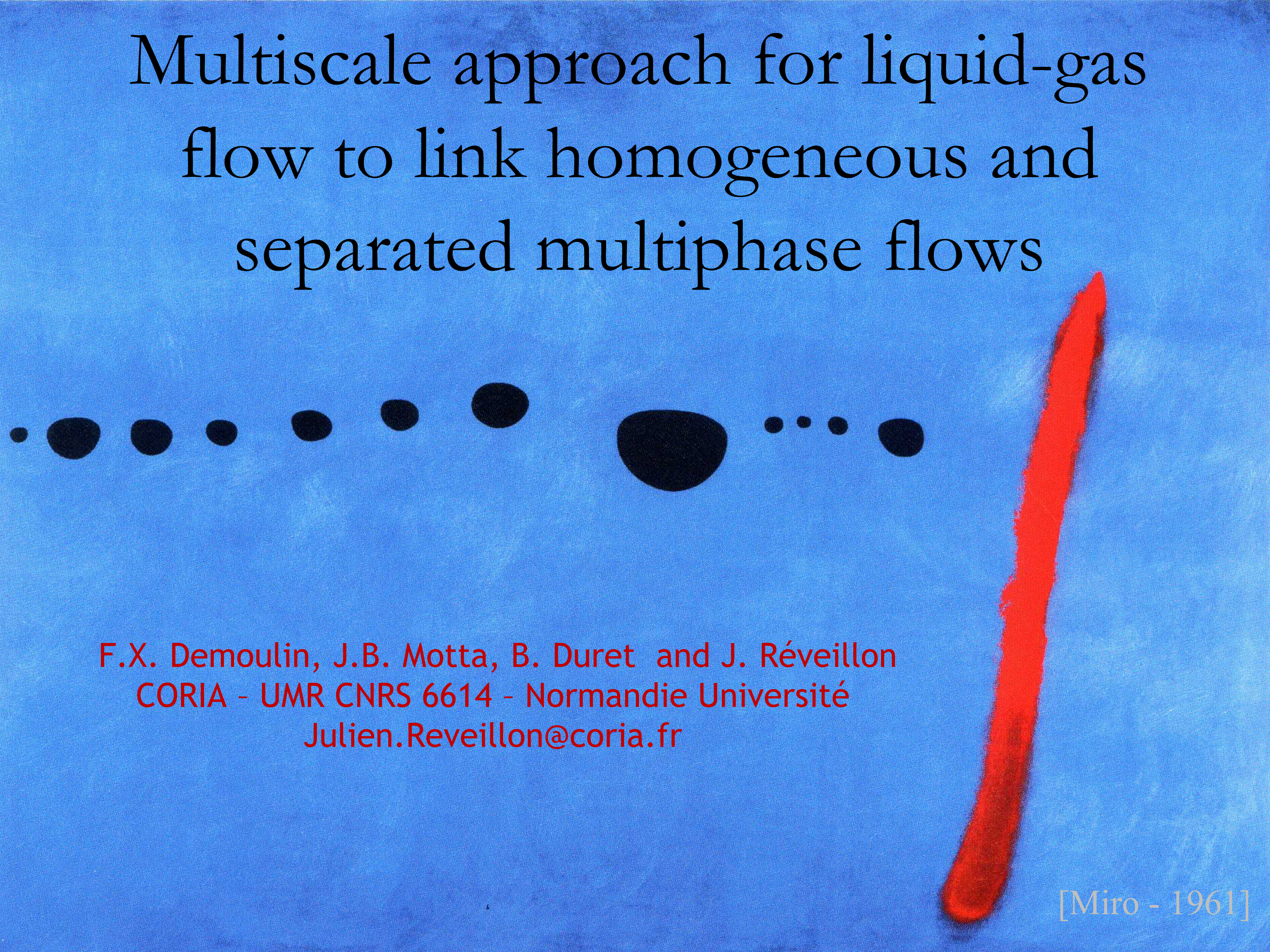
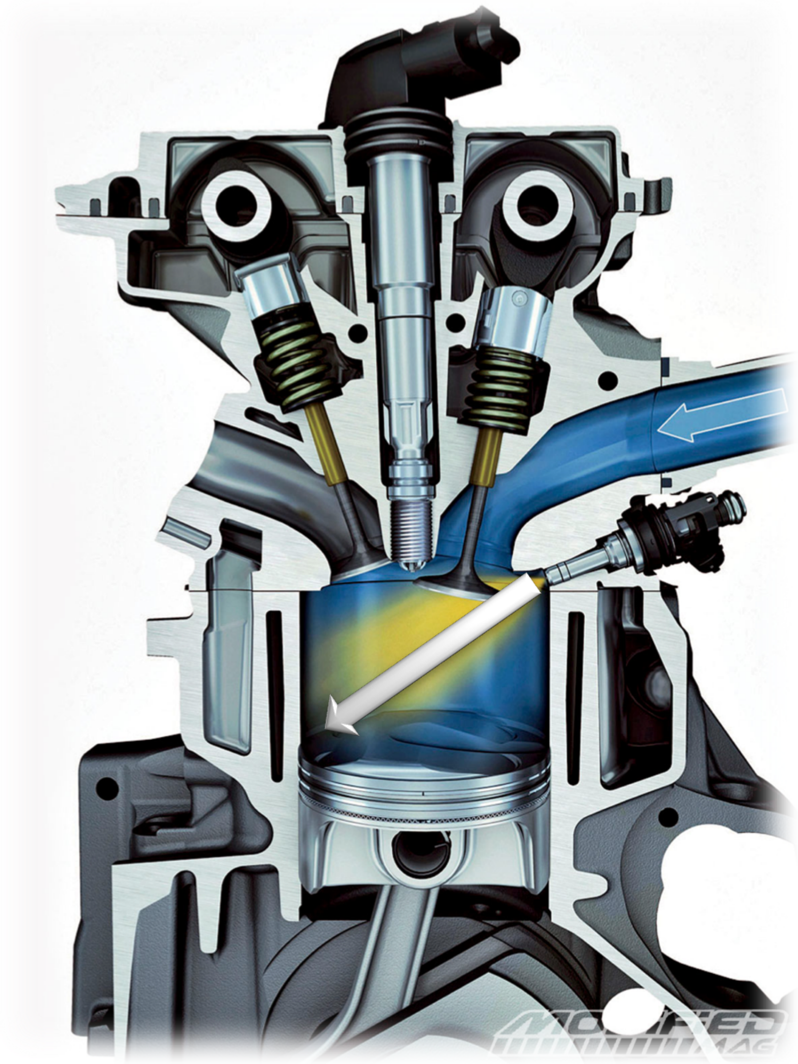
Multiscale approach for liquid-gas flow to link homogeneous and separated multiphase flows

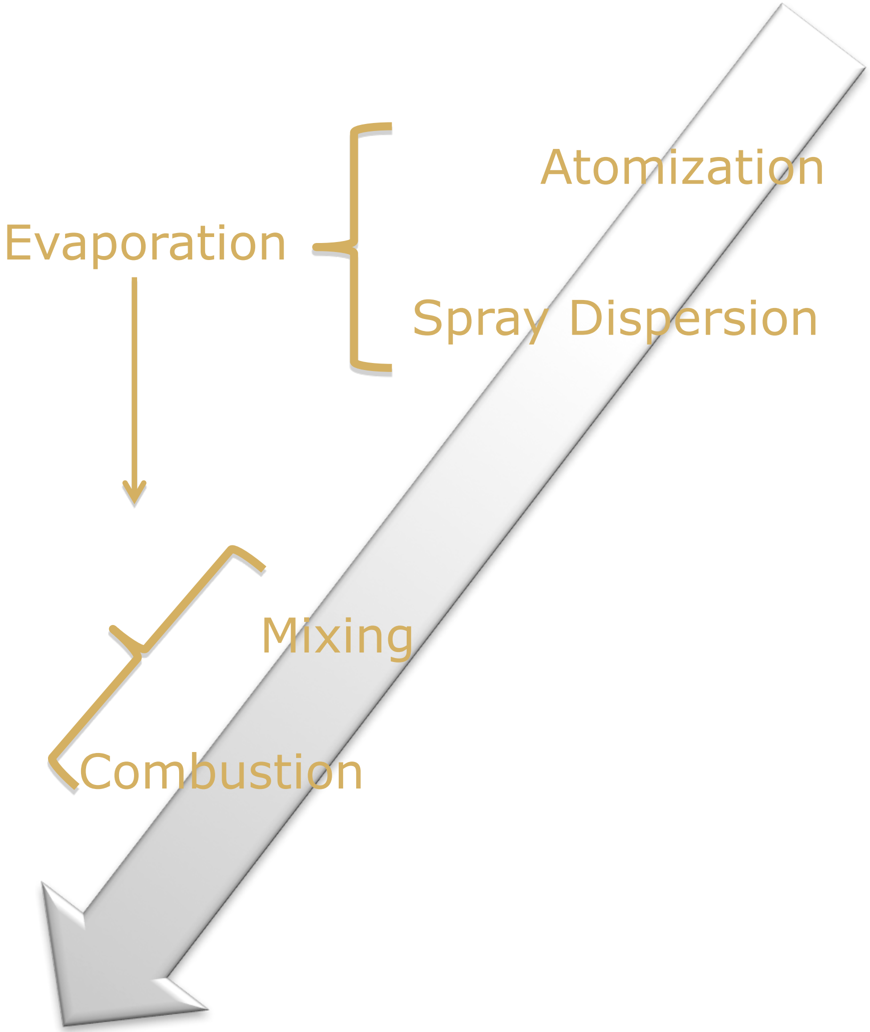


F.X. Demoulin, J.B. Motta, B. Duret and J. Réveillon
CORIA – UMR CNRS 6614 – Normandie Université
Julien.Reveillon@coria.fr

[Miro - 1961]

Atomization in combustion chamber





Atomization

Spray Dispersion

Evaporation

Mixing

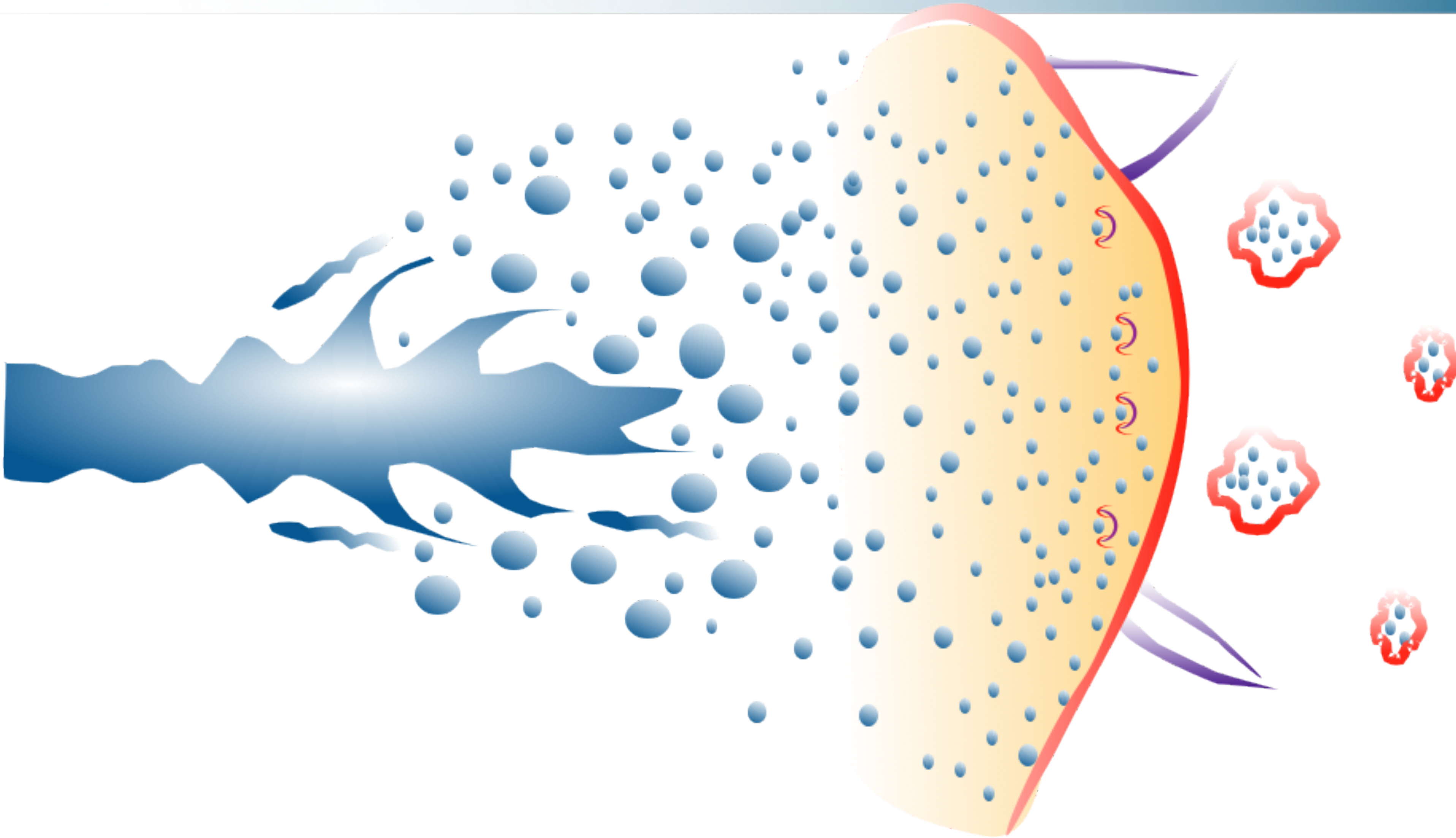
Combustion

Atomization process:

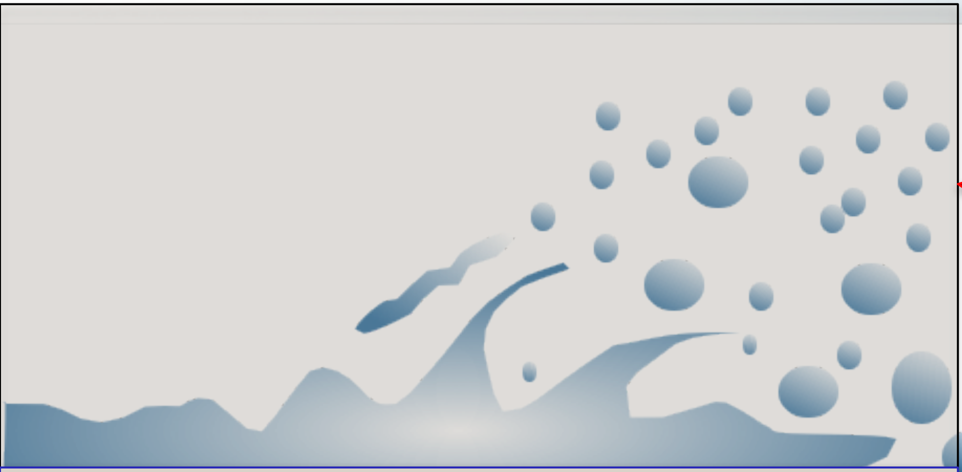
As simple as…holes

Yet, impossible to predict…

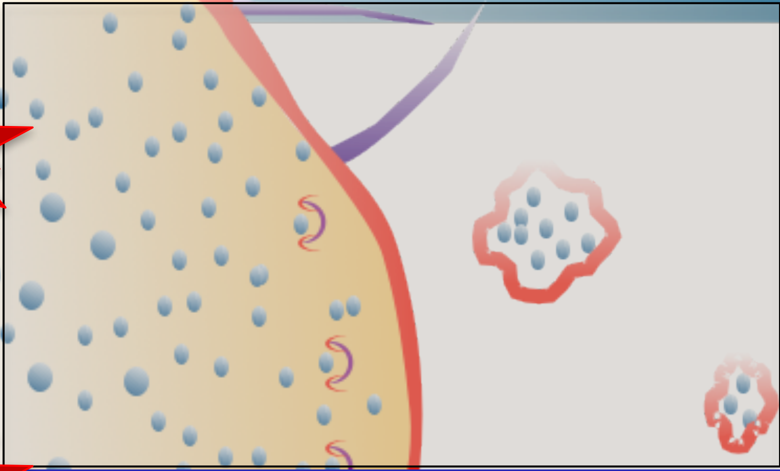
A matter of scales …



Junction stumbling block



- Incompressible flows
- Level-Set / VOF / SPH
- Non-Vaporizing
- m and cm scales



- Compressible or dilatable flows
- Simple or complex chemistry
- Dispersed phase (Lagrangian or Eulerian)
- Small spherical droplets
- mm and µm scales

Different numerical methods, physical outcomes and communities !!!

To describe a complex liquid phase …

Generalized liquid-gas flows:

1) Single flow with two phase
2) Turbulent liquid flux
3) Surface density
4) Switch to Blobs / Droplets

Blobs / Droplets : Multiphase flow

1) Carrier Phase and Discrete phase
2) Liquid and Gas velocity
3) Droplet radius

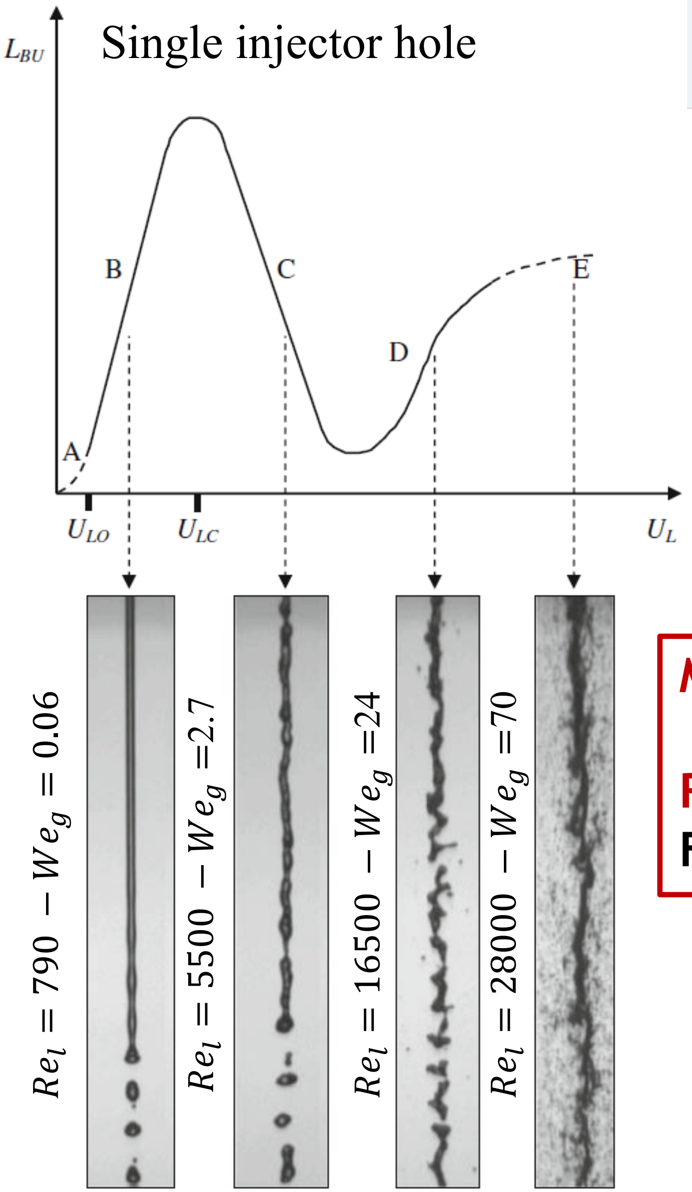
Most Used : "Lagrangian method"

J. K. Dukowicz, 1980.

Eulerian method available also :

Multiphase, sectional, Qmom,…

To describe a complex liquid phase …



C. Dumouchel,2008

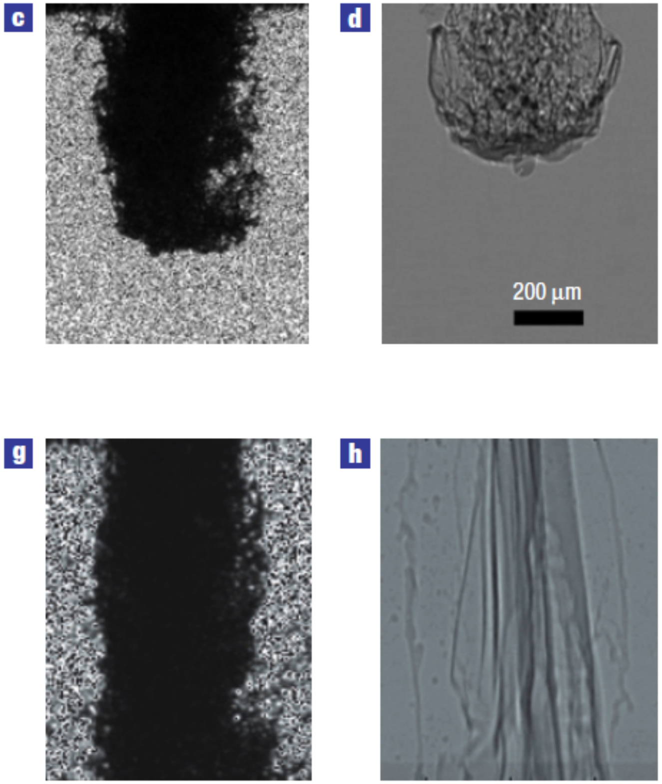
Atomization Regimes

B: Rayleigh regime
C: First wind-induced regime
D: Second wind-induced regime
E: Atomization regime

Modeling:

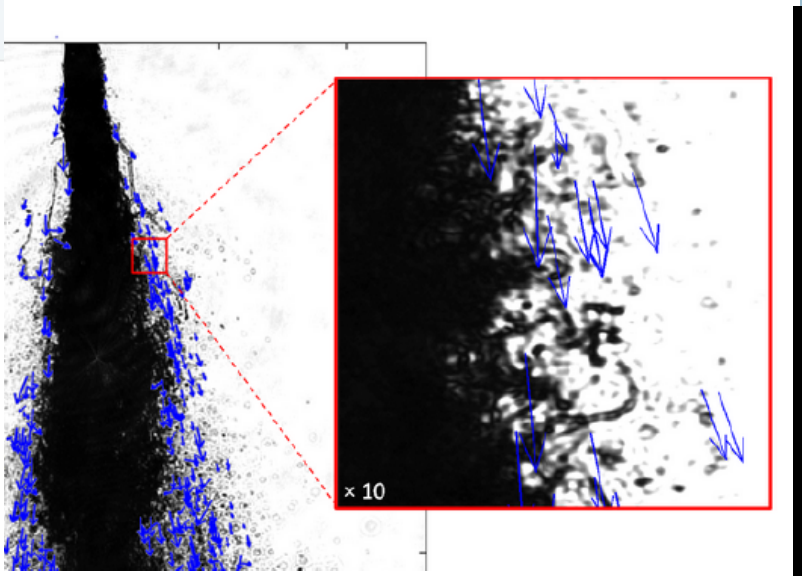
RANS ➔ Big enough Re and We number (D and E)
For simplicity: $\rho_l = cst$ and $\rho_g = cst$

Atomization regime



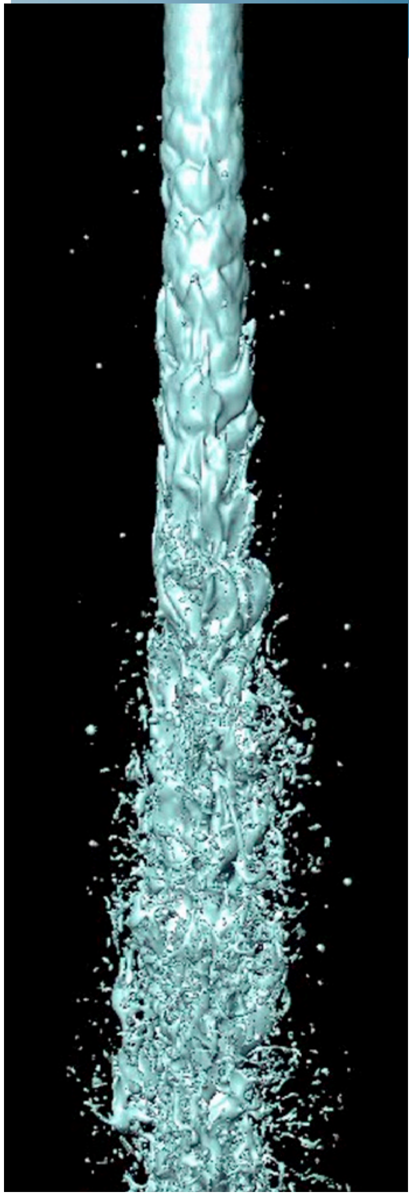
Ultrafast X-RAY

Y. Wang et al., 2008



Ultrafast shadow imaging
double-pulsed femtosecond laser

K. Lounnaci et al, 2015

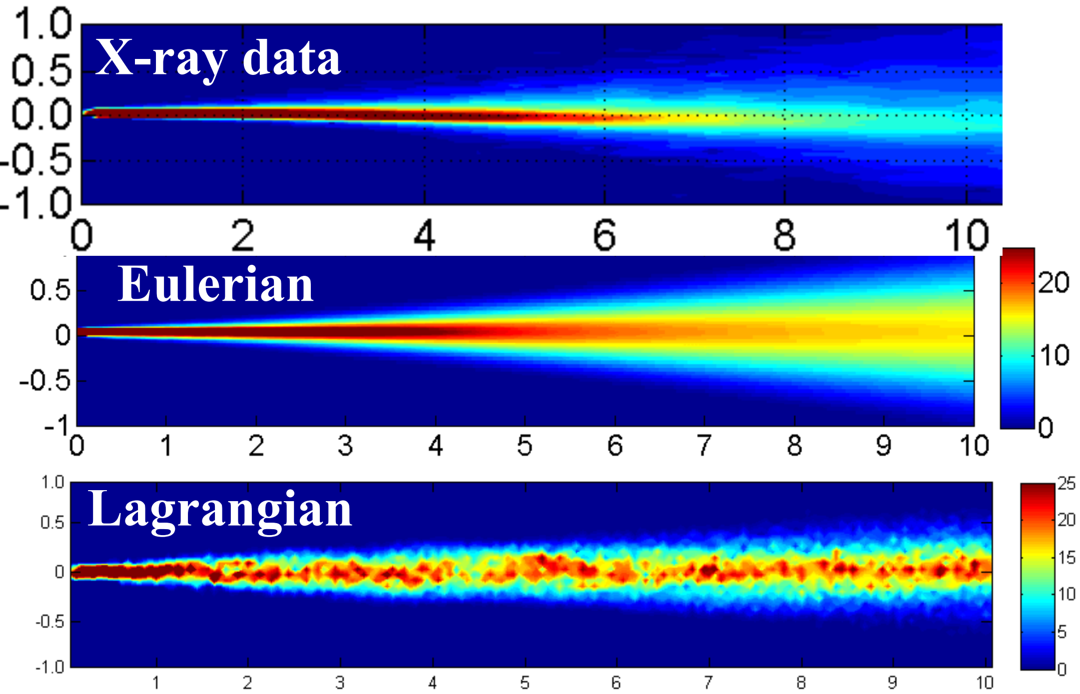


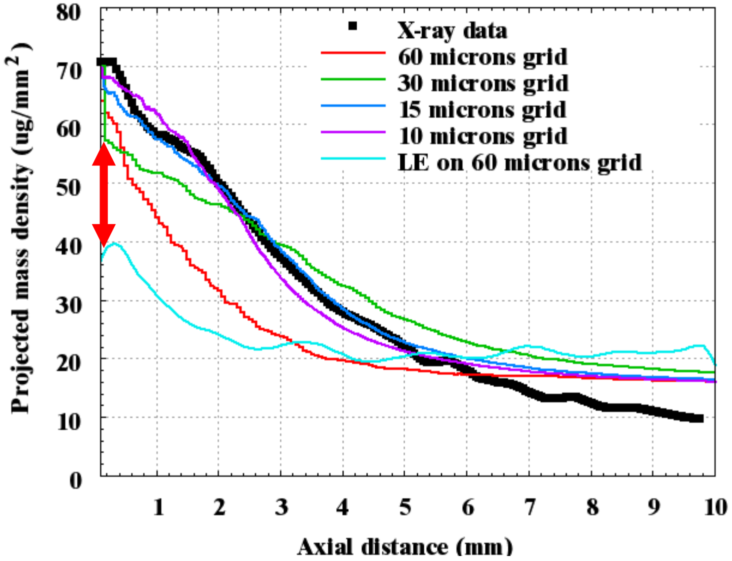
Interface Capturing Method

T. Menard et al, 2007

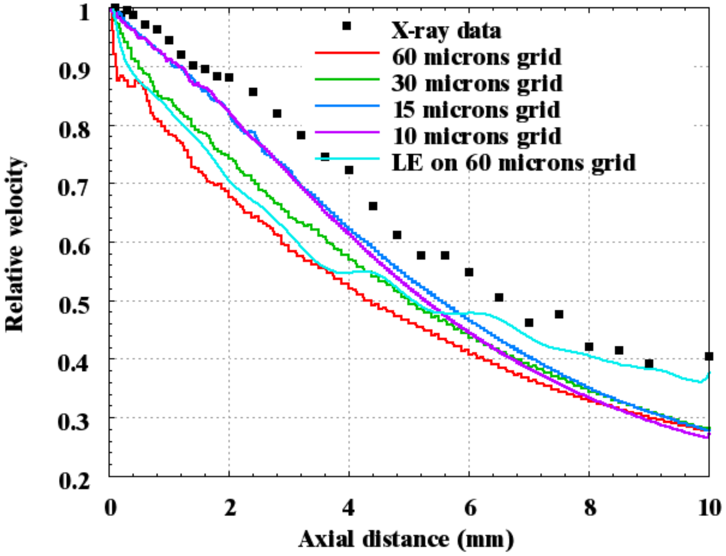
Much more : *ECN (ecn.sandia.gov), M. Linne, 2013, …*

Spray A: EE vs. LE at Argonne





Projected mass density along spray axis



Mass-averaged velocity along axis

- Eulerian model is better than traditional Lagrangian approach in the near nozzle region
- Lagrangian simulations: 62.5µm minimum resolution, blob injection model, 300,000 parcels

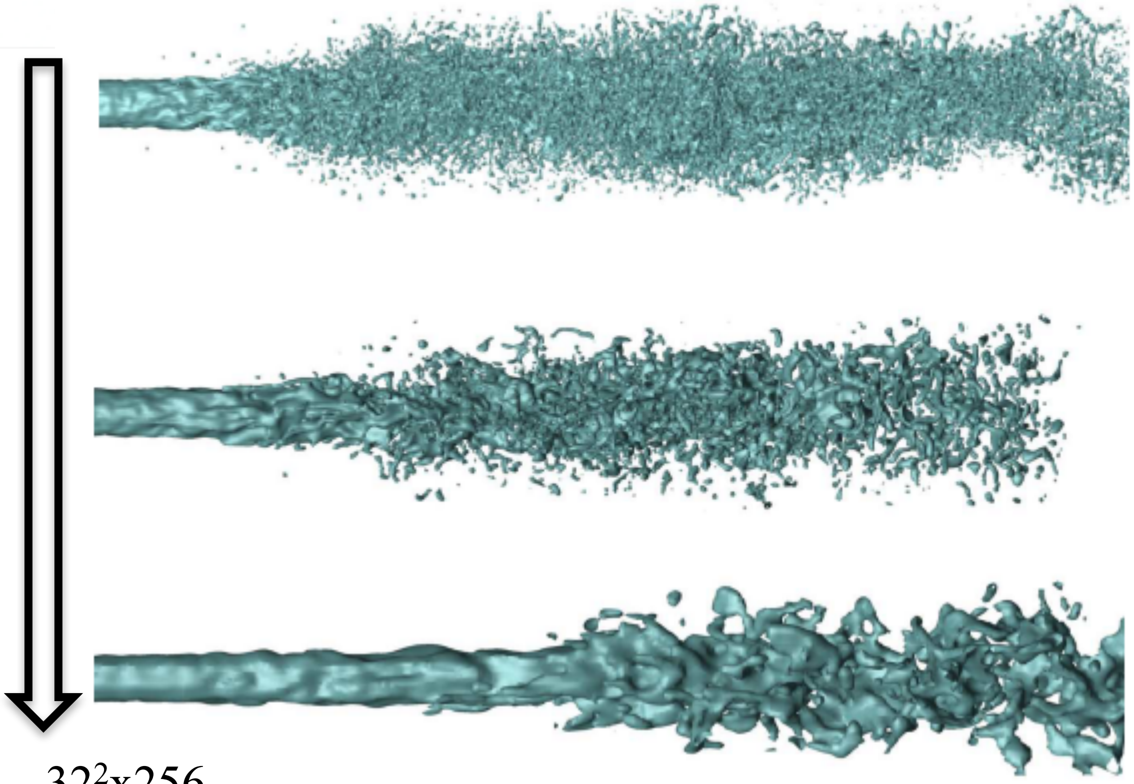
LES Modeling issue

Generally : no subgrid term in ICM methods

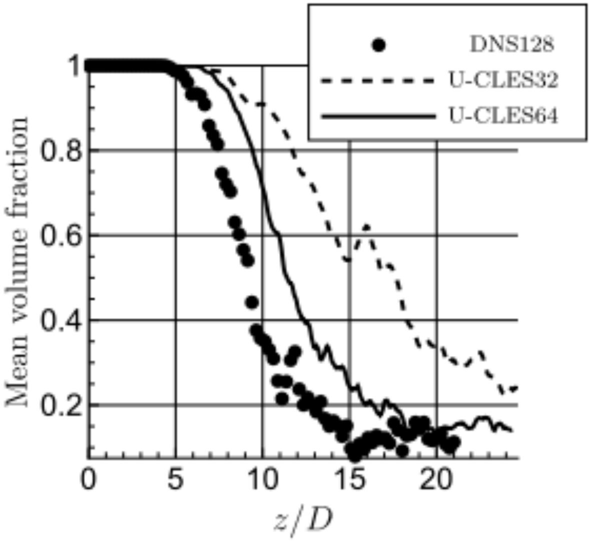
$$\frac{\partial \bar{\alpha}}{\partial t} + \frac{\partial \overline{u_j}\,\bar{\alpha}}{\partial x_j} = \underbrace{\cancel{\frac{\partial \overline{R_\alpha}}{\partial x_j}}}_{\text{Subgrid Term}}$$

under-resolved dynamic

128^2x1024



32^2x256



Low resolution ➔Low dispersion

Low resolution ➔Numerical interface stabilization

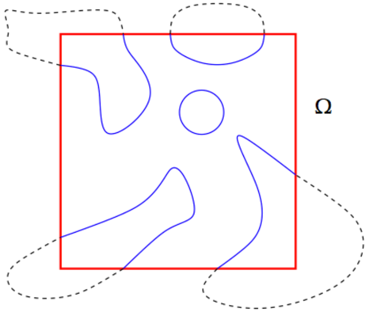
[1] J. Chesnel, J. Reveillon, T. Menard, and F.X. Demoulin, *Large eddy simulation of liquid jet atomization.* Atomization and Sprays, **21**(9): p. 711-736, 2011

Interface + SG Surface density (E/E)

Description of the subgrid spray :

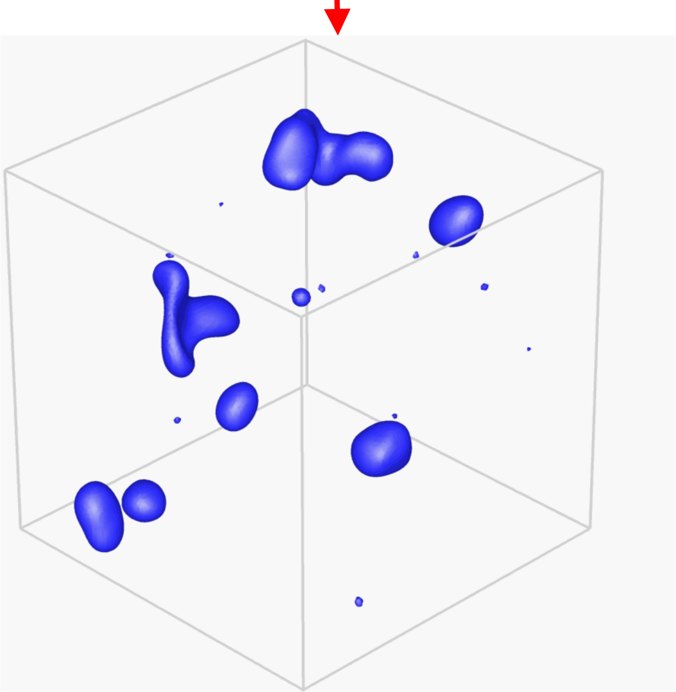
- Eulerian description
- Multiple objects characterization (drops, blobs, ligaments, liquid sheets, etc)

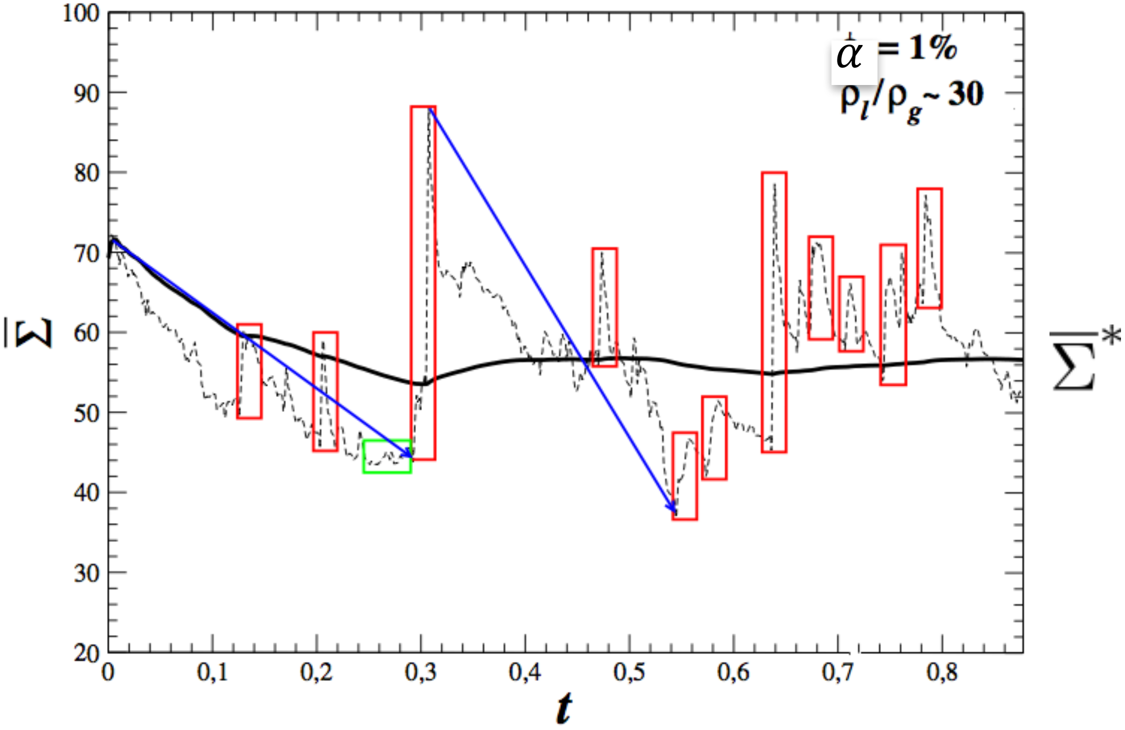
$$\text{Interface density}\,\overline{\Sigma} = \frac{\text{Interface area}}{\text{Control volume}}$$



$$\frac{\partial \overline{\Sigma}}{\partial t} + \frac{\partial \overline{u}_j \overline{\Sigma}}{\partial x_j} = \frac{\partial}{\partial x_\alpha}\left(\overline{\Sigma}(\overline{u}_\alpha - \overline{u}_{\Gamma\alpha})\right) + \dot{\overline{\Sigma}}$$

To study source term ➔ DNS





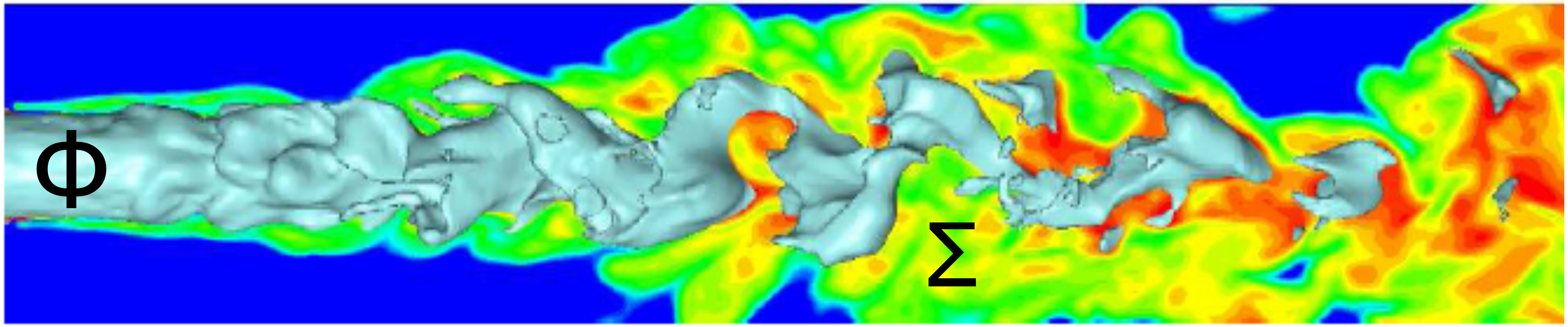
Coalescence: →

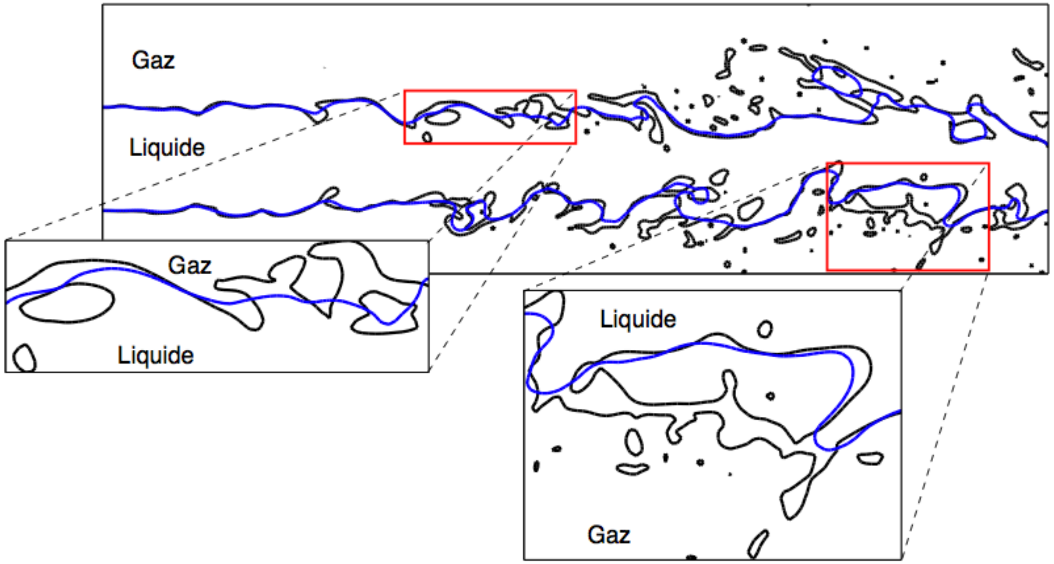
Collision: 🟥

Balance: Surface tension ⇔ Turbulence stretching 🟩

Interface + SG Surface density (E/E)

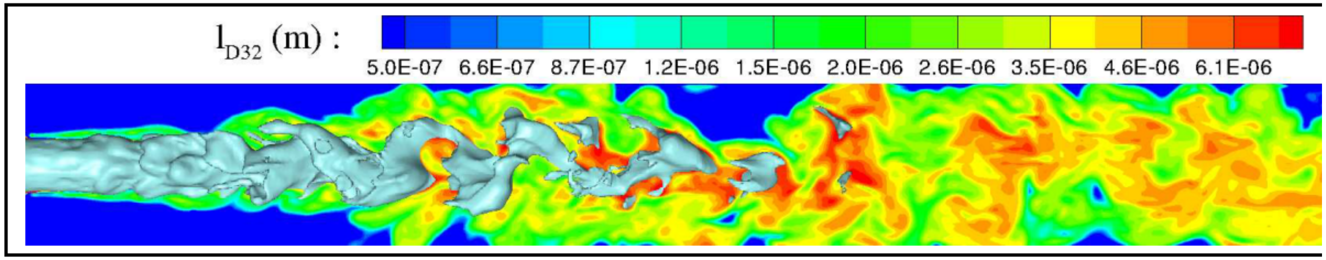
- Subgrid interface density

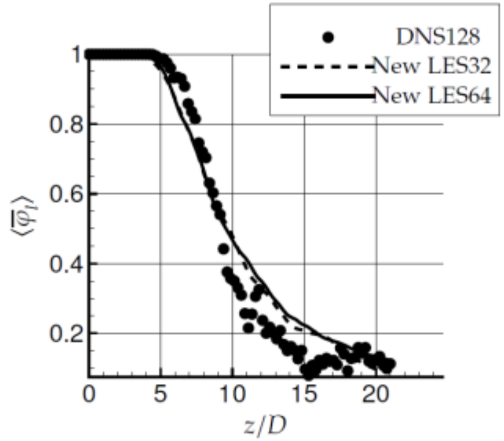




How to combine ICM + subgrid term

J. Chesnel et al., Atomization and Spray, 2011





! Incompatibility issue !
Subgrid term ⬄ICM

$$\tau_{\varphi j} = \underbrace{Random\ motion}_{Diffusion}$$

$$\frac{\partial \overline{\varphi_l}}{\partial t} + \frac{\partial \overline{u_j}\,\overline{\varphi_l}}{\partial x_j} = \underbrace{\cancel{\frac{\partial \tau_{\varphi_j}}{\partial x_j}}}_{\text{Subgrid Term}}$$

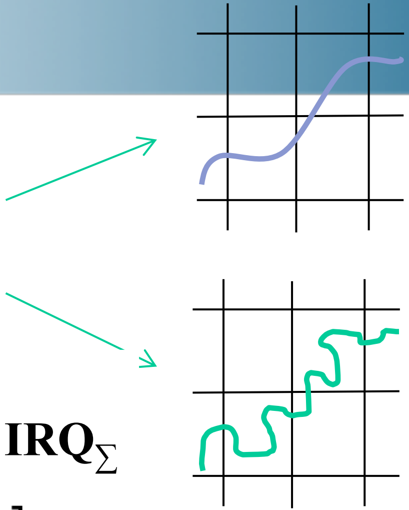
🡄ICM Method VOF, Level Set

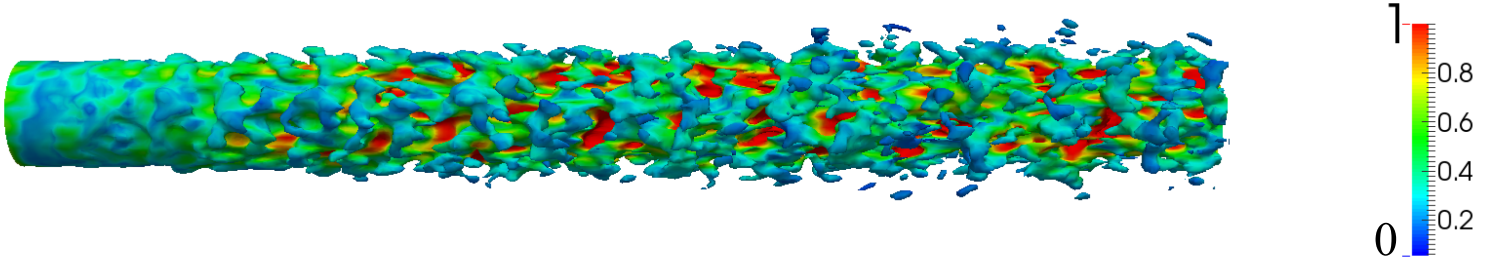
$$\frac{\partial \varphi_l}{\partial t} + \frac{\partial u_j \varphi_l}{\partial x_j} + \underbrace{\frac{\partial C_\alpha u_{Cj} \varphi_l (1-\varphi_l)}{\partial x_j}}_{\text{ICM}-\text{interFoam}} = (1\text{-}\ C_\alpha)\tau_{\varphi j}$$

1/0 ? Criteria needed !

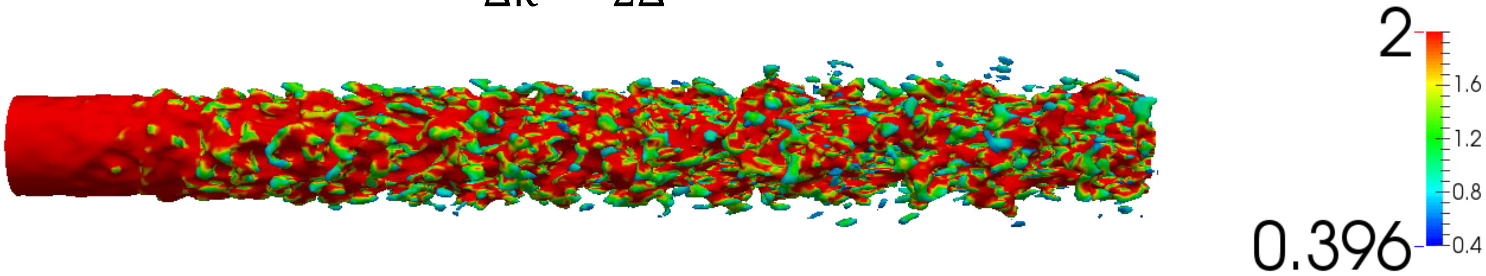
Interface Resolution Quality

$$\mathrm{IRQ}_{\Sigma} = \frac{\Sigma_{min}}{\Sigma} : \frac{\text{Resolved Interface}}{\text{Total Interface (ELSA)}}$$

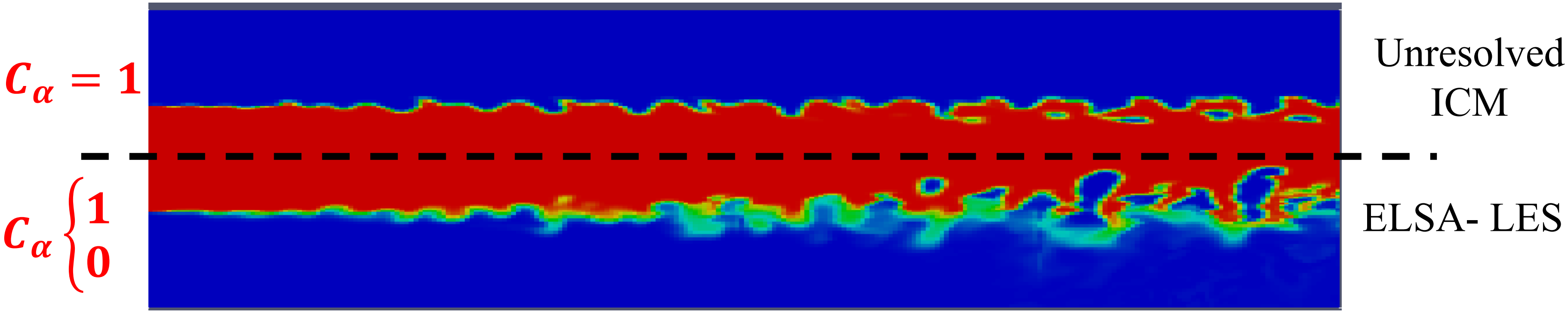


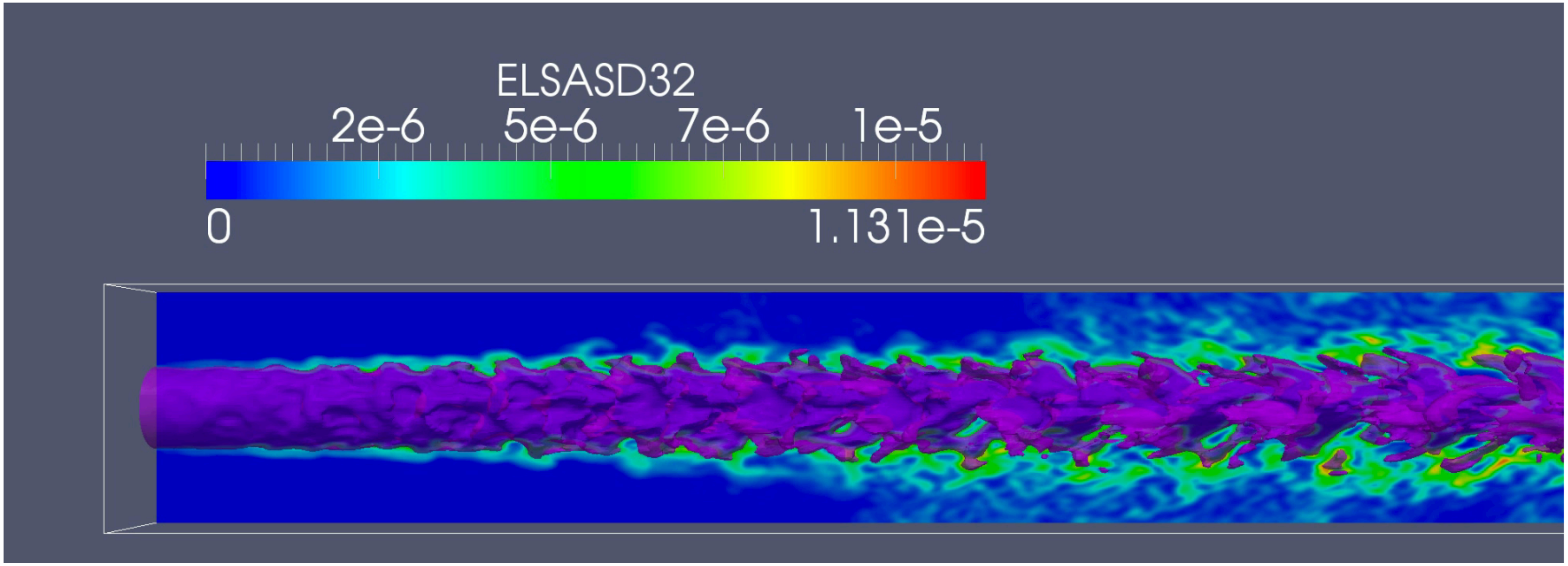


$$IRQ_{\kappa} = \frac{1}{\Delta\kappa} = \frac{R}{2\Delta}$$

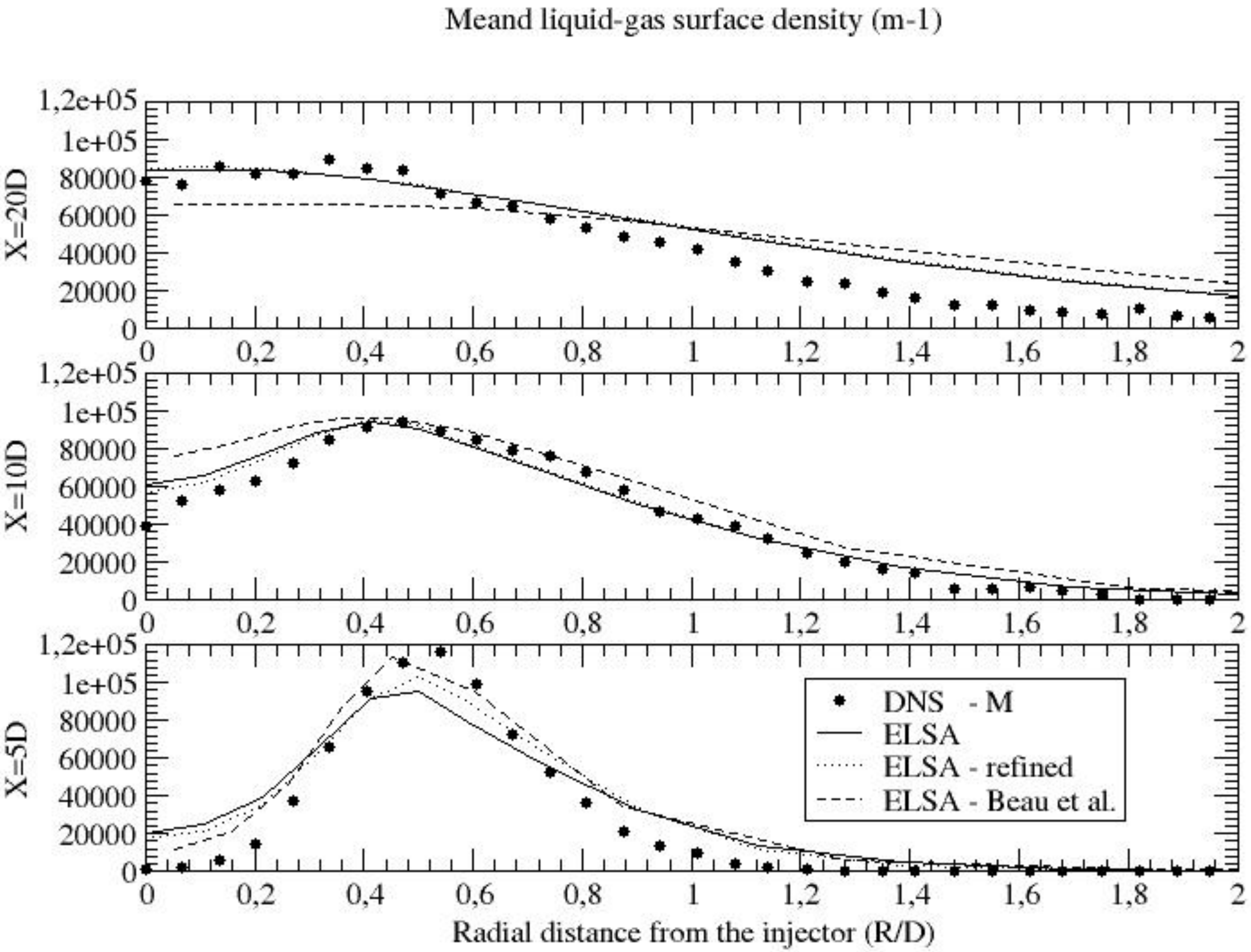


ICM combined with subgrid modeling





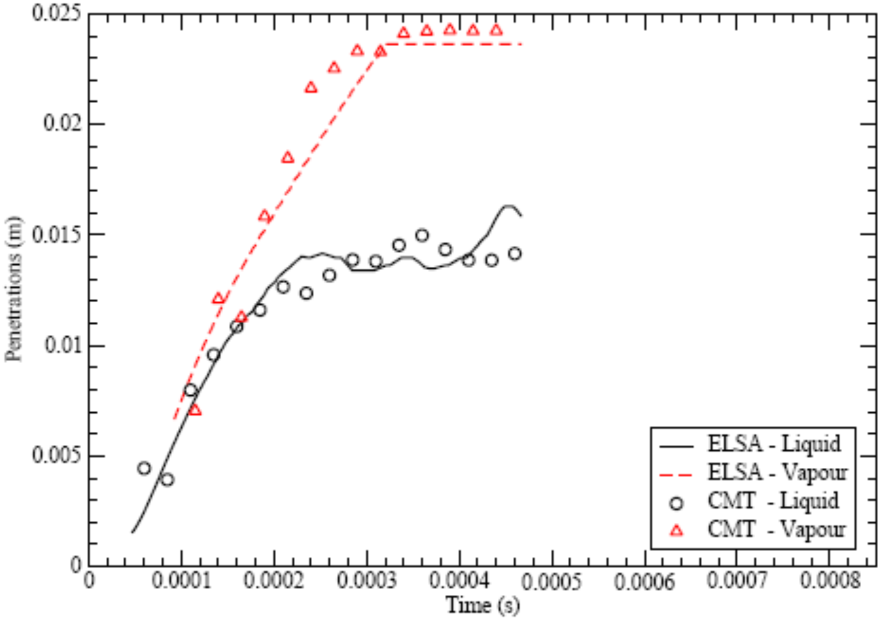
DNS Validation

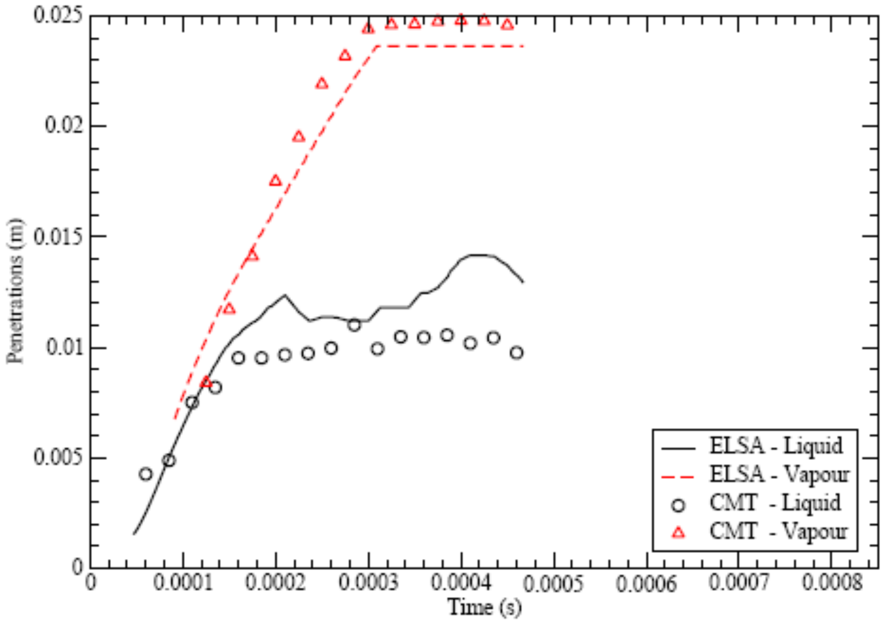


Exp. External Validation

Ambient gas temperature impact on liquid and vapor penetration

Liquid and vapor penetration for the injector 1 for $P_{inj} = 180 MPa$

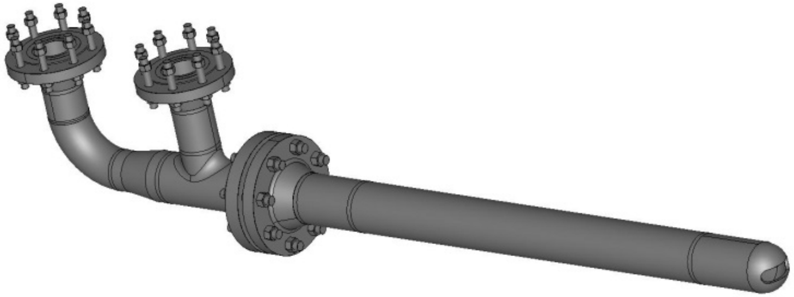




$T_{ch} = 790°K$

$T_{ch} = 935°K$

ICM combined with subgrid modeling



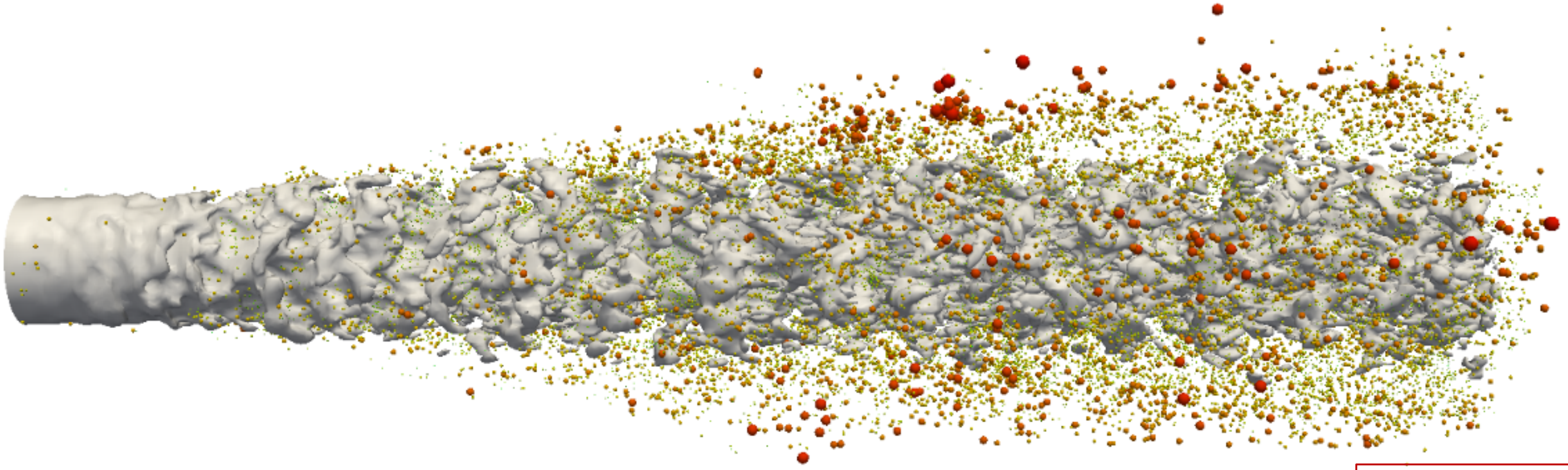
ICM + ELSA + Lagrange
Dynamic adaptive numerical methods

In the dispersed aera: lack of Information

- Very small liquid volume fraction
- Wrong description of the velocity (slip velocity needed)

Solution:

- Addition of a Lagrangian description (diluted aera <10%)
- To transport information and correct Eulerian formulation



Work in Progress

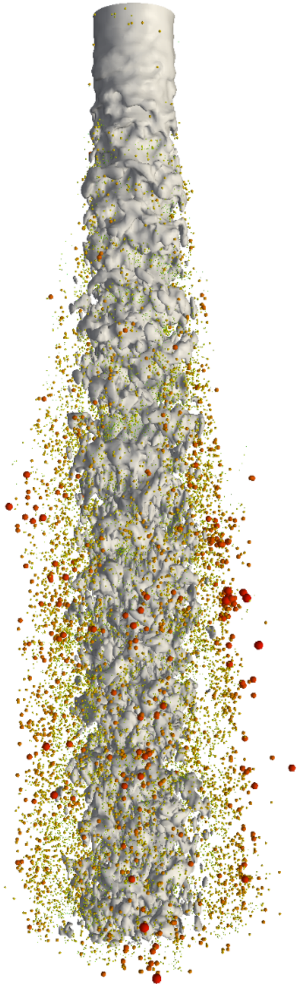
- **Foam ELSA family of Solvers**

Based on : twoLiquidMixingFoam, interFoam, compressibleInterFoam, cavitatingFoam + Lagrangian

ELSABaseFoam:

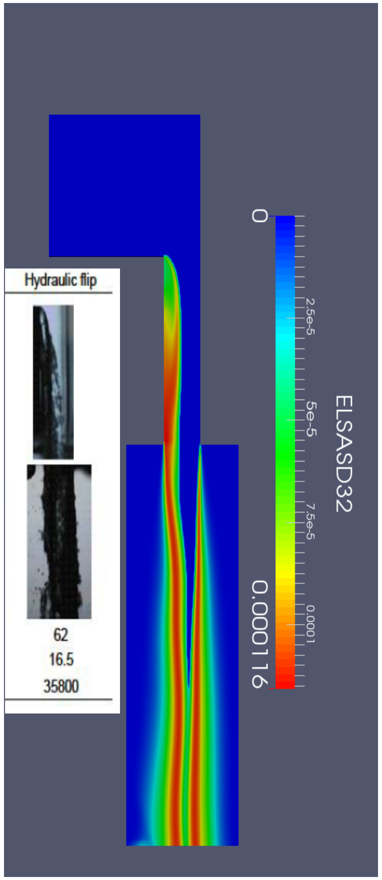
Javier Perdomo

ELSALESInterFoam:



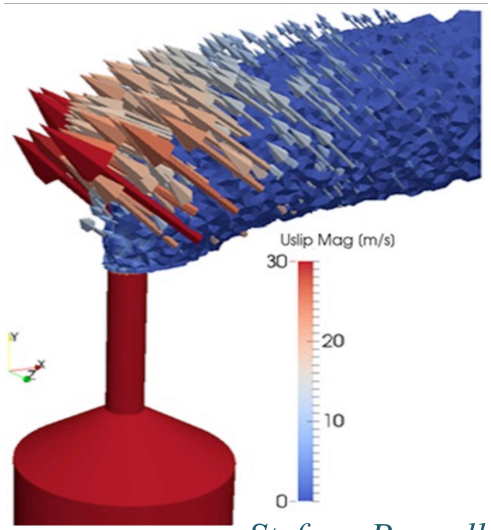
Nicolas Hecht (2016)

ELSACavitationFoam:



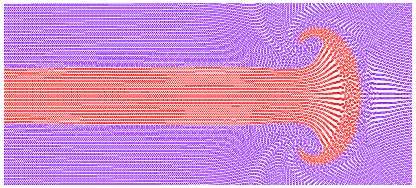
Yan Meslem (2013)
Raghavan Lakshmanan

ELSAQMEFoam:



Stefano Puggelli

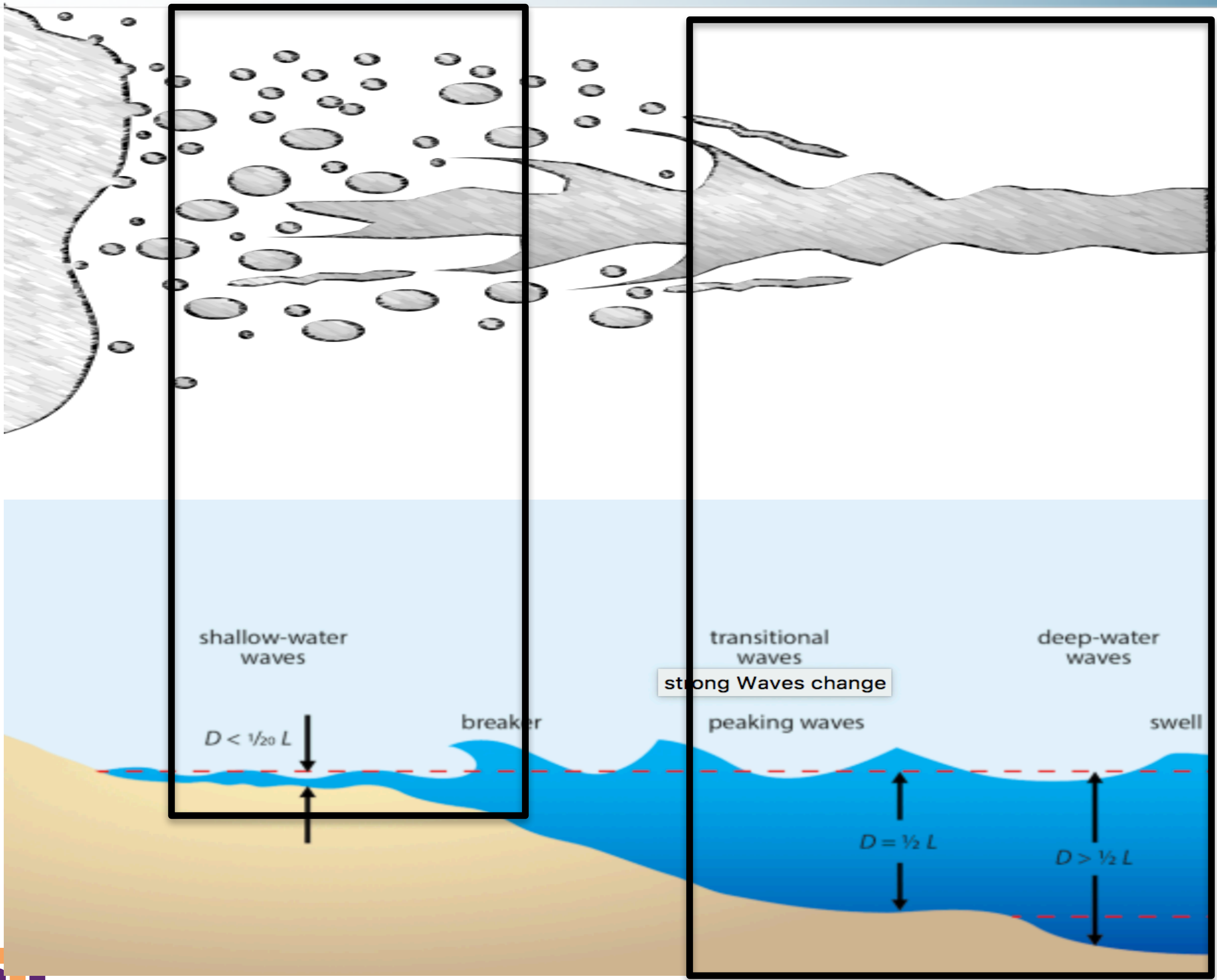
ELSASPHFoam:



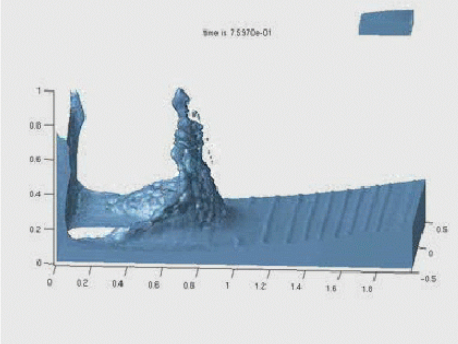
Félix Dabonneville

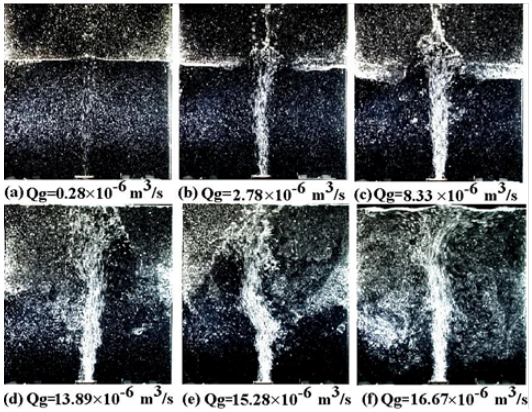
➔ www.foam-u.fr **(French OpenFoam User Community)**

Conclusion : a matter of scales



Other applications : gas/liquid mixing, unresolved interface

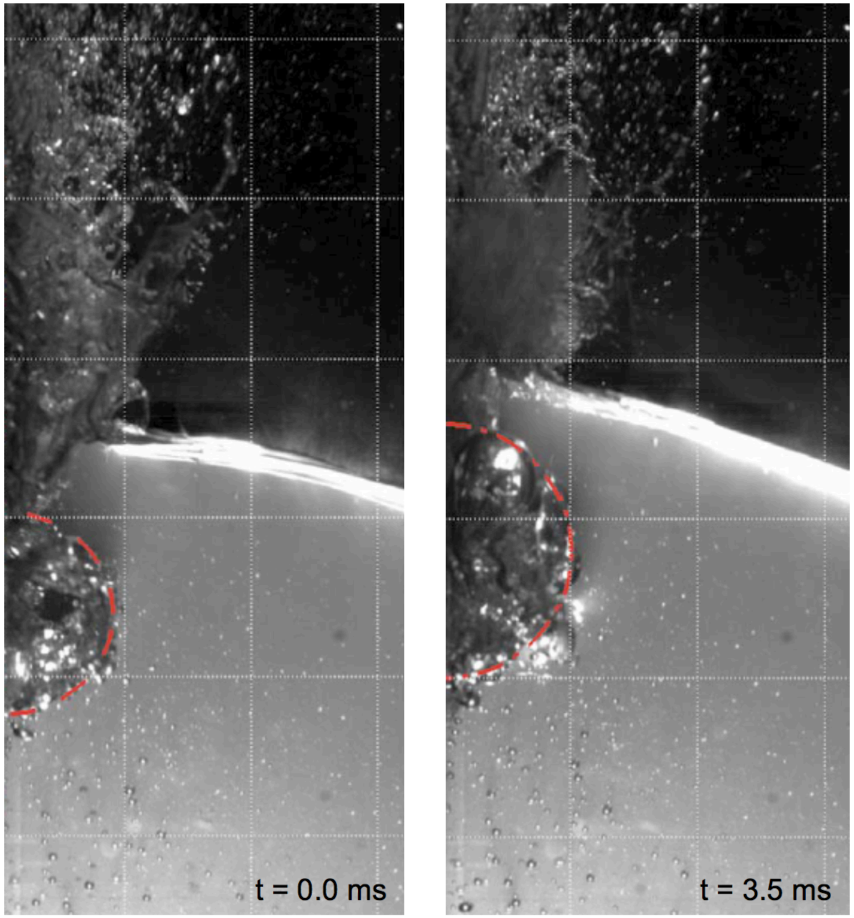




(a) $Q_g=0.28\times10^{-6}$ m^3/s (b) $Q_g=2.78\times10^{-6}$ m^3/s (c) $Q_g=8.33\times10^{-6}$ m^3/s

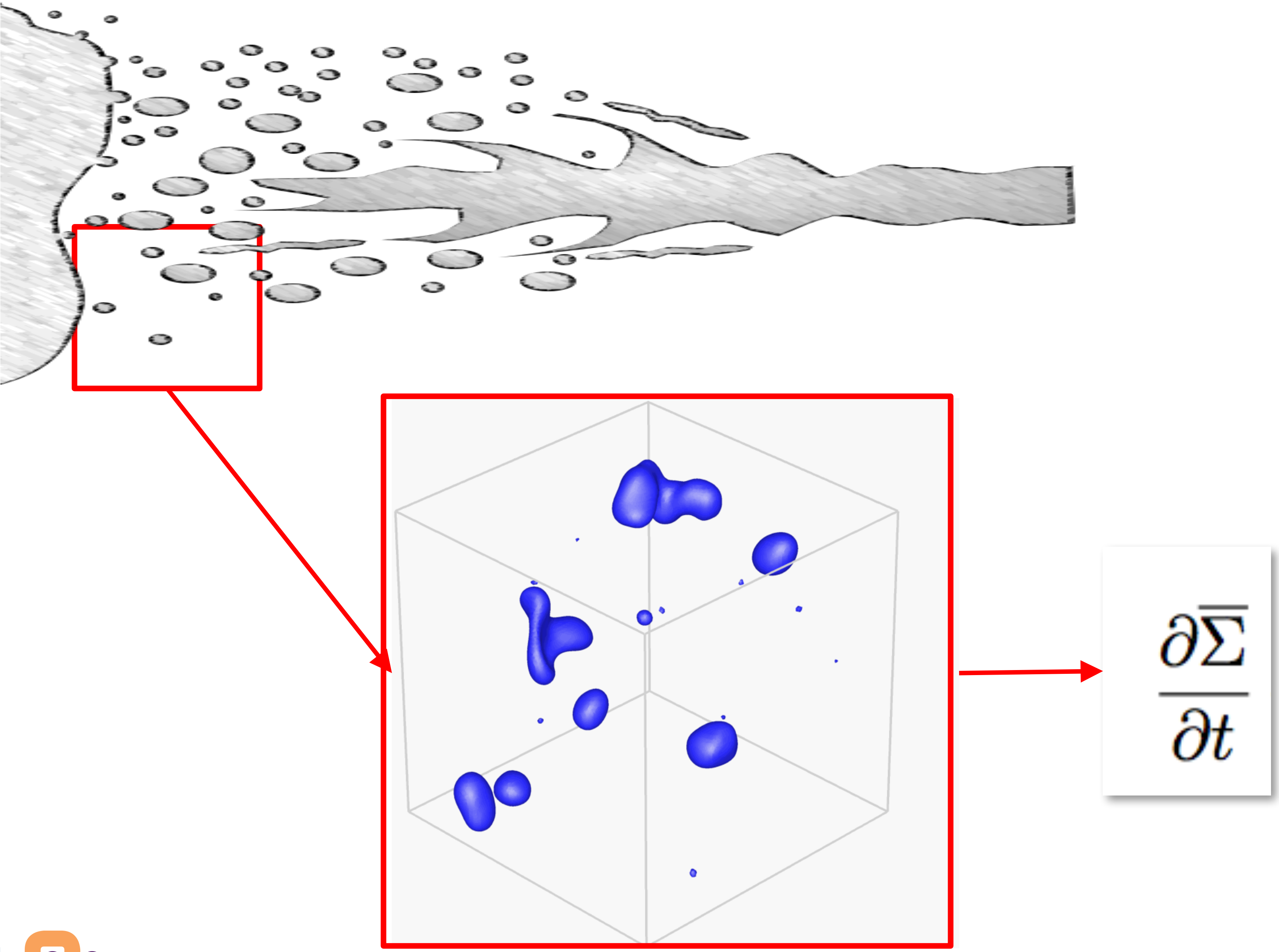
(d) $Q_g=13.89\times10^{-6}$ m^3/s (e) $Q_g=15.28\times10^{-6}$ m^3/s (f) $Q_g=16.67\times10^{-6}$ m^3/s

Objectives : apply ELSA to aeration modeling

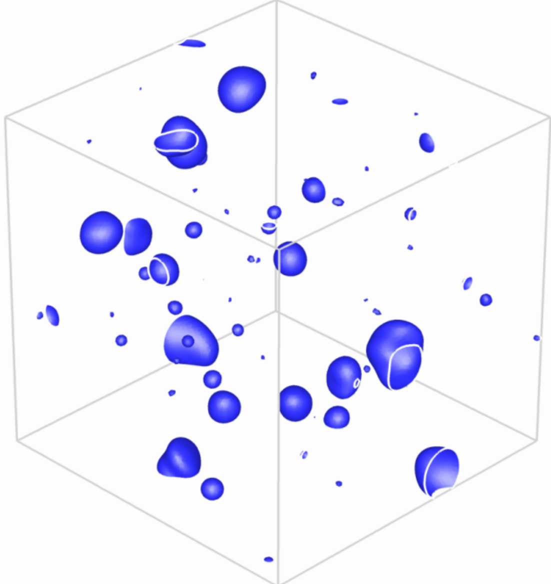


"Evolution of the air cavity during a depressurized wave impact."
Lugni et al.
[Femto Engineering, Water wave impact on rigid wall, 2011]

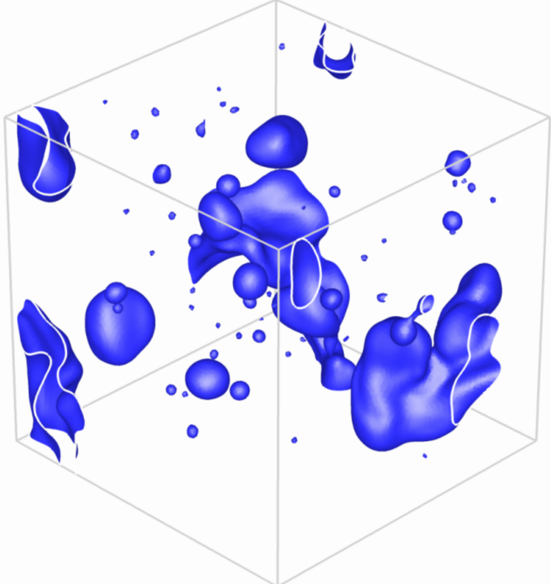
Actual ELSA modeling



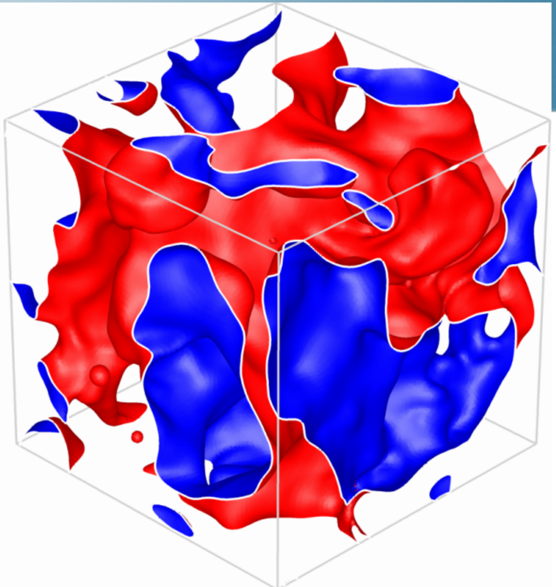
$$\frac{\partial \overline{\Sigma}}{\partial t}$$



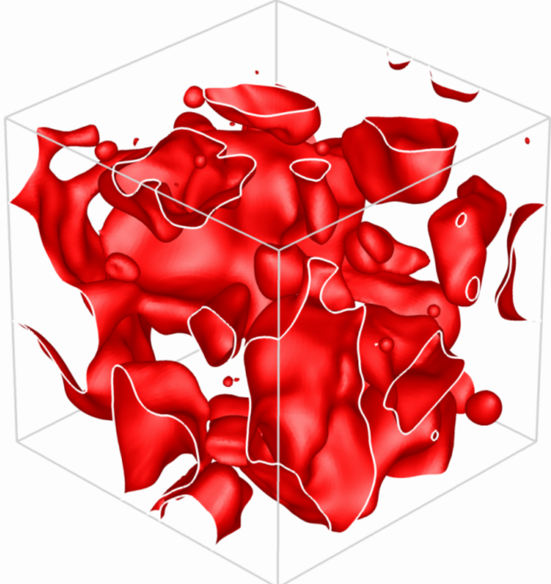
$\phi_l = 1\%$



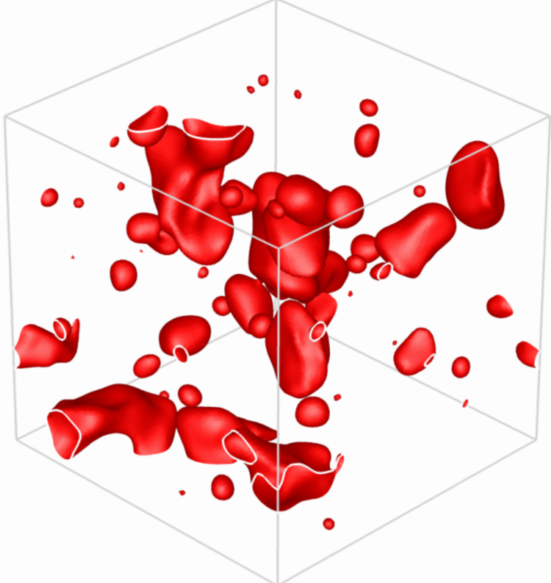
$\phi_l = 5\%$



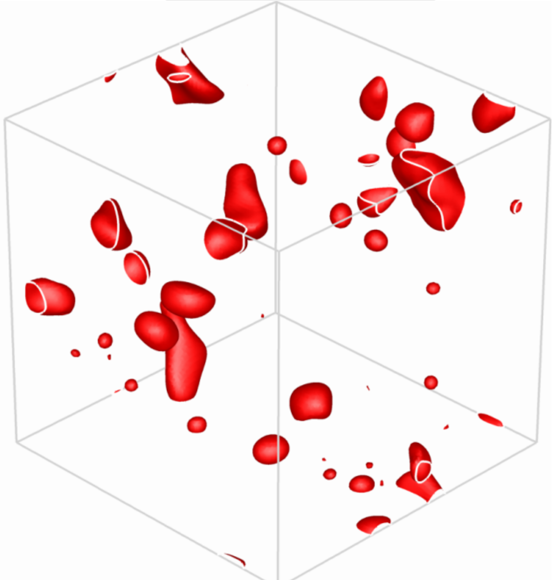
$\phi_l = 50\%$



$\phi_l = 75\%$

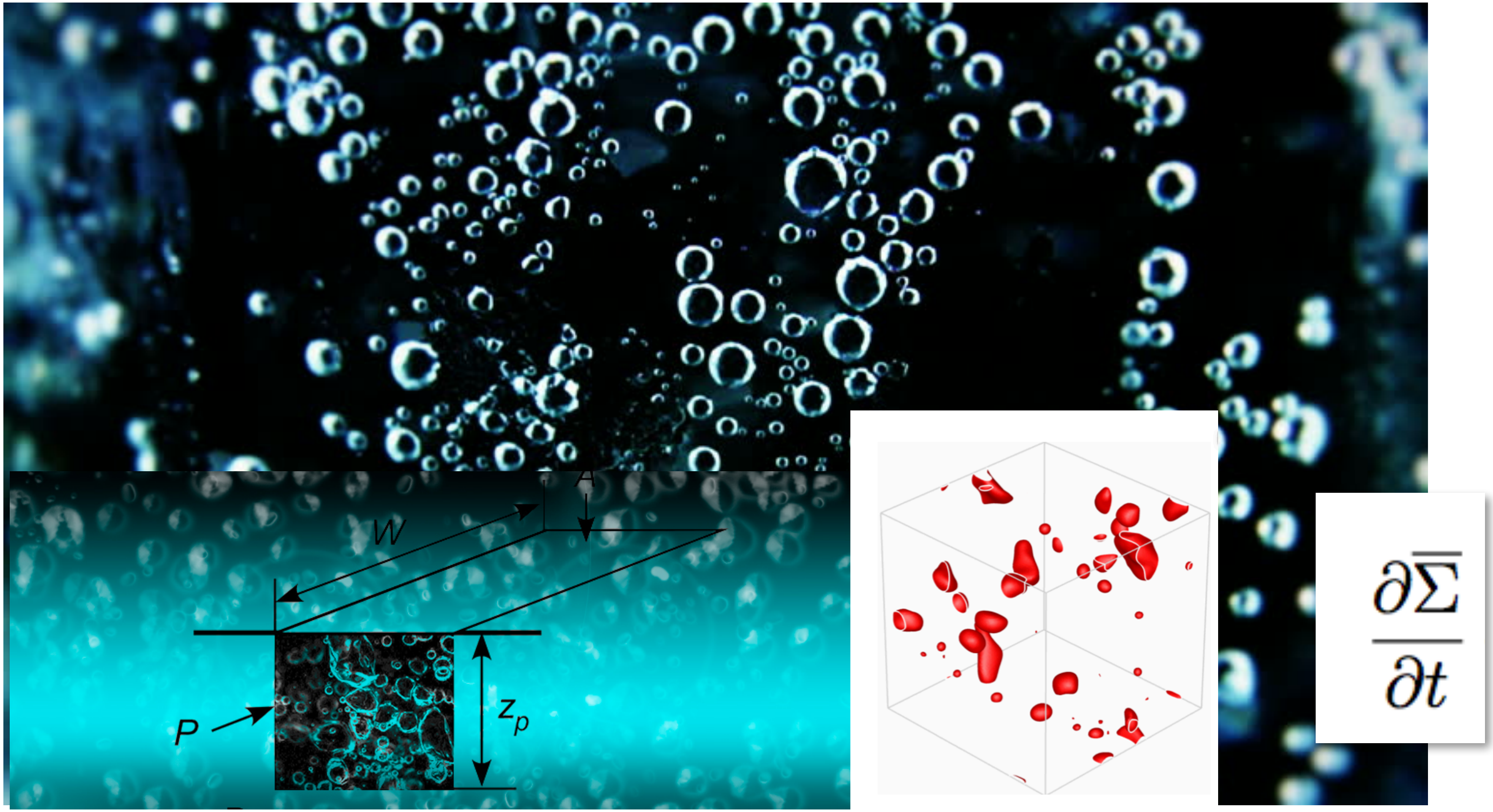


$\phi_l = 95\%$



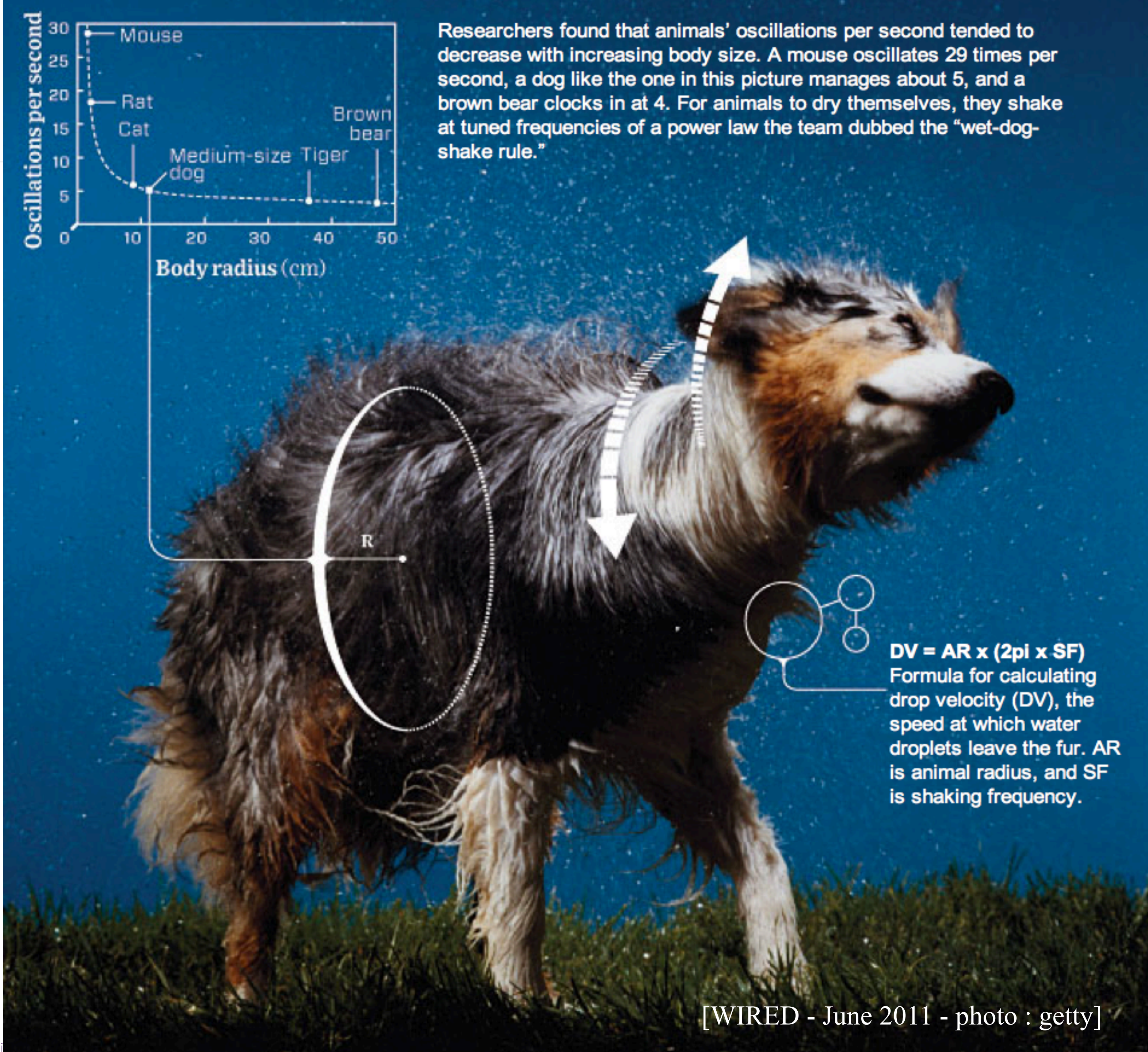
$\phi_l = 99\%$

Objectives : apply ELSA to aeration modeling



$$\frac{\partial \overline{\Sigma}}{\partial t}$$

Other Atomization systems



Researchers found that animals' oscillations per second tended to decrease with increasing body size. A mouse oscillates 29 times per second, a dog like the one in this picture manages about 5, and a brown bear clocks in at 4. For animals to dry themselves, they shake at tuned frequencies of a power law the team dubbed the "wet-dog-shake rule."

DV = AR x (2pi x SF)
Formula for calculating drop velocity (DV), the speed at which water droplets leave the fur. AR is animal radius, and SF is shaking frequency.

[WIRED - June 2011 - photo : getty]