Gouttes et bulles, un univers fascinant à l'intérieur des solutions des équations de Navier-Stokes

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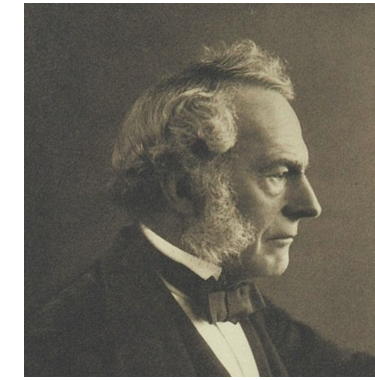
Collaborators in the past ten years on atomisation.

Ruben Scardovelli, Stephane Popinet, Daniel Fuster, Tomas Arrufat, Peng Cheng, Gretar Tryggvason, Leon Malan, Yue Stanley Ling, Alexandre Guion, Subin Tomas, Taraneh Sayadi, Florence Marcotte, Wojciech Aniszewski, Sagar Pal, Nelson Joubert, Marco Crialesi, Youssef Saadeh, Alexandre Limare, Raphael Villiers.

Current students and postdocs

Tomas Fullana, Mandeep Saini, Saeed Bidi, Ahmed Basil K., Cesar Pairetti, Jacob Maarek, Leonardo Chirco, Yash Kulkarni, Xiangbin Chen, Désir-André Koffi-Bi, Damien Thomas, Tobias Bauer, Elena Batzella, Jieyun Pan, Tian Long.

George Gabriel Stokes



The Navier-Stokes equations (incompressible, single phase)

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

$$\rho(\partial_t \mathbf{u} + (\mathbf{u} \cdot \nabla)\mathbf{u}) = -\nabla p + \mu \Delta \mathbf{u} + \rho \mathbf{g}$$

Henri Navier

George Gabriel Stokes

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Henri Navier

the view in this talk

$$\rho(\partial_t \mathbf{u} + (\mathbf{u} \cdot \nabla)\mathbf{u}) = -\nabla p + \mu \Delta \mathbf{u} + \phi \nabla C + \rho \mathbf{g}$$

C: phase characteristic function ϕ: surface tension. Constant viscosity (for simplification). Incompressible, no coupling with thermal effects (pandora box).

Claude Louis Marie Henri Navier, « Mémoire sur les lois du mouvement des fluides » (lu à l'Académie royale des sciences le 18 mars 1822), *Mémoires de l'Académie royale des Sciences de l'Institut de France*, Paris, vol. 6, 1827, p. 389-440

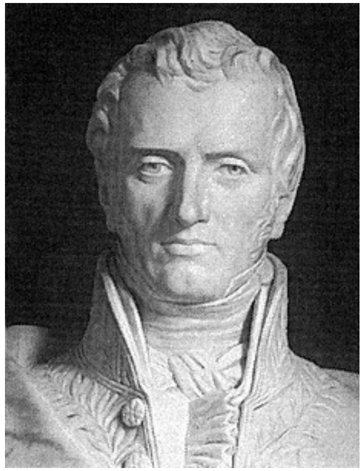
George Gabriel Stokes, *Transactions of Cambridge Philosophical Society*, vol. 8, 1845, p. 287–305.

Boundary conditions

$$\mathbf{u} = \mathbf{u}_{\mathbf{solid}}$$

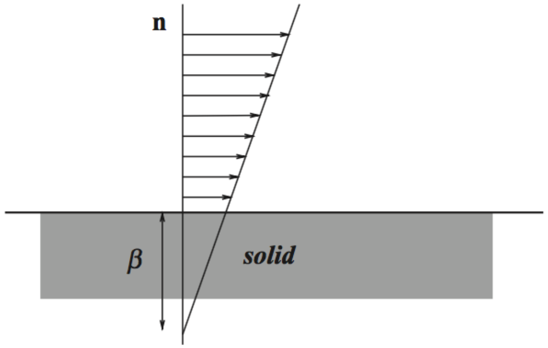
lead to severe singularities with two phase flow with contact lines.

Henri Navier



- A Navier Boundary Condition (NBC) is often used as a regularization

$$u = \lambda \frac{\partial u}{\partial y}$$



- λ is called the slip length, and is measured to be of the order of a nanometer or less.

Applications, motivations

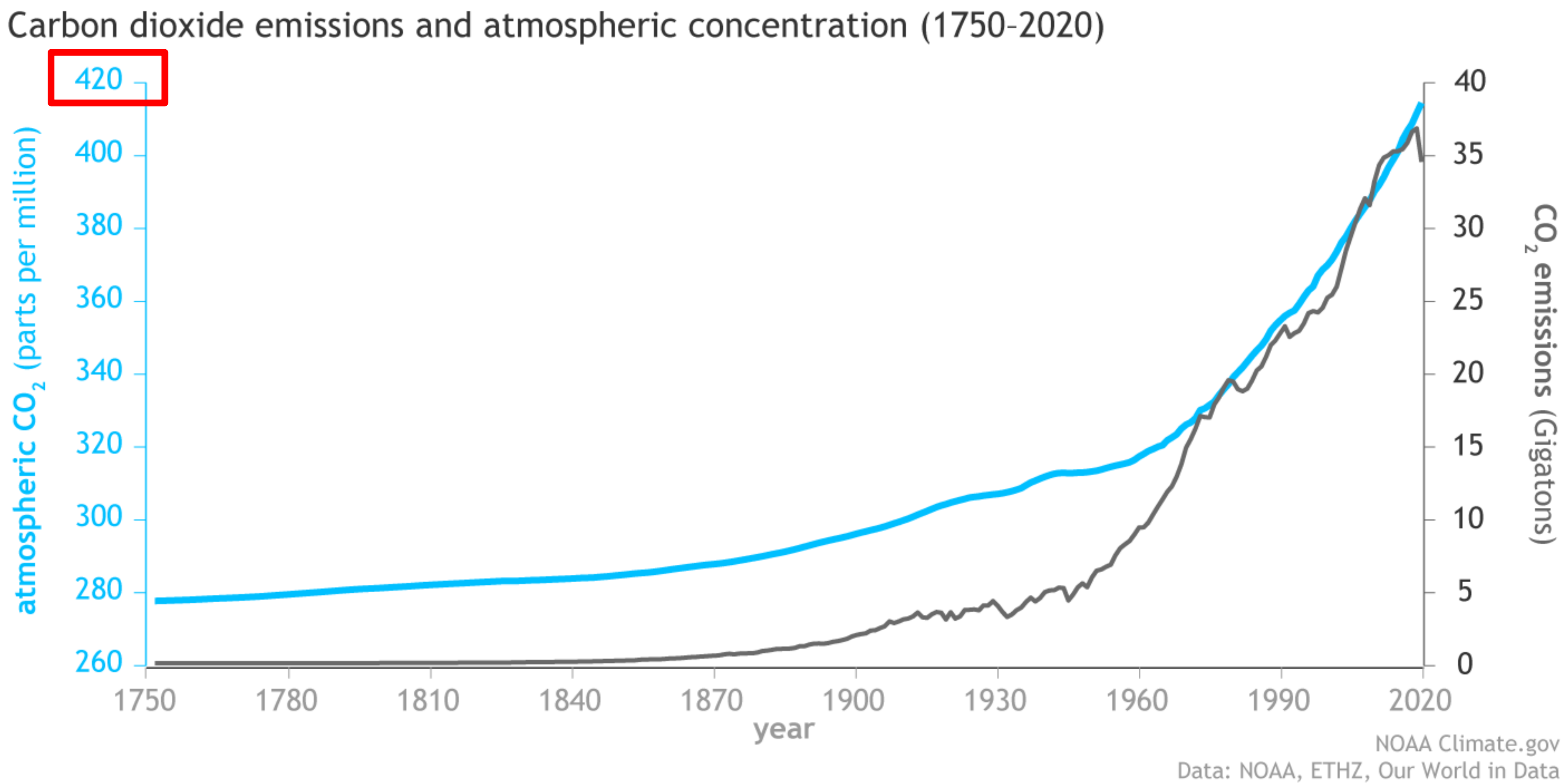
420

Ten times the number 42 ?

421 ppm is the current CO_2 level in earth's atmosphere

If you measure more than 421 ppm in a room, it is a sign that aeration is not sufficient and you are at risk of contamination by a respiratory disease such as SARS, MERS, Covid-19, the flu or a common cold.

The 420 CO2 level is also the result of 150 years of fossil fuel burning



ipcc

INTERGOVERNMENTAL PANEL ON climate change

Climate Change 2022

Mitigation of Climate Change

Summary for Policymakers

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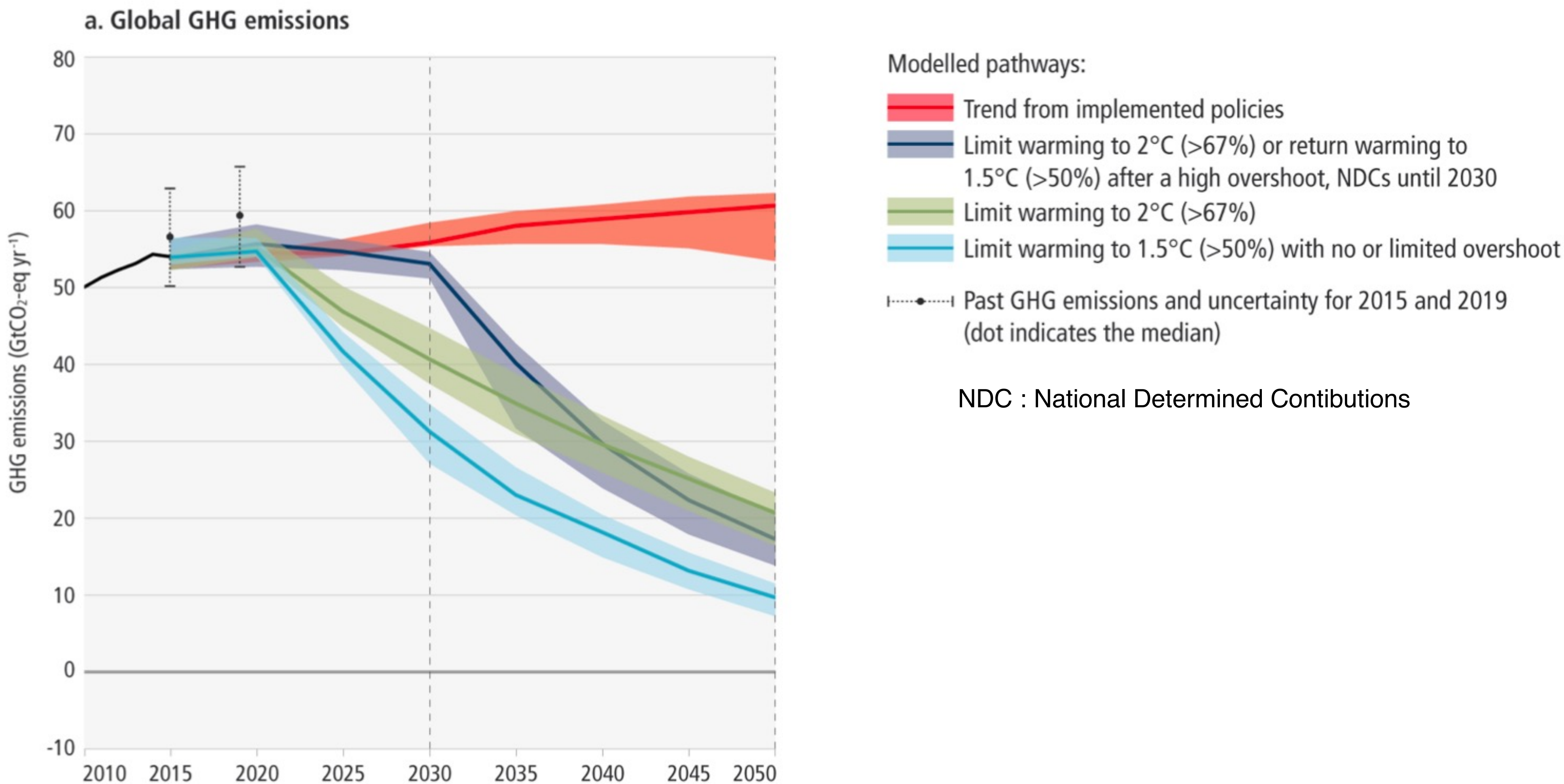
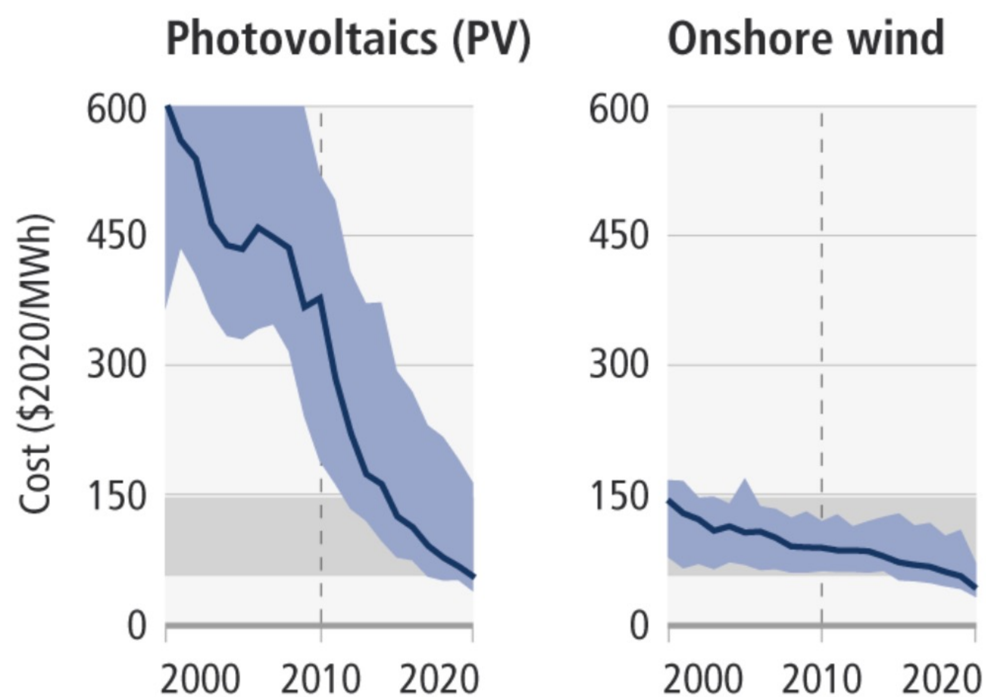
pathways

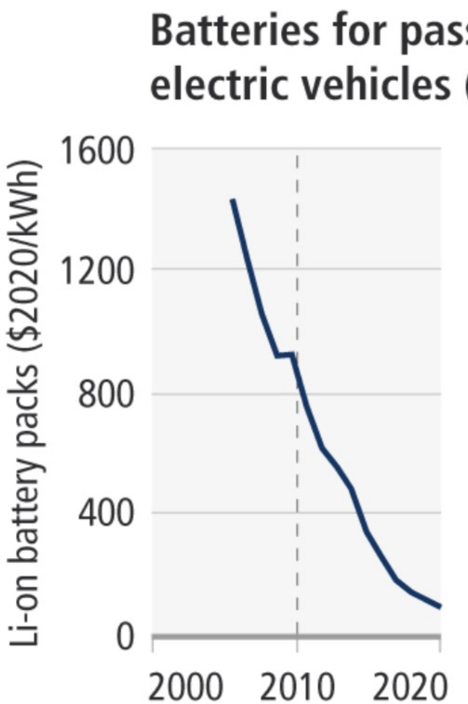


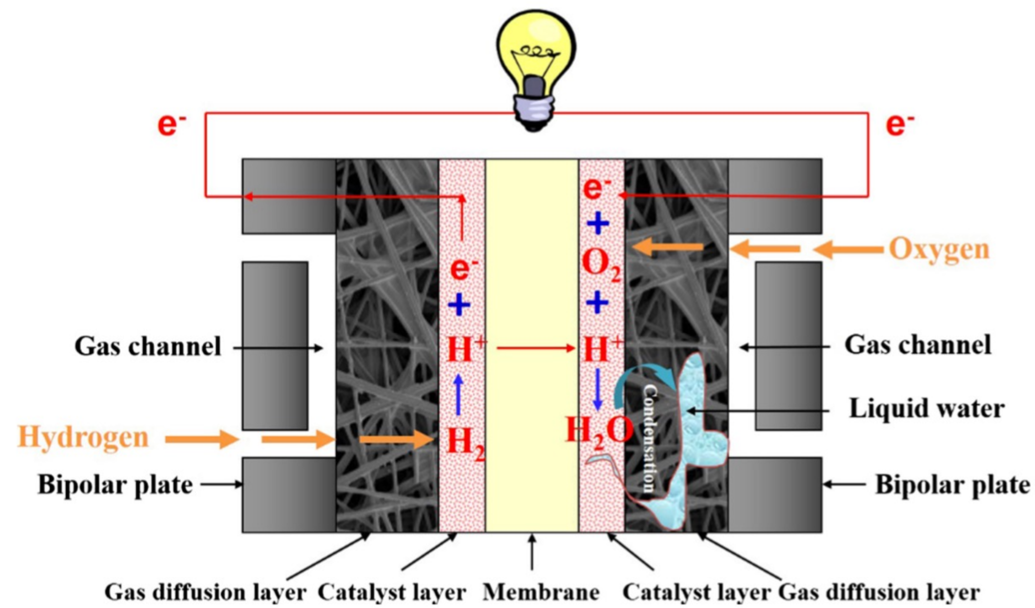
NDC : National Determined Contibutions

Soilutions are available: wind and solar have become much cheaper



But energy storage remains a big issue. To compensate for the intermittency and annual oscillation of wind and solar power, about six months of storage of a country's energy consumption is needed. Sadly, although now cheaper to produce, batteries last only a few hours...





Fuel cell

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The number 421 is thus connected to two of the main issues discussed in this lecture:

- Energy and climate : production, storage, usage, ocean-atmosphere interactions
- Respiratory disease transmission by aerosols.

Climate change and the emission reductions necessary to mitigate it are related to many natural phenomena and technologies.

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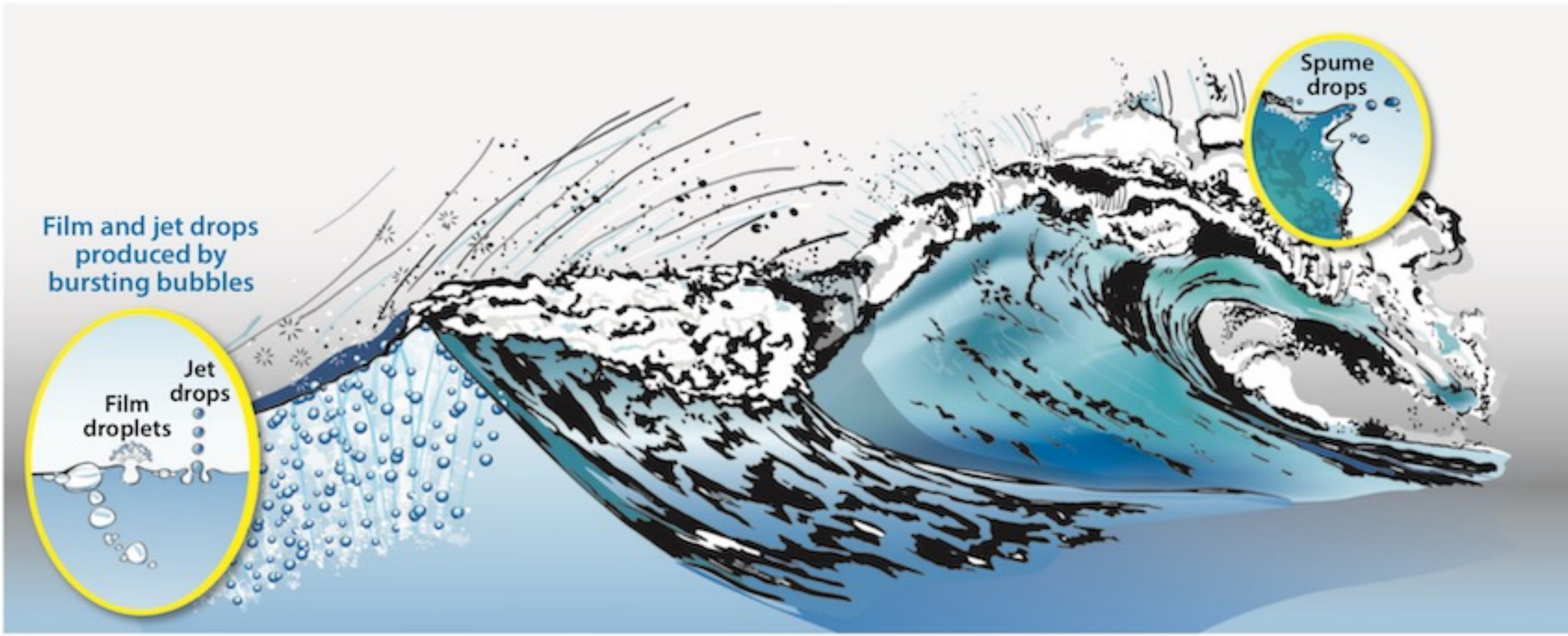
An essential phenomenom is the ocean-atmosphere interface.

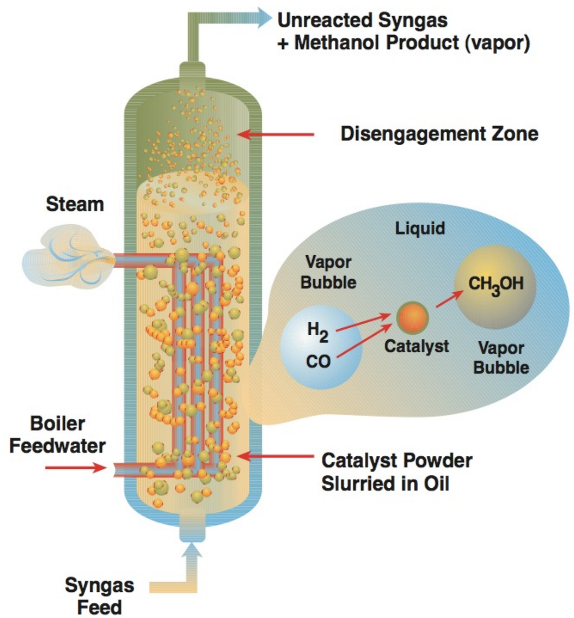


From Véron, ocean spray, 2015

Chemical and process engineering

Bubble Columns

From:http://p2pays.org/ref/16/15865.pdf



Liquid Phase Methanol (LPMEOH™) Process

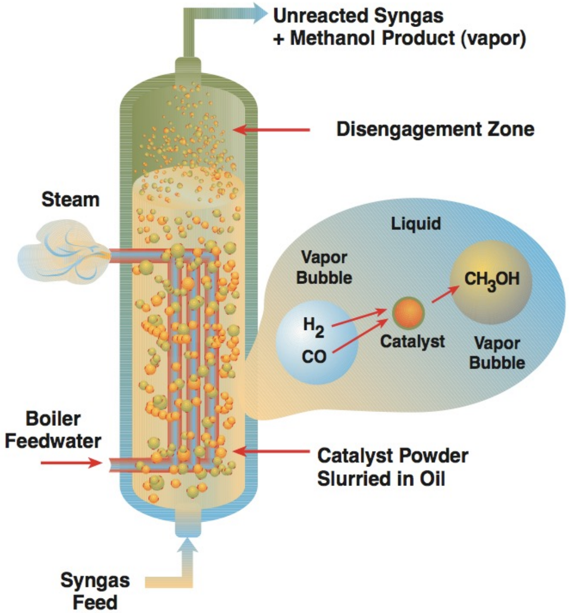
Examples of Applications of Bubble Columns

Process	Methods and/or Reactants
Acetone	Oxidation of cumene
Acetic acid	Oxidation of acetaldehyde
	Oxidation of sec-butanol
	Carbonylation of methanol
Acetic anhydride	Oxidation of acetaldehyde
Acetaldehyde	Partial oxidation of ethylene
Acetophenone	Oxidation of ethylbenzene
Barium chloride	Barium sulfide and chlorine
Benzoic acid	Oxidation of toluene
Bleaching powder	Aqueous calcium oxide and chlorine
Bromine	Aqueous sodium bromide and chlorine
Butene	Absorption in aqueous solutions of sulfuric acid
Carbon Dioxide	Absorption in ammoniated brine
Carbone tetrachloride	Carbon disulphide and chlorine
Copper oxychloride	Oxidation of cuprous chloride
Cumene	Oxidation of phenol
Cupric chloride	Copper and cupric acid or hydrochloric acid
Dichlorination	Oxychlorination of ethylene
Ethyl benzene	Benzene and ethylene
Hexachlorobenzene	Benzene and chlorine
Hydrogen peroxide	Oxidation of hydroquinone
Isobutylene	Absorption in aqueous solutions of sulfuric acid
Phtalic acid	Oxidation of xylene
Phenol	Oxidation of cumene
Potassium bicarbonate	Aqueous potassium carbonate
Sodium bicarbonate	Aqueous sodium carbonate
Sodium metabisulphides	Carbon dioxide, aqueous sodium carbonate, and sulfur dioxide
Thiuram disulphides	Dithiocarbamates, chlorine, and air
Vinyl acetate	Oxidation of ethylene in acetic acid solutions
Water	Wet oxidation of waste water

After: S. Furusaki, L.-S. Fan, J. Garside**. The Expanding World of Chemical Engineering** (2nd ed), Taylor & Francis 2001

Bubble Columns

From:http://p2pays.org/ref/16/15865.pdf



Liquid Phase Methanol (LPMEOH^{TM}) Process

Transform back CO into fuel

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Cupric chloride	Copper and cupric acid or hydrochloric acid
Dichlorination	Oxychlorination of ethylene
Ethyl benzene	Benzene and ethylene
Hexachlorobenzene	Benzene and chlorine
Hydrogen peroxide	Oxidation of hydroquinone
Isobutylene	Absorption in aqueous solutions of sulfuric acid
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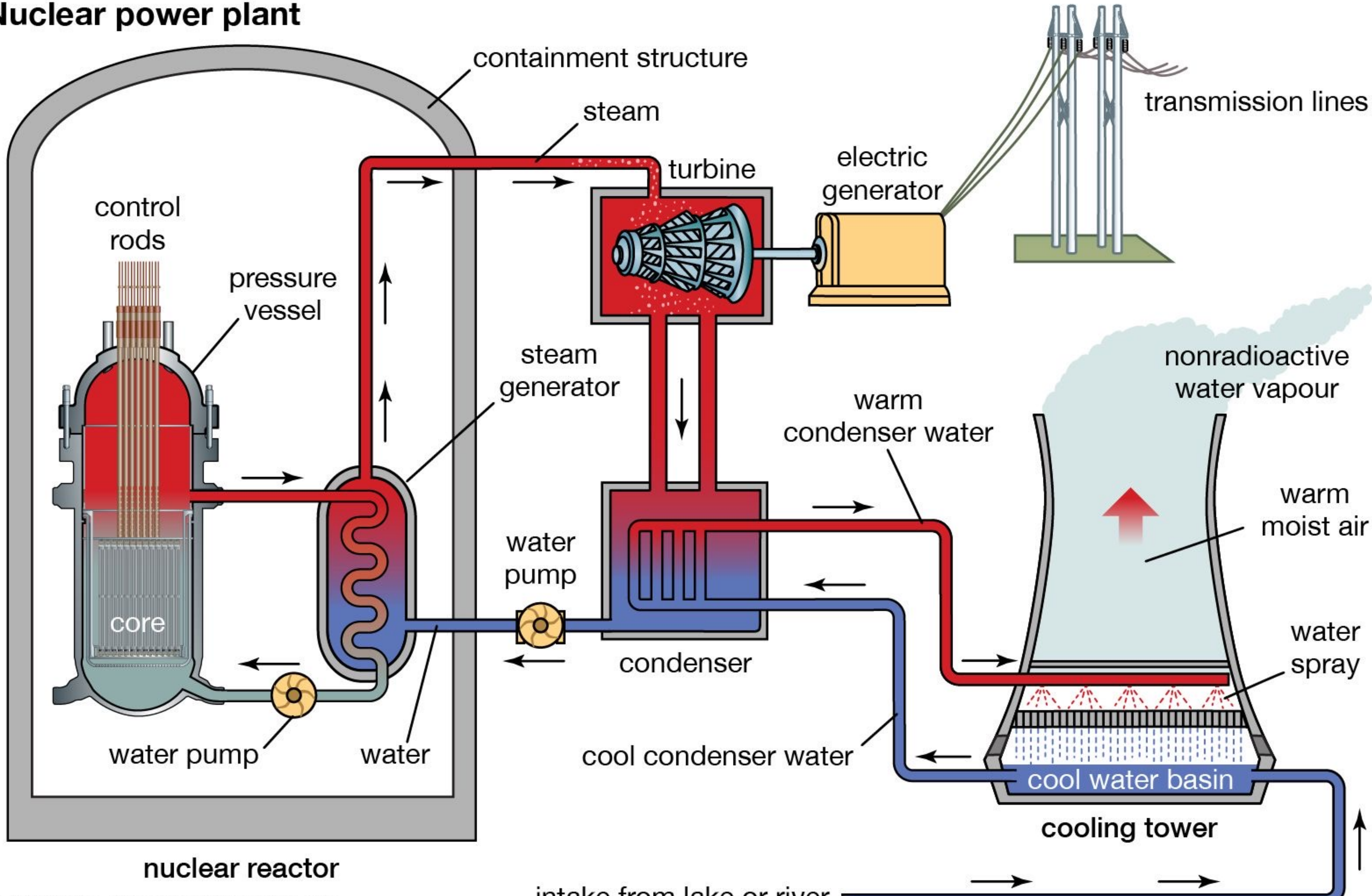
capture CO2

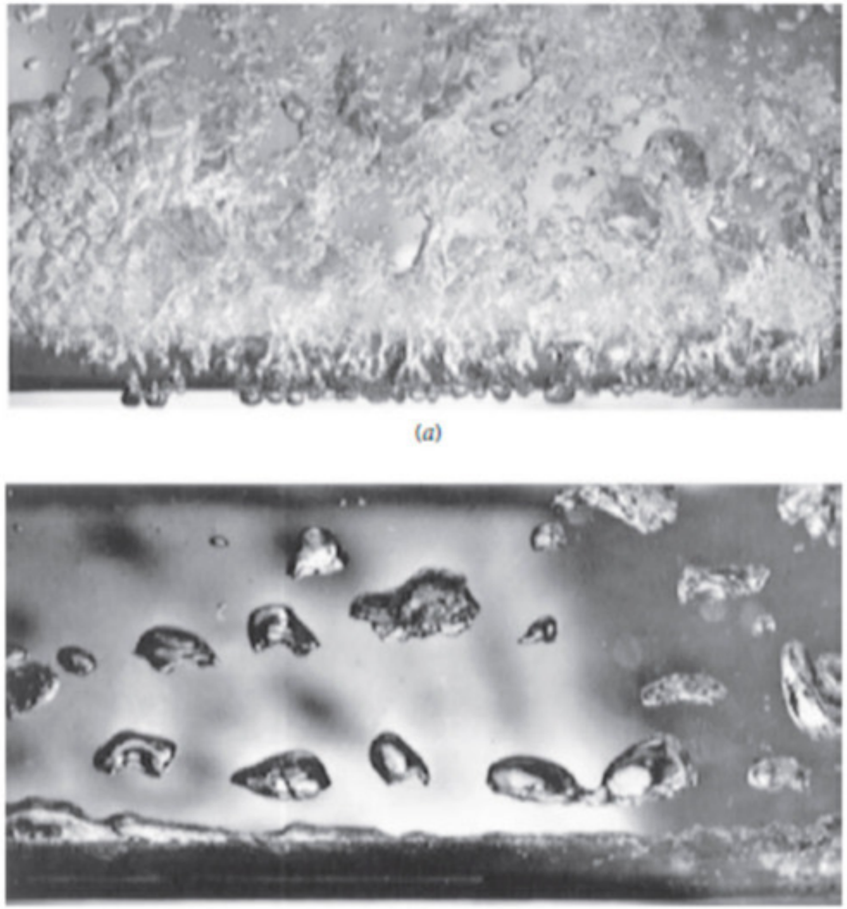
After: S. Furusaki, L.-S. Fan, J. Garside. **The Expanding World of Chemical Engineering** (2nd ed), Taylor & Francis 2001

Boiling

Nuclear power plant



Boiling


(a)
(b)

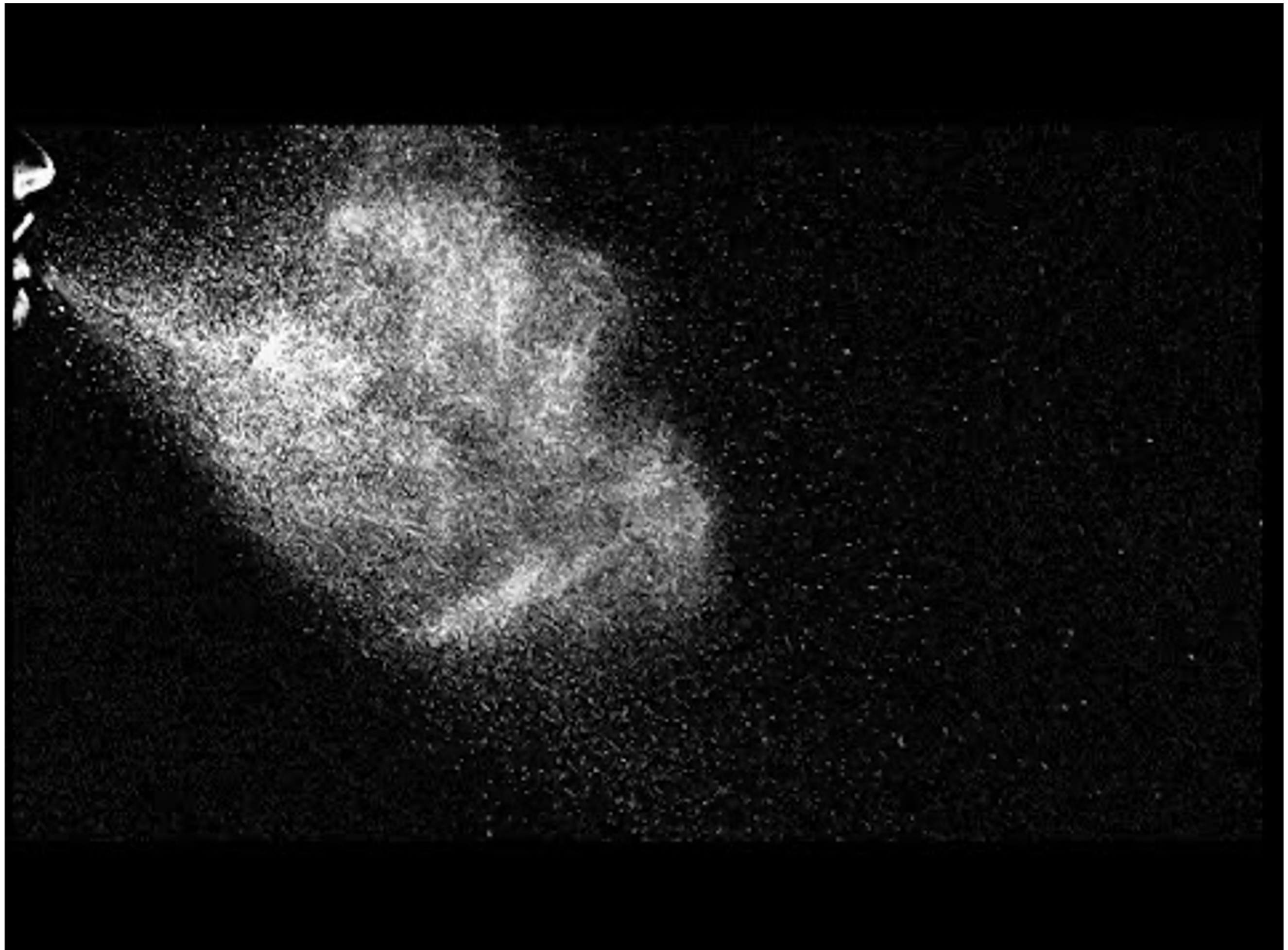
Bergman, T.L.; Incropera, F.P.; DeWitt, D.P.; Lavine, A.S. *Fundamentals of Heat and Mass Transfer*; John Wiley & Sons: Hoboken, NJ, USA, 2011.

Covid and atomization

Recent motivation: respiratory disease transmission

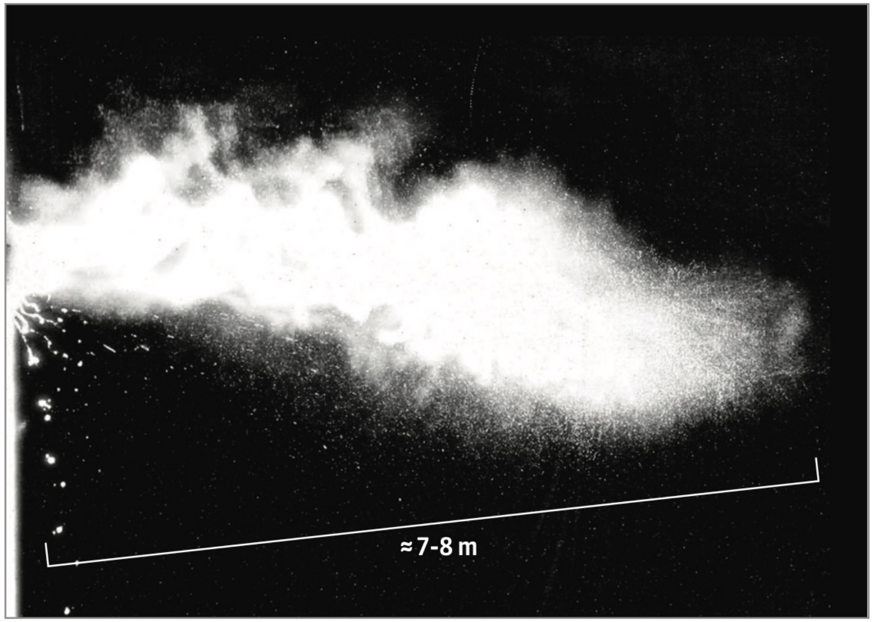
A short history of epidemiology and droplets

- Pasteur thought that pathogens were transmitted by dust particules. (Hence vacuum cleaners, waxing floors etc.)
- Paradox: why mandatory masks and no mandatory vacuuming ?
- No paradox: masks and waxing floors at time 1918 influenza epidemic
- In 1930 Wells introduces the distinction between « droplets » and « aerosols » or « droplet nuclei ». Studies tuberculosis. Makes assumptions about the droplet size distribution. Introduces arbitrary 5 micron limit.



turbulent puff.

From *Bourouiba L. Turbulent gas clouds and respiratory pathogen emissions: potential implications for reducing transmission of COVID-19. Jama. 2020 Mar 26.*

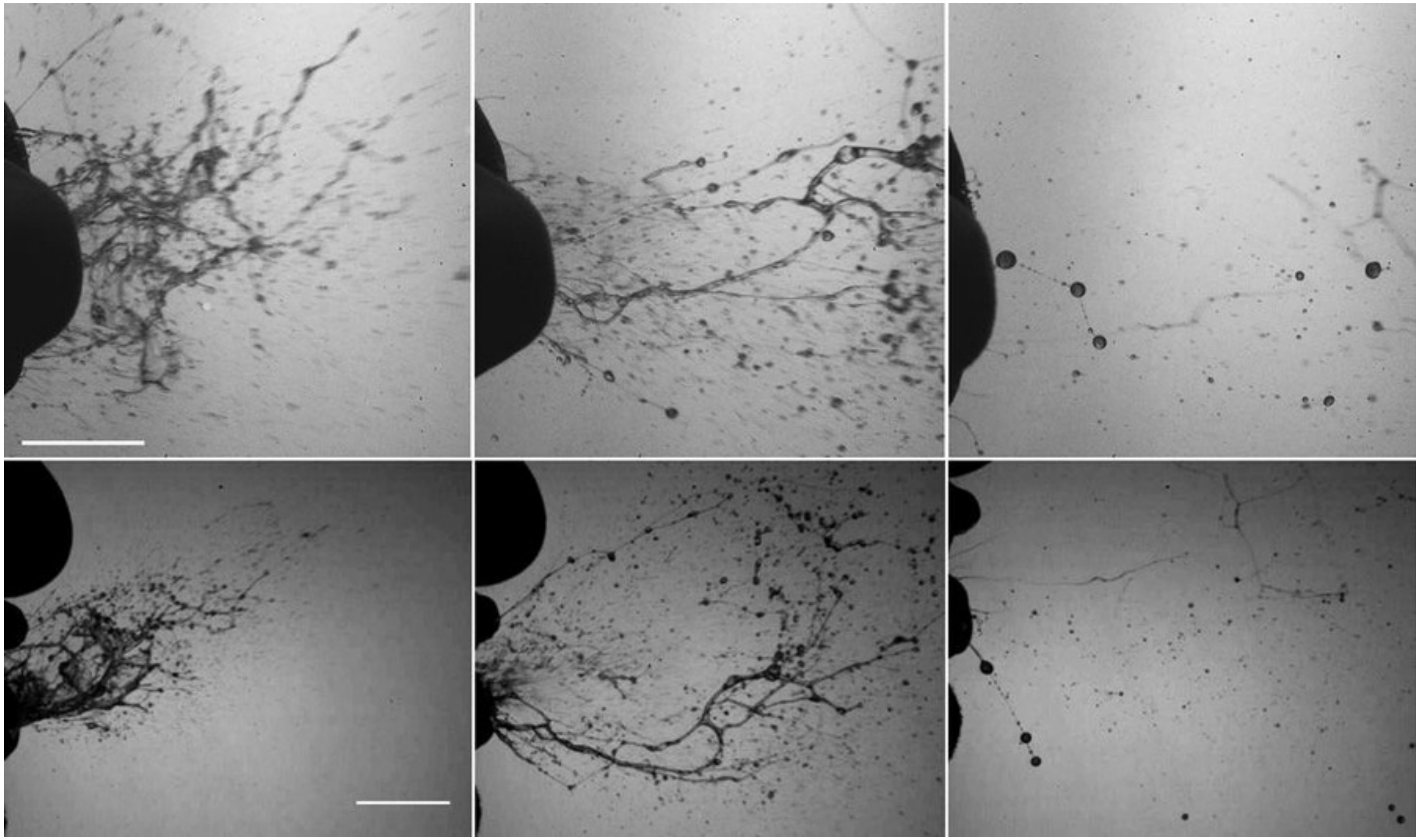


A turbulent puff created by a sneeze. The larger droplets (approx > 100 microns) fall to the ground in less than a meter. Smaller droplets are entrained into the turbulent puff. The image is from *Bourouiba L. Turbulent gas clouds and respiratory pathogen emissions: potential implications for reducing transmission of COVID-19. Jama. 2020 Mar 26.*

vidéo

The hotter turbulent puff can rise by natural convection and either stagnate near the ceiling or be entrained into the HVAC system and spread to other rooms.

Disease Transmission *via* Bioaerosols



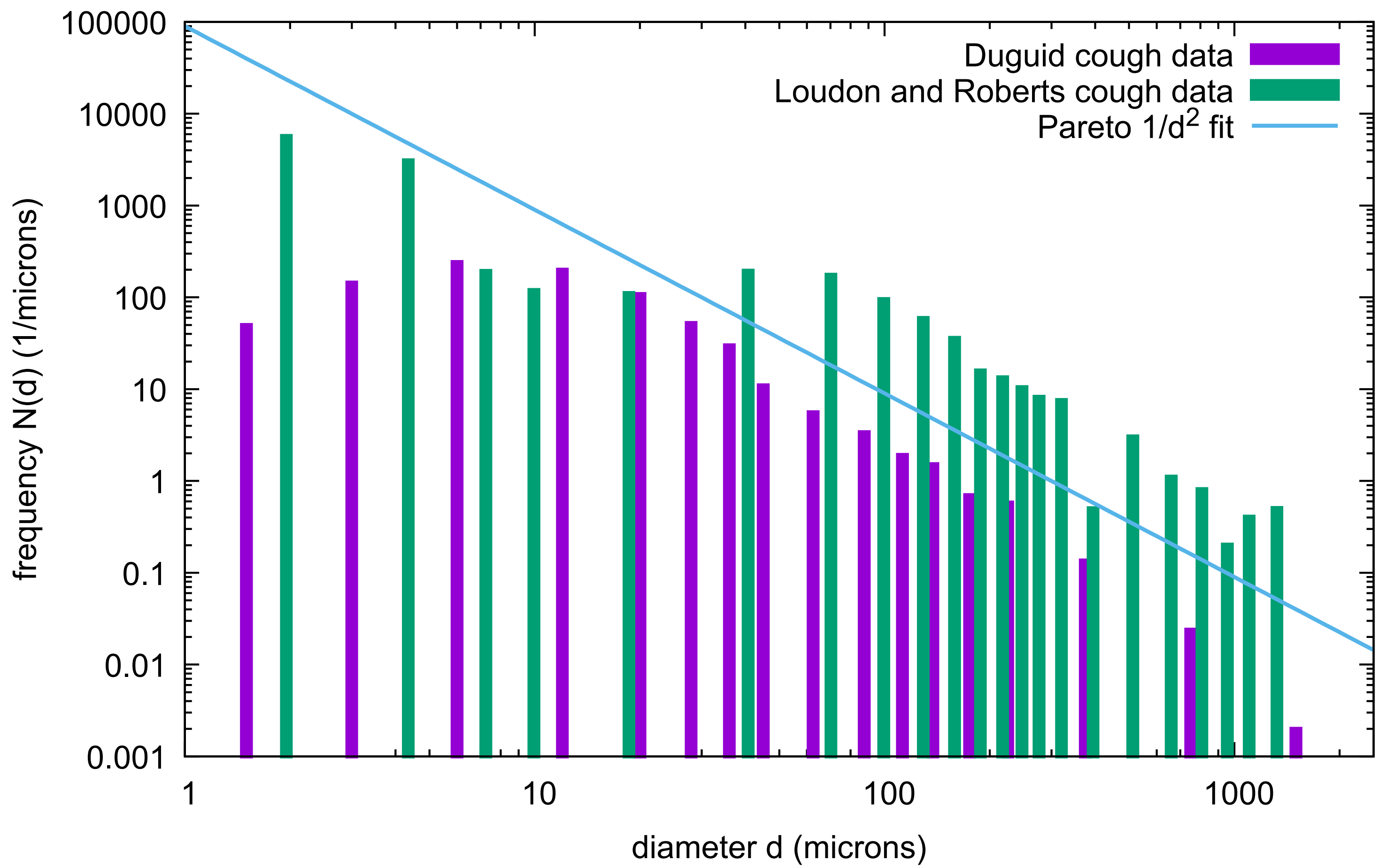
- Wide range of d !
- Viscoelastic !

Scharfman, et al. *Experiments in Fluids* (2016)

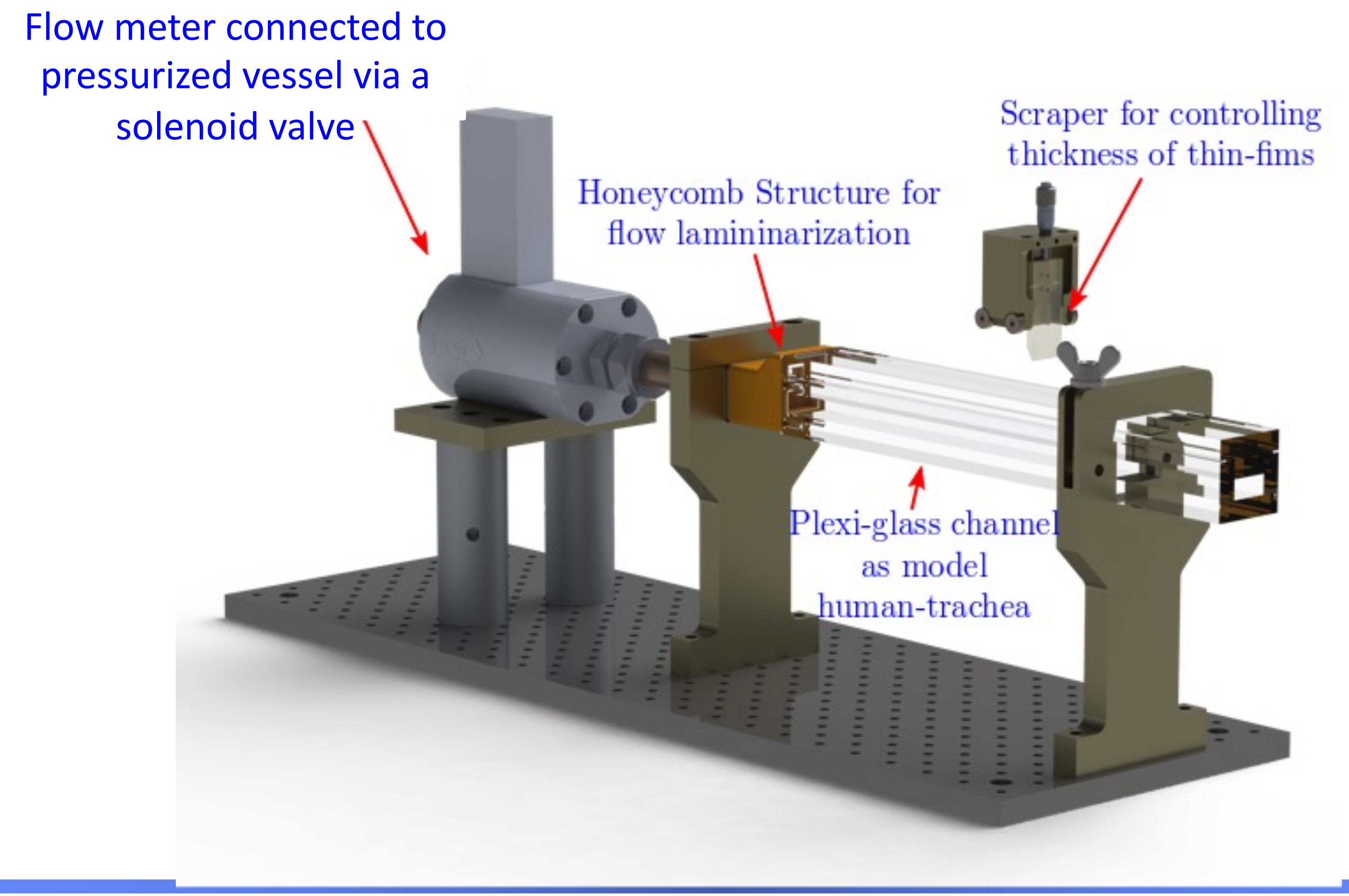
Question: what is the size of the droplets in the atomisation process ?

First experimental answer from Duguid (1946) … Hard to do better since

Pareto N(d) ~1/d^2 fit



Cough Machine (with D. Lohse, P. Kant)

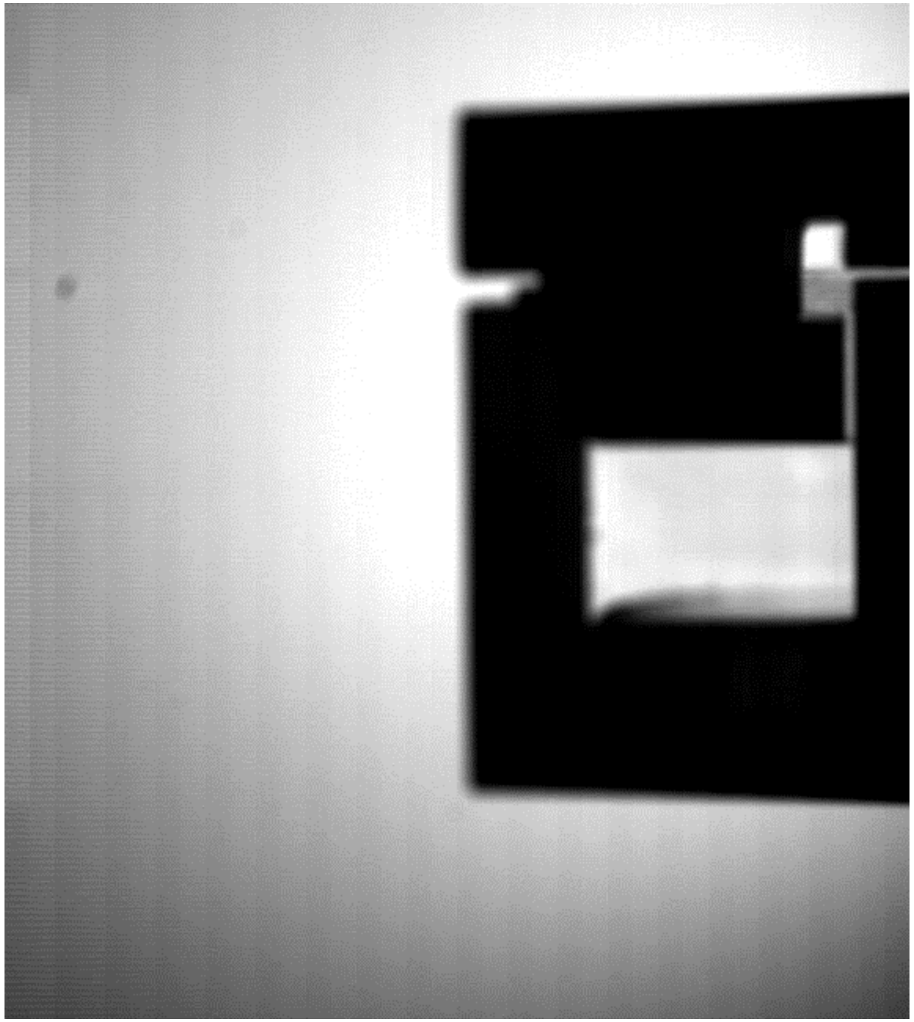


Cross-section
2 cm x 1cm

Experimental Parameters

- Liquid film : water-glycerol mixture
- Liquid viscosity : 2 – 100 10^{-3} kg m^{-1} s^{-1}
- Surface tension : 62 – 72 mN/m
- Flow velocity : 10 - 30 m/s

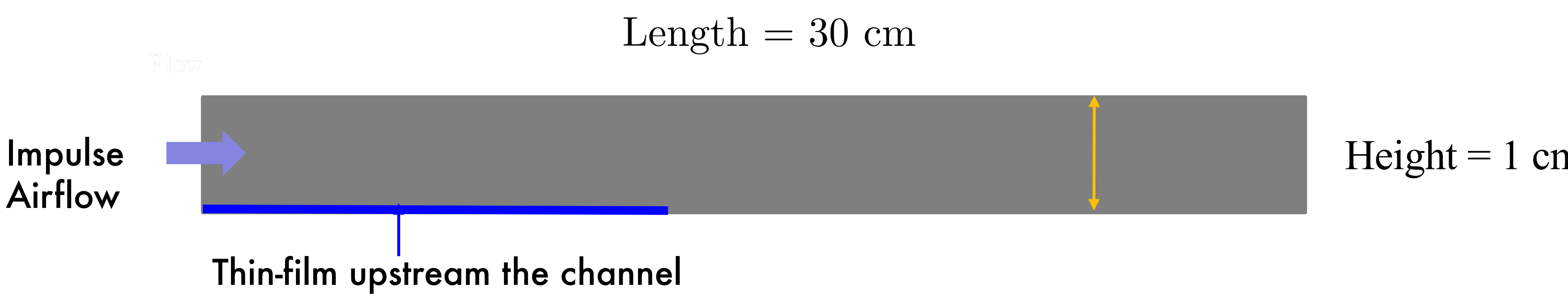
Droplet Generation



- Fine droplets are produced deeper in the channel
- Larger droplets form at the exit

Film Thickness $\mathcal{H}_\mathrm{f} = 1\ \mathrm{mm}$
Mean Flow Velocity $U \sim 29\ \mathrm{m/s}$

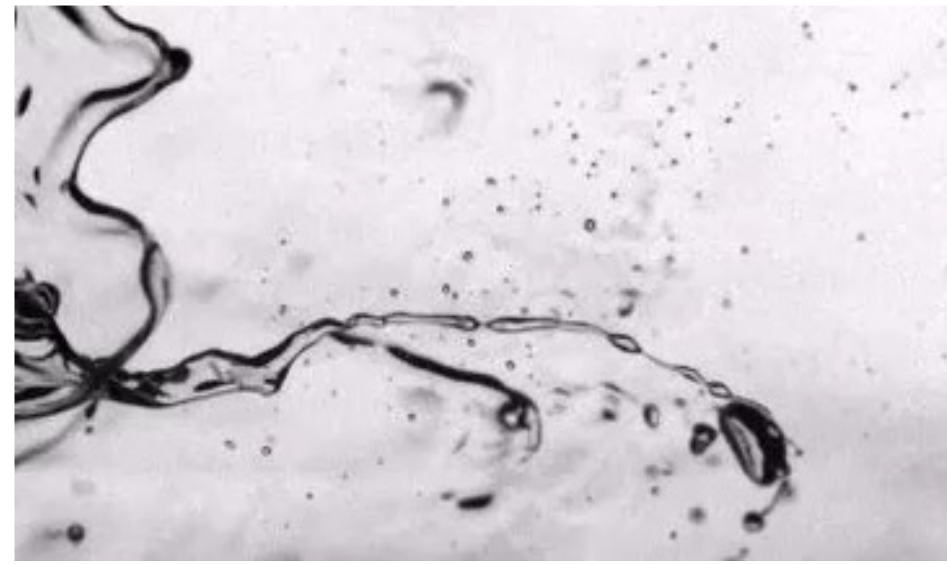
Experimental configuration



Bag rupture mechanism

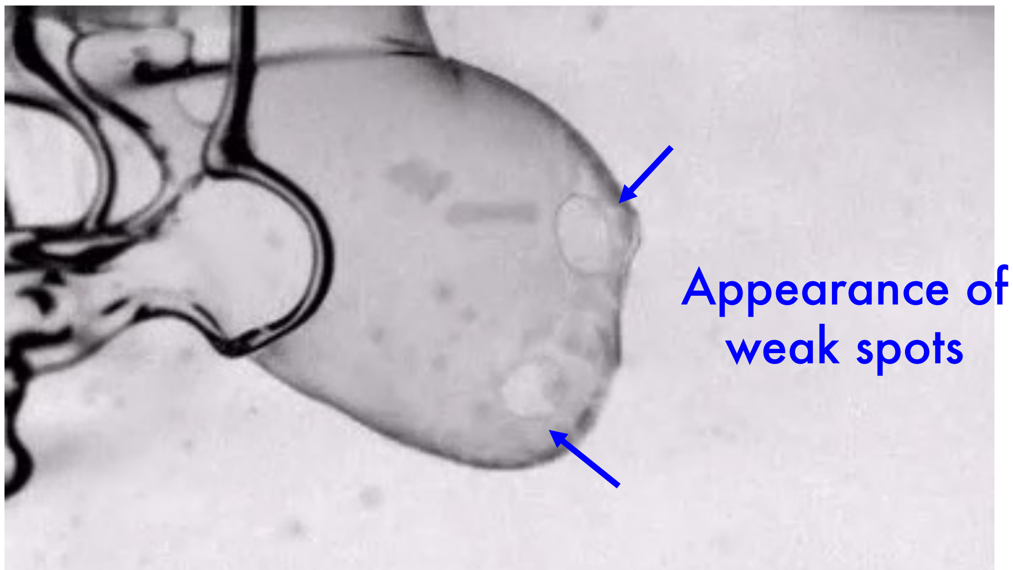
Example - 1

Example - 2



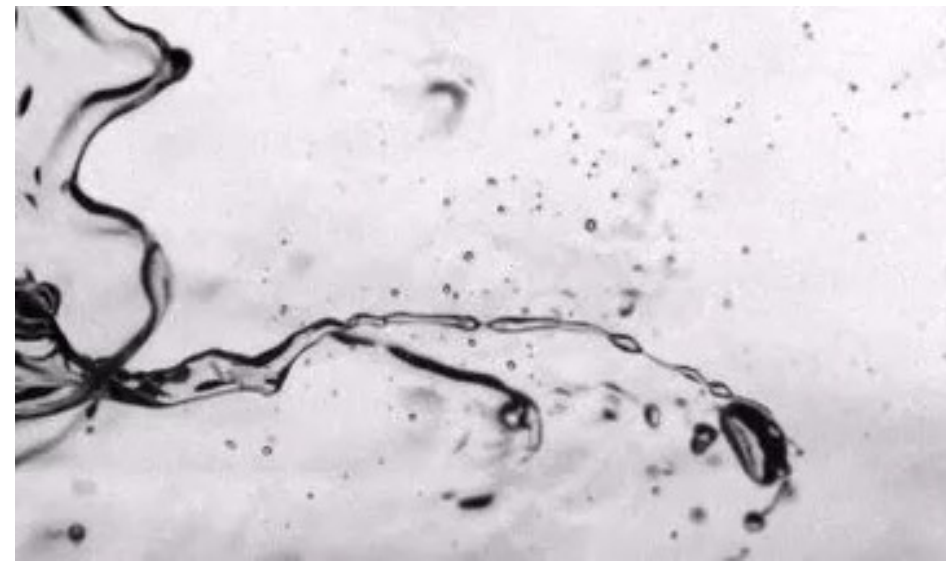
Bag rupture mechanism: Weak Spots

Example - 1



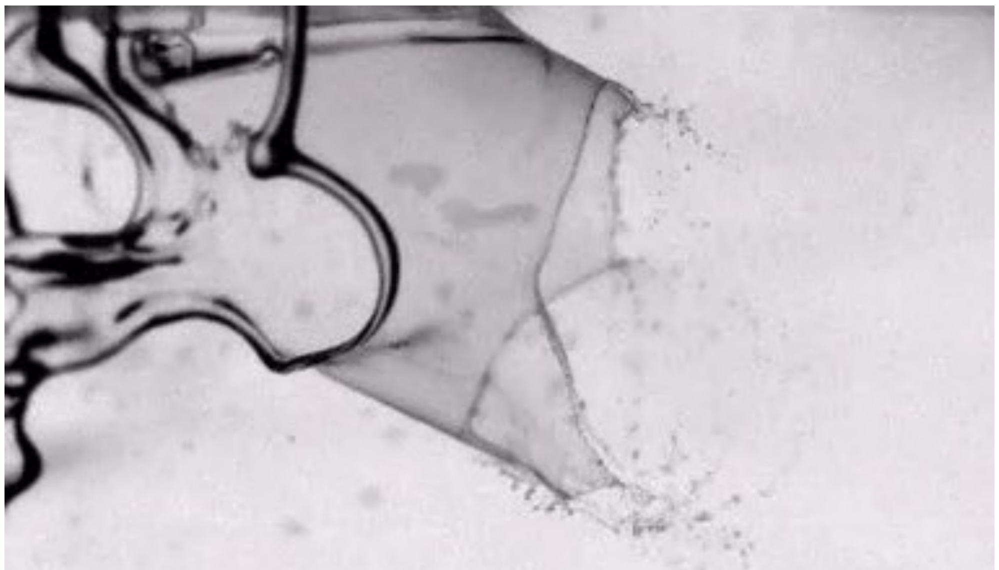
Unstable motion of retracting sheet generates small droplets $d \leq 50\,\mu\mathrm{m}$

Example - 2



Bag rupture: Appearance of Weak Spots

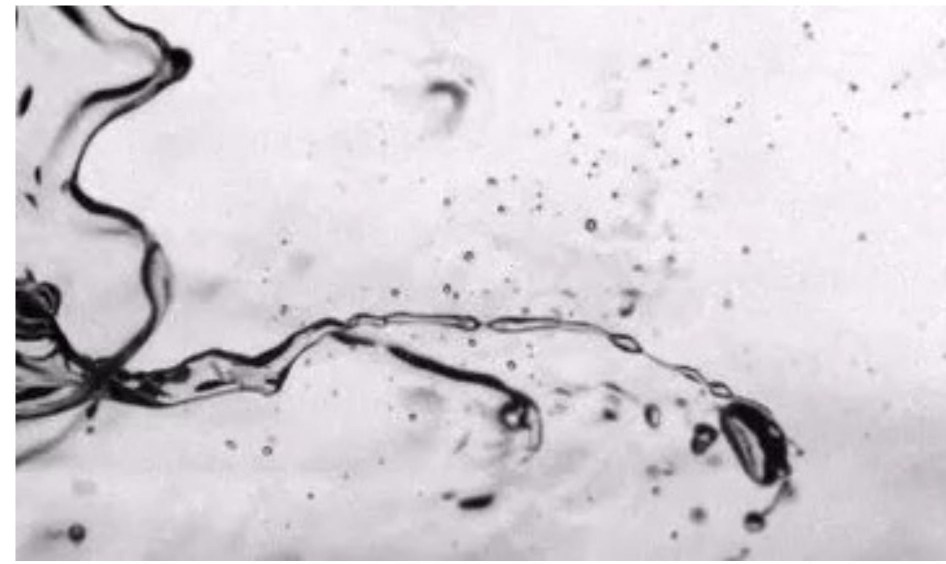
Example - 1



Finally the breakup of rim creates larger droplets

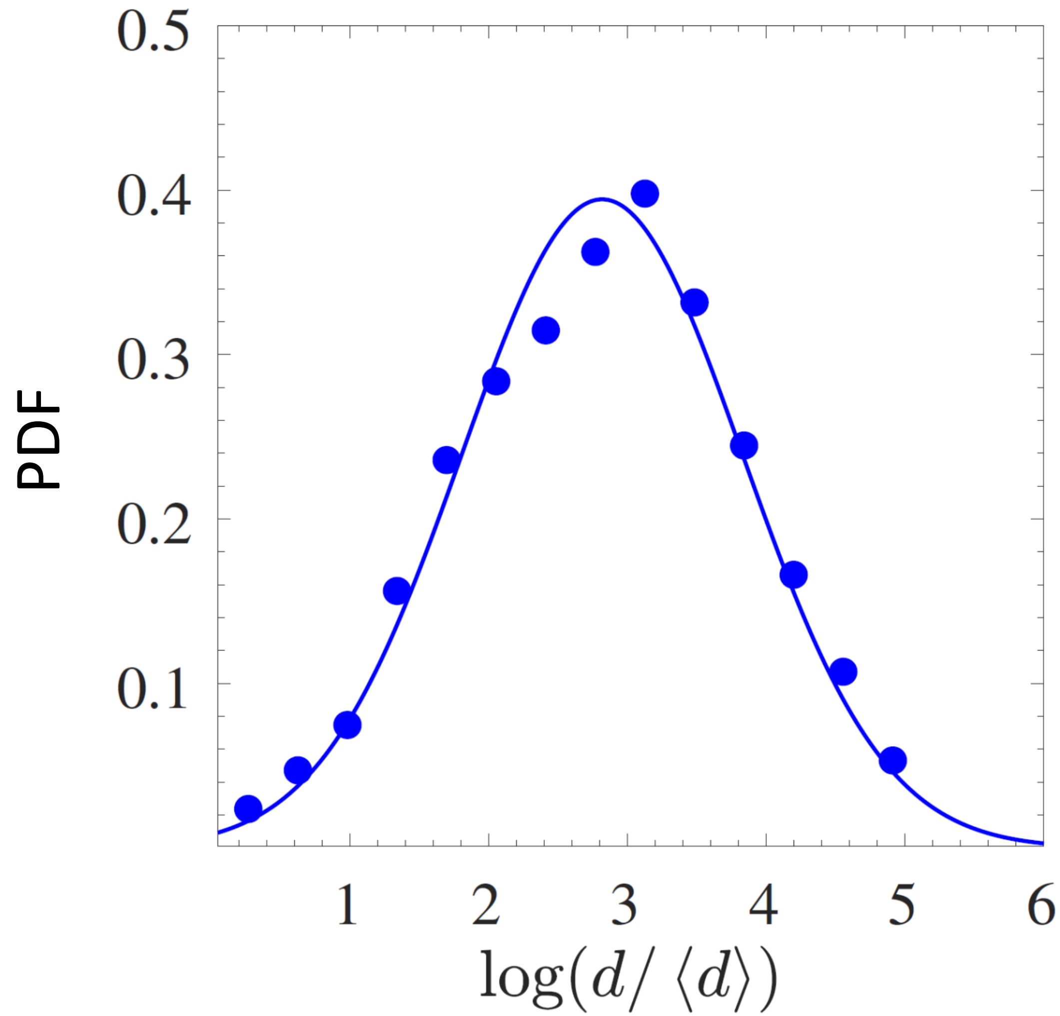
$d > 200\,\mu\mathrm{m}$

Example - 2

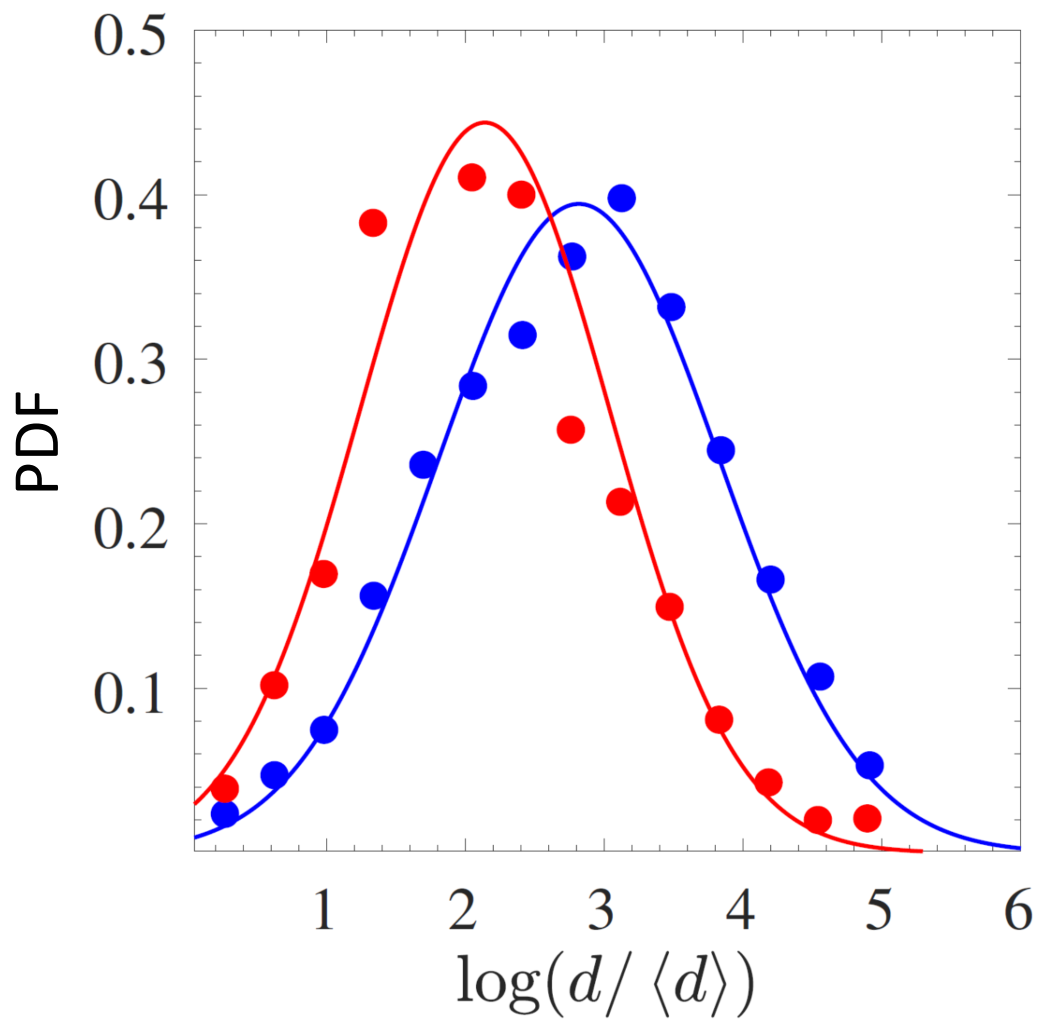


Droplet size distribution : Log-normal

$\nu = 5$ cst



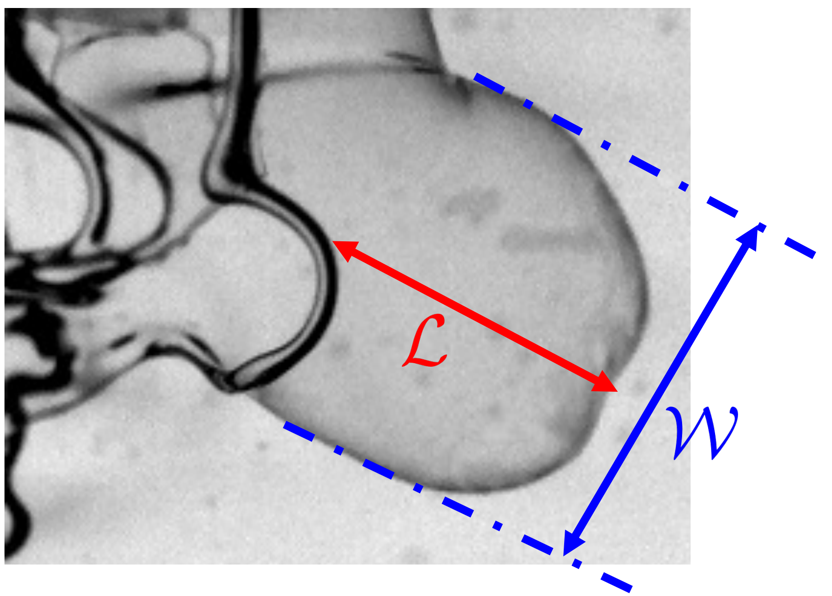
Droplet size distribution : Influence of viscosity

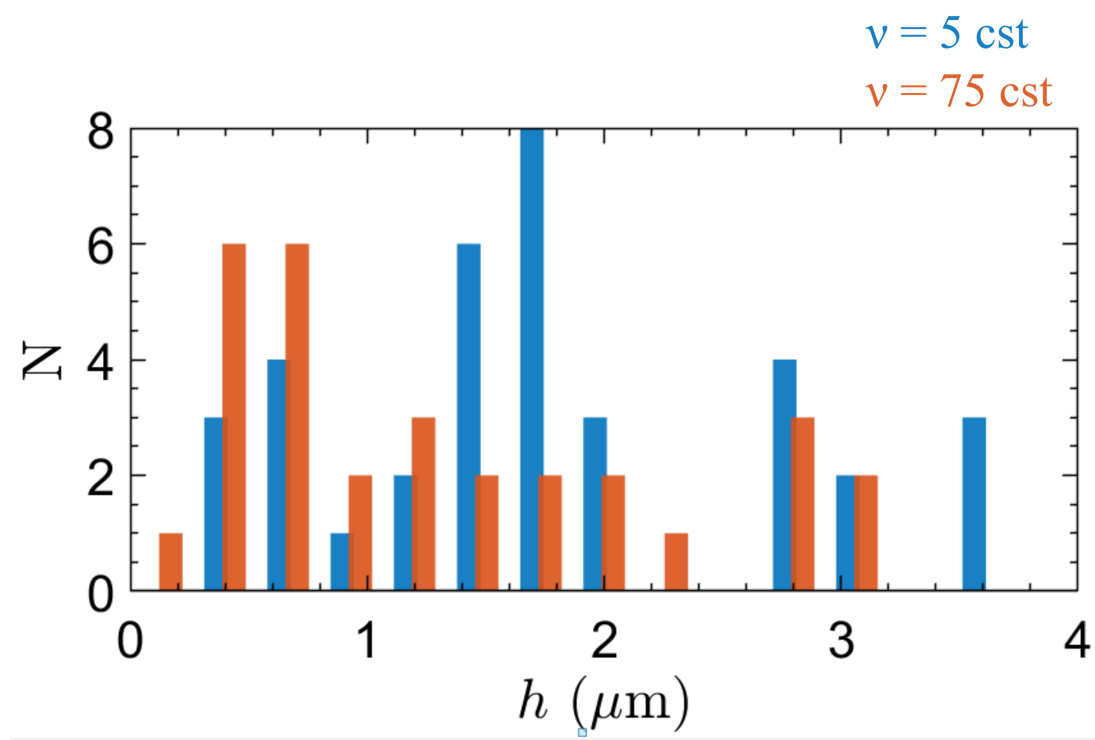


$\nu = 5$ cst
$\nu = 75$ cst

Mathematicians help !

Influence of viscosity: Bag thickness

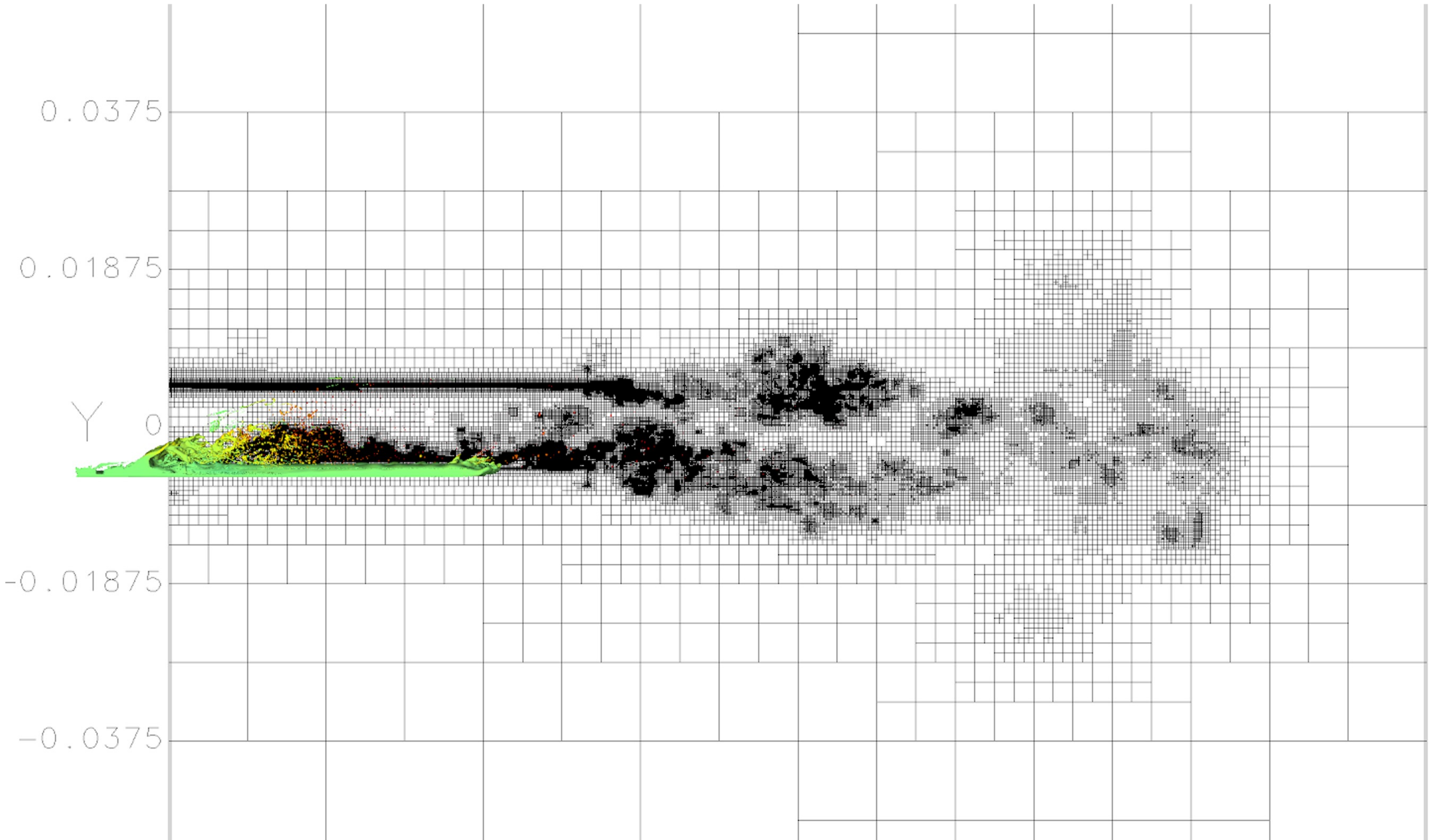




Experimental Conclusion

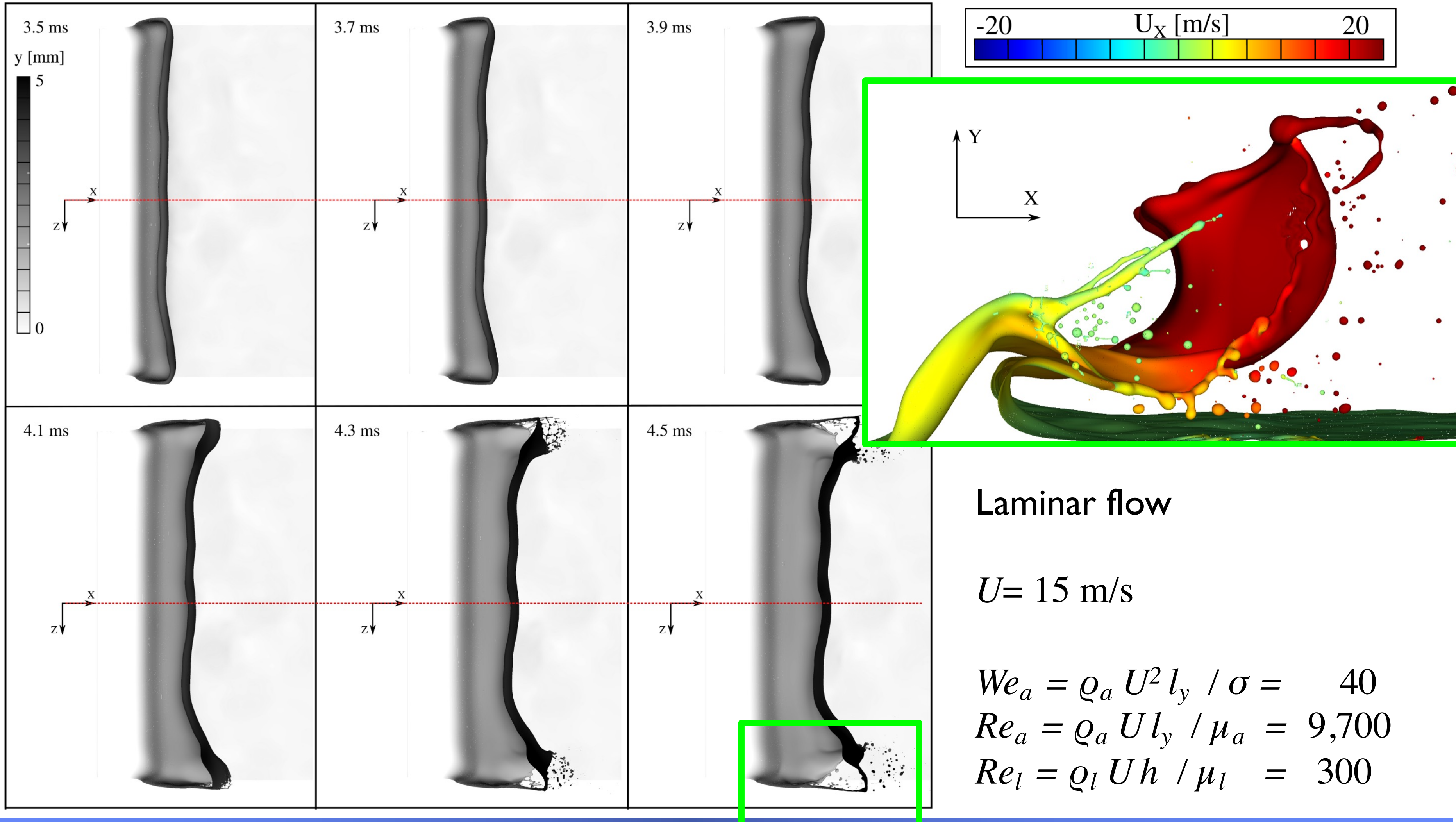
Viscosity promotes formation of deeper, wider and thinner bags, thus smaller droplets are generated.

Numerics of cough : octree grid (basilisk code by S. Popinet)



Sheet inflation and perforation regimes

The experimental setup allows to study more viscous configurations, closer to saliva properties (silicon oil experiments). Air velocity during sneeze can also be smaller.

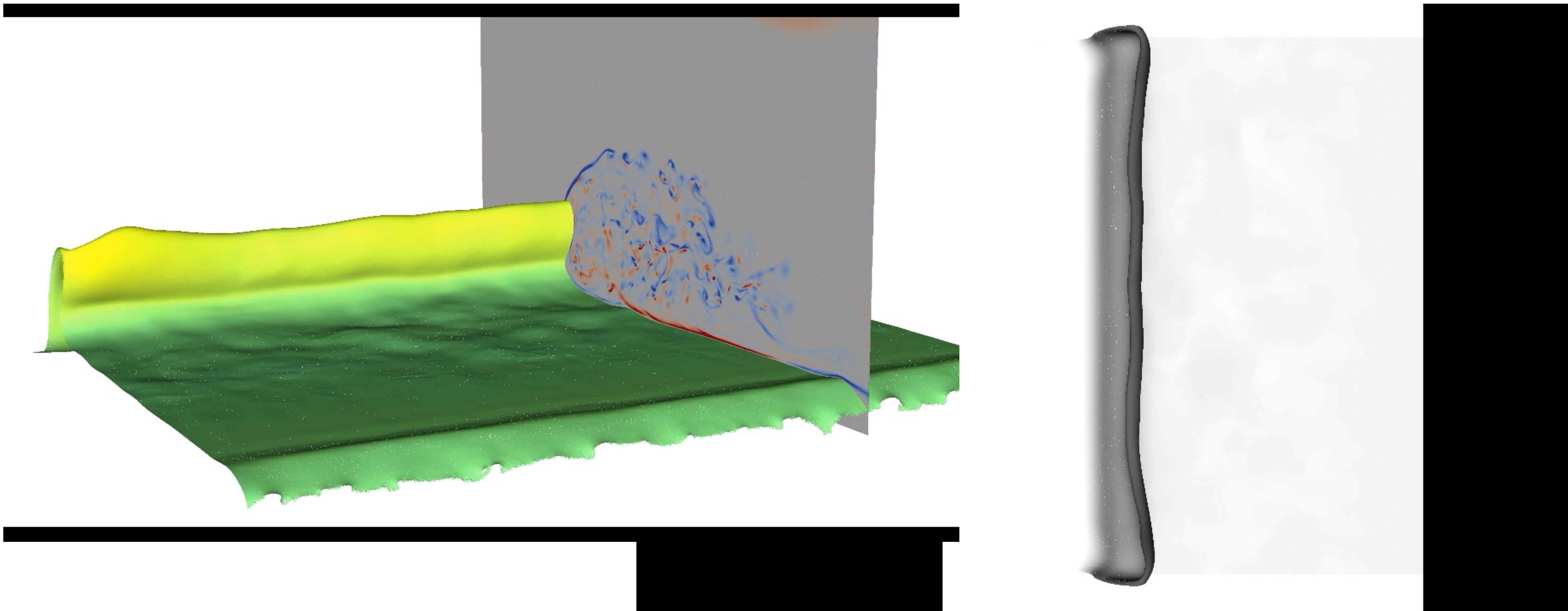


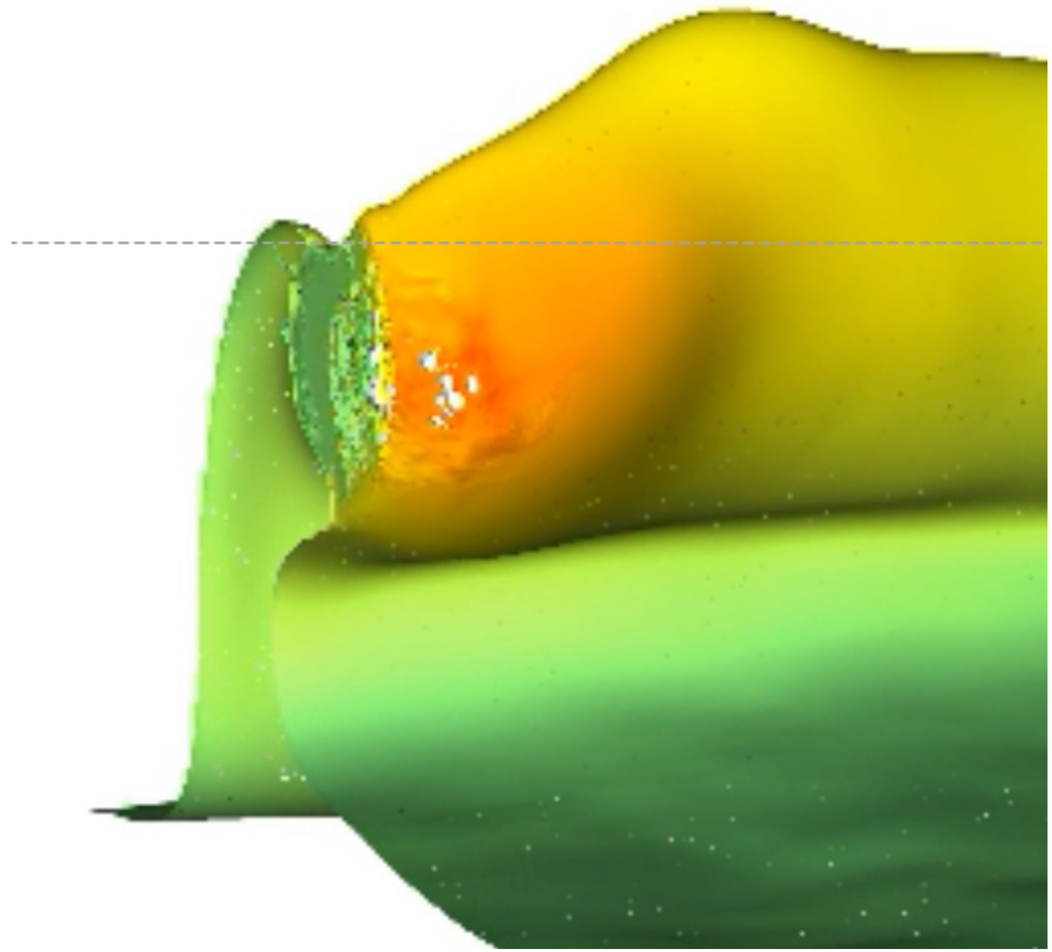
Laminar flow

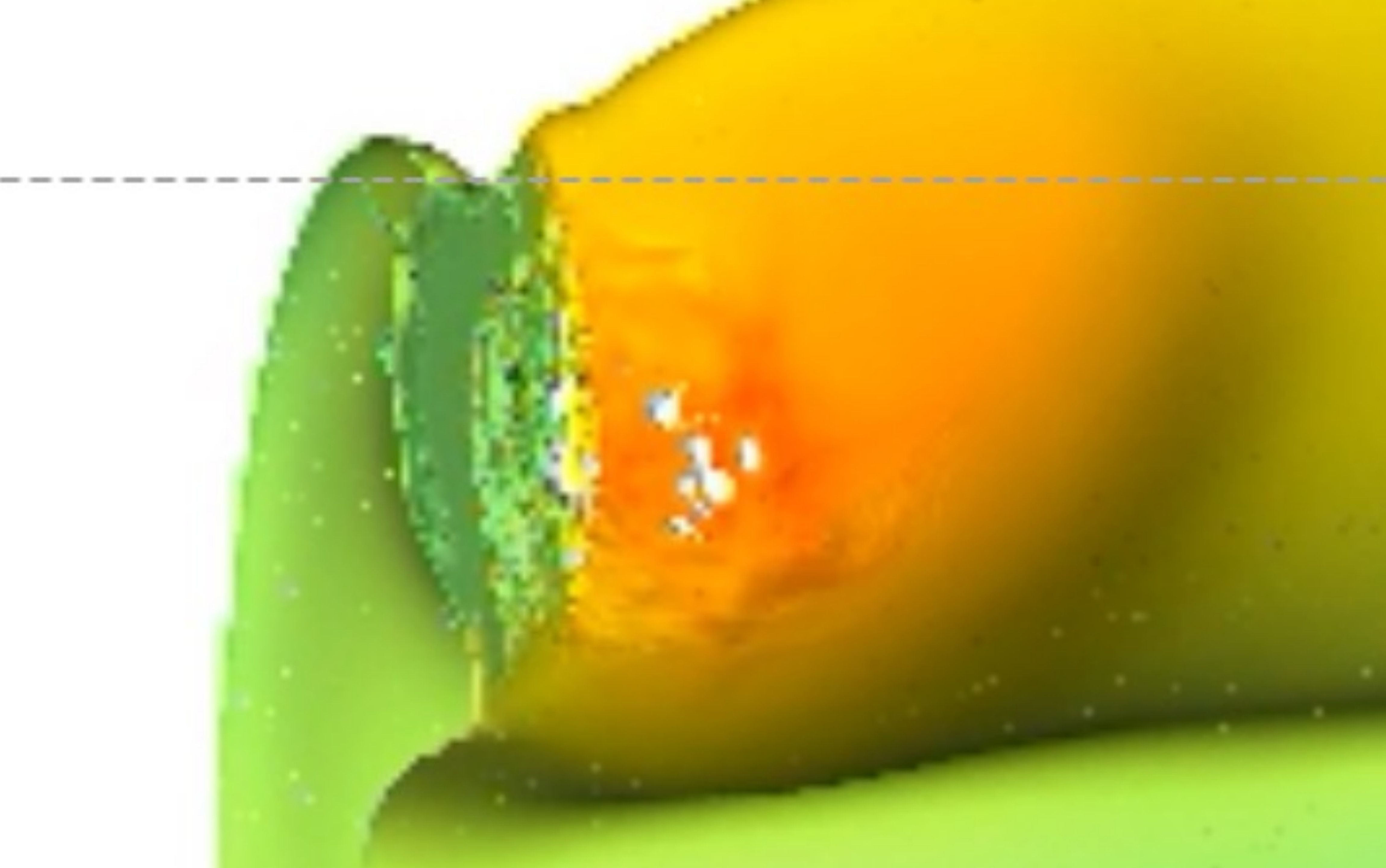
U= 15 m/s

$$We_a = \varrho_a U^2 l_y / \sigma = 40$$
$$Re_a = \varrho_a U l_y / \mu_a = 9{,}700$$
$$Re_l = \varrho_l U h / \mu_l = 300$$

The liquid sheet close to the side wall deforms faster, thinning rapidly until perforation. The hole expansion forms ligaments that eventually fragment.

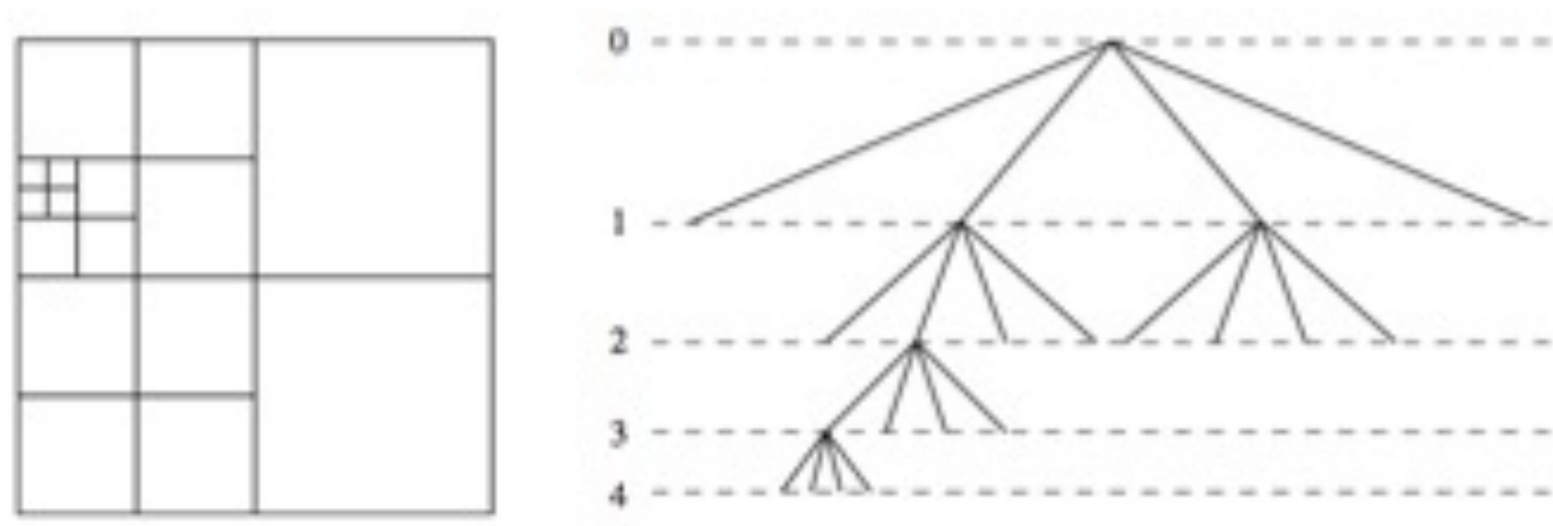






Ligament formation is similar to experiment.
We still need more computer power to determine the droplet size.

Efficient numerical methods: the octreee grid.



The octree grid

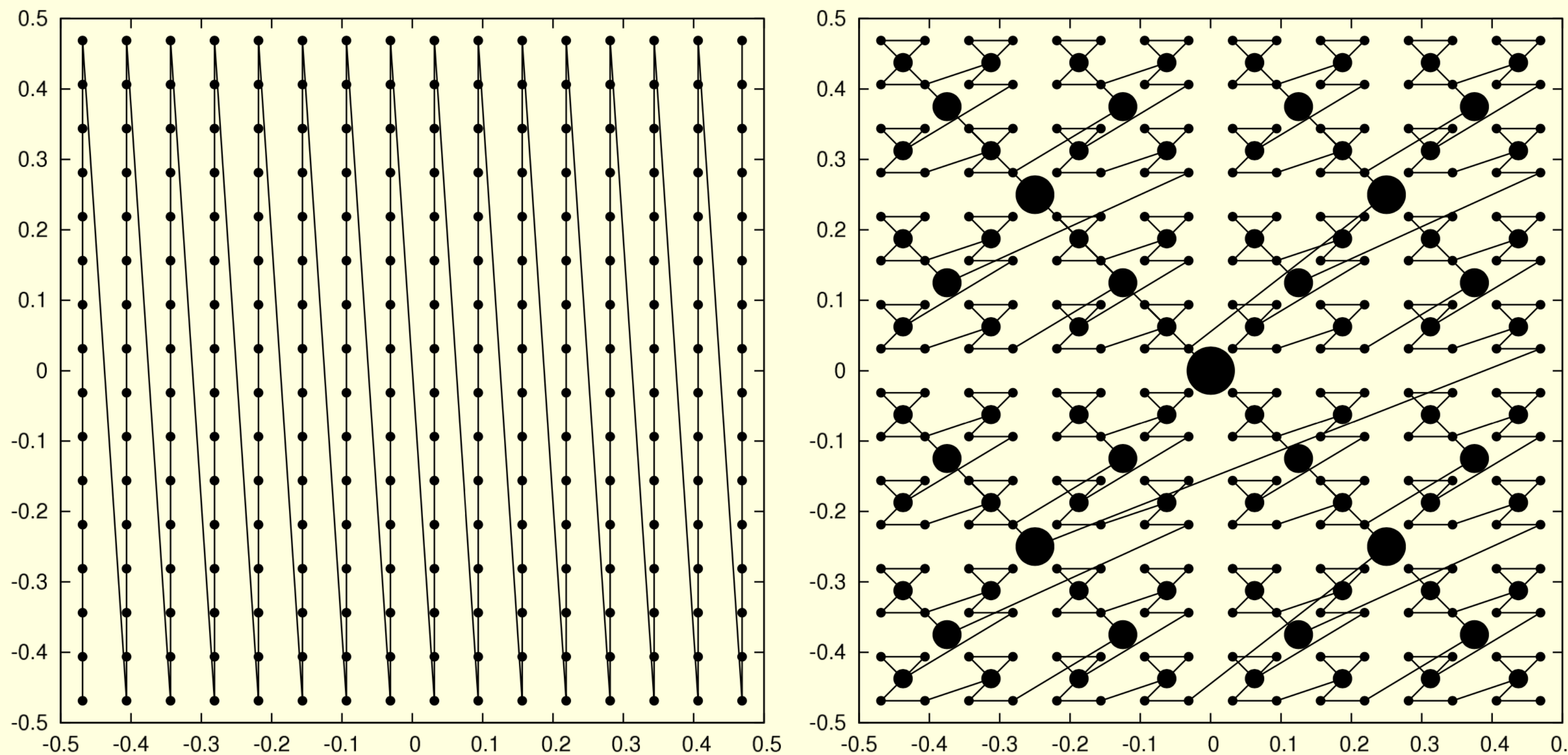
Considerable CPU time can be gained by using adaptive grids.

In 2003 S. Popinet introduces Gerris, an octree code using the "forest of trees" parallelization method.

However massive parallelisation with Gerris was difficult.

Around 2016 Popinet releases a multiphase version of Basilisk, a new octree code with much better parallel performance. The forest of tree approach is replaced by space-filling curve

Memory accesses Cartesian/quadtree



Cartesian, column by column

quadtree, Z-ordering

As a result, we have a very efficient, massively parallel, adaptive method.

Add massive computers


富岳
FUJITSU


summit
IBM

Impossible problems

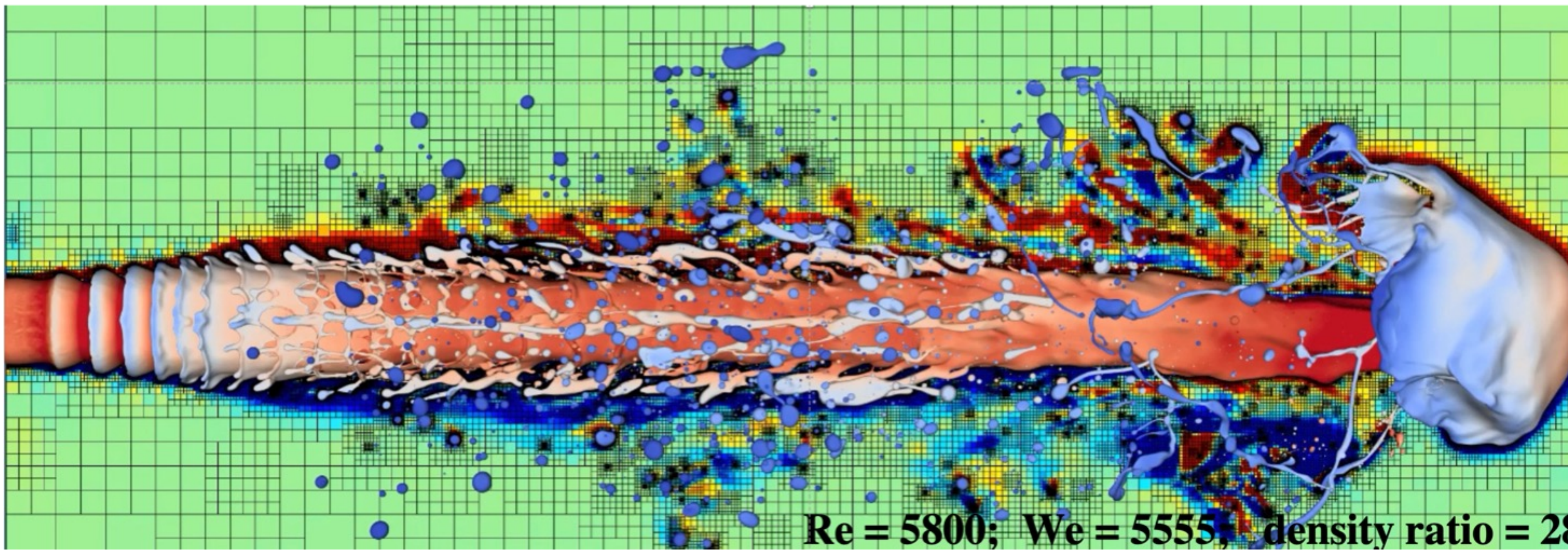
Impossible problems

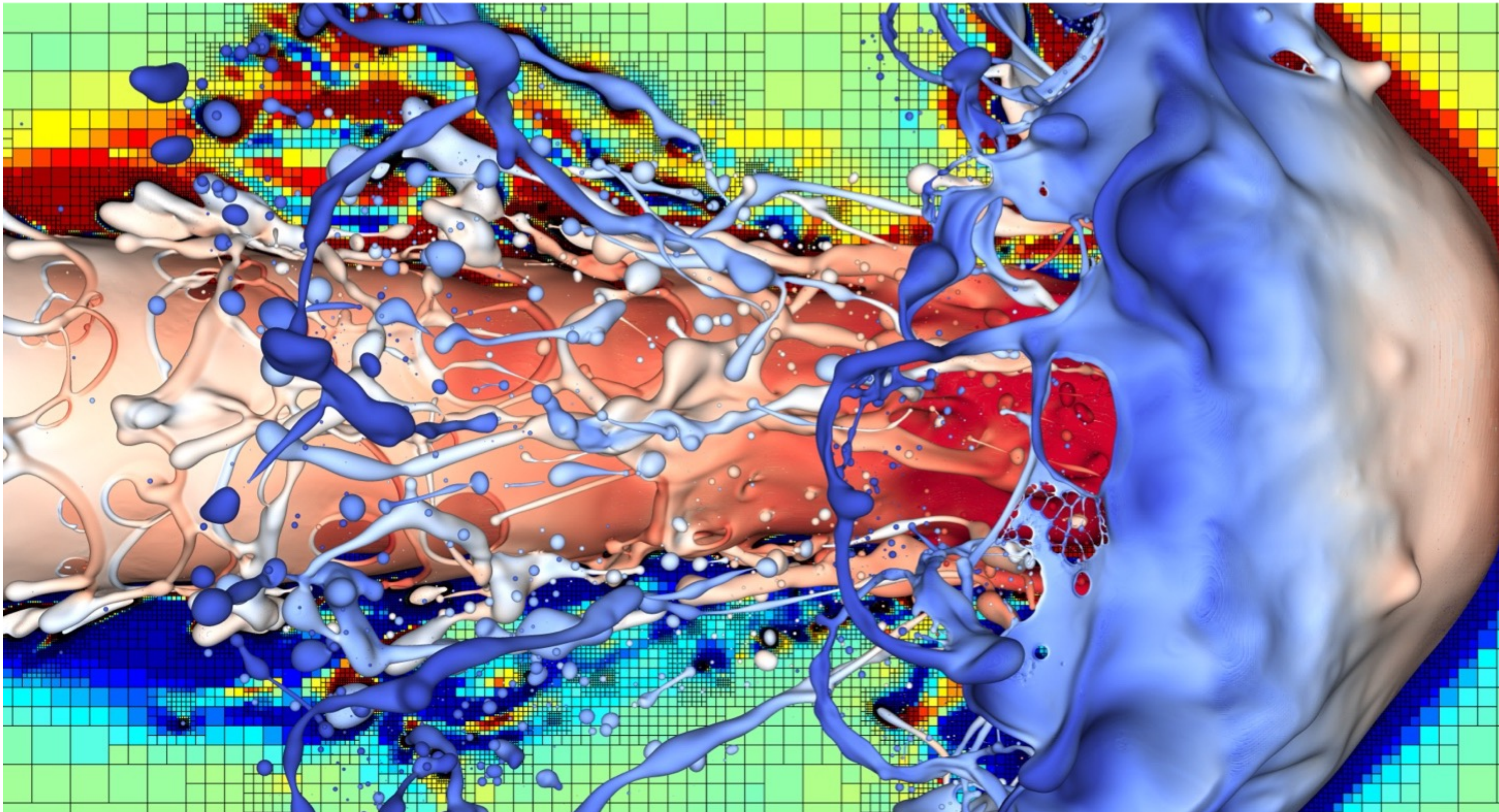
Thin liquid sheets: too thin, nanometer scale
compared to meter scale experiments or industrial processes

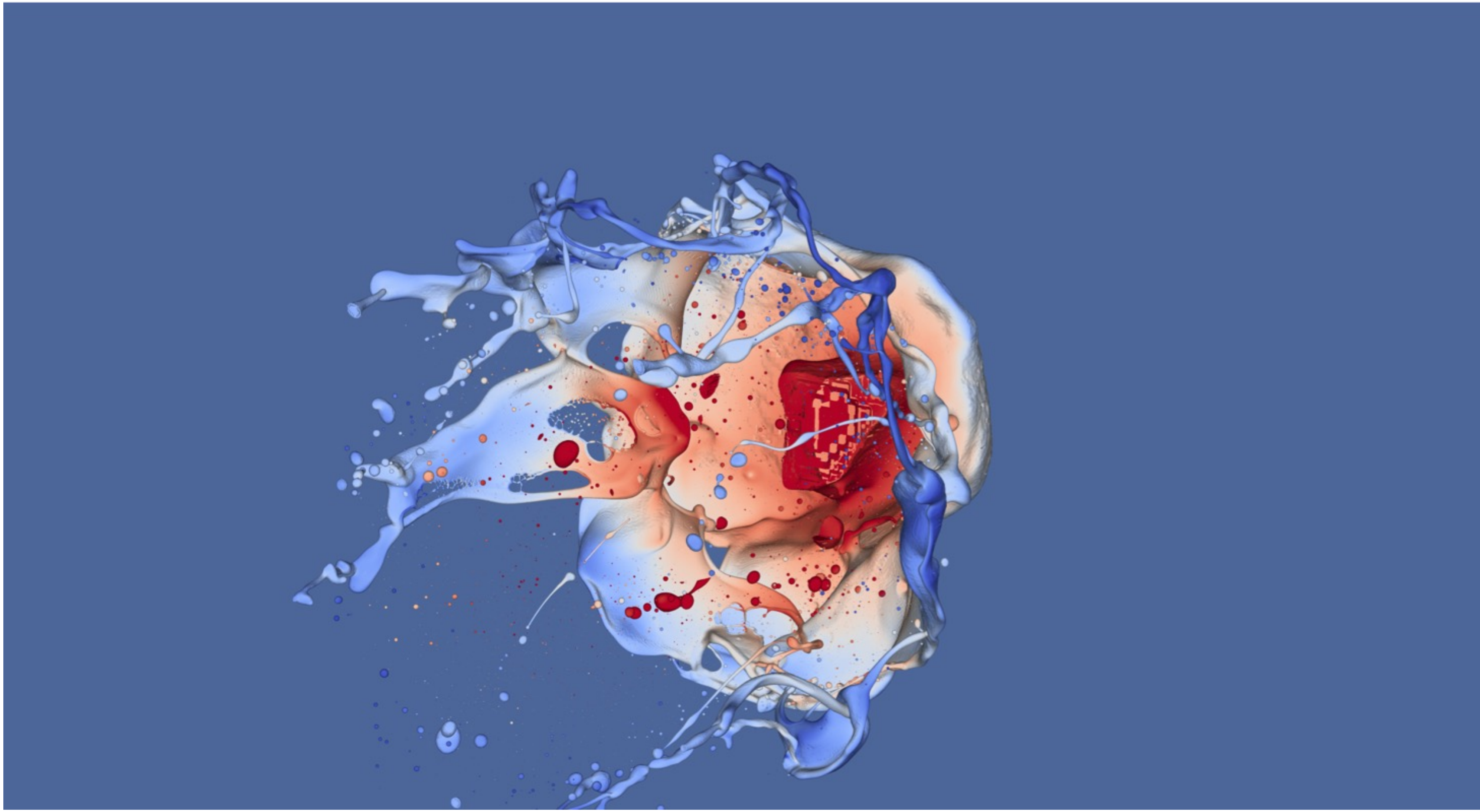
Impossible problems

Thin liquid sheets: too thin, nanometer scale
compared to meter scale experiments or industrial processes

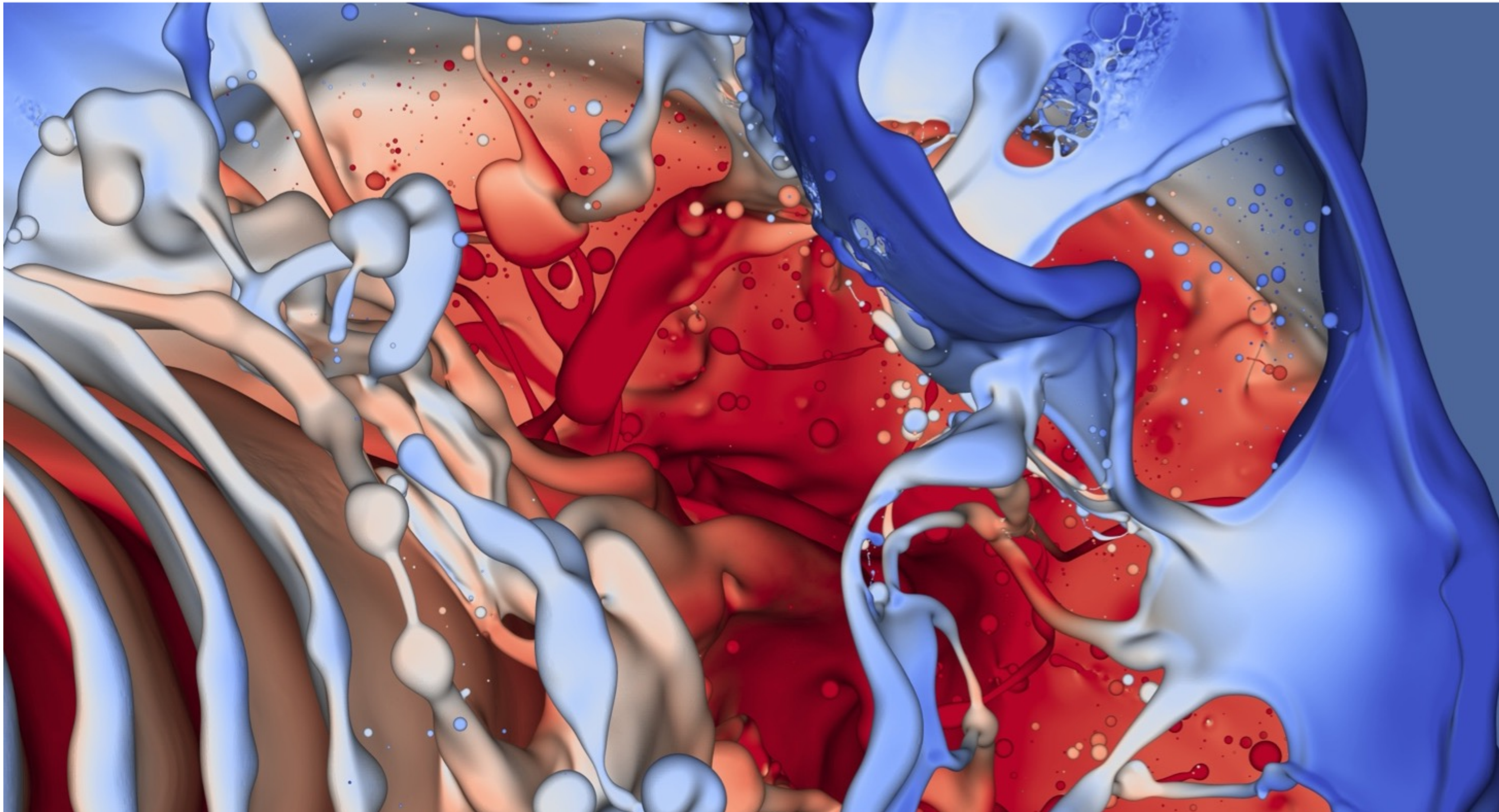
Pulsed jet case


Re = 5800; We = 5555; density ratio = 28

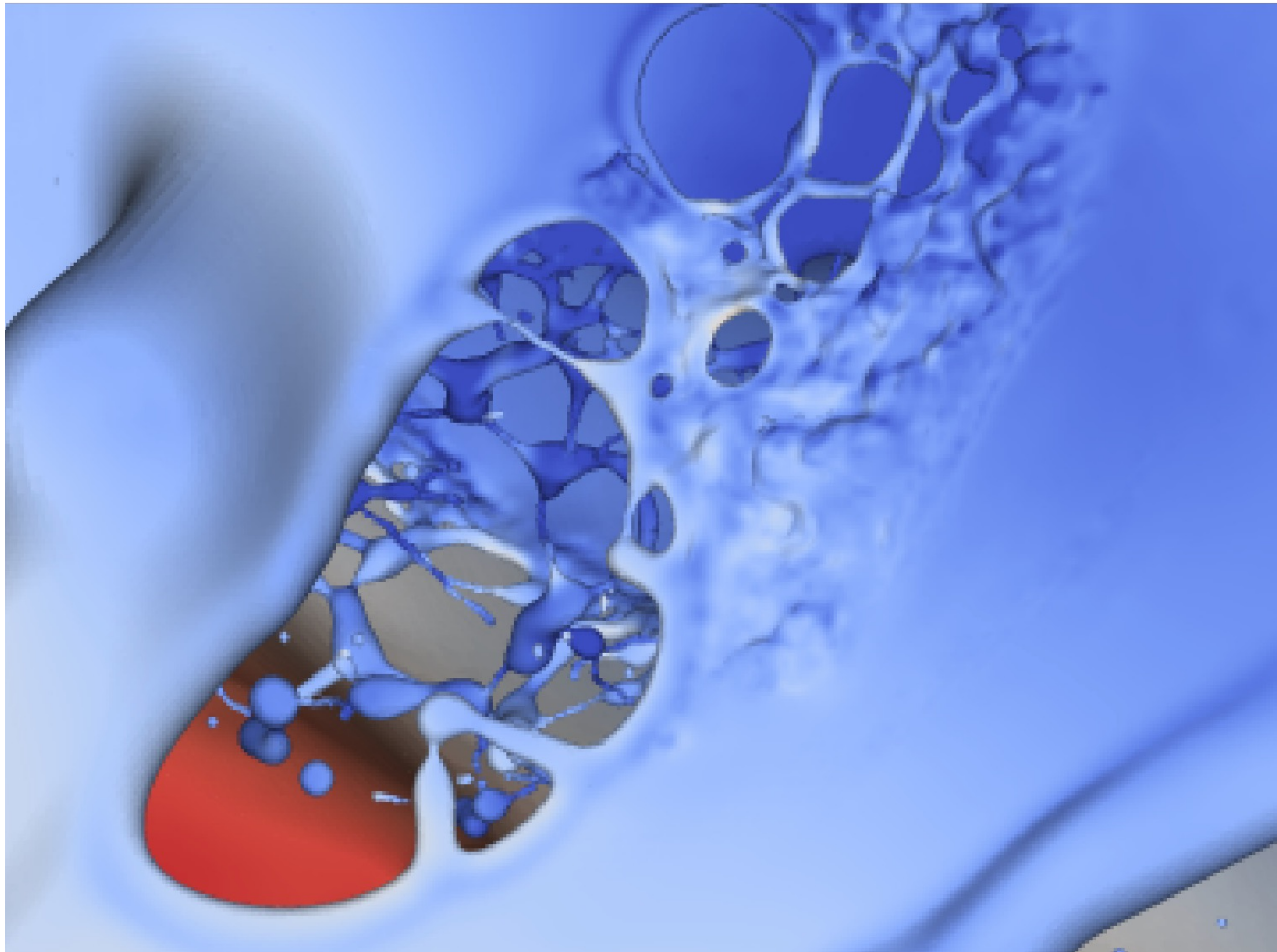




View of the mushroom head from behind



Further zoom on the mushroom head



Further zoom : manifold death

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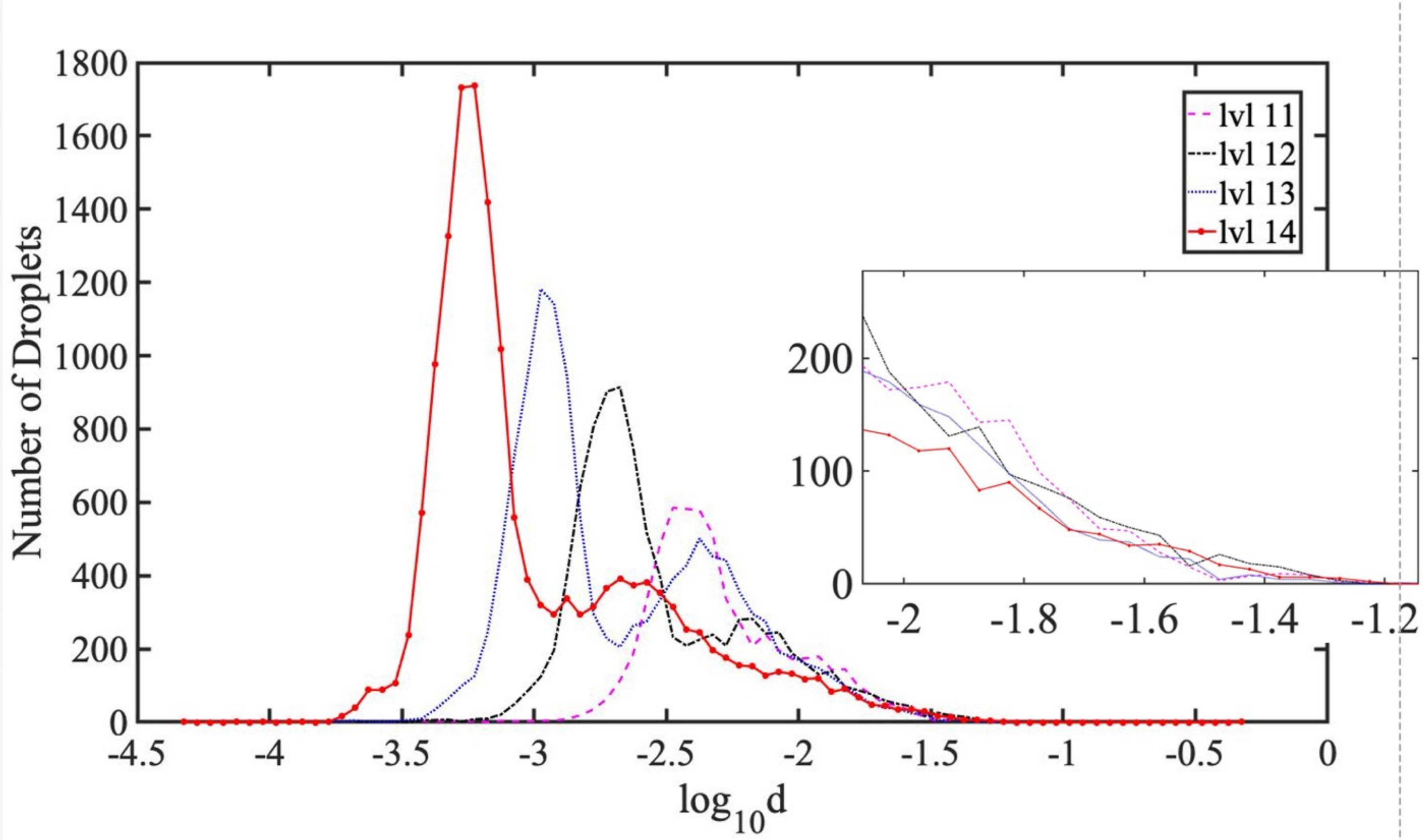
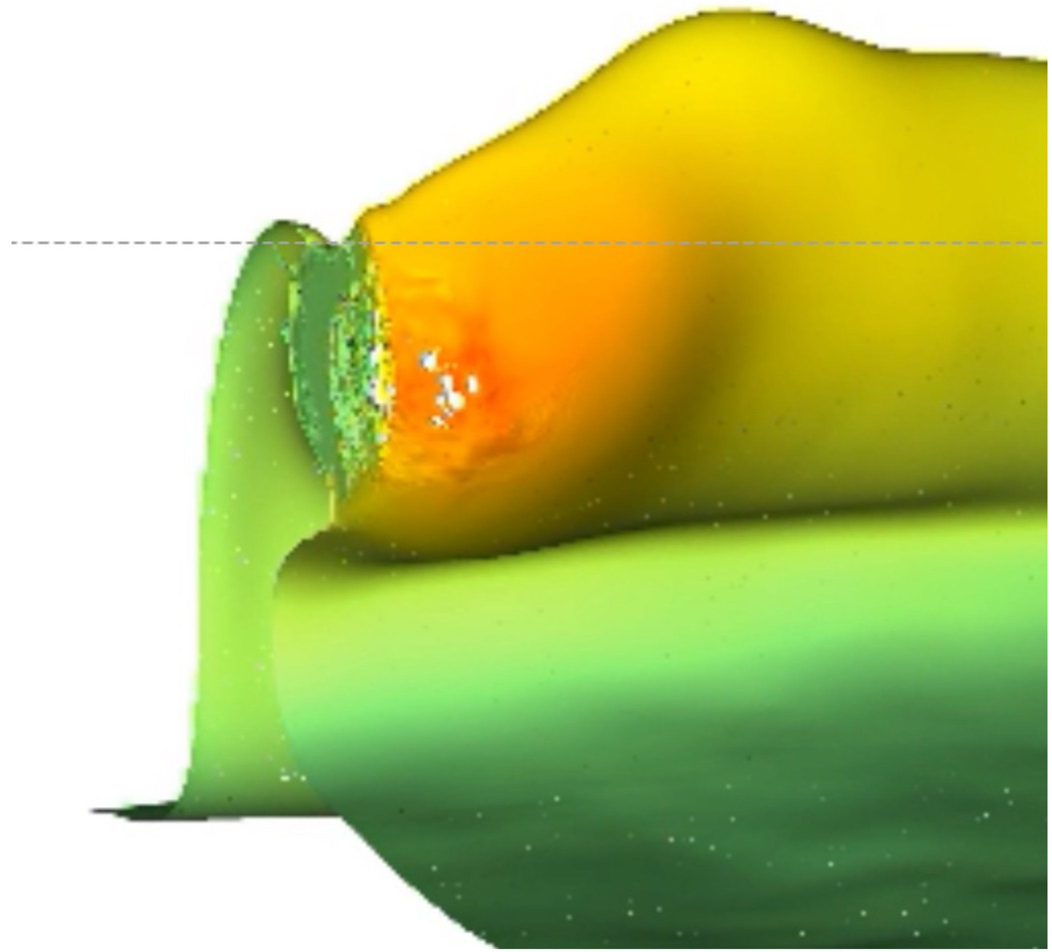
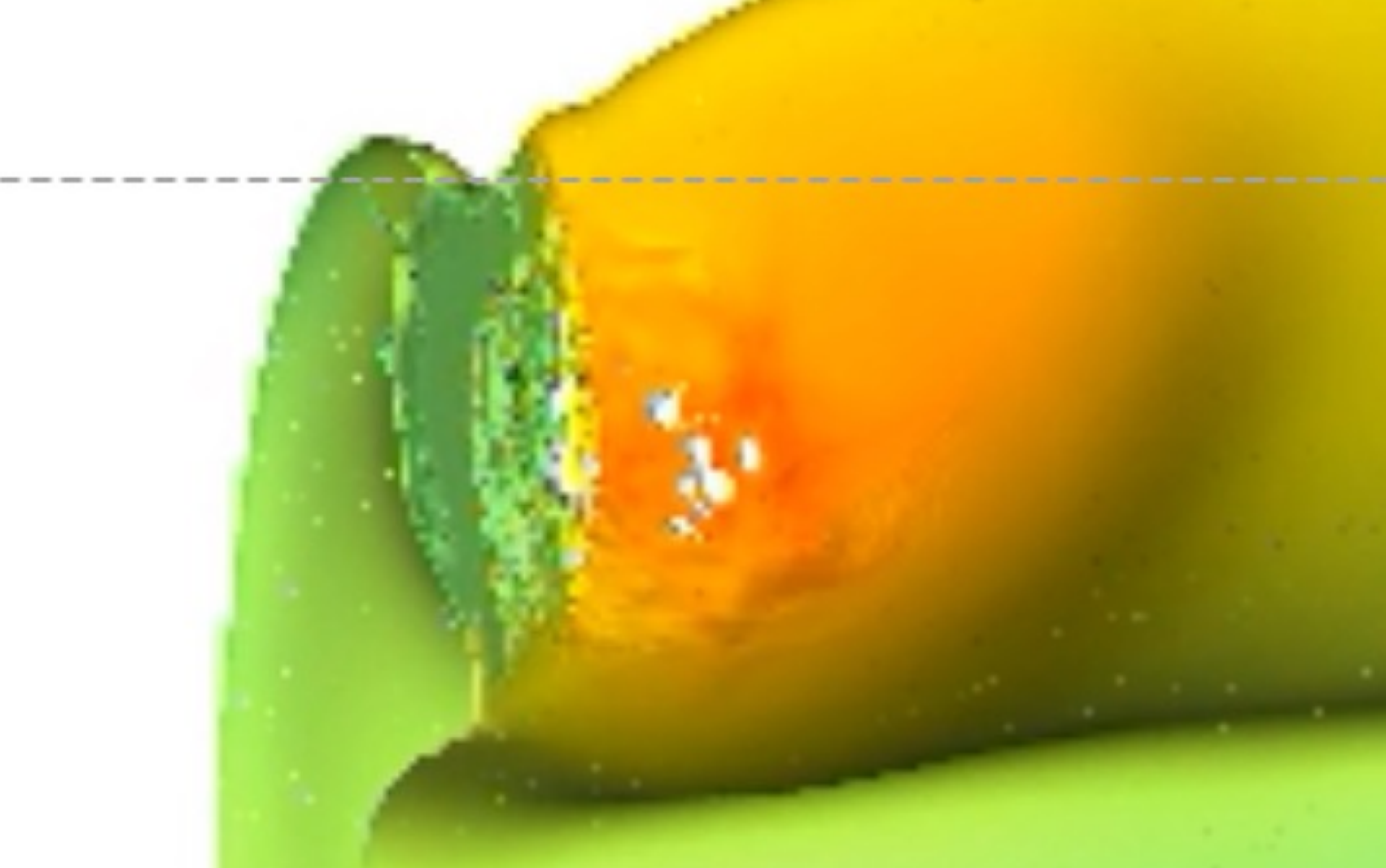
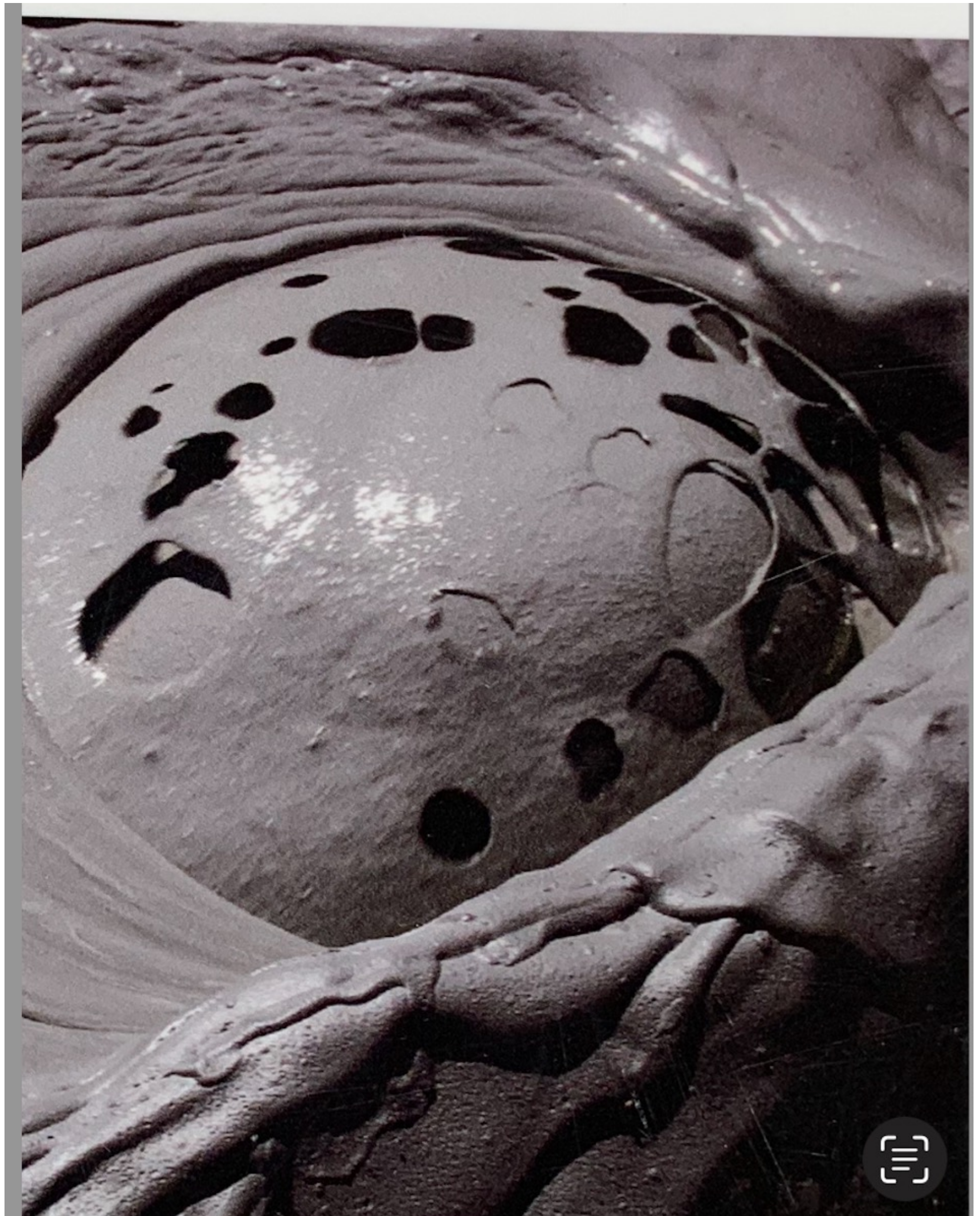


sequence of droplet size PDF with increasing resolution.



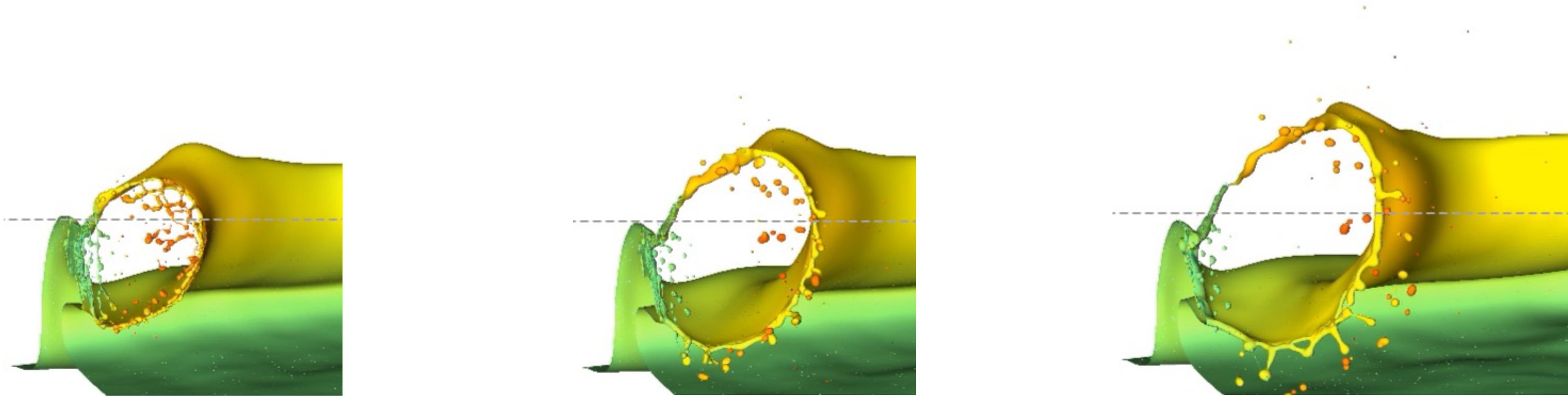




Real life is different

Mud volcano, Salse di Nirano

You can obtain something similar at high resolution



The expanding annular ring is killing the sheet (sheet = 2D manifold).
But it is imperfect: depends on grid size, and is unphysical at the initiation.

A possible solution : the “Manifold Death” procedure.

(with Leonardo Chirco)

Liu Cixin Death Eternal*

In the last volume of Liu Cixin's trilogy, there are multiple intertwinned universes which are each manifolds of dimension D, with 1 < D < 14. War between advanced alien civilizations living in those universes results in each region after the other of any universe being destroyed by ennemy aliens. The alien weapon causes a region of dimension D to be "perforated" . The weapon is a small element of dimension D-1 inserted in it.

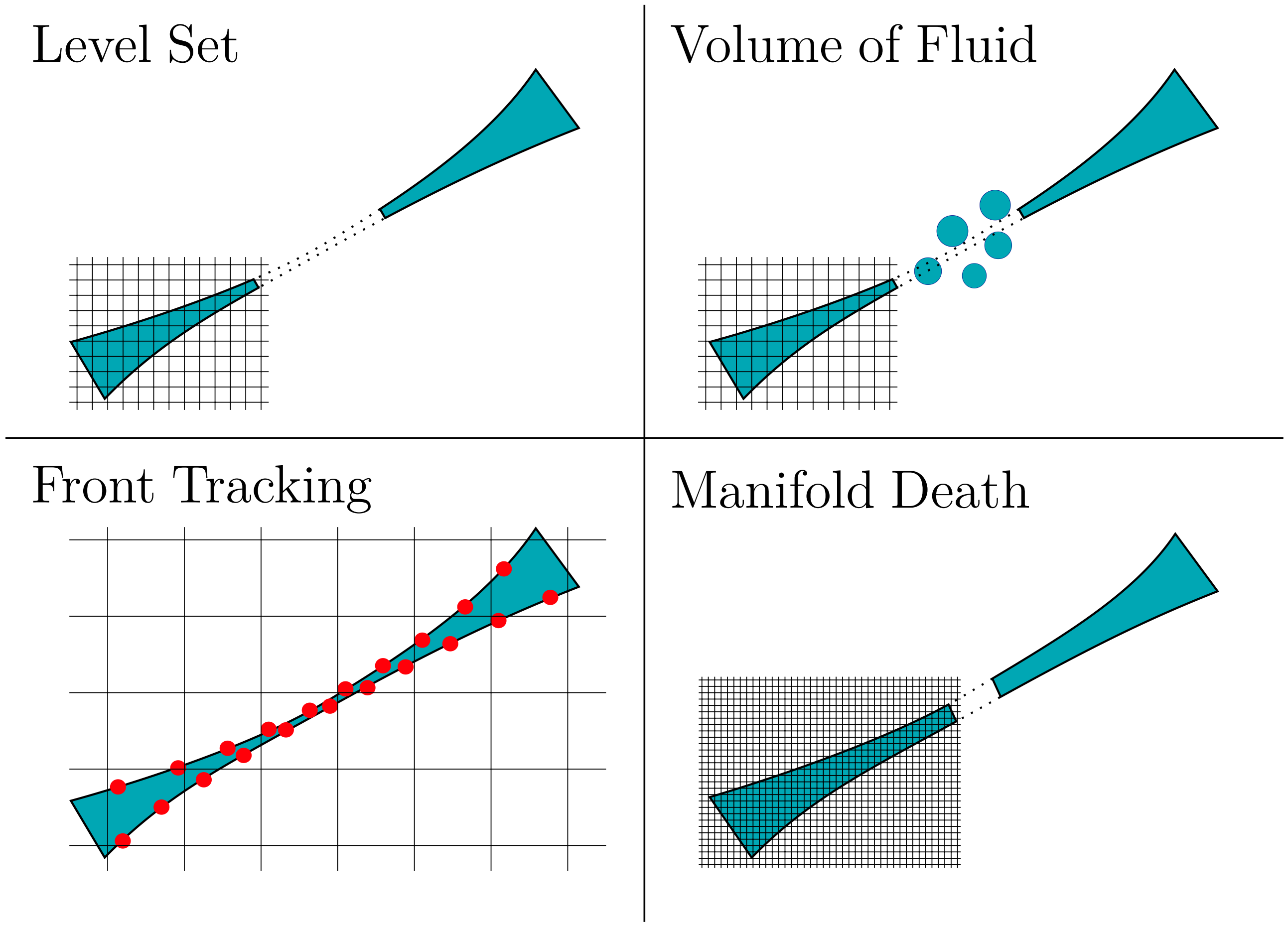
Thus our 3D solar system is destroyed by an attack by a small post-it-sized thin sheet (2D manifold).

The lesson is that destruction of a D dimensional manifold is realized by a D-1 manifold, not a D-2 manifold. Thus a sheet (D=2) is destroyed by an expanding annular ring (D=1) not by a tiny point hole (D=0).

As a result we (Leonardo Chirco and I) call this topological transtion "Manifold Death" (MD). But the term "death" is also used for bursting bubbles.

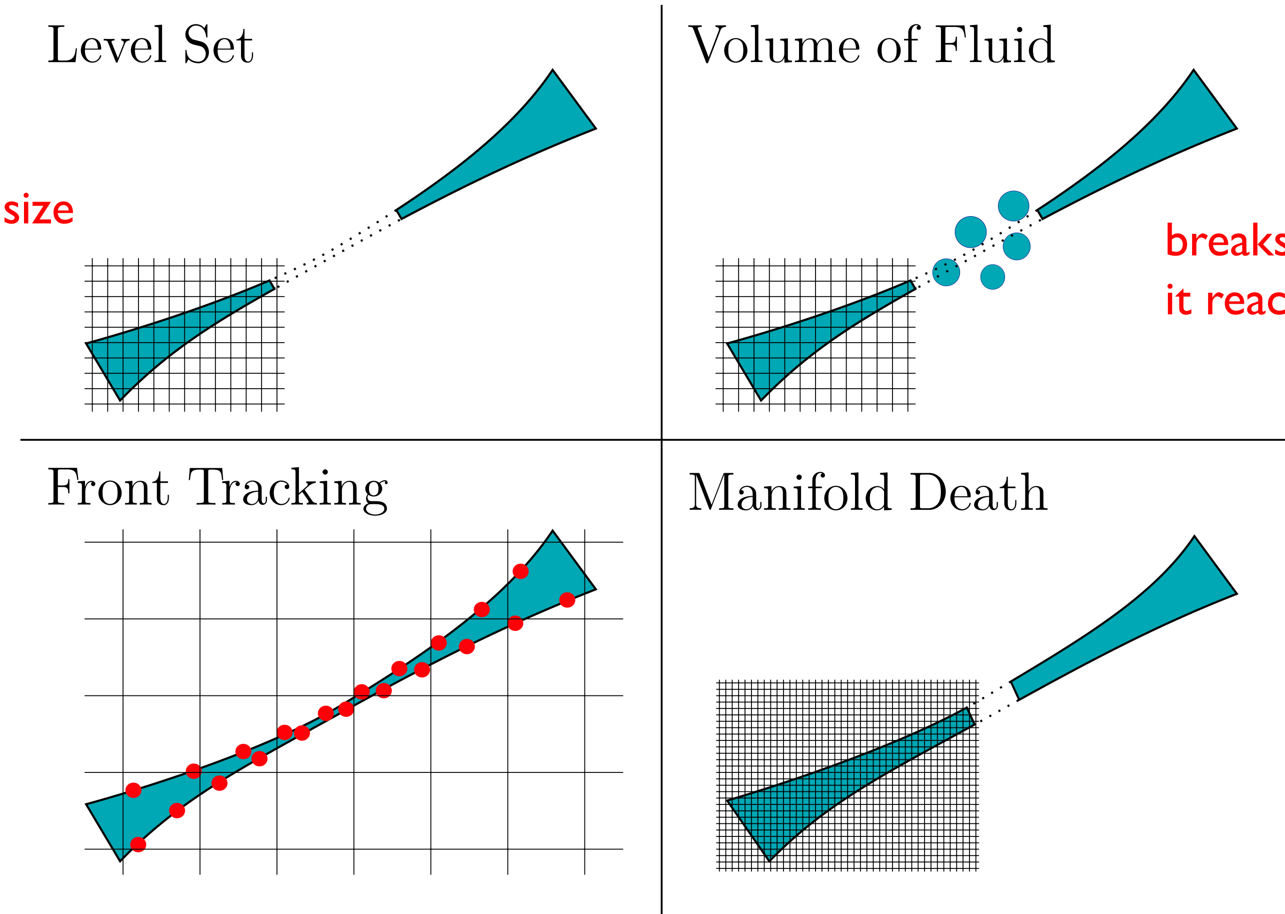
**Remembrance of Earth's Past* (Chinese: 地球往事) trilogy, the whole series is normally referred to as *The Three-Body Problem*

What happens to thin sheets in multiphase flow simulations ?



What happens to thin sheets in multiphase flow simulations ?

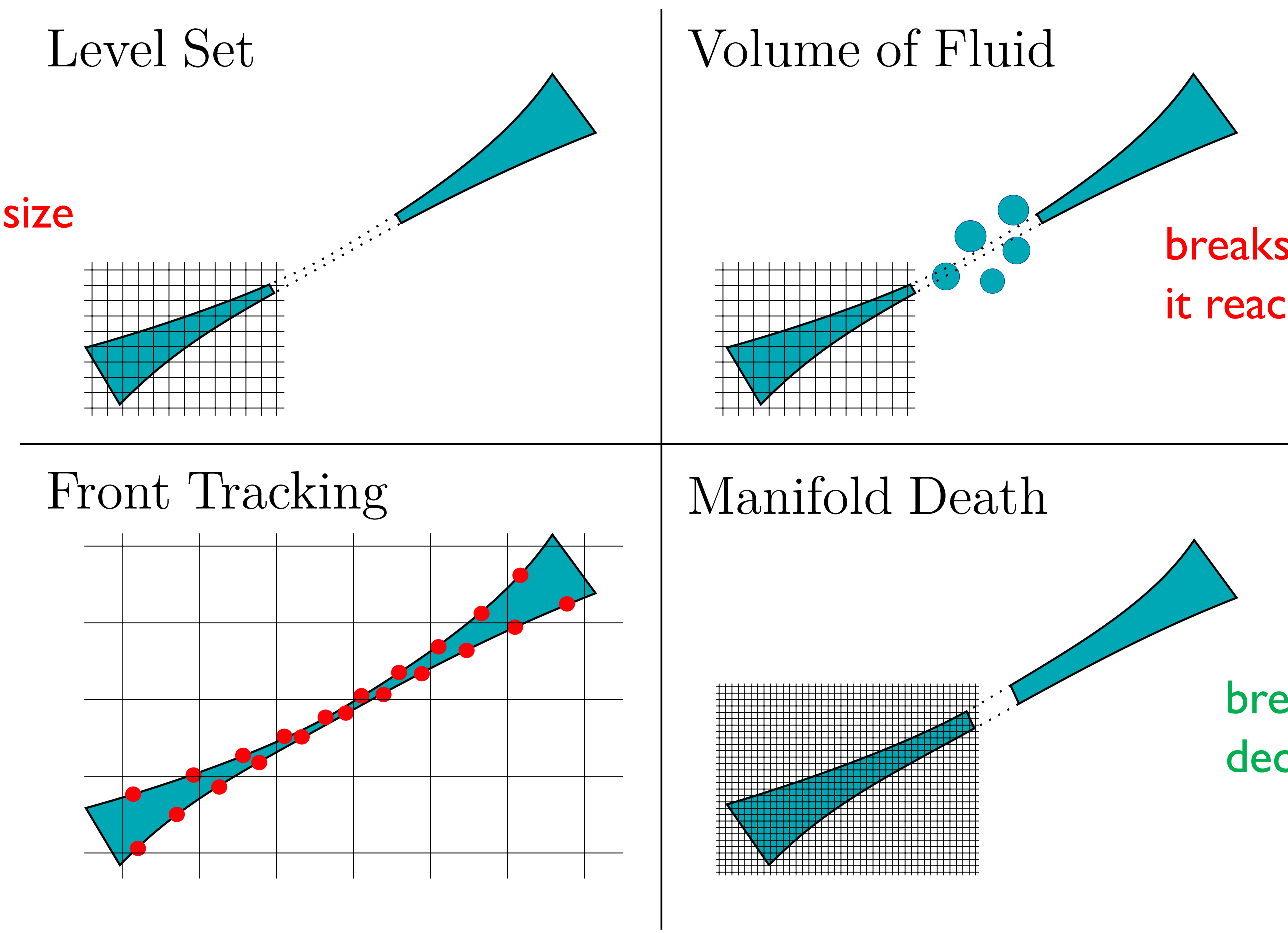
evaporates when
it reaches the grid size



breaks into big droplets when
it reaches the grid size

What happens to thin sheets in multiphase flow simulations ?

evaporates when
it reaches the grid size



breaks into big droplets when
it reaches the grid size

never breaks

breaks when we
decide.

The Navier-Stokes equations must be supplemented with a law that specifies when thin sheets (manifolds) break or “die”.

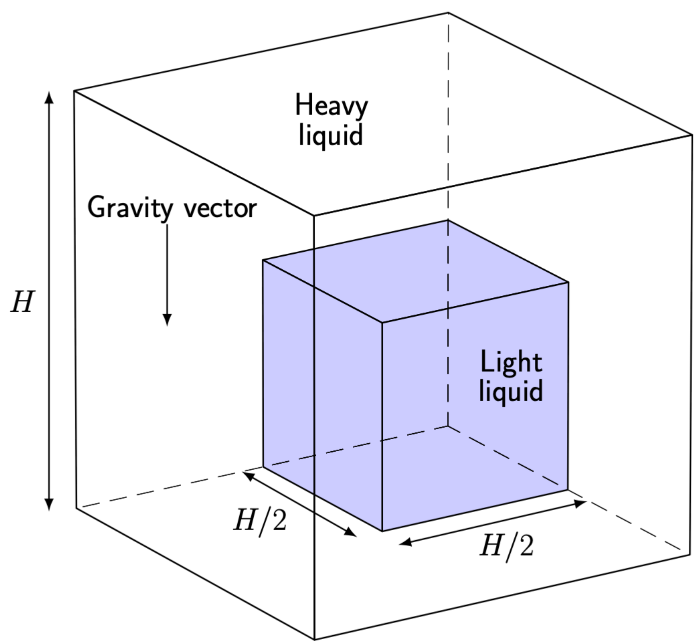


Figure 7: Configuration for the phase inversion test.

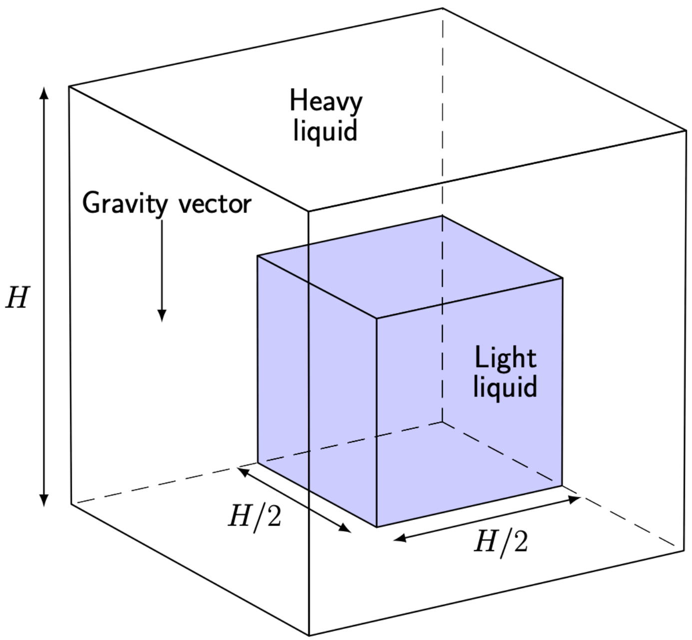
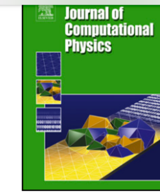


Figure 7: Configuration for the phase inversion test.



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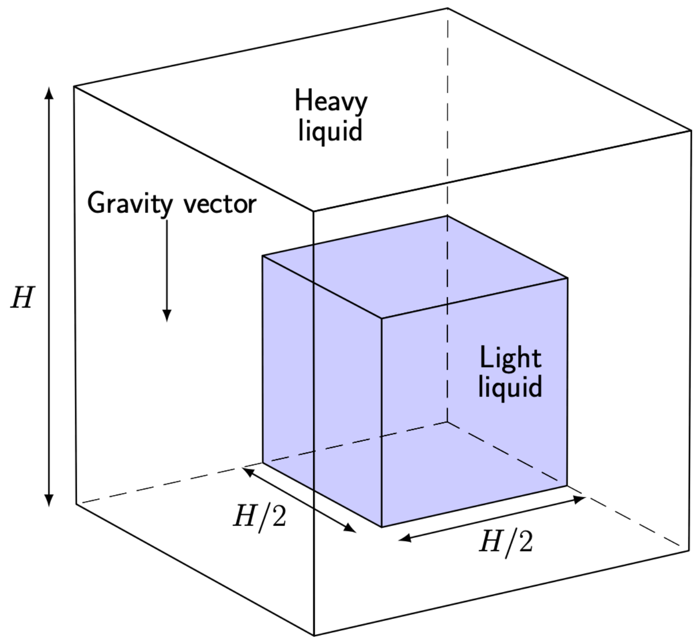
[h] Institut Universitaire de France, Paris, France



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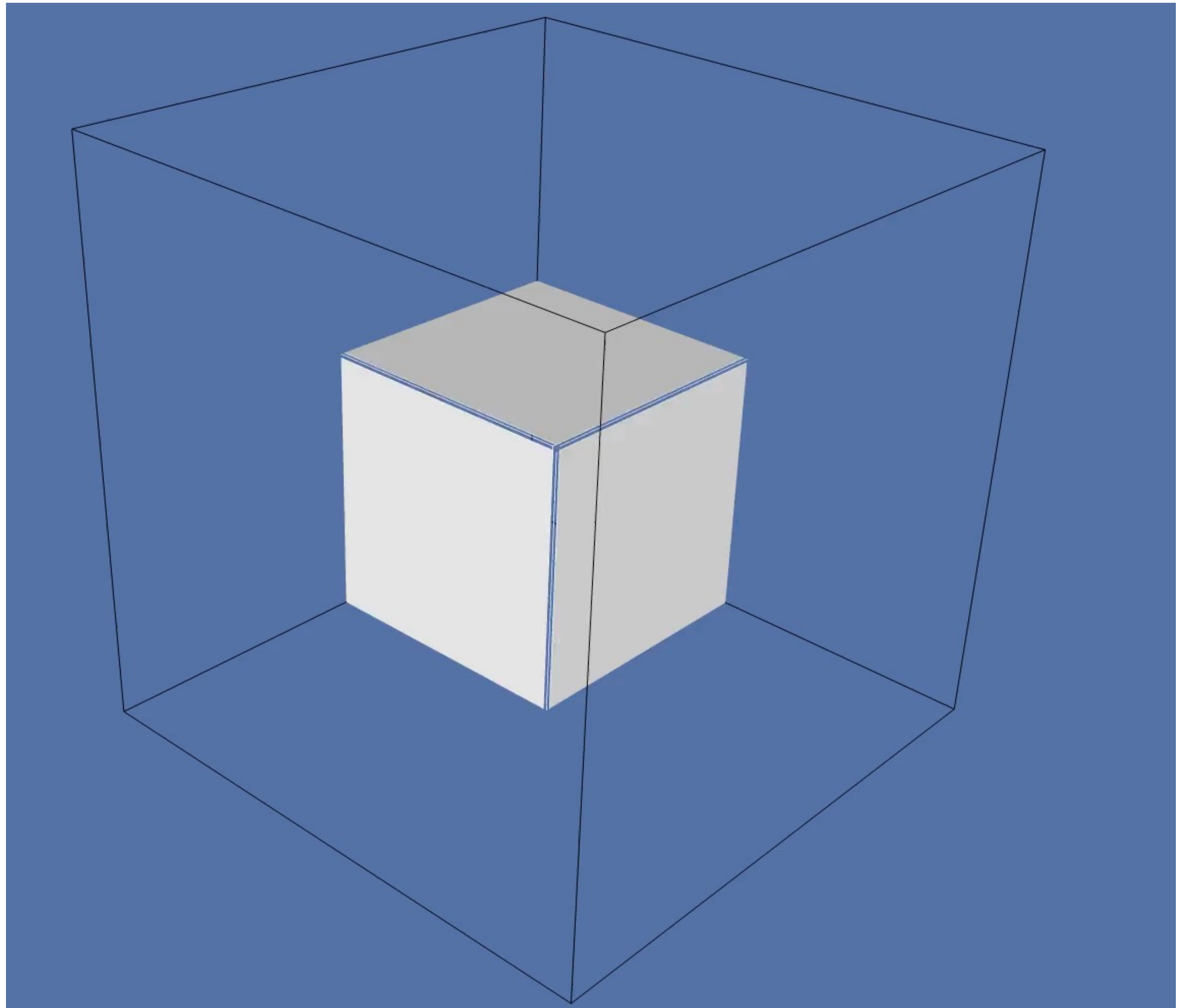
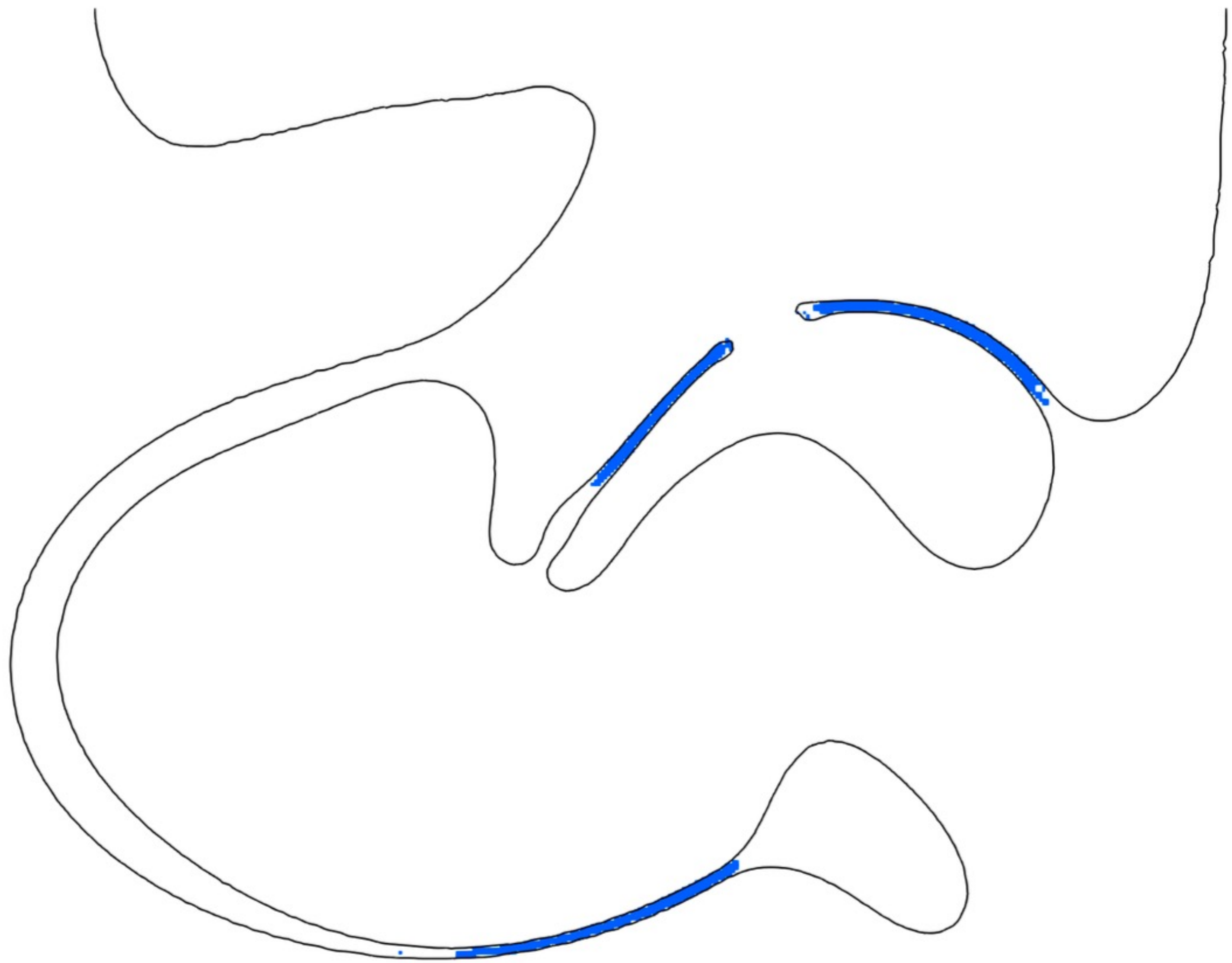
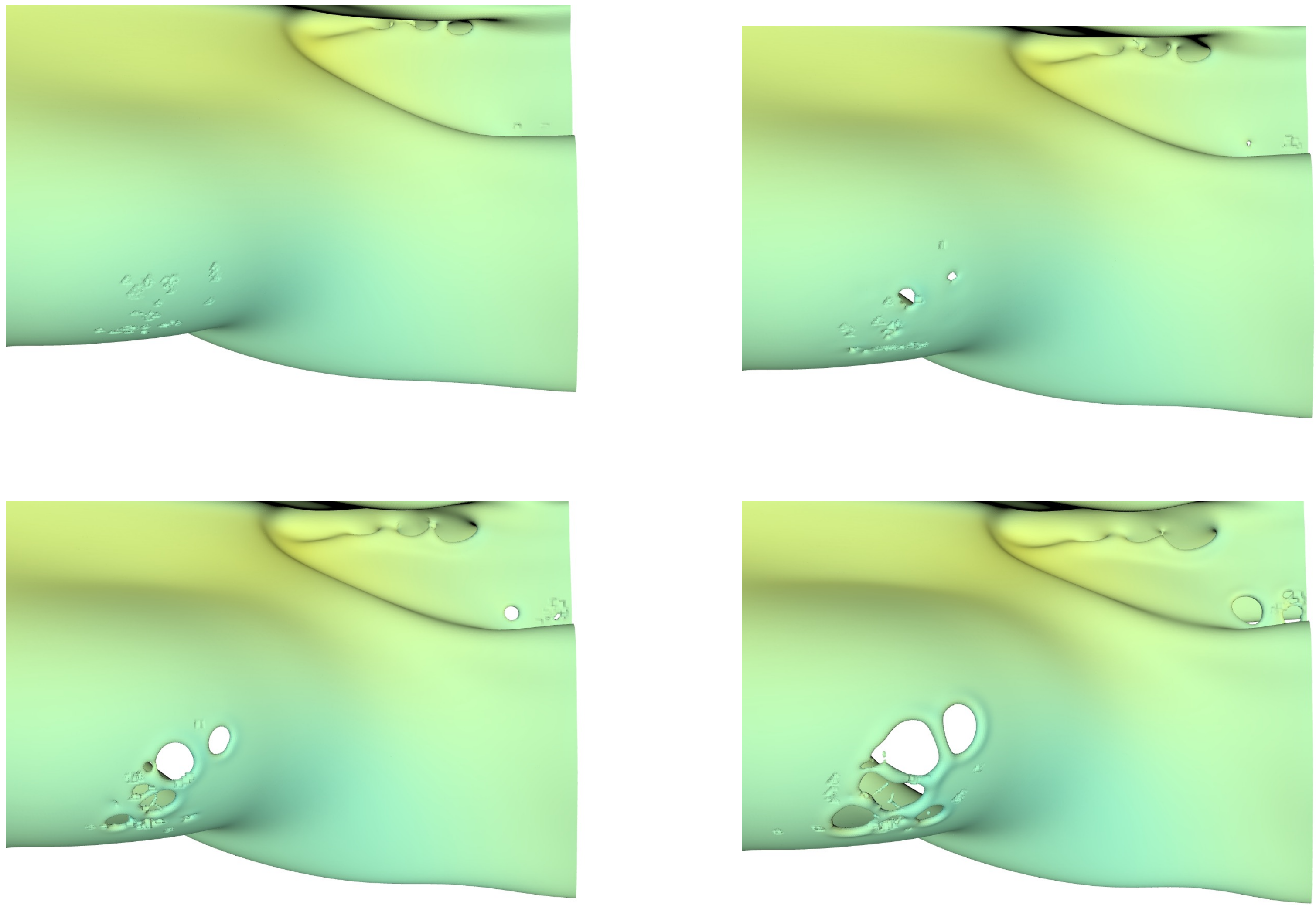
New case with smaller Reynolds numbers

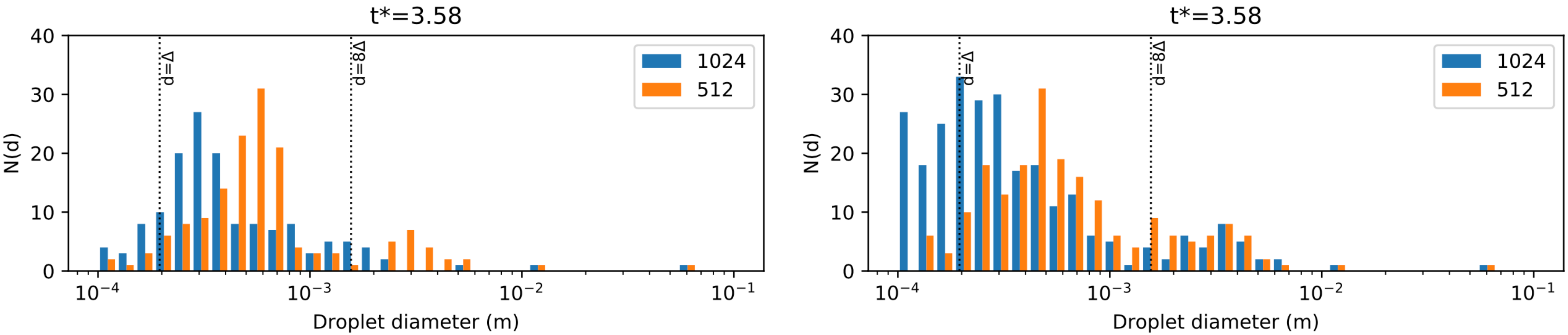
Results for case B



Sheet detection

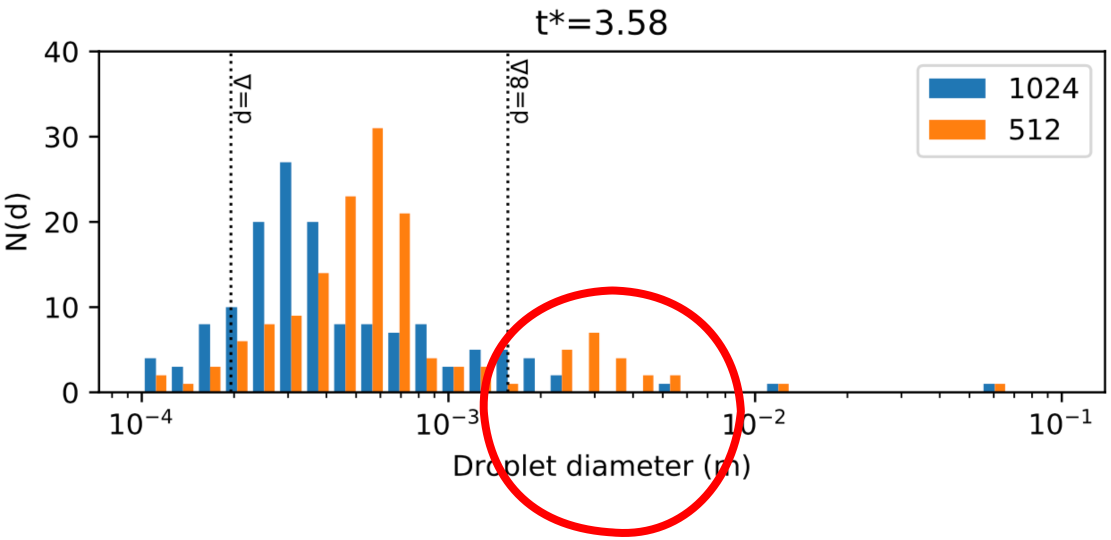




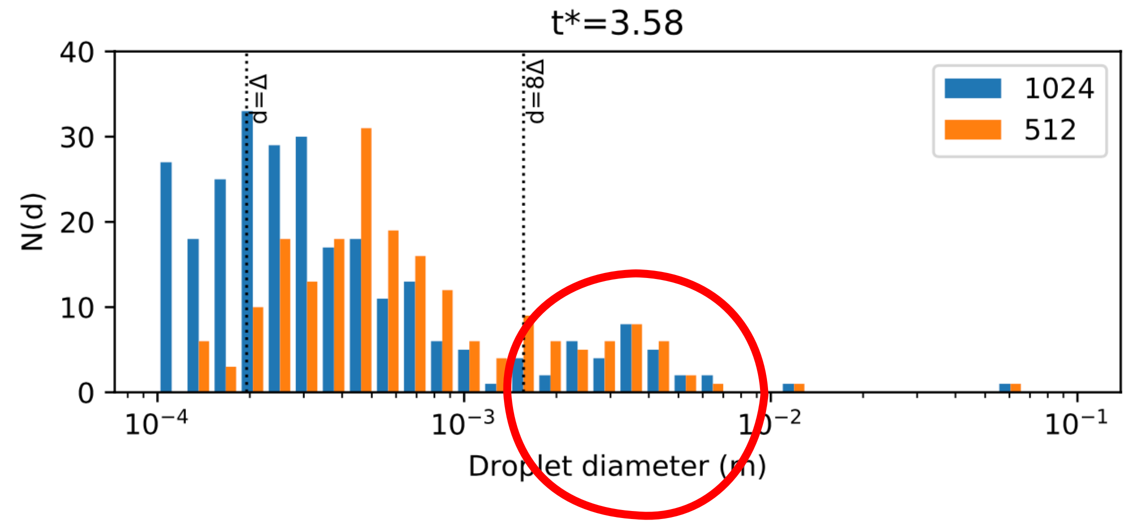


Droplet size distributions in the phase inversion test case

left: without manifold death right: with manifold death



Not converging



Converging

Droplet size distributions in the phase inversion test case

left: without manifold death right: with manifold death

Conclusion

the story of the explorations of complex multiphase solutions of the Navier Stokes equations is only beginning.

The End