

Doctoral Course in:

Modelling Turbulent Dispersed Flows



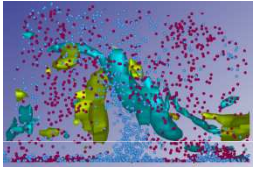
*Particles, Vortices, Coherent Structures and Turbulence:
Physics, computations and a little literary review*

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Lausanne, 7 May 2008



A complicated scientific application...

Our motivation is turbulent dispersed and reactive flow modelling

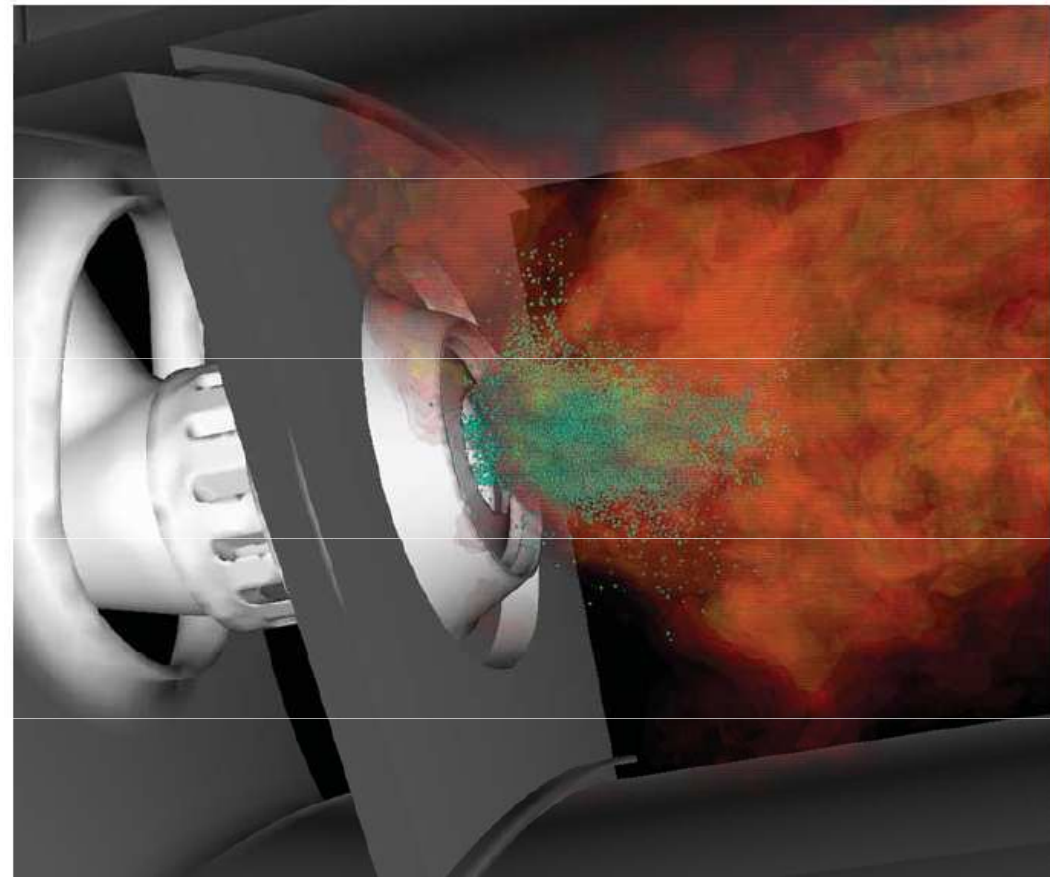


In this picture...

**A sophisticate recent simulation
Of a dispersion of droplets burning
Into a Pratt & Whitney gas Turbine
Combustor.**

Modelling Problems:

- 1. Turbulence**
- 2. Droplets and turbulence**
- 3. Droplet evaporation and reaction**
- 4. Droplet droplet interaction..**
- 5. ...**



Large-Eddy Simulation of a modern Pratt & Whitney gas turbine combustor (Mahesh et al. 2005, Moin & Apte 2005).



Bull (Plate I. - December 5 1945)



Bull (Plate II. - December 12 1945)



Bull (Plate III. - December 18 1945)



Bull (Plate IV. - December 22 1945)



Bull (Plate V. - December 24 1945)



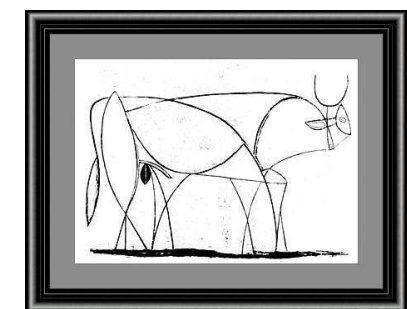
Bull (Plate VI. - December 26 1945)



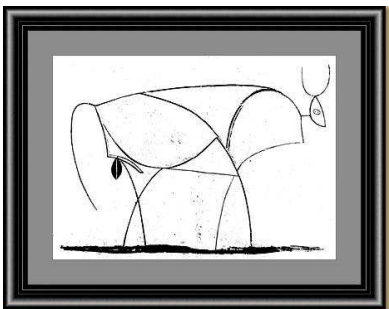
Bull (Plate VII. - December 28 1945)



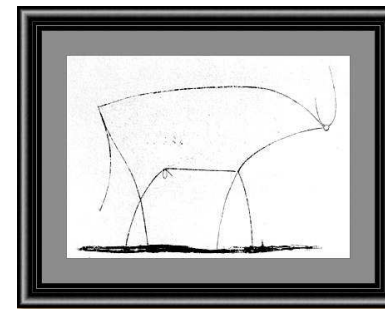
Bull (Plate VIII. - January 2 1946)



Bull (Plate IX. - January 5 1946)



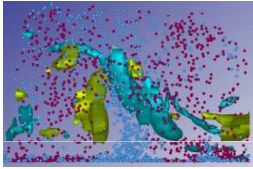
Bull (Plate X. - January 10 1946)



Bull (Plate XI. - January 17 1946)

*He has ended up where he should have started!
He had gone in successive stages through all the
other bulls. When you look at that line you cannot
imagine how much work it involved. He had in
mind to retrieve the bull's constituent parts, his
dream bull - bred of pure lines - an elemental,
disembodied, quintessential bull-ness*

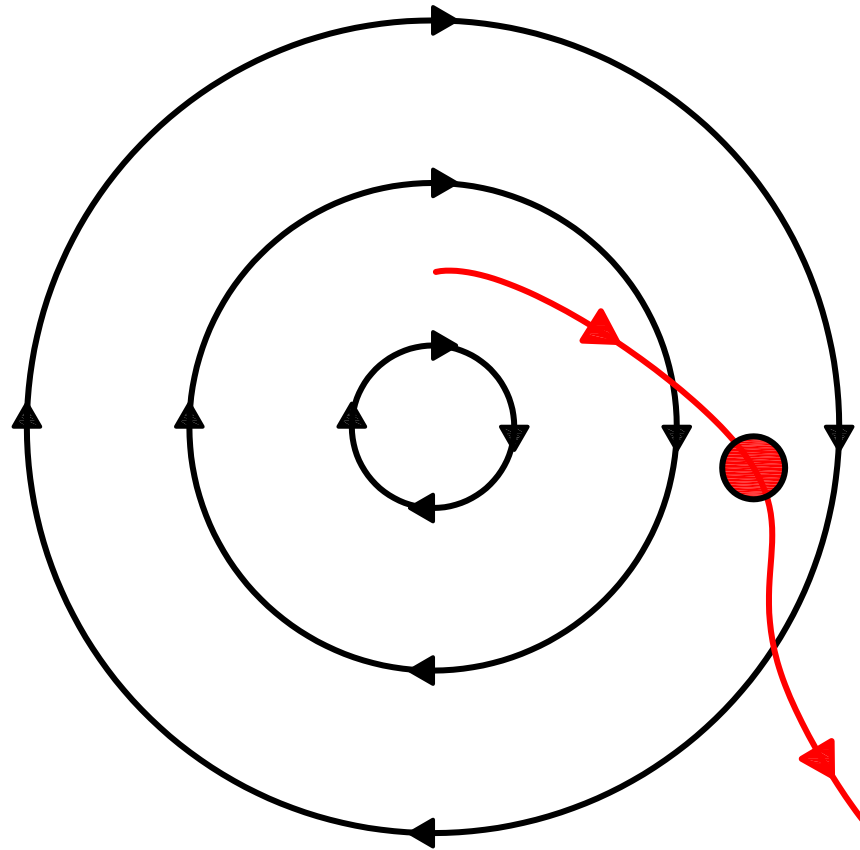
Picasso

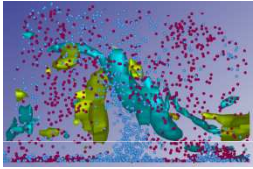


The simplest problem...



- We focus on the problem of the one single particle in a fixed vortex*





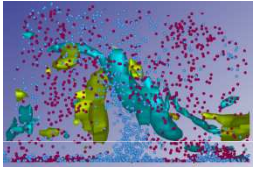
... A little Literature search on the influence of inertia on the Behavior of a floating body immersed in a vortical fluid



*Sirens
in*



Homer let Circe tell the sailor experinece to Odysseus...

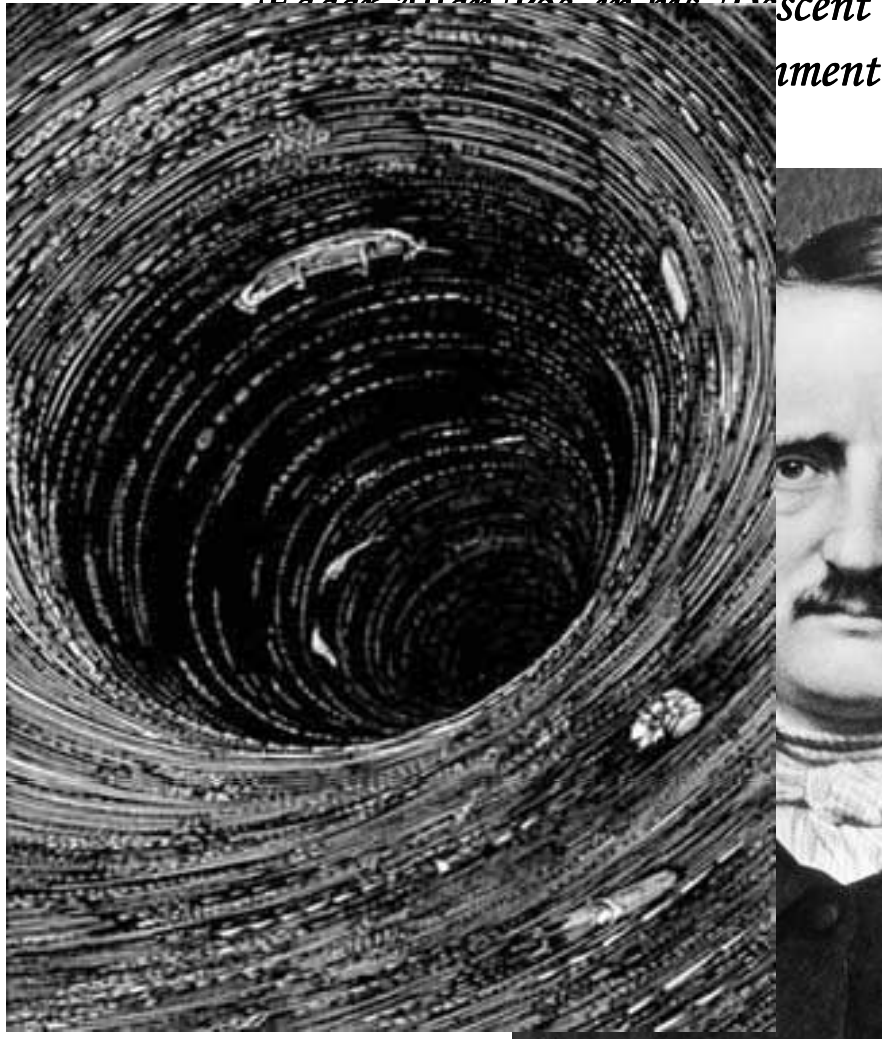


... A famous 'local' vortex, 2....

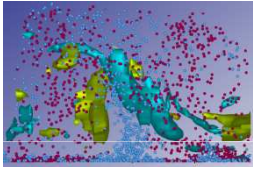
An important difference between elongated bodies and spheres



*Edgar Allan Poe in his Descent
into Hell*



F. Eichenberg



... Essentially, we learn that inertia controls particle dynamics
This is expressed via the particle relaxation time scale



The dynamics of a particle is controlled by the drag parameter τ_p (in the simplest dynamic model)

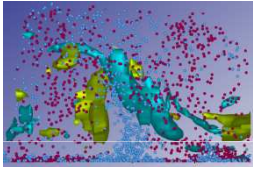
$$\frac{d m_p \bar{v}_p}{dt} = \frac{1}{2} C_D^* \pi \frac{D_p^2}{4} (\bar{u}_f - \bar{v}_p) |\bar{u}_f - \bar{v}_p|$$

which reduces to: $\frac{d \bar{v}_p}{dt} = \frac{\bar{u}_f - \bar{v}_p}{\tau_p}$

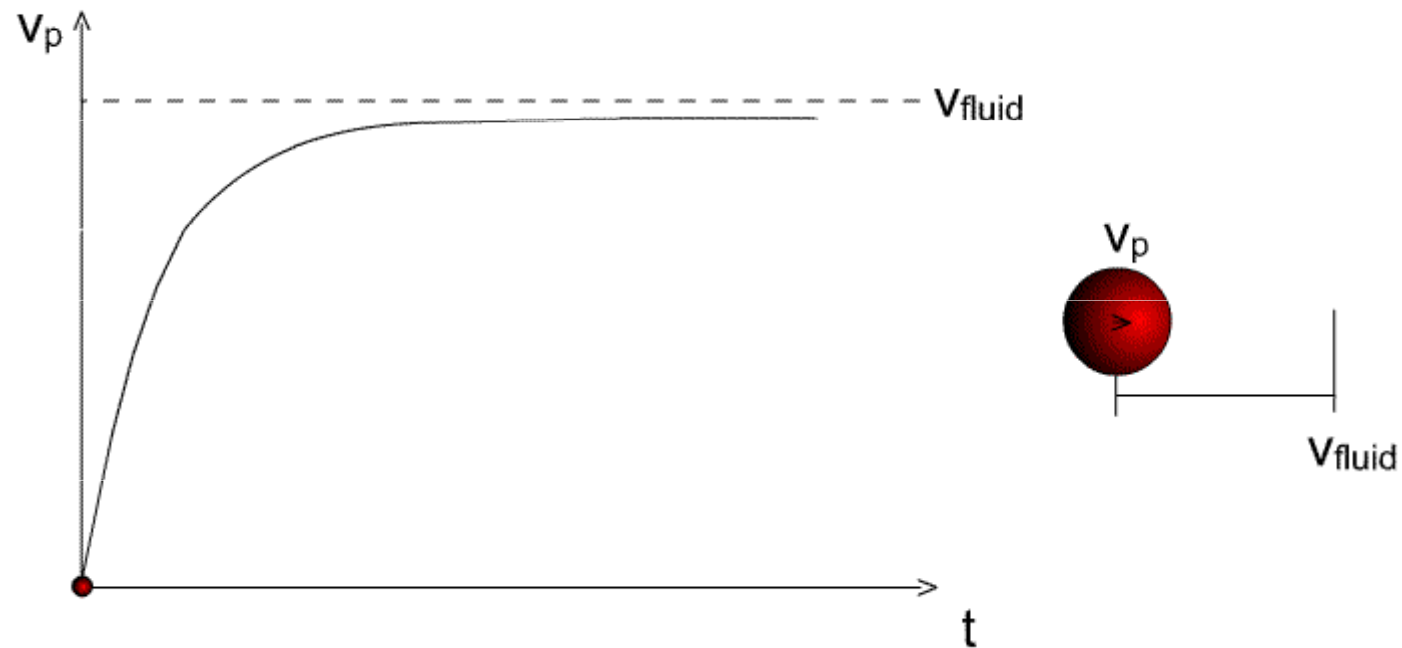
$\tau_p =$ particle denser.

$$\text{Time scale} = \frac{\rho_p D_p^2}{18 \mu}$$

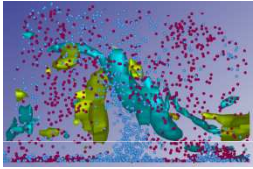
*purely creeping flow (Stokes flow)



*... Essentially, we learn that inertia controls particle dynamics
This is expressed via the particle relaxation time scale*



*.. The particle relaxation time scales with the time
It takes to accelerate a particle to the ambient fluid velocity*



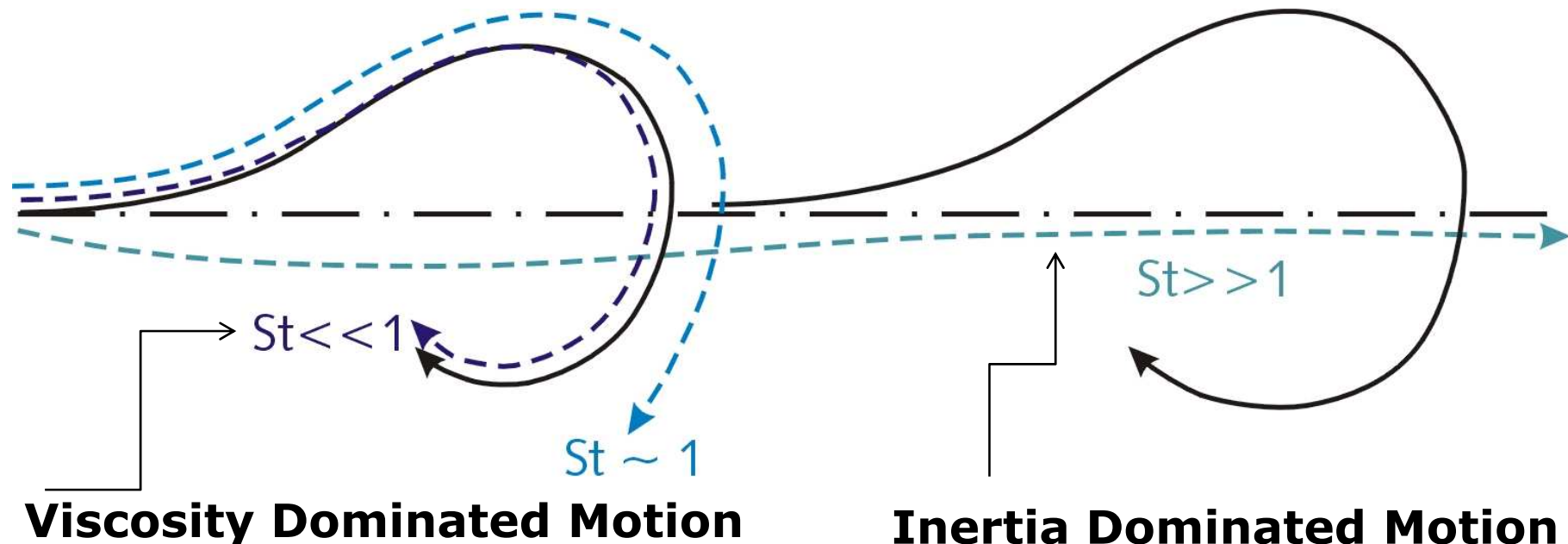
The characteristic particle time scale has a meaning when compared with a relevant Flow Time scale

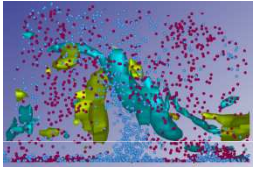


Particle Relaxation Time, $\tau_p = d_p^2 \rho_p / 18$

Flow Time Scale, τ_f^μ

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



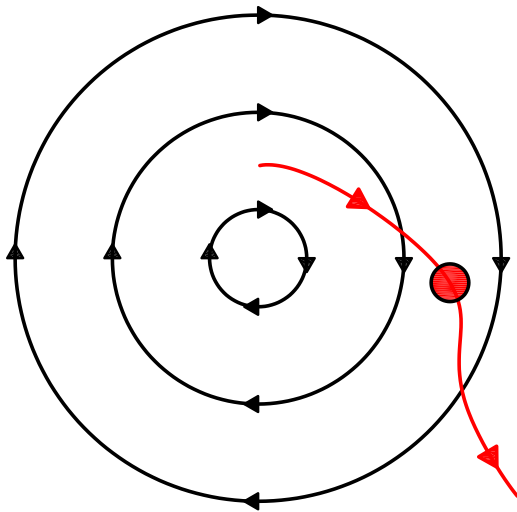


And now, we can get more complicate...



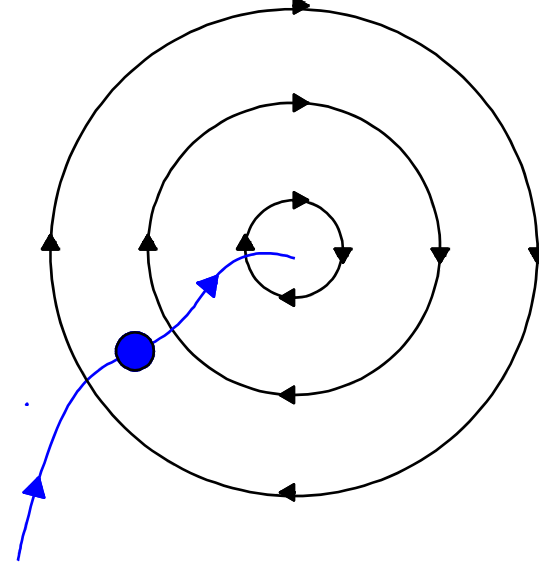
We start with two-D vortices and pointwise spheres....

□ **Particle (Aerosol):** $\rho_p \gg \rho_F$

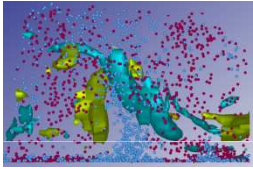


□ **Particles are expelled from the vortices via the slingshot effect**

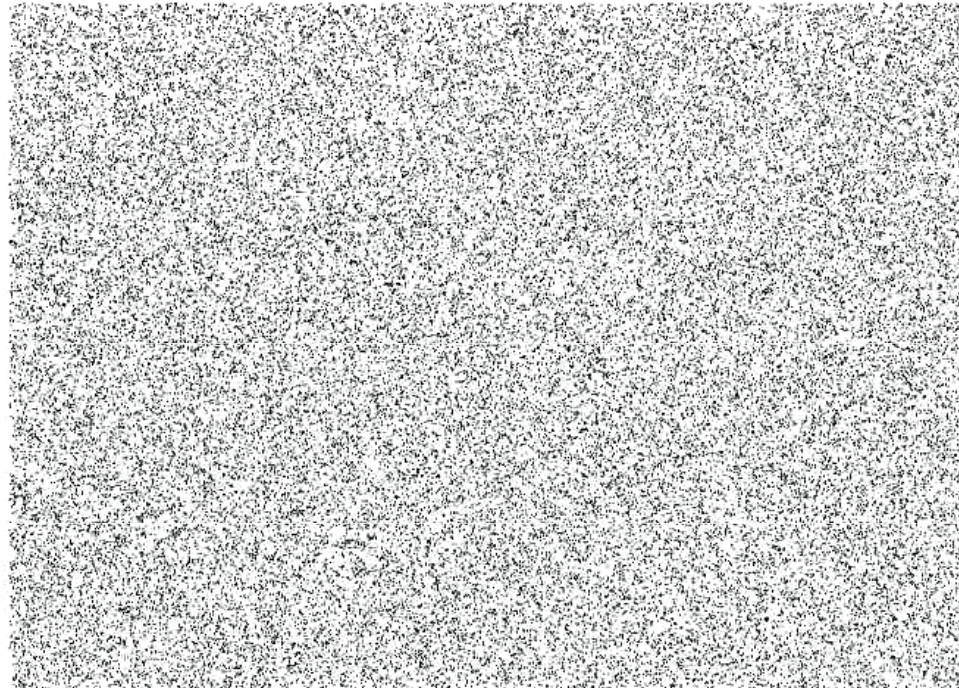
□ **Bubble:** $\rho_p \ll \rho_F$



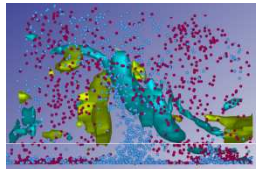
□ **Bubbles are driven inward, due to the lesser inertia**



... So, in a more pictorial view, if there are no vortices we can picture particle settling under gravity as...



Particles settle at the velocity determined by the equilibrium between Drag (Stokes) and Gravity: v_s
$$= d_p^2 2g(\rho_p - \rho_f) / (18 \mu)$$



*.. What if we add vortices? The problem of light/heavy particle settling under gravity becomes non-trivial (Maxey 1987)
... preferential segregation*

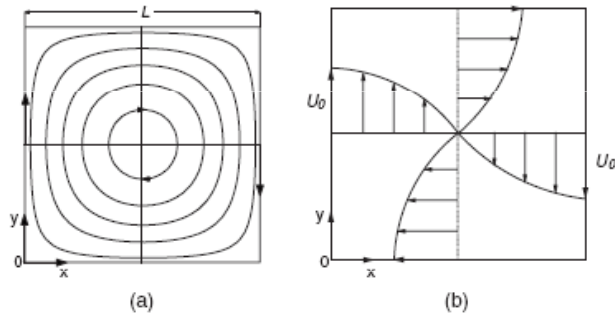
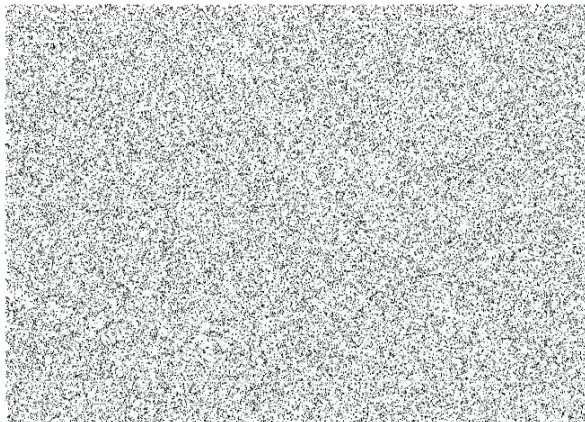
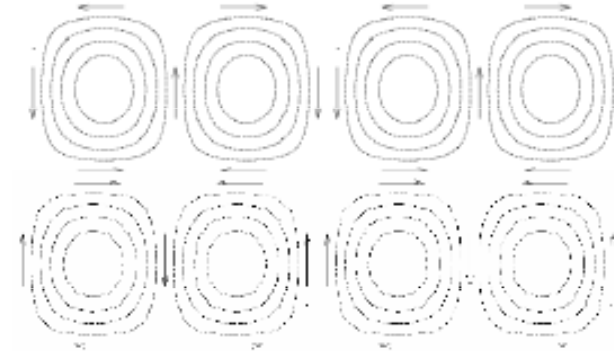


FIG. 1. (a) Streamlines and (b) velocity profiles for the periodic cellular flow field. The arrows show direction of the flow.

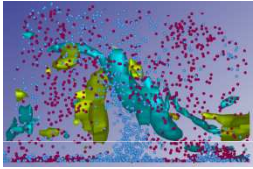


Heavy Particles

Heavy particles are propelled out of the vortices while settling down. Light bubbles are propelled inward while rising up. Globally, there is a general influence on the effective settling velocity (Maxey, Phys Fluids 1983)



Light Bubbles



...with this in mind, the following experiments become inexplicable...



Turbulence increases the average settling velocity of phytoplankton cells

by the author, Diego M. M. and Francisca P. et al.

Abstract: We conducted an experimental study to investigate the effect of turbulence on the settling velocity of phytoplankton cells. We used a microfluidic device to generate controlled turbulence in a channel. The settling velocity of cells was measured using a high-speed camera. We found that the settling velocity of cells increases with the intensity of turbulence. This is in contrast to the theoretical prediction that the settling velocity of particles in a fluid is independent of the flow velocity. Our results suggest that turbulence can significantly affect the settling velocity of phytoplankton cells in natural environments. This has implications for the study of phytoplankton dynamics in lakes and oceans.

1. Introduction: Phytoplankton in the upper mixed layer of lakes and oceans live in a turbulent flow regime. This turbulence can affect many aspects of their physiological and morphological functioning, including the efficiency of nutrient assimilation (1), gene expression (2), and cell division (3). One of the most important effects of turbulence on phytoplankton is its effect on sedimentation rates. A complementary role is usually assumed for turbulence, especially for organisms with flagella, other organelles, or cilia, that sink from the surface to depth. However, this potential role remains unclear. The effect of turbulence on the settling velocity of cells. The results presented in this paper clearly demonstrate that turbulence increased the settling of phytoplankton cells, regardless of the species considered, and independent of turbulence-generation devices or velocity-measurement techniques. Our evidence questions the traditionally accepted notion that turbulence decreases phytoplankton settling in the ocean.

2. Methods: Experimental particles: Four phytoplankton species (*Chlorella* sp., *Microcystis* sp., and *Phaeodactylum* sp.) of different sizes (20, 10, 25, and 10 µm equivalent spherical diameter (ESD), respectively) and morphology were measured in films of various turbulence intensities, and particle settling velocities were independently recorded. Additional experiments were done with commercial pollen grains (Clematis, 9.5 µm ESD), polystyrene spheres (175-µm ESD), and disrupted rat liver cells (20-µm ESD) as examples of particles in the size range of large phytoplankton and with a tendency to sink (pollen and rat liver) or float (rat liver).

3. Results: All experiments were made with particle concentrations 10^6 cells per volume, with negligible effects on the flow. It is also a low concentration to observe significant deviations from Stokes terminal velocity due to interactions between the fields generated by two falling particles (4). These deviations scale to the ratio of particle diameter to distance between particles (5). The value of the latter can be estimated as the average ratio (over of the particle concentration ($$10^6$ cells per volume) divided by individual volume (function of particle ESD). Ratio of ESD to distance between particles of the order of 0.01 are obtained. Deviations from Stokes terminal velocities observed in our experiments are much higher (see below). Therefore, interactions between particles cannot be the exclusive origin of the results presented below. On the other hand, suspensions containing more than one degree of freedom, the structure of the suspensions with a negligible effect on particle velocity due to velocity changes.$

4. Discussion: We carried out a series of experiments with different turbulence-generation devices and particle velocity measuring techniques. These experiments were aimed at guaranteeing that the experimental setup was not hindered by artifacts caused by either the device implemented, or generated due to the techniques used to record particle velocities. A set of experiments generated turbulence by creating a thin cylinder where cylindrical tanks of different diameters in a Couette device type of design with its corresponding instrumentation implemented for measuring velocities (Fig. 1) and by. A series of experiments was conducted with a vertical rotating grid and a horizontal 320-µm diameter cylinder at tank (Fig. 1). In the same, different levels of turbulence intensity were obtained through frequency variation of the oscillating grid and velocity recorded by acoustic methods. Neither the Couette nor the grid system generated large stable structures in the flow. Therefore, the behavior of particles in the bulk flow is the result of their interaction with turbulence at small scales.

5. Conclusions: Our results show that the smaller volume means a smaller Stokes number and a larger critical Reynolds number, with diameters of 1 µm and 20 µm, respectively, are that with gentle flow. However, our results with a phytoplankton culture. The small cylinder was spun at angular velocities $$1$ between 1.5 and 0.1 rad per s to produce different levels of turbulence intensity. Reynolds (Re) and Taylor (T) numbers characterize the level of flow instability within Couette devices (5). These numbers can be calculated as (6):$

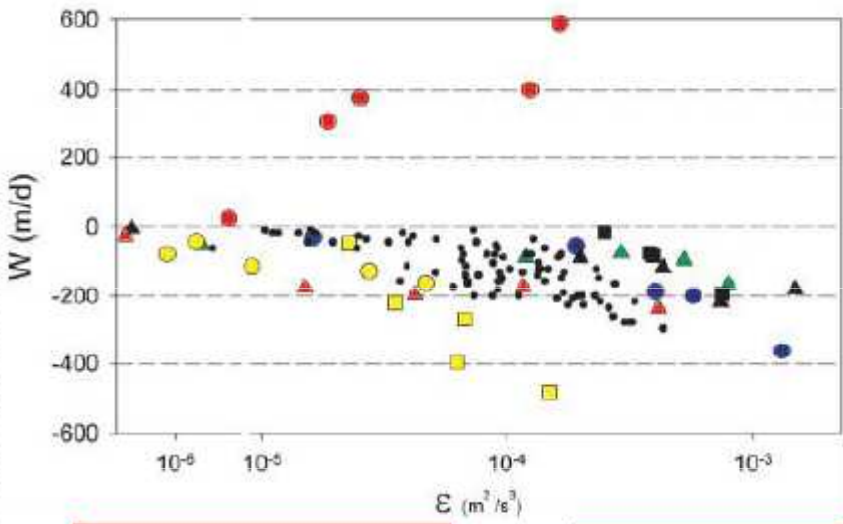
$$Re = \frac{\rho \omega r^2}{\mu}$$

$$T = \frac{4\pi \rho \omega^2 r^3}{g(\rho - \rho_f)}$$

where r is the radius of the inner cylinder, ω is the outer cylinder rotation rate, ρ is the kinematic viscosity, and ρ_f is divided by the radius of outer cylinder. For those experiments (see below) where the inner cylinder spins in opposite direction to the inner one, g is the angular velocity of the outer cylinder divided by 2.

6. Acknowledgments: This work was supported by the Spanish Ministerio de Ciencia e Innovación (MCI) through the project PID2019-105881GB-I00. We thank Dr. J. M. García for his help in the initial stages of this work.

7. References: (1) M. J. Behr, *Journal of Great Lakes Research*, vol. 42, pp. 1-10, 2016. (2) M. J. Behr, *Journal of Great Lakes Research*, vol. 42, pp. 1-10, 2016. (3) M. J. Behr, *Journal of Great Lakes Research*, vol. 42, pp. 1-10, 2016. (4) M. J. Behr, *Journal of Great Lakes Research*, vol. 42, pp. 1-10, 2016. (5) M. J. Behr, *Journal of Great Lakes Research*, vol. 42, pp. 1-10, 2016. (6) M. J. Behr, *Journal of Great Lakes Research*, vol. 42, pp. 1-10, 2016.

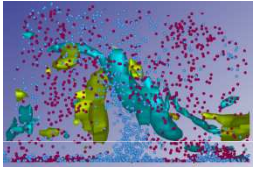


$$\langle v_y \rangle > v^{Stokes}$$

$$\rho \approx \rho^{water}$$

A species of phytoplankton (●, *Artemia Salina* Eggs) rise with:

At a recent conference this paper was brought to the attention of an audience largely Inexperienced of Biocomplexity problems... How can be a particle heavy enough to take the Vortex uplift and still light enough to rise?



...but this because there is more than just gravity, drag and inertia... there are the non-stationary effects and others...



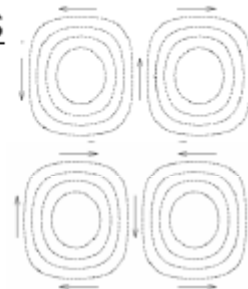
- many forces dominate particle motion: *added mass, lift, Basset...*

$$m_p \frac{d\bar{v}_p}{dt} = (m_p - m_F) \bar{g} + m_F \frac{D\bar{u}}{Dt} - \frac{1}{2} m_F \frac{d}{dt} (\bar{v}_p - \bar{u}) - 6\pi a \mu (\bar{v}_p - \bar{u}) - 6\pi a^2 \mu \int_0^t \frac{d(\bar{v}_p - \bar{u})/d\tau}{\sqrt{\pi\nu(t-\tau)}} d\tau$$

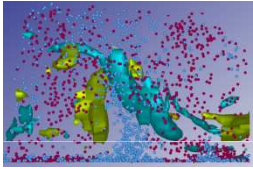
Maxey and Riley, 1983

Object is to study the behavior of particle only slightly lighter than the surrounding fluid in a Taylor-Green Cellular Flow.

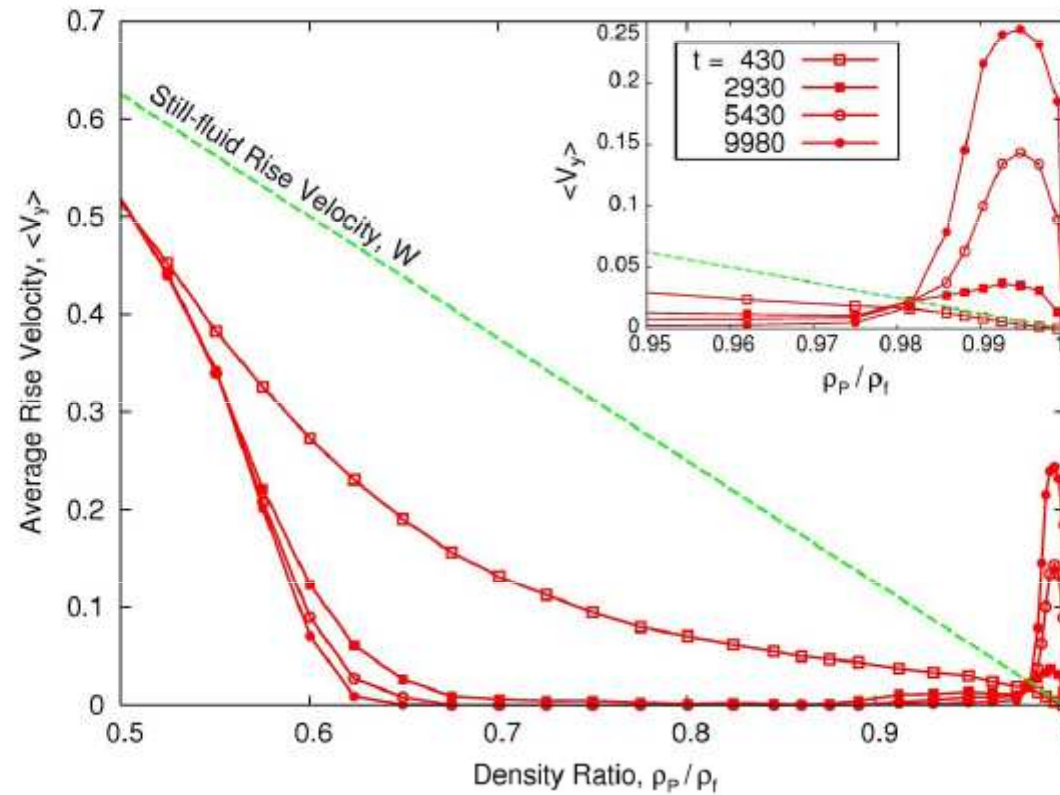
- We will reproduce the numerical model of Maxey PoF (1987);
- Particle/fluid density: ρ_p/ρ_f [0.5:1.0]
- Forces Acting: Inertia; Gravity; Buoyancy; Added Mass



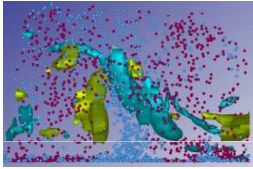
Albeit an unsatisfactory model, this equation is probably the most accurate Representation of the forces acting on a particles moving in a fluid under no restrictive Assumption beside being pointwise (!!!)



...just adding the added mass effect the rise velocity of plankton can change dramatically....



Mean rise velocity, $\langle V_y \rangle$, of light particles in (Taylor-Green) vortex flow versus particle-to-fluid density ratio, ρ_p / ρ_f (Marchioli et al., Physics of Fluids, 2007)



... intermezzo... but please, remain seated

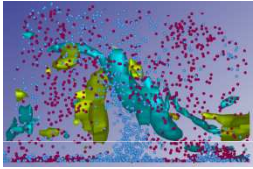


First half:

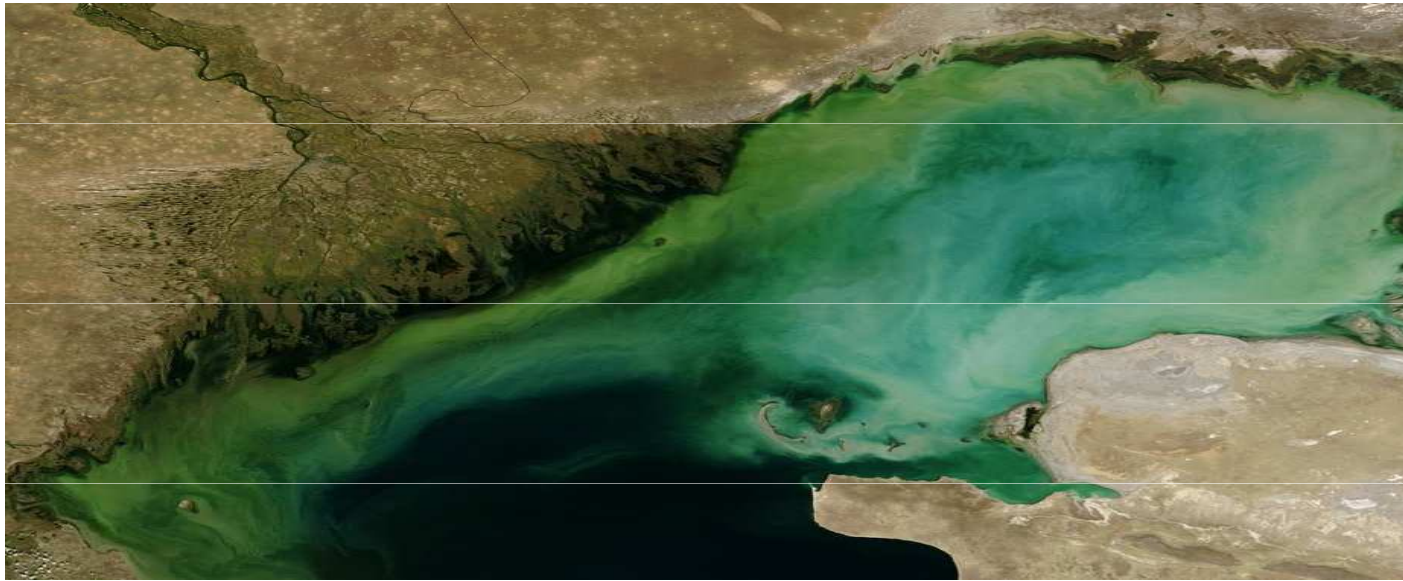
*The problem of particle dispersion in vortical flows is
Definitely non-trivial... there is still room for simple models*

Second Half:

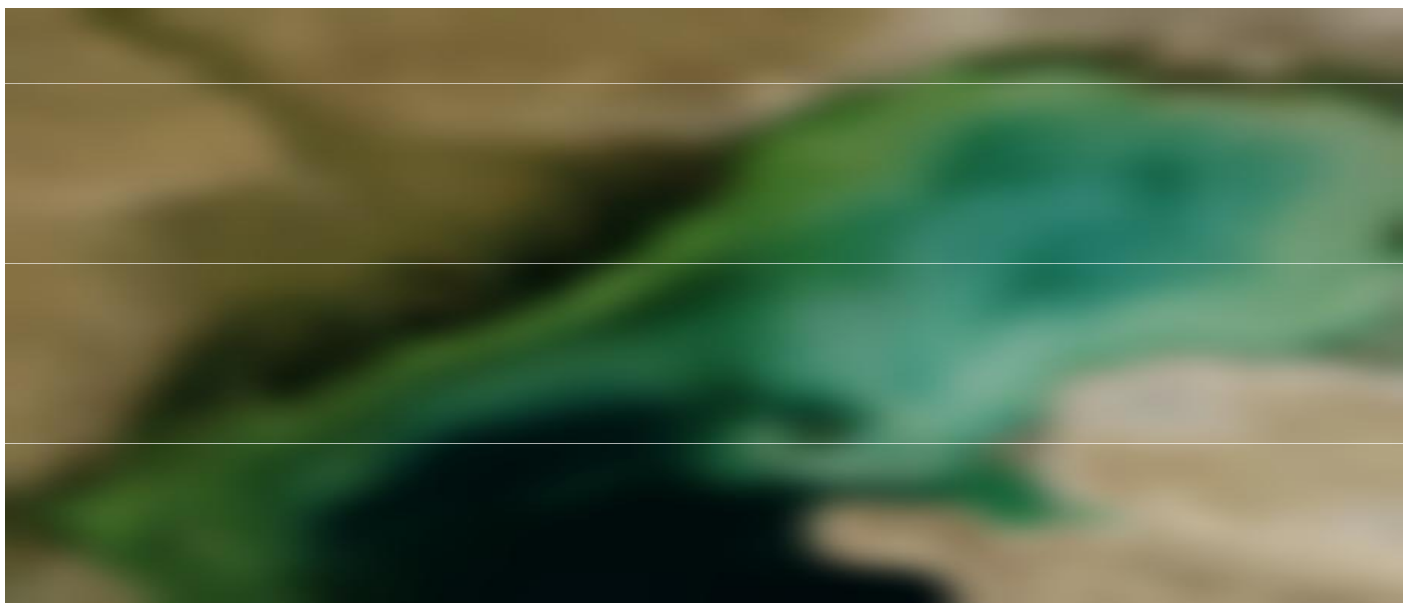
And what can we do with complicate models?



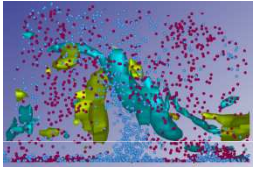
*We want to solve for turbulence...how accurately?
Pollution in the Caspian sea (from B.G.)*



Non Filtered



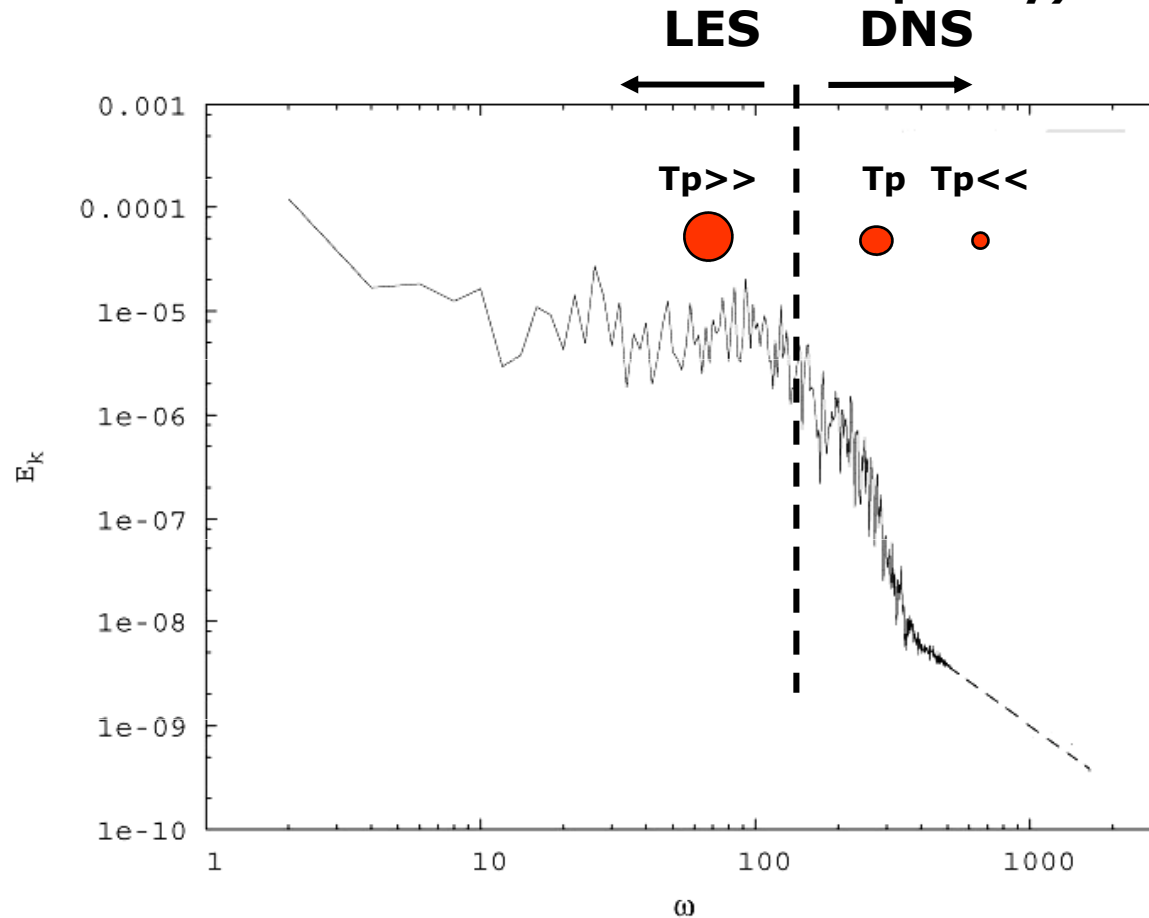
Filtered



but, in (albeit dilute) multiphase Turbulent flow, which are the relevant scales we should solve for particle motion?



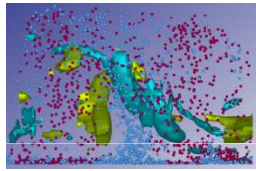
This is a generic turbulence spectrum (Energy Associated with frequency)



Any filter will prevent particles from being exposed to small scales which can modify their local behavior, segregation,

Inaccurate particle dispersion will bring errors into subsequent particle motion and fluid

The scatter in the data is too large, even for Engineers! And these data Are actually used for modelling practice



*So, how can we solve all these scales? We do not want to filter
Out any relevant scale of motion! ...*



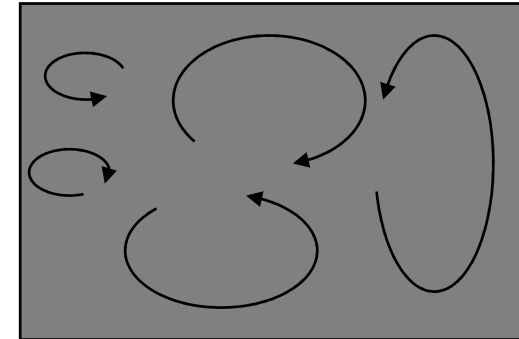
Reynolds Averaged Techniques

(Fluent, StarCD, CFX, etc.)

- Need extensive empirical data for constants
 - Geometry specific
- Underlying assumption of isotropy (sometimes)

$$\langle u_i^l u_j^l \rangle$$

$$\langle u_i^l T^l \rangle$$



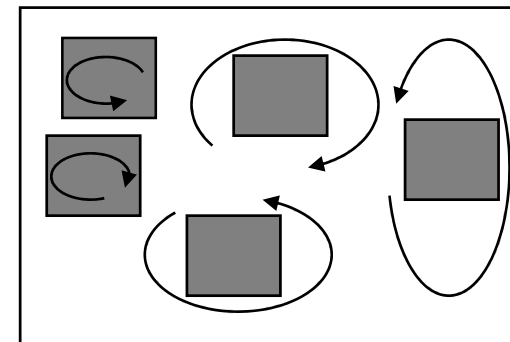
Macro-scale

Large-Eddy Simulations (LES) (Commercial Research, etc.)

- Resolve the large eddies
- Average over small scales
- Simple universal models (may be)

$$u_i^l u_j^l$$

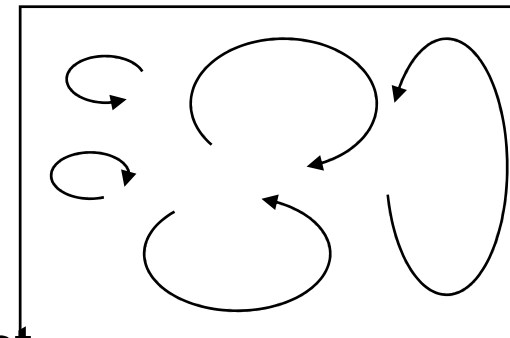
$$u_i^l T^l$$



Meso-scale

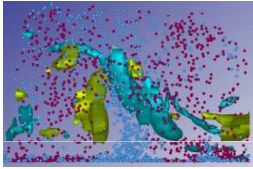
Direct Numerical Simulation (DNS)

- Valid for resolution finer than smaller eddies
- Applicable to low Reynolds number turbulent flows (-> due to limited computational power)



Micro-scale

Operative def. DNS: No need of subgrid
Models to predict smaller scales motion/effect.



The downside of Direct Numerical Simulation

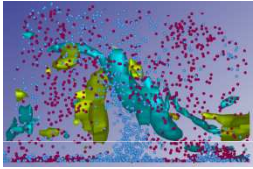
Numerical Issues: Spatial Resolution



-
- Influenced by numerical method used (spectral methods are better)
 - Differentiation error and errors due to nonlinearity of governing equations also affect
 - Reynolds number is most important. DNS is restricted (by cost considerations) to low Re flows.

$$N_{DNS} = (0.088 Re_h)^{9/4}$$

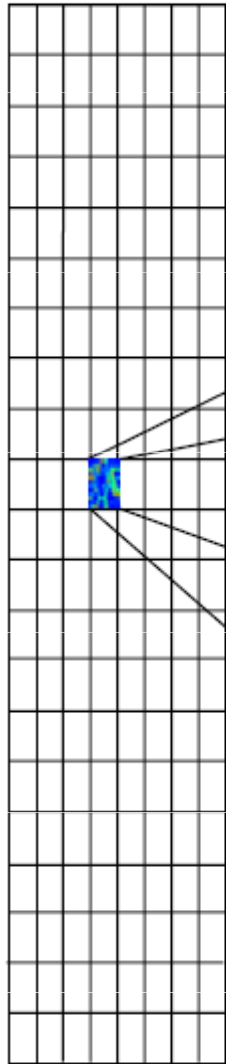
- ⇒ Re of 10^6 requires 133 billion grid points!!
- But, since the higher Re the smaller (and faster) the vortices, the cost is proportional to $Re^{(11/4)}$
- Optimal Re depends upon application. Re of DNS need not actually match real-life Re to be useful



Our approach is the following: we solve smaller problems in the belief that they 'Control' the macroscale behavior

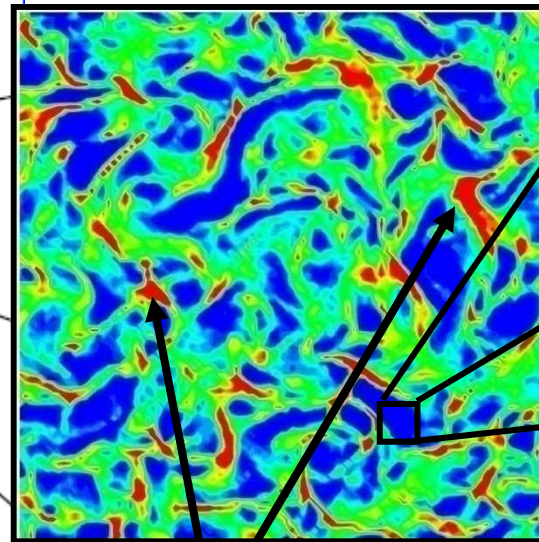


Schematic of riser with mesh used for simulations



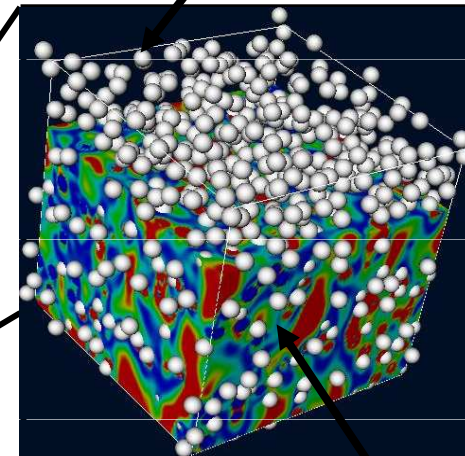
Solid Volume Fractions

25% 20% 15% 10% 5% 0%



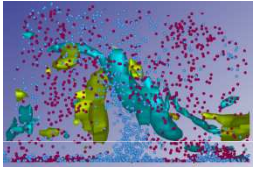
Particle Clusters

Solid Particle



Gas

Macro-scale (cm-m) Meso-scale (mm – cm) Micro-scale (μm)

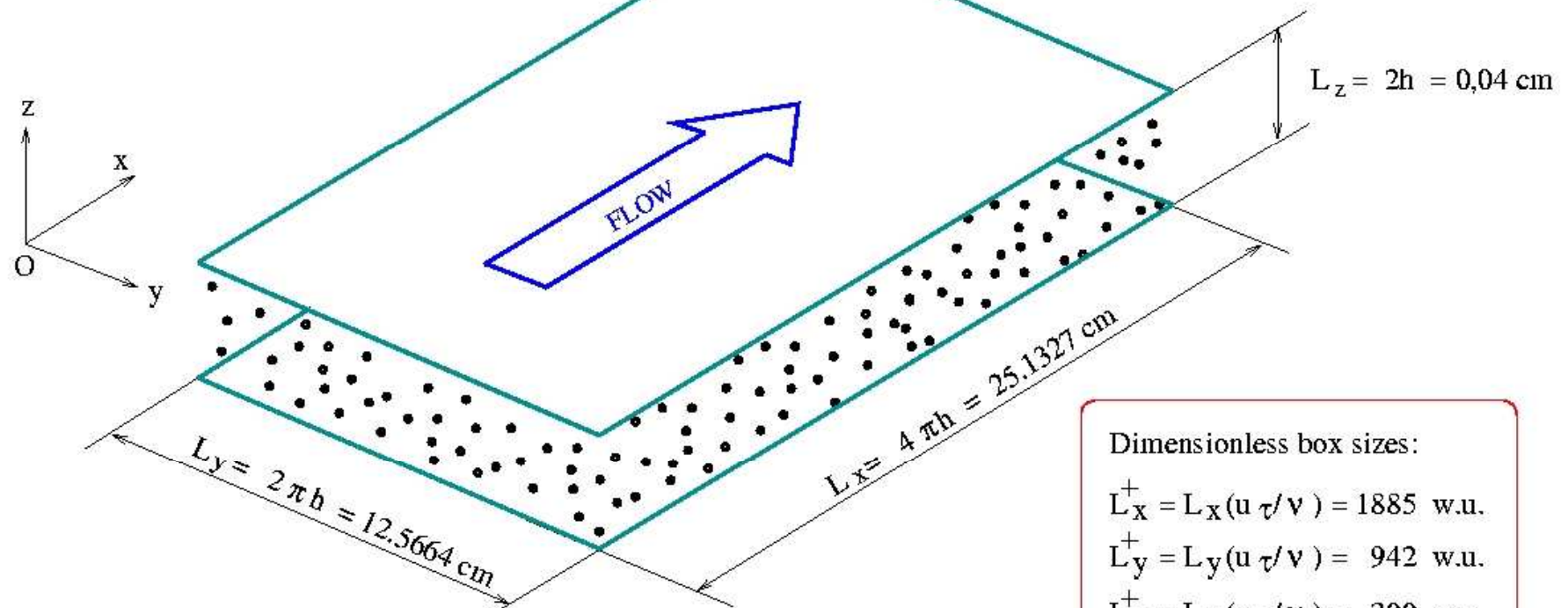


...What we do in our lab is Direct Numerical Simulation to Understand the Physics and develop simpler models for engineering practice

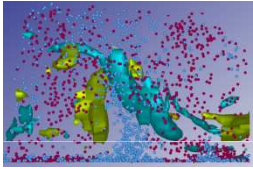


We focus on this problem

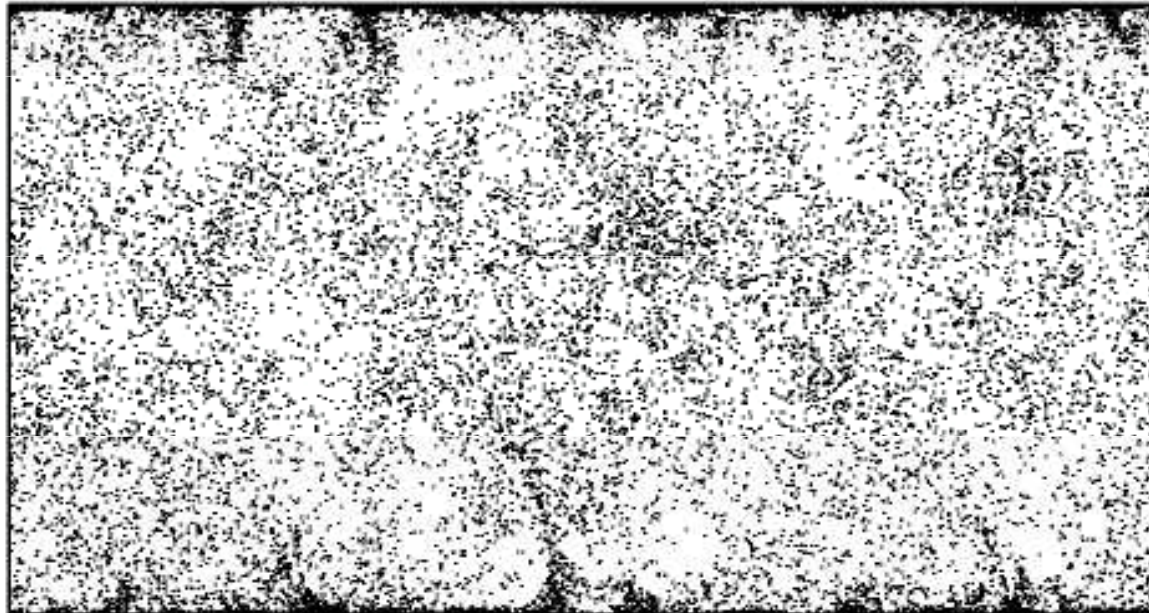
pseudo-spectral DNS of the turbulent gas flow field at $Re_\tau = u_\tau h / \nu = 150, 300, 600^*$



Calculations under way as I talk!



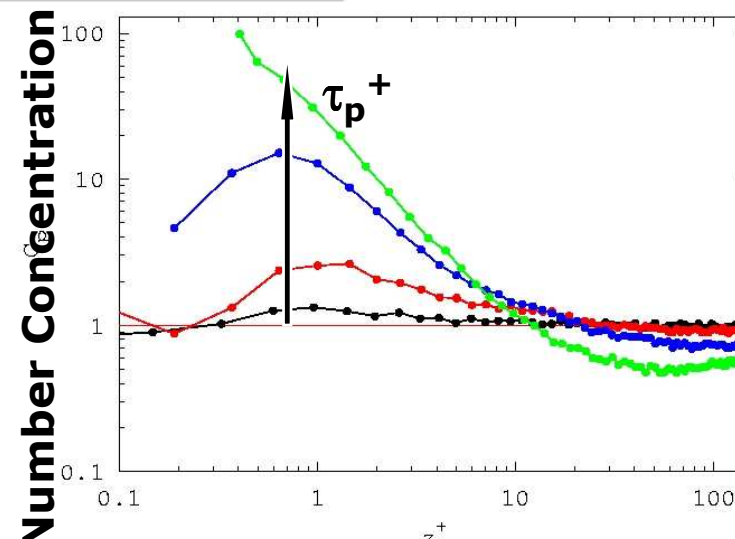
This is the typical result of our computational experiments!



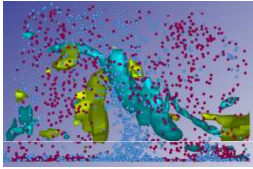
Observation –

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)



$\tau_p^+ = 25$
 $\tau_p^+ = 5$
 $\tau_p^+ = 1$
 $\tau_p^+ = 0.2$



*Rule of Thumb for Maximum Segregation/Deposition:
Matching between particles and wall flow scales*

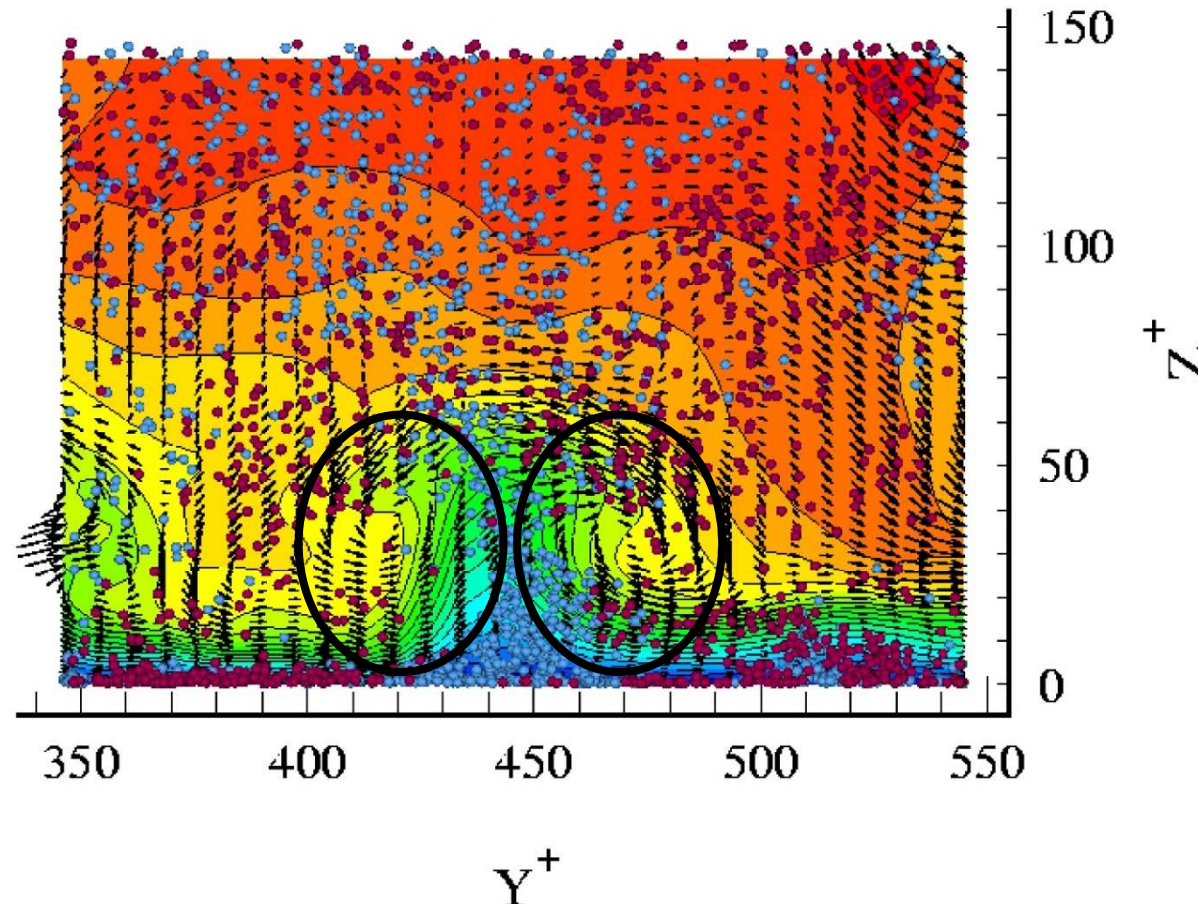


Red: high
Streamwise vel.

Blue: low
Streamwise vel.

Purple Particles:
to the wall

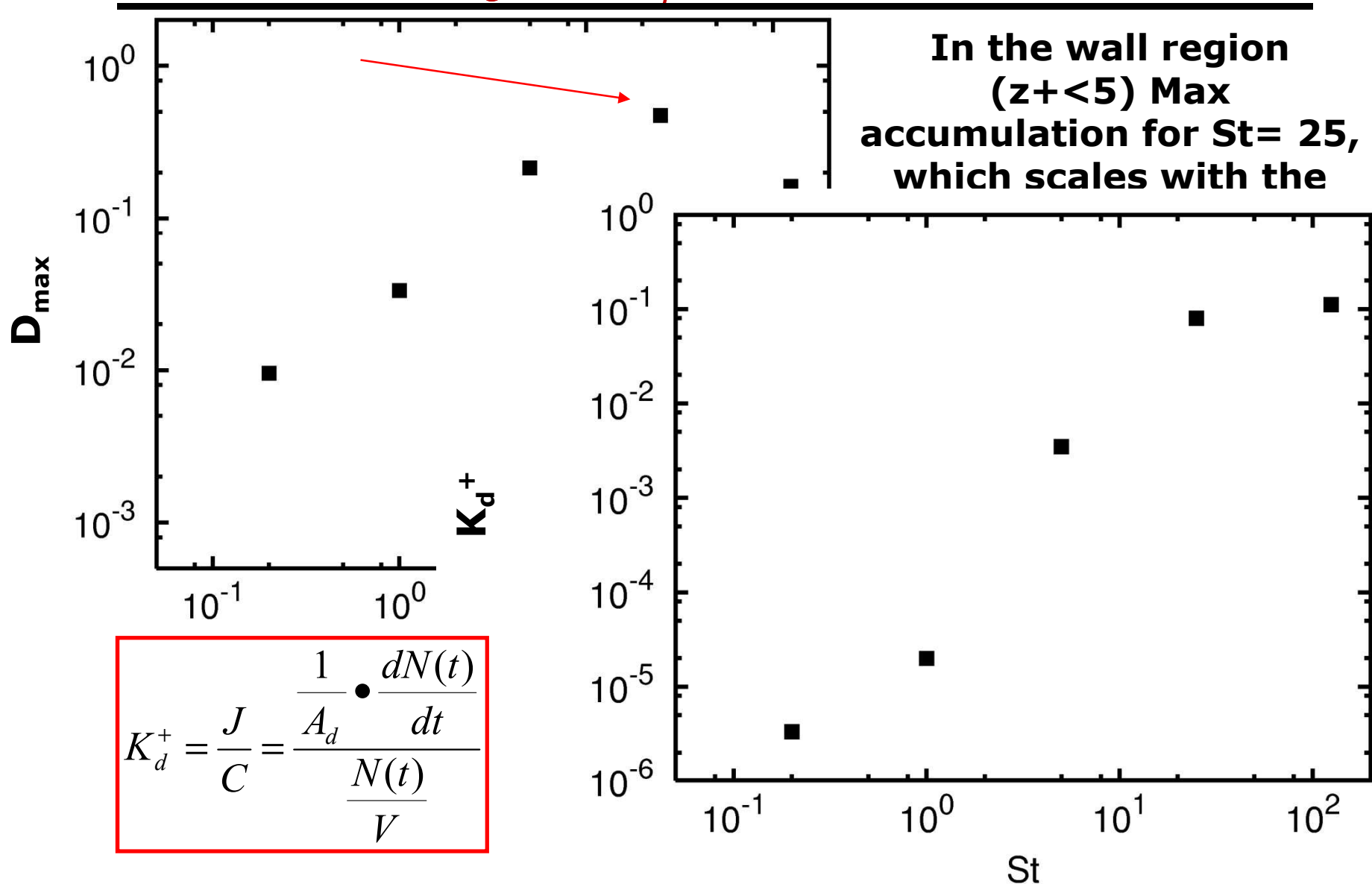
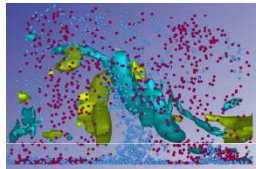
Blue Particles:
off the wall

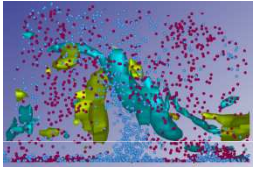


**In the context of industrial modelling of turbulent dispersed flows:
... is an accurate quantification of this effect currently available? (practical issue)
... will Large Eddy Simulation be able to capture this effect? (modelling issue)**

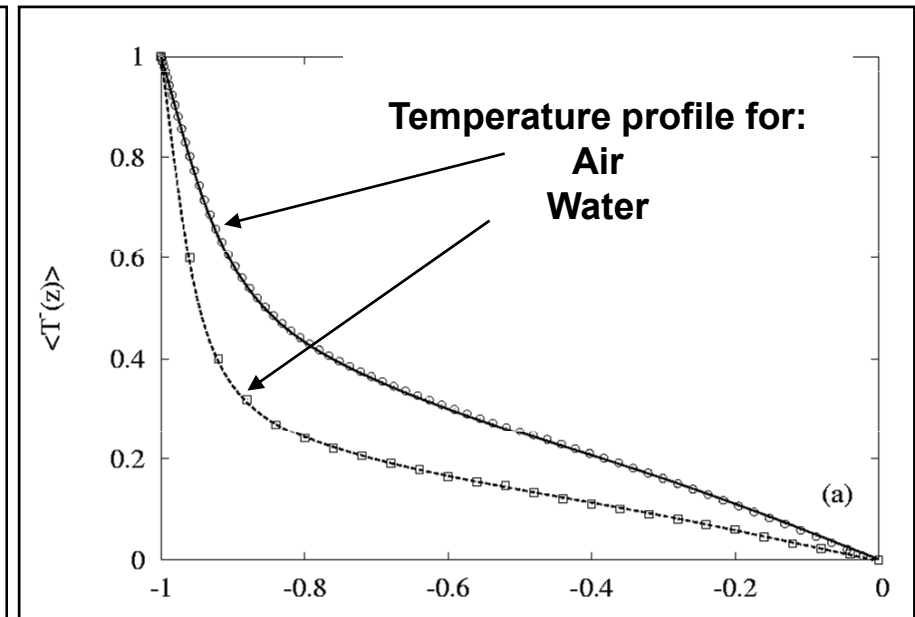
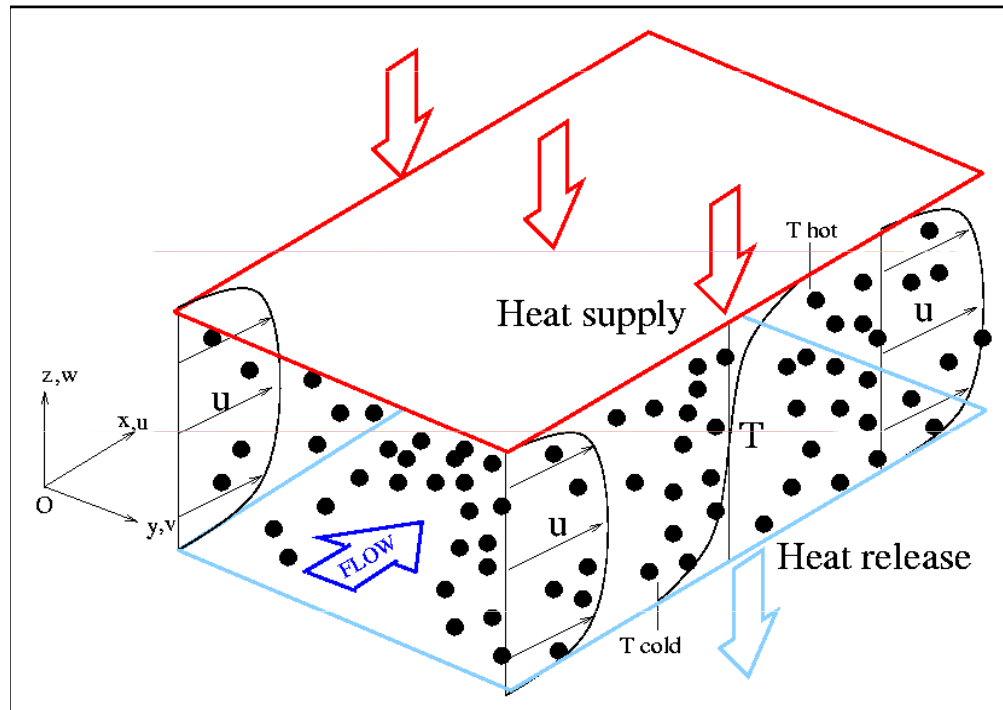


*Deposition happens in two stages:
First: Accumulation near the wall
Second: deposition at the wall*





*And now a fancy application: we added many micro and nano particles to a
Turbulent fluid in between differentially heated walls (Paper in the special issue)*

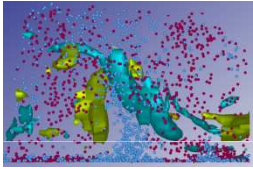


Removable heat flux (flux at the wall)

$$q_w = k \left. \frac{\partial T}{\partial z} \right|_w$$

**and k is low for
water and air**

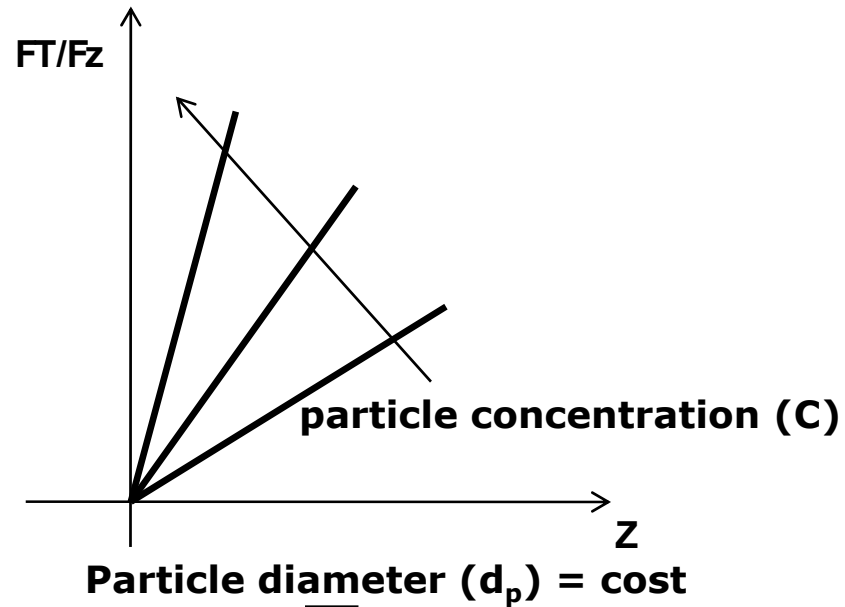
if we can use only water and we want to increase turbulent heat transfer...



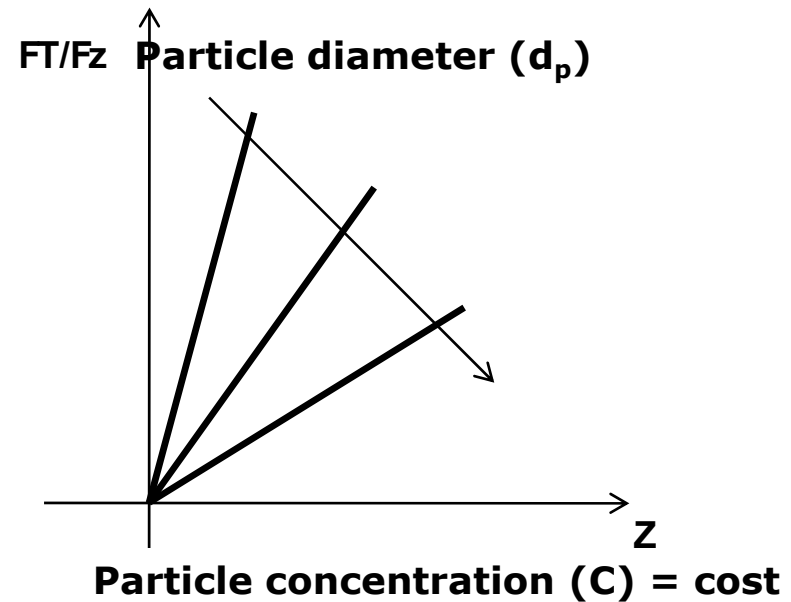
Nanofluids [nænflu:ids] n. (fis.) dilute liquid suspensions of nanoparticulate solids including particles, nanofibers, nanotubes



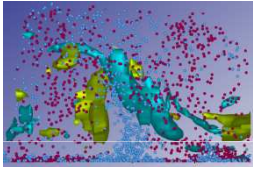
Influence of particles on carrier fluid Temperature field



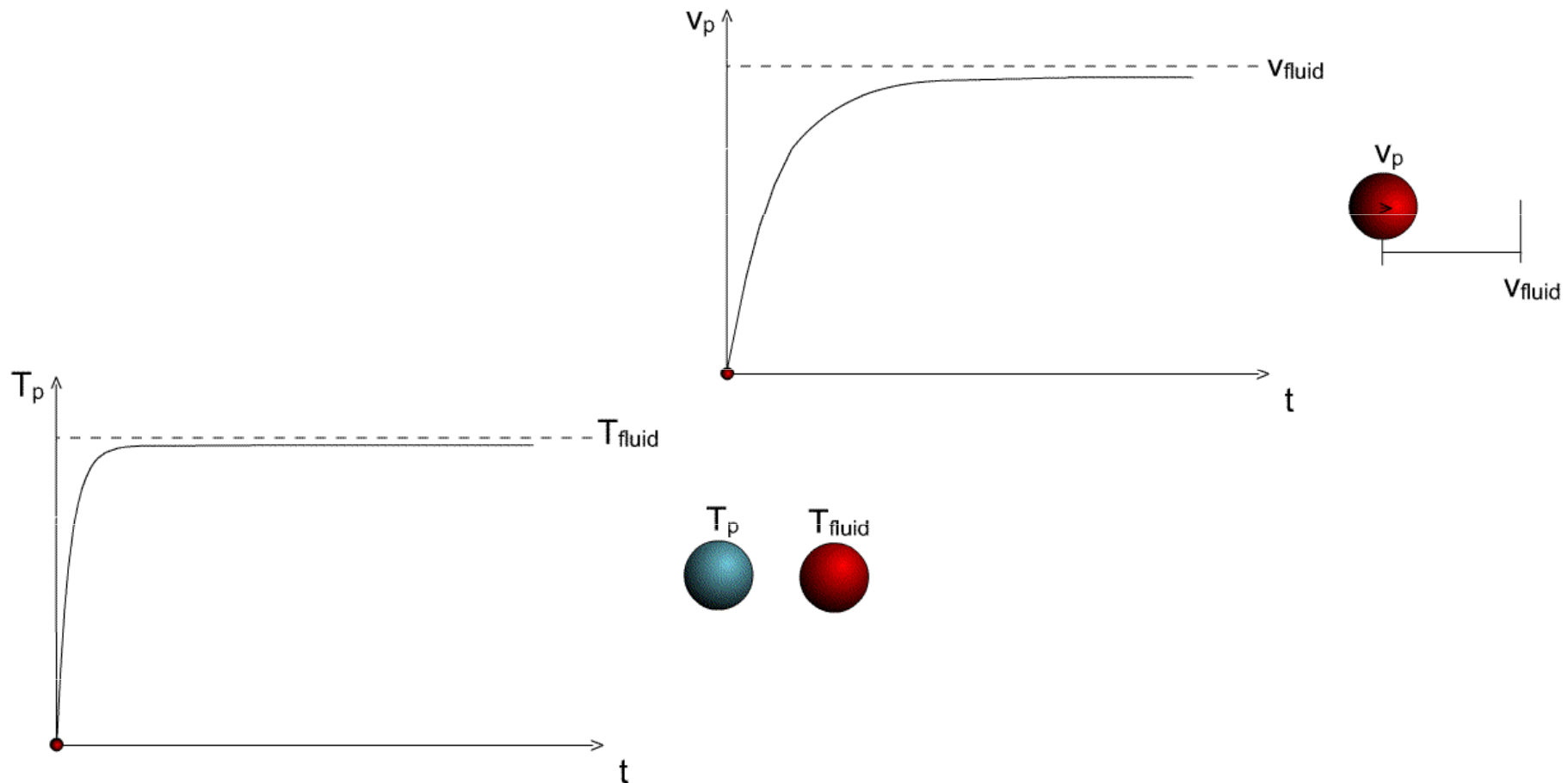
↑ Concentration → ↑ Wall Heat flux



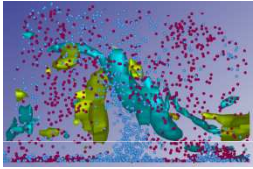
↓ Particle diameter → ↑ Wall Heat flux



*... The trick here is to use particles with small inertia
but large thermal inertia*



*.. So particles should behave like fluid but should carry the heat a longer time...
Exactly the opposite of what is shown*



... and what did we obtain insofar?
 ...heavy computations but not much quantitative satisfaction



Mass Conservation

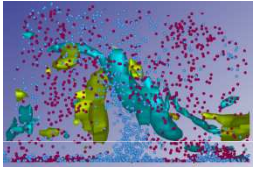
Mom. Conservation
 (Navier-Stokes)

Heat Transport

Momentum Cons.
 For each particle

Energy Cons.
 For each particle

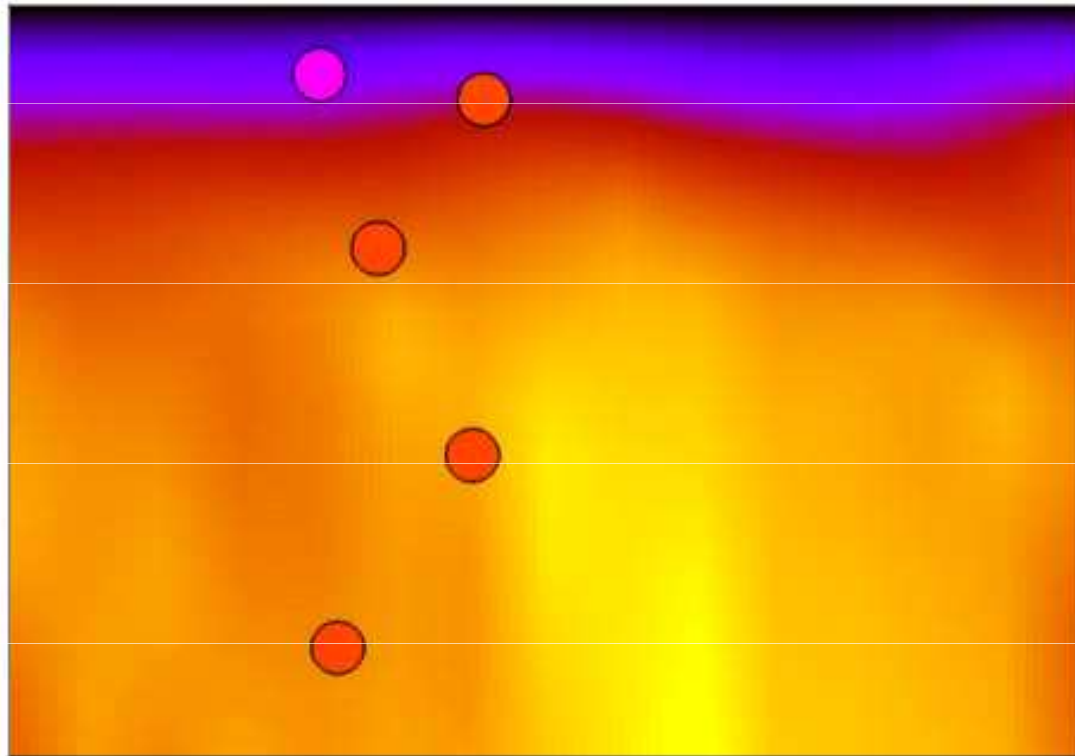
$$\left\{ \begin{array}{l}
 \frac{\partial u_i}{\partial x_i} = 0 \quad i=1,2,3 \\
 \quad \quad \quad \quad \quad \quad \quad j=1,2,3 \\
 \\
 \frac{\partial u_i}{\partial t} = - \frac{\partial u_i u_j}{\partial x_j} + \delta_{ia} + \frac{\nu}{Re} \frac{\partial^2 u_i}{\partial x_j \partial x_j} - \frac{\partial p}{\partial x_i} \\
 \\
 \frac{\partial \bar{T}}{\partial t} = - \frac{\partial \bar{T} u_j}{\partial x_j} + \frac{1}{Re \cdot Pr} \frac{\partial^2 \bar{T}}{\partial x_j \partial x_j} \\
 \\
 \bullet \quad m_p \frac{d\vec{v}_p}{dt} = \sum_i \vec{f}_i \approx f(\vec{v}_p, \vec{v}_T) \\
 \\
 \bullet \quad m_p c_p \frac{d\vartheta}{dt} = h_p \pi d_p^2 (\tilde{v} - \vartheta_p) \approx f(\vec{v}_p, \vartheta_p)
 \end{array} \right.$$



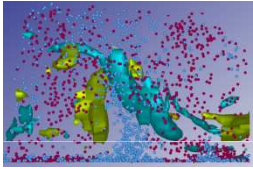
*...and what have we obtained insofar?
a collection of qualitative results...*



COLD WALL



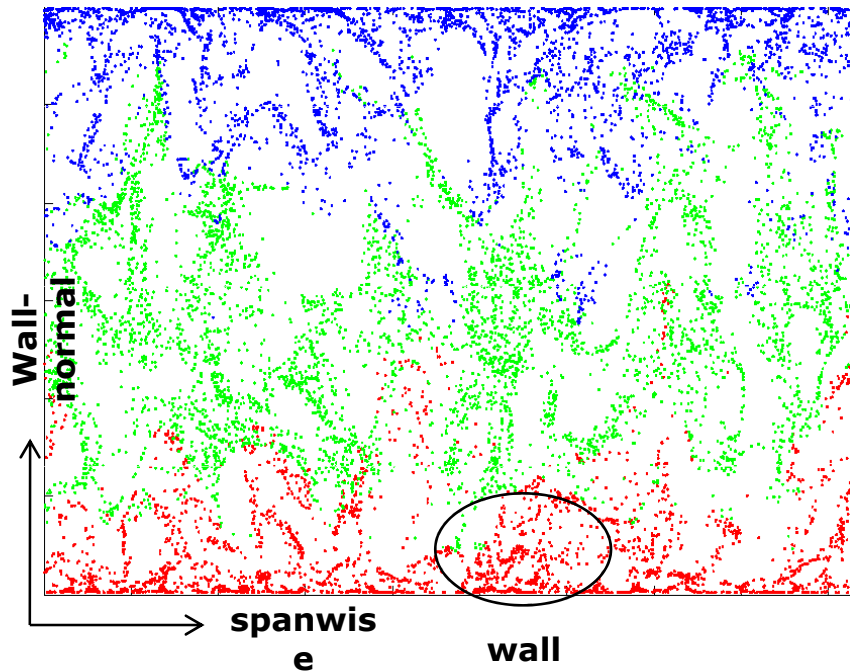
BACKGROUND:
From Yellow (highest) to
black (lowest) temperature.



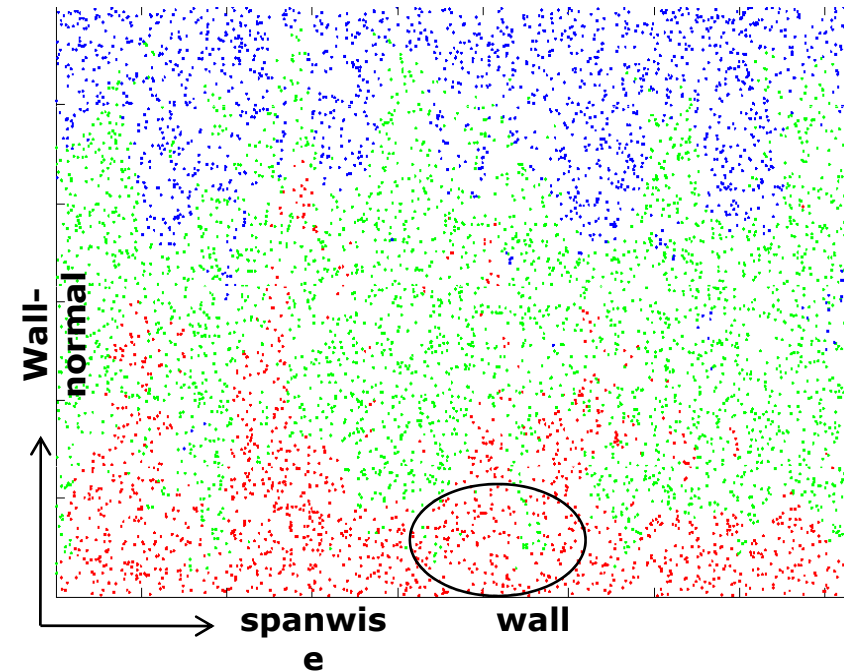
*...but in this case we have to avoid preferential distribution.
Size matters, the smaller the better!*



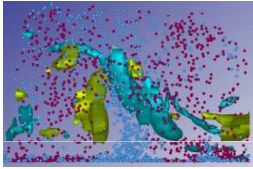
Solids (Gold in this case) have thermal conductivity orders of magnitude higher than water, but their size matters...



8 micron particles segregate



4 micron particles are already uniformly distributed



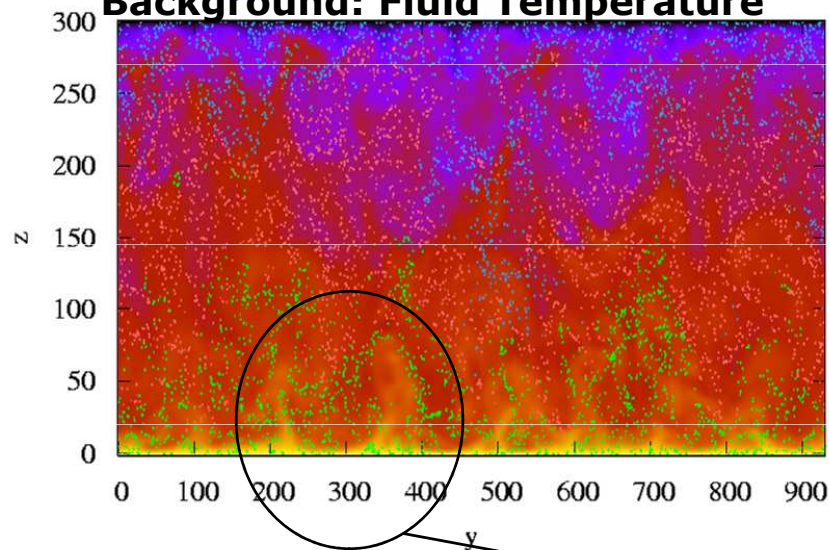
*...and what have we obtained insofar?
a collection of qualitative results...*



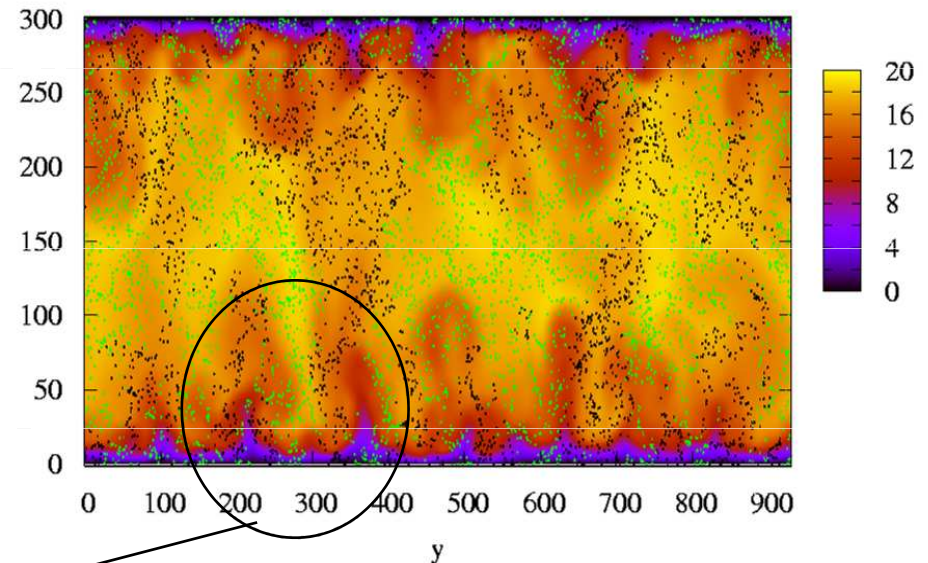
Preliminary Computations: DNS + Lagrangian Particle Tracking and 2 way coupling approach

Green Particles: High Temperature
Purple Particles: Mean Temperature
Blue Particles: Low Temperature

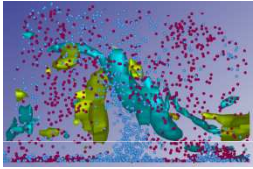
Background: Fluid Temperature



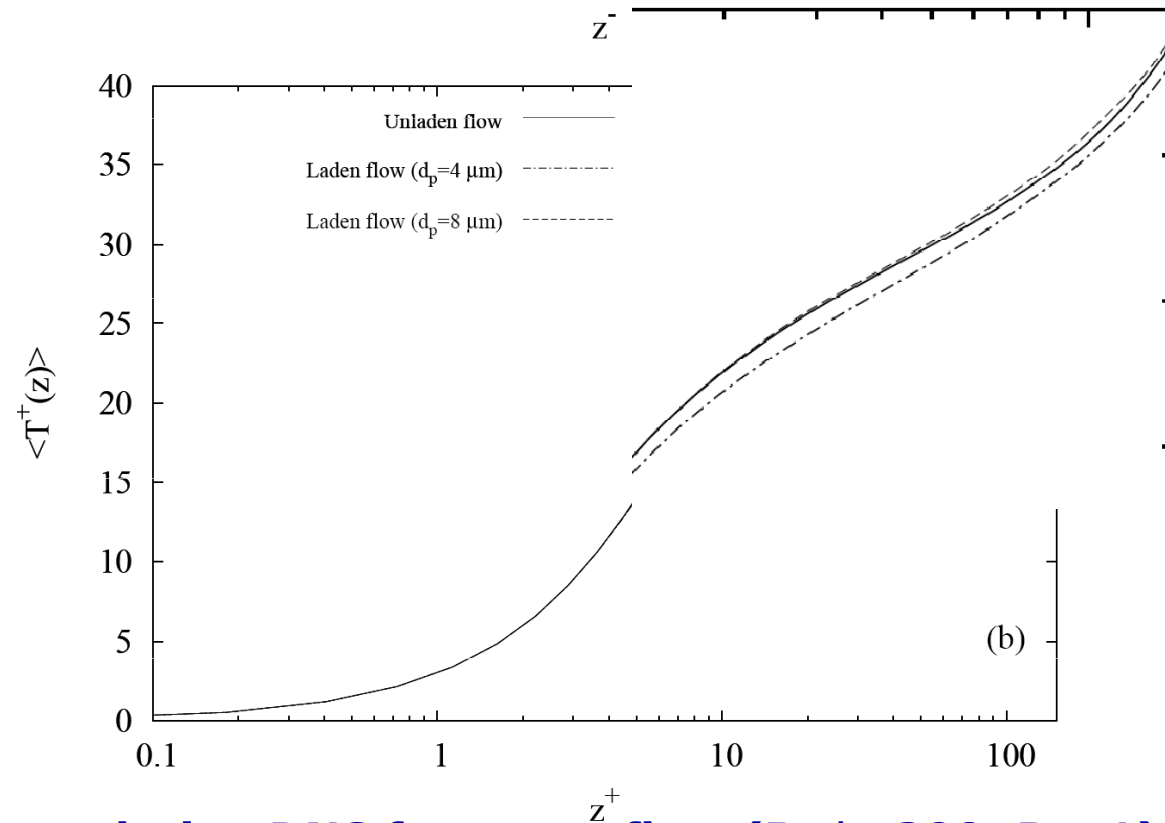
Green Particles: $w' < 0$
Black Particles: $w' > 0$
Background: Fluid Streamwise Velocity



Turbulence structures advect Temperature and drive Particles



*... and what did we obtain insofar?
...heavy computations but not much quantitative satisfaction*



Hi resolution DNS for water flow ($Re^*=300$; $Pr>1$)

Mass fraction (at least $\Phi_m=10^{-2}$) $\rightarrow 10^9$

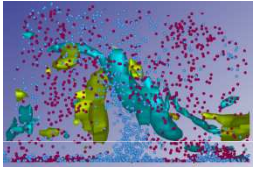
n.particles

Small time step size (low inertia particles)

Data storage: 10 -100 TBytes disk space

RAM memory: 50 Gbytes

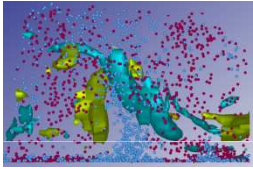
Computational time: 1,000,000 CPU hours



... and finally



... The seminar is over



... and the course 1/2



Doctoral Course:

Modelling of Turbulent Dispersed Flows (28 hrs)

Lecturer:

Professor Alfredo Soldati, University of Udine, Italy (<http://158.110.32.35/alfredo.html>)

Seminars by Dr. Abdel Dehbi, Paul Scherrer Institute, CH... ???

Motivation:

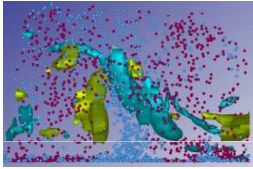
Turbulent dispersed particle flows play a part in several technological areas. Since the individual particle motion can involve the transport and exchange of mass, momentum and heat with the carrier fluid, insights into detailed physics of this motion and how it influences and is influenced by its surroundings can lead to significant technological advancements.

Object:

cover the current methodologies for predicting turbulent dispersed flows. Specific attention will be devoted to the fundamental modelling aspects and to the physical phenomena involved. In particular, i) Fluid particle interactions including particle exchanges of momentum, heat and mass with the fluid. ii) Turbulence structure and the several simulation methodologies including assumptions and modelling. iii) Some issues related to the computational aspects will be discussed.

Extra Activities:

To focus on the described issues, small hands-on-computer projects and seminars on specific applications and issues will be given. The course will be addressed to PhD students in Engineering and Applied Sciences.



... and the course 2/2



Location: The course will be held in room ??? with the following schedule:

- 1. Wednesday May 7: 14 pm to 18 pm**
Introductory seminar. Fundamentals on Stokes flow around a sphere.
- 2. Wednesday May 14: 14 pm to 18 pm**
Forces acting on a sphere. Steady and transient forces
- 3. Wednesday May 21: 14 pm to 18 pm**
Heat and Mass transfer from a sphere.
- 4. Wednesday May 28: 14 pm to 18 pm**
Special topic on PDF approaches: Dr Abdel Dehbi, PSI.
- 5. Wednesday June 4: 14 pm to 18 pm**
NOT COVERED (JRT Course).
- 6. Wednesday June 11: 14 pm to 18 pm**
Particle dispersion in synthetic turbulence. Project description
- 7. Wednesday June 18: 14 pm to 18 pm**
Particle Turbulence Interactions. Are particles a compressible flow?
- 8. Wednesday June: 25 14 pm to 18 pm**
Project Discussion.
- 9. Wednesday July: 2 14 pm to 18 pm**
To be confirmed. Final Remarks