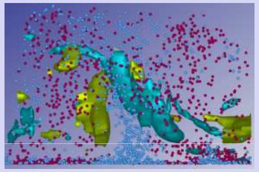


UNIVERSITAS STUDIORUM UTINENSIS

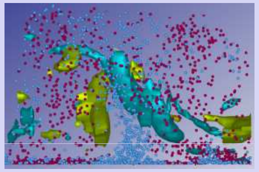
Doctoral Course in:

Modelling Turbulent Dispersed Flows

Lesson Five:

Particles Entrainment, Deposition, Dispersion and Segregation

Lausanne, 11 June 2008



A complicated scientific application…

UNIVERSITAS STUDIORUM UTINENSIS

Our motivation is turbulent dispersed and reactive flow modelling

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1. **Wednesday May 7: 14 pm to 17 pm**
   - ☑ **Introductory seminar. Fundamentals on Stokes flow around a sphere.**
2. **Wednesday May 14: 14 pm to 17 pm**
   - ☑ **Forces acting on a sphere. Steady and transient forces**
   - ☑ **Heat and Mass transfer from a sphere.**
   - ☑ **Introduction to DNS of Turbulent Flow.**
3. **Wednesday May 21: 14 pm to 17 pm**
   - ☑ **Particles Interaction with Vortices;**
   - ☑ **Characterization of a Vortex;**
   - ☑ **Vortex Dynamics in Boundary Layers**
   - ☑ **Particle dispersion in synthetic turbulence. Project description**
4. **Wednesday May 28: 14 pm to 17 pm**

   Special topic on PDF approaches: Dr Abdel Dehbi, PSI.
5. **Wednesday June 4: 14 pm to 17 pm**

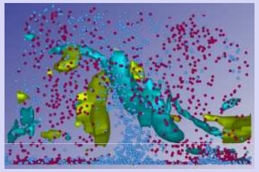
   NOT COVERED (JRT Course).
6. **Wednesday June 11: 14 pm to 17 pm**

   Particle/Turbulence Interactions: Deposition & Entrainment in Boundary Layers.
   Are particles a compressible flow? Indicators for particles segregation
   Questions and Updates on the project
7. **Wednesday June 18: 14 pm to 17 pm**

   Particle dispersion in synthetic turbulence. Project Advancement/Discussion
8. **Wednesday June: 25:14 pm to 17 pm**

   Project Discussion.
9. **Wednesday July: 2: 14 pm to 17 pm**

   To be confirmed. Final Remarks



Summary

- What we know from previous lectures:

1 Forces acting on a sphere: We know EVERYTHING!

2 Unsteady and Turbulent Flows: We know something

3 Vortex Dynamics and Flow Structures in Boundary Layers and Shear Flows: We Know something

- What we will learn in today lecture:

1 Modelling/Simulation approaches (We will refresh some of the early concepts)

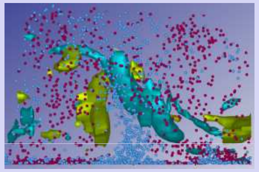
2 If we know the flow field at discrete points (Simulations), which fluid velocity will we use?

3 How Flow Structures in Boundary Layers control Deposition/Entrainment?

4 Measuring Particle Segregation/Dispersion

5 Updates on the Homeworks and Project

6 ??? Perhaps a Seminar on Bubbly Turbulent Flow (or next Wednesday)



Refreshing the memory…
same concepts folded and unfolded differently…

- **What we will learn in today lecture:**

1 **Modelling/Simulation approaches (We will refresh some of the early concepts)**

2 **If we know the flow field at discrete points (Simulations), which fluid velocity will we use?**

3 **How Flow Structures in Boundary Layers control Deposition/Entrainment?**

4 **Measuring Particle Segregation/Dispersion**

5 **Update on Homeworks and Project.**

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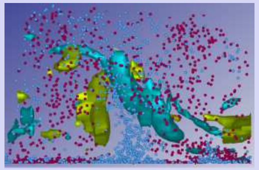
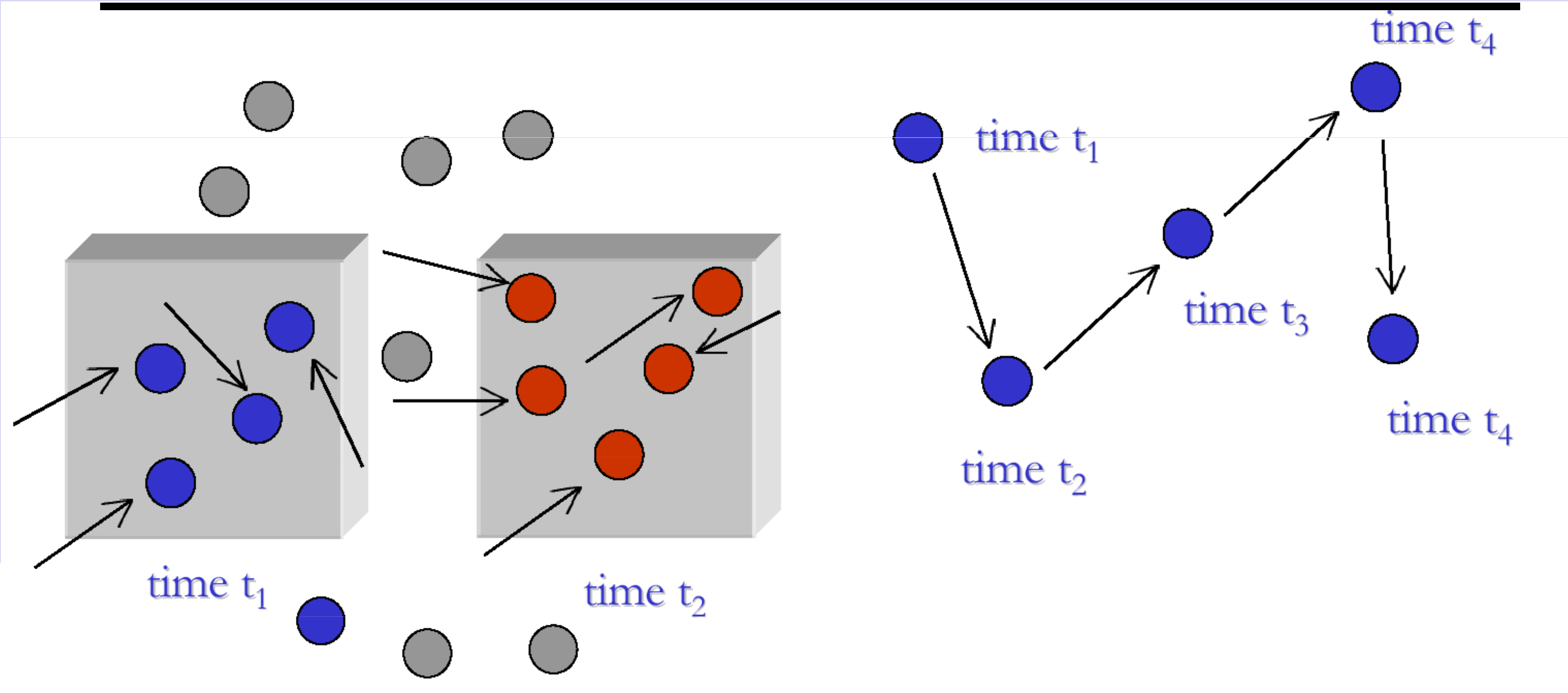
1. Modelling the dispersed phase >>(pointwise approximation);
2. Forces acting on particles;
3. 1Way/2Way/4Way coupling;
4. Interpolation methods.

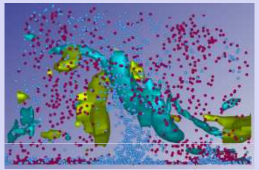


Lagrangian or Eulerian Modelling

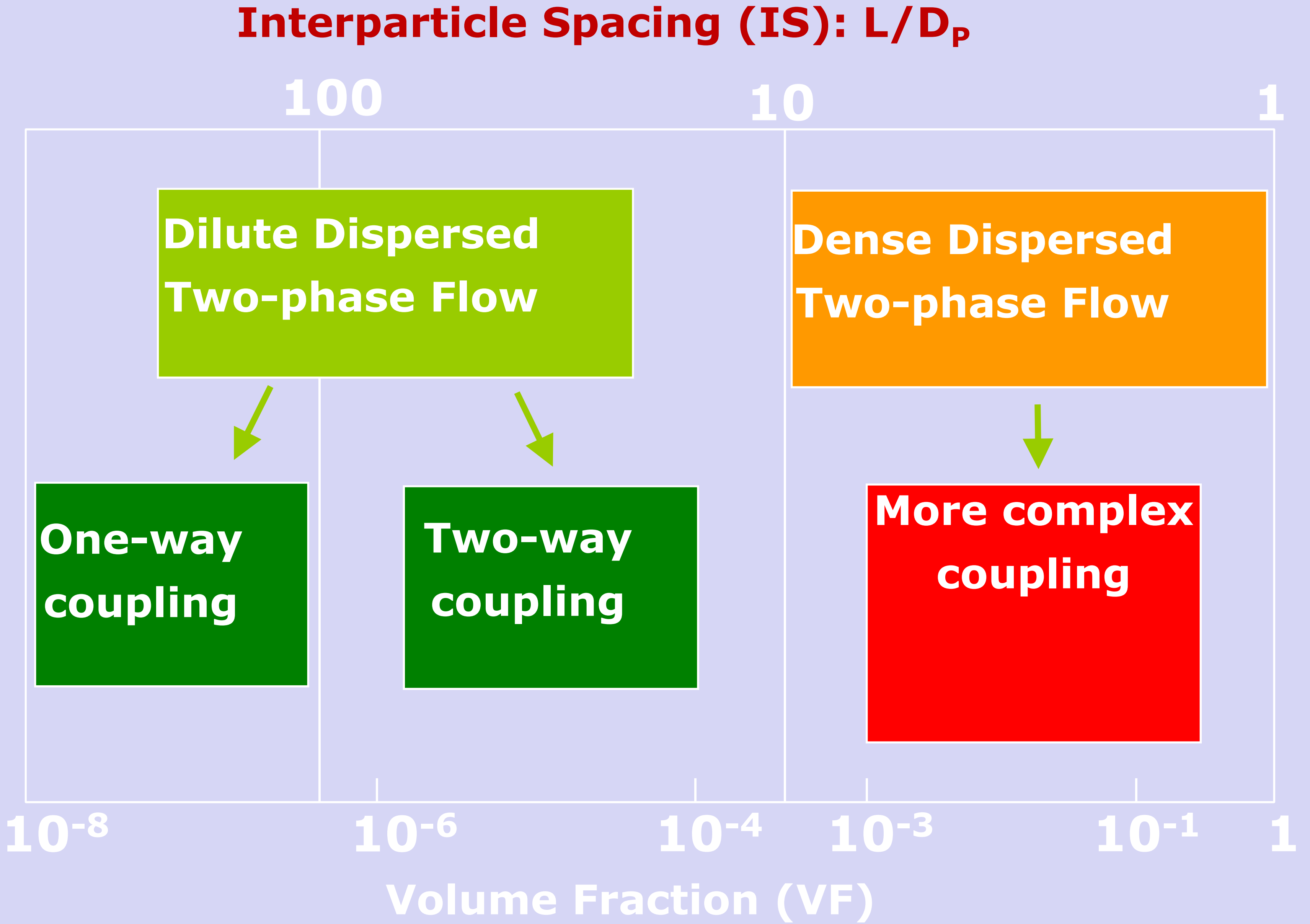


Lagrangian Approach: **Focus on particle tracks**

Eulerian Approach: **Focus on control volume**



One-way/Two-way/... coupling



Interparticle Spacing (IS): L/D_P

100

10

1

Dilute Dispersed Two-phase Flow

Dense Dispersed Two-phase Flow

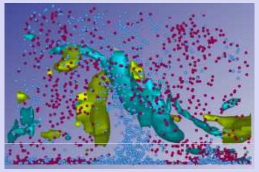
One-way coupling

Two-way coupling

More complex coupling

10^{-8} 10^{-6} 10^{-4} 10^{-3} 10^{-1} 1

Volume Fraction (VF)



One-way/Two-way/... coupling

One-way coupling **($VF < 10^{-6}$; $IS > 100$): (Particle Momentum Balance)**

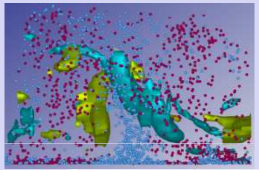
Particles do not influence significantly the flow field → Allows to investigate the effect of flow structure on particle motion/dispersion/distribution;

Two-way coupling **($10^{-6} < VF < 10^{-4}$; $10 < IS < 100$) (Particle Momentum Balance; Fluid Momentum Balance)**

Particles influence the flow field dynamics → allows investigation of flow modulation by particles.

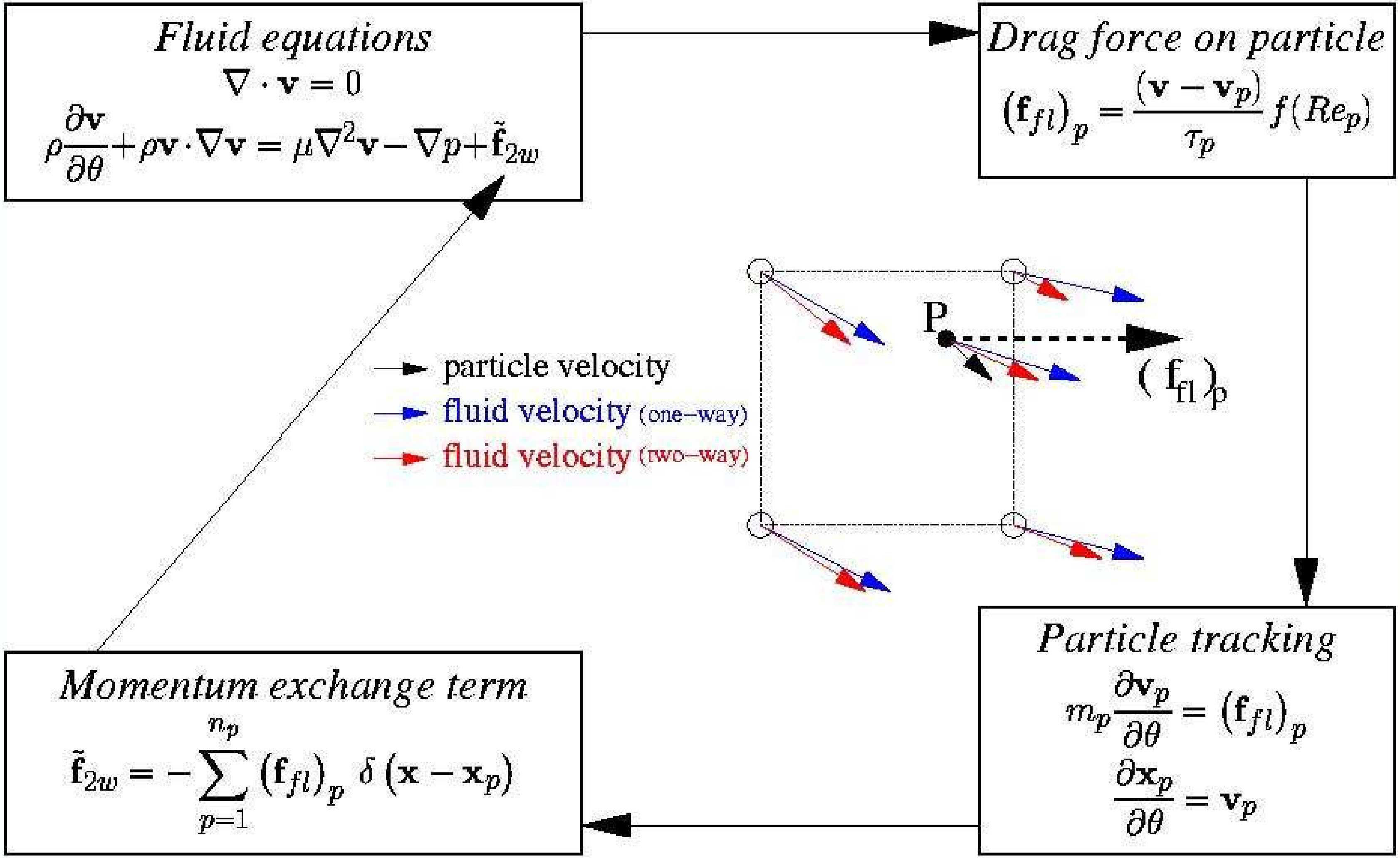
More complex coupling **($10^{-3} < VF < 10^{0}$; $1 < IS < 10$) (Particle Momentum Balance; Fluid Momentum Balance; Fluid Mass Balance)**

Particles influence the flow field dynamics → allows investigation of flow modulation by particles.



Two-Way Coupling:
The fluid Feels particle Momentum Exchange

TWO–WAY EFFECT (point–force approximation)



Fluid equations

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

$$\rho \frac{\partial \mathbf{v}}{\partial \theta} + \rho \mathbf{v} \cdot \nabla \mathbf{v} = \mu \nabla^2 \mathbf{v} - \nabla p + \tilde{\mathbf{f}}_{2w}$$

Drag force on particle

$$(\mathbf{f}_{fl})_p = \frac{(\mathbf{v} - \mathbf{v}_p)}{\tau_p} f(Re_p)$$

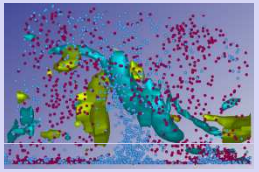
Particle tracking

$$m_p \frac{\partial \mathbf{v}_p}{\partial \theta} = (\mathbf{f}_{fl})_p$$

$$\frac{\partial \mathbf{x}_p}{\partial \theta} = \mathbf{v}_p$$

Momentum exchange term

$$\tilde{\mathbf{f}}_{2w} = - \sum_{p=1}^{n_p} (\mathbf{f}_{fl})_p \, \delta(\mathbf{x} - \mathbf{x}_p)$$



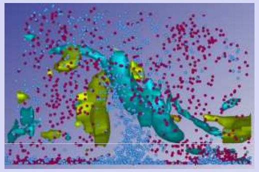
Two-way coupling:
PSI-CELL model (Crowe et al., 1977)

According to PSI-CELL (Particle-Source-In Cell) model for fluid-patricle coupling: fluid sees the particle as momentum and energy source;

total force exerted by each particle on the fluid is a *body force* distributed over faces or vertices of the cell containing the particle;

such force acts as a disturbance force on fluid flow and pressure field:

$$\mathbf{V}^{\text{two-way}}=\mathbf{V}^{\text{one-way}}+\mathbf{V}^{\text{disturbance}};\ \mathbf{p}^{\text{two-way}}=\mathbf{p}^{\text{one-way}}+\mathbf{p}^{\text{disturbance}}$$



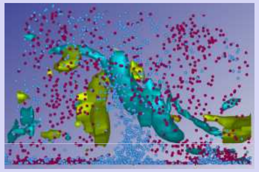
Two-way coupling:
PSI-CELL model (Crowe et al., 1977)

(A) Particle in the turbulent flow

(B) Overall pressure/flow field= disturbance pressure/flow field + undisturbed fluid pressure/flow field

(C)additional stress over particle surface

(D) Overall force acting on the particle



PSI-CELL model

Navier-Stokes Equation including *particle* body force:

$$\frac{\partial \mathbf{v}}{\partial t}+\mathbf{v}\cdot\nabla\mathbf{v}=-\frac{\nabla p}{\rho}+\nu\nabla^2\mathbf{v}+\mathbf{s}_p$$

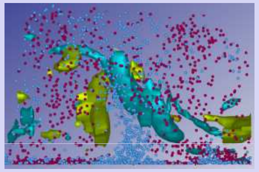
Particle-source Term:

$$\mathbf{s}_p=-\sum_{n=1}^{N_p}\left[-\frac{\nabla p_n^{\text{two-way}}}{\rho}+\nu\nabla^2\mathbf{v}_n^{\text{two-way}}\right]$$

where N_p=Overall Particle Number.

.B. PSI-CELL model neglects particle-particle interactions!

Part III



Forces Acting on a Particle

drag

gravity & buoyancy

particle inertia

$$\frac{d\; m_p\, \mathbf{v}_p}{d\; t} = -\; 3\,\pi\, d_p\, \mu\, (\mathbf{v}_p - \mathbf{v}) \;+\; (m_p - m_f)\,\mathbf{g}$$

$$+\; m_f \frac{D\mathbf{v}}{D\; t} \;-\; \frac{1}{2}\, m_f \left(\frac{d\mathbf{v}_p}{d\; t} - \frac{D\mathbf{v}}{D\; t}\right)$$

$$-\; \frac{3}{2}\,\pi\, d_p{}^2\, \mu \int_0^t \left(\frac{d\mathbf{v}_p}{d\tau} - \frac{d\mathbf{v}}{d\tau}\right) \frac{d\tau}{[\pi\; \nu\; (t-\tau)]^{0.5}}$$

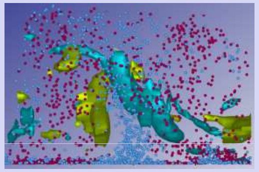
$$[\; +\; m_f\, C_L\, (\mathbf{v} - \mathbf{v}_p) \times \omega \;]$$

added mass

pressure gradient

lift

Basset (history)



Drag Force acting on a Particle

- Drag force:

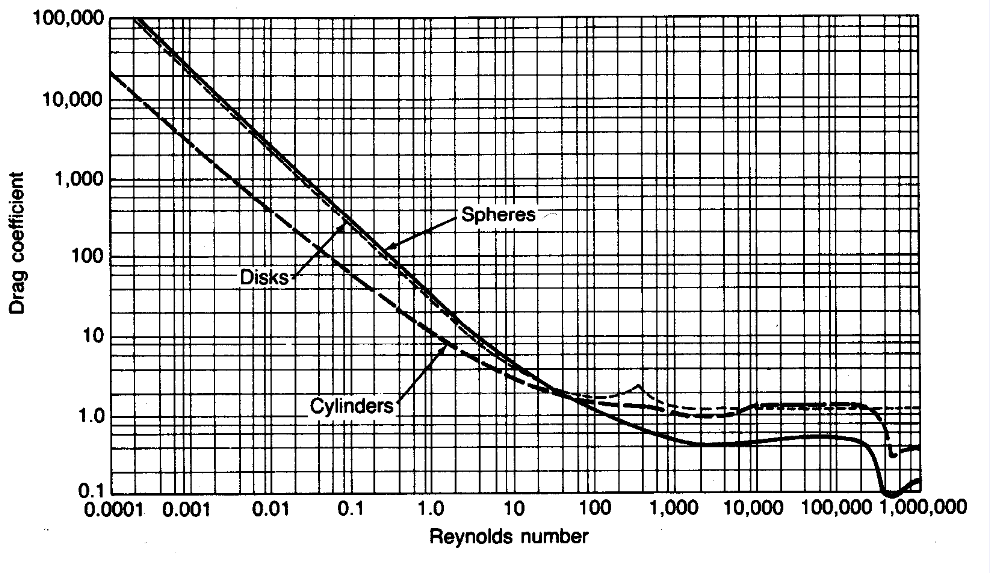
$$\mathbf{F}_D = \frac{1}{2} C_D \rho \frac{\pi D_p^2}{4} (\mathbf{v} - \mathbf{v_p}) \,|\, \mathbf{v} - \mathbf{v_p} \,|$$

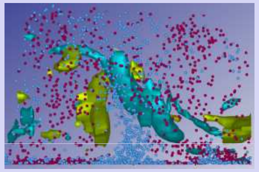
Drag coefficient

Particle Reynolds Num.

$$\begin{cases} C_D = \dfrac{24}{\mathrm{Re}_p} \left[1 + 0.15\,\mathrm{Re}_p^{\;0.687} \right] \\ \mathrm{Re}_p = \dfrac{\rho \left| \mathrm{v} - \mathrm{v}_p \right| d}{\mu} \end{cases}$$

$C_d = f(Re_p)$!

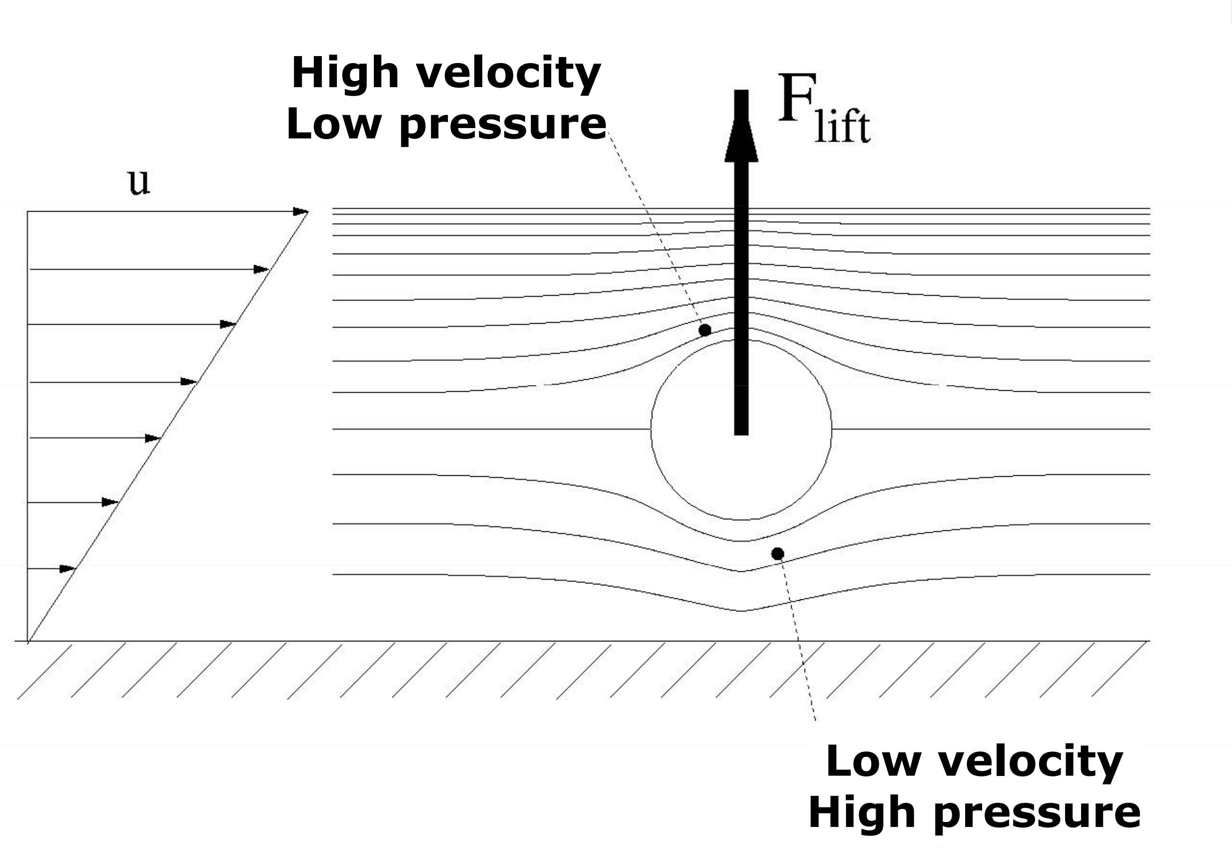




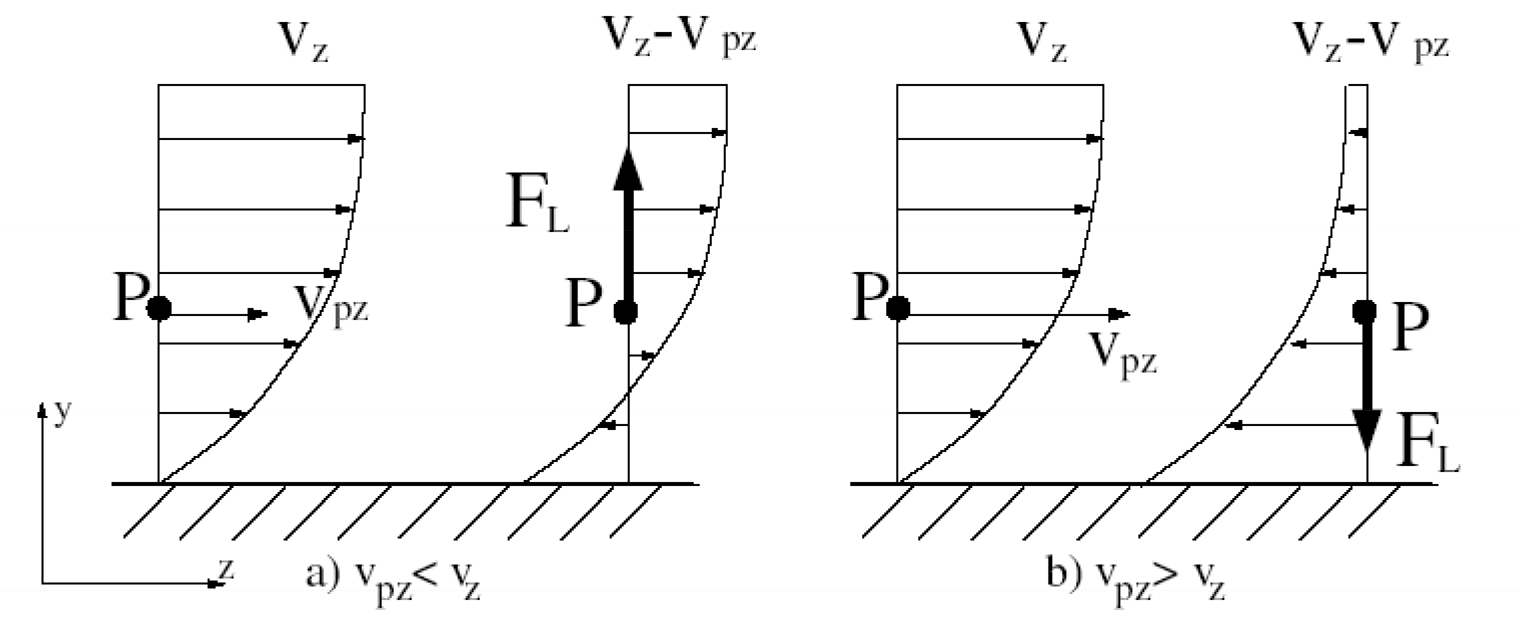
Lift Force acting on a Particle

Lift force:

$$\mathbf{F}_{lift} = C_L m_f \left(\mathbf{v} - \mathbf{v}_p\right) \times \boldsymbol{\omega}$$

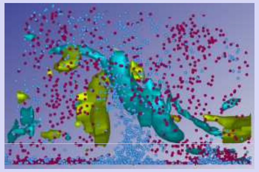


Sign of the lift force



a) $v_{pz} < v_z$

b) $v_{pz} > v_z$



Other Forces Acting on a Particle

- **Gravity & buoyancy:**

$$\mathbf{F}_{grav} = \left(m_p - m_F\right)\mathbf{g}$$

- **Pressure gradient:**

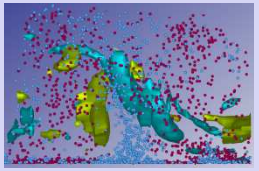
$$\mathbf{F}_{prgr} = m_F \frac{D\mathbf{v}}{Dt}$$

- **Added mass term:**

$$\mathbf{F}_{addm} = -m_F \frac{1}{2}\left(\frac{d\mathbf{v}_p}{dt} - \frac{D\mathbf{v}}{Dt}\right)$$

- **Basset (*hystory*) term:**

$$\mathbf{F}_{Bass} = -\frac{3}{2}\pi d_p^2 \mu \int_{-\infty}^{t}\left(\frac{d\mathbf{v}_p}{d\tau} - \frac{d\mathbf{v}}{d\tau}\right)\frac{d\tau}{\left[\pi\nu\left(t-\tau\right)\right]^{1/2}}$$



Other Forces Acting on a Particle

- **Buoyancy force:**

$$\mathbf{F}_B = (\rho_p - \rho) V_p \mathbf{g}$$

- **Lift force*:**

$$\mathbf{F}_{lift} = C_L m_f (\mathbf{v} - \mathbf{v}_p) \times \boldsymbol{\omega}$$

***Lift Coefficient defined only in the simpler 1-D case**

$$C_L = C_L\ (Re_p, Sr_p)$$

$$Sr_p = \frac{\left|\frac{\partial v_z}{\partial y}\right|\ d_p}{|v_z - v_{p,z}|}$$

$$Re_p = \frac{|v_z - v_{p,z}|\ d_p}{\nu}$$

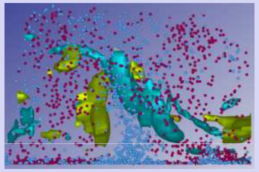
$$C_{L,Saff} = \frac{3.084}{(Re_p\ Sr_p)^{0.5}}$$

$$C_{L,McL} = C_{L,Saff} \frac{J(\varepsilon)}{2.255}$$

$$\varepsilon = \sqrt{\frac{Sr_p}{Re_p}}$$

$$C_{L,KuKo} = K_0 \left(\frac{Sr}{2}\right)^{0.9} + K_1 \left(\frac{Sr}{2}\right)^{1.1}$$

$$K_0, K_1 = f\,(Re_p) \quad [tabulated]$$



Importance of the Forces

$$F_{drag} \quad \longrightarrow \quad O\left(St^{-1}\right)$$

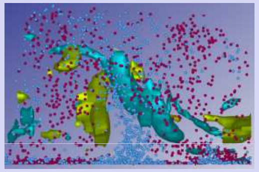
$$F_{prgr} \quad \longrightarrow \quad O\left(\frac{\rho_f}{\rho_p}\right)$$

$$F_{addm} \quad \longrightarrow \quad O\left(\frac{\rho_f}{\rho_p}\right)$$

$$F_{Bass} \quad \longrightarrow \quad O\left(\left(\frac{\rho_f}{\rho_p}\right)^{1/2}\right)$$

$$F_{lift} \quad \longrightarrow \quad O\left(d_p{}^2 \frac{\sqrt{dv \,/\, dy}}{\nu}\right)$$

For heavy particles:
only drag and gravity



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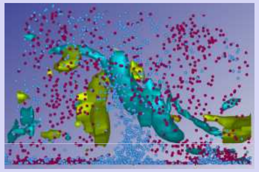
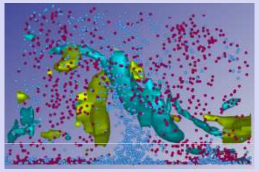


…

Hope the memory is now refreshed….



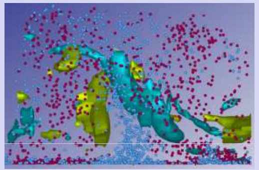
Memory refreshed

- **What we will learn in today lecture:**

1. **Modelling/Simulation approaches (We will refresh some of the early concepts)**
2. **If we know the flow field at discrete points (Simulations), which fluid velocity will we use?**
3. **How Flow Structures in Boundary Layers control Deposition/Entrainment?**
4. **Measuring Particle Segregation/Dispersion**
5. **Update on Homeworks and Project.**

1 Interpolation methods…

* Caveat: I will not explain them (!) I will just list some of the most employed in this business… eventually, you will know what to read/use

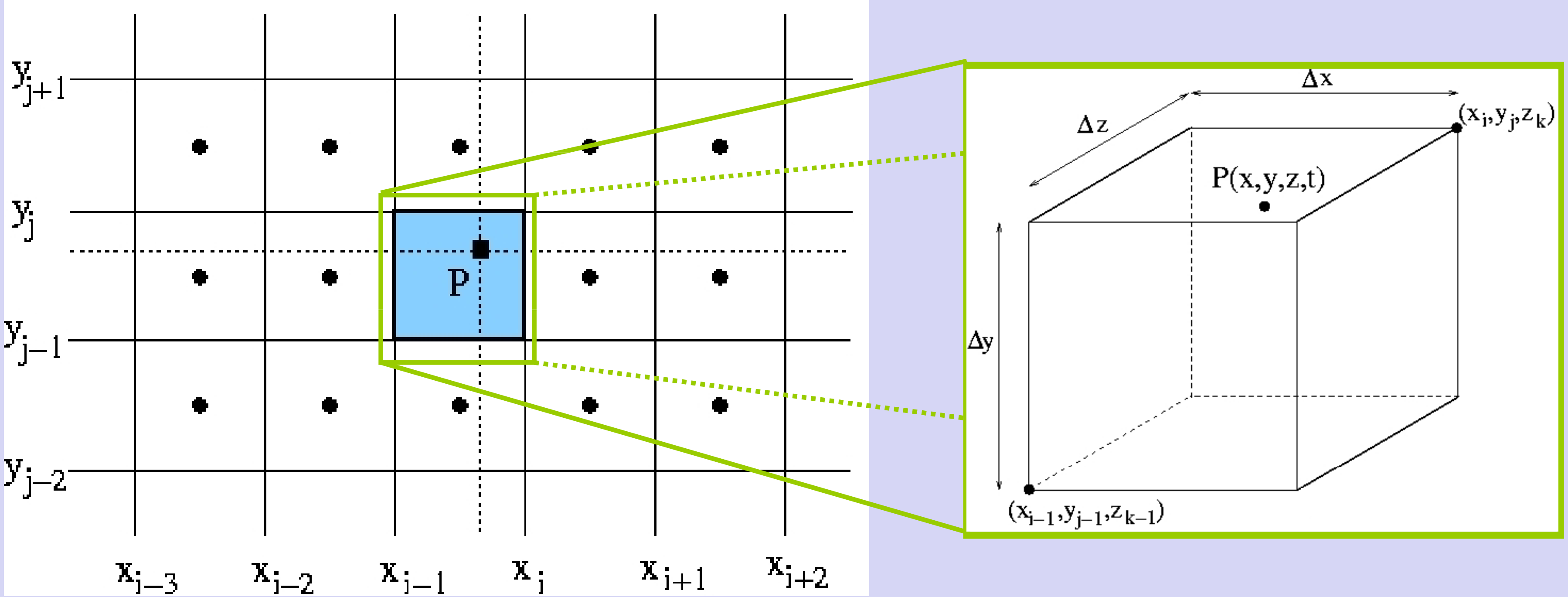


Interpolation Methods

Momentum Equation for particle:

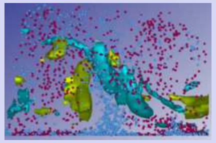
- **X(t) = Lagrangian trajectory of the particle**
- **u(X(t),t) = particle velocity**

$$\frac{d\mathbf{X}(t)}{dt} = \mathbf{u}(\mathbf{X}(t), t)$$



Schematics of Cartesian grid: P(x,y,z,t) = Instantaneous patricle position

Part III



Linear Interpolation

Given the fluid velocity at grid nodes, u(x_i,y_j,z_k,t), the interpolated velocity value is:

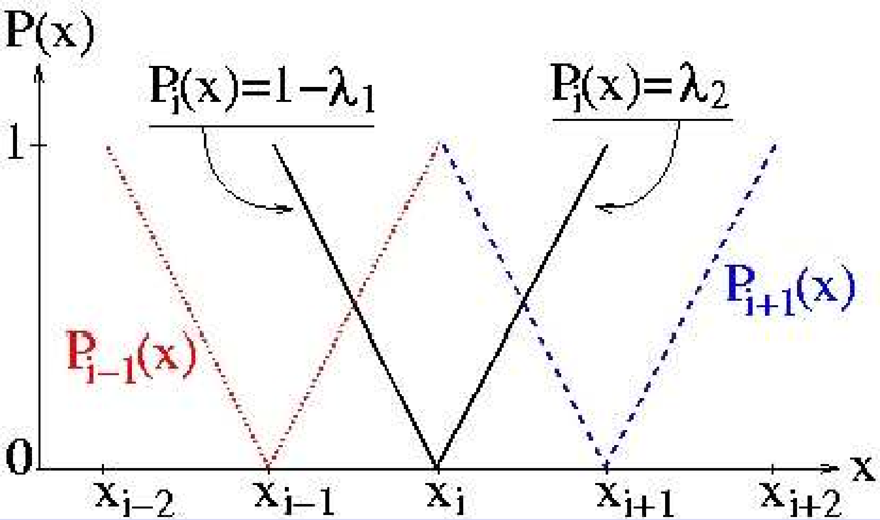
$$\mathbf{u}_{\text{int}} = \sum_{i=0}^{N_x}\sum_{j=0}^{N_y}\sum_{z=0}^{N_z}\mathbf{u}(x_i, y_j, z_k, t)P_i(x)P_j(y)P_k(z) \qquad \textbf{(1)}$$

where:

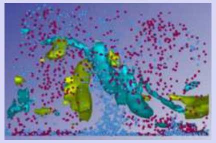
$$P_i(x) = \begin{cases} 0 & x < x_{i\text{-}1}\;,\; x > x_{i+1} \\ 1-\lambda_1 & x_{i-1} \le x \le x_i \\ \lambda_2 & x_i < x < x_{i+1} \end{cases}$$

$$\lambda_1 = \frac{(x - x_{i-1})}{\Delta x} \qquad \lambda_2 = \frac{(x - x_i)}{\Delta x}$$

Linear Interpolation coefficients



Part III



Lagrange Interpolation

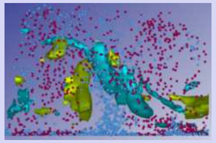
Given the fluid velocity at grid nodes, u(*x_i*,*y_j*,*z_k*,*t*), the interpolated velocity value is:

$$\mathbf{u}_{\text{int}} = \sum_{i=0}^{N_x} \sum_{j=0}^{N_y} \sum_{z=0}^{N_z} \mathbf{u}(x_i, y_j, z_k, t) L_i(x) L_j(y) L_k(z) \qquad (2)$$

Definition of Lagrange polynomials:

$$L_i(x) = \frac{(x-x_0)(x-x_1)\ldots(x-x_{i-1})(x-x_{i+1})\ldots(x-x_{n-1})(x-x_n)}{(x_i-x_0)(x_i-x_1)\ldots(x_i-x_{i-1})(x_i-x_{i+1})\ldots(x_i-x_{n-1})(x_i-x_n)} = \sum_{j=0}^{n} \frac{x-x_j}{x_i-x_j}\,; \quad i=0,1,\ldots,n$$

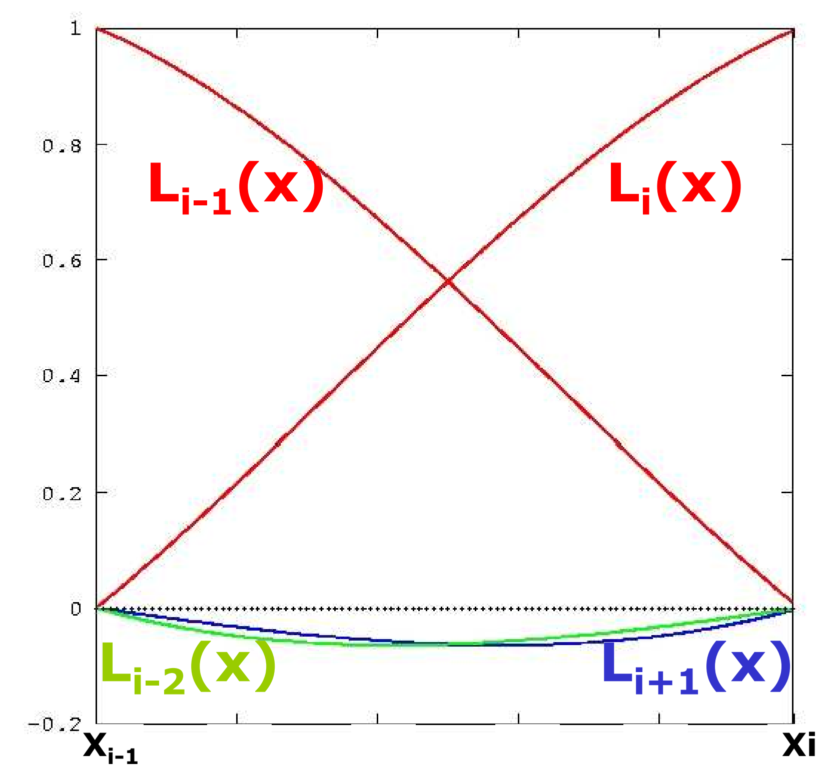
where *n* is the degree of the Polynomial.



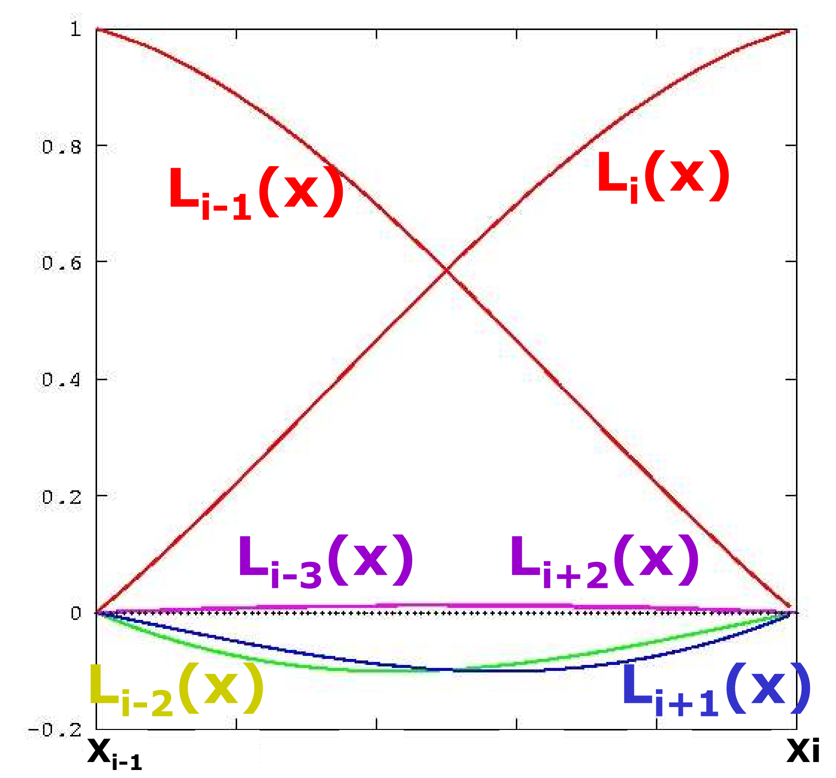
Lagrange Interpolation

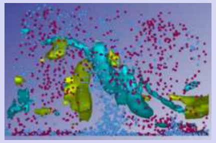
$n=2$: Lagrange Interpolation= Linear Interpolation!

$n=4$: 4th order Lagrange Interpolation



$n=6$: 6th order Lagrange Interpolation





Shape Functions Method

Given the fluid velocity at grid nodes, u(x_i,y_j,z_k,t), the interpolated velocity value is:

$$\mathbf{u}_{\text{int}} = \sum_{i=0}^{N_x}\sum_{j=0}^{N_y}\sum_{z=0}^{N_z}\Big[\mathbf{u}(x_i, y_j, z_k, t)H_i(x)H_j(y)H_k(z) +$$

$$+\frac{\partial \mathbf{u}}{\partial x}(x_i, y_j, z_k, t)G_i(x)H_j(y)H_k(z)$$

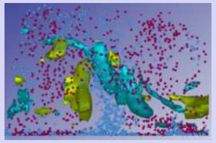
$$+\frac{\partial \mathbf{u}}{\partial y}(x_i, y_j, z_k, t)H_i(x)G_j(y)H_k(z)$$

$$+\frac{\partial \mathbf{u}}{\partial z}(x_i, y_j, z_k, t)H_i(x)H_j(y)G_k(z)$$

(3)

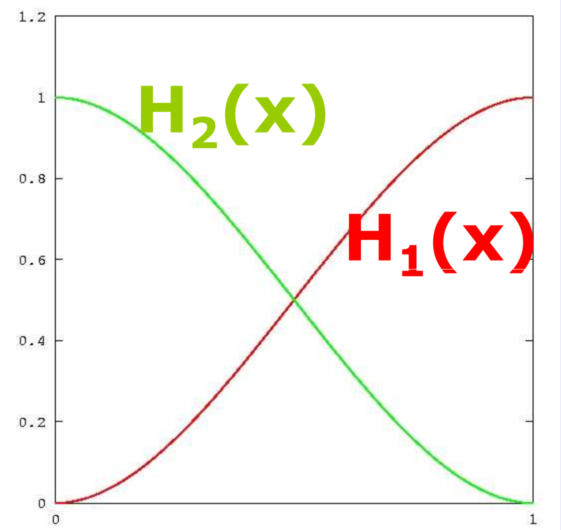
The method is based on using the derivatives of u(x_i ,y_j ,z_k ,t) in the 8 nodes of the cell containing the particles together with the Shape Functions G and H.

Part III

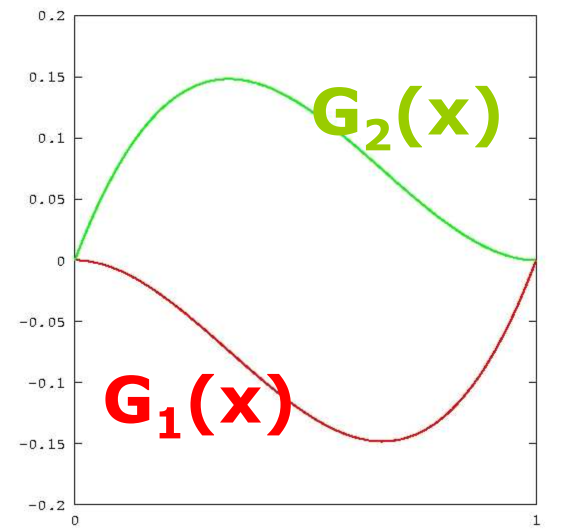


Shape Functions Method

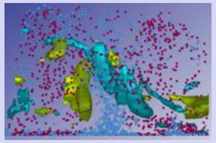
$$H_i(x)=\begin{cases} 0 & x< x_{i-1} \\ \lambda_1(3-2\lambda_1) & x_{i-1}<x< x_i \\ (1-\lambda_2)^2(1+2\lambda_2) & x_i<x< x_{i+1} \\ 0 & x> x_{i+1} \end{cases}$$



$$G_i(x)=\begin{cases} 0 & x< x_{i-1} \\ \Delta x(\lambda_1-1)\lambda_1^{\,2} & x_{i-1}<x< x_i \\ \Delta x(1-\lambda_2)^2\,\lambda_2 & x_i<x< x_{i+1} \\ 0 & x> x_{i+1} \end{cases}$$



Part III



Comparison

Interpolation	Computational Cost	Truncation Error[B]
Linear/Lagr. ord. 2	$24\,\mathrm{M}$	$E_t \propto O(\Delta x)^2$
Shape Function	$96\,\mathrm{M}$	$E_t \propto O(\Delta x)^4$
Lagrangian order 4	$2\cdot(3\cdot 4^3\cdot \mathrm{M})$	$E_t \propto O(\Delta x)^4$
Lagrangian order 6	$2\cdot(3\cdot 6^3\cdot \mathrm{M})$	$E_t \propto O(\Delta x)^6$

Cost ↓

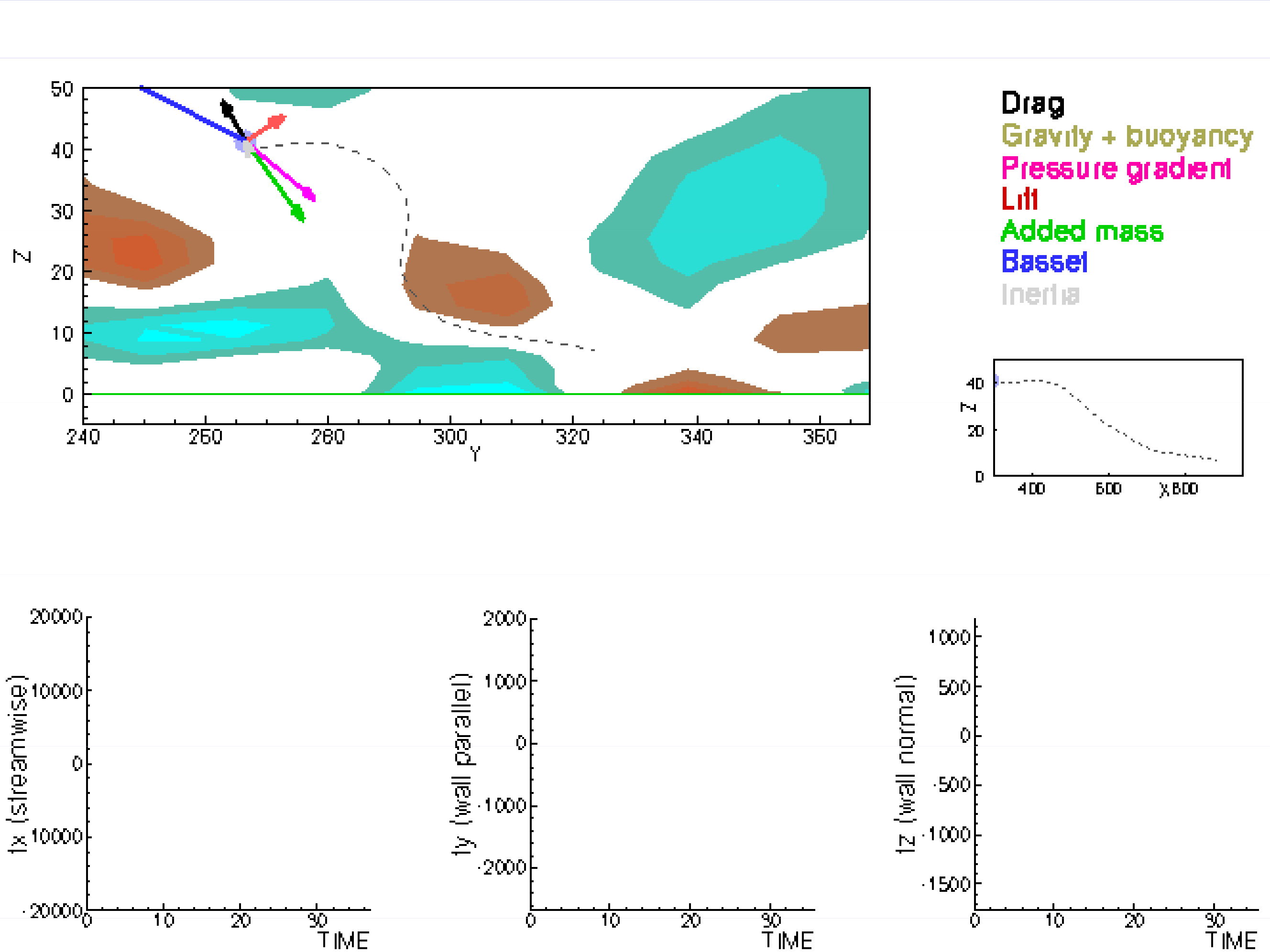
Accuracy ↓

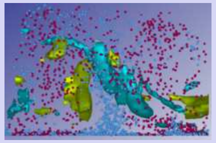
[A] For a number of particles M, the computational cost is given by the number of floating-point operations required to compute the triple sum in Eqs. (1), (2), (3).

[B] The truncation error, defined as the difference between exact and interpolated velocity values, gives an estimate of interpolation accuracy.

Part III

Example of influence of interpolation





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Simple and accurate scheme for fluid velocity interpolation for Eulerian–Lagrangian computation of dispersed flows in 3D curvilinear grids

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Abstract

Particle tracking in turbulent flows in complex domains requires accurate interpolation of the fluid velocity field. If grids are non-orthogonal and curvilinear, the most accurate available interpolation methods fail. We propose an accurate interpolation scheme based on Taylor series expansion of the local fluid velocity about the grid point nearest to the desired location. The scheme is best suited for curvilinear grids with non-orthogonal computational cells. We present the scheme with second-order accuracy, yet the order of accuracy of the method can be adapted to that of the Navier–Stokes solver.

An application to particle dispersion in a turbulent wavy channel is presented, for which the scheme is tested against standard linear interpolation. Results show that significant discrepancies can arise in the particle displacement produced by the two schemes, particularly in the near-wall region which is often discretized with highly-distorted computational cells.

1. Introduction

The interpolation of a field computed over a discrete grid is required to know the field values in physical points not coinciding with the grid nodes. In the specific case of applications which involve flows with dispersed species, solid particles, droplets or bubbles, best-suited simulations are those based on the Eulerian–Lagrangian approach which, at the ever-decreasing price of a larger computational effort, grants easy coding and reliable representation of the physics. In this approach, accurate Lagrangian tracking of the dispersed phase requires accurate interpolation of the Eulerian carrier flow field.

In previous papers focused on dispersed flows, several interpolation methods (among others: hybrid Lagrange/Chebyshev polynomials; cubic splines and quadratic interpolation) were used by many researchers [1–6] in simple geometries such as channels, pipes and boundary layers, in which the Eulerian grid was Cartesian and uniform in two directions (for further details see the review by Soldati [7]).

However, if the physical problem is such to require non-uniform and non-Cartesian grids for discretization of complex and irregular flow domains, interpolation may not be straightforward and may lead to inaccuracies. Recently, we had to face this issue in the frame of our work on particle/droplet deposition and entrainment over a wavy interface [8], which mimics the dynamics of the droplets sprayed over capillary waves at the ocean/atmosphere interface.

While literature interpolation techniques (viz. spectral, partial Hermite, Lagrangian, shape function methods, cubic splines, etc.) have been extensively studied and

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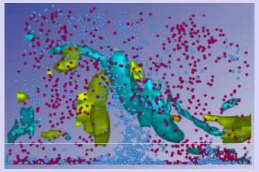


Refreshing the memory…
same concepts folded and unfolded differently…

- **What we will learn in today lecture:**

1 **Modelling/Simulation approaches (We will refresh some of the early concepts)**

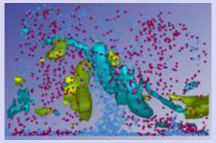
2 **If we know the flow field at discrete points (Simulations), which fluid velocity will we use?**

3 **How Flow Structures in Boundary Layers control Deposition/Entrainment?**

4 **Measuring Particle Segregation/Dispersion**

5 **Update on Homeworks and Project.**

•1 Interactions of Inertial Particles and Coherent Structures;
\>> From Microscale Interaction to Macroscale Effects.



Examples of Particle/Structure Interaction

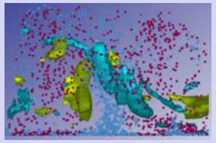
1. Turbulent Boundary Layer

   >> Particle Trapping in the wall region.

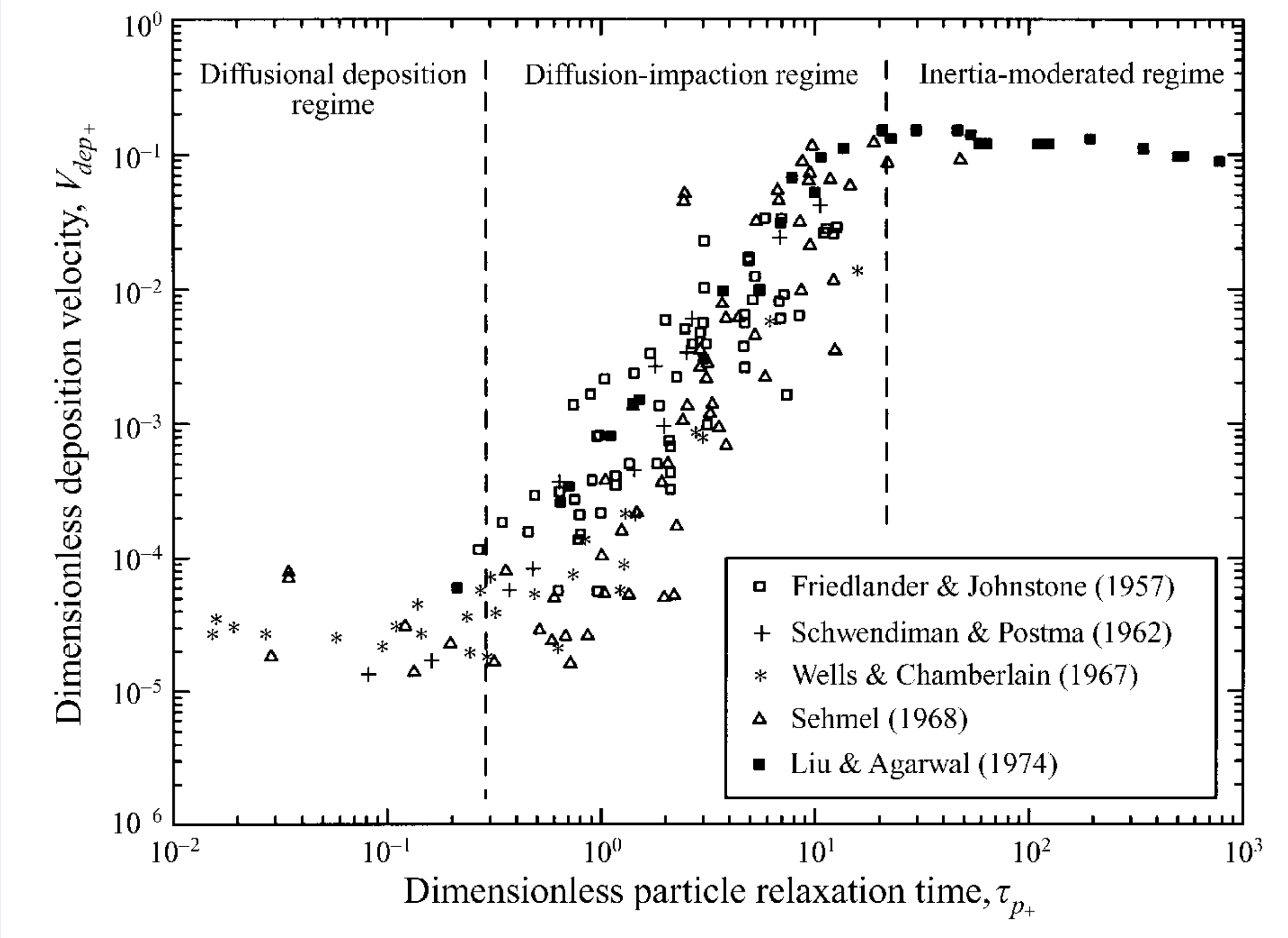
2. Confined Jet

   >> Selective Mechanisms for particle radial dispersion

Part III

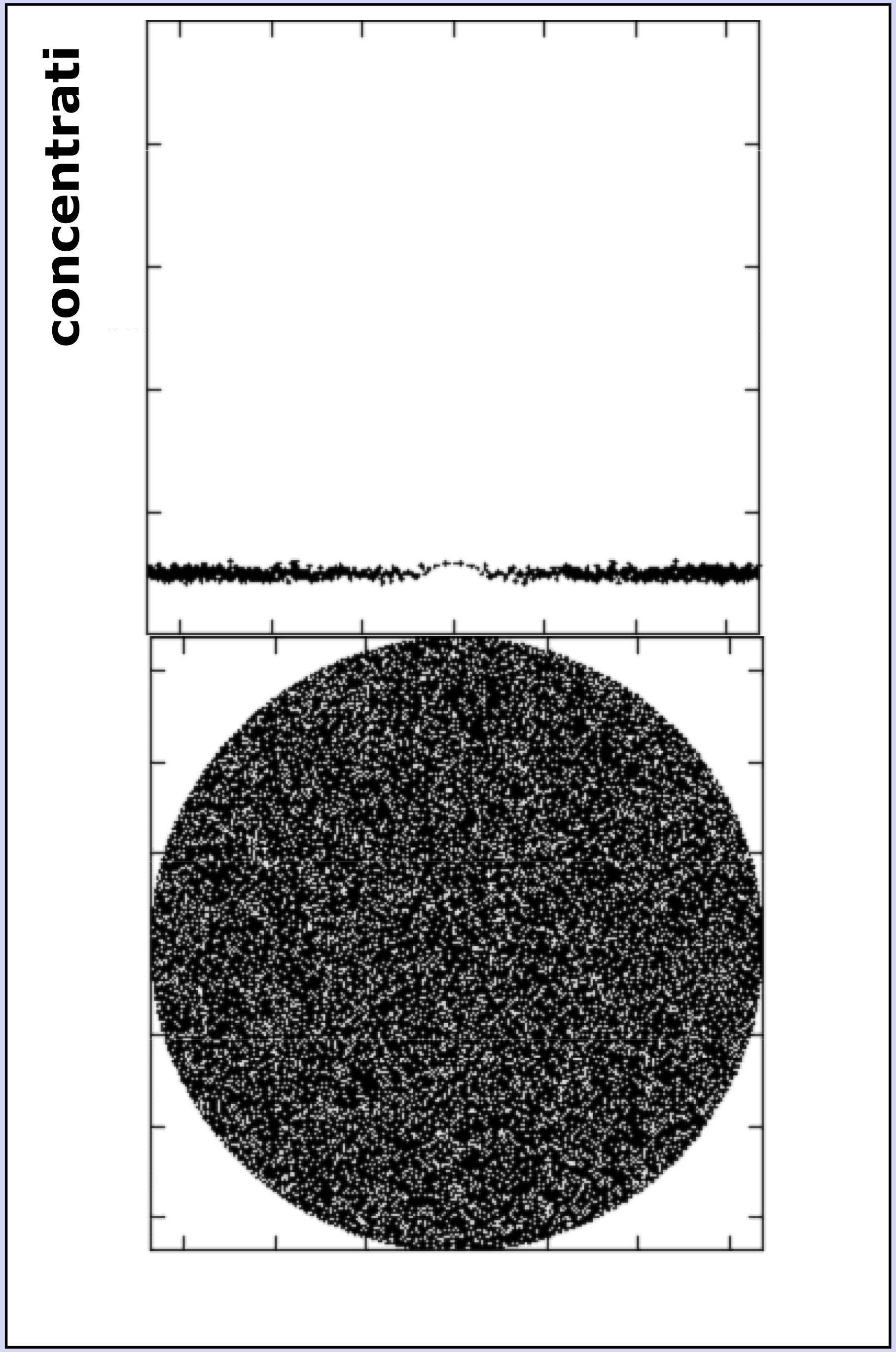


Just to remind you a motivation…
Status of Experimental Data on Particle Wall Deposition….
Uncertainty -> Orders of magnitude…

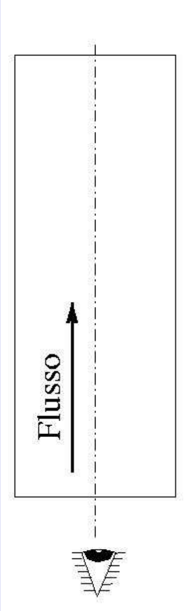


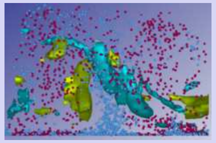
Wall Segregation in Pipe flow

(Cfr. Young & Hanratty, *AIChEJ*, 1993)

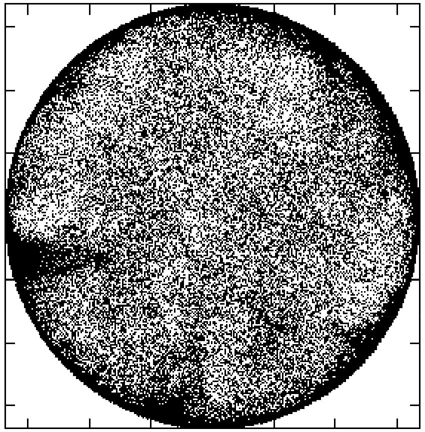


$\tau_p^+ = 2.8$

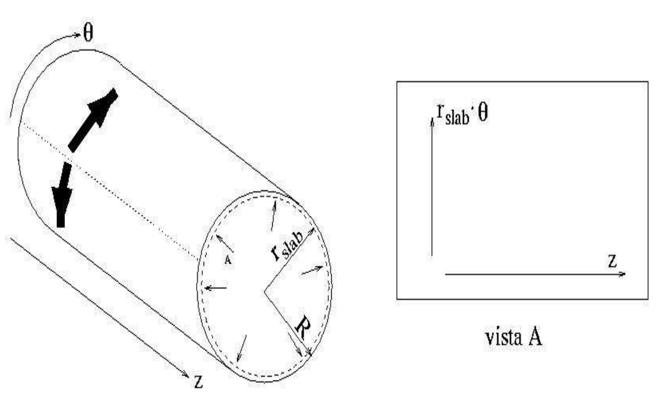


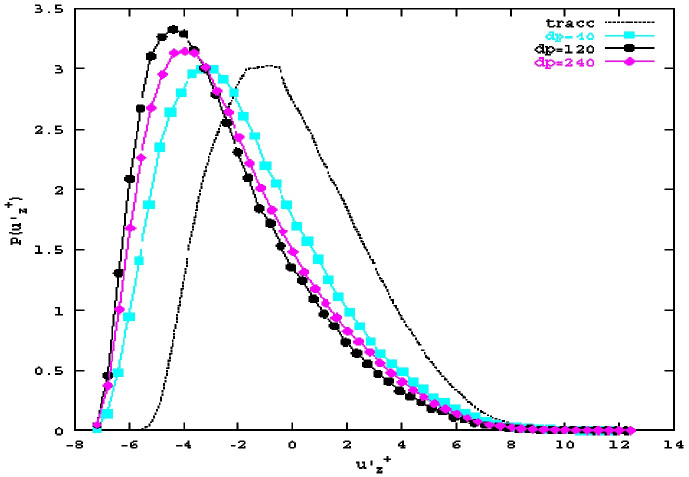


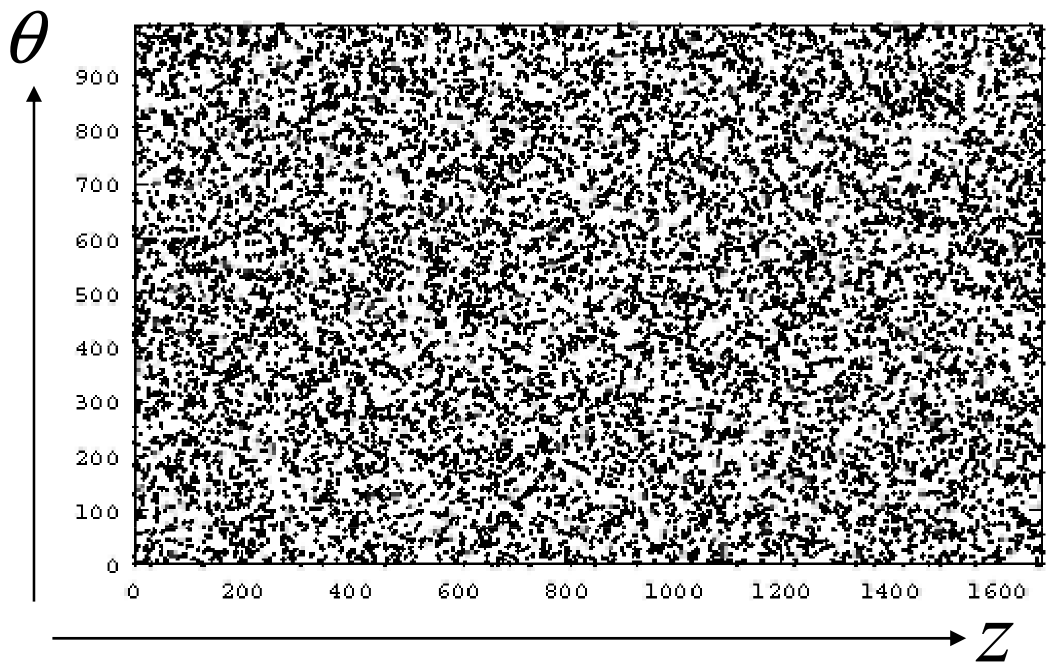
1. Turbulent Boundary Layer: From microscale phenomena to Macroscale Effects

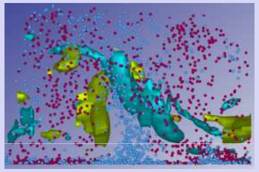


Look Closer:
In the Pipe,
once at the wall, particles segregate into low-speed regions

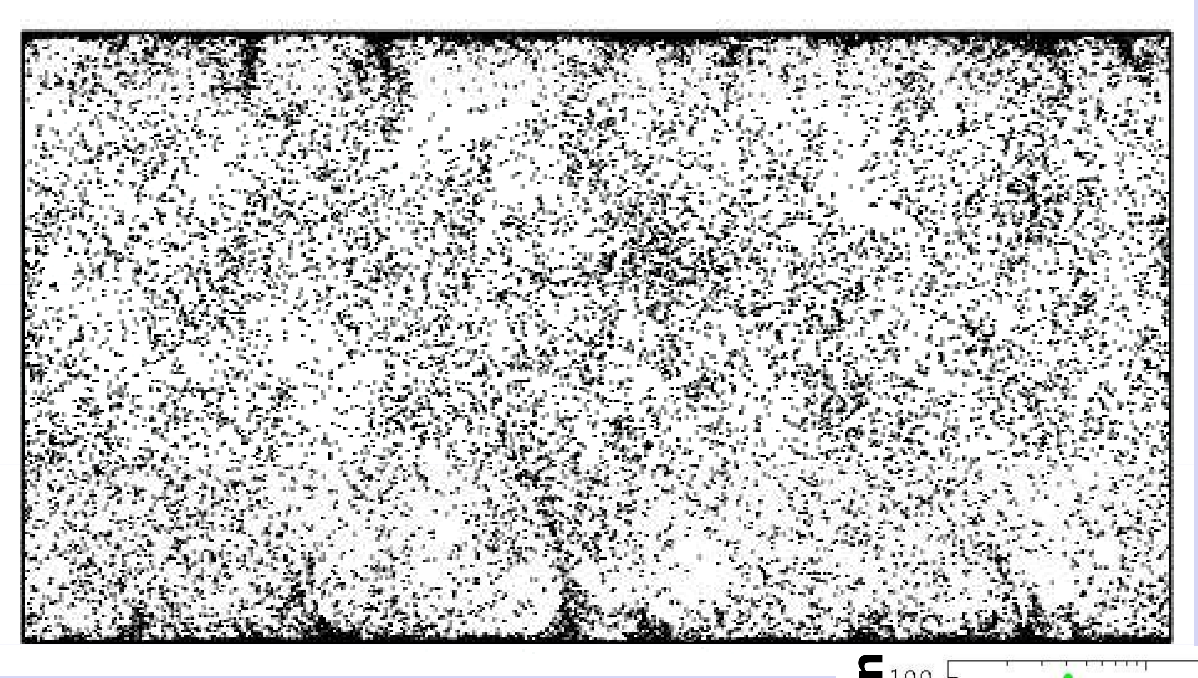








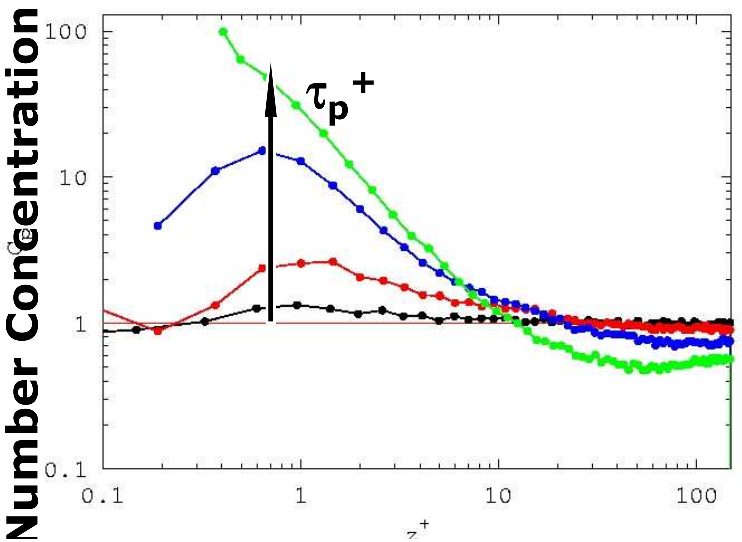
This is the typical result of our computational experiments!



Observation –

In Bounded flows particles accumulate at the wall at different rates depending on their inertia (forces:drag and inertia)

Accumulation at the wall is turbulence induced and non uniform. Phenomenon will persist from a qualitative viewpoint until gravity will dominate (large particles)

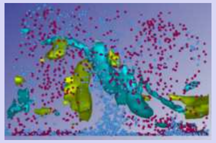


$\tau_p^+ = 25$

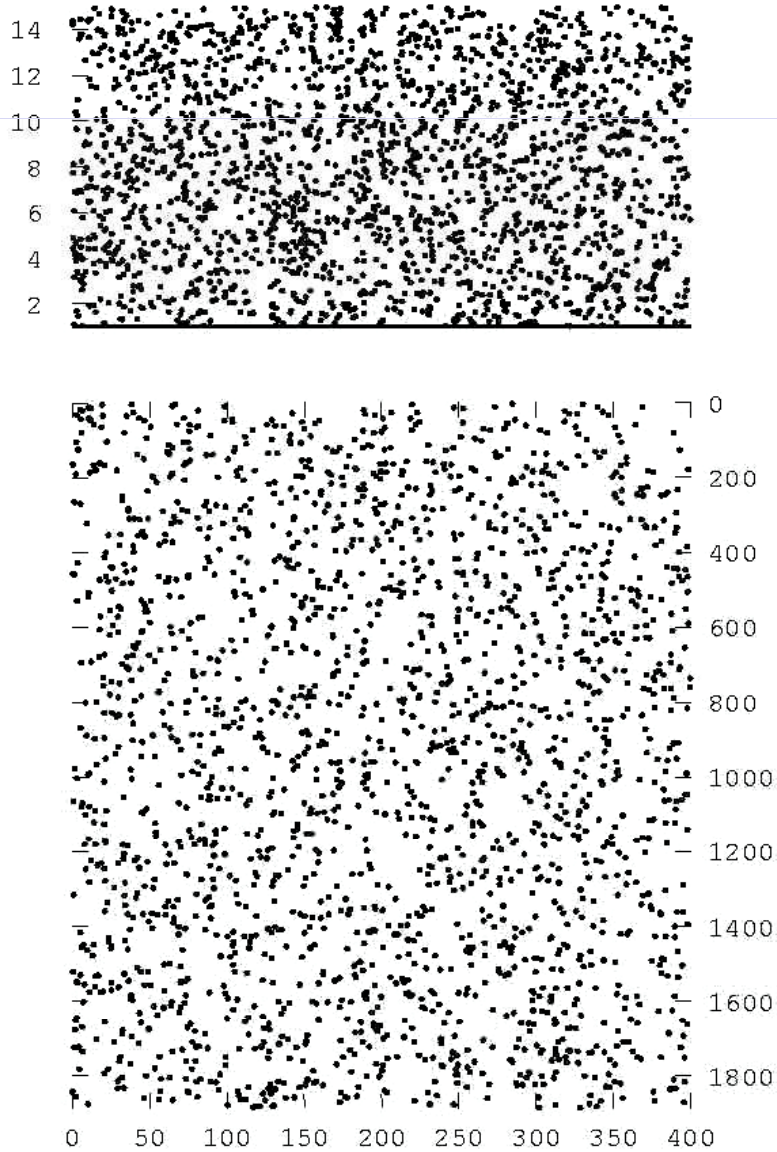
$\tau_p^+ = 5$

$\tau_p^+ = 1$

$\tau_p^+ = 0.2$



1. Turbulent Boundary Layer: From microscale phenomena to Macroscale Effects

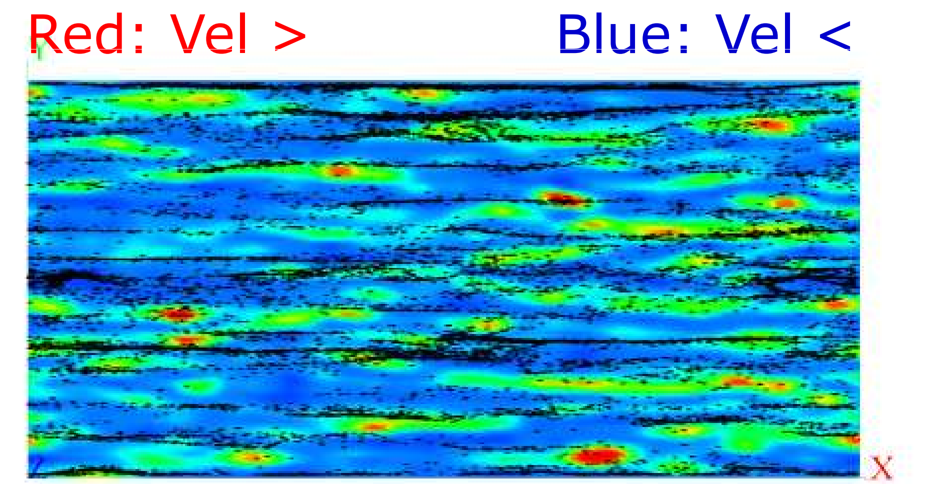


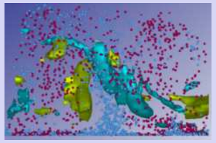
Front View

$\tau_p^+ = 25$

Look Closer: Particle in the Channel, ***once at the wall, segregate into low-speed regions***

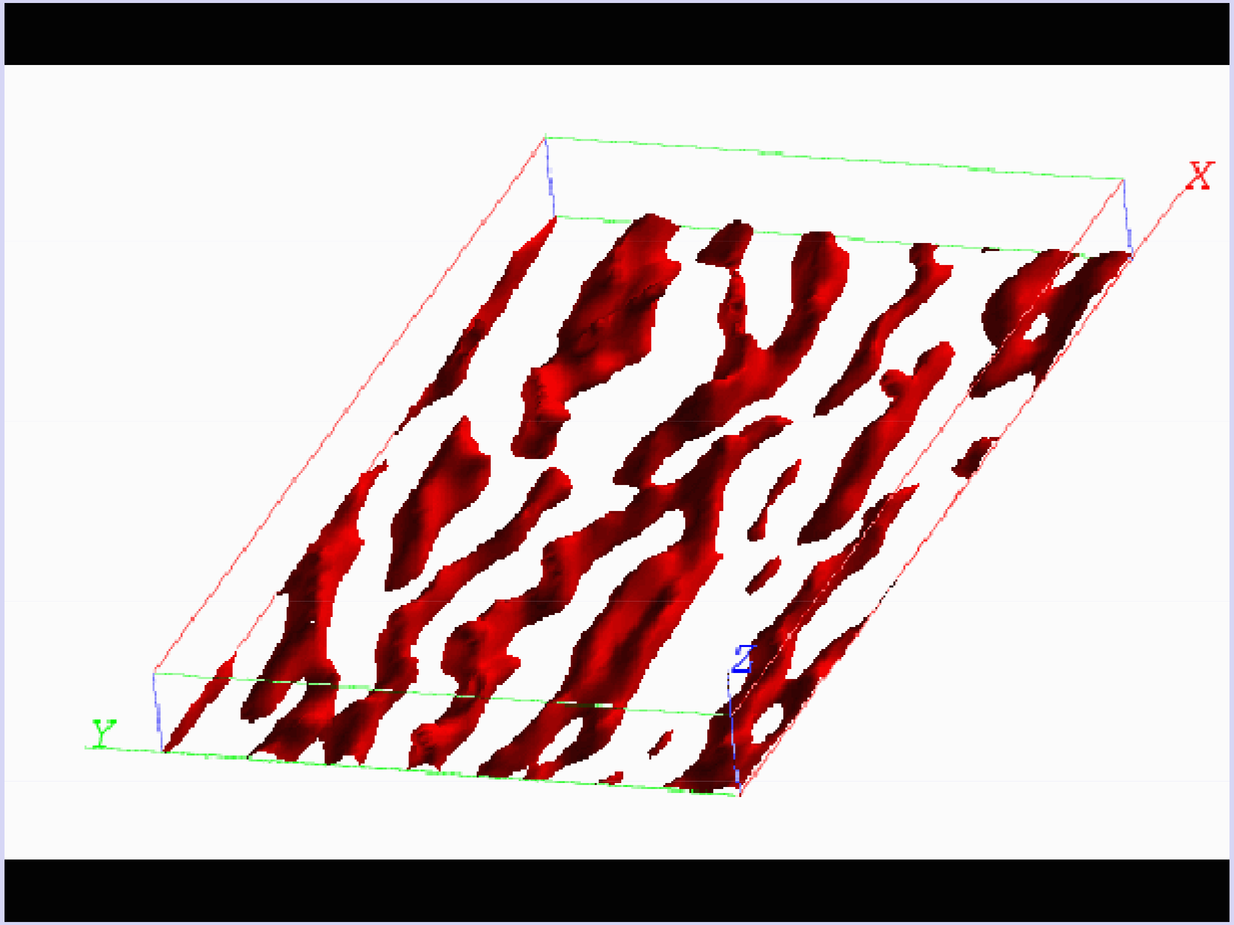
Top View





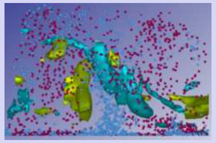
1. Turbulent Boundary Layer: From microscale phenomena to Macroscale Effects

What are the Low Speed Streaks? Consider an isosurface of Streamwise velocity u=0.56 Uc



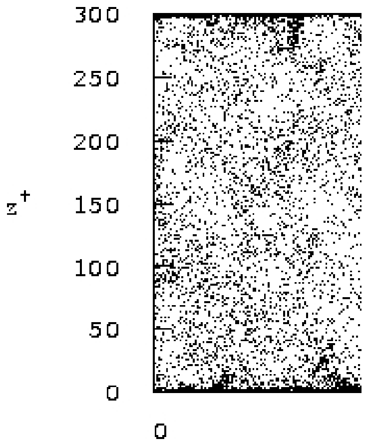
Red: Low-Speed Streamwise Streaks

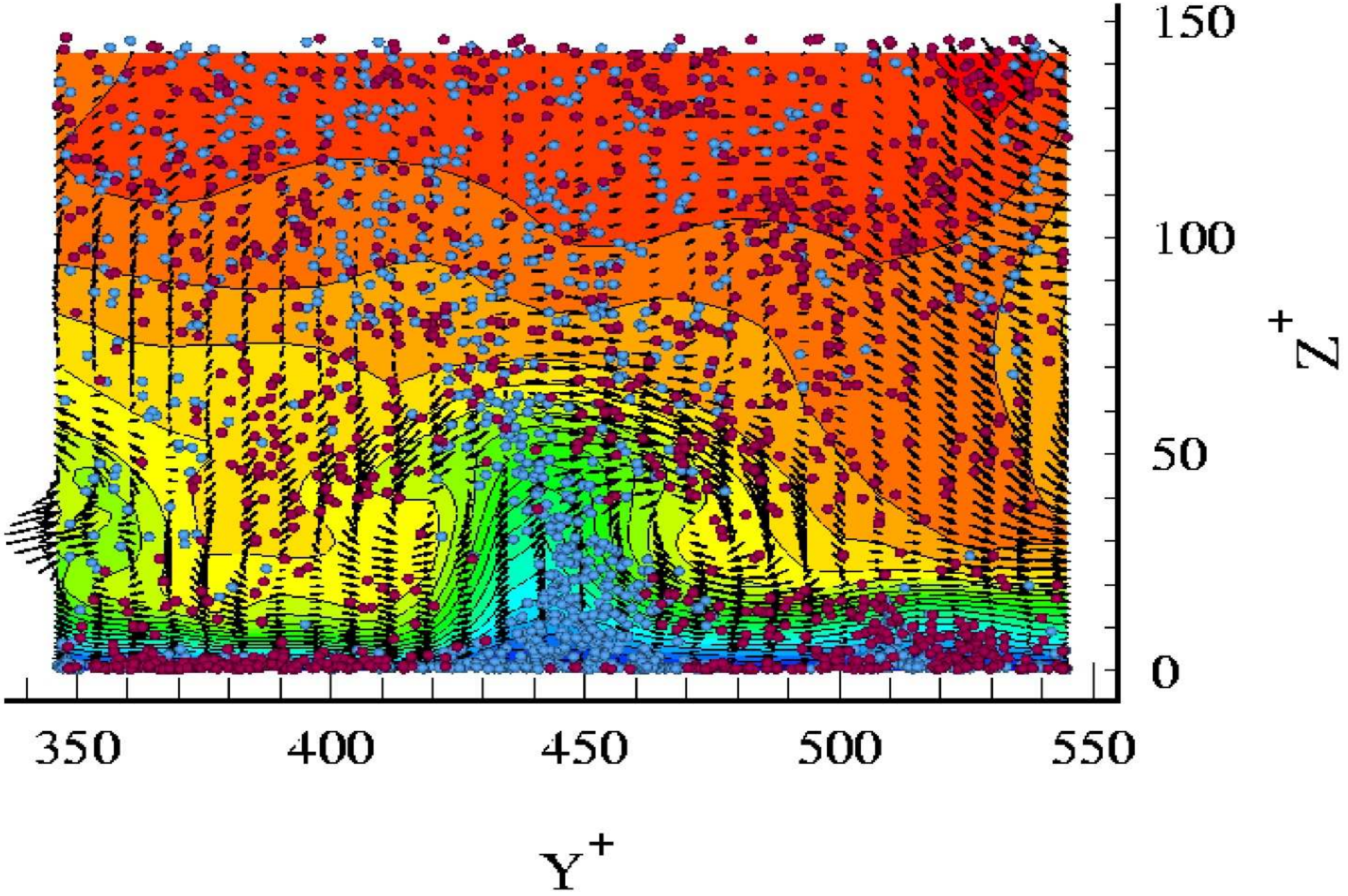
Part III



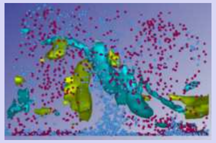
1. Turbulent Boundary Layer:
From microscale phenomena to Macroscale Effects

Observation – The same thing that generates the Low-Speed Streaks controls particle Transfer and segregation





Red: high Streamwise vel.
Blue: low Streamwise vel.
Purple Particles: To the wall
Blue Particles: off the wall



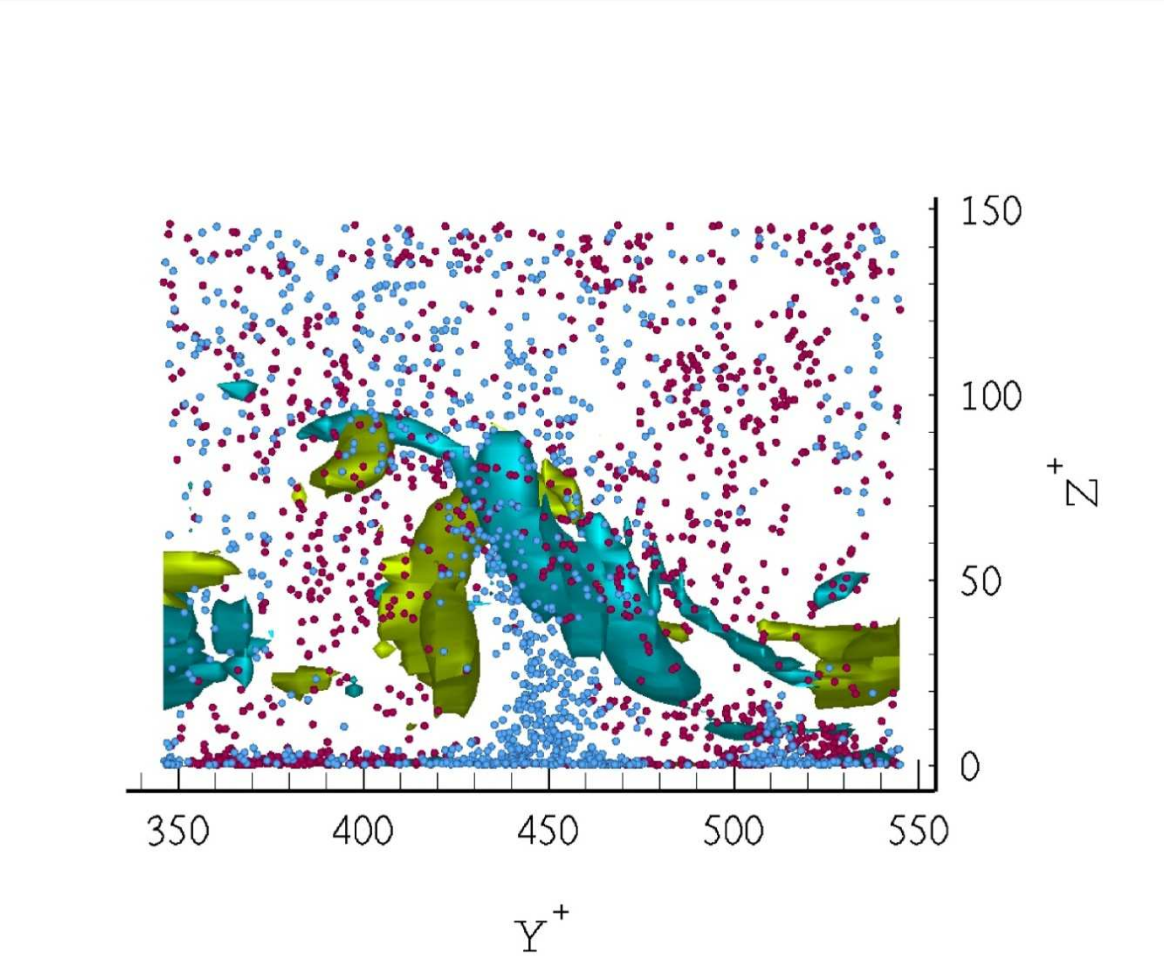
Conclusion –
Wall structures dominate particle wall transfer fluxes

Green:
CounterCLKWS
Rotating Quasi Strmws
Vortex (ω_x)

Blue:
CLKWS
Rotating Quasi Strmws
Vortex (ω_x)

Red:
Particles Approaching the Wall

Pale Blue:
Particles Leaving the Wall



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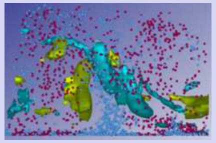
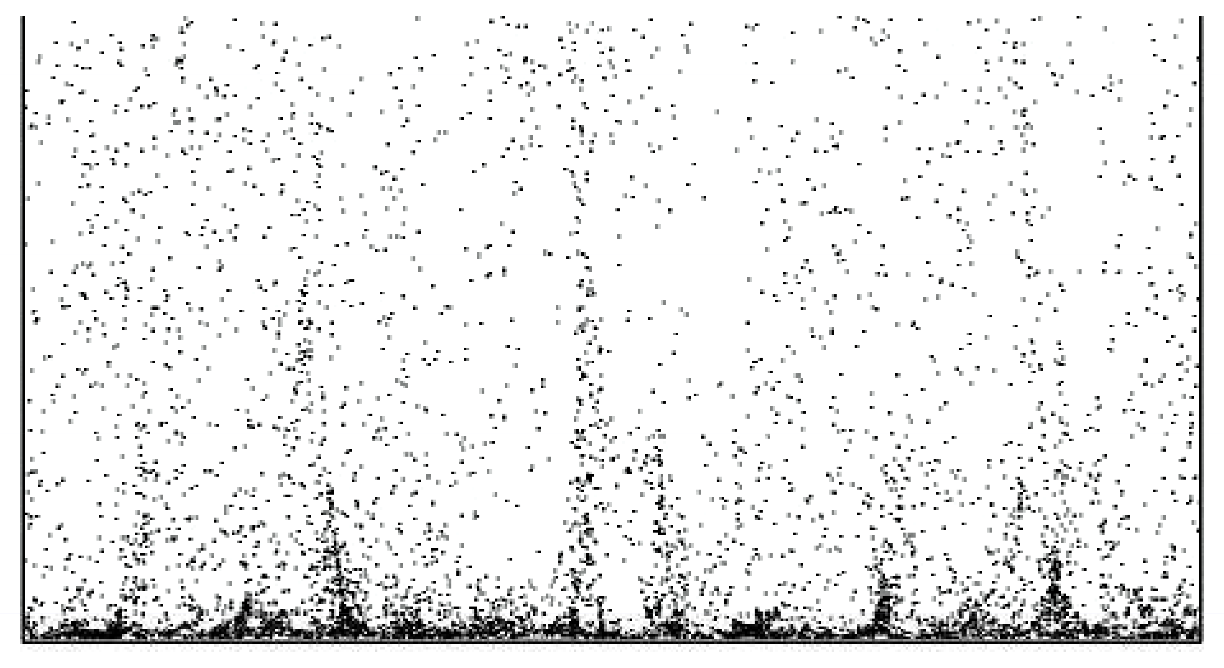


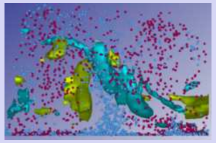
1. Turbulent Boundary Layer: From microscale phenomena to Macroscale Effects

Conclusion –
Wall structures dominate particle wall transfer fluxes



Close up (z+ < 50) of the buffer region of the TBL.
$\tau_p{}^+=25$ particles under (Drag Force Only) are effectivelyTransferred by Coherent Structures

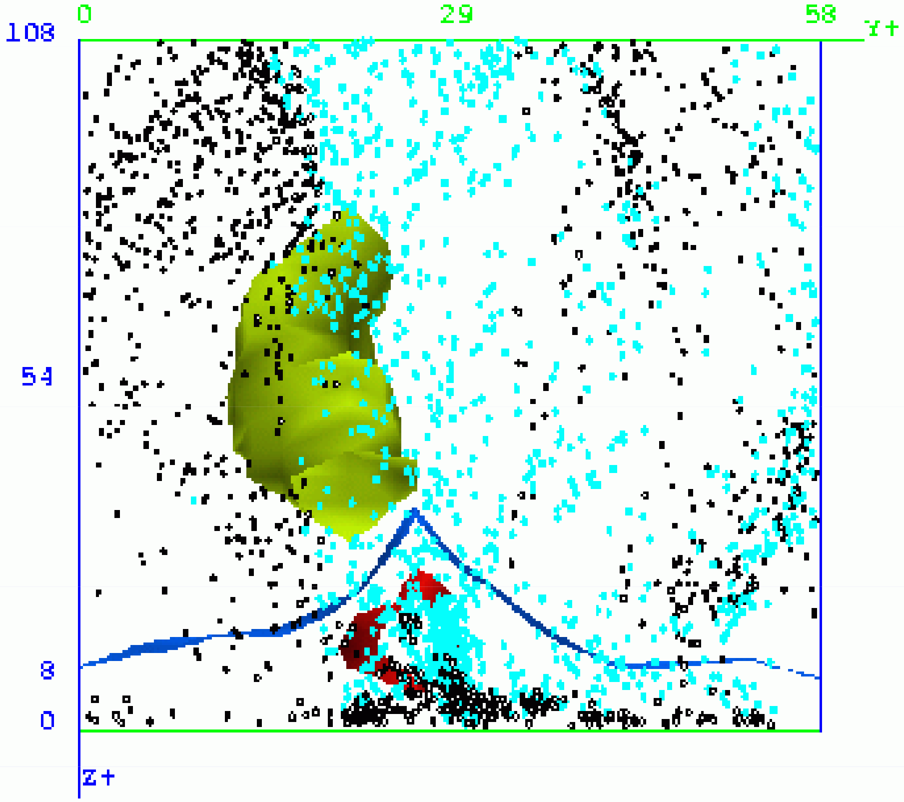
Part III

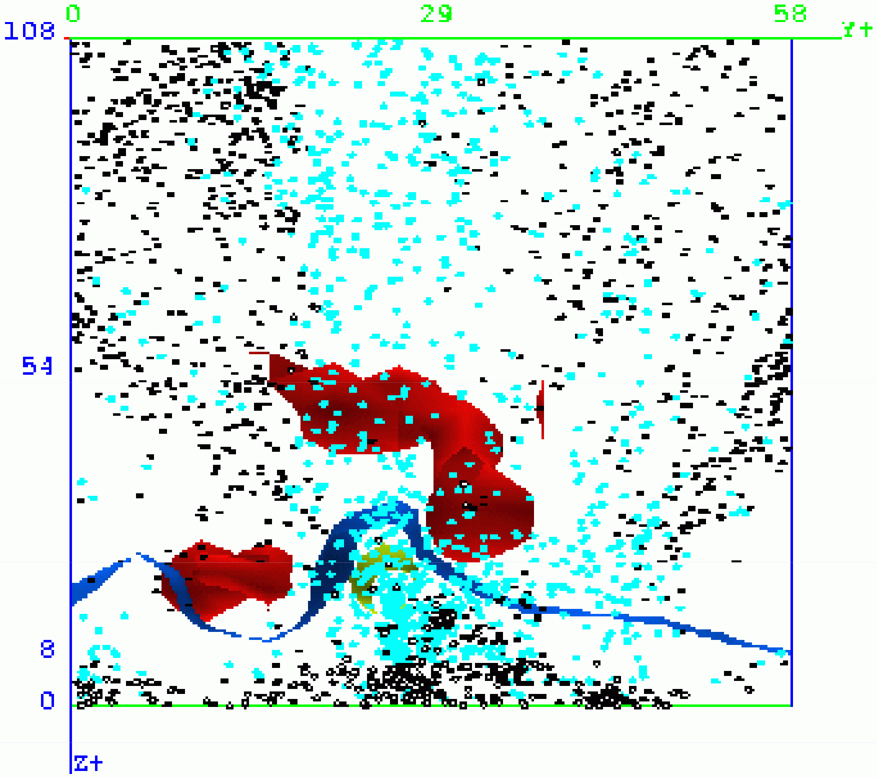


1. Turbulent Boundary Layer:
From microscale phenomena to Macroscale Effects

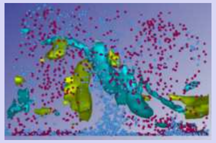
Snapshot of Inertial Particles and Wall Structures.1.

Back ⇒ to the wall Blue ⇒ off the wall Circles ⇒ Neglig. Vel.

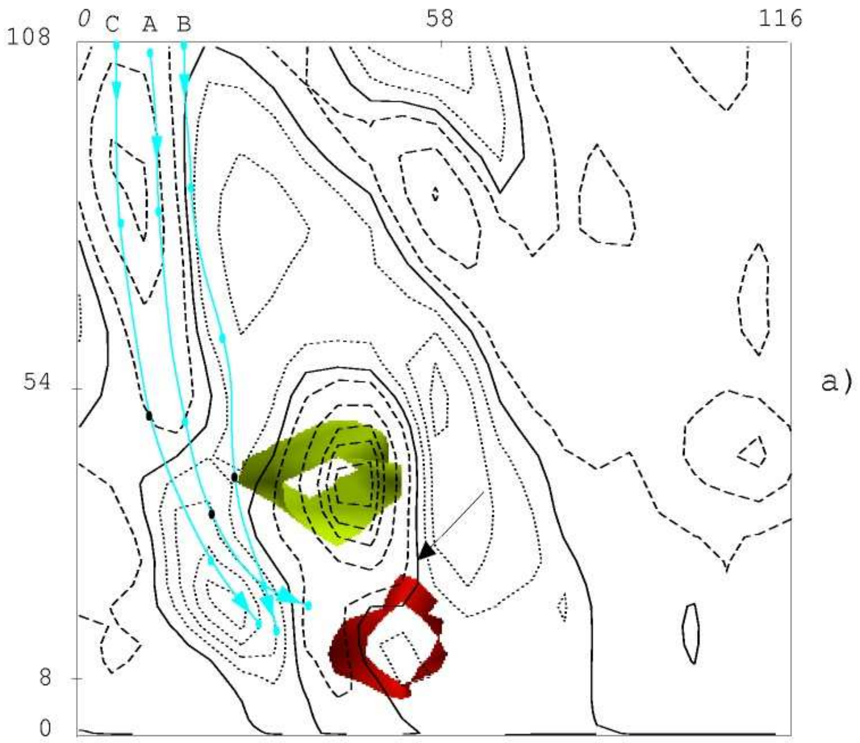


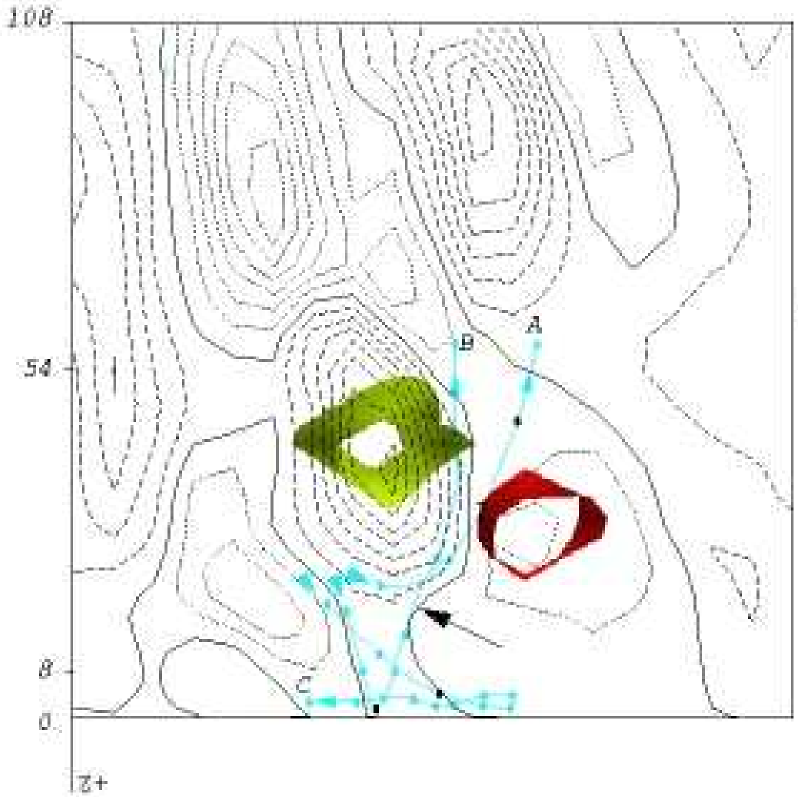


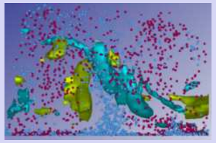
Blue ribbon ⇒ LSS Green ⇒ Clckws vort Red ⇒ Cnt Clckws vort



Snapshot of Inertial Particles and Wall Structures.2. Preceeding vortex tail forbid ejection area to some particles

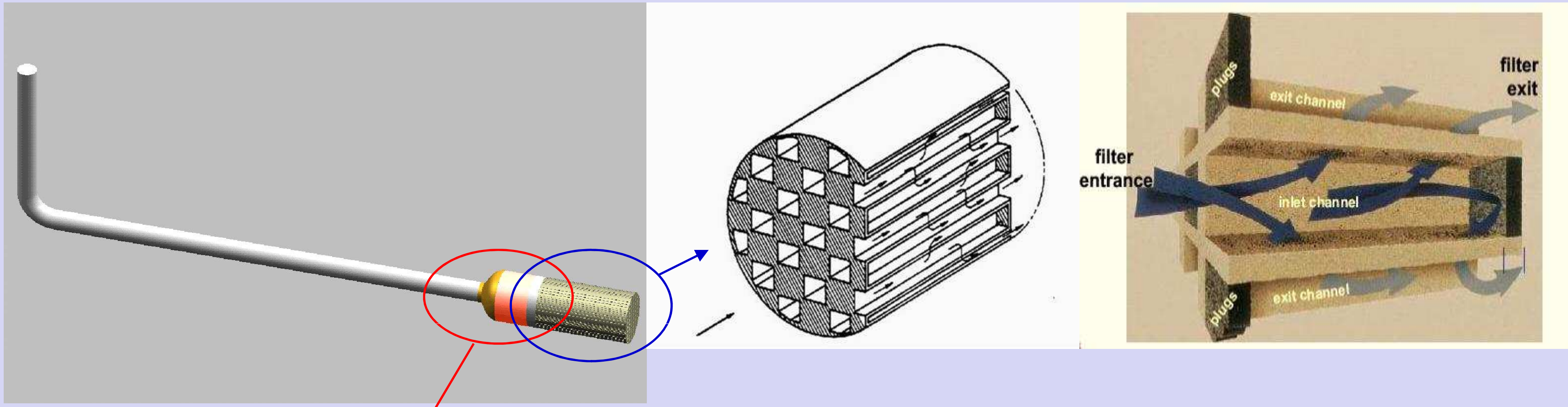


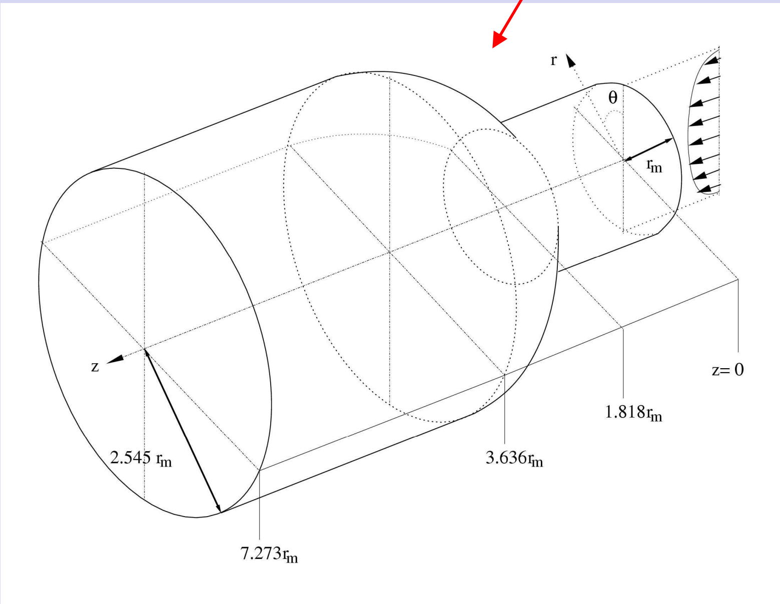




2. Bounded Jet:
From microscale phenomena to Macroscale Effects

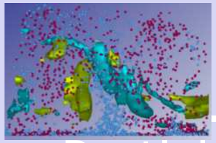
Motivation and Flow Geometry: Diesel Exhaust Filtering System





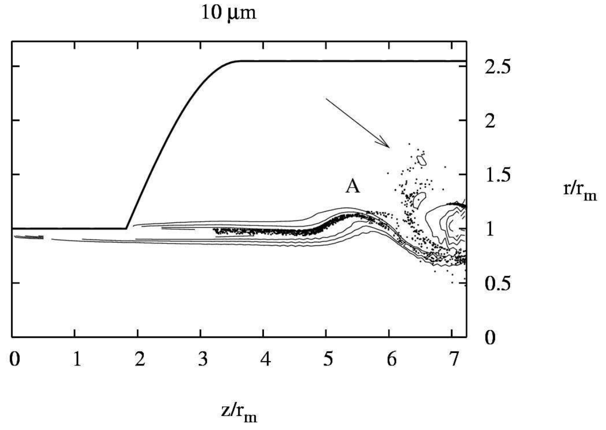
Numerical study, using Large-Eddy Simulation (LES) of a diffuser placed in the exhaust line of a Diesel vehicle. Evaluation of particle dispersion upstream and inside the (wall-flow) particulate filter through Lagrangian tracking of particles.

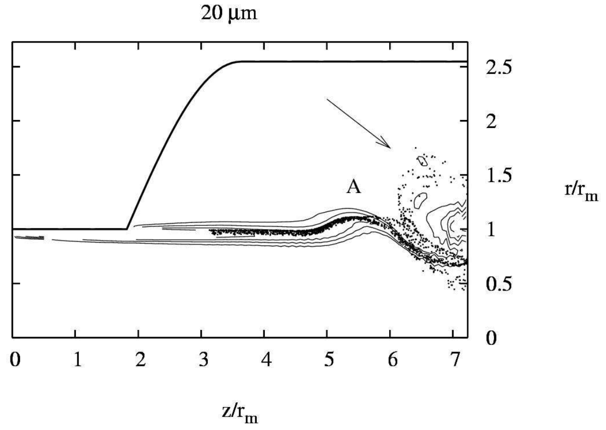
Part III

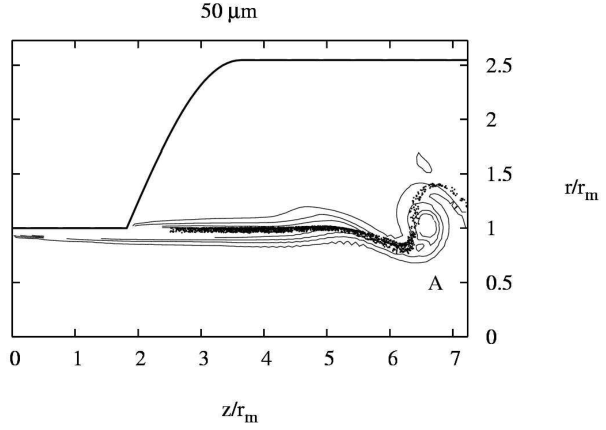


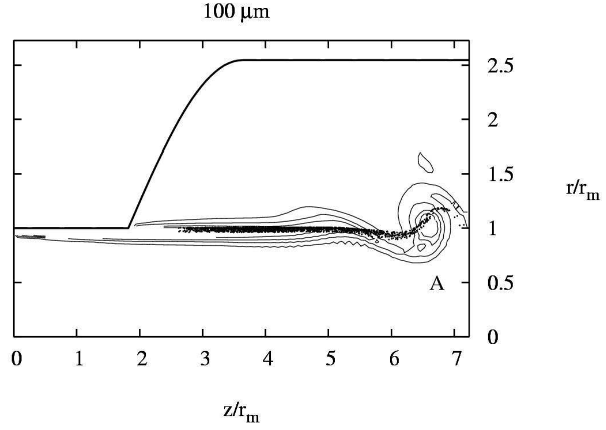
2. Bounded Jet:
From microscale phenomena to Macroscale Effects

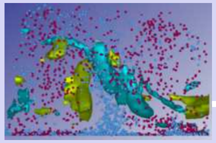
Particles undergo selective Radial Dispersion due to their different inertia


10 μm


20 μm

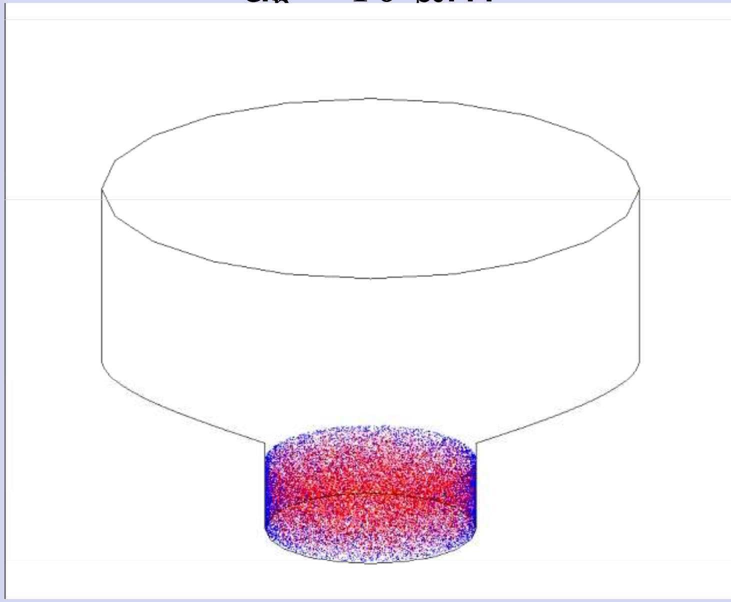

50 μm


100 μm

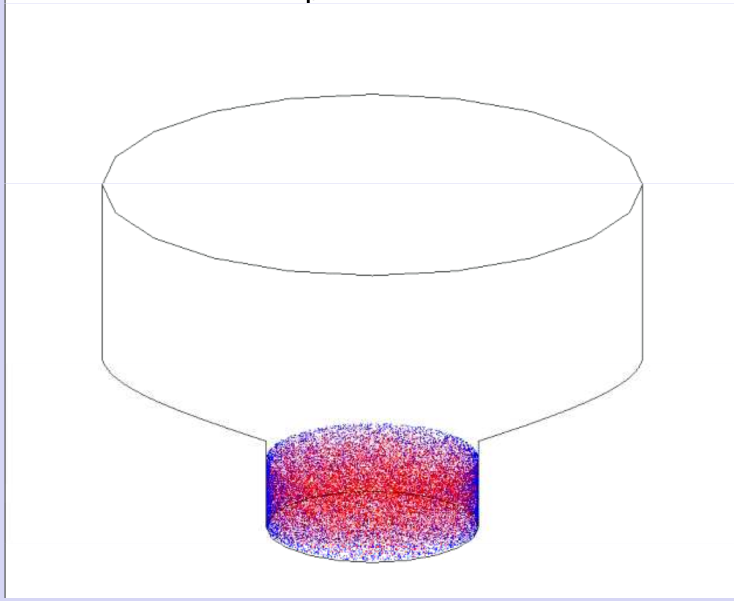


2. Bounded Jet: From microscale phenomena to Macroscale Effects

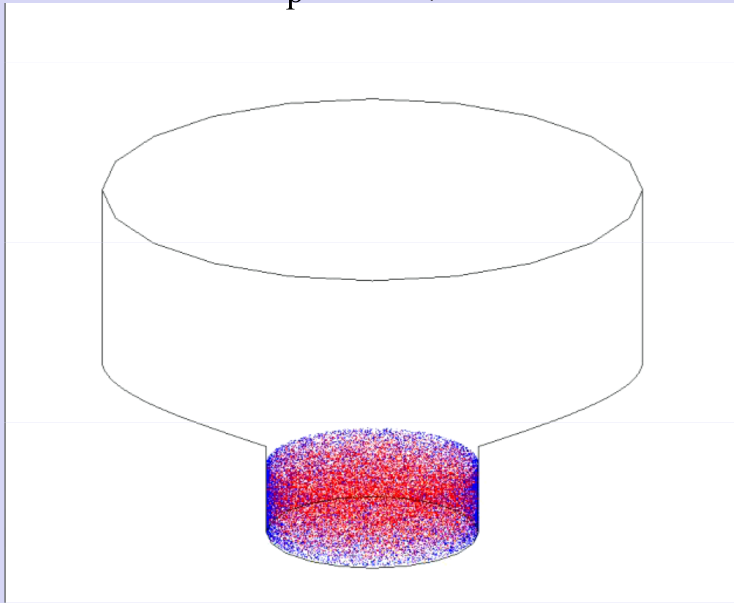
$d_p = 10\ \mu m$



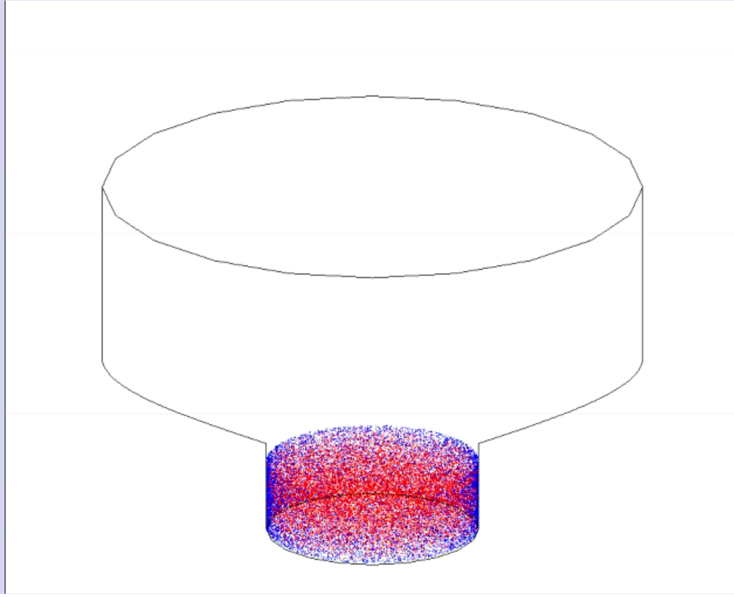
$d_p = 20\ \mu m$



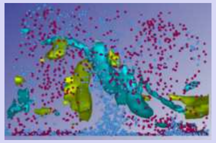
$d_p = 50\ \mu m$



$d_p = 100\ \mu m$

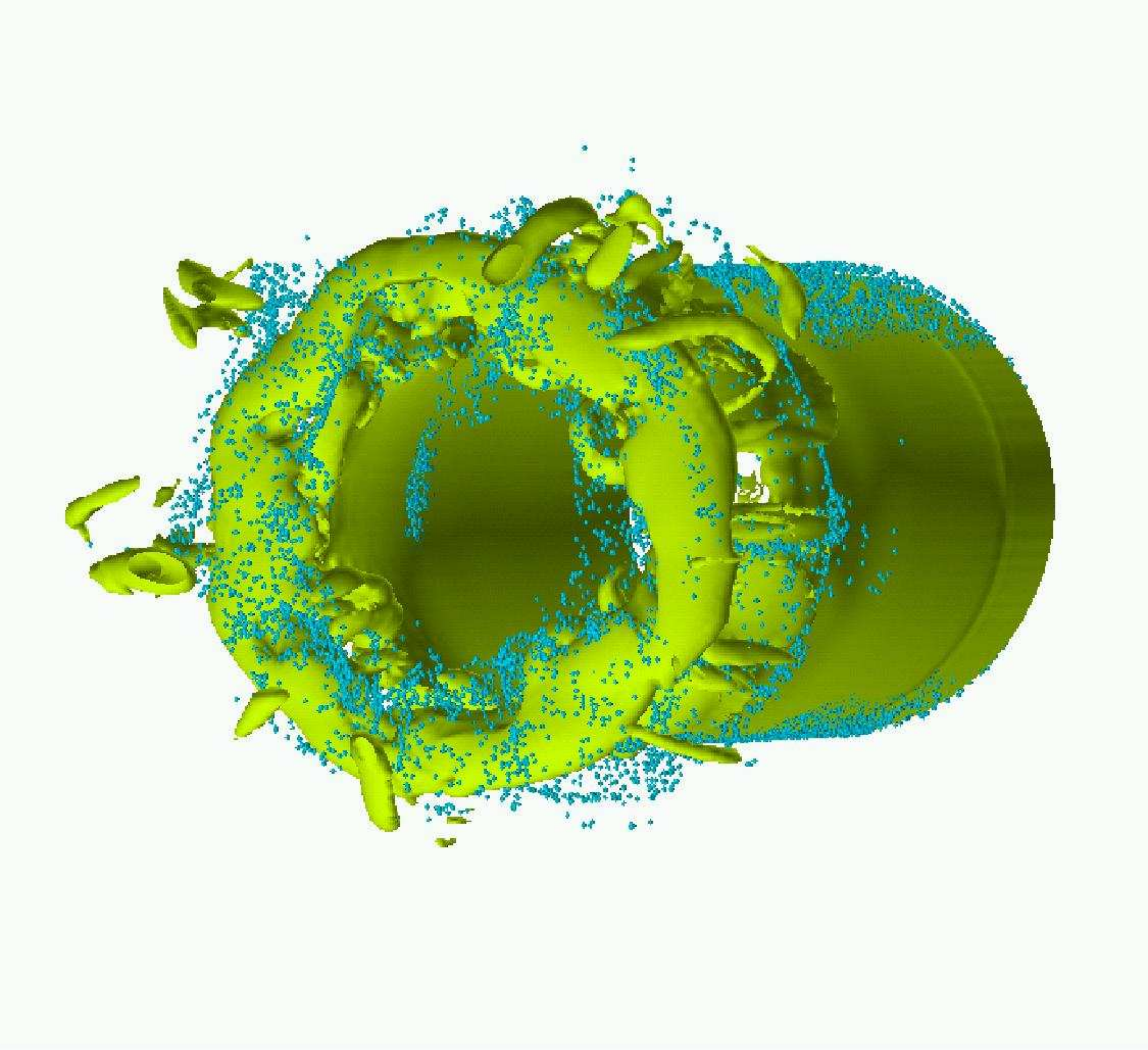


Particles (Blue: Pipe boundary layer; Red: Pipe bulk flow) undergo different dispersion mechanisms due to their different inertia. Larger particles are entrained by larger vortices only; Smaller particles are entrained by

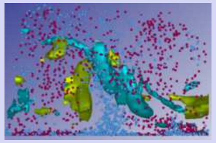


2. Bounded Jet:
From microscale phenomena to Macroscale Effects

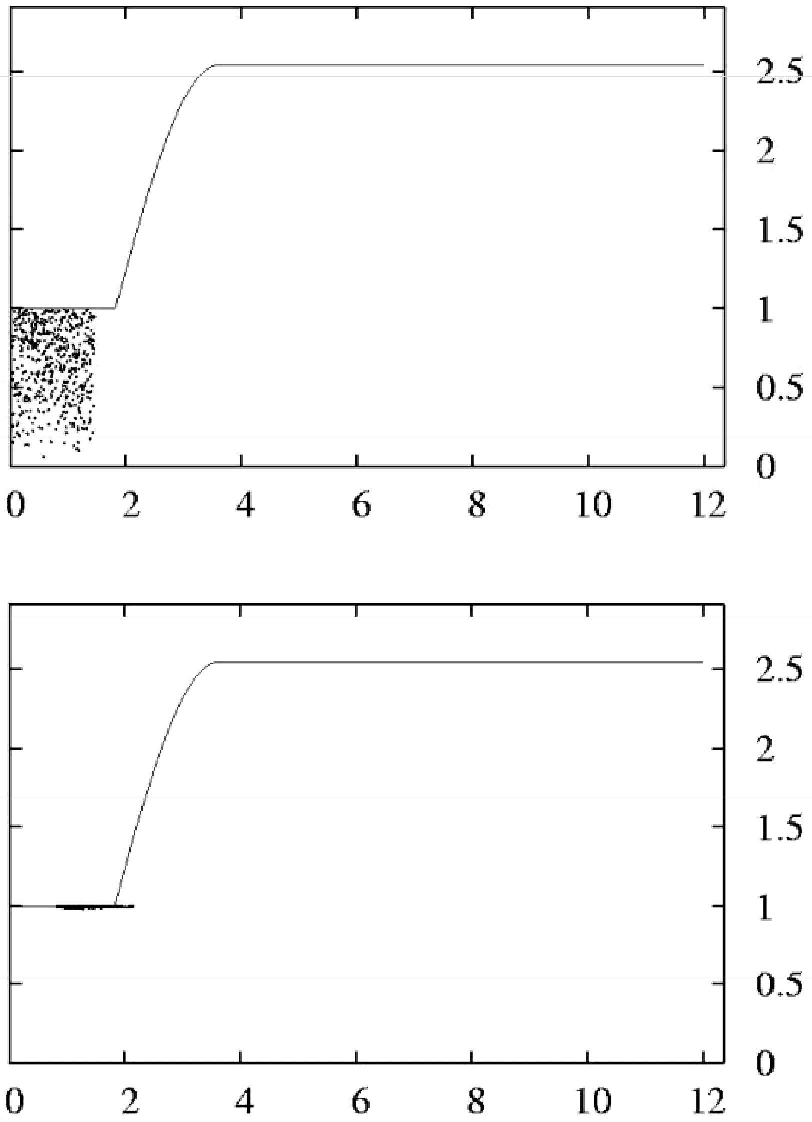
Interaction among small particles (10 μm) and all flow structures characterized by vorticity modulus.



Part III



2. Bounded Jet: Particle behavior



INNER PARTICLES

follow initially the jet core.

Entrainment in the shear-layer.

Large dispersion in the outer region.

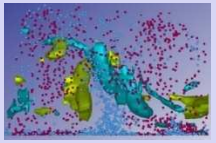
OUTER PARTICLES

Follow the shear-layer foldup.

After pairing, vortex dissociates into smaller structures.

Annular ***CLUSTERS*** observed.

Larger dispersion generated by **LOCALLY GENERATED TURBULENCE** and NOT by upstream-generated (inlet) turbulence



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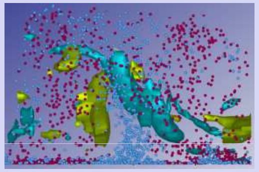
Part III



Refreshing the memory…
same concepts folded and unfolded differently…

- **What we will learn in today lecture:**

1 Modelling/Simulation approaches (We will refresh some of the early concepts)

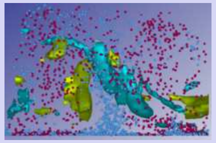
2 If we know the flow field at discrete points (Simulations), which fluid velocity will we use?

3 How Flow Structures in Boundary Layers control Deposition/Entrainment?

4 Measuring Particle Segregation/Dispersion

5 Update on Homeworks and Project.

1 Measurements of particle preferential distribution;
>> Examples in Archetypal Flows



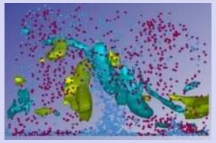
Particle clustering

Objectives:

1. Measure non homogeneity in particle distribution

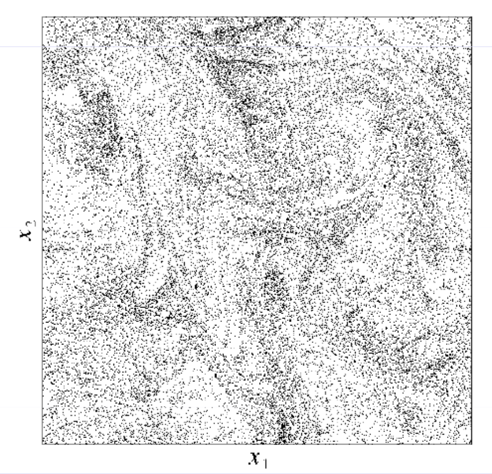
2. Understand non homogeneity in particle distribution

→ Identify parameters to control particle distribution…

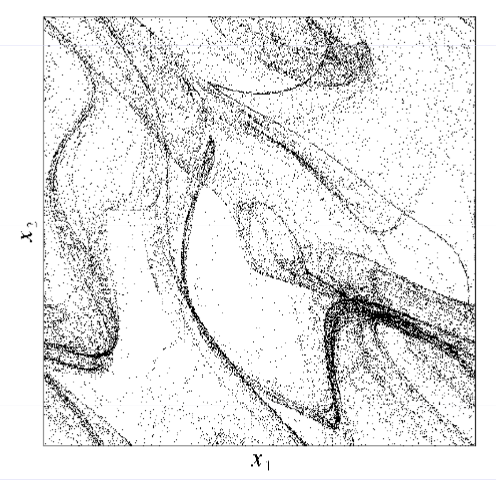


Small-scale particle clustering (Bec et al.,2004)

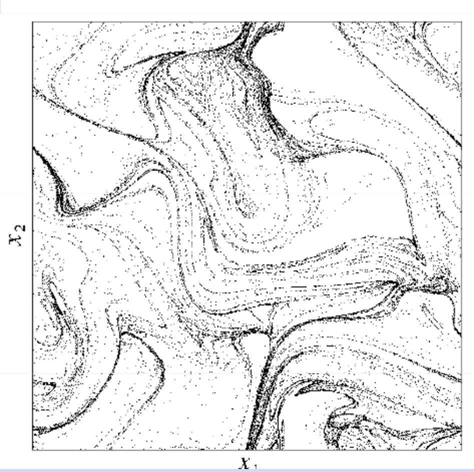
Observation



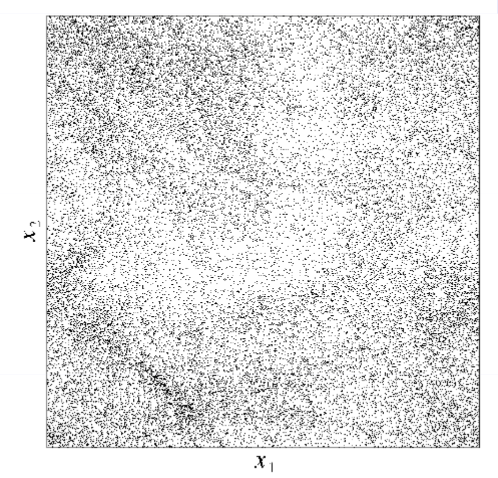
St=10^{-3}



St=10^{-2}



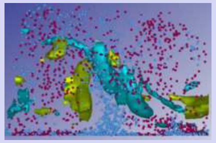
St=10^{-1}



St=1

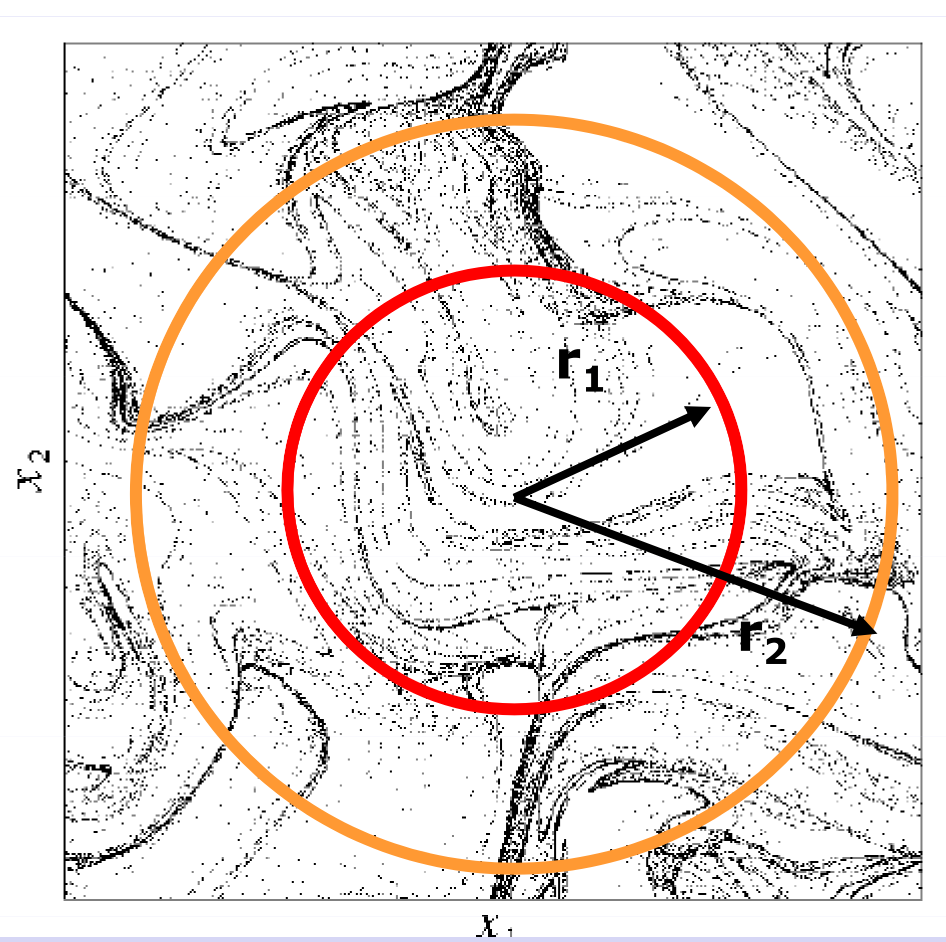
Particle distribution in 2-D turbulent flow is NOT homogeneous

How much?



Measuring clustering:1. Correlation dimension

Ref: Grassberger & Procaccia, Physica D, 1984



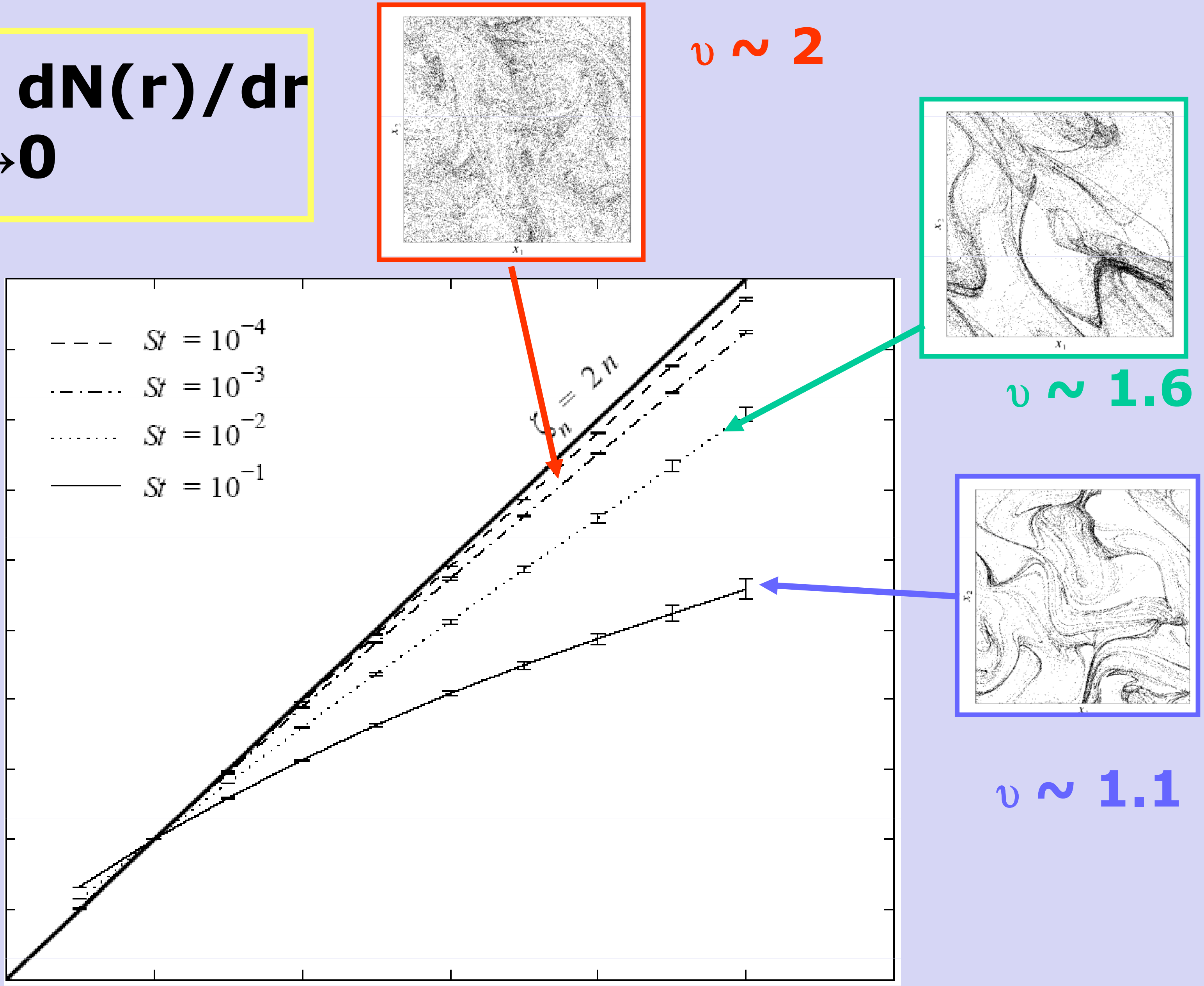
The number of particles in a sphere of radius r identifies the Fractal dimension of the sub-space where particles cluster

$$N(r) \propto r^{\upsilon}$$

$$\upsilon = \lim_{r \to 0} dN(r)/dr$$

υ = **correlation dimension**

$$\upsilon = \lim_{r \to 0} dN(r)/dr$$



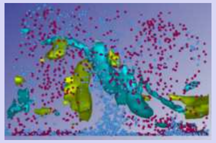
$\upsilon \sim 2$

$\upsilon \sim 1.6$

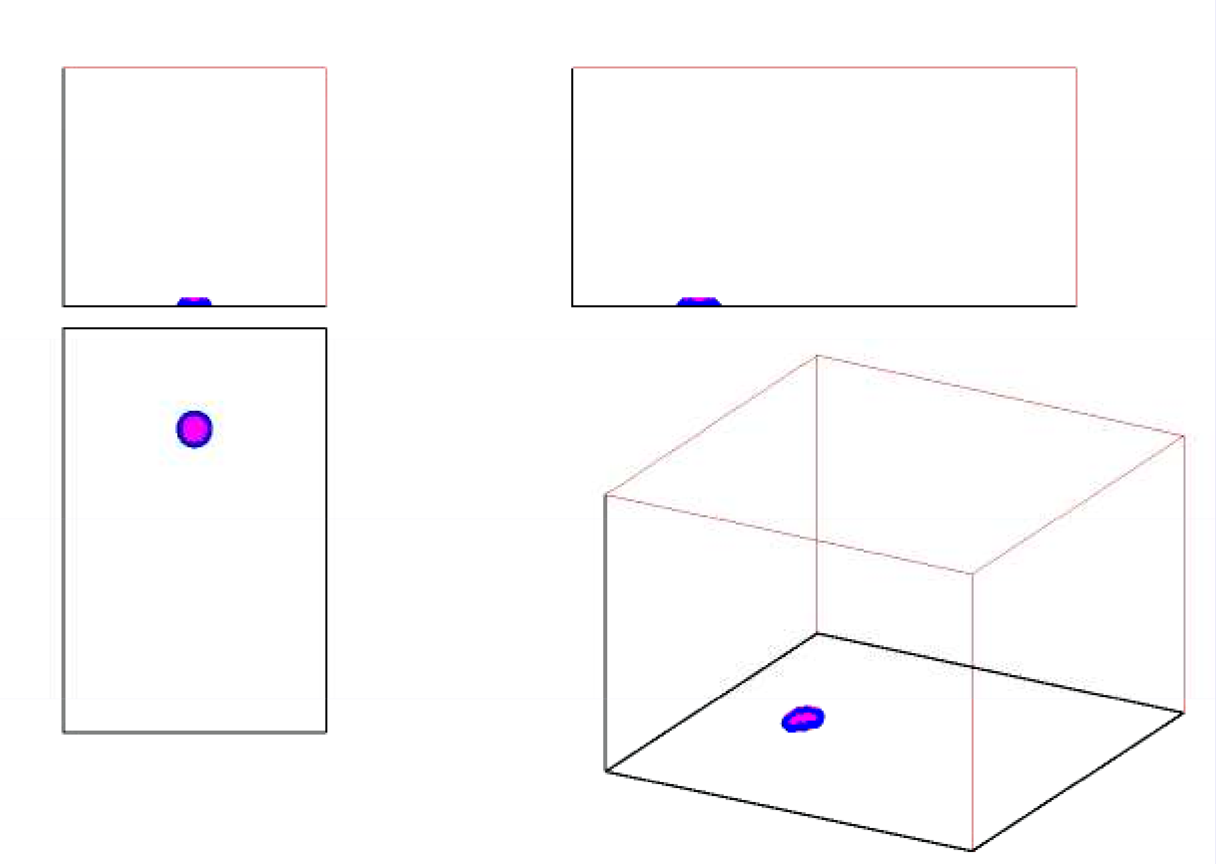
$\upsilon \sim 1.1$

log N(r)

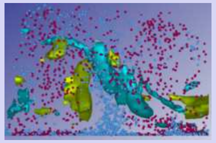
log r



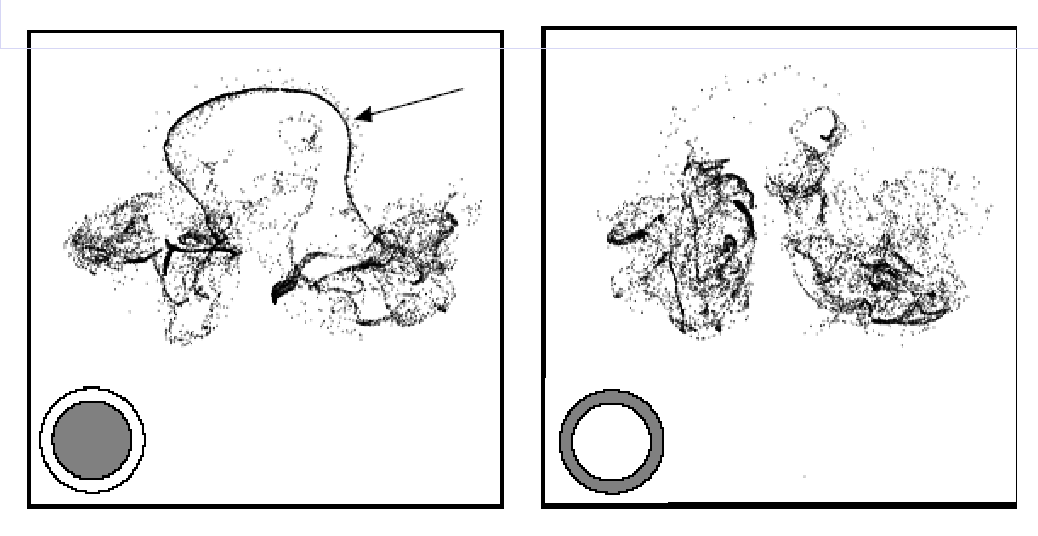
1-D Correlation or 4-D Simulation?
Example 4. Particle Laden Jet in Crossflow



- **10 micron particles**
- **Particles follow the coherent structures.**
- **Collect in the high-strain low-vorticity regions between vortices (Squires & Eaton, 1991)**

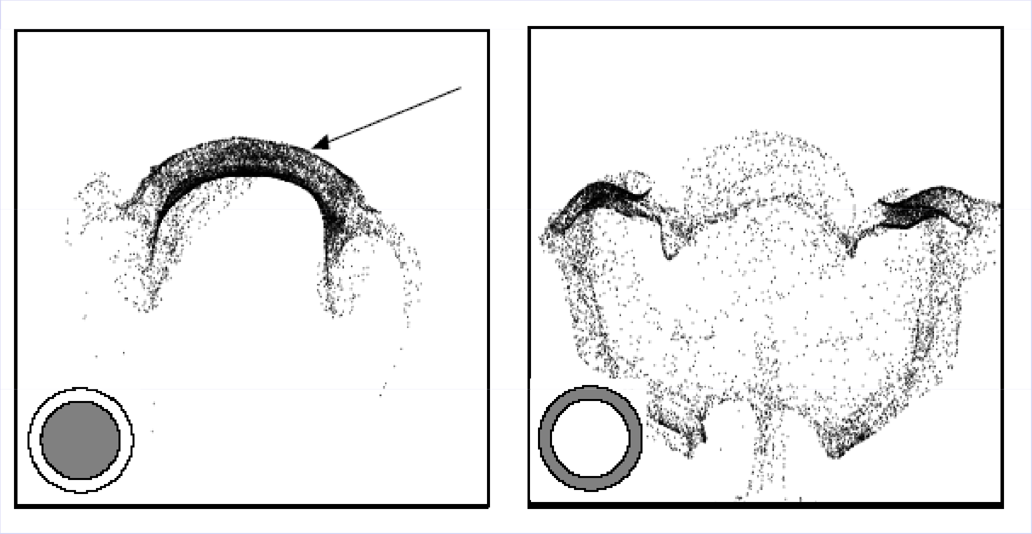


Example of particle clustering: JICF



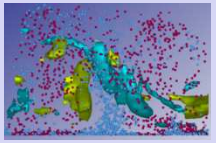
D_p=10 μm

υ =1.47

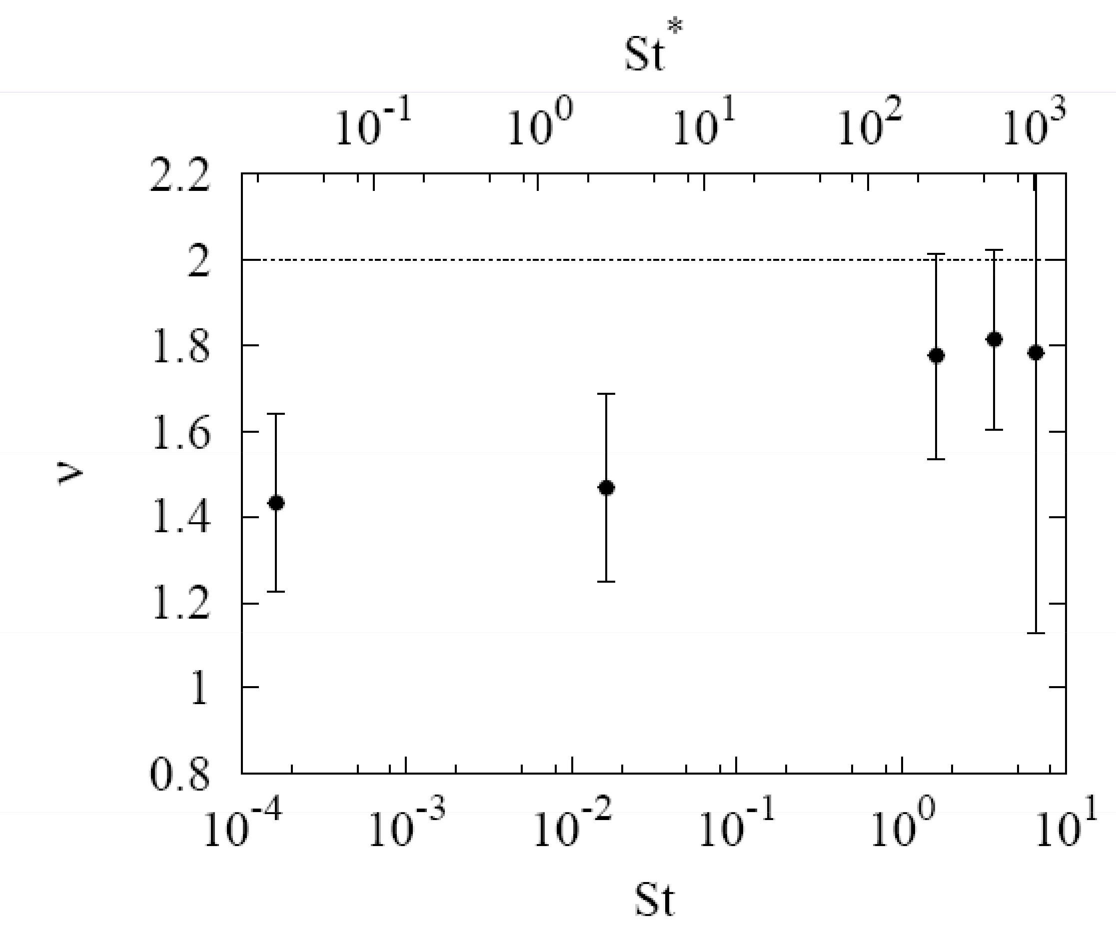


D_p=100 μm

υ =1.78



Correlation dimension: JICF

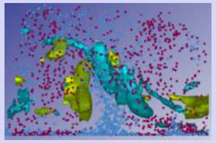


$$St^* = \tau_p / T_{slv}$$

$$St = \tau_p / T_{roll-up}$$

T_{slv} circulation of shear layer vortices

$T_{roll-up}$ formation of shear layer vortices



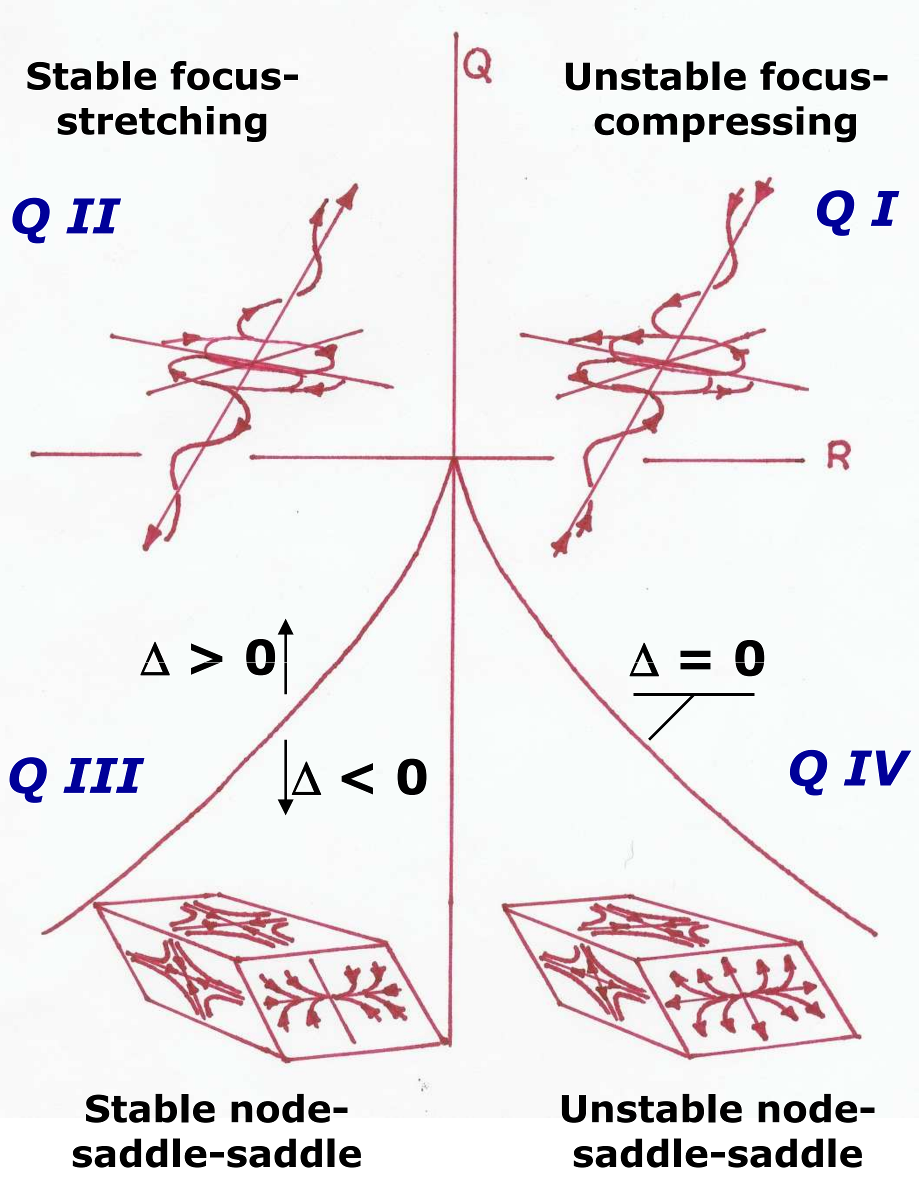
Particle clustering: 3. Flow topology characterization

$$Q > 0 \Rightarrow \Omega_{ij}\Omega_{ij} > S_{ij}S_{ij}$$

Rotation Rate > Strain Rate

Q I, QII = Vortical Flow Regions

Q III, QIV = Convergence Regions



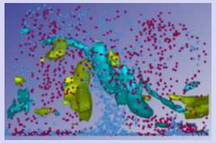
Stable focus-stretching

Unstable focus-compressing

Stable node-saddle-saddle

Unstable node-saddle-saddle

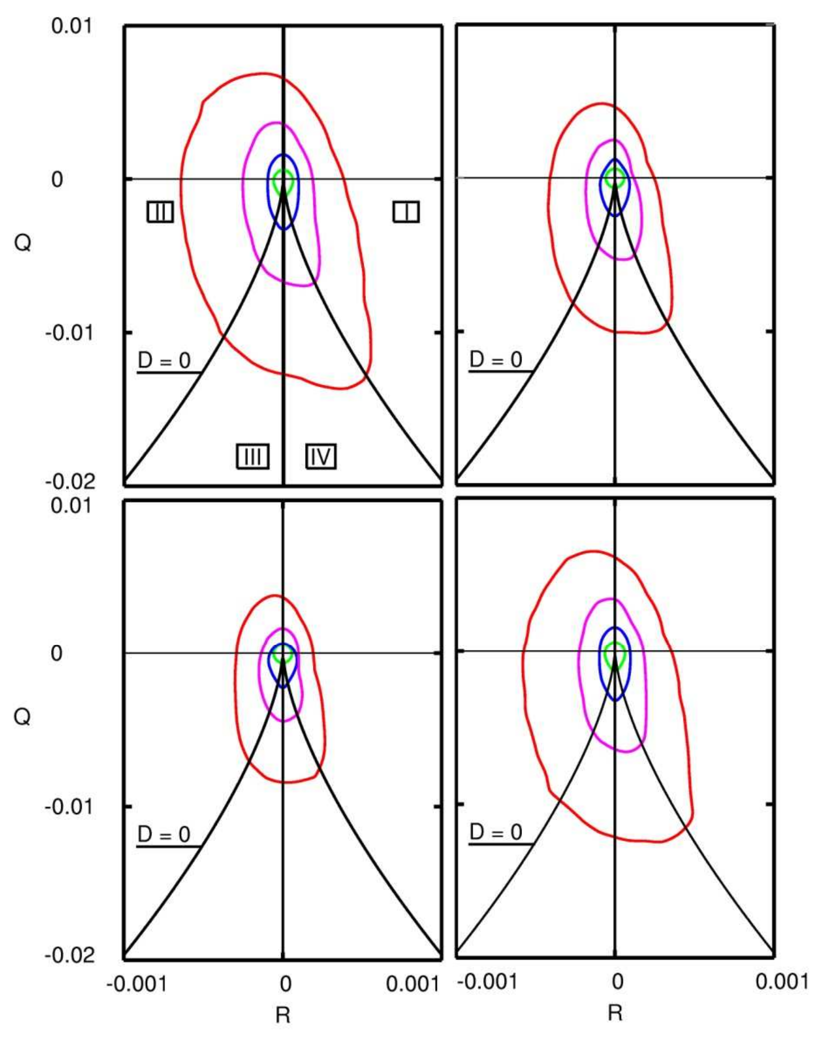
Part IV



Particles and Flow Topology.3. Wall region ($z^+ < 5$)

$\tau_p^+ = 1$

$\tau_p^+ = 5$

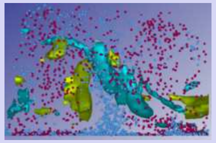


$\tau_p^+ = 25$

$\tau_p^+ = 125$

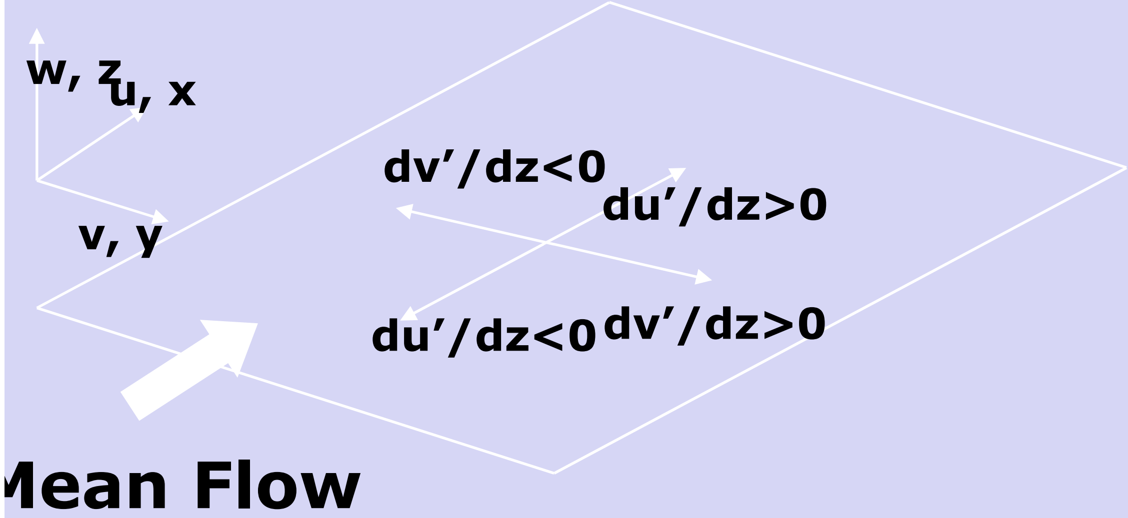
re than 70 % of particles in the convergence regions (III and IV

Hard to see the regions in a 3D space…

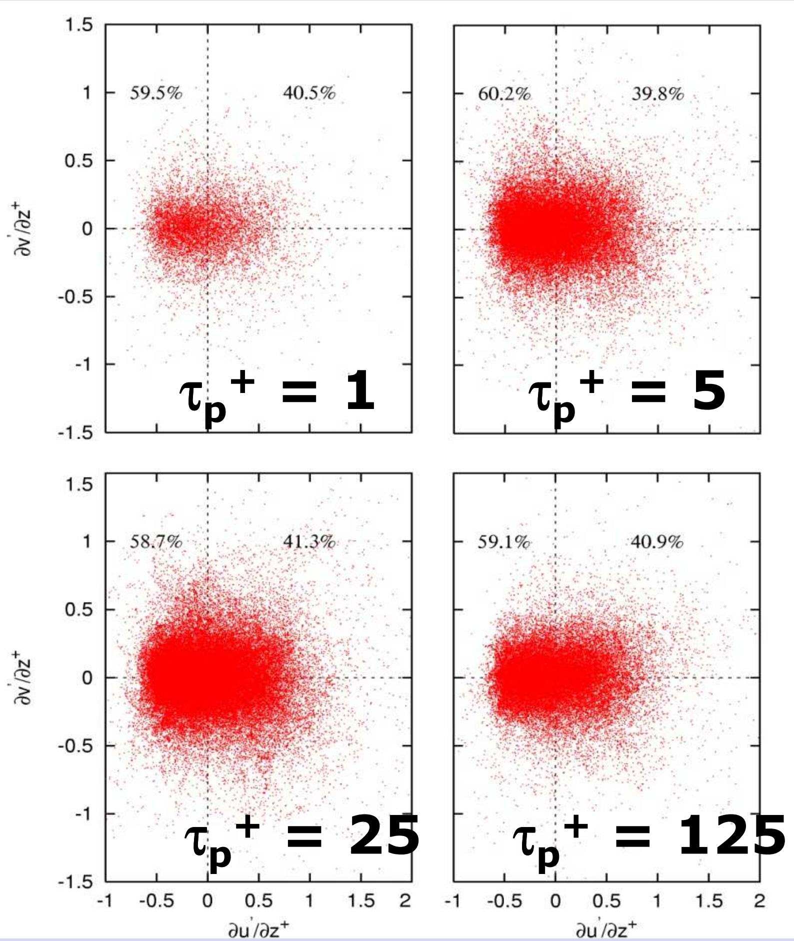


Particles and Flow Topology.4.

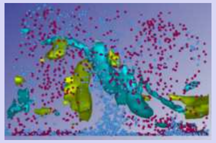
At the wall the velocity gradient tensor degenerates: only du'/dz and dv'/dz are non zero (z+=0).



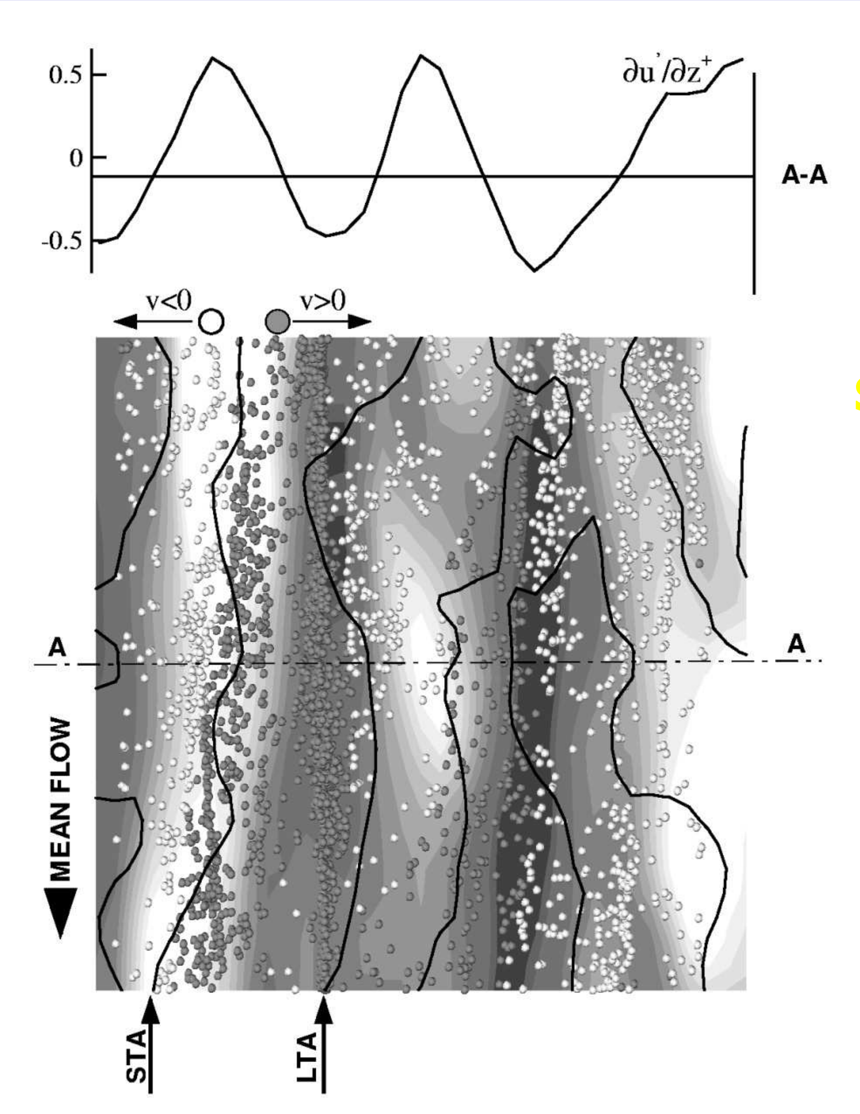
$$\begin{pmatrix} 0 & 0 & \partial u'/\partial z \\ 0 & 0 & \partial v'/\partial z \\ 0 & 0 & 0 \end{pmatrix}$$



Average statistics



A possibility to control wall particle distribution is to control instantaneous wall shear stress.



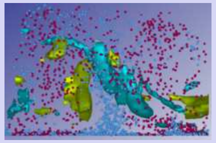
Behavior of the spanwise strain rate component along the line A-A

STA: Short Term Accumulation

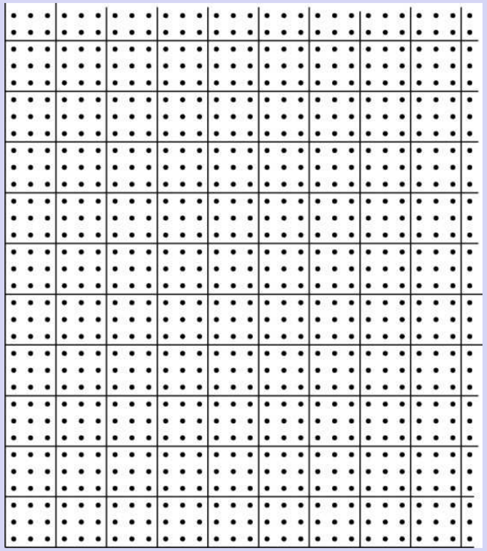
LTA: Long Term Accumulation

Instantaneous St=25 particle distribution in the viscous sublayer, z+5.

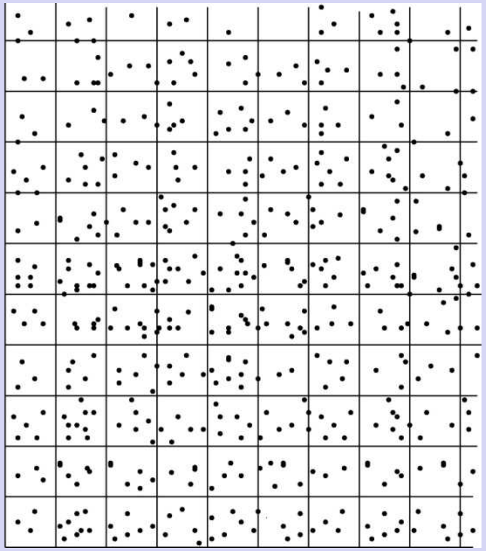
The mean flow is directed top down.



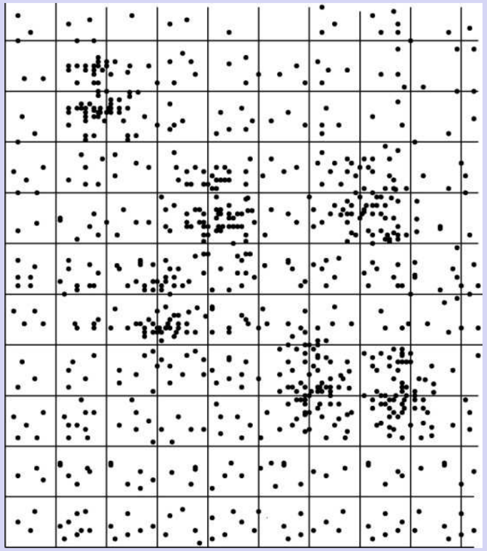
is there an optimum for particle non-uniform distribution?
To characterize their non-uniformity...



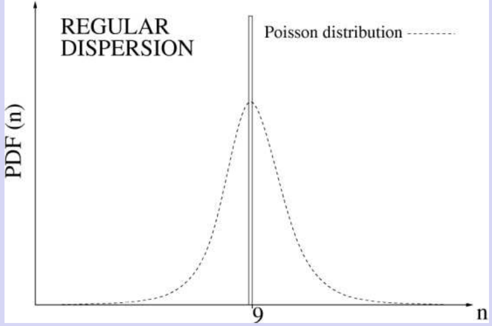
Regular distribution

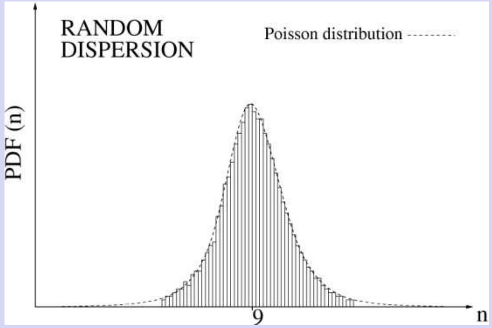


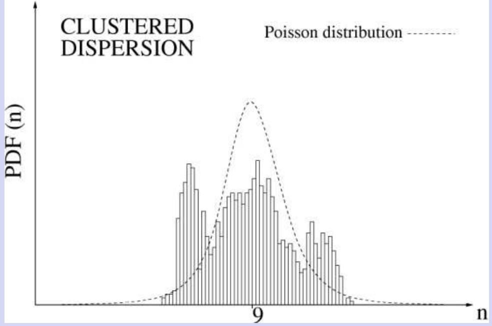
Random distribution



Clustered Distribution

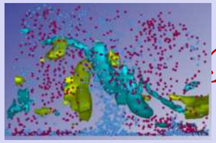




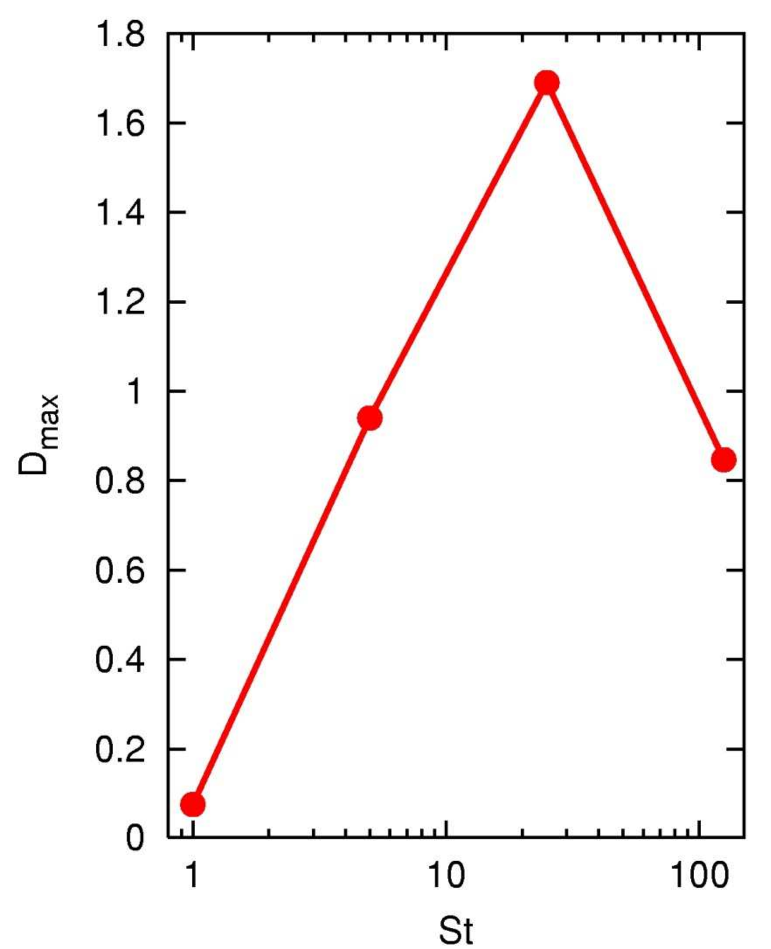


$D = (\sigma - \sigma_p)/\lambda$, with λ = average number of particle per cell

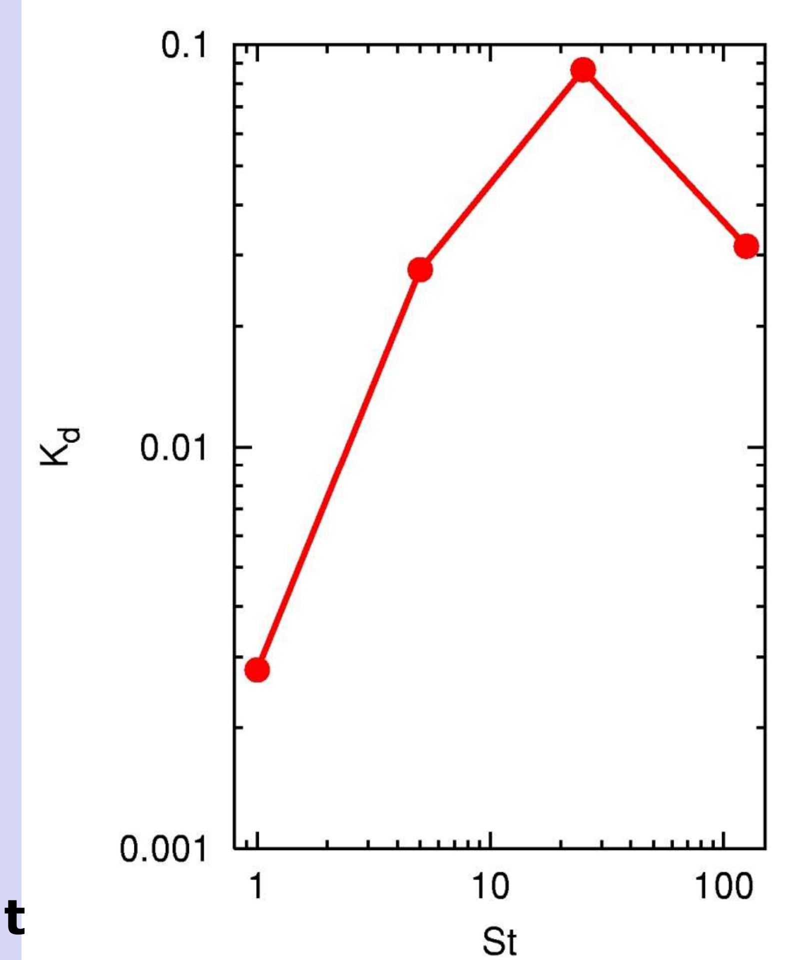
σ = standard deviation of the PDF



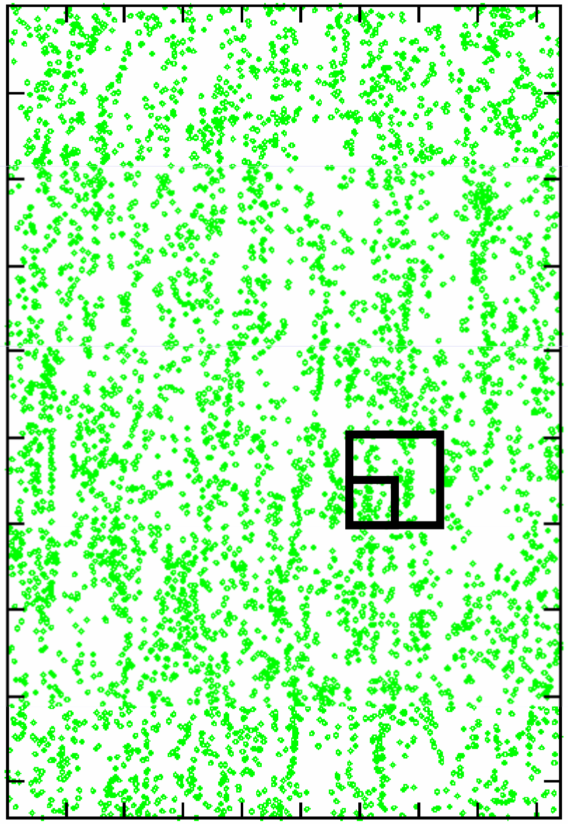
Particles are non-uniformly distributed and they have an optimum.
Wall region ($z^+ < 5$)

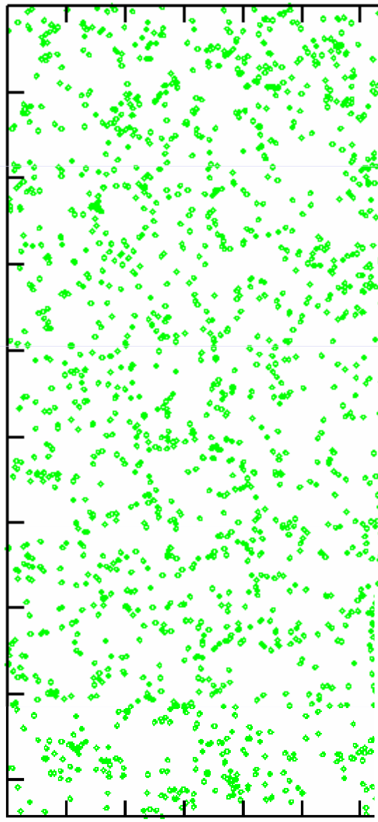


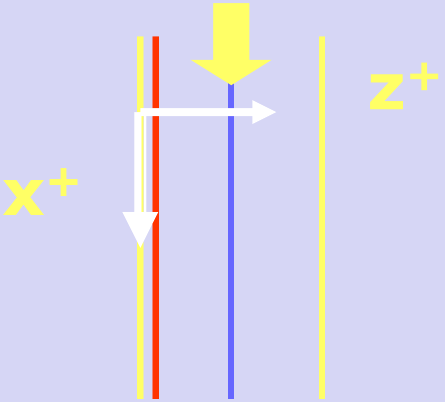
The optimum is for St= 25, which scales with the time

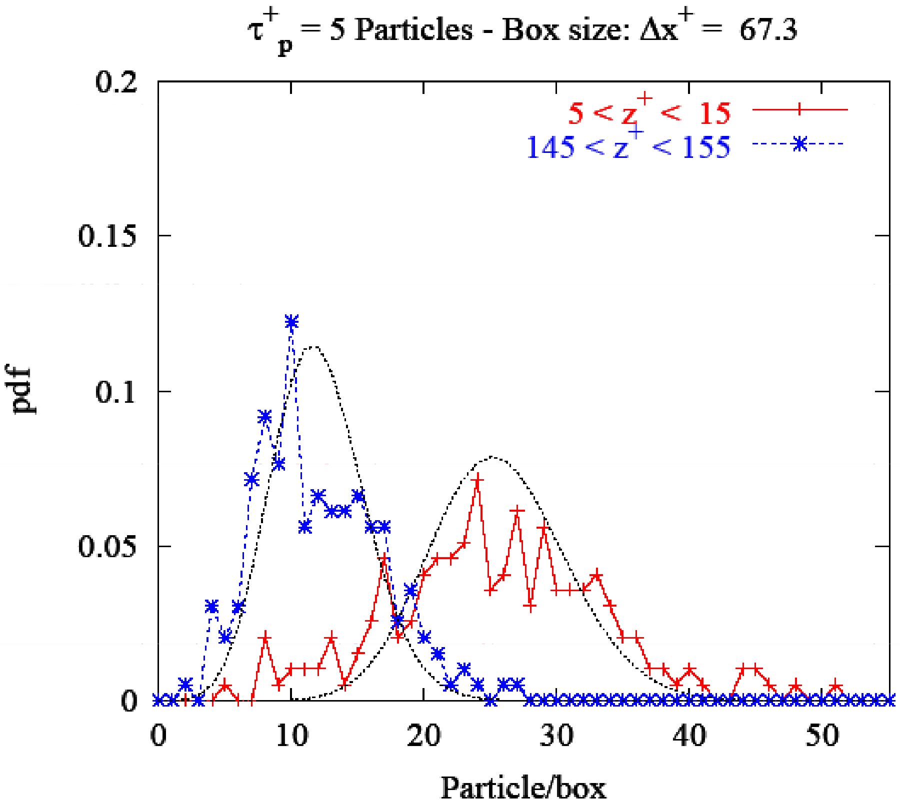


Kd = Deposition coefficient





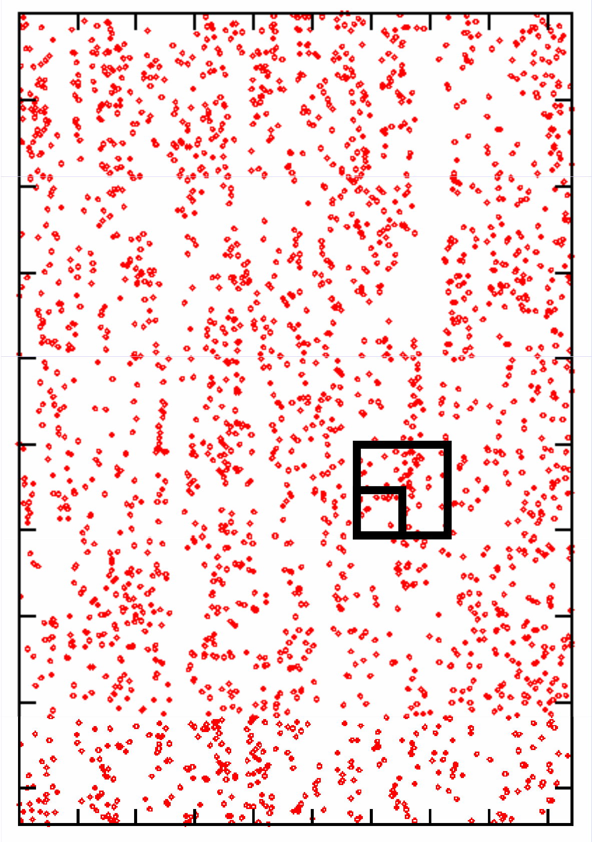


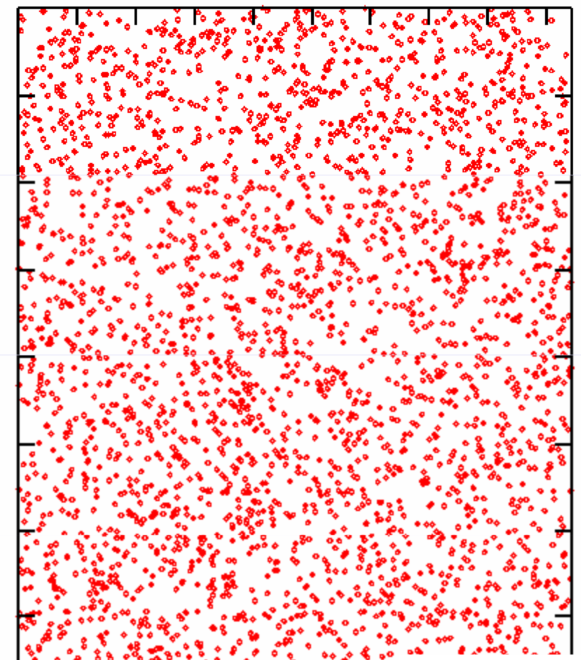


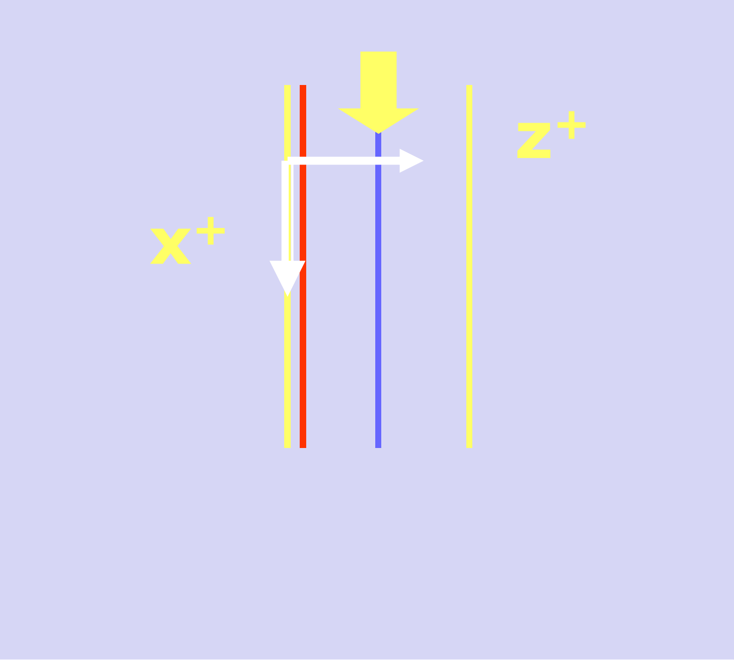
$5<z^+<15$

$145<z^+<$
5

Poisson distribution for particles

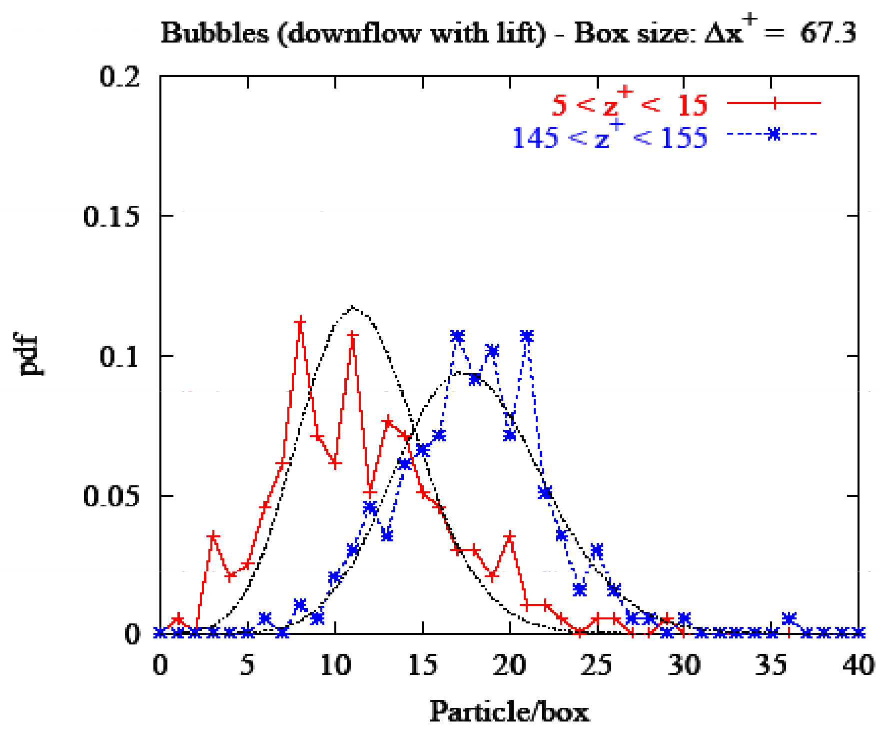




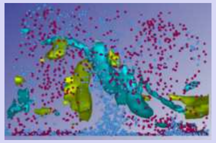


$5<z^+<15$

$145<z^+<$
5

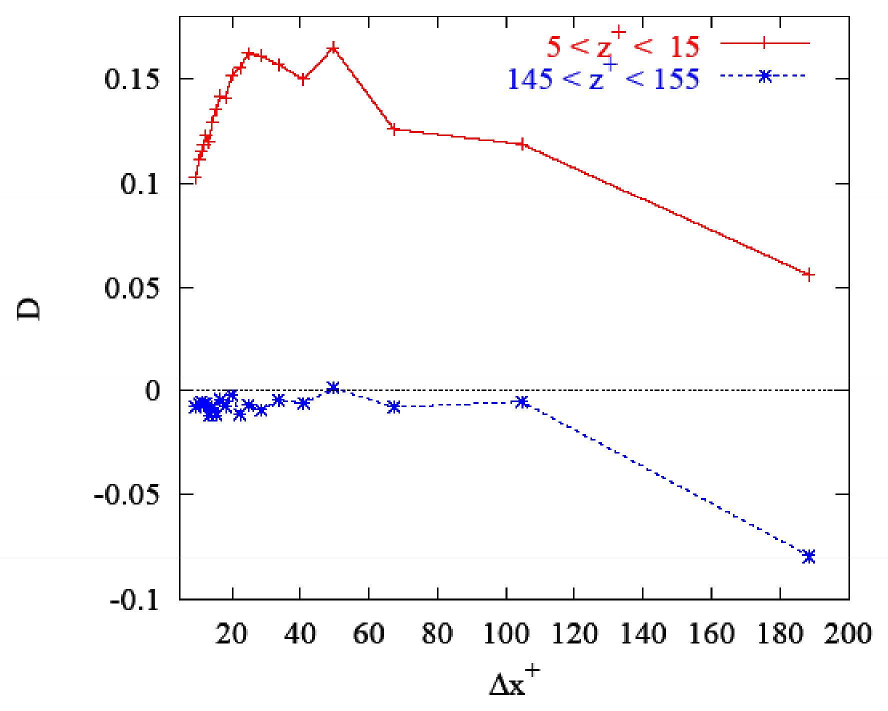


Poisson distribution for bubbles

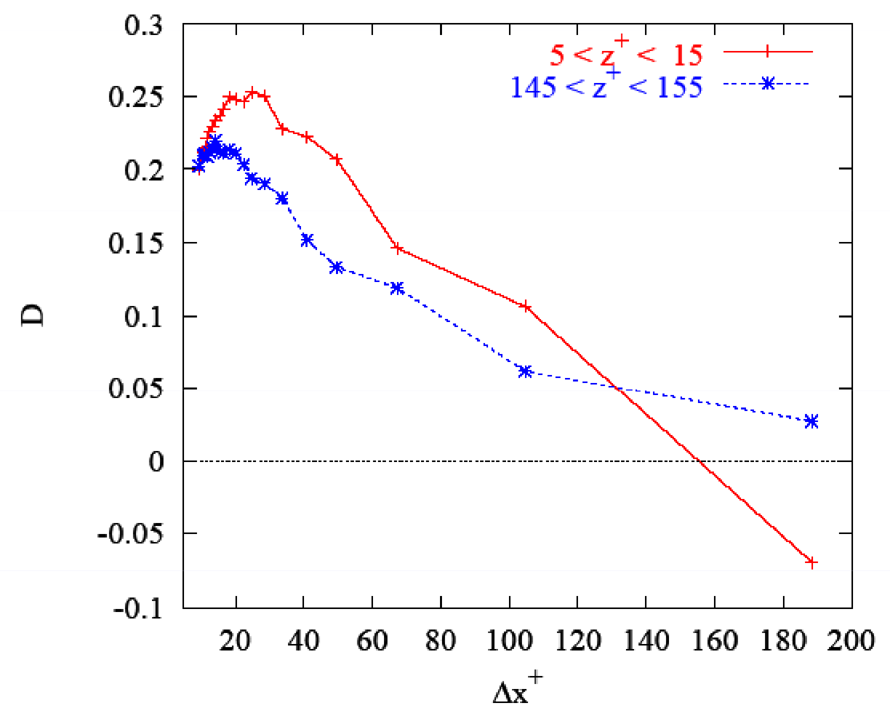


Deviation from random distribution

Bubbles



Particles



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Tang, Wen, Yang, Crowe, Chung, Troutt, “Self-organizing particle dispersion mechanism in plane wake”, *Phys. Fluids*, 4, 2244, 1992

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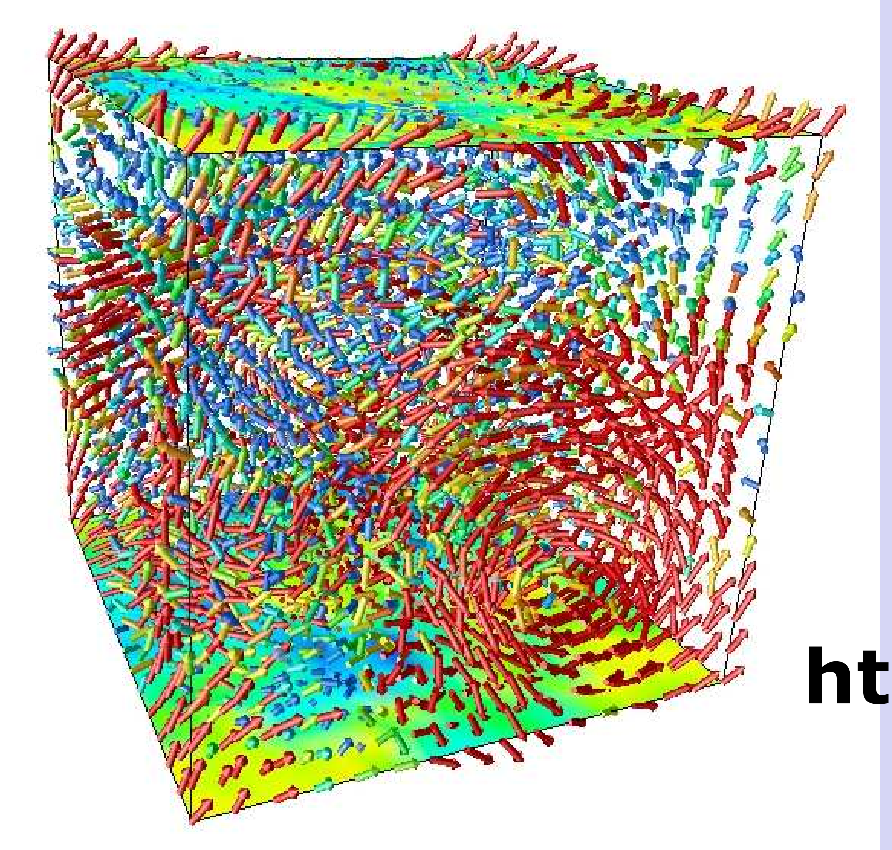
Picciotto, Marchioli, and Soldati “Characterization of near-wall accumulation regions for inertial particles in turbulent boundary layers”, *Phys. Fluids*, 17, 2005

Computational Fluid Dynamics database



Free CFD database, kindly hosted by Cineca supercomputing center (Bologna, Italy).

Over than 1 Tbyte DNS fluid-dynamics data available on line at:

http://cfd.cineca.it/cfd