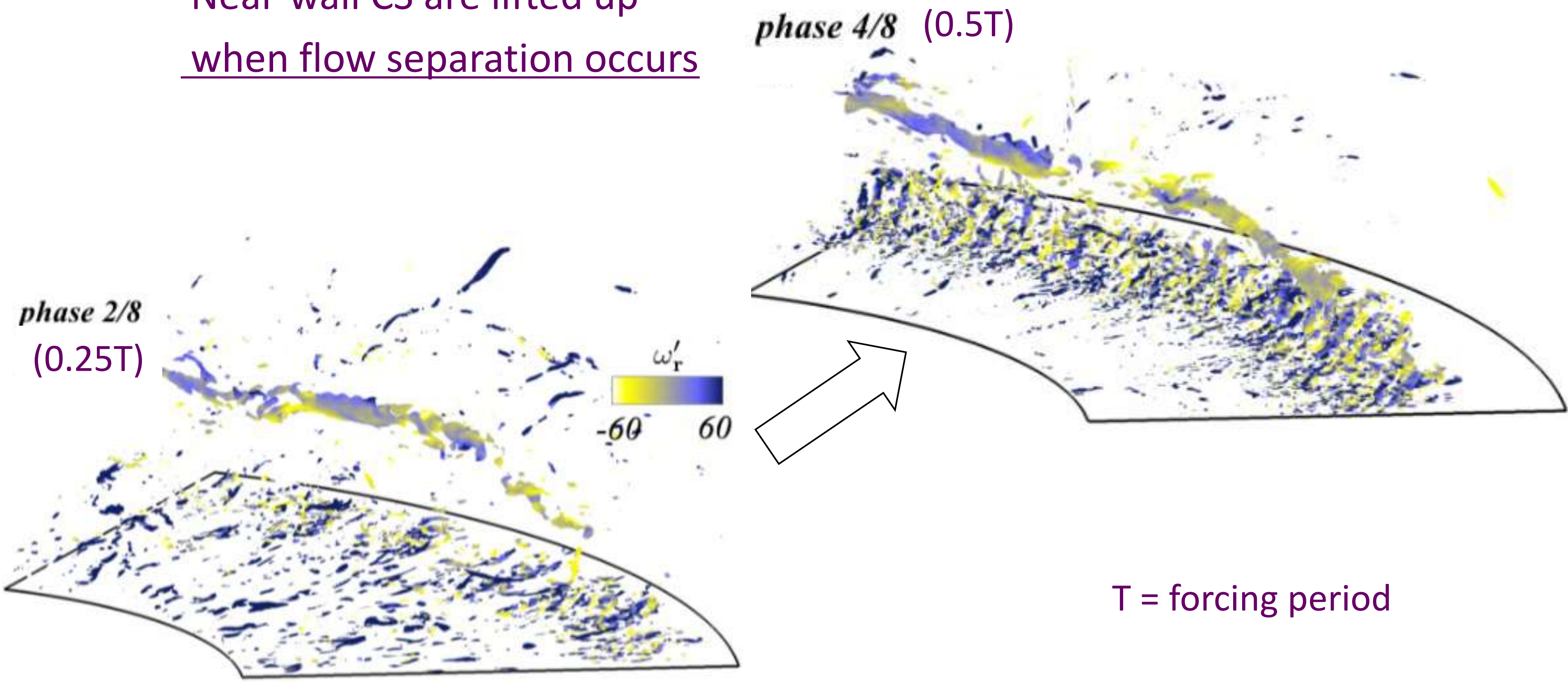



Wu et al., Particle resuspension by periodically-forced impinging jet.
*Journal of Fluid Mechanics*, vol. 820 *(2017)*



# Jet-induced particle resuspension

- Different behaviors for identical particles
  - Near-wall CS are lifted up
    when flow separation occurs




T = forcing period



Wu et al., Particle resuspension by periodically-forced impinging jet. *Journal of Fluid Mechanics*, vol. 820 *(2017)*

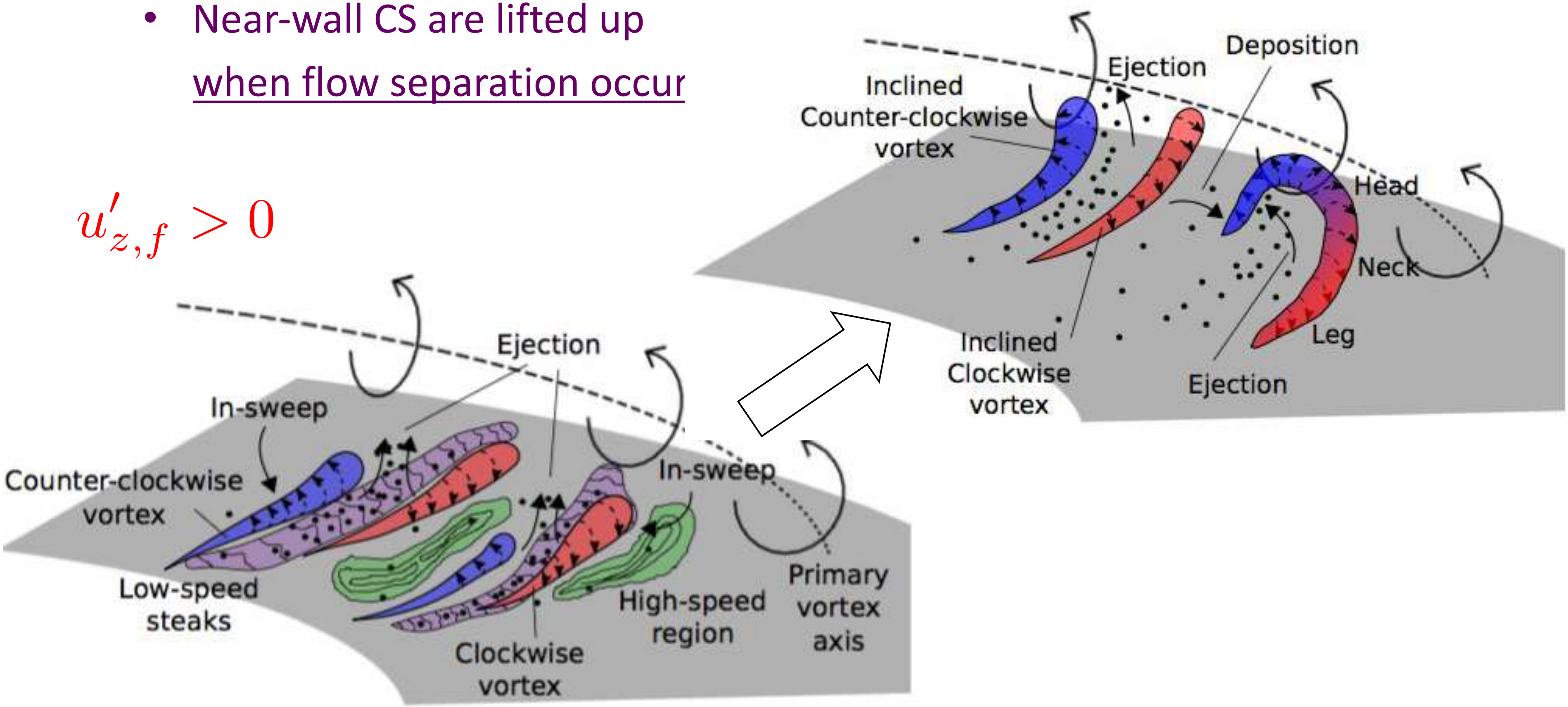
# Jet-induced particle resuspension



- Different behaviors for identical particles
  - Near-wall CS are lifted up
    when flow separation occur

$u'_{r,f} < 0$

$u'_{z,f} > 0$

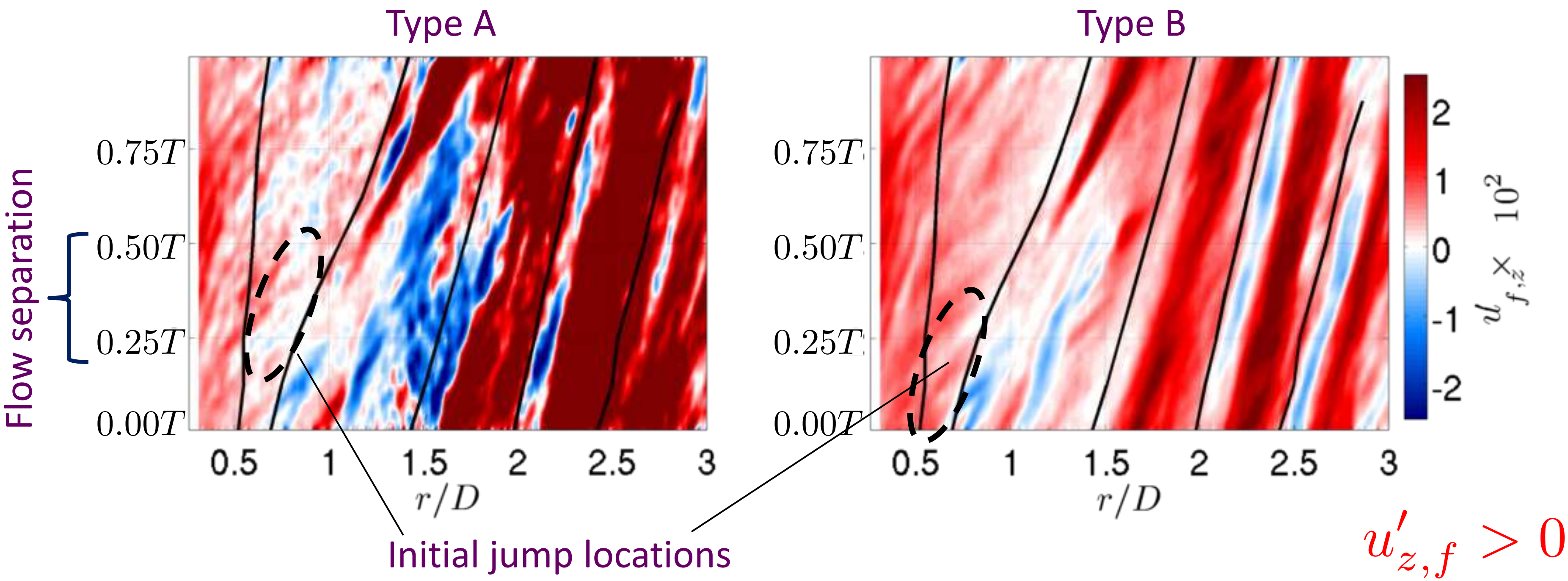





Wu et al., Particle resuspension by periodically-forced impinging jet. *Journal of Fluid Mechanics*, vol. 820 *(2017)*

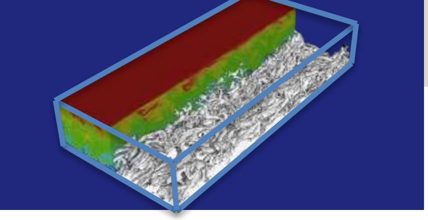
# Jet-induced particle resuspension

- Different behaviors for identical particles
  - Ejection by near-wall streaks
    - Type B particles: meet the right vortices, but at a wrong time





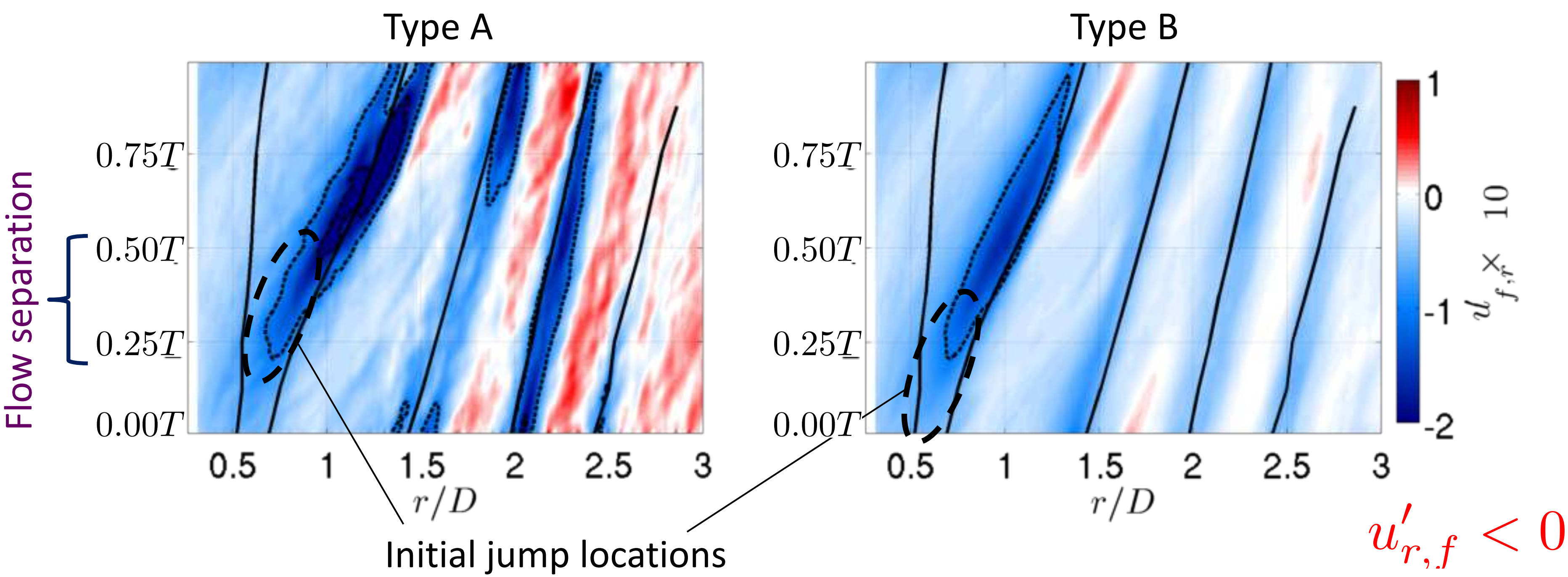

Wu et al., Particle resuspension by periodically-forced impinging jet. *Journal of Fluid Mechanics*, vol. 820 *(2017)*



# Jet-induced particle resuspension



- Different behaviors for identical particles
  - Ejection by near-wall streaks
    - Type B particles: meet the right vortices, but at a wrong time
    - Jump earlier, but streaks cannot sustain continuous ejection yet






Wu et al., Particle resuspension by periodically-forced impinging jet. *Journal of Fluid Mechanics*, vol. 820 *(2017)*

# Jet-induced particle resuspension



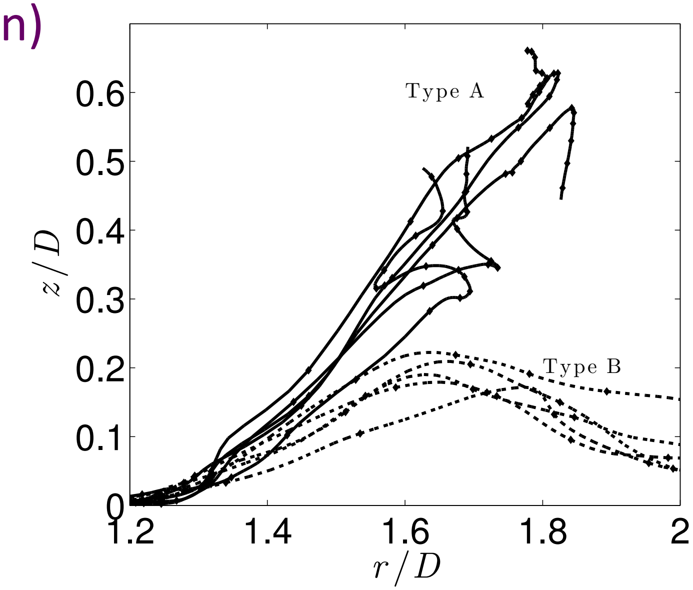
- Different behaviors for identical particles
  - **Mechanism 1**: in order to be continuously ejected in the near-wall region, a particle must
    1. meet the "right" streaks (the low-speed ones)
    2. at the "right" time (when the streaks are strong enough, namely near the separation region)



Wu et al., Particle resuspension by periodically-forced impinging jet.
*Journal of Fluid Mechanics*, vol. 820 *(2017)*

# Jet-induced particle resuspension

- Different behaviors for identical particles
  - **Mechanism 1**: in order to be continuously ejected in the near-wall region, a particle must
    1. meet the “right” streaks (the low-speed ones)
    2. at the “right” time (when the streaks are strong enough, namely near the separation region)



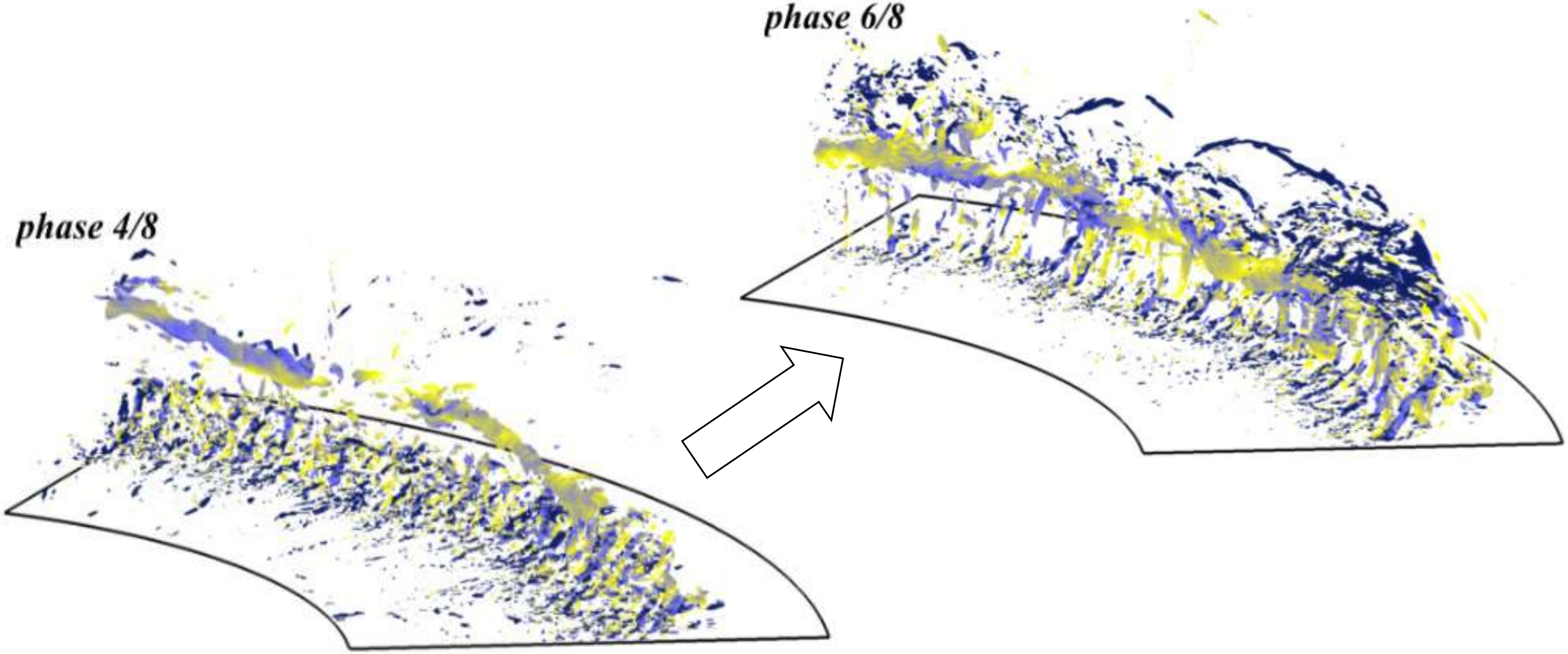

- Further question: how do particles get re-entrained far away from the wall and remain airborne?

Wu et al., Particle resuspension by periodically-forced impinging jet. *Journal of Fluid Mechanics*, vol. 820 *(2017)*

# Jet-induced particle resuspension



- Lift-off of flow CS






Wu et al., Particle resuspension by periodically-forced impinging jet.
*Journal of Fluid Mechanics*, vol. 820 *(2017)*

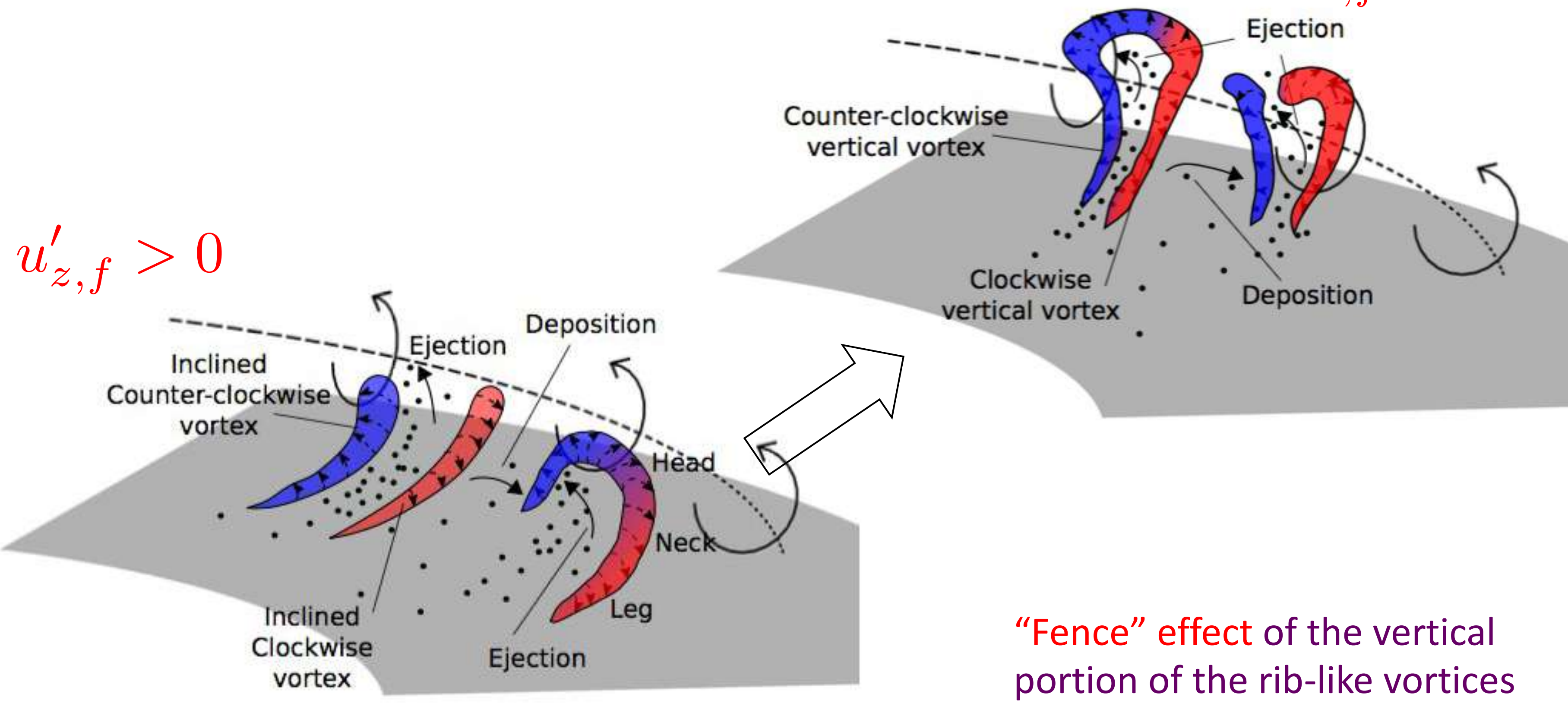
# Jet-induced particle resuspension



- Lift-off of flow CS

$u'_{r,f} < 0$

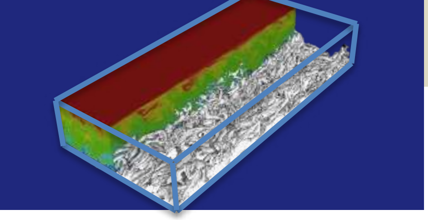
$u'_{z,f} > 0$




"Fence" effect of the vertical portion of the rib-like vortices



Wu et al., Particle resuspension by periodically-forced impinging jet. *Journal of Fluid Mechanics*, vol. 820 *(2017)*



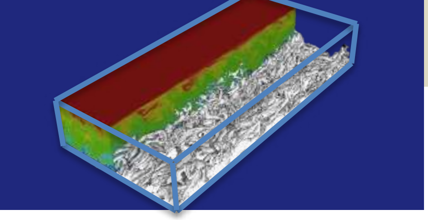


# Jet-induced particle resuspension

- Different behaviors for identical particles
  - **Mechanism 1**: in order to be continuously ejected in the near-wall region, a particle must
    1. meet the “right” streaks (the low-speed ones)
    2. at the “right” time (when the streaks are strong enough, namely near the separation region)
  - **Mechanism 2**: in order to be re-entrained far away from the wall (long-term resuspension), a particle must
    1. meet the “right” vortices (the rolled-up, rib-like vortices)
    2. at the “right” time and place (in the low-speed regions between lifted fluid streaks)



Wu et al., Particle resuspension by periodically-forced impinging jet. *Journal of Fluid Mechanics*, vol. 820 *(2017)*

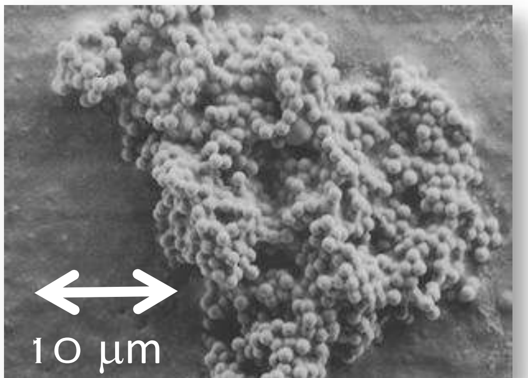






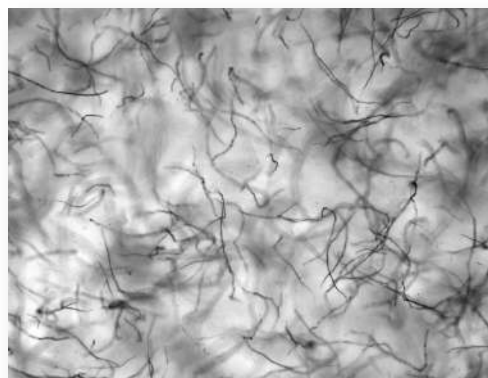
# However, most of the times inertia is not the only source of bias!

- Non-sphericity

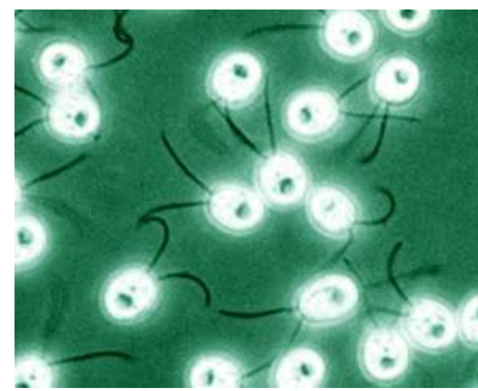


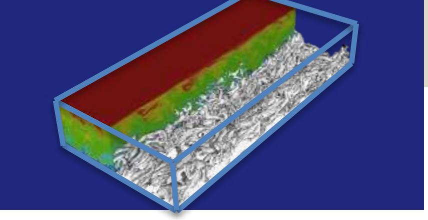

**Complexity arises from** { **Anisotropy of turbulence** + **Anisotropy of particles** }

- Flexibility



- Motility

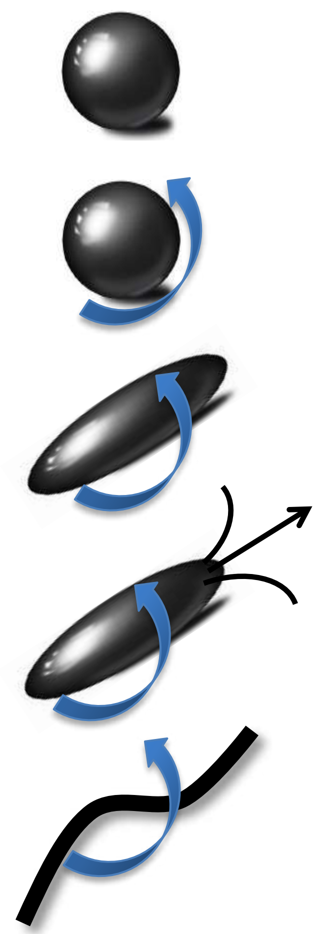






Multiphase Flow Laboratory
University of Udine

# Source of bias (in this talk):
# Non-sphericity, flexibility & motility



$\mathbf{x}(t)$, $\mathbf{v}(\mathbf{x}(t),t)$

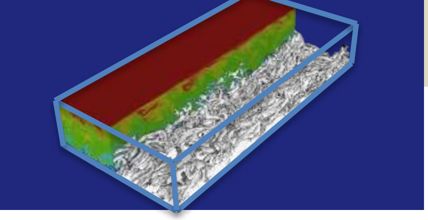
$\mathbf{x}(t)$, $\mathbf{v}(\mathbf{x}(t),t)$, $\omega(\mathbf{x}(t),t)$

$\mathbf{x}(t,\lambda)$, $\mathbf{v}(\mathbf{x}(t,\lambda),t,\lambda)$, $\omega(\mathbf{x}(t,\lambda),t,\lambda)$

$\mathbf{x}(t,\lambda)$, $\mathbf{v}(\mathbf{x}(t,\lambda),t,\lambda)$, $\omega(\mathbf{x}(t,\lambda),t,\lambda)$, $\mathbf{p}(\mathbf{x}(t,\lambda),t,\lambda)$

$\mathbf{x}(t,\lambda)$, $\mathbf{v}(\mathbf{x}(t,\lambda),t,\lambda)$, $\omega(\mathbf{x}(t,\lambda),t,\lambda)$, $\mathbf{p}(\mathbf{x}(t,\lambda),t,\lambda)$, $\psi(\mathbf{x}(t,\lambda),t,\lambda)$

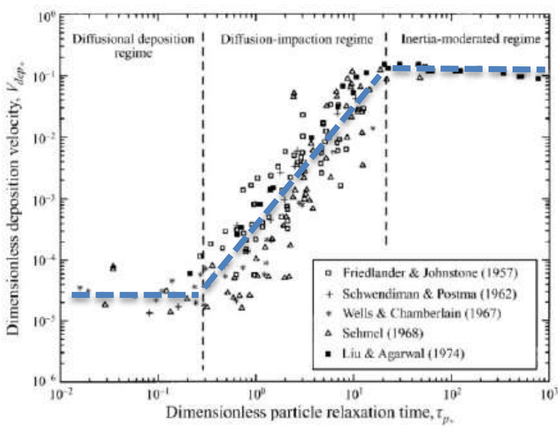
Additional particle functionalities must be modelled!



# DNS of particle-laden turbulent channel flow


**NS** $$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u}\cdot\nabla)\mathbf{u} + \frac{1}{Re_\tau}\nabla^2\mathbf{u} - \nabla p + \mathbf{F}$$

**LPT** $$\frac{d\mathbf{v}_{p_i}}{dt} = \sum F_{p_i} \;,\; \frac{d\mathbf{x}_{p_i}}{dt} = \mathbf{v}_{p_i} \;,\; i = 1, ..., N$$



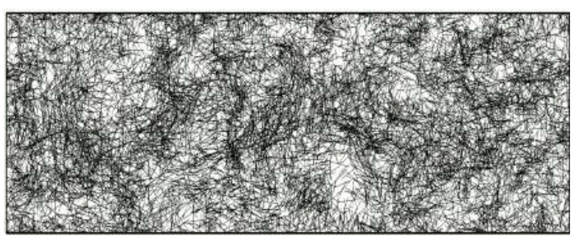

## One-way coupling DATABASE:

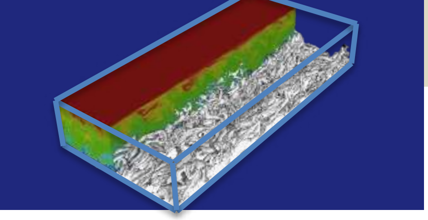
**Spherical particles**

| | |
|---|---|
| $Re_\tau$ | 150, 300 |
| St | 1, 4, 5, 20, 25, 100, 125 |

**Flexible fibers**

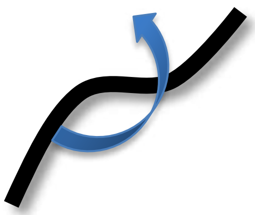
| | |
|---|---|
| $Re_\tau$ | 150, 300 |
| $St_r$ | 1, 5, 30 |
| $\lambda_r$ | 2, 5 |



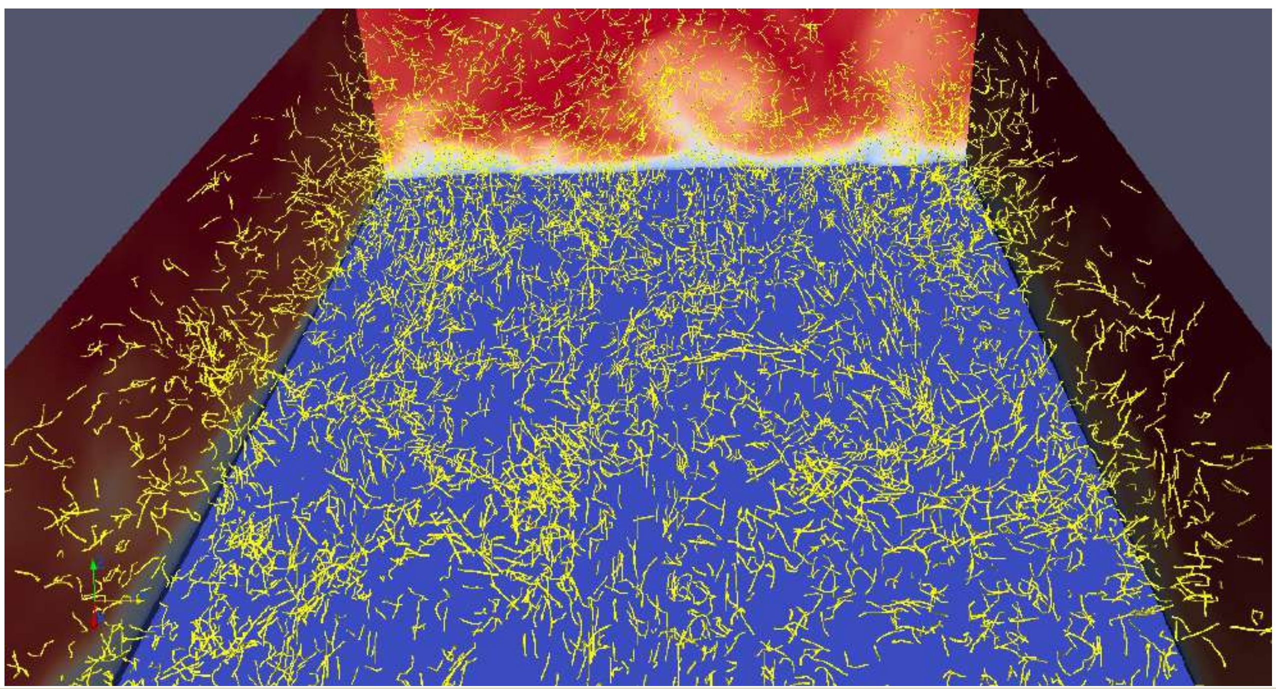




# Sources of bias:
# Non-sphericity & Flexibility

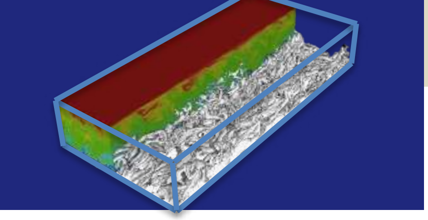


$\mathbf{x}(t,\lambda)$, $\mathbf{v}(\mathbf{x}(t,\lambda),t,\lambda)$, $\omega(\mathbf{x}(t,\lambda),t,\lambda)$, $\mathbf{p}(\mathbf{x}(t,\lambda),t,\lambda)$, $\psi(\mathbf{x}(t,\lambda),t,\lambda)$





Dotto & Marchioli, Orientation, distribution, and deformation of inertial flexible fibers in turbulent channel flow. *Acta Mechanica*, vol. 230 *(2019)*



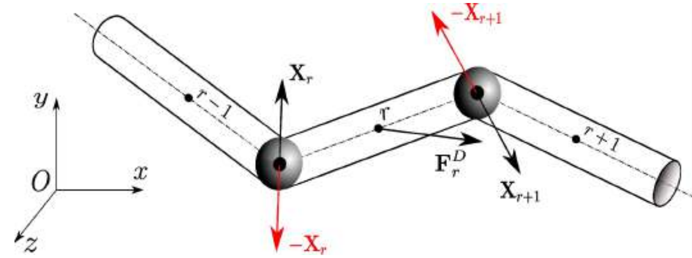




# Modelling flexibility: How to "mimic" a flexible fiber?

**Bead model**: flexible fiber = chain of segments/spheres connected by ball-and-socket joints (Delmotte et al '15; Andric et al '13; Slowicka et al '13; Derksen '10; Lindstrom & Uesaka '07)

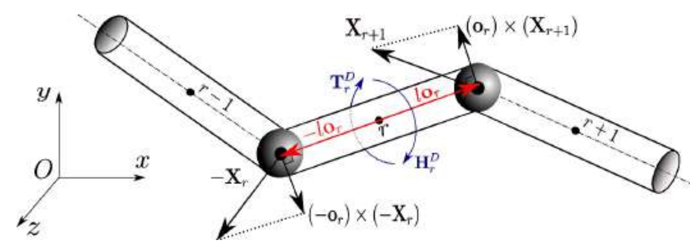
- Solve for Euler's 1st and 2nd law for each segment:




$$m_p \frac{d\mathbf{v}_r}{dt} = \mathbf{F}_r^D + (\mathbf{X}_{r+1} - \mathbf{X}_r)$$

$$\frac{d\left(\bar{\bar{\mathbf{J}}}_r \boldsymbol{\omega}_r\right)}{dt} = \mathbf{T}_r^D + \mathbf{H}_r^D + l\mathbf{o}_r \times (\mathbf{X}_{r+1} + \mathbf{X}_r)$$

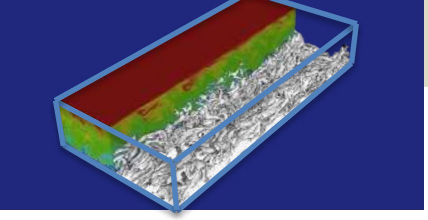
- Impose connectivity constraints between segments:




$$\begin{cases} \dfrac{\partial \boldsymbol{\Psi}_r}{\partial t} = \mathbf{v}_{r+1} - \mathbf{v}_r + \lambda a \left(\boldsymbol{\omega}_r \times \mathbf{o}_r + \boldsymbol{\omega}_{r+1} \times \mathbf{o}_{r+1}\right) = \mathbf{0} \\ \boldsymbol{\Psi}_r|_{t=0} = \mathbf{0} \qquad \boldsymbol{\Psi}_r = \mathbf{p}_r + l\mathbf{o}_r - (\mathbf{p}_{r+1} - l\mathbf{o}_{r+1}) = \mathbf{0} \end{cases}$$



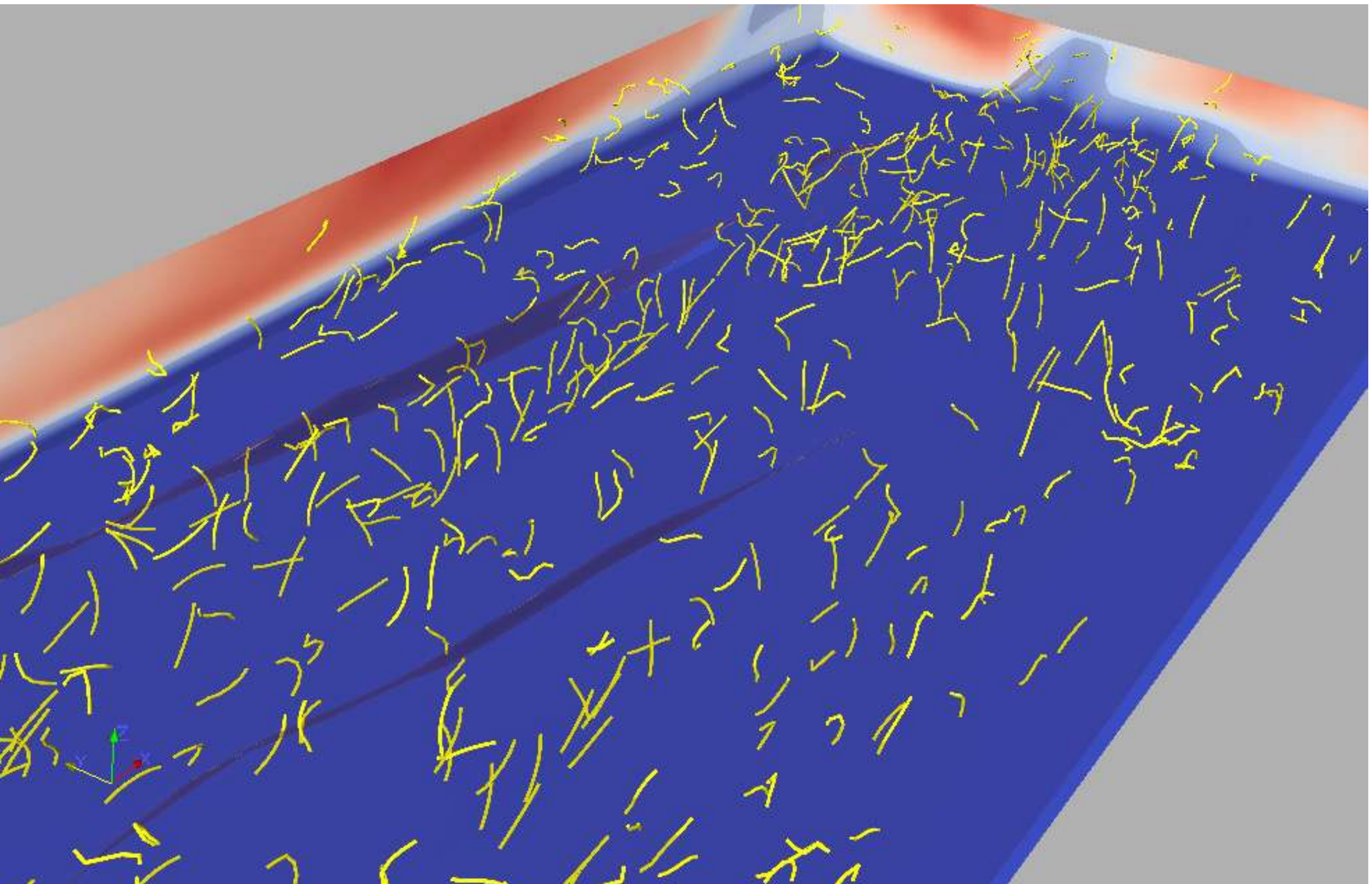
Dotto & Marchioli, Orientation, distribution, and deformation of inertial flexible fibers in turbulent channel flow. *Acta Mechanica*, vol. 230 *(2019)*





Multiphase Flow Laboratory
University of Udine

# Near-wall accumulation of flexible fibers in turbulent channel flow

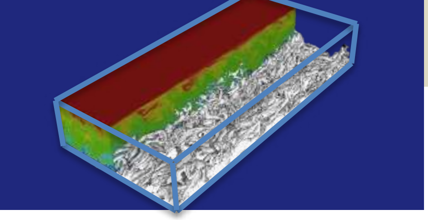


Dilute suspension of small flexible fibers in turbulent channel flow

- Shear Reynolds number: $Re_\tau$=150
- Segment Stokes number: $St_r$=5
- Segment aspect ratio: $\lambda_r$=5
- Number of segments: 7
- Number of fibers: 200,000

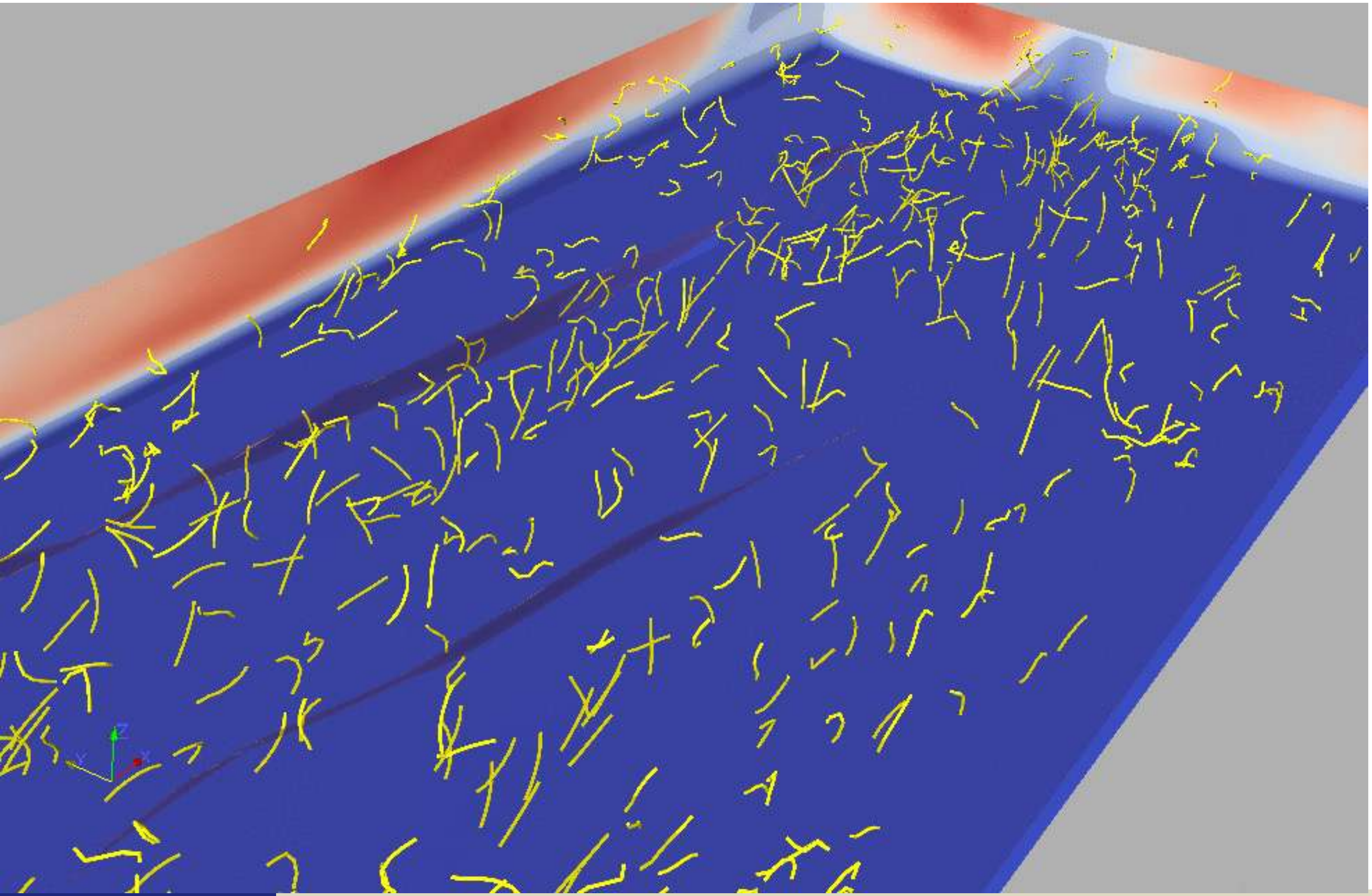


Dotto & Marchioli, Orientation, distribution, and deformation of inertial flexible fibers in turbulent channel flow. *Acta Mechanica*, vol. 230 *(2019)*



Multiphase Flow Laboratory
University of Udine

# Near-wall accumulation of flexible fibers in turbulent channel flow

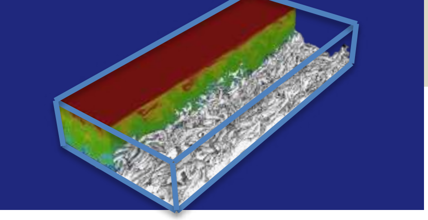


Dilute suspension of small flexible fibers in turbulent channel flow

- Shear Reynolds number: $Re_\tau$=150
- Segment Stokes number: $St_r$=5
- Segment aspect ratio: $\lambda_r$=5
- Number of segments: 7
- Number of fibers: 200,000



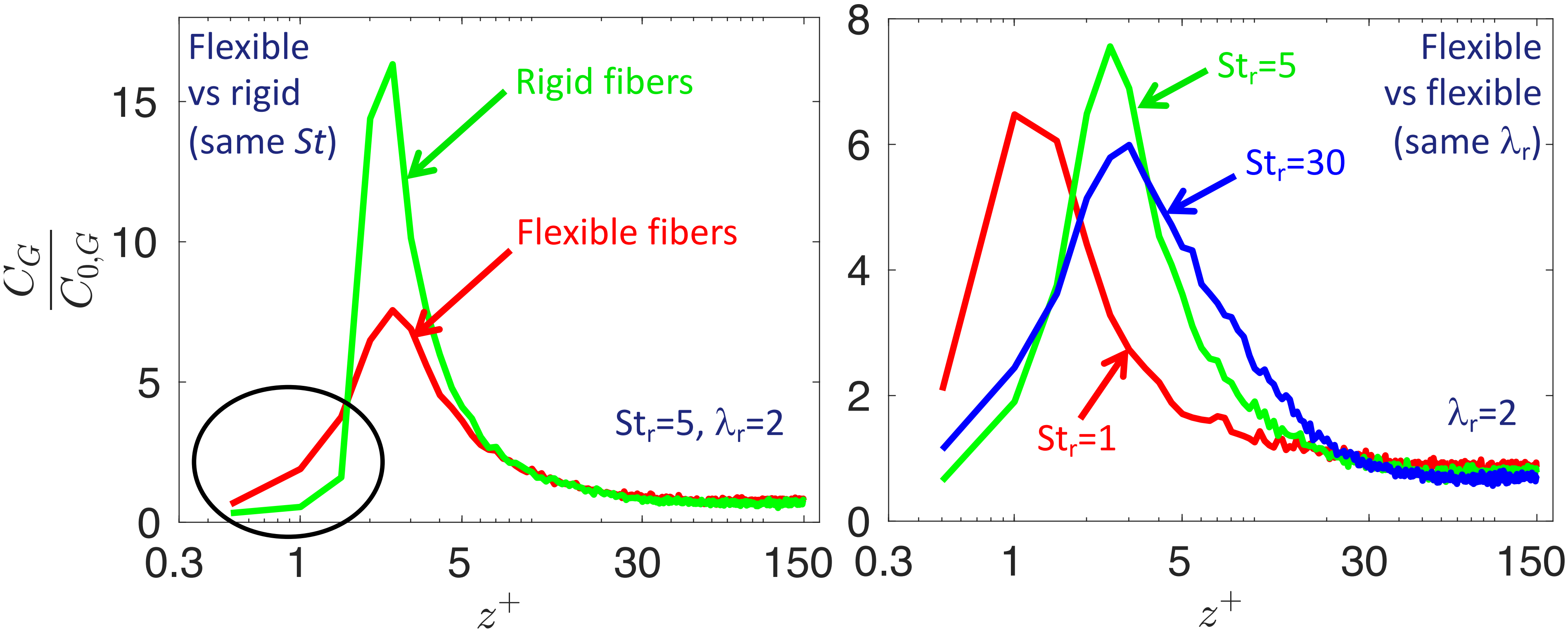
Dotto & Marchioli, Orientation, distribution, and deformation of inertial flexible fibers in turbulent channel flow. *Acta Mechanica*, vol. 230 *(2019)*





# Near-wall accumulation of flexible fibers in turbulent channel flow

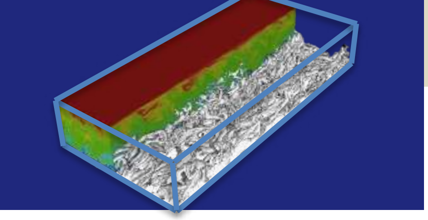
Effect of flexibility on near-wall accumulation




Normalized fiber concentration, $C/C_0$, along the wall-normal direction



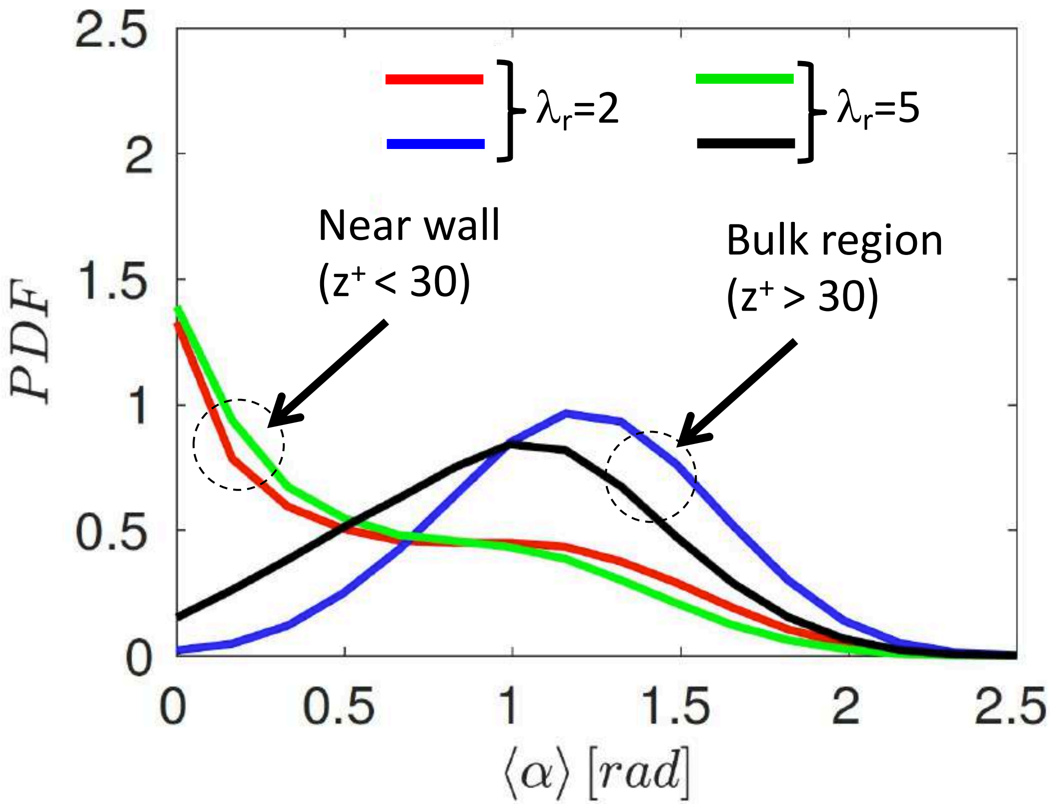
Dotto & Marchioli, Orientation, distribution, and deformation of inertial flexible fibers in turbulent channel flow. *Acta Mechanica*, vol. 230 *(2019)*



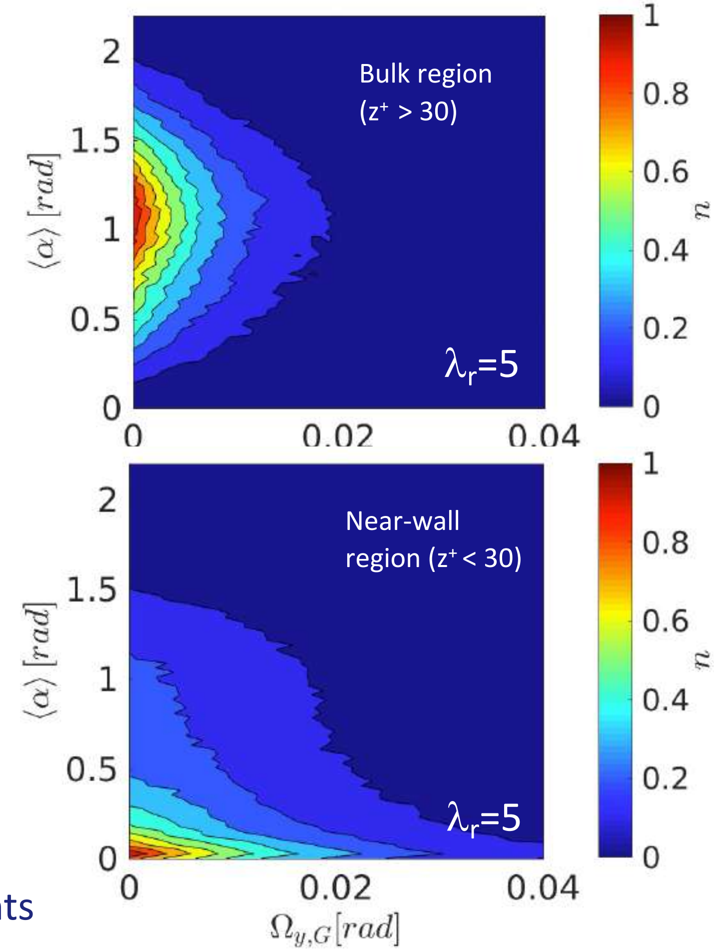


# Deformation of flexible fibers in turbulent channel flow

Effect of flexibility on bending (for $St_r$=30)

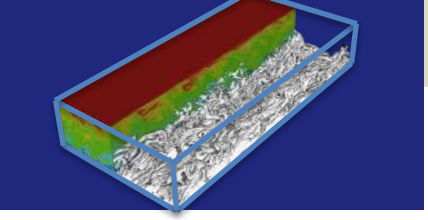



PDF of relative orientation between neighboring fiber elements





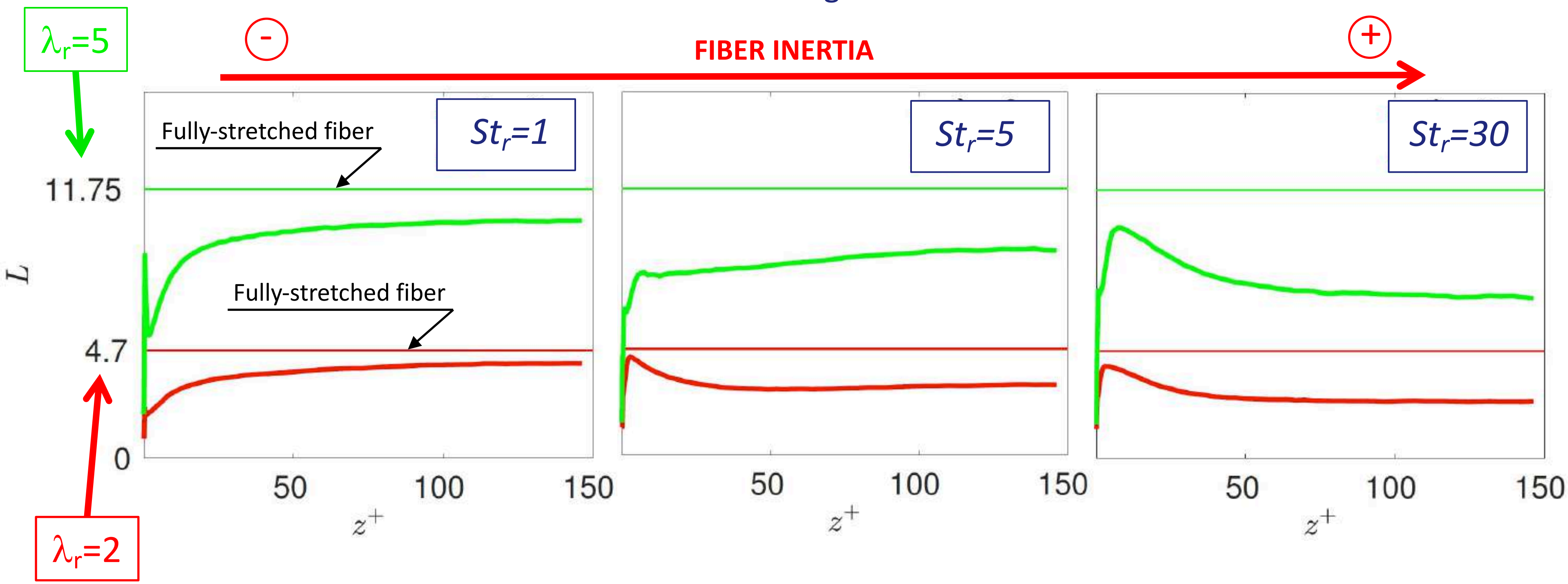

Dotto & Marchioli, Orientation, distribution, and deformation of inertial flexible fibers in turbulent channel flow. *Acta Mechanica*, vol. 230 *(2019)*





# Deformation of flexible fibers in turbulent channel flow

Fiber "end-to-end" distance along the wall-normal direction




Fiber bending dynamics change with fiber inertia:

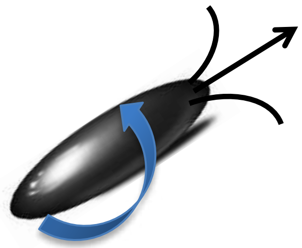
Flexible fibers with low inertia are more stretched by turbulence in the bulk flow region (higher bending near the wall)

Flexible fiber with large inertia inertia are more stretched by turbulence in the near-wall region

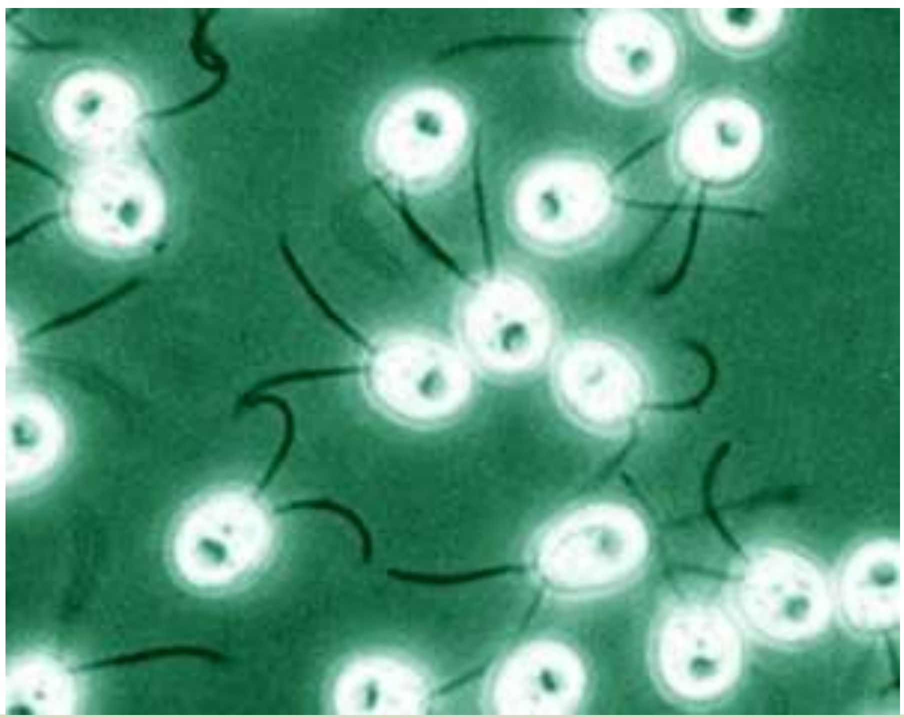


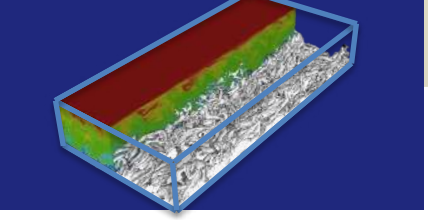
Dotto & Marchioli, Orientation, distribution, and deformation of inertial flexible fibers in turbulent channel flow. *Acta Mechanica*, vol. 230 *(2019)*

# Source of bias: Motility



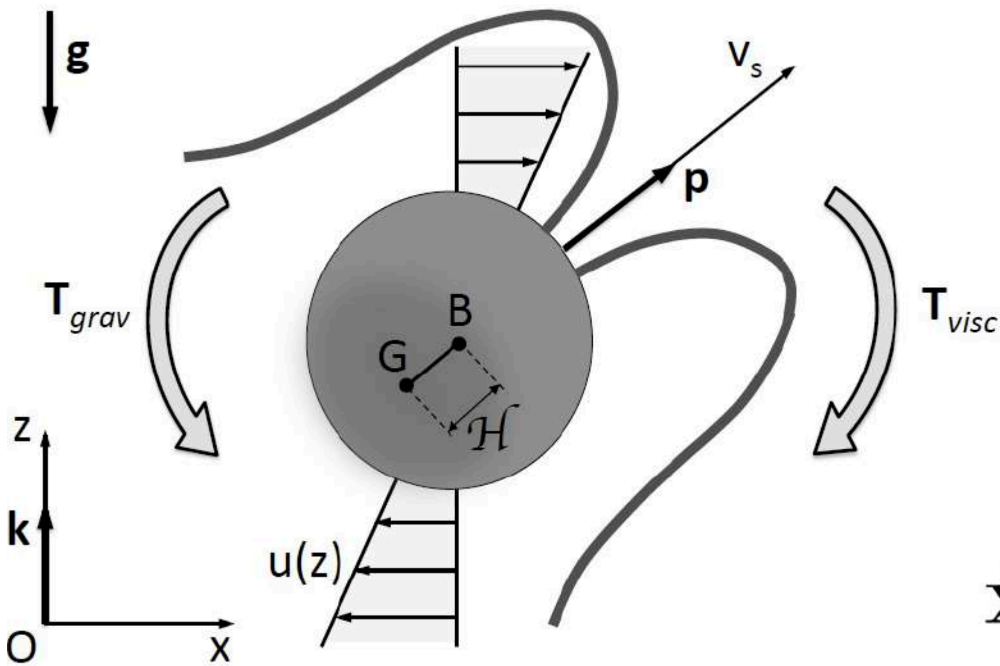
$\mathbf{x}(t,\lambda)$, $\mathbf{v}(\mathbf{x}(t,\lambda),t,\lambda)$, $\boldsymbol{\omega}(\mathbf{x}(t,\lambda),t,\lambda)$, $\mathbf{p}(\mathbf{x}(t,\lambda),t,\lambda)$







# Effect of particle motility on preferential concentration




Swimming provides a way for micro-organisms to escape fluid streamlines (Kessler, *Hydrodynamic focusing of motile algal cells*, Nature, 1985)

**Gyrotaxis**: any directed locomotion resulting from the combination of gravitational and viscous torques in a flow

Assumptions :

- dilute suspension of neutrally-buoyant micro-organisms
- Sub-Kolmogorov size
- Negligible inertia
- Swimming at constant $\mathbf{v}_s$ aligned with **p**

$$\dot{\mathbf{X}} = \mathbf{u}(\mathbf{X}, t) + v_s \mathbf{p}$$

$$\dot{\mathbf{p}} = \underbrace{\frac{1}{2B}[\mathbf{k} - (\mathbf{k}\cdot\mathbf{p})\mathbf{p}]}_{\text{Re-orientation term due to gravitational torque}} + \underbrace{\frac{1}{2}\omega \times \mathbf{p}}_{\text{Vorticity term}}$$

Re-orentation term due to gravitational torque

Vorticity term

# Effect of particle motility on preferential concentration

Two controlling parameters:

$$V_s \simeq 10 - 1000 \mu m/s \longrightarrow \boxed{\Phi = v_s/u_\tau}$$ Swimming number

$$B \simeq 0.1 - 10 s \longrightarrow \boxed{\Psi = \frac{1}{2B}\frac{\nu}{u_\tau^2}}$$ Stability number

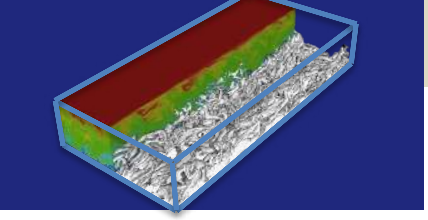
Values considered in our study:

$\Phi = 0.048$ — Dimensionless swimming speed

$\Psi_L = 0.0113$ — Low gravitaxis (slow re-orientation) ▶ $\Psi_L \cdot \tau^+_{K,max} \sim \mathcal{O}(10^{-1})$

$\Psi_I = 0.113$ — Intermediate gravitaxis ▶ $\Psi_I \cdot \tau^+_{K,max} \sim \mathcal{O}(1)$

$\Psi_H = 1.13$ — High gravitaxis (fast re-orientation) ▶ $\Psi_H \cdot \tau^+_{K,max} \sim \mathcal{O}(10)$



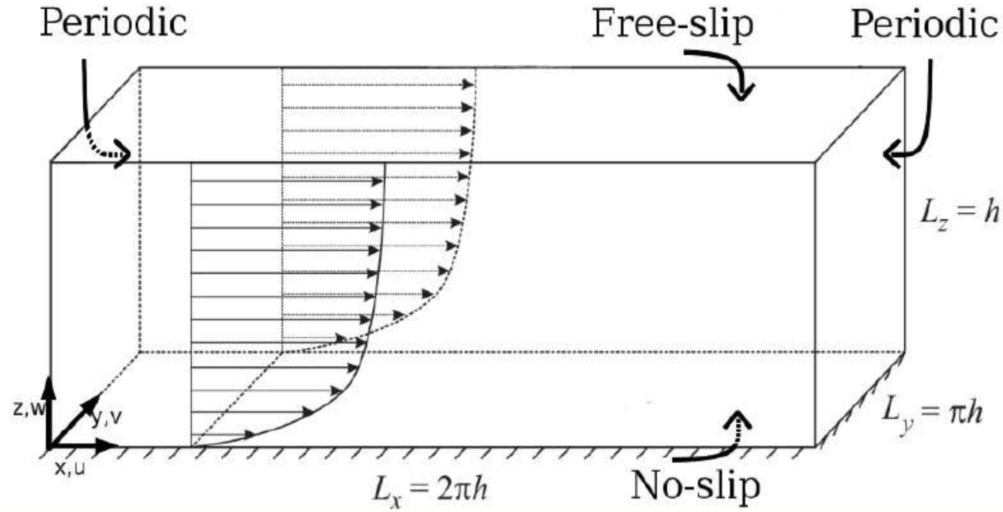


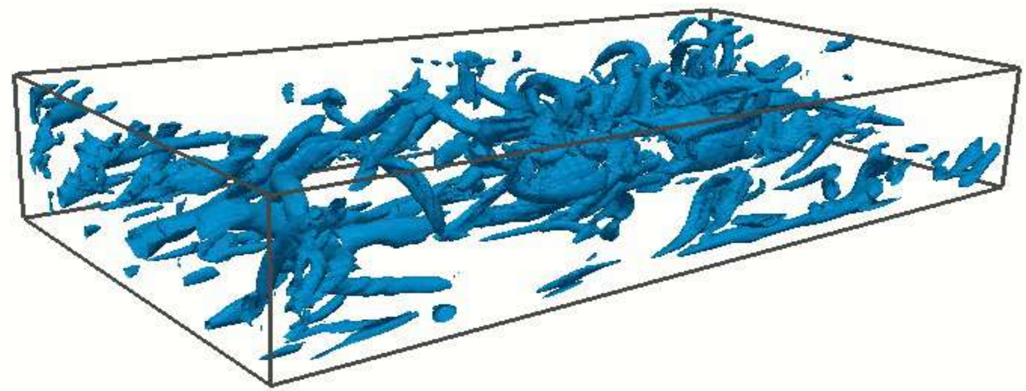
# Physical problem and flow configuration

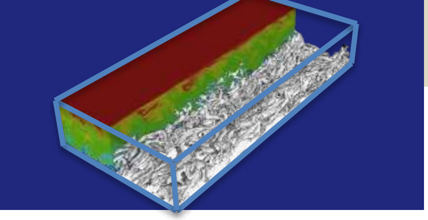
**Flow solver:**

- $$\frac{\partial u_i}{\partial x_i} = 0$$
- $$\rho\left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}\right) = -\frac{\partial P}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_j^2}$$

- 3D time-dependent turbulent water flow
- Shear Reynolds number:
  **$Re_{\tau}$= 171, 510, 1020**
- Channel size:
  **$L_x \times L_y \times L_z = 2\pi h \times \pi h \times h$**
- Pseudo-spectral DNS
- Time integration:
  Adams-Bashforth (convective terms)
  Crank-Nicolson (viscous terms)







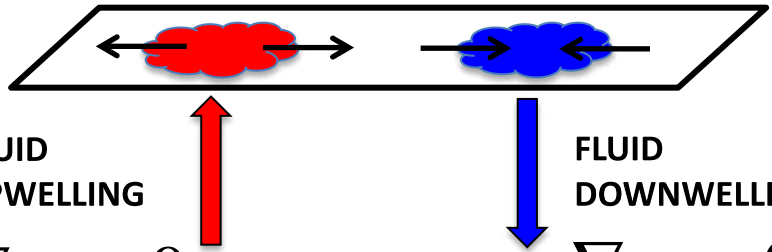


# Flow topology at the free surface

**Surface divergence**

$$\nabla_{2D} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = -\frac{\partial w}{\partial z}$$

**SOURCE** **SINK**



**FLUID UPWELLING**

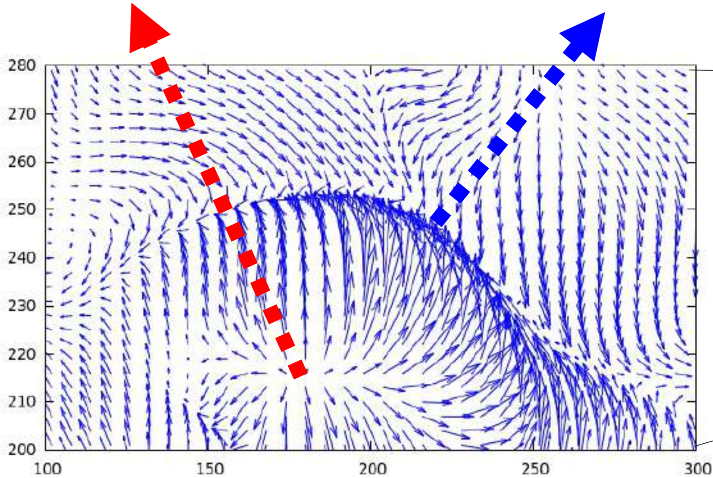
$$\nabla_{2D} > 0$$

**FLUID DOWNWELLING**

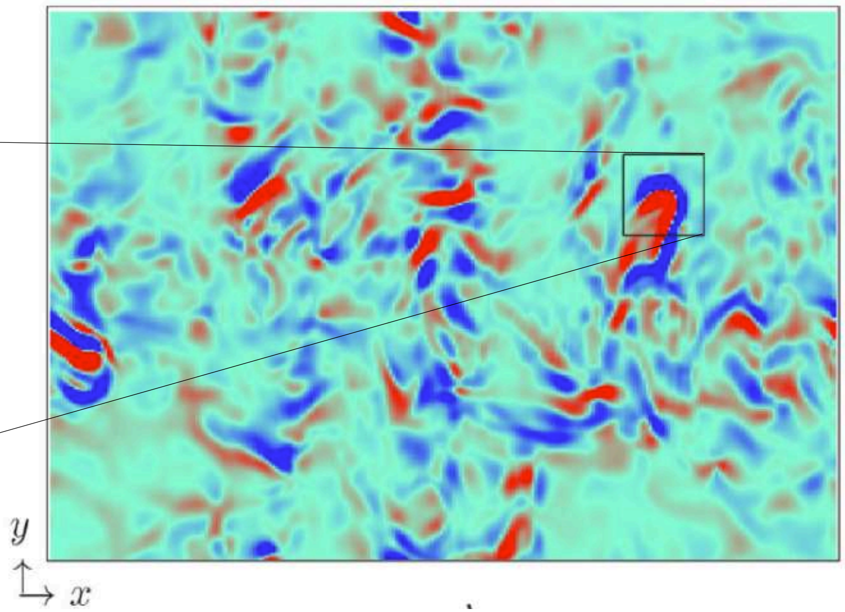
$$\nabla_{2D} < 0$$

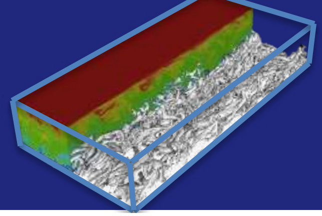
**Velocity source**

**Velocity sink**



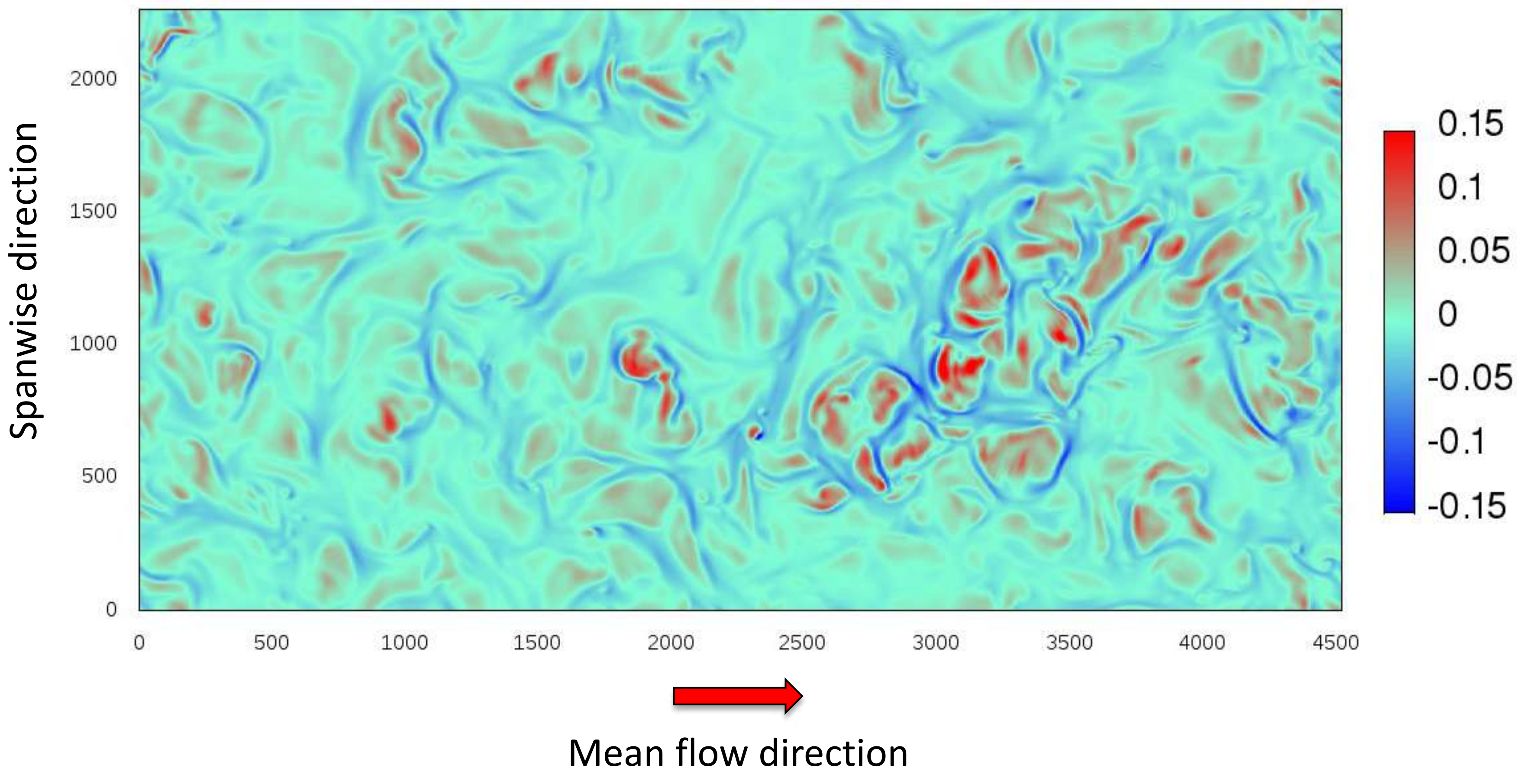

$\nabla_{2D}$

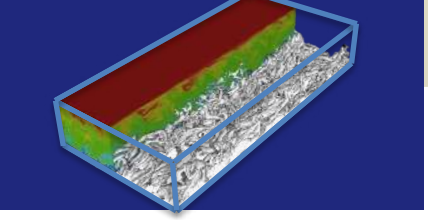




# Swimmer clustering at the free surface

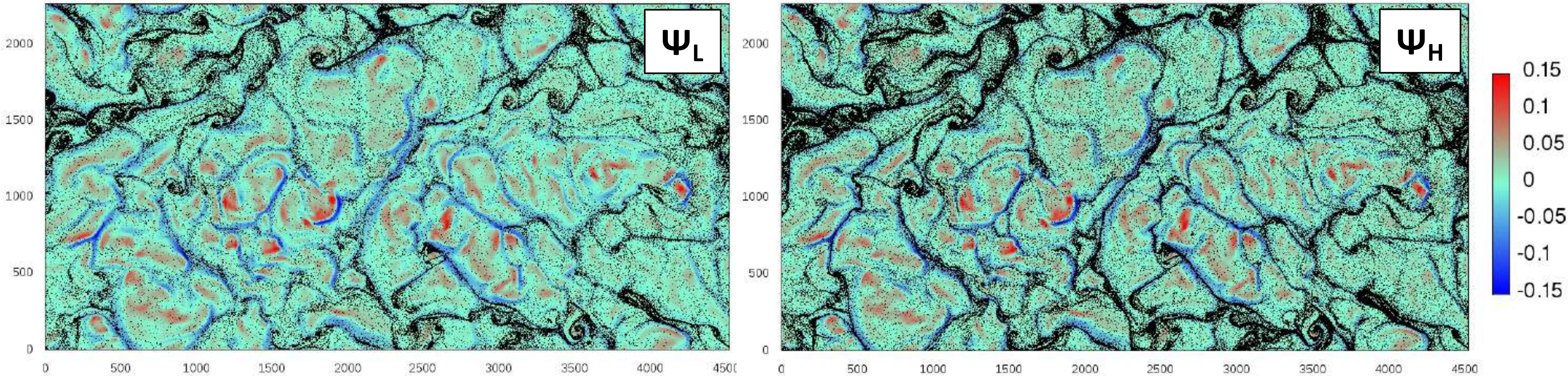
Top view of swimmers' surfacing





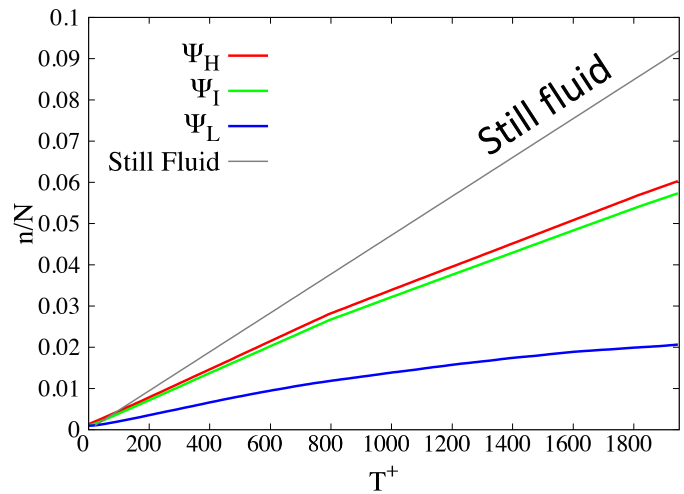


# Swimmer clustering at the free surface




Slow to re-orient

Fast to re-orient




$\Psi_H$ Fast

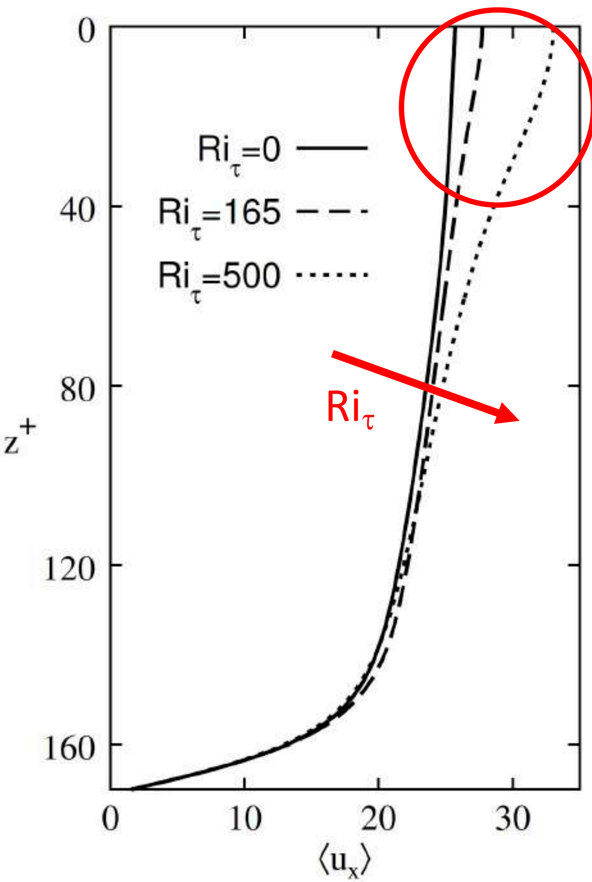
$\Psi_L$ Slow

Swimmers that have reached the surface: 600k

# Swimmer dynamics in thermally-stratified turbulence

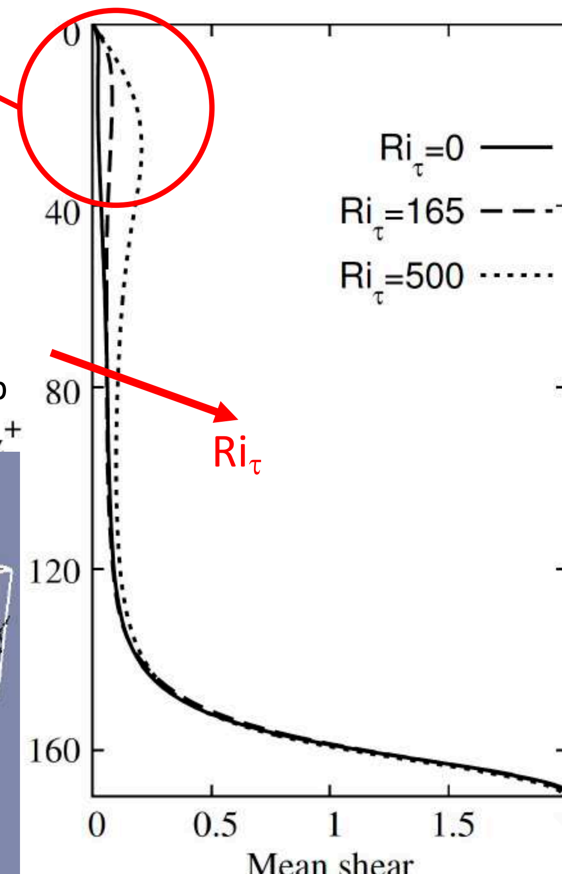
**Lovecchio et al Adv. Wat. Res (2014)**

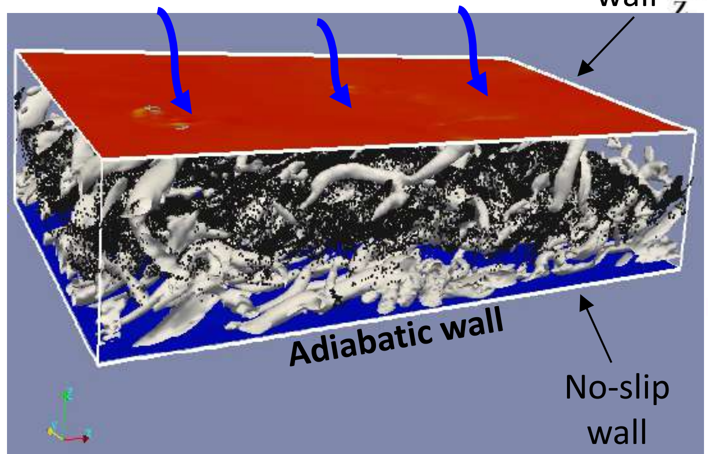
Mean streamwise velocity




"Thermocline": potential barrier due to density distribution

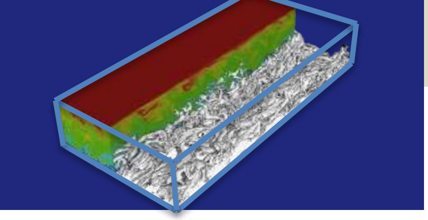
Mean shear





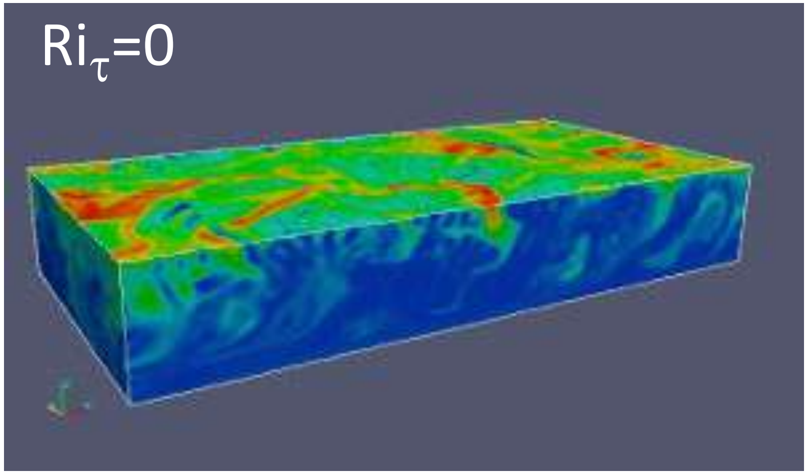

Lovecchio et al., Thermal stratification hinders gyrotactic micro-organism rising in free-surface turbulence. *Phys. Fluids*, vol. 29 *(2017)*

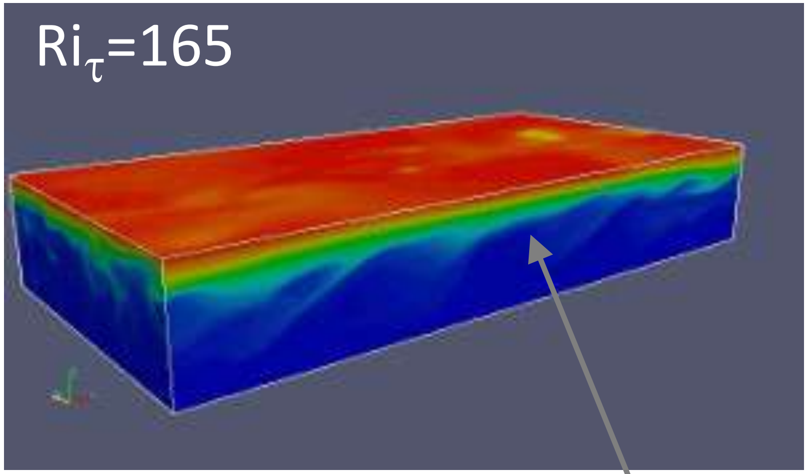




# Stably-stratified turbulent channel

## Temperature field



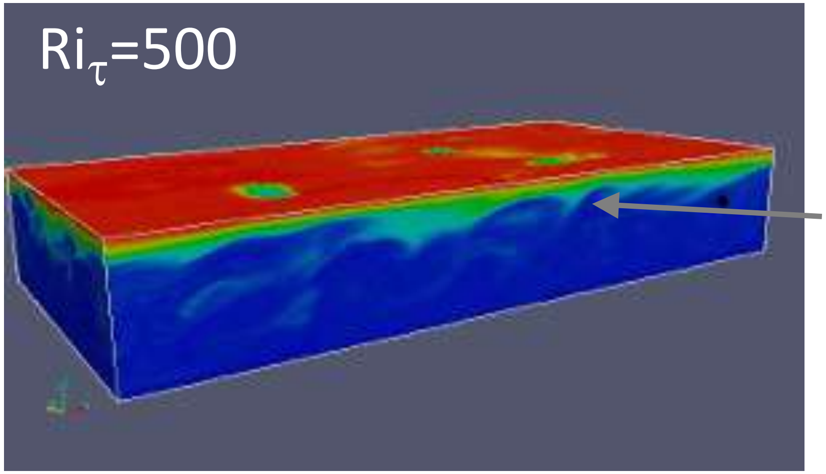

$$\nabla \cdot \mathbf{u} = 0 \,,$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = \frac{1}{Re_\tau} \nabla^2 \mathbf{u} - \nabla p + \frac{Gr}{Re_\tau^2} \theta \boldsymbol{\delta}_g + \boldsymbol{\delta}_p,$$

$$\frac{\partial \theta}{\partial t} + \mathbf{u} \cdot \nabla \theta = \frac{1}{Re_\tau Pr} \nabla^2 \theta - \beta_T,$$

$$Ri = \frac{Gr}{Re_\tau^2}$$

$$Gr = \frac{g \beta \frac{\partial T}{\partial z}|_{sup} (2h)^3 h}{\nu^2}$$

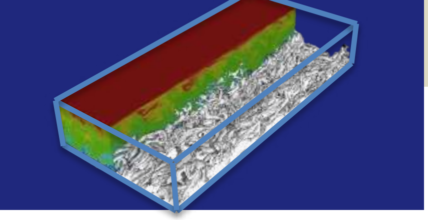



Thermocline (barrier)

All sim. @ Re=171 & Pr=5



Lovecchio et al., Thermal stratification hinders gyrotactic micro-organism rising in free-surface turbulence. *Phys. Fluids*, vol. 29 *(2017)*

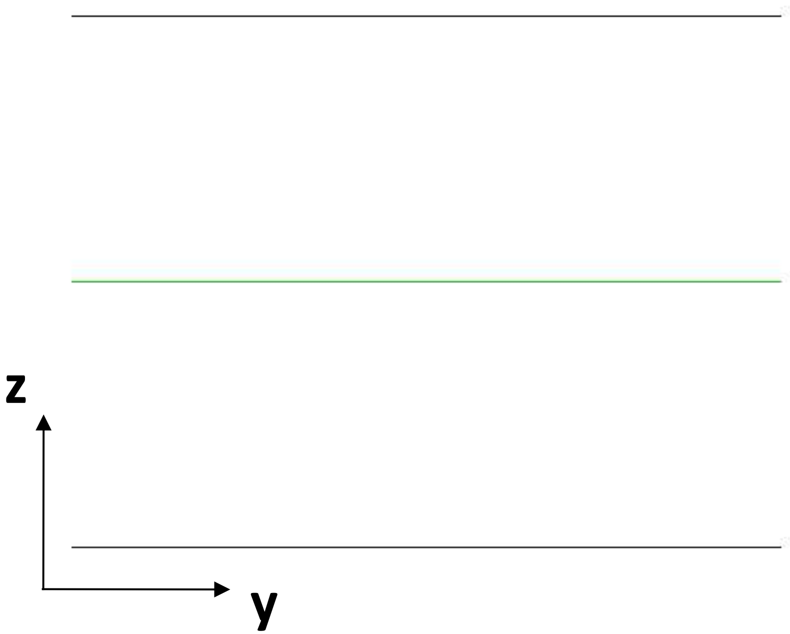


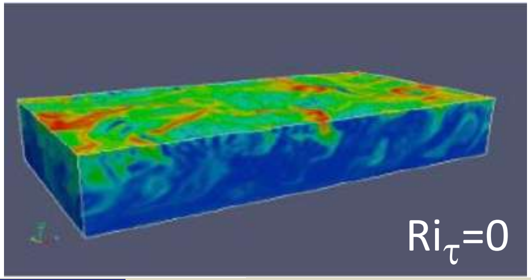


# Vertical motion of swimmers with low stability number

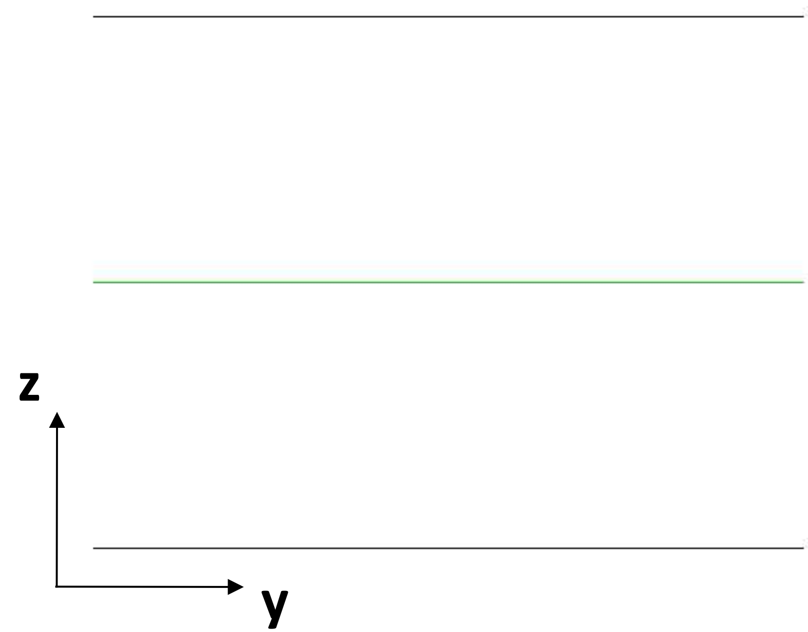
## (Slow to realign against gravity)

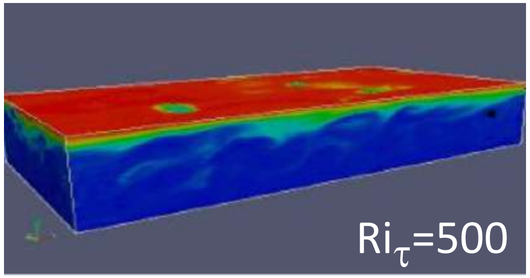
**UNSTRATIFIED FLOW**



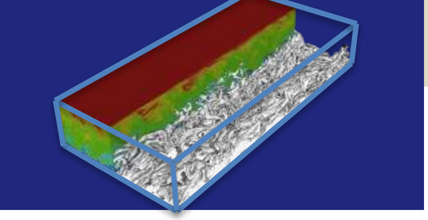

**STRATIFIED FLOW**






Lovecchio et al., Thermal stratification hinders gyrotactic micro-organism rising in free-surface turbulence. *Phys. Fluids*, vol. 29 *(2017)*

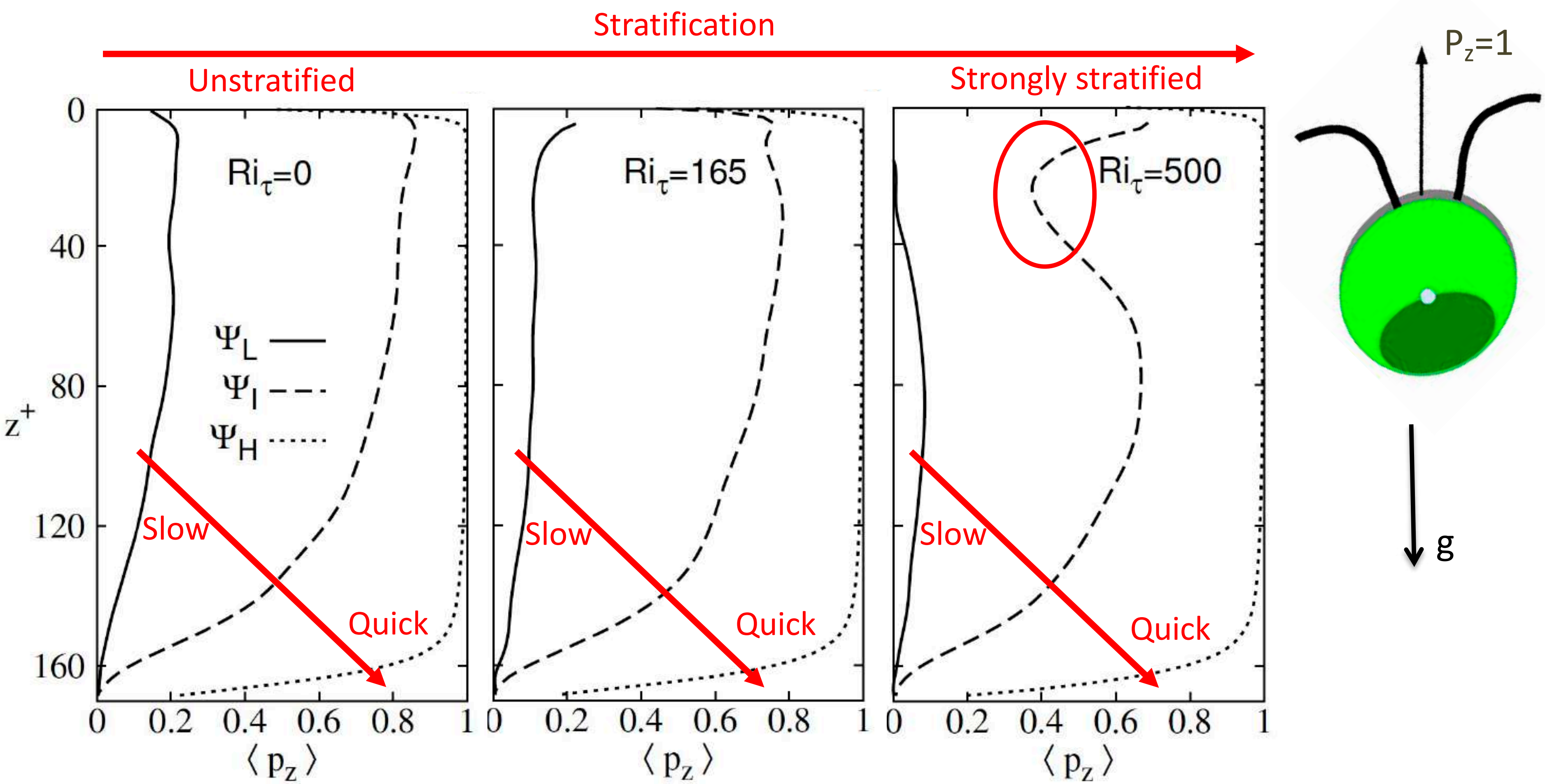






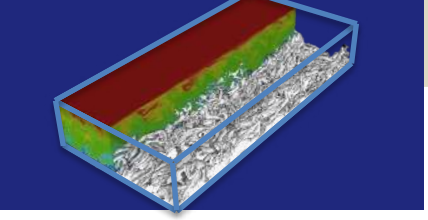
# Swimmers' preferential orientation

## Mean orientation in vertical direction ($p_z$)



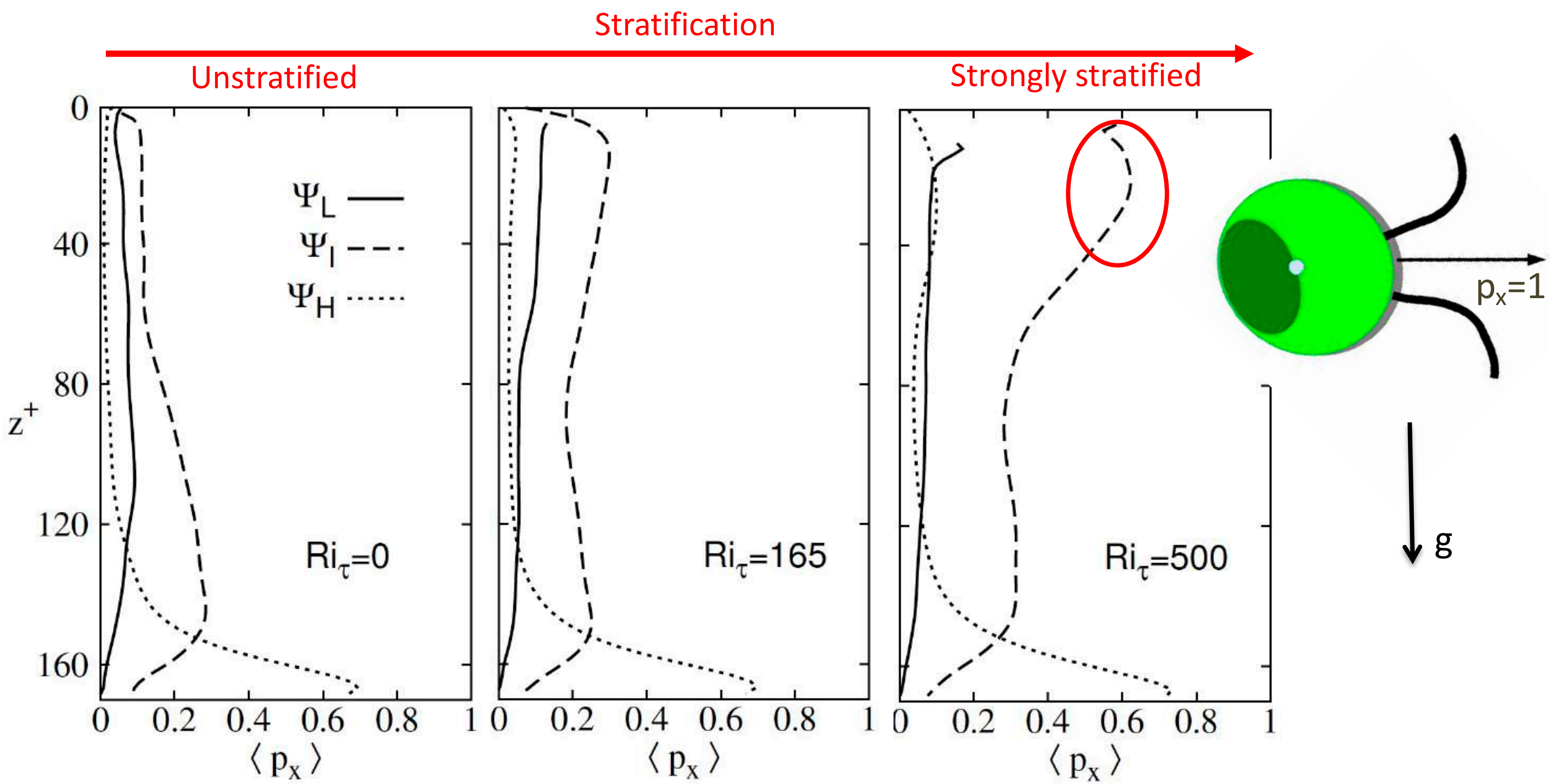



Lovecchio et al., Thermal stratification hinders gyrotactic micro-organism rising in free-surface turbulence. *Phys. Fluids*, vol. 29 *(2017)*



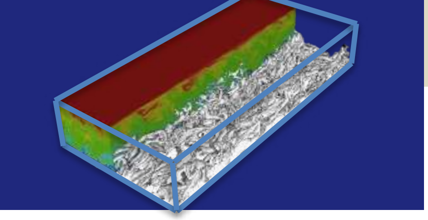
# Swimmers' preferential orientation

## Mean orientation in horizontal direction ($p_x$)





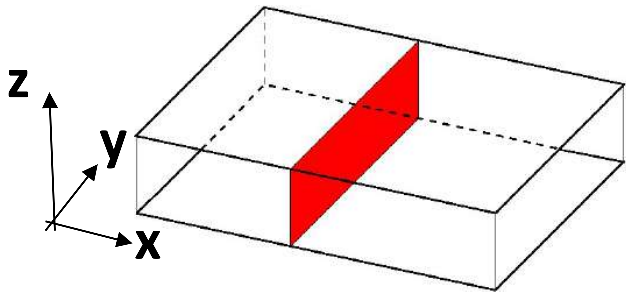

Lovecchio et al., Thermal stratification hinders gyrotactic micro-organism rising in free-surface turbulence. *Phys. Fluids*, vol. 29 *(2017)*

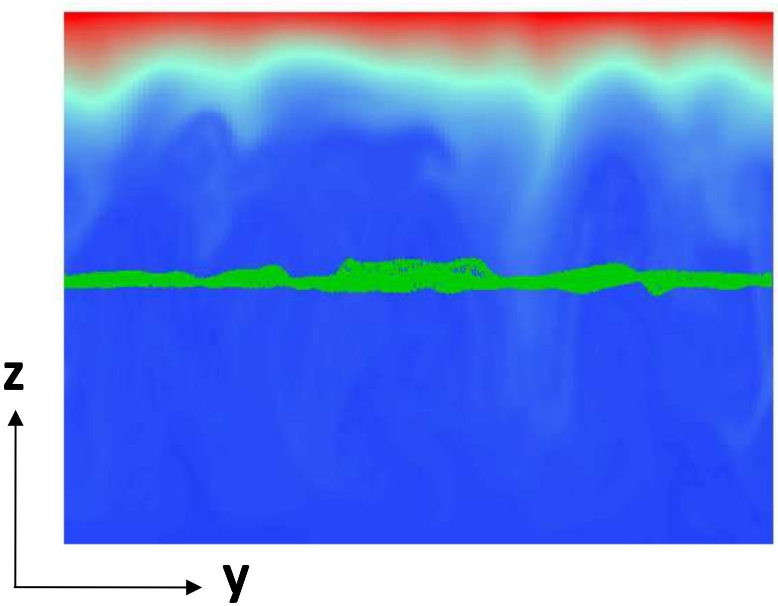


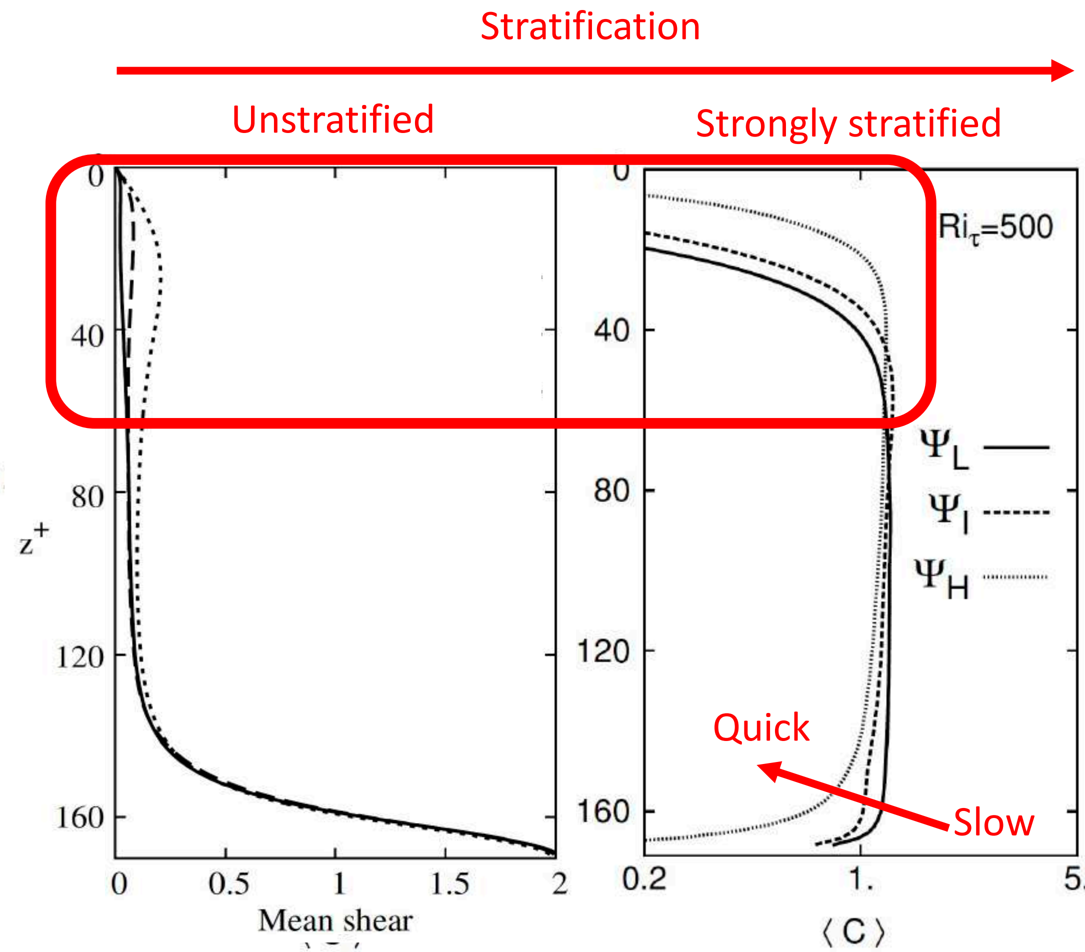


# Swimmers' preferential concentration

## Number density in the vertical direction

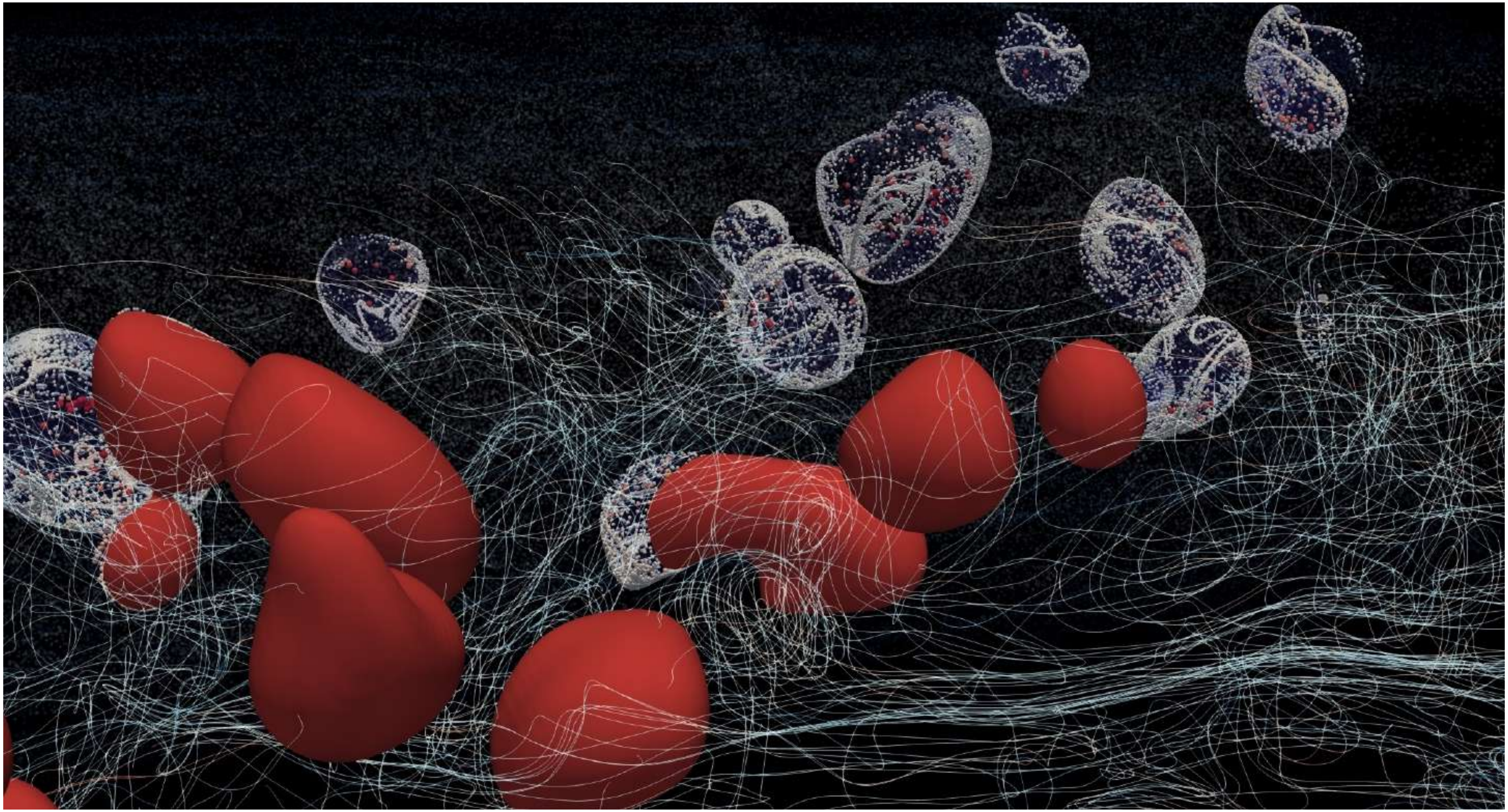


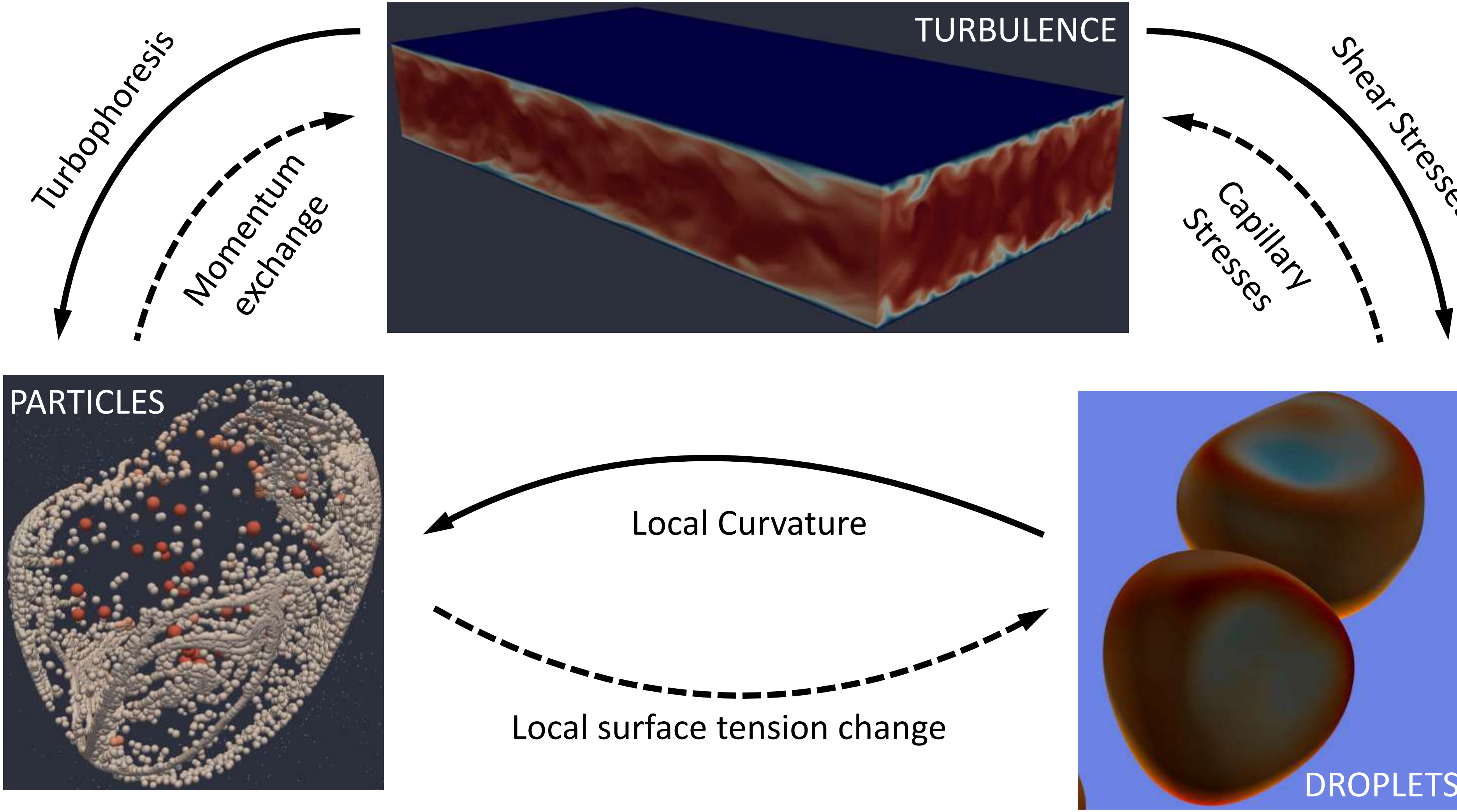



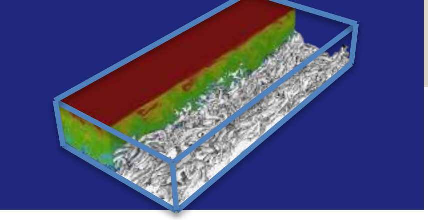

Lovecchio et al., Thermal stratification hinders gyrotactic micro-organism rising in free-surface turbulence. *Phys. Fluids*, vol. 29 *(2017)*

# Source of bias: Fluid interface



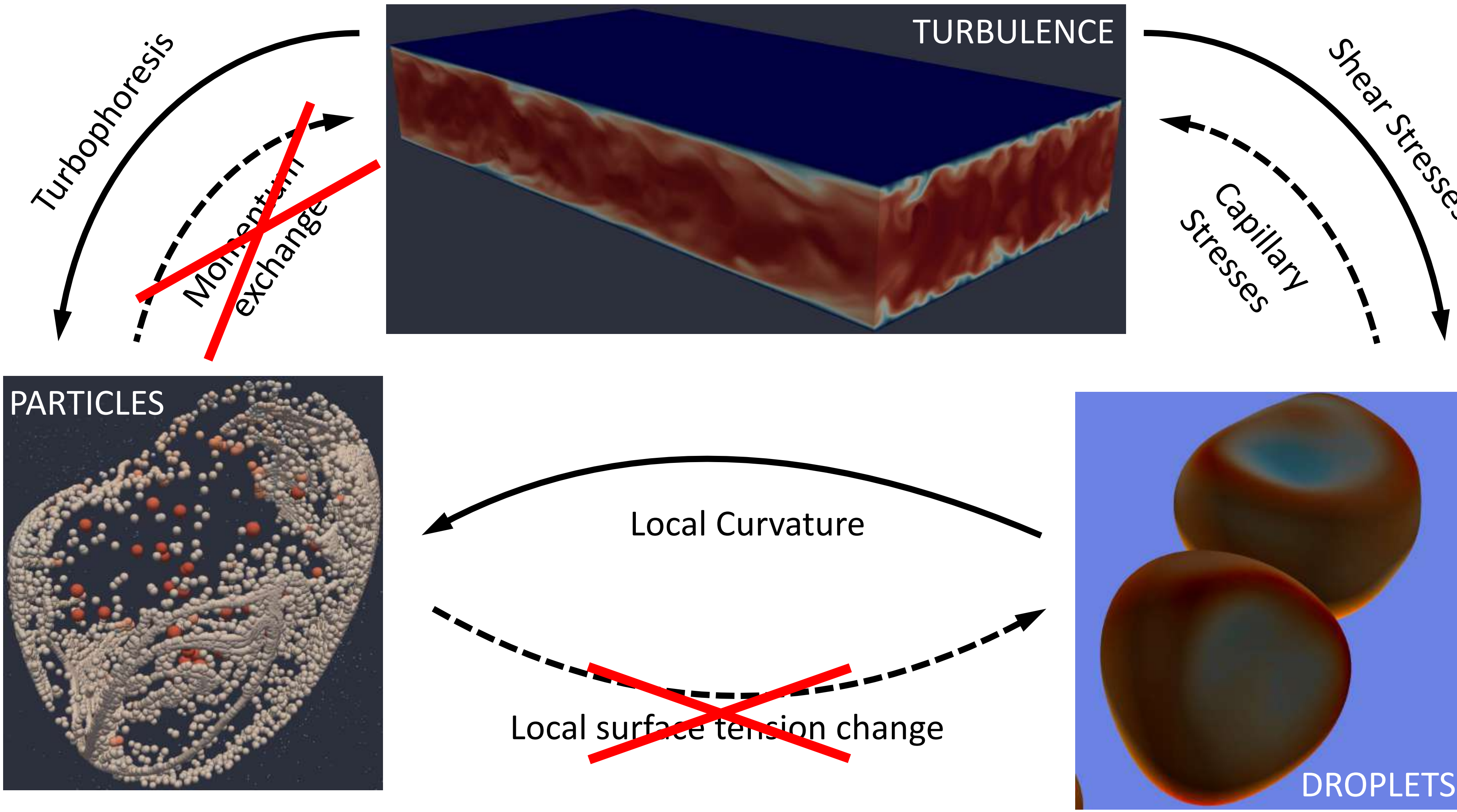
# Three-phase laden flow







# Three-phase laden flow



# Methodology



## Continuity and Navier-Stokes equation:

$$\nabla \, . \, u = 0$$

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = -\nabla p + \frac{1}{Re_\tau}\nabla^2 u + \overbrace{\frac{Ch}{We}\frac{3}{\sqrt{8}}\nabla \cdot \tau_c}^{\text{Surface Tension Force}}$$

**Assumptions**:

Matched Density

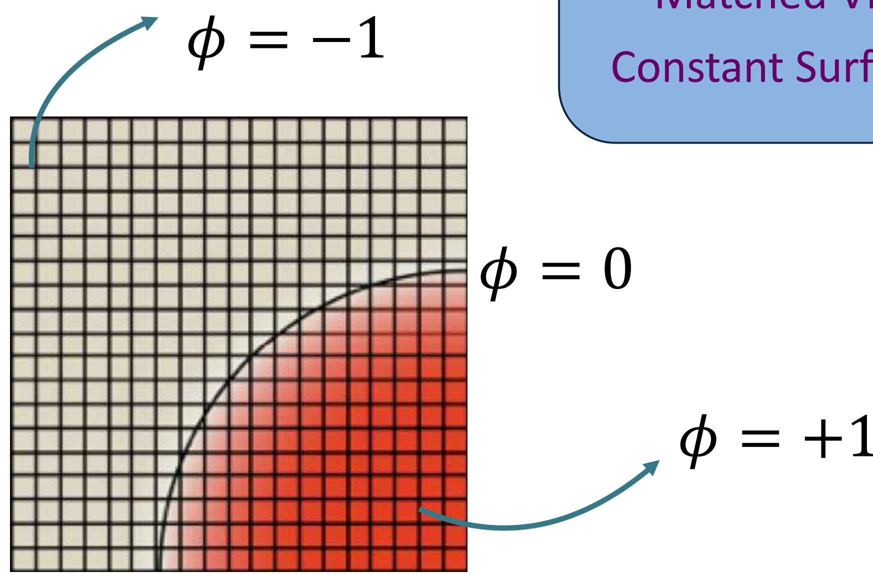
Matched Viscosity

Constant Surface Tension

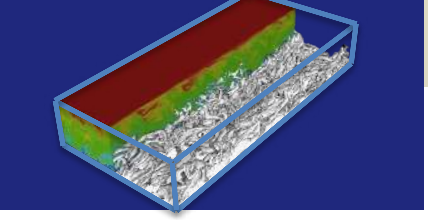
## Cahn-Hilliard Equation:

$$\frac{\partial \phi}{\partial t} + u \, . \, \nabla \phi = \frac{1}{Pe}\nabla^2 \mu$$

$$\mu = \phi^3 - \phi - Ch^2 \nabla^2 \phi$$




Hajisharifi, et al., Particle capture by drops in turbulent flow.
*Physical Review Fluids*, *6.2 (2021)*





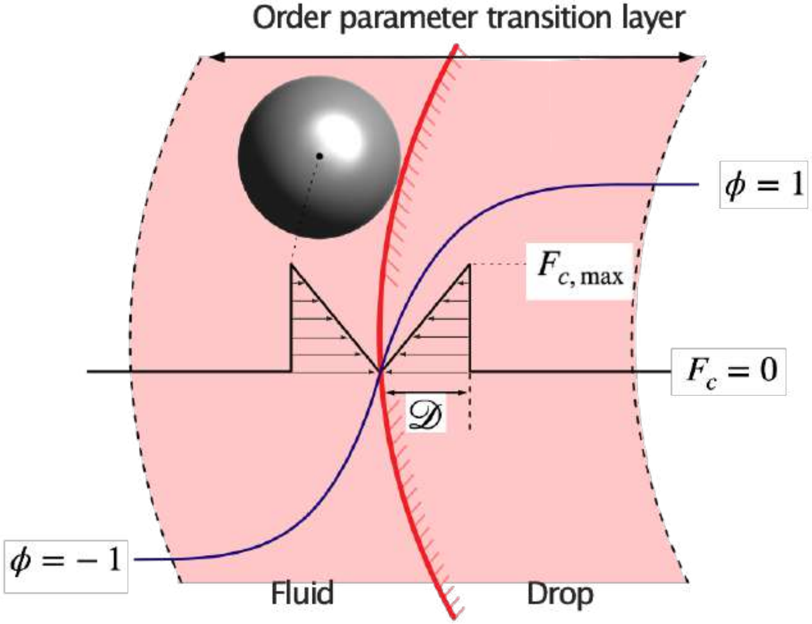
# Methodology



## Lagrangian Equation of Motion:

$$\frac{\partial x_p}{dt} = u_p$$

$$\frac{\partial u_p}{\partial t} = \underbrace{\frac{u - u_p}{St} f_D}_{\text{Drag Force}} + \underbrace{\frac{6A}{\frac{\rho_p}{\rho_f}} \frac{Re}{We} \frac{d^+}{dp^{+3}}}_{\text{Capillary force}}$$



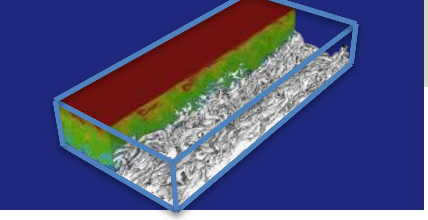

See: Ettelaie & Lishchuk, Soft Matter, 2015
Gu & Botto, Soft Matter, 2016

- *St* : Particle inertia
- *d*$^+$ : Min distance from particle center to interface
- $d_p^+$ : Particle diameter

$$d^+ = \frac{\sqrt{2}}{2}\, Ch\ ln\left(\frac{1 + \phi_{pp}}{1 - \phi_{pp}}\right)$$



Hajisharifi, et al., Particle capture by drops in turbulent flow. *Physical Review Fluids*, *6.2 (2021)*





# Simulation parameters

- **Flow Field:**

No-slip at the walls

$$u(x, y, \pm 1) = 0$$

**Boundary conditions**

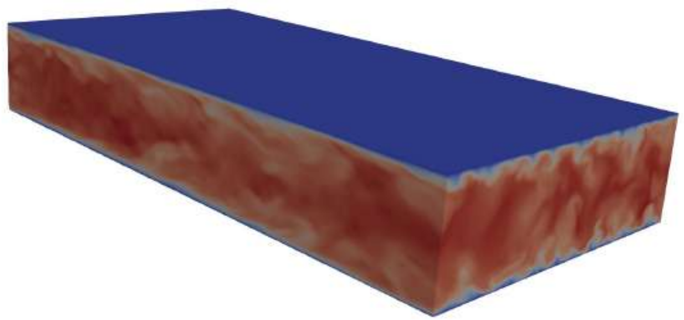
Periodicity along x and y

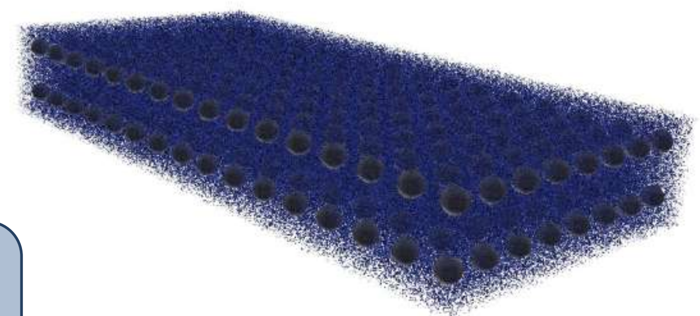
$$u(0,y,z) = u(L_x, y, z)$$

$$u(x,0,z) = u(x, L_y, z)$$

**Initial Condition**

Fully developed turbulence





- **Phase field:**

$$\frac{\partial \phi}{\partial z}(x, y, \pm 1) = 0$$

$$\frac{\partial^3 \phi}{\partial z^3}(x, y, \pm 1) = 0$$

Periodicity along x and y

$$\phi(0,y,z) = \phi(L_x, y, z)$$

$$\phi(x,0,z) = \phi(x, L_y, z)$$

- **Simulation Parameters:**

Grid points = 512 x 256 x 257

Size = $4\pi$h x $2\pi$h x 2h

$Re_\tau$ = ***150***

*We* = ***0.75***, *1.5*

*St* = ***0.1***, *…*, *0.8*

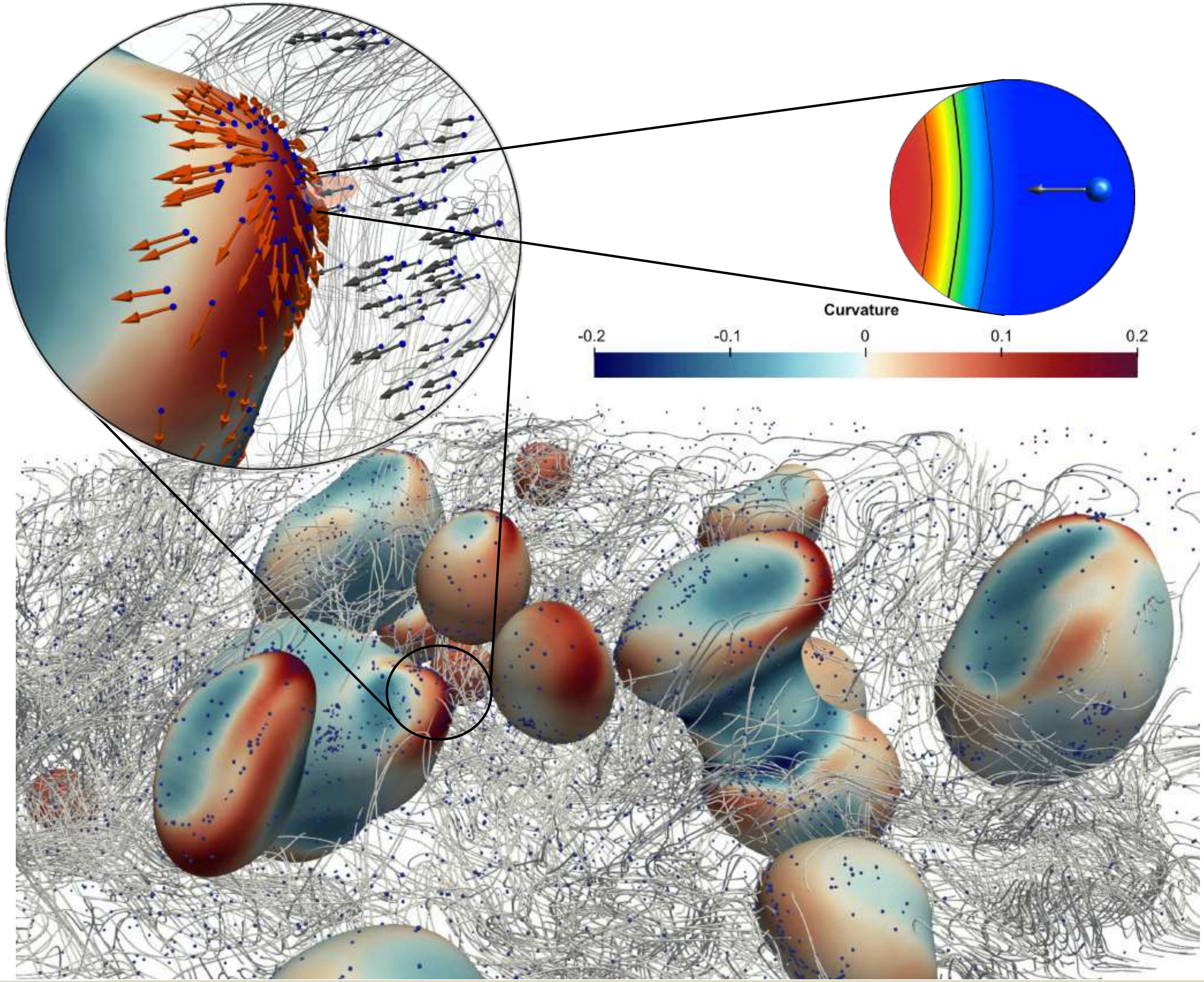
256 Droplets

$10^6$ Particles



Hajisharifi, et al., Particle capture by drops in turbulent flow. *Physical Review Fluids*, *6.2 (2021)*

# Particle capture at the drop interface

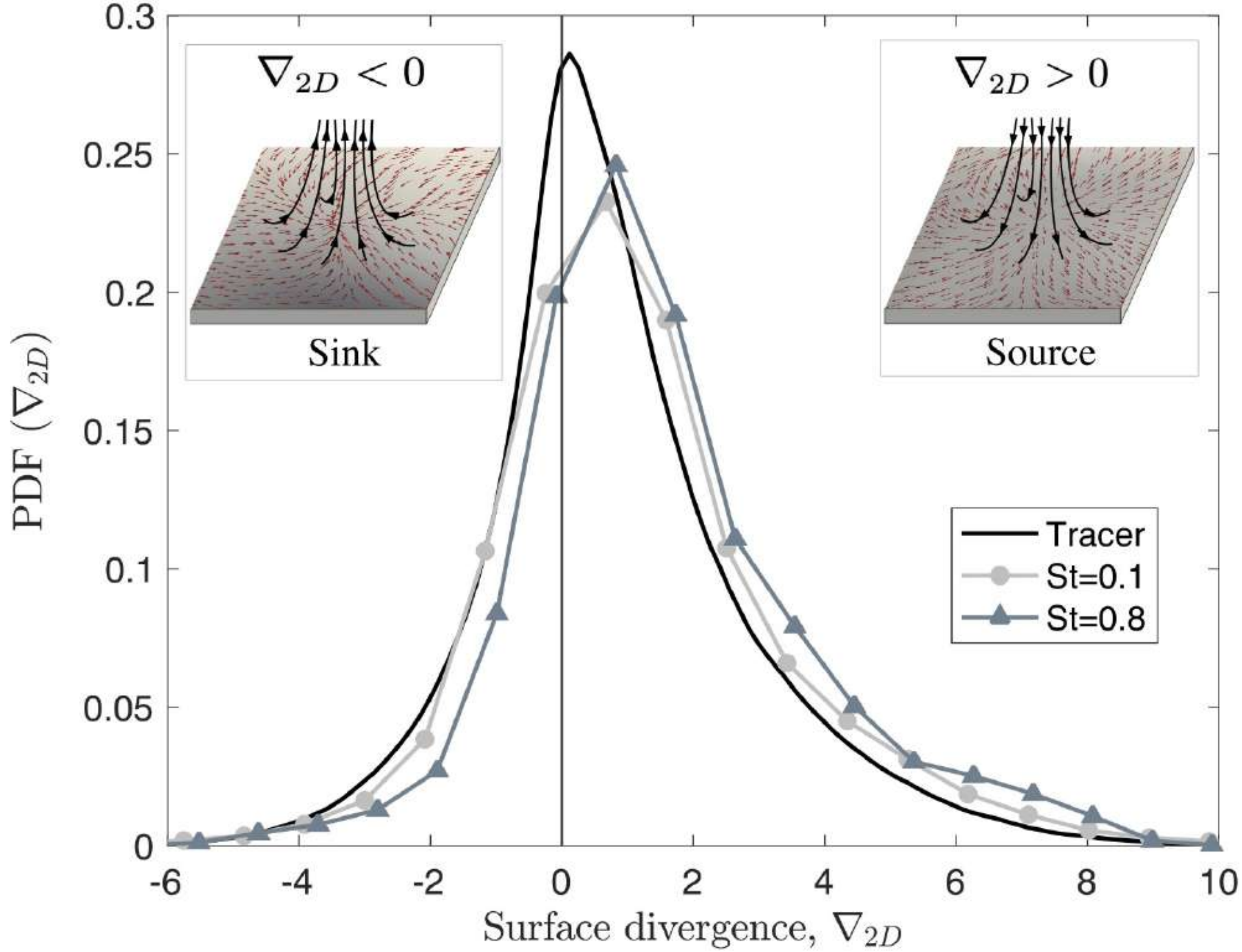



Hajisharifi, et al., Particle capture by drops in turbulent flow. *Physical Review Fluids*, *6.2 (2021)*

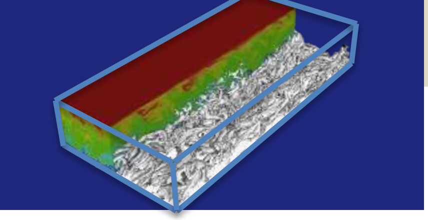
# Particle capture at the drop interface



$$\nabla_{2D} = \mathbf{n} \cdot \nabla \times (\mathbf{n} \times \mathbf{u})$$



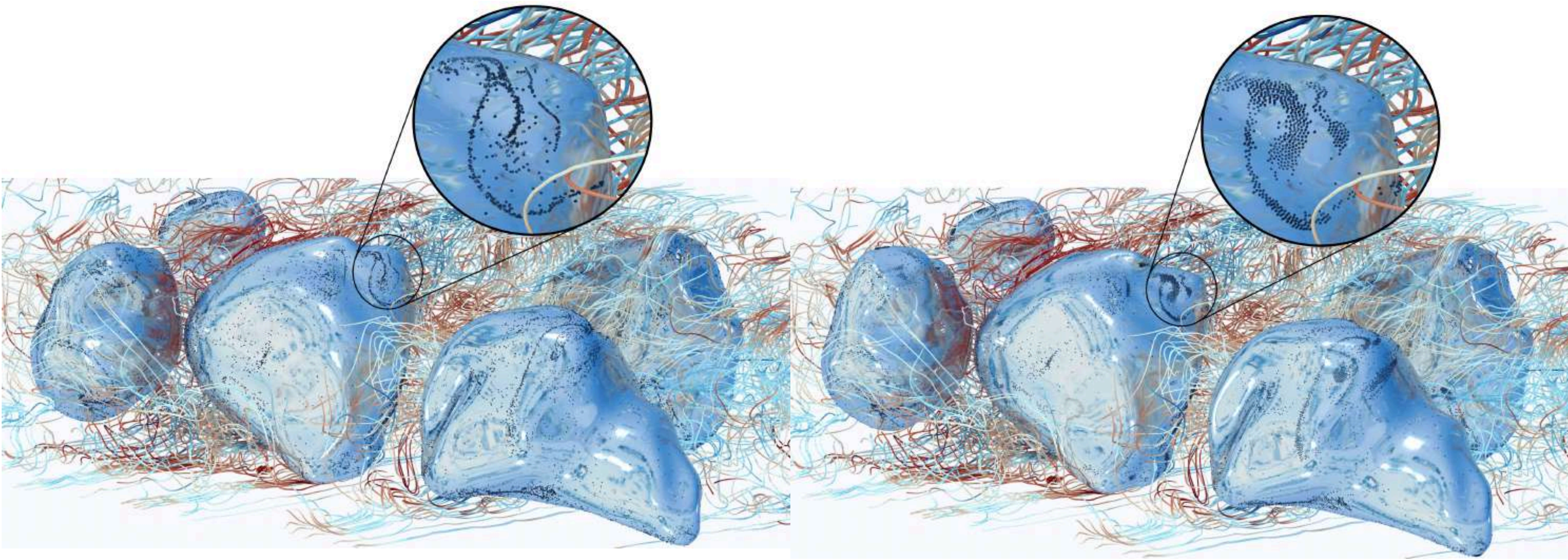

Hajisharifi, et al., Particle capture by drops in turbulent flow.
*Physical Review Fluids*, *6.2 (2021)*





# Particle trapping at the drop interface





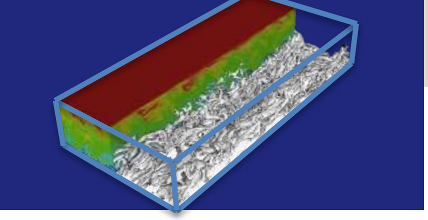
Without Excluded-Volume Effects (EVE) — With Excluded-Volume Effects (EVE)

Excluded-Volume Effects (EVE) are accounted for via particle-particle collisions

Collision algorithm: hard-sphere proactive collisions (Sundaram & Collins, 1996)

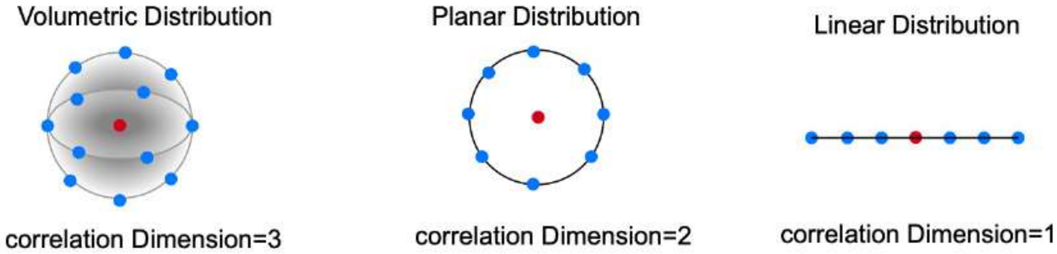


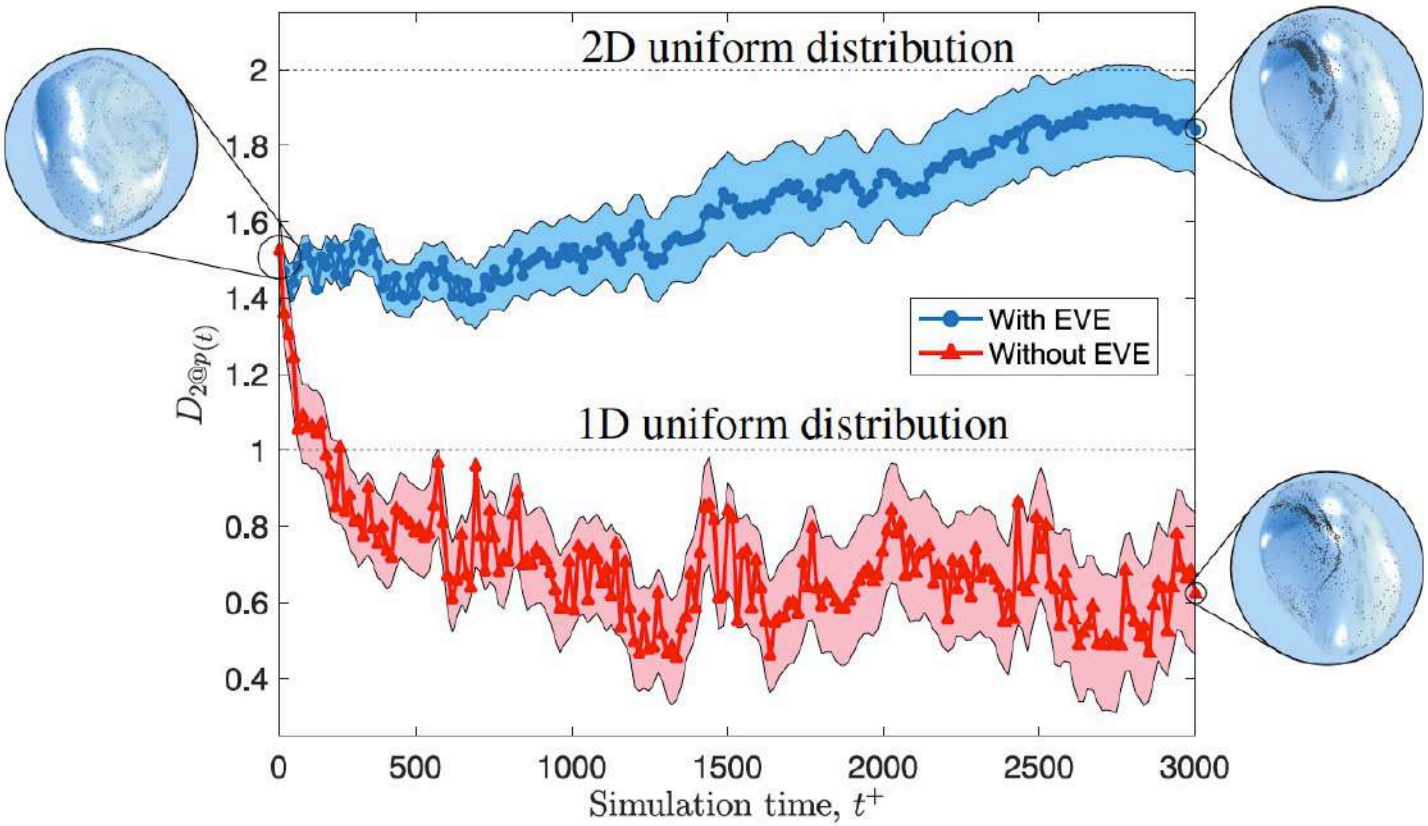
Hajisharifi, et al., Interface topology and evolution of particle patterns on big drops in turbulence, *J Fluid Mech*, *submitted (2021)*





# Particle trapping at the drop interface



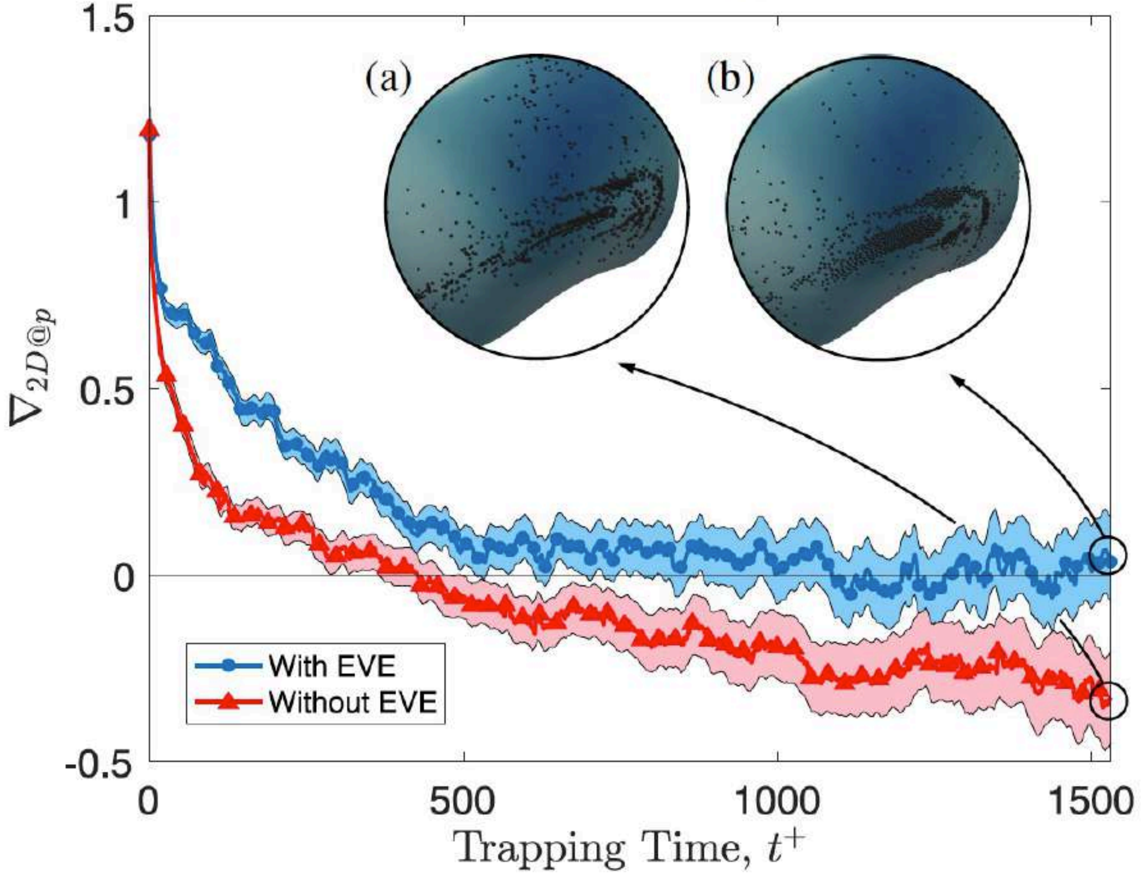



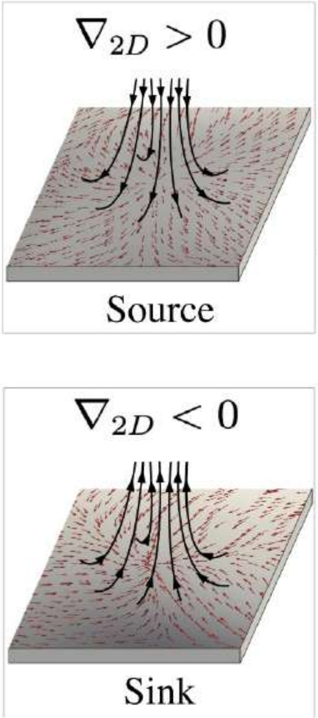

Hajisharifi, et al., Interface topology and evolution of particle patterns on big drops in turbulence, *J Fluid Mech*, *submitted (2021)*

# Particle trapping at the drop interface



$$\nabla_{2D} = \mathbf{n} \cdot \nabla \times (\mathbf{n} \times \mathbf{u})$$




Shaded area:
$\mathcal{X}(t) = \nabla_{2D@p}(We, St, t) - \nabla_{2D@p}(0.75, 0.1, t)$

Profiles refer to We=0.75, St=0.1

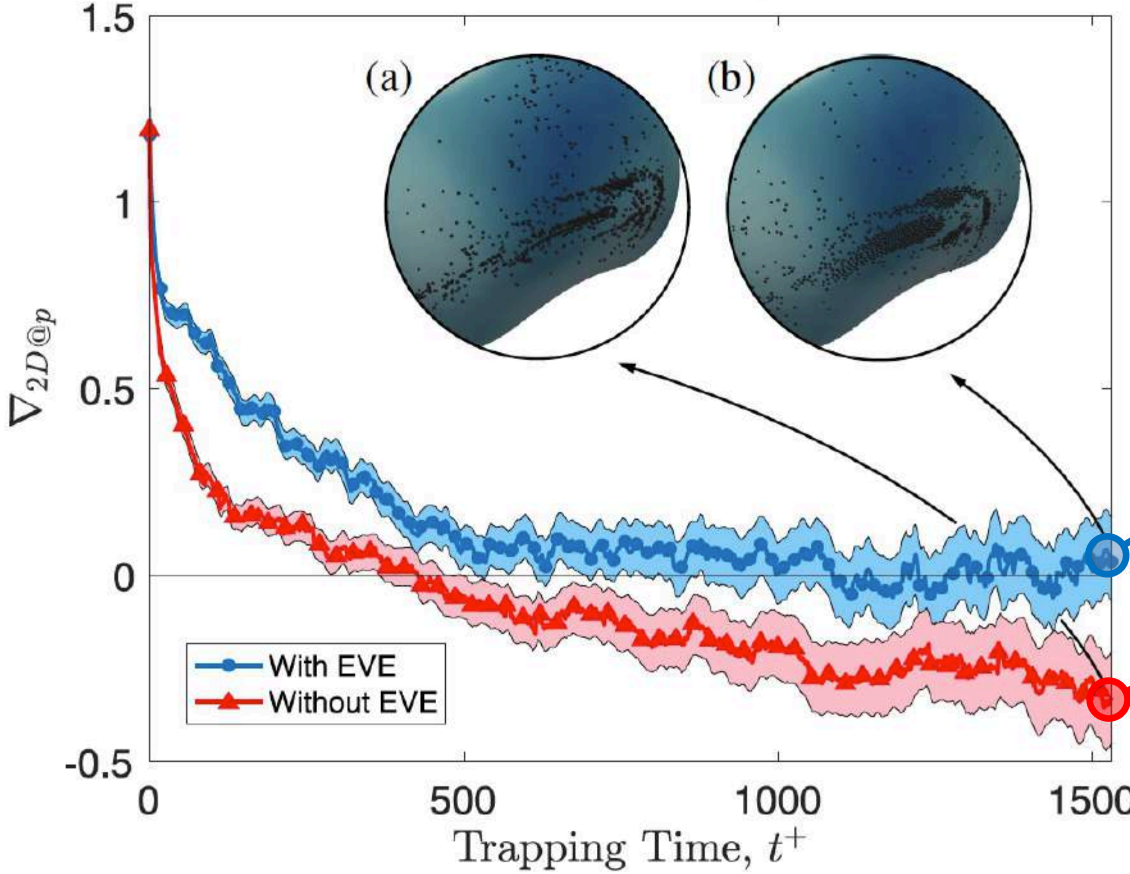


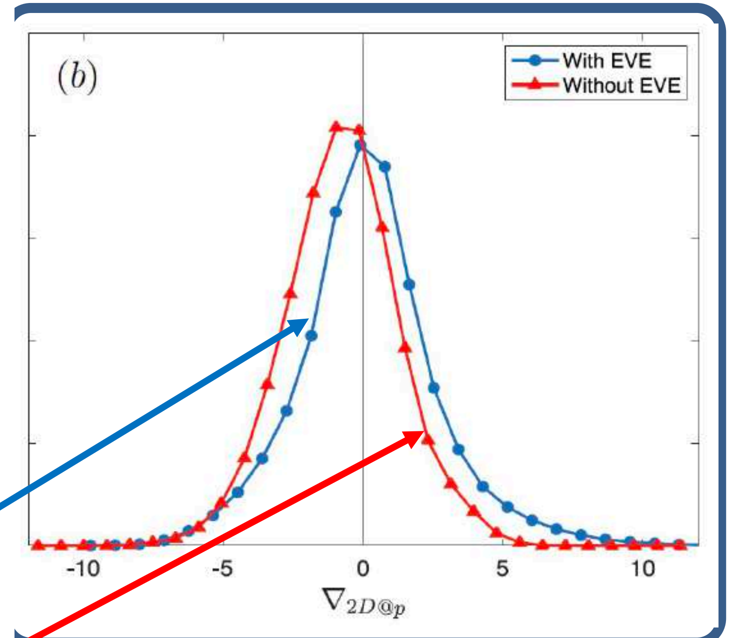
Hajisharifi, et al., Interface topology and evolution of particle patterns on big drops in turbulence, *J Fluid Mech*, *submitted (2021)*

# Particle trapping at the drop interface



$$\nabla_{2D} = \mathbf{n} \cdot \nabla \times (\mathbf{n} \times \mathbf{u})$$



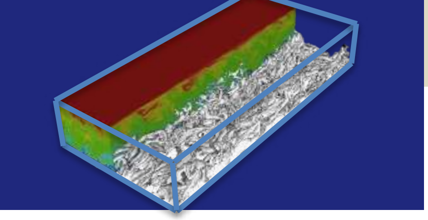




PDF of $\nabla_{2D@p}$ sampled at the position of the trapped particles at time $t^+$=1500 after capture

Shaded area:
$\mathcal{X}(t) = \nabla_{2D@p}(We, St, t) - \nabla_{2D@p}(0.75, 0.1, t)$

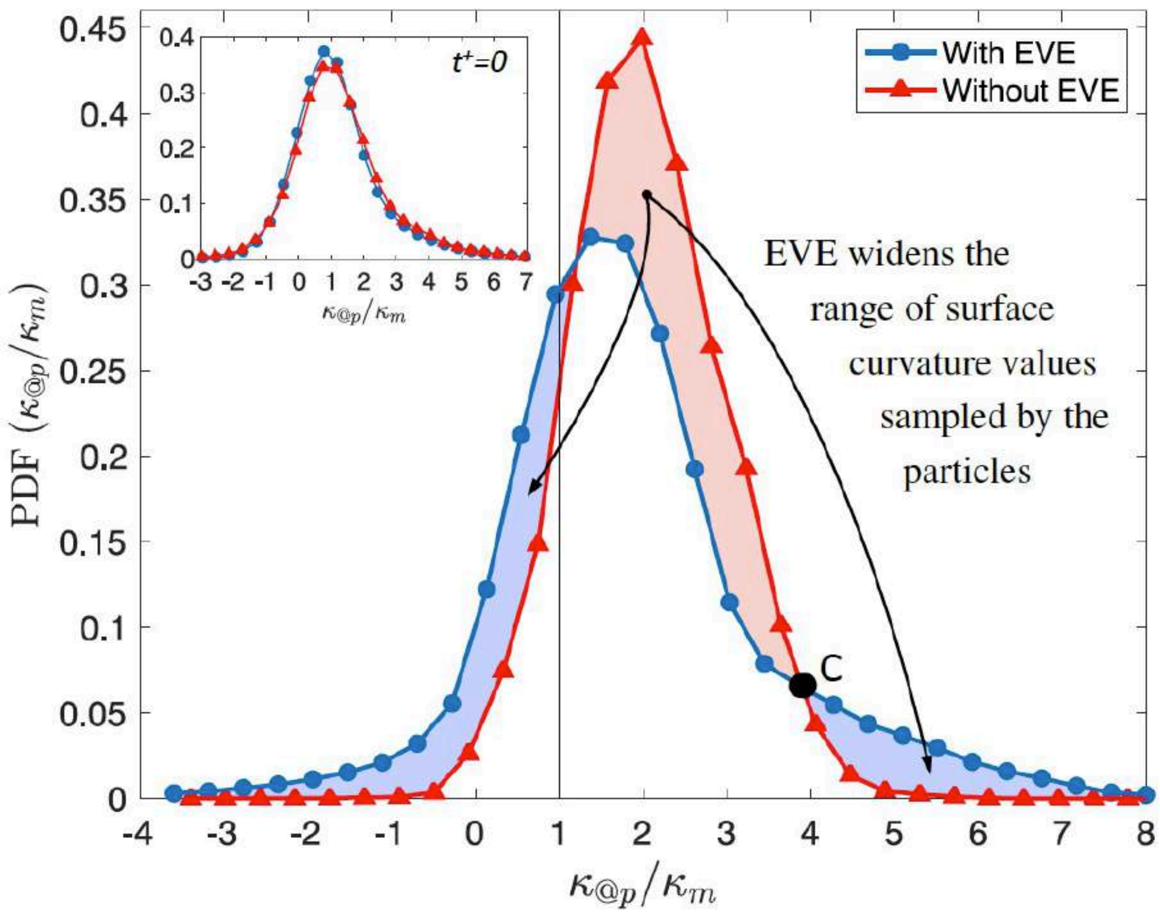


Hajisharifi, et al., Interface topology and evolution of particle patterns on big drops in turbulence, *J Fluid Mech*, *submitted (2021)*



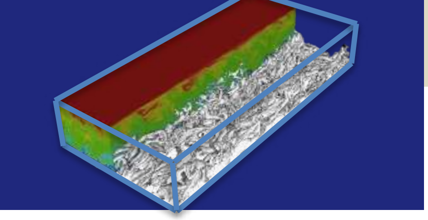
# Particle trapping at the drop interface

$$\kappa = -\nabla \cdot \left( \frac{\nabla \phi}{|\nabla \phi|} \right) = -\frac{\nabla^2 \phi}{|\nabla \phi|} + \frac{1}{|\nabla \phi|^2} \nabla \phi \cdot \nabla(|\nabla \phi|)$$






Hajisharifi, et al., Interface topology and evolution of particle patterns on big drops in turbulence, *J Fluid Mech*, *submitted (2021)*





# Acknowledgments

Special thanks to:

Alfredo Soldati, Francesco Zonta (TU Wien)

Wen Wu (Univ. Mississippi), Giovanni Soligo (OIST, Okinawa), Ugo Piomelli (Queens Univ.)

Salvatore Lovecchio, Diego Dotto, Harshit Bhatia, Arash Hajisharifi (Univ. Udine)

**Thank you very much for your kind attention!**