Simulation numérique de l’atomisation

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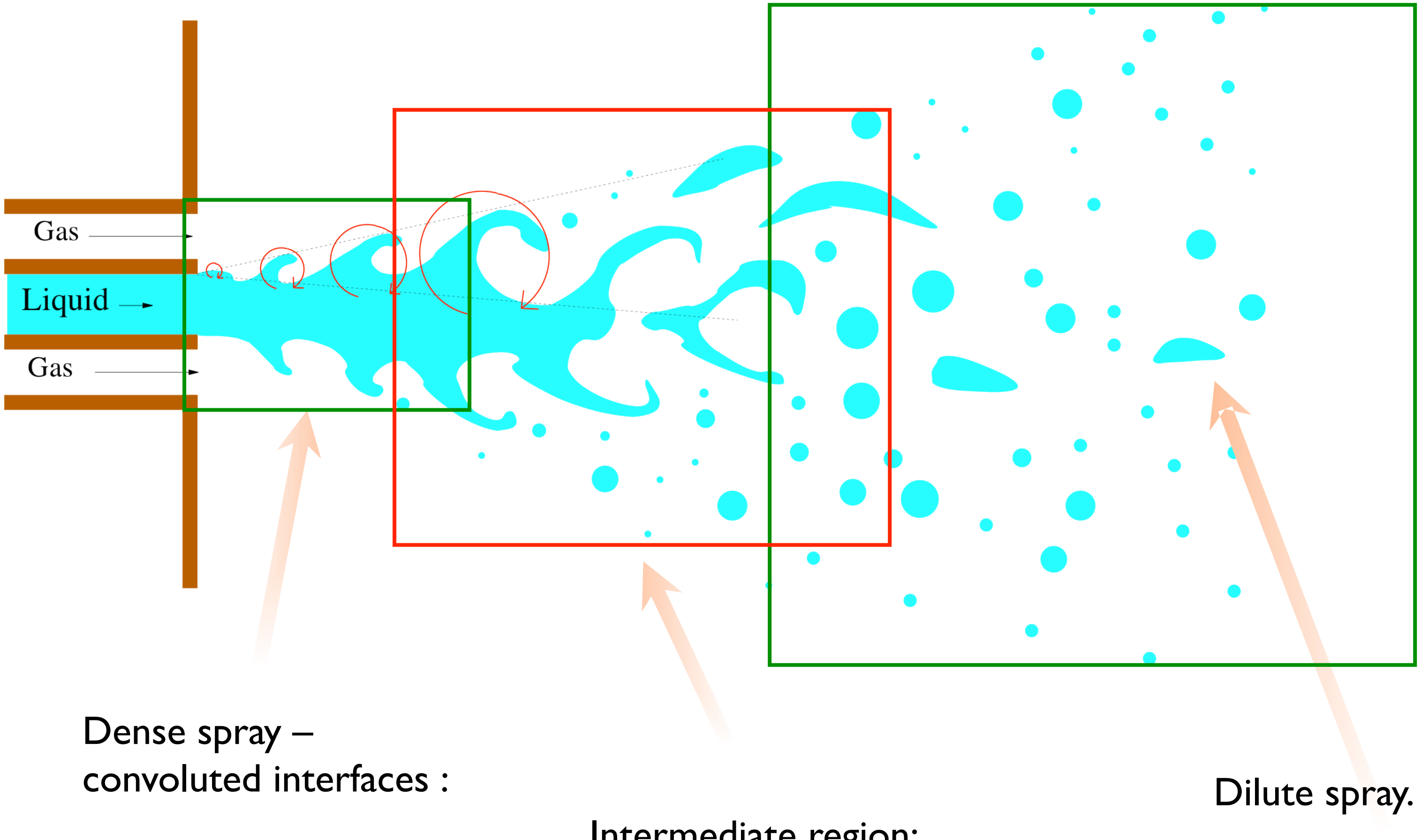
Typical structure and simulation strategy

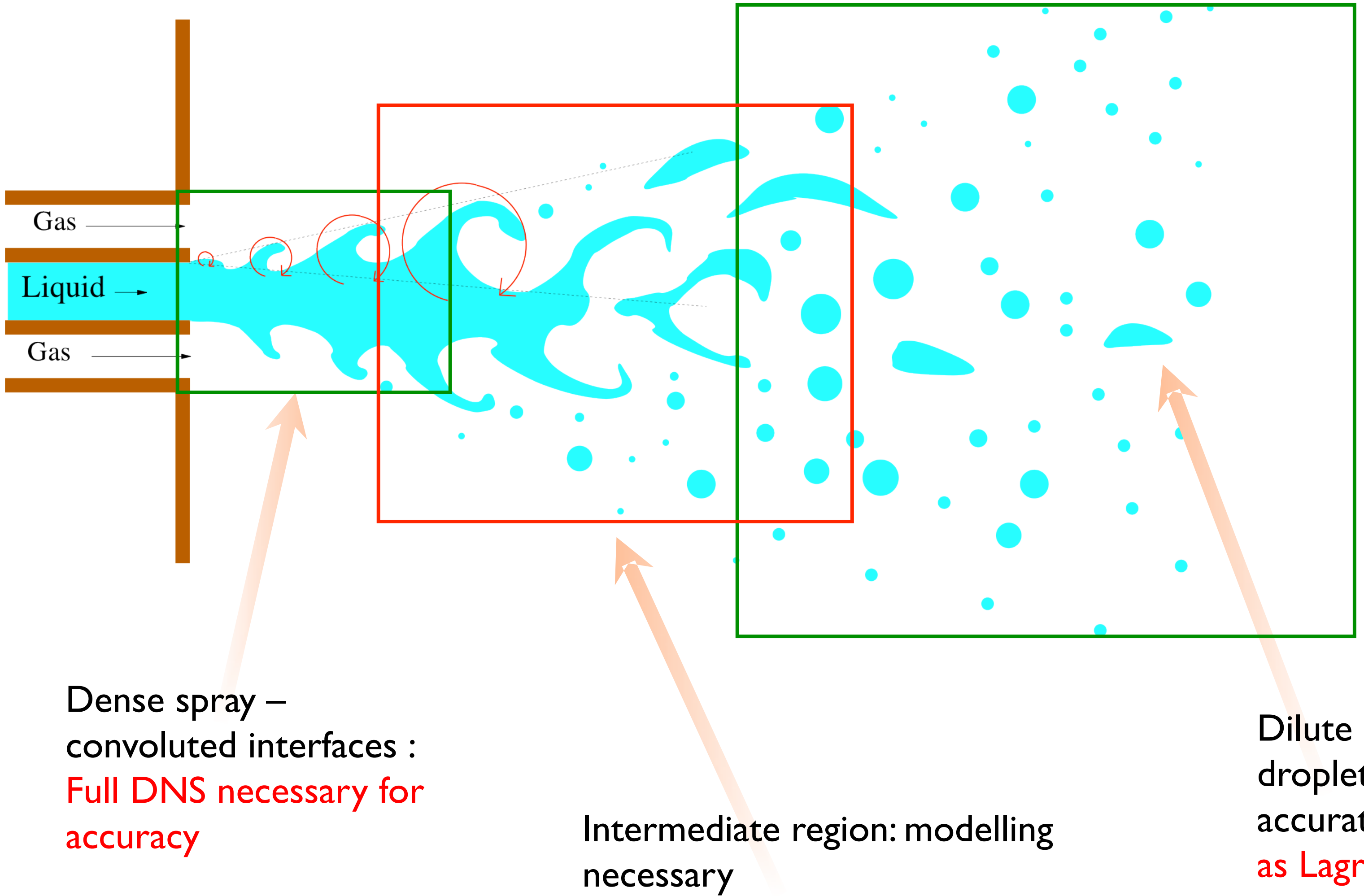


Dense spray –
convoluted interfaces :

Intermediate region:
progressive coarsening
downstream.

Dilute spray.

Simulation methodology



Dense spray –
convoluted interfaces :
Full DNS necessary for
accuracy

Intermediate region: modelling
necessary

Dilute spray:
droplets may be
accurately modelled
as Lagrangian
particles.

VOF methodology

- 1 Compute an evolving surface : computational geometry

- Solve

2 the Navier-Stokes equations with

3 surface tension,

and

4 variable viscosity and density,

5 ensure robustness,

6 have a multiscale approach.

Old Codes:

Surfer
Gerris gfs.sf.net

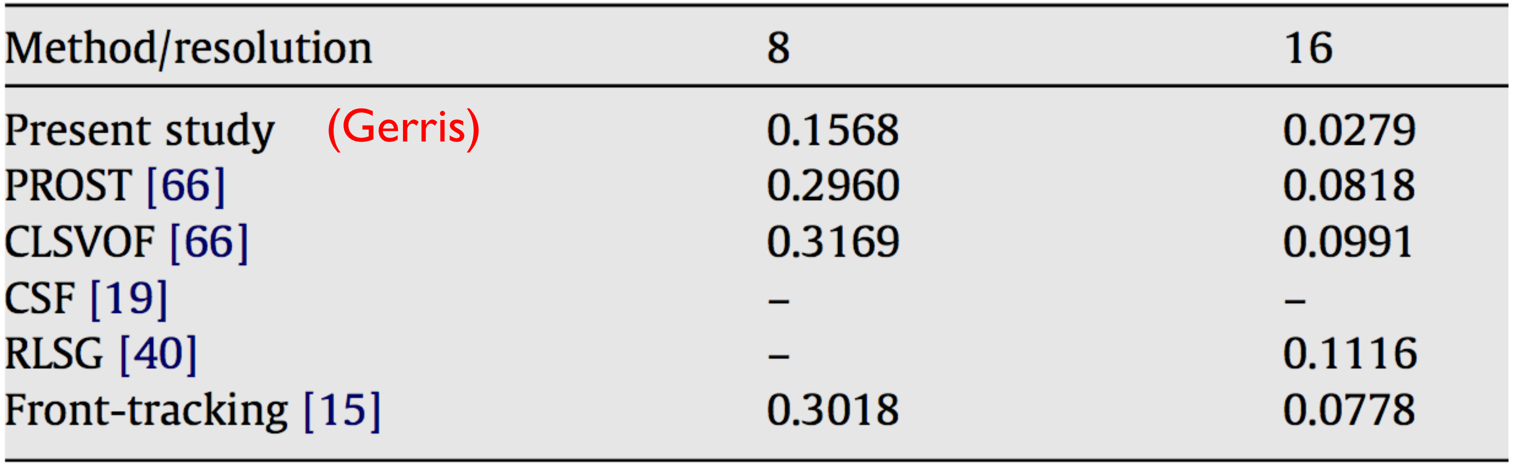
New codes

Basilisk basilisk.fr
ParisSimulator parissimulator.sf.net

Improvements: better stability, accuracy, faster, HPC-compatible.

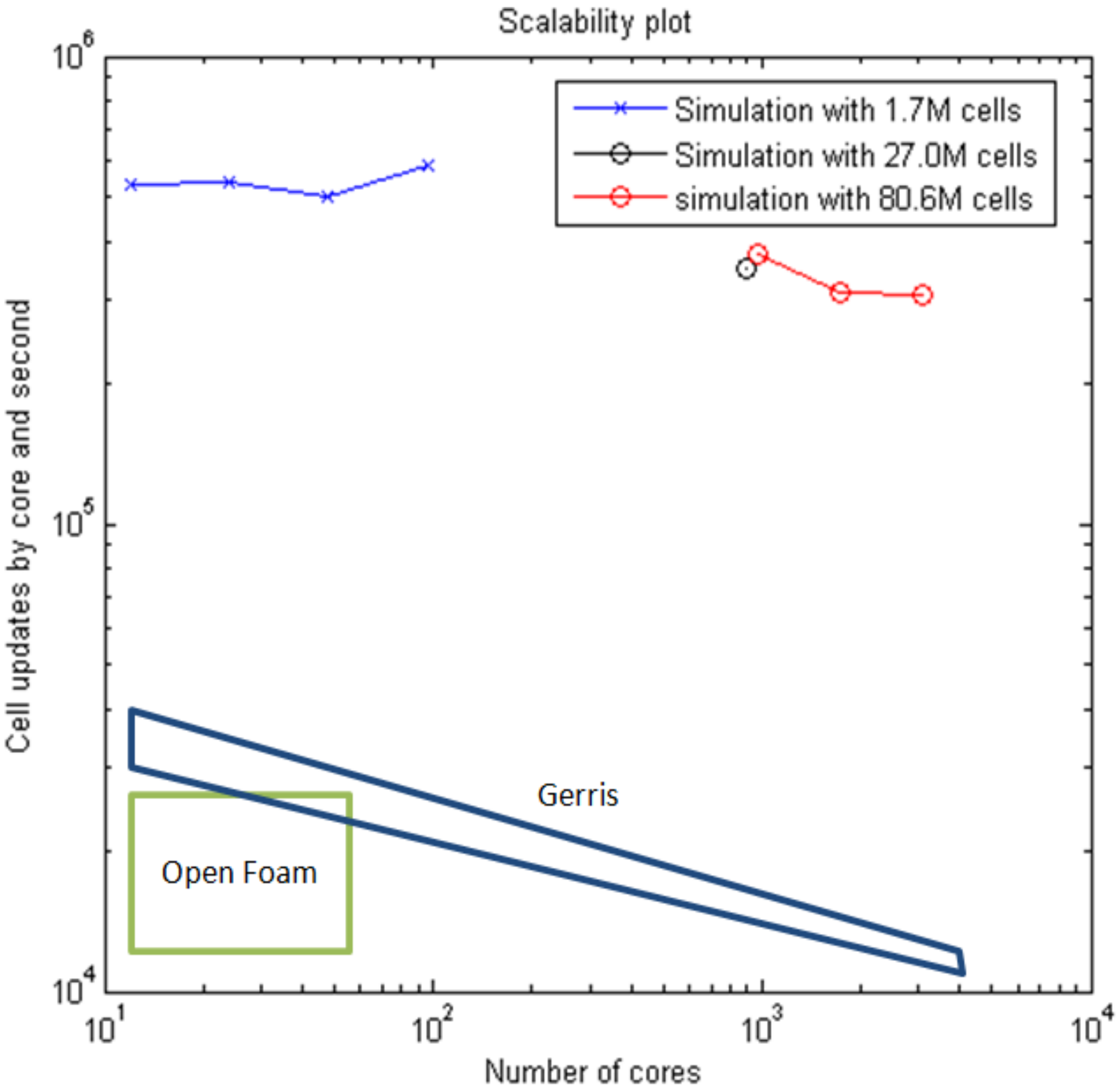
All our codes are free.

Gerris is very accurate: Capillary wave test. L_2 error norm:



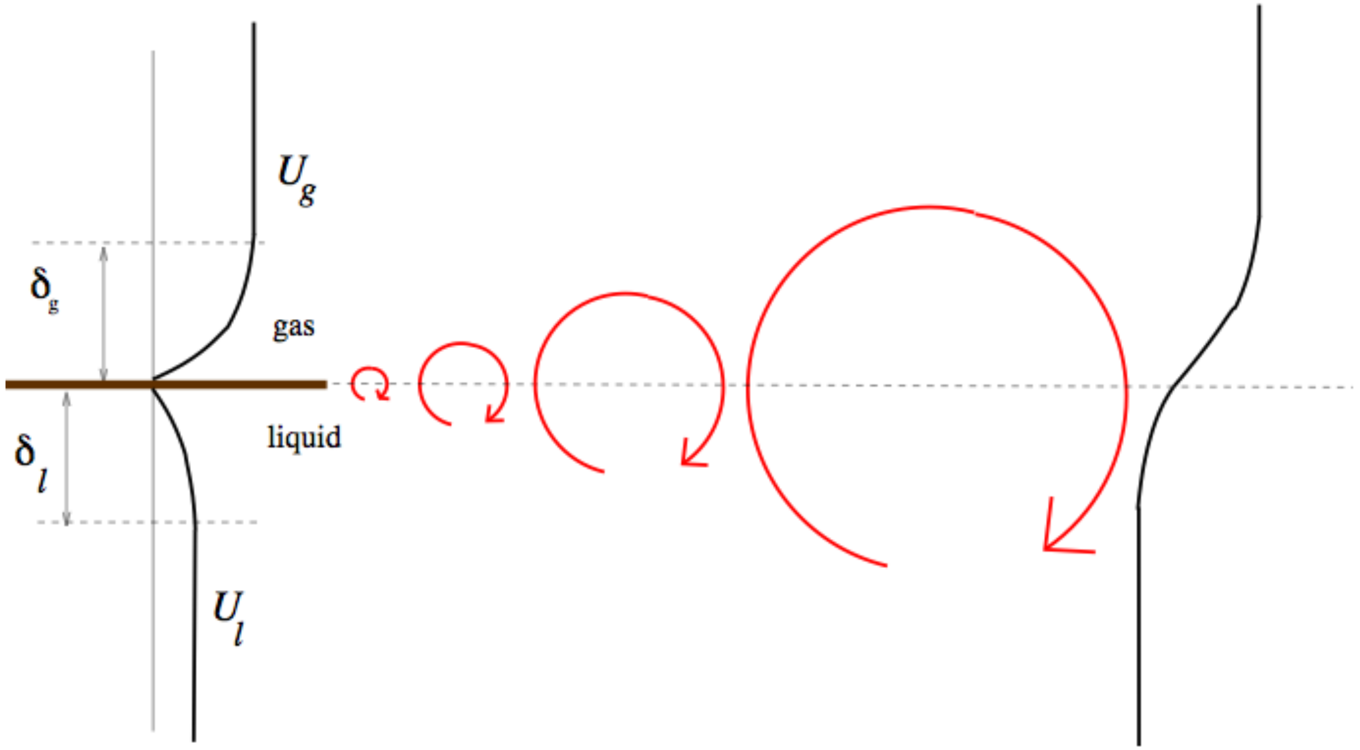
Method/resolution	8	16
Present study (Gerris)	0.1568	0.0279
PROST [66]	0.2960	0.0818
CLSVOF [66]	0.3169	0.0991
CSF [19]	–	–
RLSG [40]	–	0.1116
Front-tracking [15]	0.3018	0.0778

But Gerris is slow. ParisSimulator and Basilisk are faster



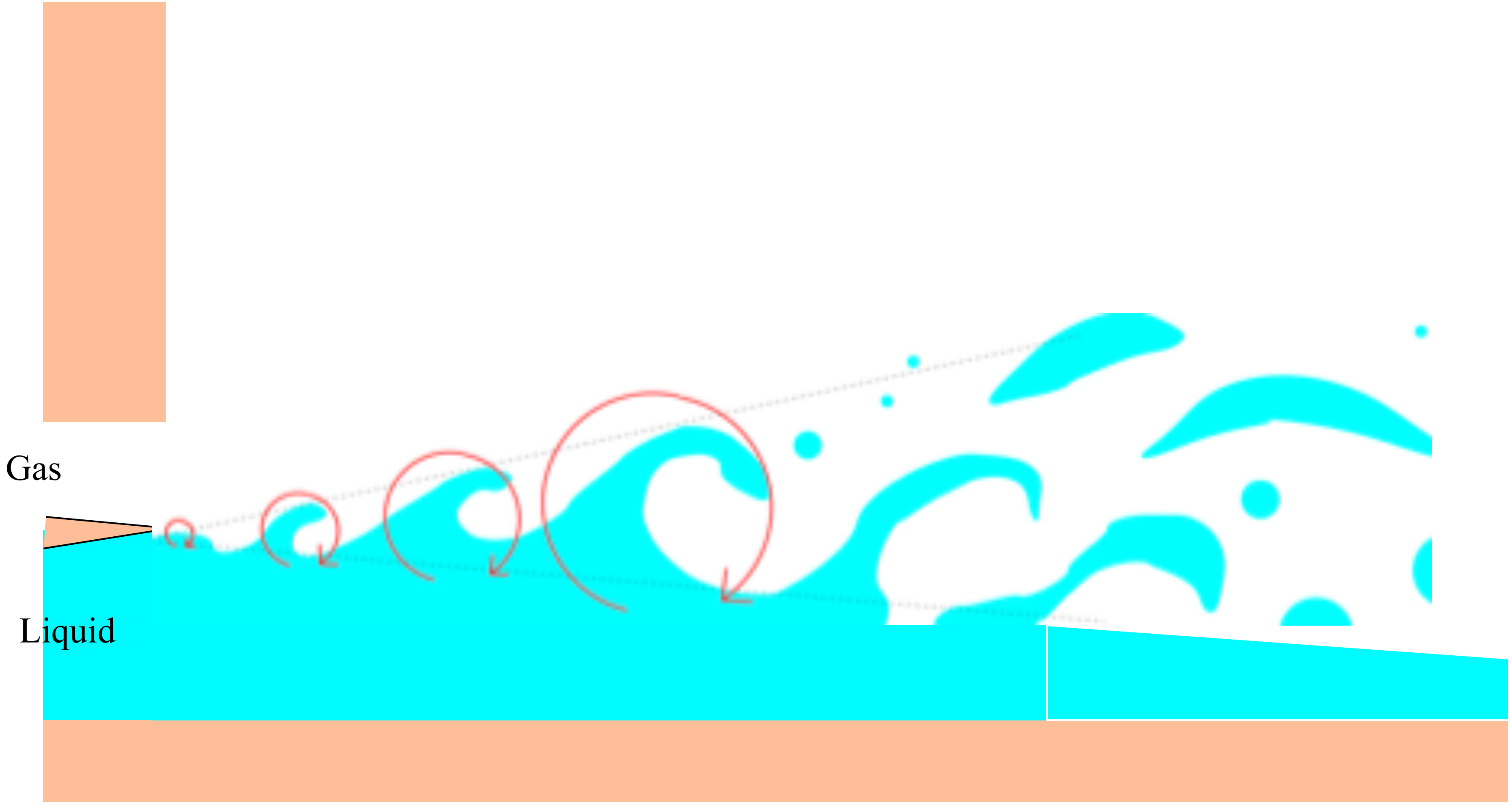
Atomization

Kelvin-Helmholtz instability : unstable shear flow

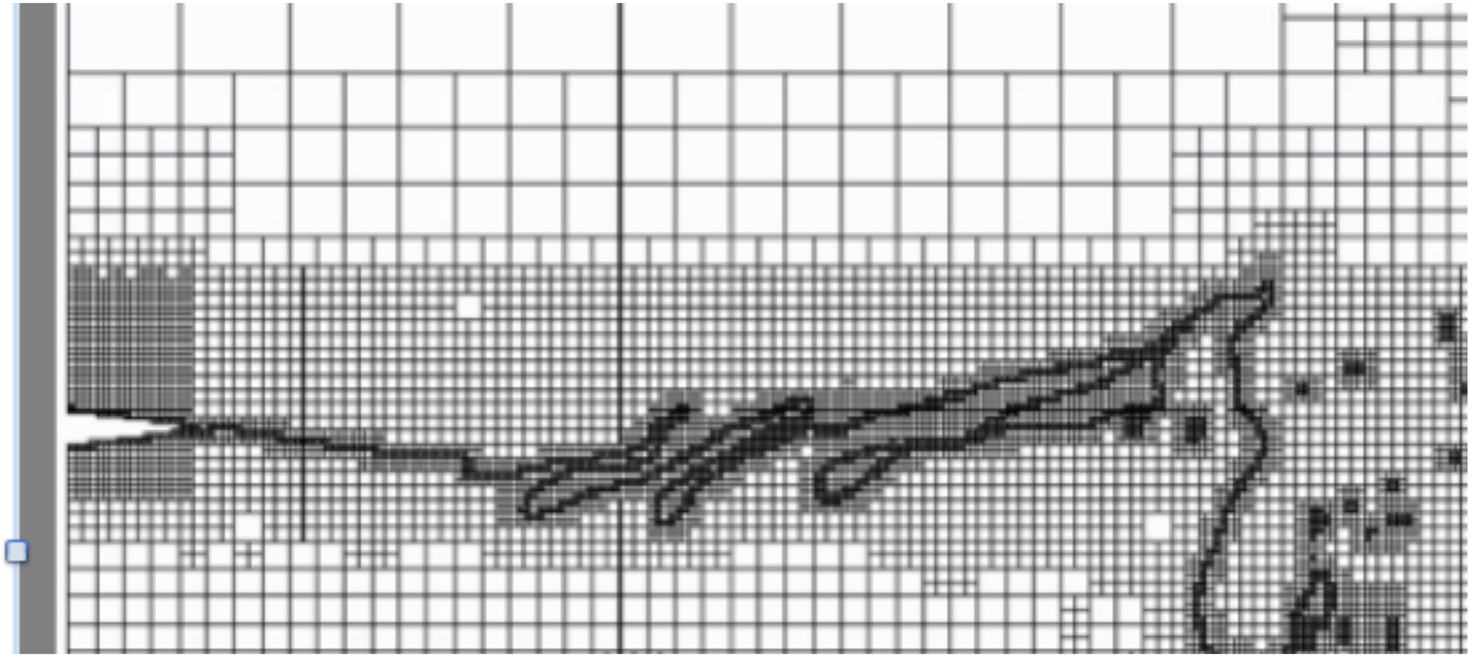


2D simulations of the planar « Grenoble » setup.

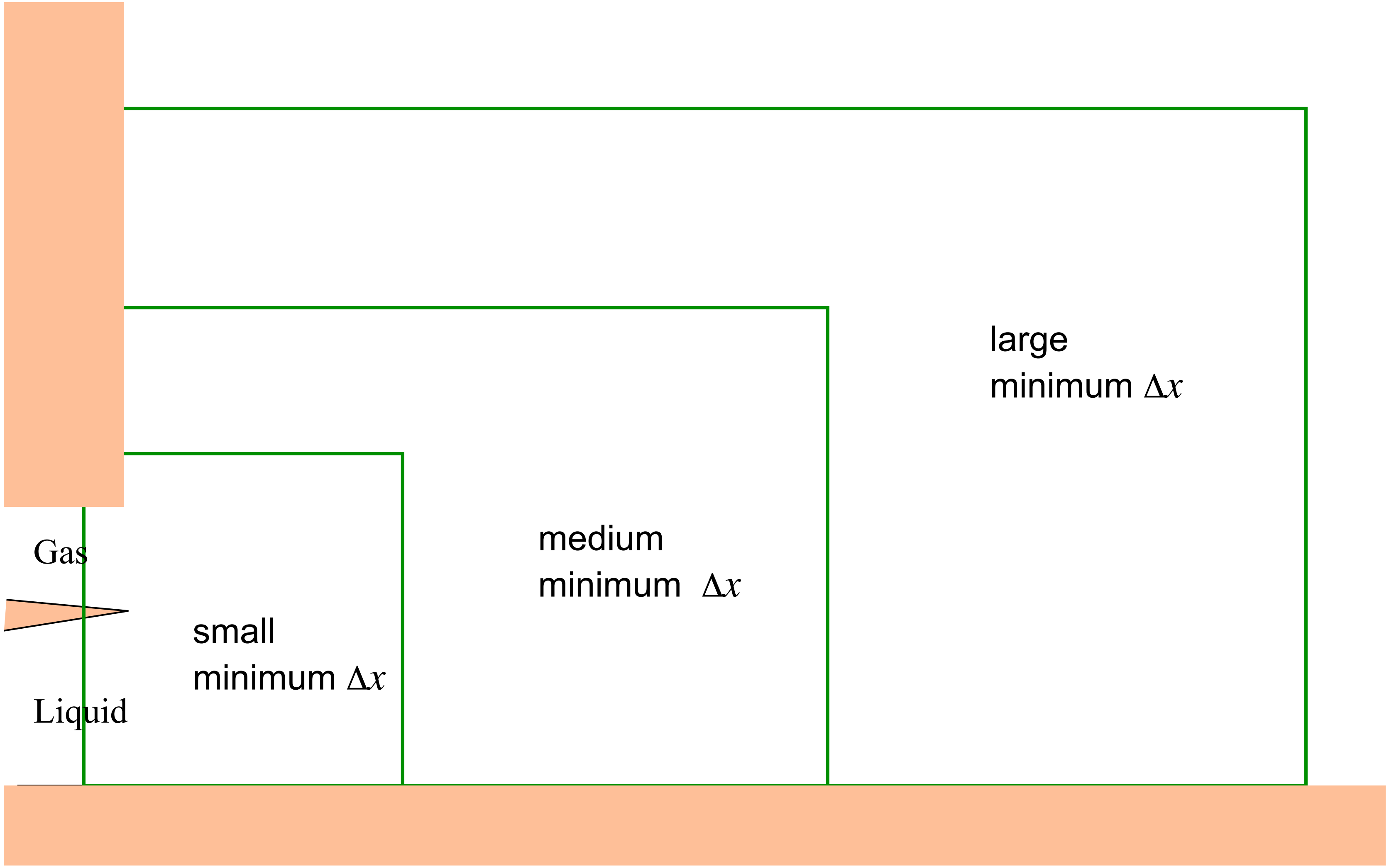
The Grenoble quasi 2D experiment set up



Use Gerris flow solver with adaptive oct-tree and quad-tree grids

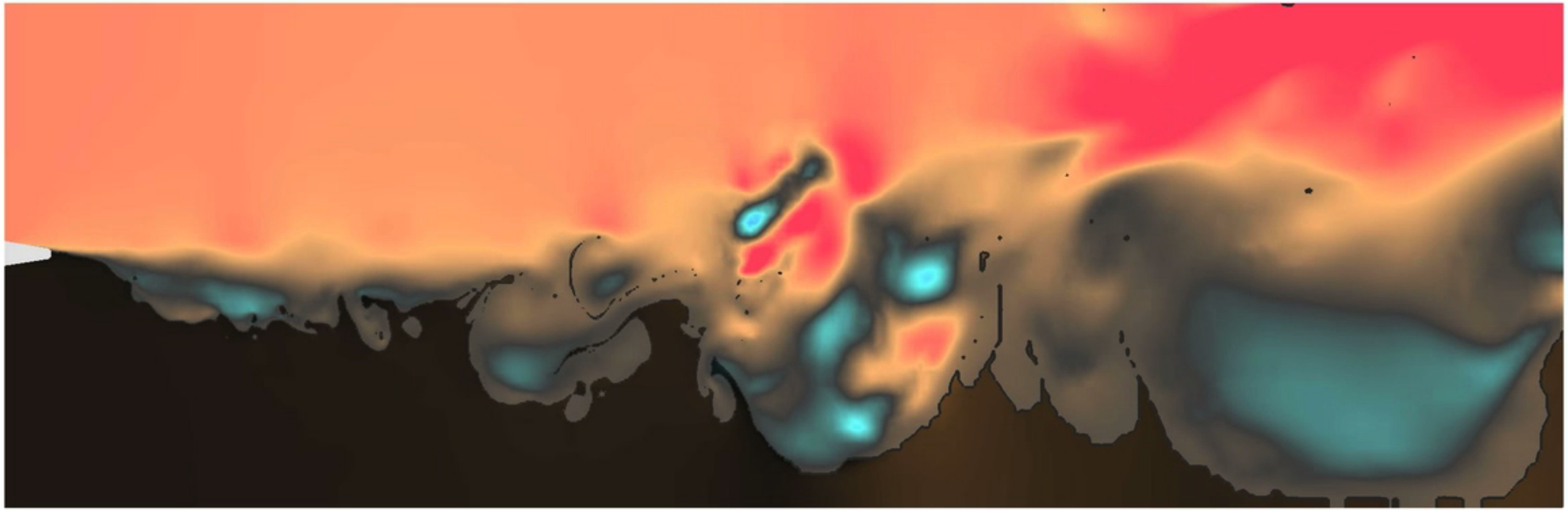


Elementary multiscale treatment: Navier-Stokes with variable minimum grid size according to a subdivision of the computational domain.

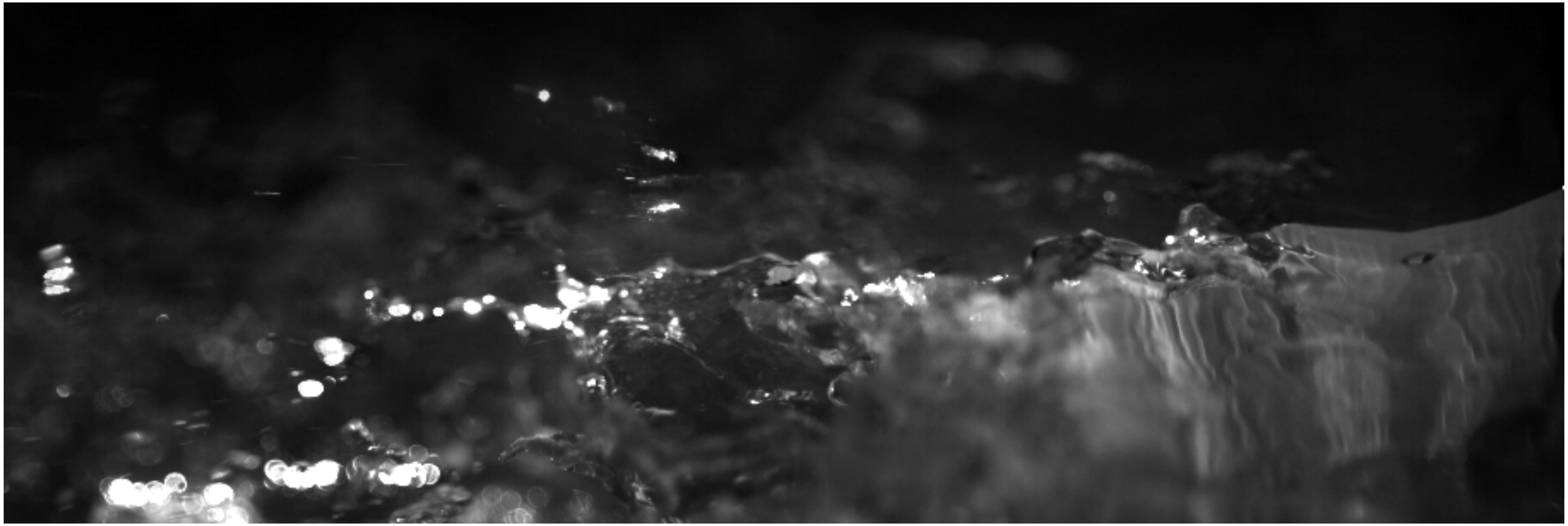


Simulation with a separator plate at density ratio (1/*r* = *100*)

m	r	Re_g	Re_l	We_g	We_l	M
0.017	0,01	2640	290	19	8	2,4



Movie by Daniel Fuster and Jérôme Hoepffner using the Gerris Flow solver



Compare to experiments in Grenoble (Cartellier, Matas) . Flow from right to left.
Video with help of Jérôme Hoepffner and Jon Soundar.

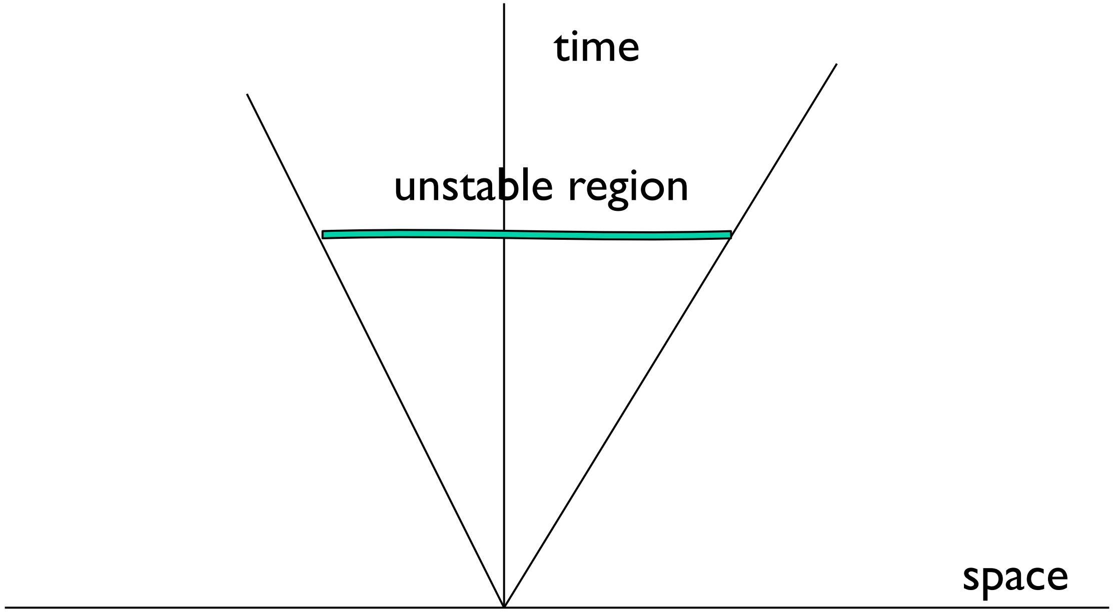
To compare numerical results with theory , we need:

Linear stability theory of the Kelvin-Helmholtz instability:
Viscous, Error-function profiles

a) Yecko, Fullana, Boeck, Zaleski,
b) Gordillo, Perez-Saborid, Ganan-Calvo,
c) Spelt, Valluri, O'Naraigh
d) Matas

Convective/absolute instabilities

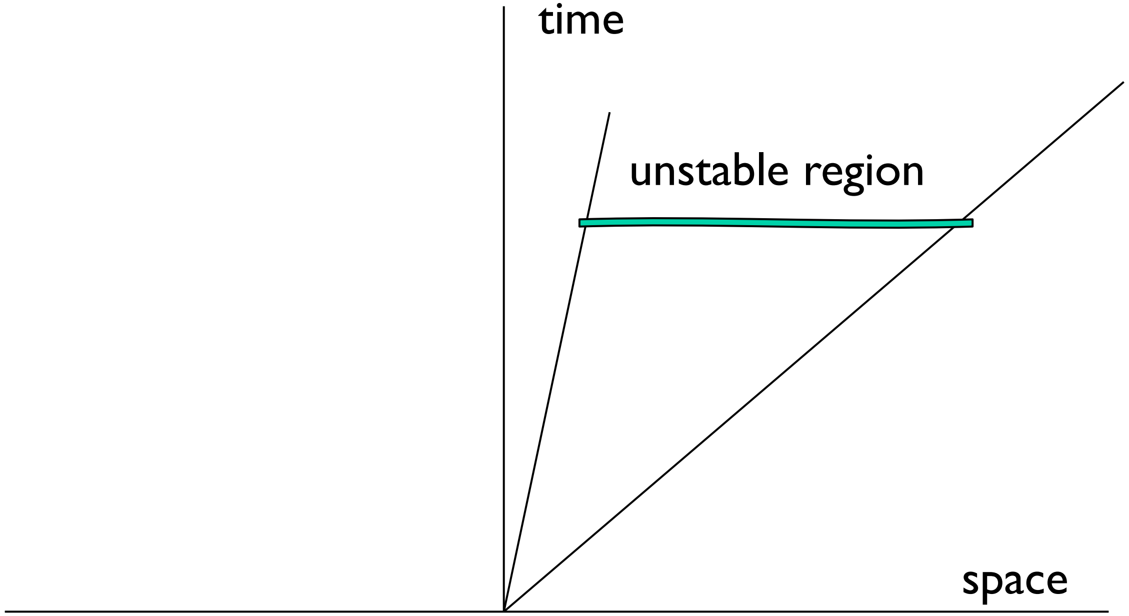
1) Absolute: a spatially localized perturbation at x=0 and t=0 grows in the entire space



corresponds to a well-defined oscillator frequency in the entire domain, a so-called « global mode ». Upstream turbulence has little influence.

Convective/absolute instabilities

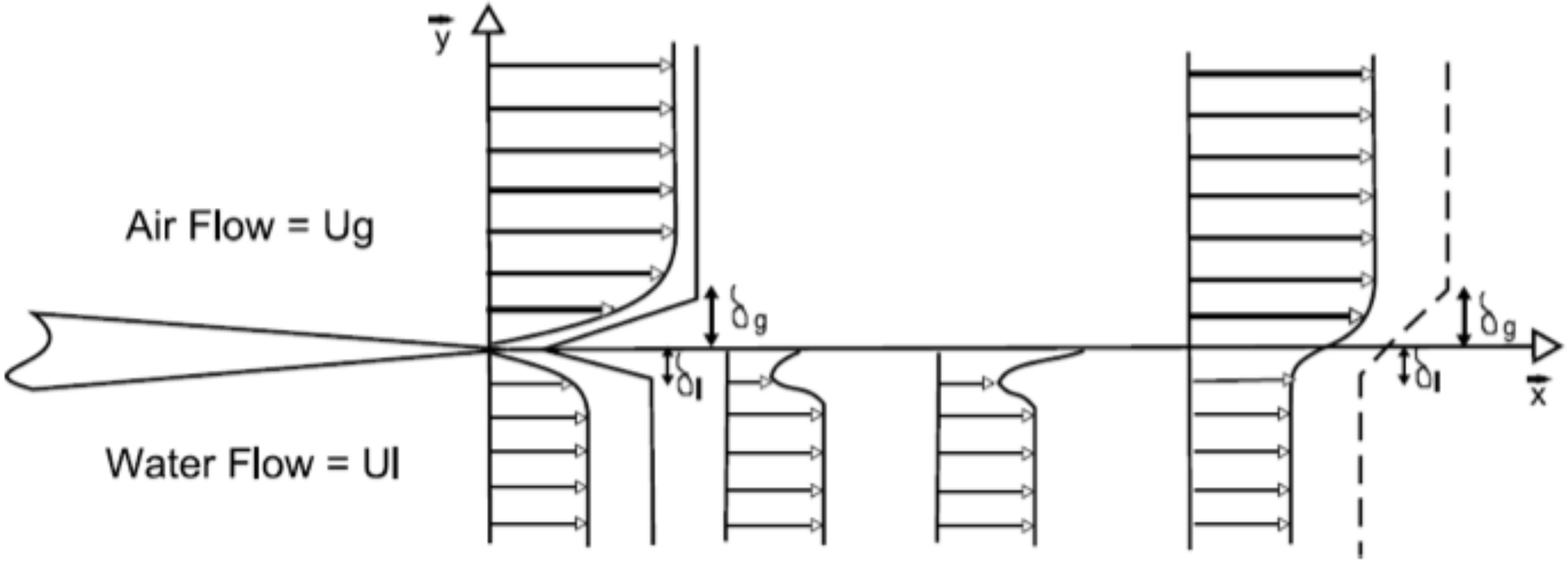
2) Convective instability: a spatially localized perturbation at t=0 is convected downstream with the flow



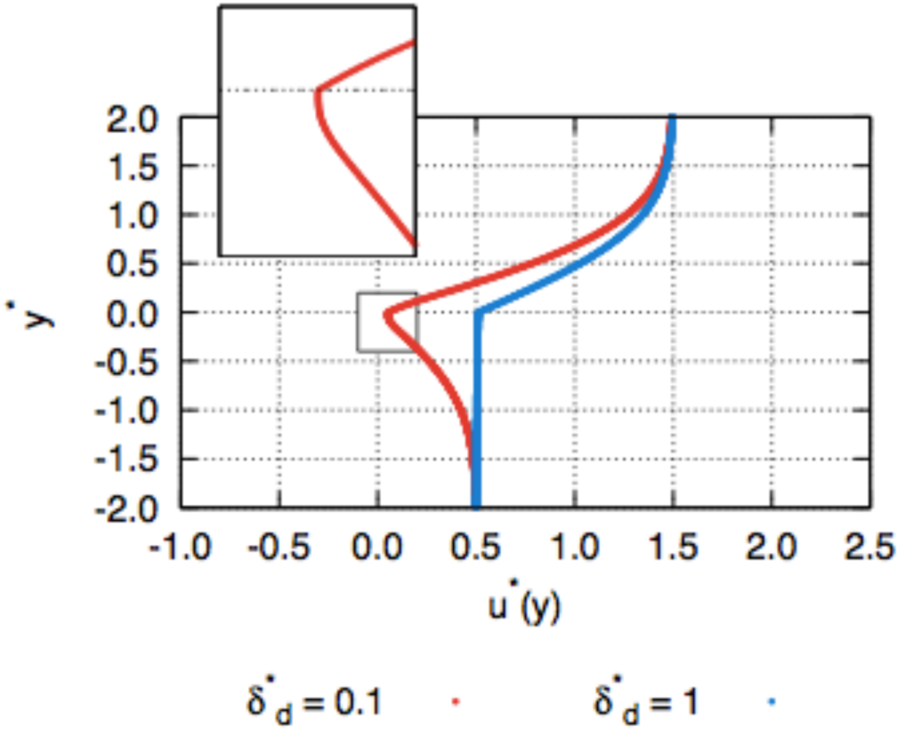
No single frequency is observed but instead, broadband noise is seen. The system is seen to be a noise amplifier. Upstream turbulence matters

So what does linear theory say about our problem ? Is it convective or absolute ?

Linear theory has an enormous dependence on the wake flow correction.



Wake flow



Simplified base flows

Effect of upstream turbulence on instability growth.

The effect of upstream turbulence will be important if the spatial analysis reveals a convective instability.

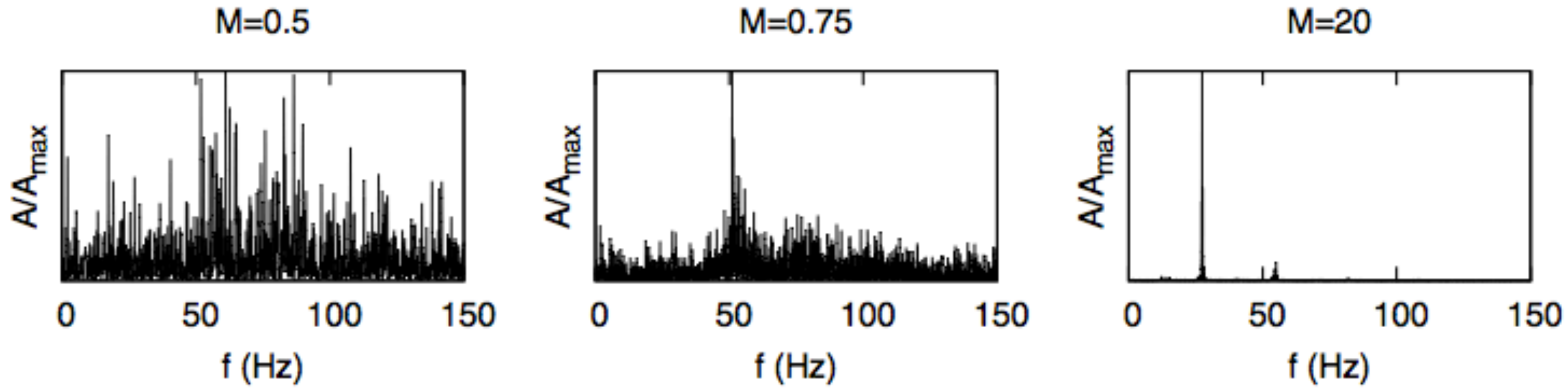
It will be unimportant if an absolute instability is found.

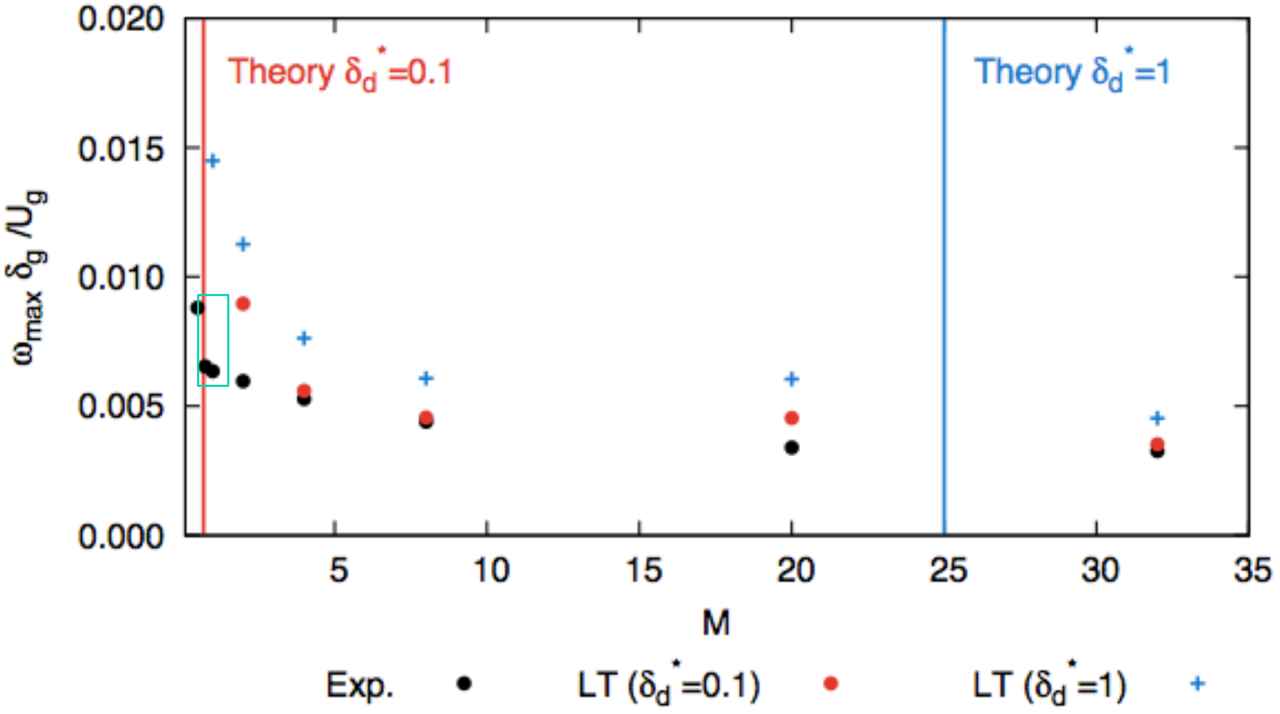
Most « important » parameter: momentum flux ratio
(or ratio of dynamic pressures. It is the only parameter that does not involve small-scale characteristics of the flow)

$$M = \frac{\rho_g u_g^2}{\rho_l u_l^2}$$

Grenoble experiments: Cartellier, Matas, Marty

convective, noise amplifier ambiguous absolute, global mode





Now the ultimate test ! Compare :

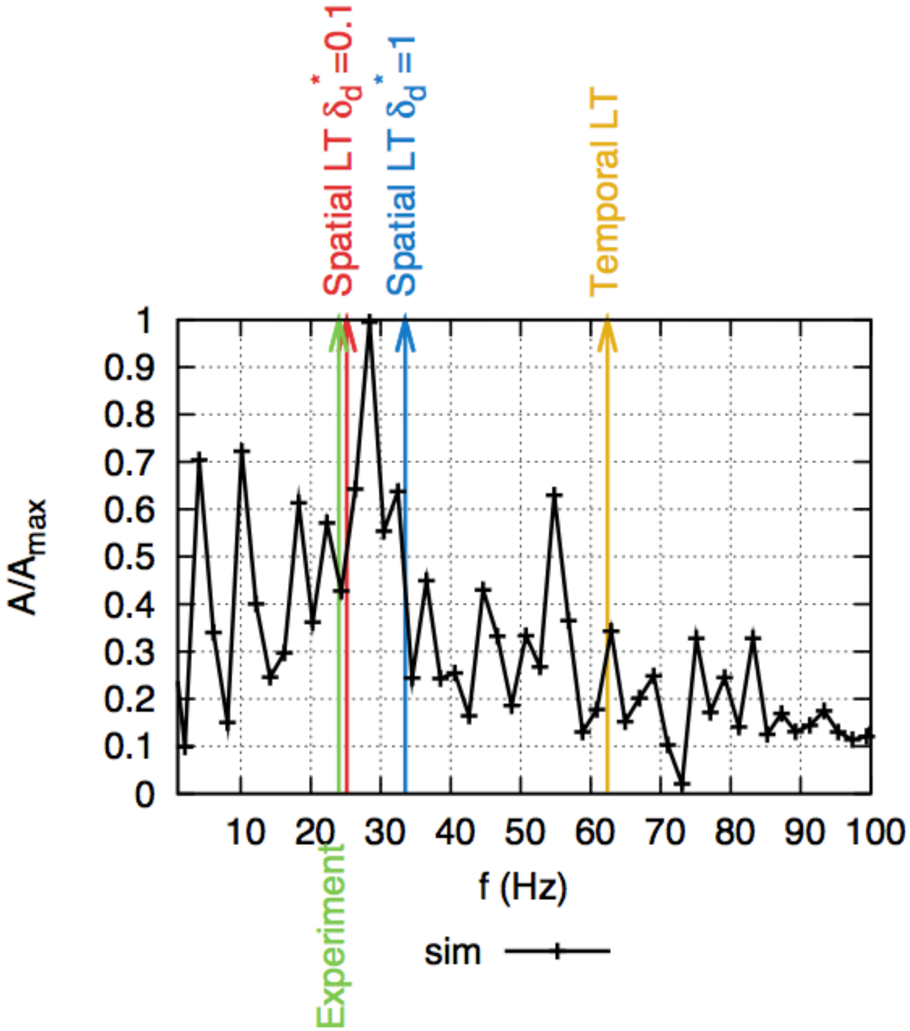
- Experiments
- Numerics
- Linear theory

We need linear theory, again but for spatially developping flows.

For that, we need to know what are absolute and convective instabilities !

What about the simulation ?

Comparison experiment-simulation



3D flows

The iconic Marmottant-Villermaux case

Air-Water
$u_{liq} = 0.6$ m s^{-1}, $u_{gas} = 35$ m s^{-1}

injection diameter D = 7.8 mm

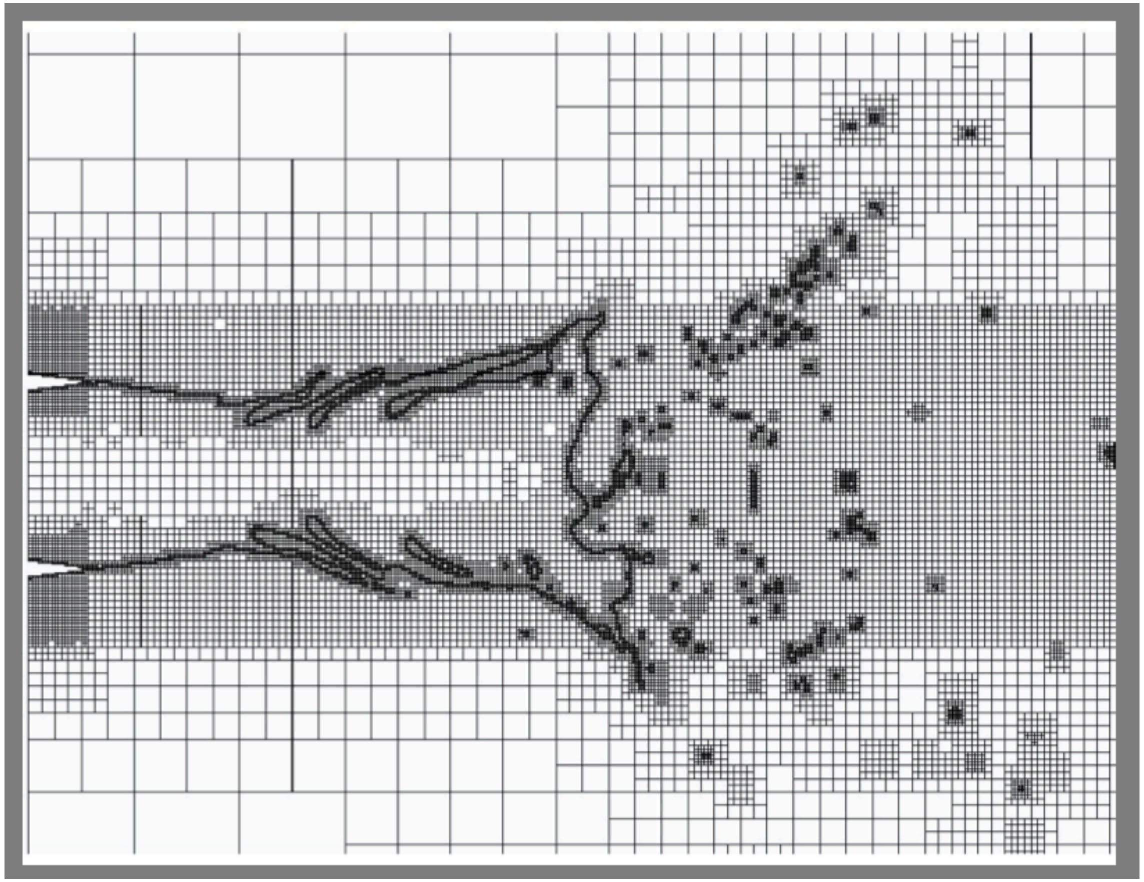
$Re_g = 16000, We_g = 200$
based on D_l

$Re_\delta = 400$

Simulation : six weeks on 64 AMD processors

line of eight 512^3 boxes – (equivalent regular mesh but we use octree adaptation)

Difficult to go to higher levels of refinement

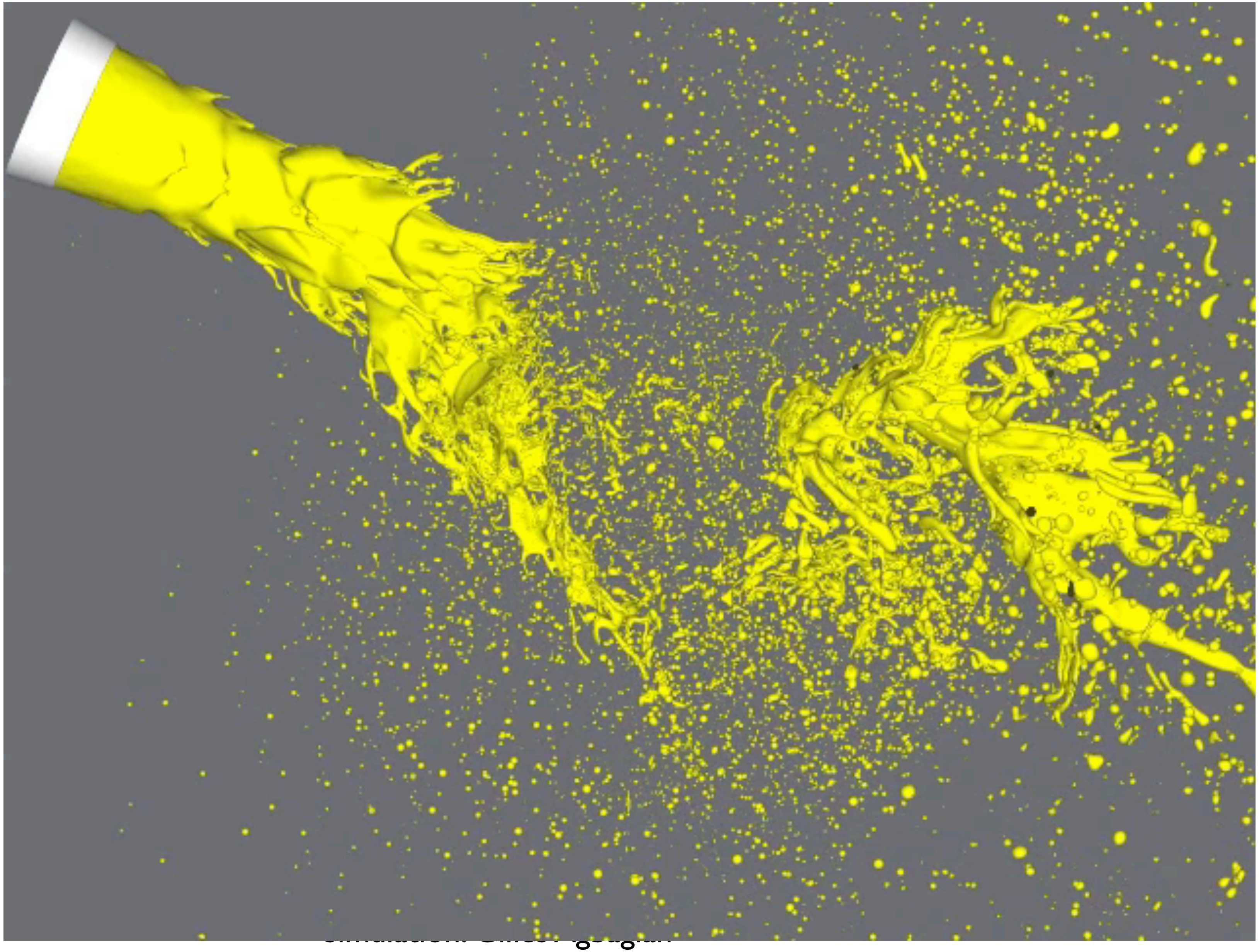


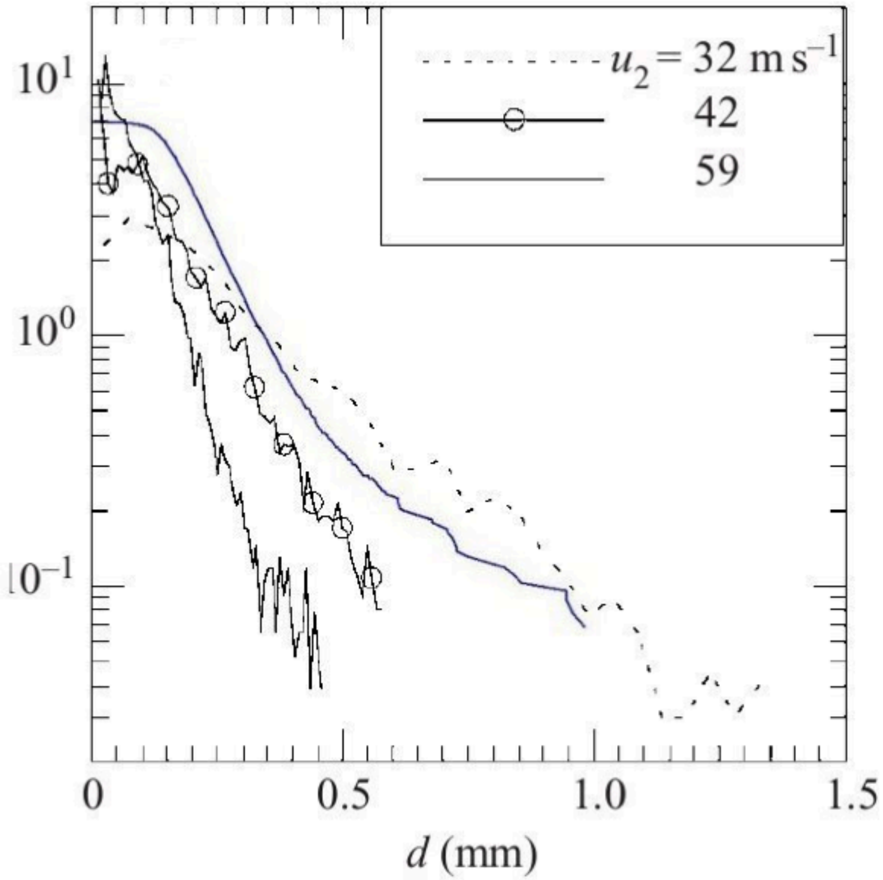
Boundary layer size
157 µm

smallest
grid size 50 µm

25µm case currently running

Injector thickness comparable.





Particle size distributions

experimental and computed at UPMC

u_2 = 35 m / s

Lagrangian Point Particle model

- Resolved Flow (*Popinet, 2009*)

$$\rho(\partial_t \boldsymbol{u} + \boldsymbol{u} \cdot \nabla \boldsymbol{u}) = -\nabla p + \nabla \cdot (2\mu \boldsymbol{D}) + \sigma\kappa\delta_s \boldsymbol{n} - \boldsymbol{f}_p$$

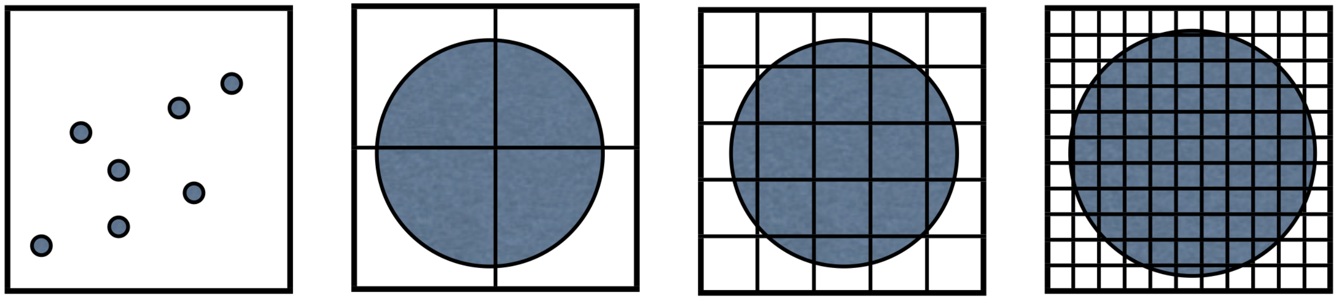
$$\nabla \cdot \boldsymbol{u} = 0$$

$$\partial_t c + \boldsymbol{u} \cdot \nabla c = 0$$

- Lagrangian Point-Particle

$$\frac{d\boldsymbol{u}_p}{dt} = \frac{\tilde{\boldsymbol{u}} - \boldsymbol{u}_p}{\tau_p}\phi + \frac{\rho}{\rho_p}\frac{D\tilde{\boldsymbol{u}}}{Dt} + \frac{C_m \rho}{\rho_p}\left(\frac{D\tilde{\boldsymbol{u}}}{Dt} - \frac{d\boldsymbol{u}_p}{dt}\right)$$

The modelling depends on the type of simulation.



dx >> d_p Conventional LPP

dx ≃ d_p dx < d_p Poorly Resolved Drop (Finite-size LPP)

dx << d_p Fully Resolved Drop

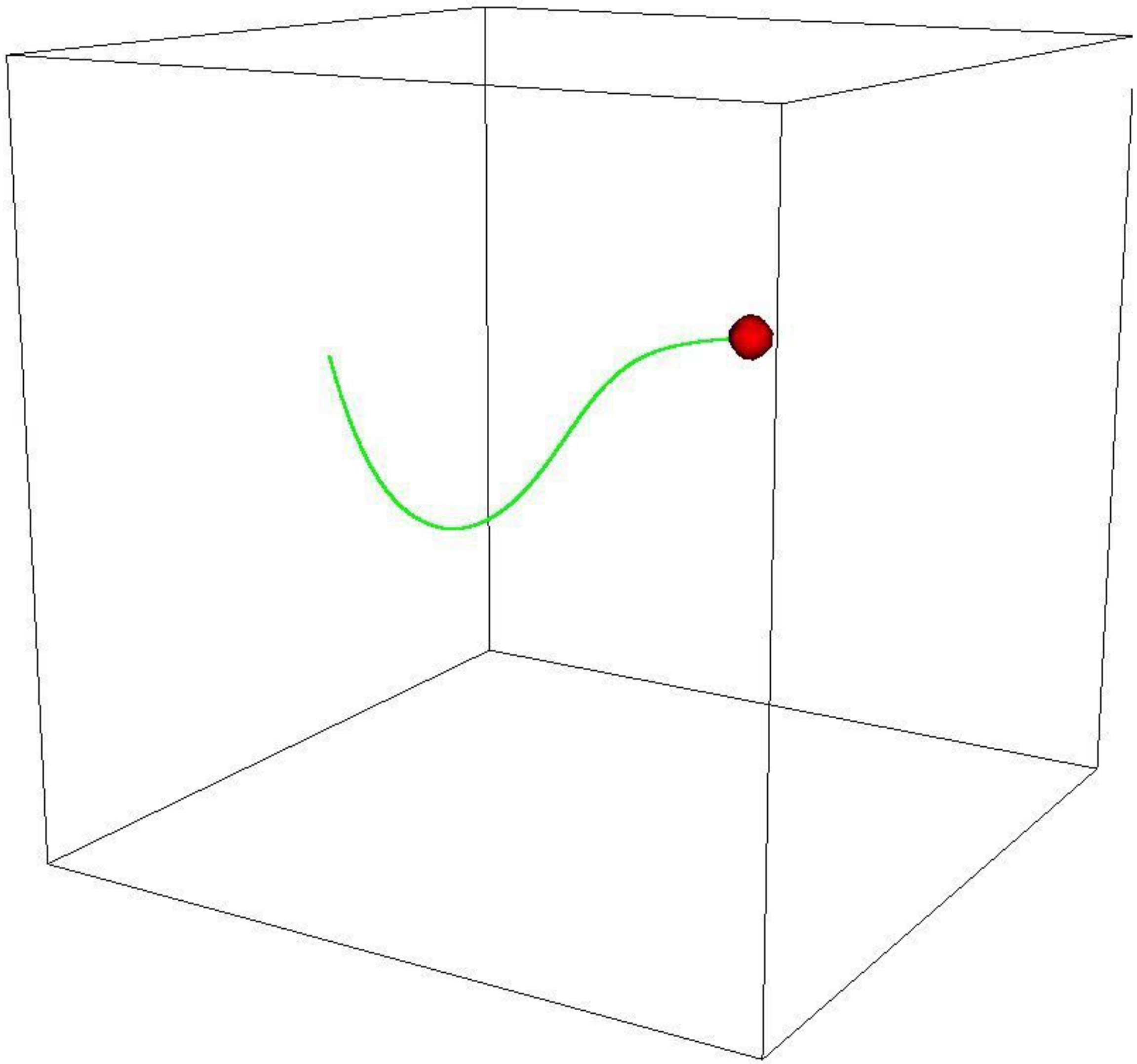
With oct-treeAMR we will move from more or less resolved cases.

Do simultaneously VOF->LPP conversion *and* massive grid coarsening ?

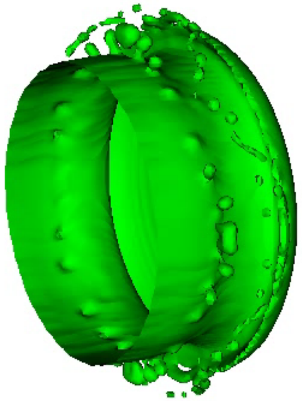
Question: (unanswered) how much accuracy do we lose by going from a fully resolved drop to a « very unresolved » one

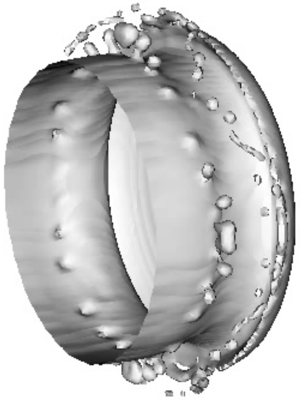
In a first step we work on a regular cubic grid code without AMR, ParisSimulator

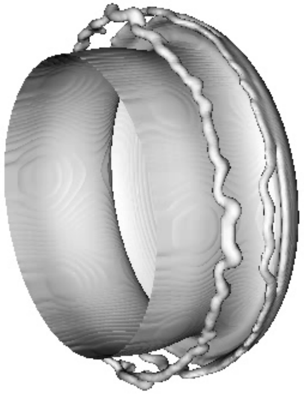
Test case : driven cavity flow with LPP. Re=16, Re_p=0,34



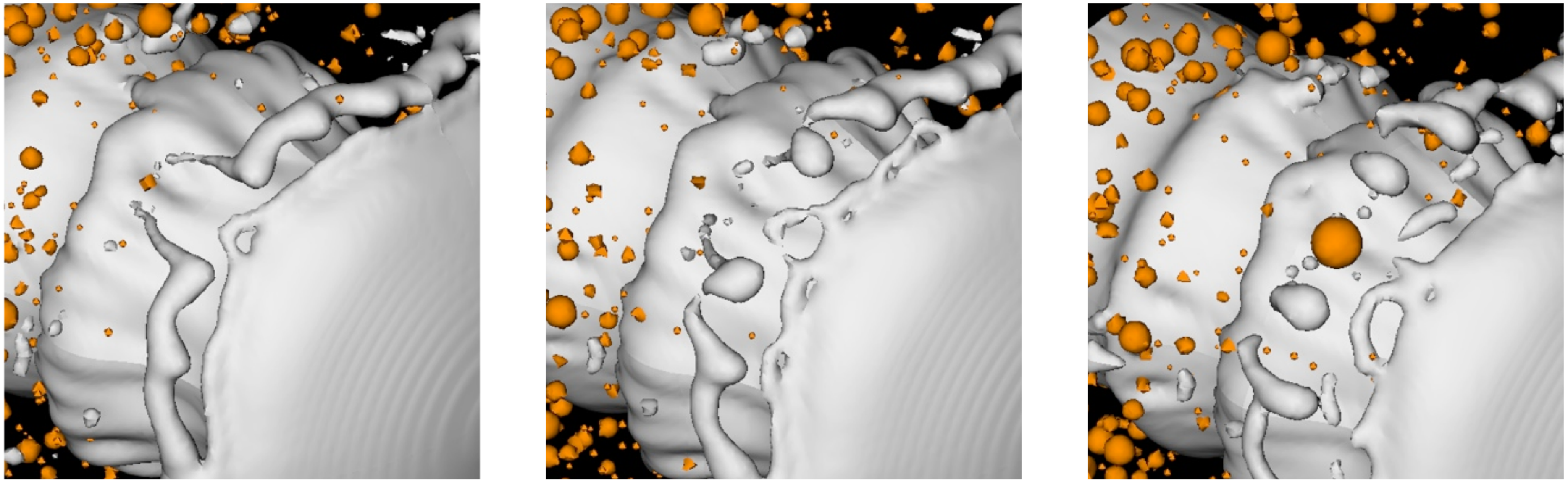
Pulsed Diesel-type jet







VOF to LPP conversion - Higher Reynolds

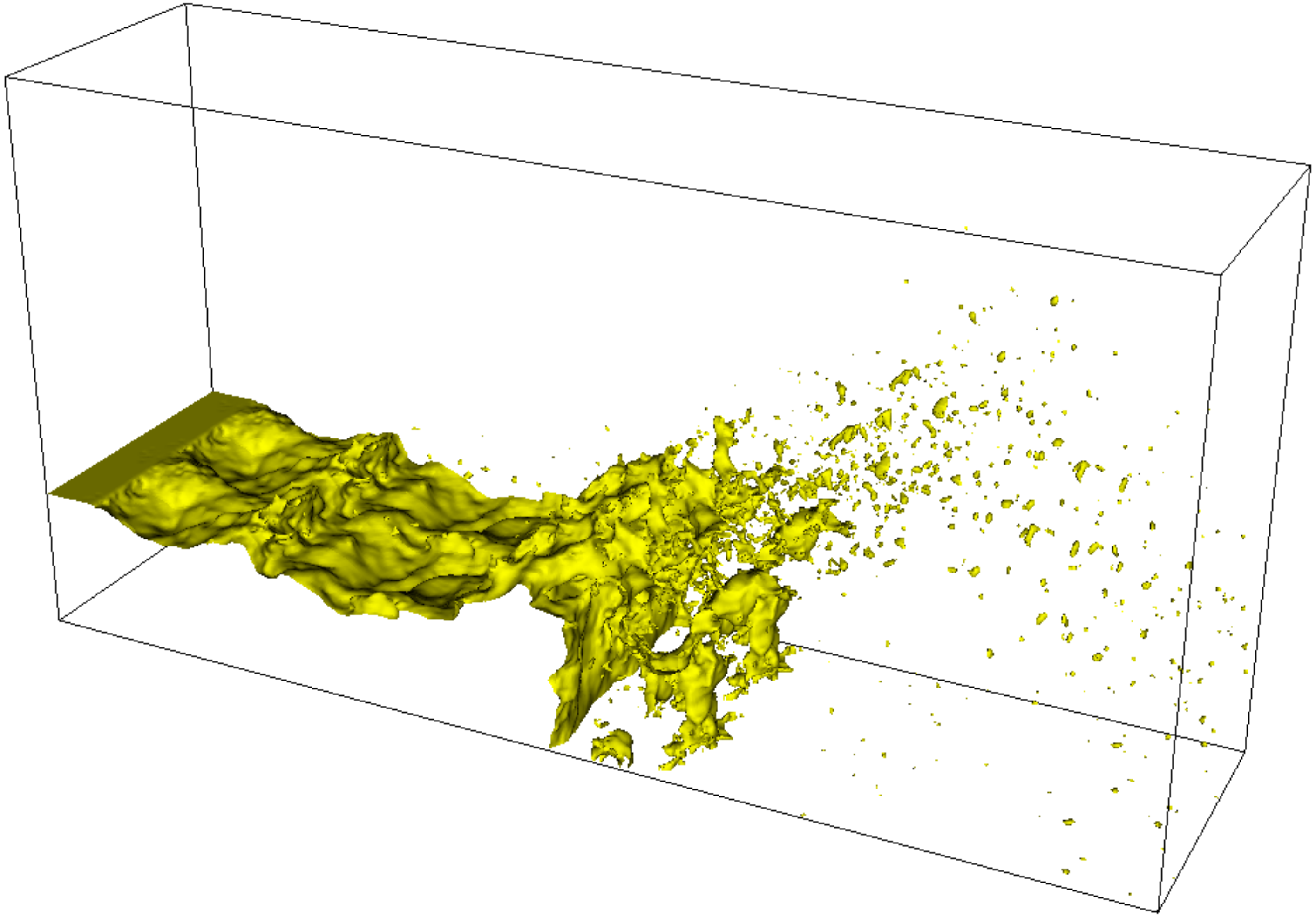


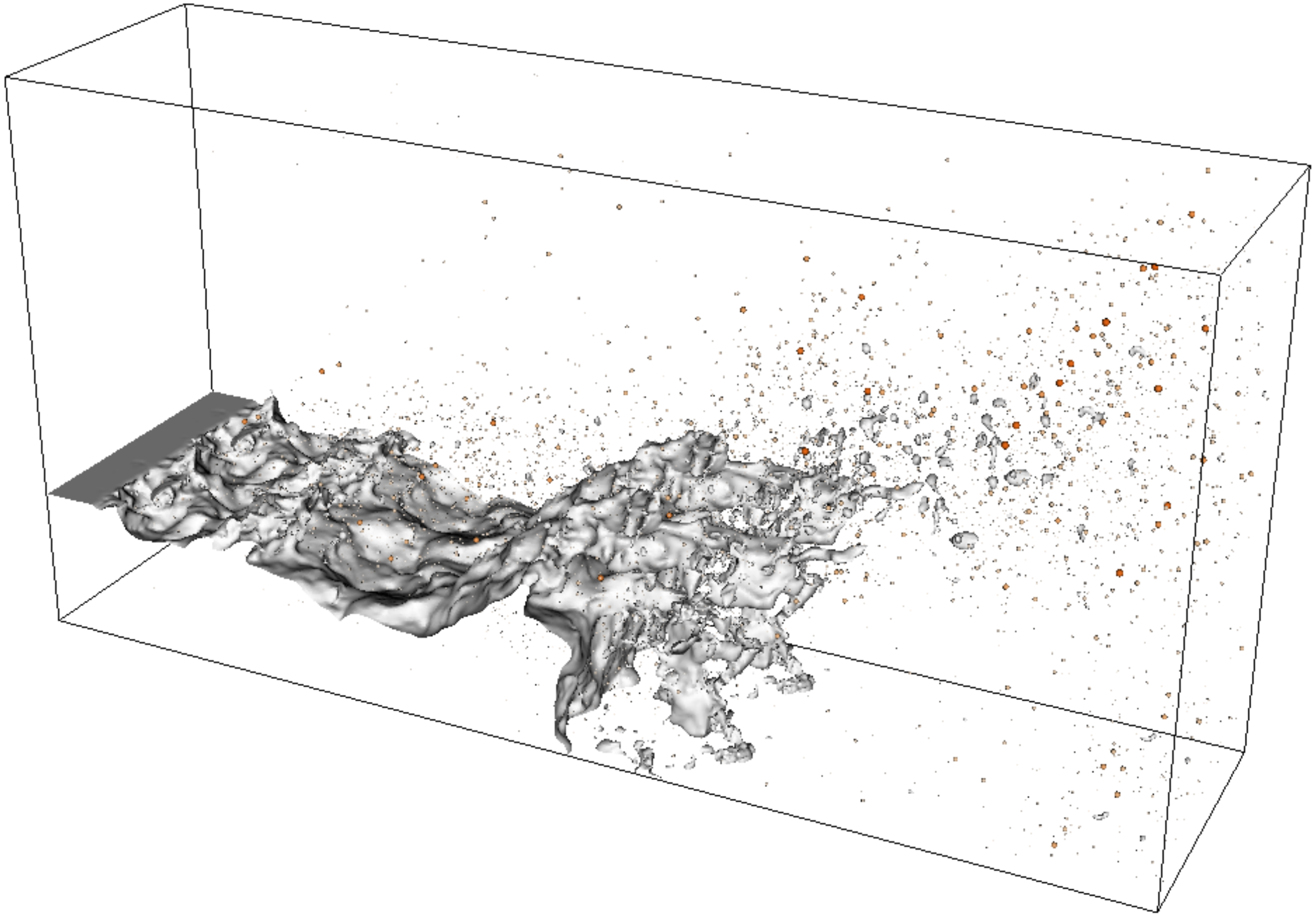
Conditions de l'article de Deschamp et al dans lequels les trajectoires de particules sont mesurées

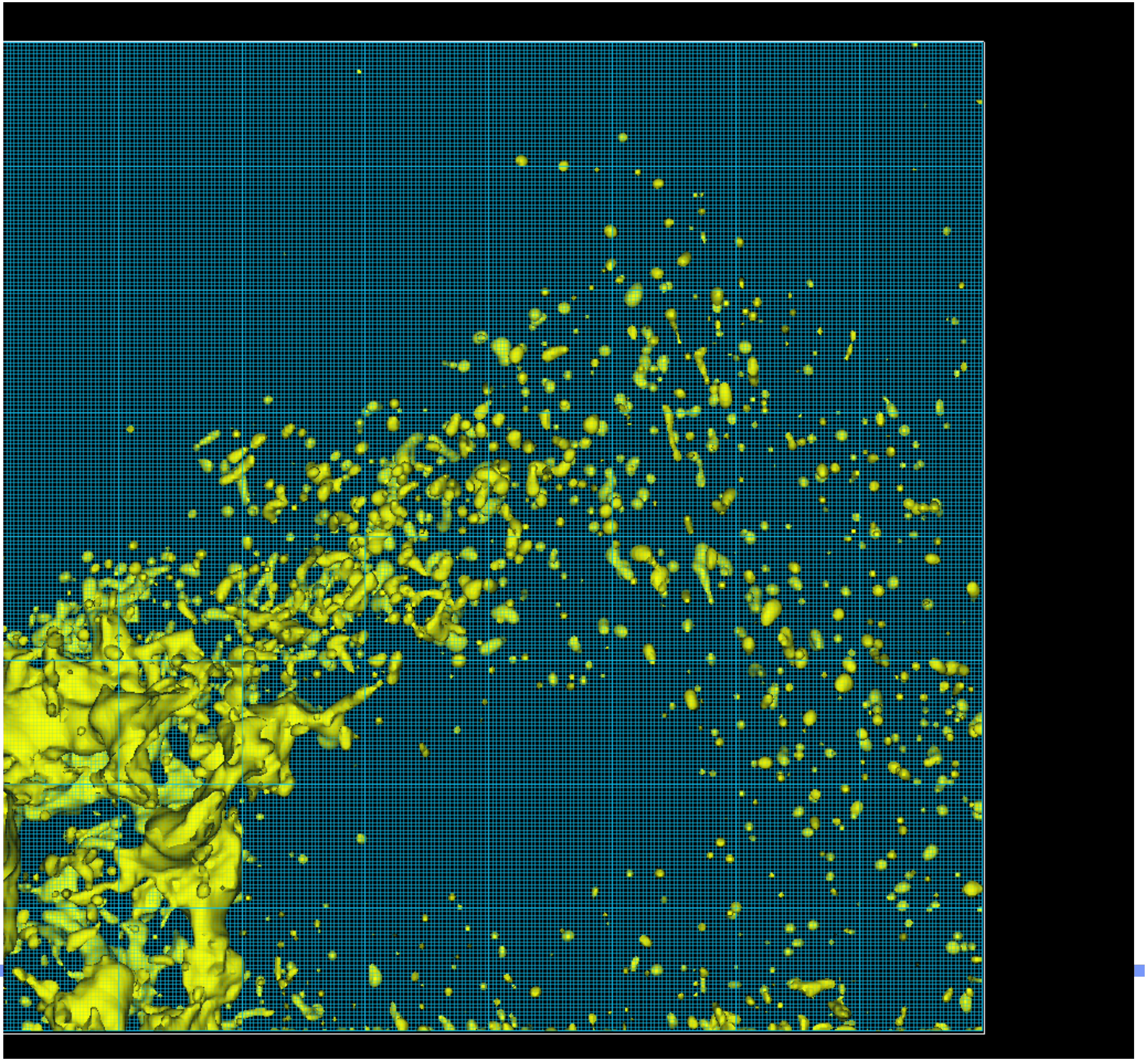
$Re_\delta = 1000$

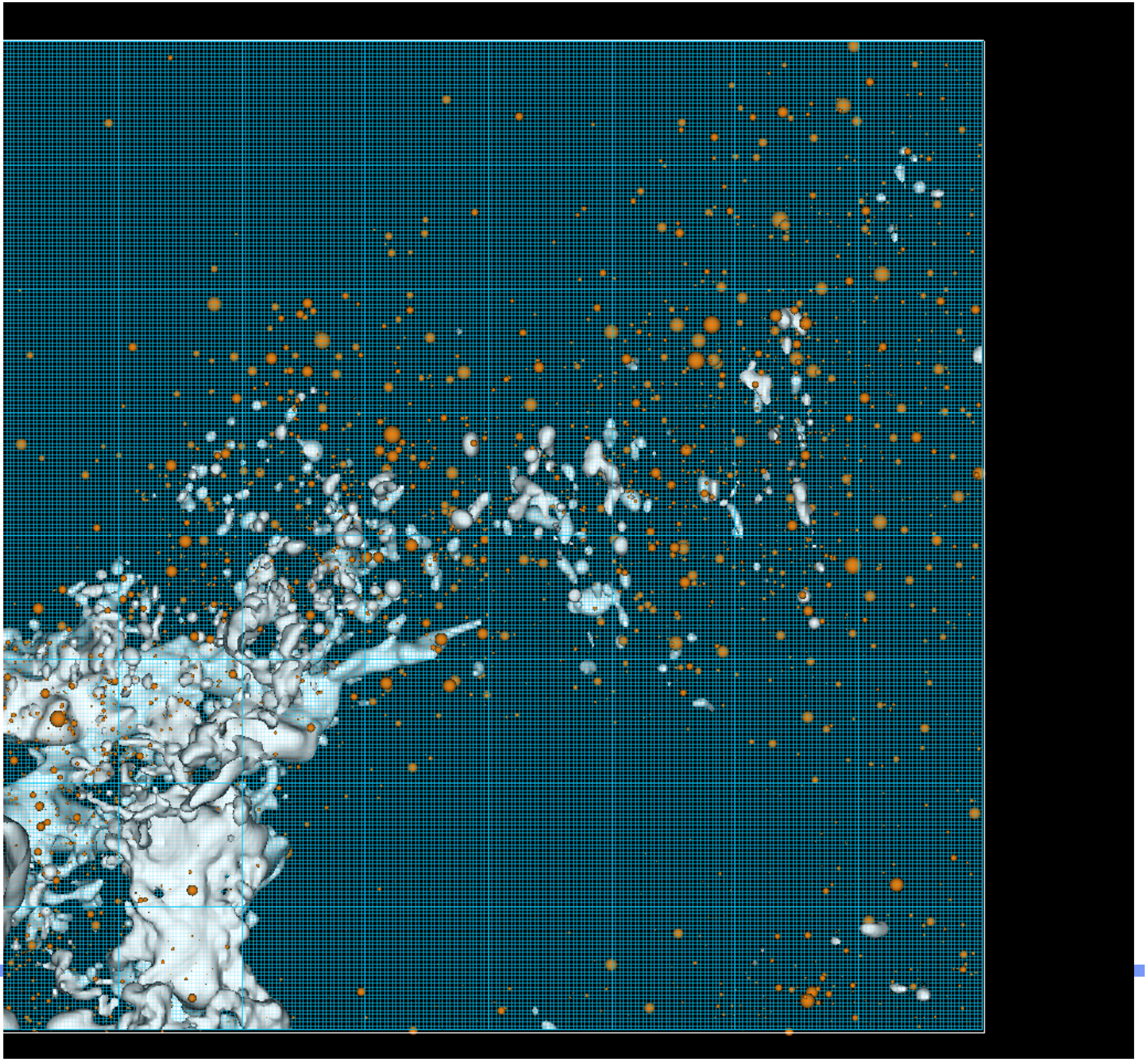
Simulation 64 x 256 x 512

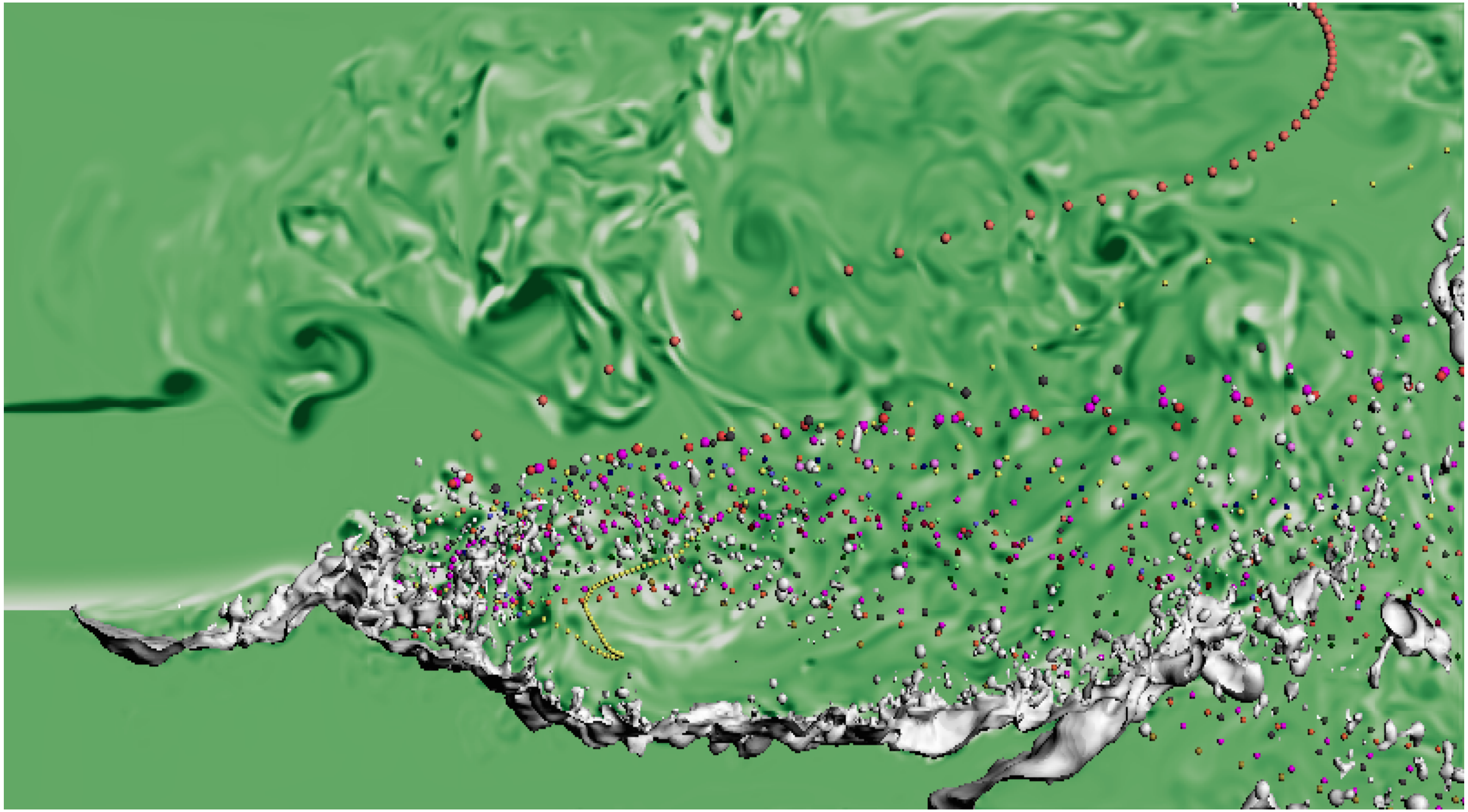
Coflowing air and liquid jets (moderate density ratio)



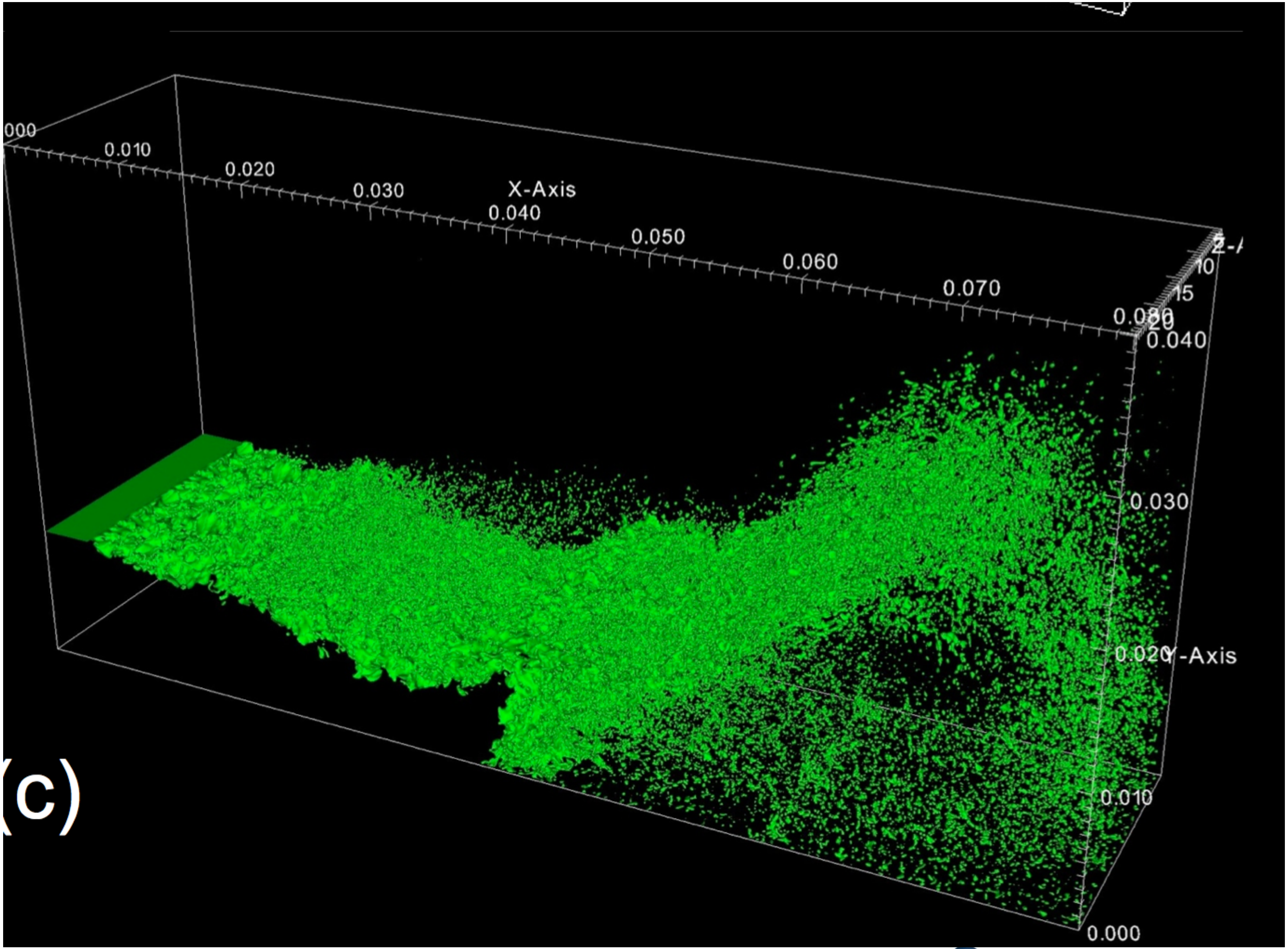


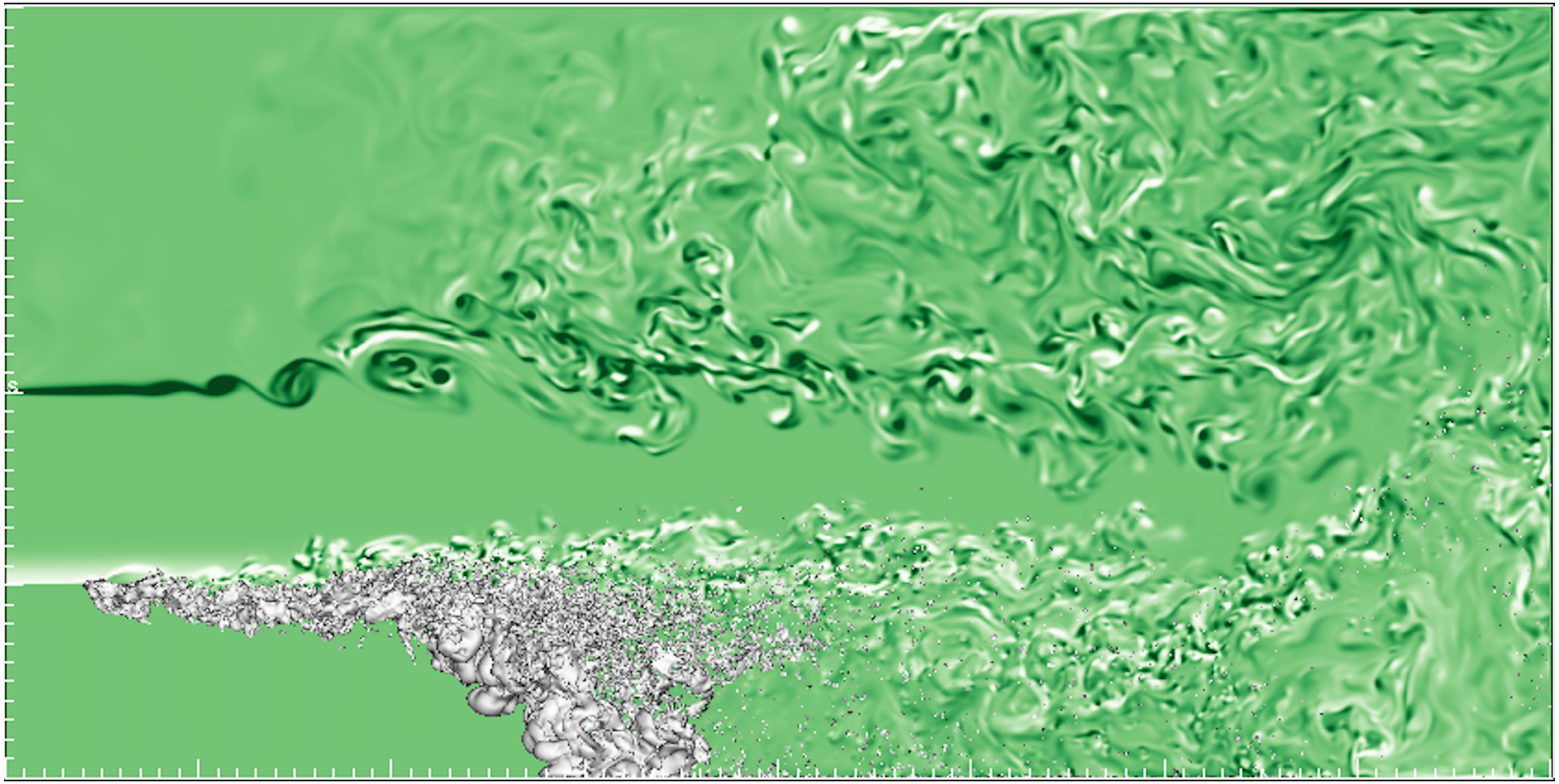


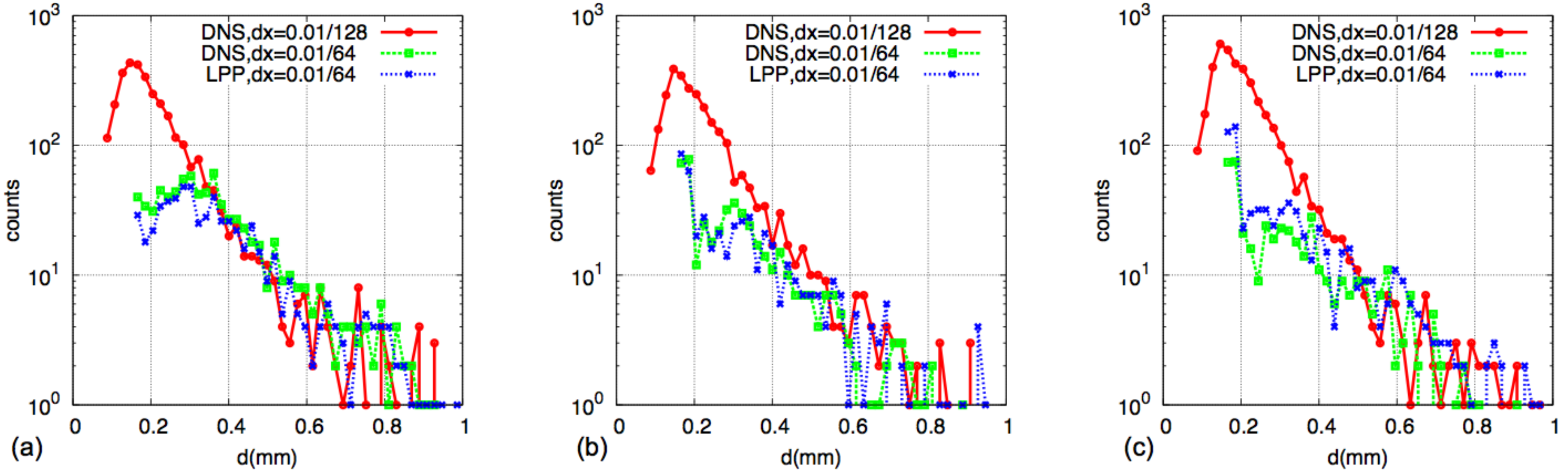




Simulation 128 x 512 x 1024


(c)
X-Axis
0.010
0.020
0.030
0.040
0.050
0.060
0.070
0.080
10
15
20
0.040
0.030
Y-Axis
0.020
0.010
0.000





PDF of droplet diameters - (a) t = 0.4s, (b) t = 0.41s, and (c) t = 0.42s.

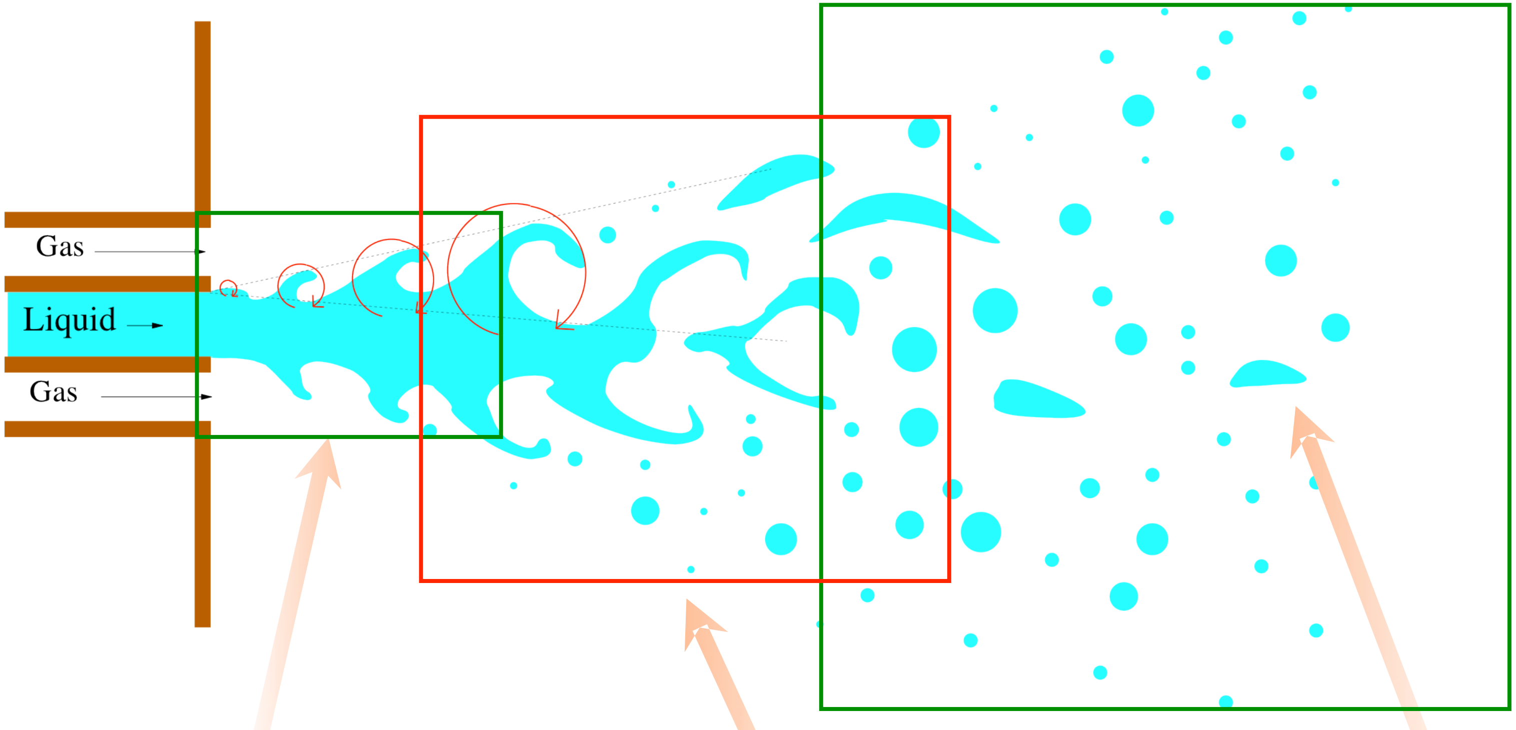
Immediate Perspectives:

- A well understood, consistent, verified theory of the 3D instability: at present many theories, and almost no numerics.
- A proof of convergence of the Lagrangian point particle model.
- VOF technology: AMR-VOF-LPP with basilisk. (new octree code).

Longer term perspectives:

- coupling with thermal / reaction effects.
- use DNS to develop and validate large-scale particle ejection models.
- full combustion chamber simulations.

Simulation methodology



High resolution

LPP

Still a lot of work !

Collaborators past and present.

Jie Li (Cambridge UK), Denis Gueyffier (ONERA Paris), Phil Yecko (Montclair, NJ), Thomas Boeck (Ilmenau), Jose-Maria Fullana (d'Alembert), Ruben Scardovelli (Bologna), Christophe Josserand (d' Alembert), Stéphane Popinet (d' Alembert), Pascal Ray (d' Alembert), Luis Lemoyne (Nevers), Shahriar Afkhami (NJIT), Gaurav Tomar (Bangalore), Daniel Fuster (d'Alembert), Anne Bagué, Jérôme Hoepffner (d'Alembert). Gilou Agbaglah (Michigan), J. John Soundar Jerome (Lyon), Arup K. Das (IITG).

Current Students and postdocs

Zhen Jian, Gounsetti Pare, Leon Malan, Bertrand Lagrée, Yue Ling, Peng Cheng (with HIT) , Alex Guion (with MIT)

The End

ρ_l (Kg/m3)	100
ρ_g (Kg/m3)	1
μ_l (Kg/s m)	1.00E-03
μ_g (Kg/s m)	1.00E-05
d_p (mm)	0.02
U_0 (m/s)	0.5