14th Workshop on Two-Phase Flow Predictions

University of Halle-Wittenberg, Halle (Saale), September 7-10, 2015

Micro-swimmer dynamics in wind-sheared free-surface turbulence

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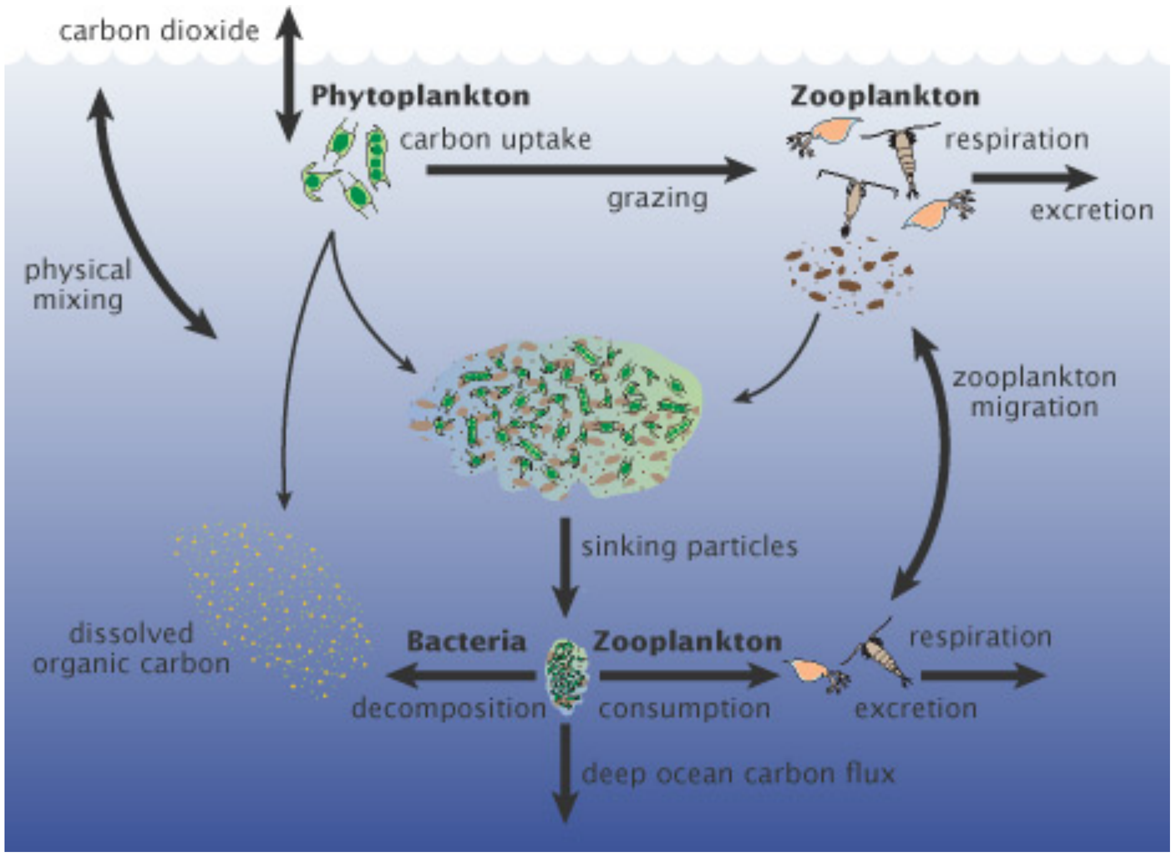
Motivation: Plankton dynamics near a free surface

Multiphase Flow Laboratory
University of Udine

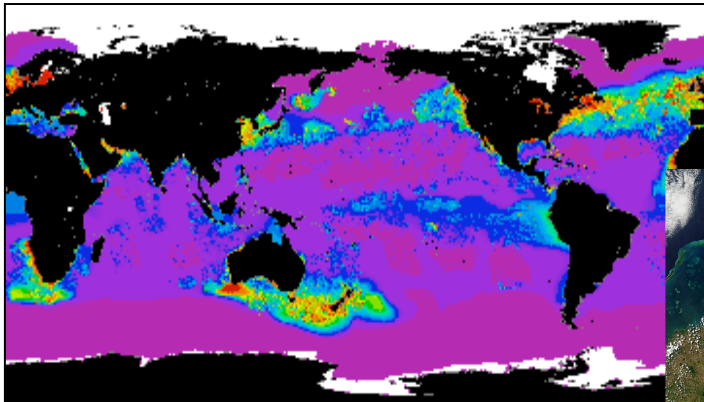


Phytoplankton is the photosynthetic part of plankton

- primary production: organic compounds from CO_2
- important part of the global carbon cycle
- provides 50% of the earth's oxygen
- sustains the aquatic food web

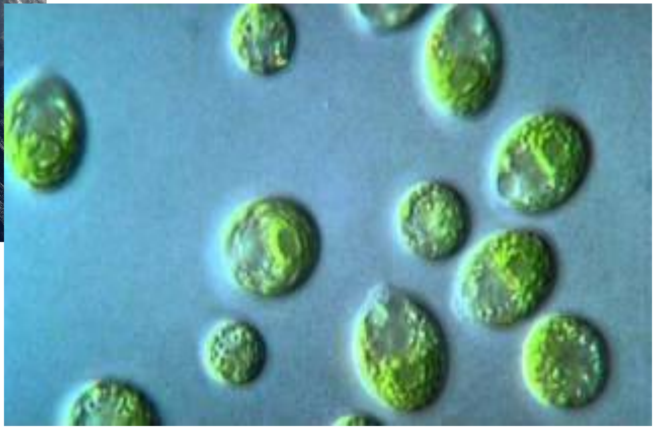
Motivation: Plankton dynamics near a free surface

Plankton patchiness occurs at different scales → no unique explanation



10^7 m

10^3 m



10^{-5} m

Bridge the gap:

- swimming
- collective population dynamics
- turbulent transport

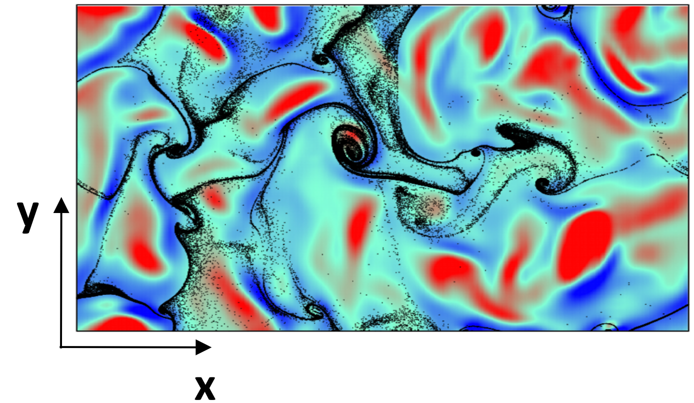
Role of surface turbulence still unclear!

Outline of the presentation

PART 1: Passive particles at a free-surface

Phytoplankton cells passively transported by the flow

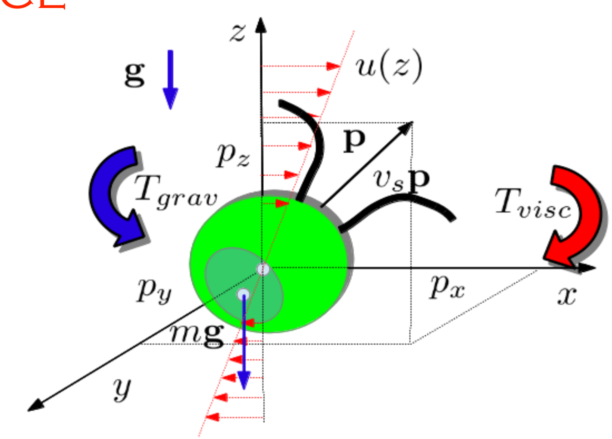
Dynamics of cluster at free-surface turbulence subject to wind stress



PART 2: Active particles at a free-surface

Self-propelled phytoplankton cells

Influence of wind stress on plankton surfacing



Fil rouge

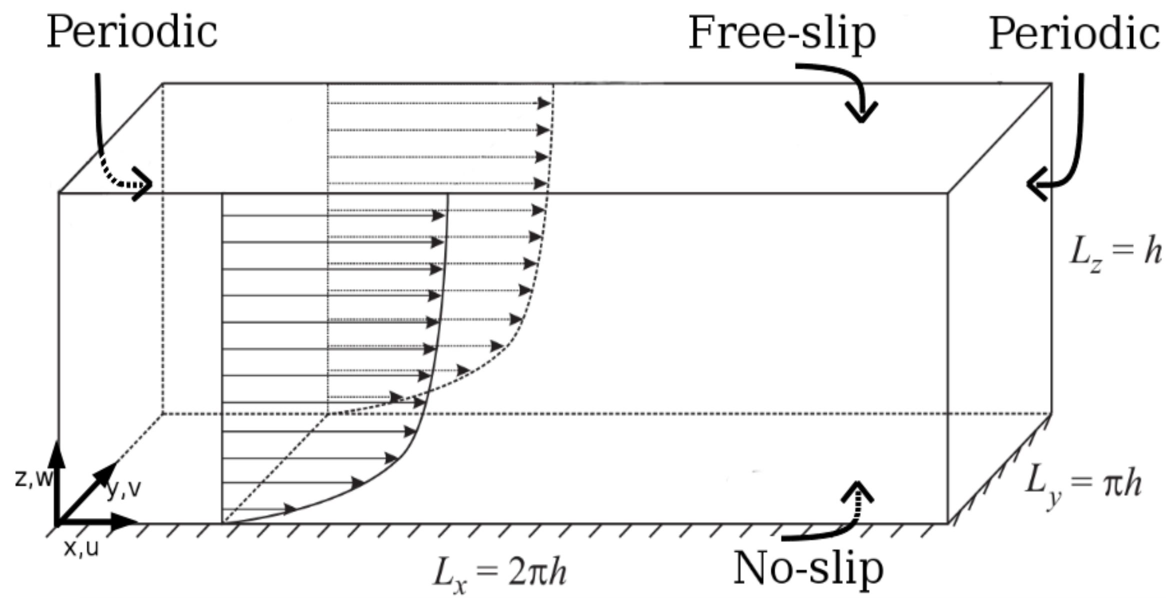
PART 1:

Passive particles at a free-surface

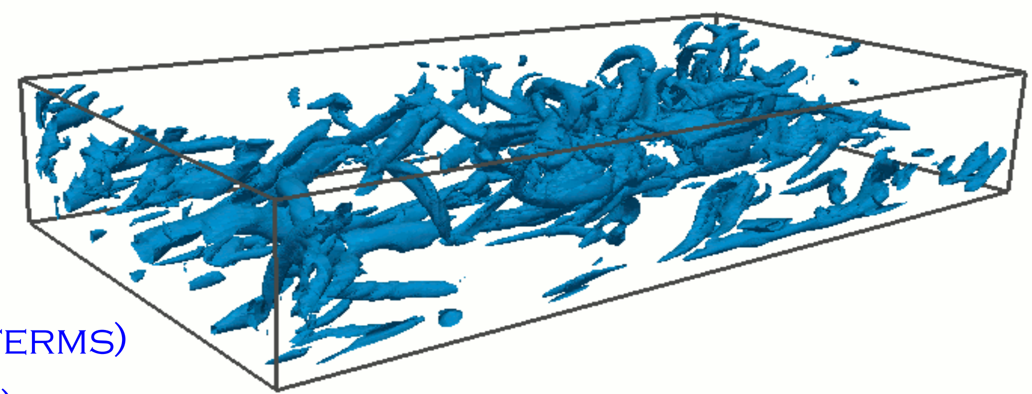
Physical problem and Modelling approach

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_τ= 171, 509**
- Channel size: **L_x x L_y x L_z = 4πh x 2πh x 2h**
- Pseudo-spectral DNS
- Time intergration:
  Adams-Bashforth (convective terms)
  Crank-Nicolson (viscous terms)



Physical problem and Modelling approach

Lagrangian particle tracking:

- $\frac{dx_i}{dt} = v_i$
- $\frac{dv_i}{dt} = (1 - \frac{\rho_f}{\rho_p}) g_i + \frac{u_i - v_i}{\tau_p} (1 + 0.15 Re_p^{0.687})$

- One-way coupling
- Fully-elastic particle-wall collision
- Time integration: 4th order Runge-Kutta
- Fluid velocity Interpolation: 6th order Lagrange polynomials

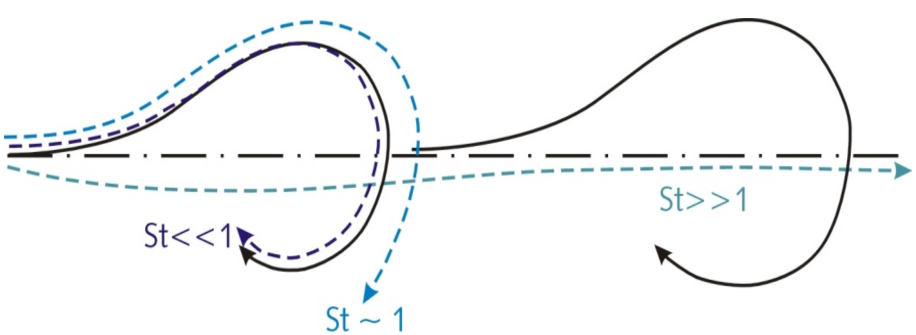
Particle Timescale – $\tau_P = d_P^2 \rho_P / 18 \mu$

Flow Timescale - $\tau_F = L/U = \nu / u_\tau^2$

Particle Stokes number, $St = \tau_P / \tau_F$

Re_τ	$St = \tau_p \cdot \nu / u_\tau^2$		
171	0.064	0.114	0.121
509	0.562	1.013	1.069
	S=0.5	0.9	0.95

S=particle-to-fluid density ratio



Topology of Free-surface turbulence

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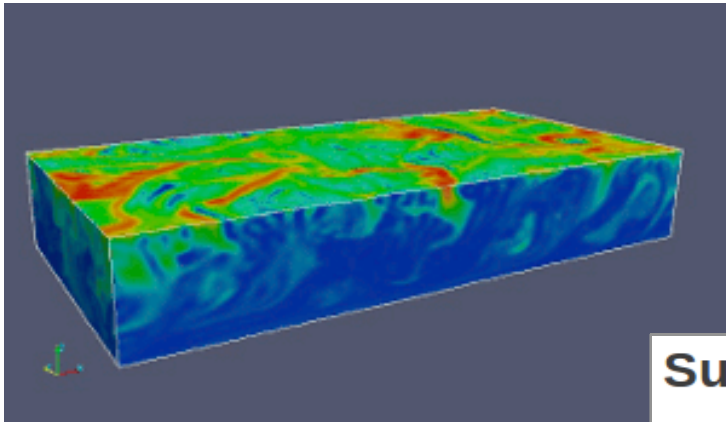
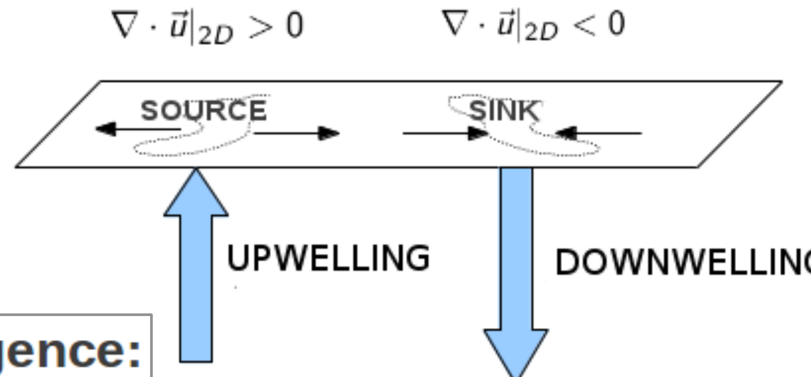


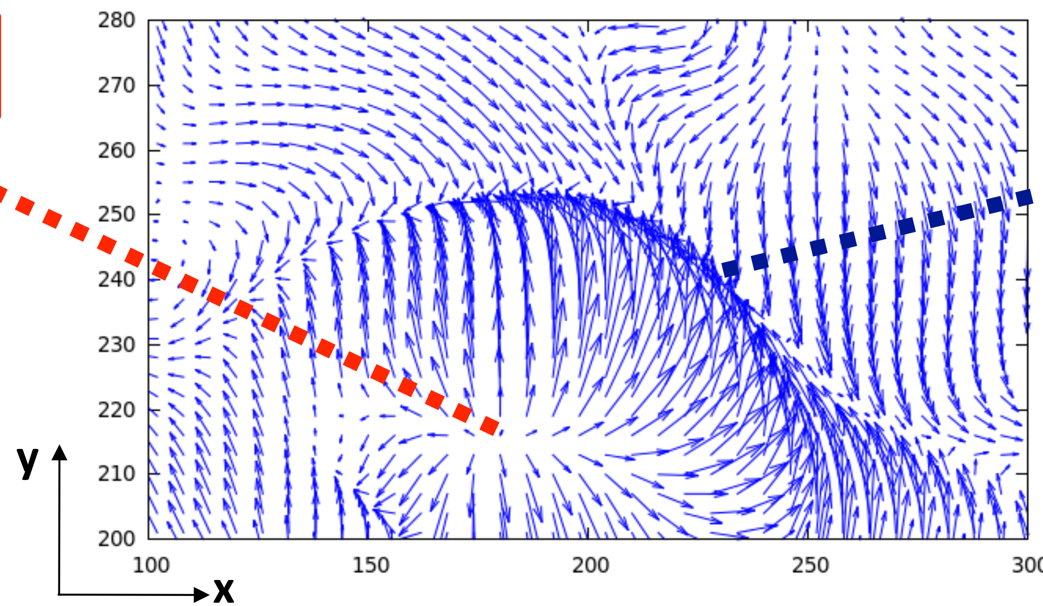


Surface divergence:

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

$\nabla_{2D} > 0$

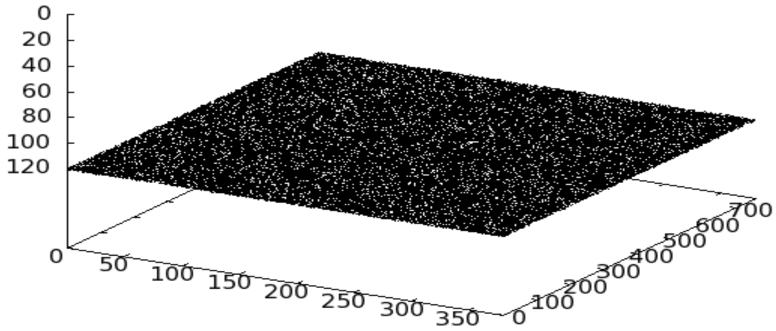
Velocity source

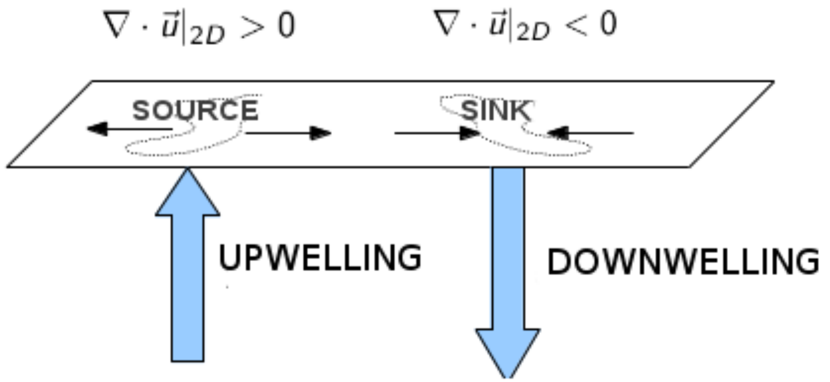


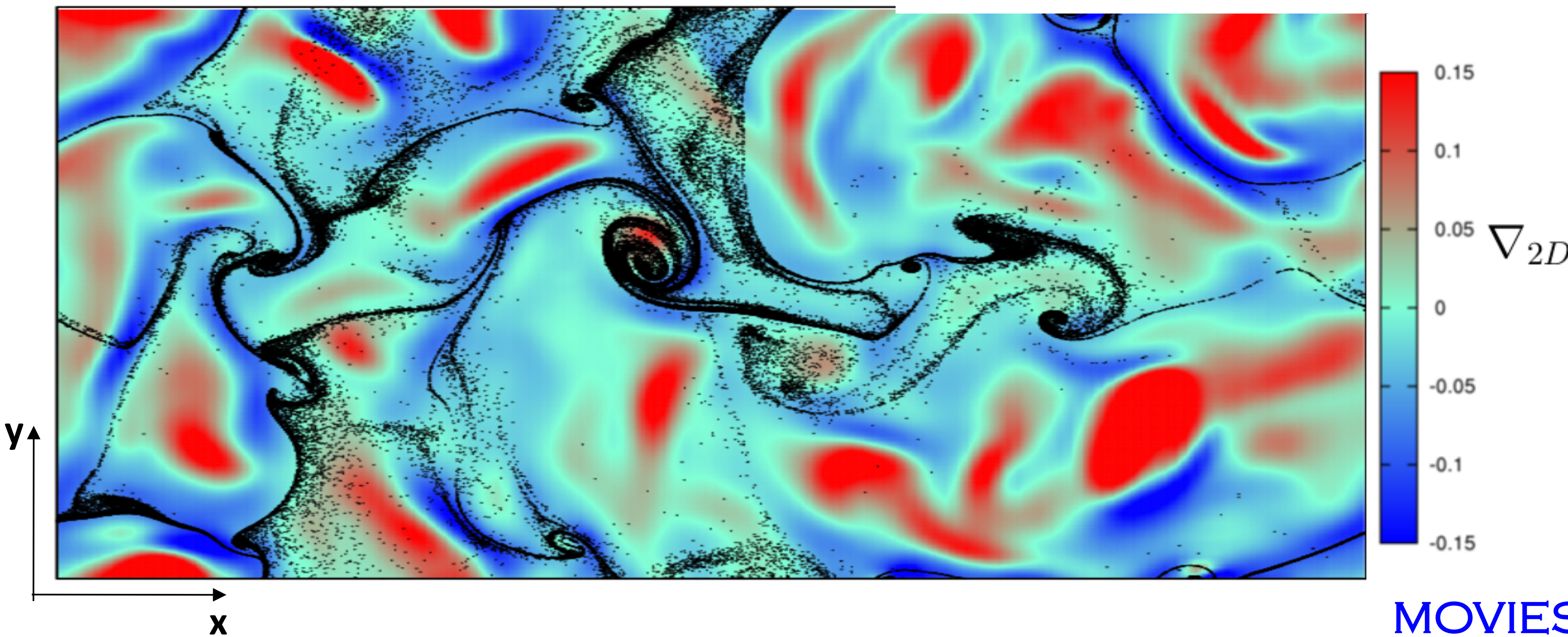
$\nabla_{2D} < 0$

Velocity sink

TOPOLOGY OF FREE-SURFACE TURBULENCE



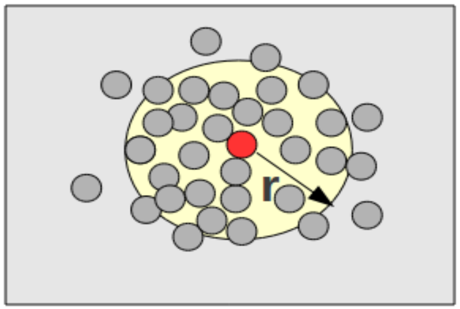




MOVIES

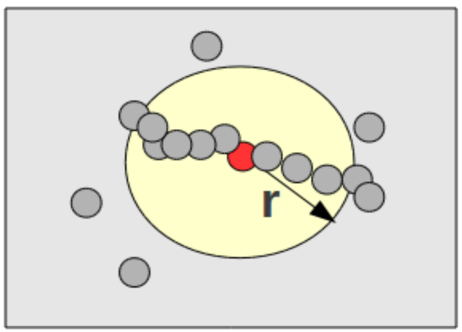
Topology of particle clusters at the free surface

Particles distributed:



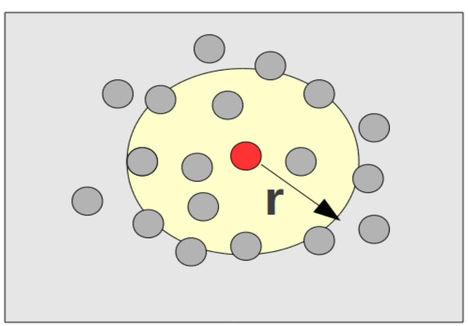
- uniformly over a surface

$$N(r) \simeq r^2$$



- uniformly along a line

$$N(r) \simeq r$$

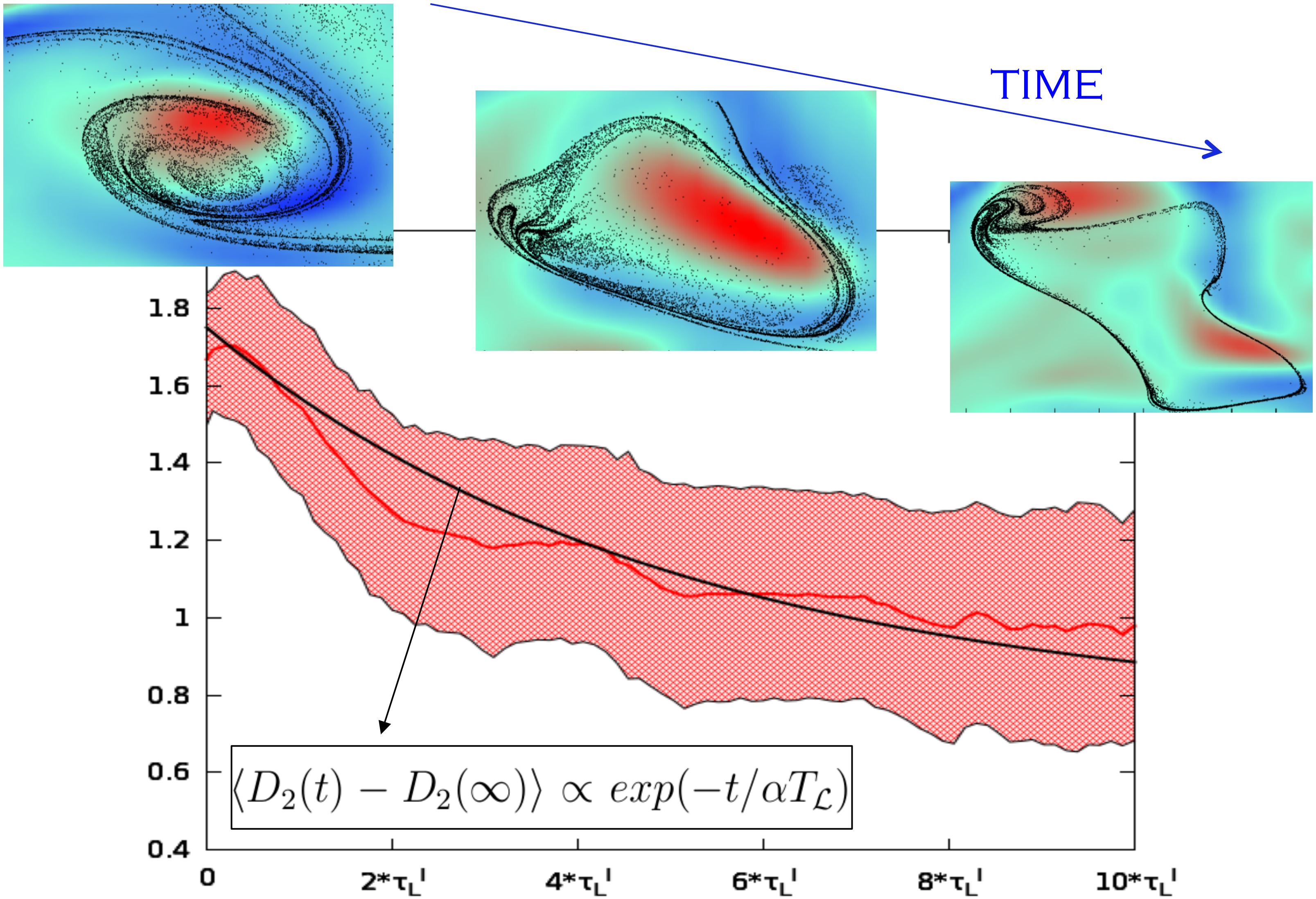


- in general

$$N(r) \simeq r^{\nu}$$

ν is the clusters' fractal dimension (correlation dim.)

Topology of particle clusters at the free surface



Results from Lovecchio et al., phys. rev. e (2013)

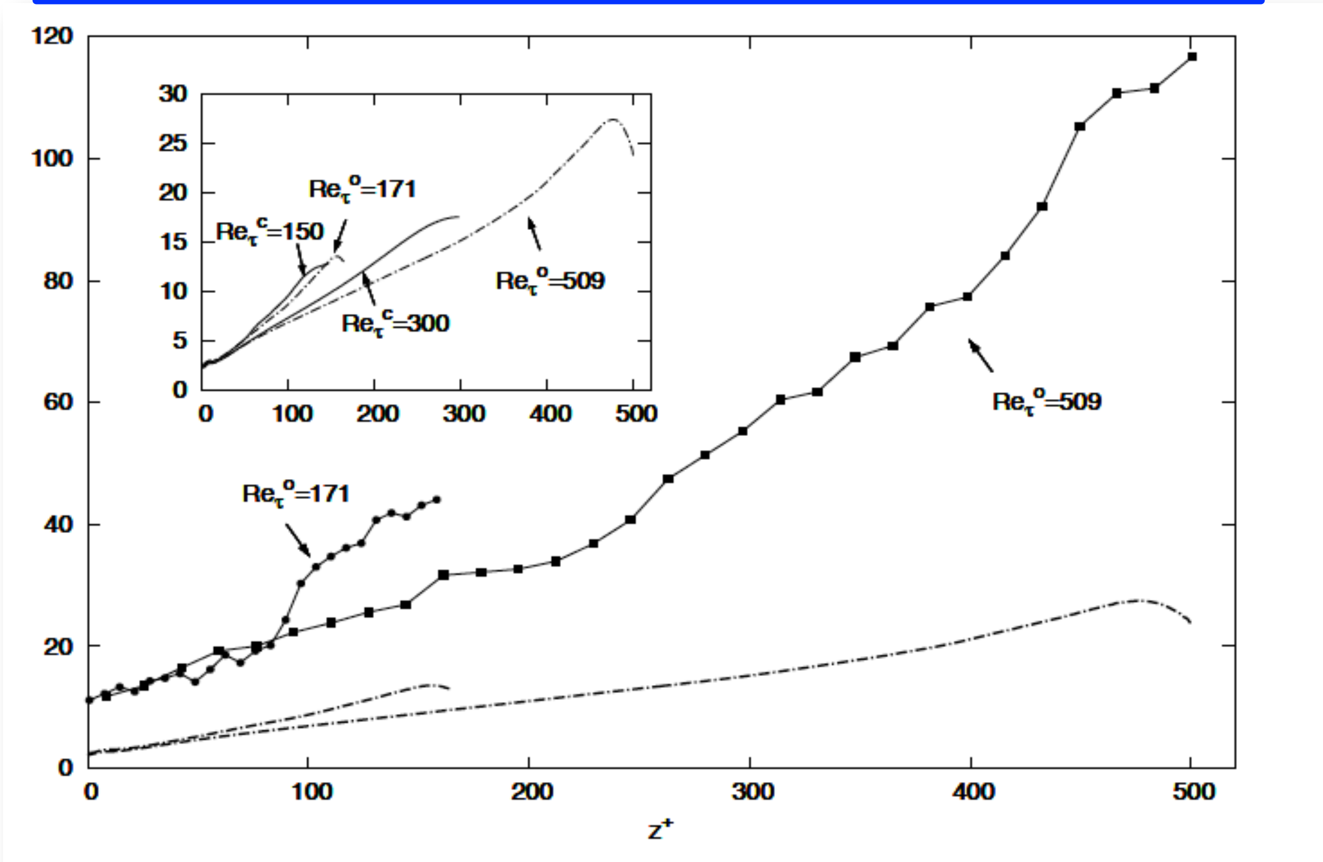
Topology of particle clusters at the free surface

$$T^t_{f,ij} = \int_0^\infty \frac{\langle u'_{f,i}(t', \mathbf{x}_f(t')u'_{f,i}(t_0, \mathbf{x}_f(t_0)\rangle_f}{\langle u'_{f,i}(t_0, \mathbf{x}_f(t_0)u'_{f,i}(t_0, \mathbf{x}_f(t_0)\rangle_f} dt'$$

$T_{\mathcal{L}} >> \tau_K$

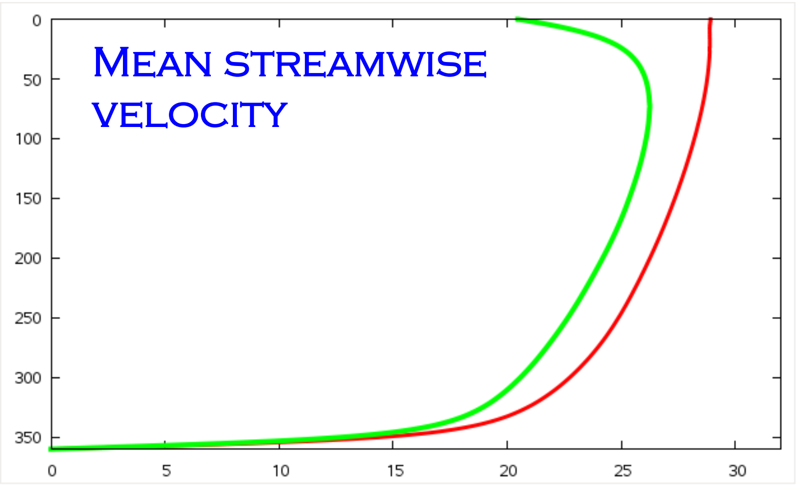
↓

Clusters are long-lived structures!

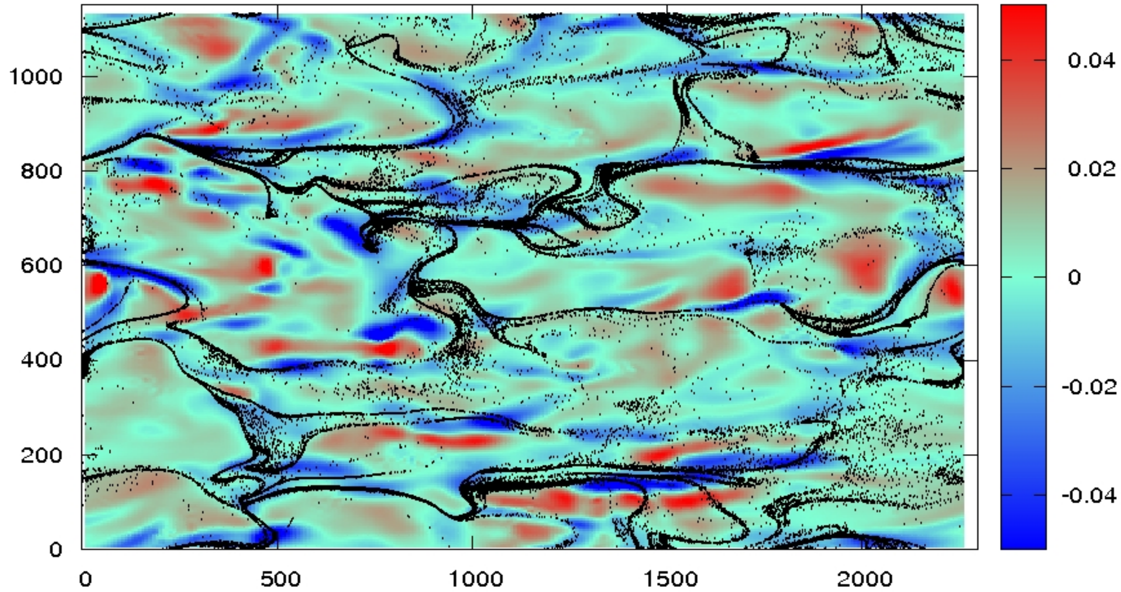


Results from Lovecchio et al., Phys. Rev. E (2013)

Effect of wind on particles at the free-surface

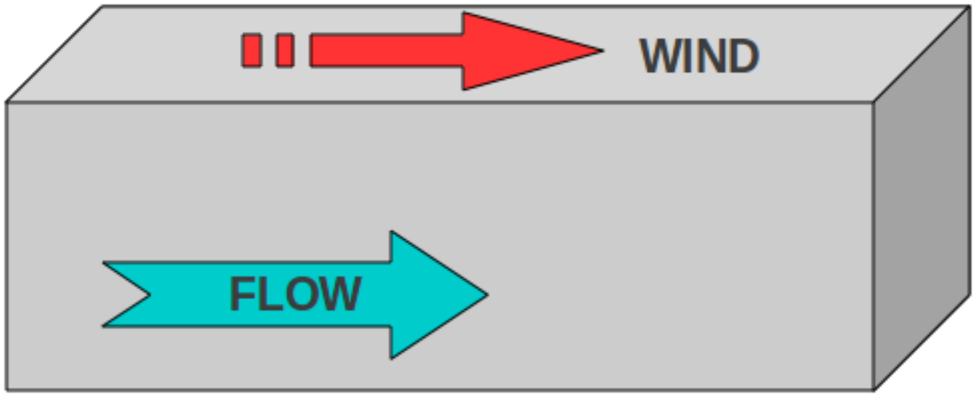


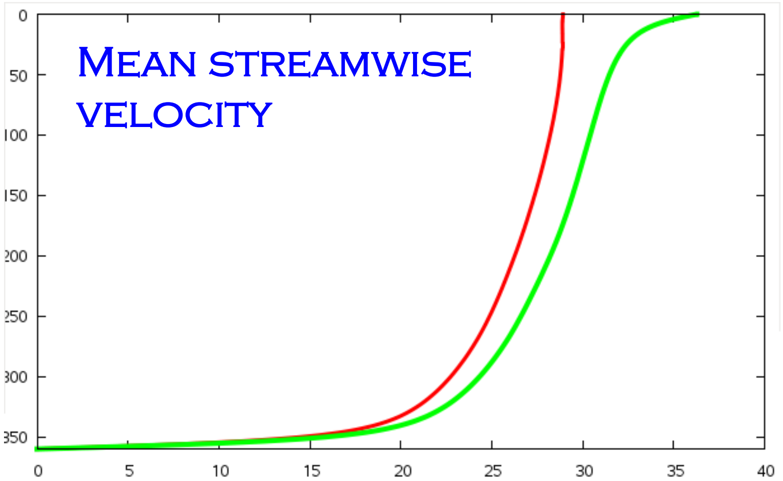
WIND OPPOSITE TO THE FLOW DIRECTION



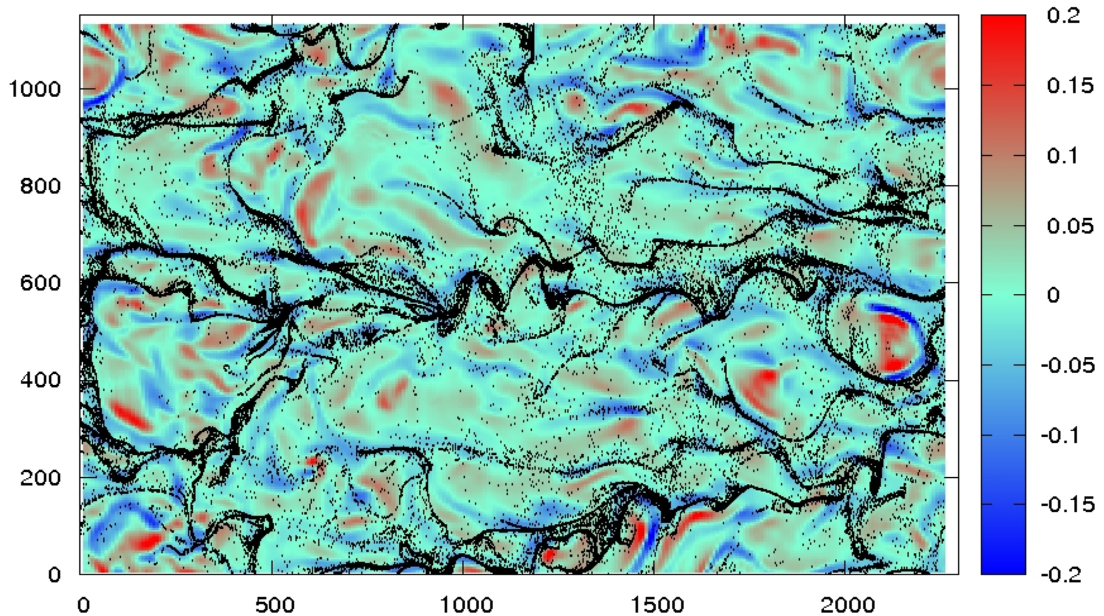
MOVIE

Effect of wind on particles at the free-surface



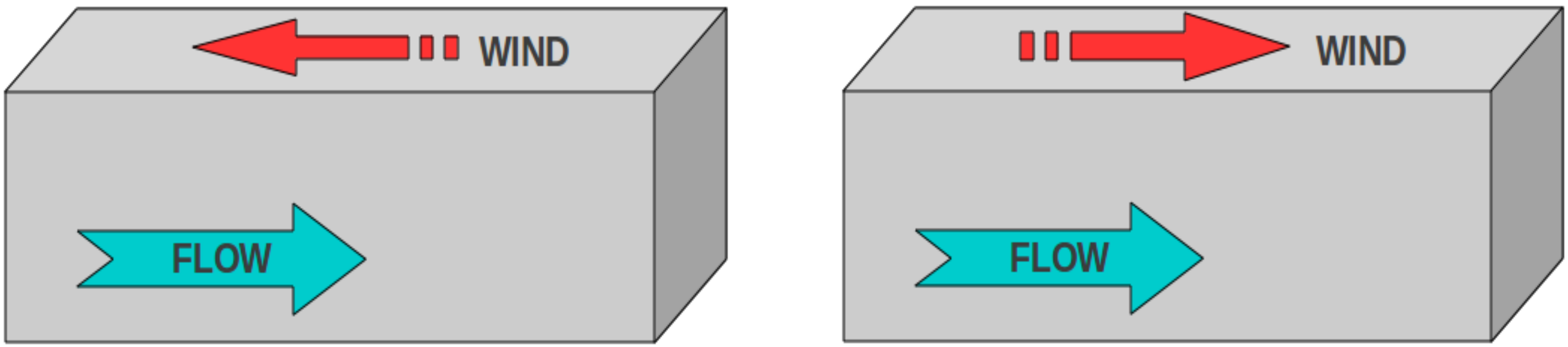


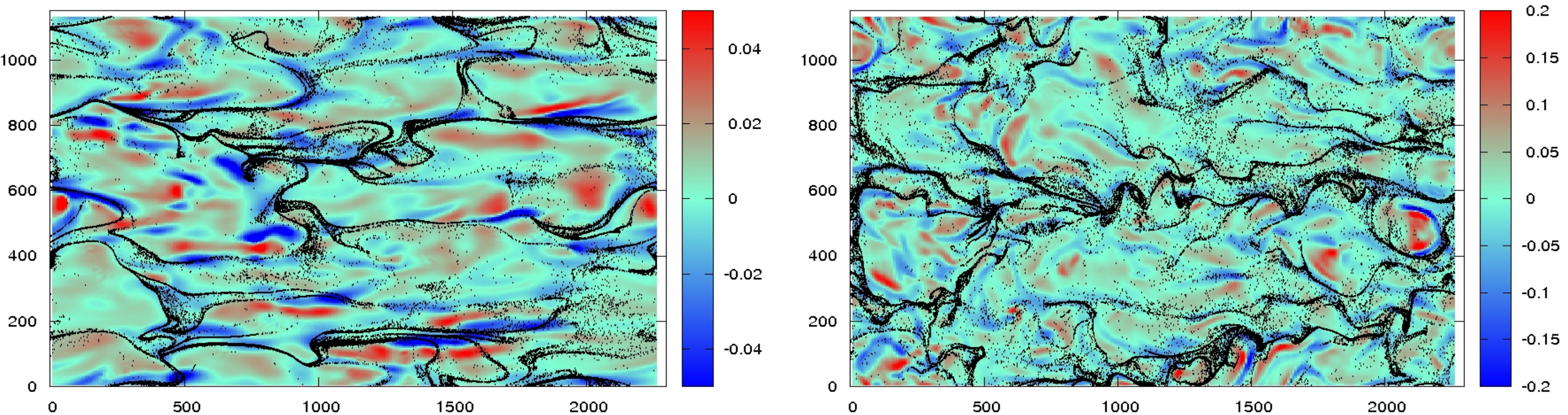
Wind along the flow direction



MOVIE

Effect of wind on passive particles at the free-surface





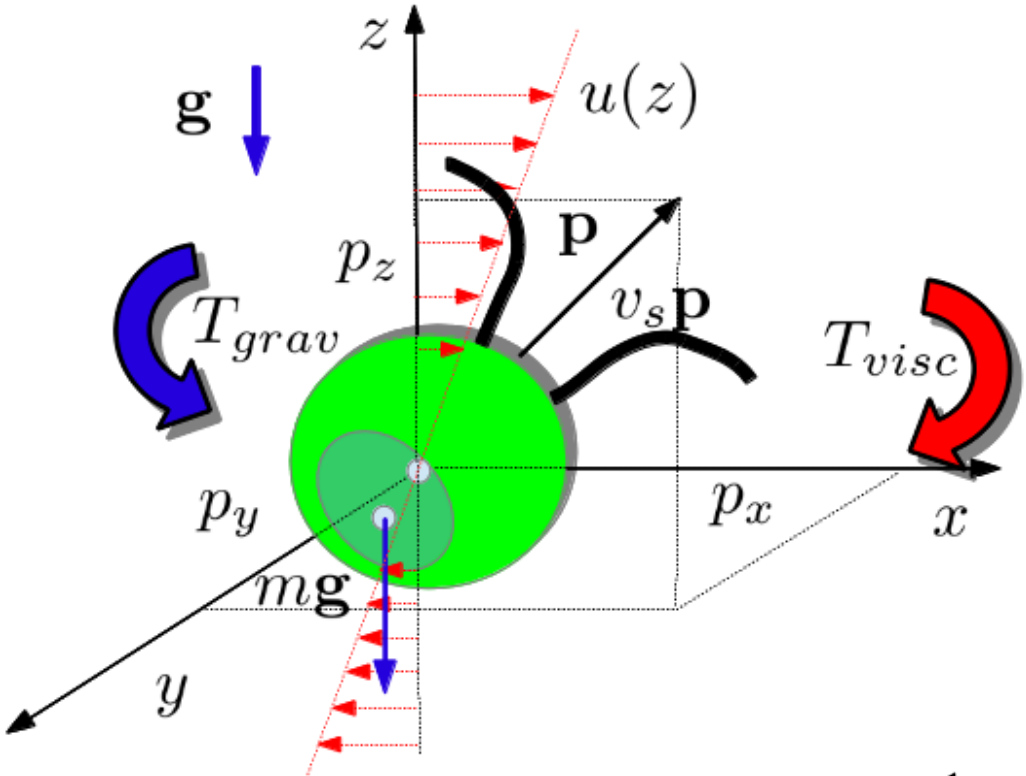
Different topology of filaments at the surface

Fil rouge

PART 2:

Active particles (swimmers) at a free-surface

Modelling micro-swimmers
lesson learned from plankton



Gyrotaxis: any directed locomotion resulting from 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 speed v_s in the direction **p**

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

$$\dot{\mathbf{p}} = \frac{1}{2B}[\mathbf{k} - (\mathbf{k}\cdot\mathbf{p})\mathbf{p}] + \frac{1}{2}\omega \times \mathbf{p}$$

Reorentation term due to gravitational torque

Vorticity term

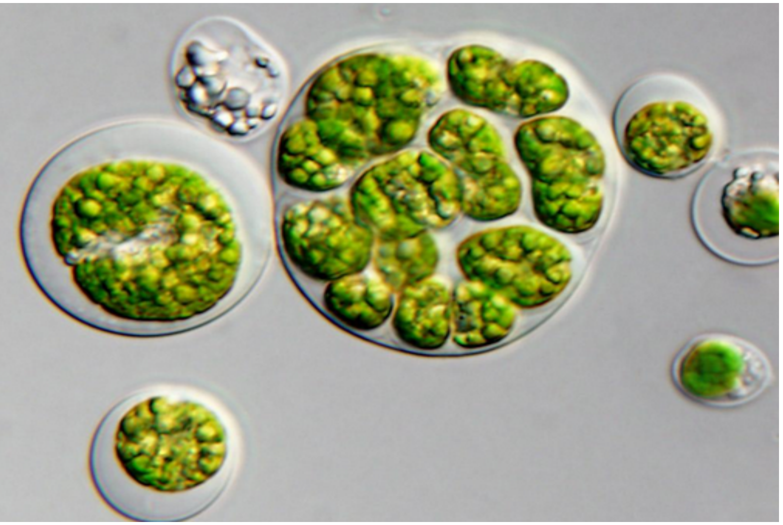
Swimming provides a way for micro-organisms to escape fluid pathlines (Kesslr J.O., Nature, 1985)

Two controlling parameters:

$V_s \simeq 10 - 1000 \mu m/s \longrightarrow \Phi = v_s / u_\tau$

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

Values considered in our study:



Chlamydomonas augustae

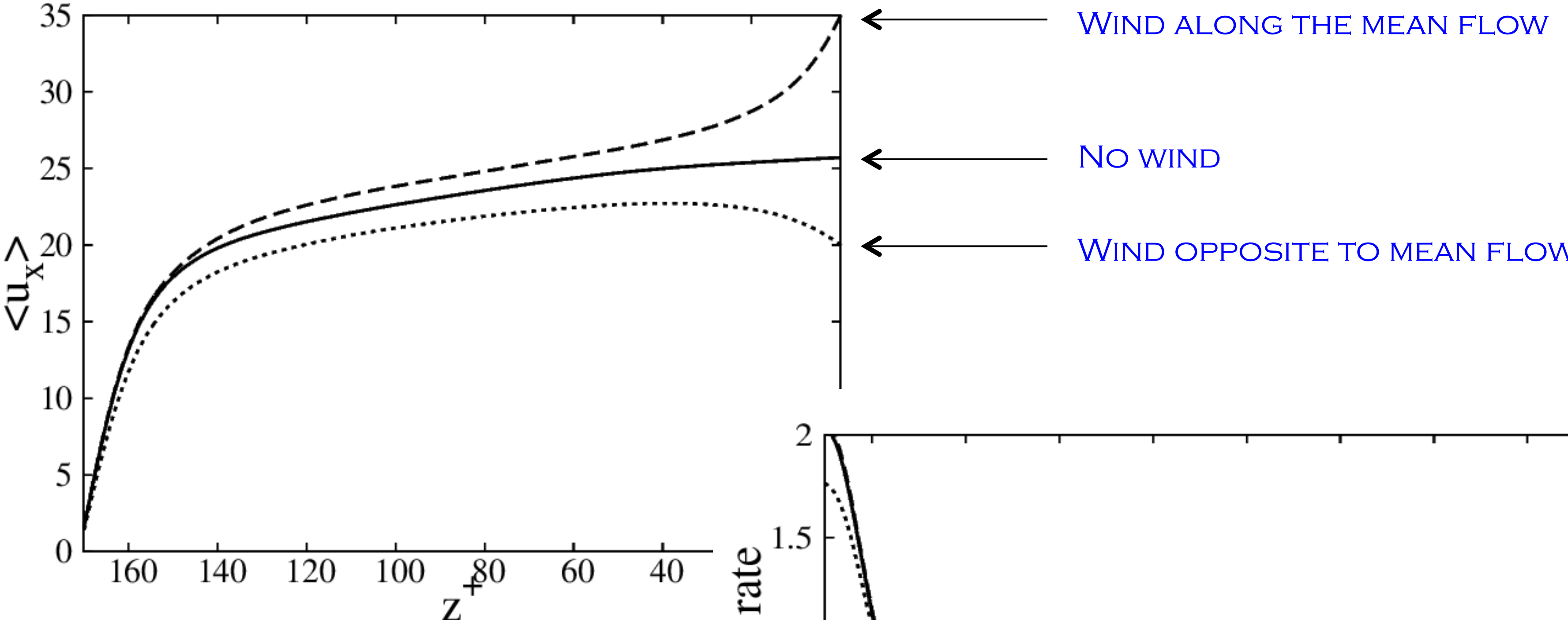
$\Phi = 0.048$ Dimensionless swimming speed

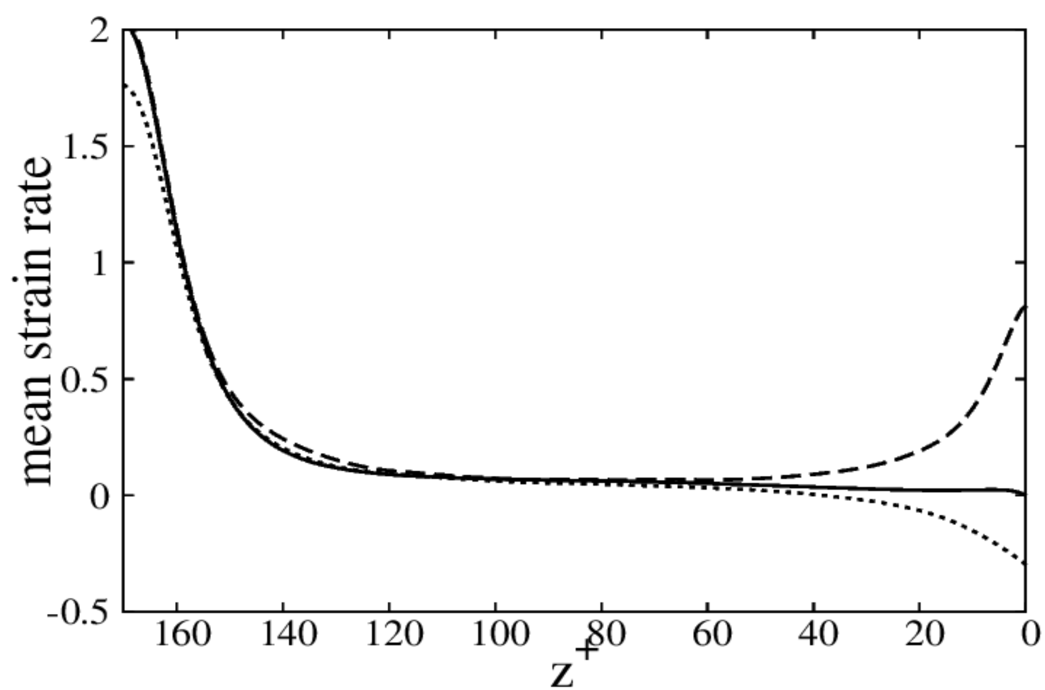
$\Psi_L = 0.0113$ Low gyrotaxis (slow re-orient.)

$\Psi_I = 0.113$ intermediate gyrotaxis

$\Psi_H = 1.13$ high gyrotaxis (fast re-orient.)

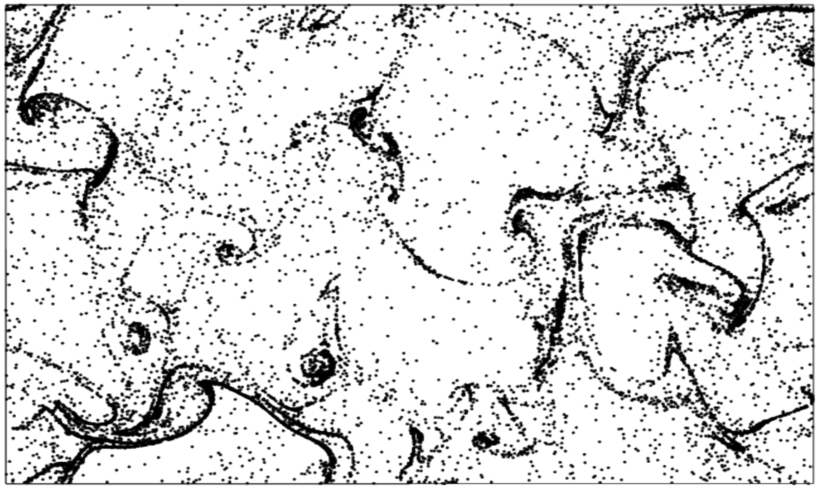
EFFECT OF WIND-SHEARED SURFACE TURBULENCE ON SWIMMER DYNAMICS





Effect of wind-sheared surface turbulence on swimmer dynamics

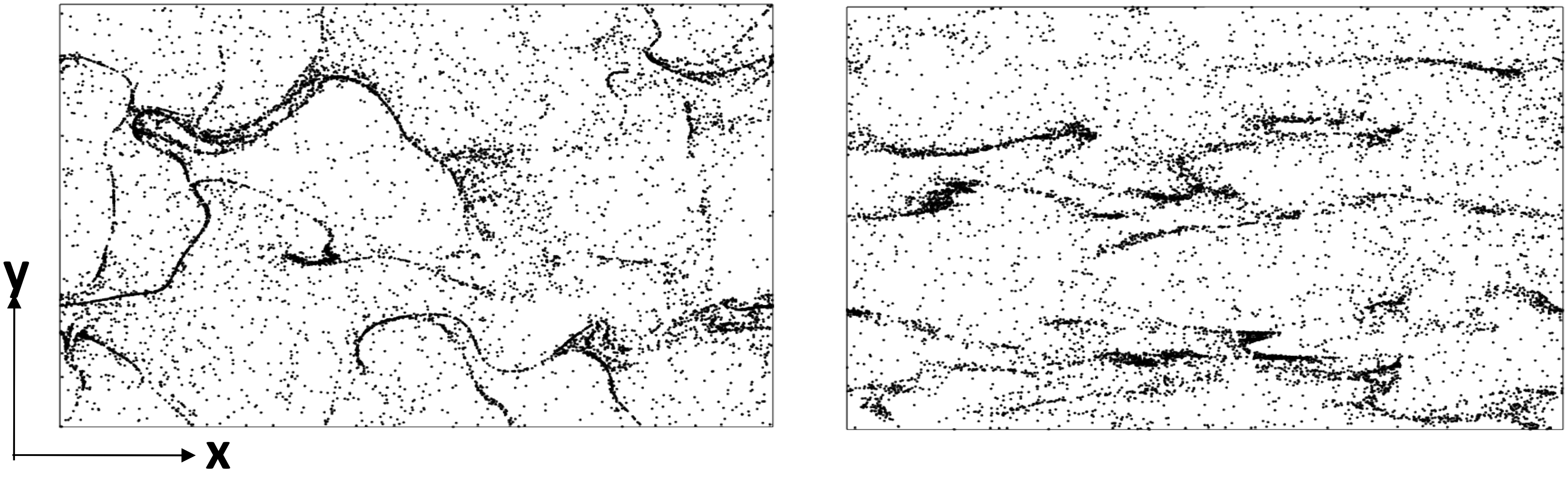
Swimmer distribution at the free-surface for $Re_\tau=171$ (Ψ_H, high Gyrotaxis case)



No wind

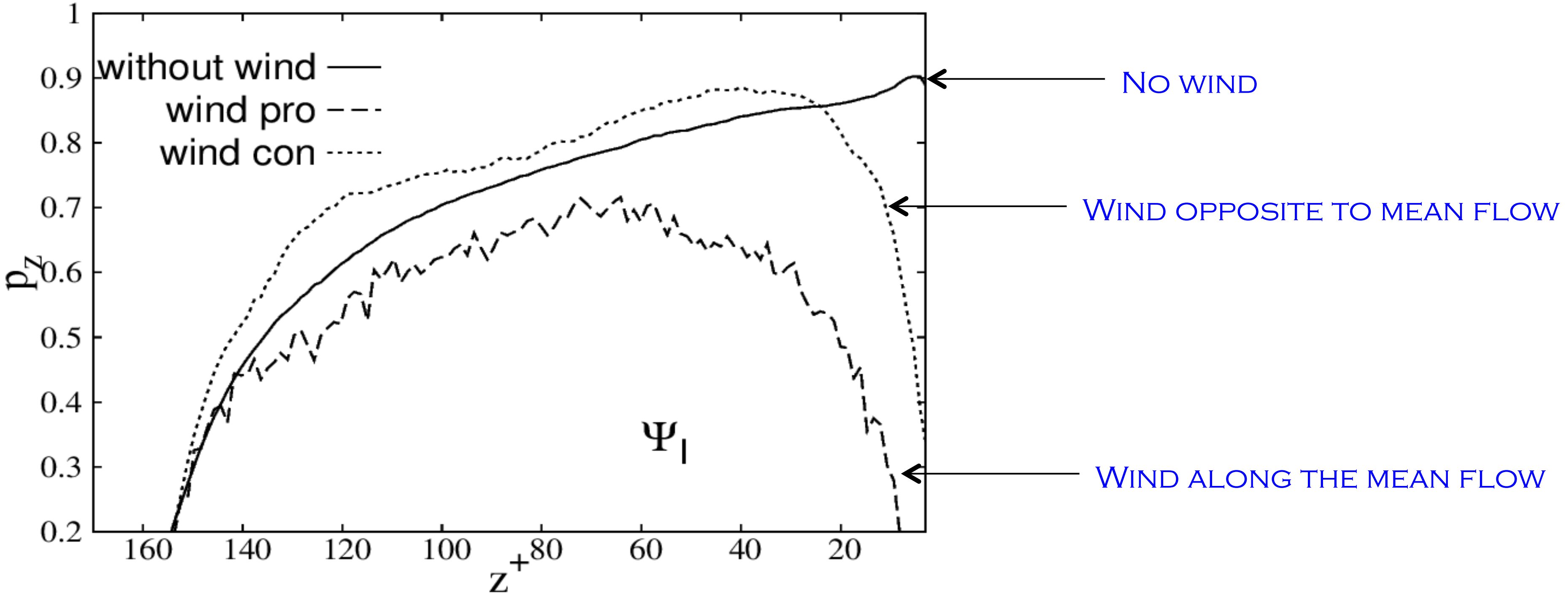
Wind opposite to mean flow

Wind along the mean flow



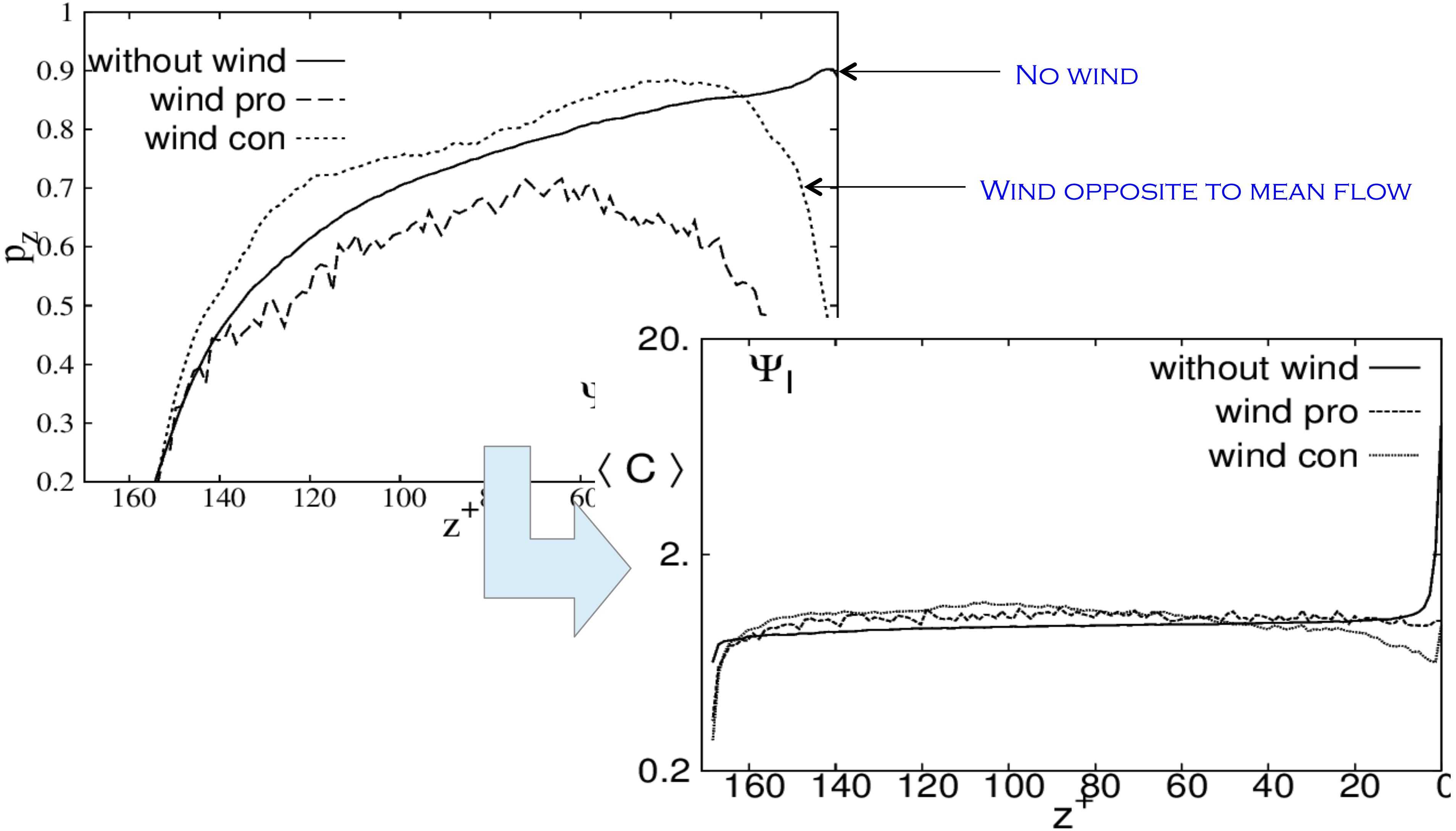
Effect of wind-sheared surface turbulence on swimmer dynamics

Orientation and vertical distribution (Ψ_l, intermediate Gyrotaxis case)

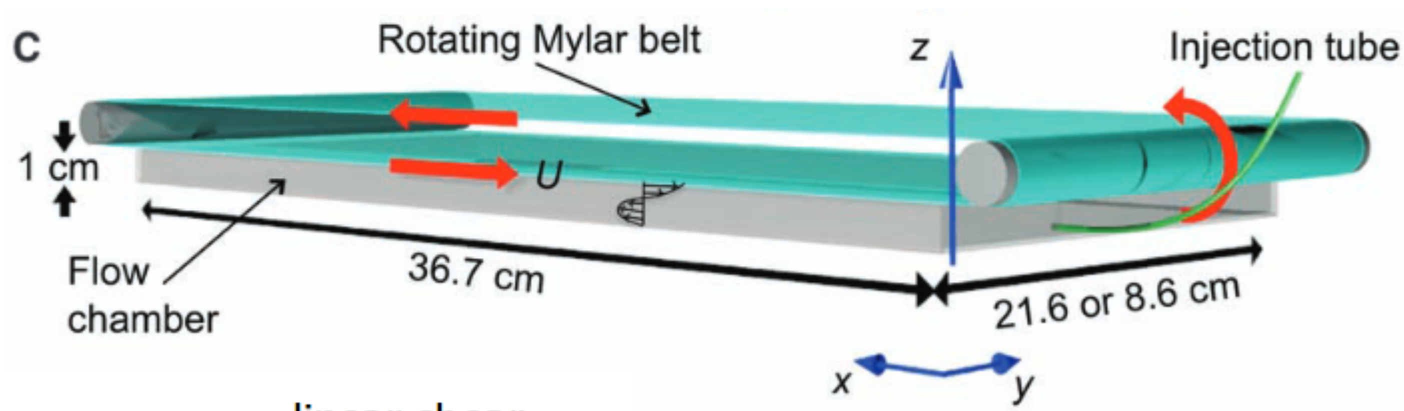


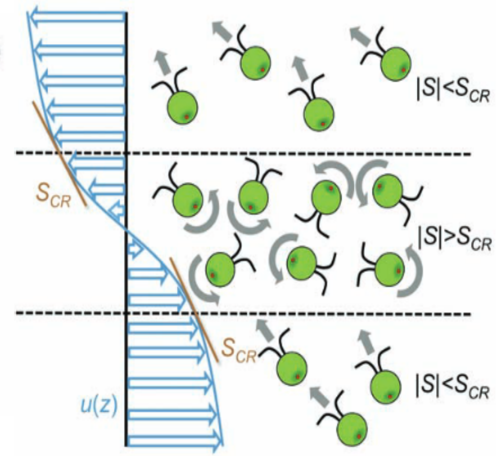
Effect of wind-sheared surface turbulence on swimmer dynamics

Orientation and vertical distribution (Ψ_I, intermediate Gyrotaxis case)



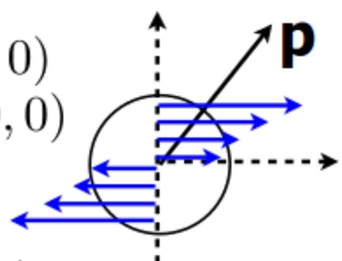
Effect of wind-sheared surface turbulence on swimmer dynamics





linear shear

$$\boldsymbol{u} = (0, \Gamma z, 0)$$
$$\boldsymbol{\omega} = (-\Gamma, 0, 0)$$



$$\dot{p}_x = -\frac{1}{2B} p_x p_z$$
$$\dot{p}_y = -\frac{1}{2B} p_y p_z + \frac{\Gamma}{2} p_z$$
$$\dot{p}_z = \frac{1}{2B}(1 - p_z^2) - \frac{\Gamma}{2} p_y$$

if BΓ<1

$$\mathbf{p}^{eq} = (0, B\Gamma, \sqrt{1-(B\Gamma)^2})$$

else

tumbling: no equilibrium

In agreement with Durham et al., science (2009): Shear can induce gyrotactic trapping!

THANK YOU FOR YOUR KIND ATTENTION!