# Dispersion and clustering of Particles in turbulent flows: Channel, Open Surface and Stratified Flows

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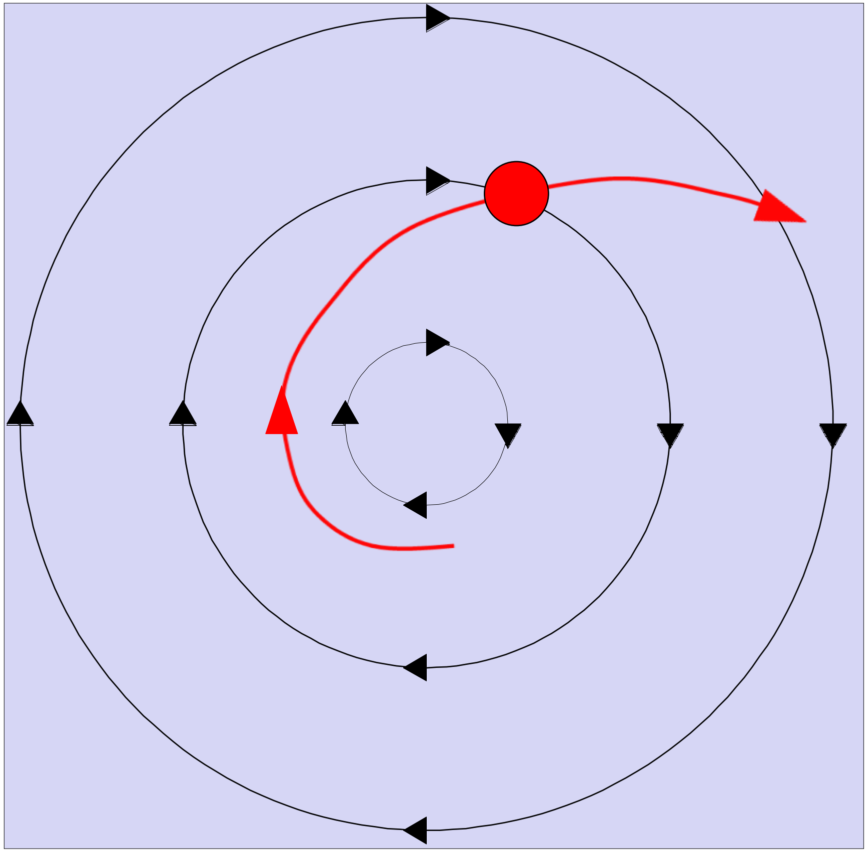
We focus on the problem of the one single particle in a fixed vortex and we try to quantify the tendency of a particle to escape the flow streamlines.



$$\rho_p >> \rho_f$$

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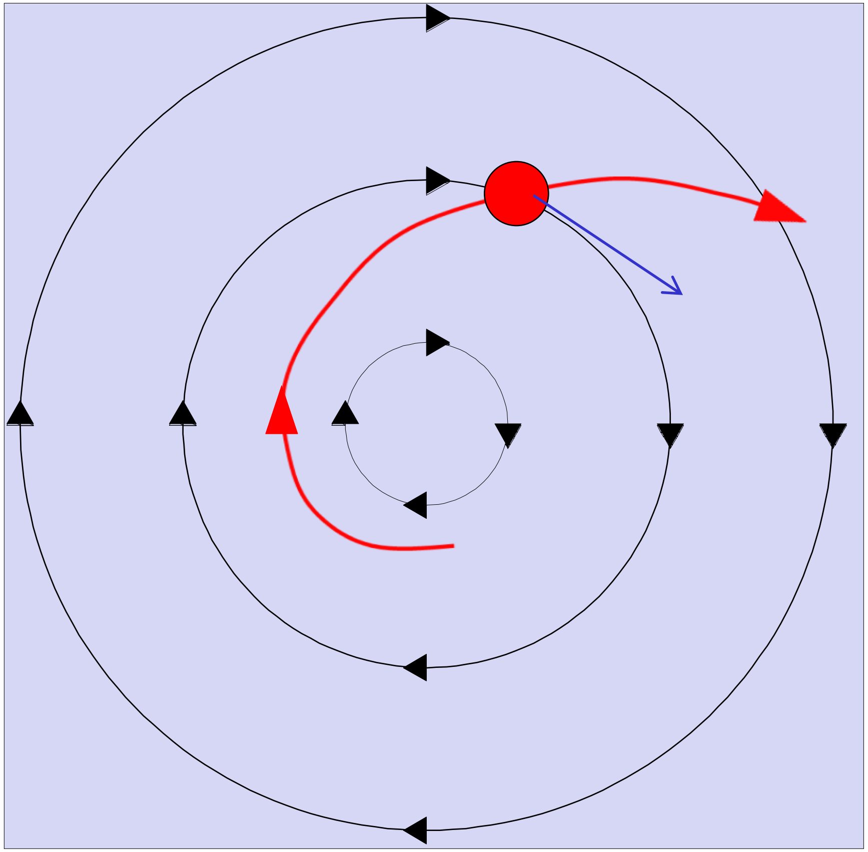

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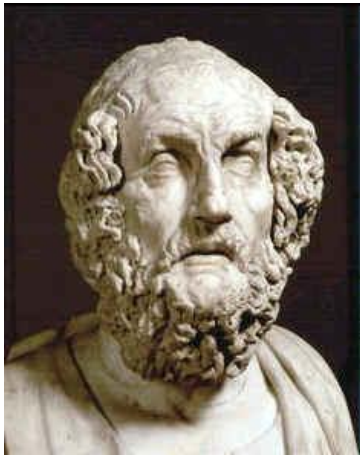

Motion Κατα φυσιν (according to Nature): Motion along the tangent

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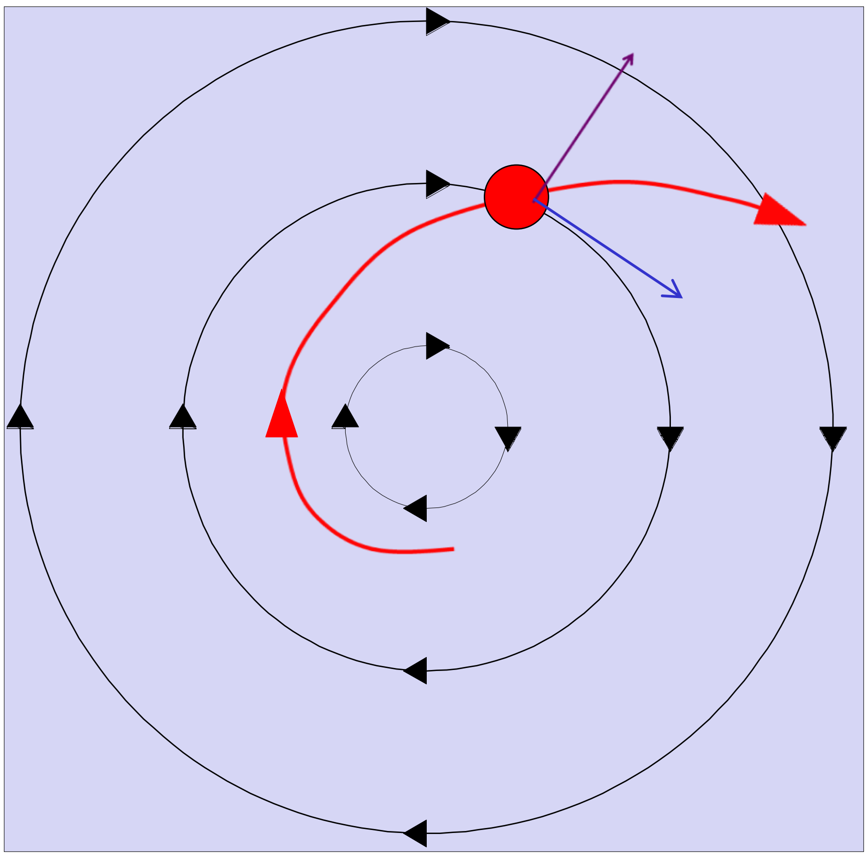

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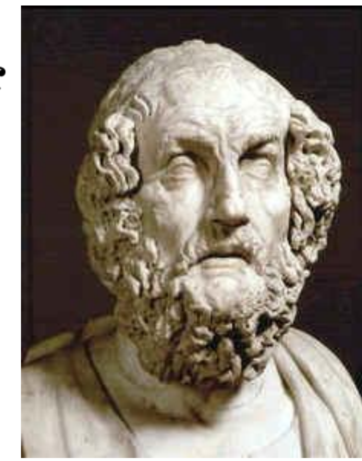
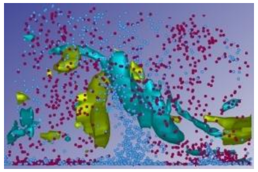


Motion Κατα φυσιν (according to Nature): Motion along the tangent

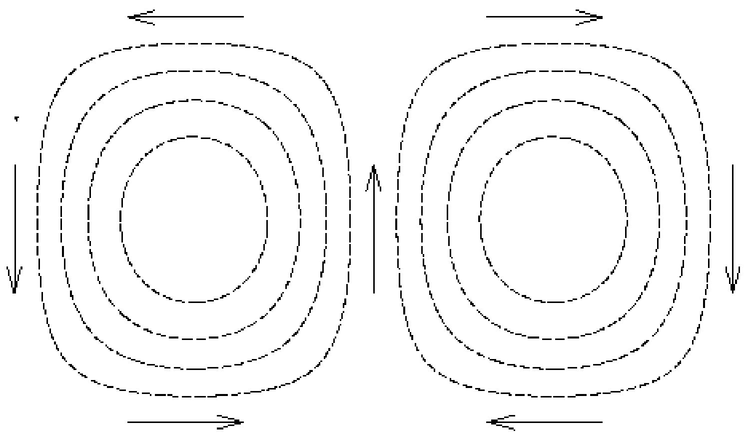
Motion Παρα φυσιν (against Nature): Centrifugal Motion



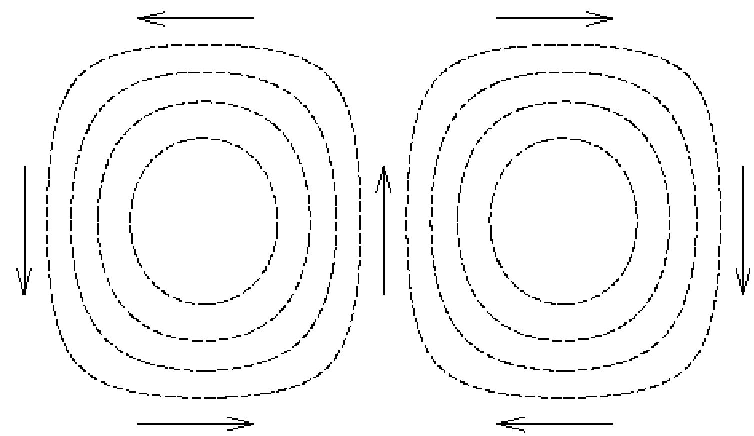
# The effect of vortices? problem becomes non-trivial

## Defintion of a Parameter

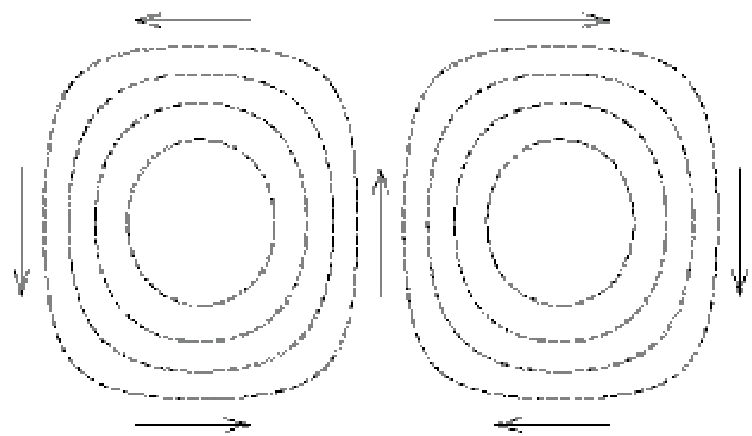
Light particles: $\tau_p << \tau_f$



Intermediate particles: $\tau_p \approx \tau_f$



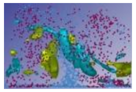
Heavy particles: $\tau_p >> \tau_f$



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

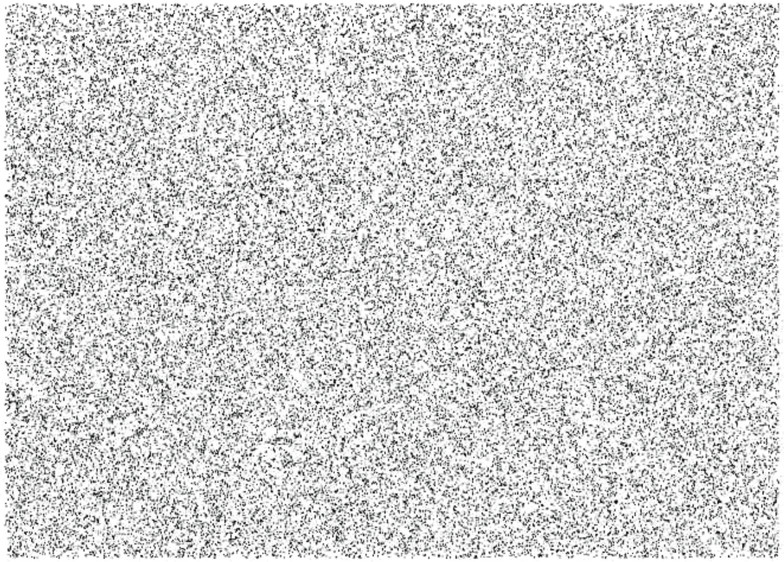
Flow Time Scale: $$\tau_f$$

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

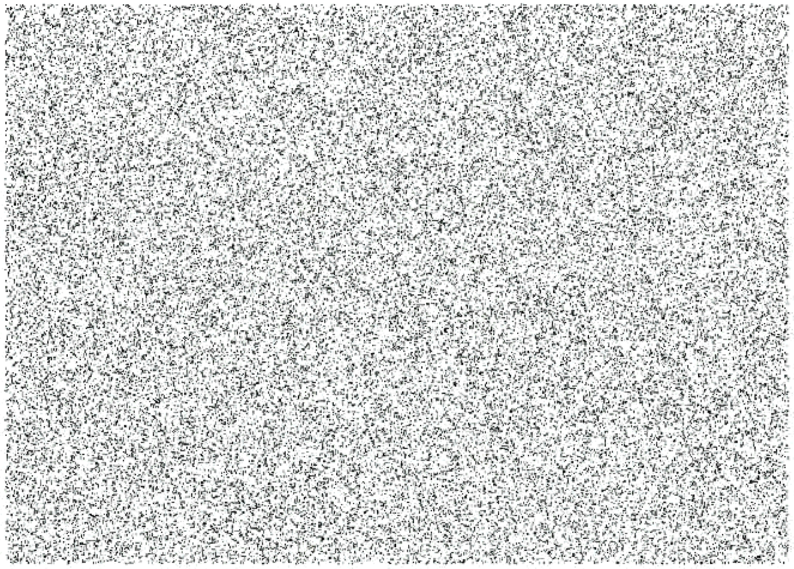


## … A very simple experiment:
## A ‘rain’ of heavy particles in Still Fluid

Heavy Particles

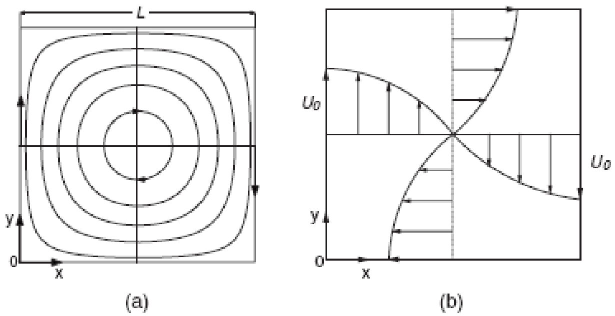


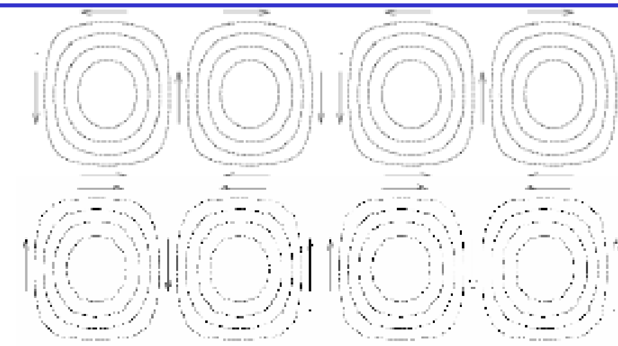
Light Bubbles

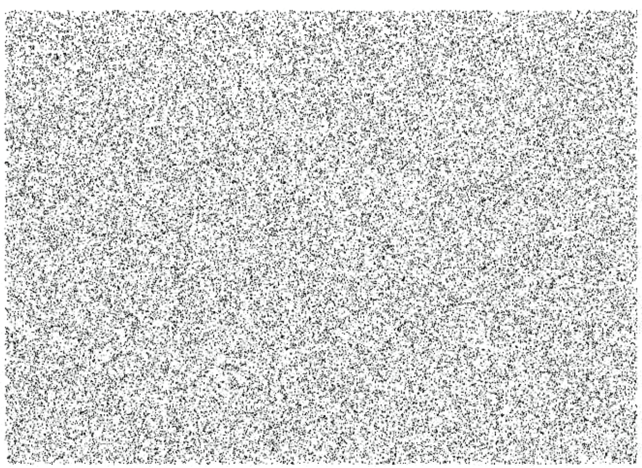


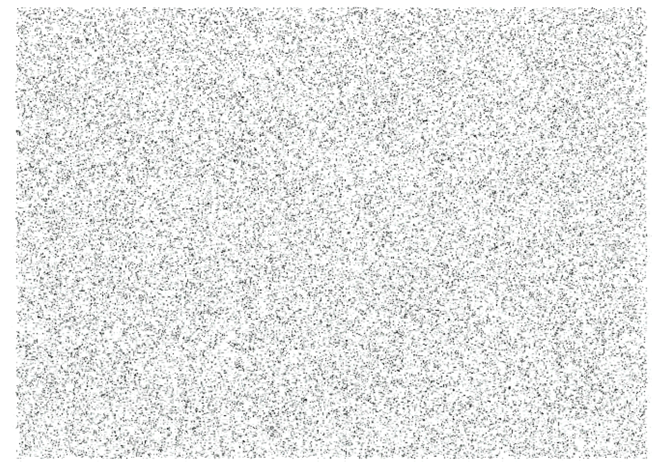
Particles settling velocity: $v_s = d_p^2 g(\rho_p - \rho_f)/(18\ \mu)$

# A less simple experiment: we add steady vortices
# Preferential segregation due to inertia arises







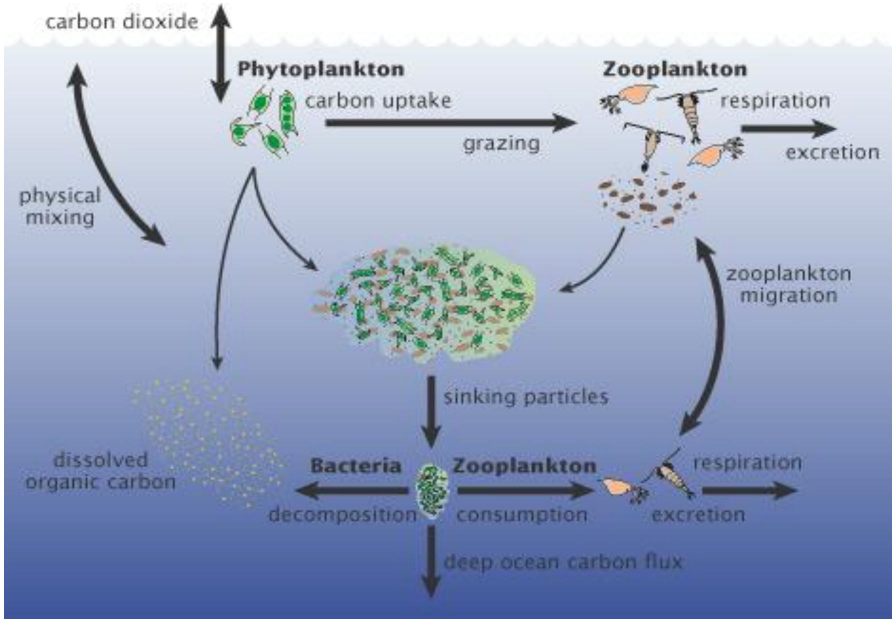
Heavy Particles

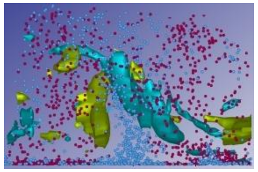
Light Bubbles

Heavy particles are propelled out of the vortices while settling down. Light bubbles are propelled inward  while rising up. there is a general influence on the effective settling velocity  (Maxey, Phys Fluids 1987)

# Environmental Motivations

Role of Turbulence still unclear ... Beside being Difficult to Model accurately for process prediction





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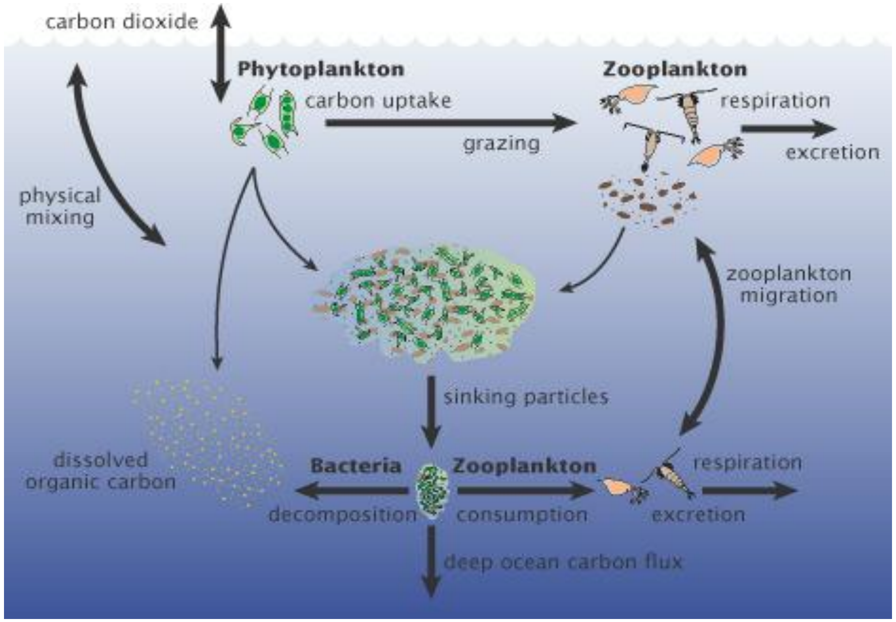
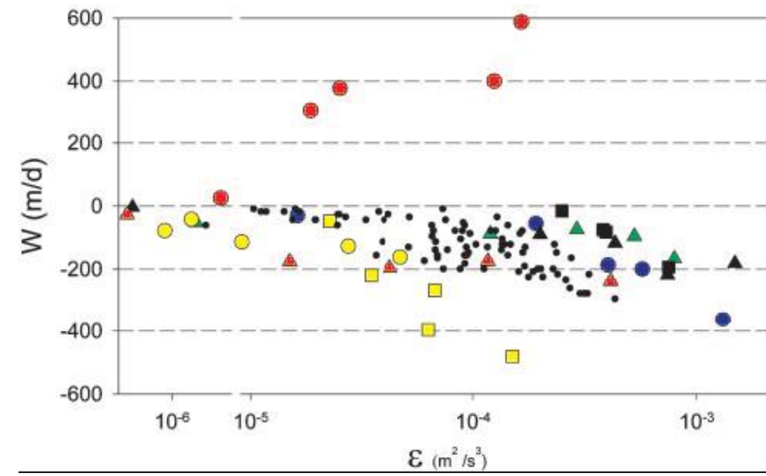


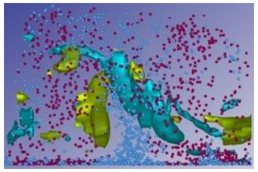

PNAS (2004) 101
Turbulence increases the average settling velocity of phytoplankton cells
J. Ruiz, D. Macìas, and F. Peters

Rise velocity




A species of phytoplankton (●, Artemia Salina Eggs) rise with: V rise > V Stokes





# Environmental Motivations

Role of Turbulence still unclear ... Beside being Difficult to Model accurately for process prediction

Phys. Fliuds (2007) 19
Influence of added mass on anomalous high rise velocity of light particles in cellular flow field: A note on the paper by Maxey 1987
C. Marchioli, M. Fantoni, and A. Soldati

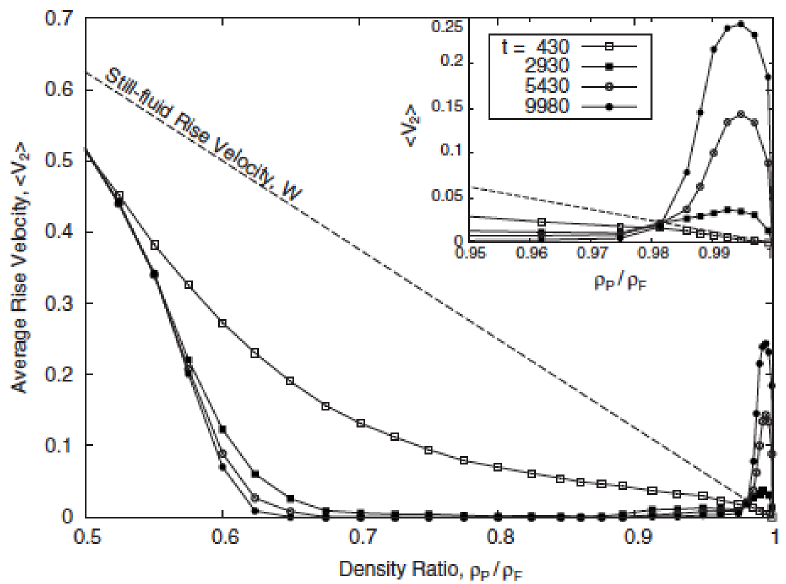



FIG. 4. Average particle rise velocity, $\langle V_2 \rangle$, against particle-to-fluid density ratio, $\rho_P/\rho_F$. Values of the parameters are $B/\pi=10$, $Q=1.25$.

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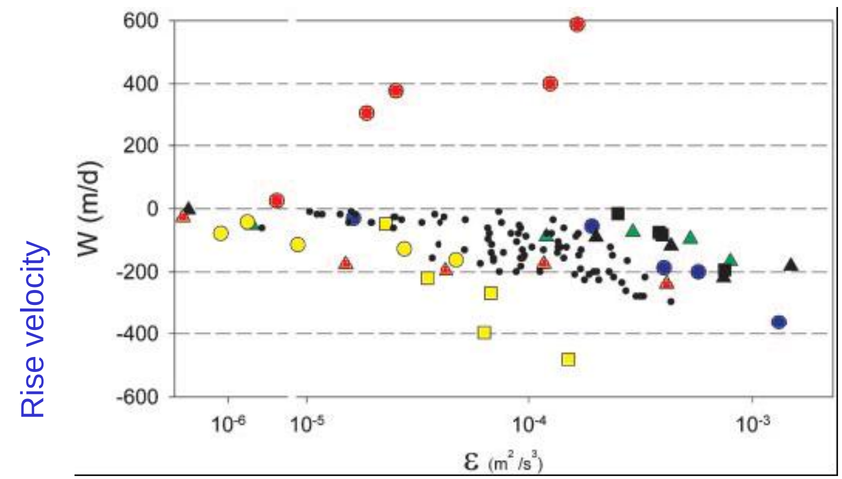


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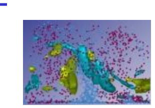

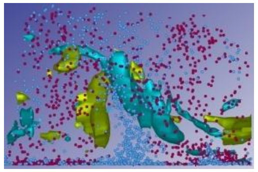

# Environmental Motivations

## Role of Turbulence still unclear ... Beside being Difficult to Model accurately for process prediction

PRL **106,** 238102 (2011) PHYSICAL REVIEW LETTERS week ending 10 JUNE 2011

**Gyrotaxis in a Steady Vortical Flow**

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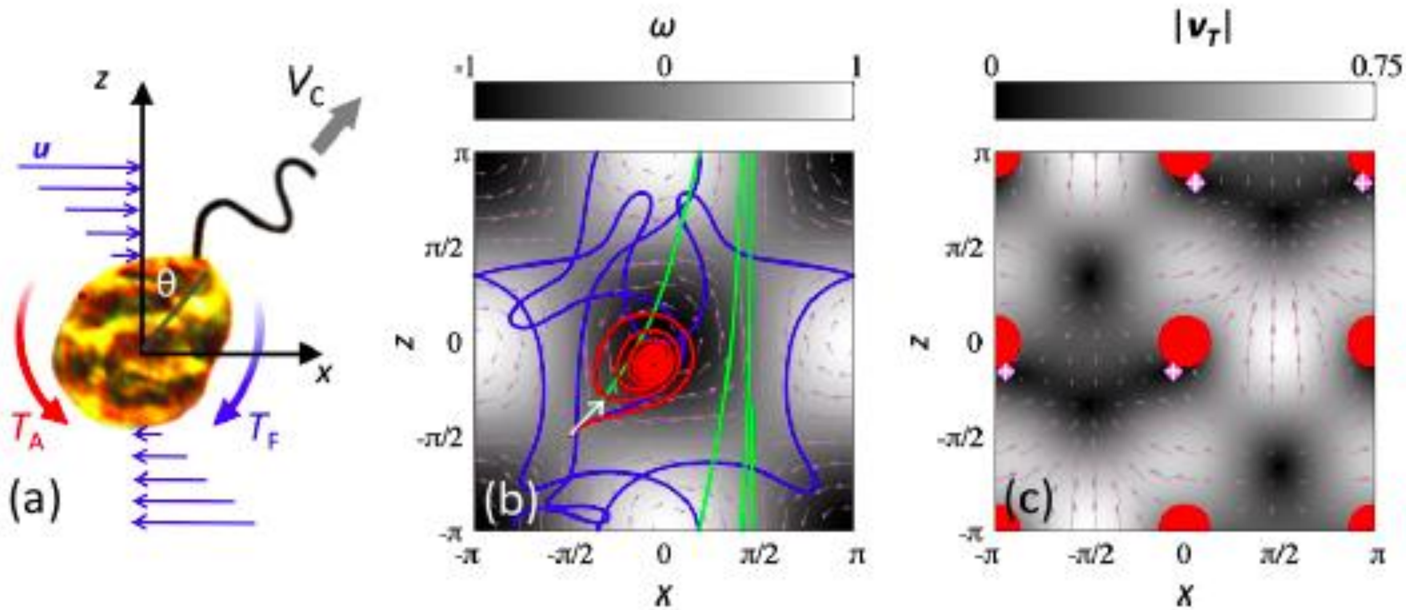
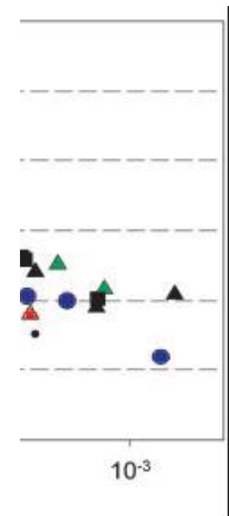
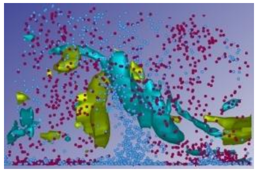
[2]*Institut de Mécanique des Fluides, Université de Toulouse, INPT-UPS-CNRS,*



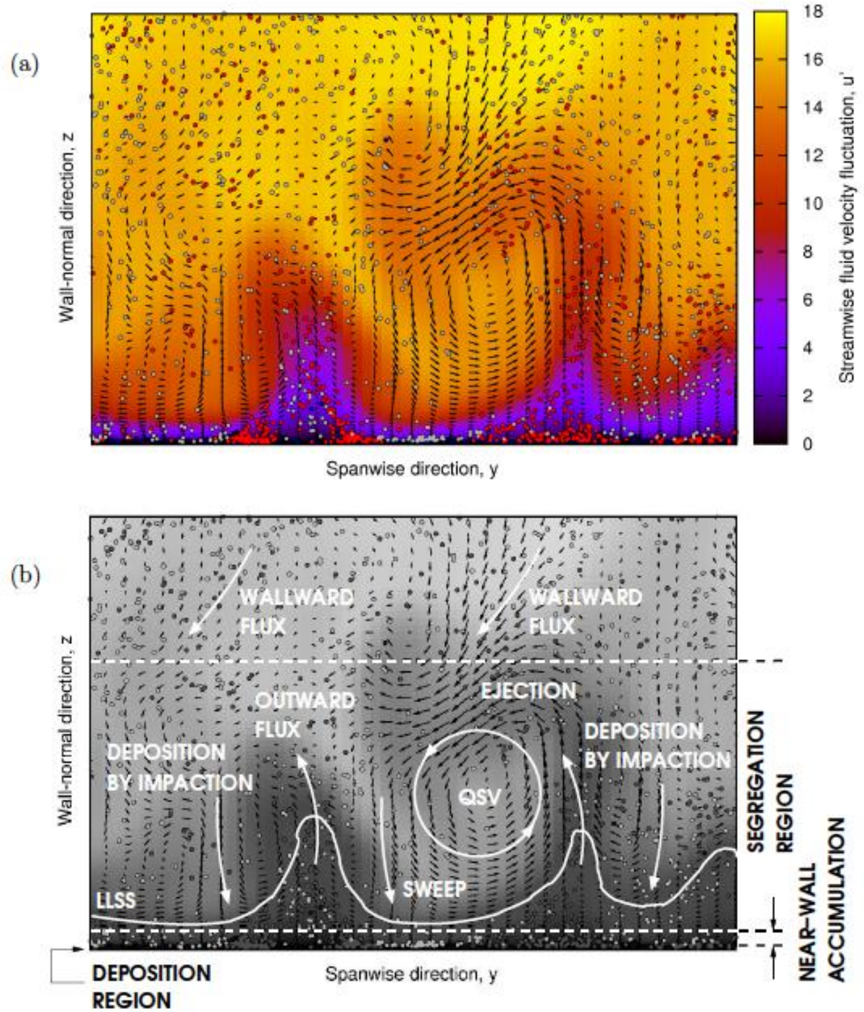


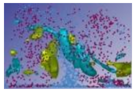
# Deposition

Role of Turbulence Clear. Difficult is accurate modelling for process optimization

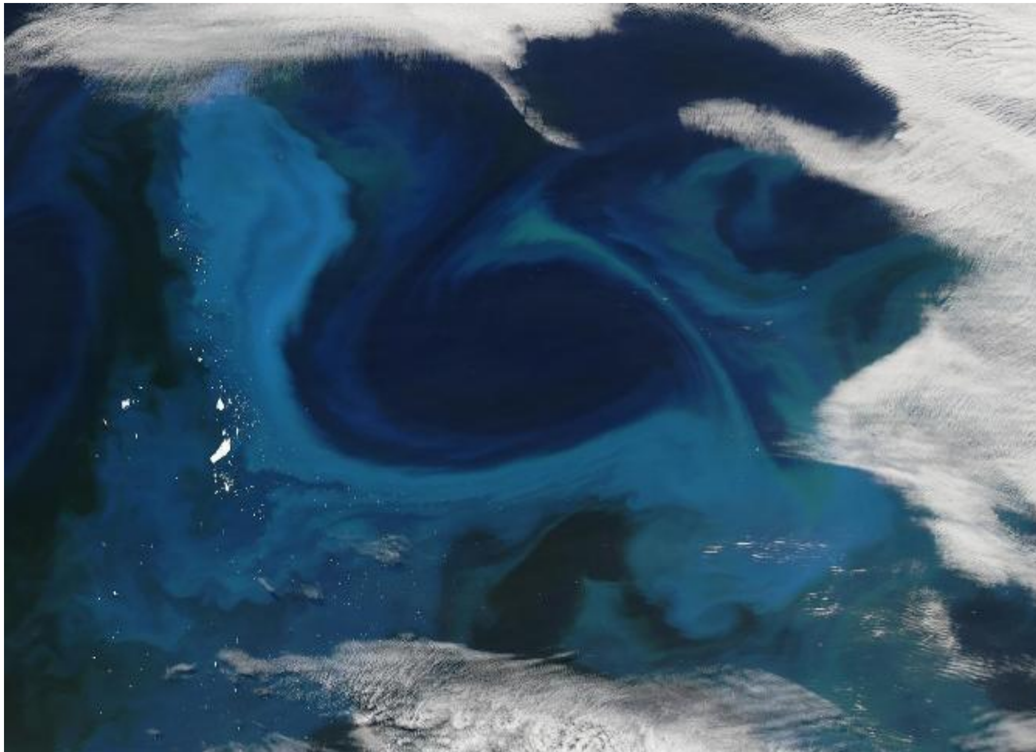
Process Issues:
Particle deposition
and Sedimentaion

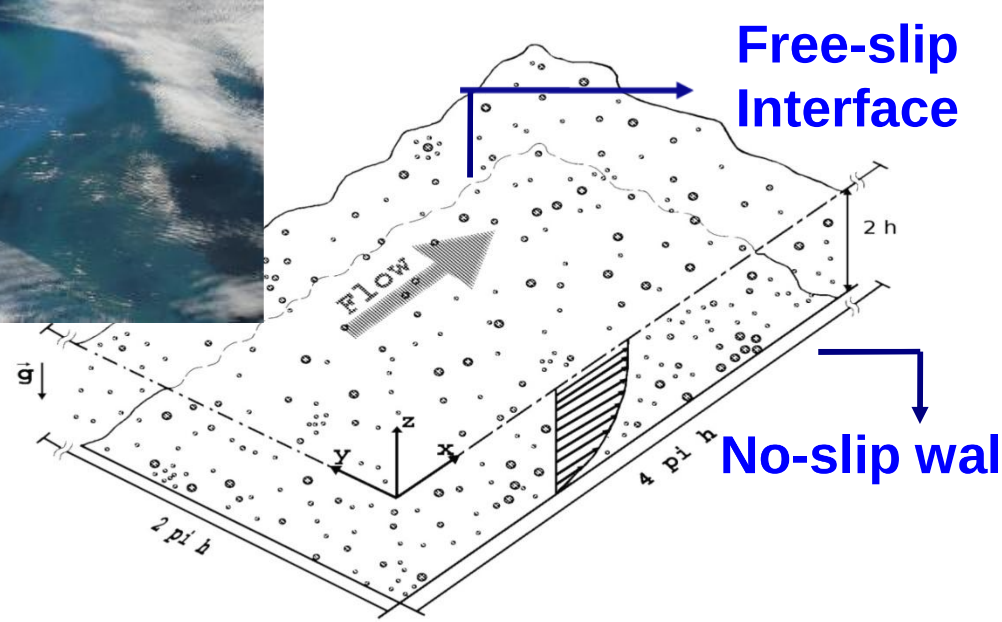


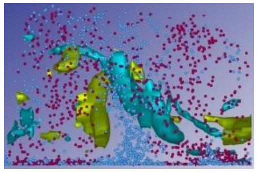


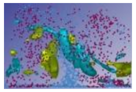



# Environmental Motivations

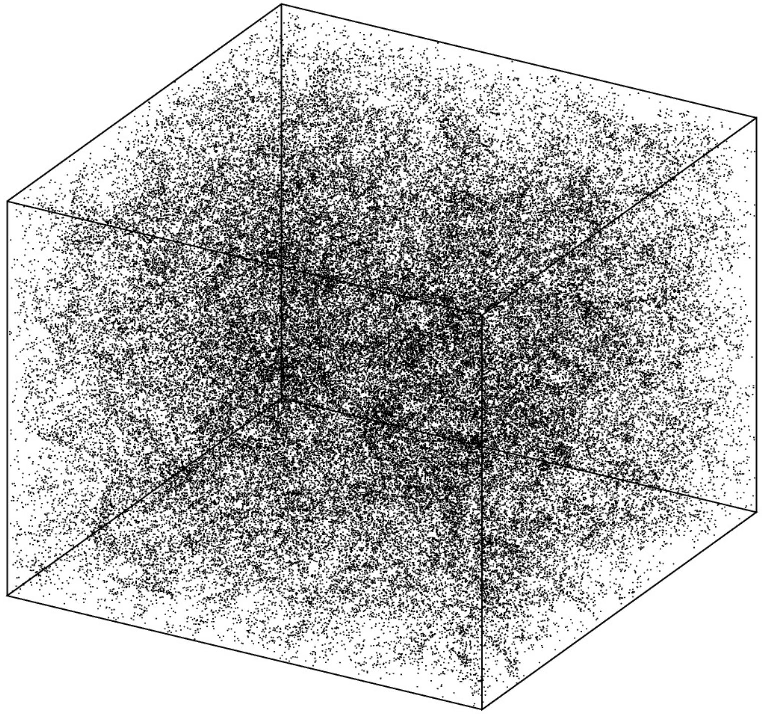




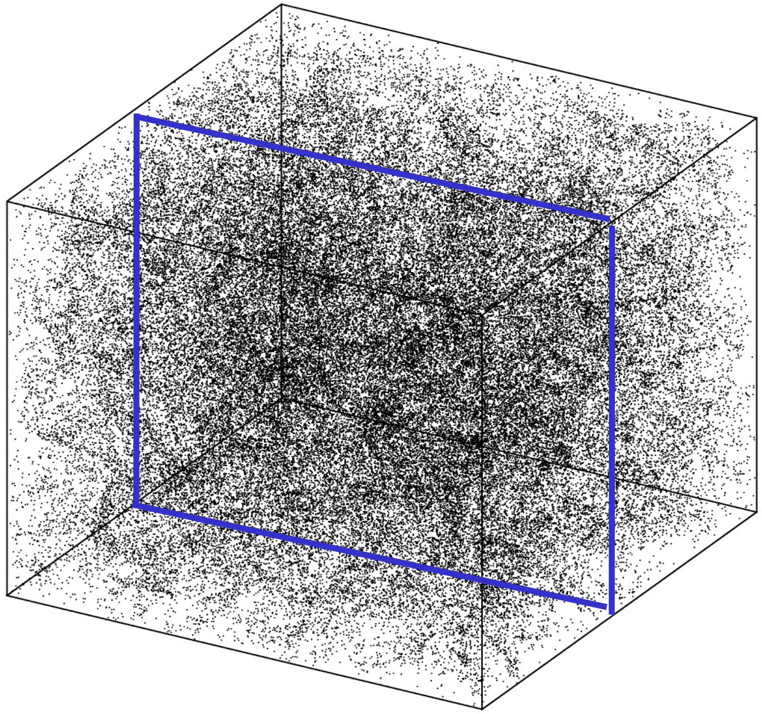




### Instantaneous position of St =1 particles

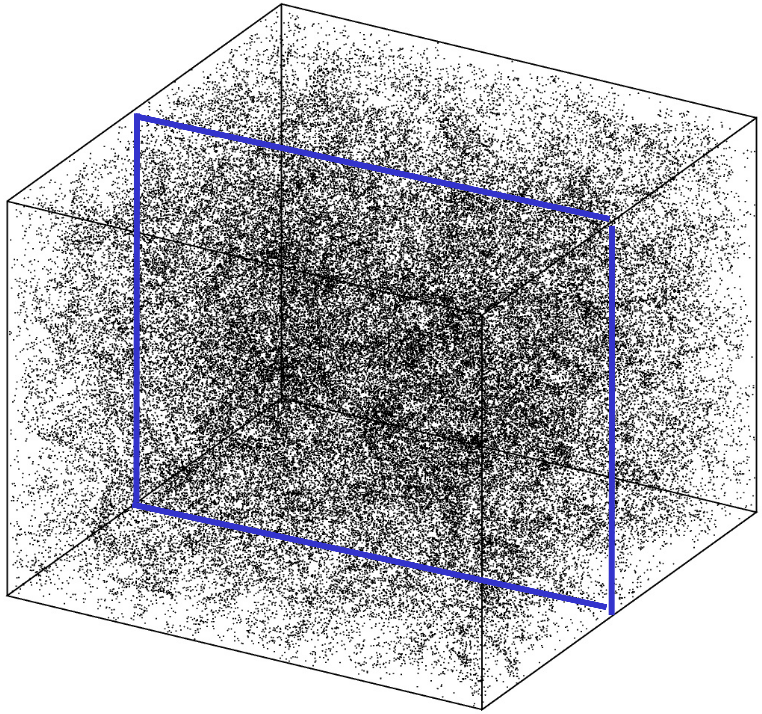


**Instantaneous position of St =1 particles**

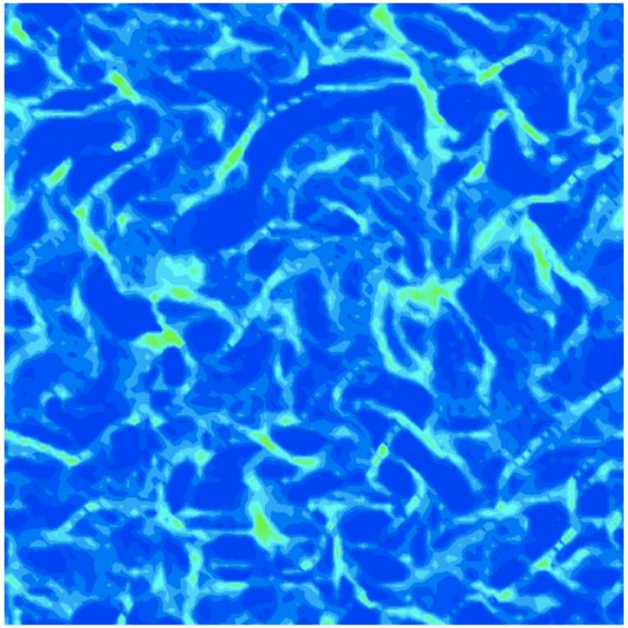


# An Interesting Feature
# Particles cluster and produce Caustics …

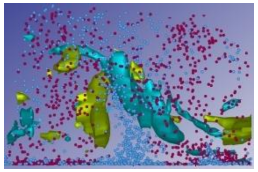
**Instantaneous position of St =1 particles**



**slice View: Particles accumulate into Regions which are called Caustics**



**Number concentration of Particles (By Maurizio Picciotto)**



# *Fil Rouge*

1. Effect of Clustering and Scales on Deposition by DNS of Turbulence with Pointwise Particles

1. Modelling issues in LES

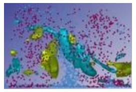
2. Surfacing and Clustering of Slightly Buoyant Particles in Free-Surface Flows

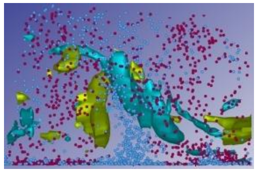
1. Thermally Stratified Flows

(4.1 Oberbeck-Boussinesq Approximation)

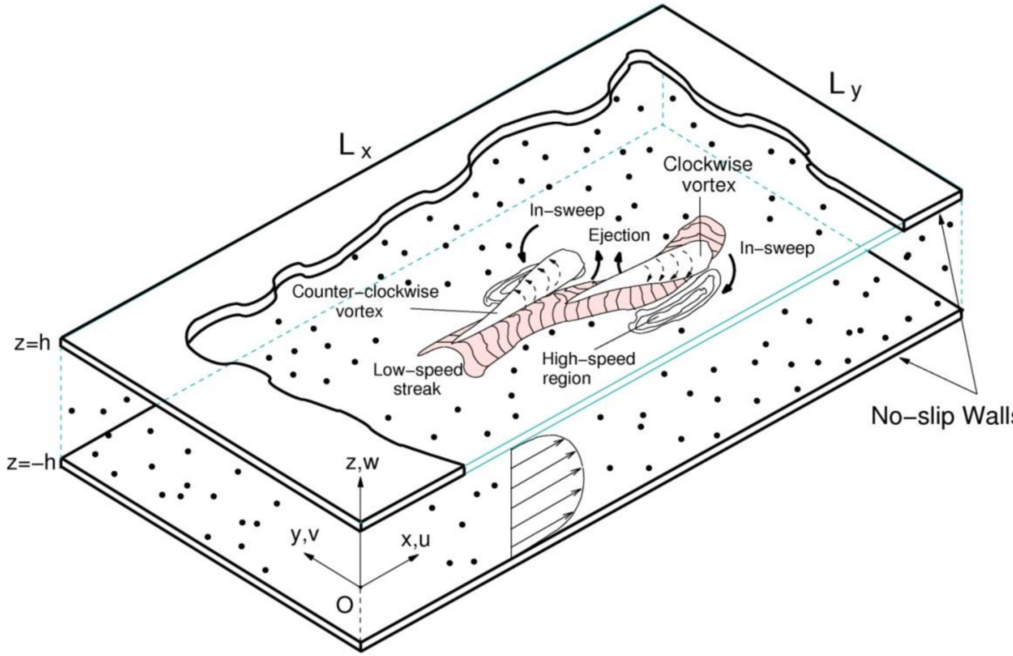
4.2 Surfacing and Clustering of Slightly Buoyant Particles in Stratified Free-Surface Flows







# Focus on particle motion near a wall.
# Flow Instances and Numerical Methodology
# Channel Flow (All Scales Solved)



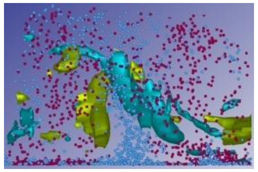

Well Resolved Pseudospectral DNS of 3D time-dependent turbulent gas flow

Shear Reynolds number:

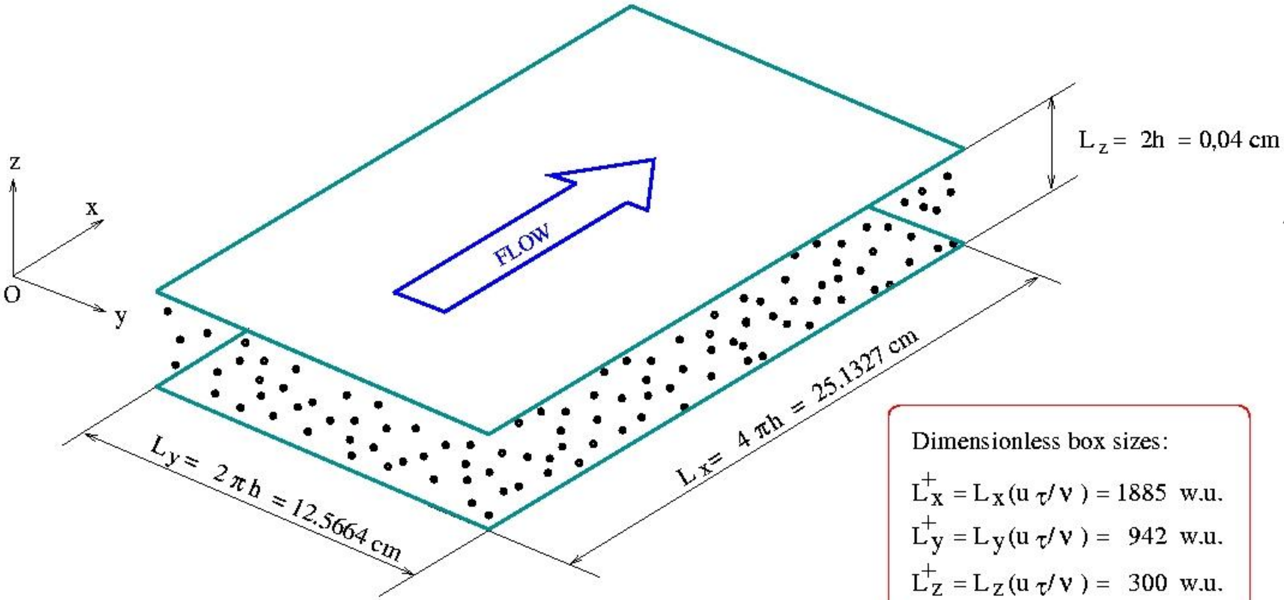
$$Re_\tau = \frac{UH}{\nu} = 150, 300$$

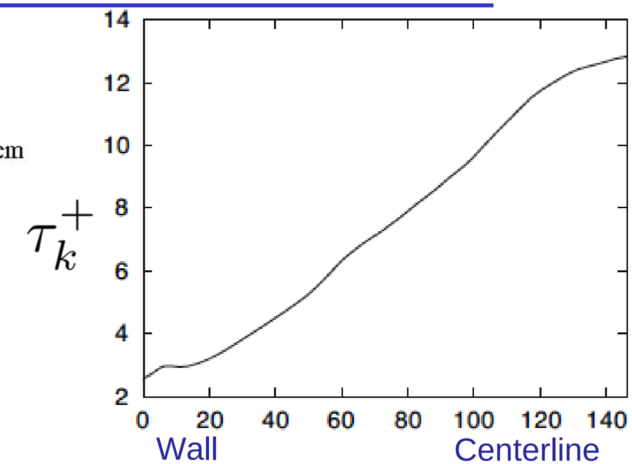
Lagrangian (Heavy) Particle Tracking

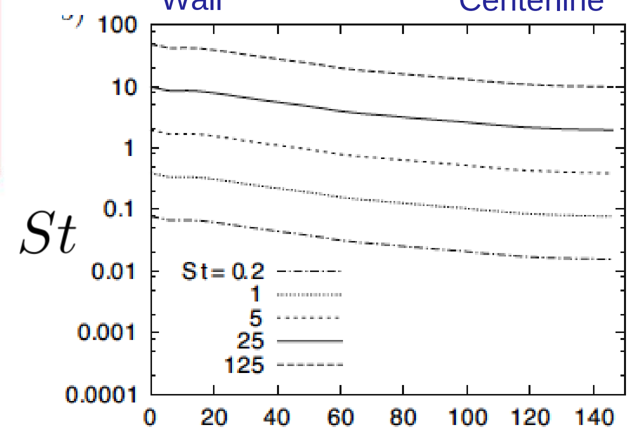
$$\frac{d\mathbf{v}_p}{dt} = \frac{\mathbf{u}_s - \mathbf{v}_p}{\tau_p}(1 + 0.15 Re_p^{0.687})$$



# ... But if we are interested in boundary Layers …
# Kolmogorov scaling seems not the right one
# Better the Wall variables scaling (Shear Based)
# All variables decrease their size approaching the wall

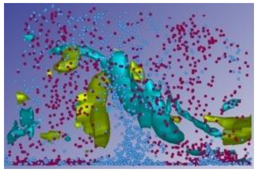


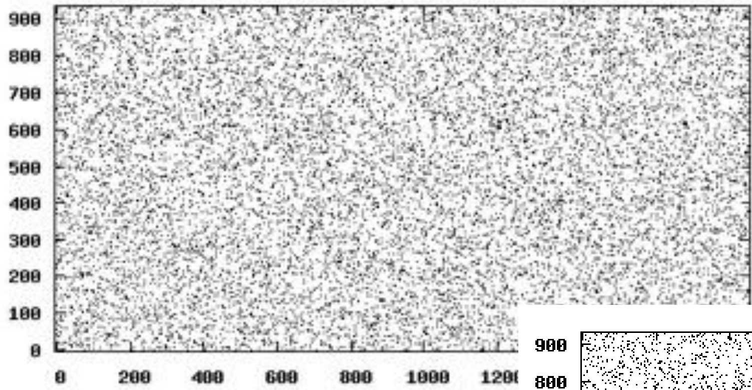

**Channel flow is a multiscale phenomenon, particles 'visit' all possible regions Of the domain and interact with ever changing scales. In addition, the strong shear which dominate the wall region gives structures a distinctly streamwise Stretched pattern.**



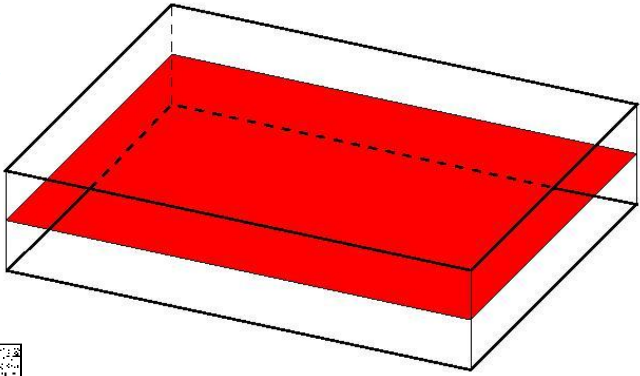


# Segregation Pattern in the Homogeneous Plane

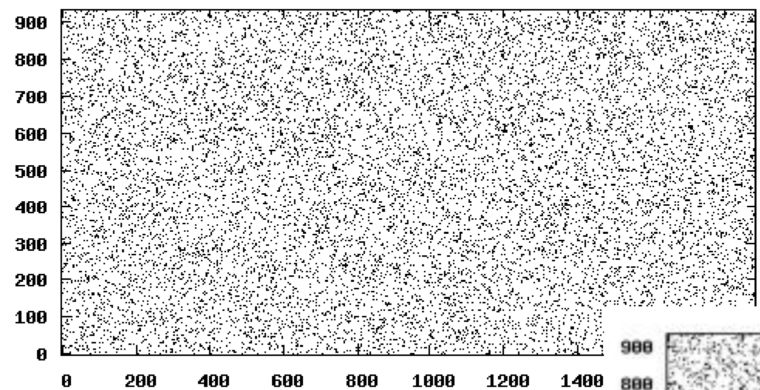
(Marchioli and Soldati, 2002, J. Fluid Mechanics)




$$St = \frac{\tau_p}{\tau_f} = \tau_p^+$$

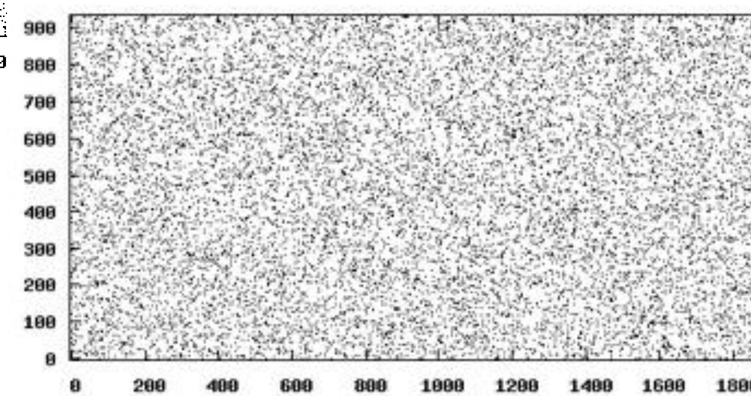


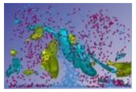
$$\tau_p^+ = 1$$



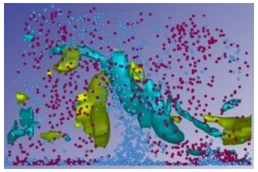

$$\tau_p^+ = 25$$

$$\tau_p^+ = 100$$



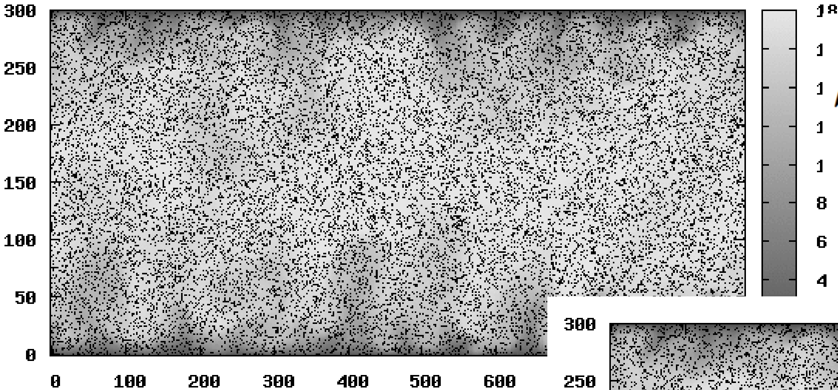



# Segregation and Transfer Patterns in the Cross-Plane

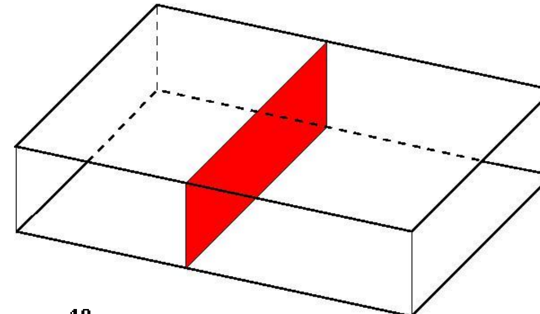


## Microscale phenomena induce Macroscale Effects

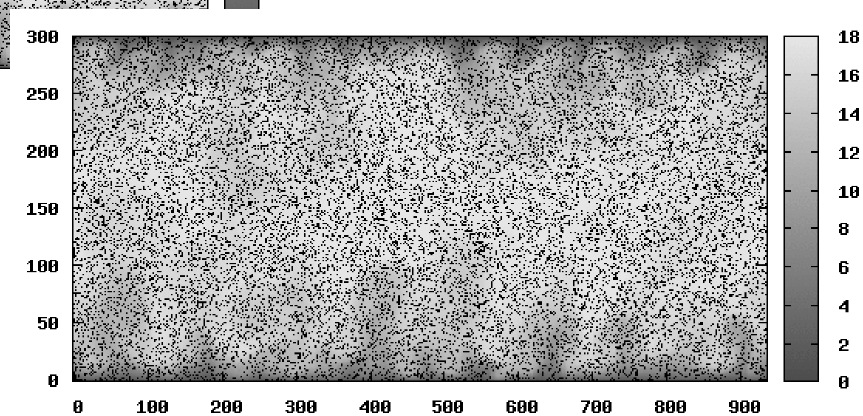
(Marchioli and Soldati, 2002, J. Fluid Mechanics)




$$St = \frac{\tau_p}{\tau_f} = \tau_p^+$$

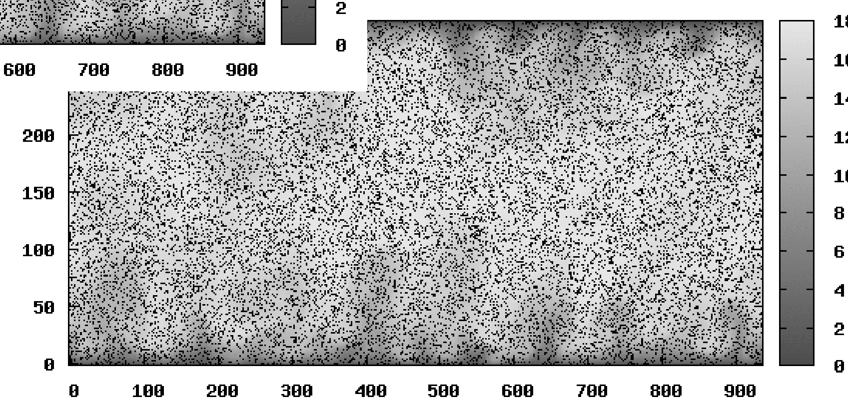


$$\tau_p^+ = 1$$



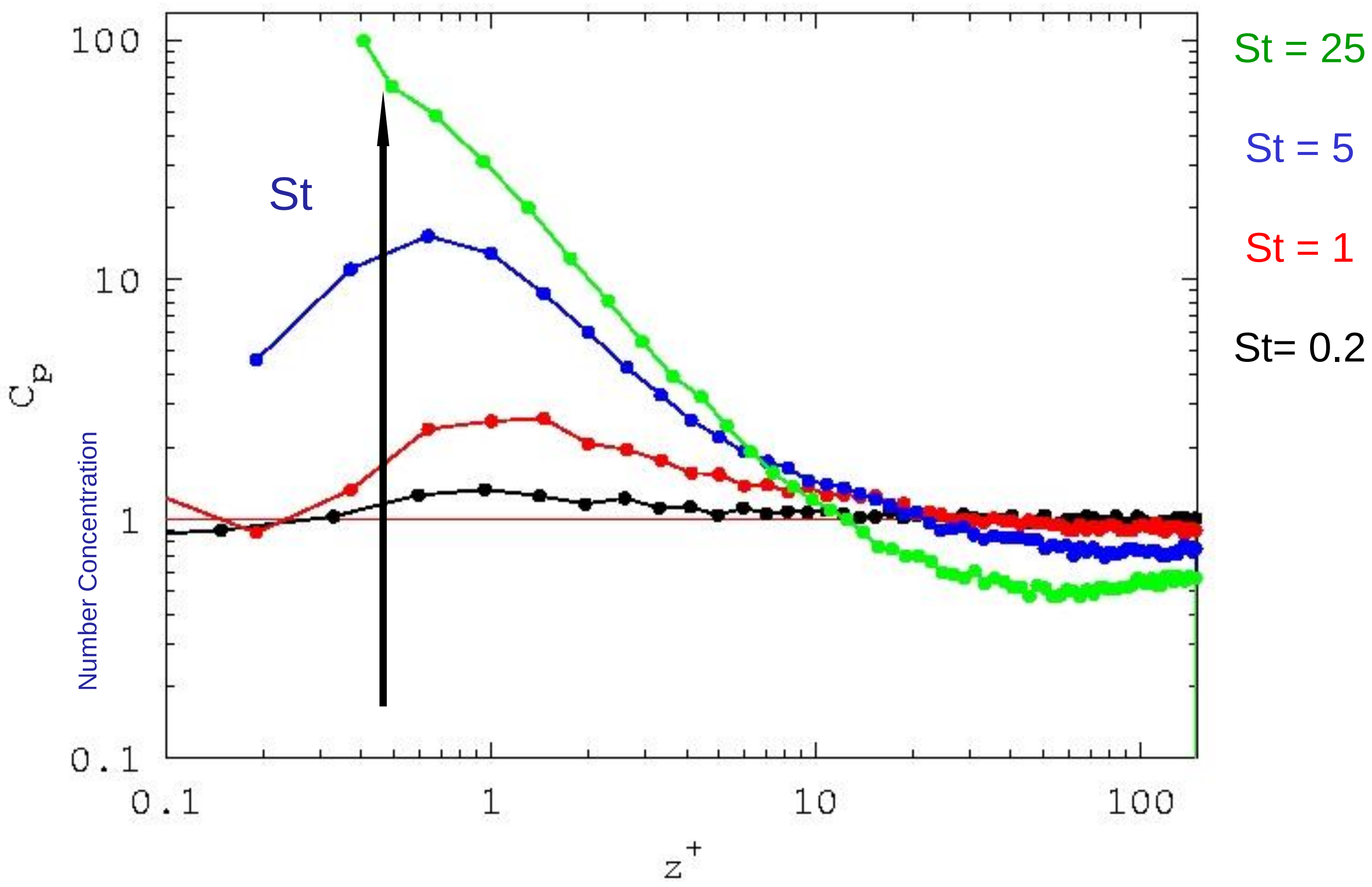

$$\tau_p^+ = 100$$

$$\tau_p^+ = 25$$

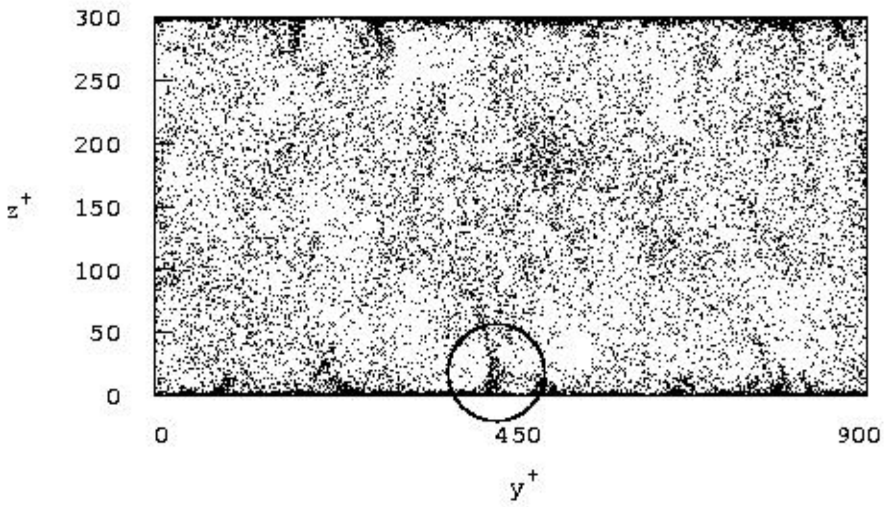


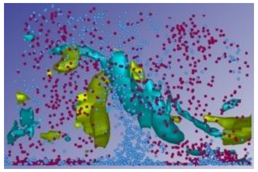

Gray shades In the animation:
White: High Streamwise velocity
Black: Low Streamwise Velocity



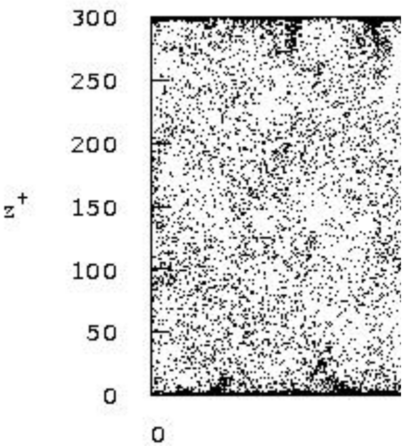

100
10
1
0.1
0.1
1
10
100
$C_p$
Number Concentration
$z^+$
St
St = 25
St = 5
St = 1
St= 0.2

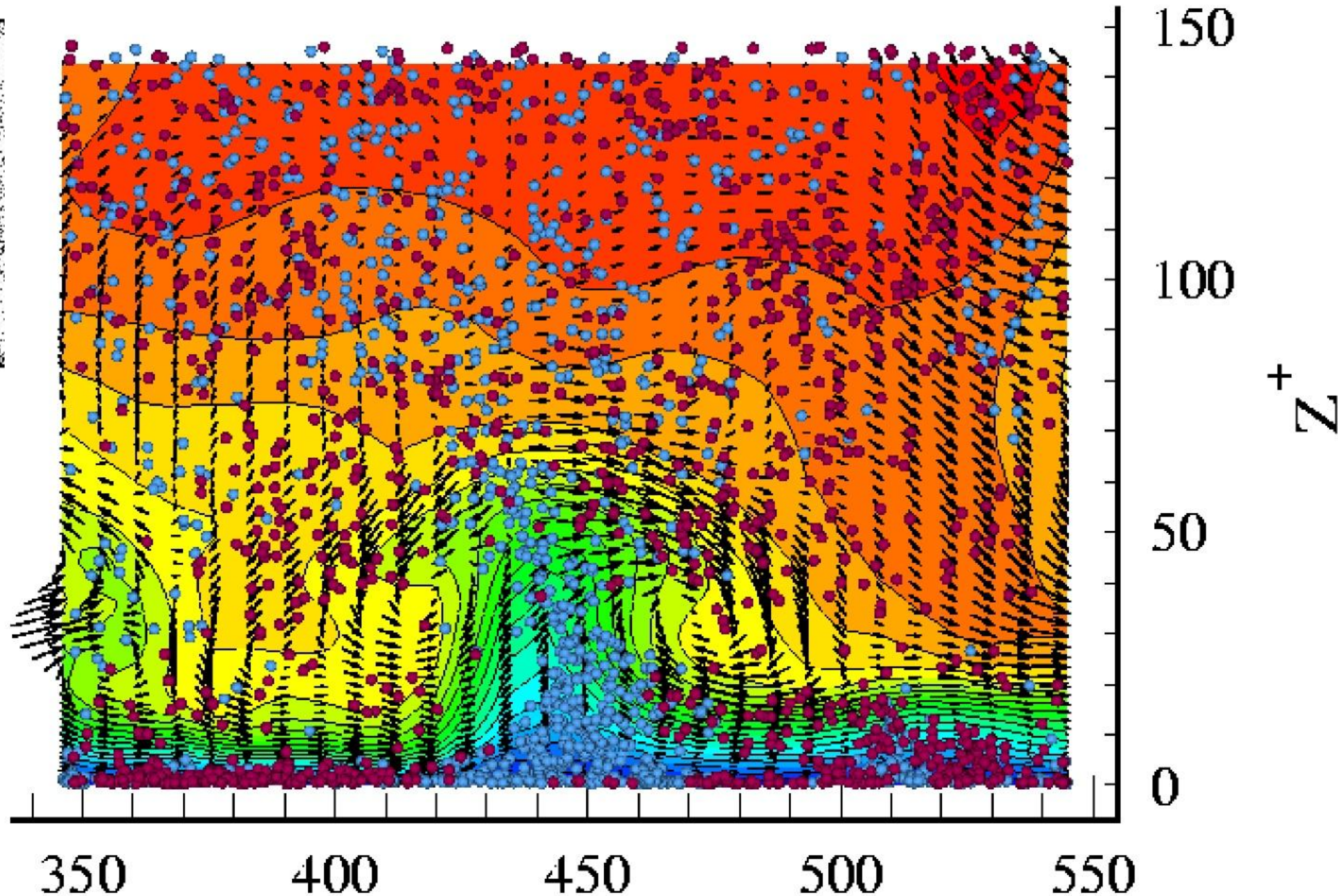
Qualitative explanation of the instantaneous transfer processes.
Deposition and Entrainment are controlled by turbulence
Structures localized in time and space





## Qualitative explanation of the instantaneous transfer processes. Deposition and Entrainment are controlled by turbulence Structures localized in time and space



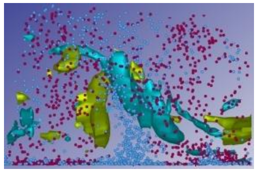

Red:
high Streamwise vel.

Blue: low
Streamwise vel.

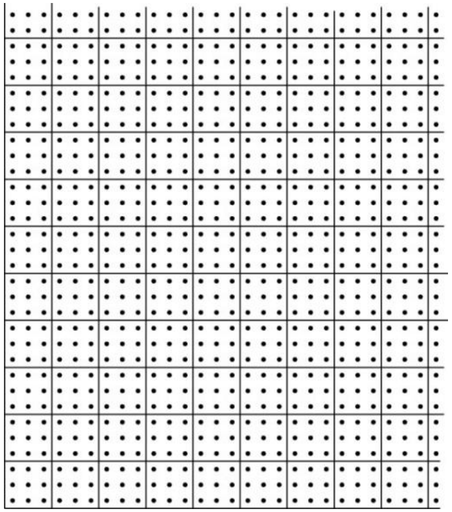
Purple Particles:
Going To the wall

Blue Particles:
Going away off the wall

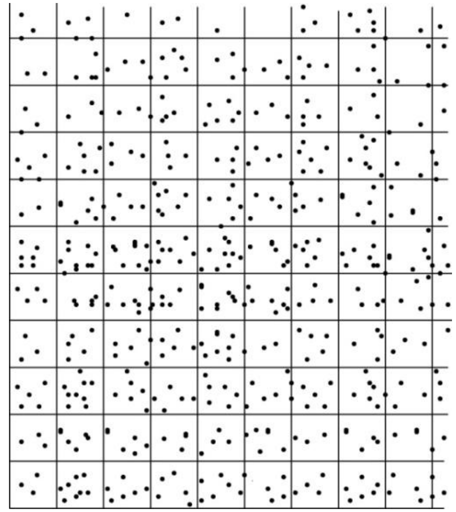




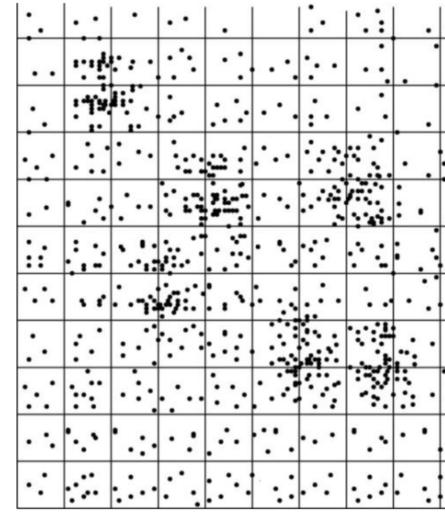
# In our view, before predicting deposition we should predict preferential segregation



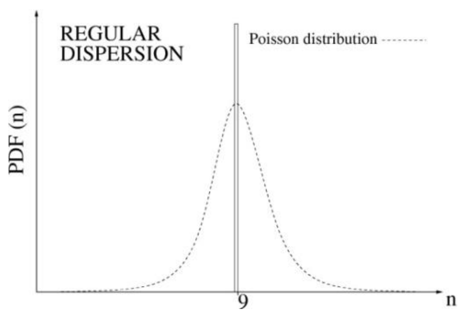
Regular distribution

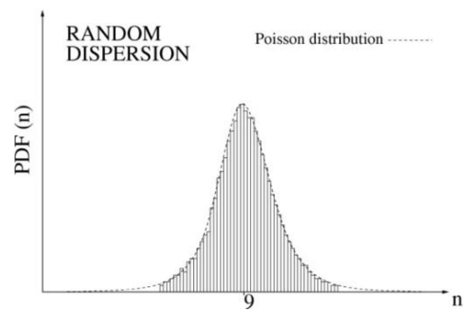


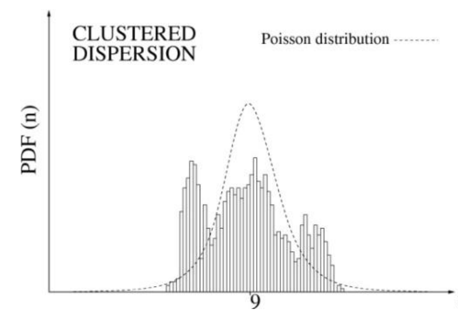
Random distribution



Clustered Distribution

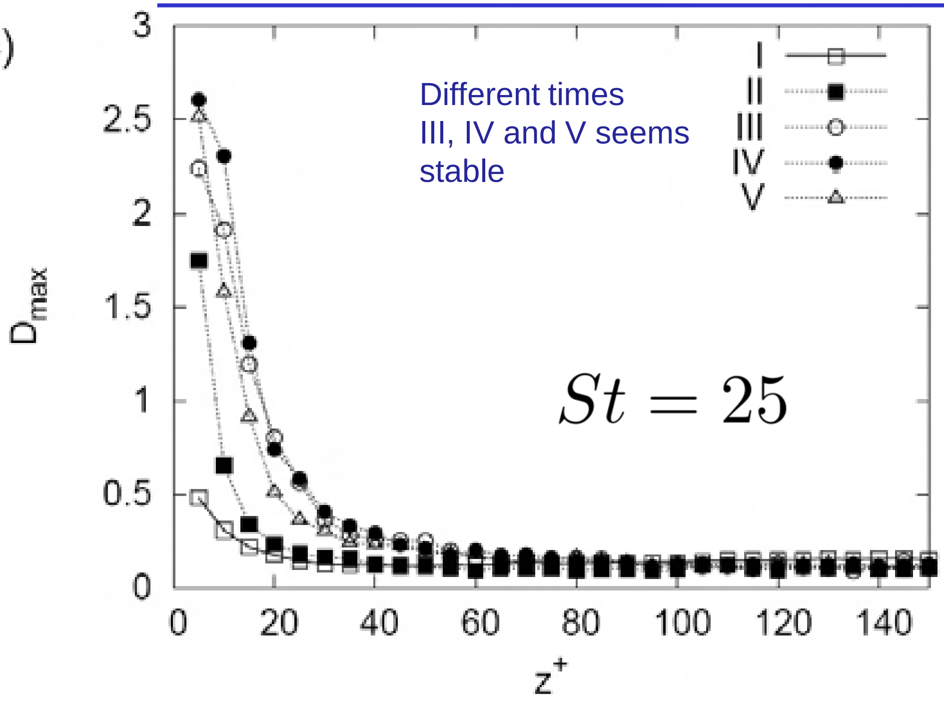


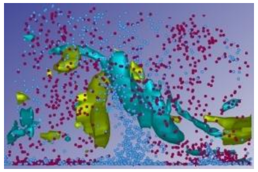




$\Sigma_p = (\sigma-\sigma_p)/\lambda$, with $\lambda$ = average n. particles per cell; $\sigma$ = standard deviation

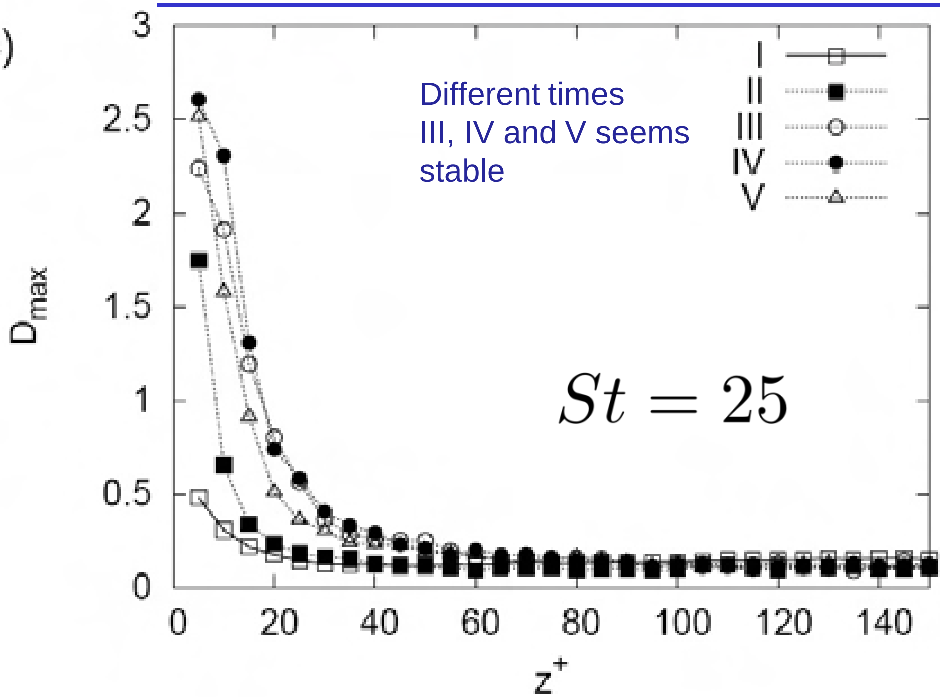





particle (st=25) tend to have maximum Segregation Around z+= 10

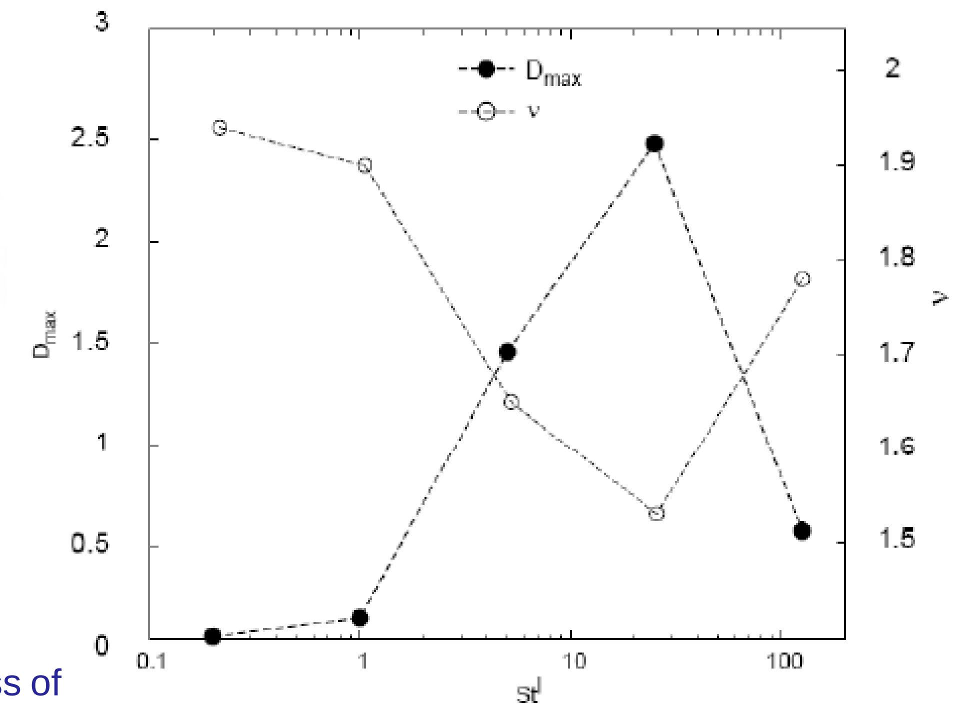


## So we can measure particle segregation, as a function of the wall distance and as a function of particle inertia



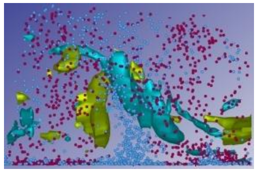

But particles of different size segregate
In different ways (at z+=10)

particle (st=25) tend to have maximum
Segregation Around z+= 10

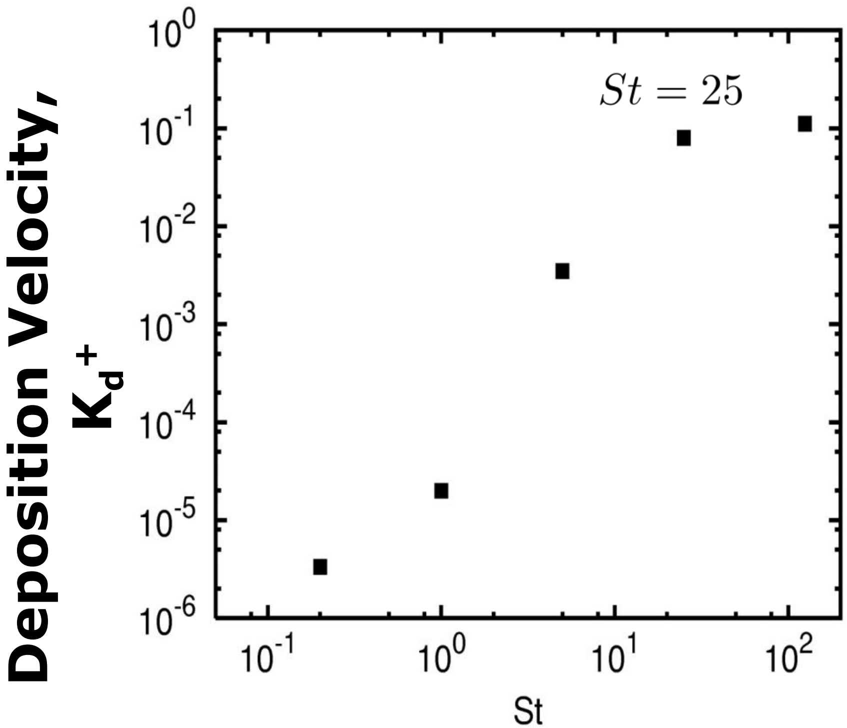



Here also the comparison of the Deviation
From Poisson with the correlation dimension
(Grassberger P, Procaccia I. Measuring the strangeness of
strange attractors. Physica D. 1983; 9: 189-194.





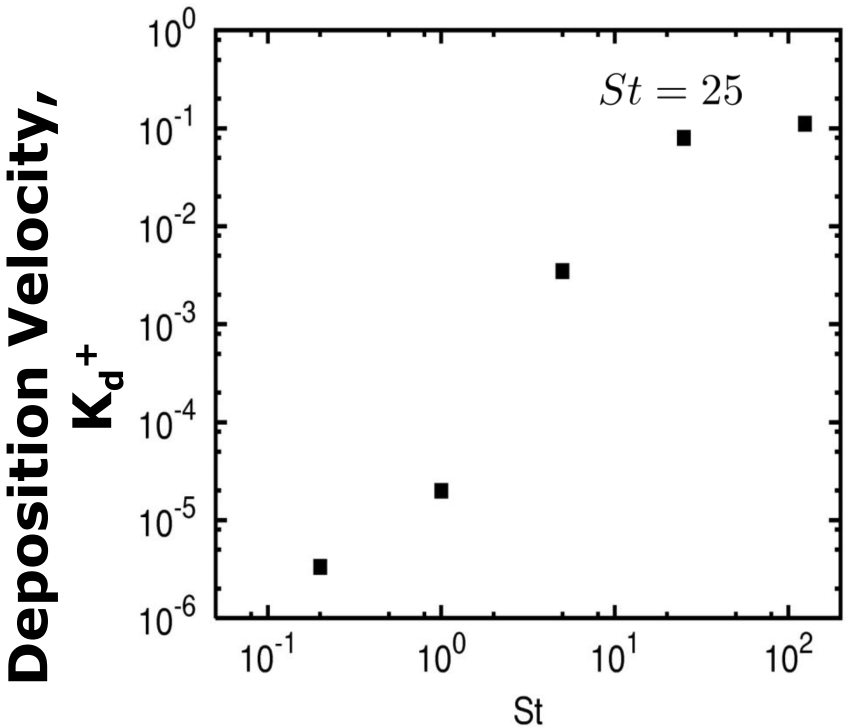
If particles are influenced (but not dominated) by inertia, the Deposition Occurs in two steps: First Segregation into a space region and then deposition to the wall.  It is found that deposition has a maximum for those particles f which segregation has a maximum

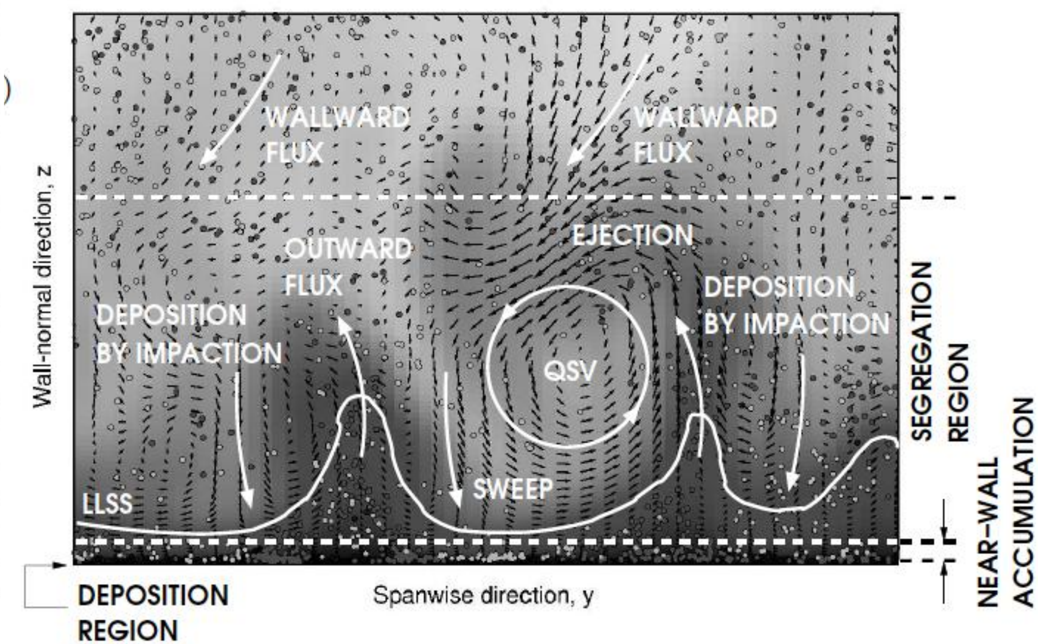



Larger particles
Will deposit due also
to their inertia,
coming directly from
Far Away

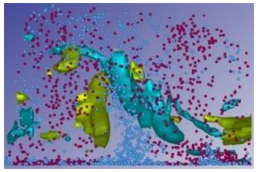
$$K_d^+ = \frac{J}{C} = \frac{\frac{1}{A_d} \bullet \frac{dN(t)}{dt}}{\frac{N(t)}{V}}$$

If particles are influenced (but not dominated) by inertia, the Deposition Occurs in two steps: First Segregation into a space region and then deposition to the wall. It is found that deposition has a maximum for those particles f which segregation has a maximum




$$K_d^+ = \frac{J}{C} = \frac{\frac{1}{A_d} \bullet \frac{dN(t)}{dt}}{\frac{N(t)}{V}}$$



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1. Modelling issues in LES

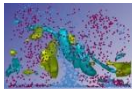
1. Surfacing and Clustering of Slightly Buoyant Particles in Free-Surface Flows

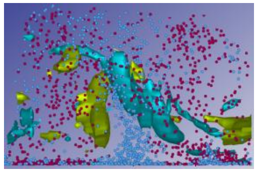
1. Thermally Stratified Flows

   (4.1 Oberbeck-Boussinesq Approximation)

   4.2 Surfacing and Clustering of Slightly Buoyant Particles in Stratified Free-Surface Flows

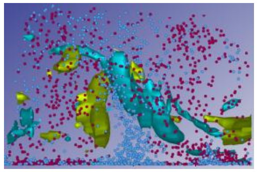






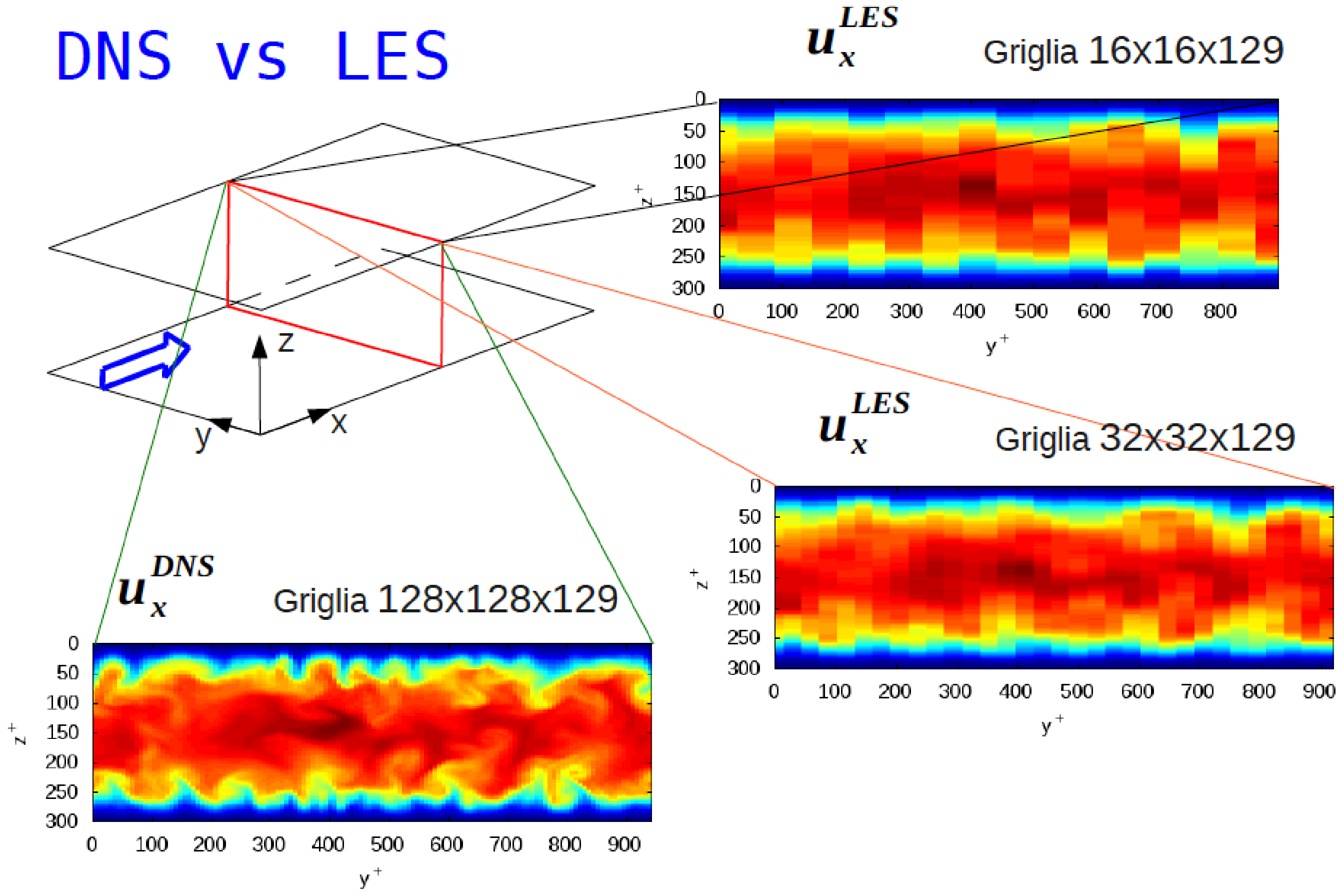
**… A Large scale problem imposes a coarse grained grid.**
**We study a-priori LES, as in the following portrait.**

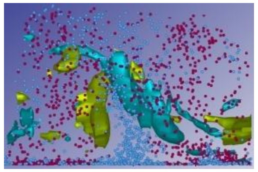
… A Large scale problem imposes a coarse grained grid.
We study a-priori LES, as in the following portrait.



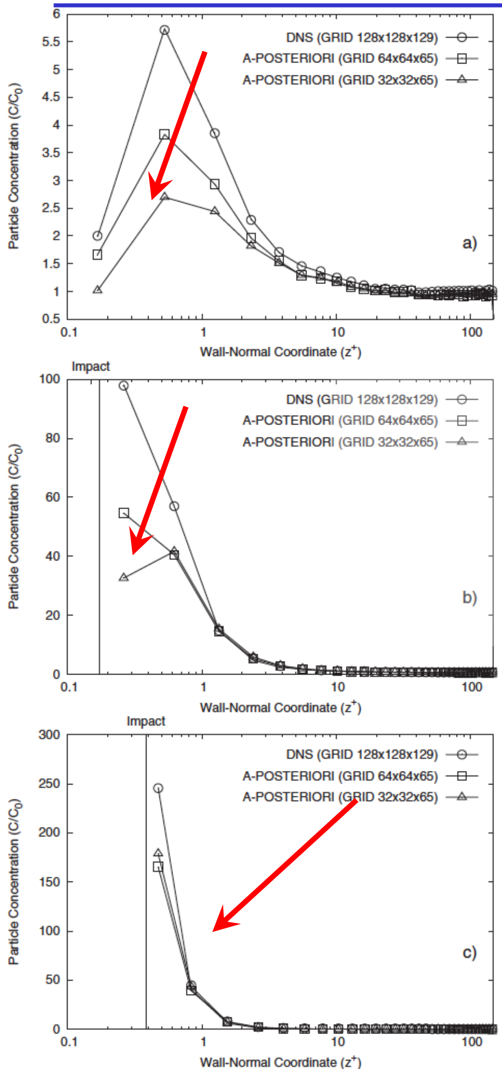
**… A Large scale problem imposes a coarse grained grid.**
**We study a-priori LES, as in the following portrait.**

# How much does filtering affect the behavior of inertial particles?





# LES is tested on the prediction of particle concentration. Unfortunately it does not maintain expectations…. Of course, the test is hard… it is the time integral of the deposition flux



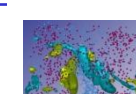

St=1

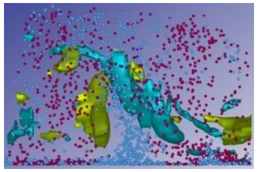
St=5

St=25

Significant underestimation of wall concentration for large particles (Concentration scales with the time Integral of Particle deposition velocity)



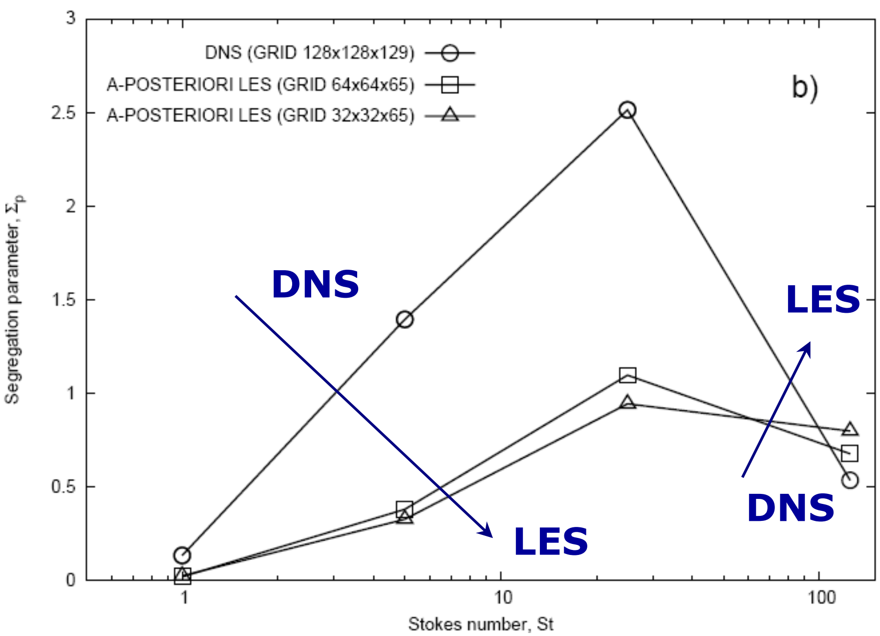




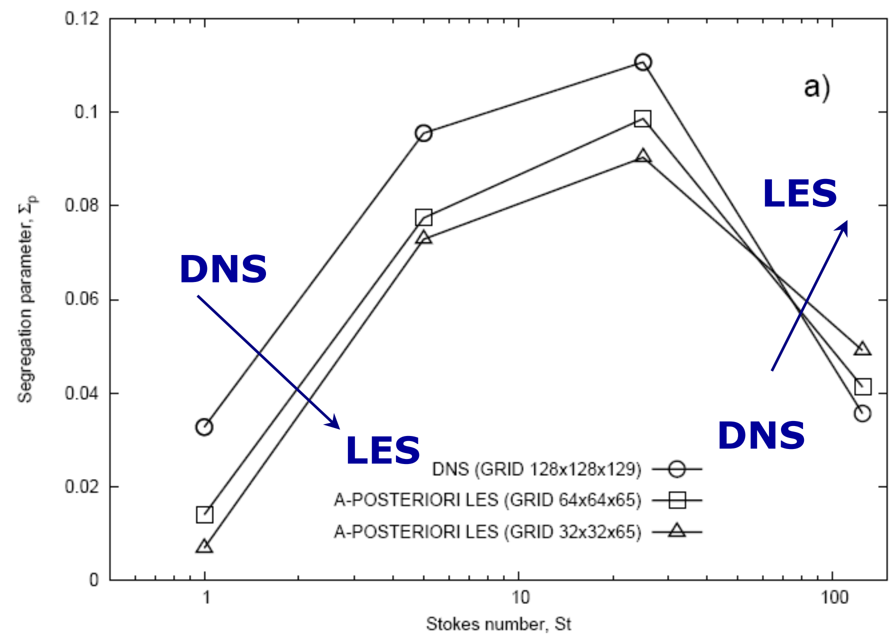
... and the reason for wrong underestimated deposition is
wrong estimate of local segregation ...

## Influence of the Stokes number on local particle segregation

**Z<0.15H (near-wall region)**

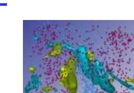



**Z=H (channel centerline)**




LES predicts LESS segregation for larger particles and MORE segregation for smaller particles. These results in bounded flow confirm previous results by Simonin in HIT





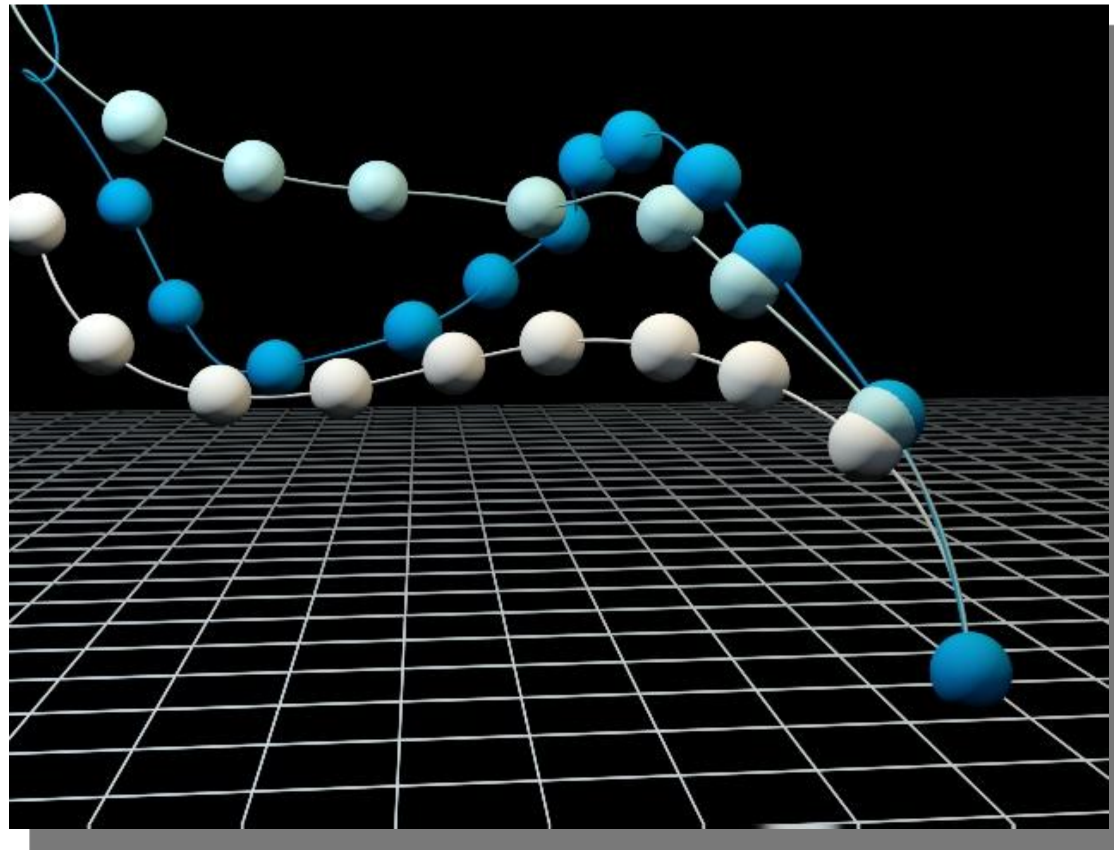
# We could put some stochastic forcing … provided that the Forcing has the right features

Bianco et al. (2012) Phys. Fluids,

DNS

LES Finer

LES Coarser



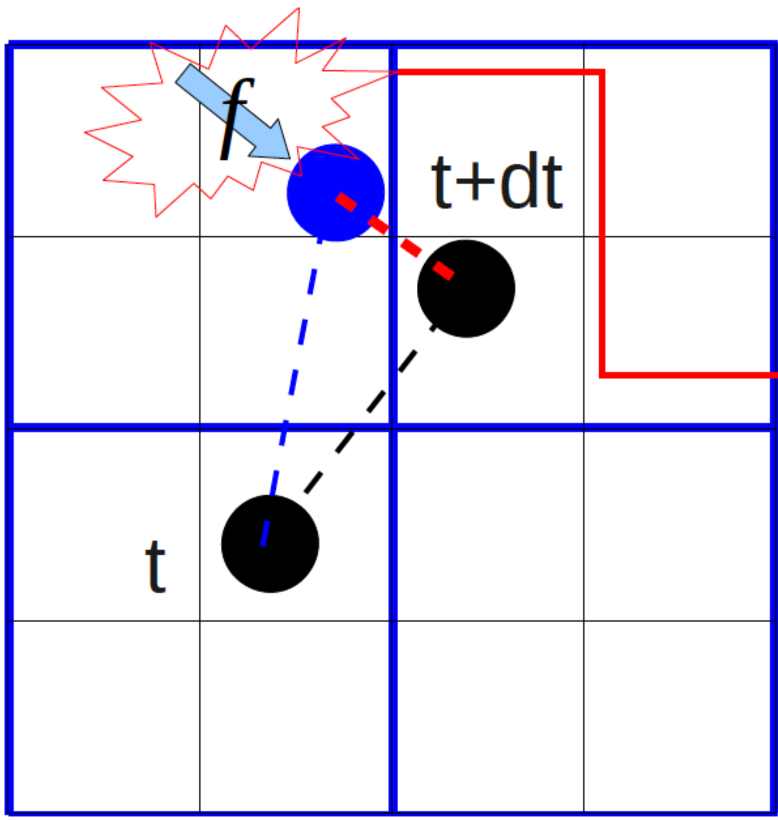
modelling has to fix two sources of errors:

1.The filtered flow field;

2.the Cumulated Particle wrong position

# We can measure what we need!

$$\frac{d\,v_p}{dt} = \sum F_{EST} = F(u_s, m_p)$$




DNS Grid
LES Grid (2x)

$$f = F^{DNS} - F^{LES}$$

$$F_{EST} = F^{LES}(u_s^{LES}, m_p)$$

$$F_{EST} = F^{DNS}(u_s^{DNS}, m_p)$$

... and before finding a model we should aim for the
Work this model should do ... Therefore compute the error

$$\delta \mathbf{u} \equiv \delta \mathbf{u}(\mathbf{x}_{p,k}(t^n), t^n) = \mathbf{u}(\mathbf{x}_{p,k}(t^n), t^n) - \bar{\mathbf{u}}(\mathbf{x}_{p,k}(t^n), t^n) \equiv \mathbf{u}_s - \bar{\mathbf{u}}_s$$

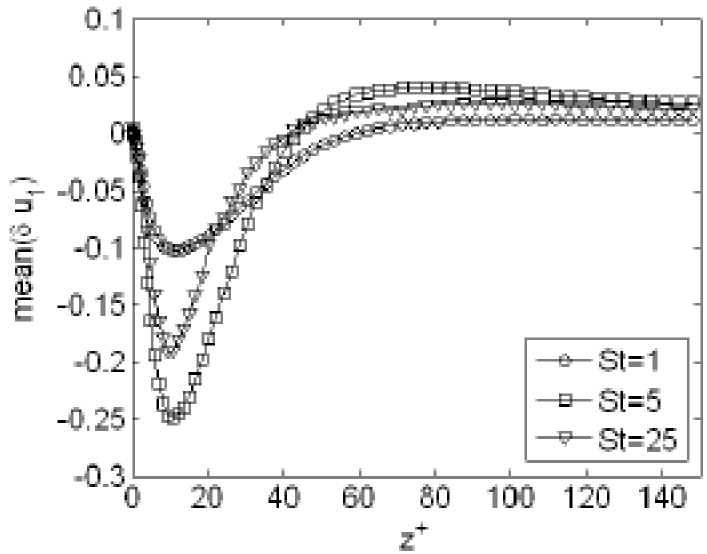



**Figure 1.** Mean values of the SGS velocity correction component in the streamwise direction as a function of $z^+$. Cut-off filter with CF=4.

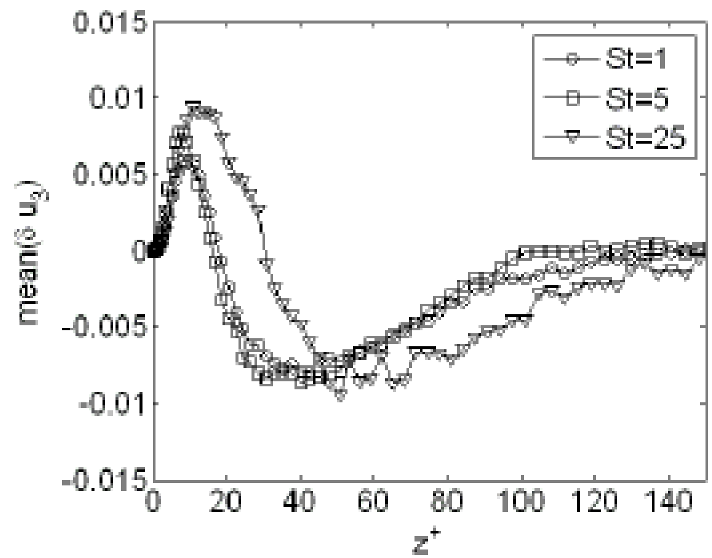
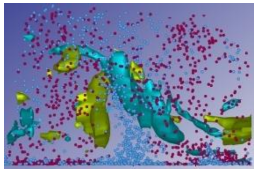
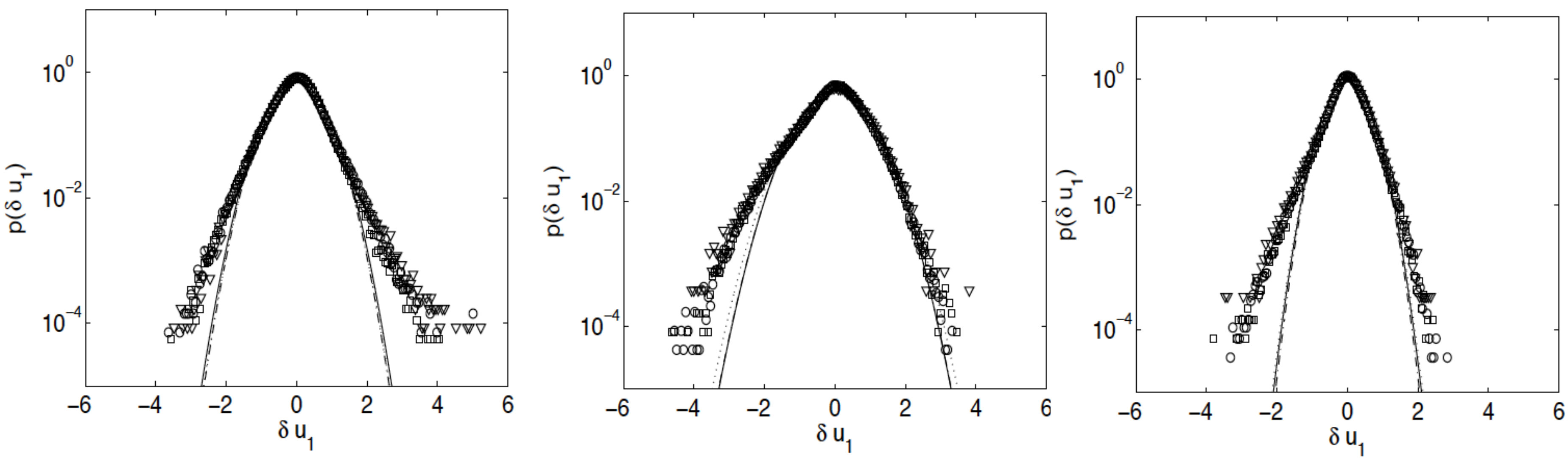



**Figure 3.** Mean values of the SGS velocity correction component in the wall-normal direction as a function of $z^+$. Cut-off filter with CF=4.

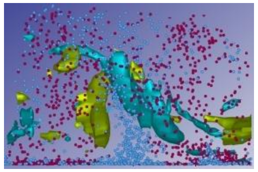


... and before finding a model we should aim for the
Work this model should do ... Therefore compute the error
... And the error has a shape which changes with space and inertia

FIG. 11. Probability density functions of the streamwise component of the filtering error for different particle inertia. Profiles refer to results obtained using cut-off filter with CF=4. Open symbols are used for the computed PDFs (∘: $St = 1$, □: $St = 5$, ▿: $St = 25$); lines for the corresponding Gaussian PDFs (— — —: $St = 1$, — · — · —: $St = 5$, · · ··: $St = 25$).




$z^+ = 4.07$ $z^+ = 37.64$ $z^+ = 65.14$



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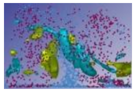
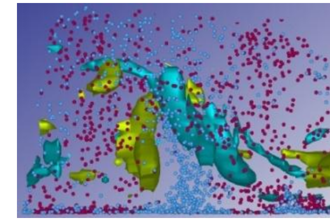
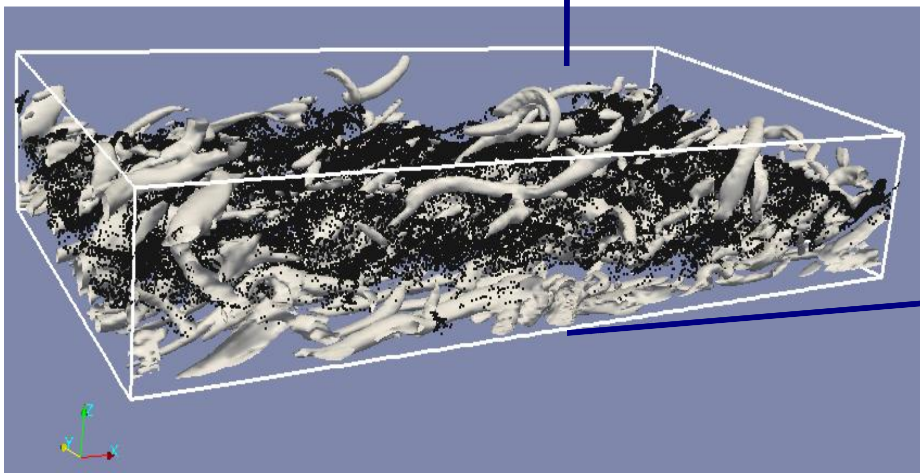




# Physical Problem/Modelling Approach: Neutrally-buoyant turbulence

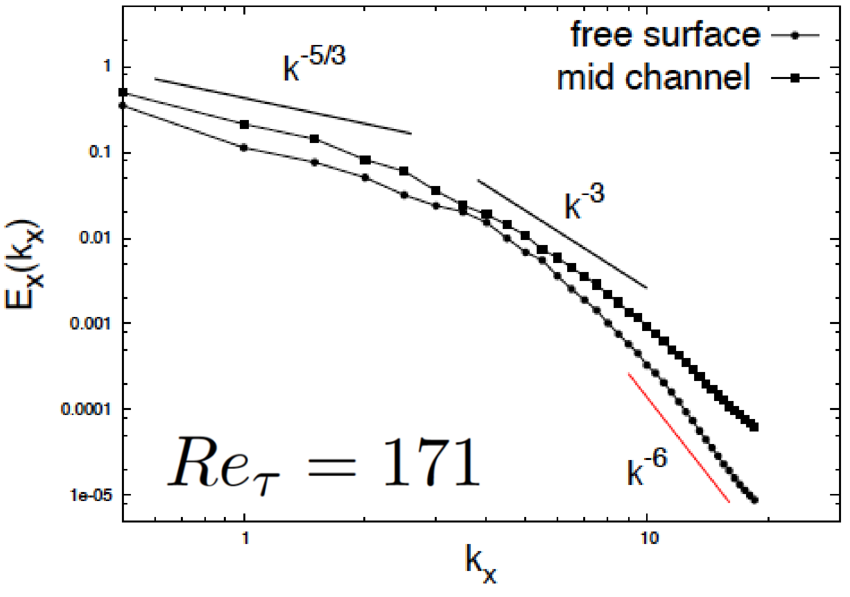


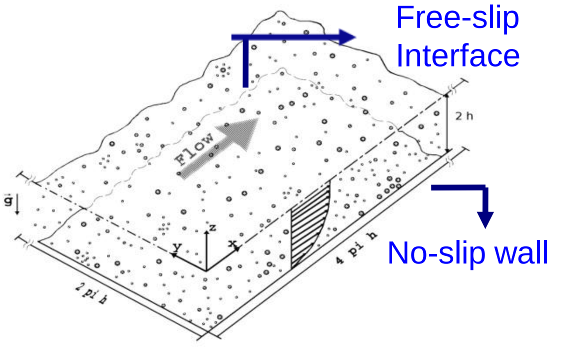

**Flow solver:**

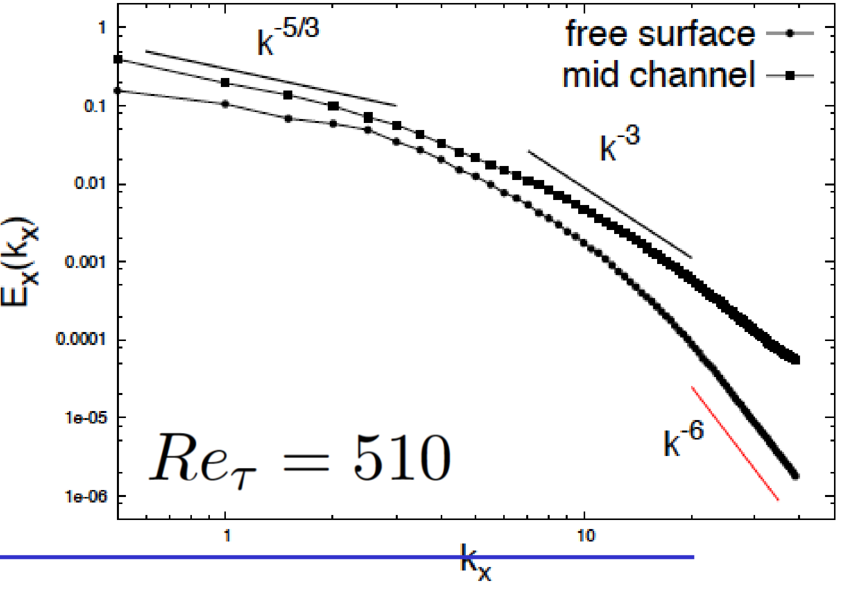
- $$\frac{\partial u_i}{\partial x_i}=0$$
- $$\rho\left(\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}\right)=-\frac{\partial P}{\partial x_i}+\mu\frac{\partial^2 u_i}{\partial x_j^2}$$

- 3D turbulent water flow field at shear Reynolds number: Re□= 171, 509
- Channel size: $L_x$ x $L_y$ x $L_z$ = 4 □□h x 2 □□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)




free surface
mid channel
k-5/3
k-3
k-6
$Re_\tau = 171$
Ex(kx)
kx

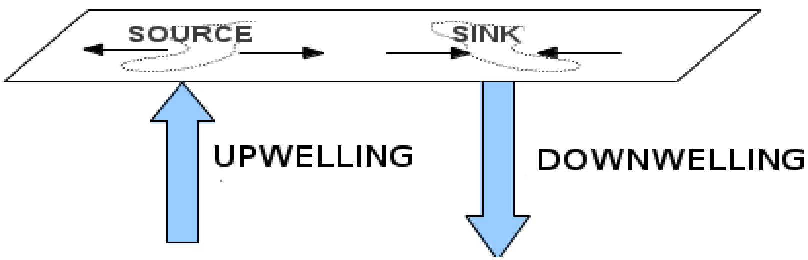

Free-slip
Interface
No-slip wall
Flow
2 h
2 pi h
4 pi h


free surface
mid channel
k-5/3
k-3
k-6
$Re_\tau = 510$
Ex(kx)
kx

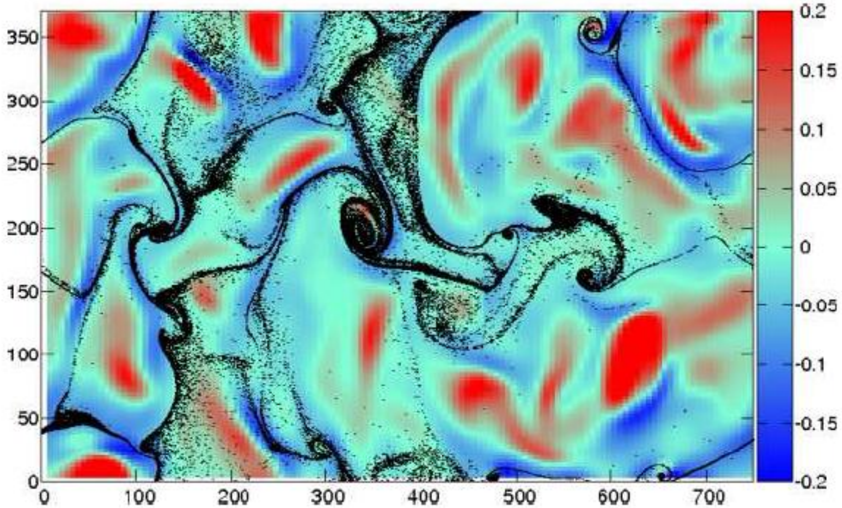
**Surface divergence:**

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

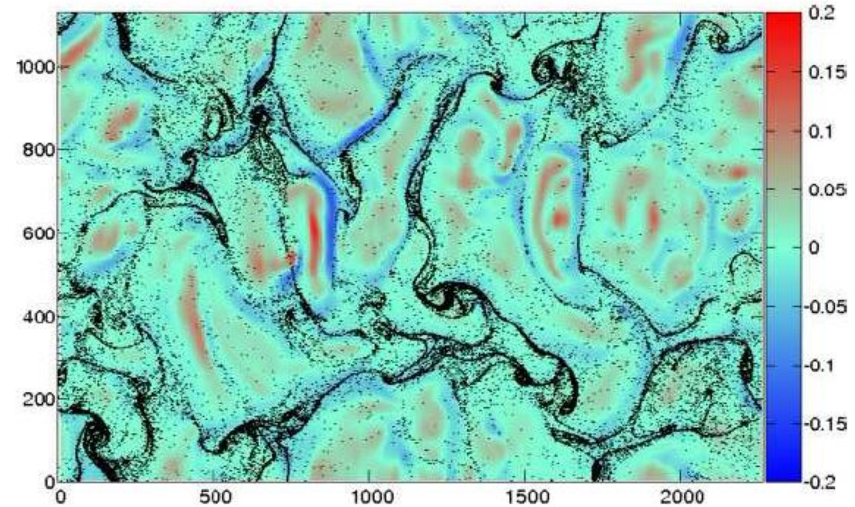
$\nabla \cdot \vec{u}|_{2D} > 0$ $\nabla \cdot \vec{u}|_{2D} < 0$



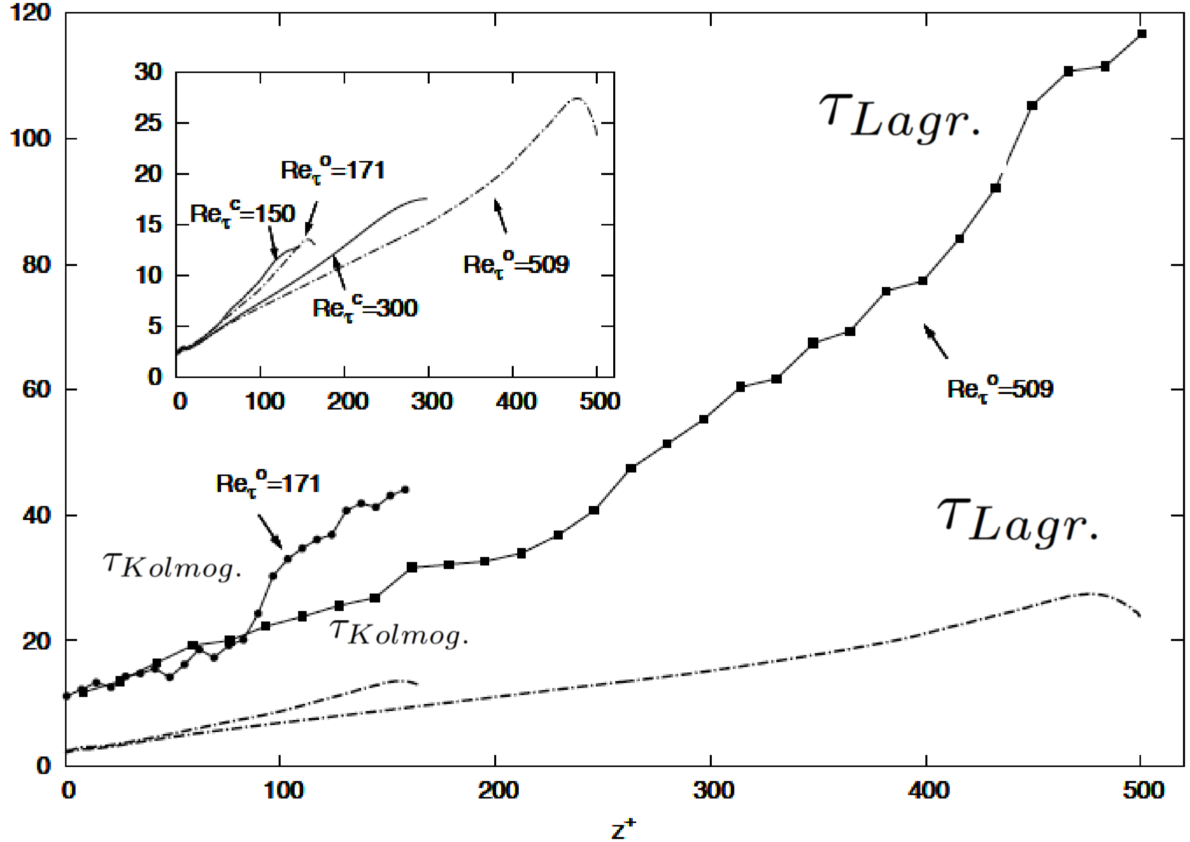

$Re_\tau = 171$

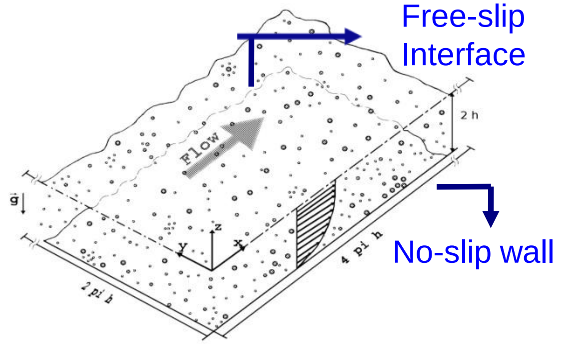



$Re_\tau = 510$

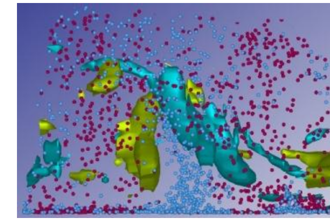


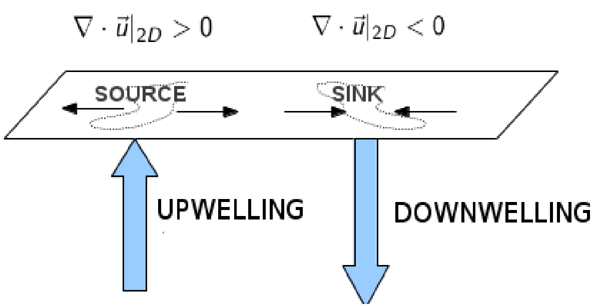
# Environmental Motivations

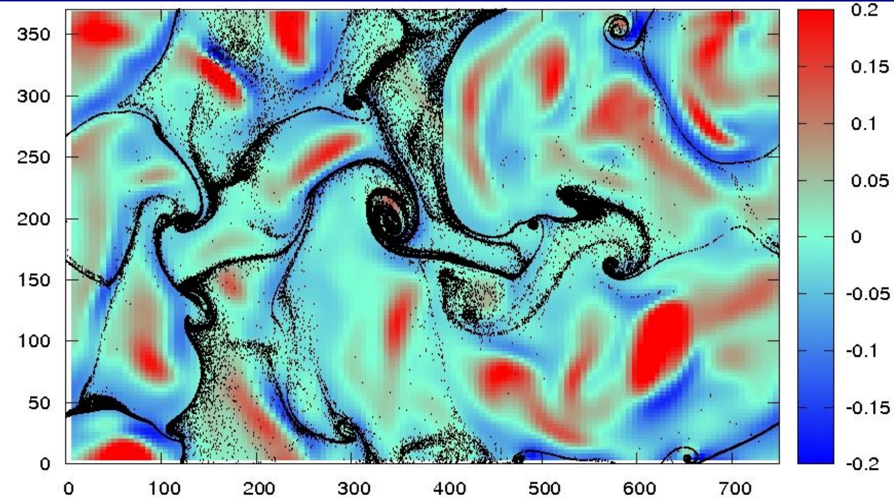


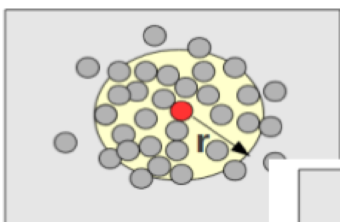



# Open channel flow:
## Particles at surface

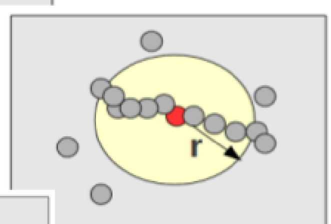




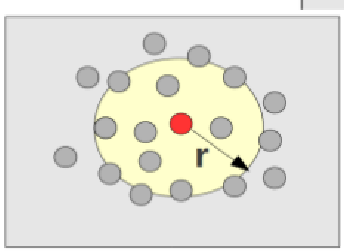



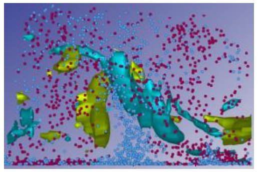

UNIFORMLY OVER A SURFACE: $N(r) \simeq r^2$




UNIFORMLY IN A LINE: $N(r) \simeq r$

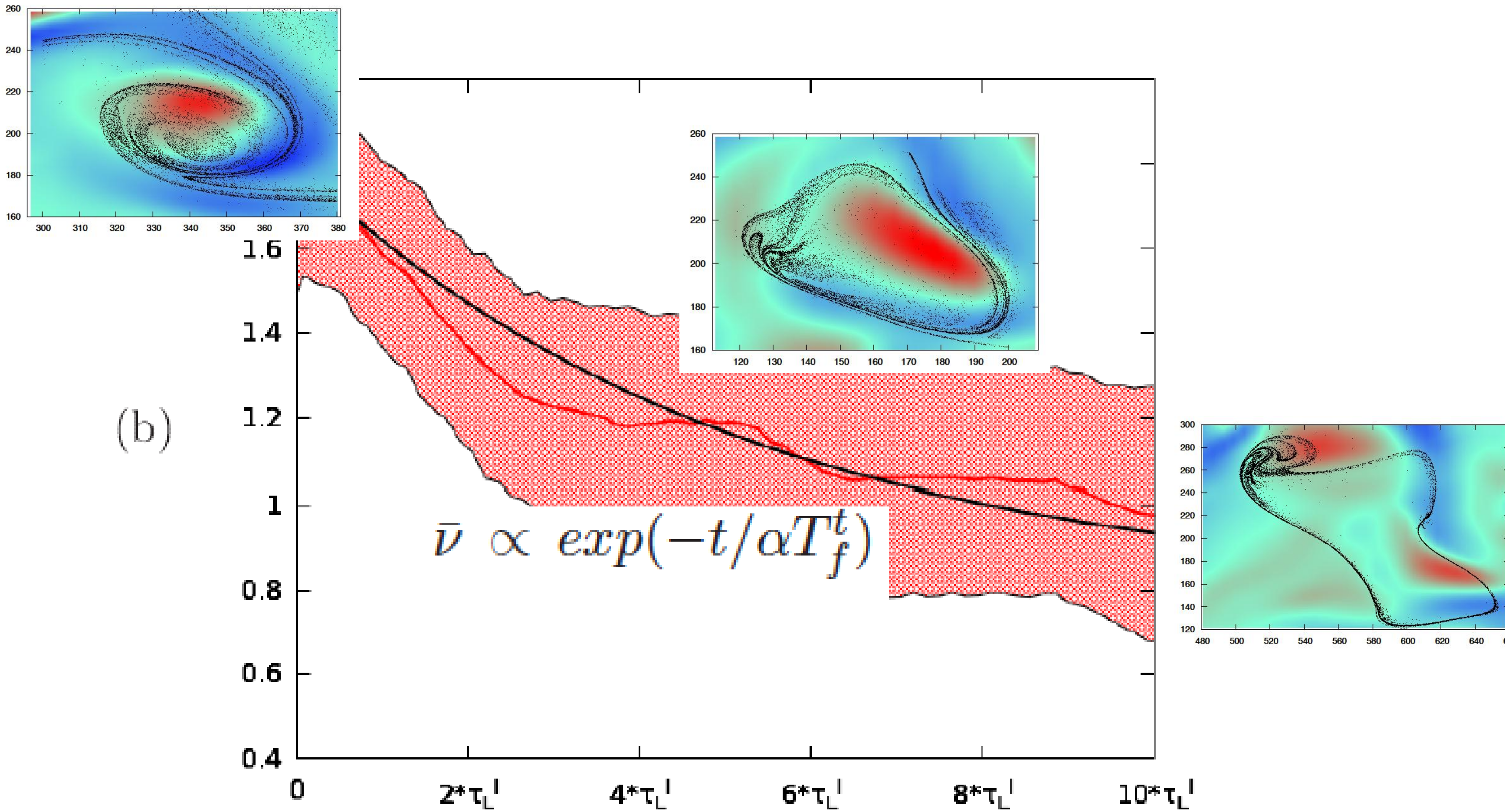



GENERALLY: $N(r) \simeq r^{\nu}$

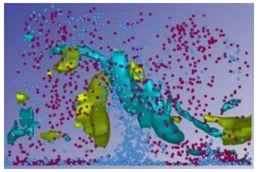


# Cluster Lifetime: They Overlive the structures which generated them.
# Evolution of Correlation Dimension

Lovecchio et al. (2013) PRE




estimate of $\bar{\nu}$ yield by an exponentially-decaying fit:



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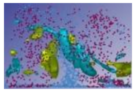
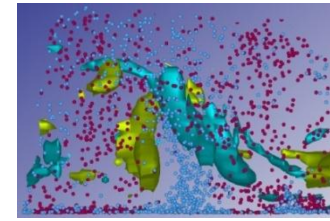
   (4.1 Oberbeck-Boussinesq Approximation)

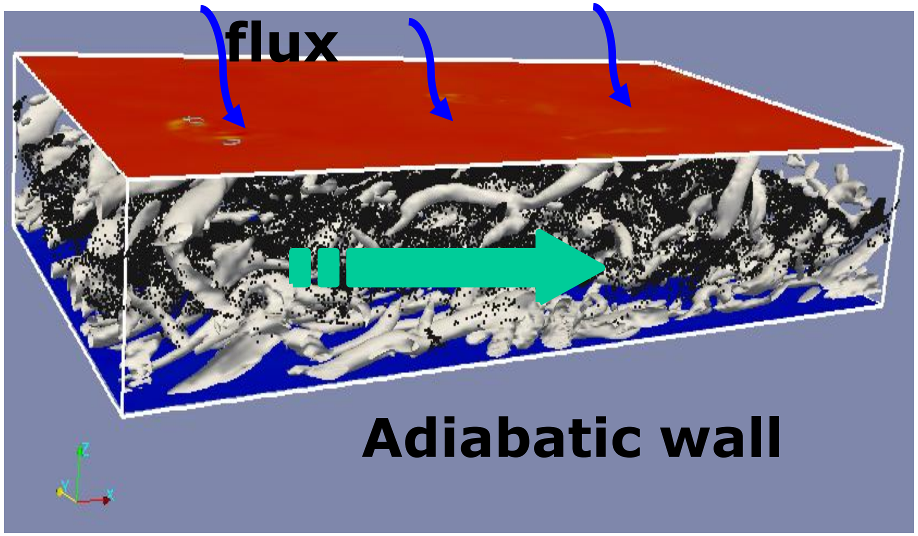
   4.2 Surfacing and Clustering of Slightly Buoyant Particles in Stratified Free-Surface Flows







# Physical Problem/Modelling Approach: Stably-stratified turbulence




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

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

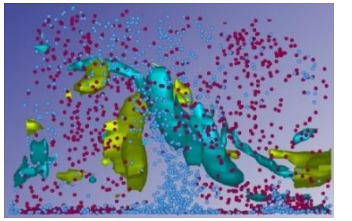
$$\nabla \cdot \mathbf{u} = \mathbf{0}$$

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

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

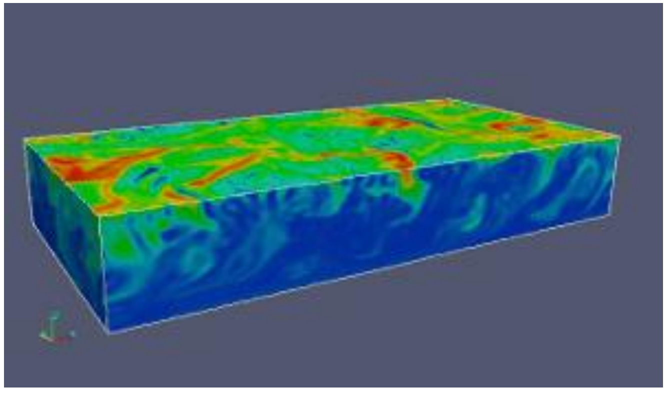
$$Gr = \frac{g\beta \frac{\partial T}{\partial z}|_{sup} (2h)^3 h}{\nu^2}$$



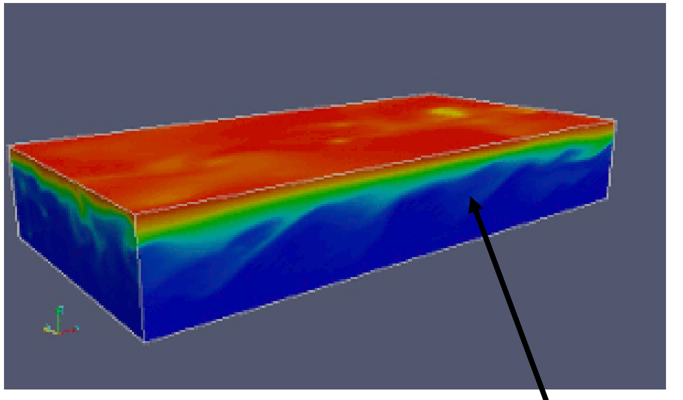


# Temperature field

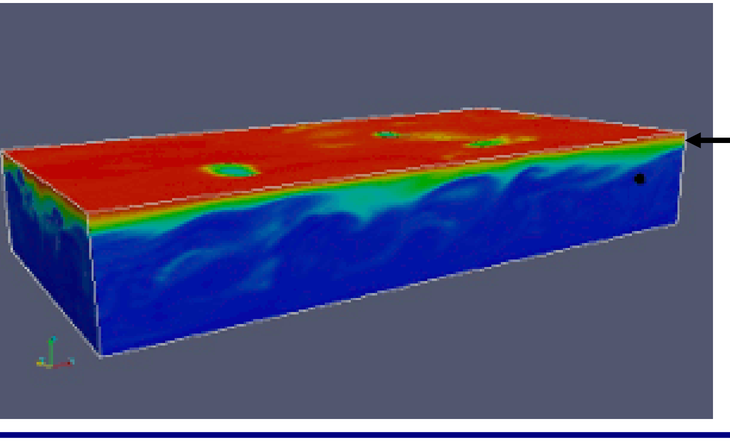
$Ri_\tau = 0$



$Ri_\tau = 164$



$Ri_\tau = 247$

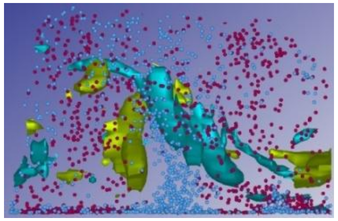


**Thermocline (barrier)**

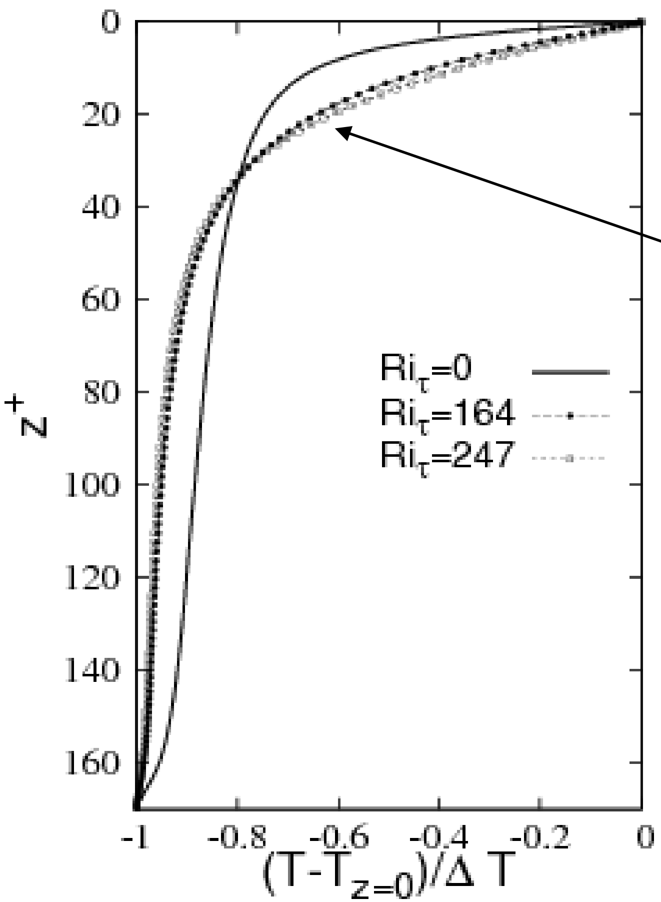
**Upwellings do not reach the surface!**



# Turbulent temperature statistics

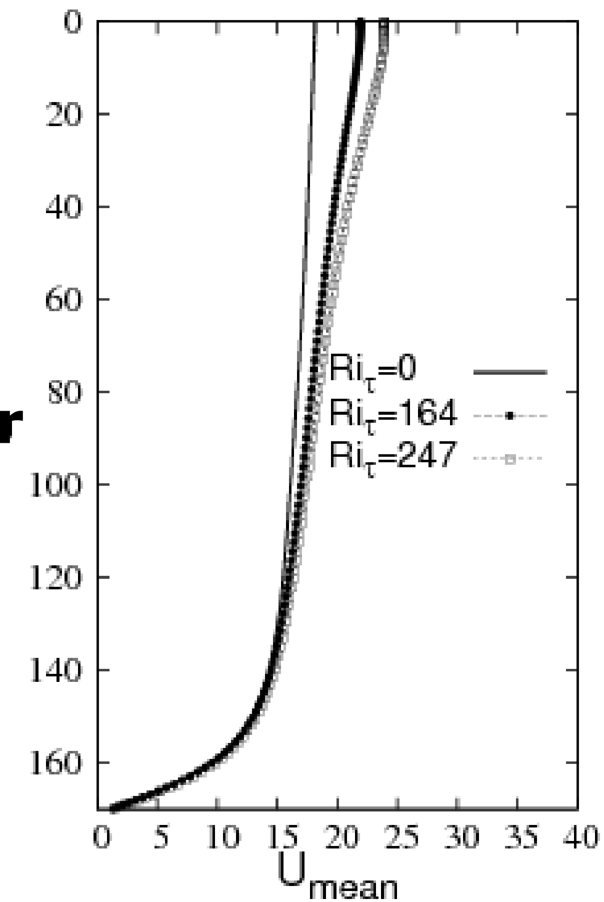


## Mean Temperature

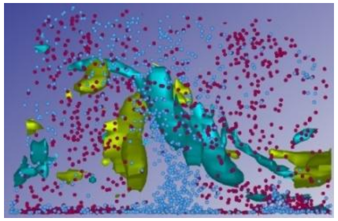


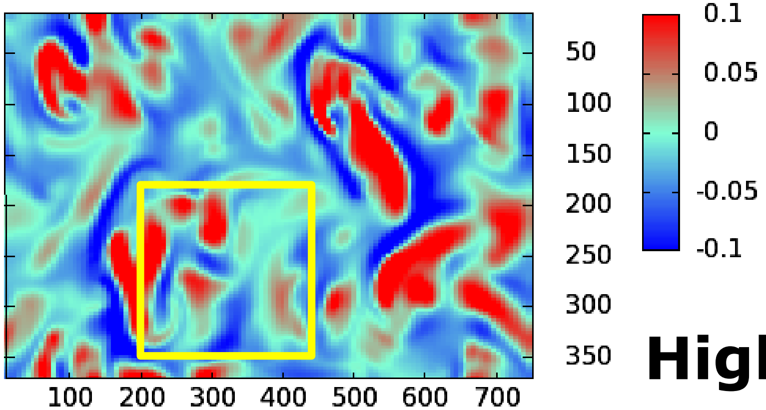

**Thermocline: Potential barrier due to density distribution**

## Mean streamwise veloc

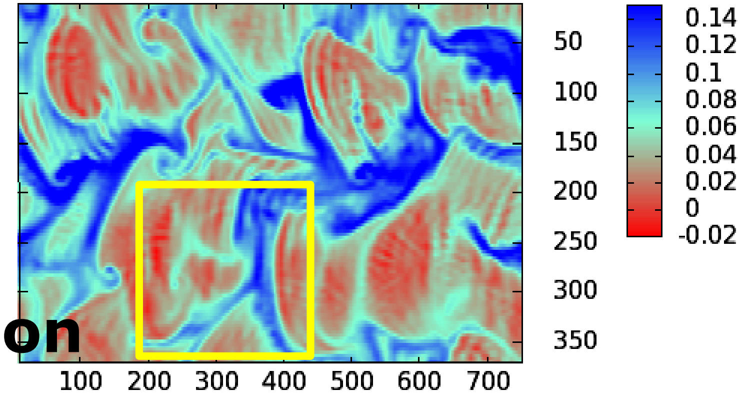


# Surface dynamics





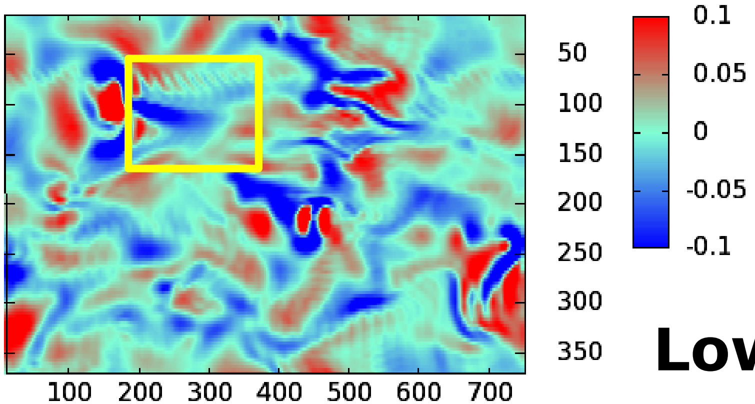

$Ri_\tau = 0$



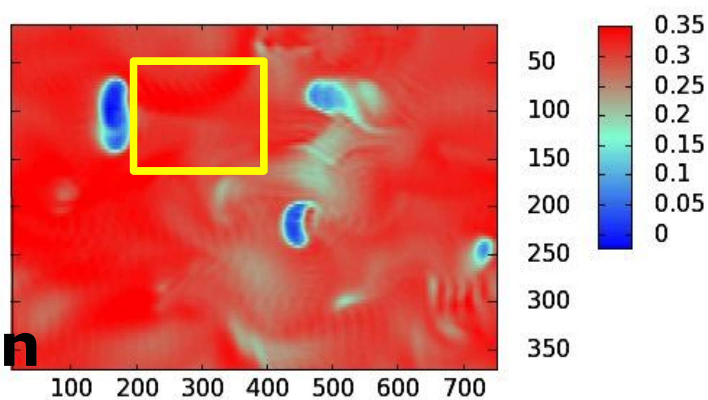

**Higher correlation**

## Surface divergence

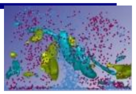
## Surface temperatu



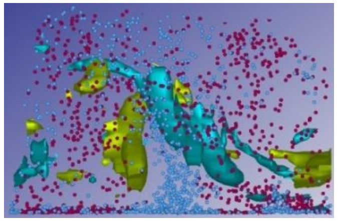

$Ri_\tau = 247$



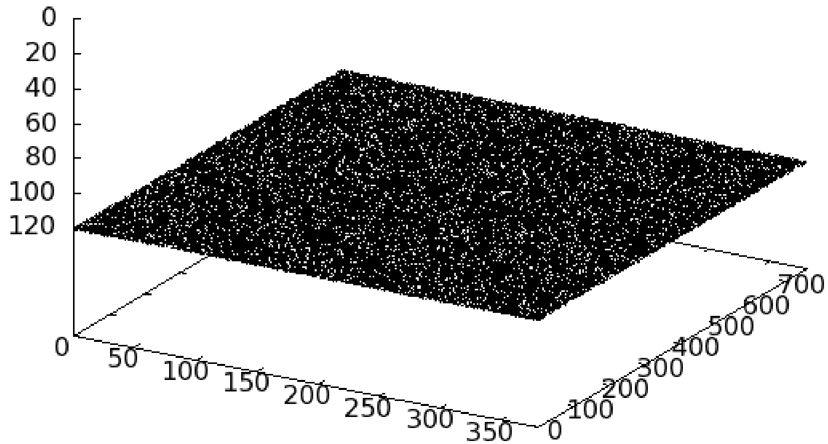

**Lower correlation**



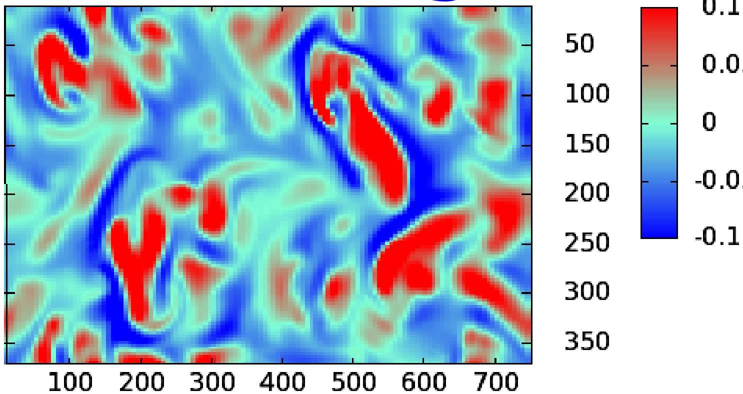
# Lagrangian Particle Tracking



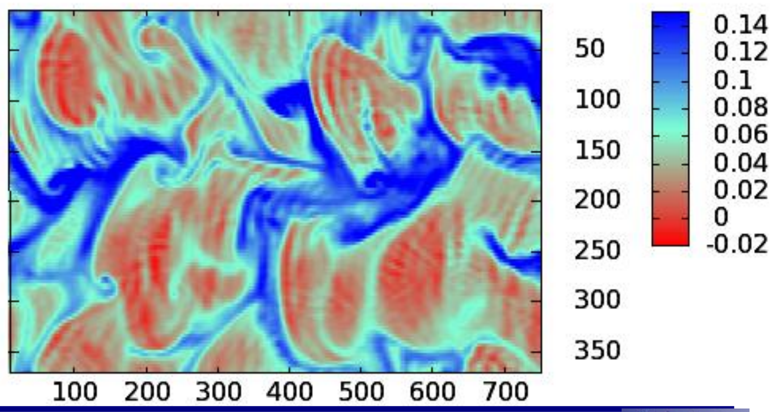
$$Ri_\tau = 0$$



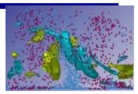

## Surface divergence

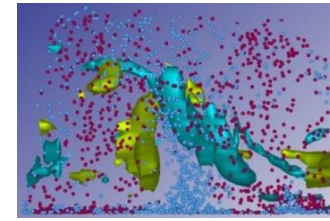



## Surface temperature



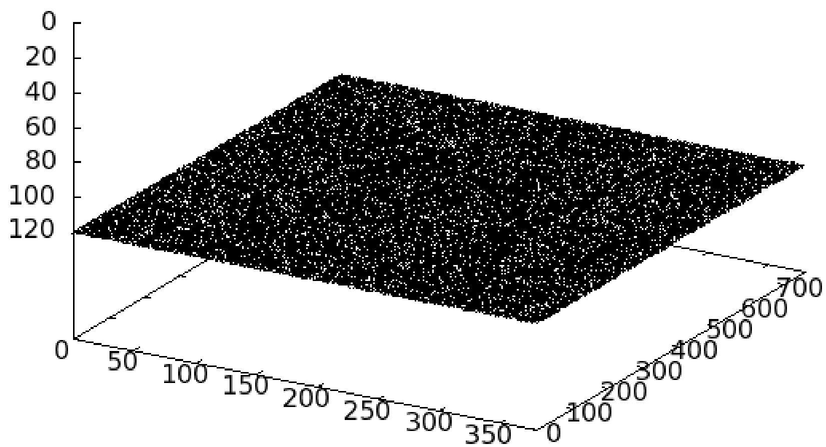


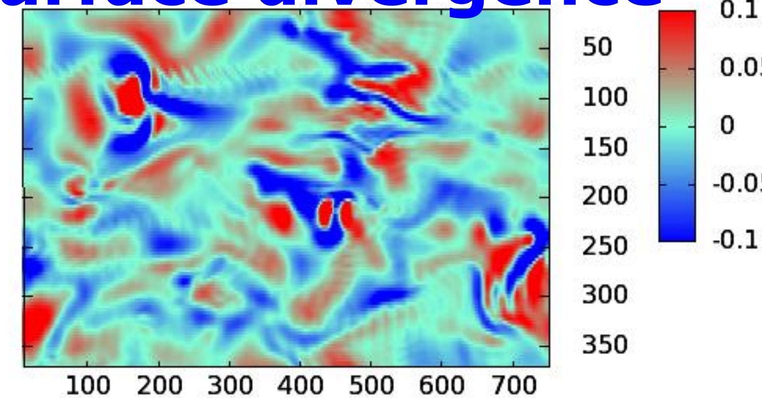


# Lagrangian Particle Tracking

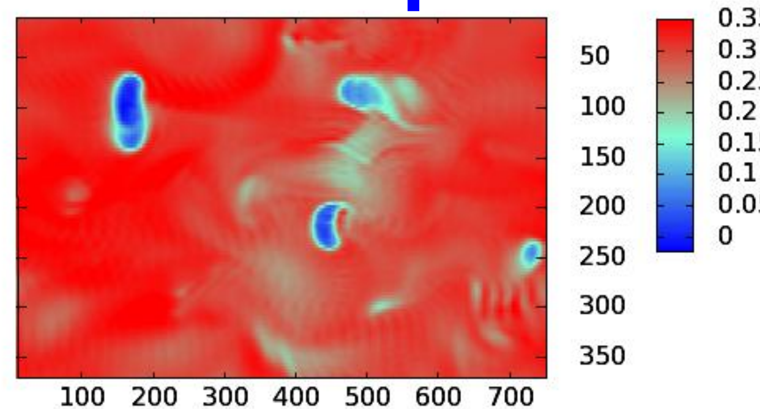
$$Ri_\tau = 247$$



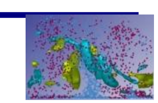

## Surface divergence



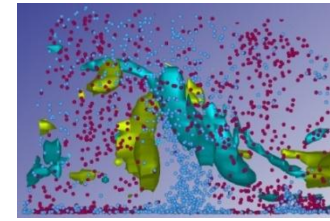

## Surface temperature

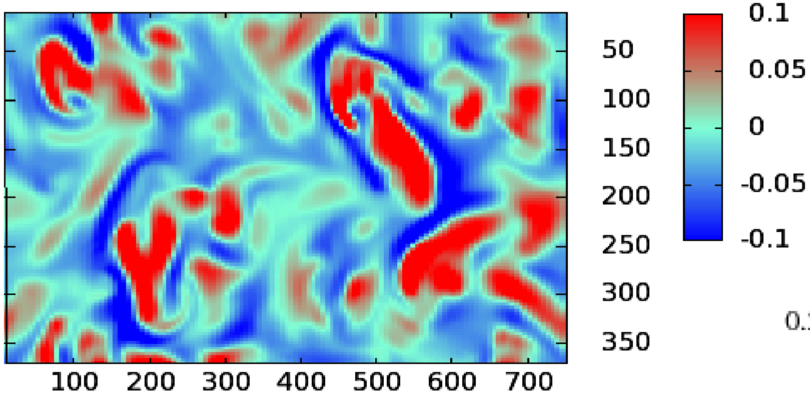


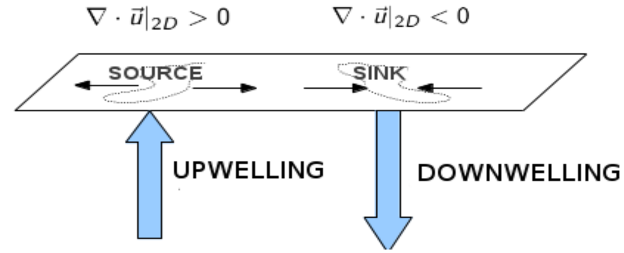


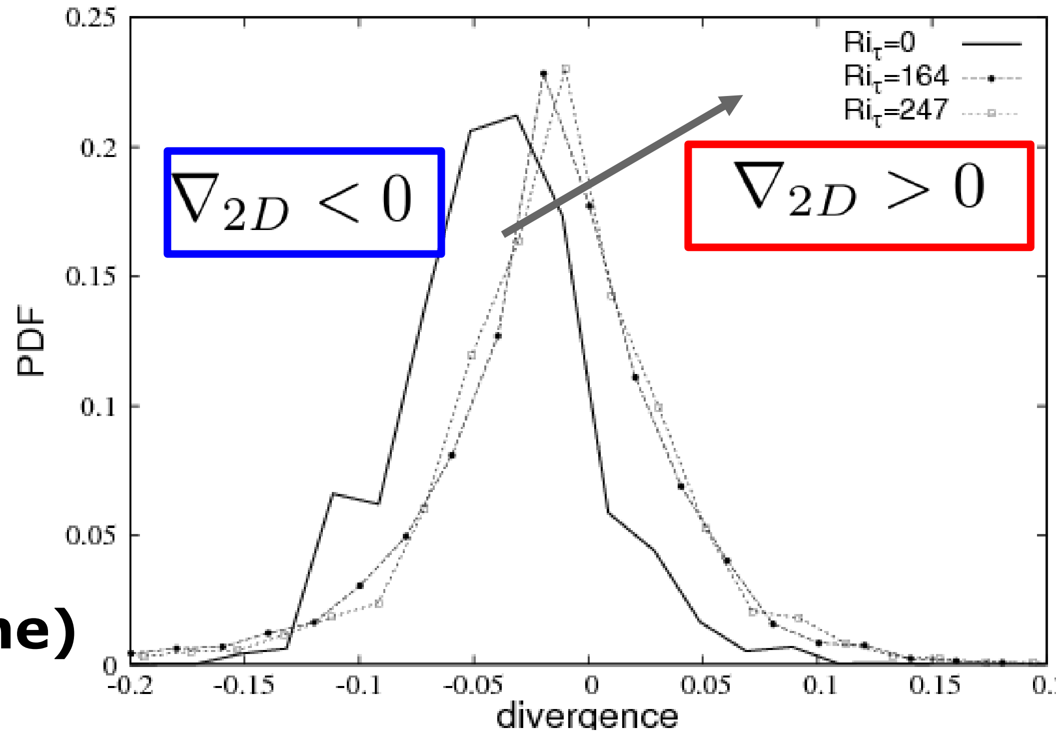



# Lagrangian Particle Tracking





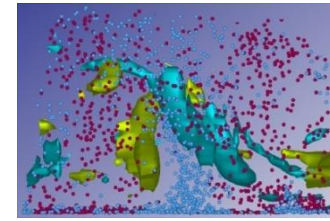

**For stratified flows,**
**Particles do not follow**
**Carefully the flow field**

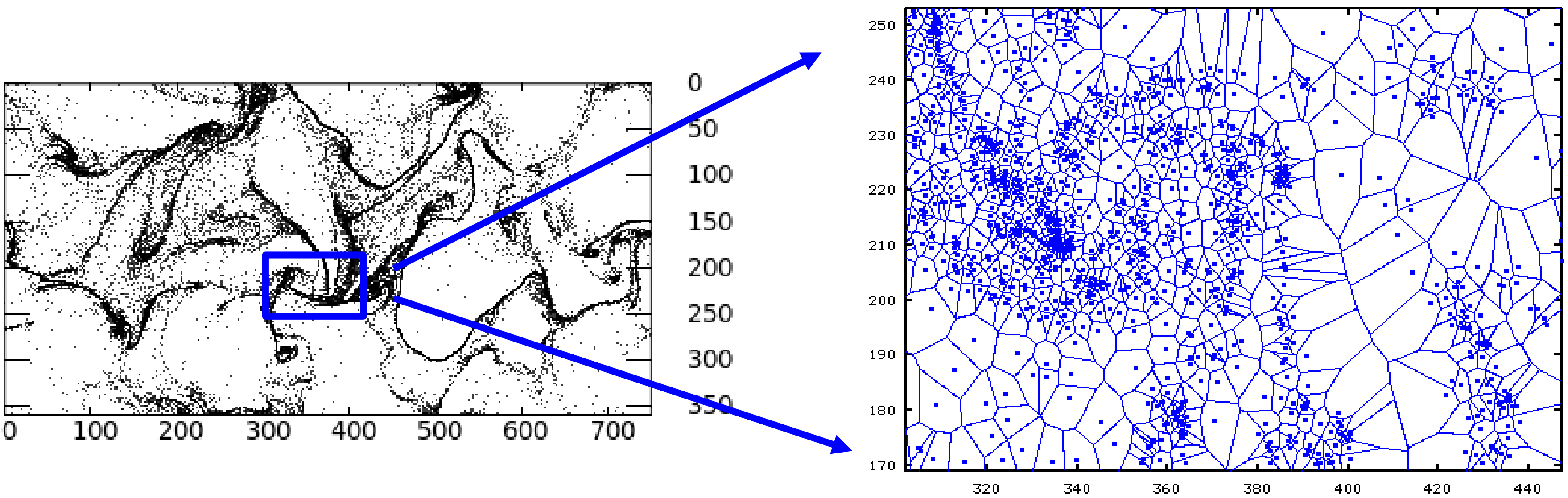
**No intense**
**Upwelling events at**
**the surface (thermocline)**



# Lagrangian Particle Tracking

## VORONOI ANALYSIS

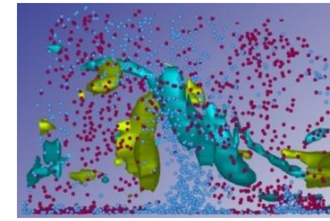


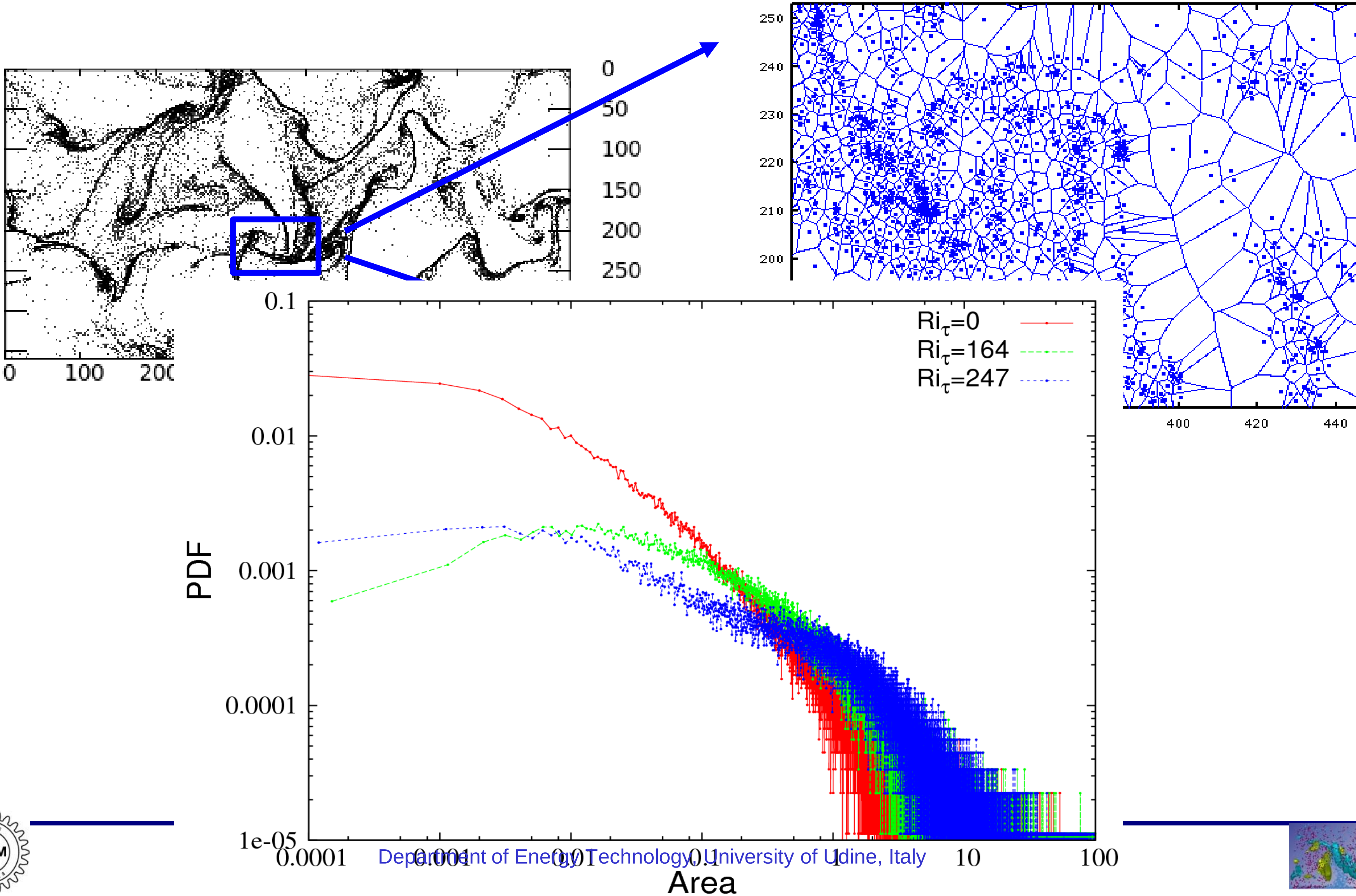


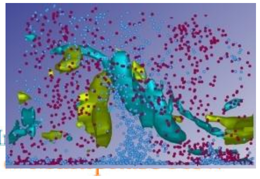



# Lagrangian Particle Tracking

## VORONOI ANALYSIS







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