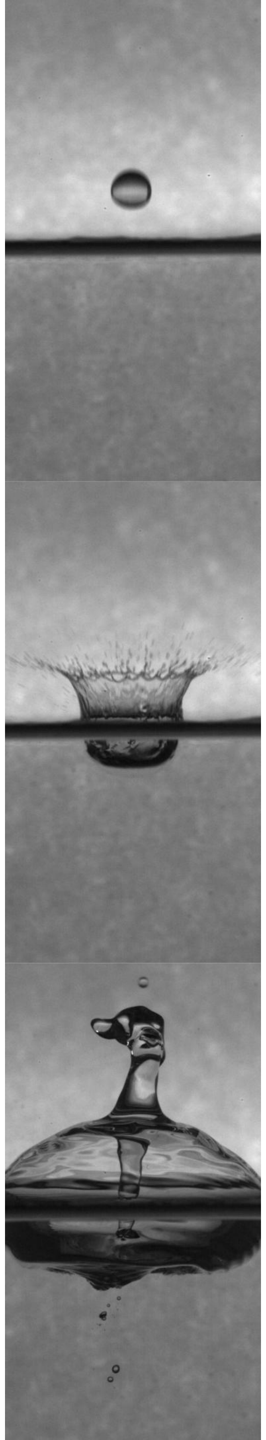

Splashing of high-speed drop impact onto deep liquid pool

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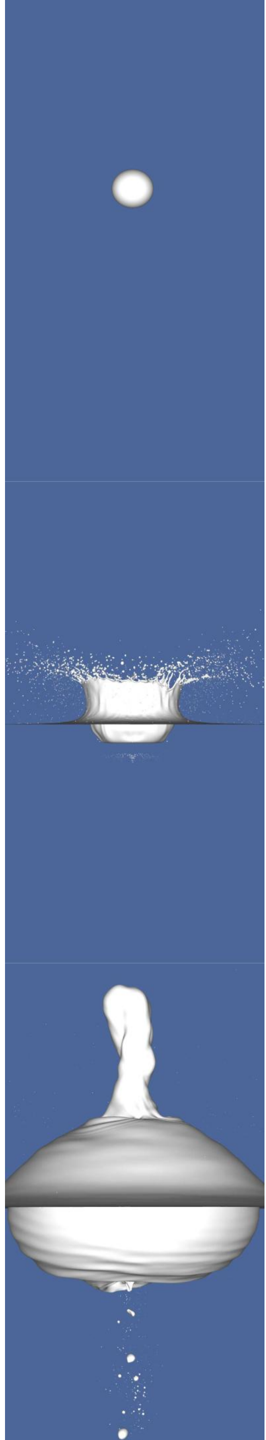
Arts et Métiers Sciences et Technologies

Laboratoire de Mécanique des Fluides de Lille Kampé de Fériet

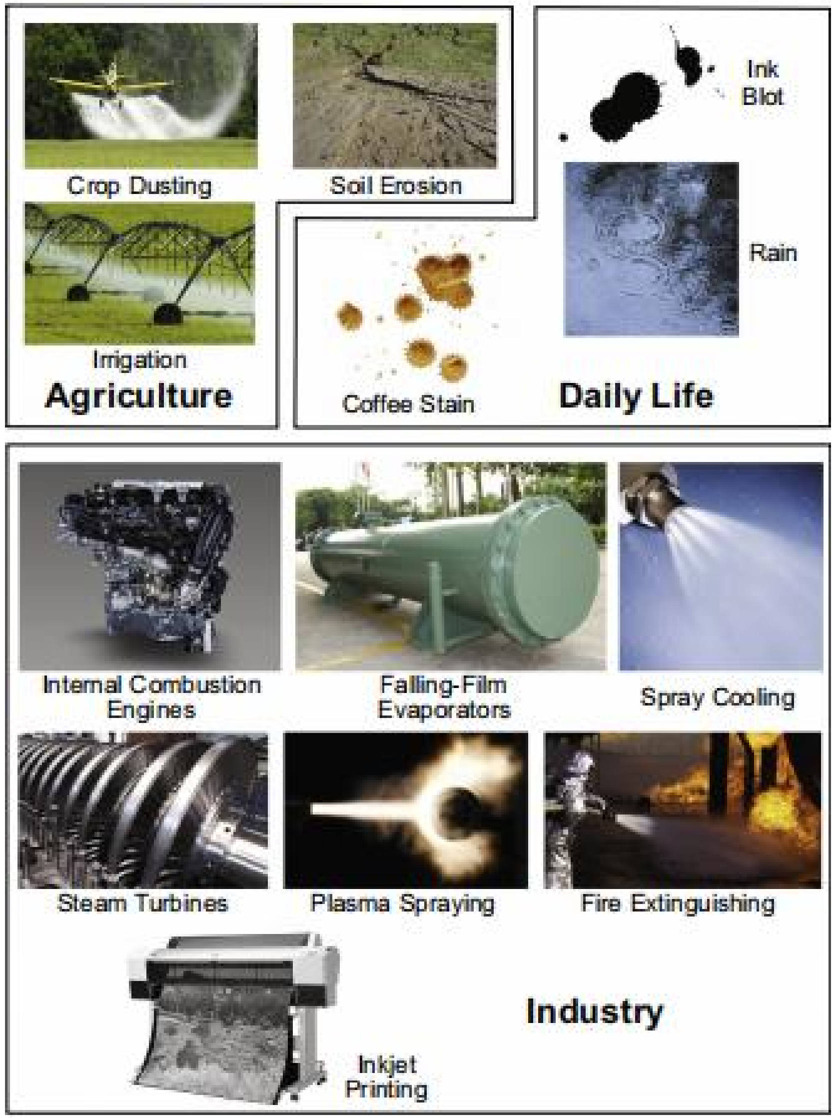
Virginia Tech

BGUM: Basilisk (Gerris) Users' Meeting 2023



Motivation

Application of drop impact



Liang *et al.* (2016)

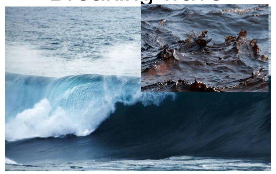
Production of Marine aerosols

Deepwater Horizon oil spill accident in Gulf of Mexico, 2010

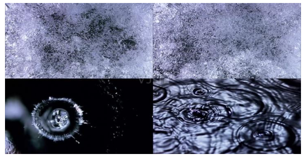
Rainfall

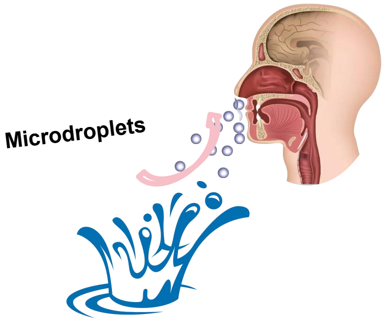
Oil dispersant

Breaking wave



Drop impact





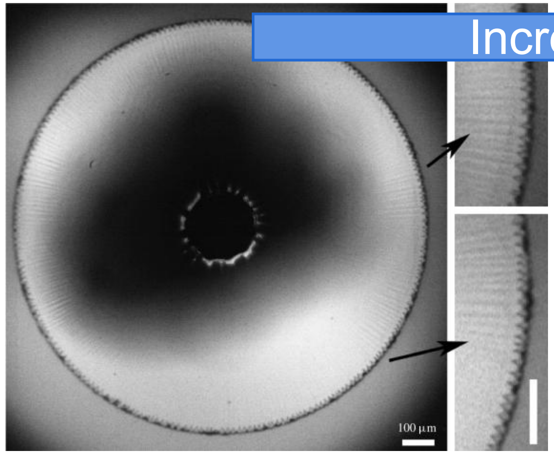
Marine ecosystem

Literature

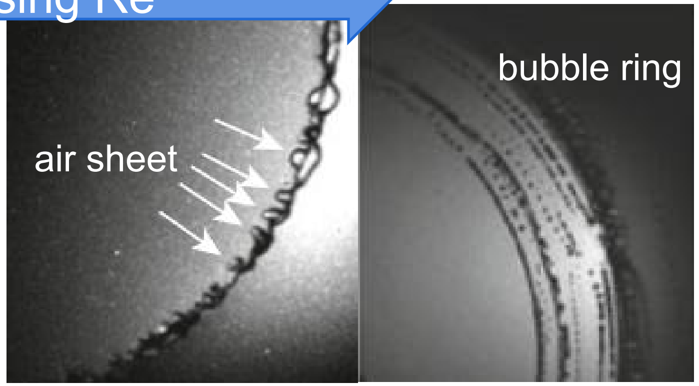
Liquid sheet & Droplet & Bubble

Azimuthal instability and bubble ring entrapment

Increasing Re

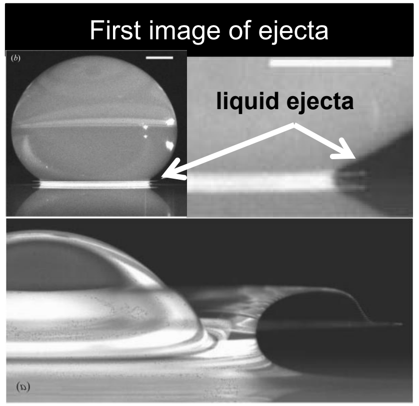


Li et al. (2018)

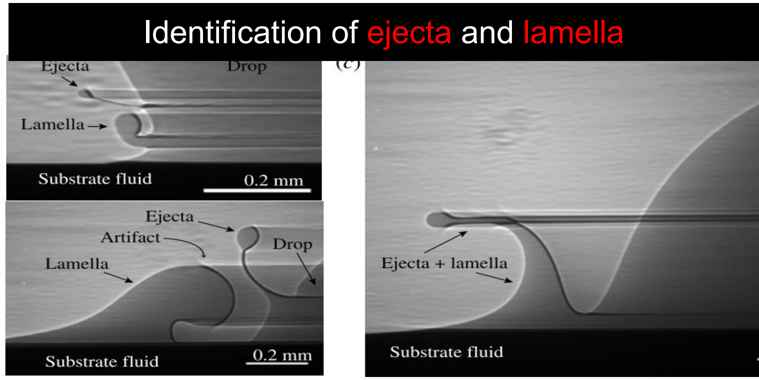


Thoraval et al. (2013)

Multiplicity of jets



Thoroddsen (2002)



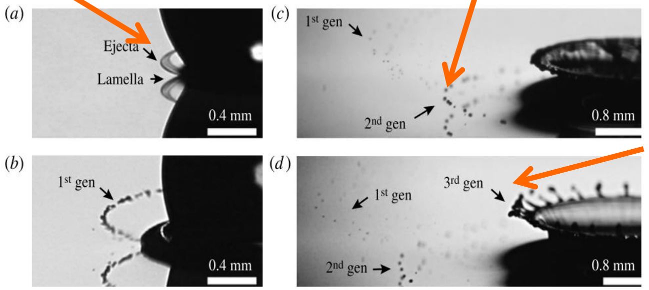
Zhang et al. (2012)

Multiple sources of droplets

Disintegration of ejecta sheet

Disintegration of lamella, or more????

Pinch off from ligaments



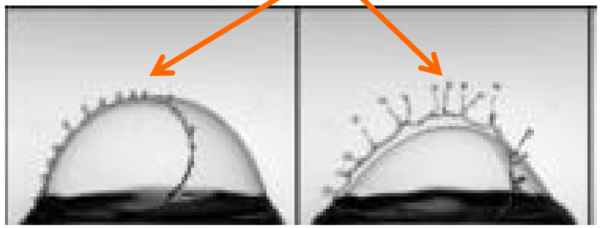
Zhang et al. (2011)

Droplet shedding from rim of the crown

Rayleigh jet breakup

Castillo et al. (2015)

Bubble bursting aerosols



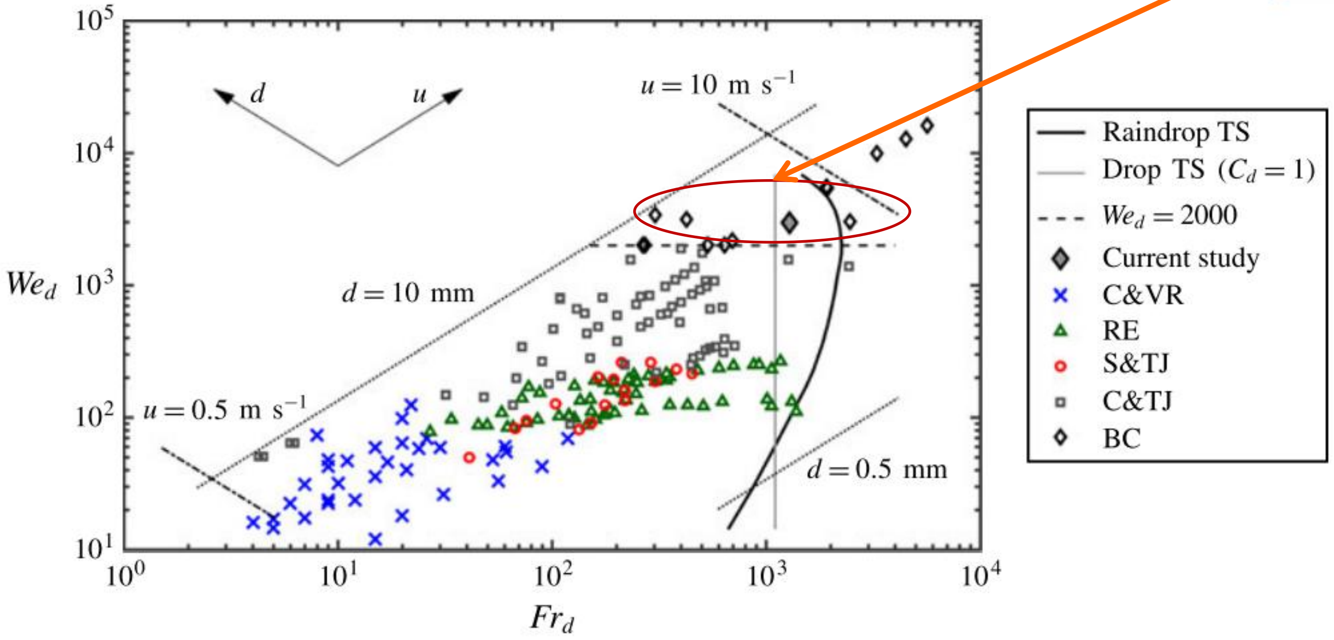
Lhuissier et al. (2012)

Literature

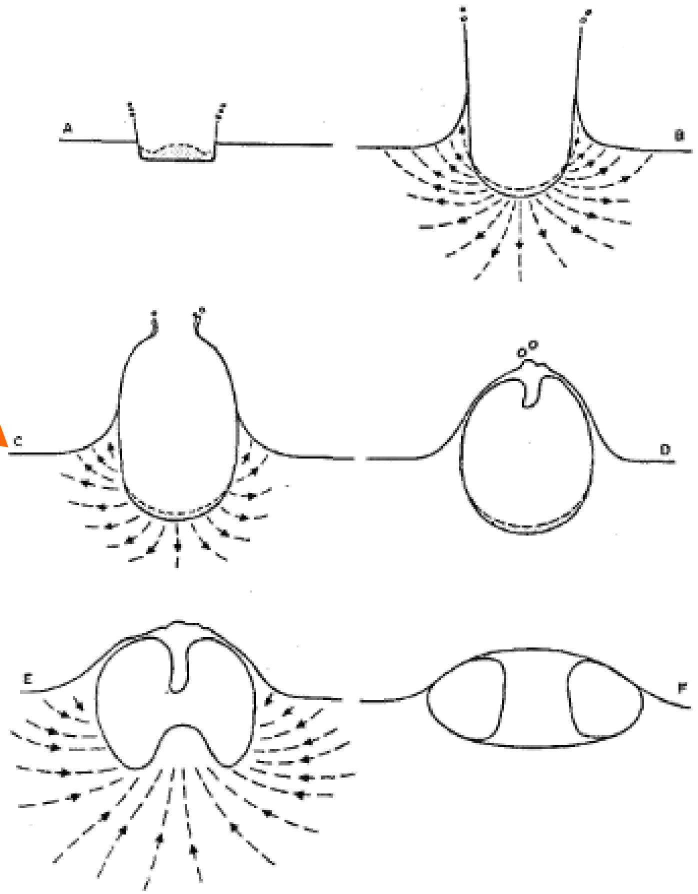
Regime map

(Murphy *et al*. JFM, 2015)

Bubble canopy (BC) regime with crown and large cavity



Various configurations of splashing reported in the literature according to the *We* and *Fr* numbers



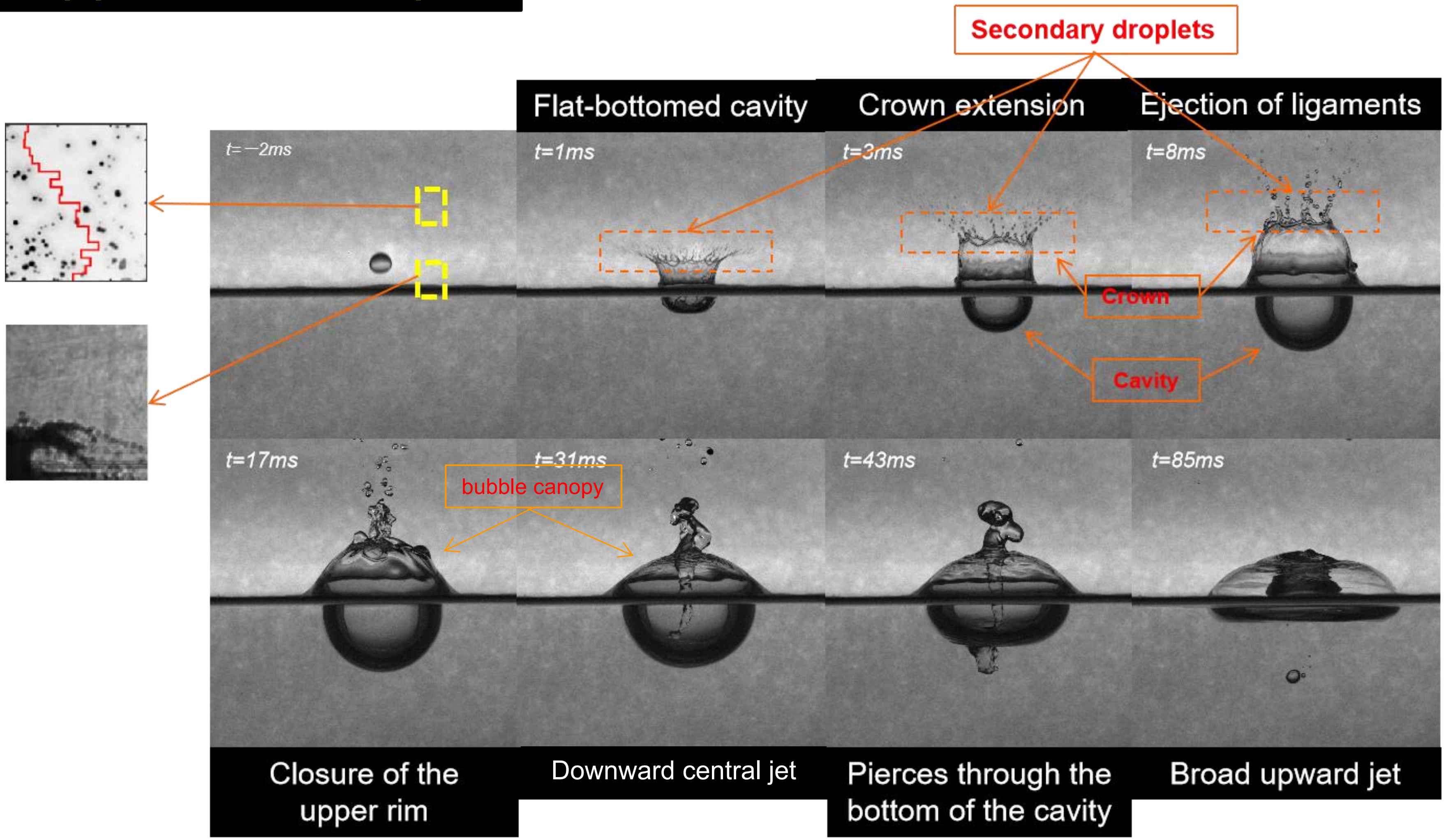
Schematic view of high-speed drop impact by Engel (1966)

The most energetic BC regime is less studied. It is the case likely to yield the most abundant phenomenon and produce the greatest number of aerosol droplets

Experiments at JHU (Murphy et al. JFM, 2015)

A thorough experimental study at Johns Hopkins University based on high-speed visualization

Drop impact on deep pool of the same liquid

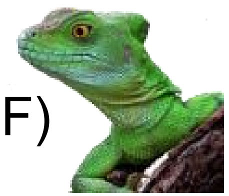


Objective

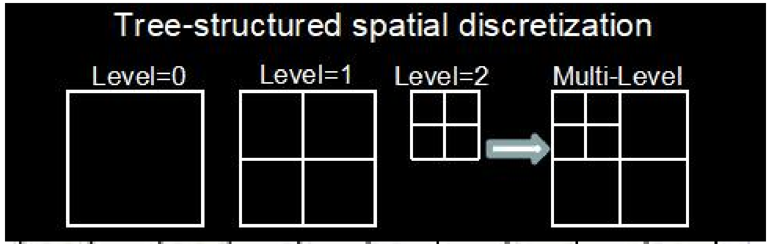
Primary objective is to conduct high-resolution Direct Numerical Simulations (DNS) of drop-pool impact in 3D, serving as an important complementary study for this issue.

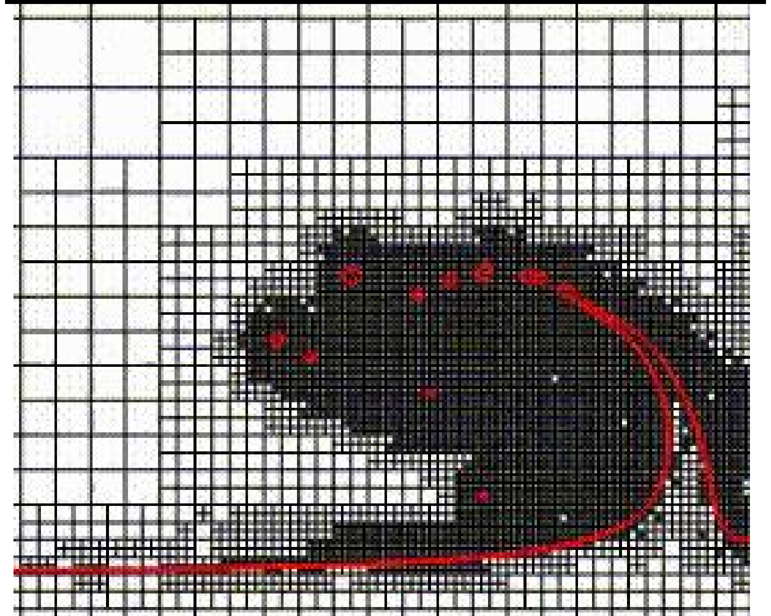
- **Detailed flow physics and spalshing behaviours**
- **Analysis of aerosol production, and especially to identify the conditions of creation of the smallest droplets, which are a major concern for environmental and health issues**

Basilisk code



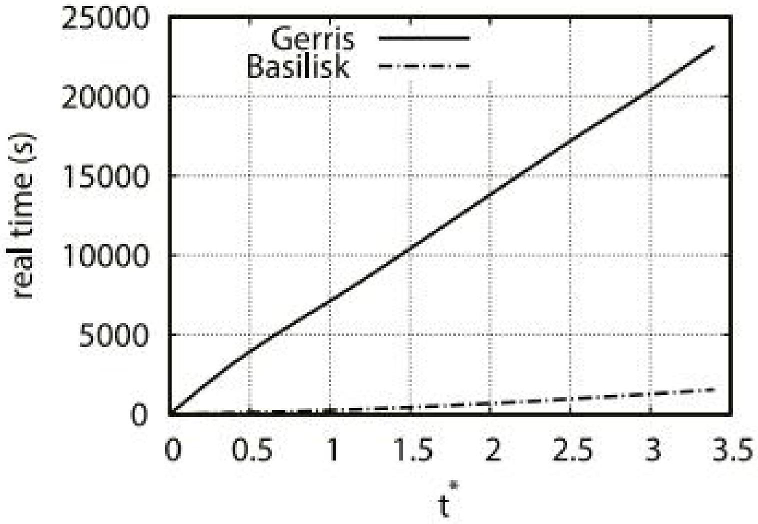
- Finite volume method (FVM)
- Momentum-Conserving Volume of Fluid (MCVOF)
- Continuum-Surface-Force(CSF)
- Tree-structured girds Qudrtree(2D)/**Octree** (3D)
- Adaptive mesh refinement (based on local dynamics)
- High parallelization performance





Incompressible Navier-Stokes & VOF

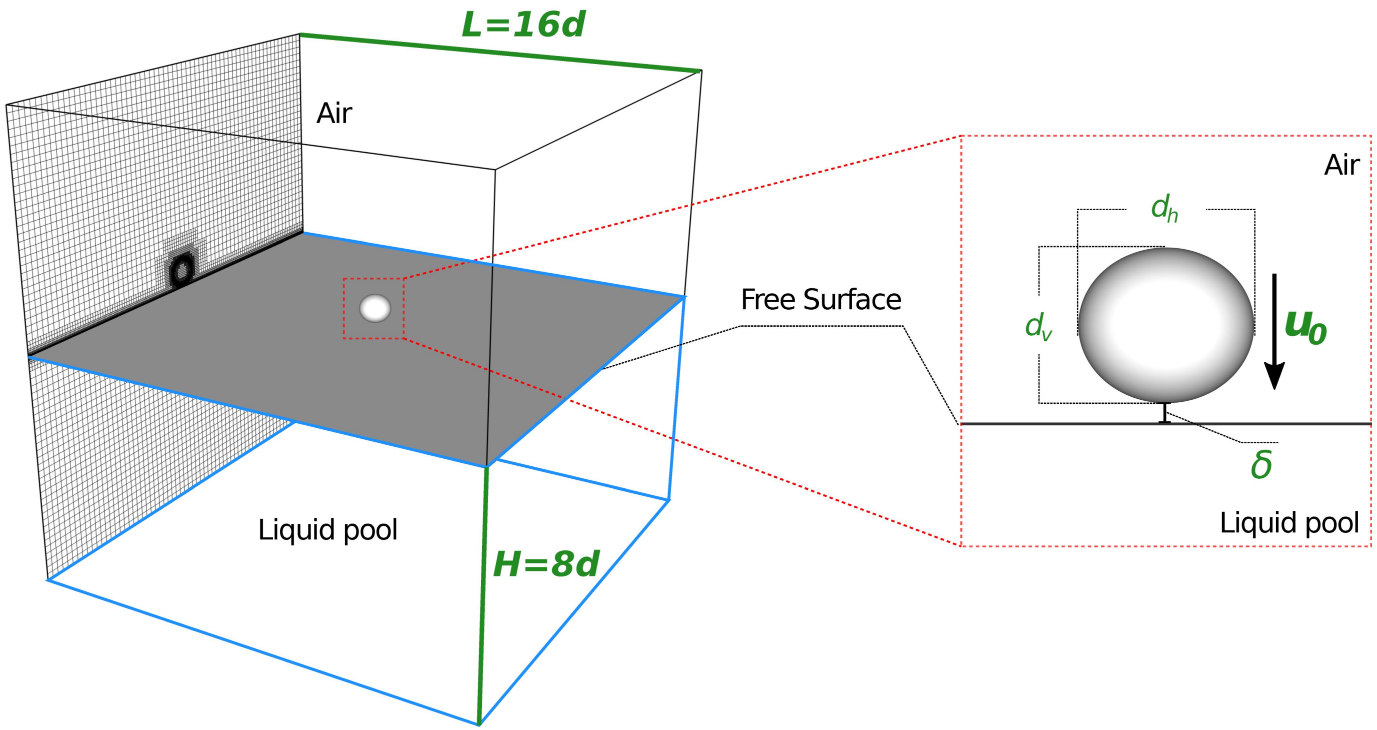
$$\begin{cases} \nabla\cdot\vec{u}=0 \\ \rho\frac{\partial\vec{u}}{\partial t}+\rho\vec{u}\cdot\nabla\vec{u}=-\nabla p+\nabla\cdot\mu\left(\nabla u+\nabla u^{T}\right)+\rho\vec{g}+\sigma\kappa\delta_{s}\vec{n} \\ \frac{\partial f}{\partial t}+\nabla\cdot\left(\vec{u}f\right)=0 \end{cases}$$

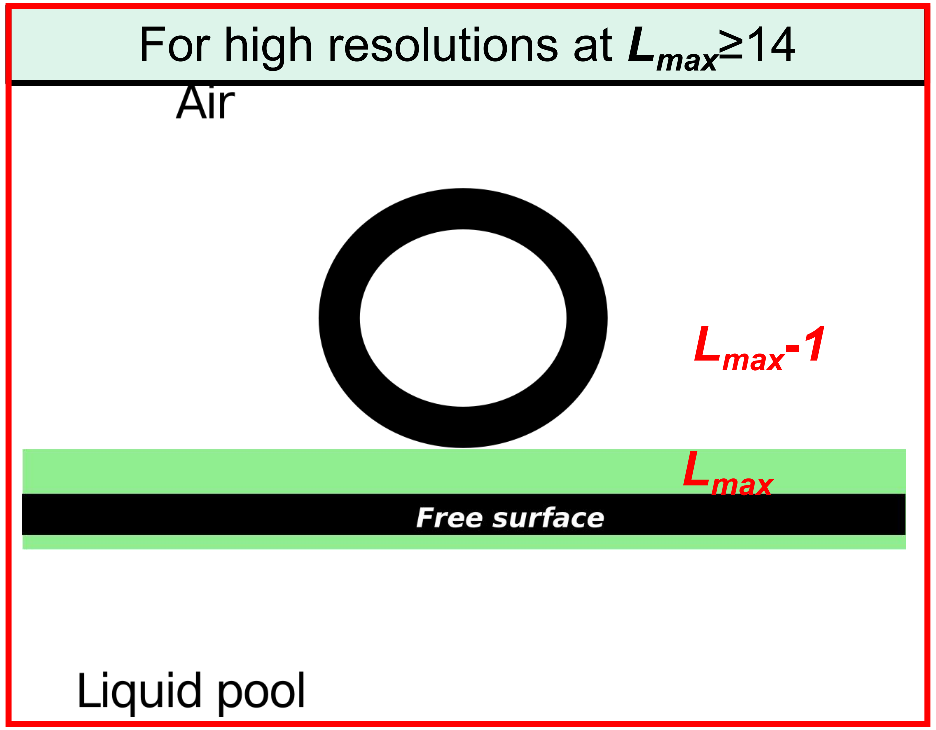


(Wu *et al.* 2020)

Numerical configuration

Initial Set-ups





Adaptive Mesh Refinement(AMR)

multi-level
- Minimum level of refinement: L_{min}
- Maximum level of refinement: L_{max}

criteria
- volume fraction field: fErr=1e-4
- velocity field: uErr=1e-2

gravity(along the initial impact velocity)

Air & seawater

ρ_w/ρ_a=783 μ_w/μ_a=56

Drop (oblate shape)

- d_h≈ 4.3mm
- d_v≈ 3.8mm

→ effective diameter d≈ 4.1mm

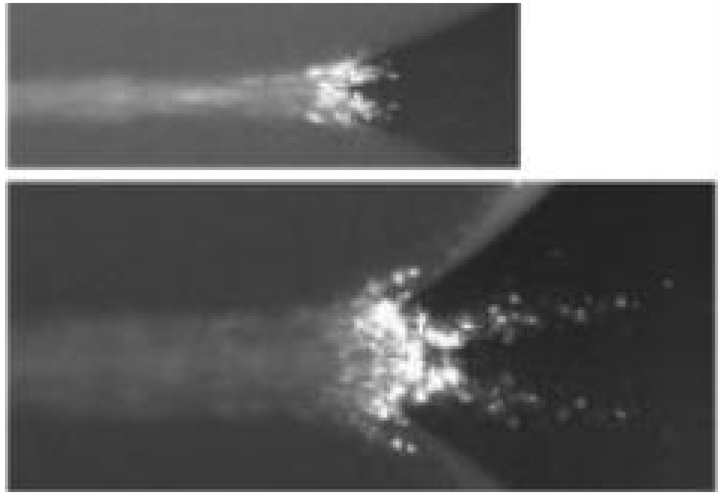
impact speed: 7.2m/s

Numerical configuration

High-energy splashing phenomenon

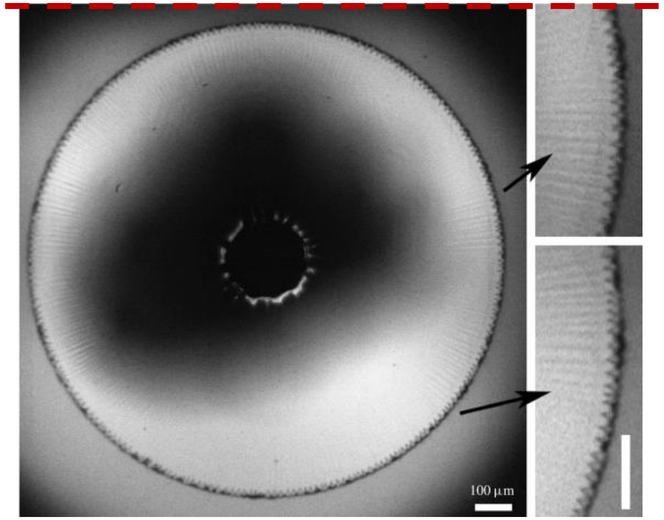
Our present case
Reynolds number: ***Re*** $= \frac{\rho d u_0}{\mu}$ = ***30060***
Weber number: ***We*** $= \frac{\rho d u_0^2}{\sigma}$ = ***2964***

What should we expect ?



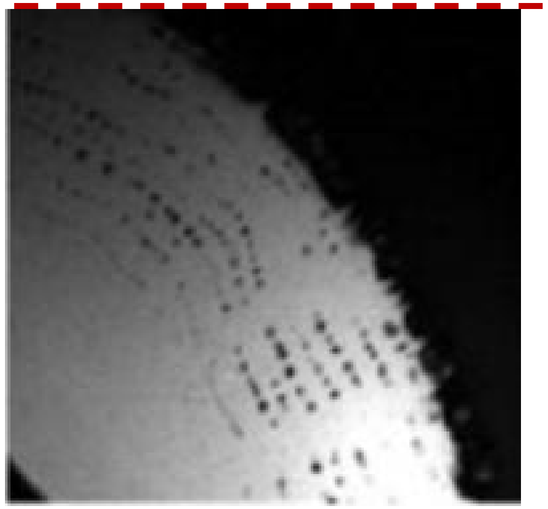
Thoroddsen et al. (2002)

Prompt splash: emerge-ruptured ejecta with very fine mircodroplets immediately after contact (Re=29000, We=1800)



Li et al. (2018)

Azimuthal instability: regular undulations at the neck of connection between drop and pool (Re=11400, We=474)

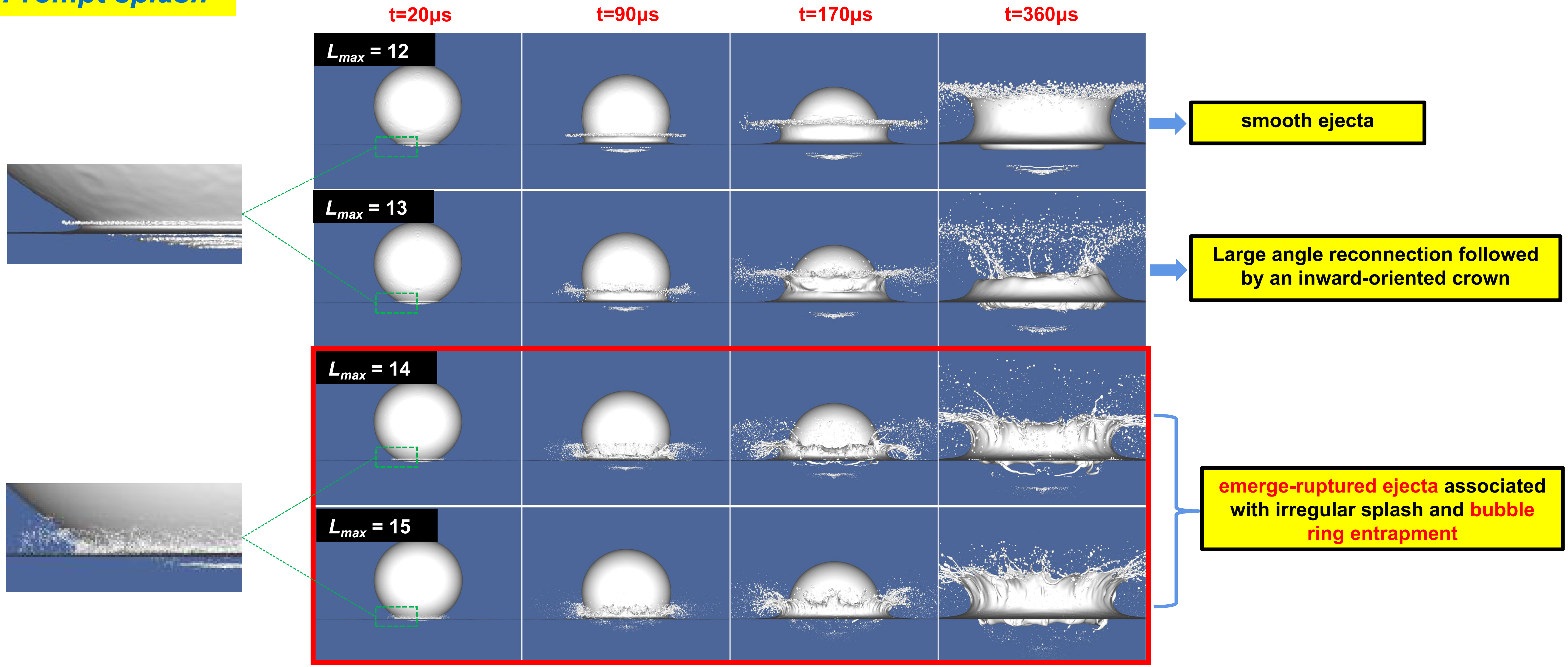


Thoraval *et al.* (2013)

Bubble ring entrapment: sequence of bubble arcs/rings at the neck region (Re=12900, We=506)

Effect of mesh resolution

Prompt splash



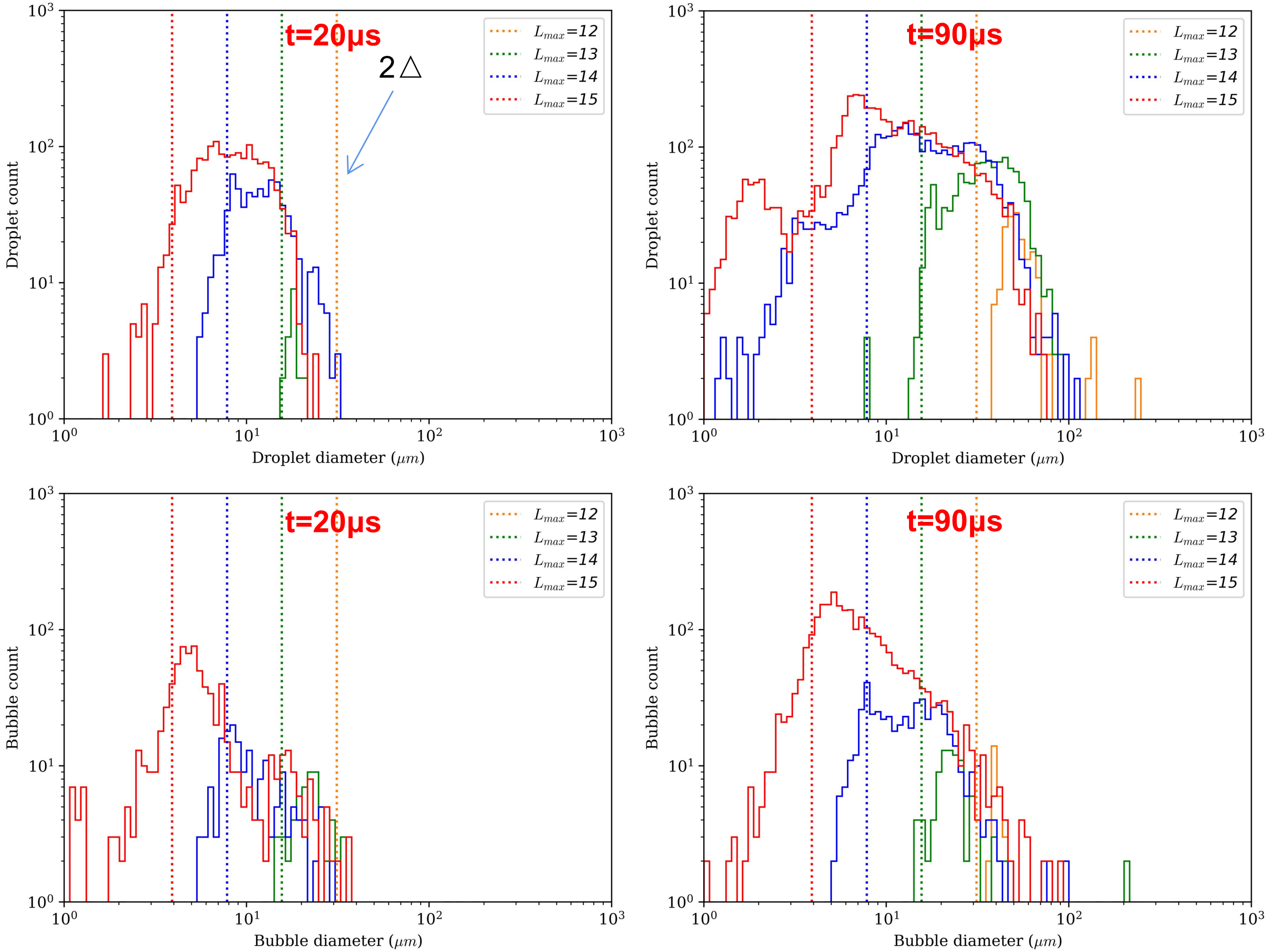
Resolution at L_{max}≥14 (1024 cells per drop diameter) is necessary for capturing the irregular "prompt splash"

Effect of mesh resolution

Prompt splash

Droplet size distribution

Bubble size distribution



- **Few droplets and bubbles at L_{max}=12, 13**
- **Similar profiles at L_{max}=14, 15, due to prompt splash**
- **The most frequent diameter is found at 2△~4△**
- **The data is approximately grid-converged for diameter >4△, for L_{max}=13, 14**

Resolution at L_{max}≥14 (1024 cells per drop diameter) is necessary for capturing the irregular "prompt splash"

Mesh refinement strategy (*50 ms* after impact)

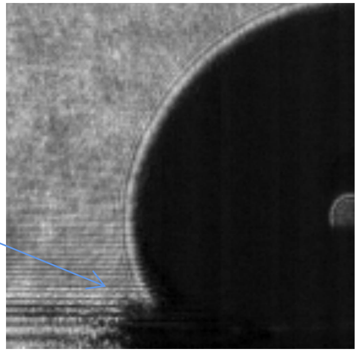
Mesh refinement strategy

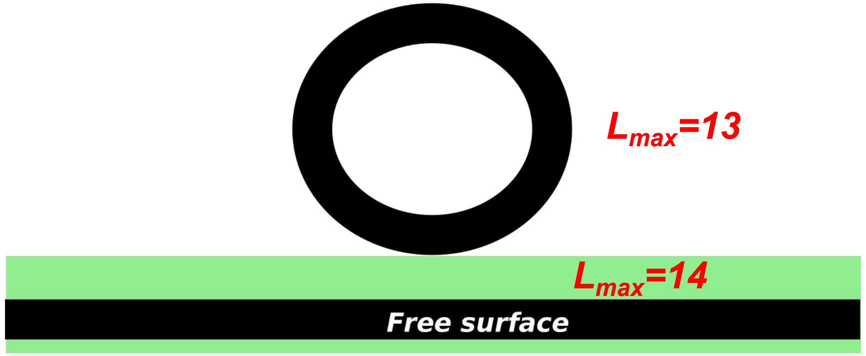
We divide the long-time simulation into three consecutive stages based on the main physical characteristics

Stage1 (S1): $t < 0.27ms$

Primary objective: to capture the **prompt splash/bubble entrapment** near the neck region

prompt splash

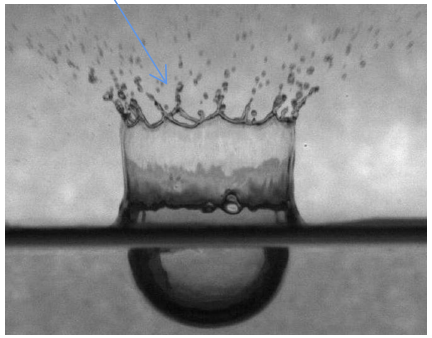




Stage2 (S2): $0.27ms < t < 4ms$

Primary objective: to capture **droplets/bubbles** statistics

crown splash

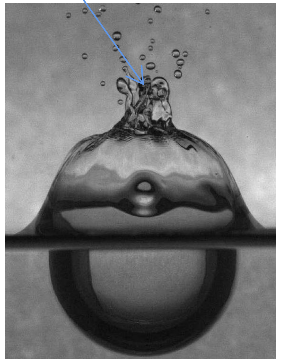


L_{max}=13

Stage3 (S3): $t > 4ms$

Primary objective: to capture the **main features of crown and cavity, bubble canopy formation**

bubble canopy



L_{max}=12

✓ **doable in a full three dimensional configuration**

✓ **can be accomplished in a "reasonable" time**

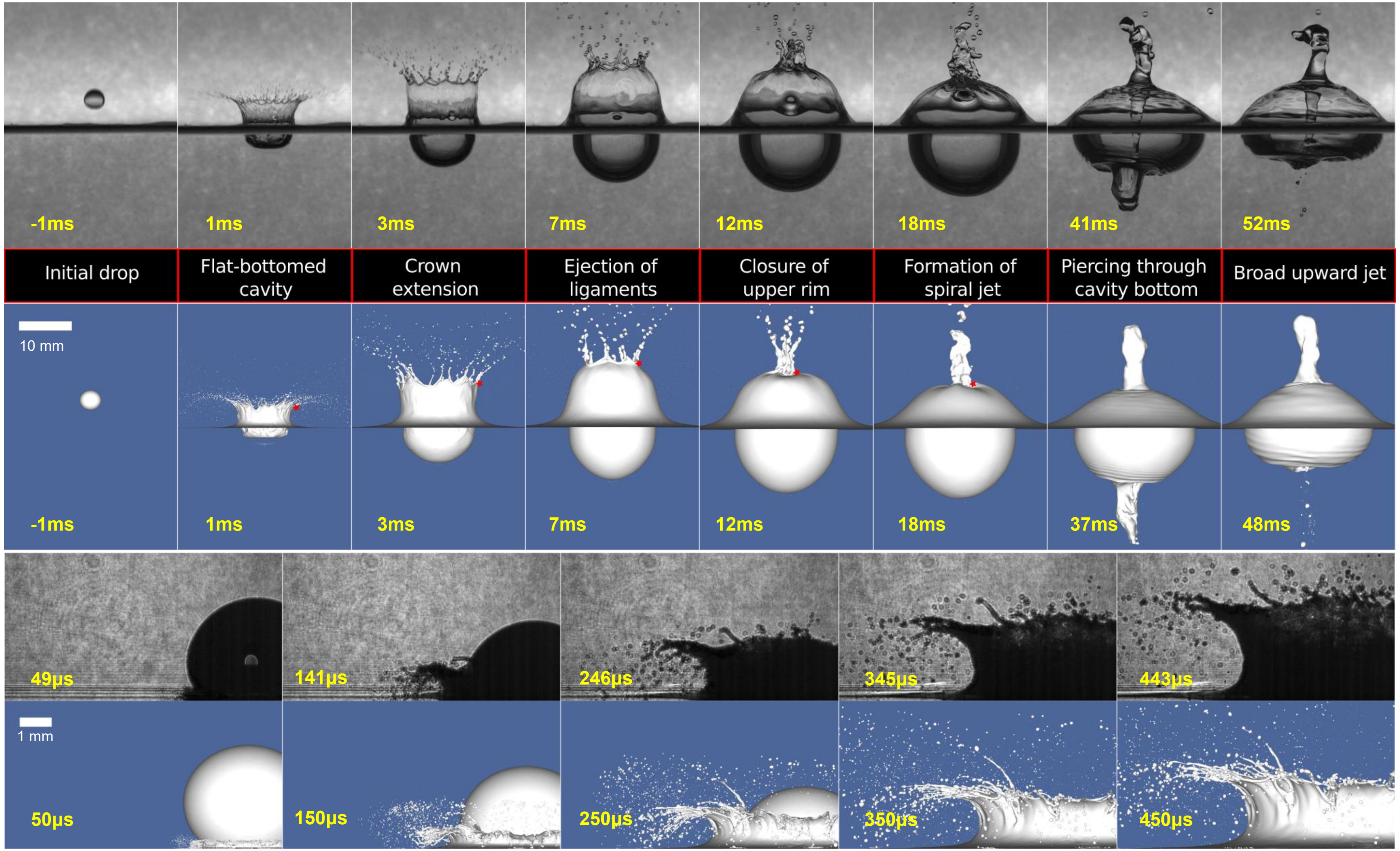
Comparion with experiments

Overall Morphology

Maximum number of cells more than 7.0x10^7, performed on 1024 cores for 33.5 days (8.21x10^5 CPU-hour), Advanced Research Computing(ARC), Virginia Tech

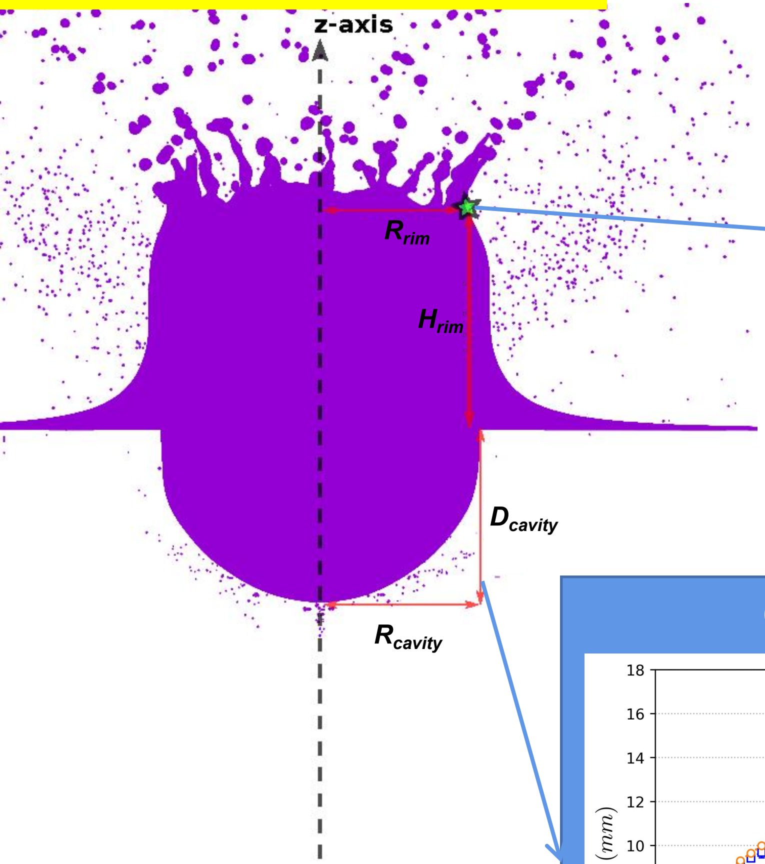
Overall dynamics

Early-time splashing

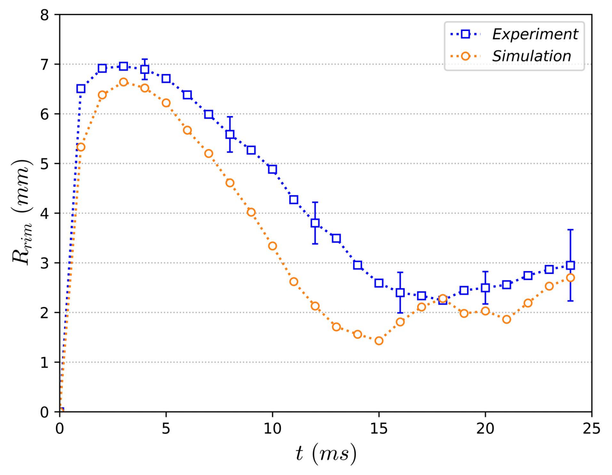


Comparion with experiments

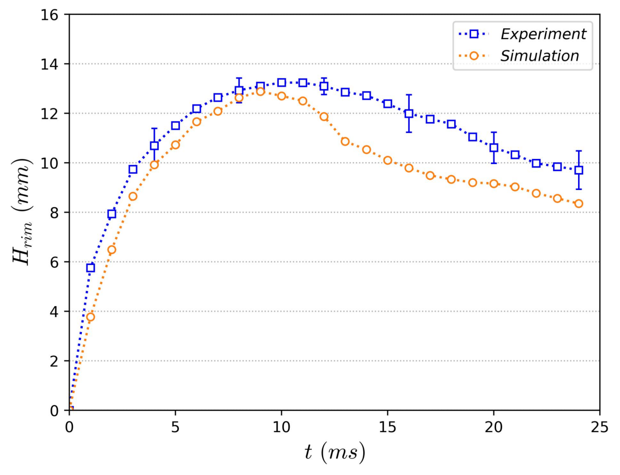
Crown/cavity kinematics



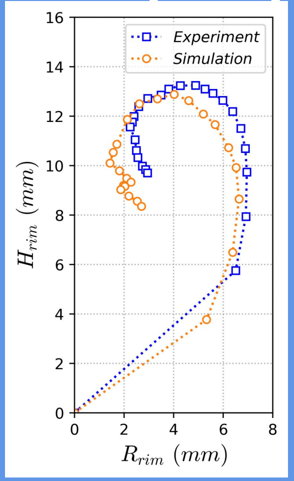
Rim radius



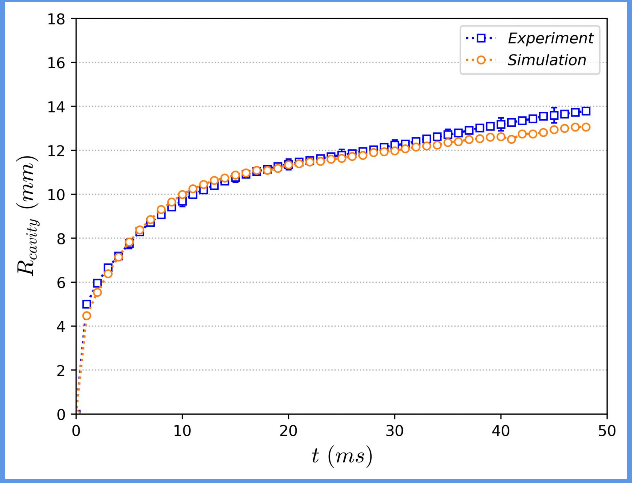
Rim height



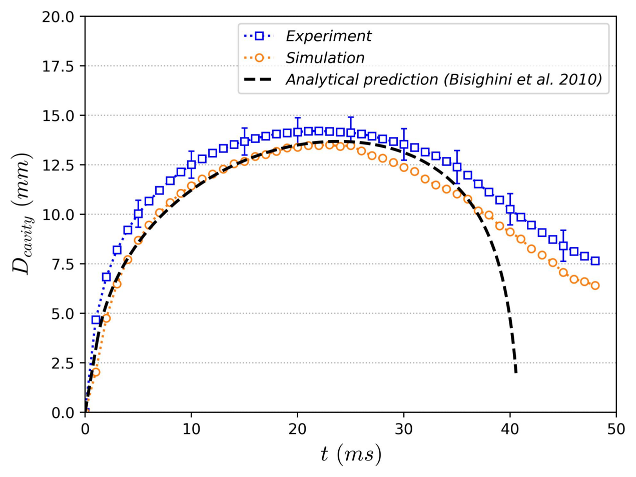
Rim trojectory



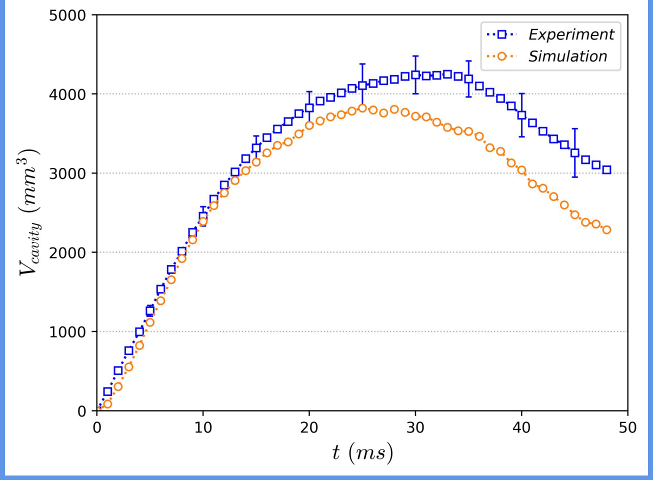
Cavity radius



Cavity depth

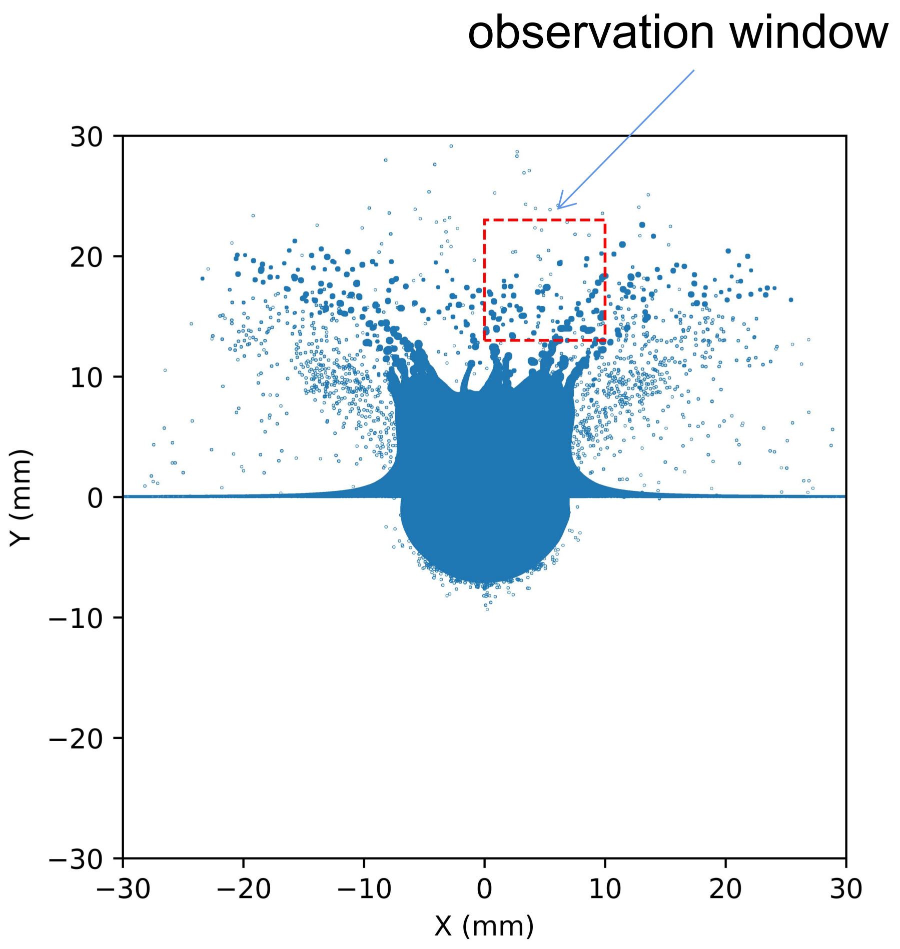


Cavity volume

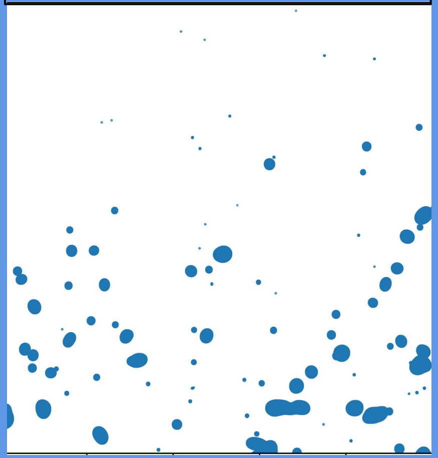


Comparion with experiments

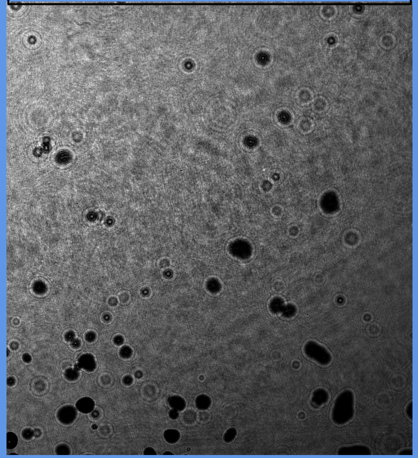
Droplet distribution in observation window



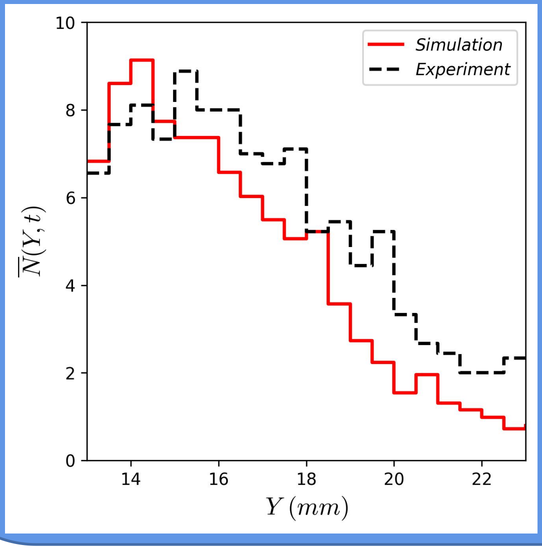
simulation



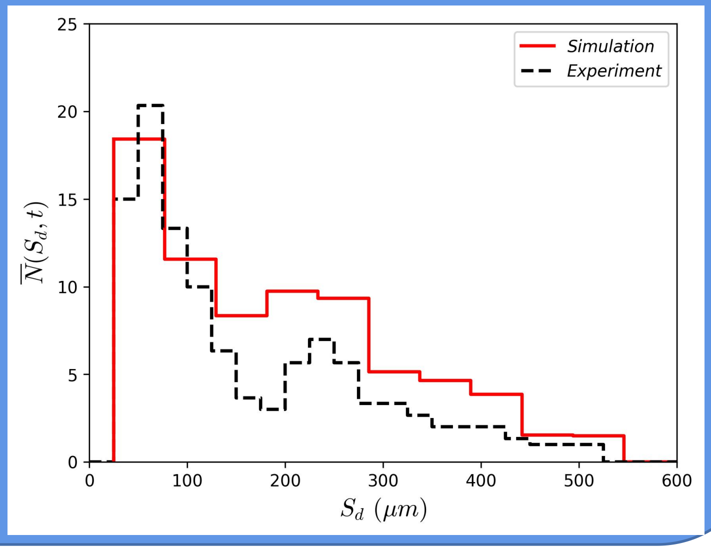
experiment



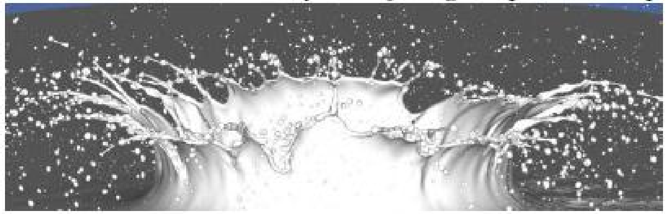
Vertical distribution



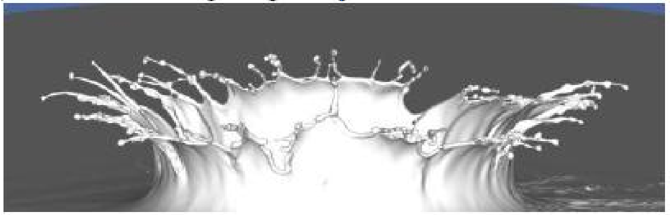
Size distribution



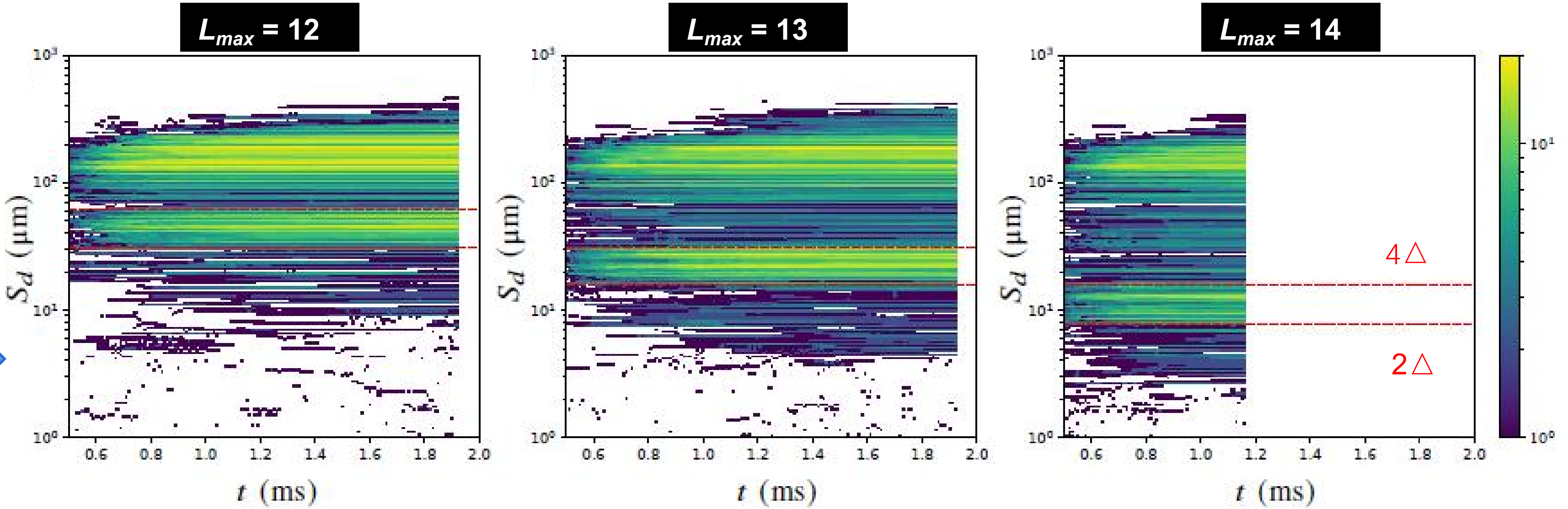
Sensitivity of droplet statistics



remove droplets



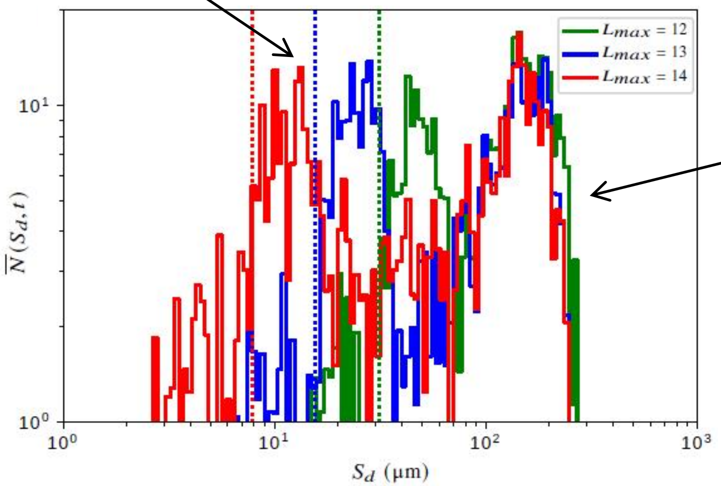
restart



temporal contours of droplet size distributions

shafted small-sized peak

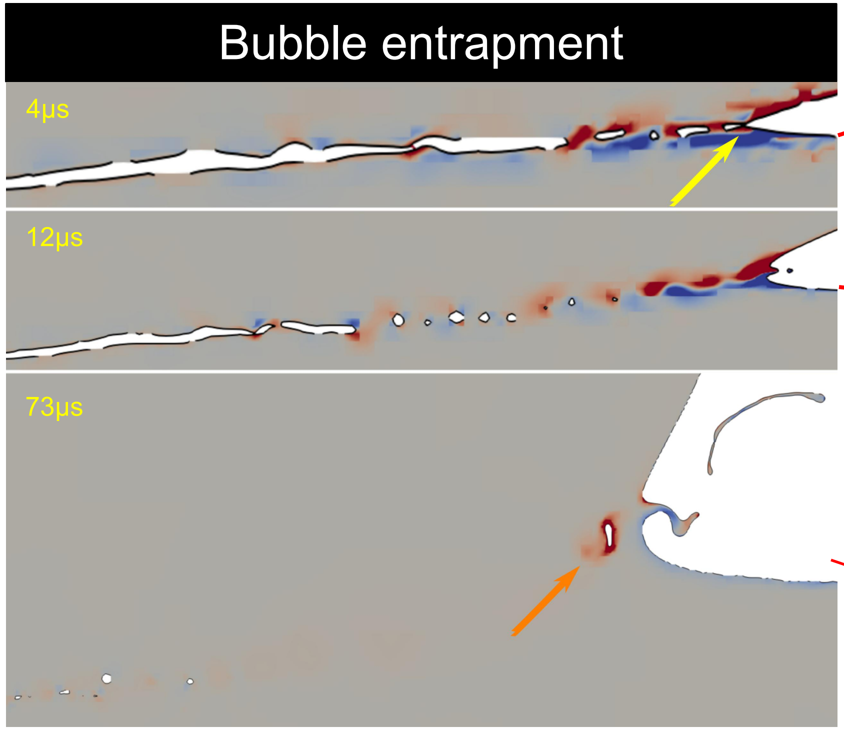
grid-converged data



time-averaged droplet size distribution

4 cells per droplet diameter are essential to obtain numerical convergence

Bubble ring entrapment



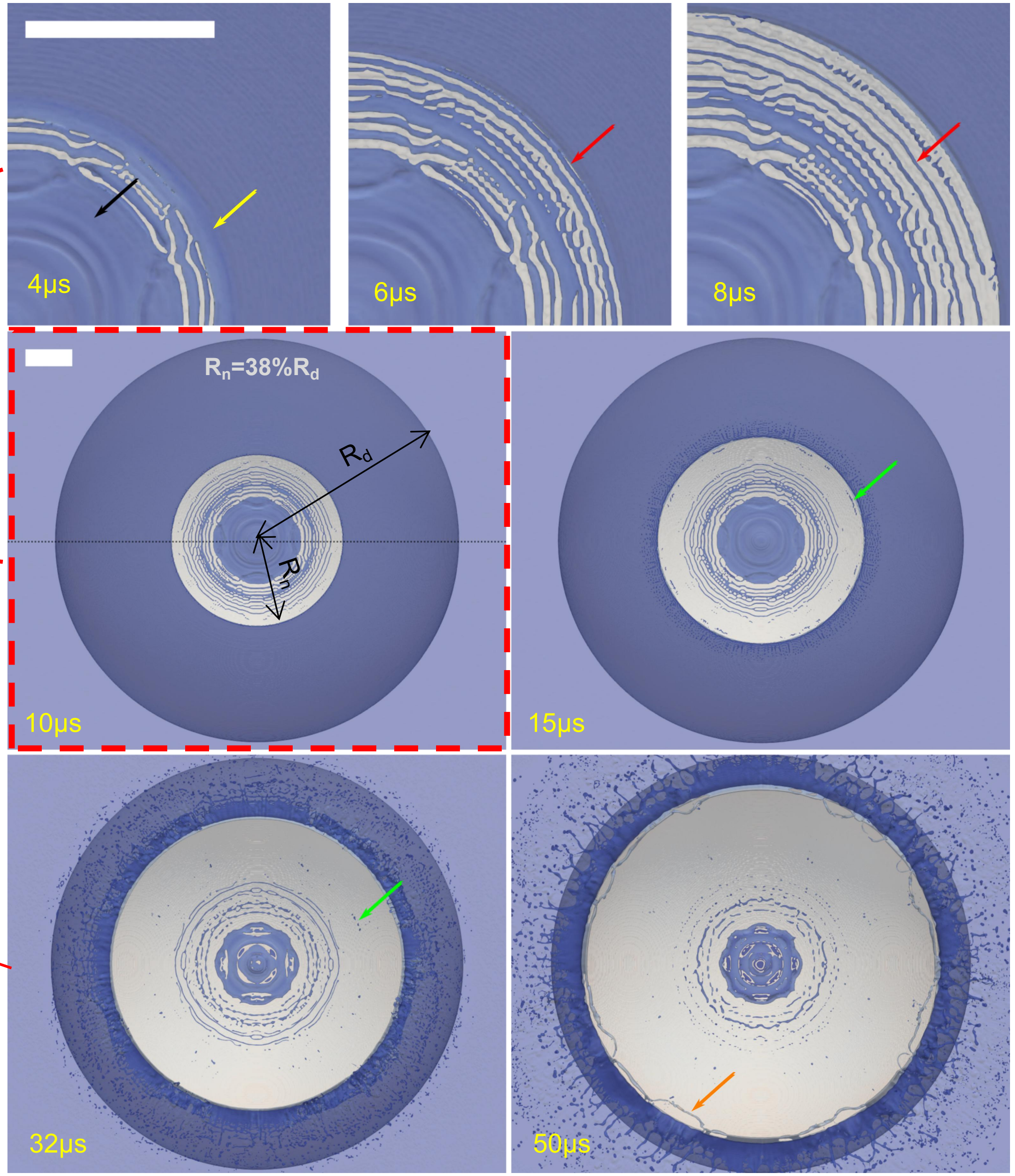
Oguz & Prosperetti (1989) bubble ring

Locolised high pressure

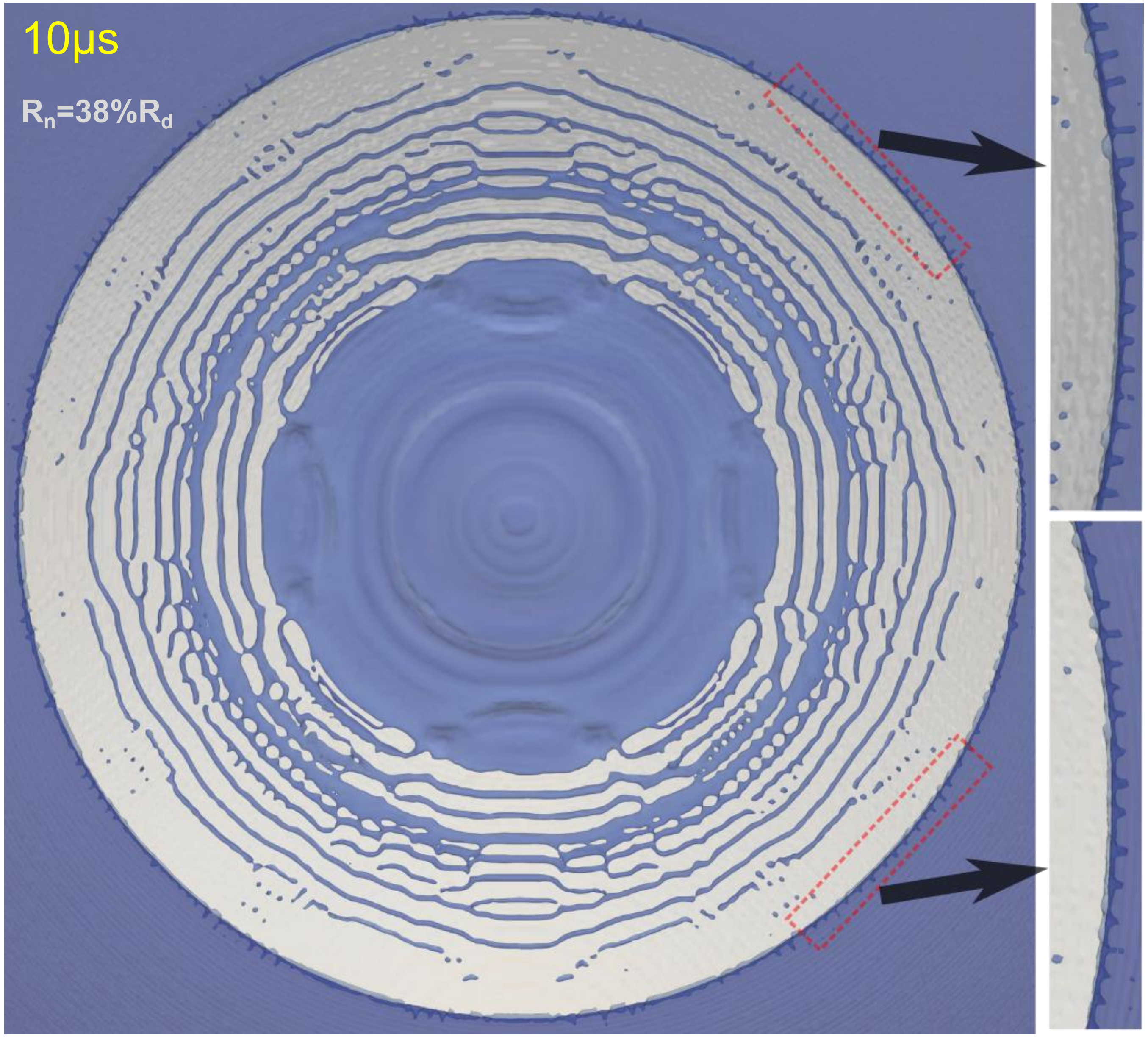
bubble arcs due to jet base oscillation

Weiss & Yarin (1999) bubble ring

Interaction between ejecta and drop/pool



Early-time azimuthal instability

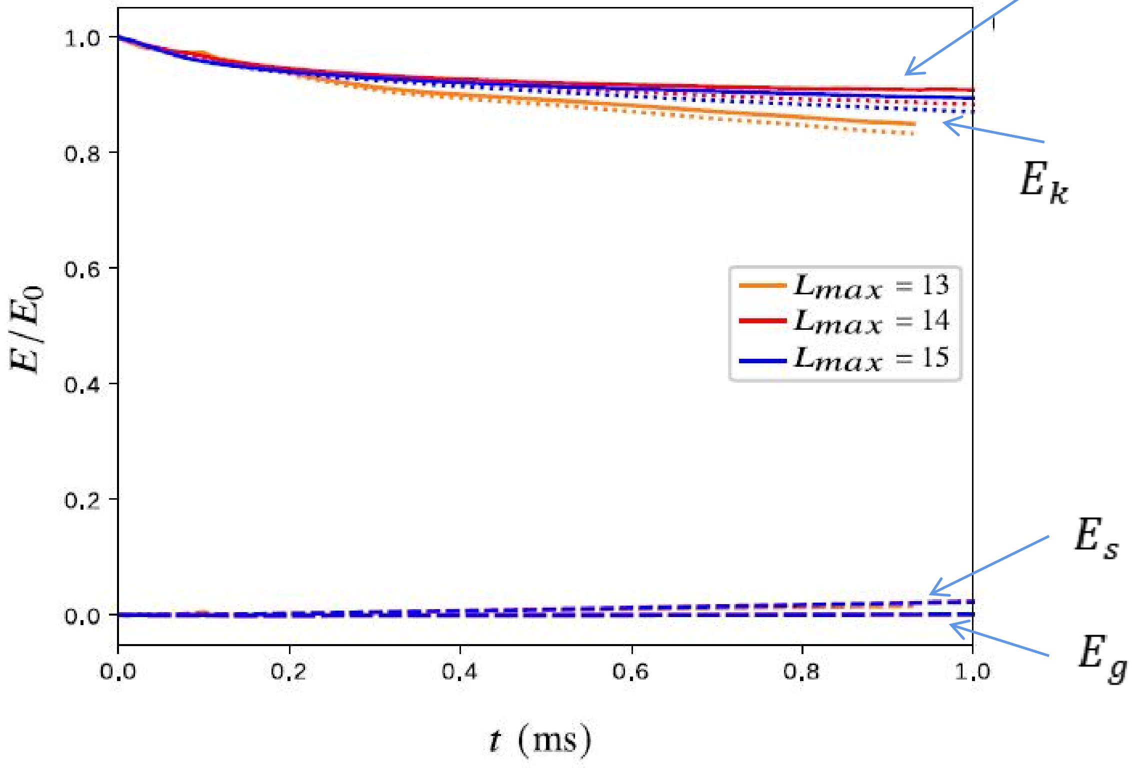


Energetics

Energy collection:

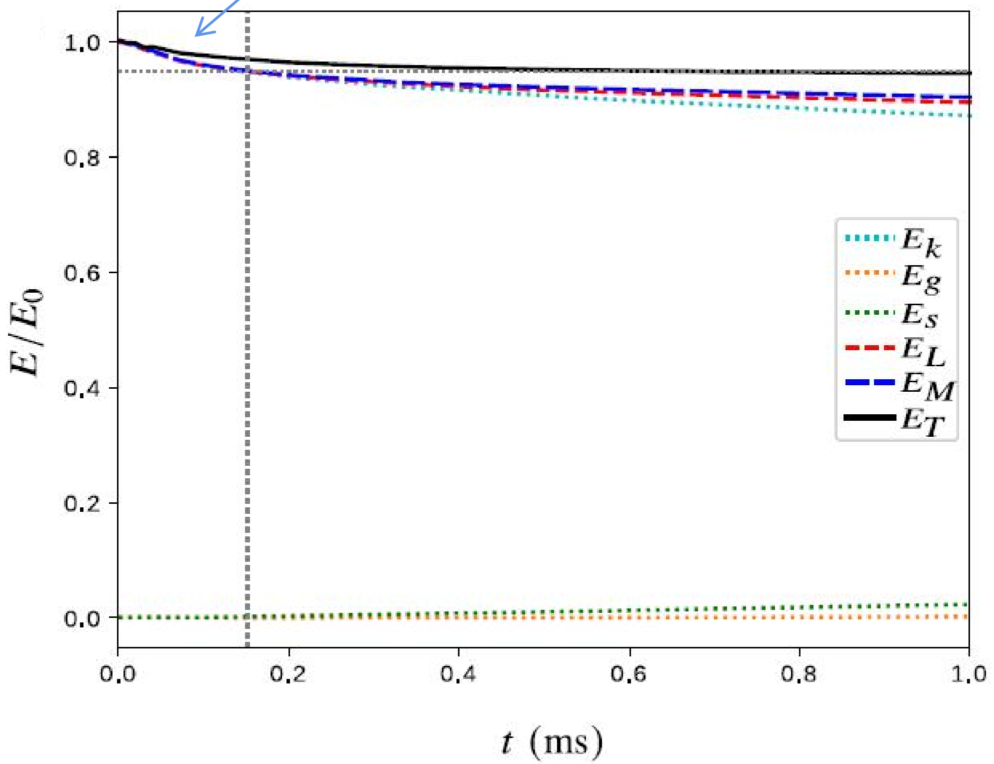
$$E_k = \frac{1}{2}\int_V \rho\|u\|^2\,dV \qquad E_g = \int_V \rho g y\,dV - E_{g0} \qquad E_s = \int_V \sigma\,dS - E_{s0} \qquad E_d(t) = \int_0^t\int_V \mu \frac{\partial u_i}{\partial x_j}\frac{\partial u_j}{\partial x_j}\,dV\,dt$$

$$E_L = E_k + E_g + E_s$$



mechanical energy under different L_{max}

5% energy loss at t<200µs during prompt splash



energy budget for case with L_{max}=15

Thank You