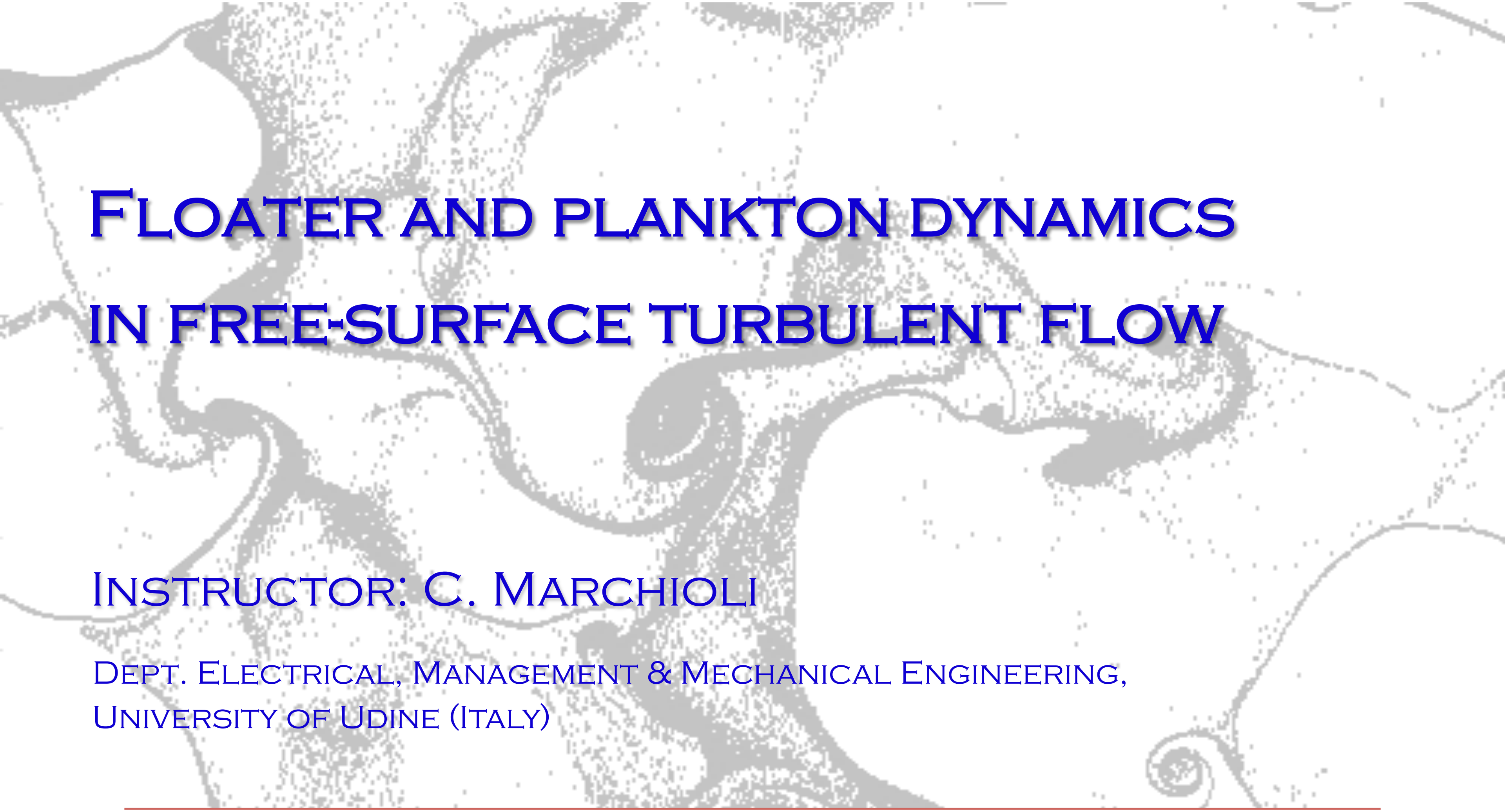
Multiphase Flow Laboratory
University of Udine

Envirnomental Transport Phenomena

LM in Ingegneria dell’Ambiente e dell’Energia



Floater and plankton dynamics in free-surface turbulent flow

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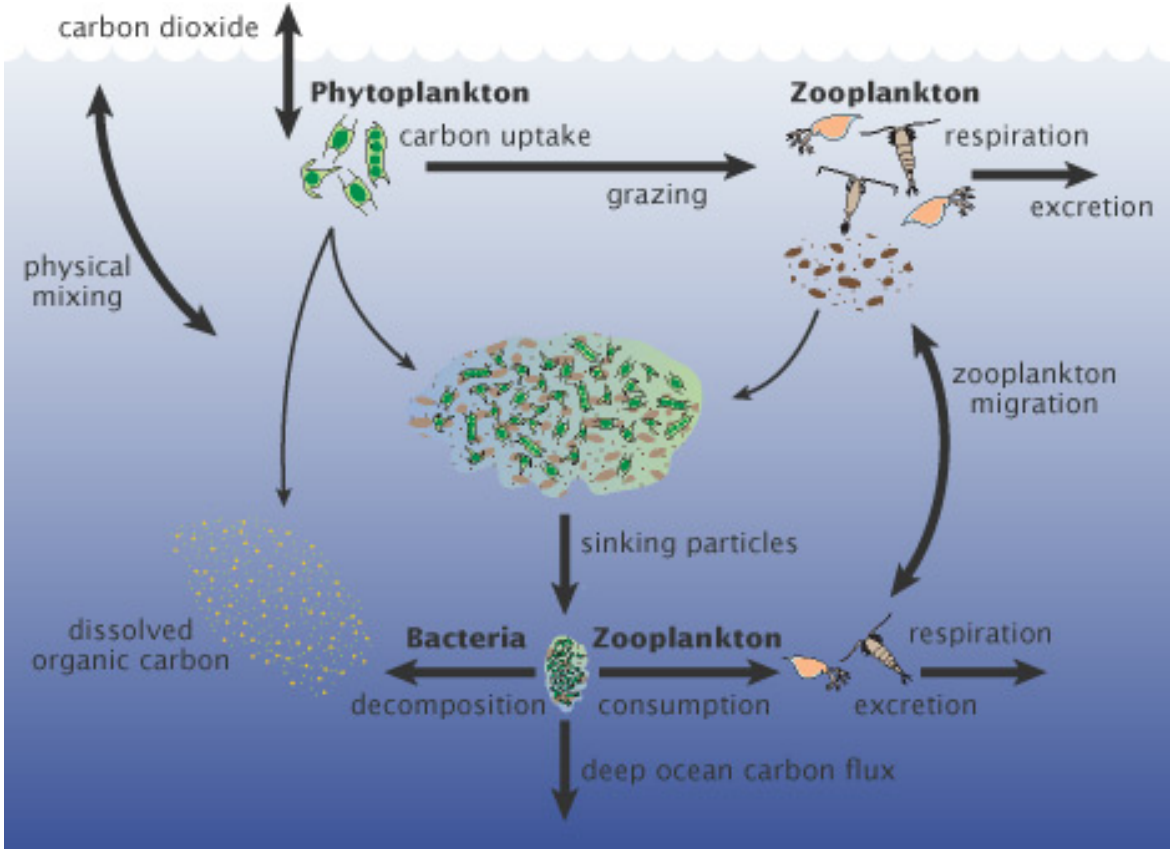
University of Udine (Italy)

Credits: A. Soldati, F. Zonta, S. Lovecchio

Motivation: Plankton dynamics near a free surface

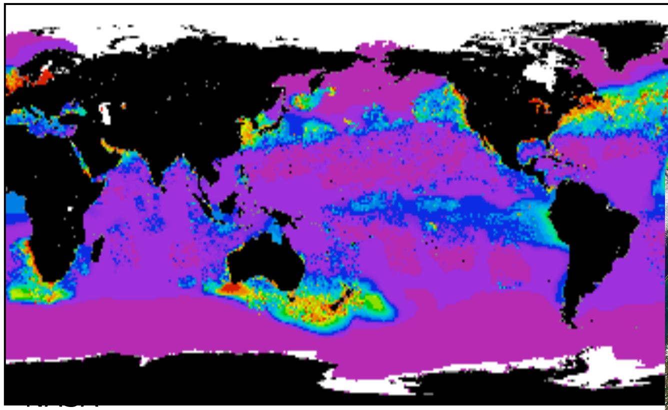


Phytoplankton is the photosynthetic part of plankton

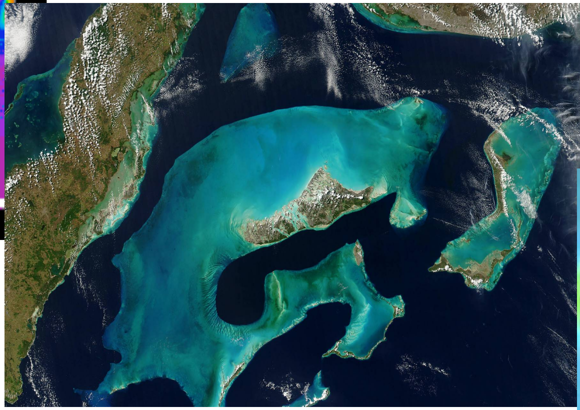
- primary production: organic compounds from CO_2
- important part of the global carbon cycle
- provides 50% of the earth's oxygen
- sustains the aquatic food web

MOTIVATION: PLANKTON DYNAMICS NEAR A FREE SURFACE

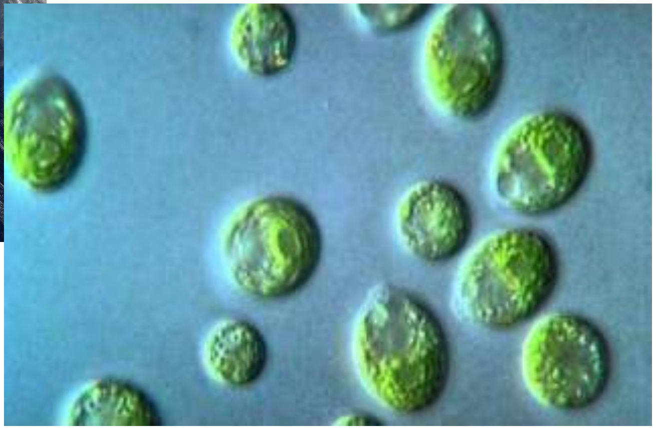
PLANKTON PATCHINESS OCCURS AT DIFFERENT SCALES → NO UNIQUE EXPLANATION



10^7 m



10^3 m



10^{-5} m

BRIDGE THE GAP:

- SWIMMING
- COLLECTIVE POPULATION DYNAMICS
- TURBULENT TRANSPORT

ROLE OF SURFACE TURBULENCE STILL UNCLEAR!

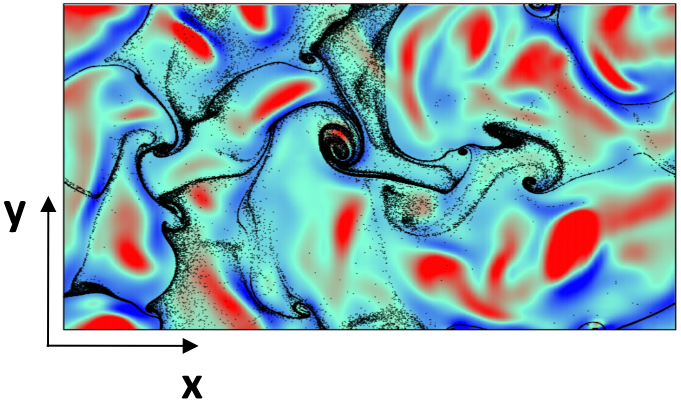
Outline of the presentation

PART 1: Passive particles at a free-surface

Phytoplankton cells passively transported by the flow

1A. Clustering at the free-surface turbulence subject to wind stress

1B. Clustering at the free-surface turbulence subject to stratification

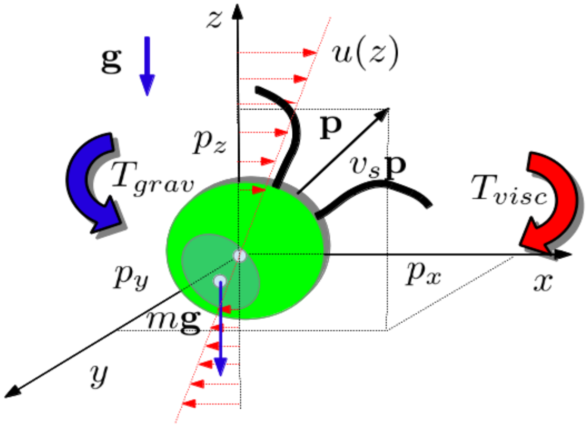


PART 2: Active particles at a free-surface

Self-propelled phytoplankton cells

2A. Influence of wind stress on plankton surfacing

2A. Influence of wind stress on plankton surfacing



FIL ROUGE

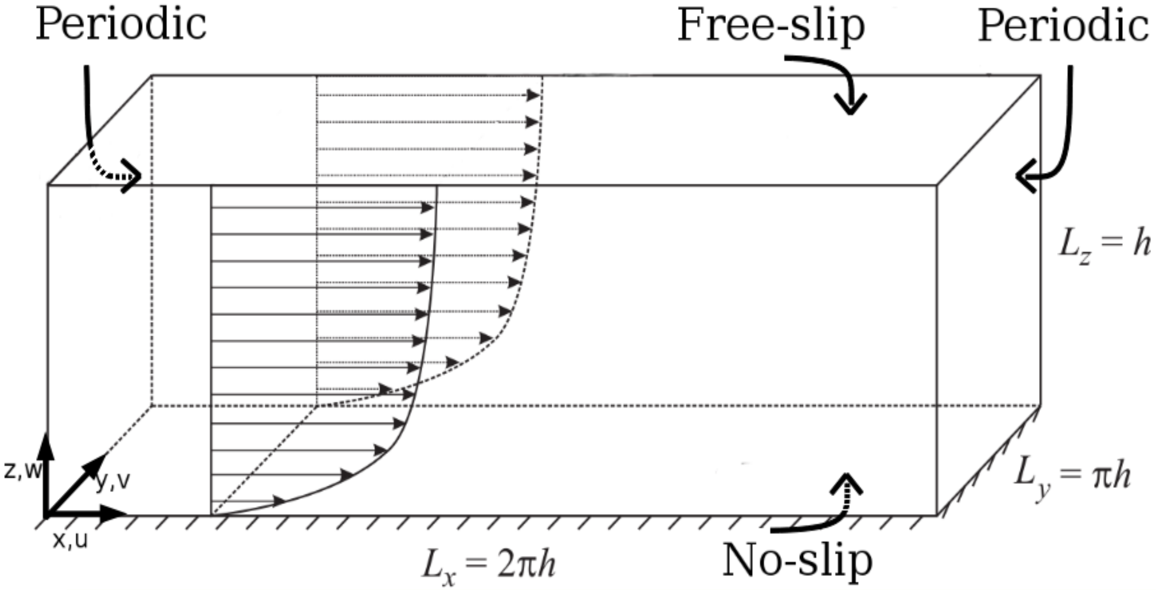
PART 1:

PASSIVE PARTICLES AT A FREE-SURFACE

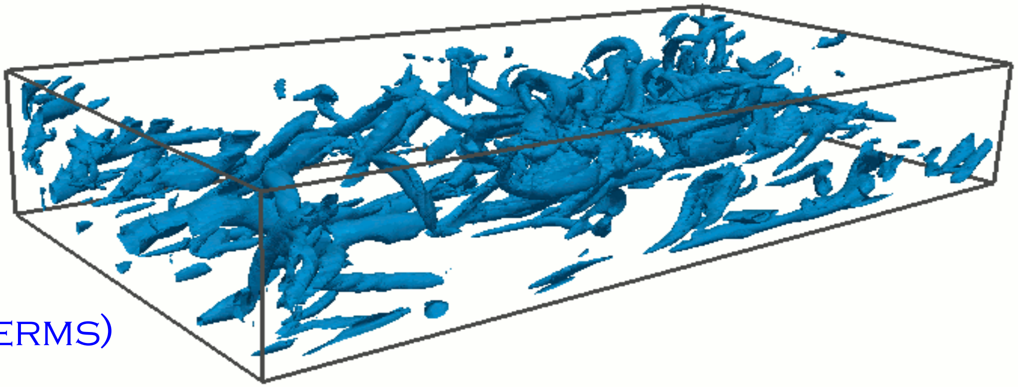
Physical problem and Modelling approach

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, 510**
- Channel size: **$L_x \times L_y \times L_z = 4\pi h \times 2\pi h \times 2h$**
- Pseudo-spectral DNS
- Time intergration:
  Adams-Bashforth (convective terms)
  Crank-Nicolson (viscous terms)



Physical problem and Modelling approach

Lagrangian particle tracking:

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

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

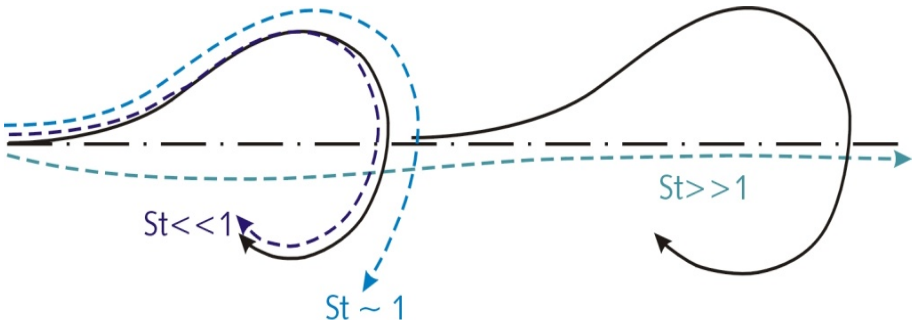
Particle Timescale – $\tau_P = d_P^2\, \rho_P / 18\, \mu$

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

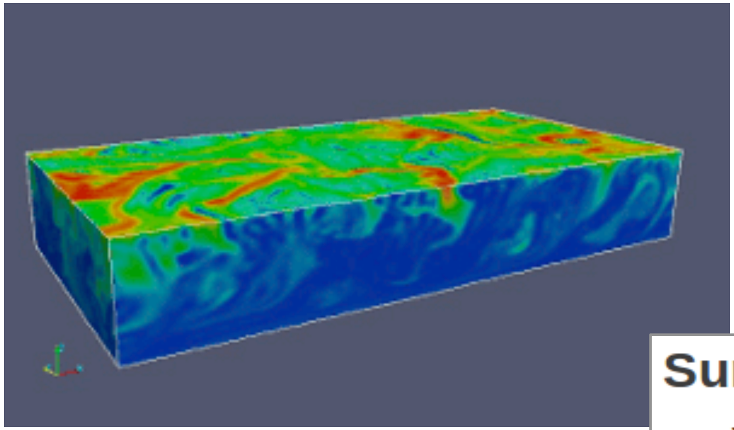
Particle Stokes number, $St = \tau_P/\tau_F$

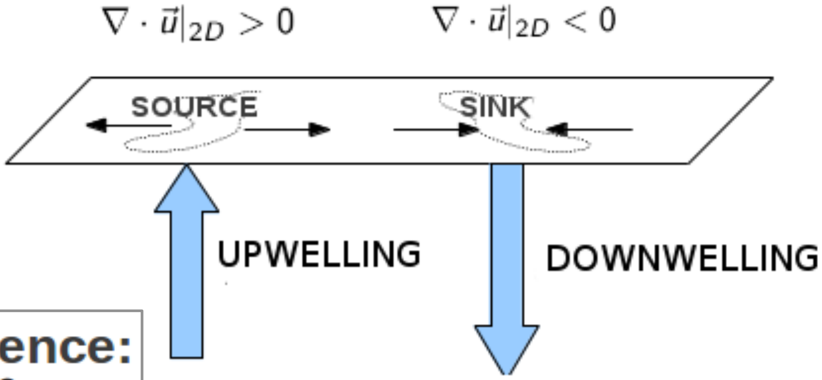
Re_τ	$St=\tau_p\cdot\nu/u_\tau^2$		
171	0.064	0.114	0.121
509	0.562	1.013	1.069
	S=0.5	0.9	0.95

S=particle-to-fluid density ratio



TOPOLOGY OF FREE-SURFACE TURBULENCE



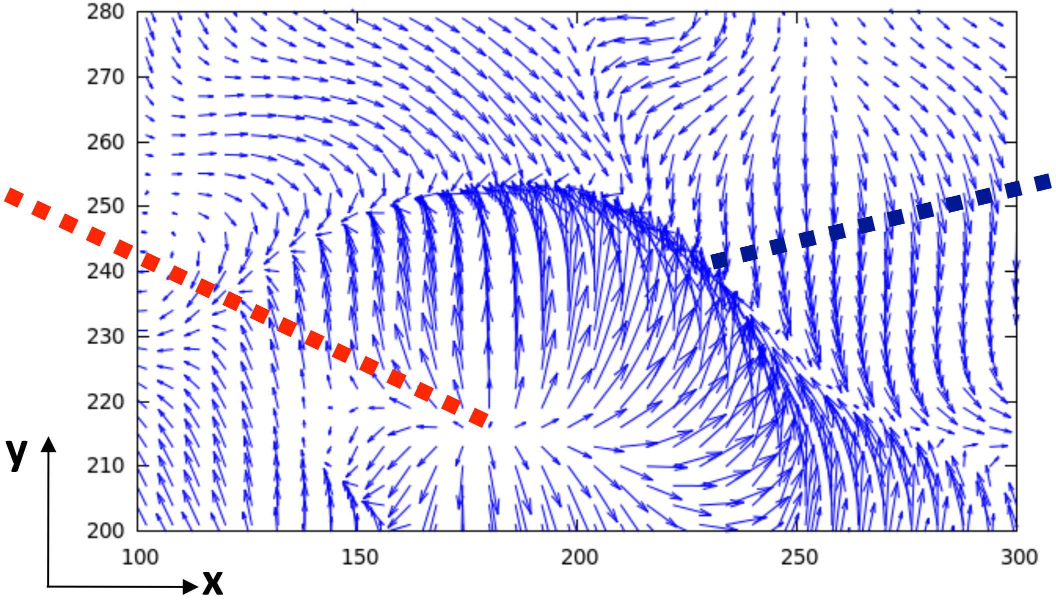


Surface divergence:

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

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

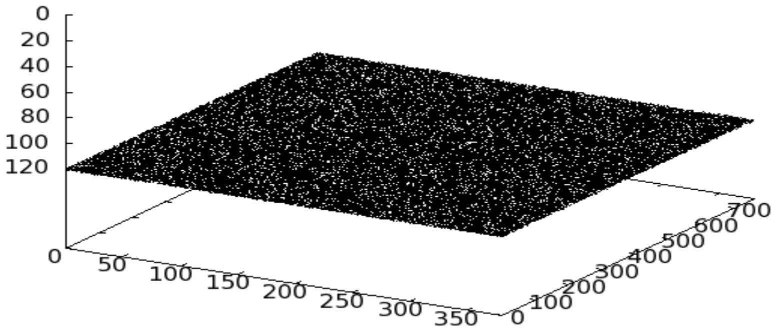
Velocity source

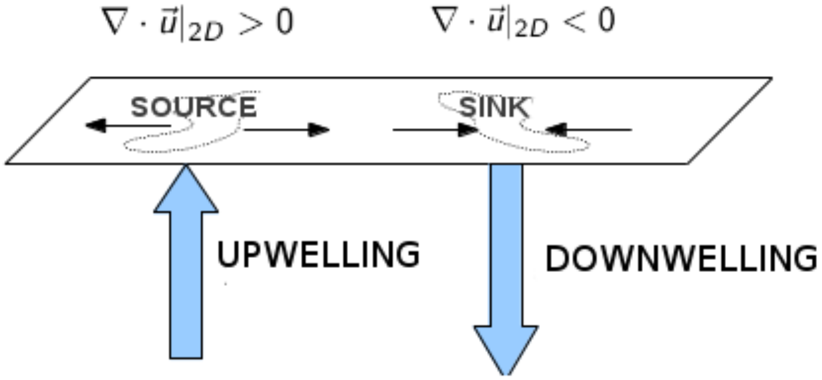


$$\boxed{\nabla_{2D} < 0}$$

Velocity sink

TOPOLOGY OF FREE-SURFACE TURBULENCE





$\nabla \cdot \vec{u}|_{2D} > 0$

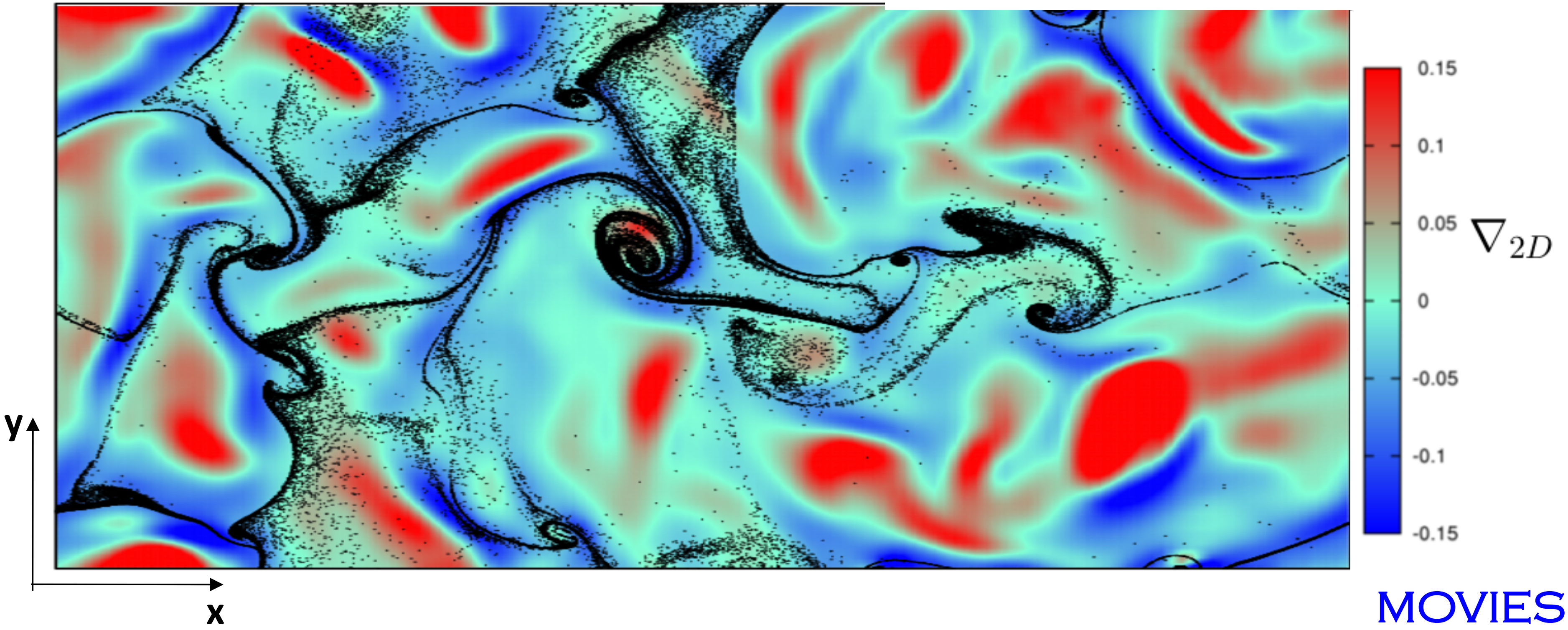
$\nabla \cdot \vec{u}|_{2D} < 0$

SOURCE

SINK

UPWELLING

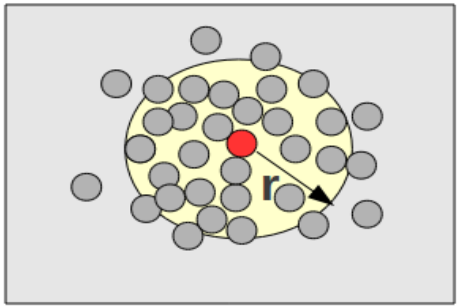
DOWNWELLING



MOVIES

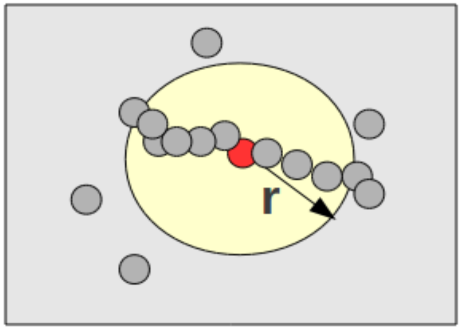
TOPOLOGY OF PARTICLE CLUSTERS AT THE FREE SURFACE

PARTICLES DISTRIBUTED:



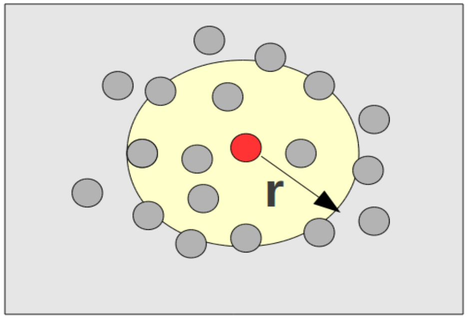
- UNIFORMLY OVER A SURFACE

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



- UNIFORMLY ALONG A LINE

$$N(r) \simeq r$$



- IN GENERAL

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

ν IS THE CLUSTERS' FRACTAL DIMENSION (CORRELATION DIM.)

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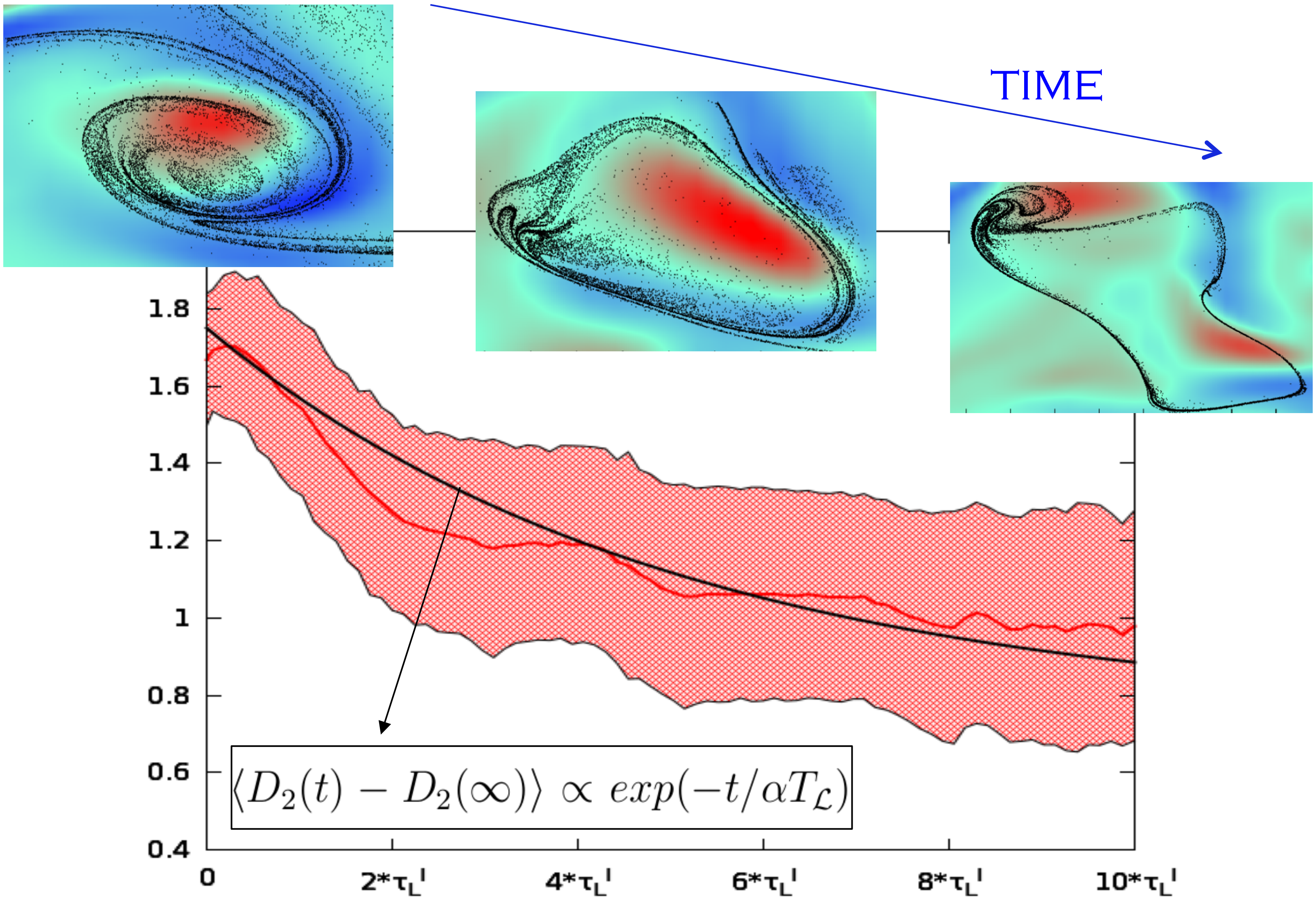
TOPOLOGY OF PARTICLE CLUSTERS AT THE FREE SURFACE



$$\langle D_2(t) - D_2(\infty)\rangle \propto exp(-t/\alpha T_{\mathcal{L}})$$

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

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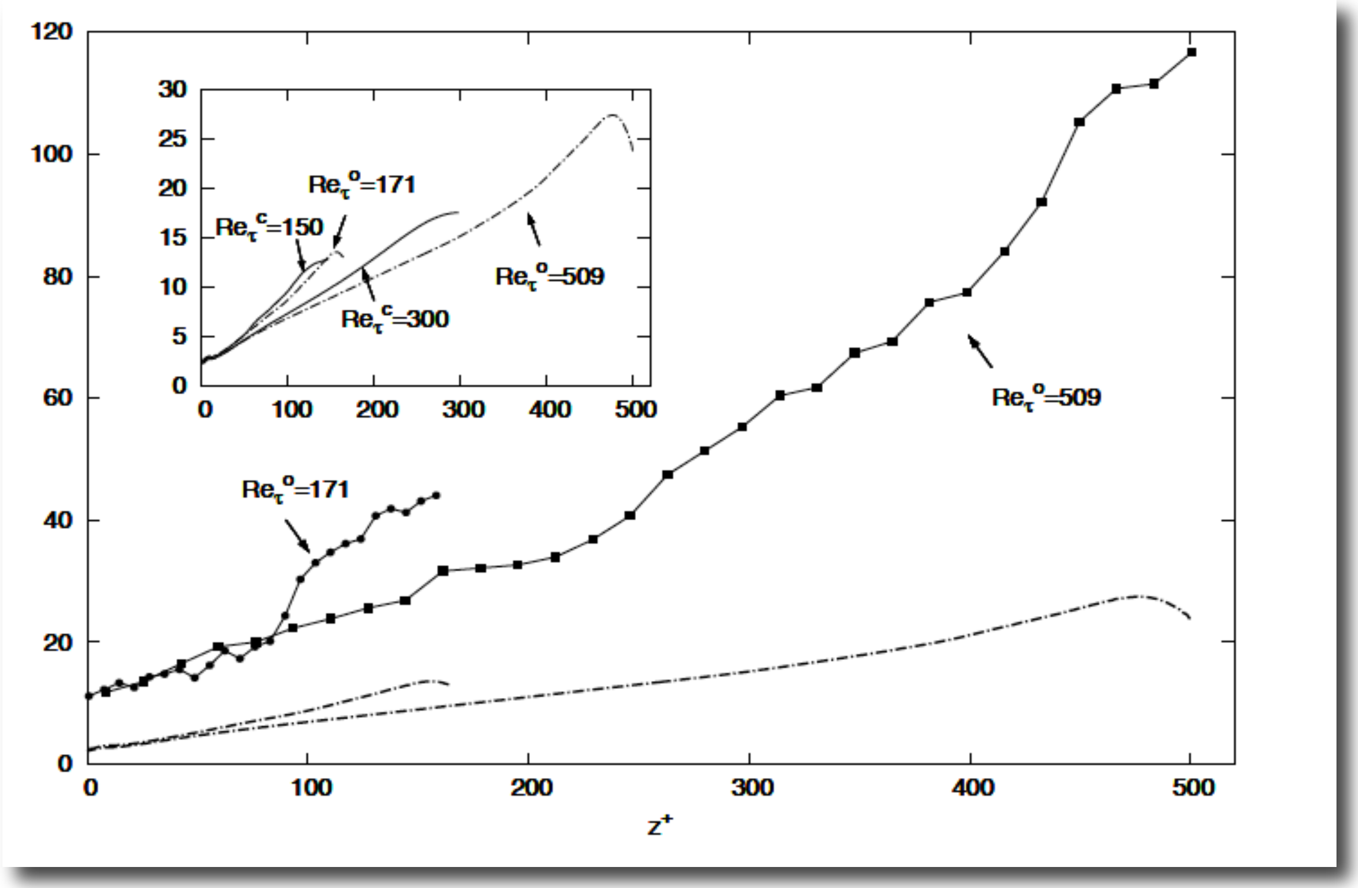
TOPOLOGY OF PARTICLE CLUSTERS AT THE FREE SURFACE

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



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

↓

CLUSTERS ARE LONG-LIVED STRUCTURES!

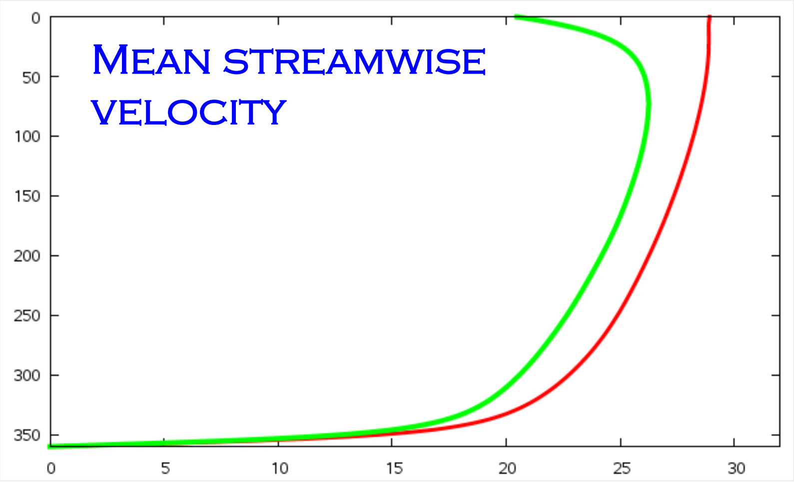
RESULTS FROM LOVECCHIO ET AL., PHYS. REV. E (2013)

FIL ROUGE

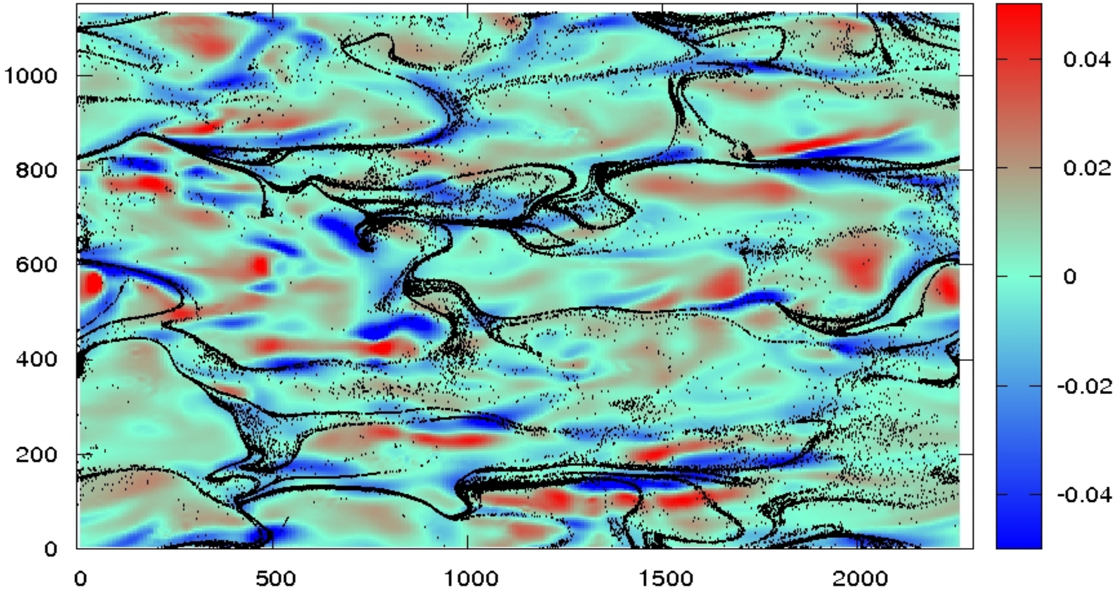
PART 1A:

CLUSTERING AT A WIND-SHEARED FREE SURFACE

EFFECT OF WIND ON PARTICLES AT THE FREE-SURFACE

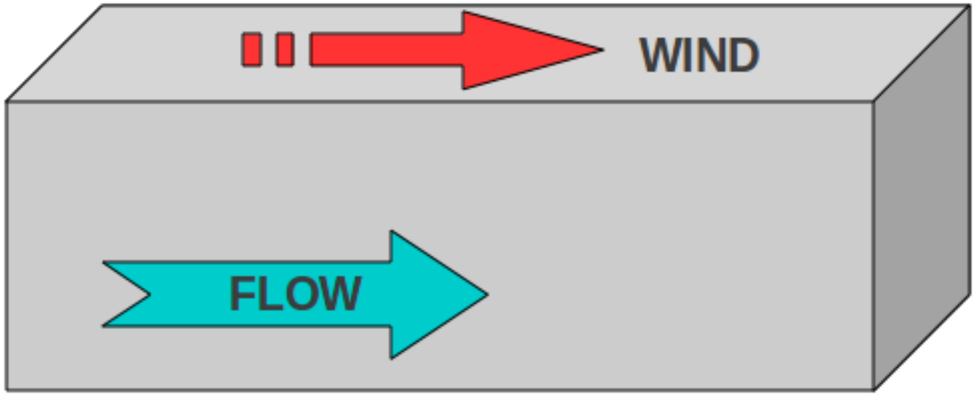


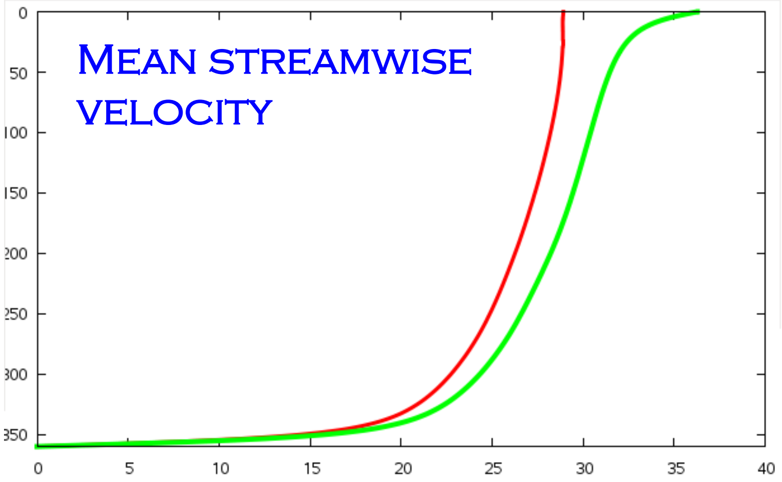
WIND OPPOSITE TO THE FLOW DIRECTION



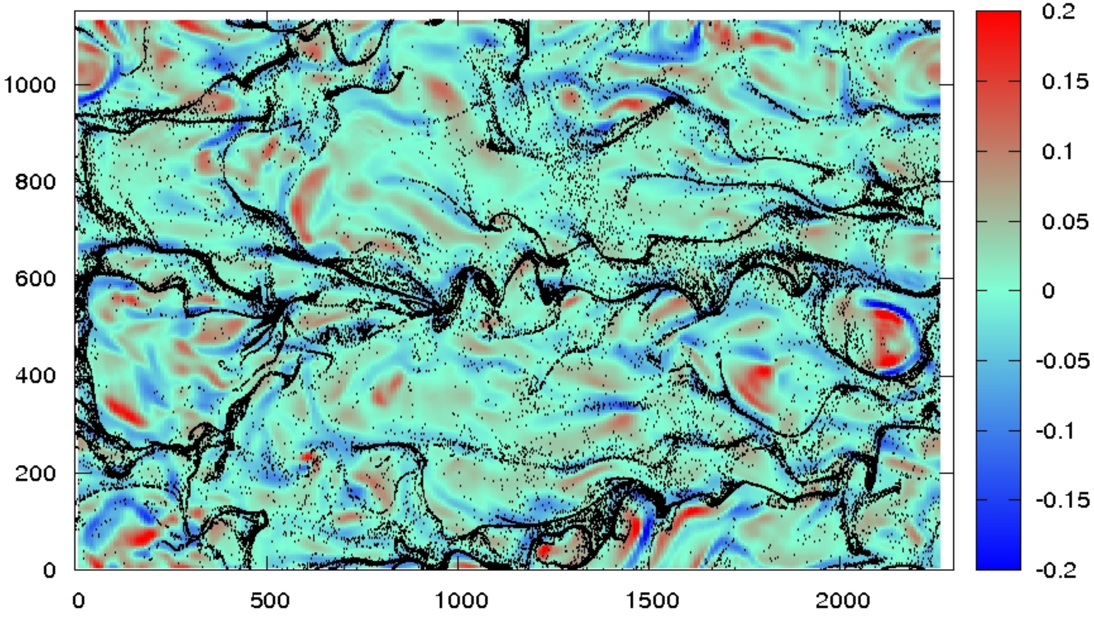
MOVIE

Effect of wind on particles at the free-surface



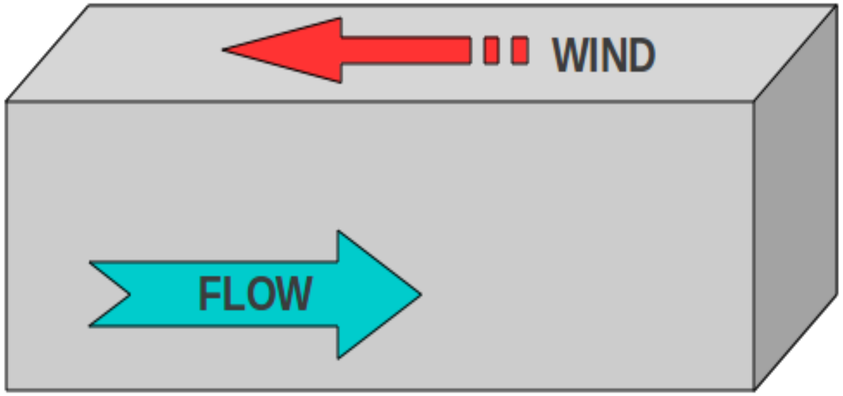

Mean streamwise velocity

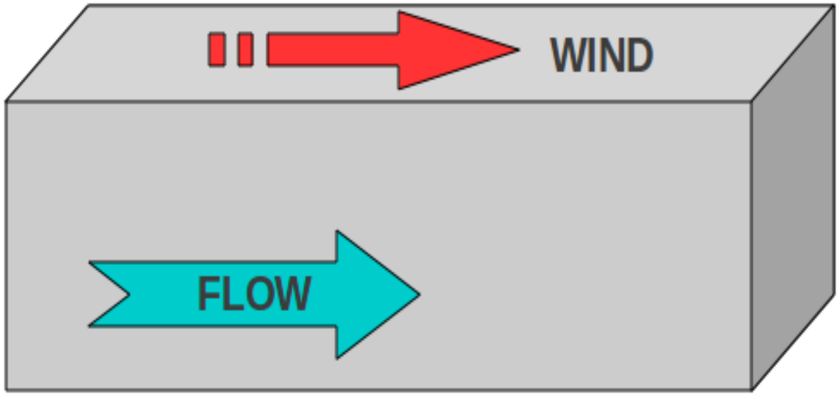
Wind along the flow direction

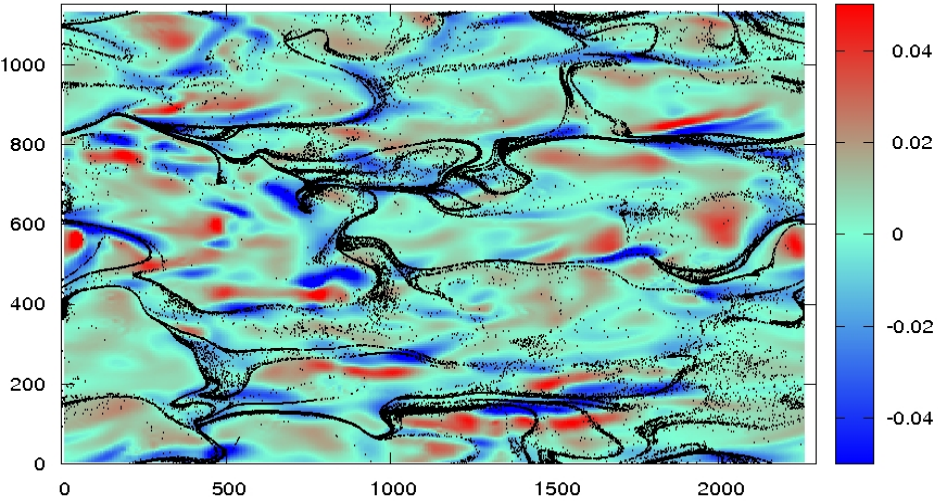


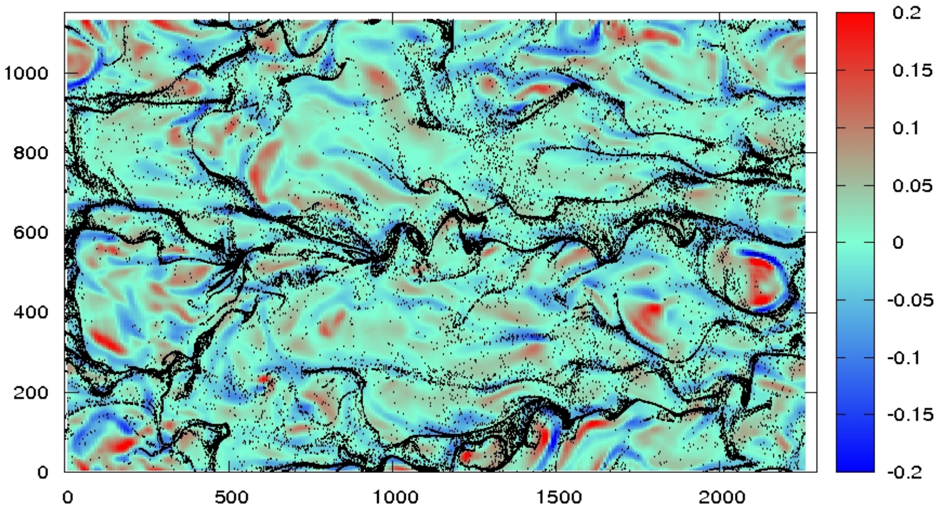
MOVIE

EFFECT OF WIND ON PASSIVE PARTICLES AT THE FREE-SURFACE









DIFFERENT TOPOLOGY OF FILAMENTS AT THE SURFACE

FIL ROUGE

PART 1B:

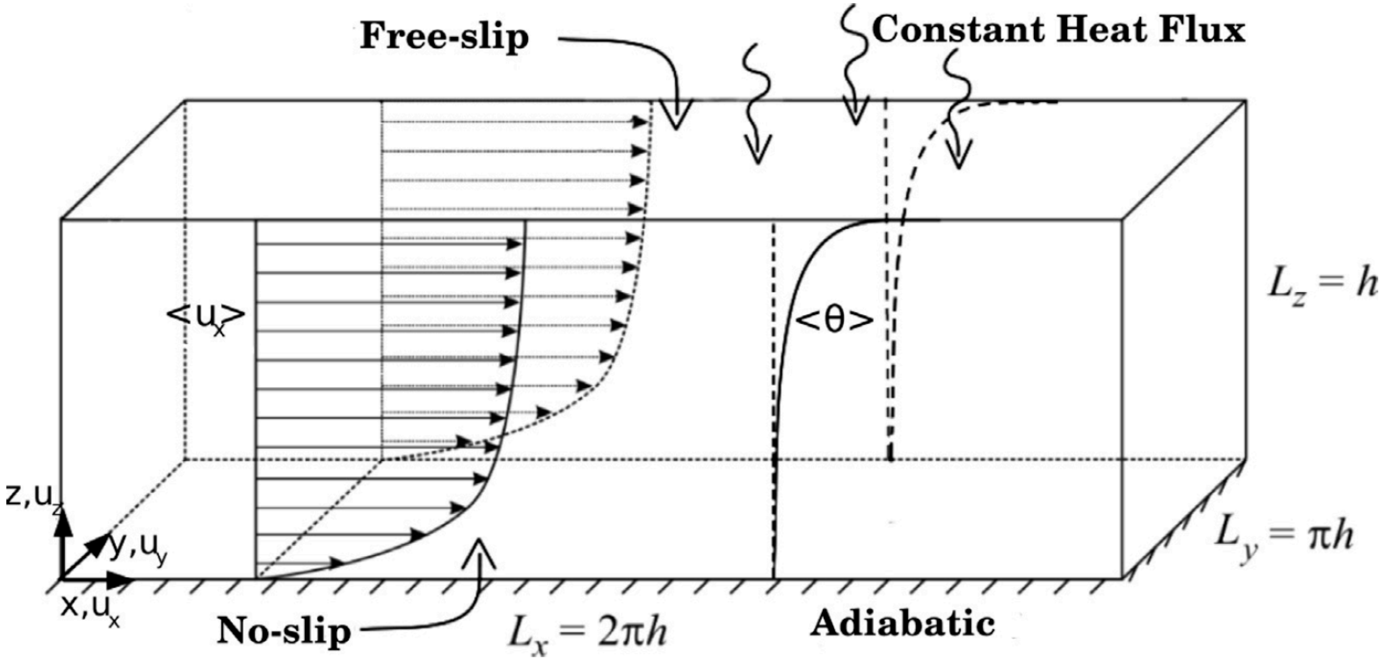
CLUSTERING AT A FREE SURFACE IN THERMALLY-STRATIFIED TURBULENCE

Fil rouge

- Physical problem and modelling approach
- Characterization of flow and temperature fields
    - Stratification effects
    - Structures at surface
- Particle surfacing and segregation
    - Surface divergence
    - Voronoi analysis
    - Time scales
- Conclusions

PHYSICAL PROBLEM AND MODELLING APPROACH

SKETCH OF THE CHANNEL FLOW CONFIGURATION:



BOUSSINESQ EQUATIONS:

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

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

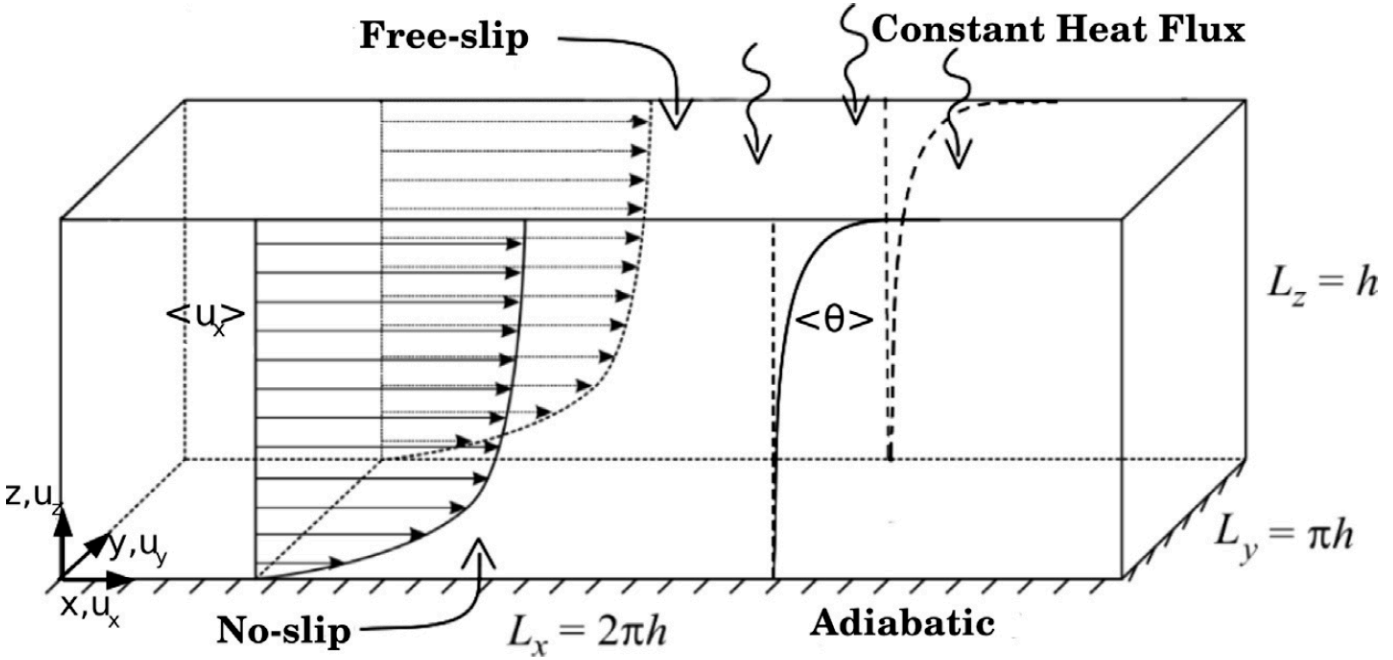
$$\frac{\partial \theta}{\partial t} + \mathbf{u} \cdot \nabla \theta = \frac{1}{Re_\tau Pr} \nabla^2 \theta - \beta_T,$$

$$\boxed{Gr = \frac{g \beta h^3}{\nu^2} \left. \frac{\partial \theta}{\partial z} \right|_s}$$

$$\boxed{Pr = \frac{\mu c_p}{\lambda}}$$

PHYSICAL PROBLEM AND MODELLING APPROACH

SKETCH OF THE CHANNEL FLOW CONFIGURATION:



SIMULATION PARAMETERS FOR THE FLUID:

Re_τ^*	171	
$u_\tau\ (m/s)$	$1.5 \cdot 10^{-3}$	
height channel (m)	$2. \cdot 10^{-2}$	
Ri_τ	165	500
Pr	5	
Ra	$4.82 \cdot 10^6$	$7.23 \cdot 10^6$

$$Gr = \frac{g\beta h^3}{\nu^2} \left.\frac{\partial\theta}{\partial z}\right|_s$$

$$Pr = \frac{\mu c_p}{\lambda}$$

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Physical problem and Modelling approach

Lagrangian particle tracking:

- $$\frac{dx_i}{dt}=v_i$$
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- One-way coupling
- Fully-elastic particle-wall collision
- Time integration: 4th order Runge-Kutta
- Fluid velocity Interpolation: 6th order Lagrange polynomials

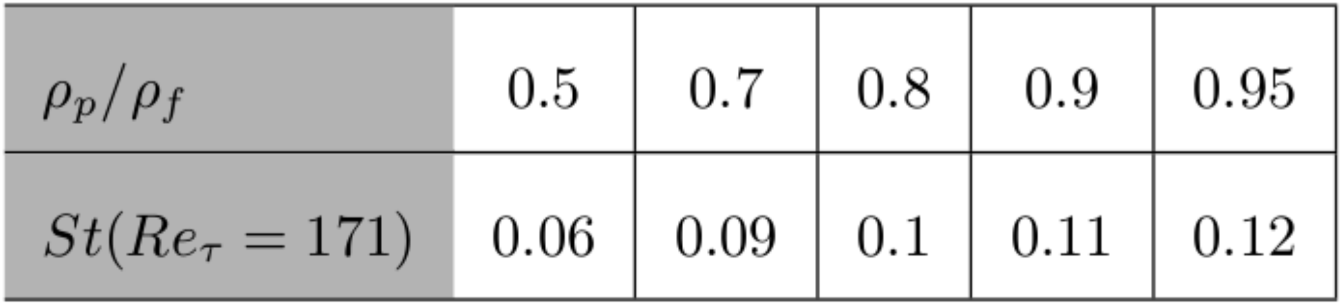
Particle Timescale – $\tau_P = d_P^2\,\rho_P / 18\,\mu$

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

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

Simulation parameters for the buoyant floaters

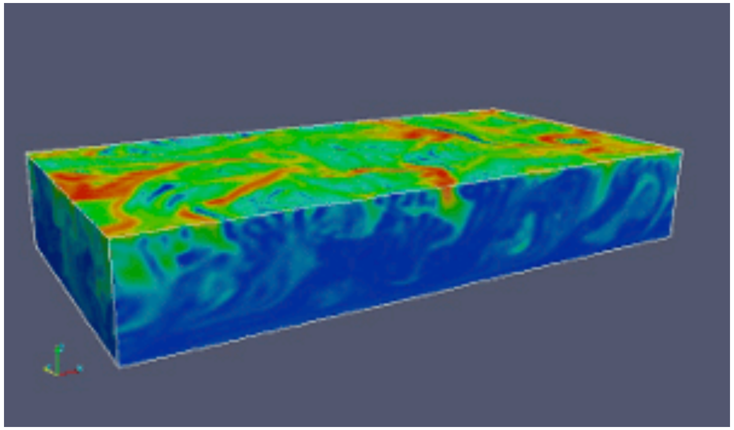
Particle-to-fluid density ratio



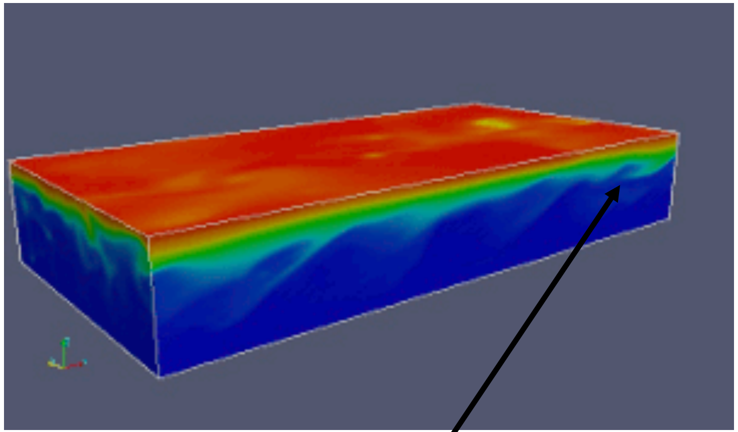
ρ_p/ρ_f	0.5	0.7	0.8	0.9	0.95
$St(Re_\tau = 171)$	0.06	0.09	0.1	0.11	0.12

Temperature Field

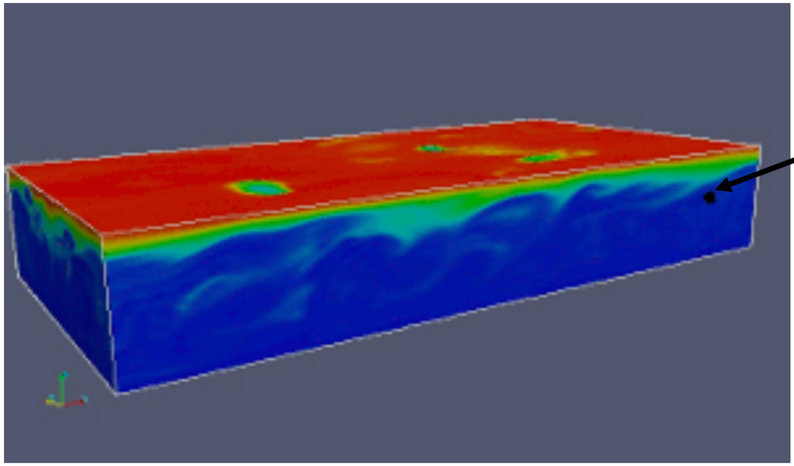
$Ri_{\tau}=0$



$Ri_{\tau}=165$



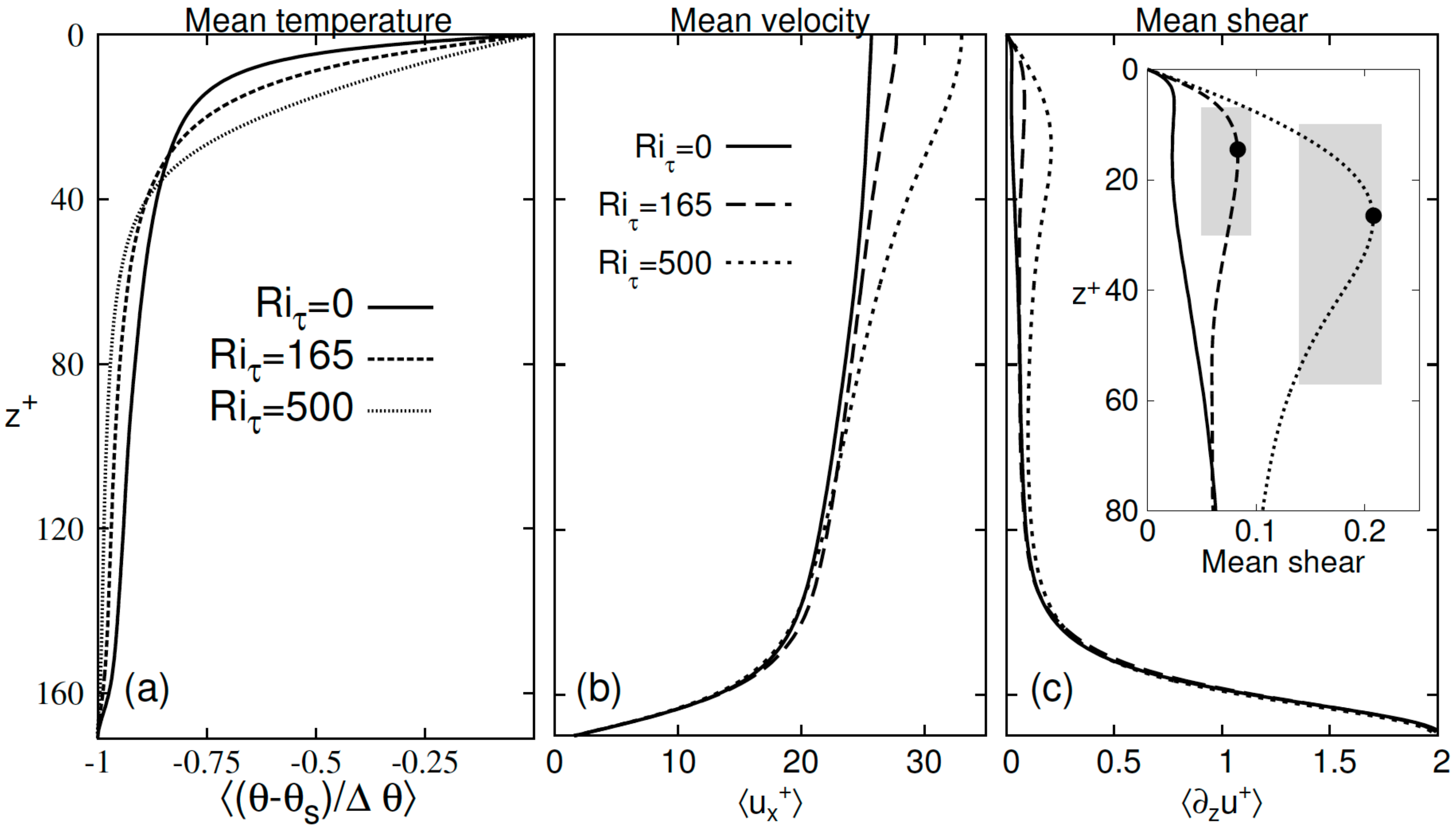
$Ri_{\tau}=500$



Thermocline (density barrier):

Upwellings are blocked by the thermocline and cannot reach the free surface!

MEAN TEMPERATURE AND VELOCITY STATISTICS



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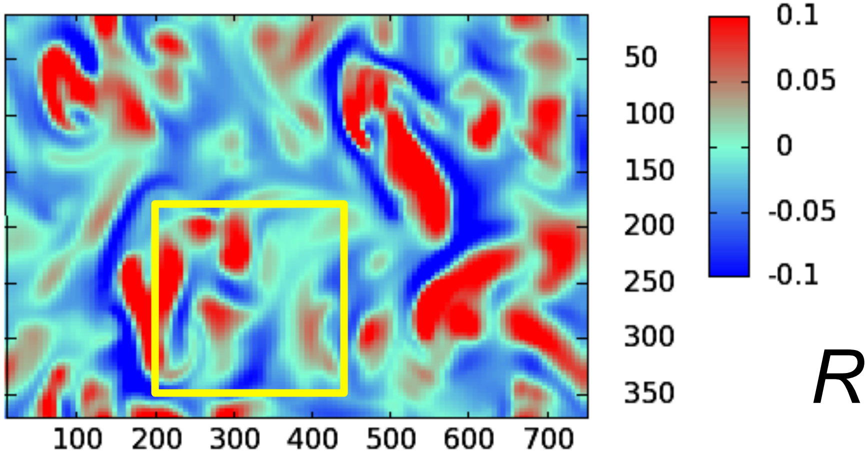
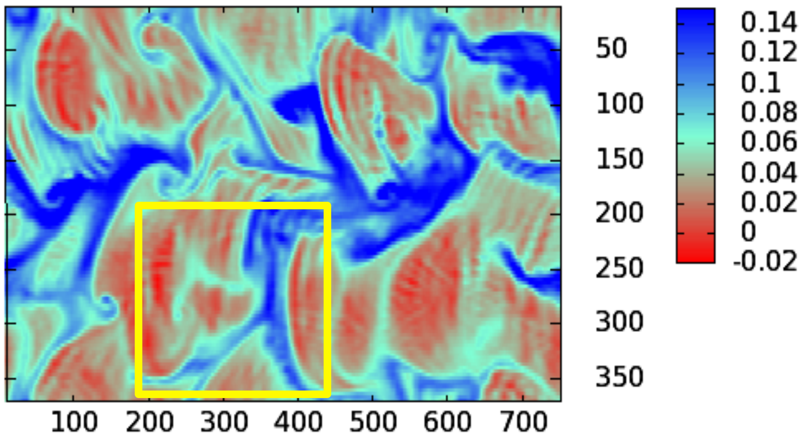
FLOW FIELD DYNAMICS AT THE FREE SURFACE

SURFACE DIVERGENCE

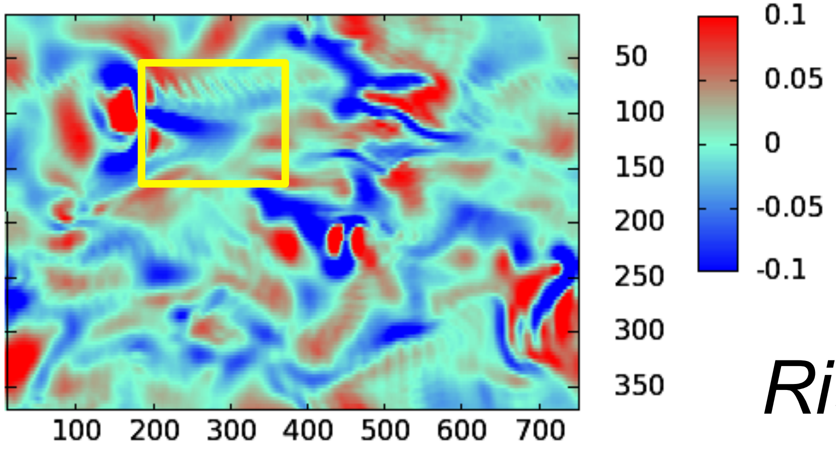
SURFACE TEMPERATURE

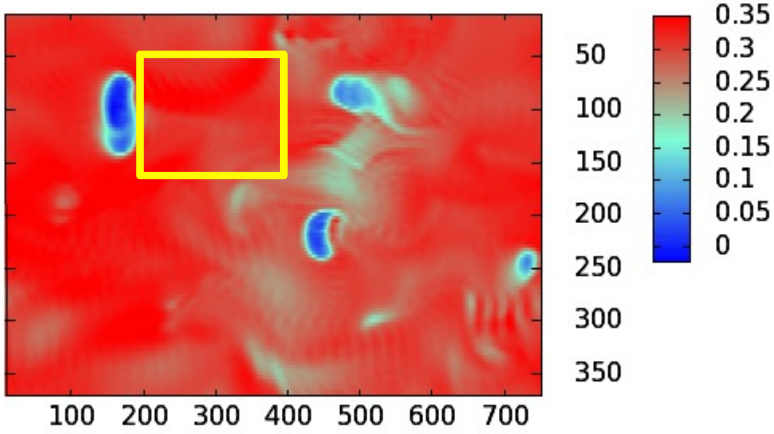




$Ri_{\tau}=0$

HIGH CORRELATION



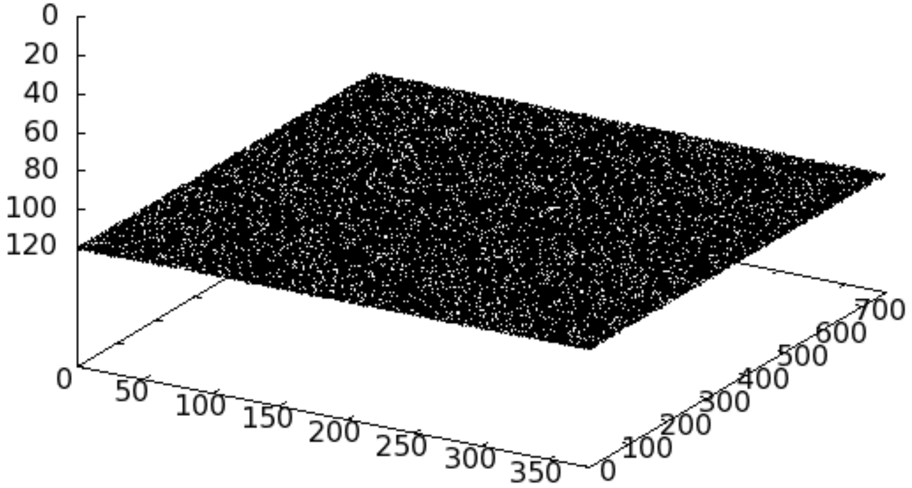


$Ri_{\tau}=500$

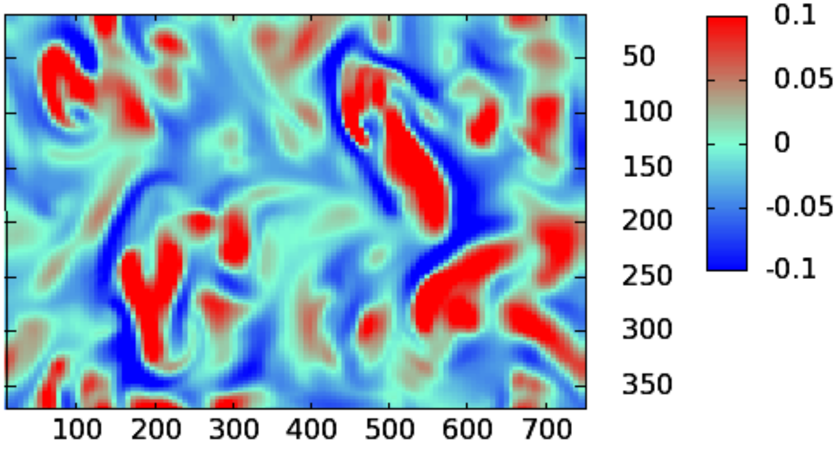
LOW CORRELATION

FLOATER SURFACING

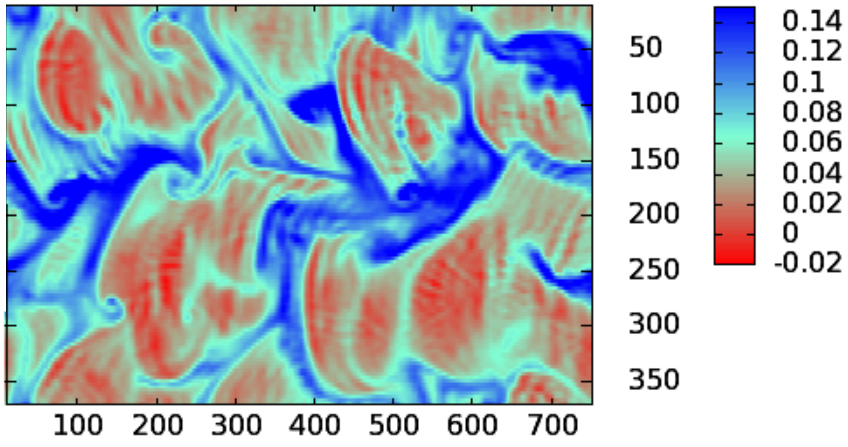
Ri_{τ}=0



SURFACE DIVERGENCE

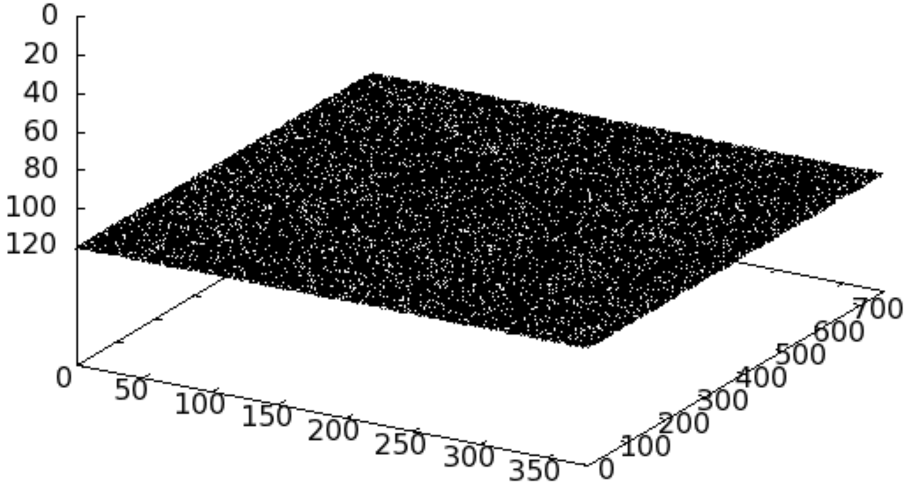


SURFACE TEMPERATURE

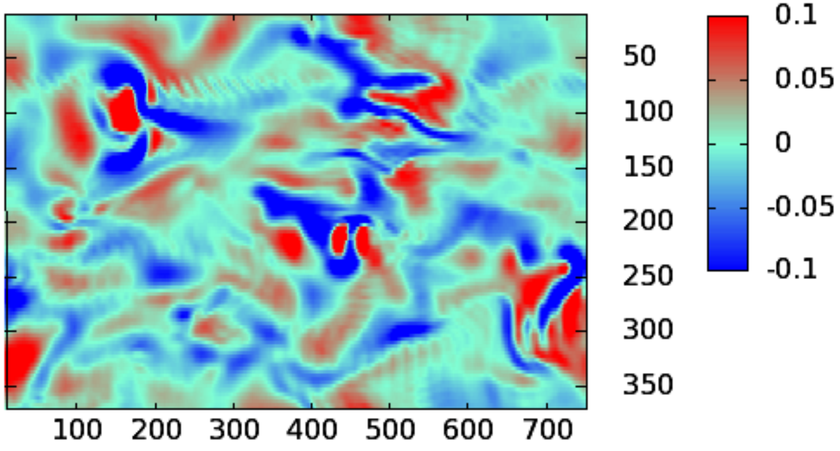


FLOATER SURFACING

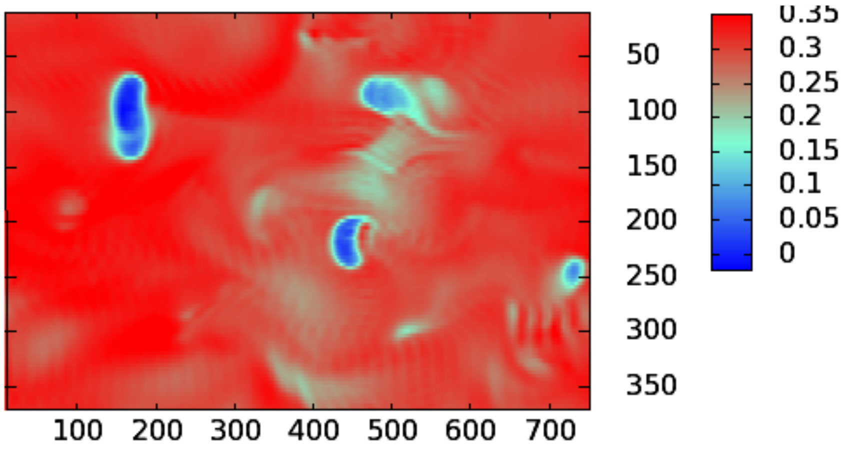
$Ri_\tau=500$



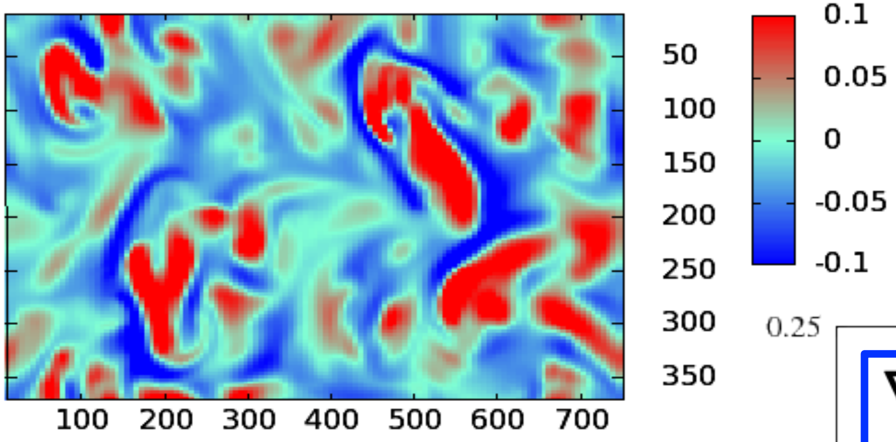
SURFACE DIVERGENCE

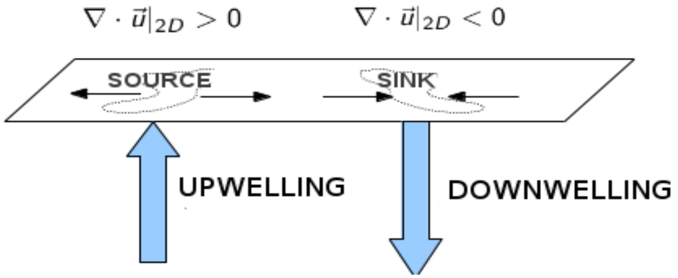


SURFACE TEMPERATURE



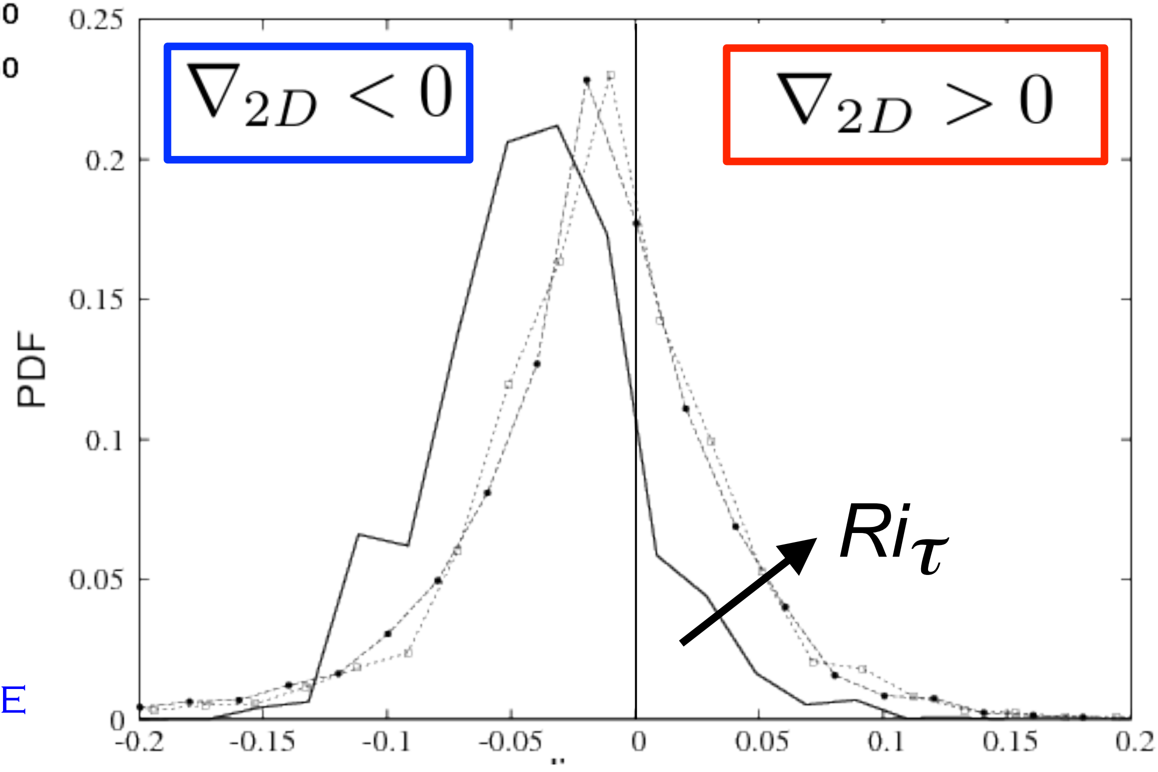
Floater clustering at the free surface





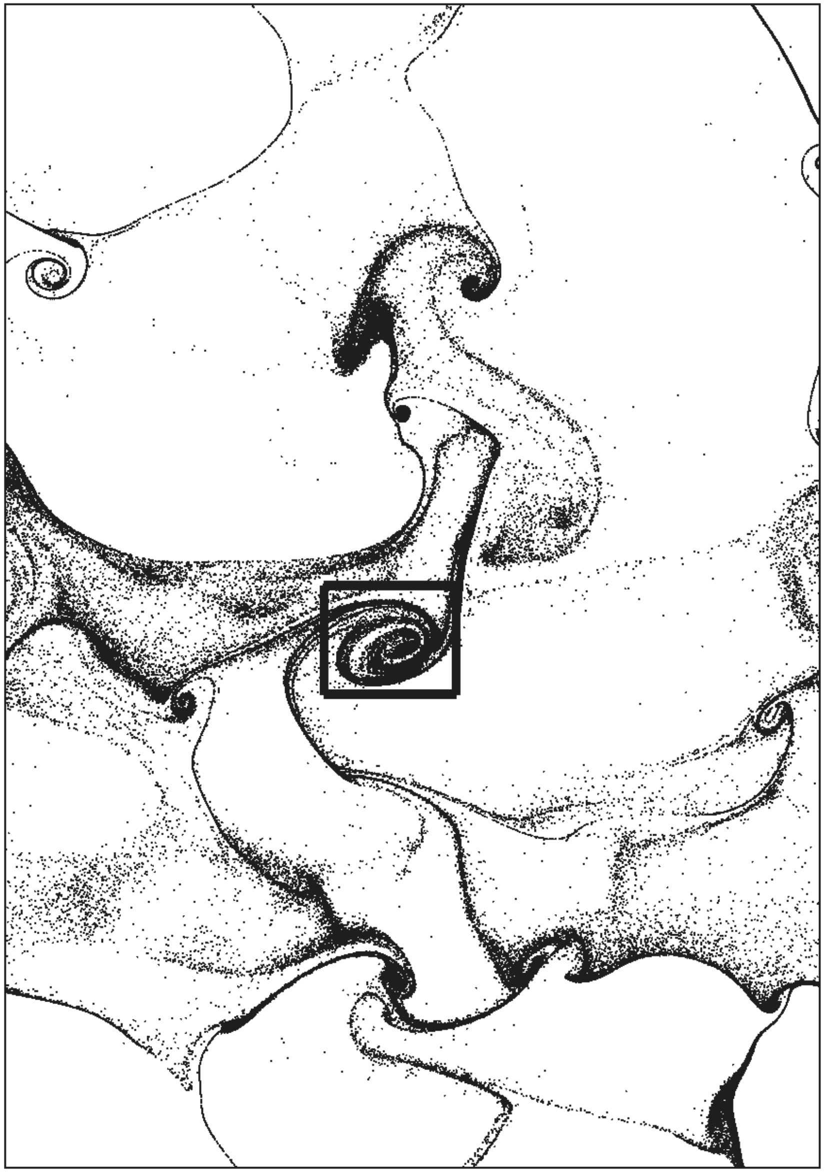
In stratified flows, floaters do not follow faithfully the flow field

No intense upwelling events occur at the free surface (due to the presence of the submarine thermocline)

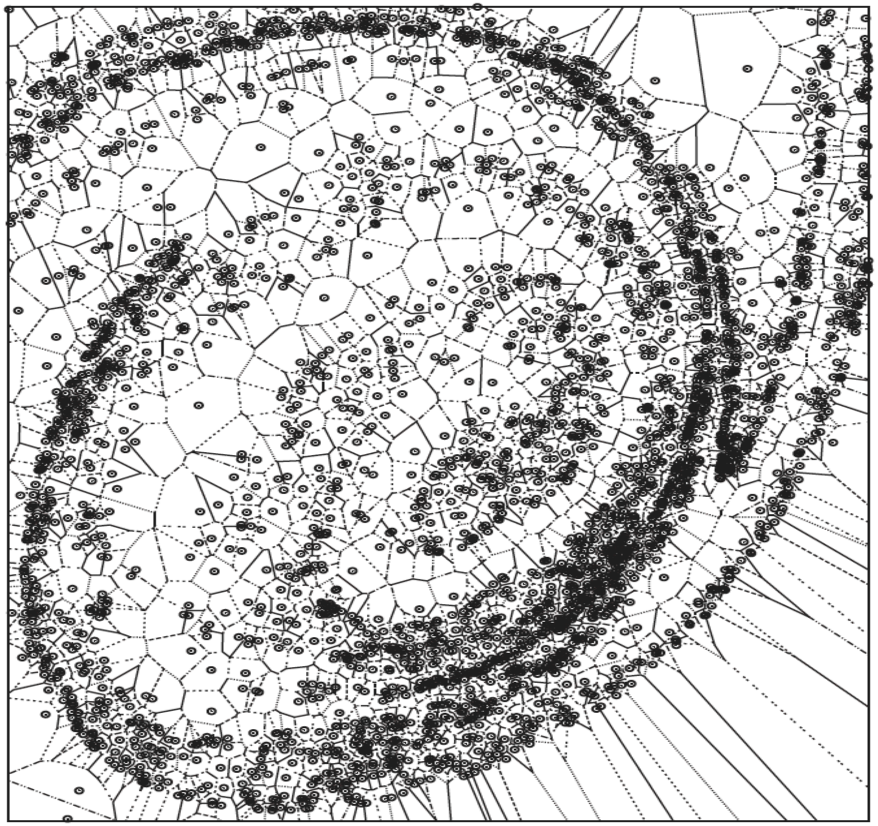


Surface divergence

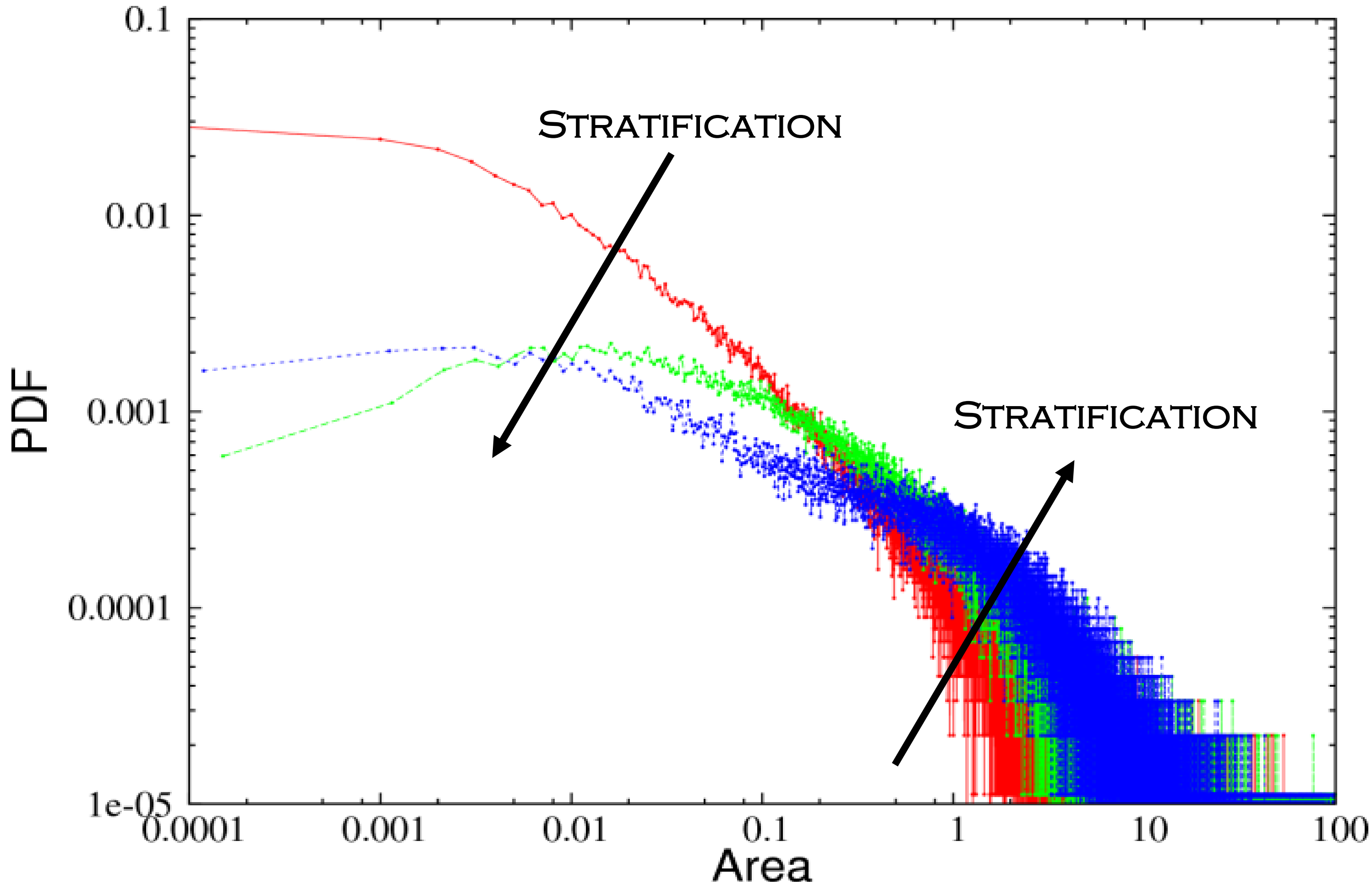
Floater clustering: A Voronoi analysis



The segments in a Voronoi Tessellation correspond to all points equidistant to the two nearest floaters.



FLOATER CLUSTERING:
A VORONOI ANALYSIS



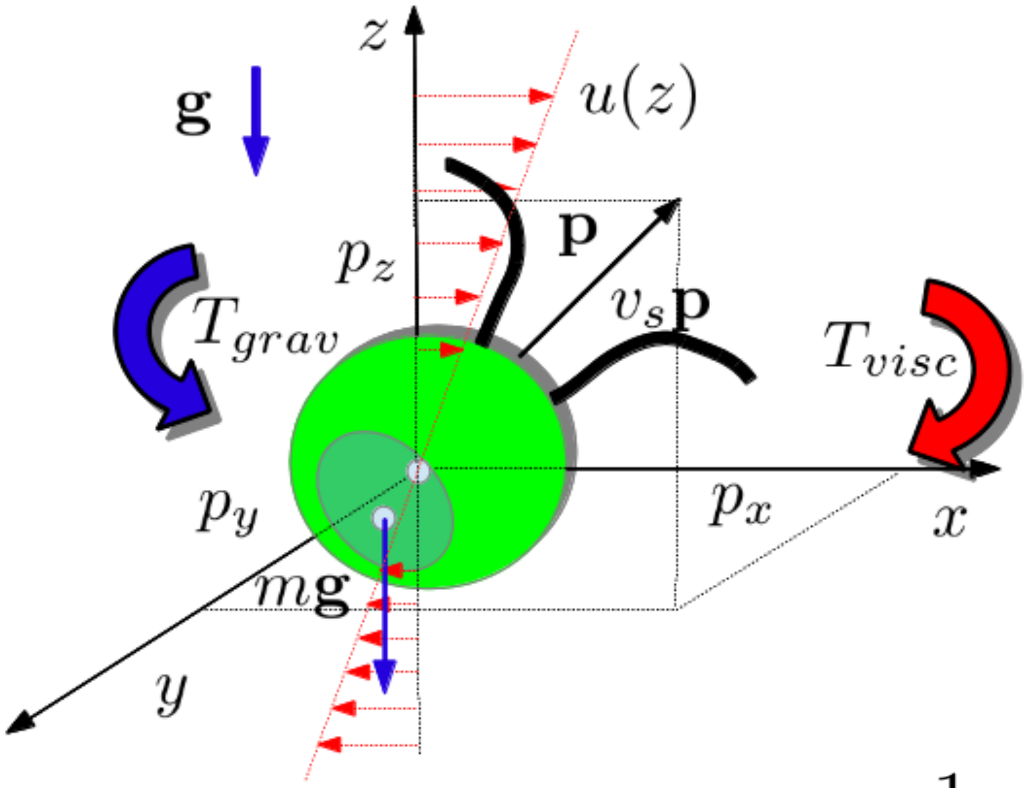
STRATIFICATION REDUCES (RESP. INCREASES) THE PROBABILITY OF FINDING VORONOI CELLS WITH SMALL (RESP. LARGE) AREA. THIS MEANS THAT STRATIFICATION REDUCES PREFERENTIAL CONCENTRATION INTO DENSE CLUSTERS

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**

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

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

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

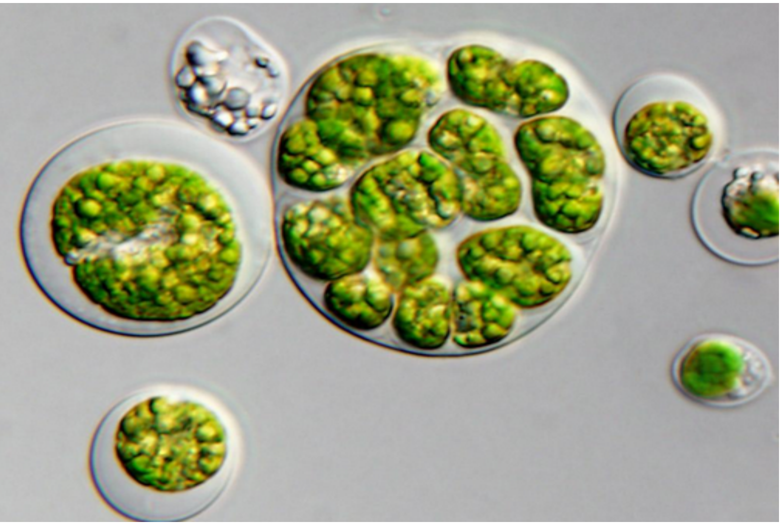
Modelling micro-swimmers
lesson learned from plankton

Two controlling parameters:

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

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

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

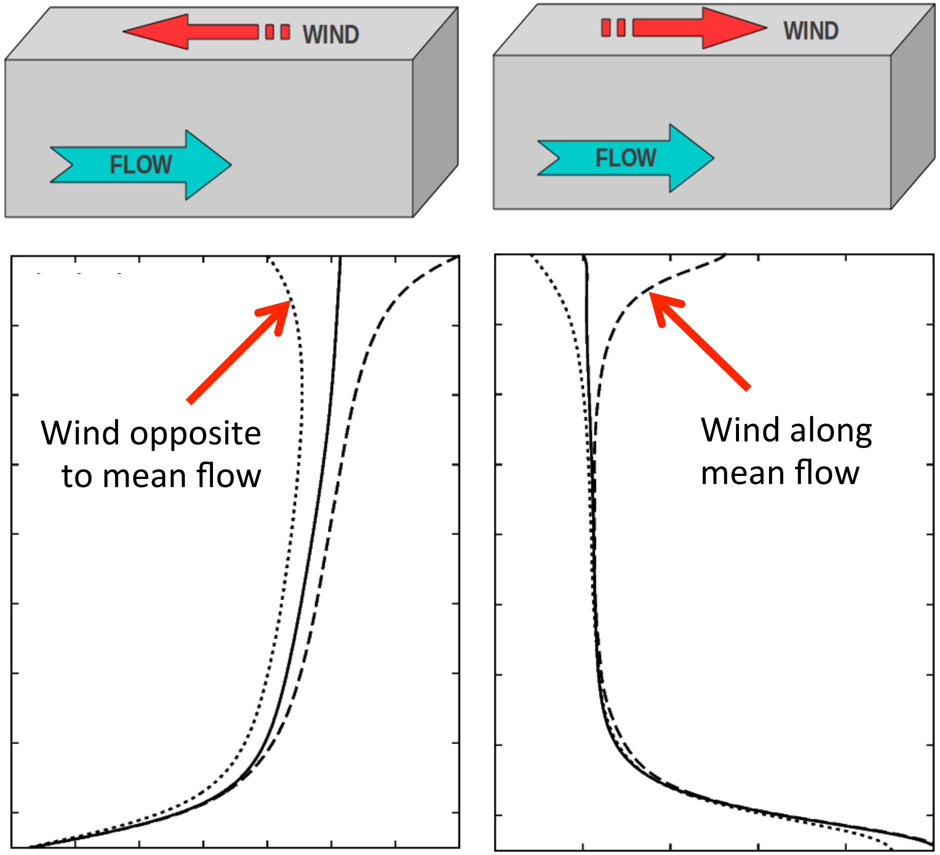
$\Psi_H = 1.13$ high gyrotaxis (fast re-orient.)

FIL ROUGE

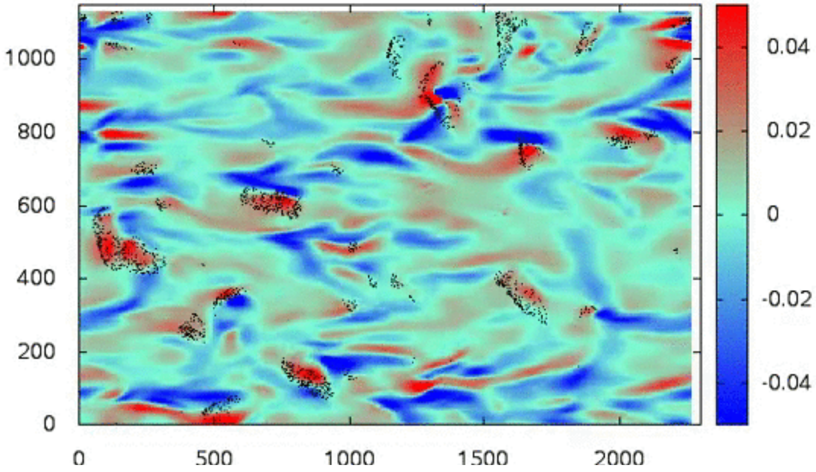
PART 2A:

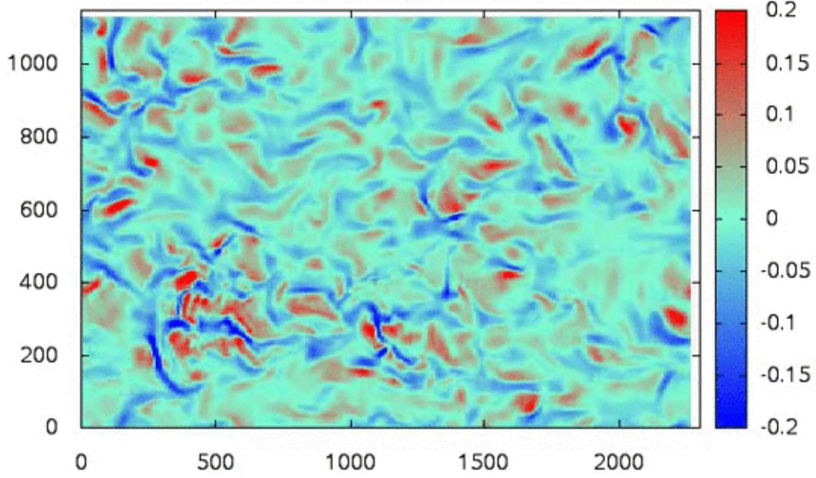
PLANKTON DYNAMICS IN WIND-SHEARED FREE-SURFACE TURBULENCE

EFFECT OF WIND-SHEARED SURFACE TURBULENCE ON SWIMMER DYNAMICS

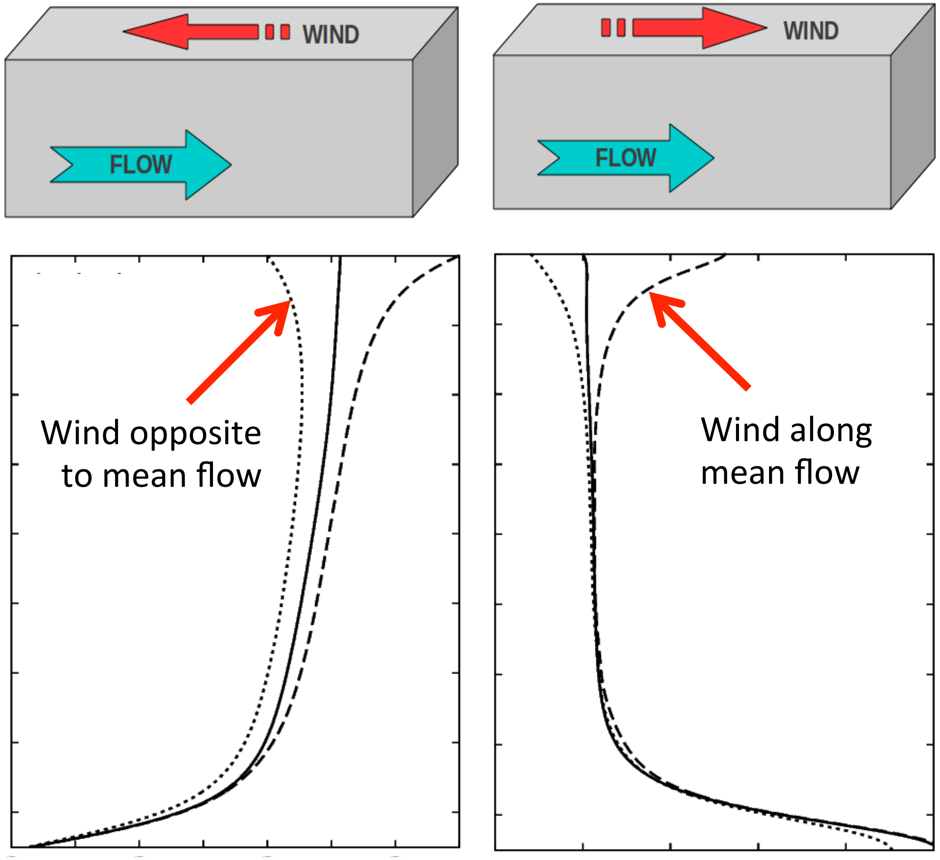


Mean streamwise velocity and mean shear


Wind opposite to mean flow


Wind along mean flow

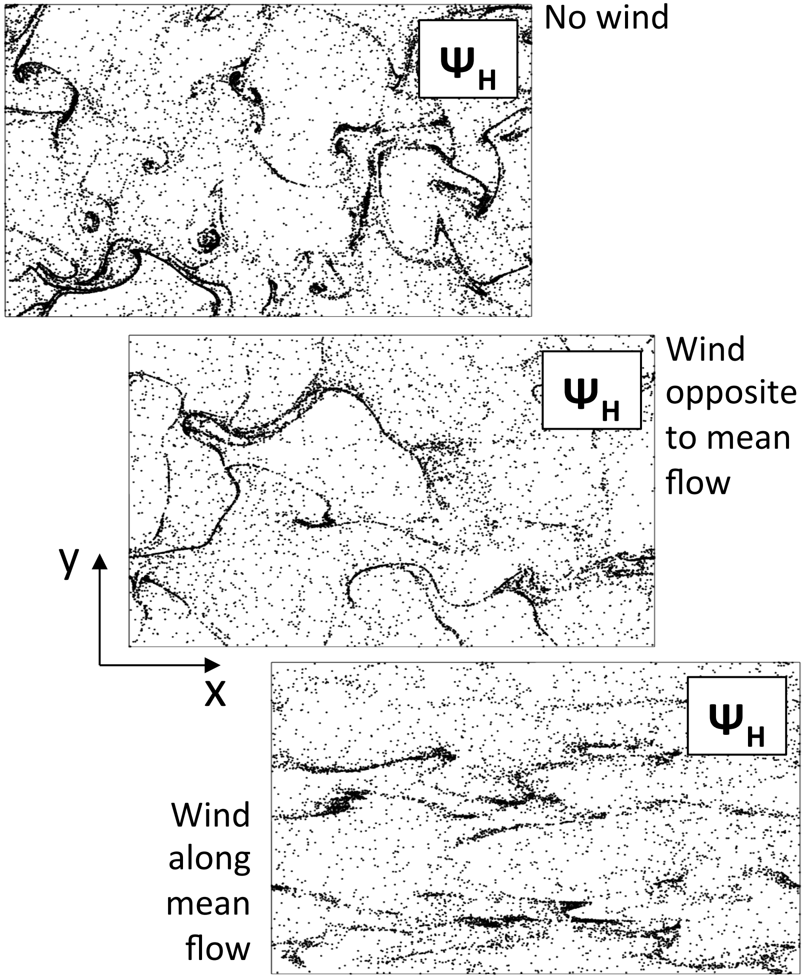
EFFECT OF WIND-SHEARED SURFACE TURBULENCE ON SWIMMER DYNAMICS



Wind opposite to mean flow

Wind along mean flow

Mean streamwise velocity and mean shear



No wind

Wind opposite to mean flow

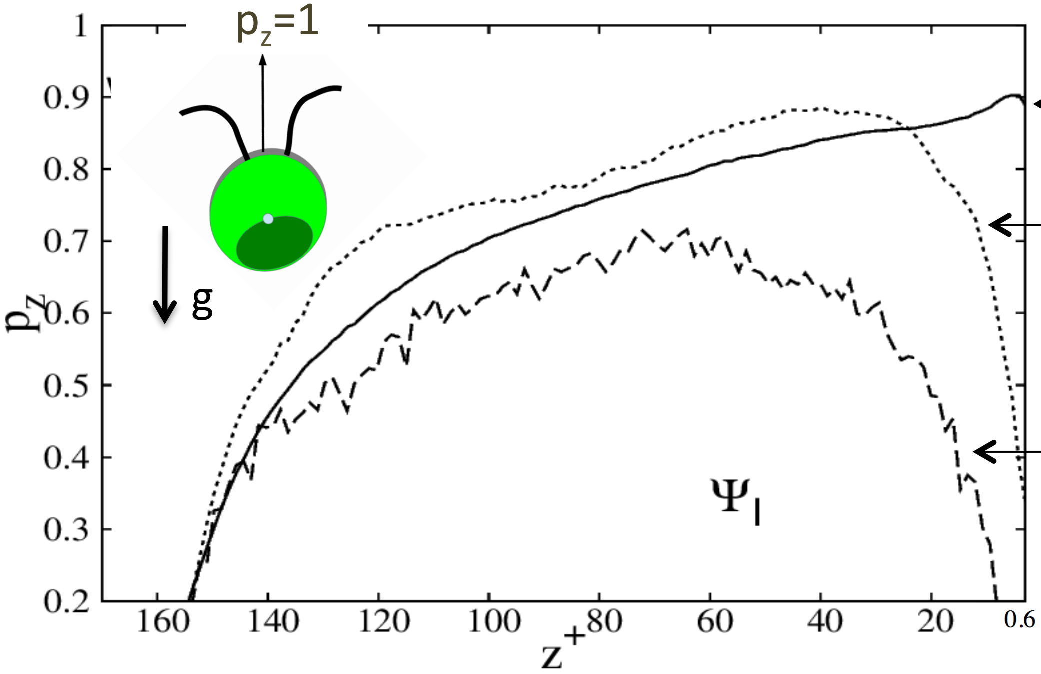
Wind along mean flow

WIND DETERMINES DIFFERENT CLUSTER TOPOLOGIES!

Multiphase Flow Laboratory
University of Udine

EFFECT OF WIND-SHEARED SURFACE TURBULENCE ON SWIMMER DYNAMICS

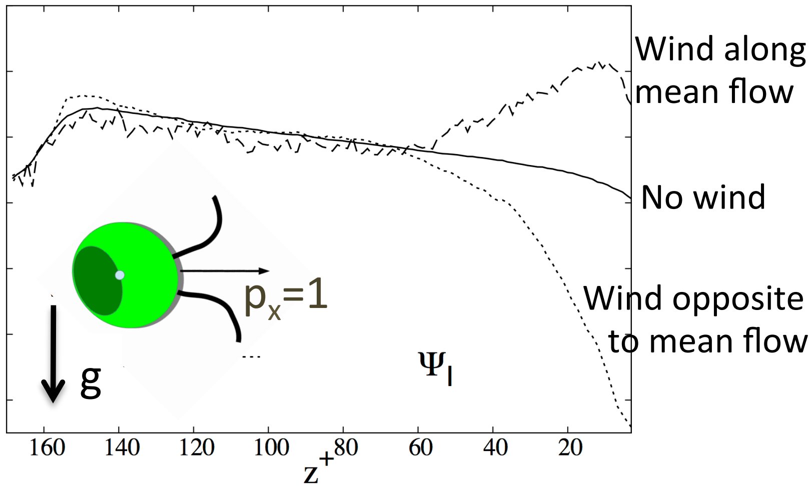
ORIENTATION AND VERTICAL DISTRIBUTION (Ψ_l, INTERMEDIATE GYROTAXIS CASE)



NO WIND

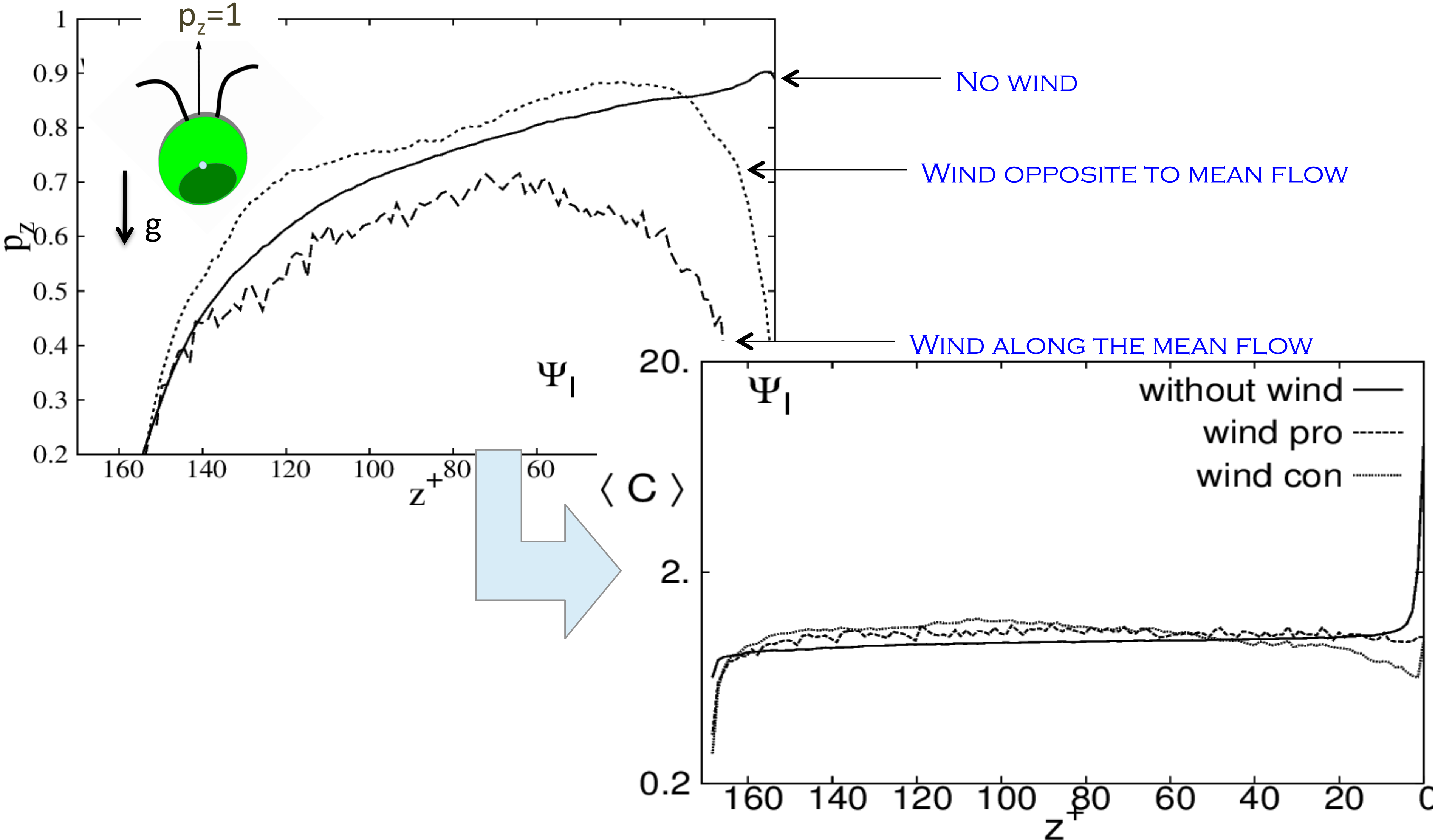
WIND OPPOSITE TO MEAN FLOW

WIND ALONG THE MEAN FLOW



EFFECT OF WIND-SHEARED SURFACE TURBULENCE ON SWIMMER DYNAMICS

Orientation and vertical distribution (Ψ_l, intermediate Gyrotaxis case)

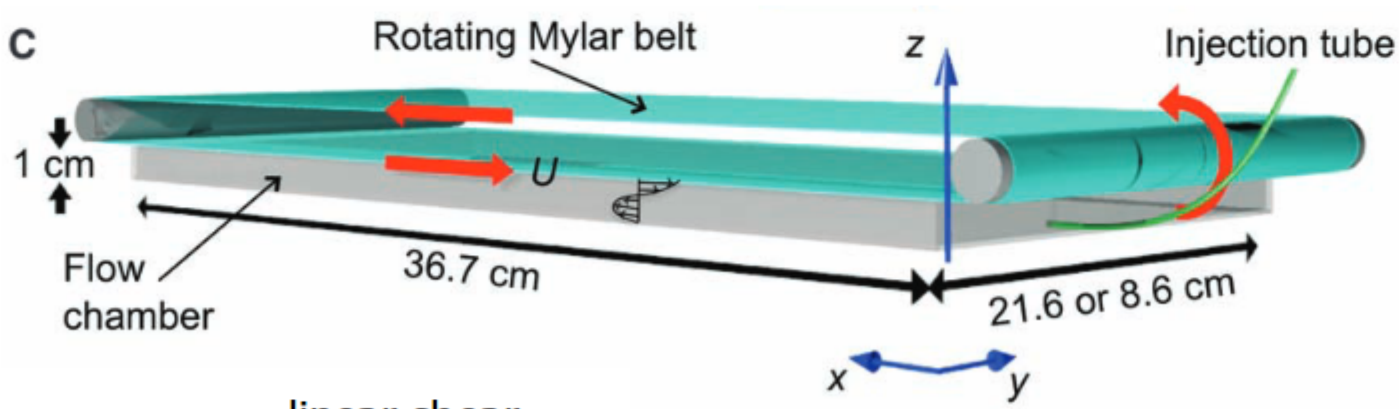


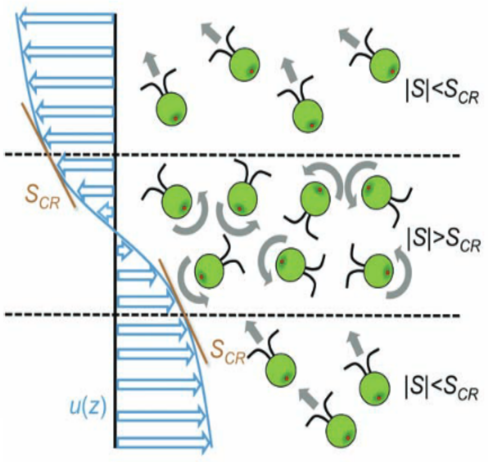
No wind

Wind opposite to mean flow

Wind along the mean flow

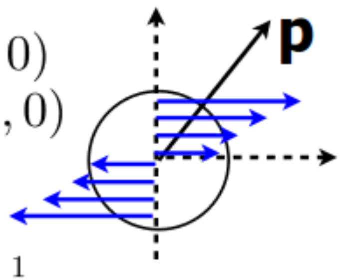
EFFECT OF WIND-SHEARED SURFACE TURBULENCE ON SWIMMER DYNAMICS





linear shear

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



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

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!

EFFECT OF WIND-SHEARED SURFACE TURBULENCE ON SWIMMER DYNAMICS

Conclusions:

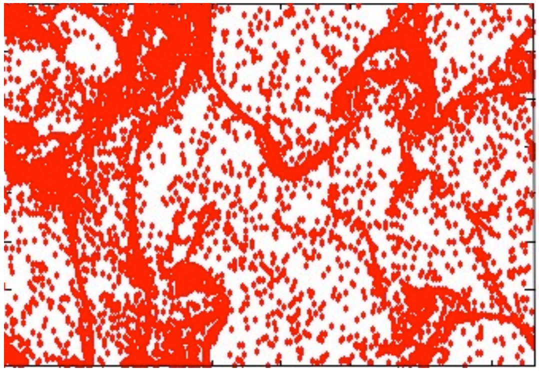
1. Wind-sheared turbulence reduces accumulation of motile micro-swimmers at the free surface

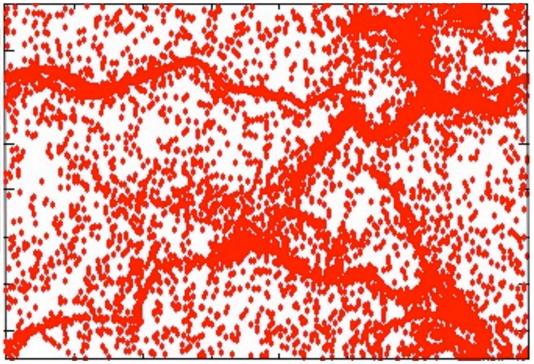
2. Swimmers start tumbling and get trapped just below the free surface

3. Blocking mechanism: shear-induced destabilization

Future development:

1. Add the effect of change/reversal in the direction of wind


No wind

Oscillating wind


FIL ROUGE

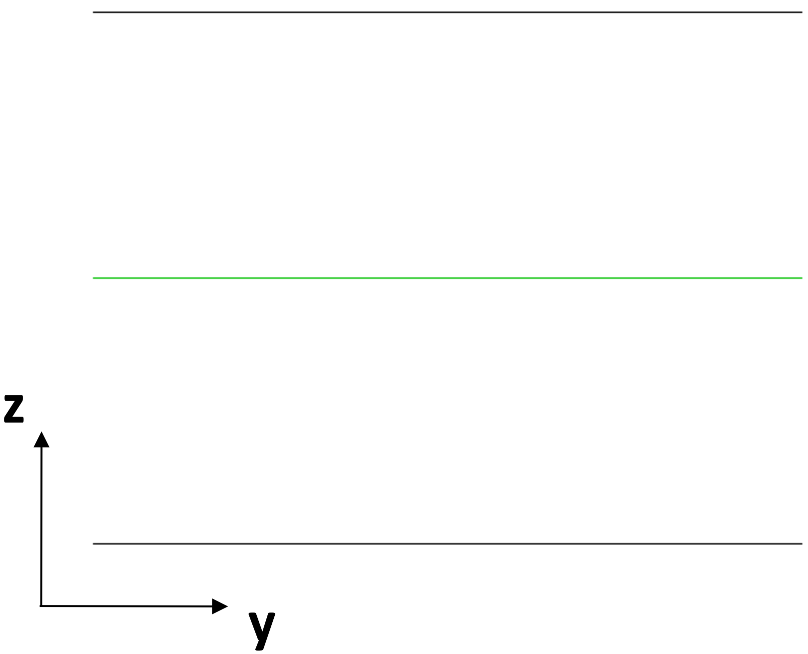
PART 2B:

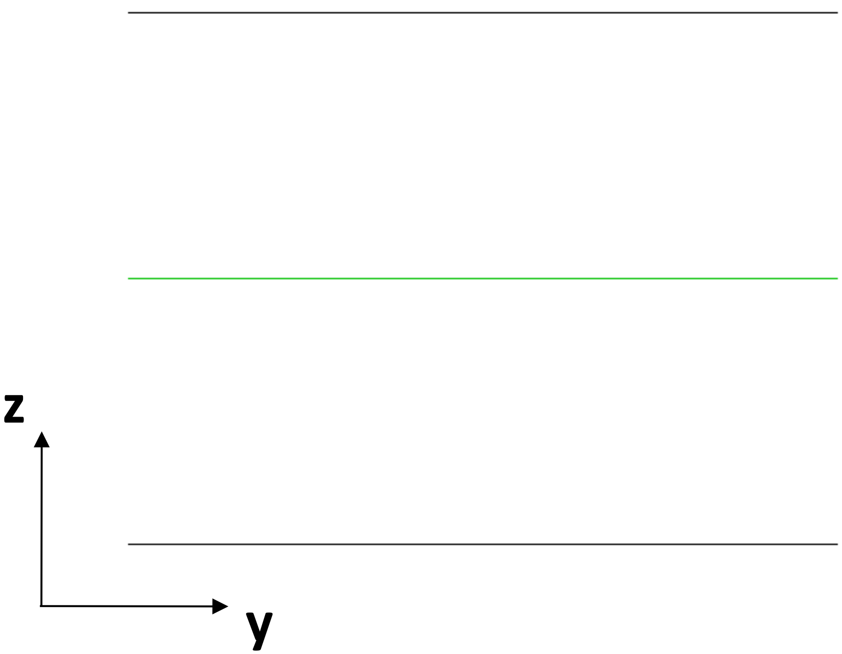
PLANKTON DYNAMICS IN STRATIFIED FREE-SURFACE TURBULENCE

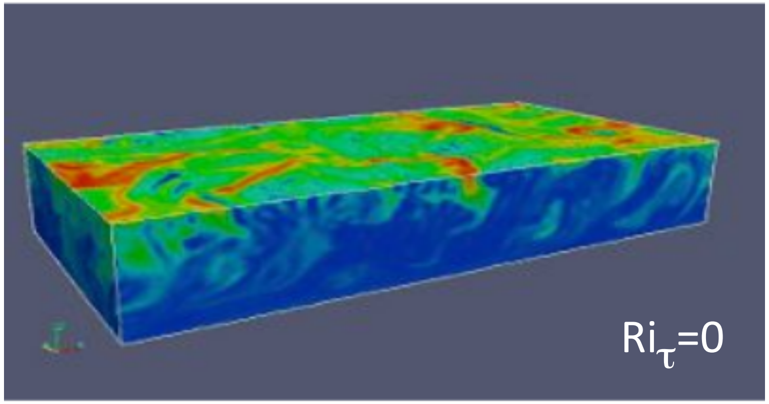
EFFECT OF STRATIFIED TURBULENCE ON SWIMMER DYNAMICS

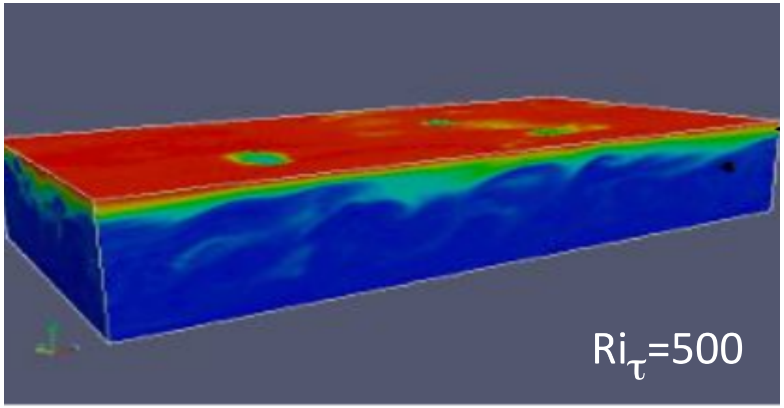
UNSTRATIFIED FLOW

STRATIFIED FLOW

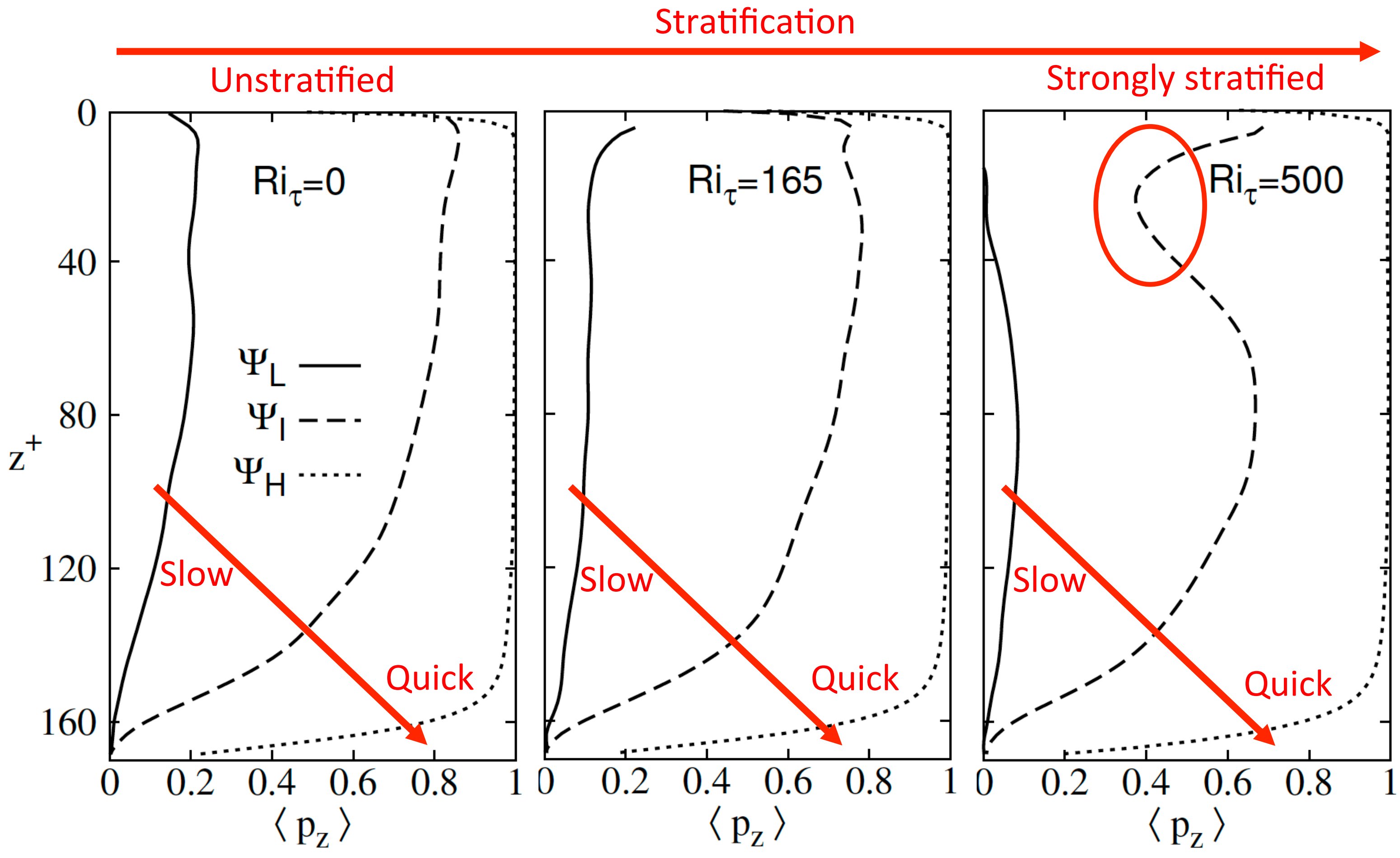


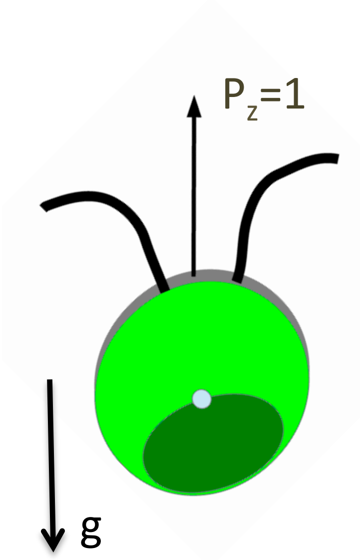






EFFECT OF STRATIFIED TURBULENCE ON SWIMMER DYNAMICS

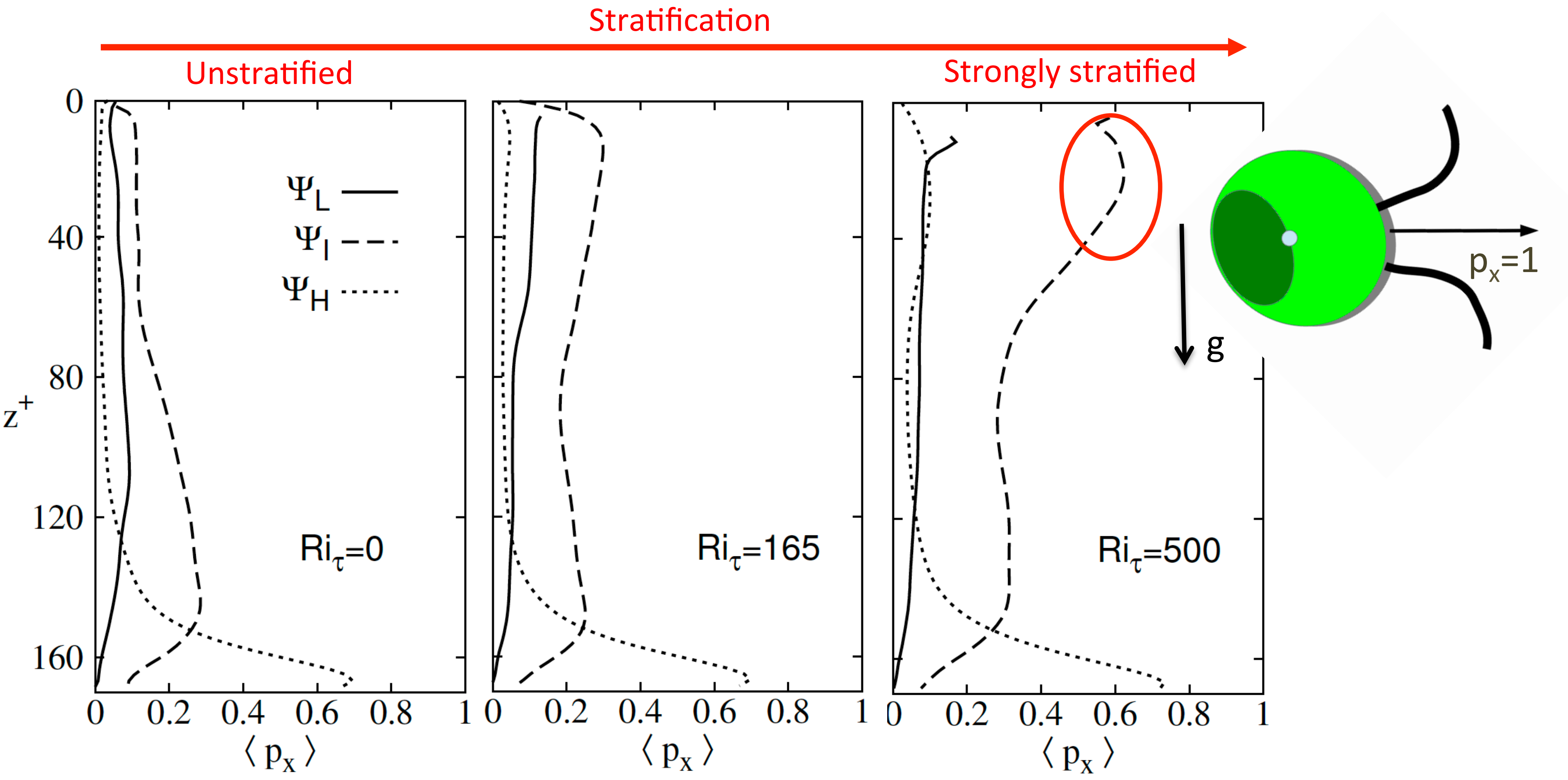




Preferential orientation of the swimmers

Mean orientation in the vertical direction (P_Z)

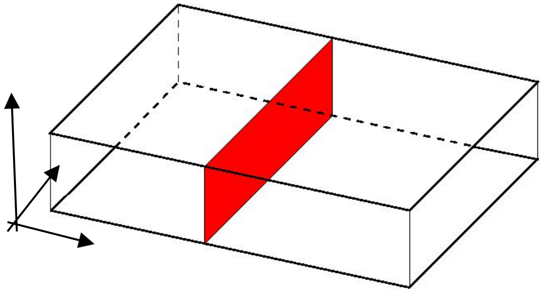
EFFECT OF STRATIFIED TURBULENCE ON SWIMMER DYNAMICS

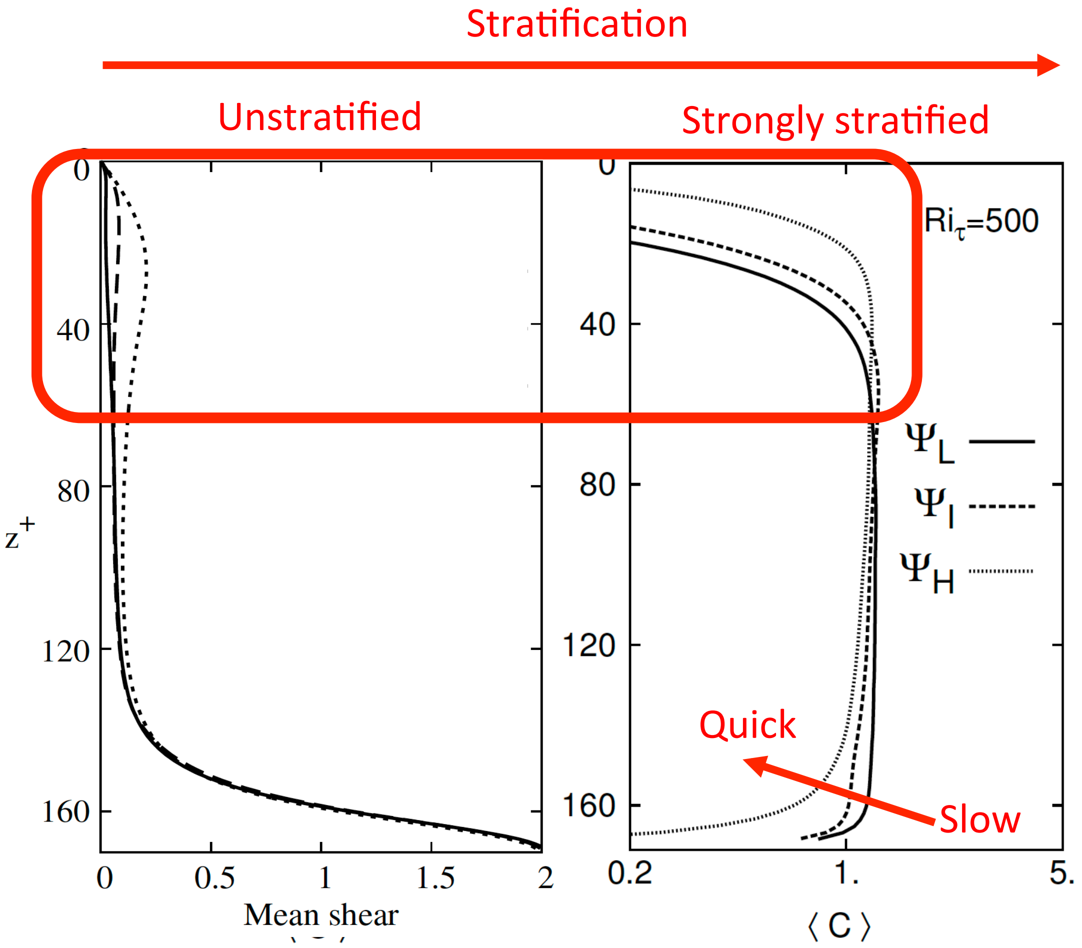


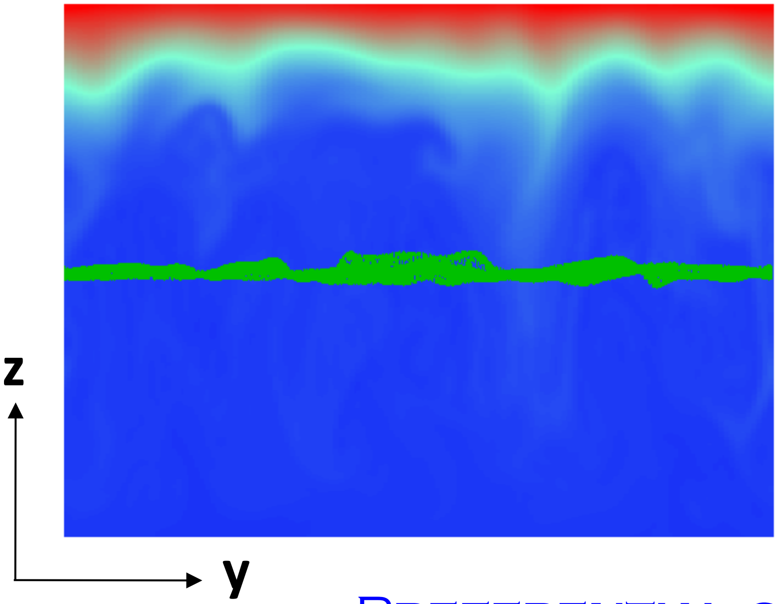
PREFERENTIAL ORIENTATION OF THE SWIMMERS

MEAN ORIENTATION IN THE HORIZONTAL DIRECTION (p_x)

EFFECT OF STRATIFIED TURBULENCE ON SWIMMER DYNAMICS

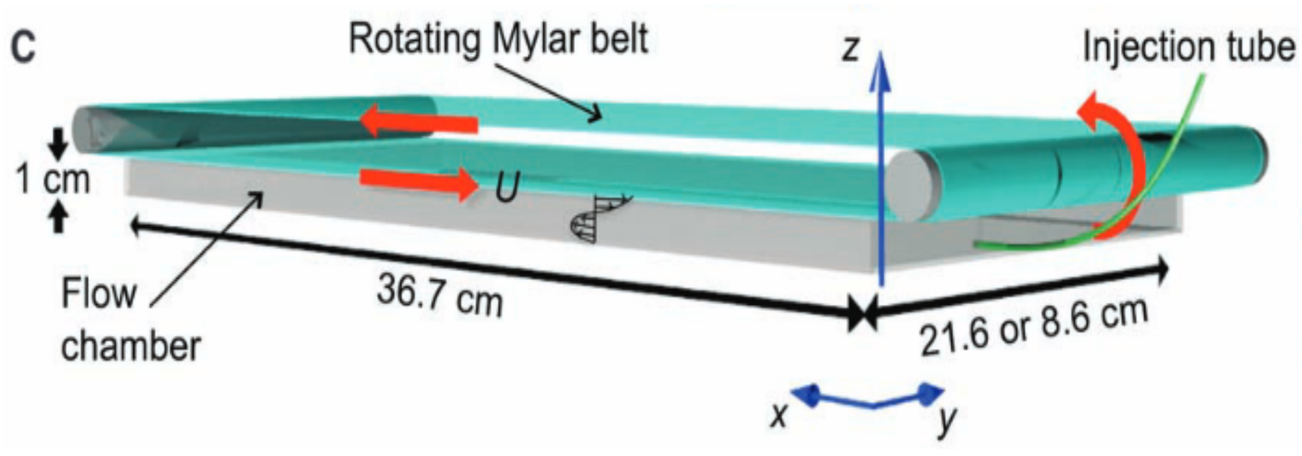


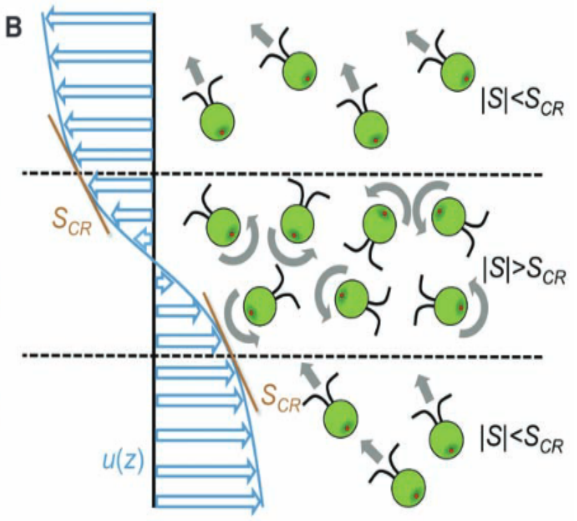




Preferential concentration of the swimmers:
Mean number density in the vertical direction

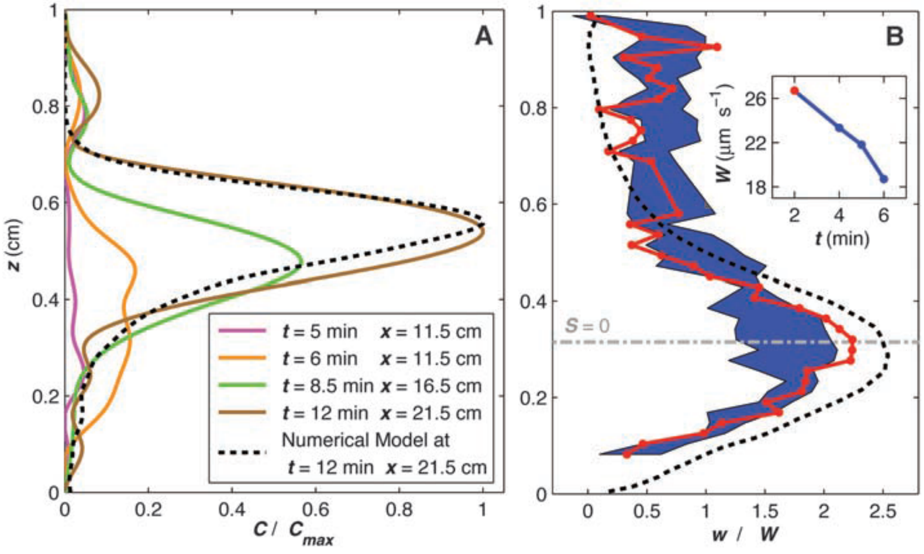
EFFECT OF STRATIFIED TURBULENCE ON SWIMMER DYNAMICS





Stratification-induced shear can keep the swimmers below the thermocline

Again, this is in qualitative agreement with the gyrotactic trapping mechanisms proposed by Durham et al., Science (2009)



EFFECT OF STRATIFIED TURBULENCE ON SWIMMER DYNAMICS

Conclusions:

1. Thermal Stratification may decrease (even prevent) surfacing of motile micro-swimmers

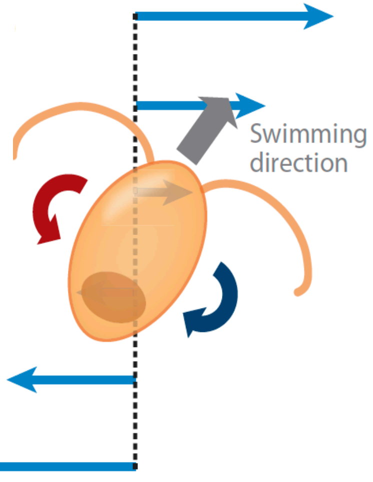
2. Swimmers may tumble and get trapped below the thermocline

3. Trapping mechanism: shear-induced destabilization

Future development:

1. Add the effect of morphology (shape)

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



THANK YOU FOR YOUR KIND ATTENTION!