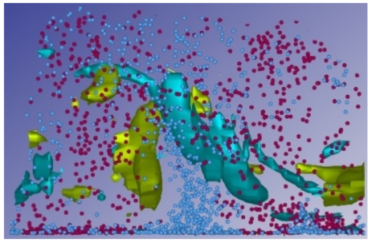

Particle dispersion in stably stratified open channel flow

Salvatore Lovecchio, **Francesco Zonta**, Alfredo Soldati

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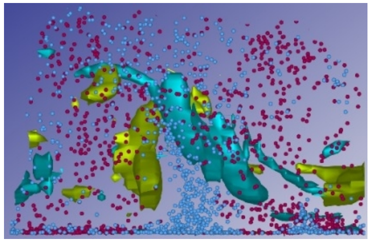
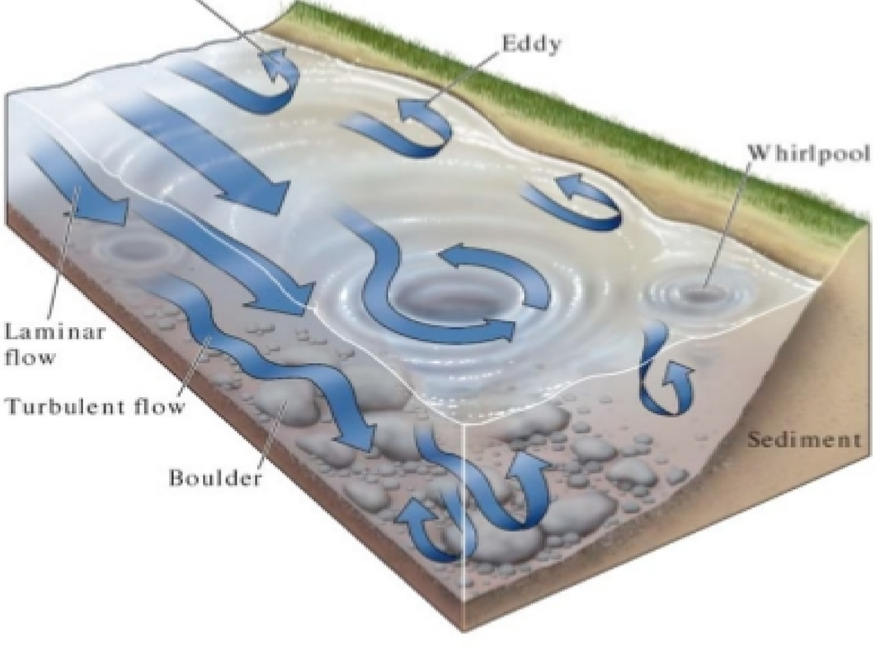
Dipartimento di Ingegneria Elettrica Gestionale e Meccanica

THESIS 2013, Chatou

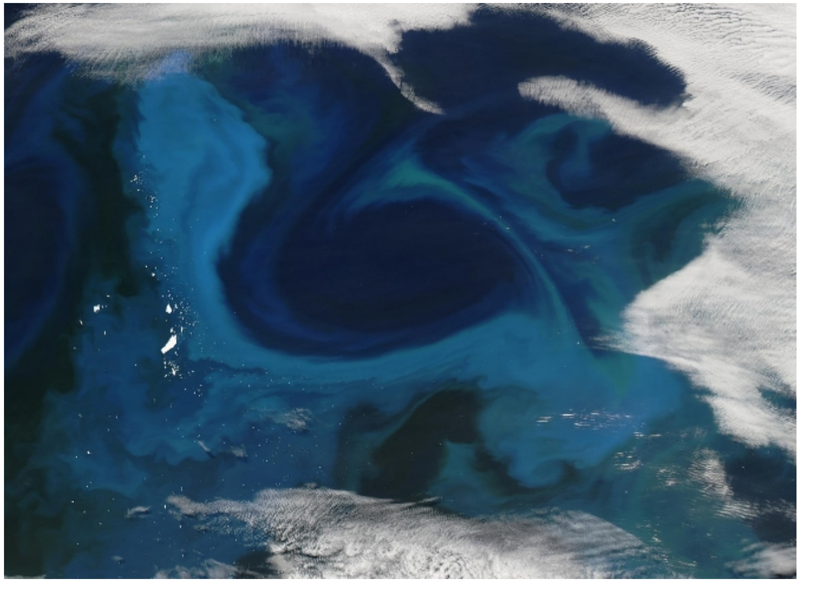


Motivation

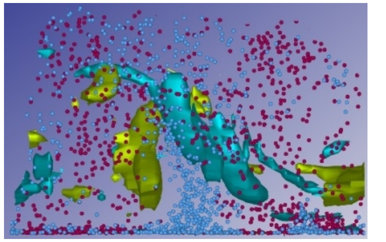
Environmental applications



- 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: Neutrally-buoyant flow

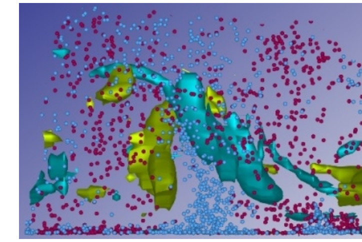
  - **1.1 Characterization of surface turbulence**
  - **1.2 Clustering of particles at the surface**

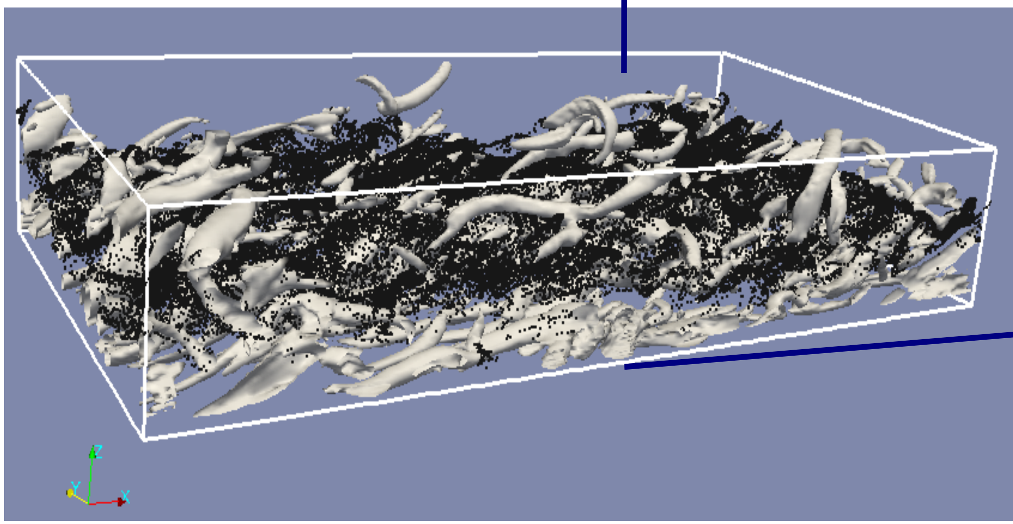
- **Part 2: Stably stratified turbulence**

  - **2.1 Behaviour of temperature and flow field at surface**
  - **2.3 Particle segregation**

- **Conclusions and future developments**

Physical Problem/Modelling Approach: Neutrally-buoyant turbulence





Free-slip wall

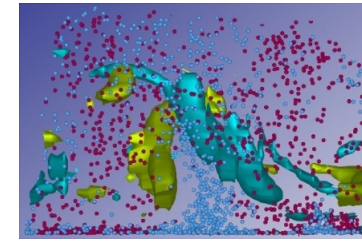
No-slip wall

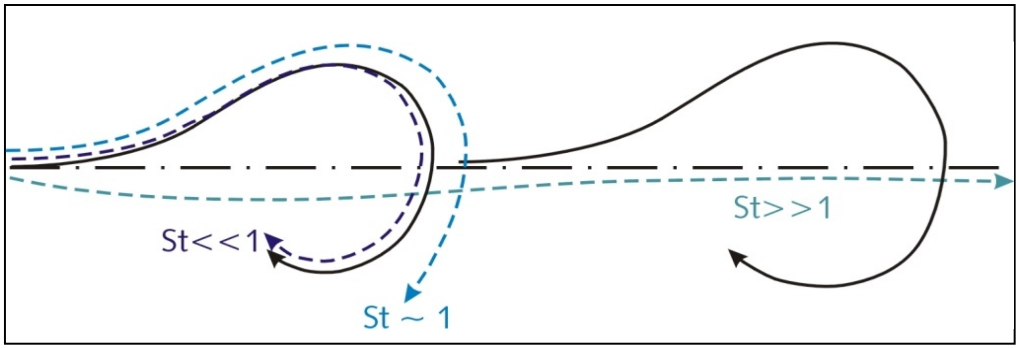
Flow solver:

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

- 3D turbulent water flow field at shear Reynolds number: Re_τ= **171, 509**
- Channel size: $\mathbf{L_x \times L_y \times L_z = 4\pi h \times 2\pi h \times 2h}$
- 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, $\tau_f = L/U = \nu / u_\tau^2$

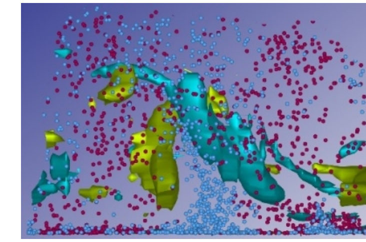
Particle Stokes number, $St = \tau_p / \tau_f$

Lagrangian particle tracking:

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

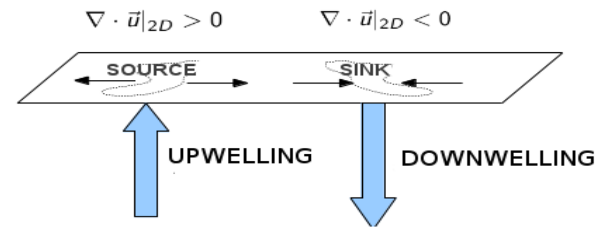
ρ_p/ρ_f	0.5	0.7	0.8	0.9	0.95
$St(Re_\tau = 171)$	0.06	0.09	0.1	0.11	0.12

Particles segregation

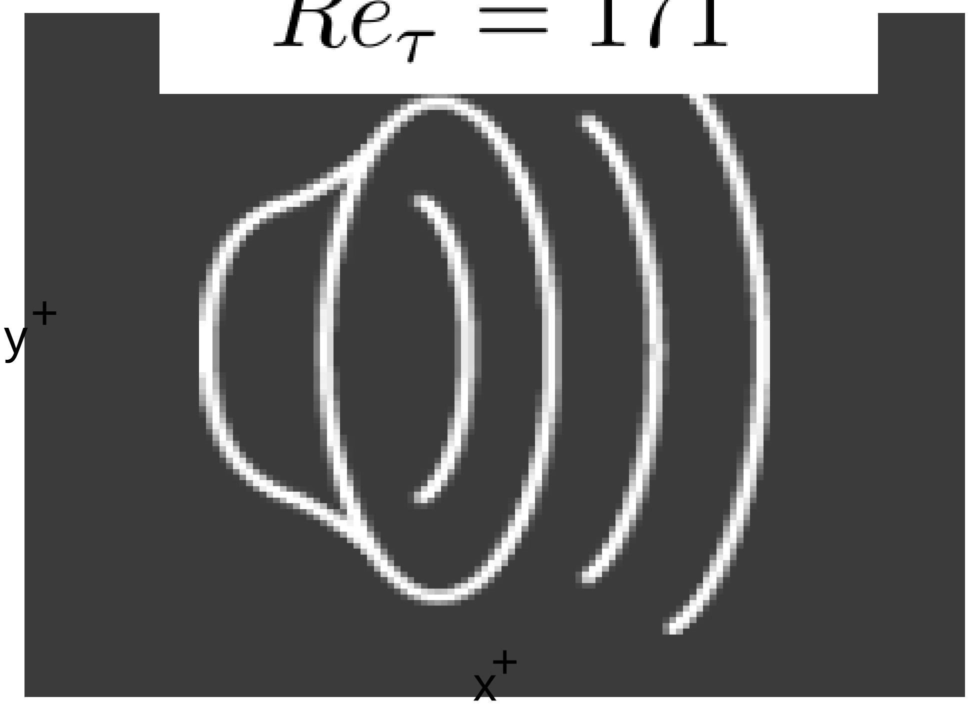


Surface divergence:

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

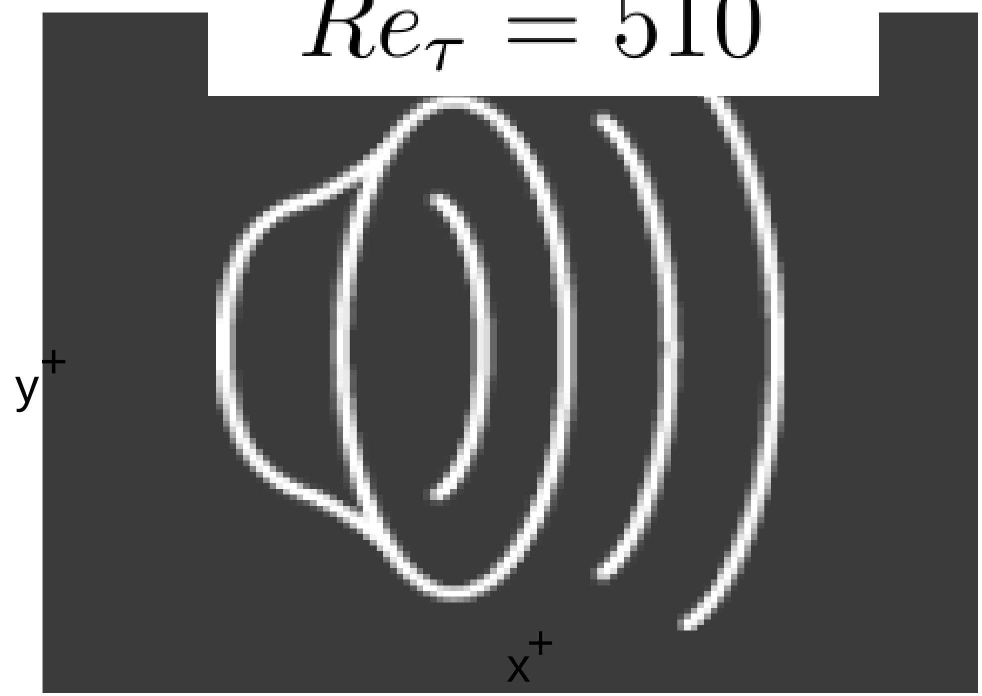


$Re_\tau = 171$



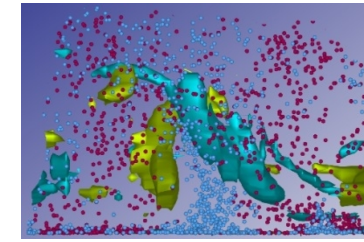
∇_{2D}

$Re_\tau = 510$

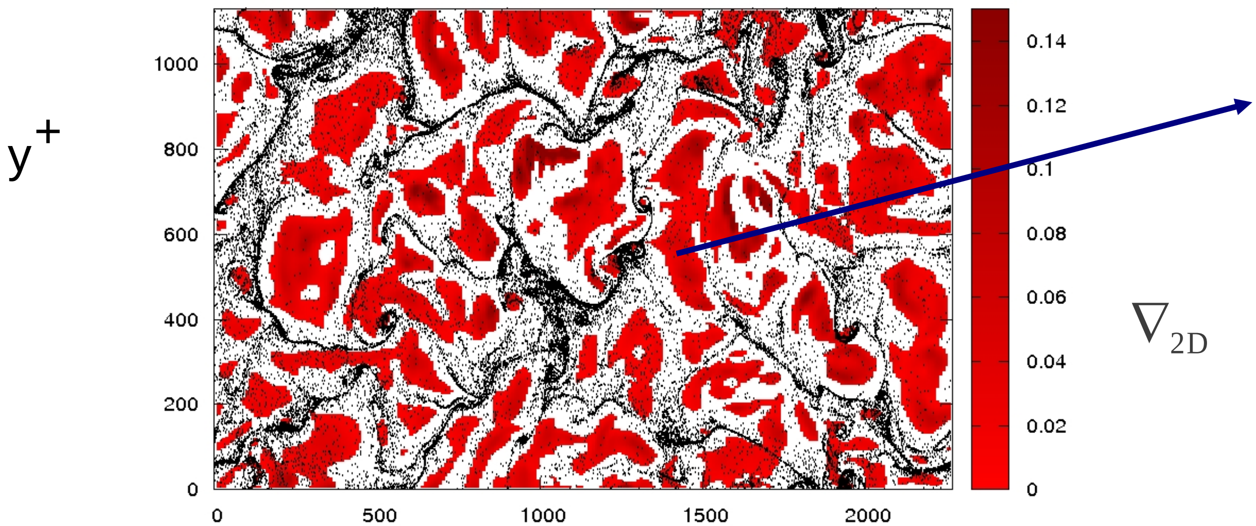


∇_{2D}

3. Surface cluster renewal

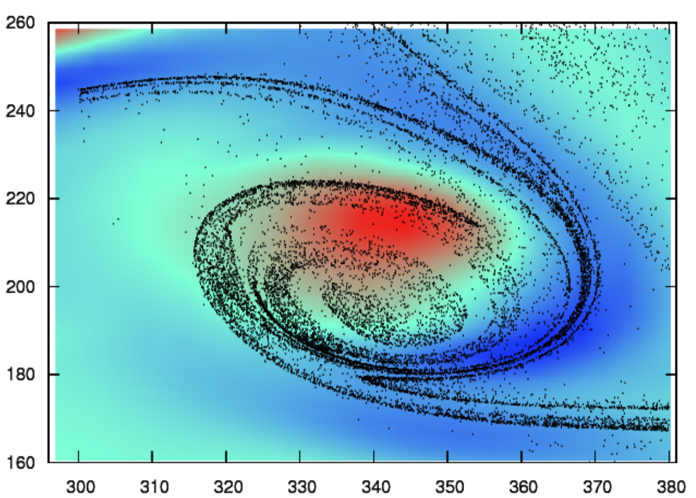


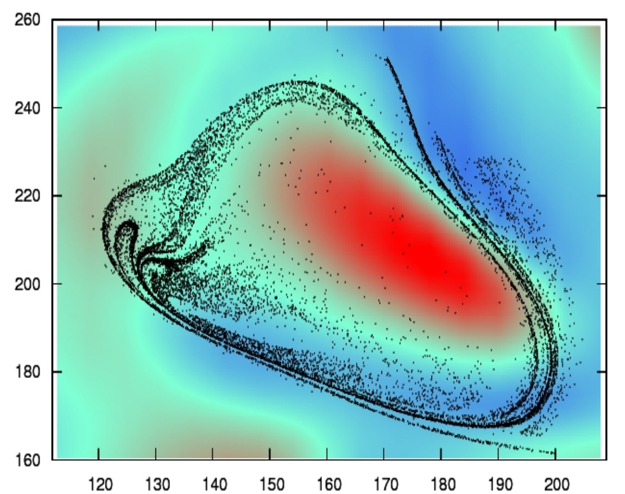
Clustering is intermittent

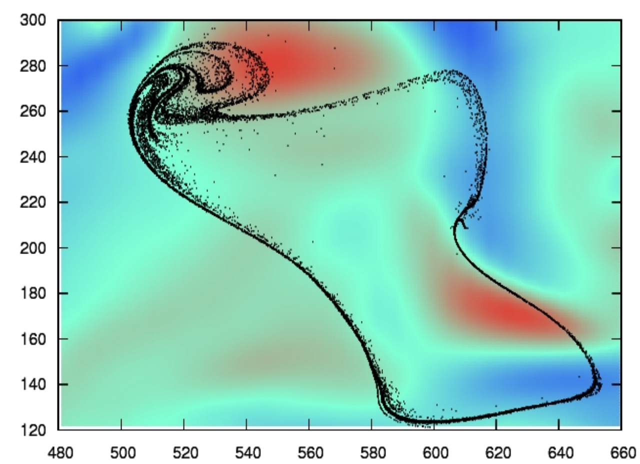


Upwellings

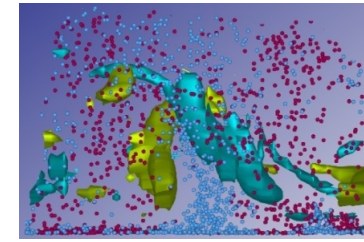
Intermittency is due to near-bottom turbulence



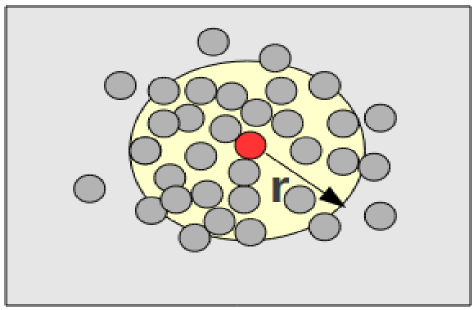




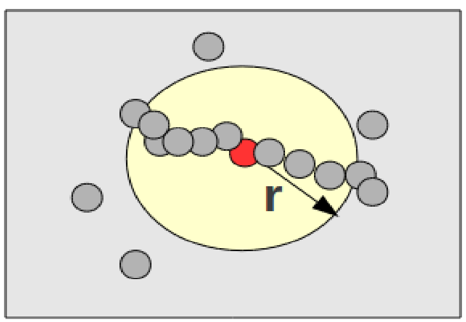
3. Correlation Dimension
Fractal dimension of cluster



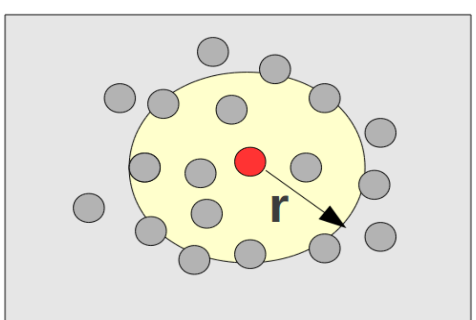
Particles distributed



- uniformly over surface: $N(r) \simeq r^2$

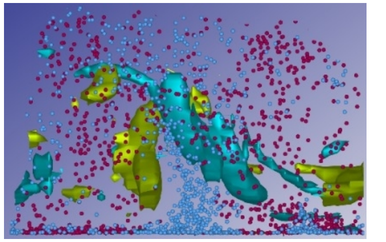


- uniformly into a line: $N(r) \simeq r$

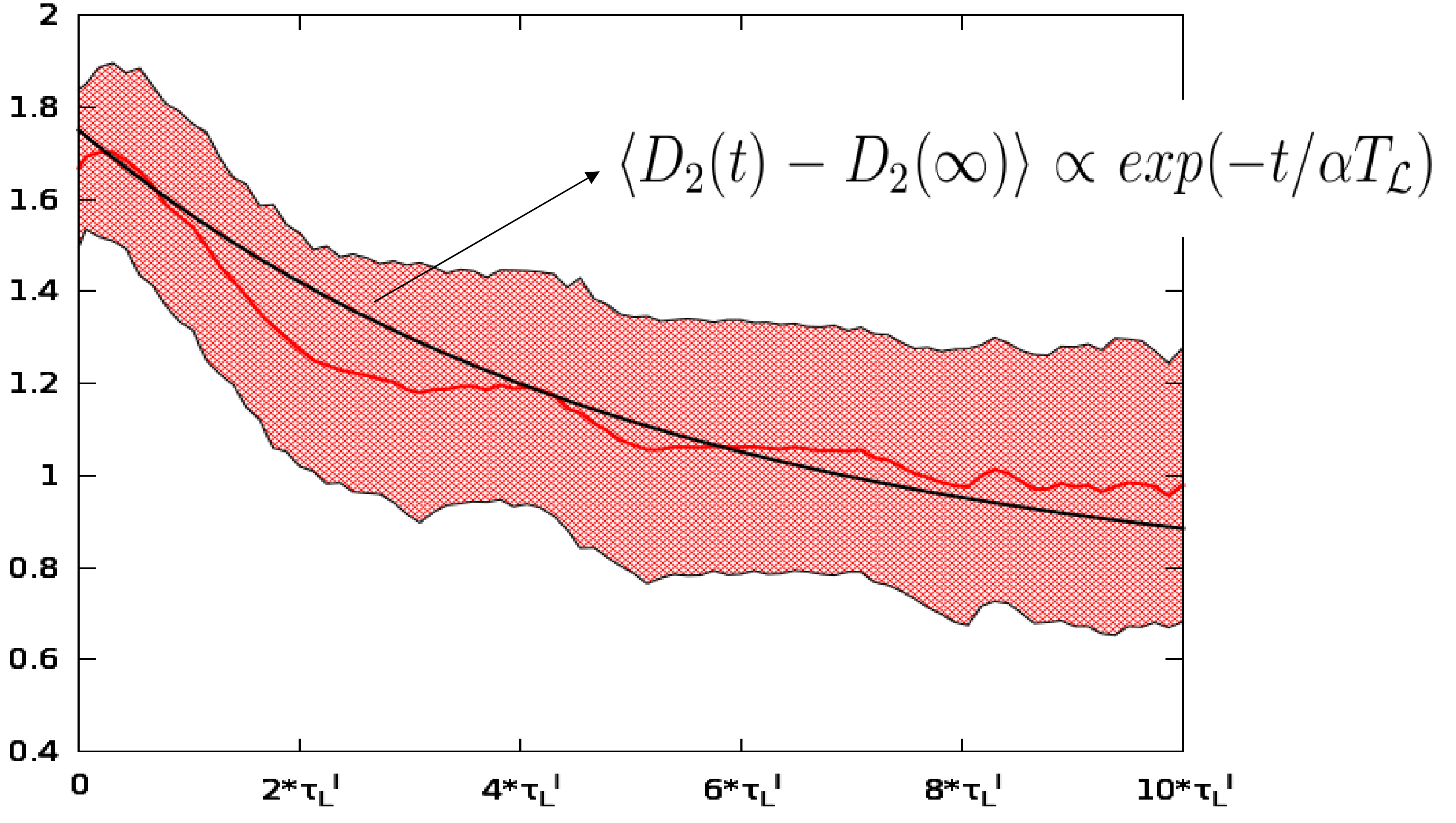


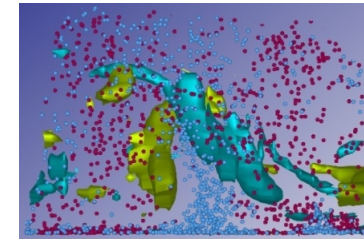
Generally: $$N(r) \simeq r^{\nu}$$

3. Correlation Dimension
Fractal dimension of cluster

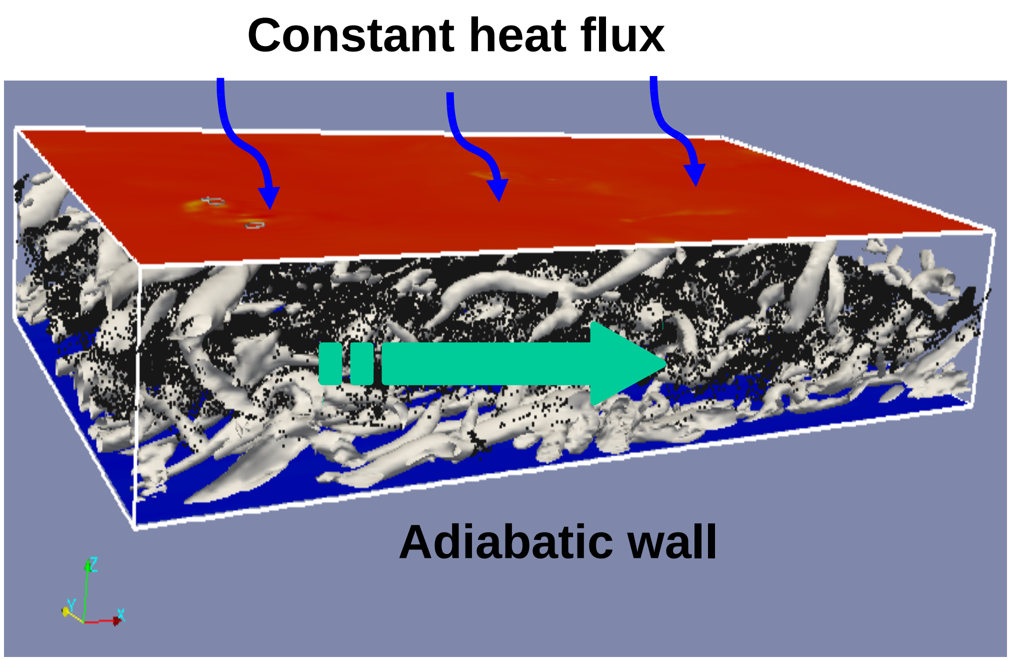


$$Re_\tau = 171$$





Physical Problem/Modelling Approach: Stably-stratified turbulence



$$\frac{D\mathbf{u}}{Dt} = -\nabla p + \frac{\nabla^2 \mathbf{u}}{Re_\tau} + \Pi \mathbf{i} + Ri_\tau \cdot T\mathbf{k}$$

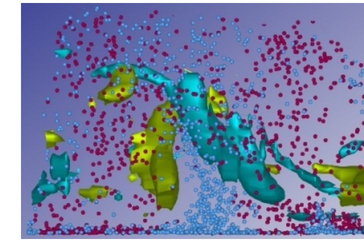
$$\frac{DT}{Dt} = \frac{\nabla^2 T}{Re_\tau Pr} - \beta_T$$

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

Re_τ^*	171	
$u_\tau \ (m/s)$	$1.5 \cdot 10^{-3}$	
height channel (m)	$2. \cdot 10^{-2}$	
Ri_τ	164	247
Pr	5	
Ra	$4.82 \cdot 10^6$	$7.23 \cdot 10^6$

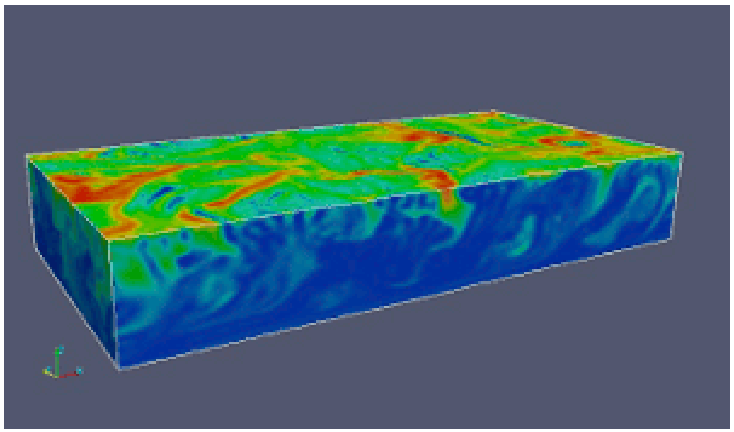
$$Ri = \frac{Gr}{Re_\tau^2}$$

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

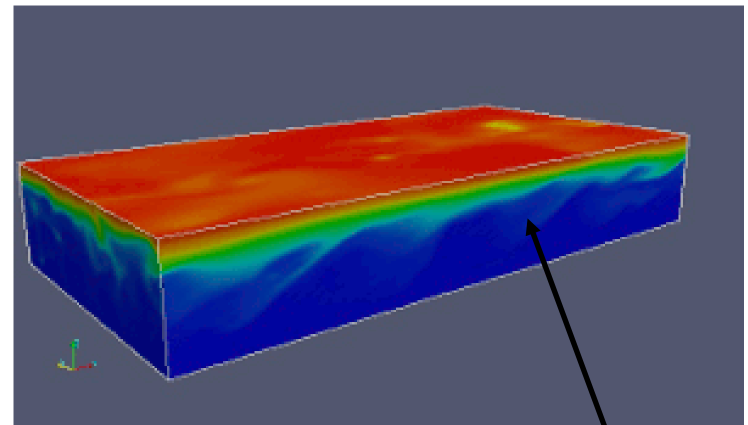


Temperature field

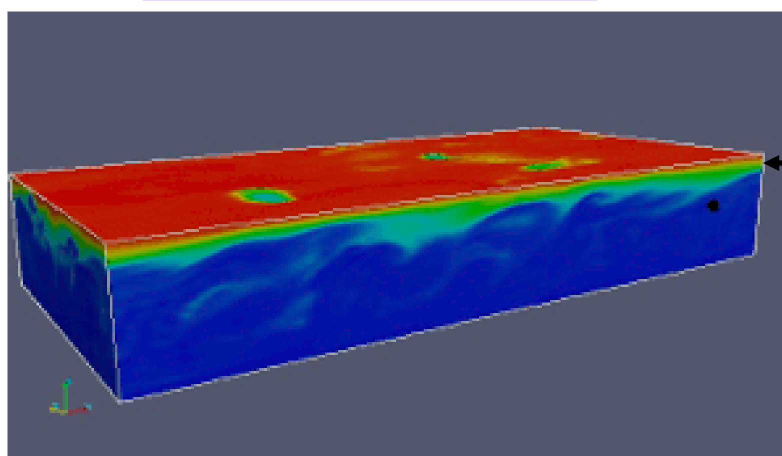
$$Ri_\tau = 0$$



$$Ri_\tau = 164$$

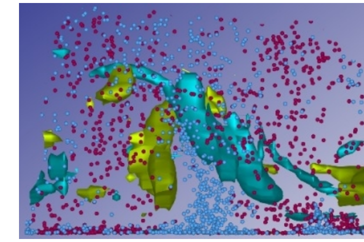


$$Ri_\tau = 247$$



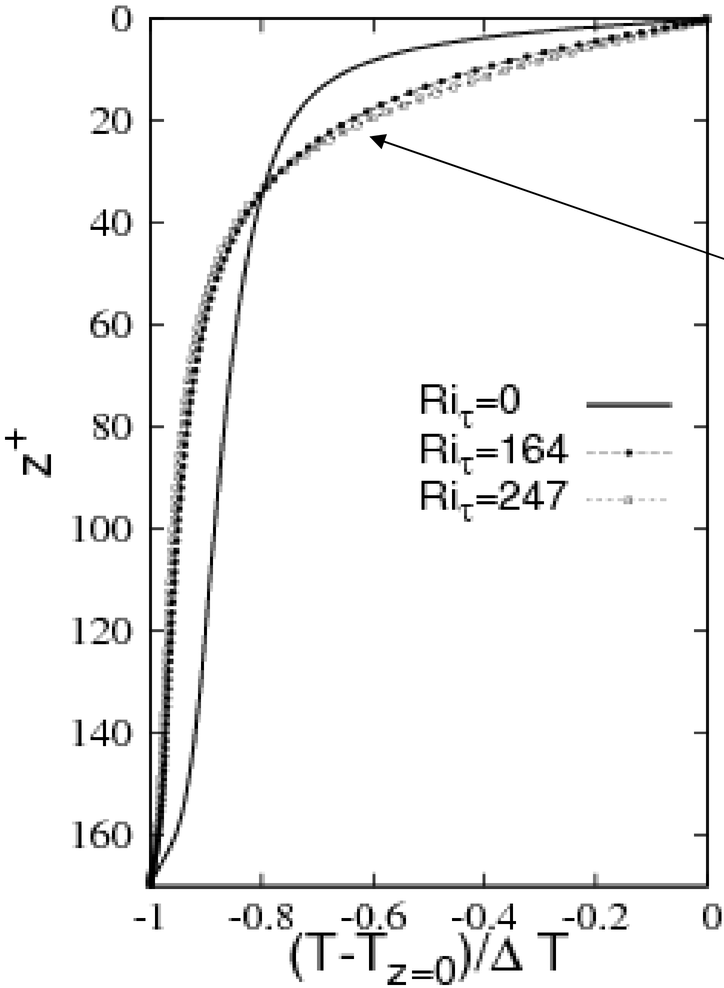
Thermocline
(barrier)

Upwellings do not reach the surface!



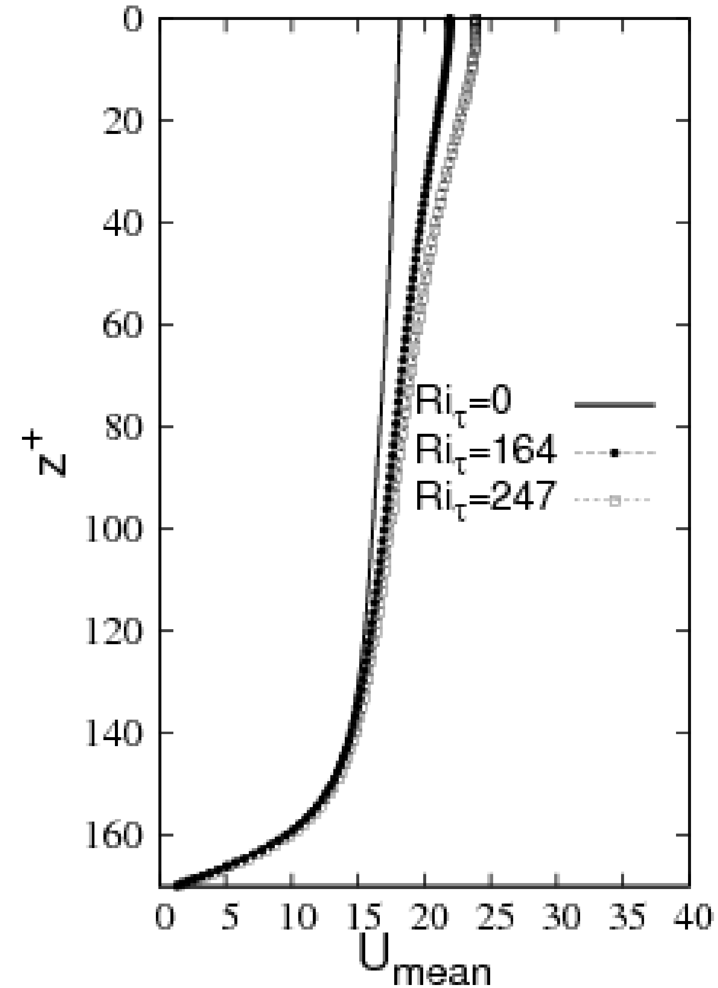
Turbulent temperature statistics

Mean Temperature

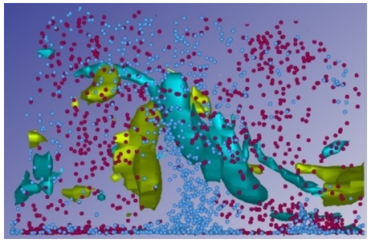


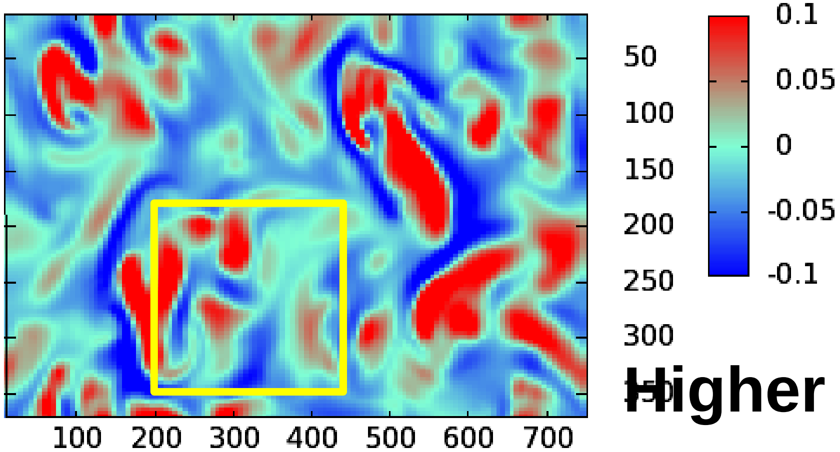
Thermocline:
Potential barrier due to density distribution

Mean streamwise velocity



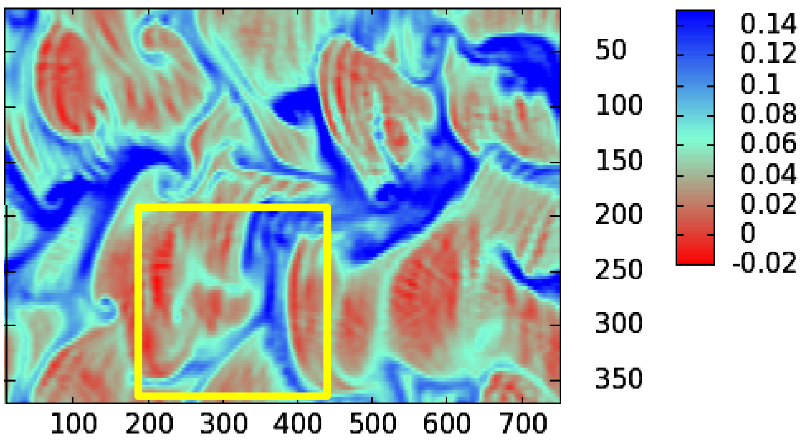
Surface dynamics





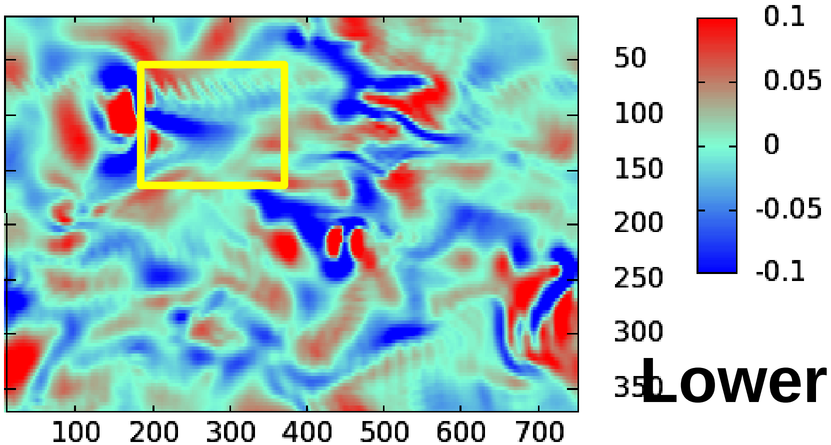
$$Ri_\tau = 0$$

Higher correlation



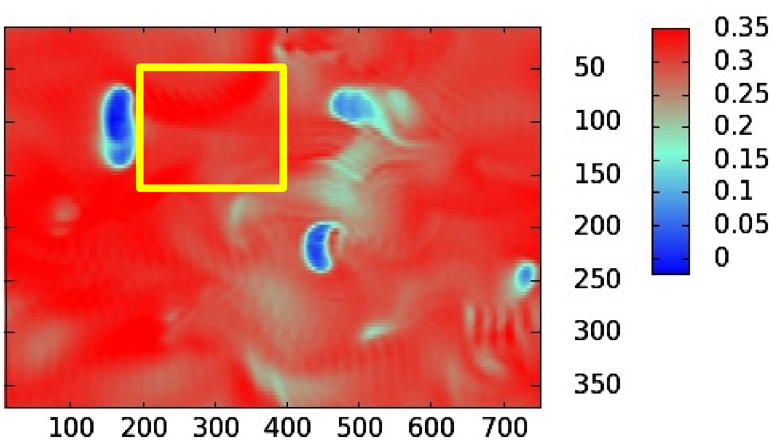
Surface divergence

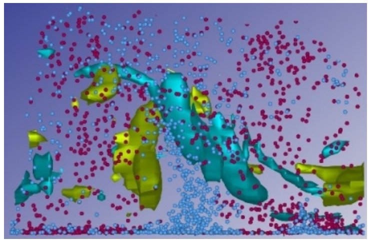
Surface temperature



$$Ri_\tau = 247$$

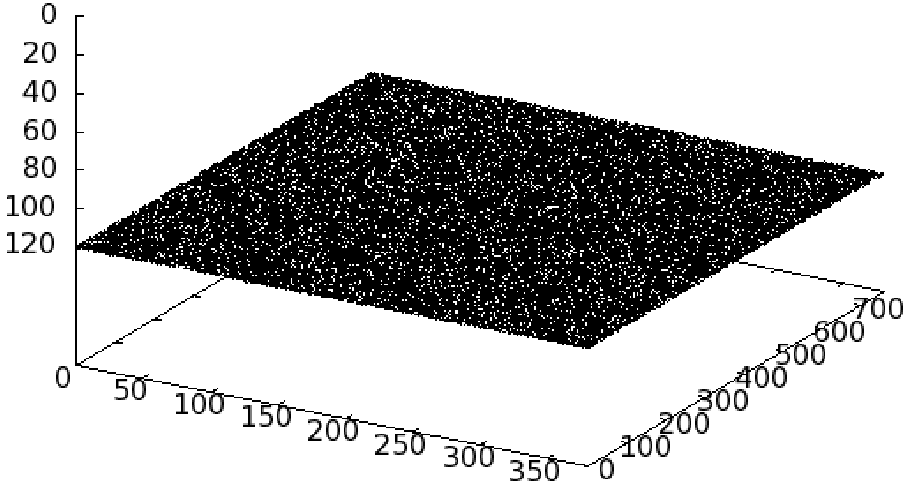
Lower correlation



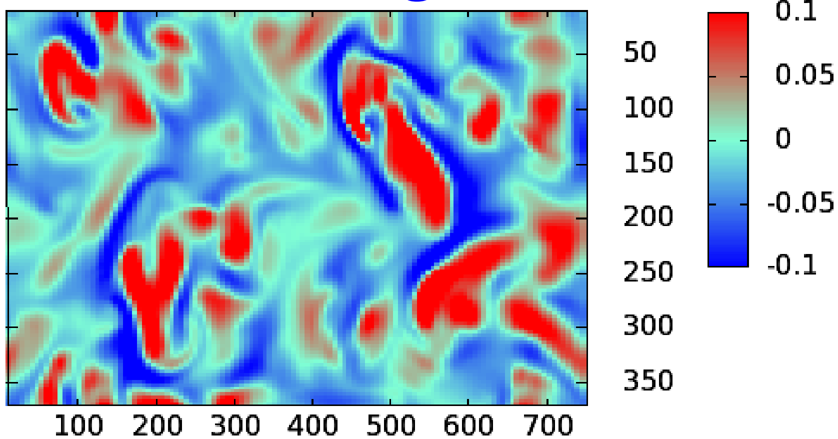


Lagrangian Particle Tracking

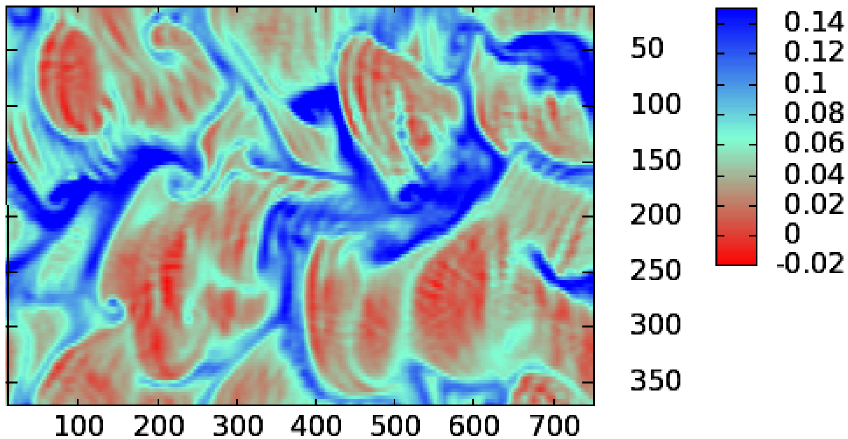
$$Ri_\tau = 0$$



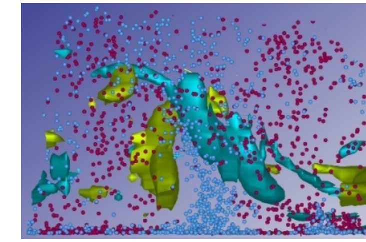
Surface divergence



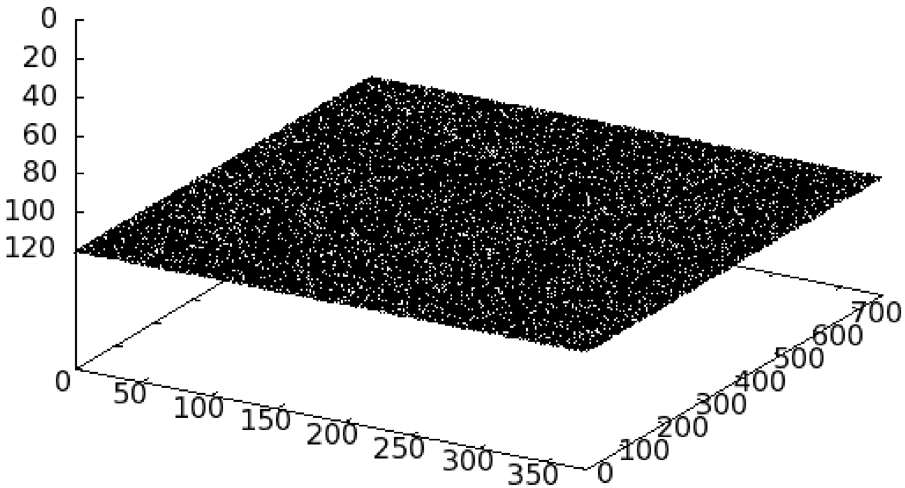
Surface temperature



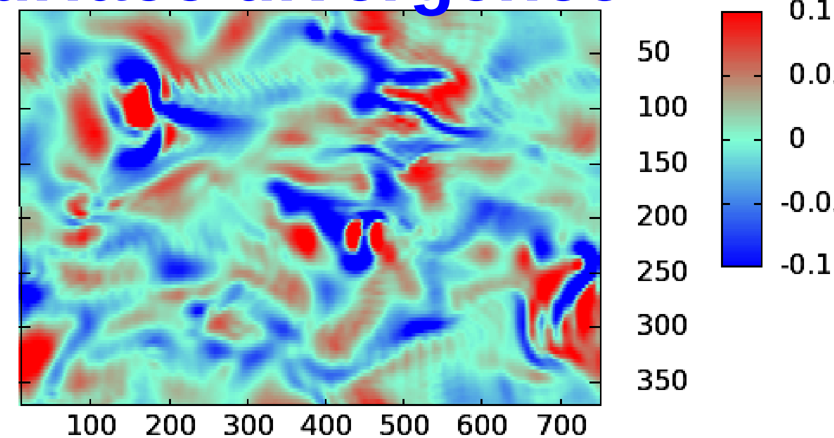
Lagrangian Particle Tracking



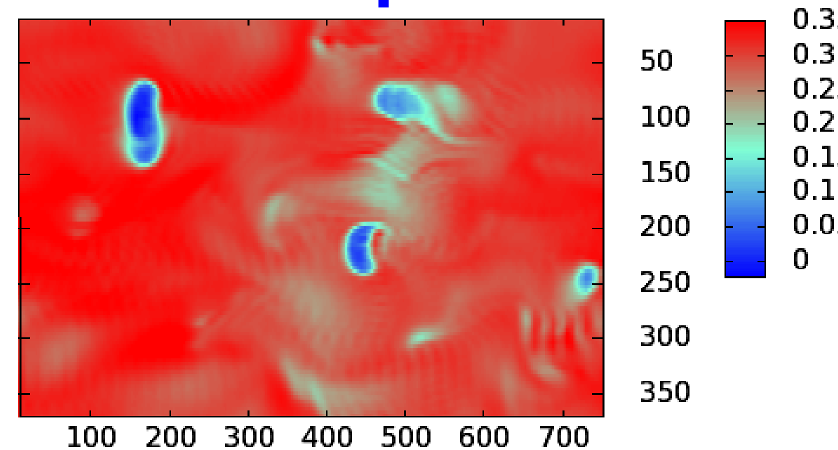
$$Ri_\tau = 247$$



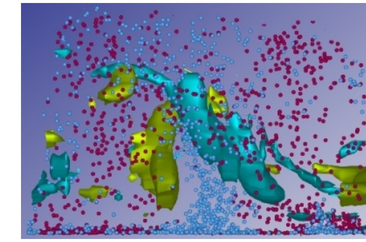
Surface divergence

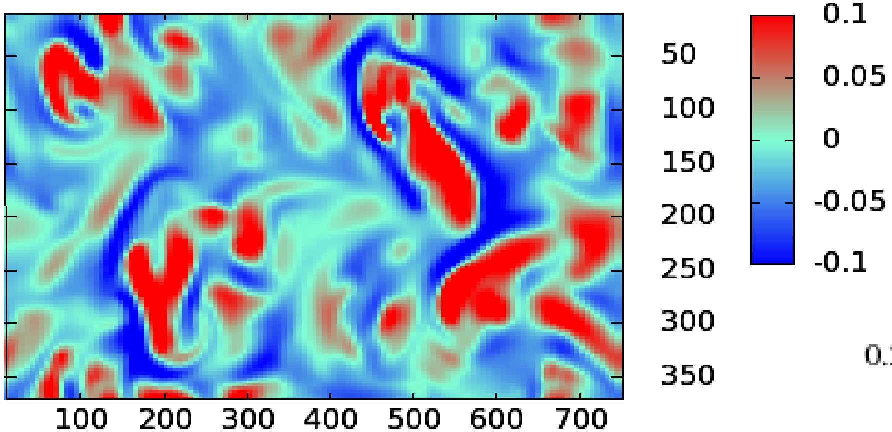


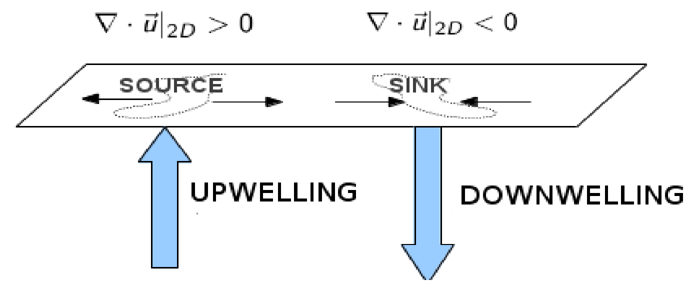
Surface temperature

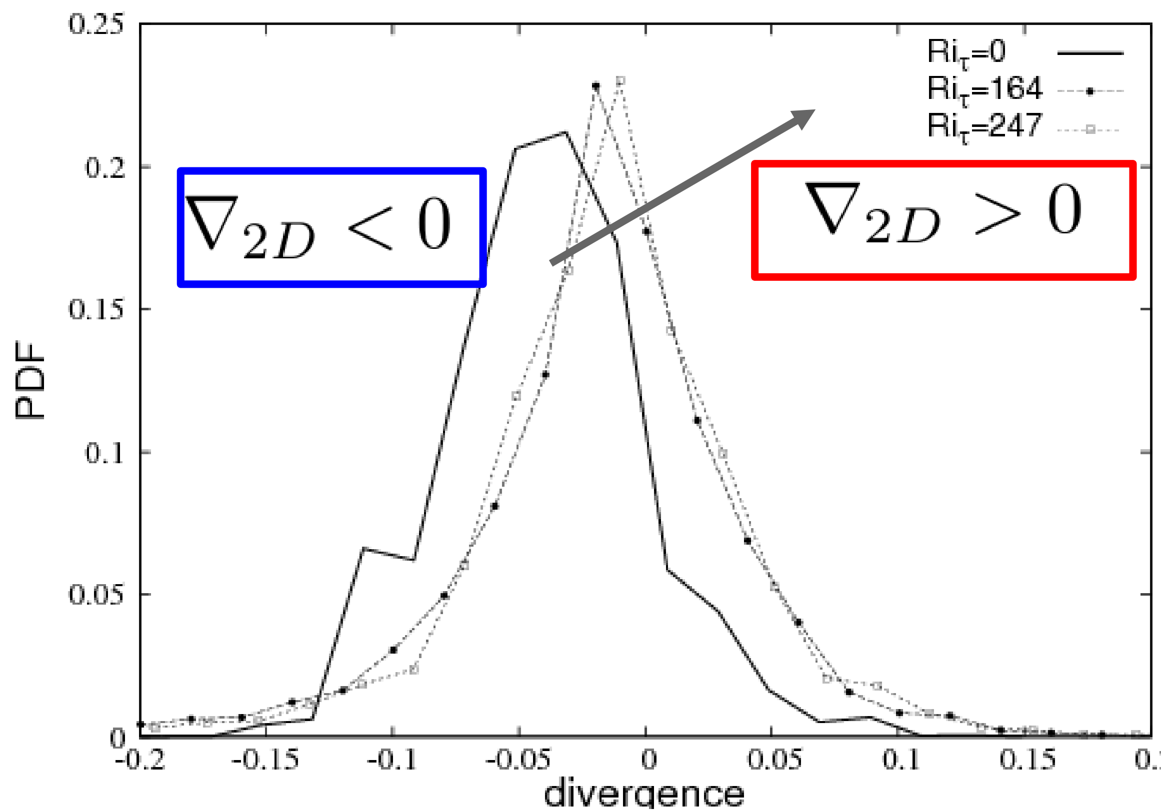


Lagrangian Particle Tracking





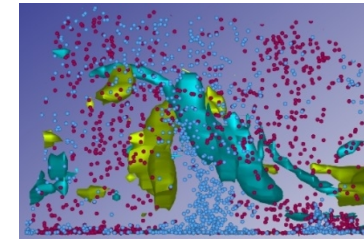




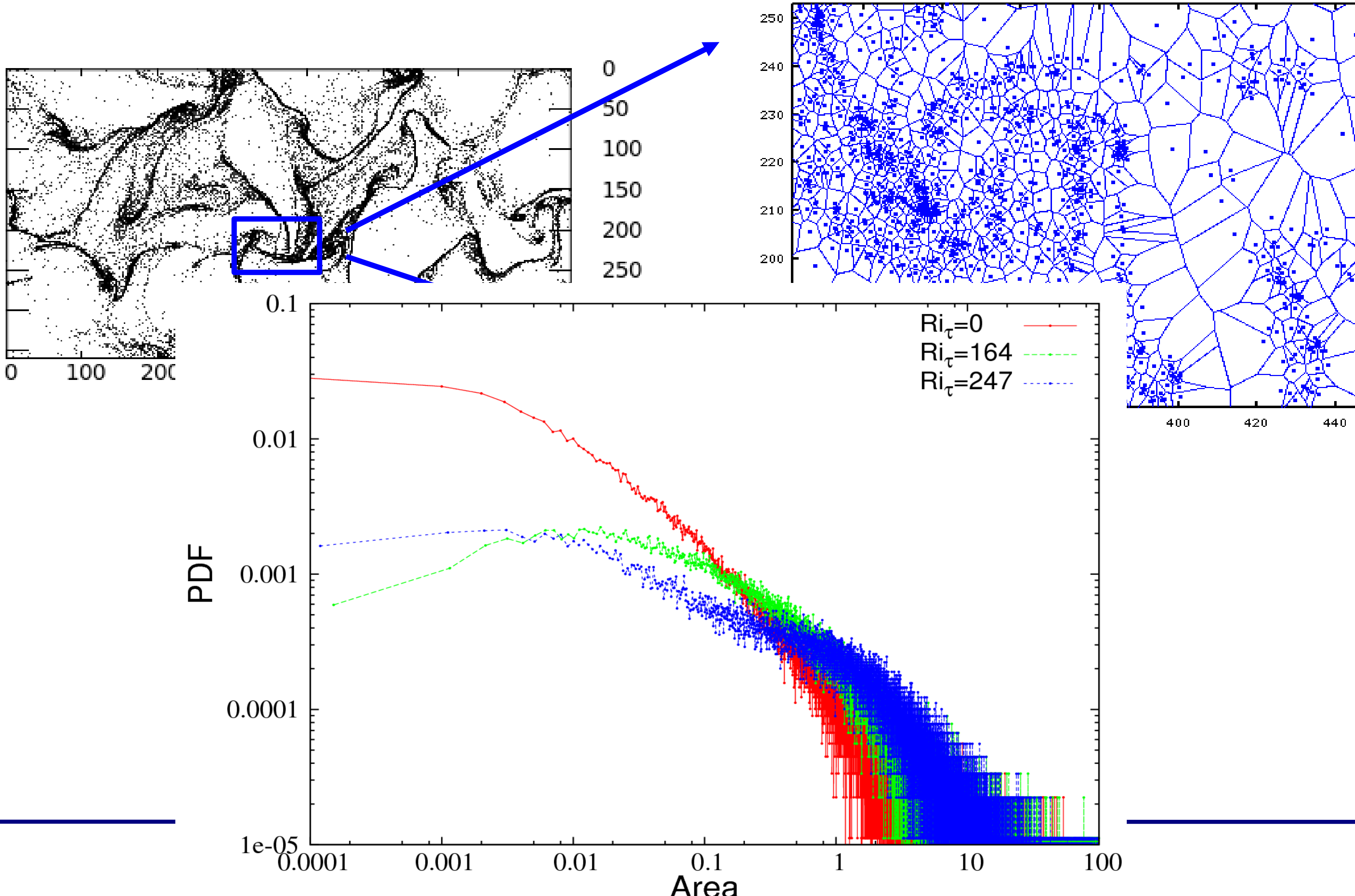
For stratified flows,
Particles do not follow
Carefully the flow field

No intense
Upwelling events at
the surface (thermocline)

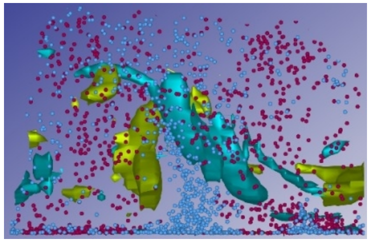
Lagrangian Particle Tracking



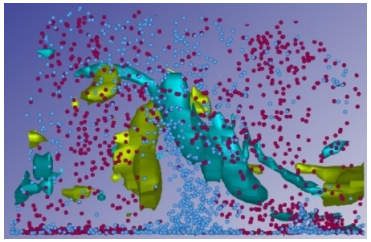
VORONOI ANALYSIS



4. Conclusion and Future Developments



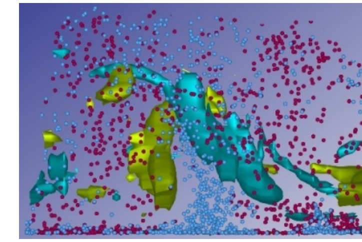
- *DNS of turbulent open channel flow at Re =171 (and Re =509) and for different stratification levels (Ri) was performed*
- *Flow at the surface was characterized by the 2D divergence*
- *In neutrally-buoyant flow, particles tend to cluster into filaments following the dynamics of source and sink induced by upwellings and downwellings.*
- *In stably stratified turbulence particles seems to sample more homogeneously the surface: upwelling/downwelling events do not easily reach the surface (thermocline)*



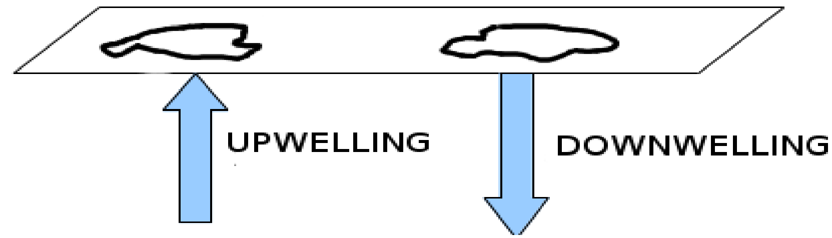
Thank you for your

kind attention

1. Flow at surface

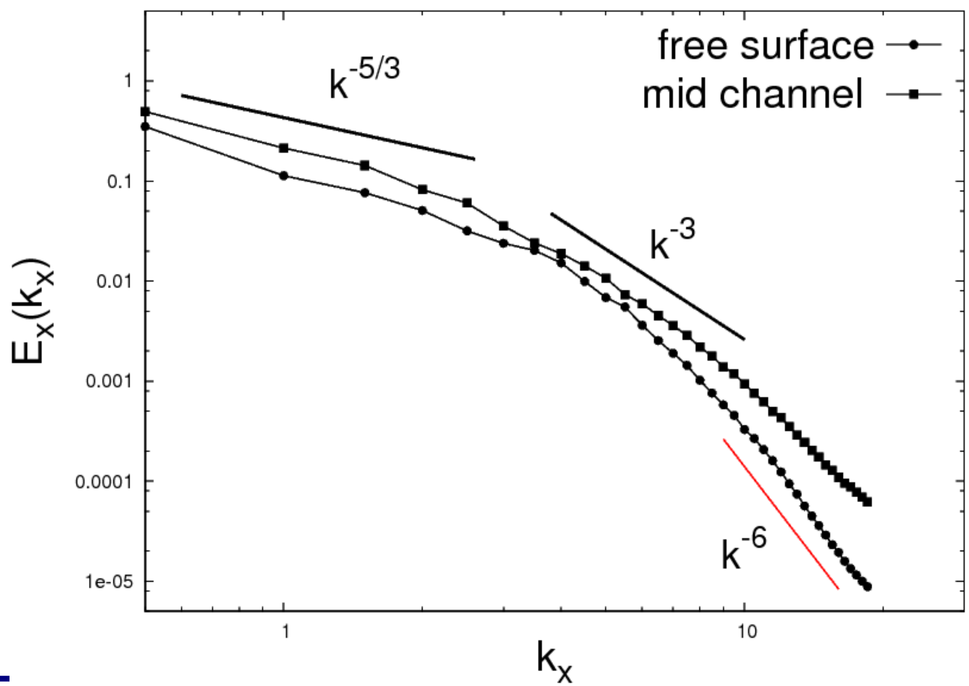


Komori et al. : **[...] Large fraction of the Near-wall burtsting events result in surface renewal events [...]**
JFM (1989)

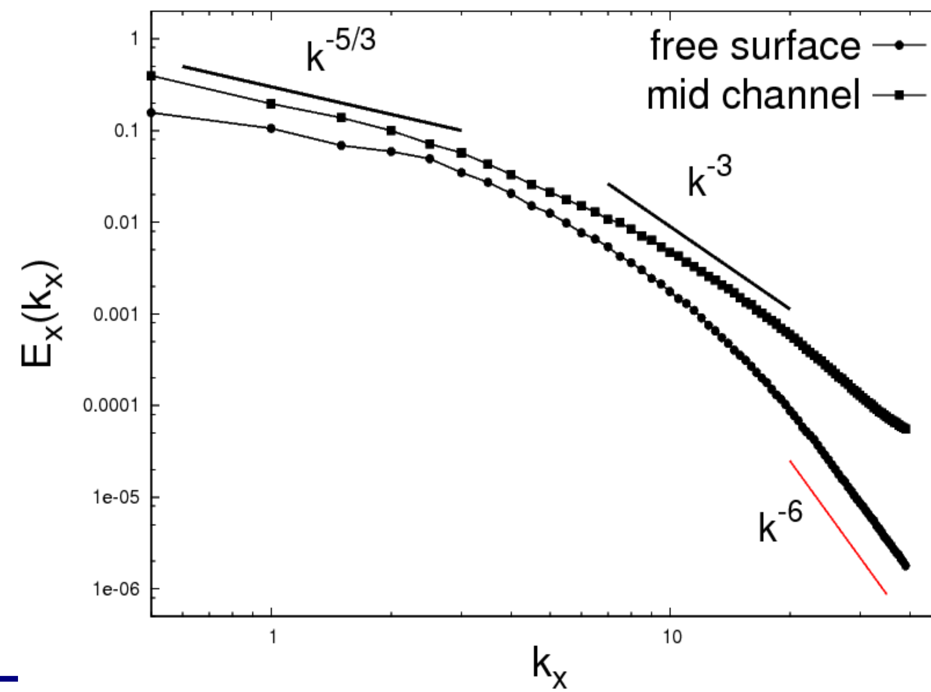


Streamwise energy spectrum of the streamwise velocity

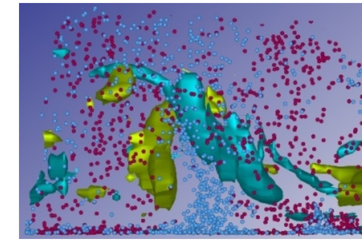
$Re_\tau = 171$



$Re_\tau = 510$



1. Flow at surface



Komori et al. : [...] Large fraction of the Near-wall burtsting events result in surface renewal events [...]
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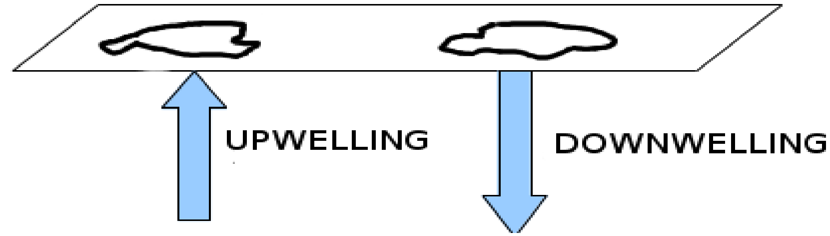
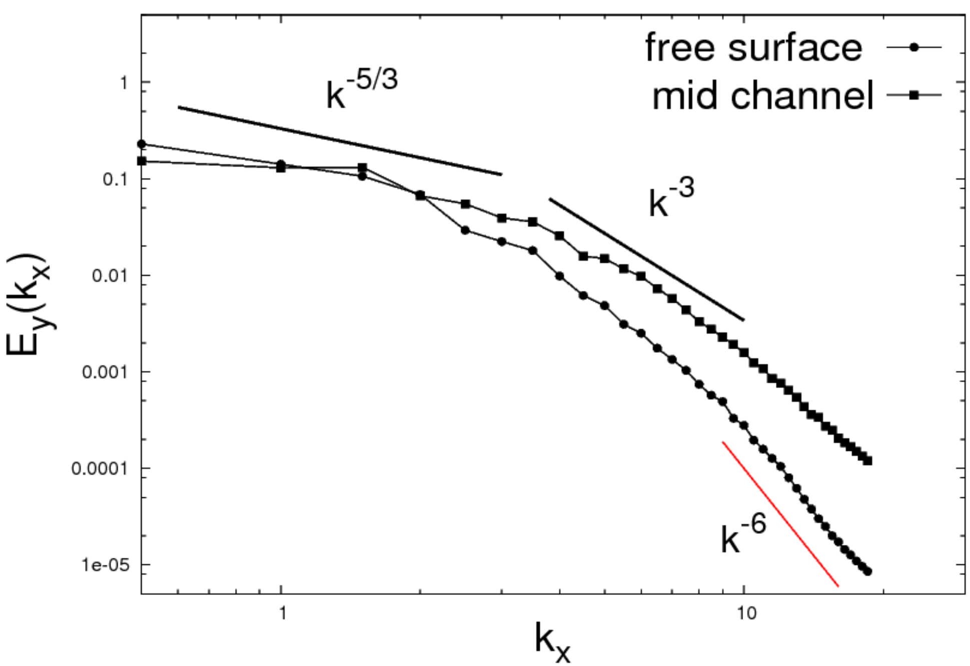
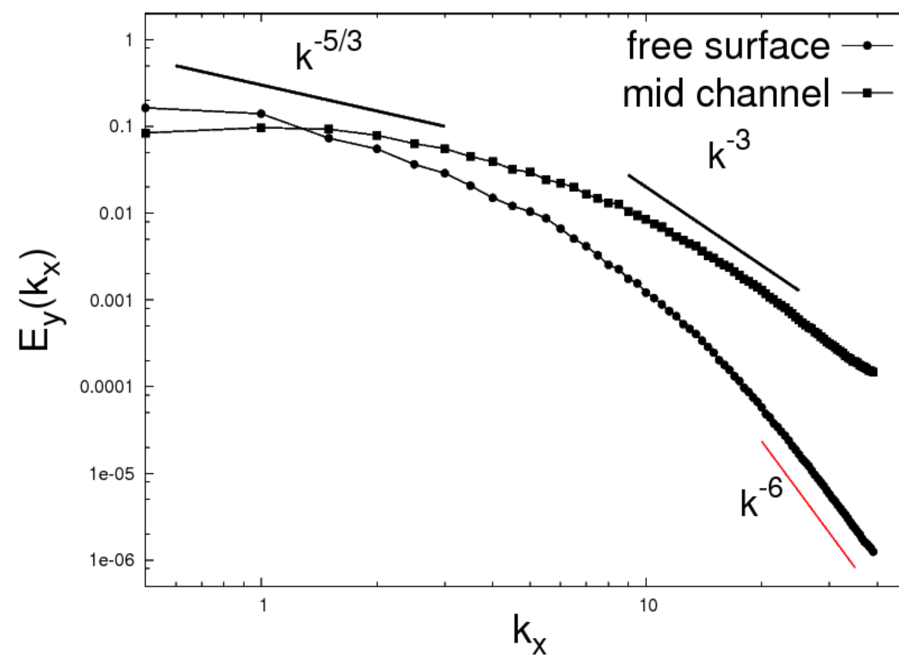


Streamwise energy spectrum of the spanwise velocity

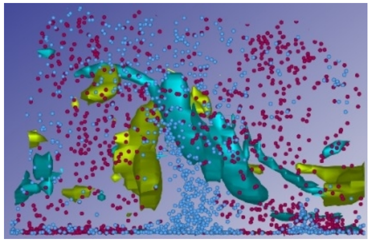
$$Re_\tau = 171 \qquad\qquad Re_\tau = 510$$





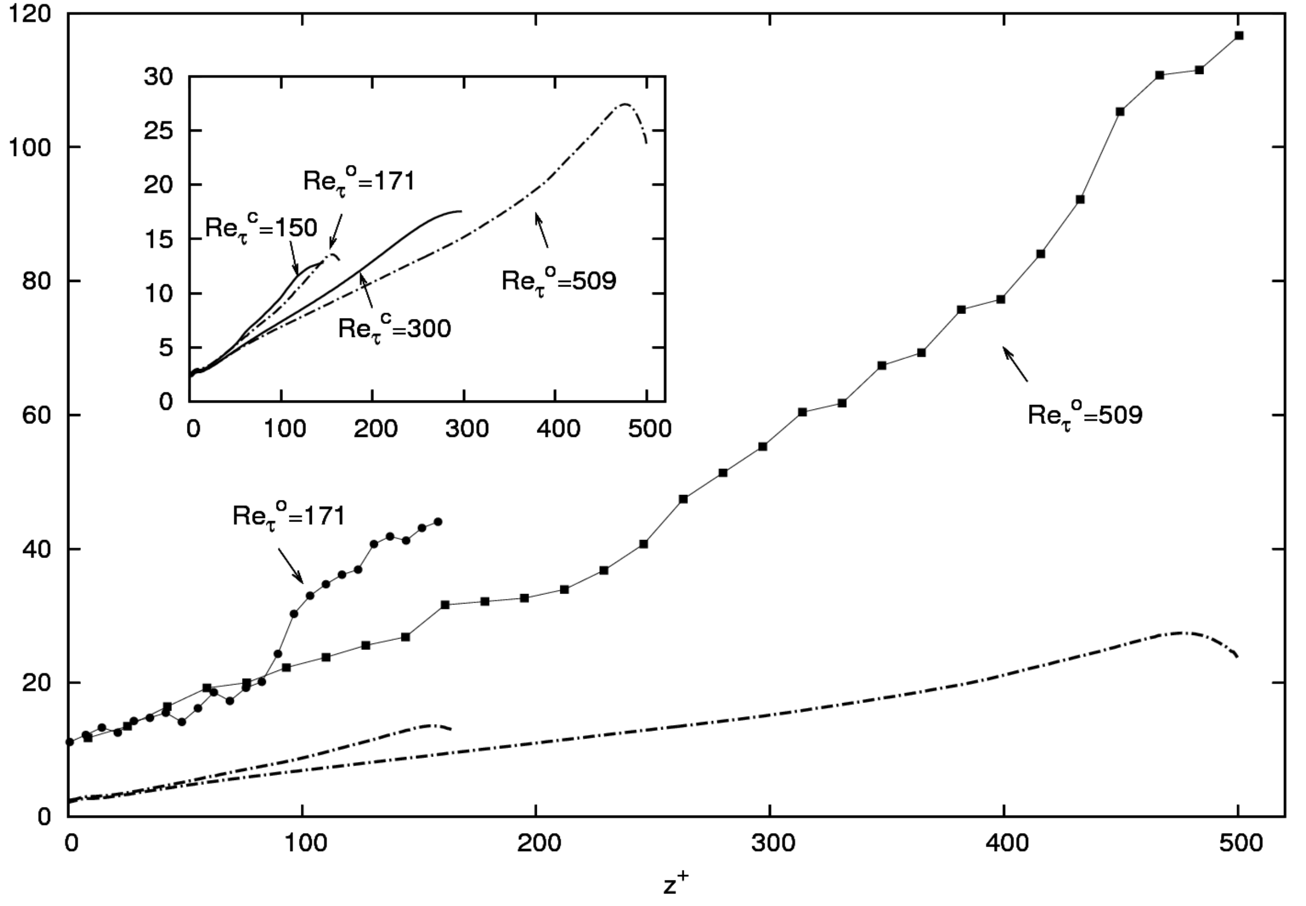
3. Cluster renewal

Flow time scale



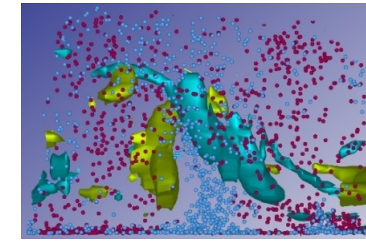
Lagrangian time scale:

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



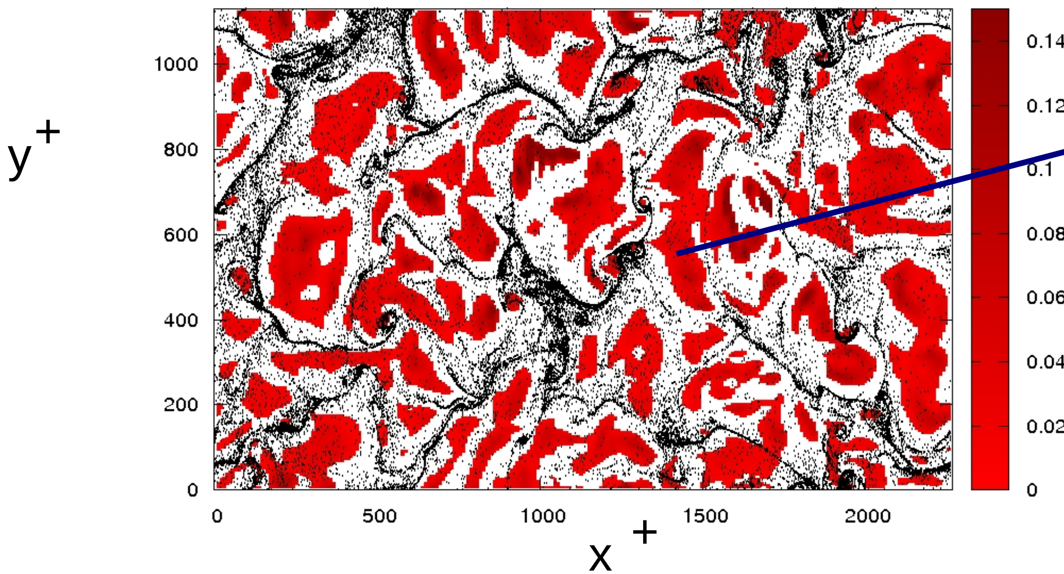
(Long) Time Persistency Of surface Structures!!

3. Surface cluster renewal



Clustering is intermittent

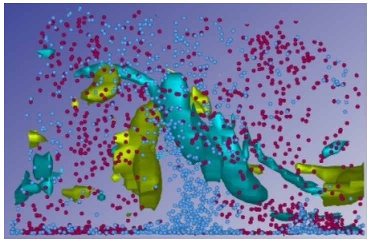
Upwellings



∇_{2D}

Intermittency is due to <u>near-bottom turbulence</u>

Lagrangian Particle Tracking



$$\rho_p = 900$$