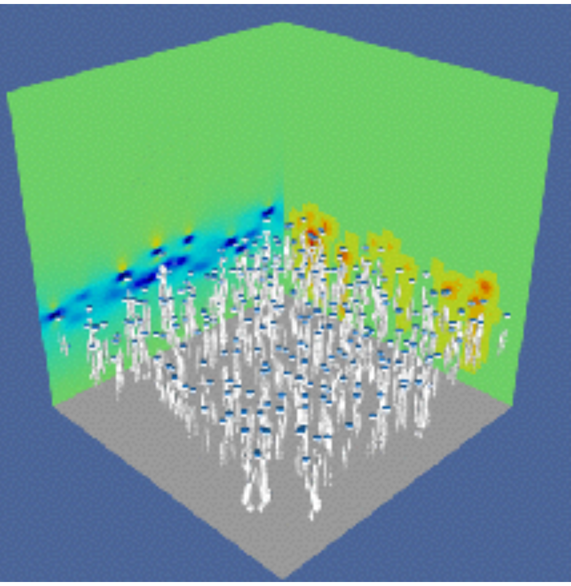

SORBONNE UNIVERSITÉ
CRÉATEURS DE FUTURS DEPUIS 1257

DNS of turbulent bubbly flows

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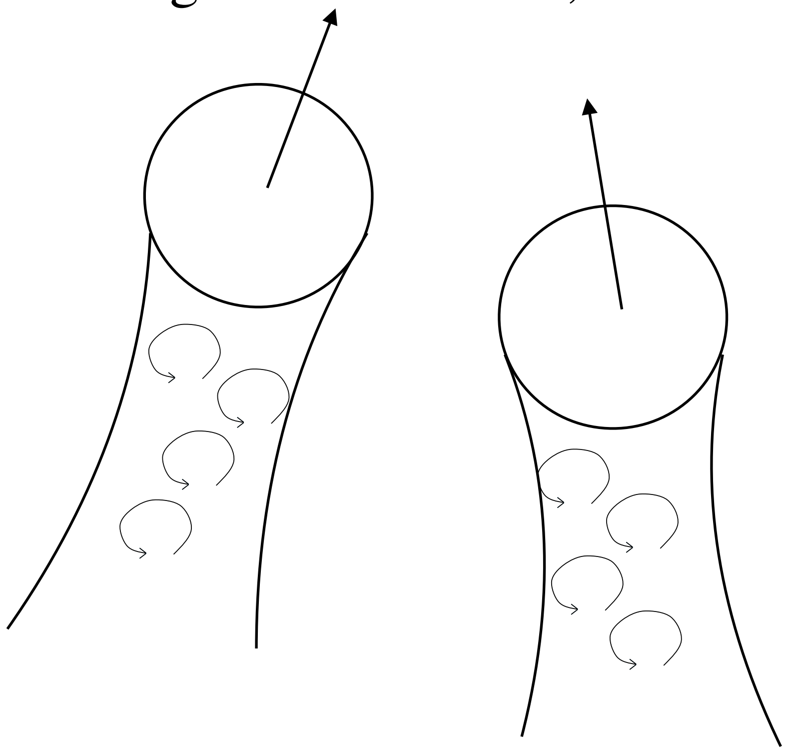
Bubbly flows

We want to study the agitation induced by bubbles in the continuous phase:

- Considering collective dynamics of many interacting bubbles

- Fully resolving the flow inside, outside and at the interface between the liquid and the bubble



- Different forces with respect to inertial particles, e.g. buoyancy, added-mass.

- Additional hydrodynamic forces due to wake interactions

We consider already formed bubbles, neglecting the phase of nucleation, growing and intrinsic dynamics.

The deformability and finite size are considered.

Numerical approach

Simulations are done with the **basilisk** code[1], an open-source software for the solution of partial differential equations on regular and adaptive Cartesian grids.

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

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \nabla \cdot (\mathbf{u} \otimes \mathbf{u}) = -\nabla P + \nabla \cdot (2\mu \mathbf{D}) + \mathbf{g} + \sigma \kappa \delta_s \mathbf{n}$$

- The two fluids have different density and viscosity and are separated by a geometrical interface;
- The interface is tracked with the Volume-of-Fluid (VOF) method;
- Curvature is estimated through the height-function;
- Possibility to use adaptive meshes (quadtree, octree).

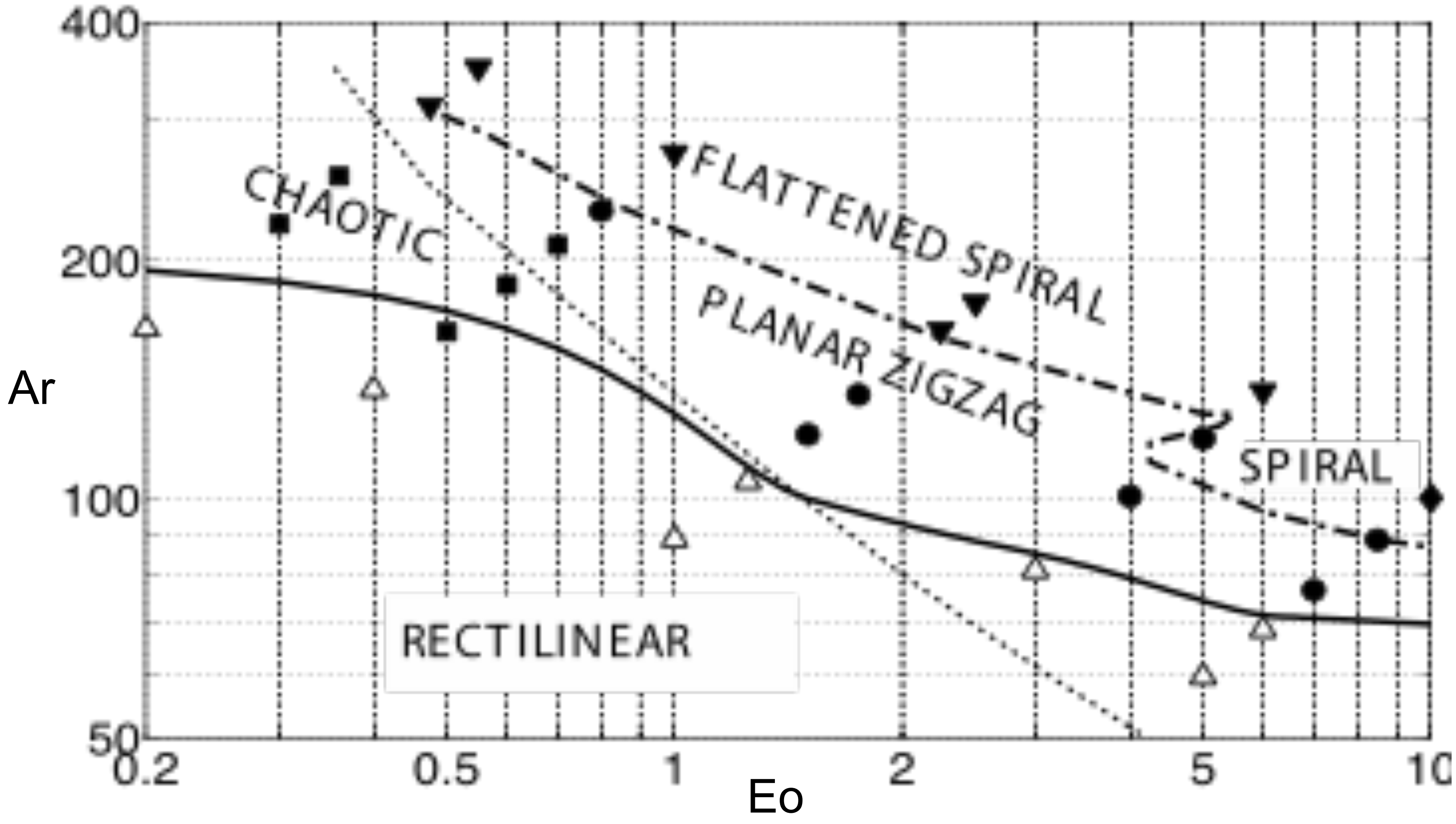
$$Ar = \frac{\sqrt{\rho_c^2 d^3 g}}{\mu_c} \qquad E_0 = \frac{\rho_c d^2 g}{\sigma}$$

ρ_b/ρ_l

μ_b/μ_l

[1] http://basilisk.fr

Regimes



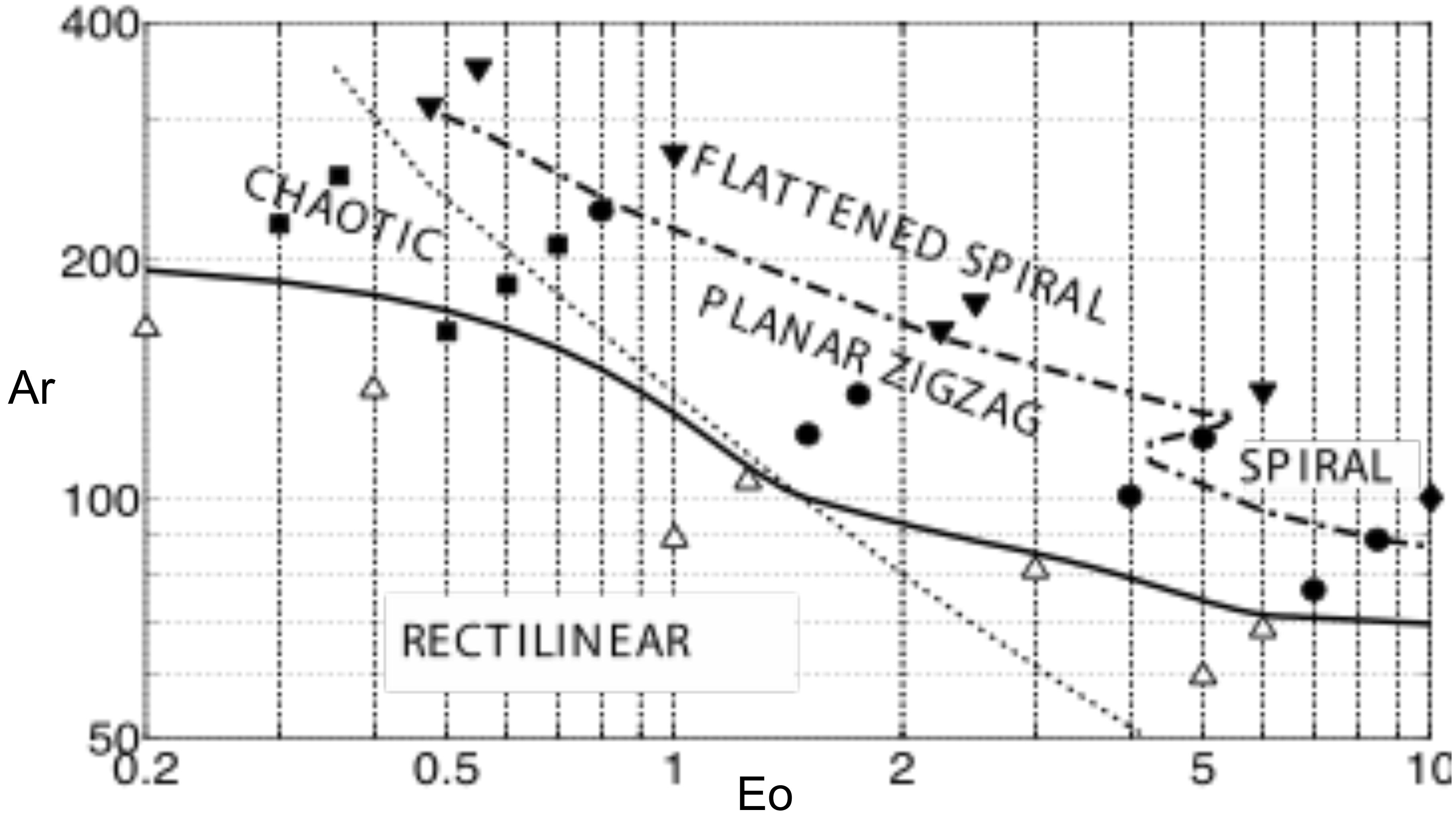
[Cano-Lozano et al. 2016]

Depending on the combination of Eo and Ar the bubbles can have

different shapes { Spherical, Ellipsoidal, Skirted }

different trajectories { Rectilinear, Spiral, Zigzag, chaotic }

Regimes



[Cano-Lozano et al. 2016]

Resolving accurately bubbles with enough points is important in order to avoid unphysical behaviors

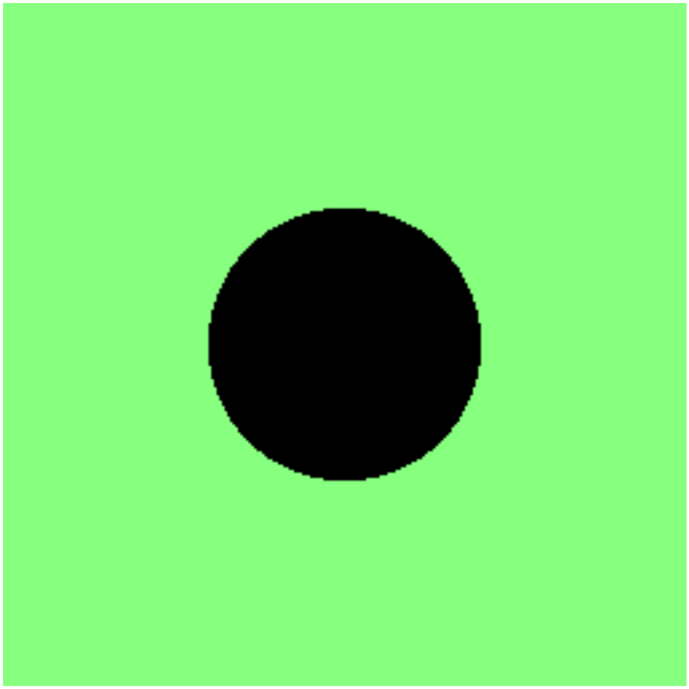
Depending on the combination of Eo and Ar the bubbles can have

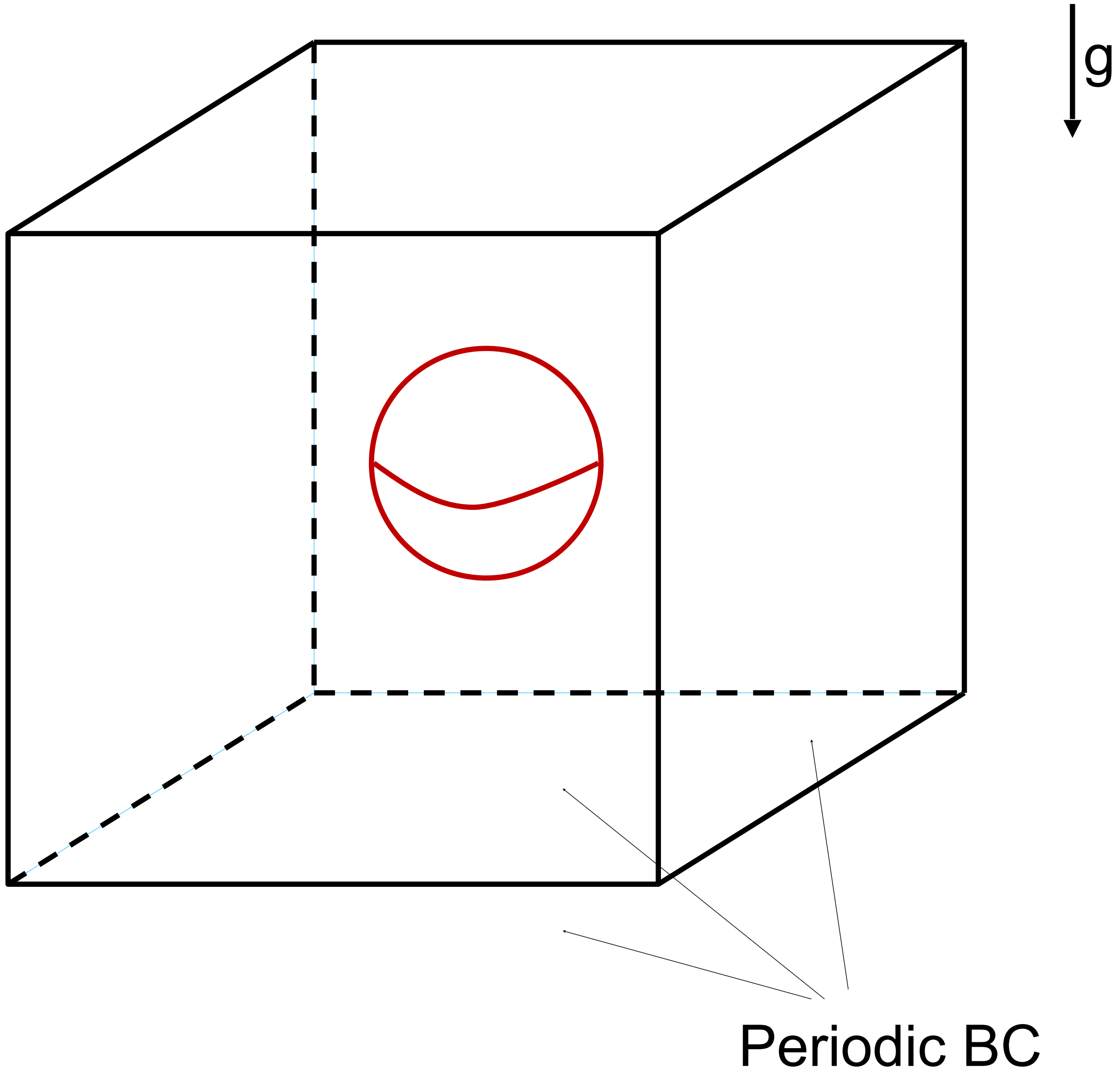
different shapes:
- Spherical
- Ellipsoidal
- Skirted

different trajectories:
- Rectilinear
- Spiral
- Zigzag
- chaotic

Periodic arrays

Computations with periodic arrays at low Reynolds number and different volume fraction



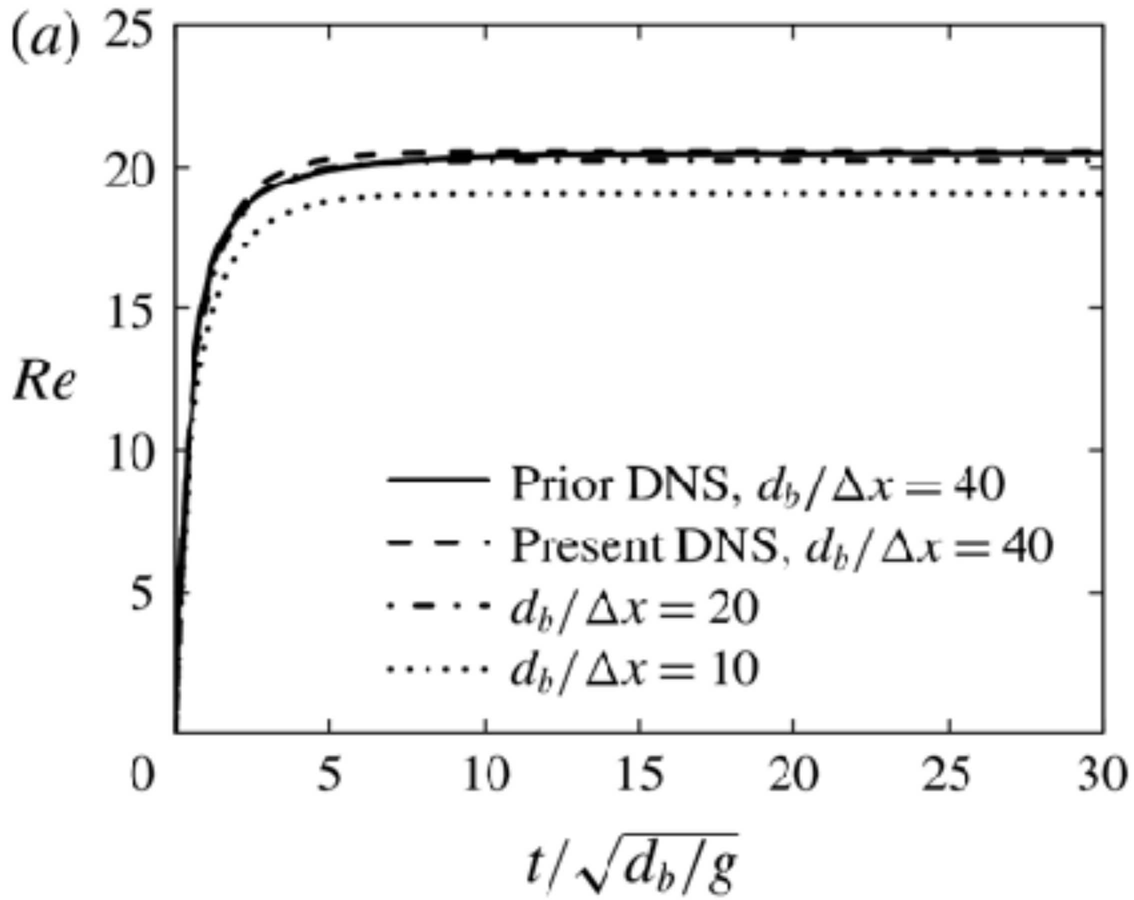


$$\mathbf{A}_k = (\rho_k - \langle\rho\rangle)\mathbf{g}$$

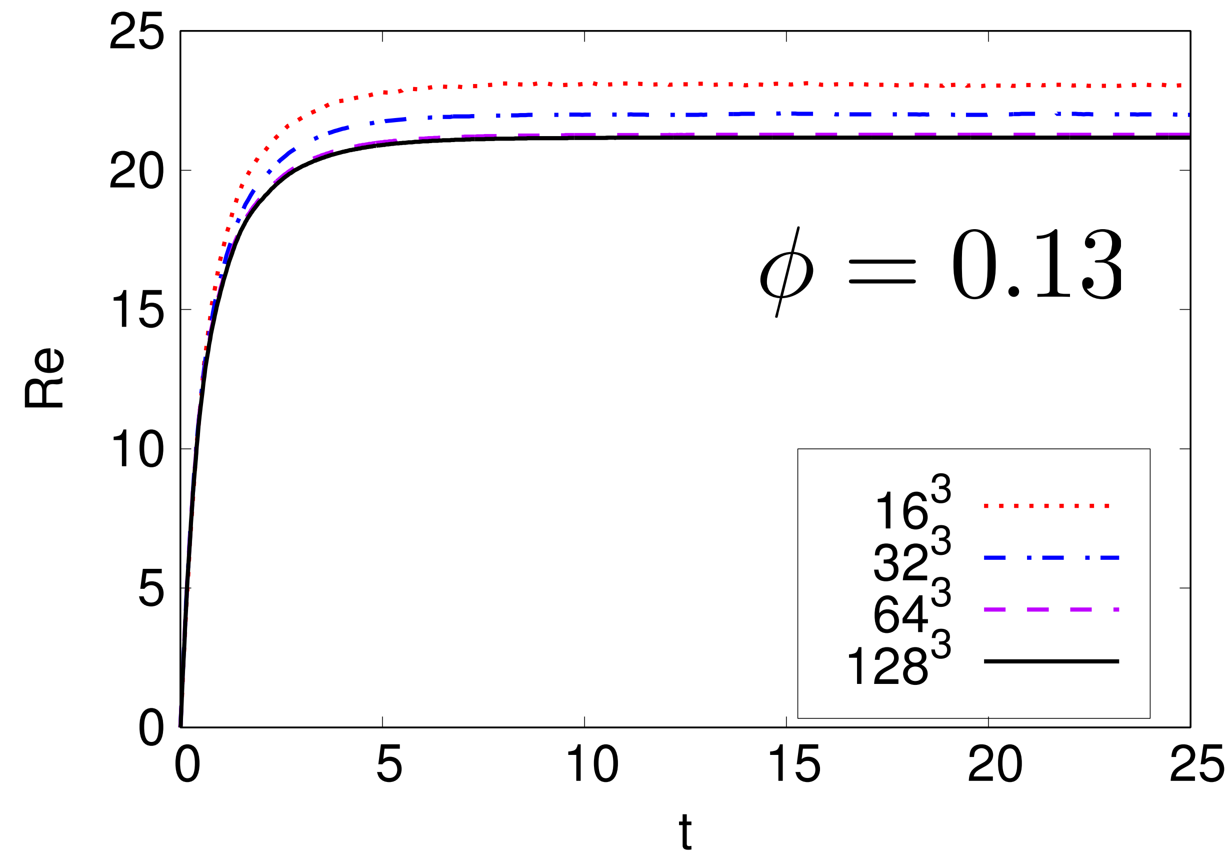
Acceleration term added in NS to avoid a mean downward flow

3D periodic array

Periodic cell with a single rising bubble (Esmaeeli & Tryggvason JFM 1999 (front-tracking), Loisy et al. JFM 2017 (Level-Set))



DNS of Loisy et al. (present DNS) and of Esmaeeli & Tryggvason (prior DNS)



$$Ar = \frac{\sqrt{\rho_c^2 d^3 g}}{\mu_c} = 29.9 \qquad \frac{\rho_d}{\rho_c} = 0.1$$

$$E_0 = \frac{\rho_c d^2 g}{\sigma} = 2 \qquad \frac{\mu_d}{\mu_c} = 0.1$$

N_{grid} x N_{grid}	d_b / Δ
16^3	10
32^3	20
64^3	40
128^3	80

Coalescence

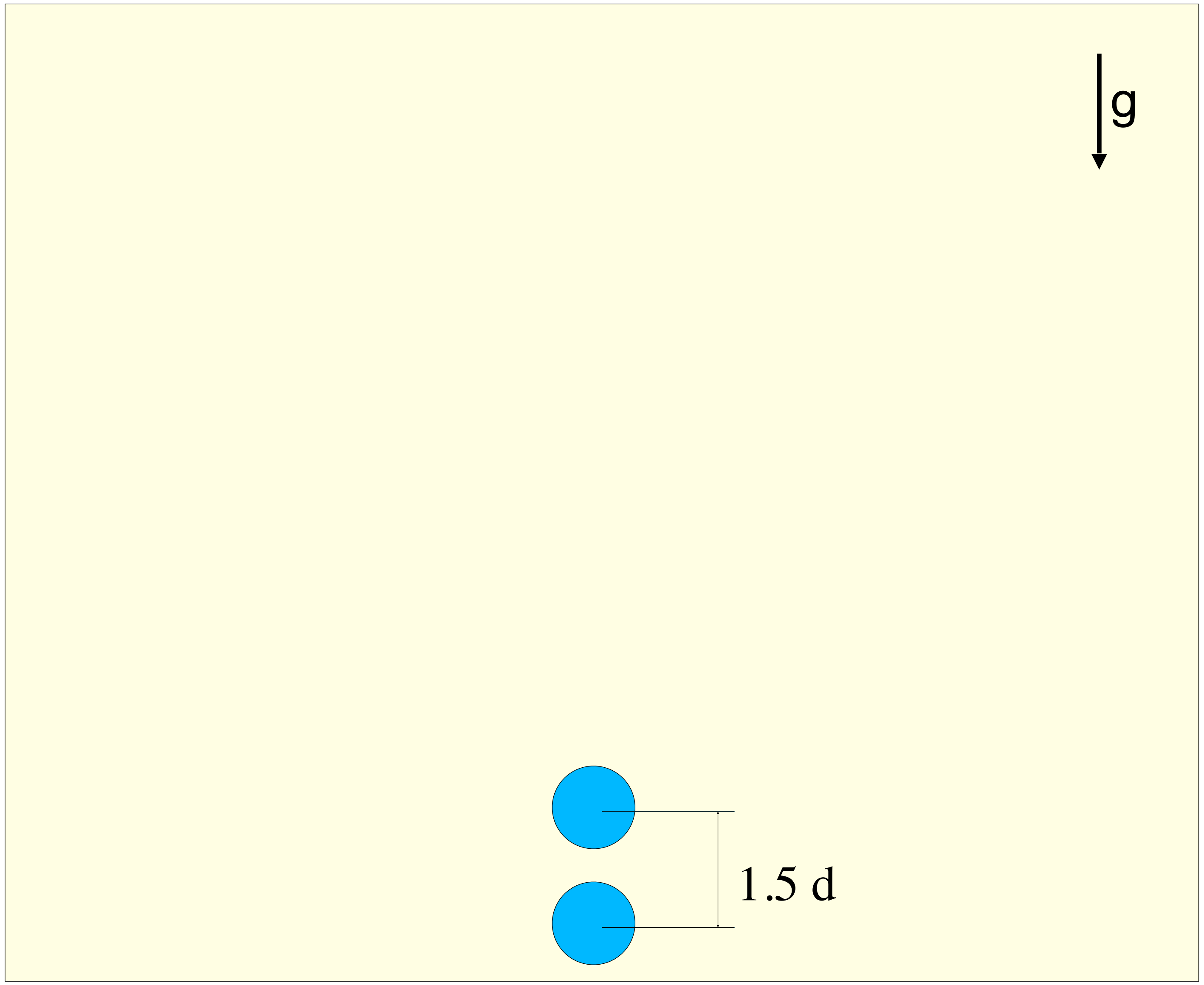
- ➢ Coalescence can affect the dynamics of bubbly flows, changing the distribution of diameters and the number of bubbles;
- ➢ VOF methods treat intrinsically the coalescence and usually overestimate it;
- ➢ There is no geometrical constraint that prevents coalescence (like in front-tracking methods)
- ➢ Empirical model that are used to avoid coalescences are not entirely satisfactory

Different grid resolution and density ratio

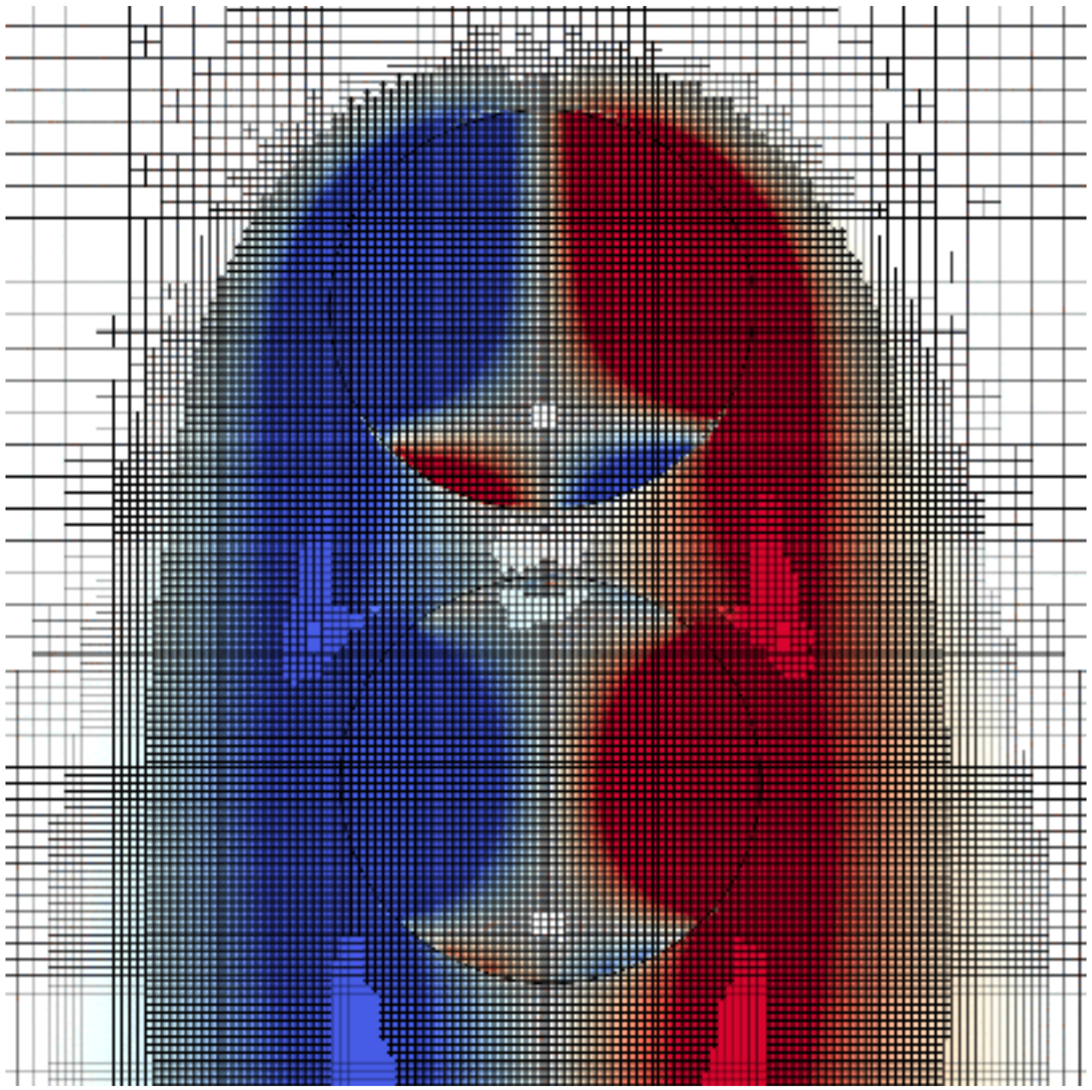
$$Ar = 30$$

$$Eo = 0.1$$

$$\mu_b/\mu_l = 0.01$$

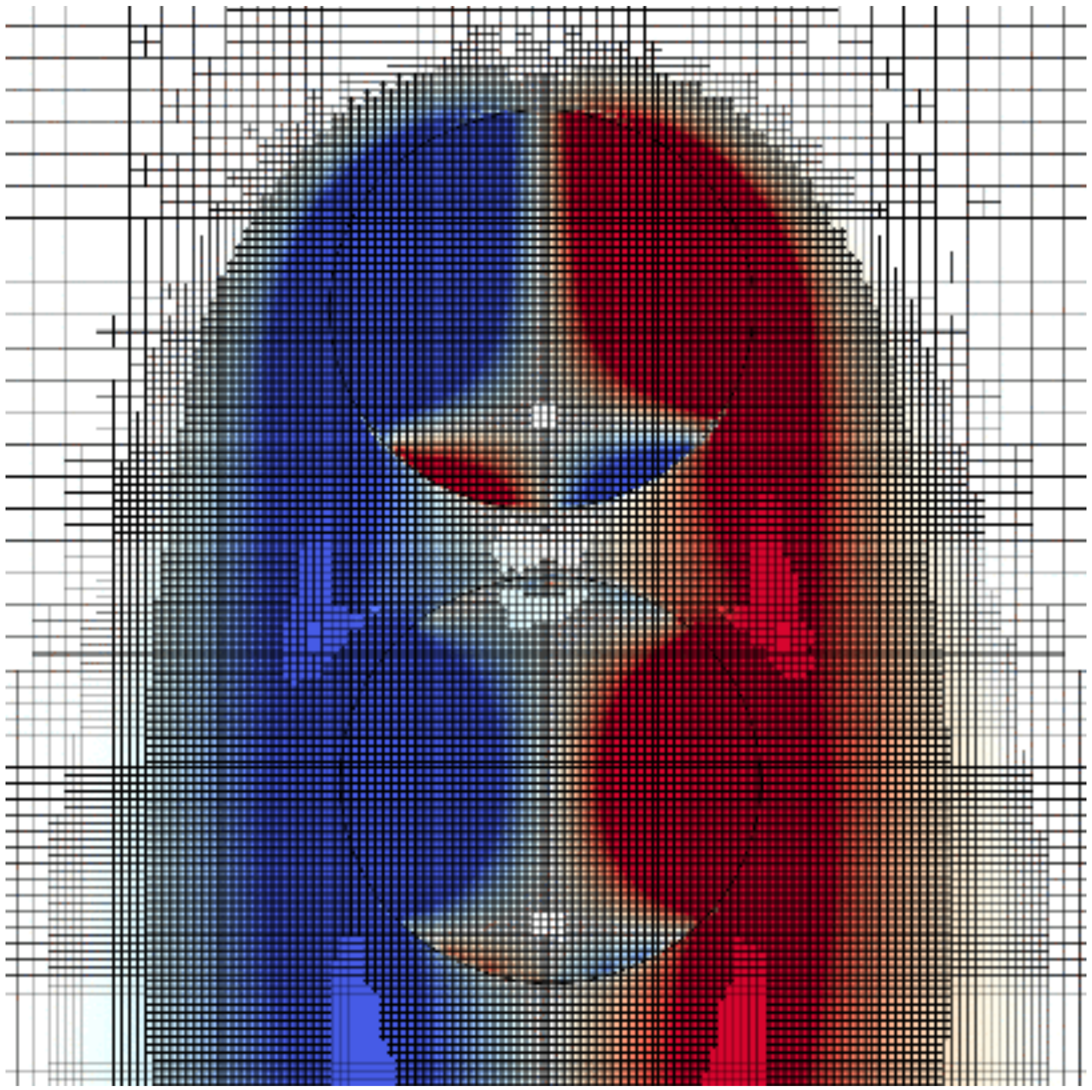


Coalescence



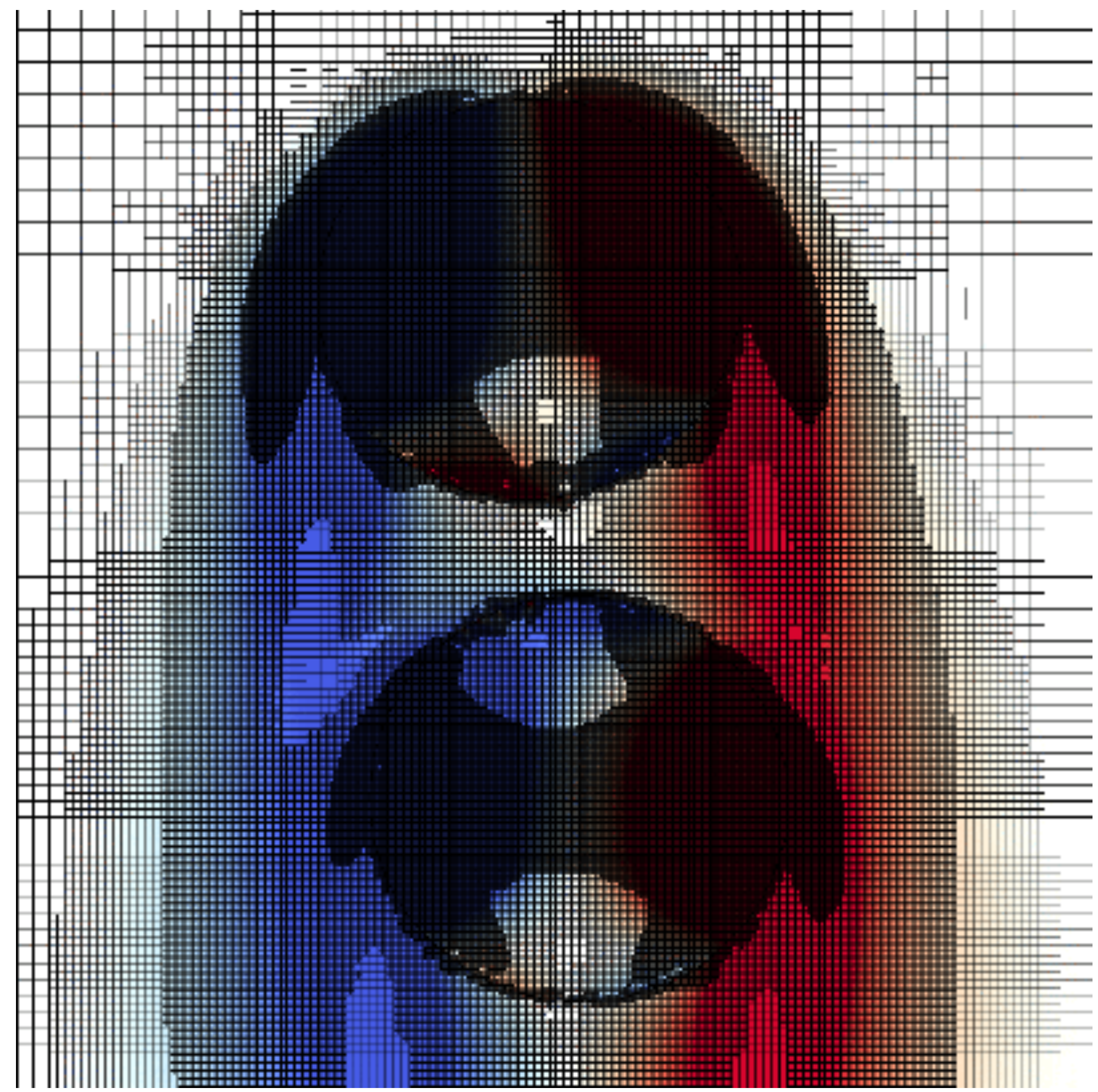
$L_{max} = 11$ ➡ $d_b/\Delta = 100$

Coalescence



$$\rho_b/\rho_l = 0.001$$

L_{max} = 12 ➡ $d_b/\Delta = 200$

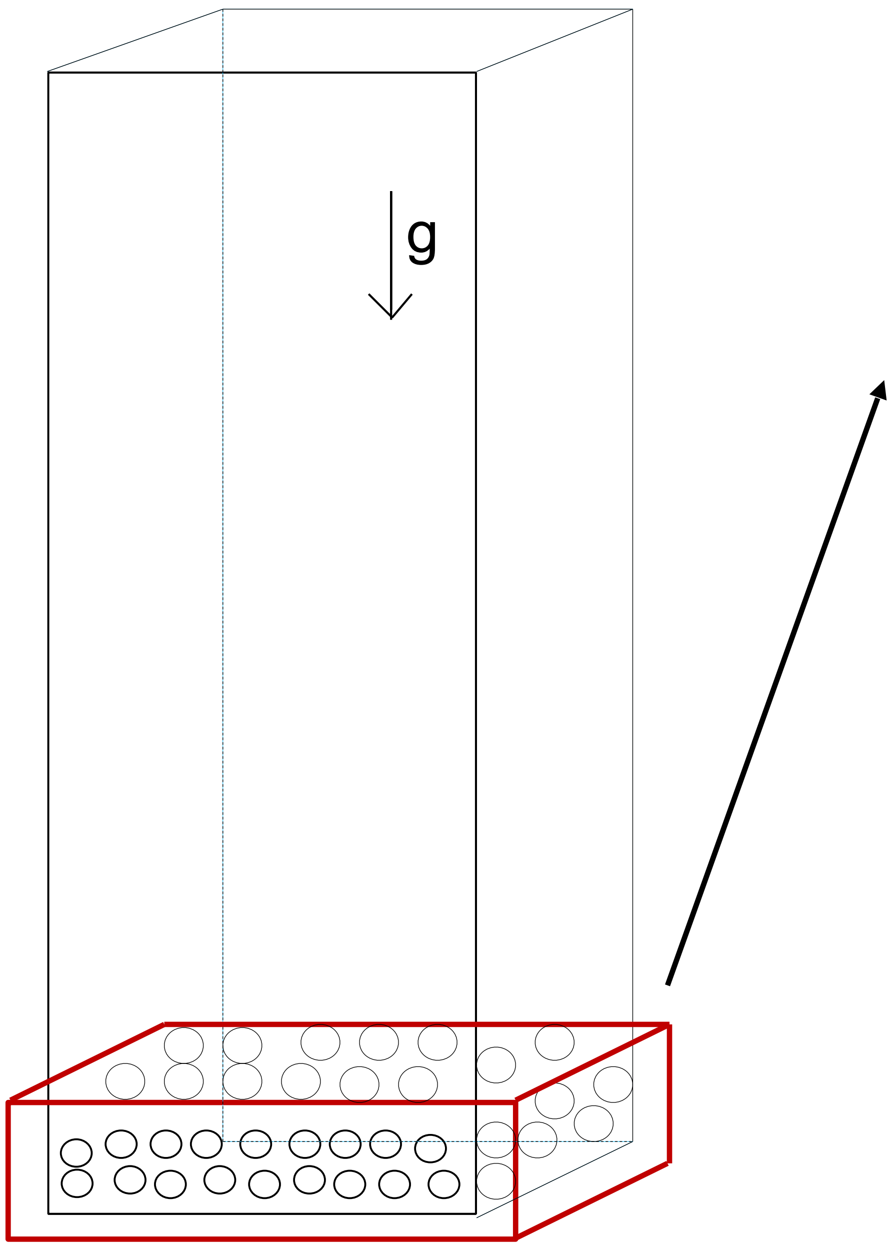


L_{max} = 11 ➡ $d_b/\Delta = 100$

Maximum level of refinement

Bubble column configuration

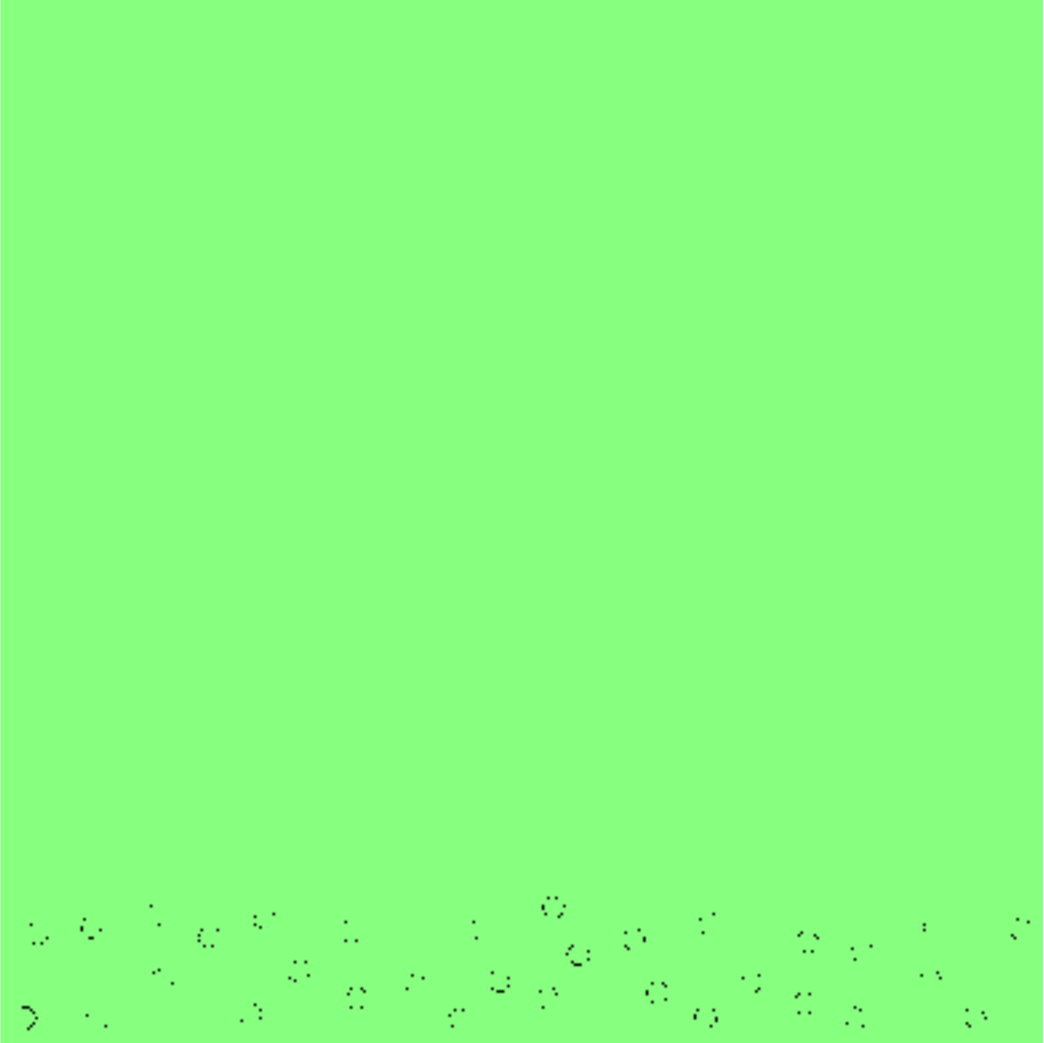
This configuration is common in many industrial applications because of the excellent heat and mass transfer characteristic



- Layer of bubbles initially at the bottom of a tank
- $\langle \alpha \rangle \simeq 0.08$
- Gravity in the downward direction

Case	Ar	Eo	N	d_b/Δ
a	100	0.12	4096	82
b	140	0.20	8192	164
c	313	0.56	16384	328

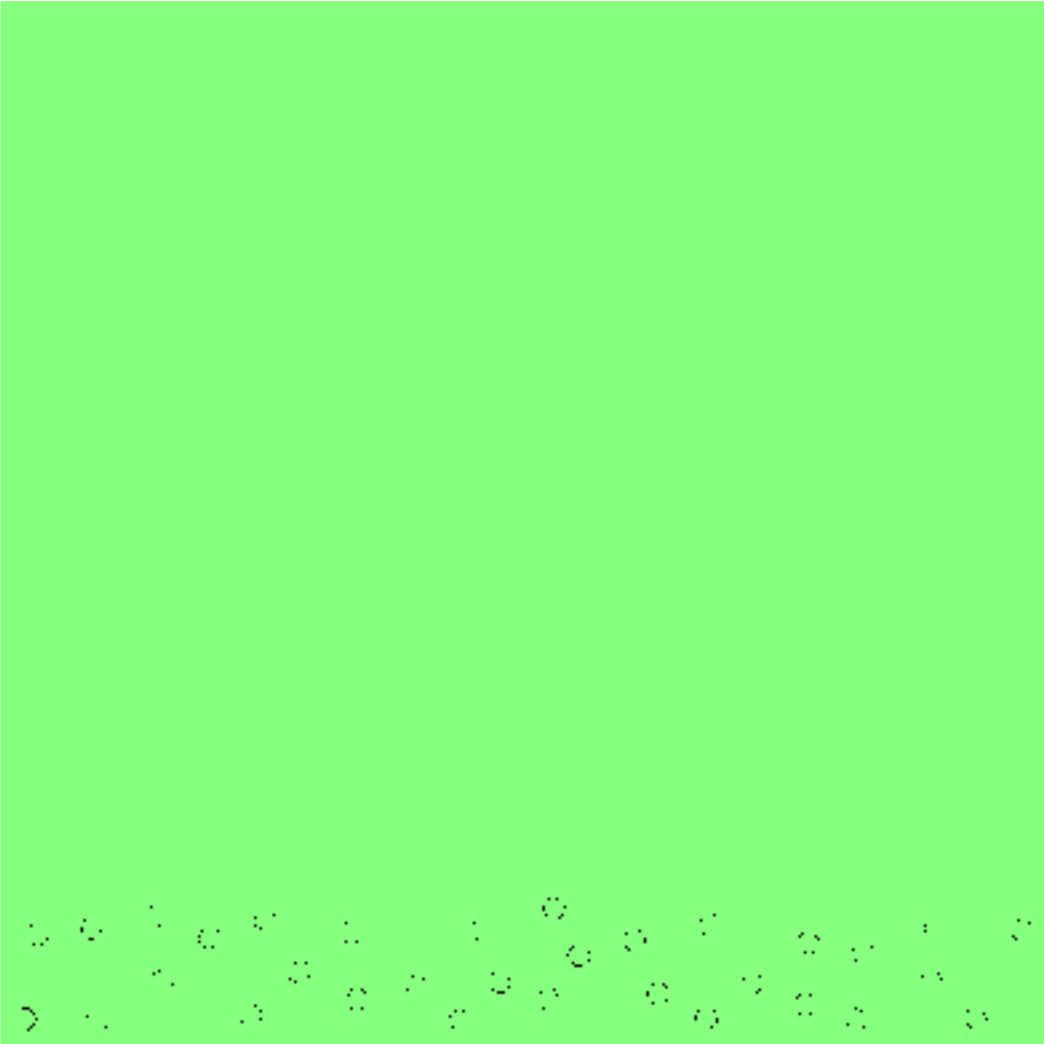
Bubble column configuration



$Ar = 100$

Vorticity field

Bubble column configuration

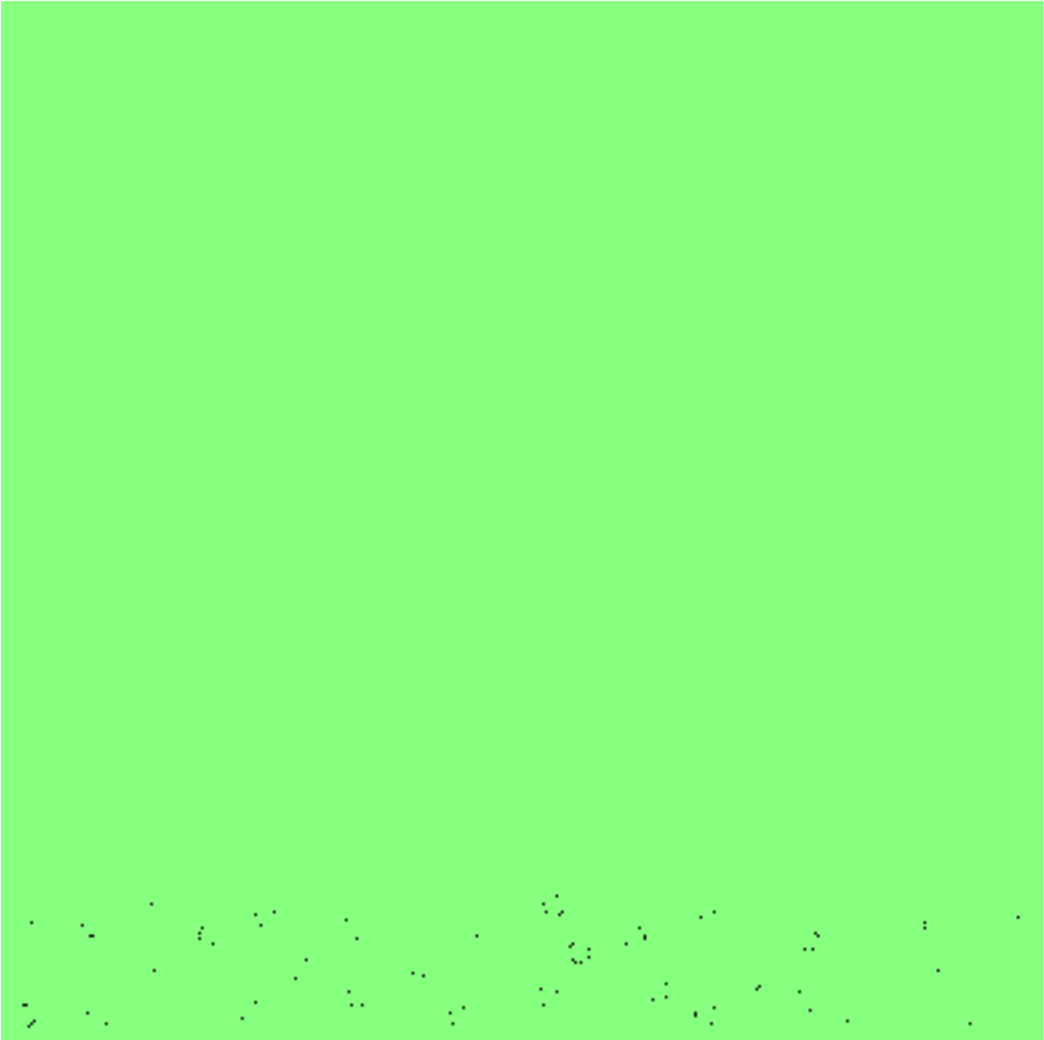


$$Ar = 100$$

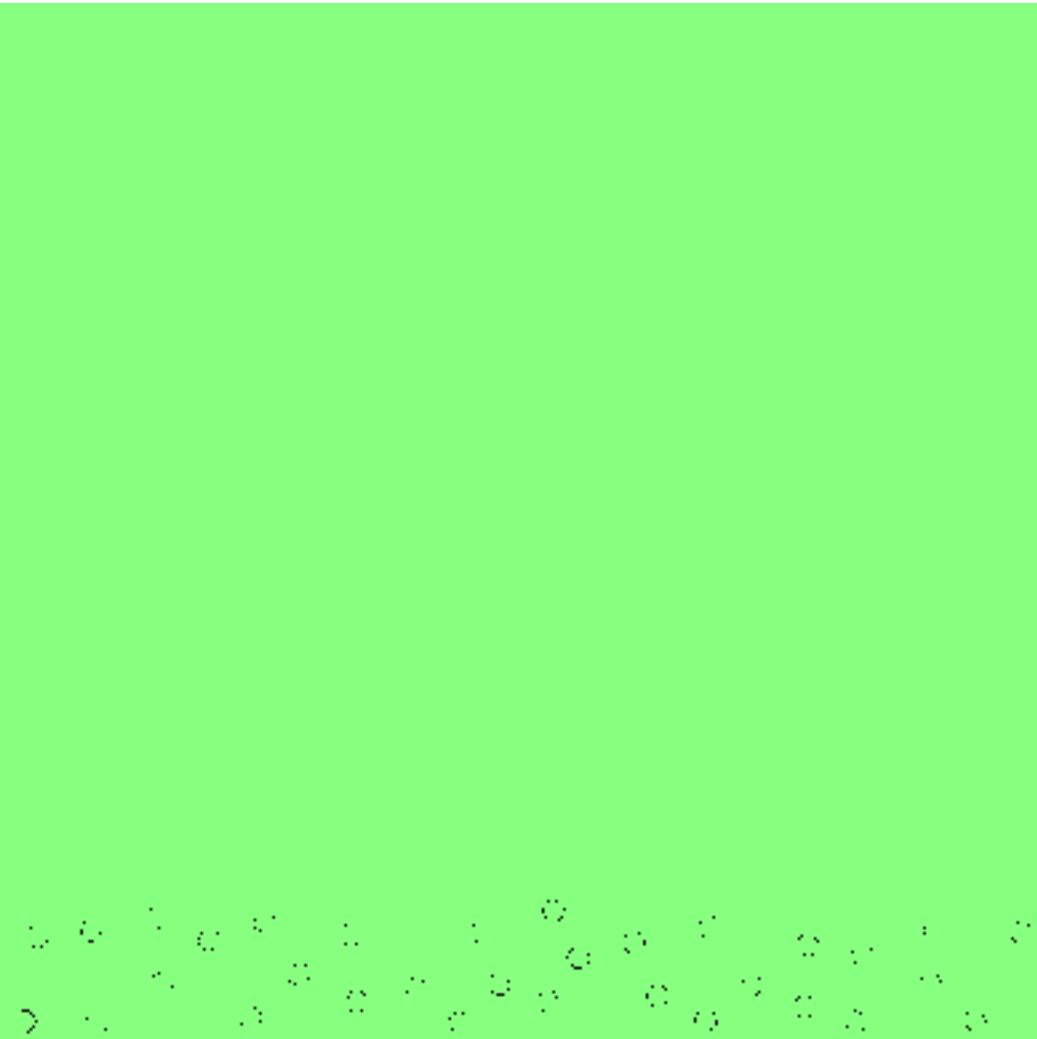
Bubbles interact strongly and deviate significantly from the vertical paths

Vorticity field

$$Ar = 140$$



Bubble column configuration



$Ar = 100$

$15d \leq l \leq 25d$

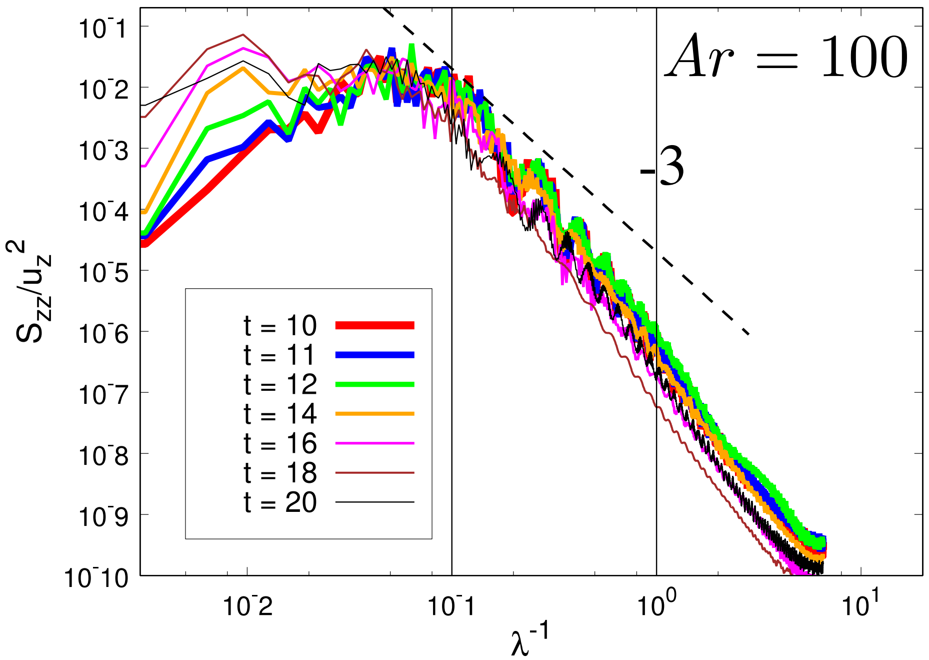
Bubbles interact strongly and deviate significantly from the vertical paths

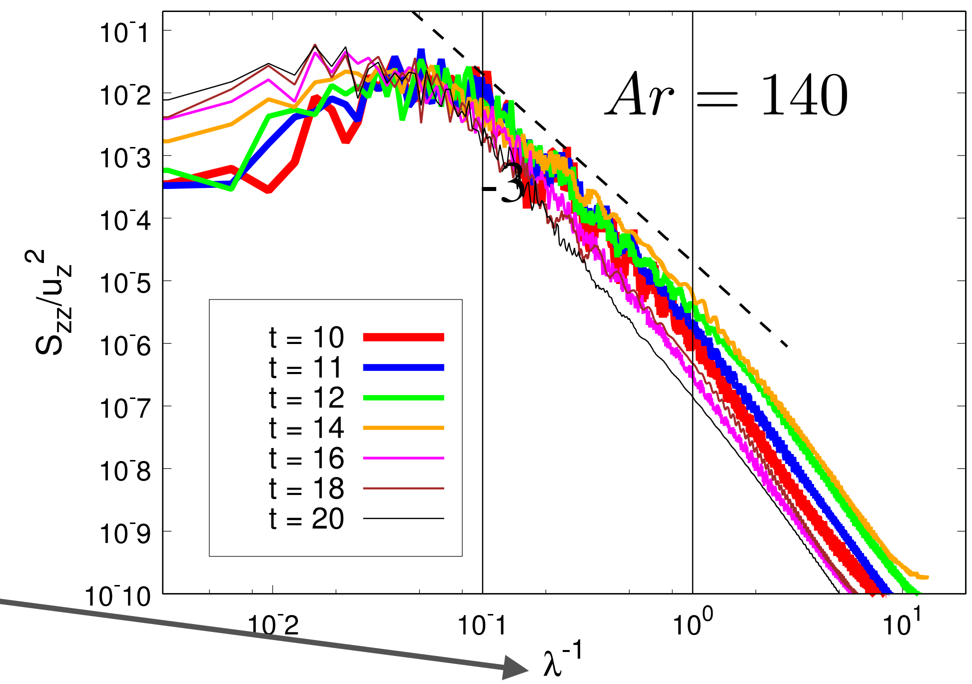
Vorticity field

$Ar = 140$

Spectra

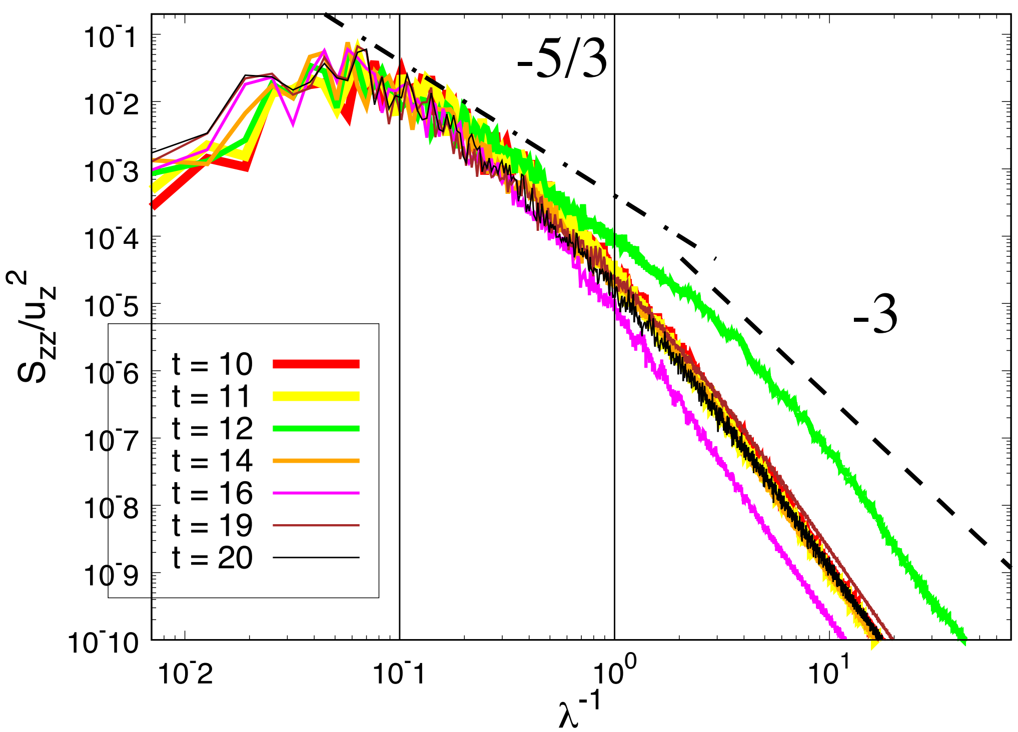
➢ For a more quantitative analysis of the fluid agitation we have evaluated the spectra of the velocity fluctuations (vertical component)

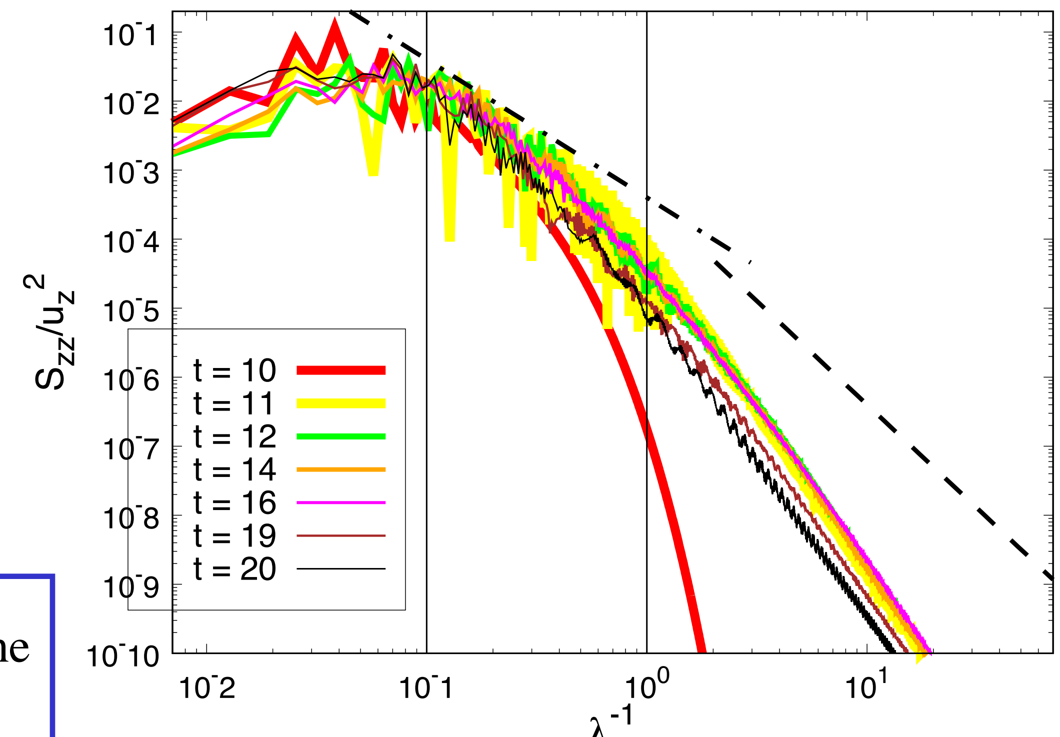




Bubble diameter

$Ar = 313$

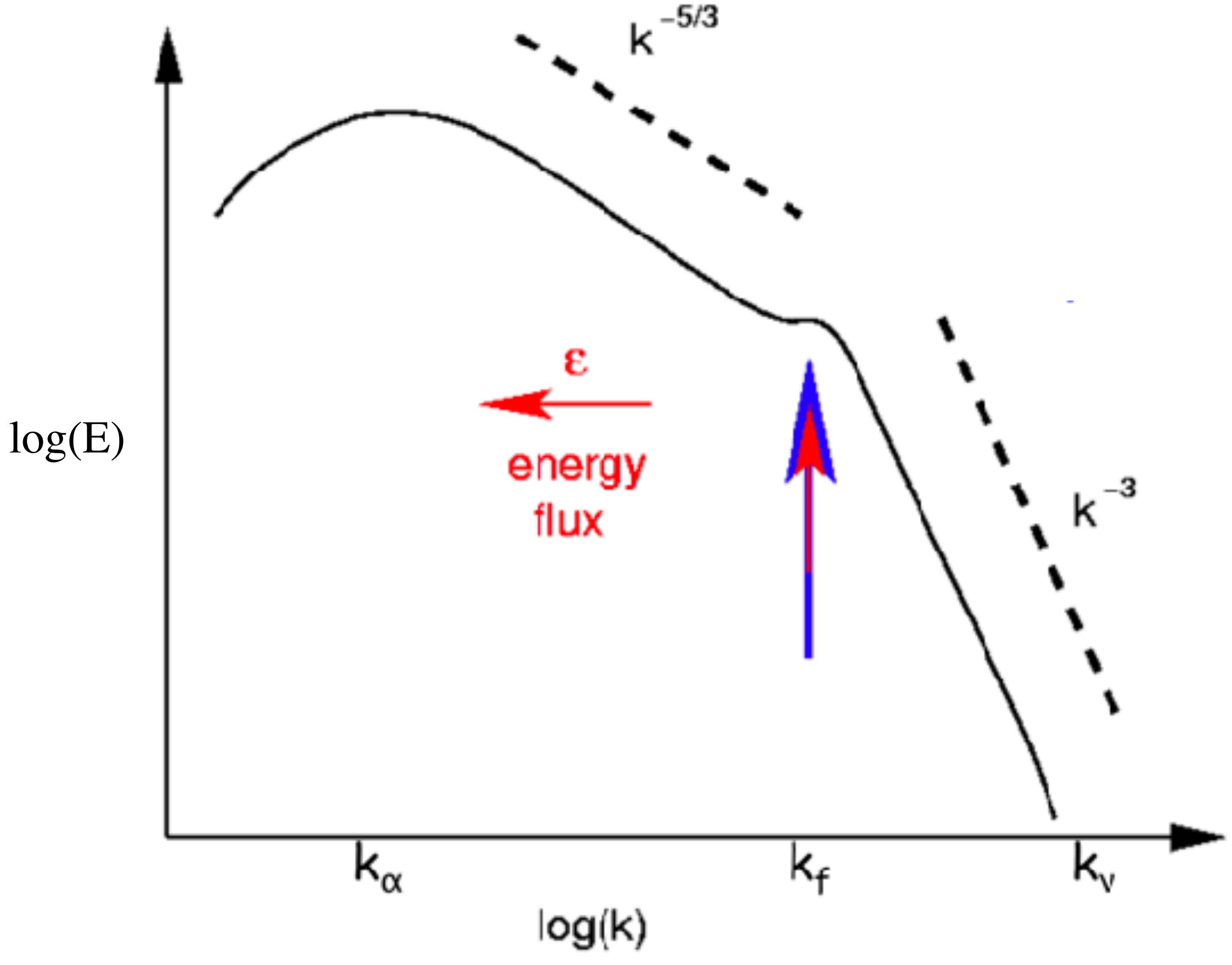




Different scaling at the higher Ar (higher Re)

2d turbulence

In two dimensions it is known that there is an inverse energy cascade when energy is injected at some intermediate scale



Injection of energy at k_f

Filtering

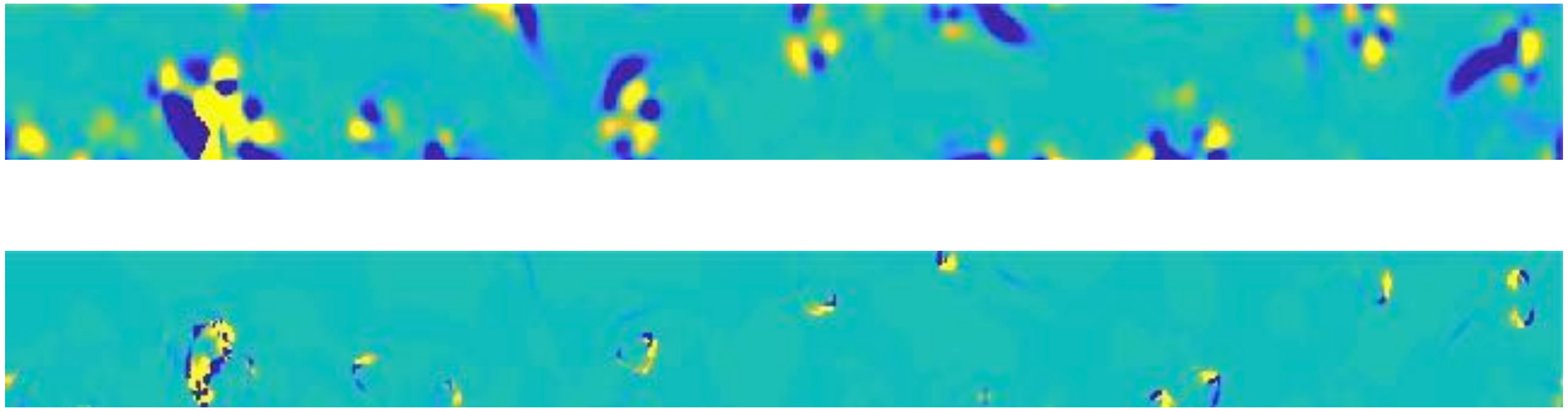
To evaluate if there is a passage of energy between the scales we use a filtering approach

$$G_l(\mathbf{r}) = \frac{1}{l^d} G\left(\frac{\mathbf{r}}{l}\right)$$ Where G is a gaussian filter and l is the filter width

$$\frac{\partial \overline{e}_l}{\partial t} + \nabla \cdot \overline{\mathbf{q}}_l = -\Pi_l - D$$ Π_l Is the **local energy flux**

$l \sim d$

$l \sim d/10$



Instantaneous snapshot of the local energy flux with two different filter width

[Chen 2006, Xiao 2009]

Filtering

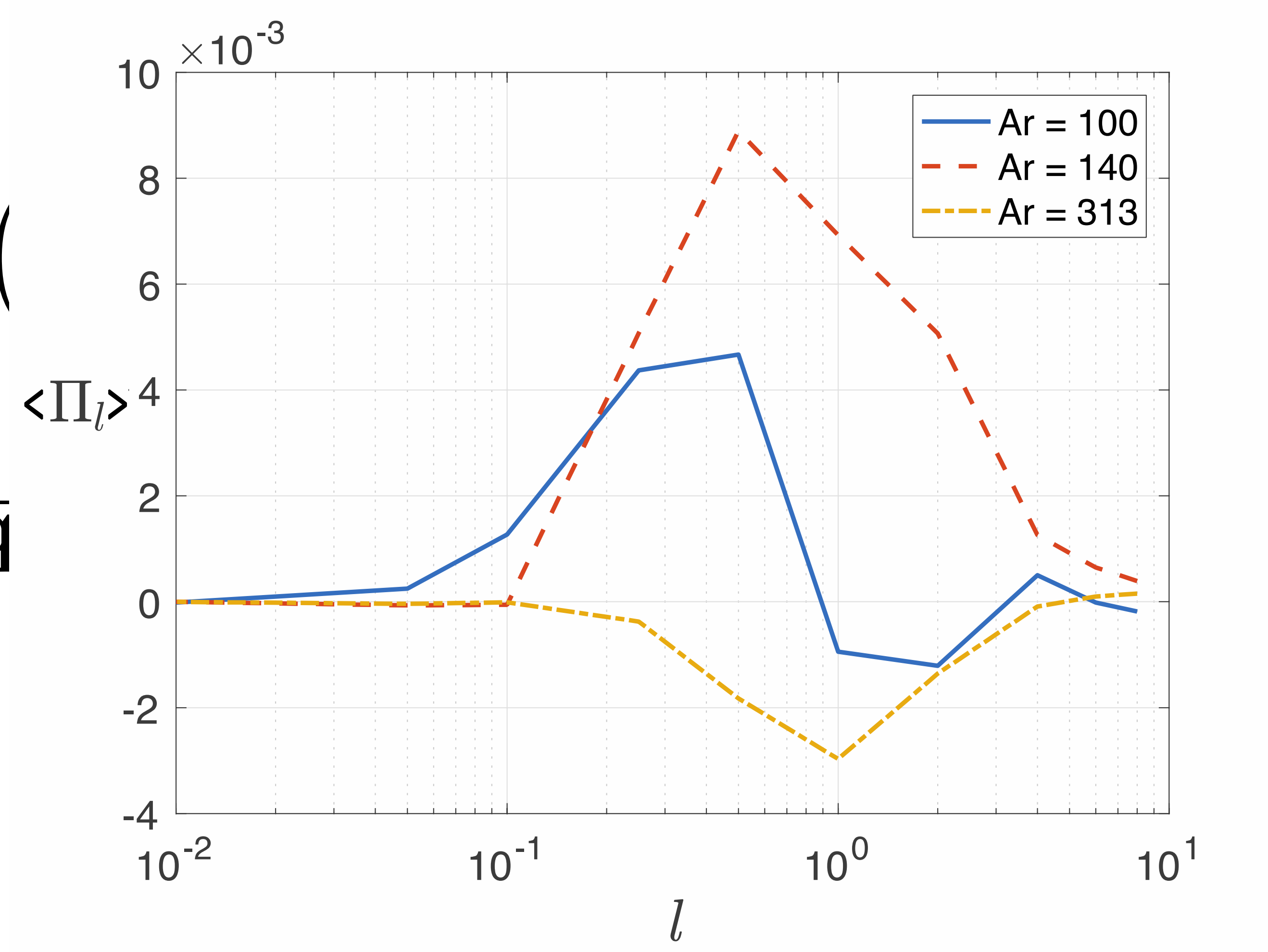
To evaluate if there is … approach

$$G_l(\mathbf{r}) = \frac{1}{l}G($$

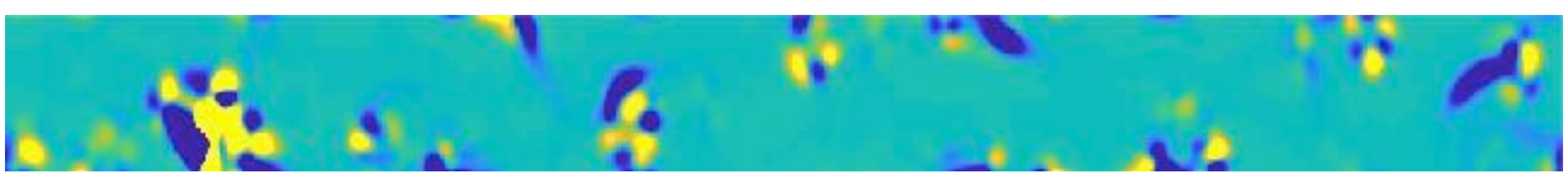
width

$$\frac{\partial \bar{e}_l}{\partial t} + \nabla \cdot \bar{\mathbf{q}}$$

gy flux



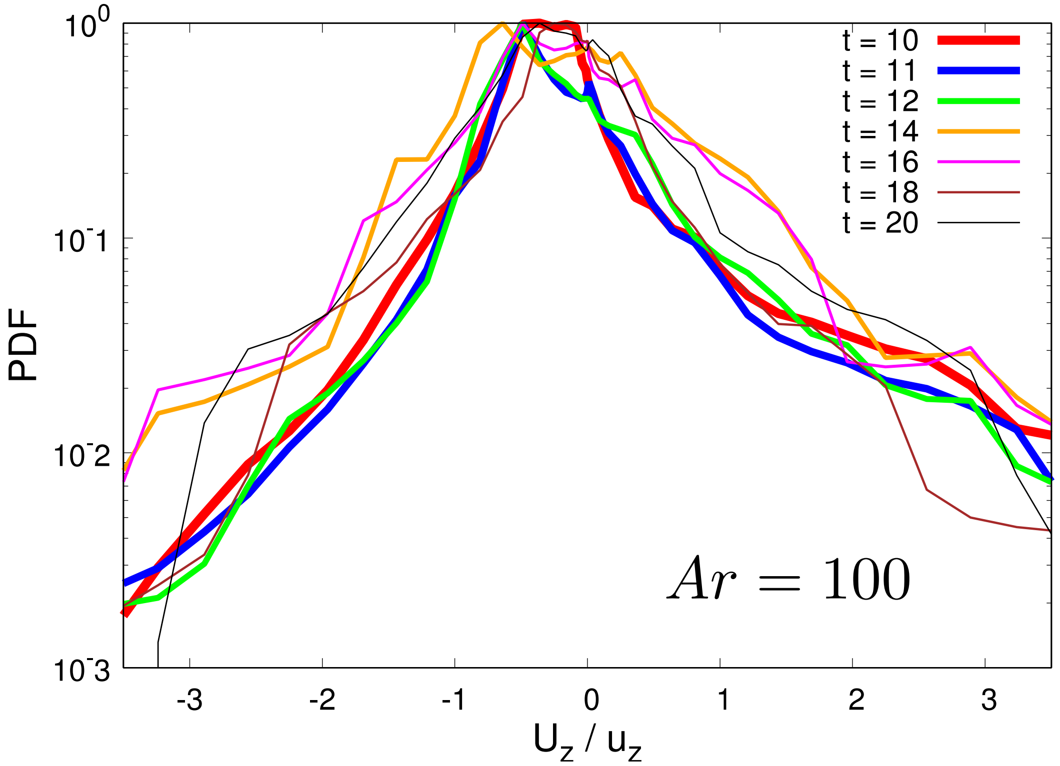
$l \sim d$

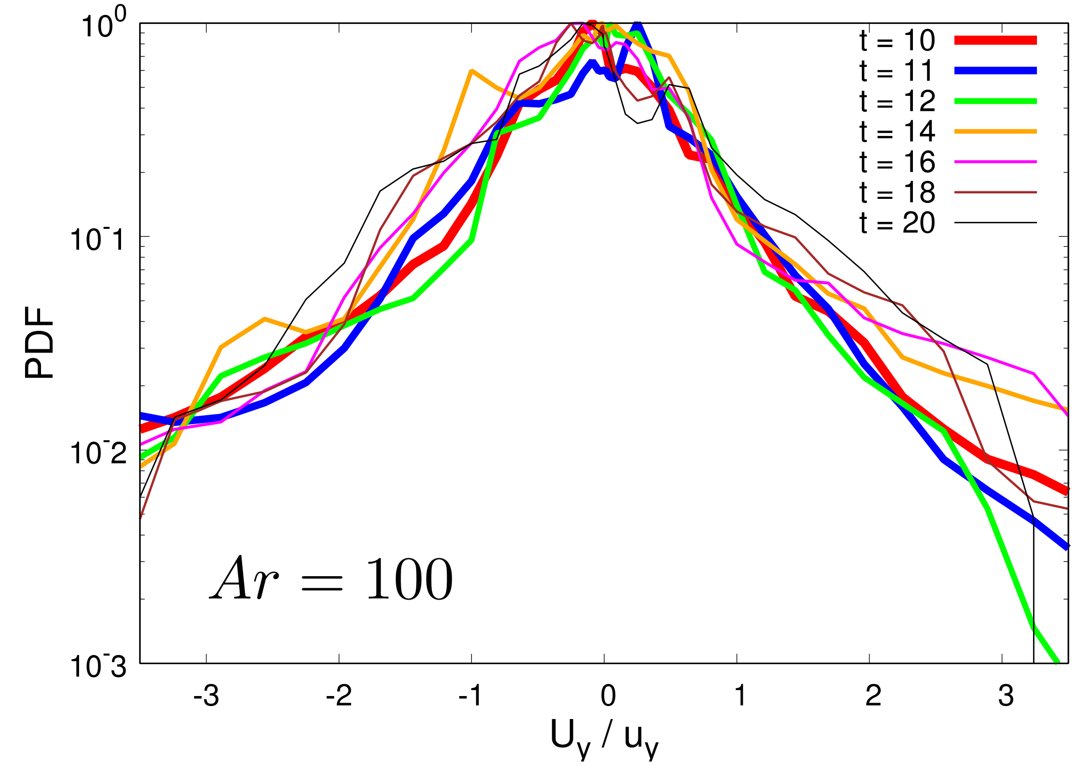


$l \sim d/10$

Instantaneous snapshot of the local energy flux with two different filter width

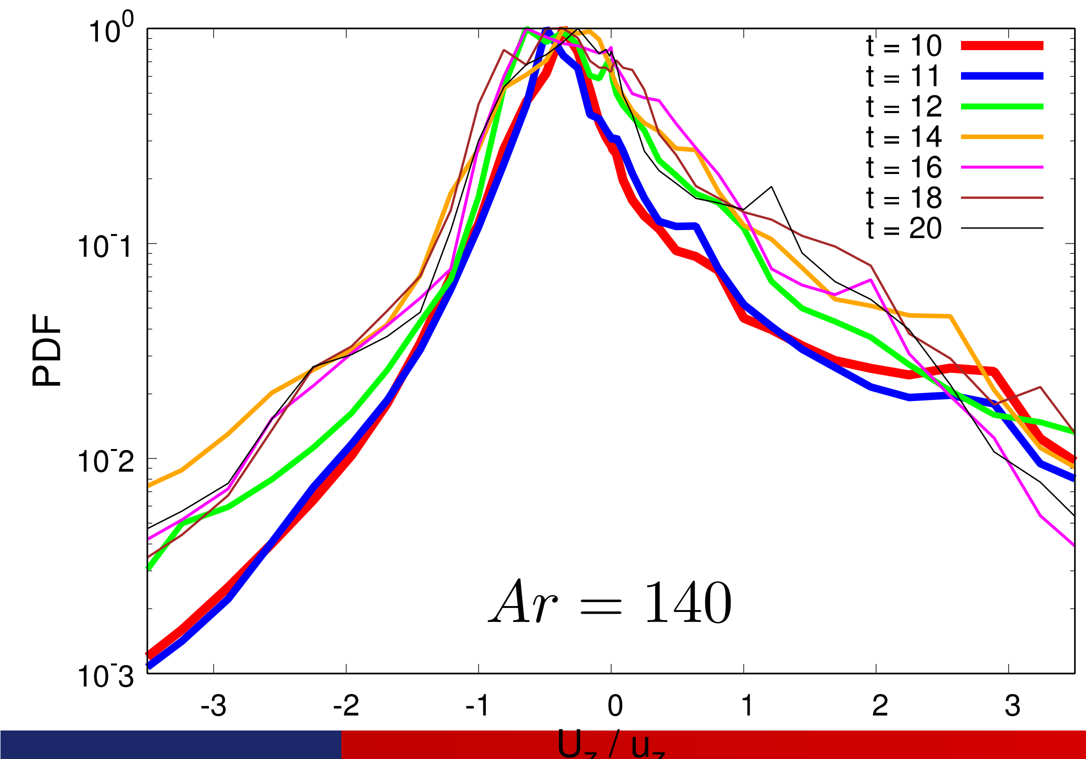
Probability density function

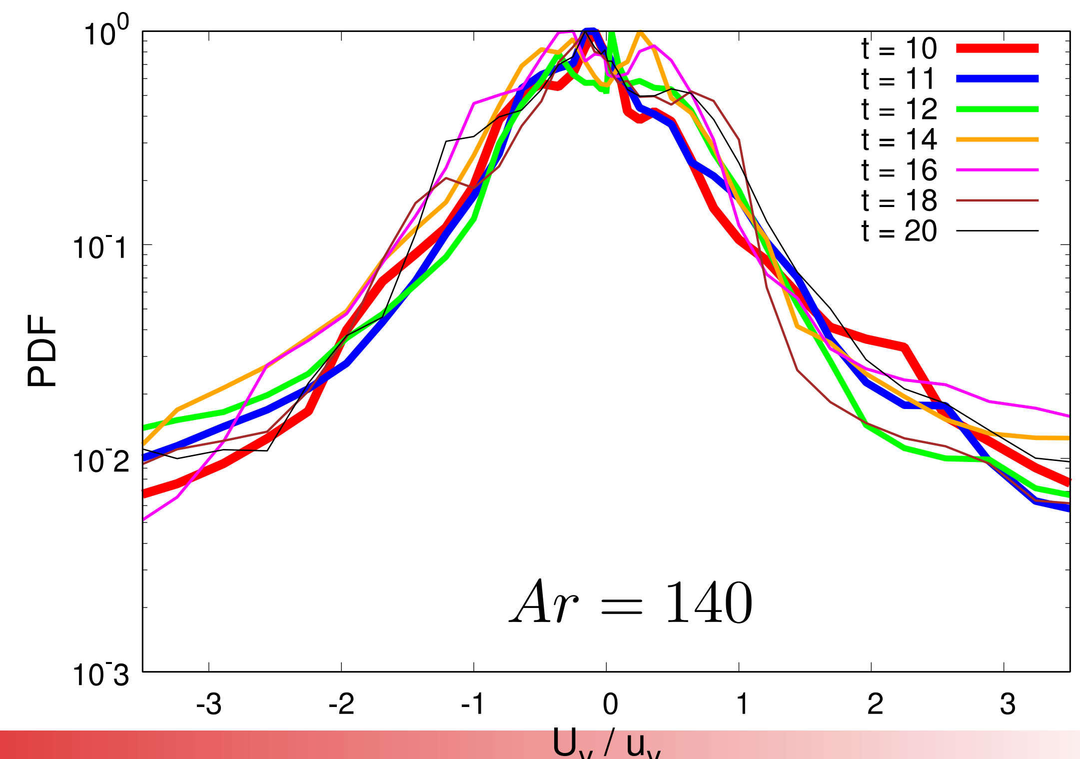




Vertical velocity fluctuations

Horizontal velocity fluctuations





3-dimensional simulation

$$Ar = 185$$

$$Eo = 0.28$$

$$\rho_l / \rho_b = 1000$$

$$\mu_l / \mu_b = 100$$

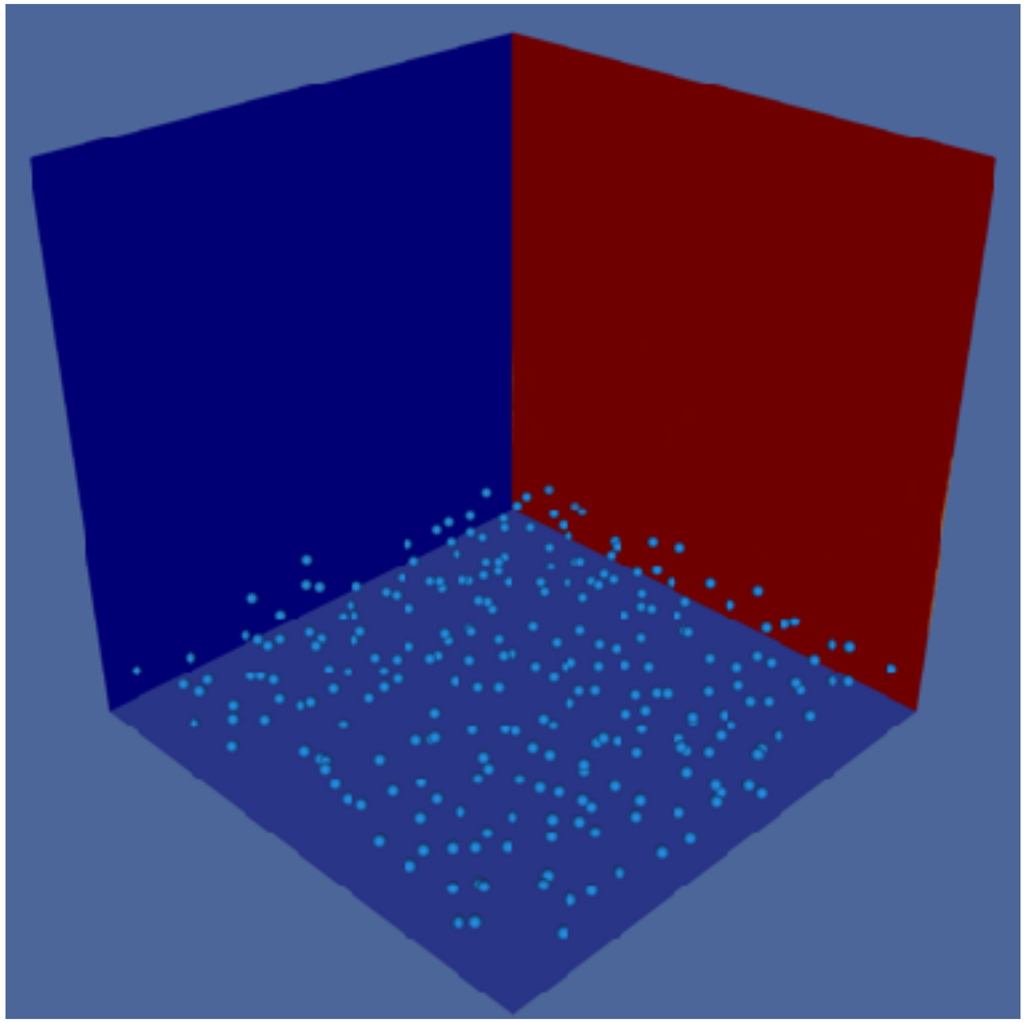
⬇

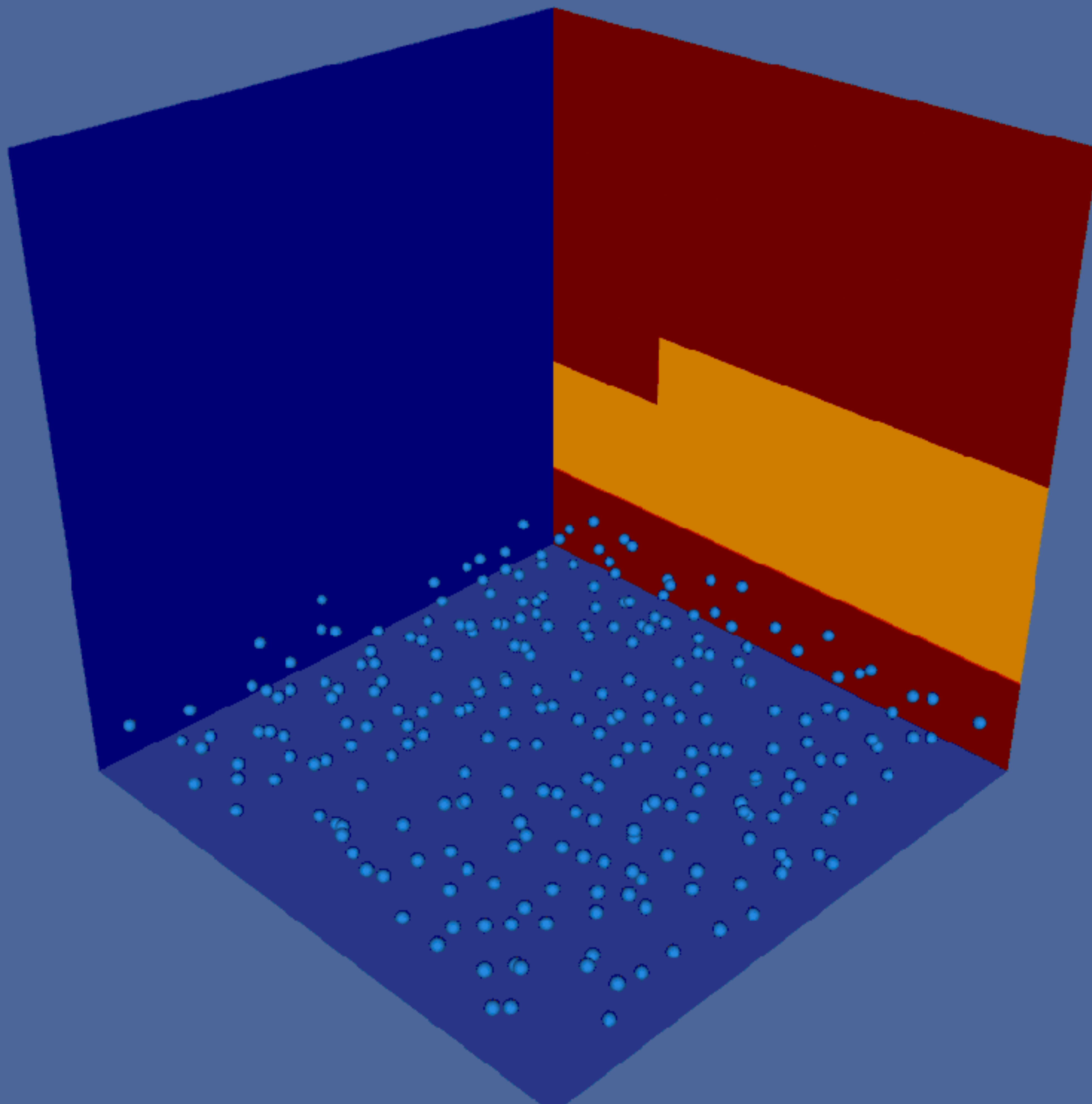
mm size air bubbles in water

From 2D simulations we have seen that a high Ar is required together with many bubbles

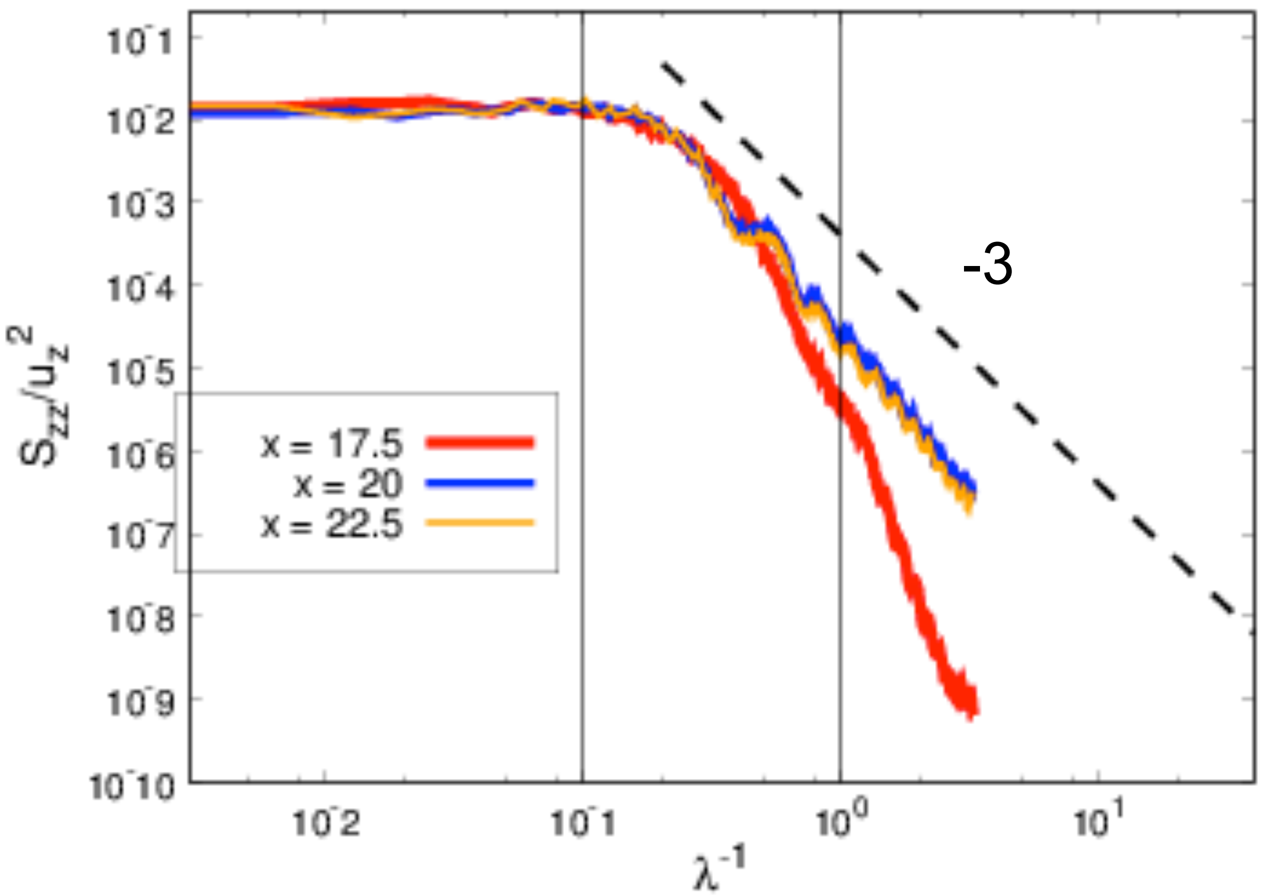
The first well-resolved simulation with many interacting bubbles in a realistic configuration at high-Re

256 bubbles
adaptive mesh L=12
N~1024^3

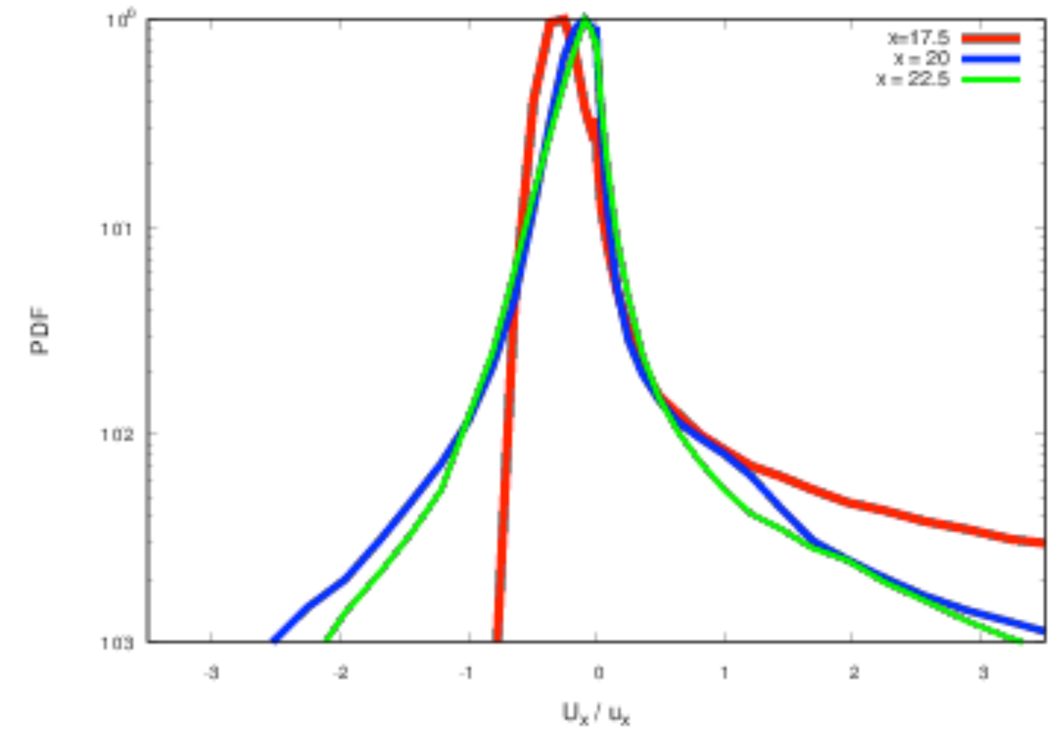




Preliminary statistical analysis

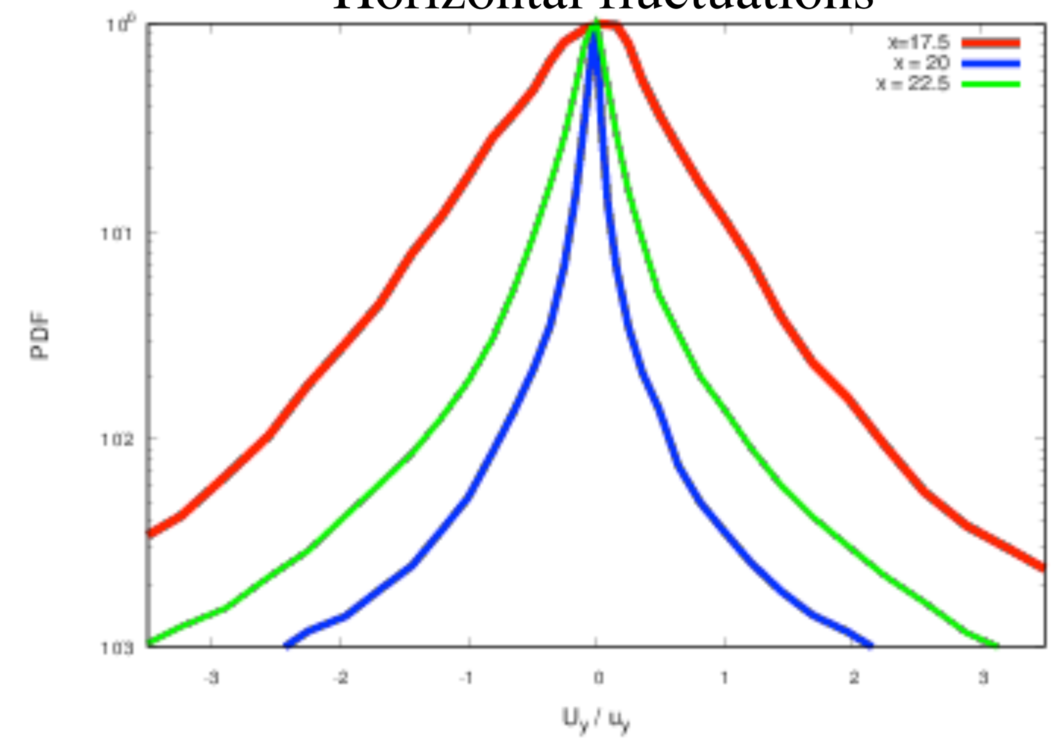


Spectrum of the velocity fluctuations in the vertical direction on different horizontal planes



Vertical fluctuations

Horizontal fluctuations



Same scaling found in a bubble column experiment of Riboux et al. 2010

Conclusions

* *To obtain physical outcomes at high-Re it is needed:*

- *Many bubbles must be included*
- *Re (Ar) should be high enough to trigger spatio-temporal chaos*
- *The number of points per bubble diameter scale roughly as ~Ar*
- *Refinement has to be sufficient to resolve boundary layers*

* *From the physical perspectives*

- *Bubble wakes/interfaces inject energy and enstrophy on a broad spectrum*
- *At high-Re (Ar) An inverse cascade is produced which shows the universality of the process*
- *Bubble agitation appears as a typical random force with small correlation*
- *The non-homogeneity plays a role in fluctuation dynamics as pointed out in experiments*
- *3D We do not know…yet*