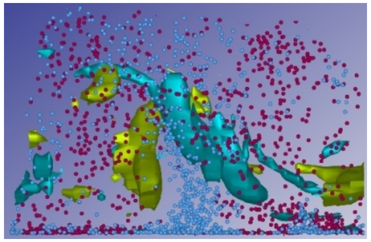


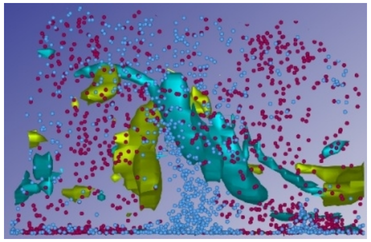
Turbulence effects on particle dispersion in a free-surface flow

Salvatore Lovecchio, Cristian Marchioli, Alfredo Soldati

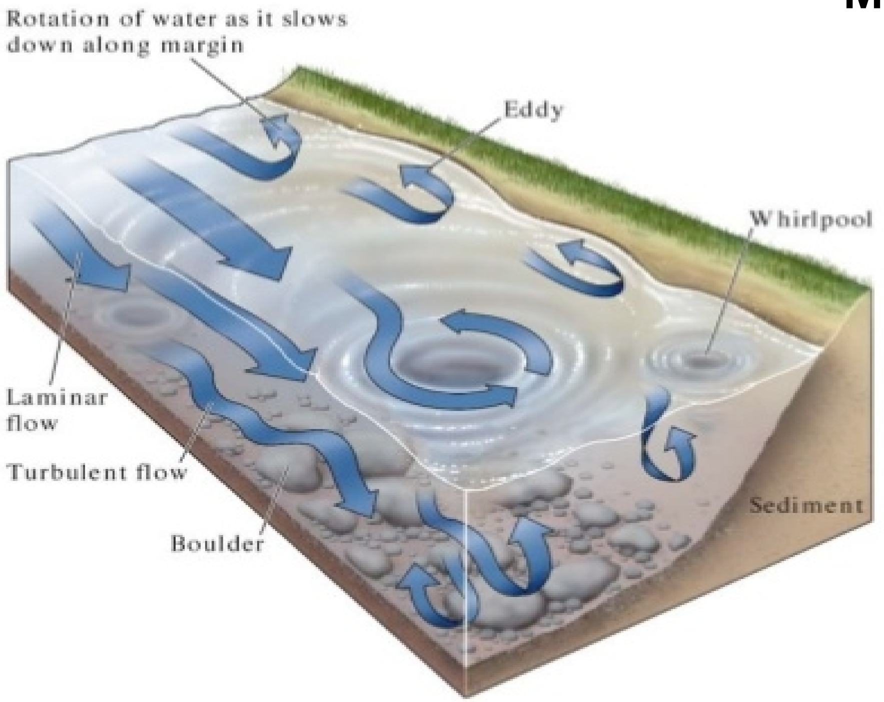
Università degli Studi di Udine

Dipartimento di Ingegneria Elettrica Gestionale e Meccanica

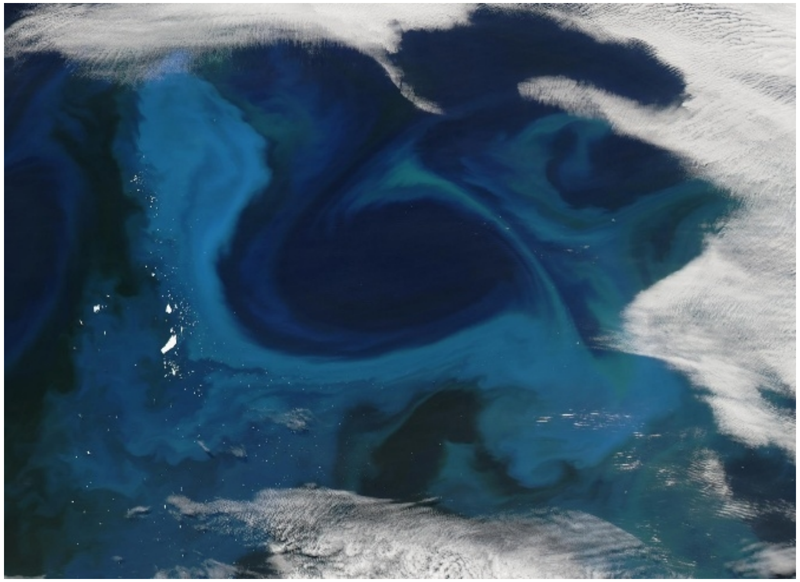
Motivation



Environmental applications

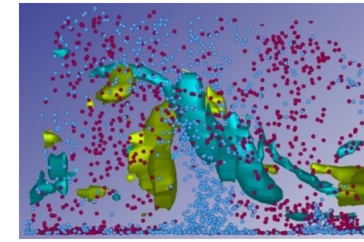


- Dispersion of drifters or floaters
  - Motion of phytoplankton

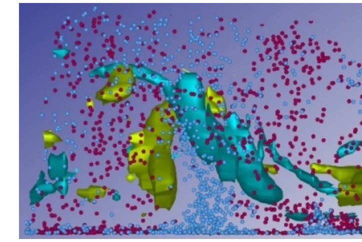


- Settling of organic and inorganic matter

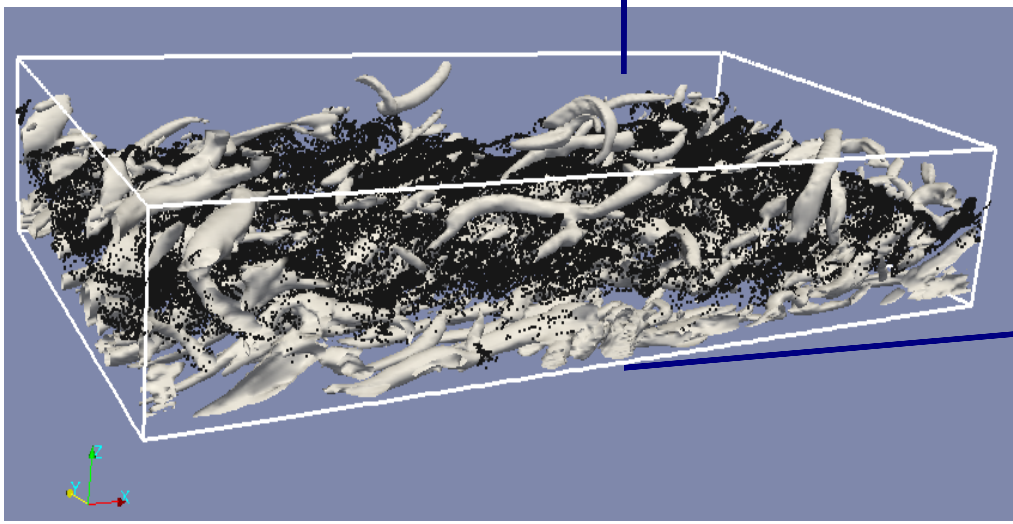
Outline of the Presentation



- **Physical Problem and Modelling Approach**
- **Part 1: Flow at surface**
  - **1.1 Energy spectra**
  - **1.2 Spectral flux energy**
- **Part 2: Particles segregation**
  - **2.1 Source-sink dynamic**
  - **2.2 Intermittency in clustering**
- **Conclusions and future developments**



Physical Problem/Modelling Approach: Neutrally-buoyant turbulence



Free-slip wall

SHEAR FREE SURFACE: No surface waves

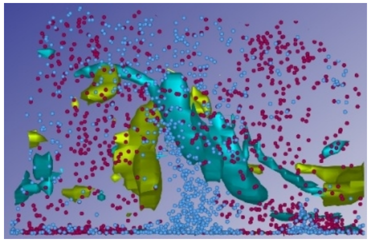
No-slip wall

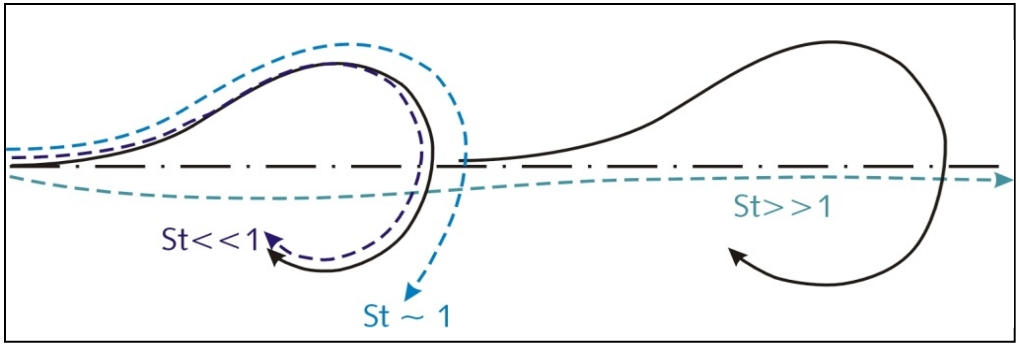
Flow solver:

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

- 3D turbulent water flow field at shear Reynolds number: Re_τ= **171, 509**
- Channel size: **L_x x L_y x L_z = 4 π h x 2 π h x 2h**
- Pseudo-spectral DNS: Fourier modes (1D FFT) in the homogeneous directions (x and y), Chebyschev coefficients in the wall-normal direction (z)
- Time intergration: Adams-Bashforth (convective terms), Crank-Nicolson (viscous terms)

Physical Problem/Modelling Approach: Neutrally-buoyant turbulence





- One-way coupling
- Particle wall-collisions: fully elastic
- Time-integration: 4th-order Runge-Kutta scheme
- Fluid velocity interpolation: 6th-order Lagrange polynomials

Influence of Inertia:

Particle Time Scale, $\tau_p = d_p^2\, \tau_p / 18\, \mu$

Flow Time Scale, $\tau_f = L/U = \nu / u_\tau^2$

Particle Stokes number, $St = \tau_p / \tau_f$

Lagrangian particle tracking:

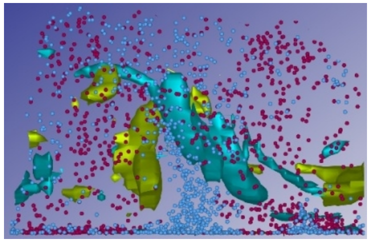
- $\frac{d x_i}{d t} = v_i$
- $\frac{d v_i}{d t} = \left(1 - \frac{\rho_f}{\rho_p}\right) g_i + \frac{u_i - v_i}{\tau_p}\left(1 + 0.15\, Re_p^{0.687}\right)$

Density ratio:

$$S = \frac{\rho_p}{\rho_f}$$

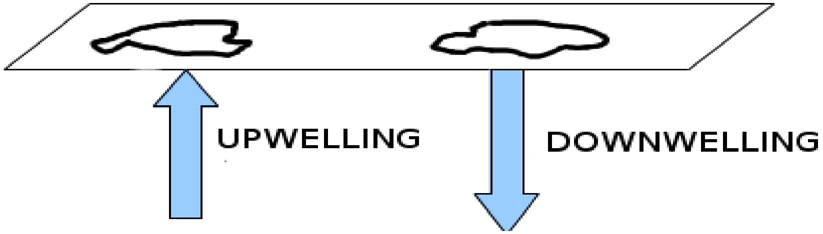
Re_τ	$St = \tau_p \cdot \nu / u_\tau^2$		
171	0.064	0.114	0.121
509	0.562	1.013	1.069
	S=0.5	0.9	0.95

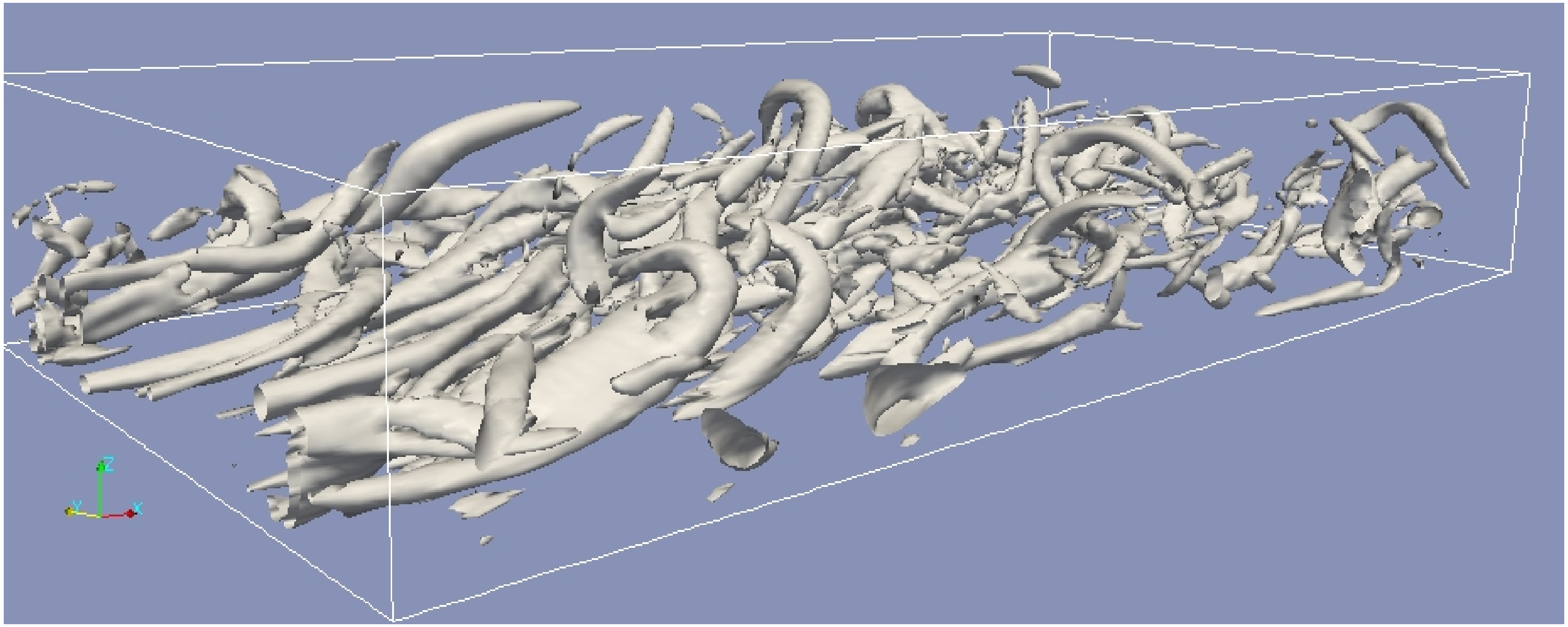
1. Flow at surface



Surface divergence:

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





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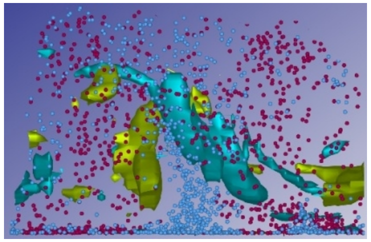

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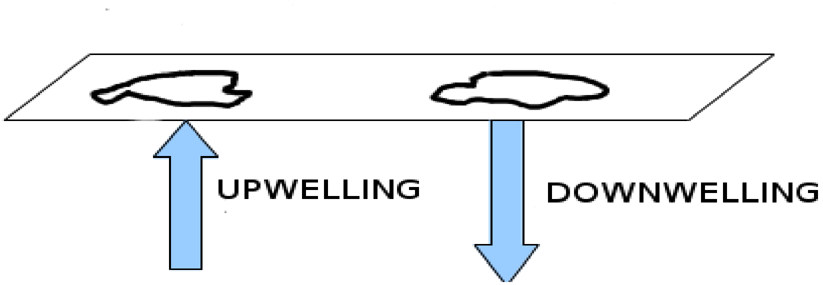
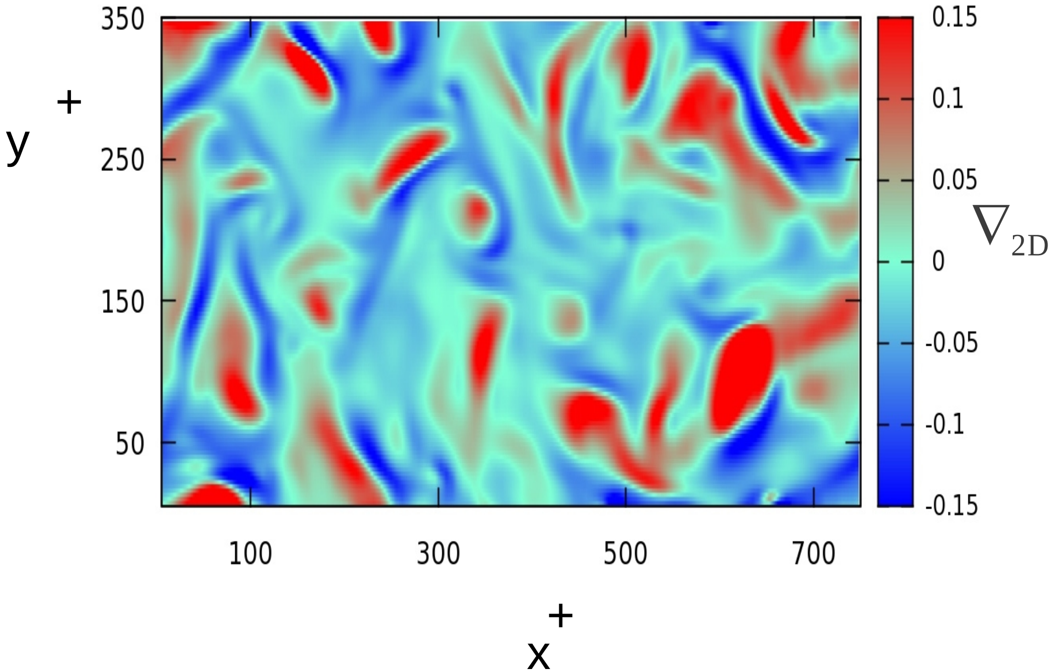
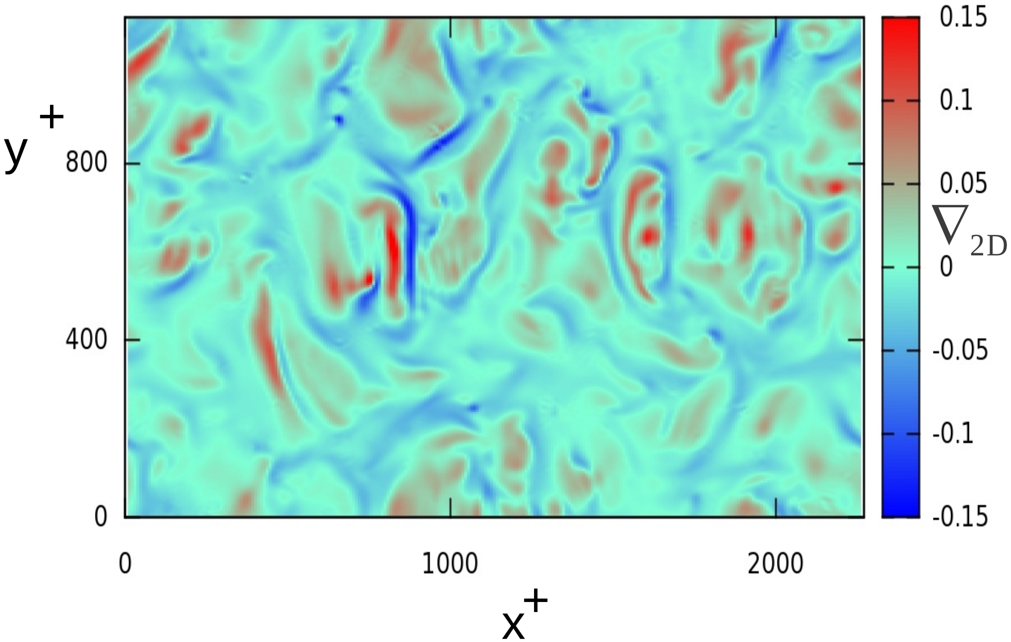


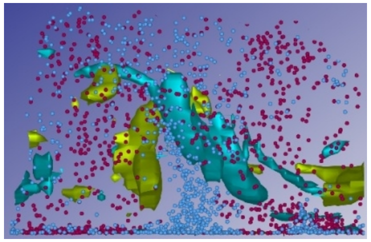
$Re_\tau = 171$

$Re_\tau = 510$





1. Flow at surface: Energy spectra



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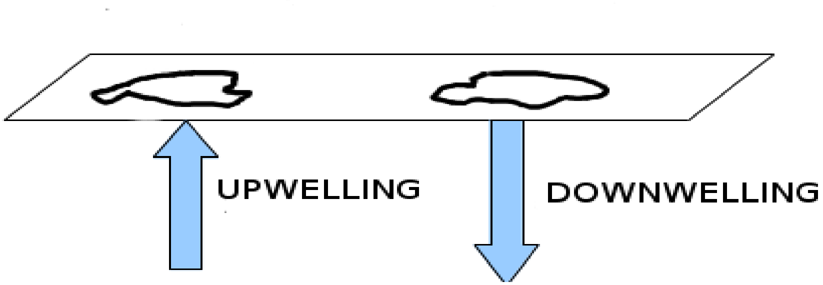
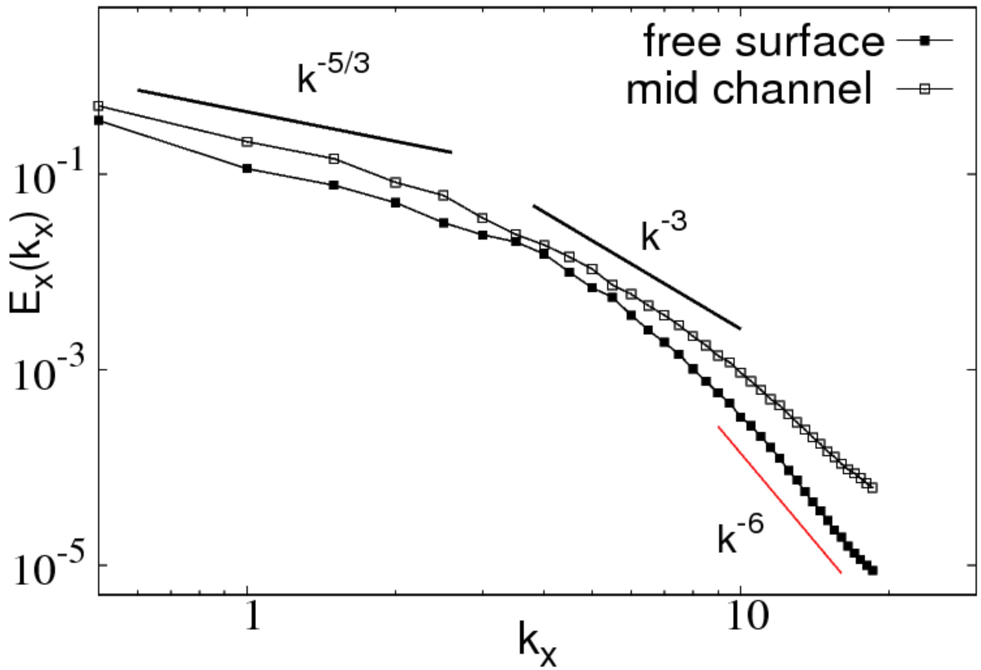
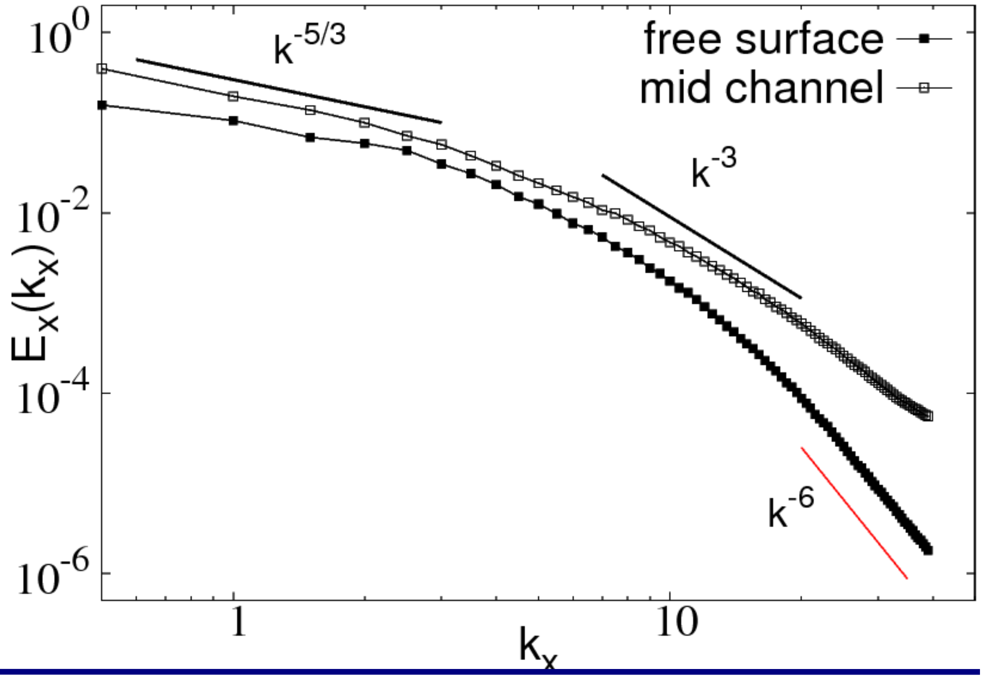


Streamwise energy spectrum of the streamwise velocity

$Re_\tau = 171$



$Re_\tau = 510$



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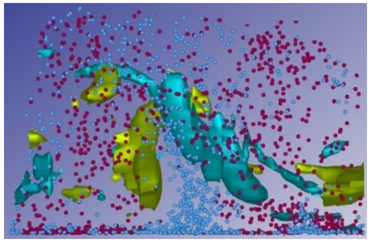

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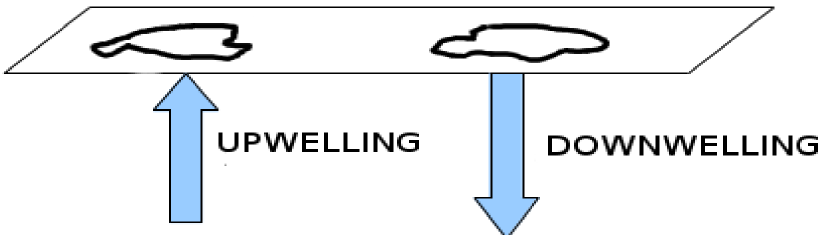

Streamwise energy spectrum of the spanwise velocity

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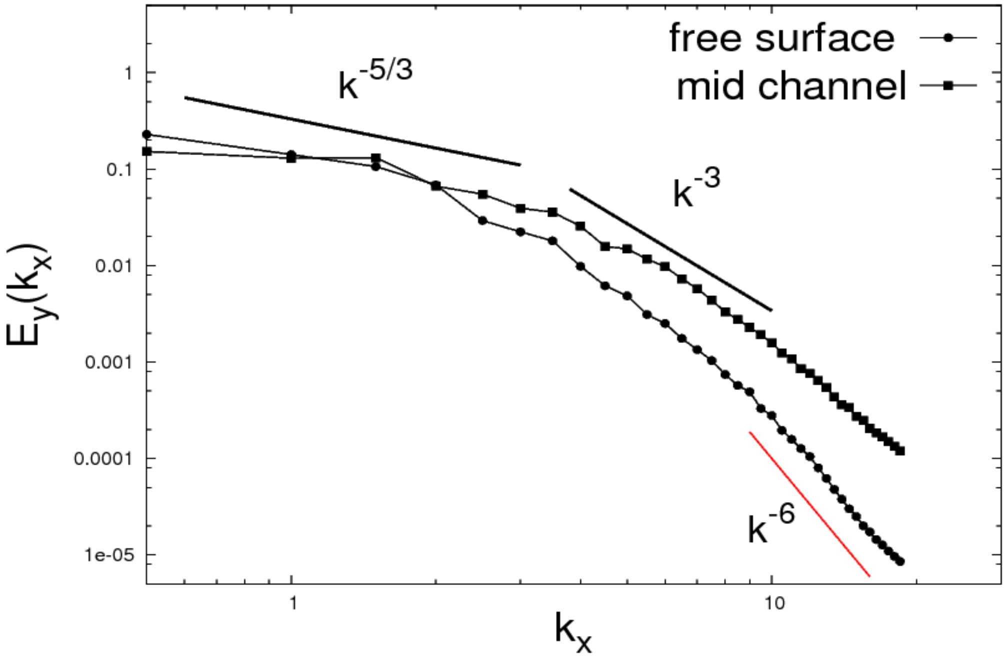

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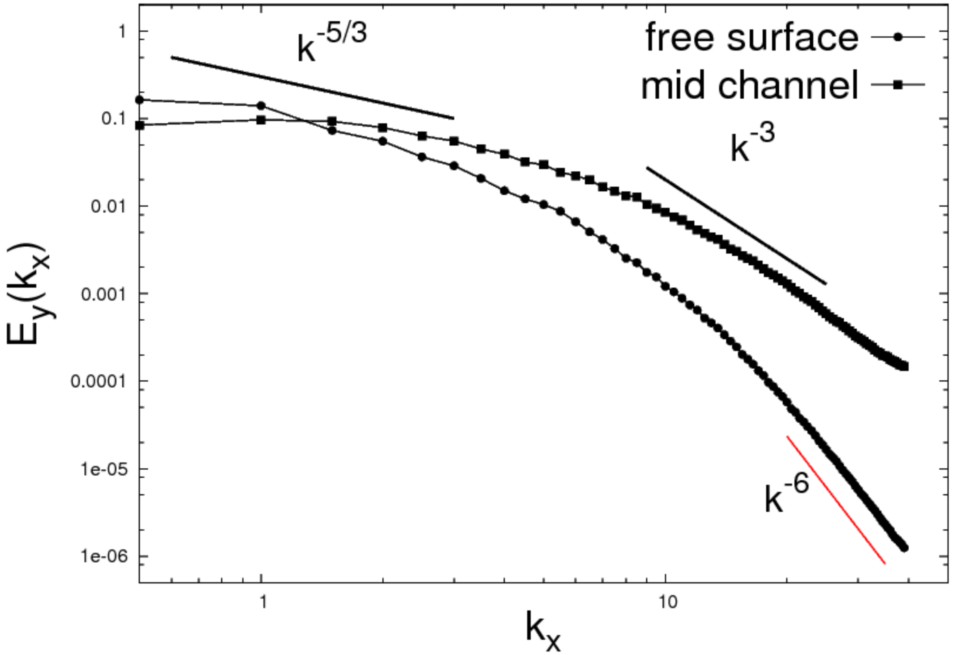

1. Flow at surface: Energy flux

Filtered space techniques (FST)

D.H.Kelley,N. T. Ouellette
Phys.Fluids 23 (2011)

Low-pass spatial filter applied to velocity field

$$u_x^{(r)}(x,y) = \int u_x(x',y')G^{(r)}(x-x',y-y')\mathrm{d}x'\mathrm{d}y'$$

Equation motion of filtered Kinetic energy

$$\frac{\partial E^{(r)}}{\partial t} = -\frac{\partial J_i^{(r)}}{\partial x_i} - \nu \frac{\partial u_i^{(r)}}{\partial x_j}\frac{\partial u_i^{(r)}}{\partial x_j} - \Pi^{(r)}$$

Energy Flux to scale < r at each space point

$$\Pi^{(r)} = -\tau_{ij}^{(r)} s_{ij}^{(r)}$$

Stress tensor induced by eddies at scales < r

$$\tau_{ij}^{(r)} = (u_i u_j)^{(r)} - u_i^{(r)} u_j^{(r)}$$

Strain tensor

$$s_{ij}^{(r)} = \frac{1}{2}\left(\frac{\partial u_i^{(r)}}{\partial x_j} + \frac{\partial u_j^{(r)}}{\partial x_i}\right)$$

$$\Pi^{(r)} = -\left[(u_i u_j)^{(r)} - u_i^{(r)} u_j^{(r)}\right]\frac{\partial u_i^{(r)}}{\partial x_j}$$

1. Flow at surface: Energy flux

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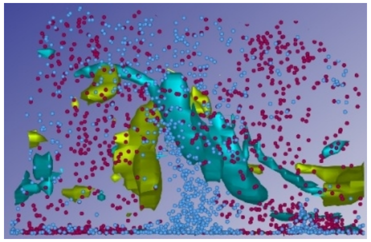
Stress tensor induced by eddies at scales < r

Strain tensor

$\Pi^{(r)}$

>0 : transfer to smaller structures
FORWARD TRANSFER

<0 : transfer to larger structures
INVERSE TRANSFER



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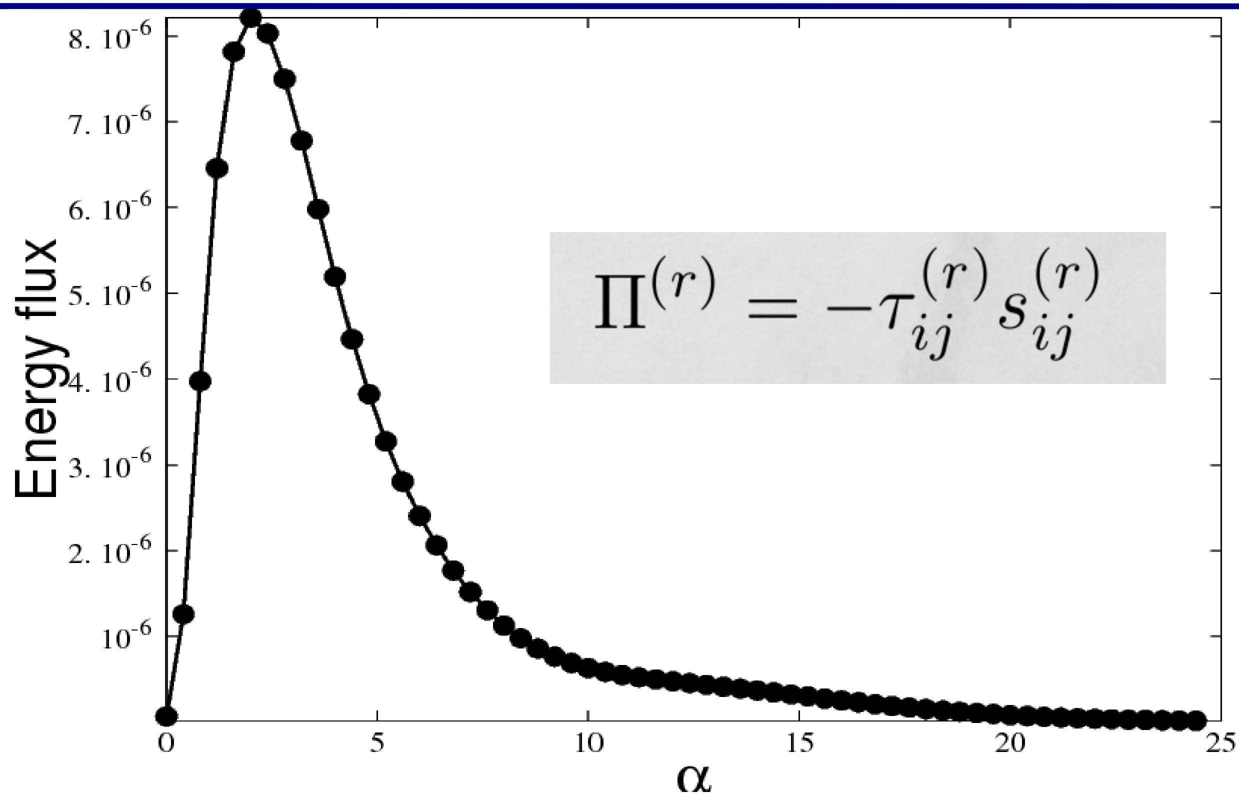
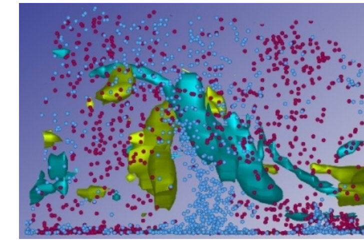
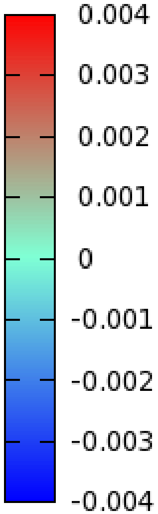


Energy flux at free surface

1. Flow at surface: Energy flux



$$\Pi^{(r)} > 0$$



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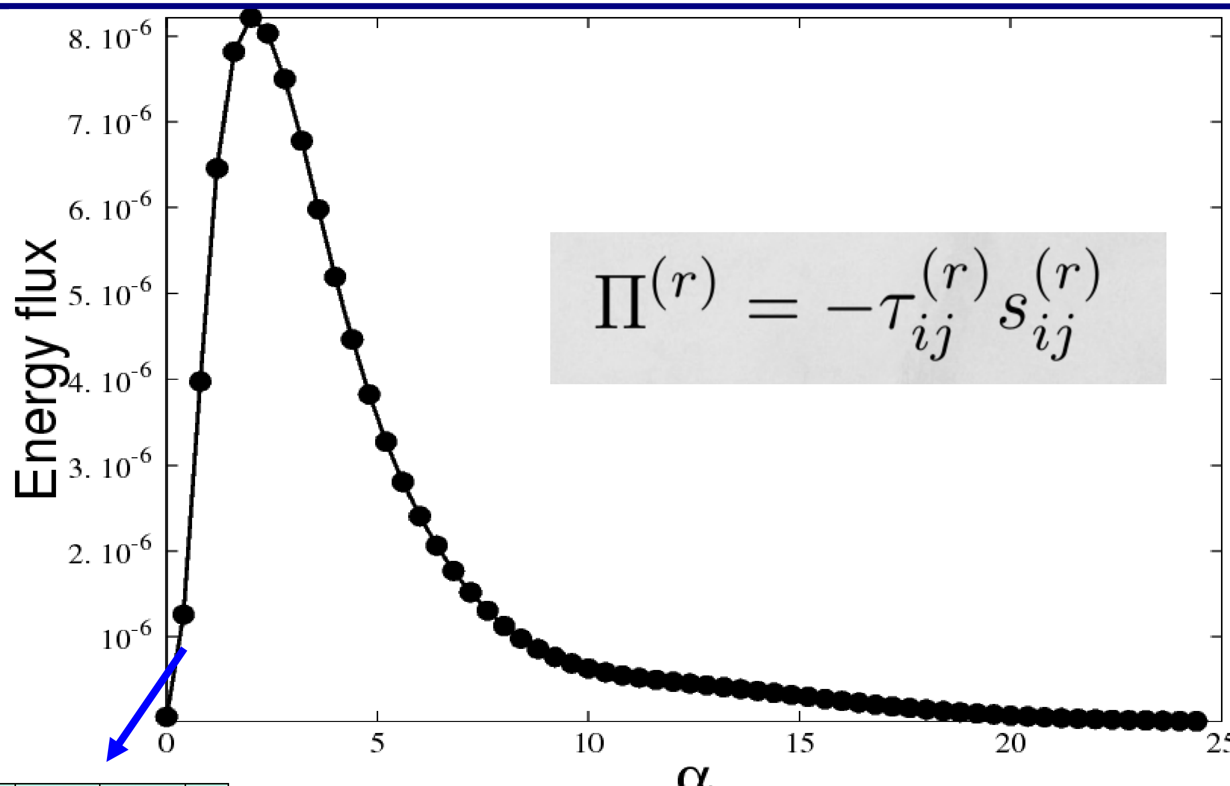
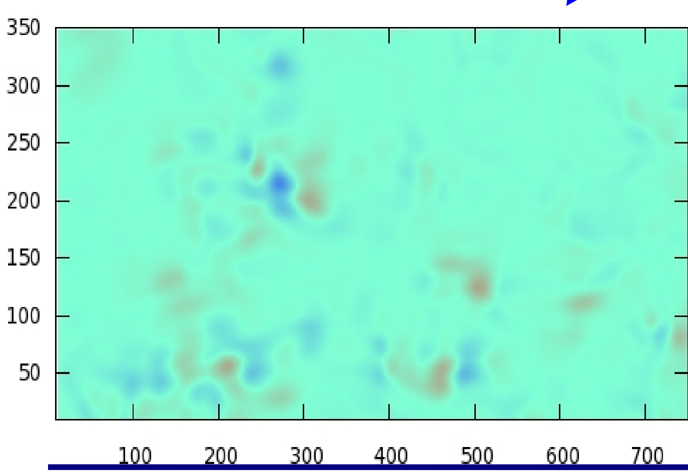
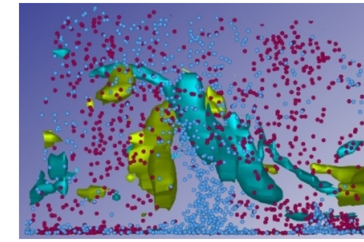
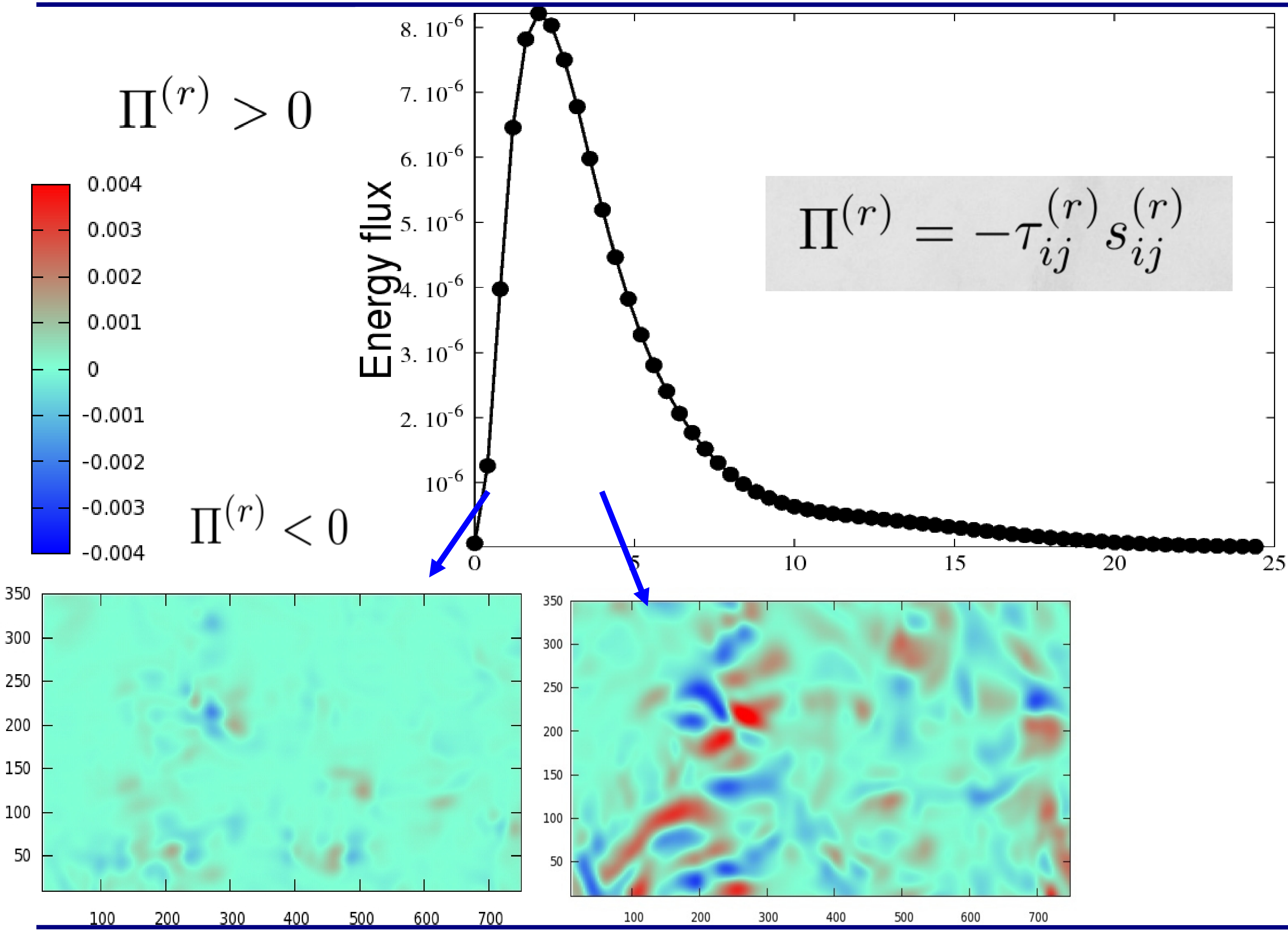


$$\Pi^{(r)} = -\tau_{ij}^{(r)} s_{ij}^{(r)}$$



1. Flow at surface: Energy flux



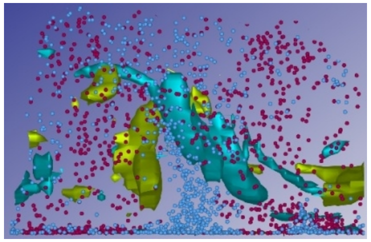


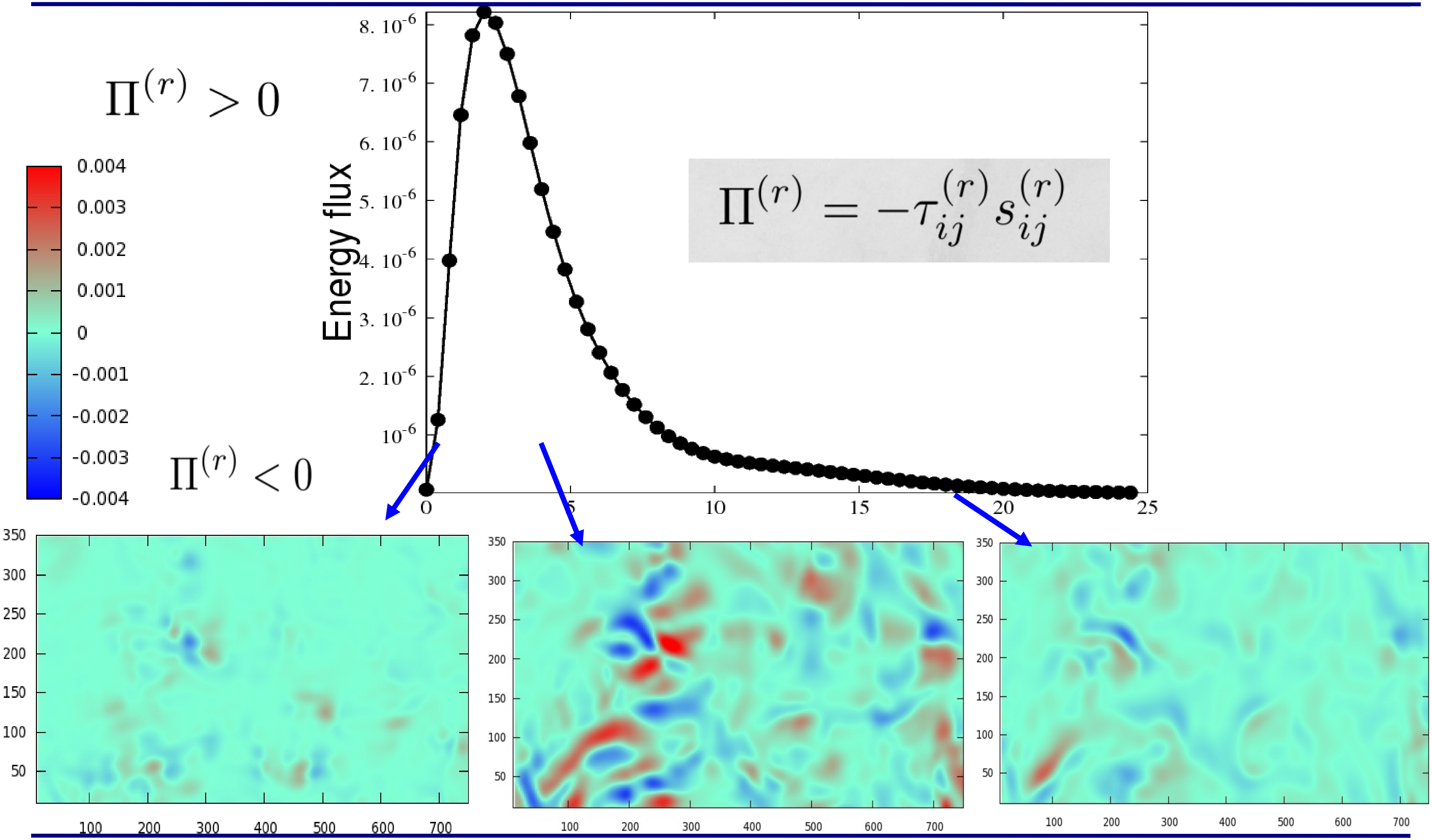
$$\Pi^{(r)} > 0$$

$$\Pi^{(r)} < 0$$

$$\Pi^{(r)} = -\tau_{ij}^{(r)} s_{ij}^{(r)}$$

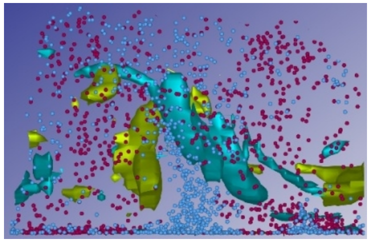
1. Flow at surface: Energy flux





2. Particles segregation

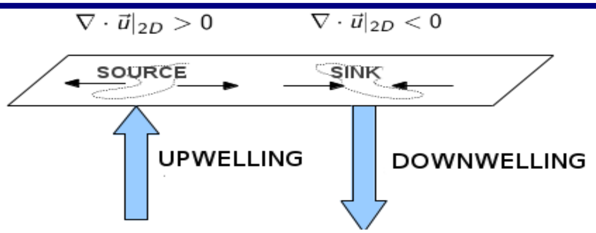
Dynamical system: source - sink



Surface divergence:

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

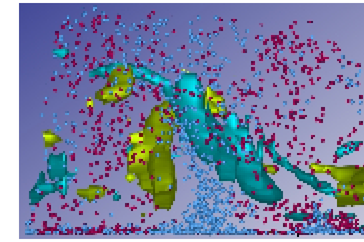
$$Re_\tau = 171$$



$$Re_\tau = 510$$

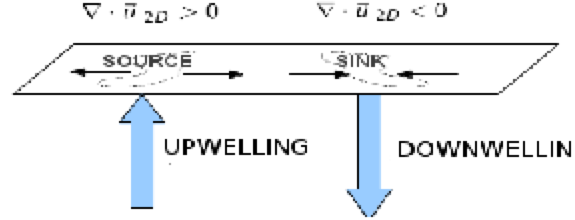
2. Particles segregation

Dynamical system: source - sink



Surface divergence:

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



$$Re_\tau = 171$$

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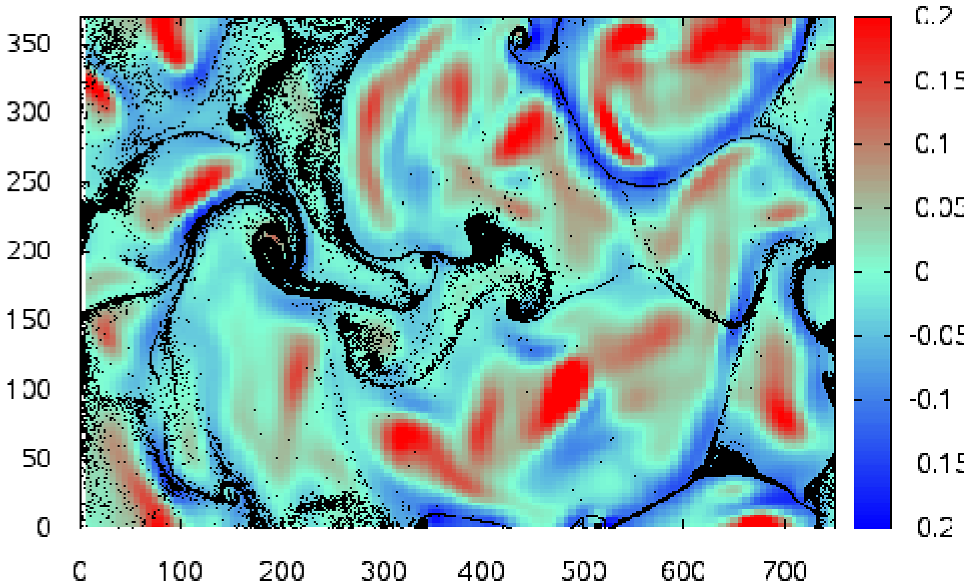
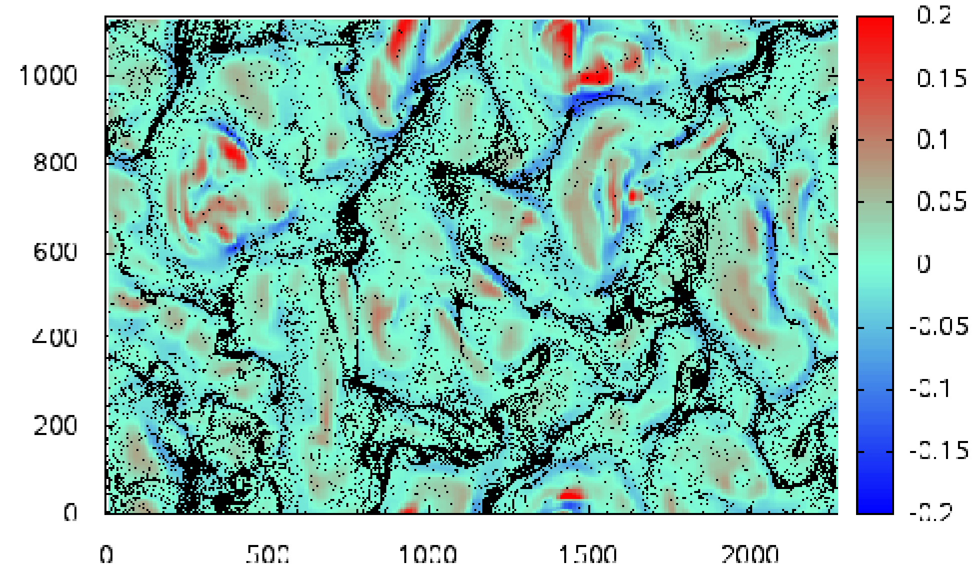
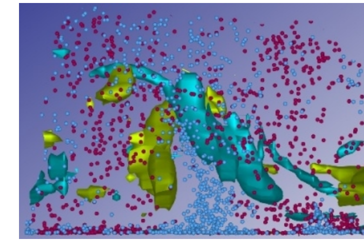
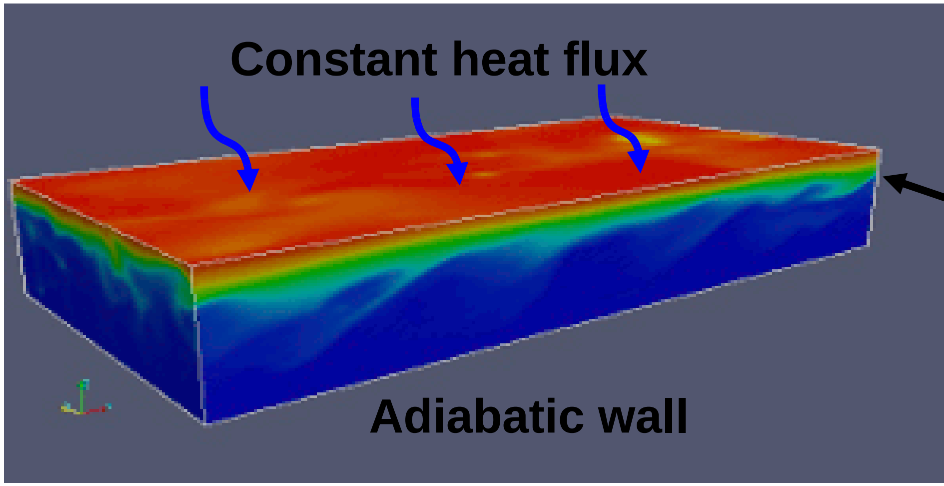




How long particle clusters survive at free surface?



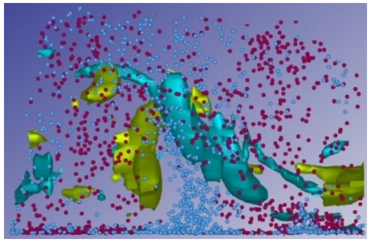
2. Particles segregation: stably stratified turbulence

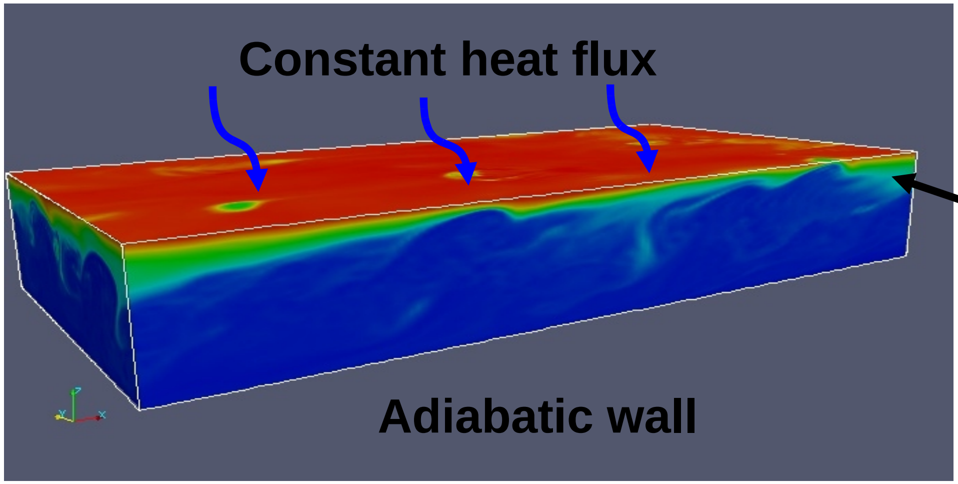


Thermocline (barrier)

Reduced number of Upwelling That reach surface

2. Particles segregation: stably stratified turbulence





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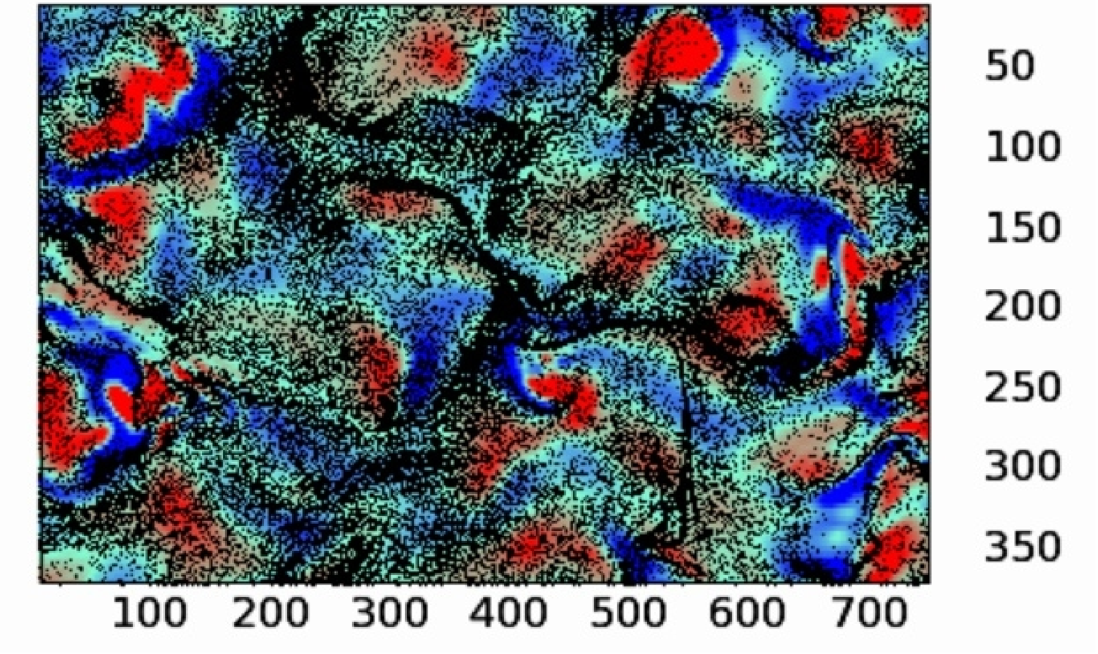
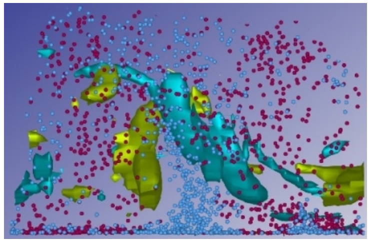


4. Conclusions

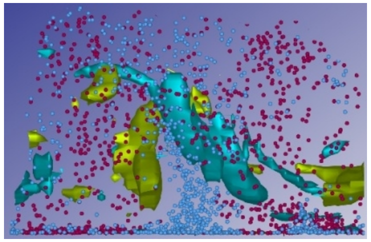


- DNS of turbulent open channel flow at Re =171 (and Re =509) and for different stratification levels (Ri) was performed

- Flow at surface was characterized by surface divergence and energy flux

- In neutrally-buoyant flow, particles tend to cluster into filaments following the dynamics of source and sink induced by upwelling and downwelling.

- In stably stratified turbulence particles seems to sample more homogeneously the surface



Thank you for your

kind attention