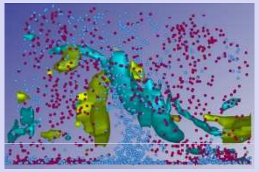


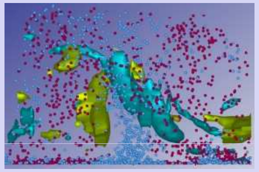
Doctoral Course in:

Modelling Turbulent Dispersed Flows

Lesson Six:

Dynamics of Bubbles in Turbulent Flows

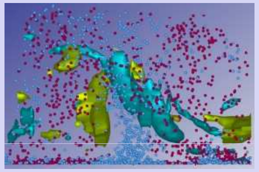
Lausanne, 18 June 2008



A complicated scientific application…

Our motivation is turbulent dispersed and reactive flow modelling

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
7. **Wednesday June 18: 14 pm to 17 pm**
   Bubble dispersion in wall turbulence.
   Project Advancement/Discussion
   Discussion and hands-on the project
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



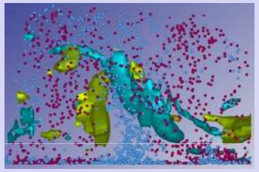
Summary

- **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**
4. **We know something on Interpolation**
5. **We know something on particle dynamics in boundary layers**
6. **We know how to quantify if particles are homogeneously distributed or not**

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

1. **What f we apply what we know to microbubbles? Are things going to be the same?**
2. **Updates on the Homeworks and Project**



Summary

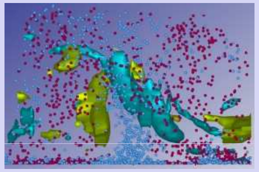
- **What we will learn in today lecture:**

1 **Some interesting physics… who can explain?**

2 **Microbubbles? Interesting applications and difference with microparticles.**

3 **Update on Homeworks and Project.**

*Reminder: Press ESC



Animal-Channel

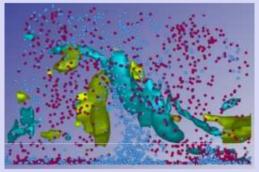
Are dolphins more skilled than human beings?
(we already know they are smarter than some of us!)

Dolphin-1.vlc

Dolphin-2.vlc

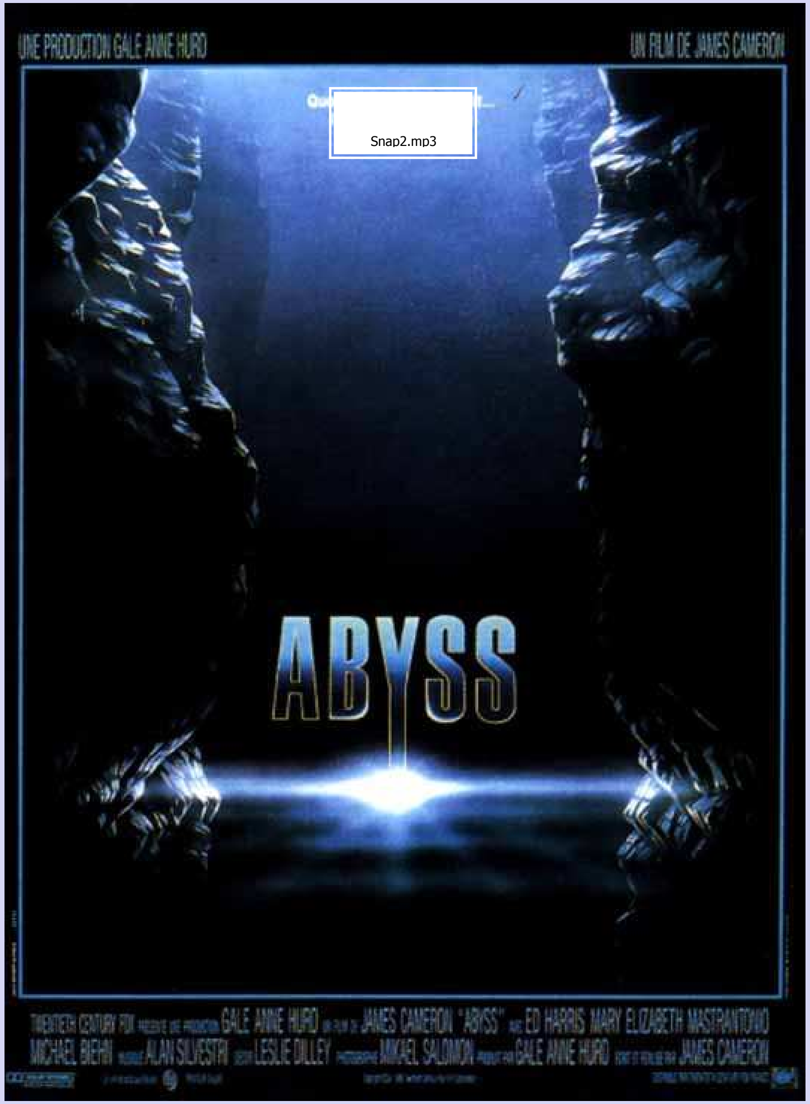
Human-Being-1.vlc

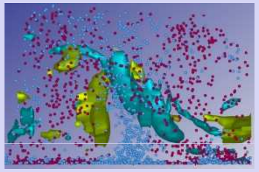
Dolphin-3.vlc



Animal Channel

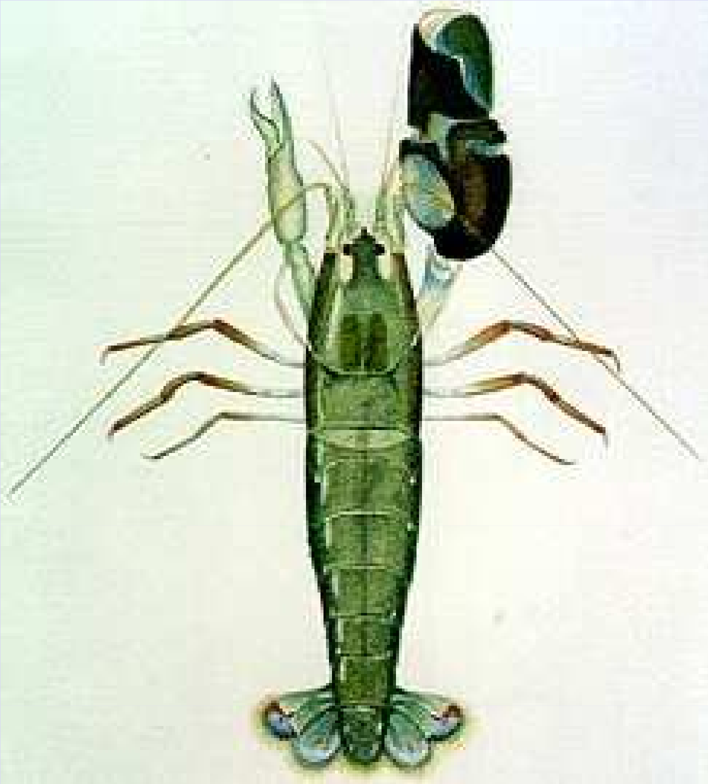
What is this noise?





Animal Channel

A deadly animal!



Snapping-Shrimp-Detlef.vlc

How Snapping Shrimp Snap: Through Cavitating Bubbles
Michel Versluis, *et al.*
Science **289**, 2114 (2000);
DOI: 10.1126/science.289.5487.2114

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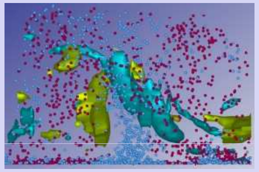


Summary

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

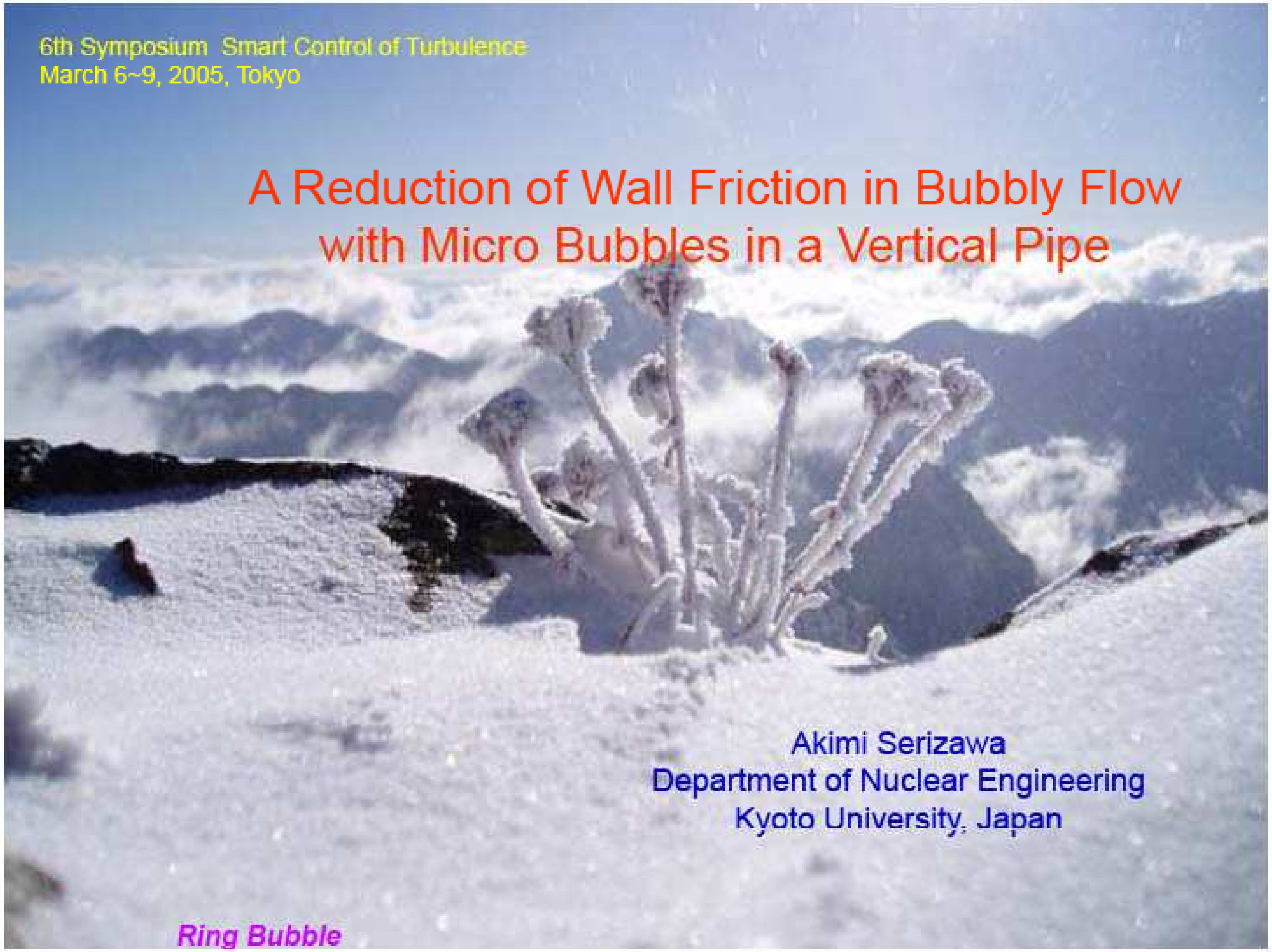
1 **Some interesting physics... who can explain?**

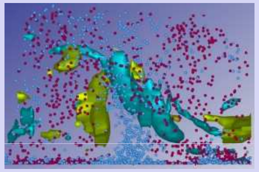
2 **Microbubbles? Interesting applications and difference with microparticles.**

3 **Update on Homeworks and Project.**

***Reminder: back to full Screen**

An Experiment by Prof Serizawa…



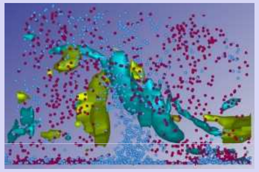


A Direct Numerical Simulation of our group

Mechanisms for microbubble transfer in the near-wall region of turbulent boundary layer.

A. Giusti, and A. Soldati

Dept. of Energy Technology
University of Udine
via delle scienze, 208, 33100, Udine, Italy
Corresponding author. Email: soldati@uniud.it

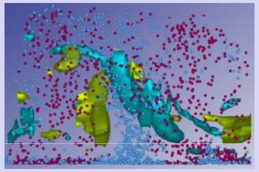


But the DNS told us what the fluid does to bubbles,
Not what bubbles do to the fluid!

NON-UNIFORM DISPERSION OF MICRO-BUBBLES

IN <u>TWO-WAY COUPLED</u> UPWARD/DOWNWARD

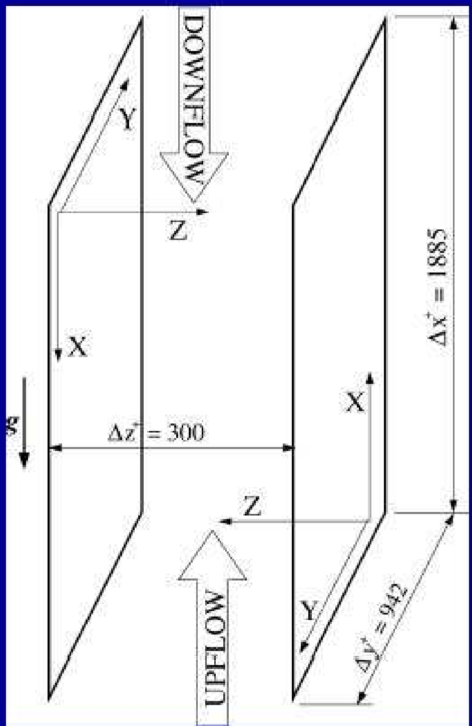
TURBULENT CHANNEL FLOW



Computational Methodology. 1 .
Momentum Coupled Dilute Two-Phase Flow

Computational Methodology - channel geometry

- *DNS of Turbulent Boundary Layer*
- *Lagrangian Tracking of Microbubbles*



Fluid simulation

$Re_\tau = 150$
grid $128 \times 128 \times 129$
B.C. x *and* y *dir. : periodic*
B.C. z *dir.: solid wall*

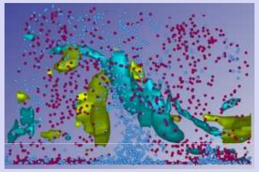
Bubble simulation

$2.3 \cdot 10^4$ *bubbles*
diameter $220\ \mu m\ (1.65\ w.u.)$

Configurations of the channel

downflow
upflow

Actual Void Fraction: $\alpha = 1.0\ 10^{-4}$



Computational Methodology. 2.
Momentum Coupled Dilute Two-Phase Flow

Computational Methodology - fluid equations

mass balance

$$\frac{\partial u_i}{\partial x_i} = 0$$

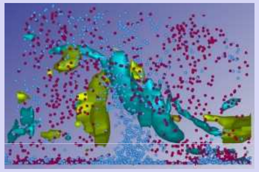
momentum balance (N.S. equations)

$$\rho \left[\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} \right] = -\frac{\partial \tilde{P}}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_j \partial x_j} + f_{2W,i}$$

Bubble backReaction on the Fluid

Hypotheses:

- *negligible void fraction*



Two-Way Momentum Coupling (PSIC): 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**

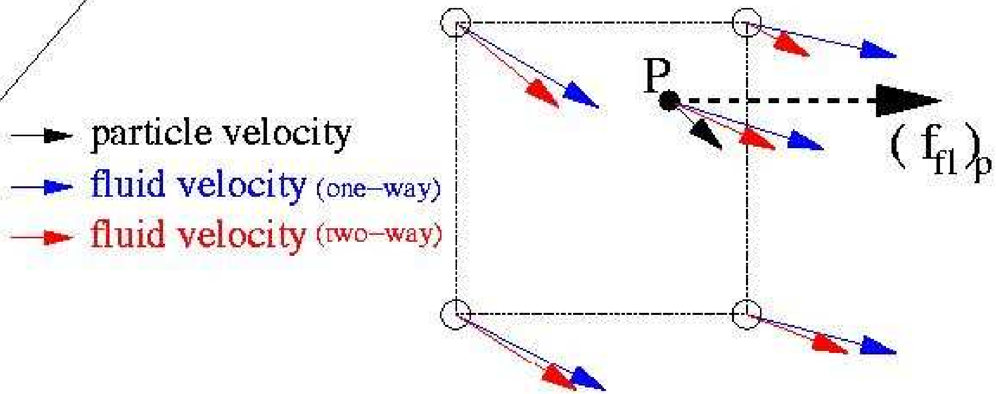
$$m_p \frac{\partial \mathbf{v}_p}{\partial \theta} = (\mathbf{f}_{fl})_p$$

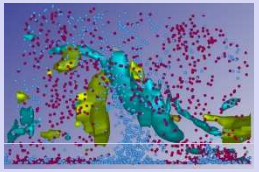
$$\frac{\partial \mathbf{x}_p}{\partial \theta} = \mathbf{v}_p$$

→ **Momentum exchange term**

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

→ Fluid equations





Computational Methodology. 4.

Forces acting on Bubbles (Still far not realistic!)

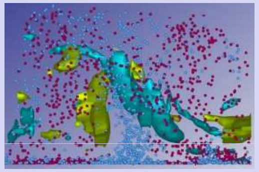
Forces on bubbles (2/3)

$$\underbrace{\frac{d\mathbf{v}_p^+}{dt^+}}_{inertia} = \underbrace{\frac{\left(\mathbf{v}^+ - \mathbf{v}_p^+\right)}{\tau_p^+} f\left(Re_p\right) C_W}_{drag} + \underbrace{\left(1 - \frac{1}{\rho_p^+}\right) \mathbf{g}^+}_{grav}$$

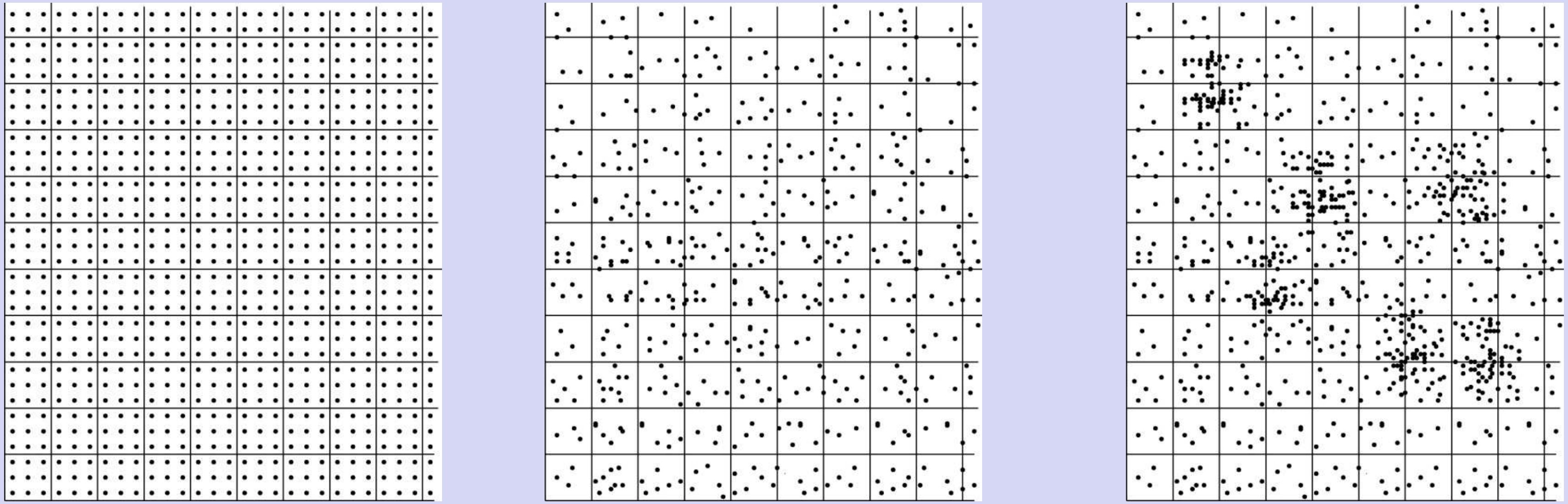
$$+ \underbrace{\frac{1}{\rho_p^+} \frac{D\mathbf{v}^+}{Dt^+}}_{press.grad.} + \underbrace{\frac{9}{d_p^+ \rho_p^+ \sqrt{\pi}} \int_0^{t^+} \left(\frac{d\mathbf{v}^+}{dt^+} - \frac{d\mathbf{v}_p^+}{dt^+}\right) \frac{d\tau^+}{\left(t^+ - \tau^+\right)^{0.5}}}_{Basset}$$

$$+ \underbrace{\frac{1}{2\rho_p^+} \left(\frac{D\mathbf{v}^+}{Dt^+} - \frac{d\mathbf{v}_p^+}{dt^+}\right)}_{added\ mass} + \underbrace{C_L \frac{1}{\rho_p^+} \left(\mathbf{v}^+ - \mathbf{v}_p^+\right) \times \omega^+ + f_{L,W}^+ \mathbf{e}_z}_{lift}$$

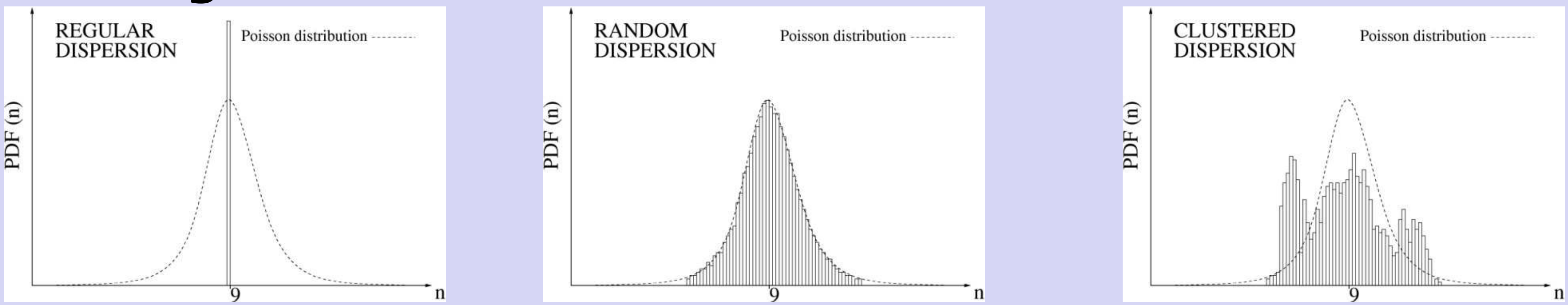
HeavyHD/CPU Load due to Basset History (Unsteady Drag) Force



And… are bubbles segregated into specific regions …from a statistical viewpoint

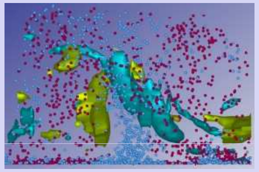


Regular **Random** **Clustered**

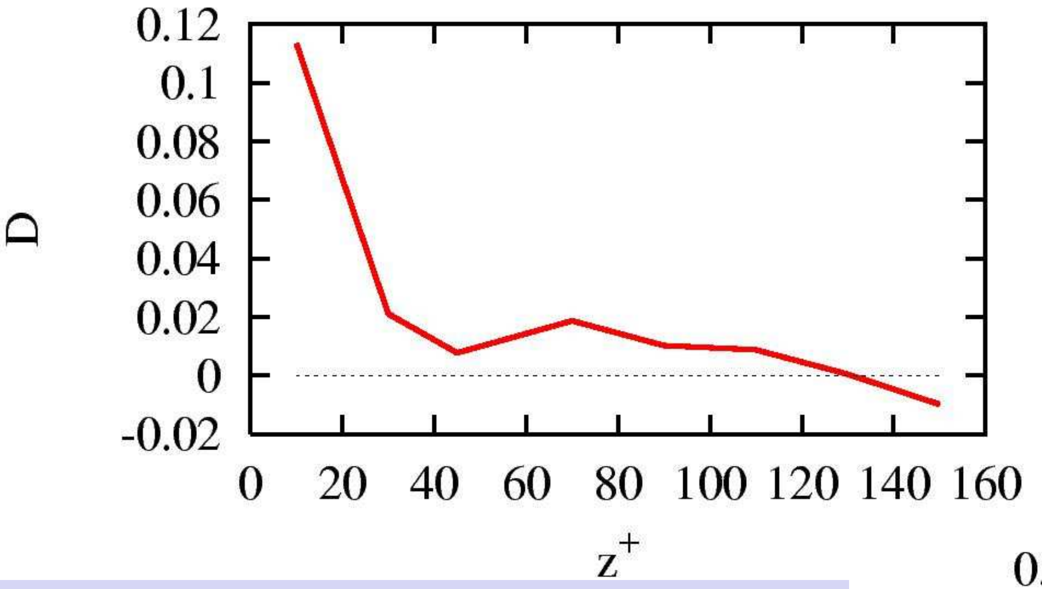


D = $(\sigma-\sigma_p)/\lambda$, with λ = average number of particles per cell

σ = standard deviation of the PDF



And… from a statistical viewpoint



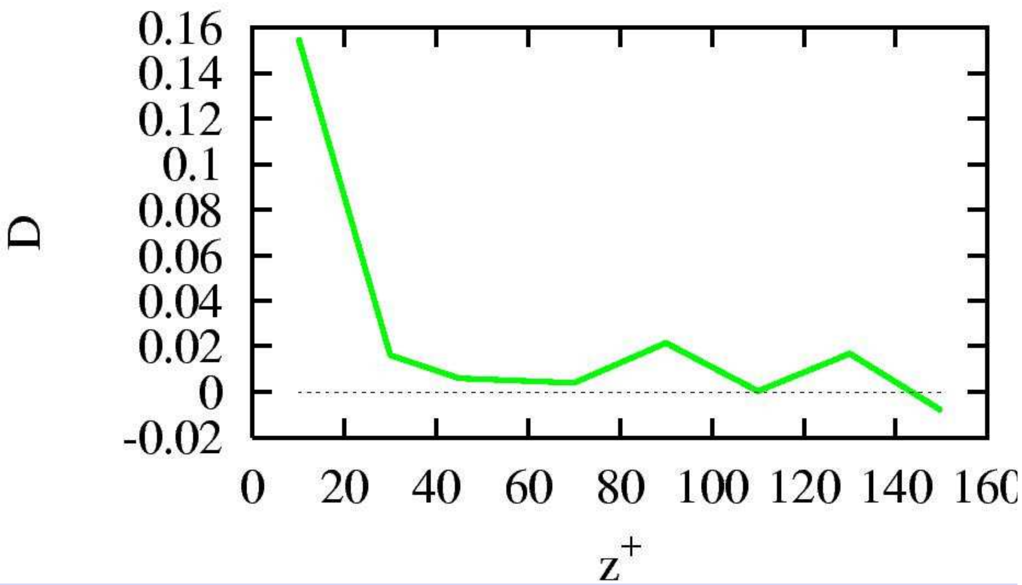
$D = (\sigma - \sigma_p)/\lambda$,

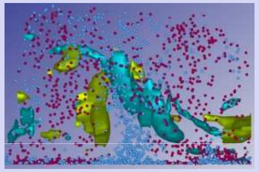
with λ = average number of particles per cell

σ = standard deviation of the PDF

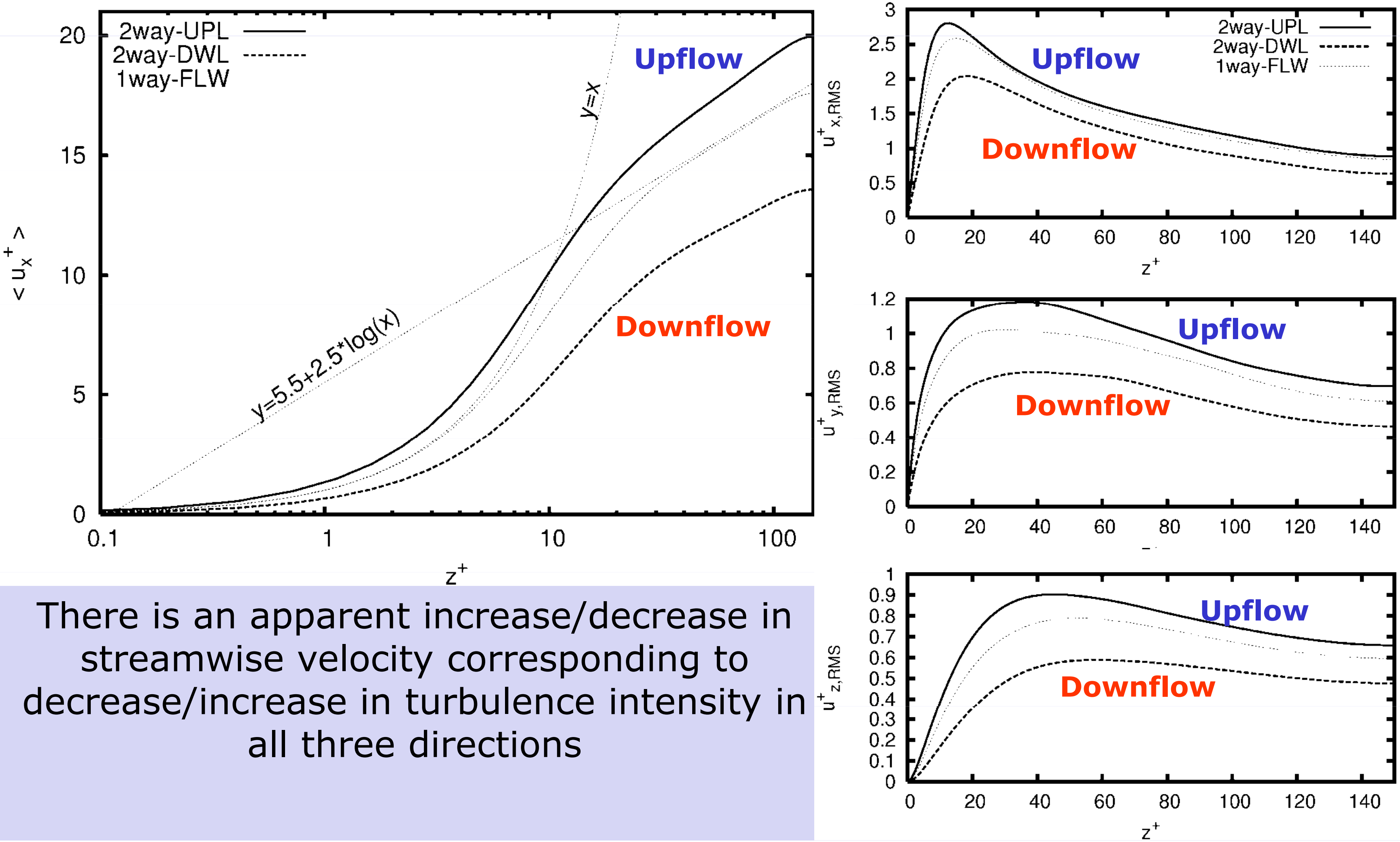
... If *manners makith tracers*, bubbles are well mannered only far from the wall...

... where the lift force is small.

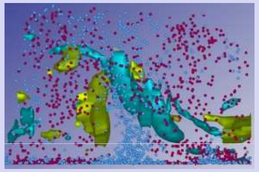




… Results on velocity statistics and Scaling
Fluid Statistics: Streamwise Velocity and RMS



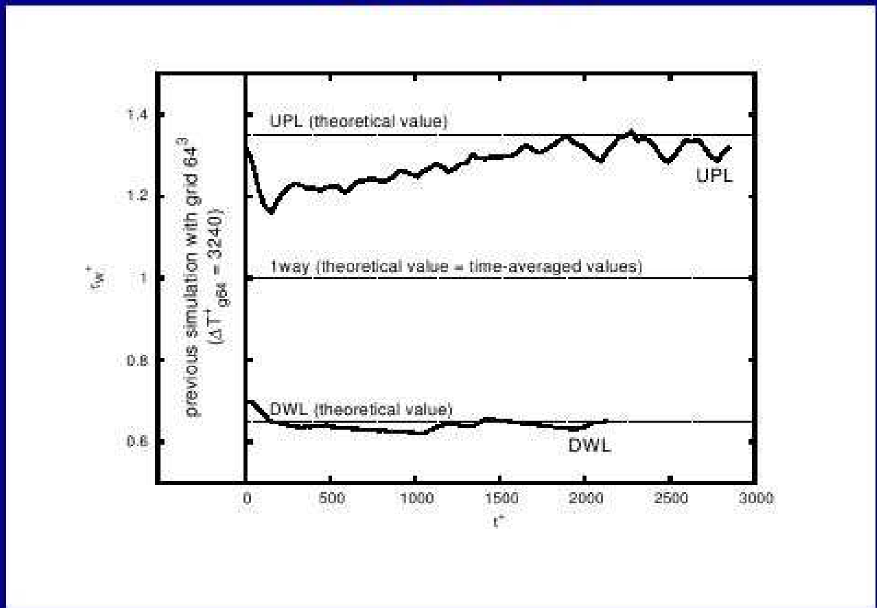
There is an apparent increase/decrease in streamwise velocity corresponding to decrease/increase in turbulence intensity in all three directions



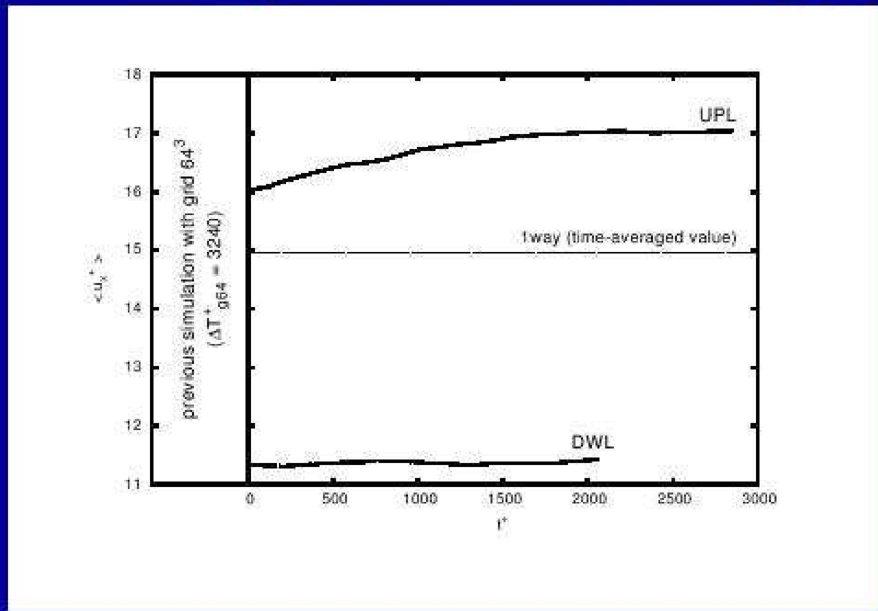
... But the usual turbulence scaling does not hold if there are bubbles forcing the flow !
We must introduce the bubble back-reaction

$\tau^+_{W,2D} = 0.65$ (*downflow*) and $\tau^+_{W,2U} = 1.35$ (*upflow*)

Wall-shear

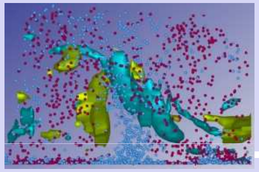


Average streamwise velocity

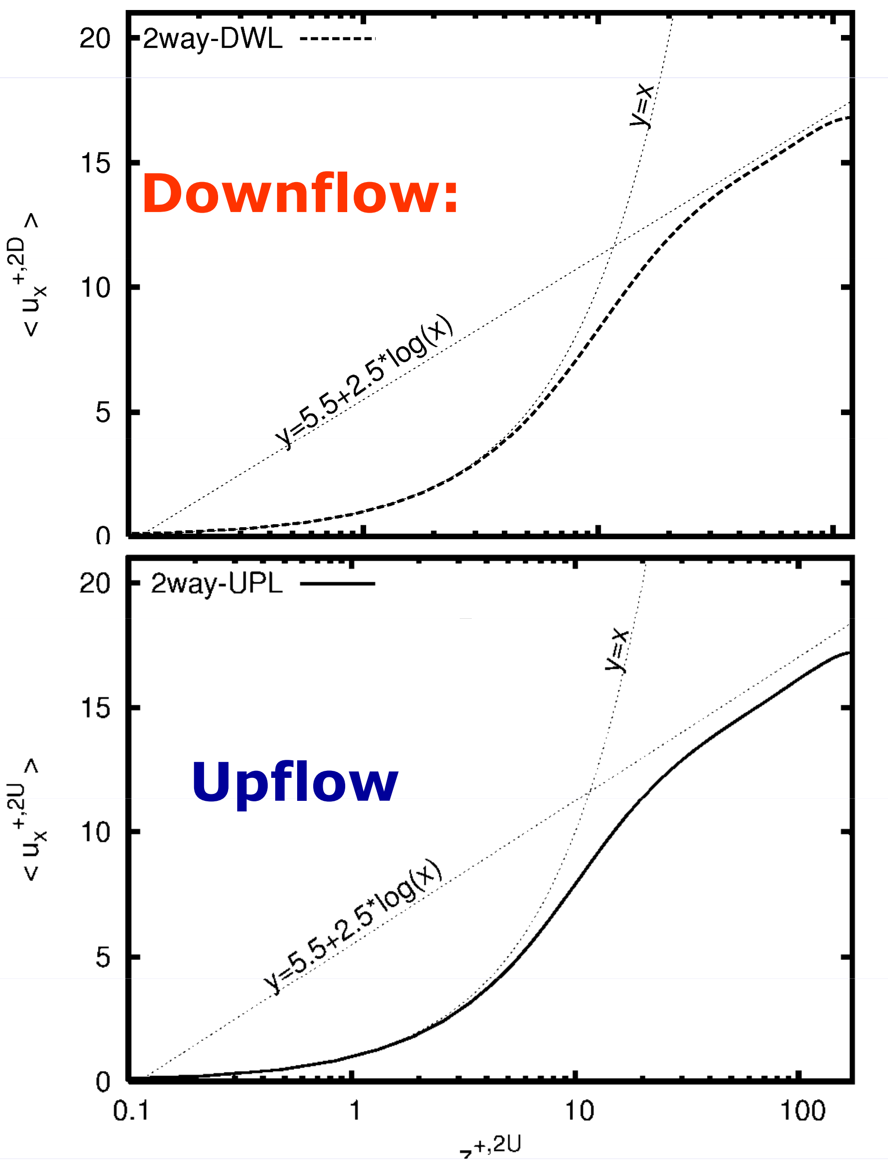


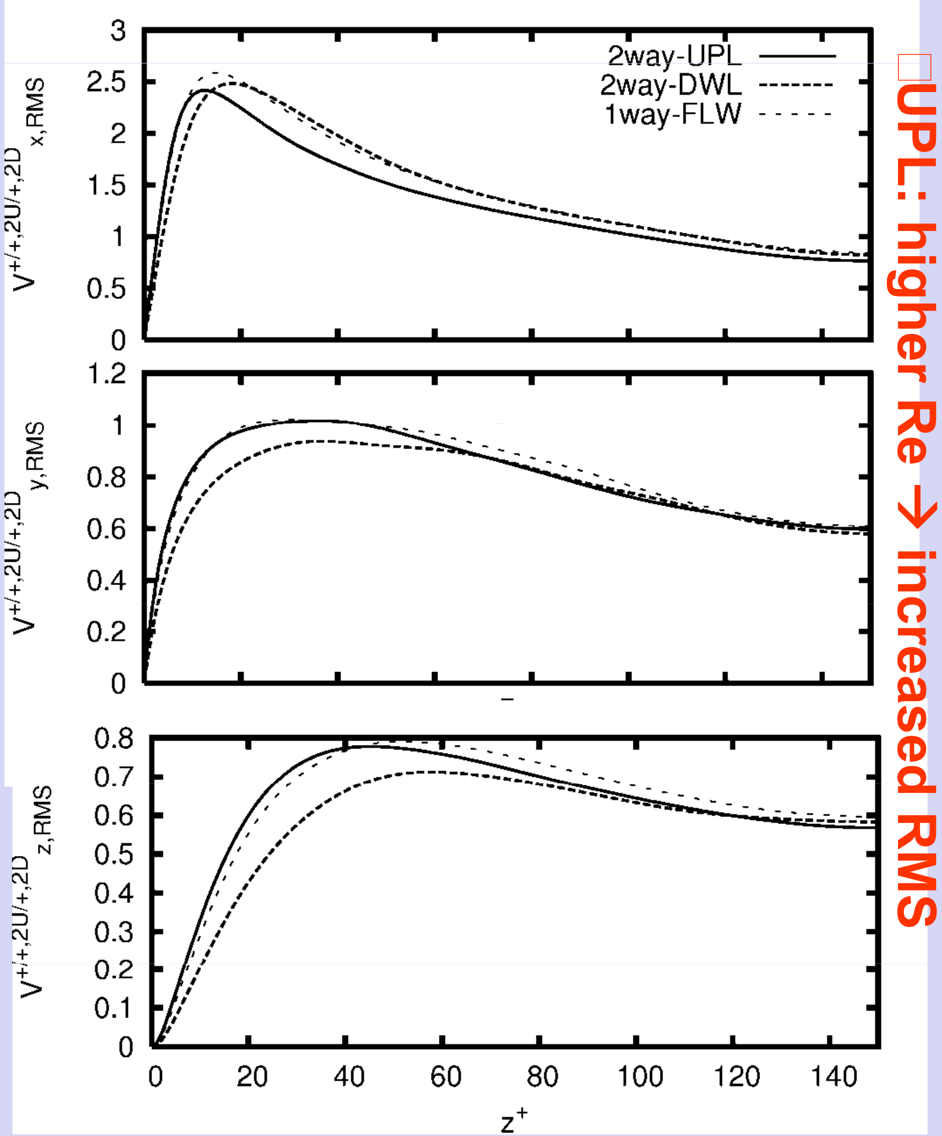
$u_{\tau,2D} = \sqrt{0.65}\, u_\tau$ — *Modified shear velocity* — $u_{\tau,2U} = \sqrt{1.35}\, u_\tau$

$Re_{\tau,2D} = 121.1$ — *Modified Reynolds numbers* — $Re_{\tau,2U} = 174.2$



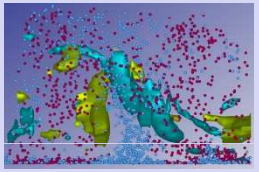
... So, if we filter bubble driving force everything comes in good order.





DWL: lower Re → decreased RMS

UPL: higher Re → increased RMS



Conclusions

1. Strongly Coherent Structure Transfer microbubbles to and away from the wall;

2. Quasi-streamwise vortical structures in connection with lift, gravity (and…) induce microbubble segregation (not shown in detail);

3. Strong influence of Force Modelling;

   (a) Lift mainly responsible of such preferential concentration;

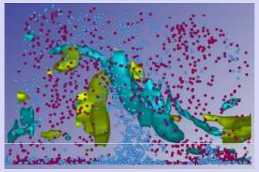
   (b) Wall effects extremely significant;

4. Not much turbulence increase/attenuation. Strong effect of buoyancy

5. High potentials of DNS+Lagrangian tracking for understanding physics and modelling;

6. Lack of accurate force models for microbubbles (wall effects?);

7. Currently only few works with DNS and Lagrangian tracking. Difficult! Yet needed to explore.



Summary and conclusion of Lecture 6

- **What have we learnt in today lecture:**

1. **Some interesting physics… who can explain?**
2. **Microbubbles? Interesting applications and difference with microparticles.**
3. **Update on Homeworks and Project.**