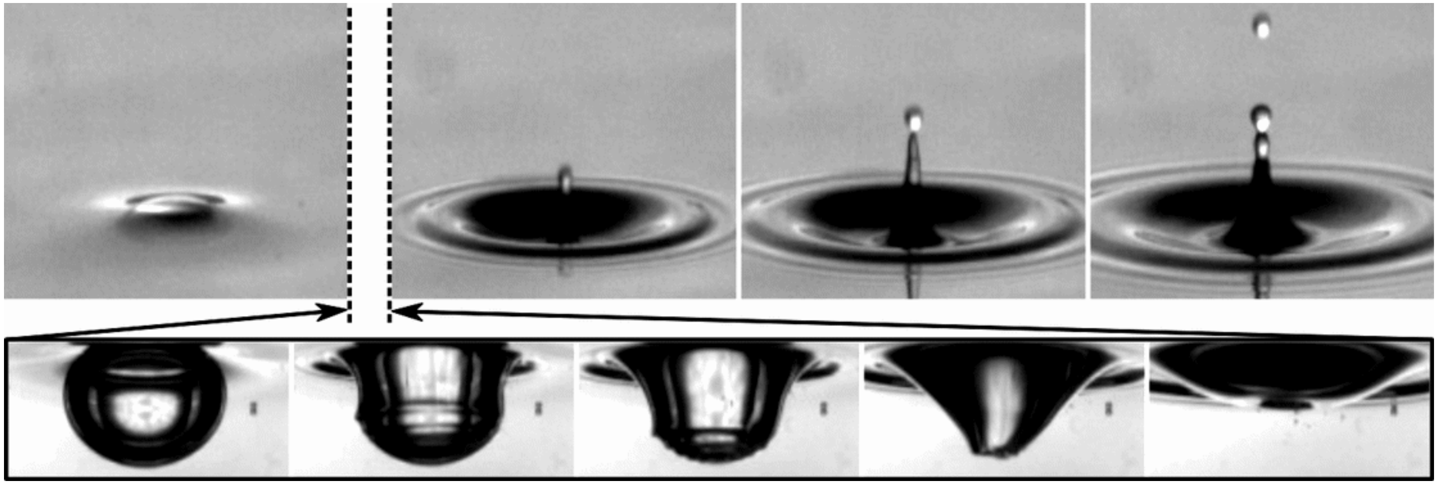


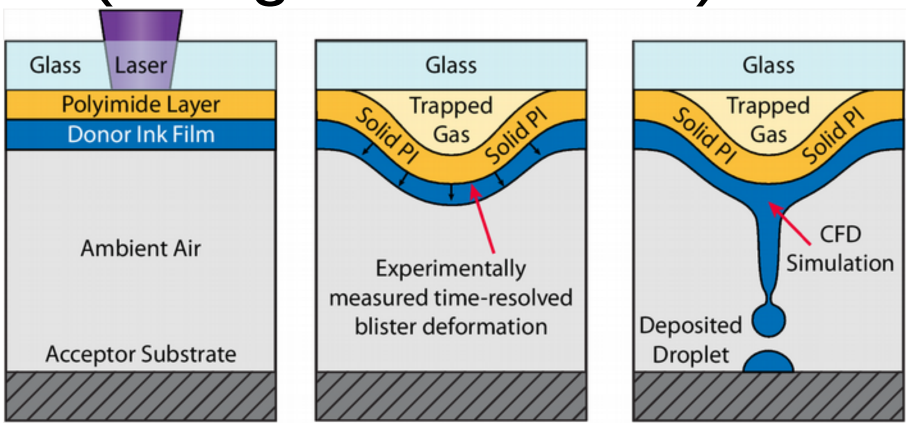
Jets and droplets from bursting bubbles

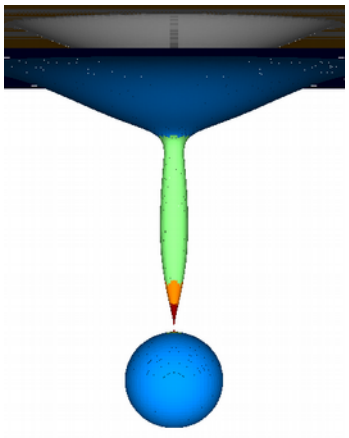
Frederik Brasz, Casey Bartlett, Peter Walls,
Elena Flynn, Estella Yu, James Bird
Boston University

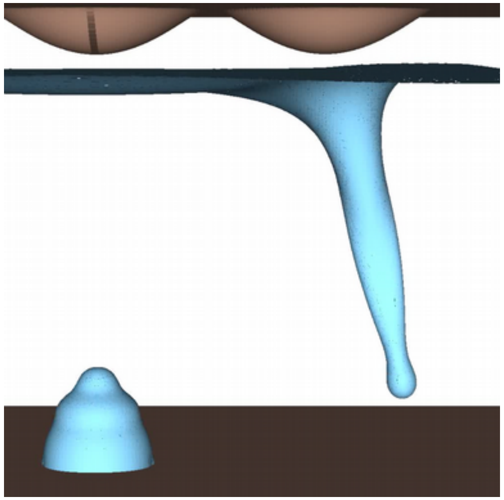
Basilisk/Gerris User's Meeting
Princeton, NJ
November 15, 2017

Introduction

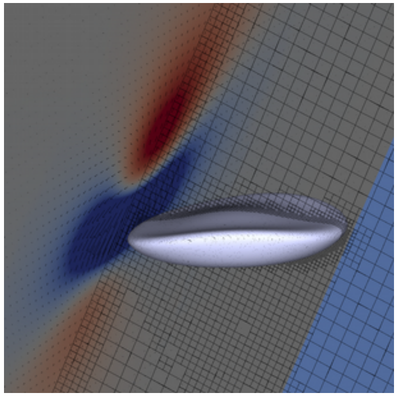
- Started using Gerris for my PhD work here in Princeton (Craig Arnold's lab) in 2012



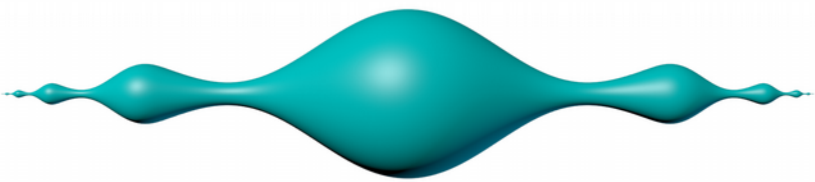




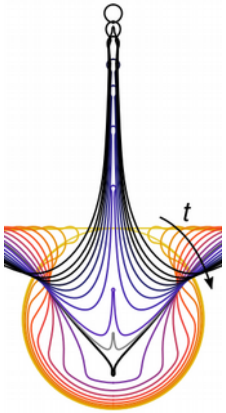
- Started postdoc at BU (Jacy Bird's lab) August 2016



Rising bubbles beneath inclined walls

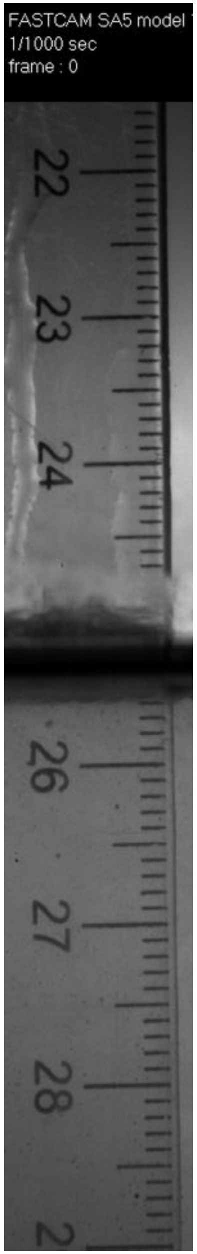


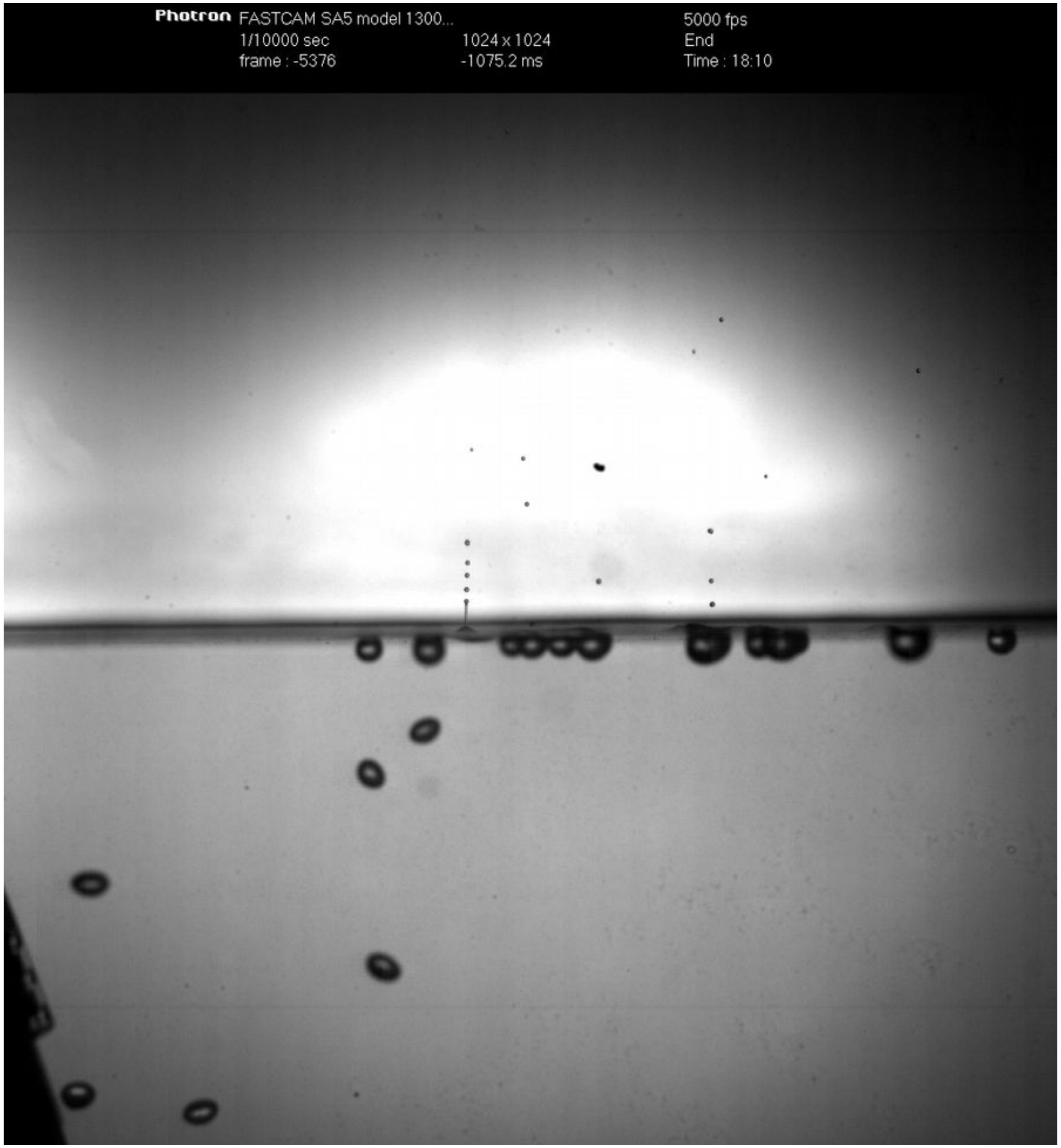
Self-similar breakup of liquid cones



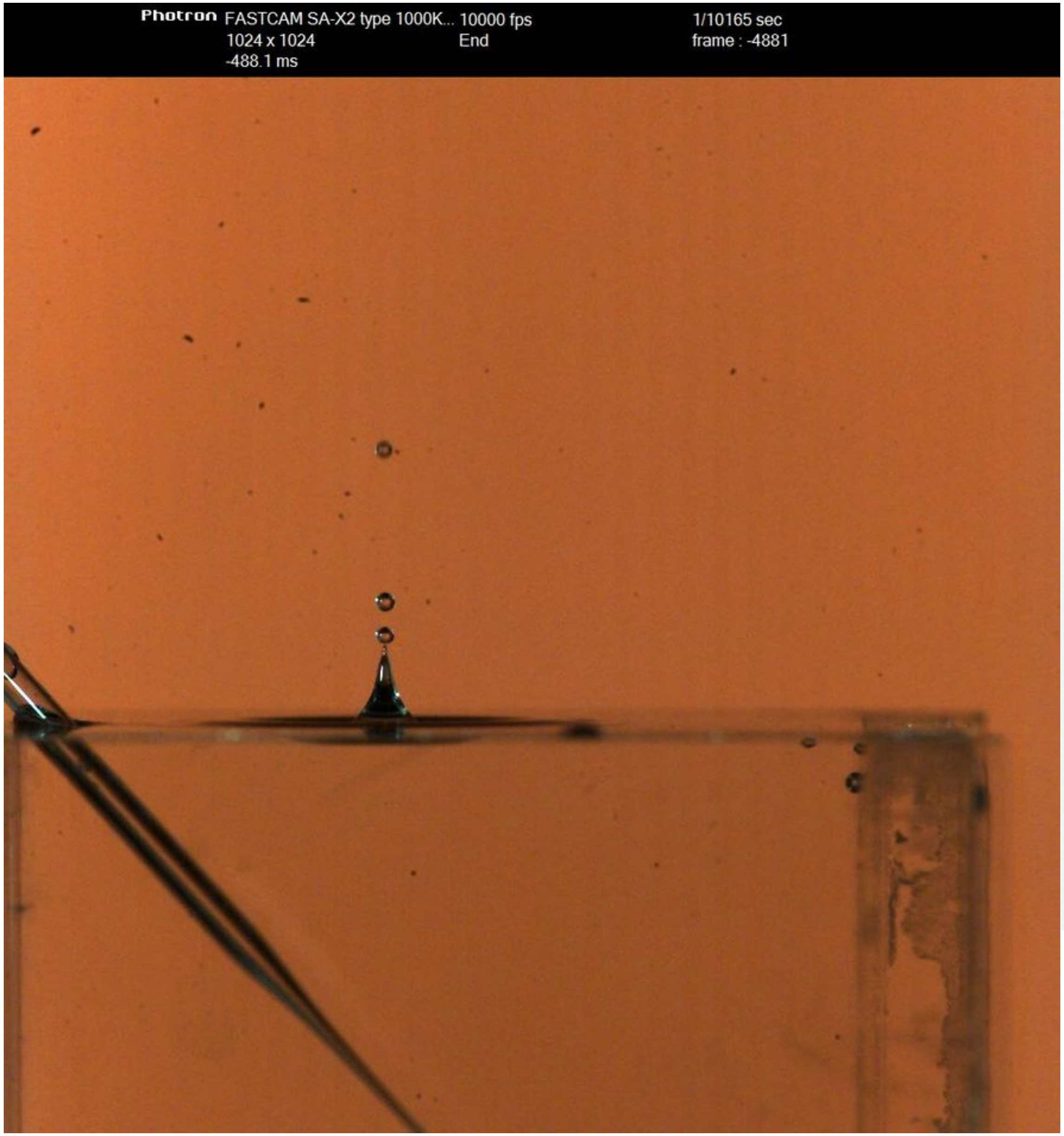
Jet drops from bursting bubbles

Jet drops from bursting bubbles





Jet drops from bursting bubbles



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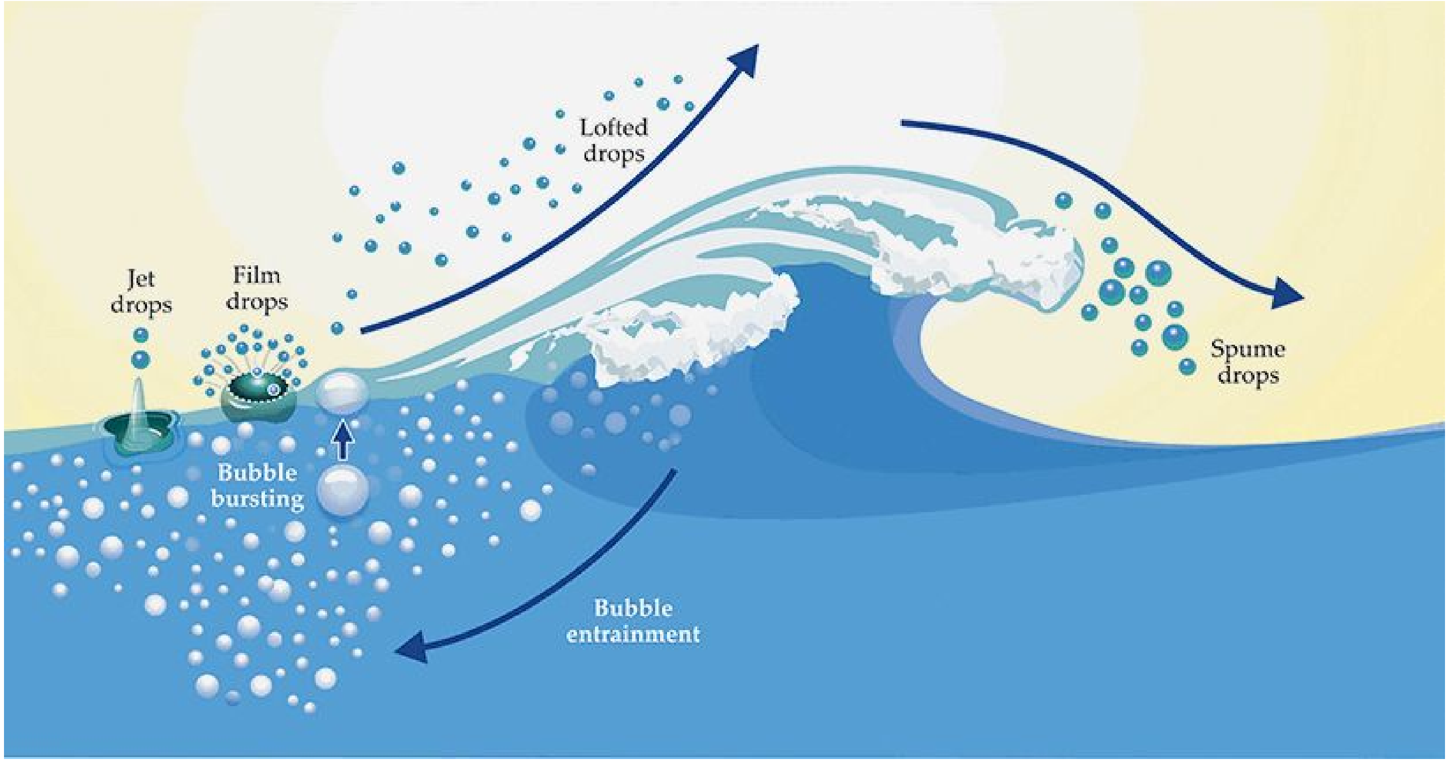
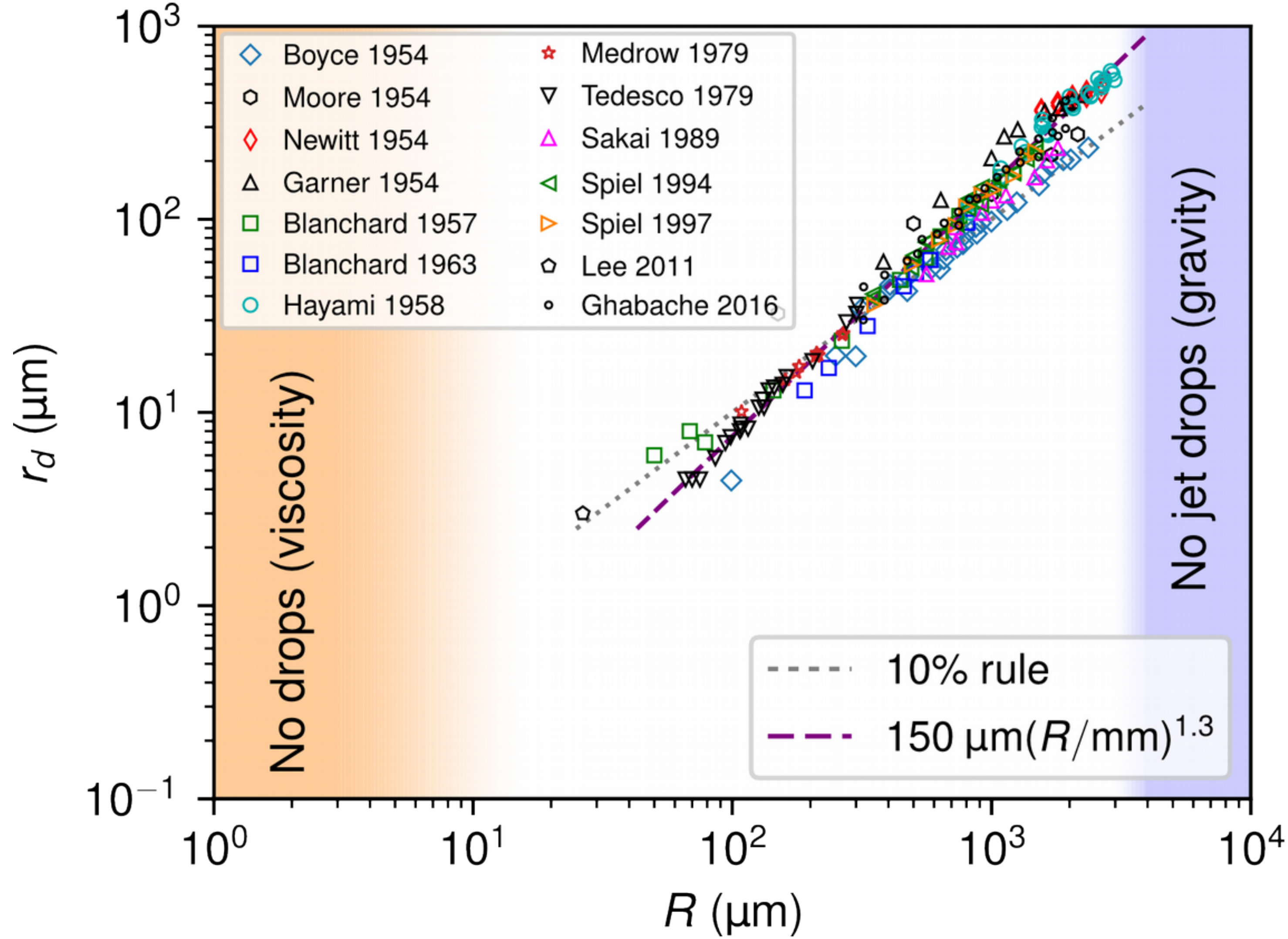
Motivation

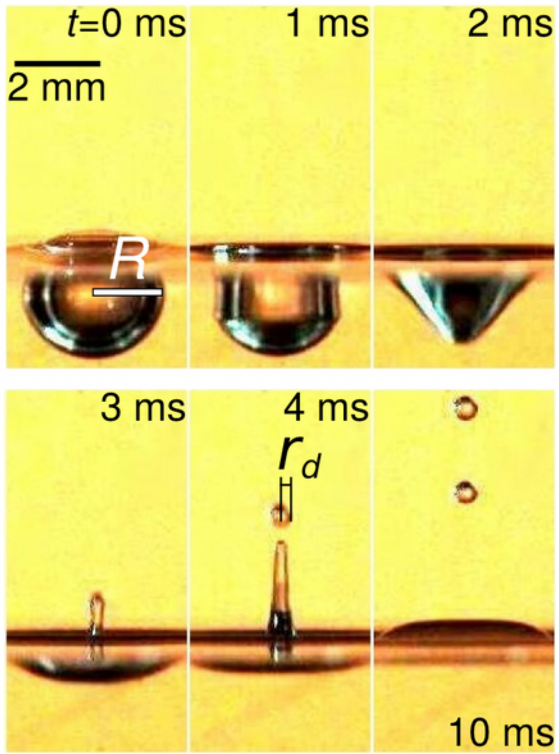
- Atmospheric science
  - Sea spray aerosol particles act as cloud condensation nuclei, scatter radiation
    - Still significant uncertainties in climate forcing by aerosols



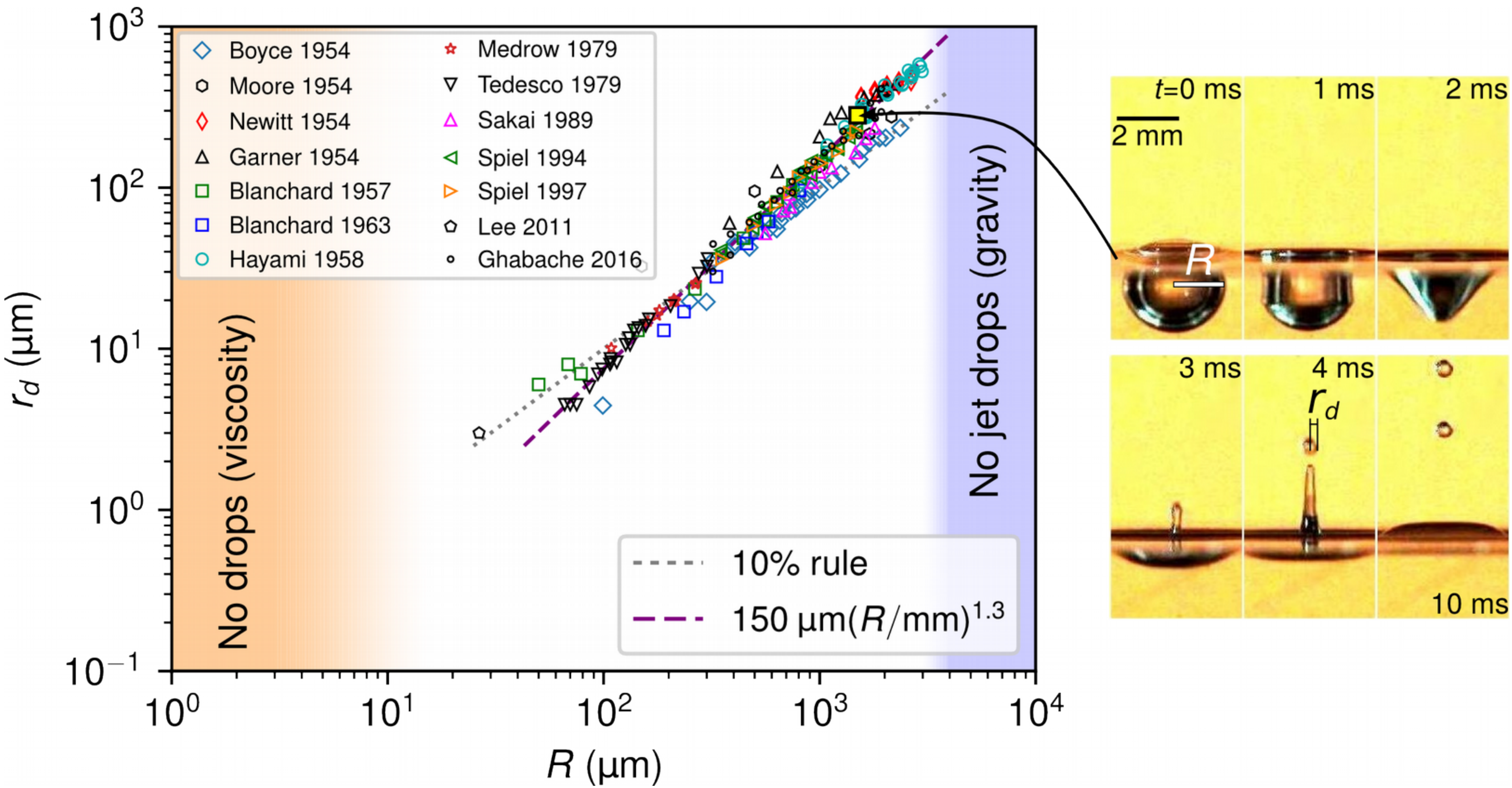
Richter & Veron 2016

Jet drop radius vs. bubble radius

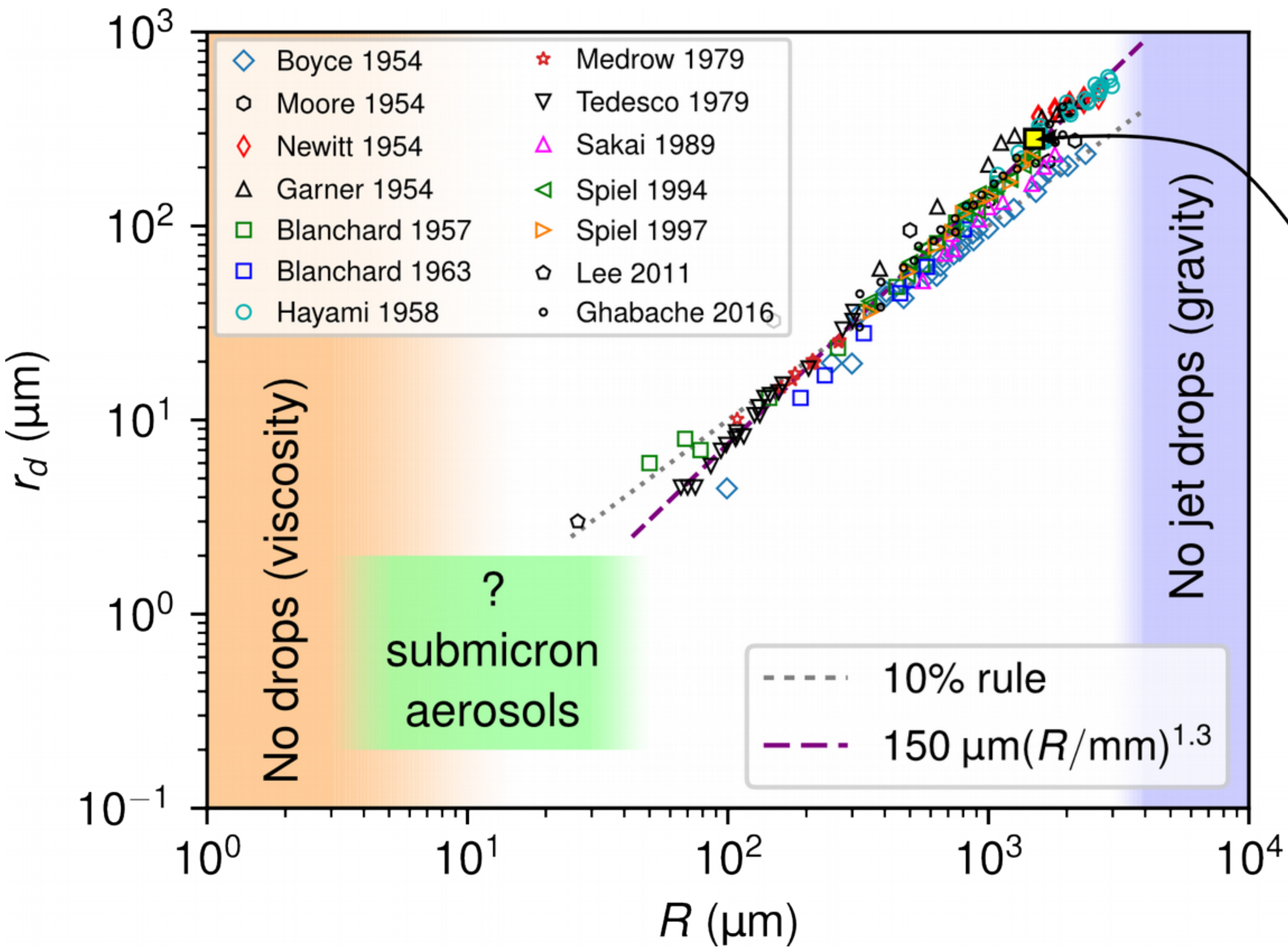


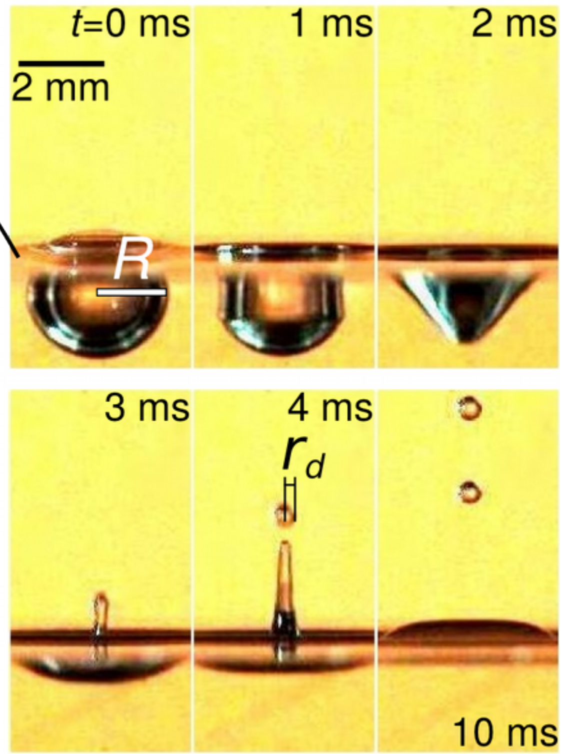


Jet drop radius vs. bubble radius



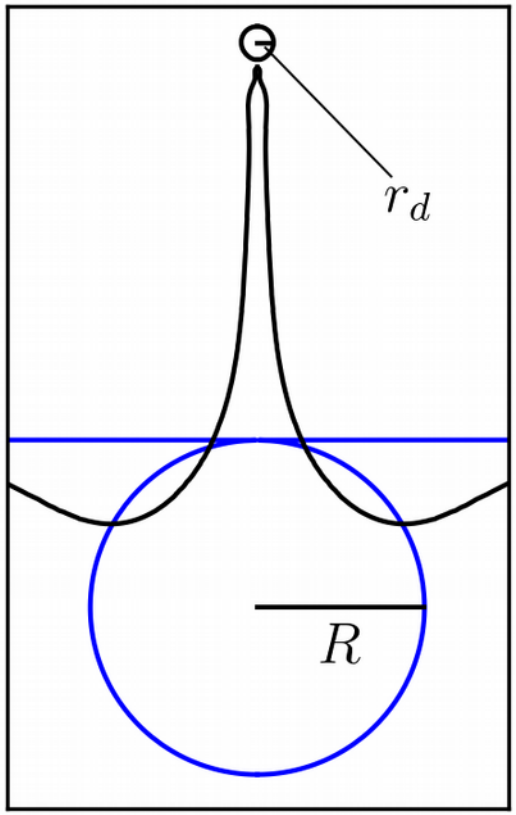
Jet drop radius vs. bubble radius





Dynamic similitude

- Nondimensionalization:
  - Length: R
  - Time: $\tau \equiv \sqrt{\rho R^3/\gamma}$
  - Neglect gravity (valid for $\mathrm{Bo} \lesssim 0.01$)
    $(\mathrm{Bo} \equiv \rho g R^2/\gamma \rightarrow R \lesssim 0.3\ \mathrm{mm})$
  - Only dimensionless parameter:
    Laplace number $\mathrm{La} \equiv \rho\gamma R/\mu^2$
    - Note: $\mathrm{La} = 1/\mathrm{Oh}^2$

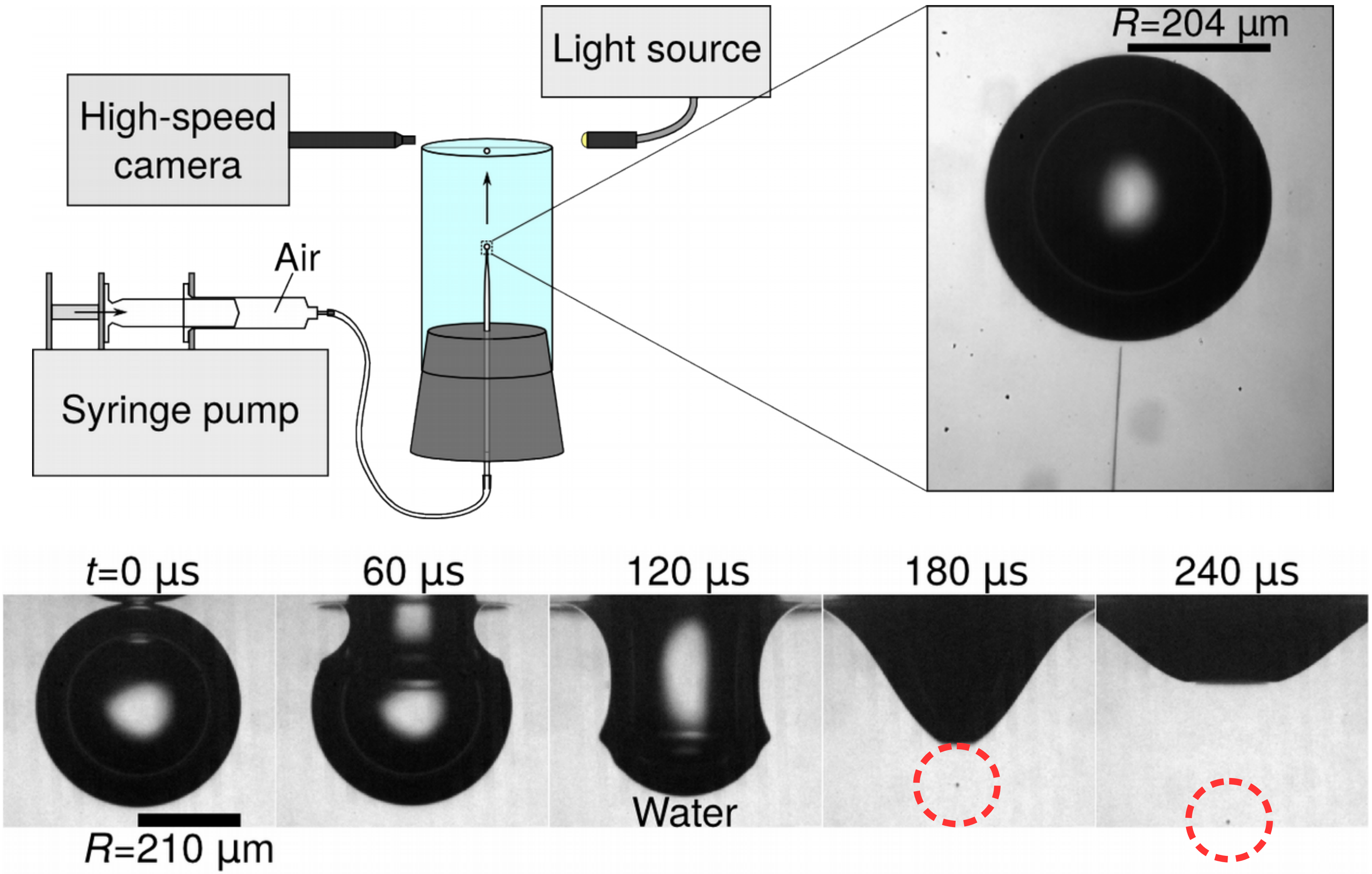


- **Increasing μ equivalent to decreasing R**

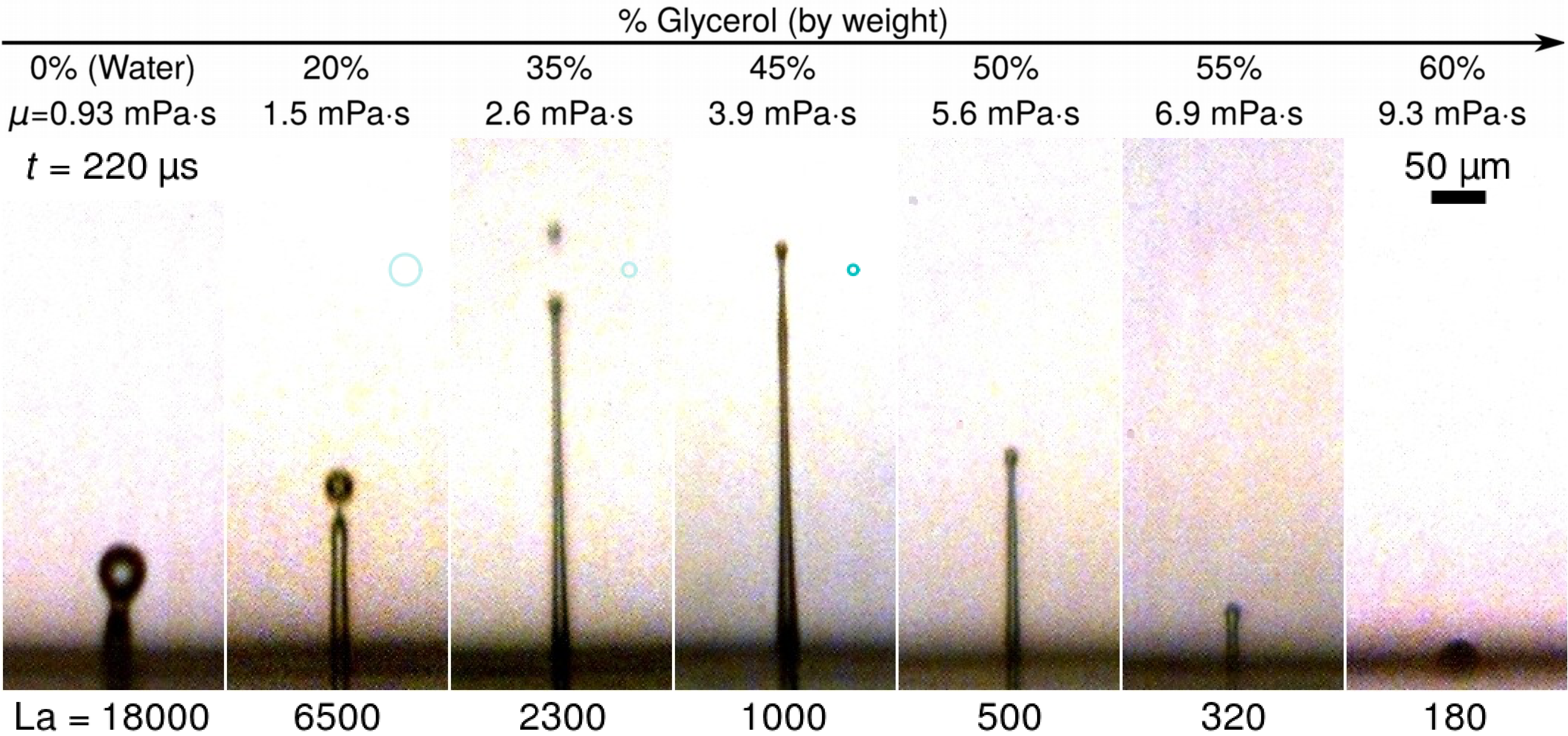
Density, surface tension, viscosity:
ρ γ μ

Bubble bursting experiments

- Use glycerol-water solutions of varying concentrations to change viscosity, keeping $R \approx 200\ \mu\mathrm{m}$

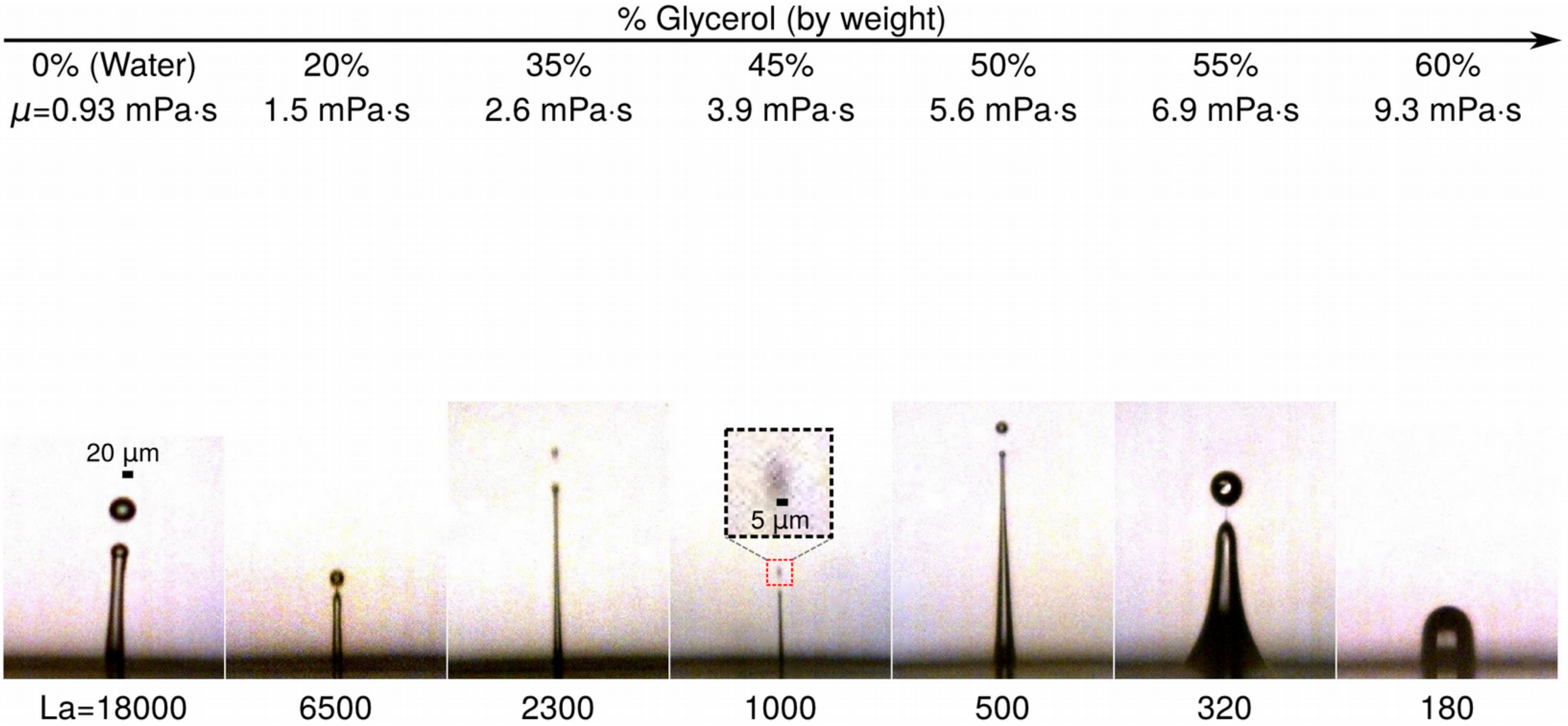


Bubble bursting experiments



- Non-monotonic relationship between size of the top jet drop and Laplace number

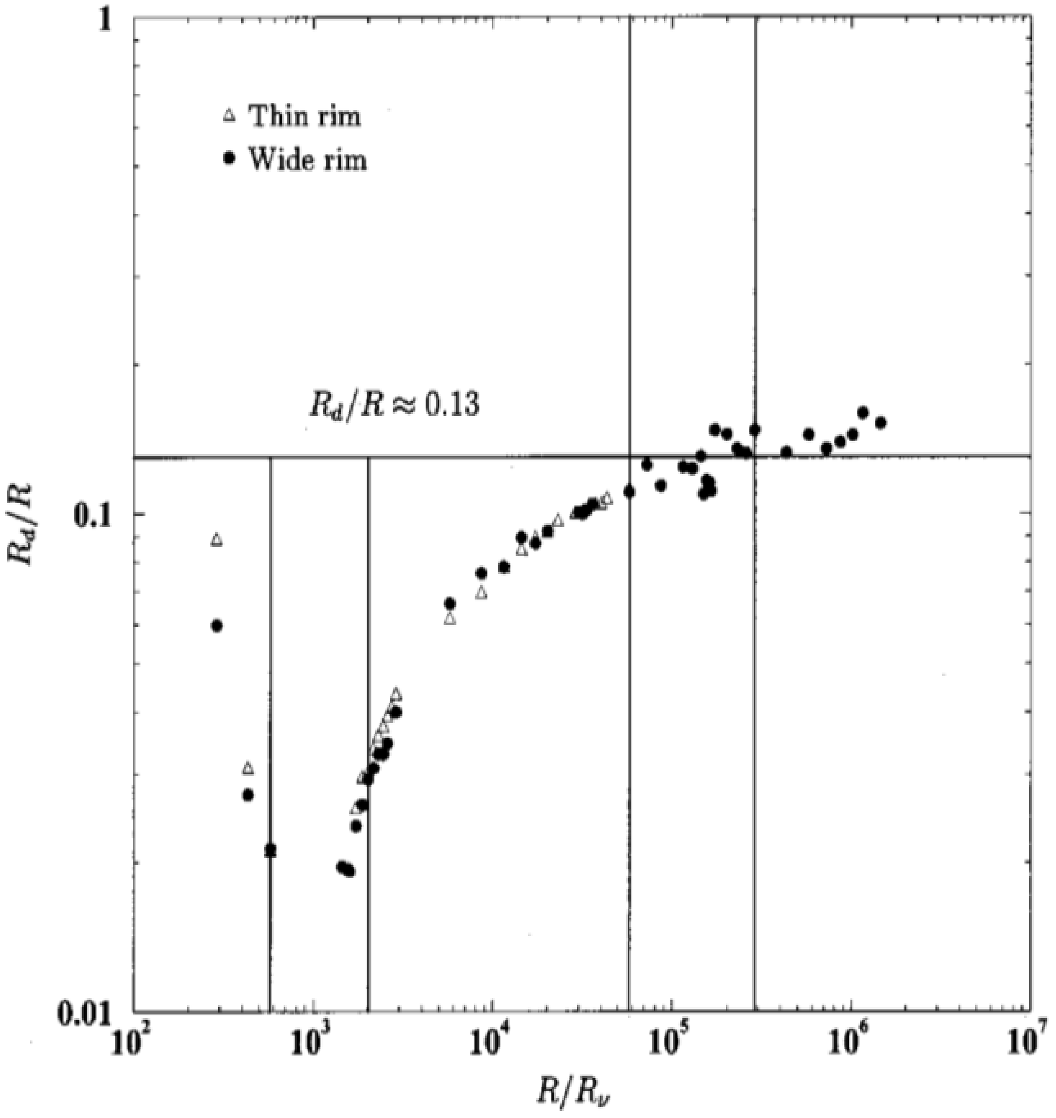
Bubble bursting experiments



- Non-monotonic relationship between size of the top jet drop and Laplace number

Previous simulations

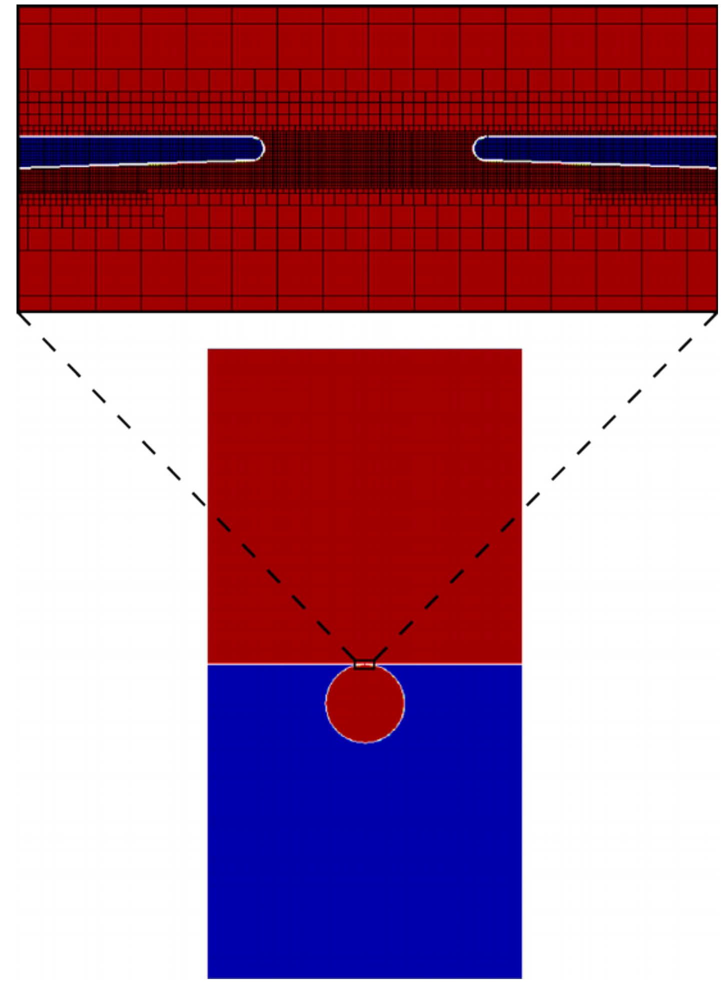
- Duchemin et al. 2002 also observed non-monotonic relationship in simulations
  - Limited resolution
  - Gap near minimum



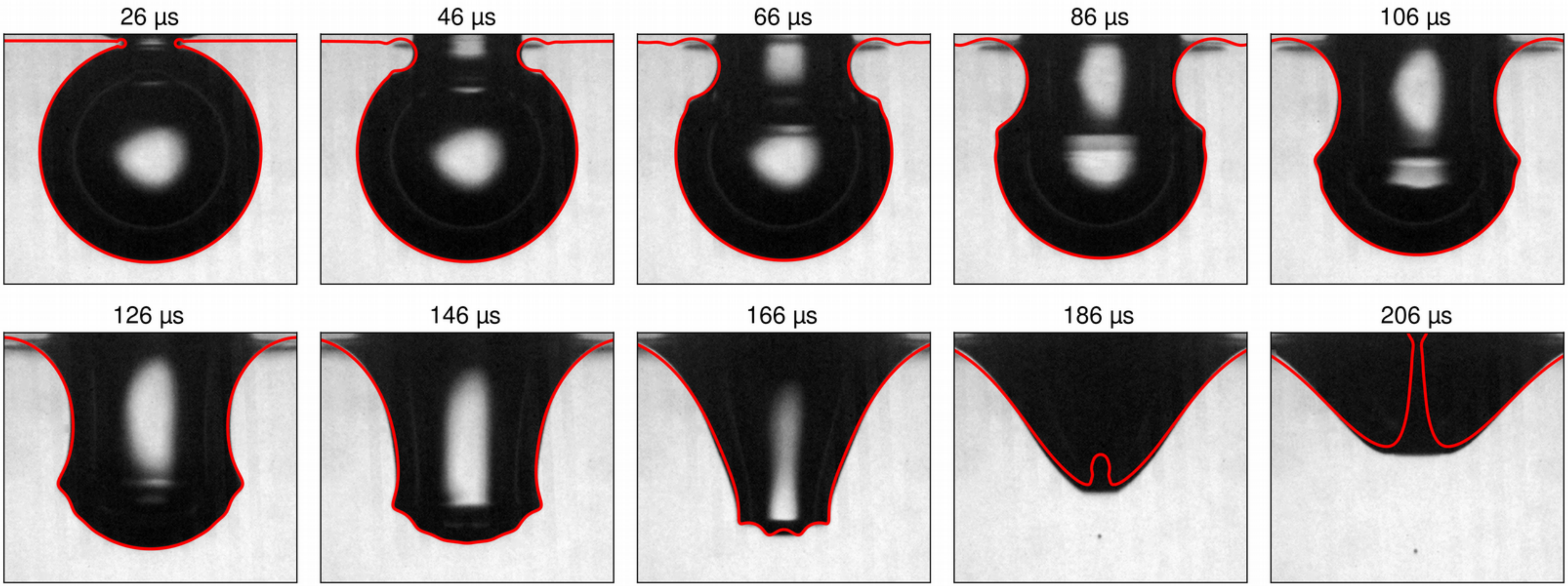
Numerical simulations

- Axisymmetric simulations run in Gerris
  - Adaptive mesh refinement in regions of high curvature, vorticity: max level 14
  - Minimum cell size = $2.4 \times 10^{-4} R$
- Initialized as spherical bubble with popped cap
  - Neglect gravity
- Vary La, fixing $\rho_g/\rho = 1.2 \times 10^{-3}$

  $\mu_g/\mu = 0.018$



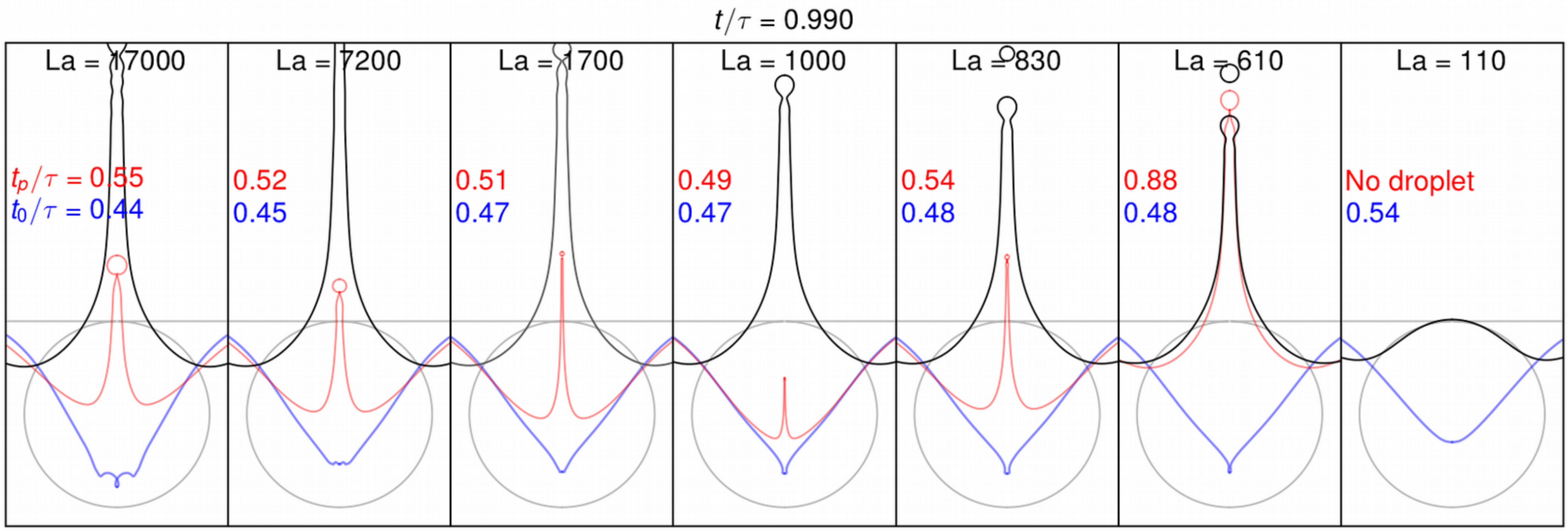
Validation



- Air bubble in water with $R = 210\ \mu\text{m}$

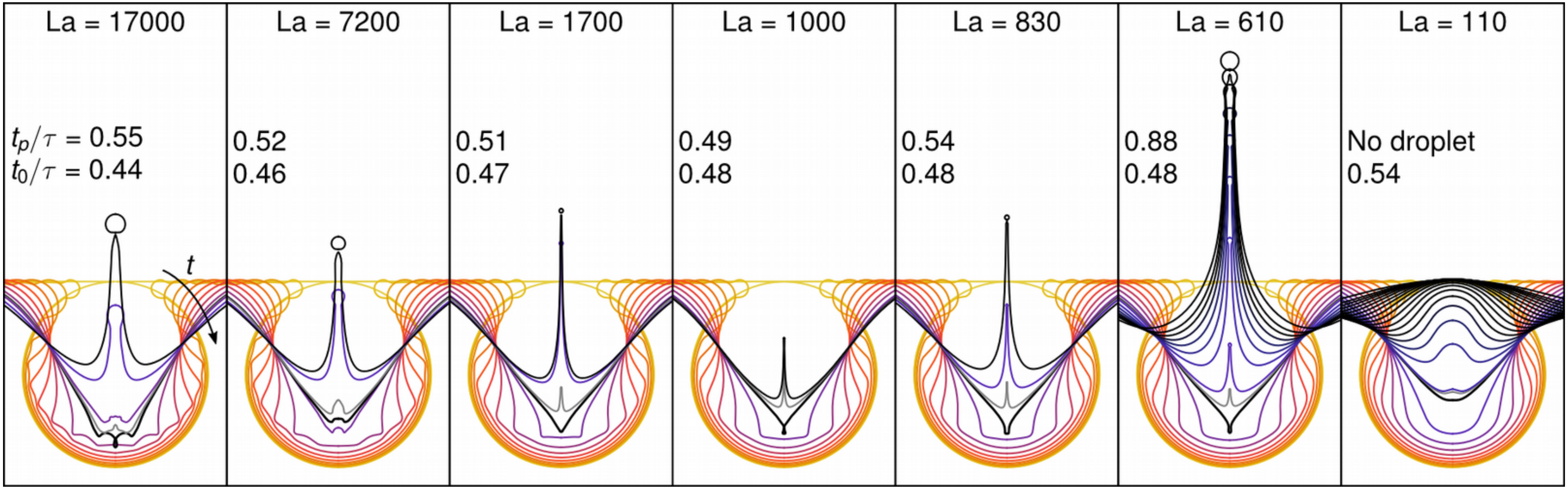
$(\text{La} = 18000)$

Simulation results



- Define inversion time t_0 as time when velocity of interface at center is maximum
  - Time of pinch-off t_p also labelled
- Same non-monotonic relationship

Simulation results



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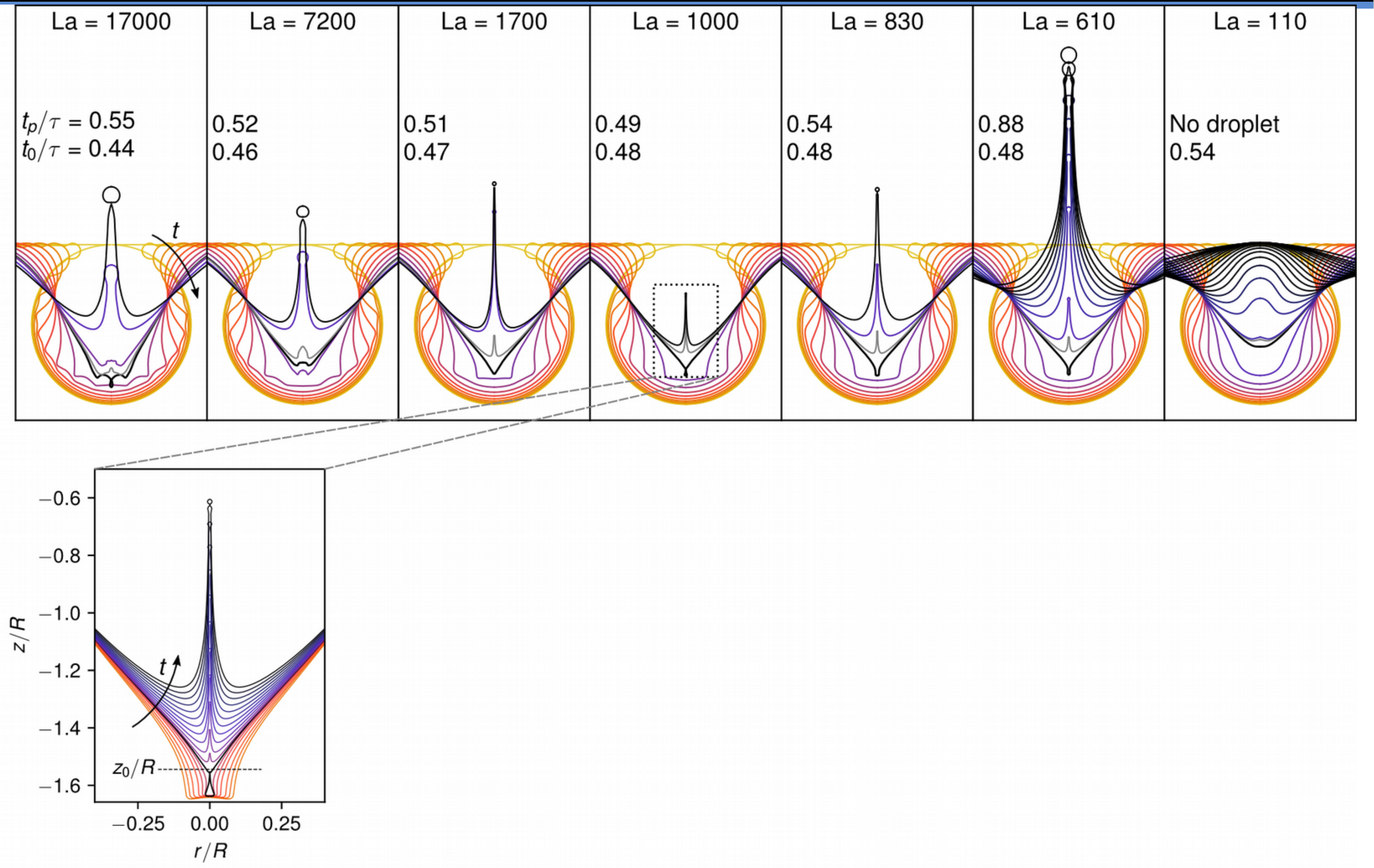
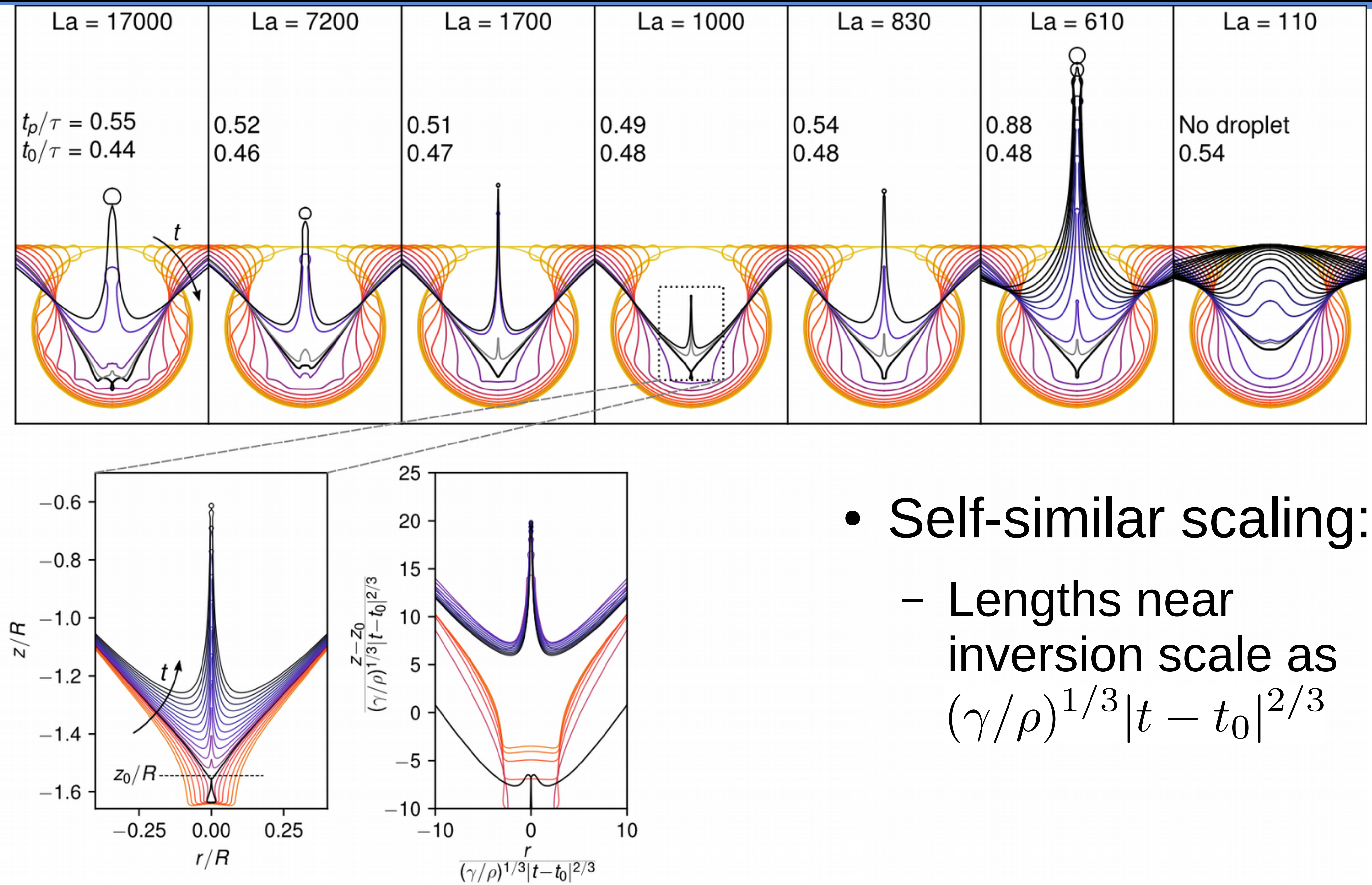
Self-similar jet growth

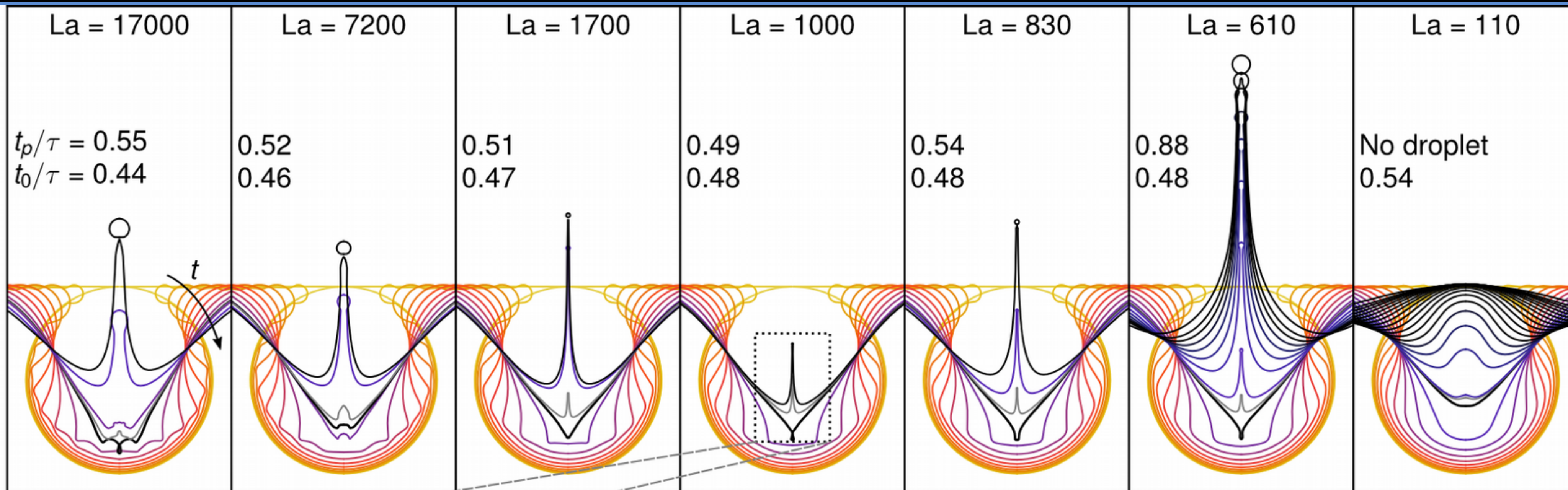


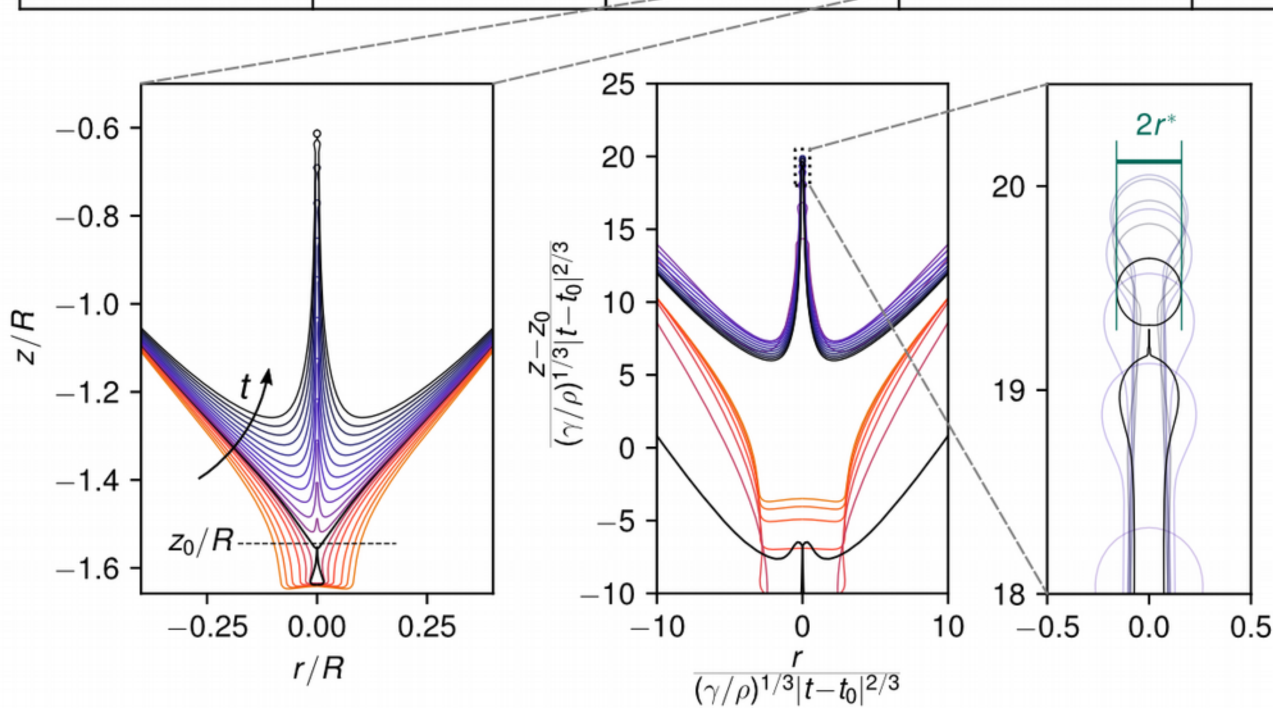
Self-similar jet growth



- Self-similar scaling:
  - Lengths near inversion scale as $(\gamma/\rho)^{1/3}|t-t_0|^{2/3}$

Self-similar jet growth

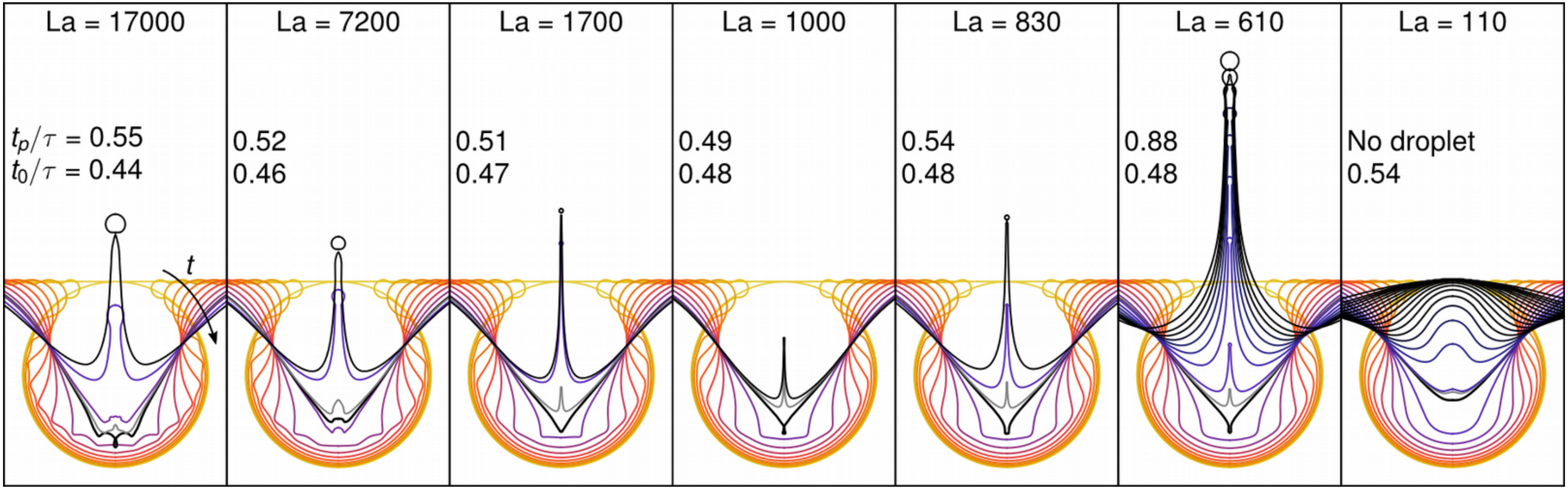




- Self-similar scaling:
  - Lengths near inversion scale as $(\gamma/\rho)^{1/3}|t-t_0|^{2/3}$

Self-similar jet growth

- Decompose drop size into
  - Shape factor $r^* \equiv r_d(\rho/\gamma)^{1/3}(t_p - t_0)^{-2/3}$
  - Jet growth time $t^* \equiv (t_p - t_0)/\tau$
- Then $r_d/R = r^*(\mathrm{La})(t^*(\mathrm{La}))^{2/3}$



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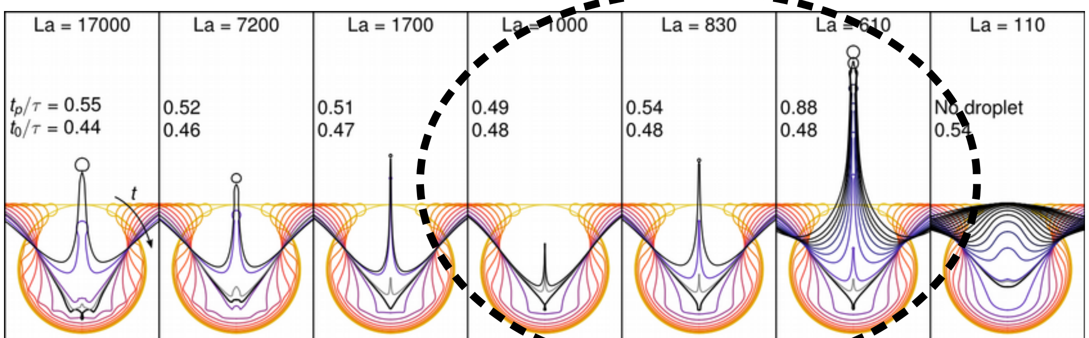

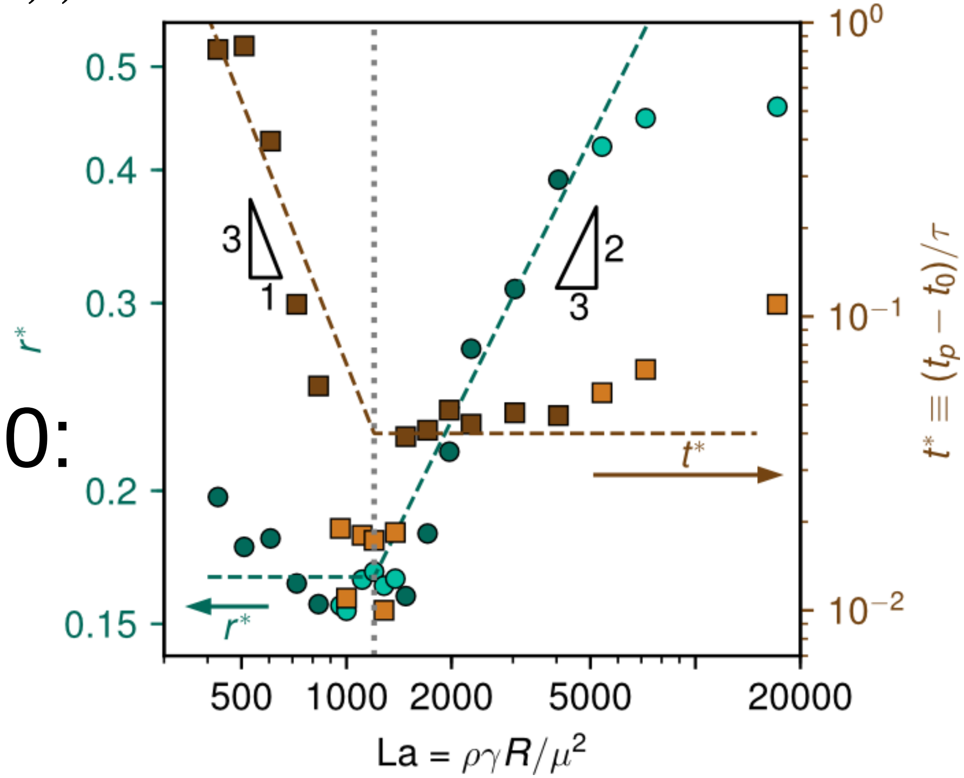

- As La decreases below 1200:
  - Viscosity delays pinch-off
  - Drop size increases with t^*

Self-similar jet growth

- Decompose drop size into
  - Shape factor $r^* \equiv r_d(\rho/\gamma)^{1/3}(t_p - t_0)^{-2/3}$
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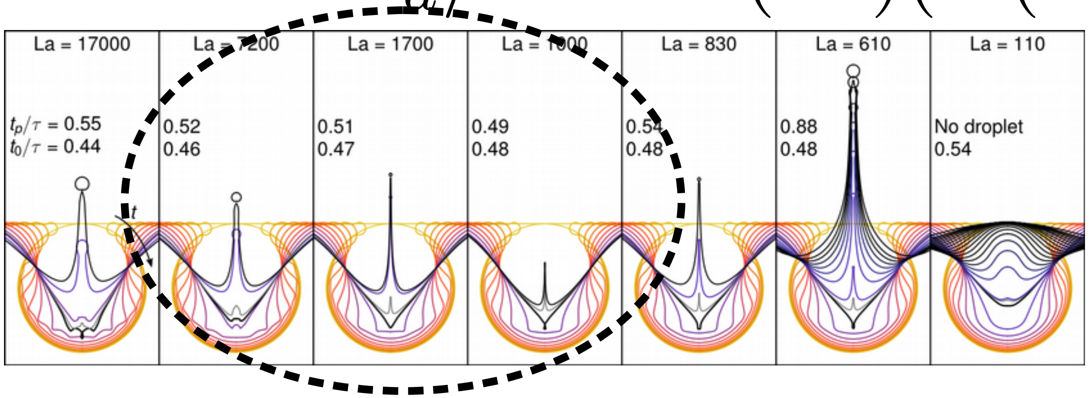
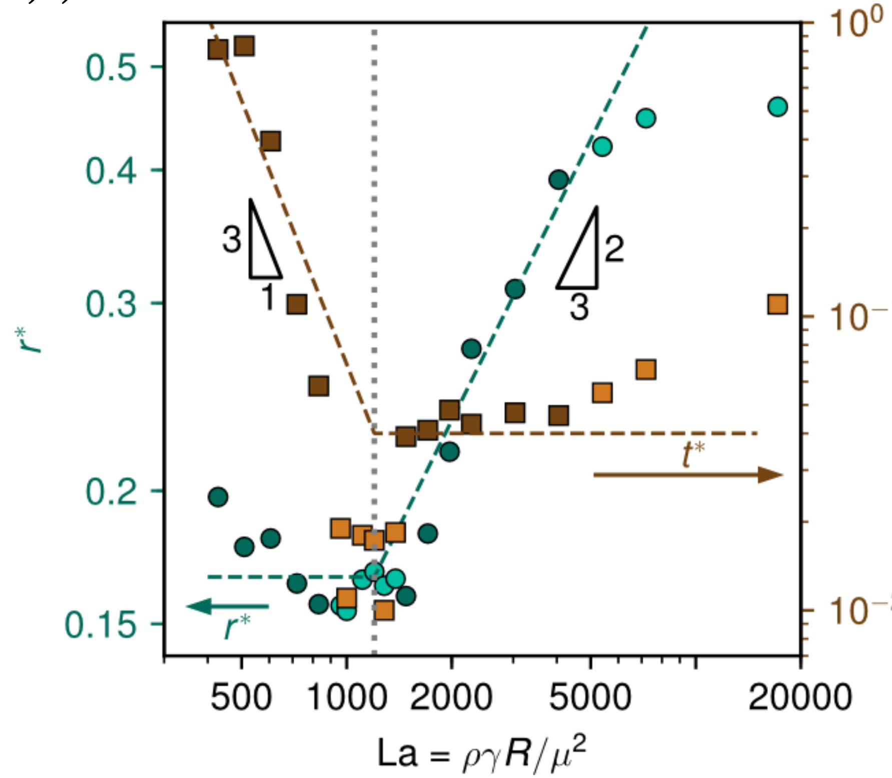
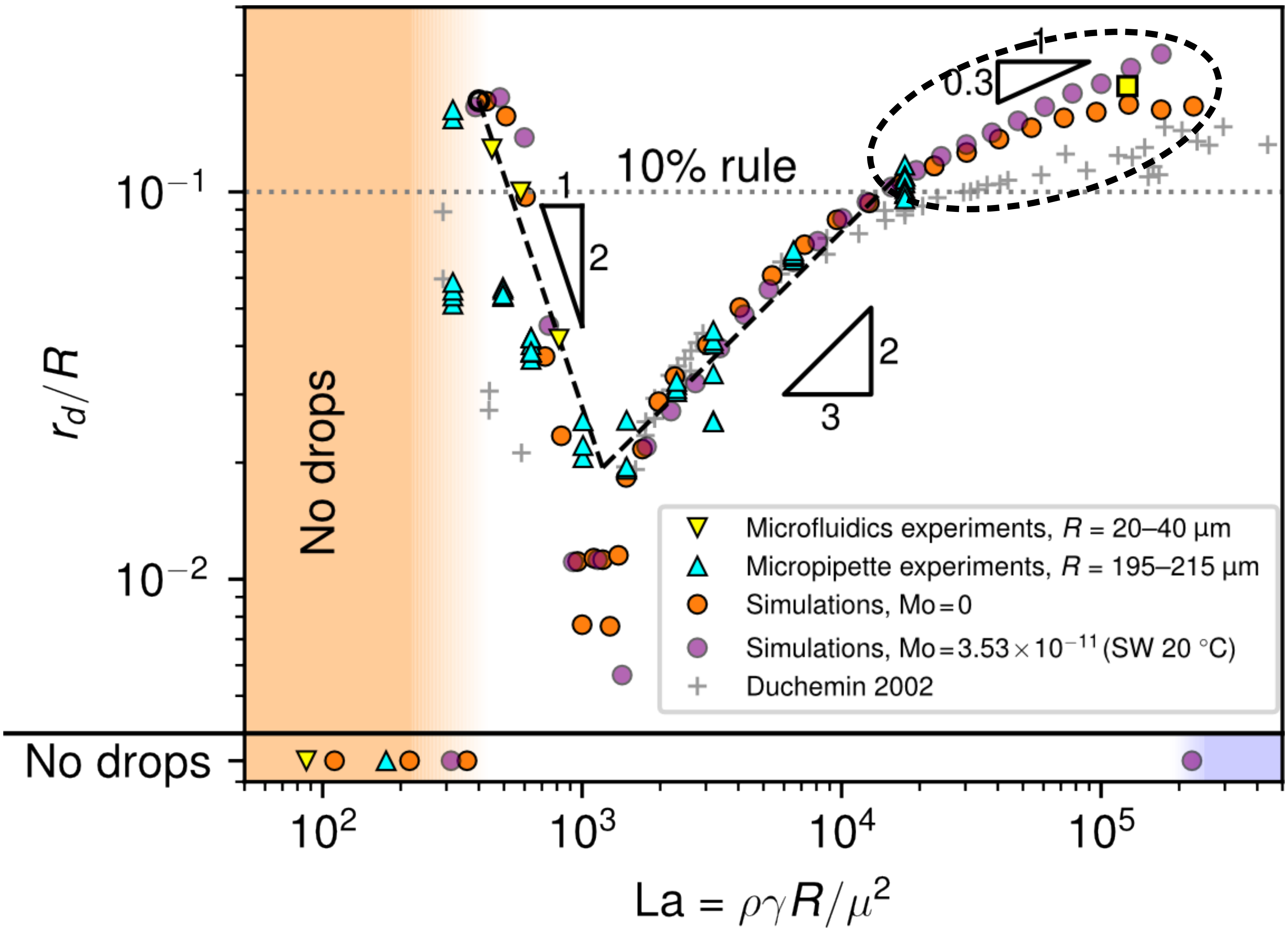




- As La increases above 1200:
  - Less focusing of cavity with undamped capillary waves (Ghabache et al., 2014)
  - Drop size increases with r^*

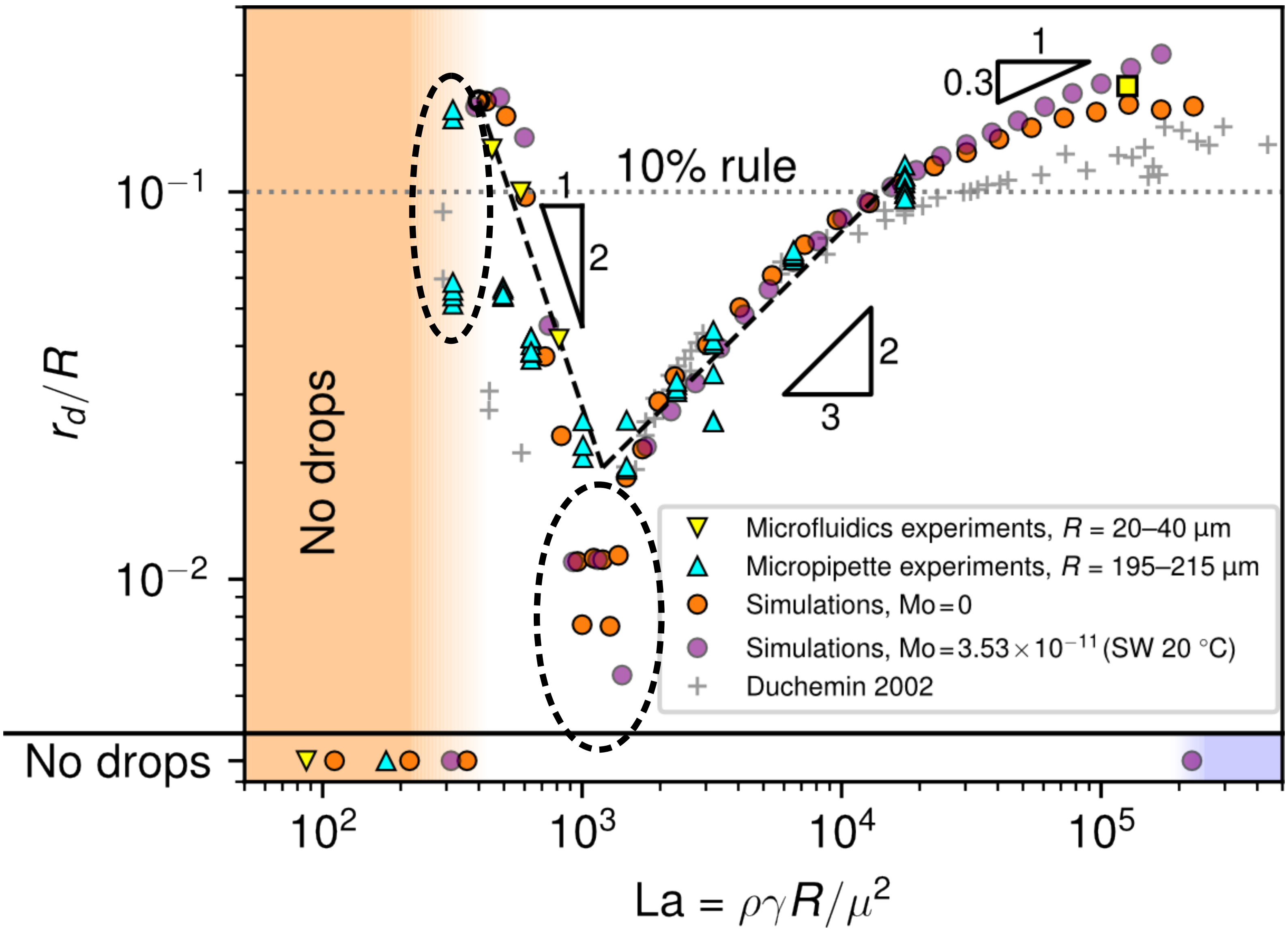
Jet drop radius vs. bubble radius



- Dashed lines: model from fits to r^* and t^*

$$r_d/R = r^*(\mathrm{La})(t^*(\mathrm{La}))^{2/3}$$

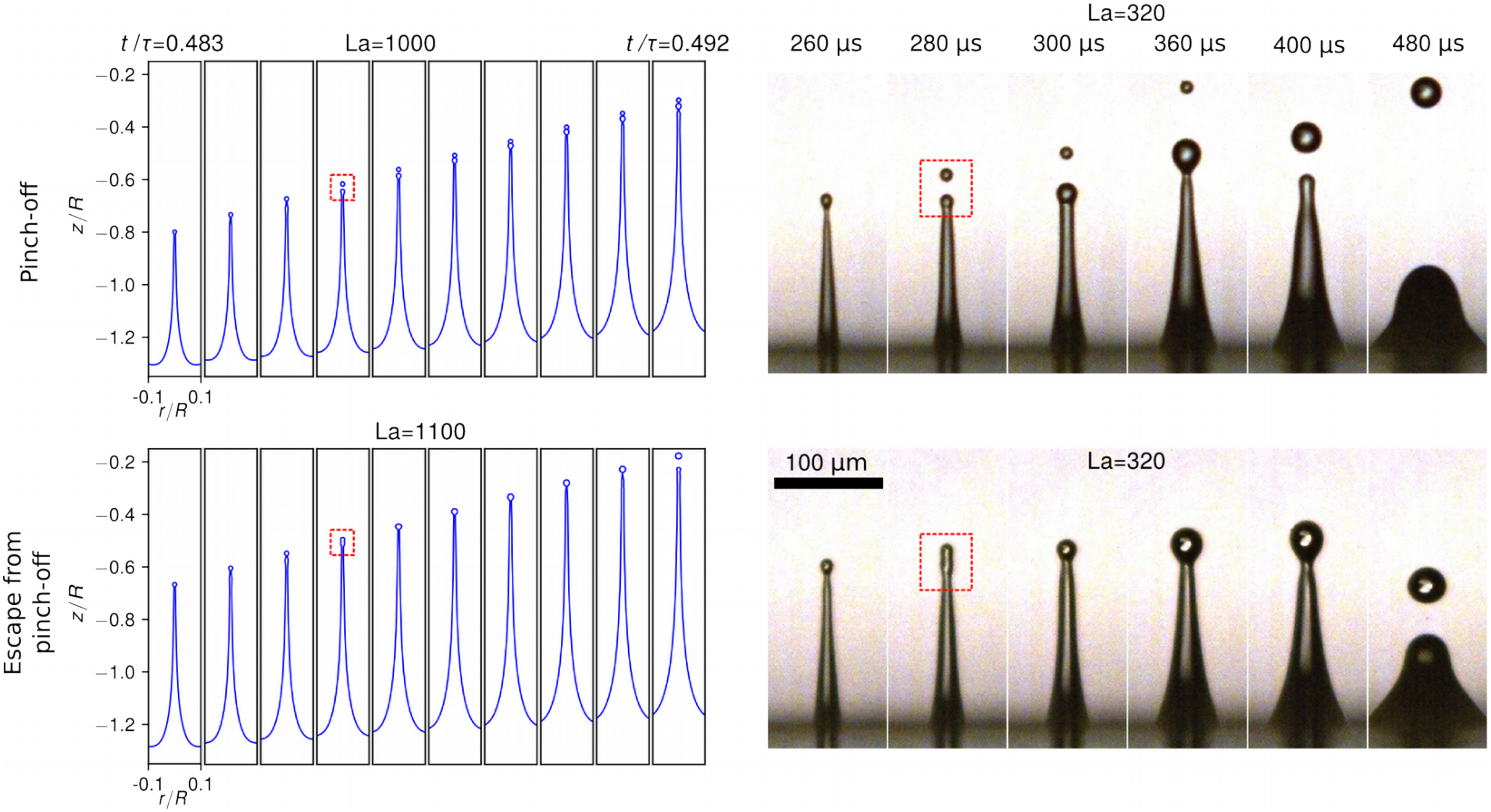
Jet drop radius vs. bubble radius



- Dashed lines: model from fits to r^* and t^*

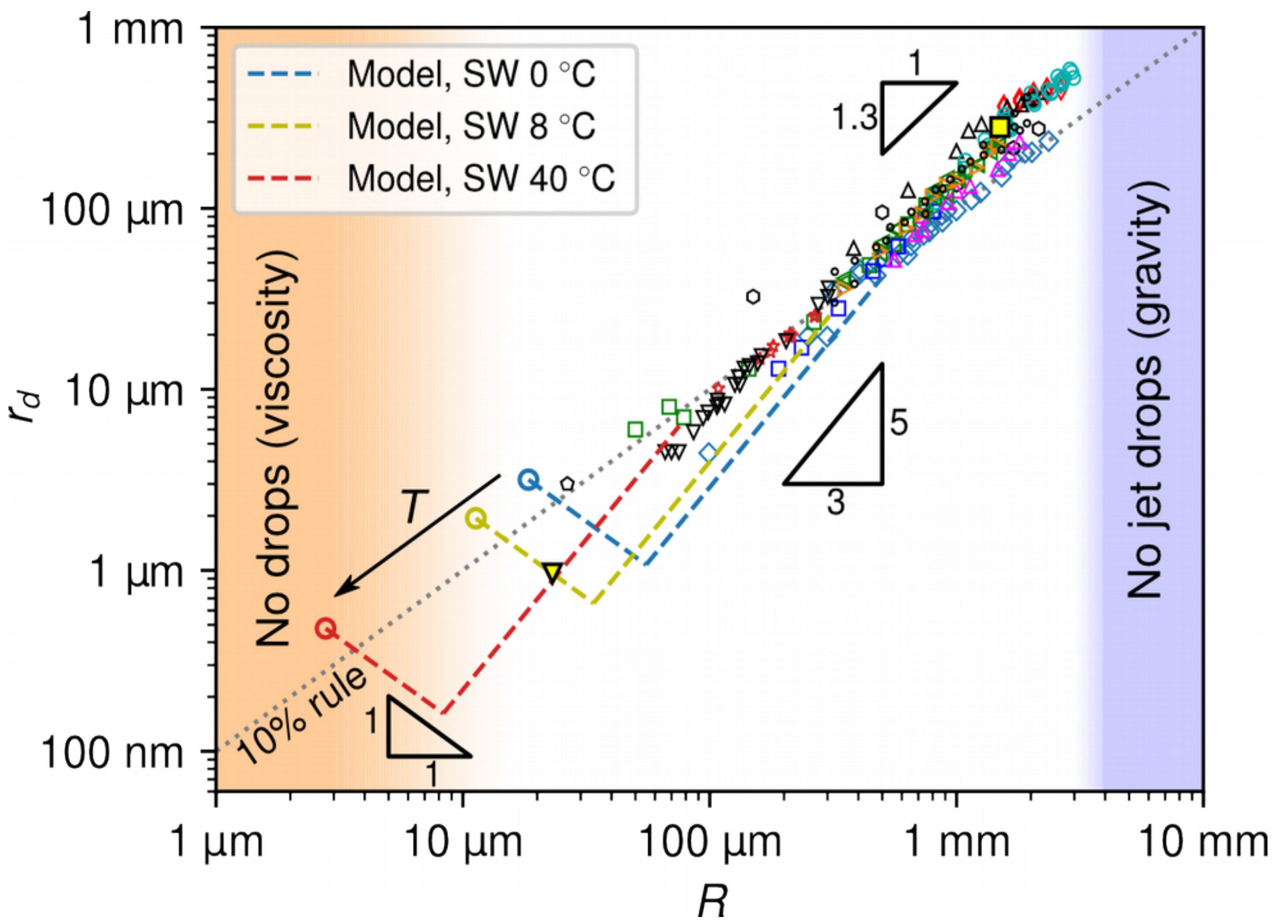
$$r_d/R = r^*(\mathrm{La})(t^*(\mathrm{La}))^{2/3}$$

Size variations due to escape from pinch-off



Hoeppfner & Paré (2013), Recoil of a liquid filament: escape from pinch-off through creation of a vortex ring

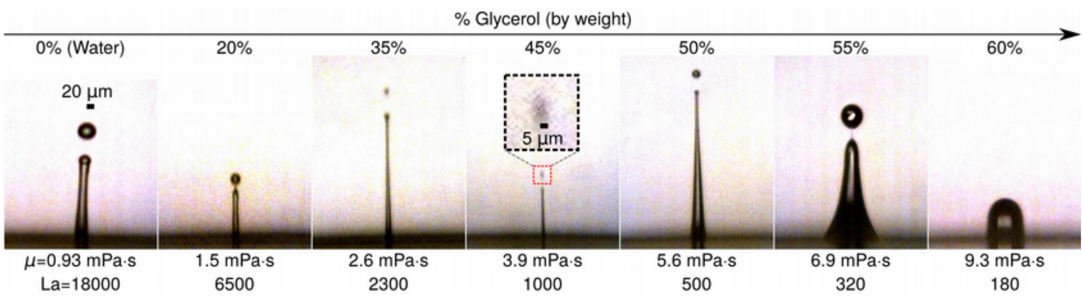
Dimensional plot:
Jet drop radius vs. bubble radius

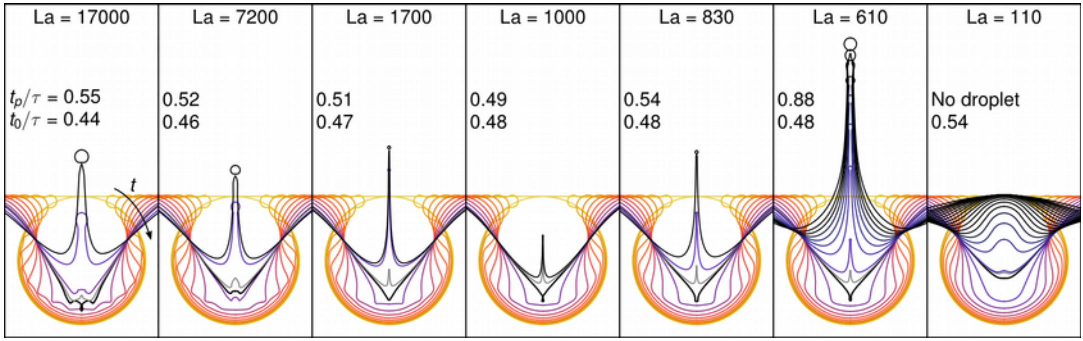


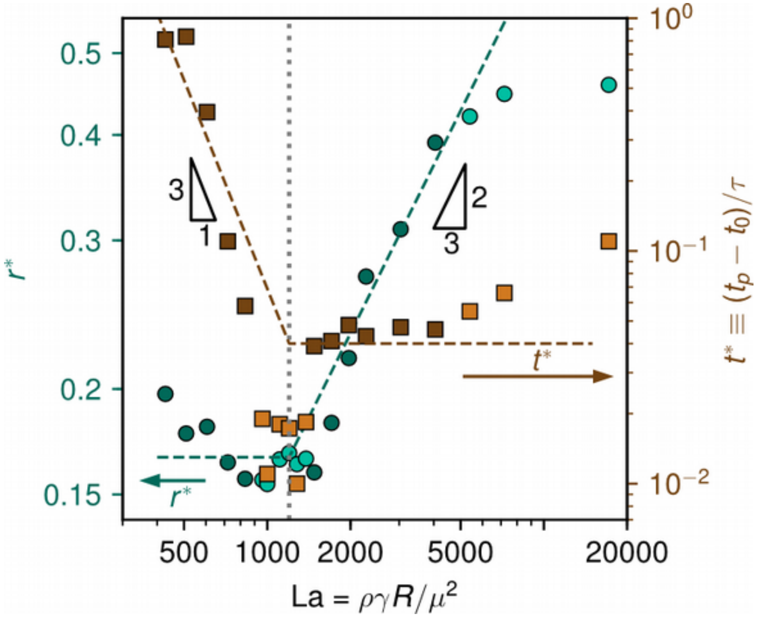
- Seawater viscosity varies by almost a factor of 3 from 0 °C to 40 °C → strong La dependence on temperature
  - Drop size increases with temperature for $R \gtrsim 50\ \mu m$
  - Jet drops as small as 200 nm predicted in tropical waters

Conclusions

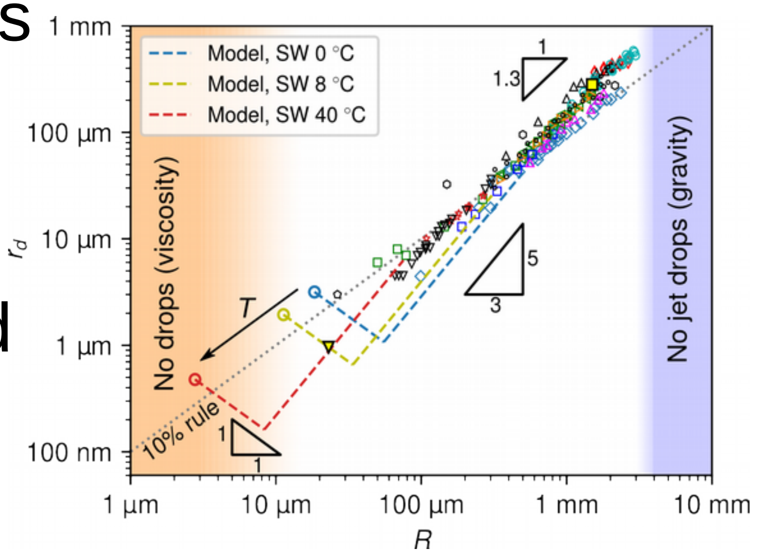
- Non-monotonic size relationship between bubble and top jet drop observed
- Decomposing self-similar jet growth into shape and time components can capture non-monotonic behavior







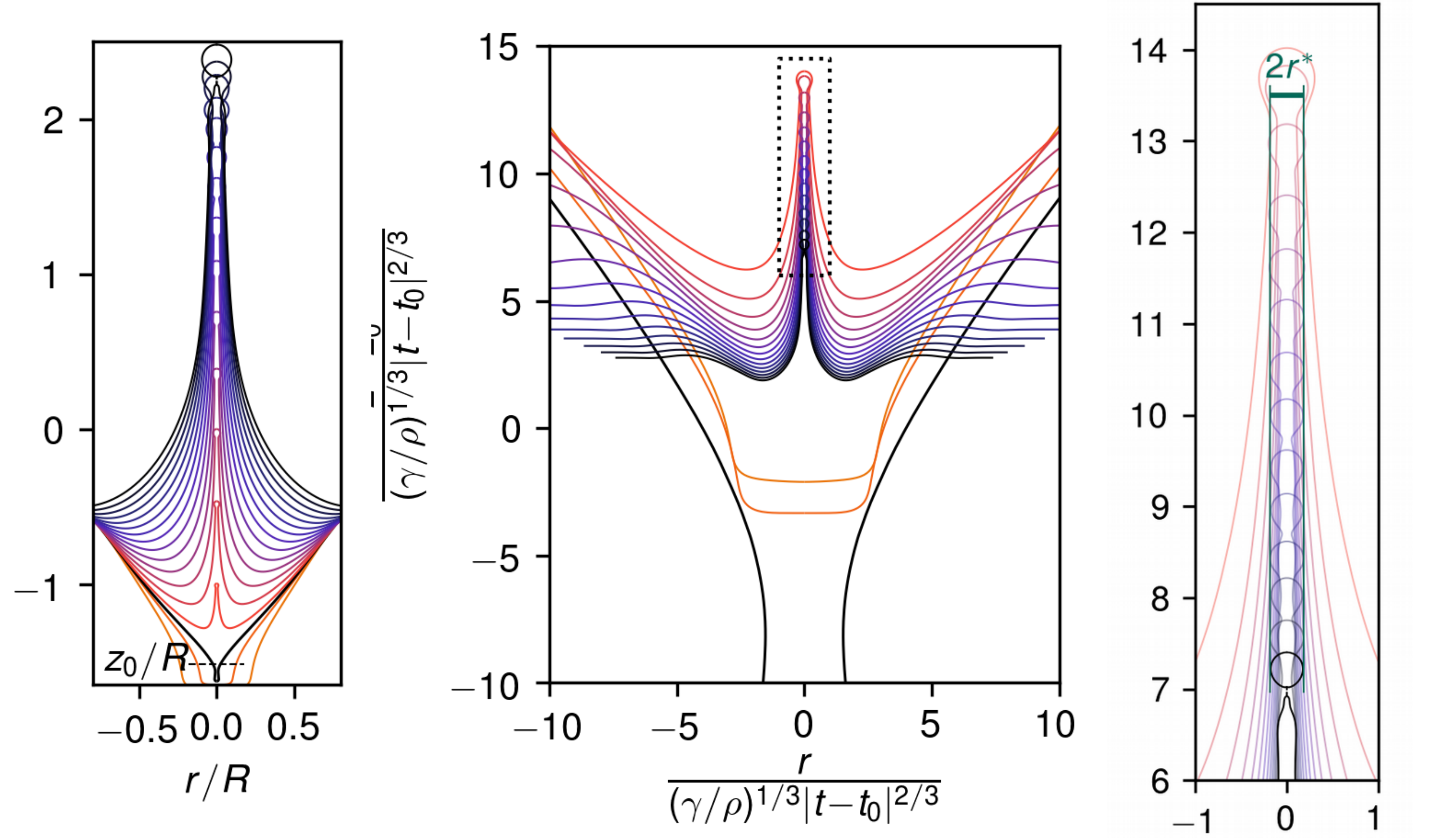
- Jet drop sizes predicted significantly smaller than 10% rule and temperature-dependent



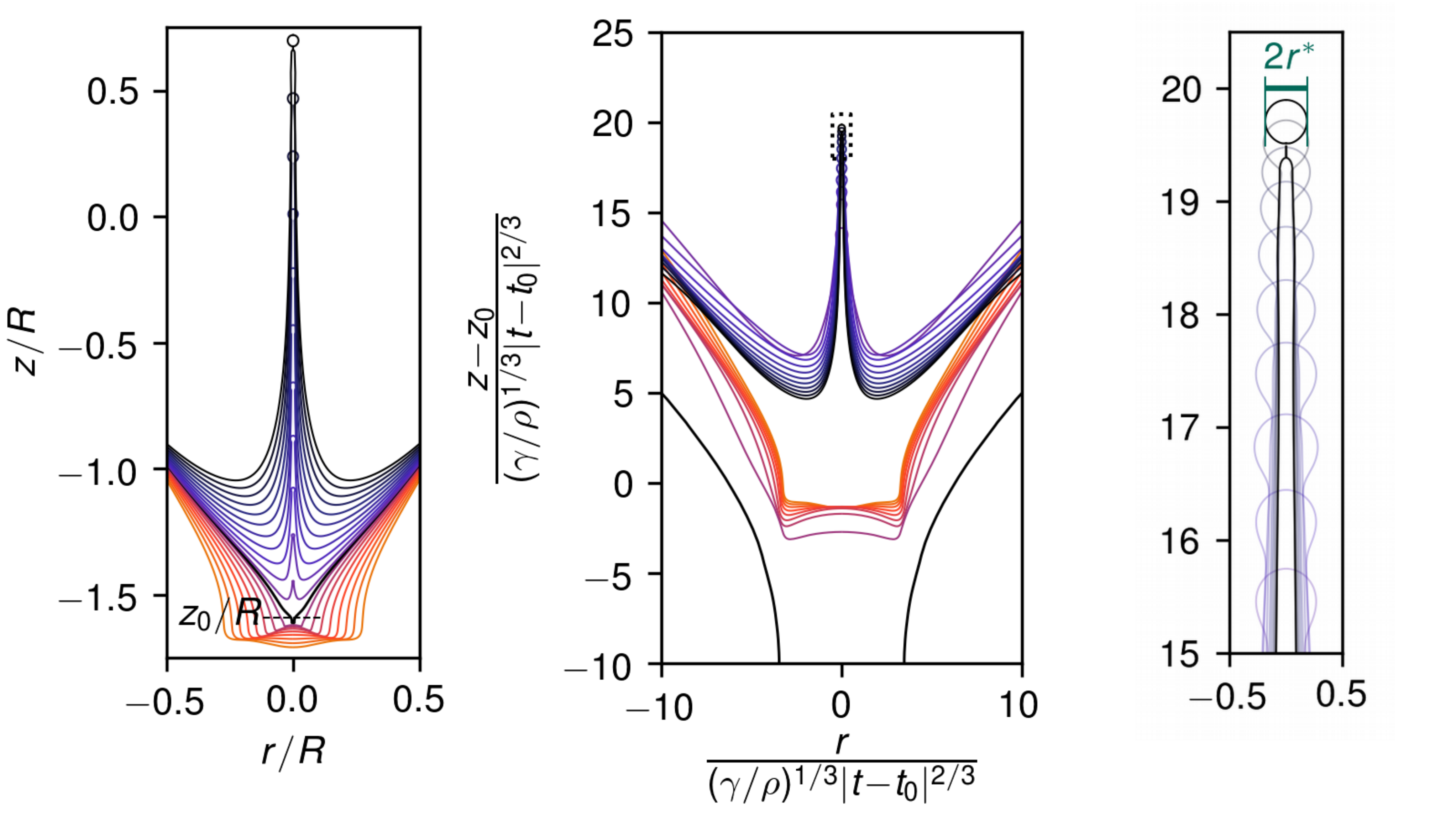
Acknowledgments

- National Science Foundation Grant No. 1351466
- Ernie Lewis

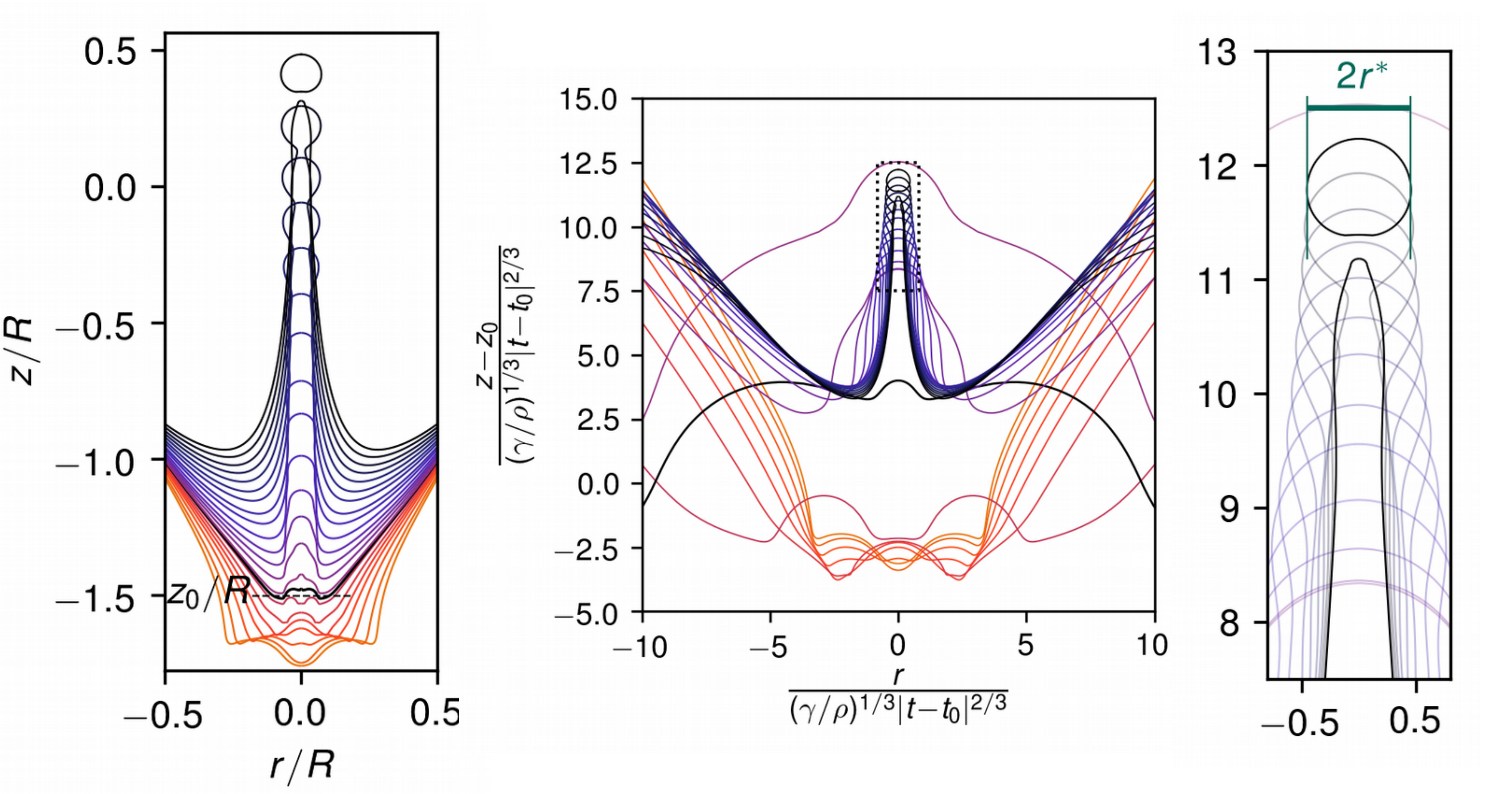
Self-similar scaling: La=610



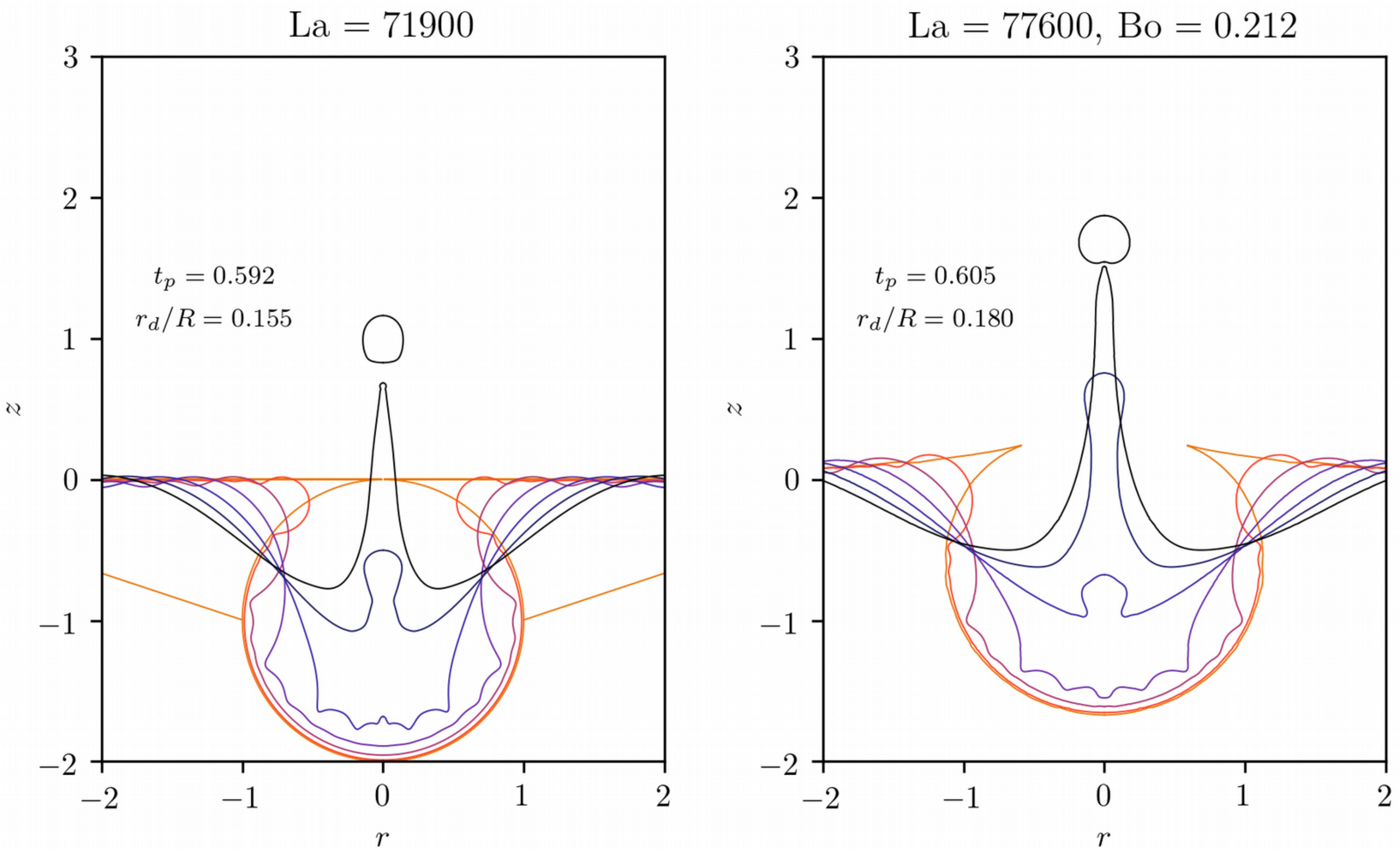
Self-similar scaling: La=1700



Self-similar scaling: La=7200



Gravity effects: Bo~0.2



Gravity effects: Bo~1