Spray Drop Generation by Breaking Waves

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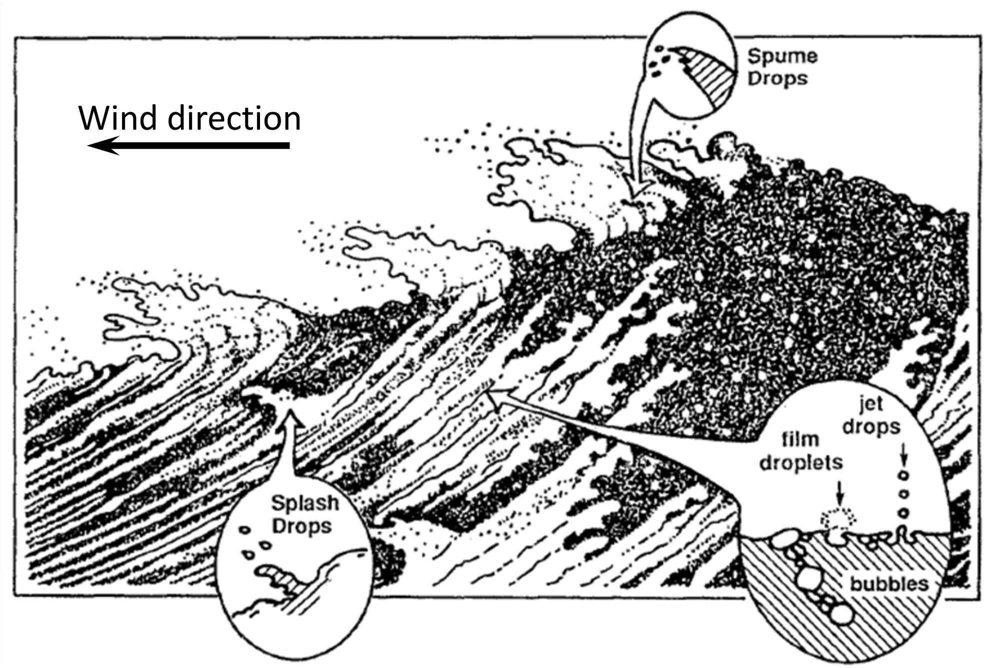
Introduction: Ocean Sprays



Major pathways of ocean spray generation [1]

- Spray formation during wave breaking
- Sprays enhance air-sea transfer processes

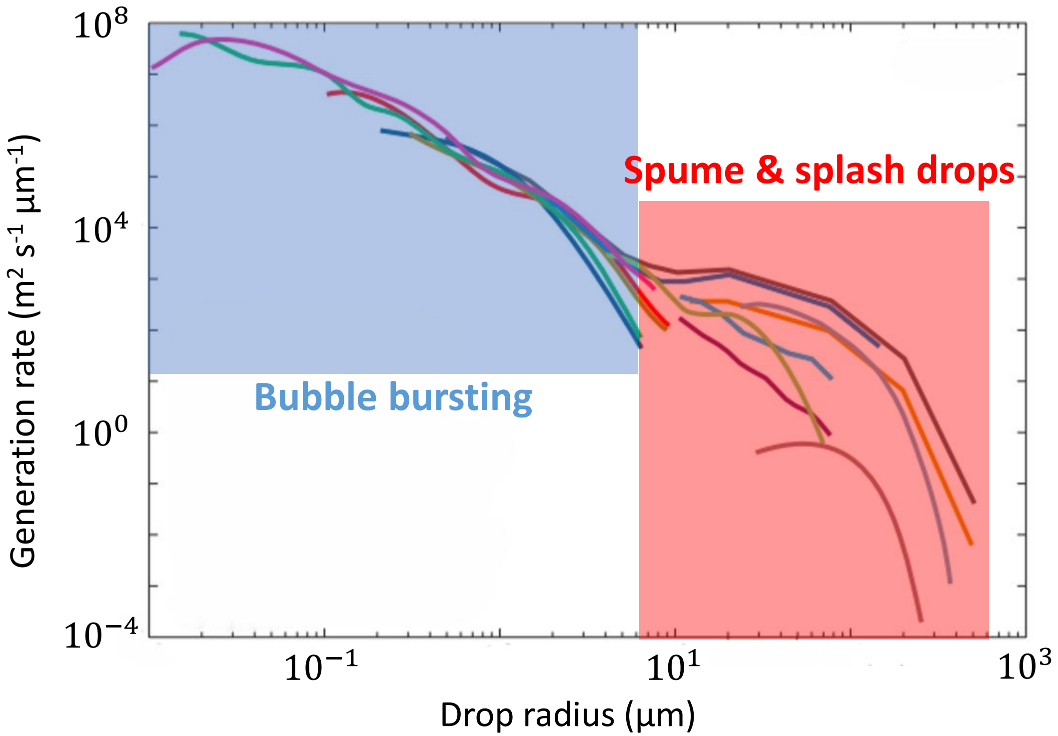
  Small drops – cloud nucleation sites

  Large drops – tropical cyclone formation

Sea-Spray Generation Function (SSGF)

No agreement at large droplet sizes

Poor knowledge of spume and splash drop generation

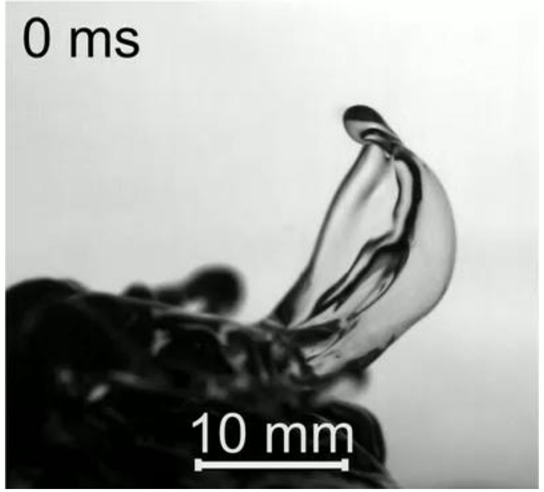


Currently available SSGFs (coloured curves) [2]

[1] E. Andreas *et al.,* 1995.
[2] F. Veron, 2015.

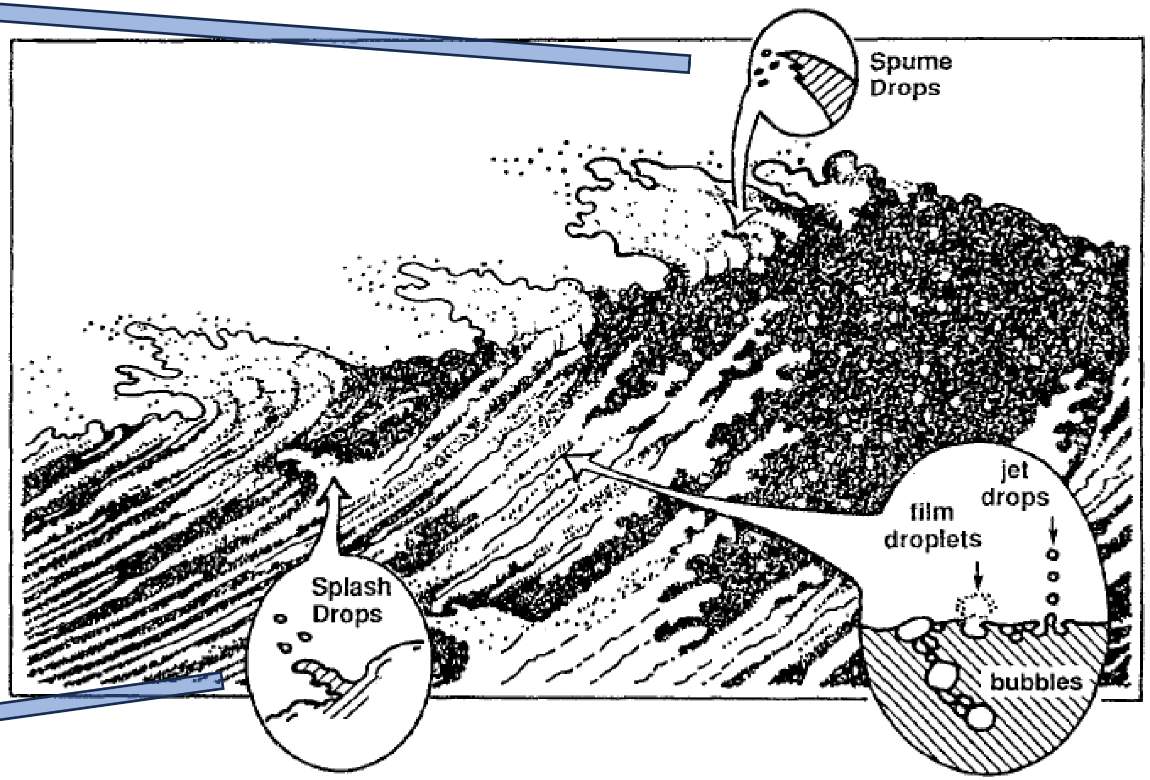
Experimental Observations

[1] F. Veron, 2015.
[2] E. Andreas *et al.*, 1995.
[3] Y. Troitskaya *et al.*, 2017.
[4] M. Erinin *et al.*, 2023.



Bag breakup at sea surface under high winds [3]

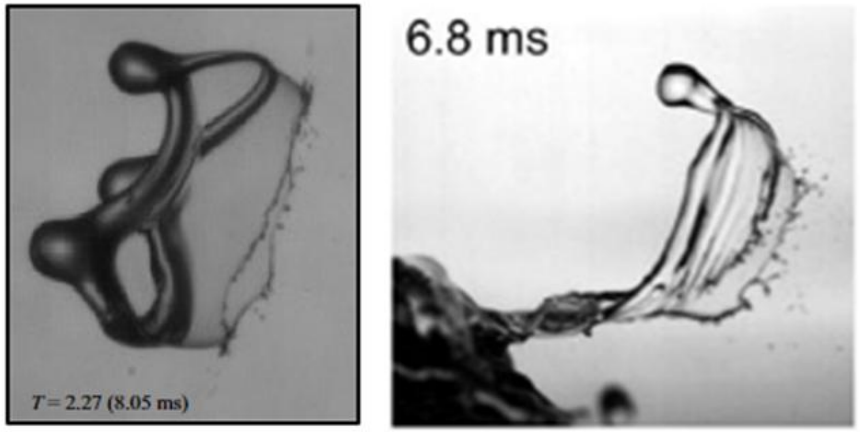
Splashing of a plunging breaker [4]



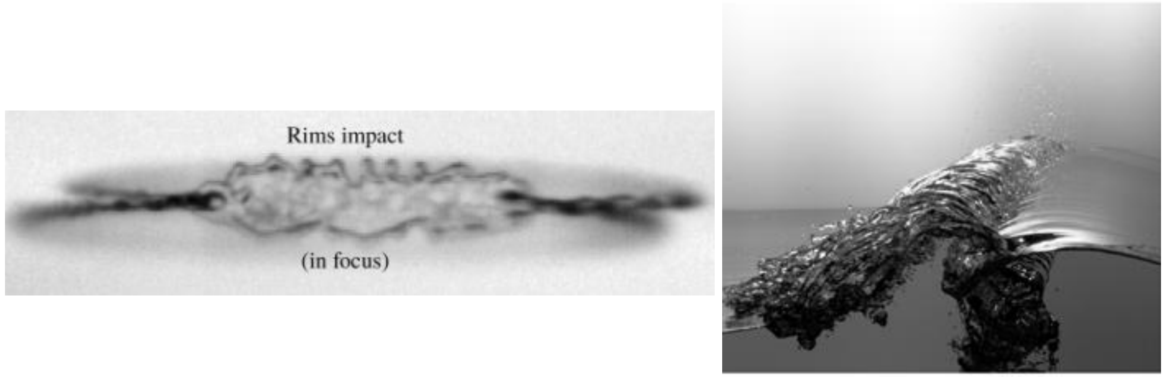
Major pathways of ocean spray generation [2]

Modelling Approach

[1] I. Jackiw and N. Ashgriz, 2022.
[2] Y. Troitskaya *et al.*, 2017.
[3] B. Néel *et al.*, 2020.
[4] M. Erinin *et al.*, 2023.
[5] E. Andreas *et al.*, 1995.



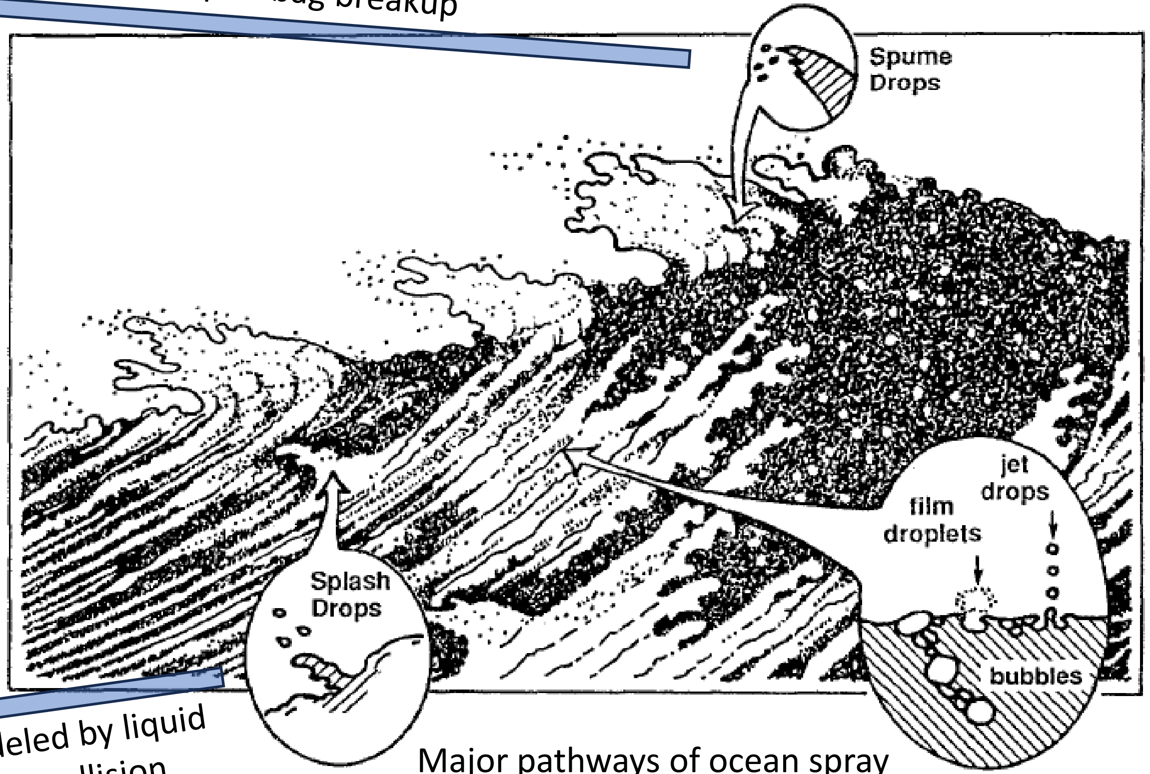
Droplet bag breakup [1] and sea surface breakup at high winds [2]



Fragmentation of colliding rims [3] and secondary wave splashing [4]

Modeled by droplet bag breakup

Modeled by liquid rim collision



Major pathways of ocean spray generation [5]

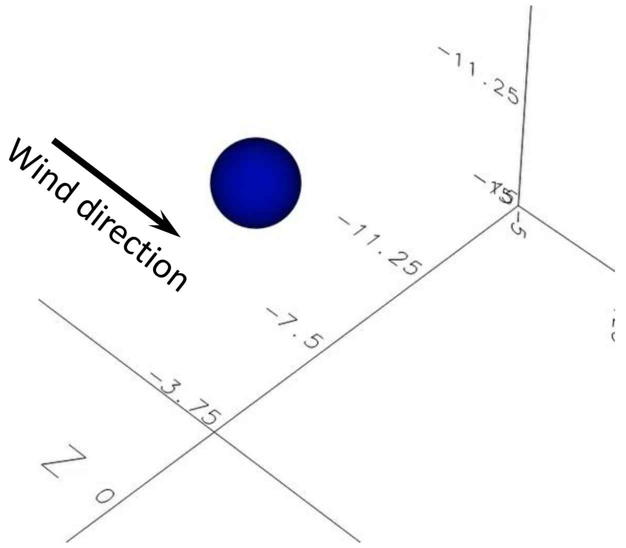
Numerical Setup

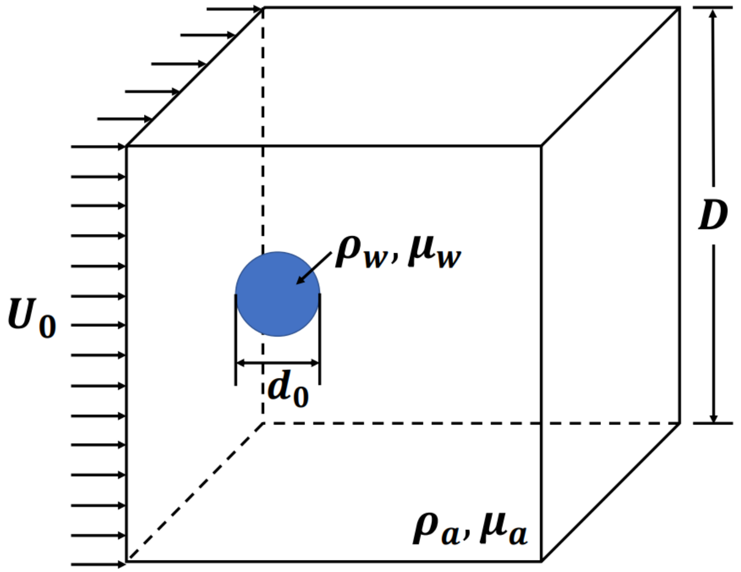
- The Basilisk Solver [1]
  - Two-phase, incompressible Navier-Stokes Equation w. surface tension
  - Finite-volume w. adaptive mesh refinement (AMR)
  - Geometric volume-of-fluid (VOF) method
- Controlling Parameters

$$\boldsymbol{We} \equiv \frac{\boldsymbol{\rho_g U_0^2 d_0}}{\boldsymbol{\sigma}}, \qquad \boldsymbol{Oh} \equiv \frac{\boldsymbol{\mu_l}}{\sqrt{\boldsymbol{\rho_l \sigma d_0}}},$$

$$\rho^* \equiv \frac{\rho_l}{\rho_g} = 833, \qquad \mu^* = \frac{\mu_l}{\mu_g} = 55.$$

- 3D Simulation Configurations
  - Film fragment statistics





3D configurations of droplet aerobreakup.

[1] Available at: http://basilisk.fr/

Physically Realistic Fragment Statistics

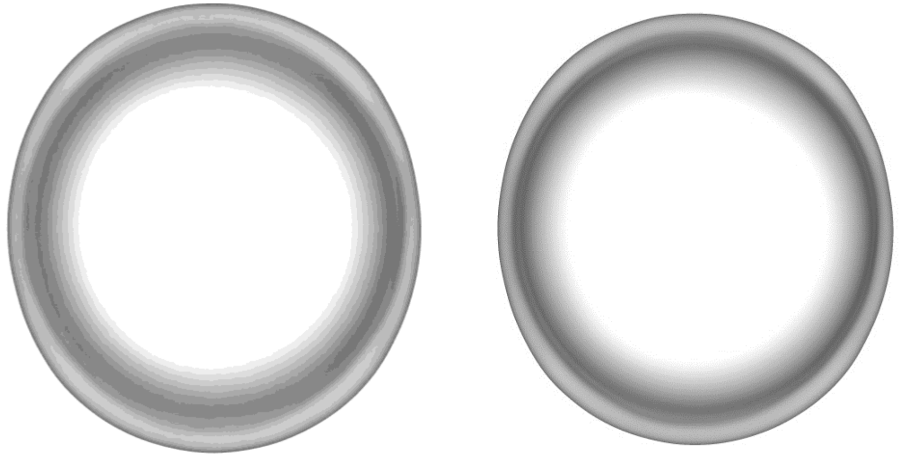
- VOF Breakup

  Film breaks when its thickness reaches grid size

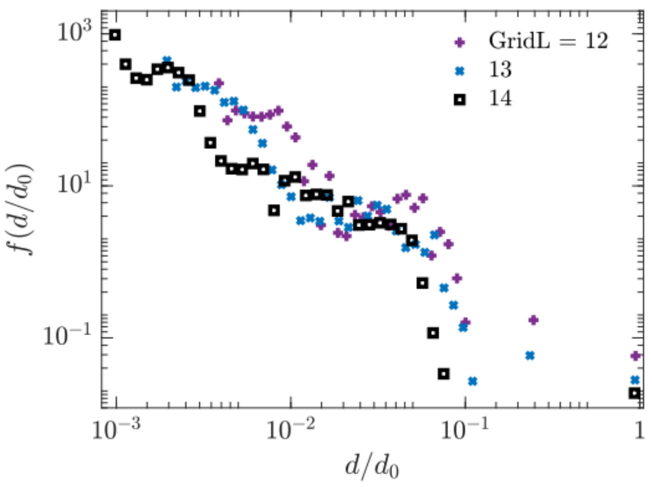
  Unphysical, numerically uncontrolled and grid-dependent
- Controlled film rupture with the MD algorithm [1]
- Convergence of fragment statistics with $d \geq 8\Delta_{13}$ and fixed L_{sig}

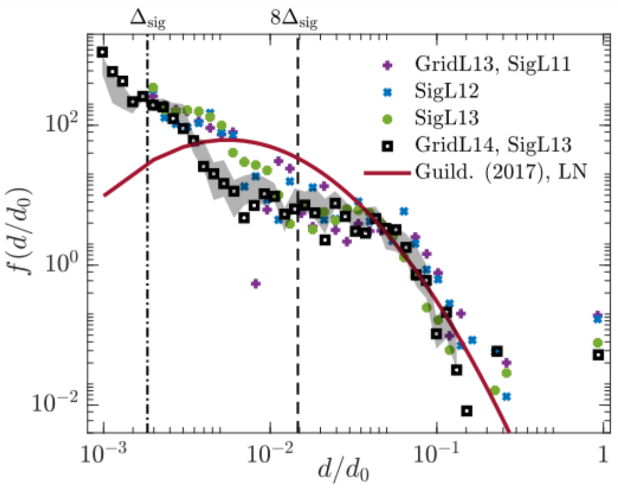
  Agreement with log-normal fit for experimental results in [1]
- Fragments with $d < 8\Delta_{13}$ not reaching grid convergence

  Ligament breakup not controlled by MD



Bag breakup without (left) and with (right) controlled film rupture.

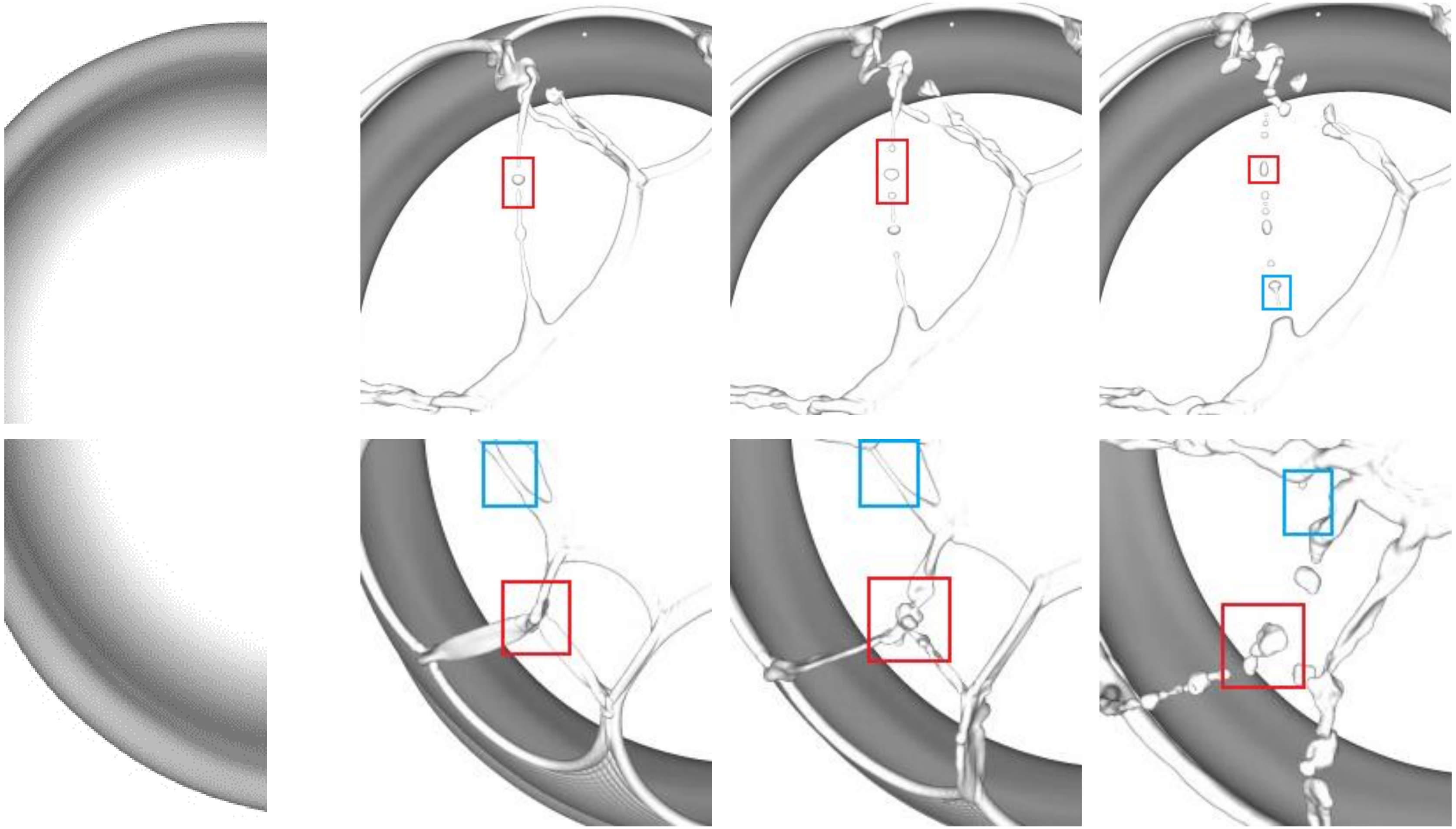




Left: experimental photograph showing thin film breakup [3]. Right: fragment size distributions with controlled film rupture.

[1] L. Chirco *et al.*, 2022.
[2] D. R. Guildenbecher *et al.*, 2017.
[3] Vledouts *et al.*, 2016.

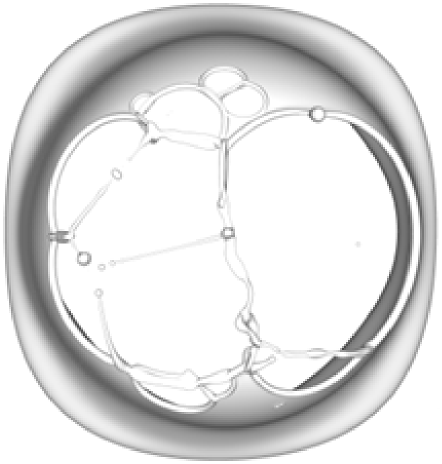
Film Breakup Mechanisms



Breakup of a long ligament (upper row), a short ligament and a liquid node (lower row).

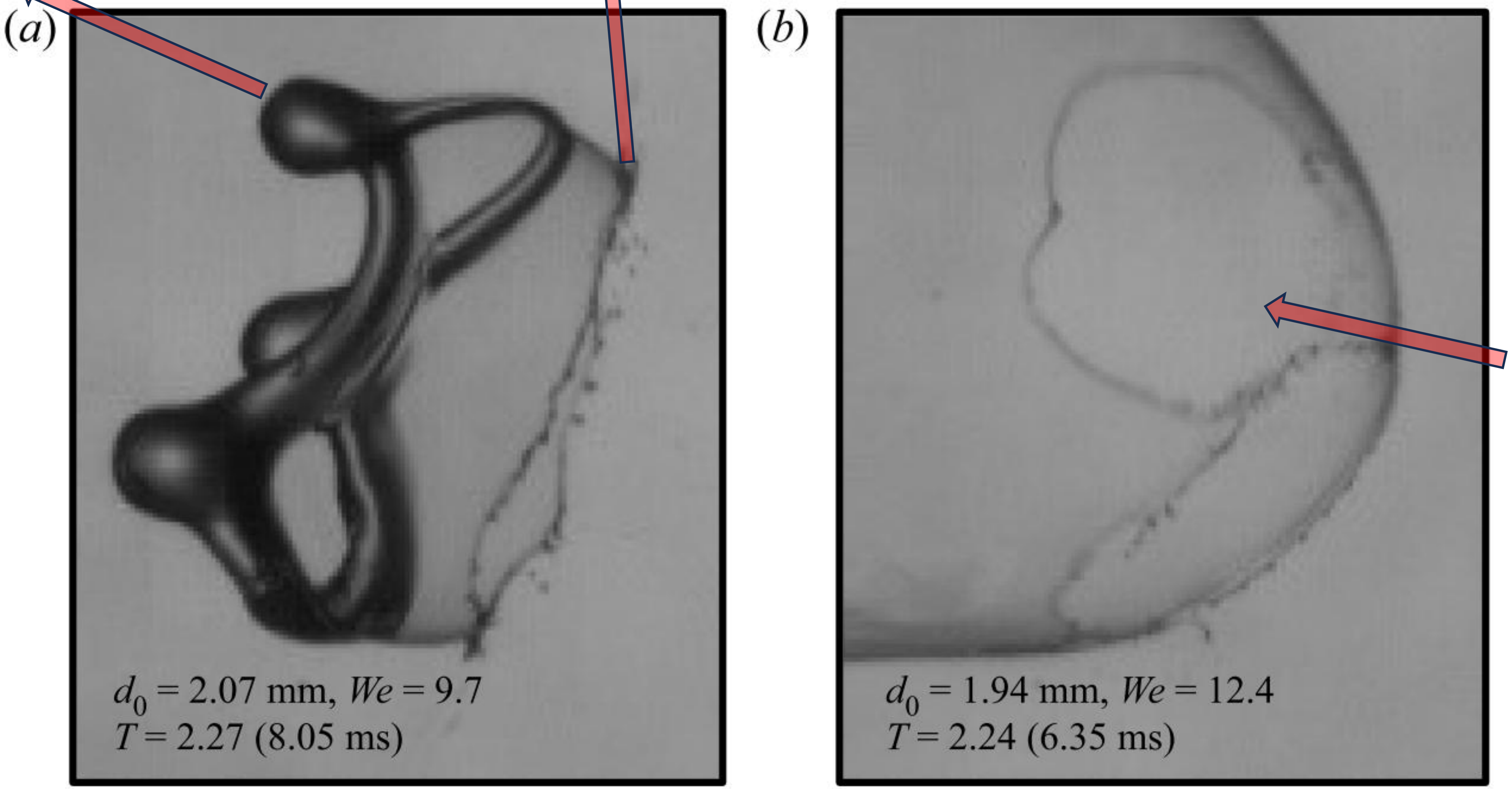
- **Long ligament breakup**
  - Primary and satellite fragments
  - Shape oscillation of primary drops (frequency measurement)
- **Short ligament breakup**
  - Formation of a single drop
- **Large node detachment**
  - Successive breakup of bordering ligaments

Comparison with Experiments



Large node detachment (perturbation by ambient airflow?)

Destabilisation of receding hole rims (large bag curvature and small thickness?)

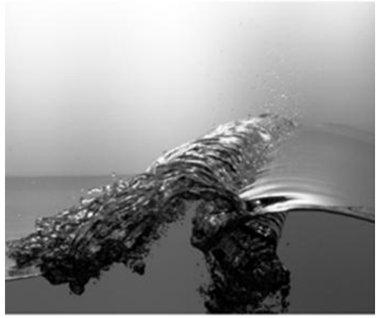


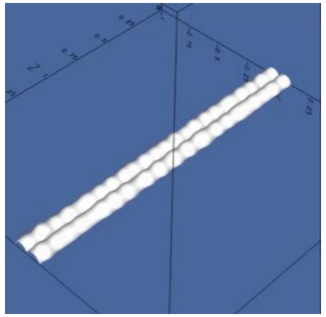
Formation of one or two large holes (sufficiently low film perforation rate?)

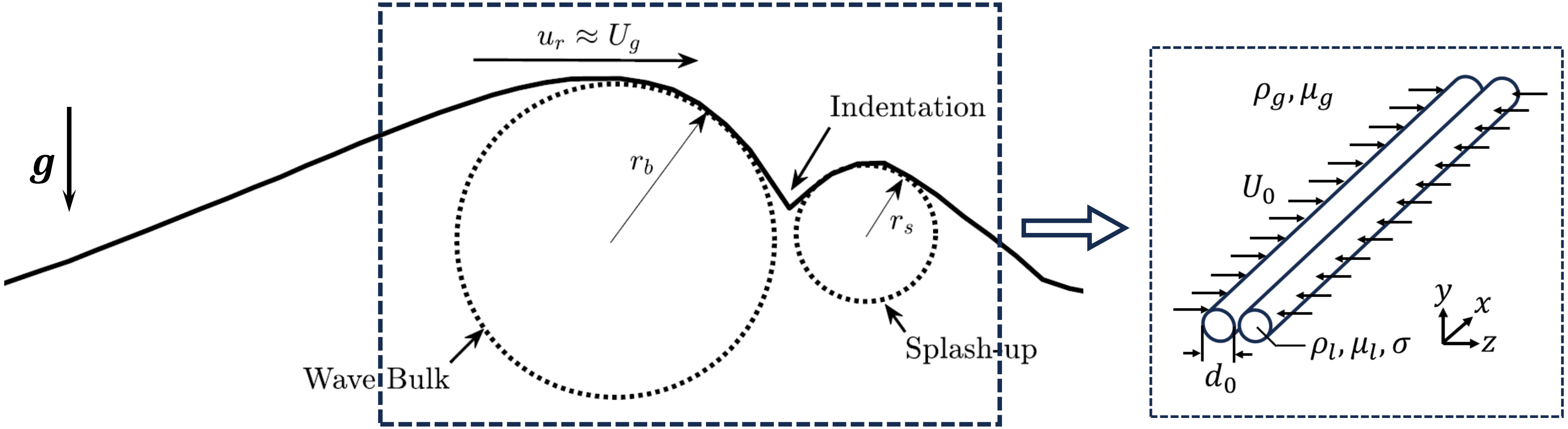
Side views of bag breakup from Ref. [1]

[1] I. Jackiw, *Journal of Fluid Mechanics*, 2022.

Problem Configuration







Configurations of secondary wave splashing (left) and rim collision (right)

Controlling Parameters

$$\boldsymbol{We} \equiv \frac{\boldsymbol{\rho_l (2U_0)^2 d_0}}{\boldsymbol{\sigma}}, \boldsymbol{Bo} \equiv \frac{\boldsymbol{\rho_l g d_0^2}}{\boldsymbol{\sigma}},$$

$$Oh \equiv \frac{\mu_l}{\sqrt{\rho_l d_0 \sigma}} = 0.01, \qquad \rho^* \equiv \frac{\rho_l}{\rho_g} = 833, \qquad \mu^* \equiv \frac{\mu_l}{\mu_g} = 55,$$

Perturbed rim surfaces with filtered white noise signal

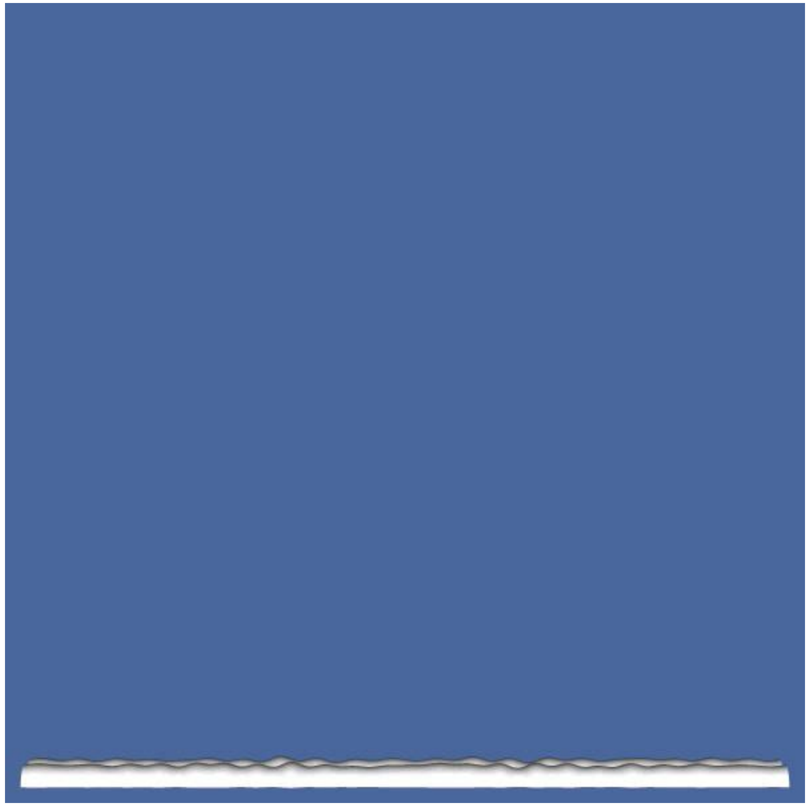
Basilisk, Two-Phase NS Equation w. AMR Scheme

Ligament Merging

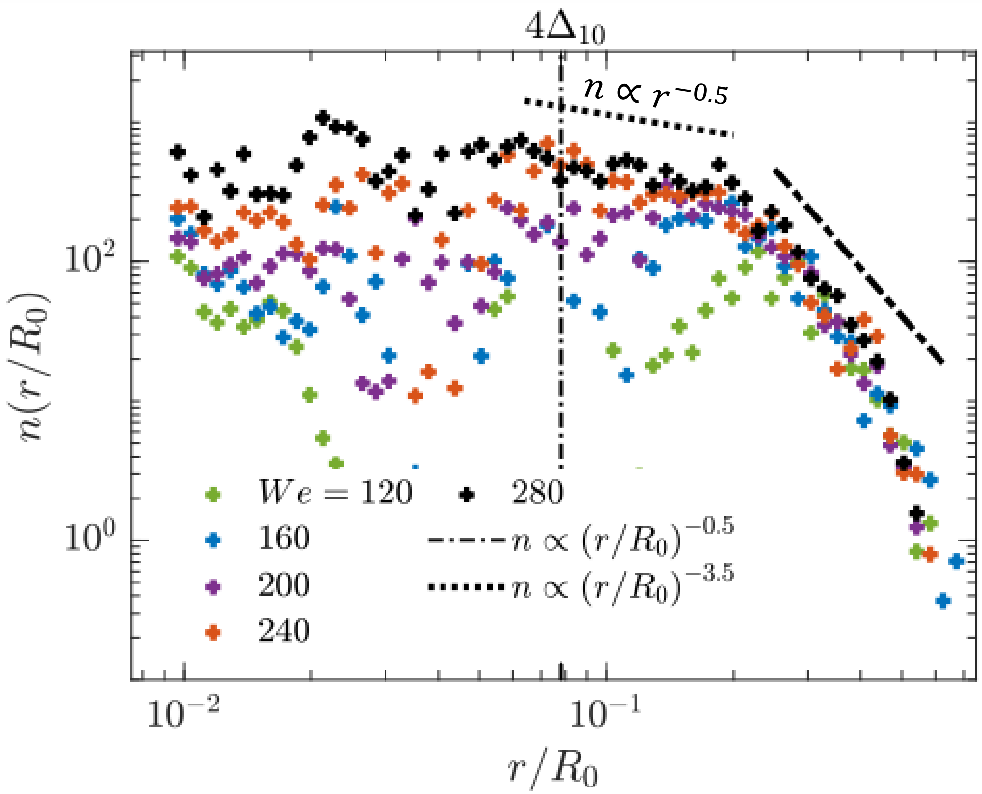
Competition of two timescales (quasi-steady):

Ligament merging $\Delta t_{\text{merge}} \propto N_{\text{lig}}^{-2}$

Drop shedding $\Delta t_{\text{shed}} \propto \sqrt{\rho_l w_{\text{lig}}^3/\sigma}$



Ligaments merging on the corrugated rim

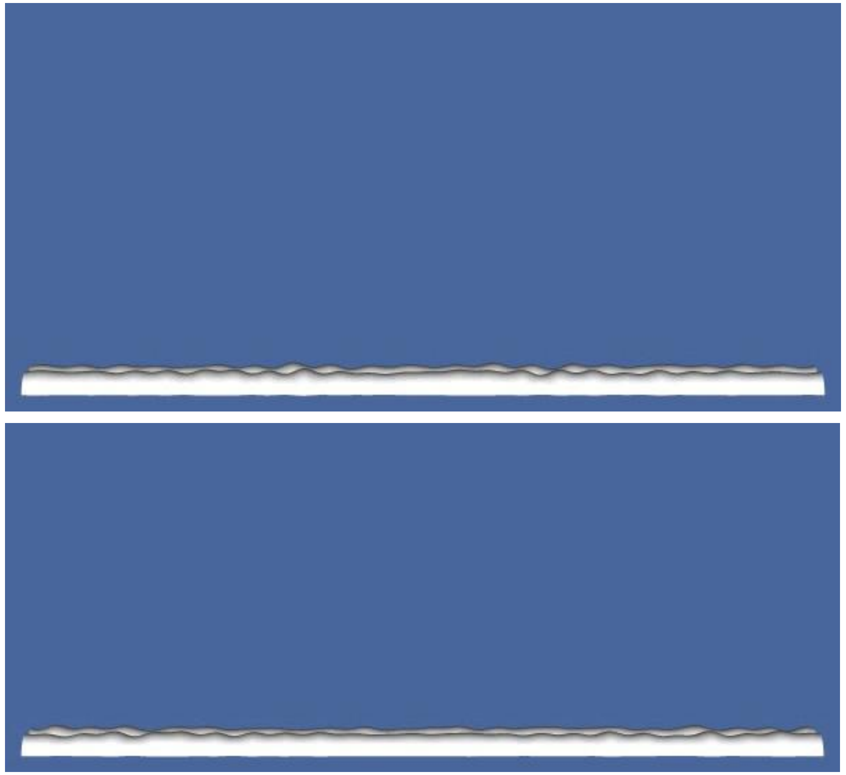


Fragment size distributions at different We

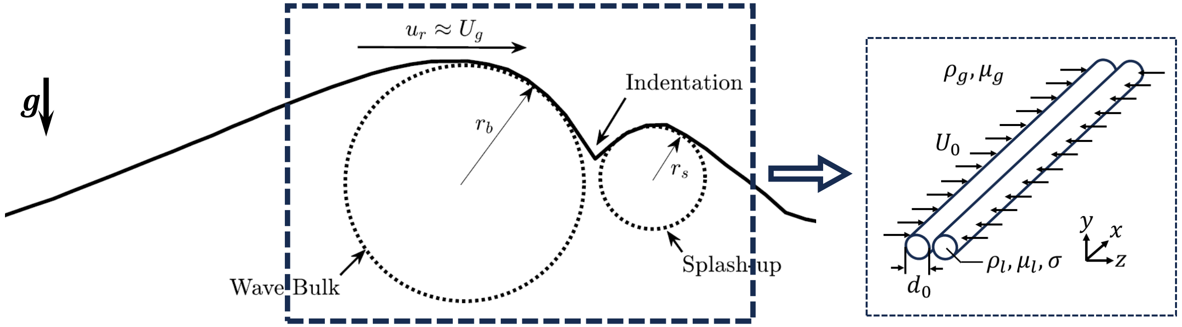
[1] Y. Wang & L. Bourouiba. 2018.

Influence of Gravity

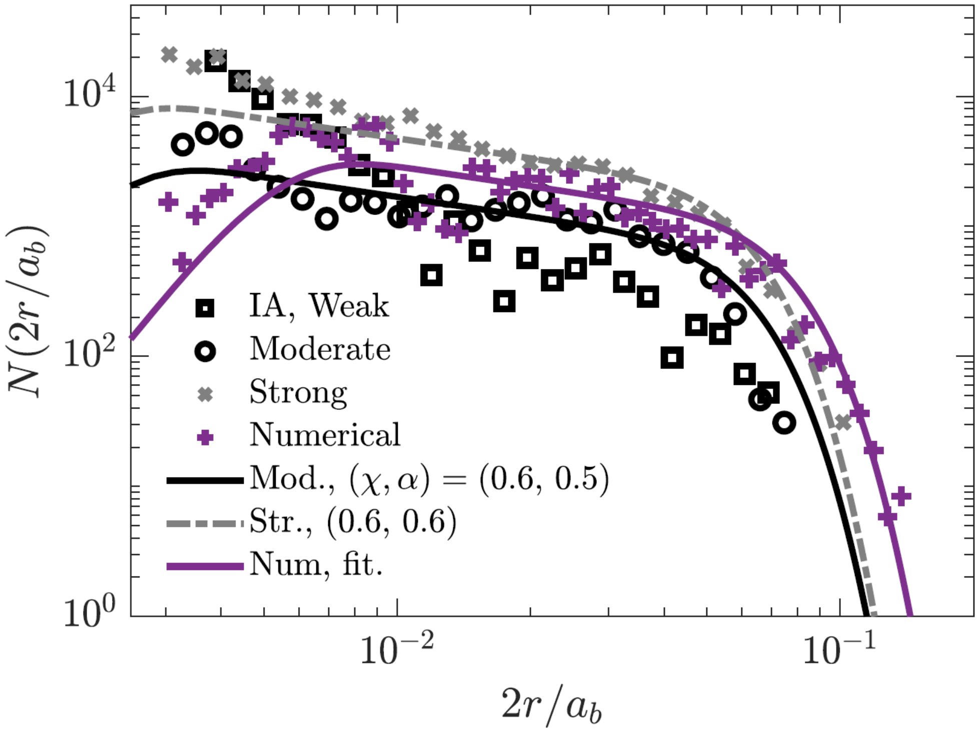
- Retraction timescale t_R
- Other dynamics unaffected
- Size distribution model predicts wave splashing data



Rim splashing without (top) and with (bottom) gravity

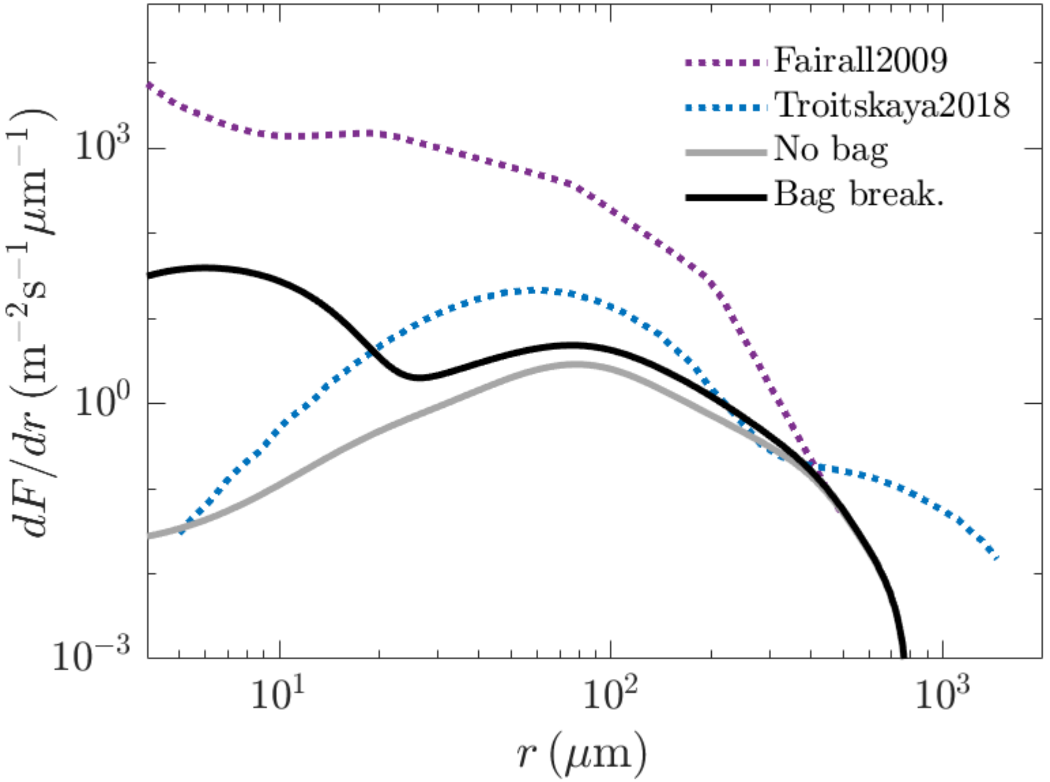


$$We = \alpha^2 \chi Bo_b S_b, \qquad Bo = \chi^2 Bo_b S_b^2$$
$$U_r = \alpha U_g, \qquad d_0 = \chi a_b$$

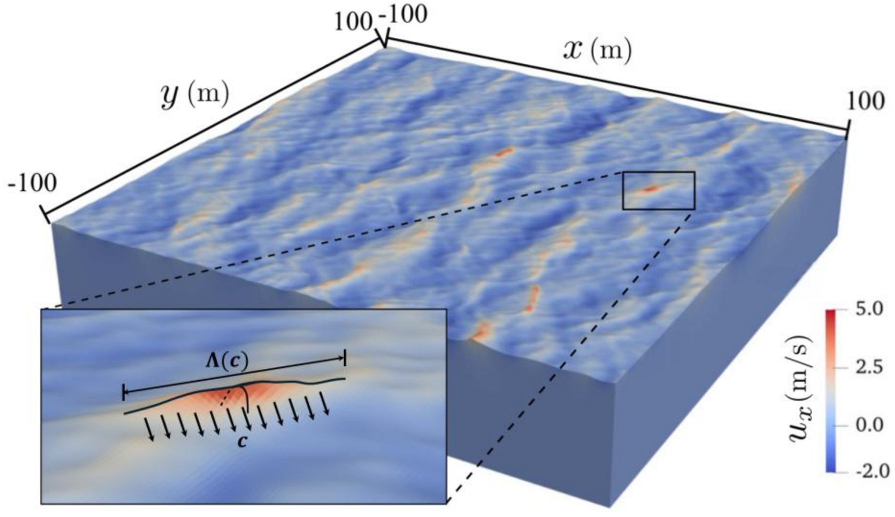


Fragment size distributions of secondary wave splashing [1] and rim splashing

SSGFs for Wave Splashing



SSGFs for wave splashing (grey and black curves), in comparison with previous results (dotted curves) [1]



A realistic sea state with wave breaking [2]

- Prerequisites
  - Distribution of breaking wave crest lengths $\Lambda(c)$ [2]
  - Splash size distribution $N(r, t_R)$
- Splash drop SSGFs
  - Contribution from splashing not negligible [1]
  - Secondary breakup
  - Finite fragment lifetime
- New possibilities and motivating observational studies

[1] F. Veron, 2015.
[2] J. Wu *et al.*, 2023.
[3] Y. Troitskaya *et al.,* 2018.

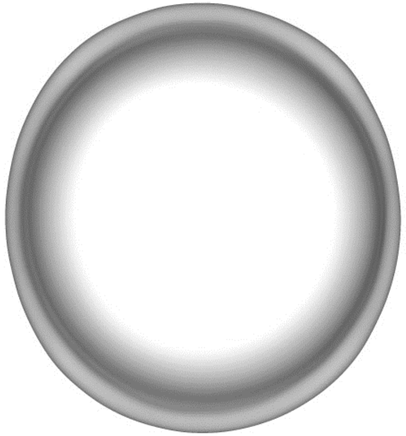
Conclusions

Droplet Bag Breakup

- Controlled bag film perforation;
- Physically-based fragment statistics;
- Good agreement with experiments:
  Rim collision and destabilization,
  Ligament and node breakup.

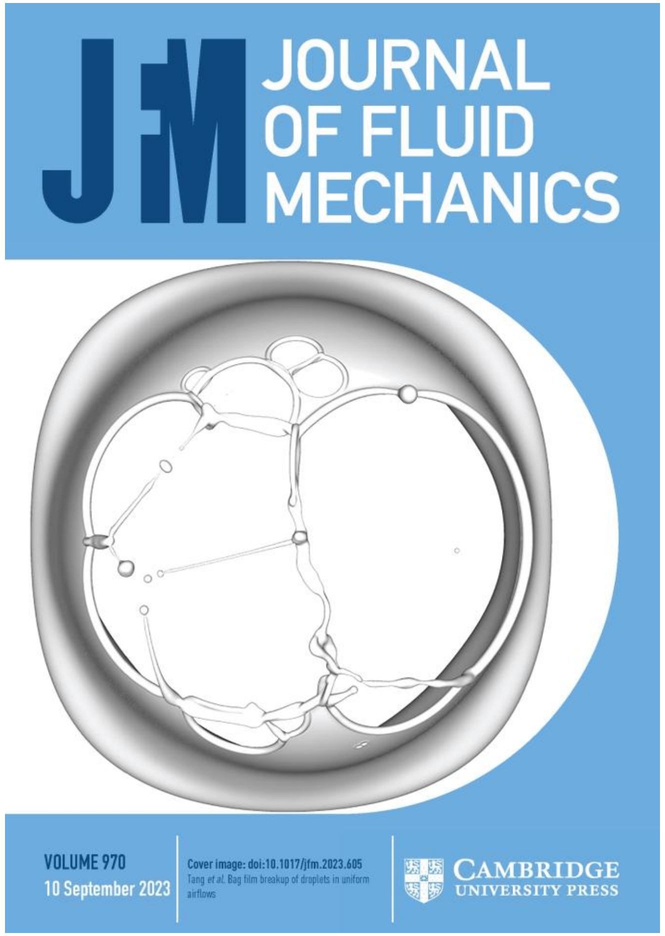
Rim Collision

- Scaling for ligament dynamics;
- Predicting fragment size distribution;
- Calculating wave splashing SSGFs:
  Arresting effects of gravity,
  Agreement with breaking wave statistics.

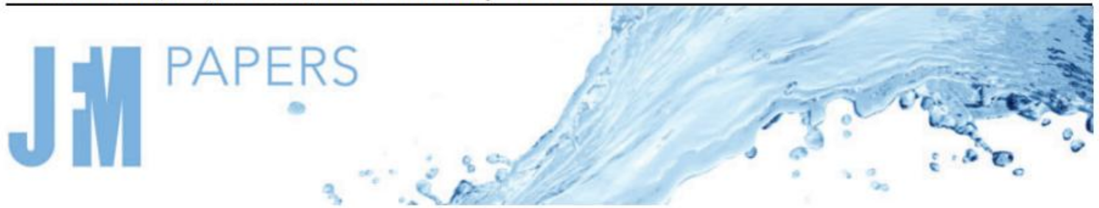


Acknowledgments

- EPSRC for accessing the UK supercomputing facility ARCHER2 via the UK Turbulence Consortium (EP/R029326/1)
- Oxford Advanced Research Computing (ARC) facility



J. Fluid Mech. (2024), vol. 987, A18, doi:10.1017/jfm.2024.392



Fragmentation of colliding liquid rims

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Editors' Suggestion

Droplet bag formation in turbulent airflows

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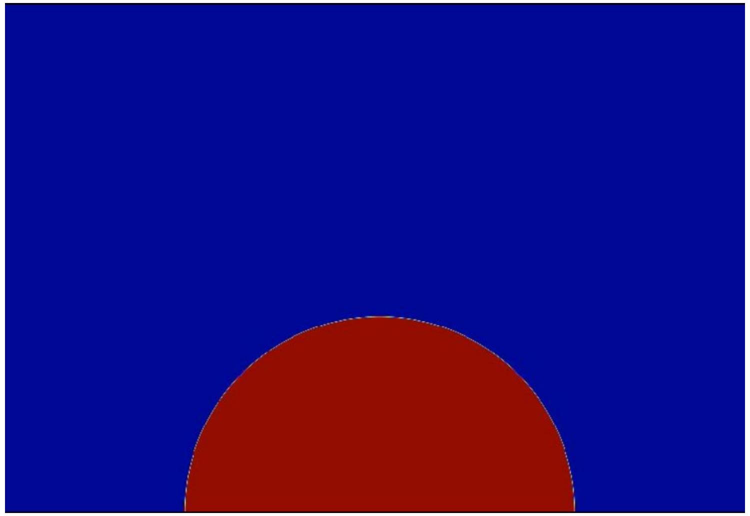
Thanks for your attention!

Future Work

- Fully resolved bag perforation at higher resolution
  - Validation against experiments
- Bag size distribution at the wind-sheared ocean surface
  - Development of physically informed SSGFs for spume drops
- Effects of surfactants, evaporation, etc.
  - Accounting for spume generation with realistic sea states



Surfactants suppress late-time bag growth [3]

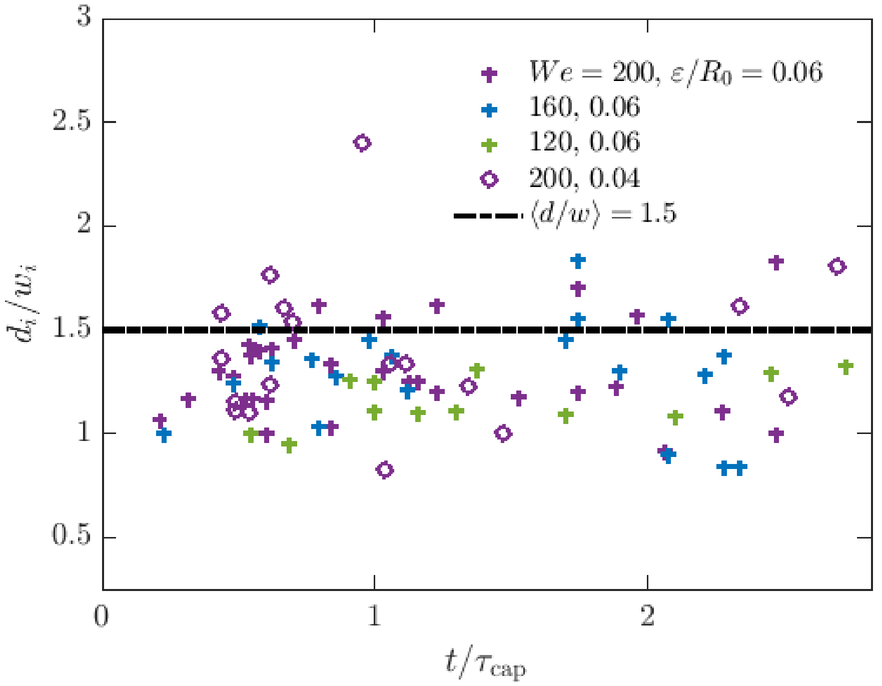
Thanks for your attention!

Acknowledgments

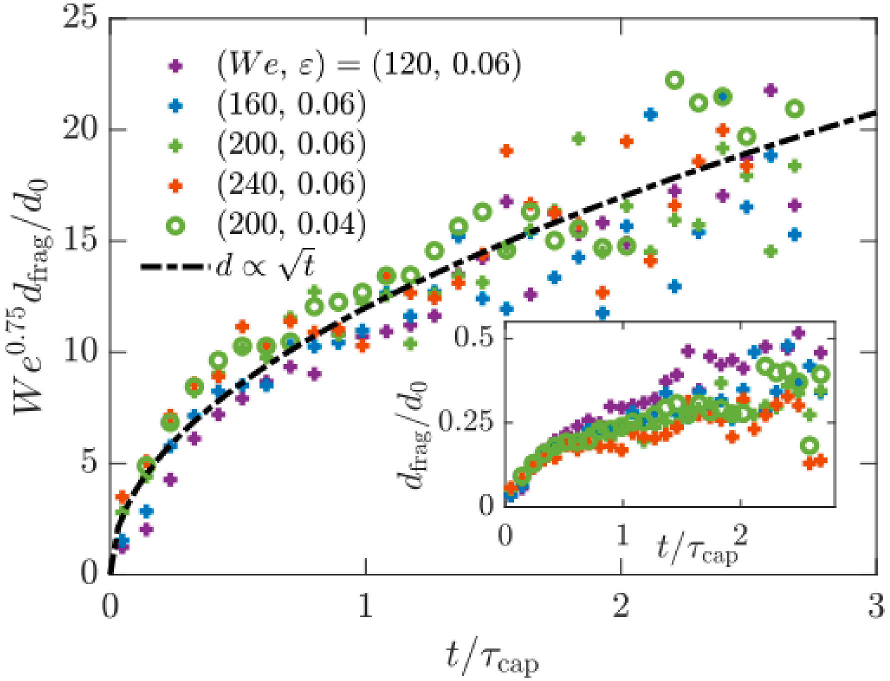
- EPSRC for the UK supercomputing facility ARCHER2 via the UK Turbulence Consortium (EP/R029326/1)
- Oxford Advanced Research Computing (ARC) facility

Ligament Merging Phenomena

$$w_{\text{lig}} \approx 0.67 d_{\text{frag}} \propto b_{\text{rim}} \propto \sqrt{t}$$



Fragment diameter d_i / parent ligament width w_i



Evolution of averaged fragment size

[1] Y. Wang & L. Bourouiba. *Journal of Fluid Mechanics*, 2018.
[2] J. M. Gordillo & F. J. Blanco-Rodríguez. *Physical Review Fluids*, 2023.

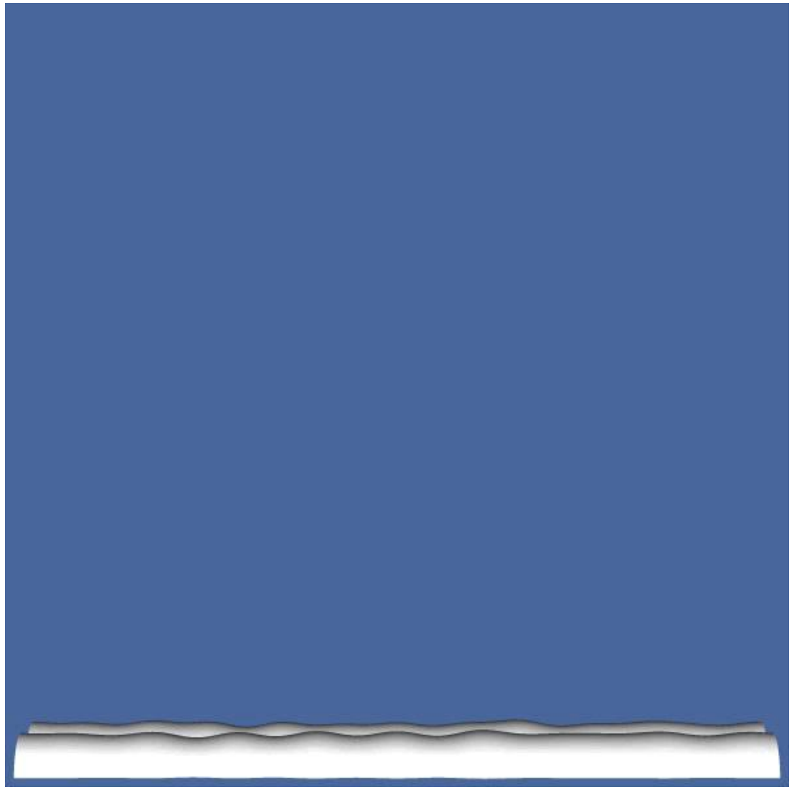
Modelling Fragment Size Distributions

Right tails evolve over time

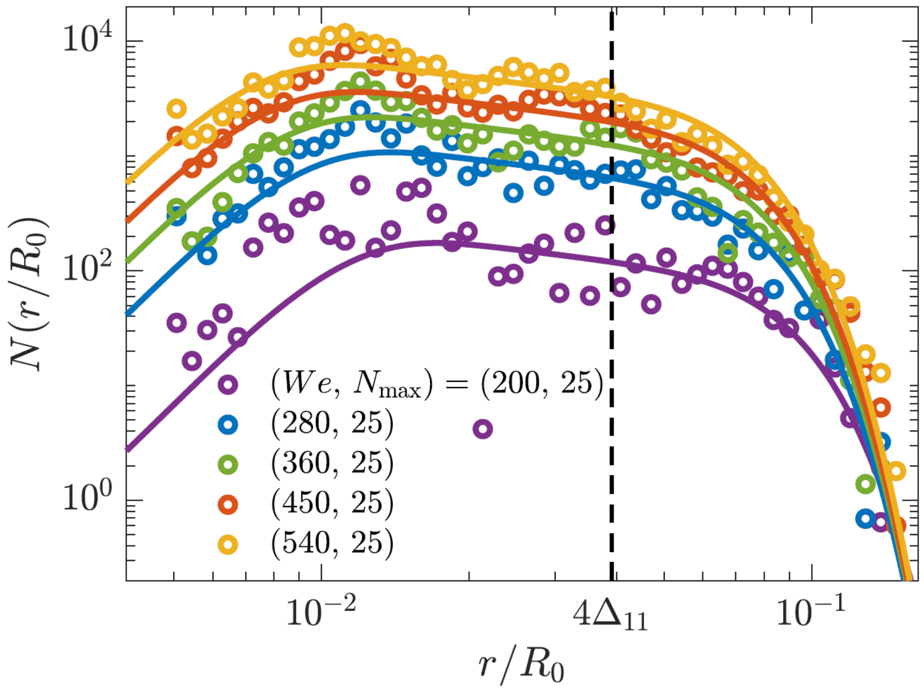
Modelled assuming time-dependent ligament width distributions

End-pinching dynamics

Predicting the full size distribution $N(r, t)$ for any We

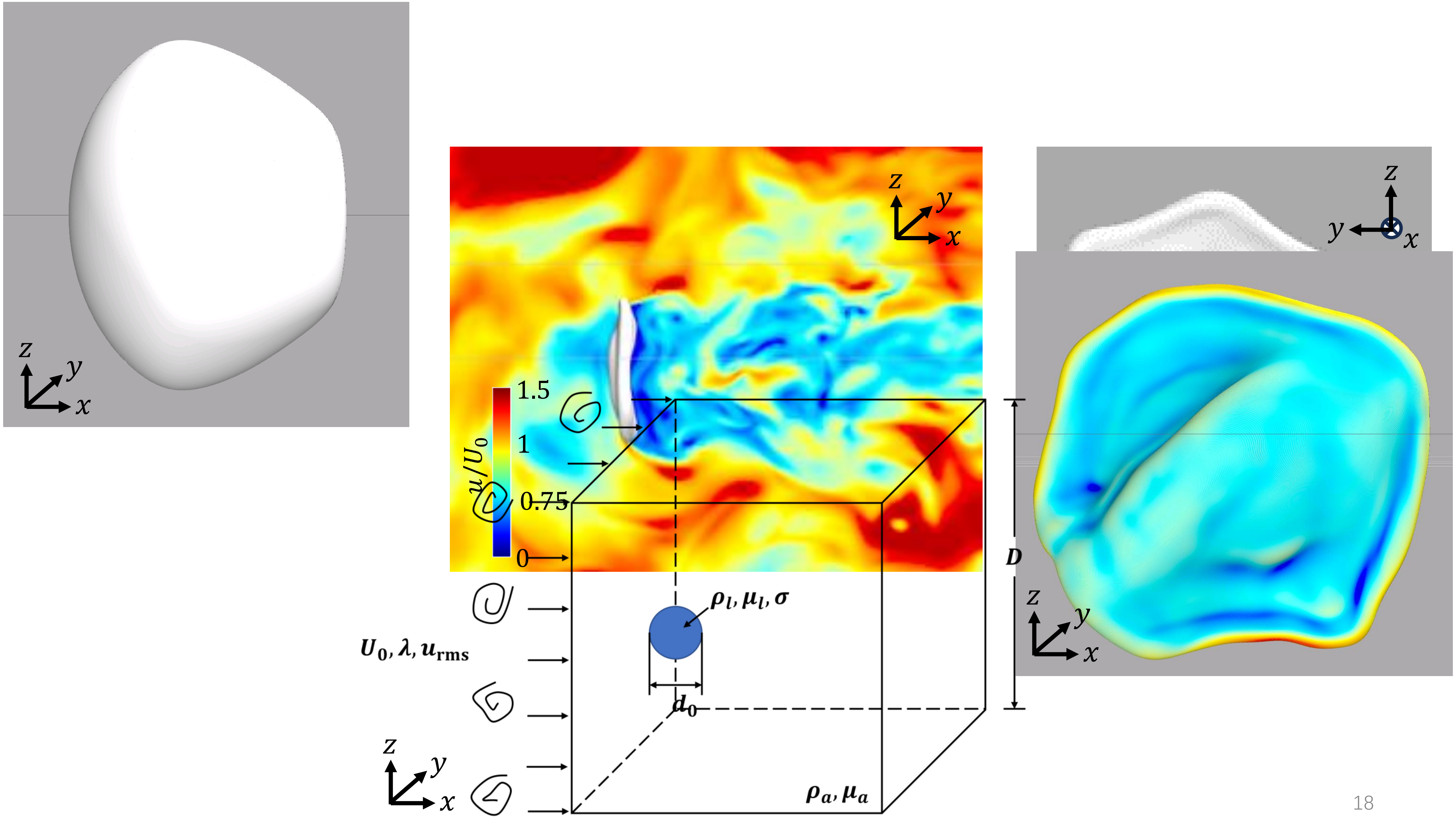


Ligaments merging on the corrugated rim



Numerical measurements of fragment size distributions in comparison with theoretical predictions

[1] Y. Wang & L. Bourouiba. *Journal of Fluid Mechanics*, 2018.


z
y
x
1.5
1
0.75
0
u/U_0
ρ_l, μ_l, σ
U_0, λ, u_{rms}
d_0
D
ρ_a, μ_a