Holey Sheets

Ayush Dixit

MIST

CoMPhy Lab

Physics of Fluids

UNIVERSITY OF TWENTE.

Coauthors

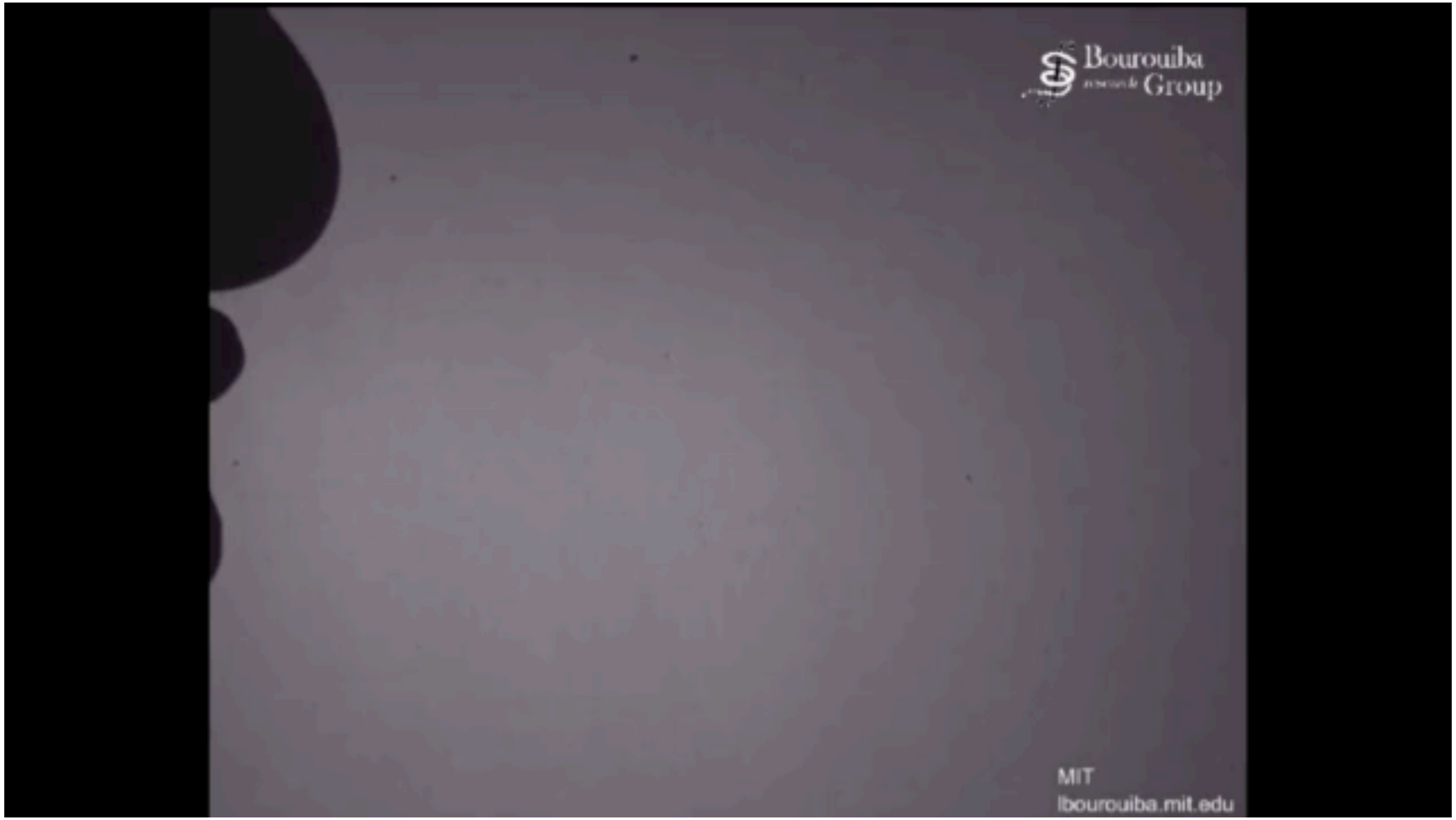
Chunheng Zhao,
CC New York

Stéphane Zaleski,
Sorbonne Université

Detlef Lohse,
Uni. Twente

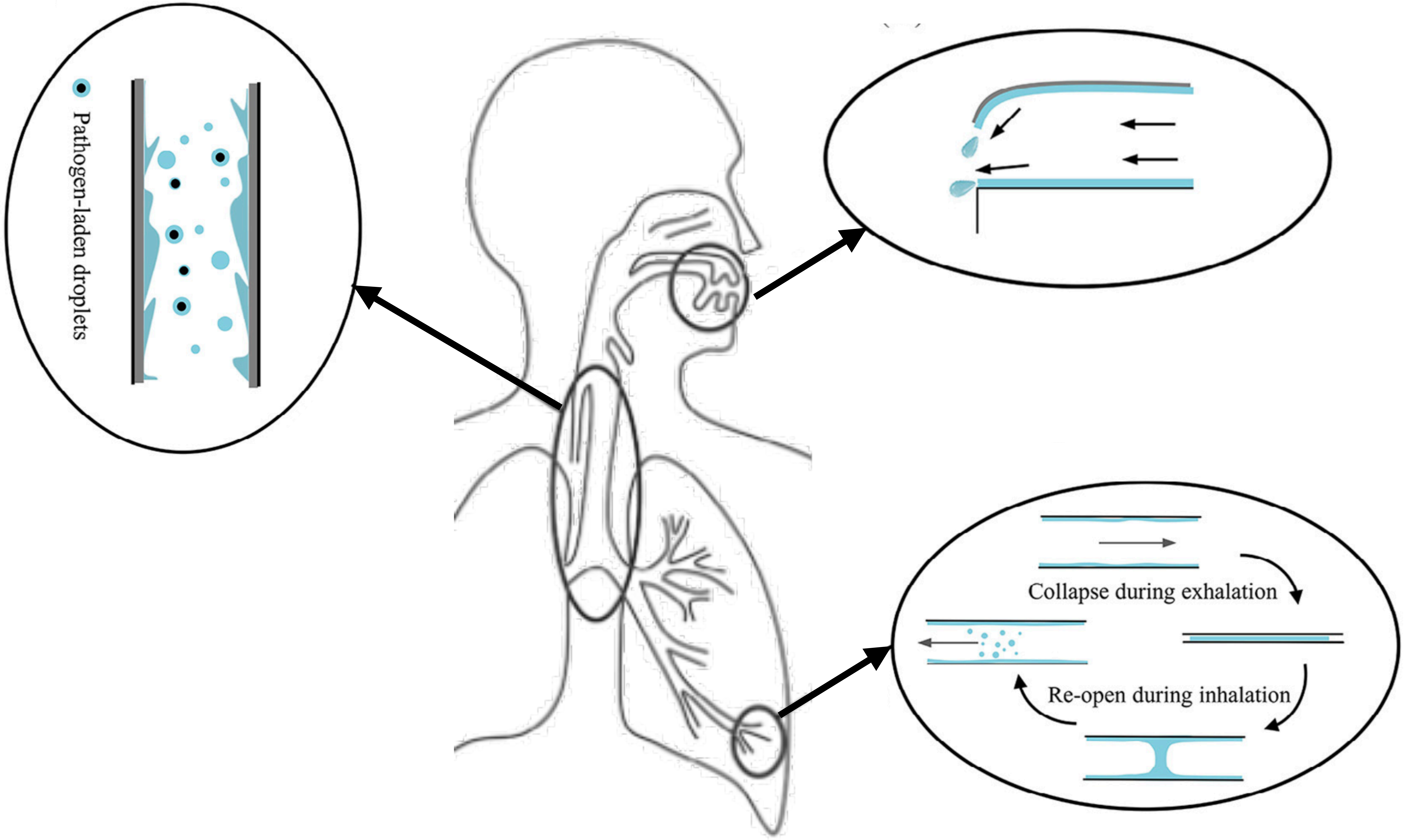
Vatsal Sanjay,
Uni. Twente,
Durham Uni.

Why do we care?



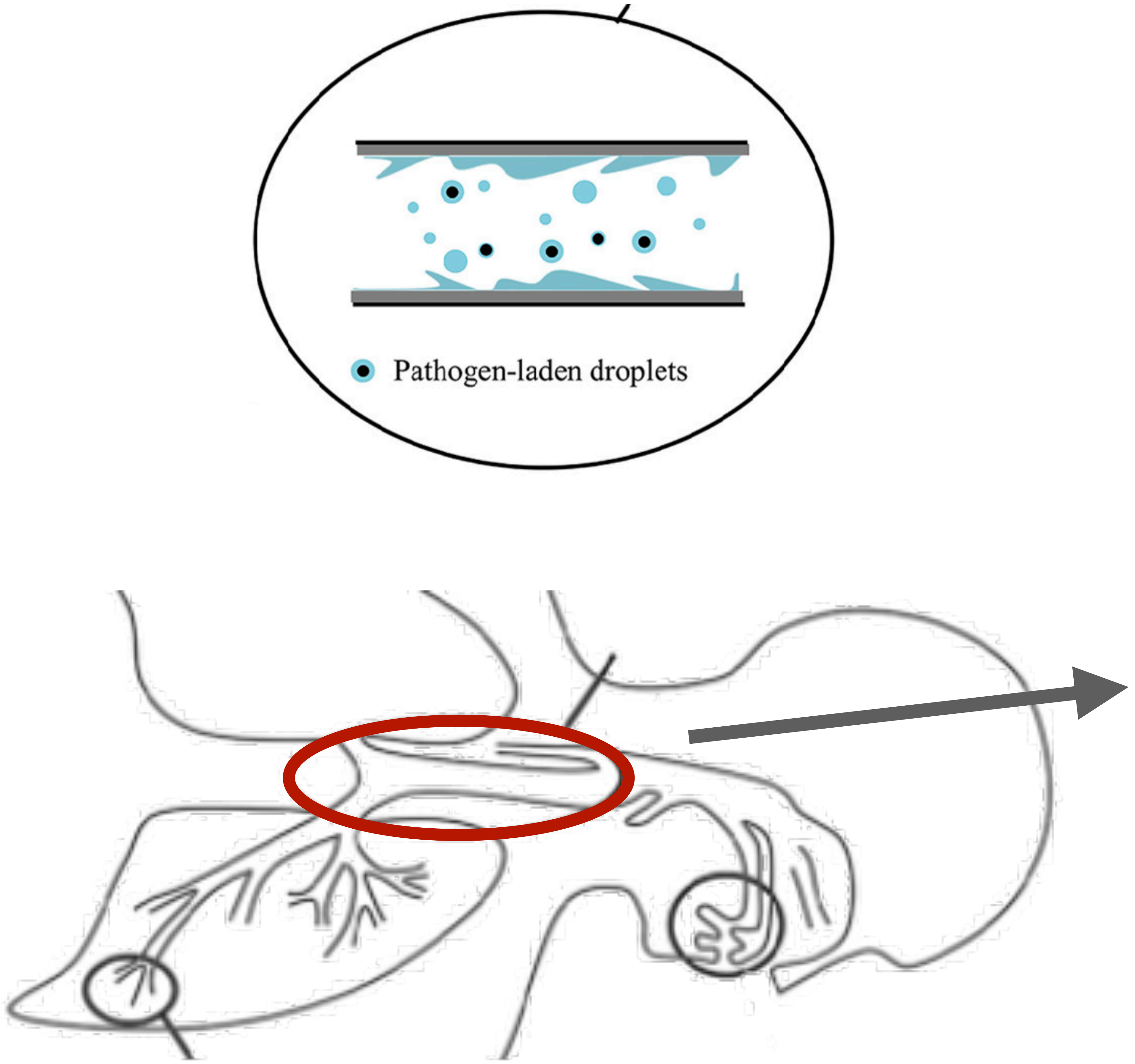
Scharfman, Techet, Bush & Bourouiba, Exp. Fluids 57, 24 (2016)

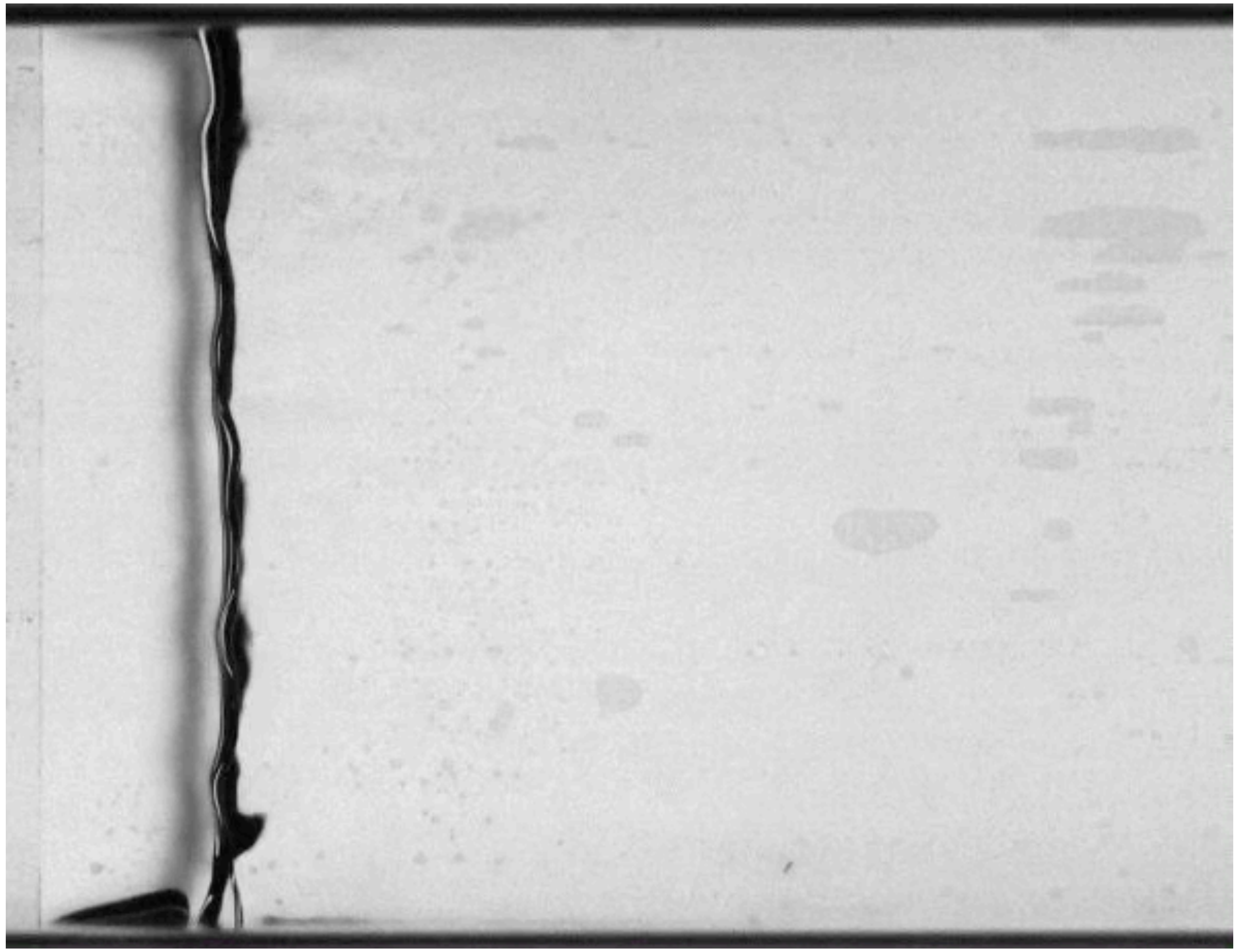
Where are the droplets coming from?



Wie & Li, Am. J. Infect. Control 44, 102 (2016)
Pöhlker, Pöhlker, Krüger et al., Rev. Mod. Phys. 95, 045001 (2023)

Coughing as mimicked in the lab





Kant, Pairetti, Saade, Popinet, Zaleski & Lohse, Phys. Rev. Fluids 8, 074802 (2023)
Li, Saade, Zaleski, Sen, Kant & Lohse, arXiv (2025)

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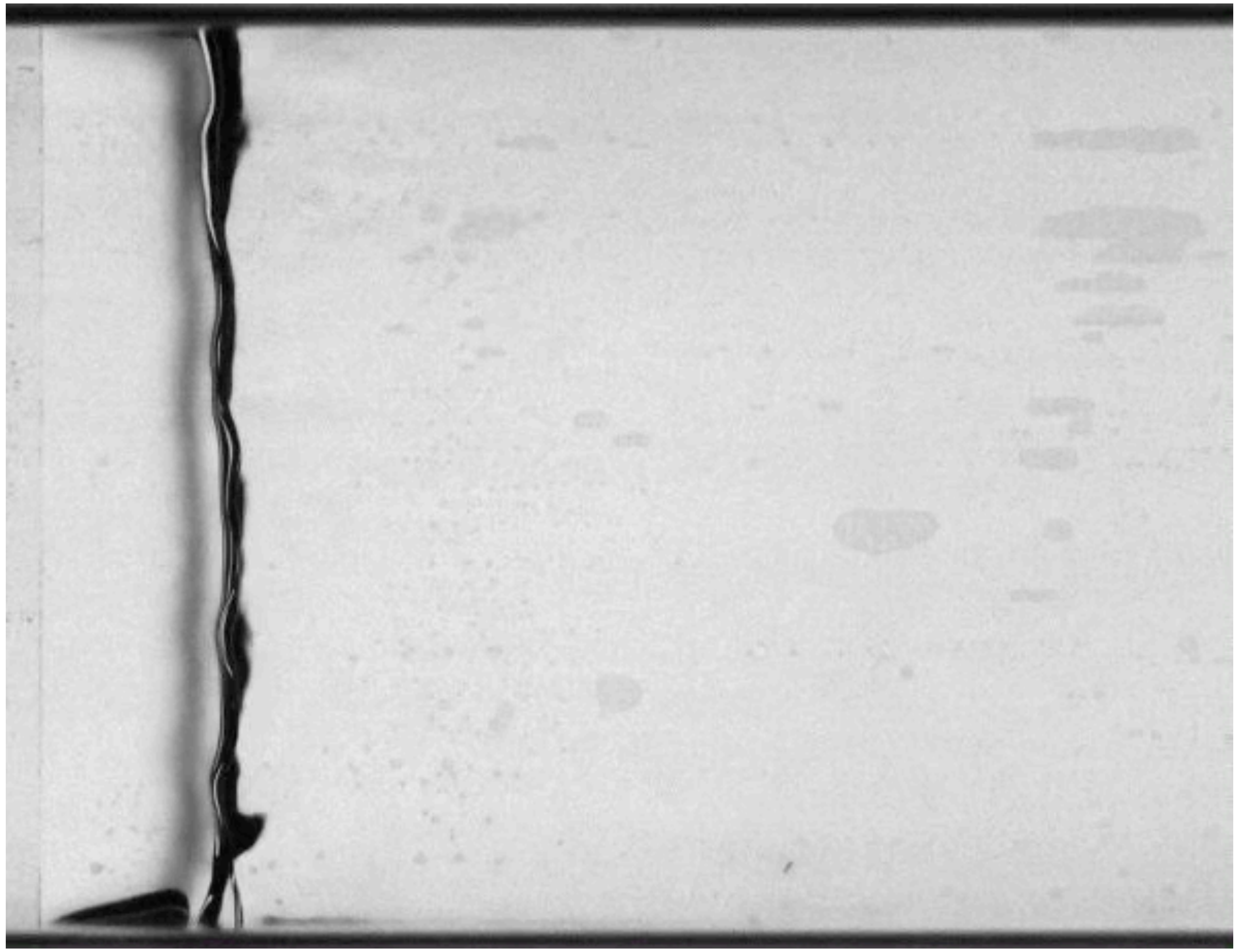
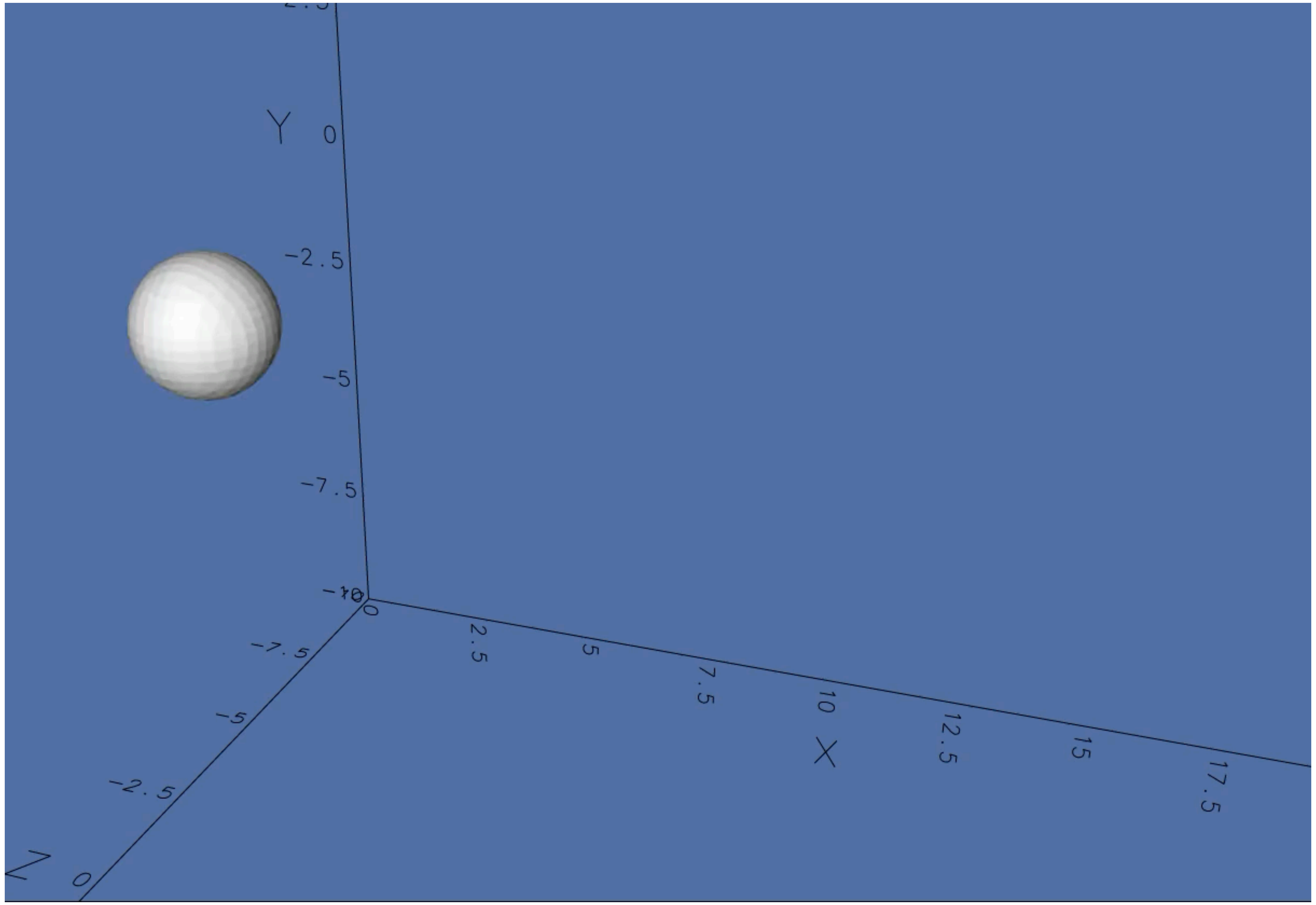


Jetting

Bag-mediated atomisation

Kant, Pairetti, Saade, Popinet, Zaleski & Lohse, Phys. Rev. Fluids 8, 074802 (2023)
Li, Saade, Zaleski, Sen, Kant & Lohse, arXiv (2025)

Bag breakup of a single droplet



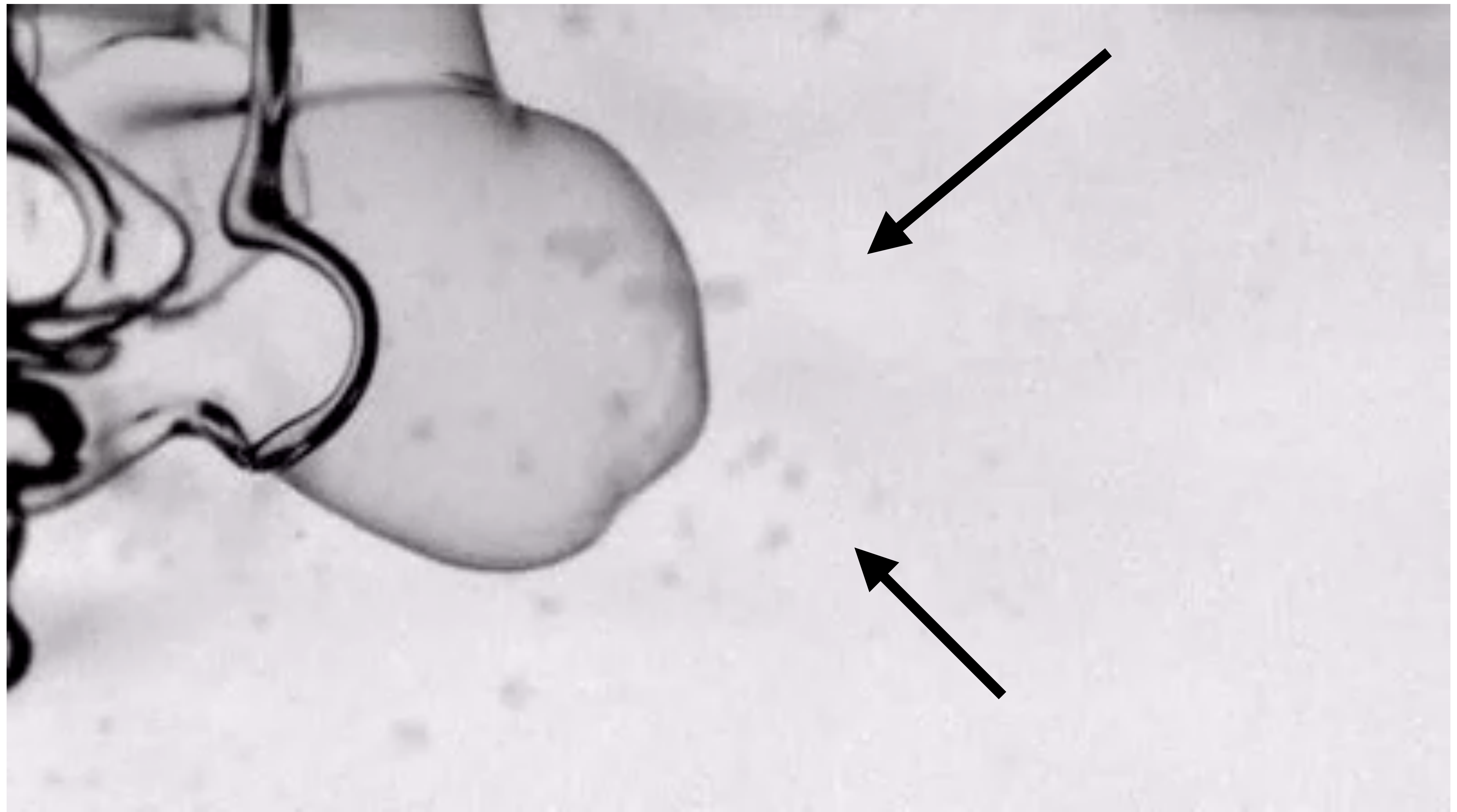
Newtonian

$$Oh = 3 \times 10^{-3}$$

$$We = 7.5$$

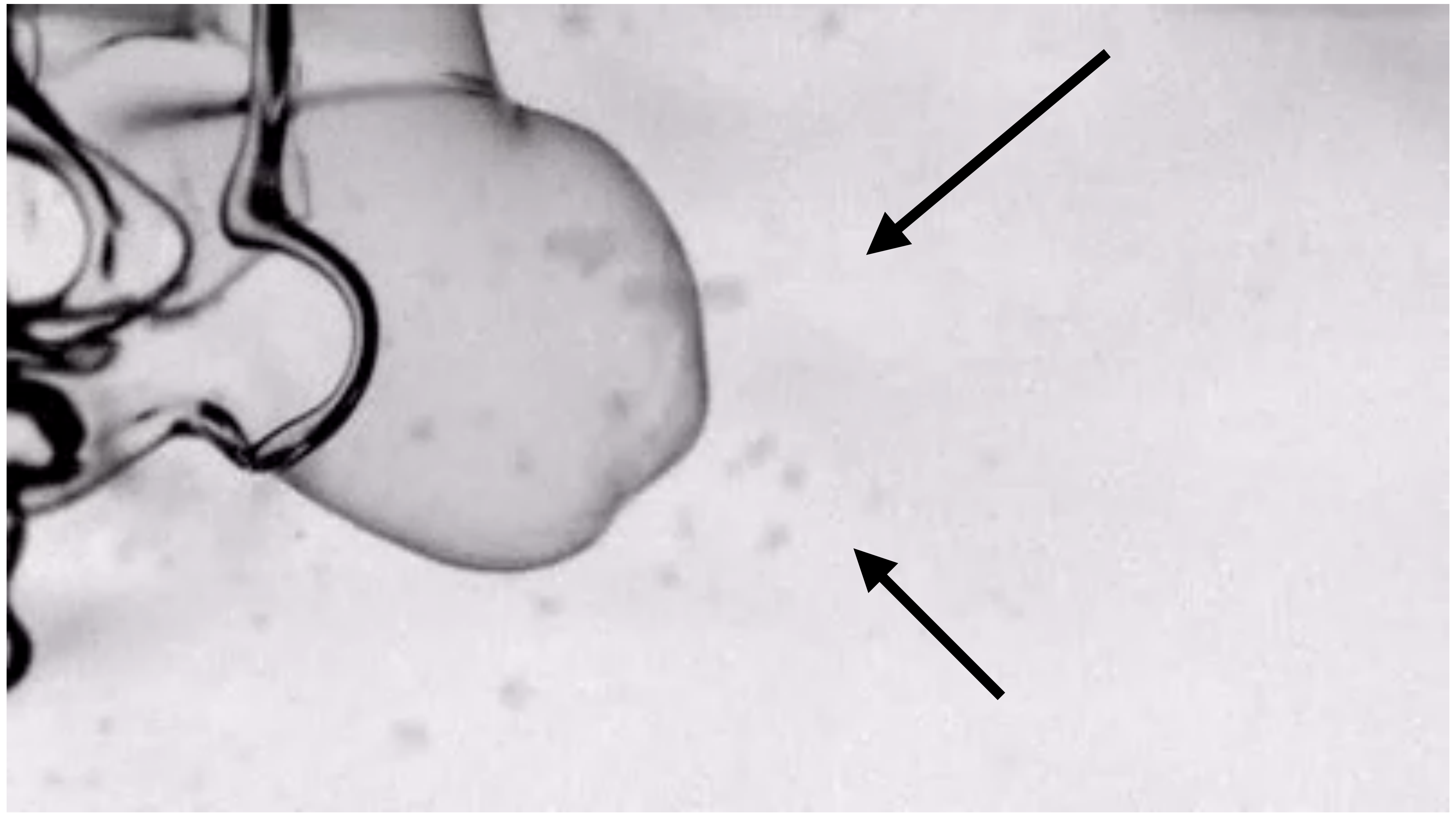
$$We = \frac{\rho_g R_0 U_0^2}{\gamma} \qquad Oh = \frac{\eta_l}{\sqrt{\rho_l \gamma R_0}}$$

Hole nucleation in the bags



Kant, Pairetti, Saade, Popinet, Zaleski & Lohse Phys. Rev. Fluids 8, 7 (2023)

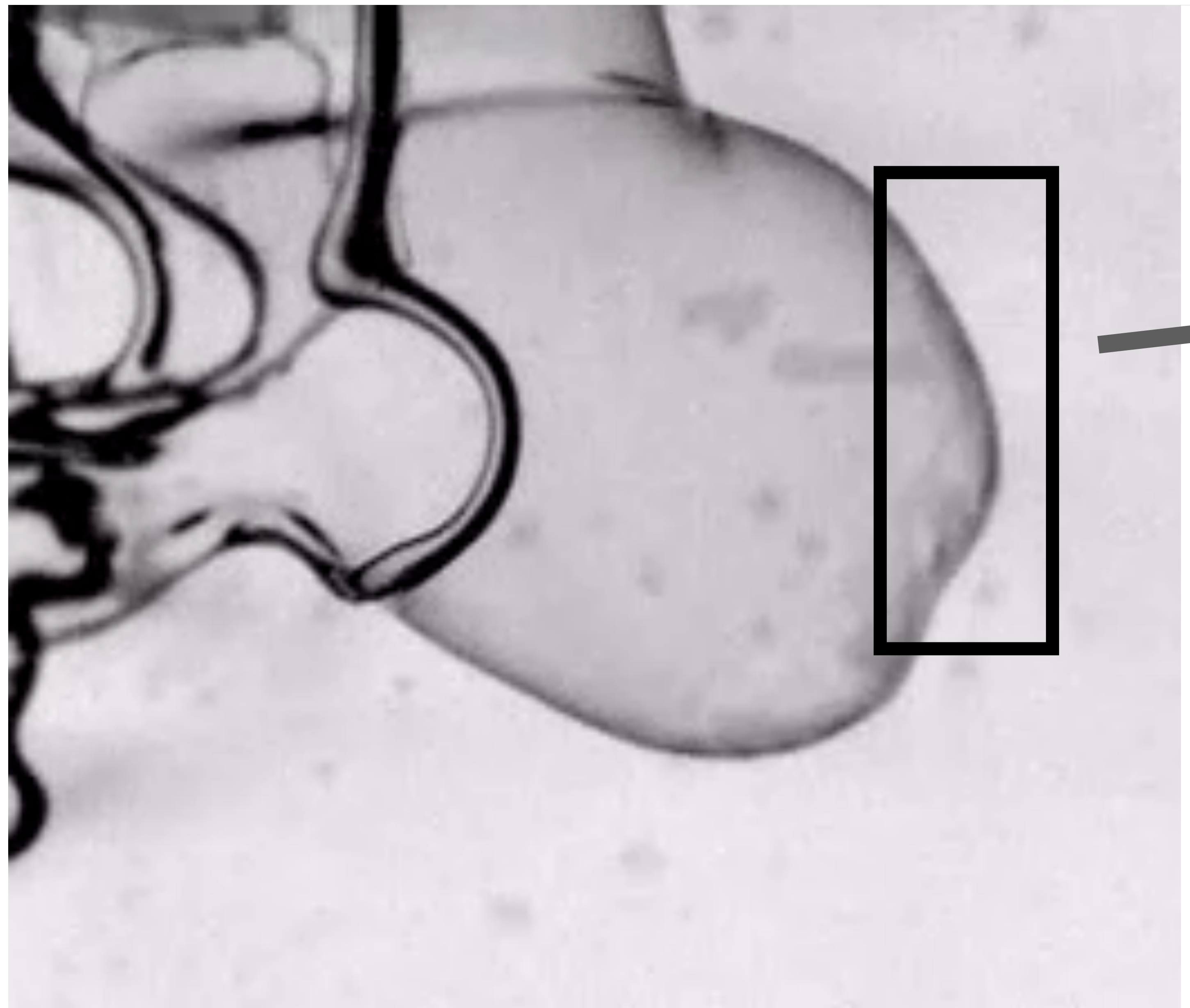
How do holes nucleate in sheets?

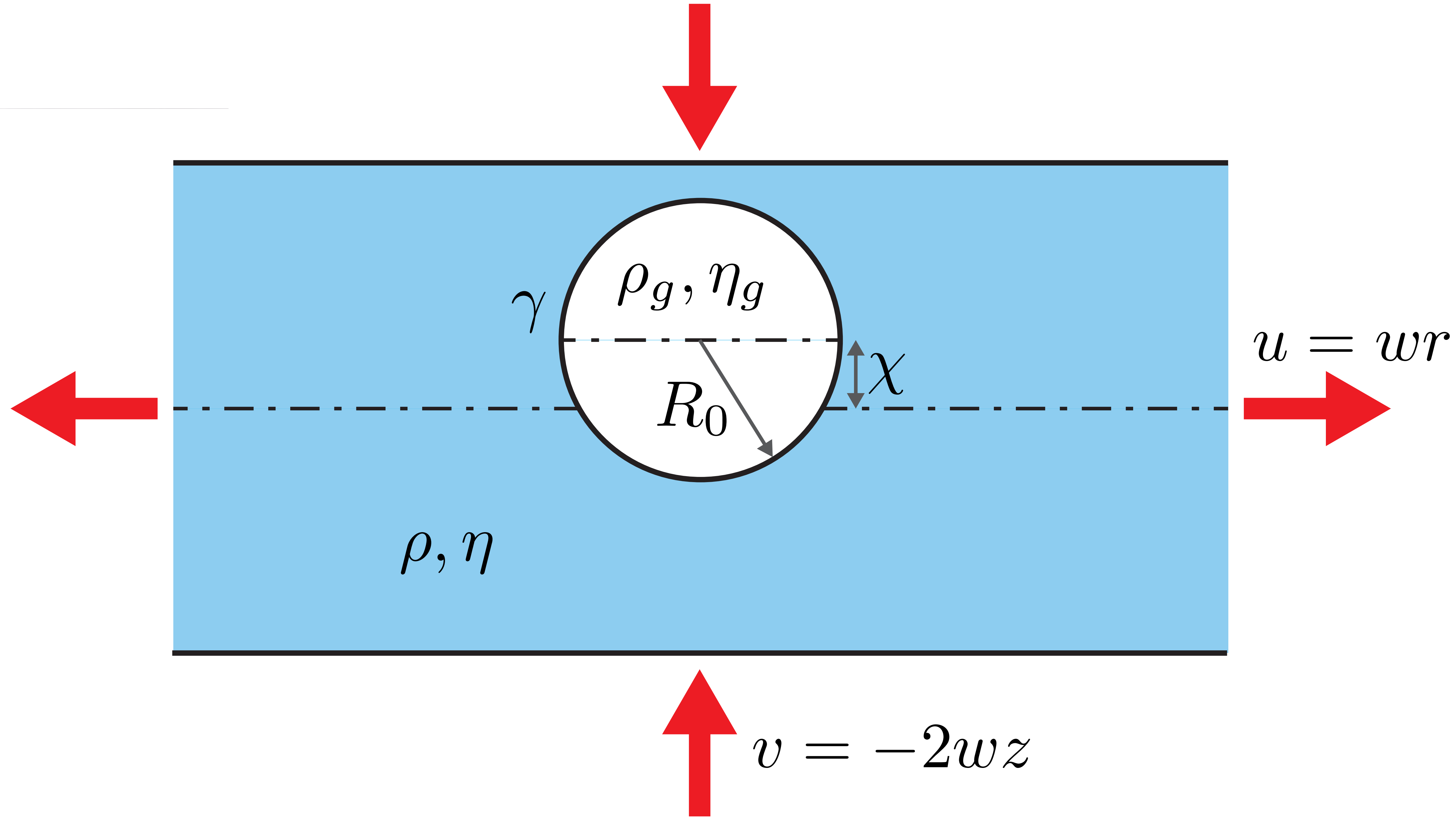


- ~~Thermal fluctuations~~
- ~~Van der Waal forces~~
- By hydrophobic particles or bubbles
- Chemical and temperature inhomogeneities

Lohse & Villermaux Proc. Natl. Acad. Sci. 117, 32 (2020)

How to model this breakup?





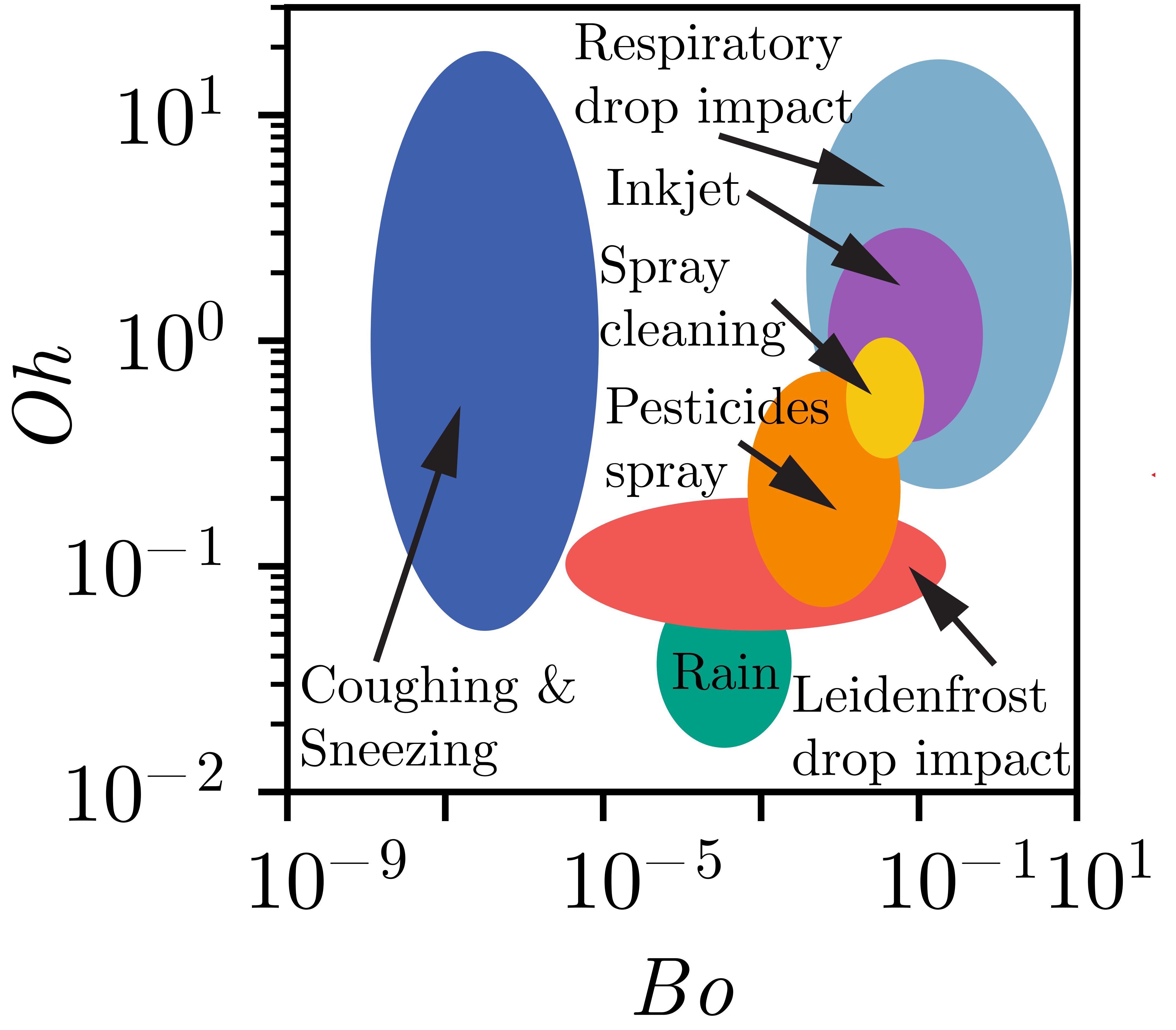
$$Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}} \qquad Bo = \frac{\rho \omega^2 R_0^3}{\gamma}$$

Asymmetry: $\frac{\chi}{R_0}$

$$\frac{\rho_g}{\rho} = 10^{-3} \qquad Oh_a = \frac{\eta_g}{\sqrt{\rho R_0 \gamma}} = 2 \times 10^{-5}$$

Relevance of omnipresent holey sheets

Dimensionless viscosity



Dimensionless driving

How do holey sheets break?

Computational **M**ultiphase **Phy**sics Lab

#ilovefs

Numerics: Basilisk C

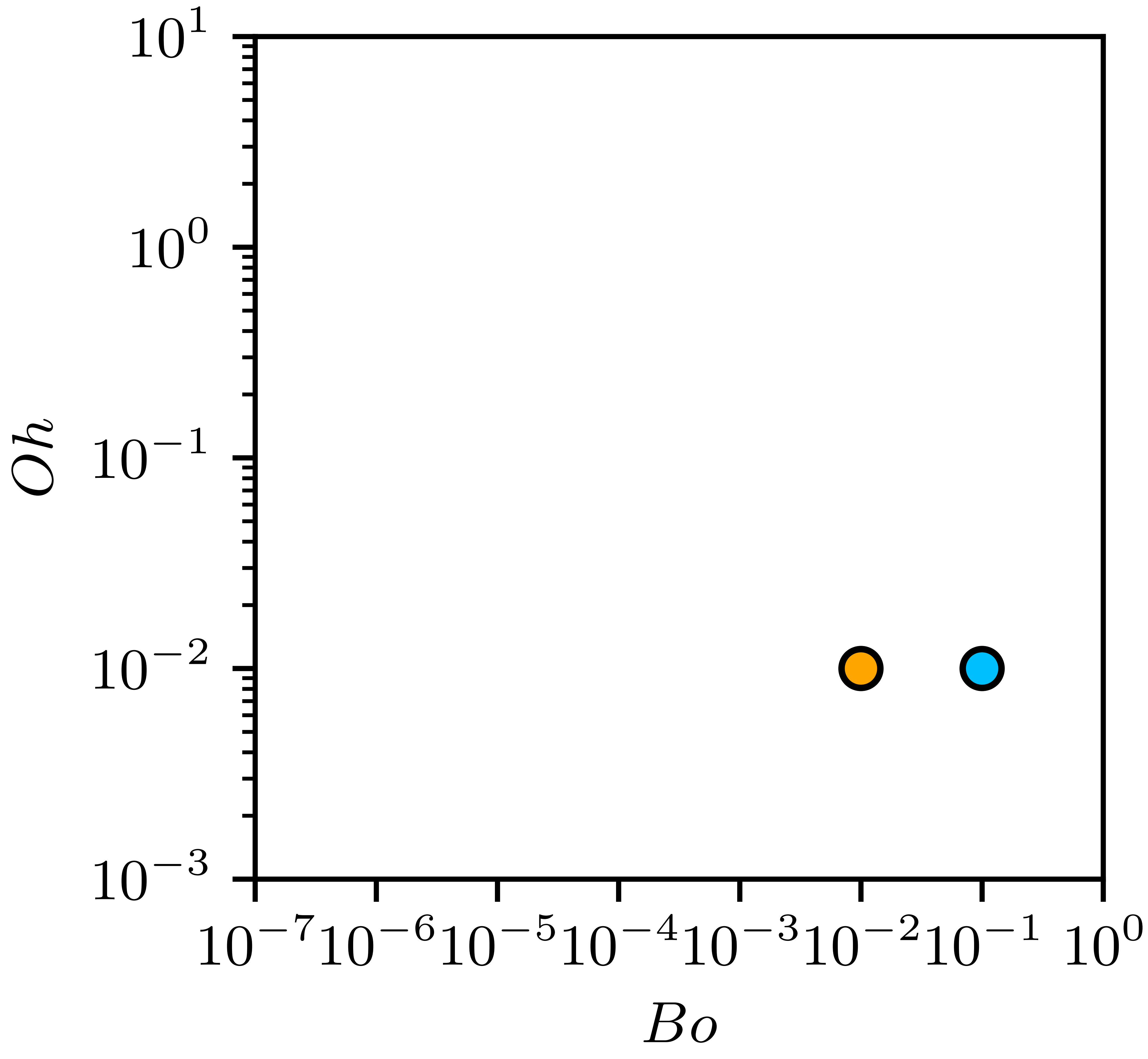
Cauchy momentum + VoF

Stéphane Popinet & collaborators

CoMPhy Lab

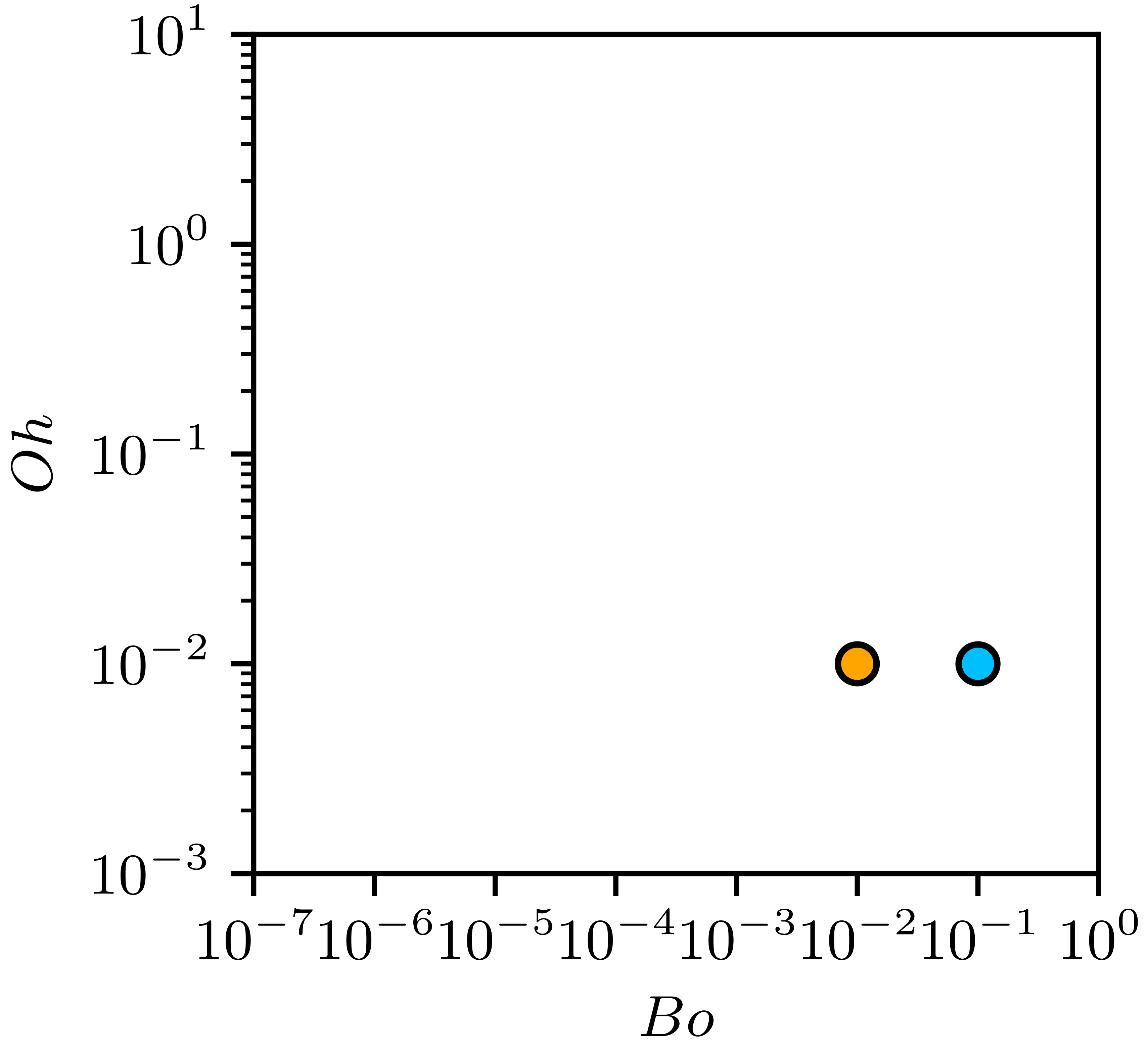
How do holey sheets break?

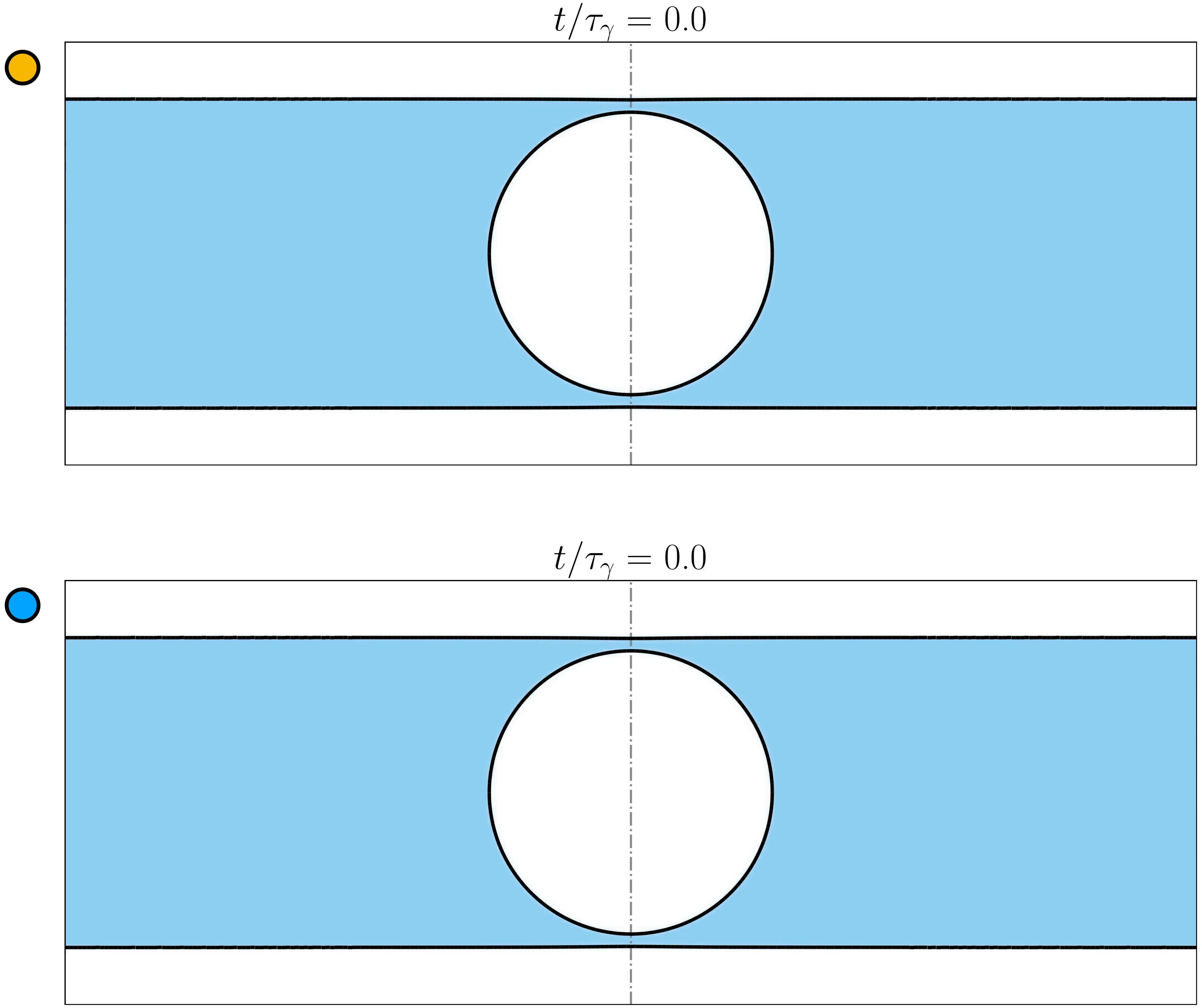
Oh-Bo parameter space



$$Bo = \frac{\rho \omega^2 R_0^3}{\gamma} \quad Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}}$$

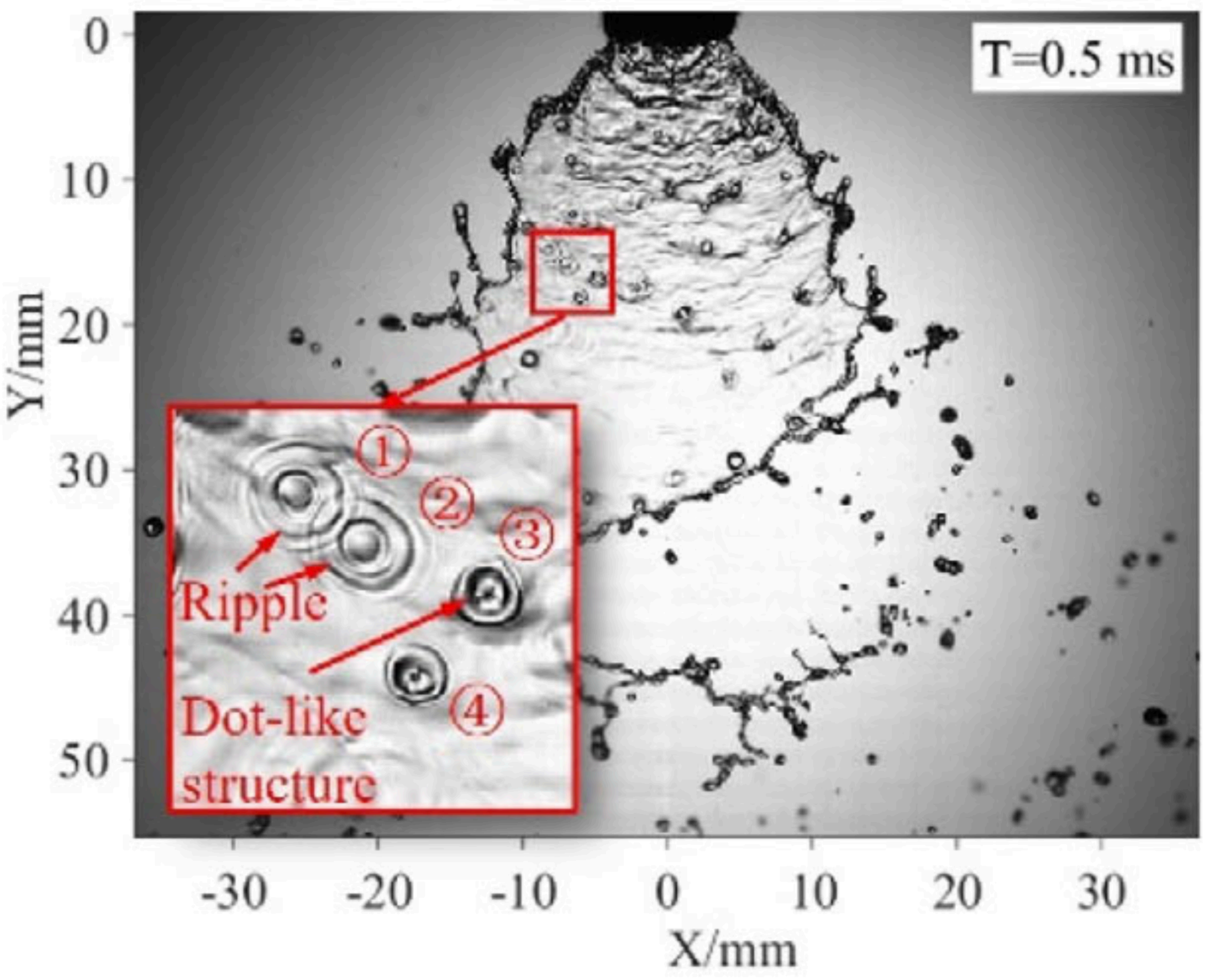
Oh-Bo parameter space

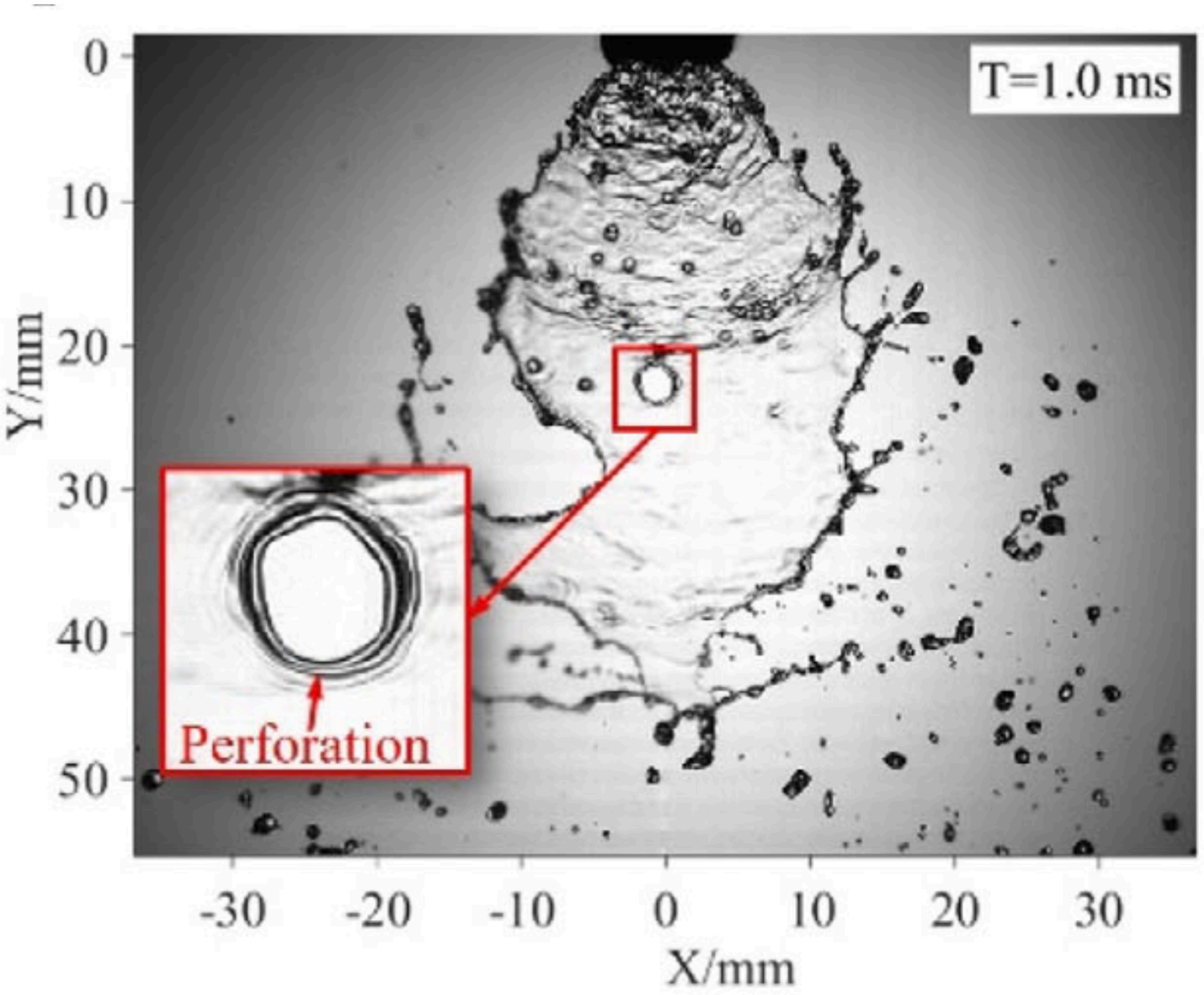




$$Bo = \frac{\rho \omega^2 R_0^3}{\gamma} \quad Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}}$$

Experimental observations

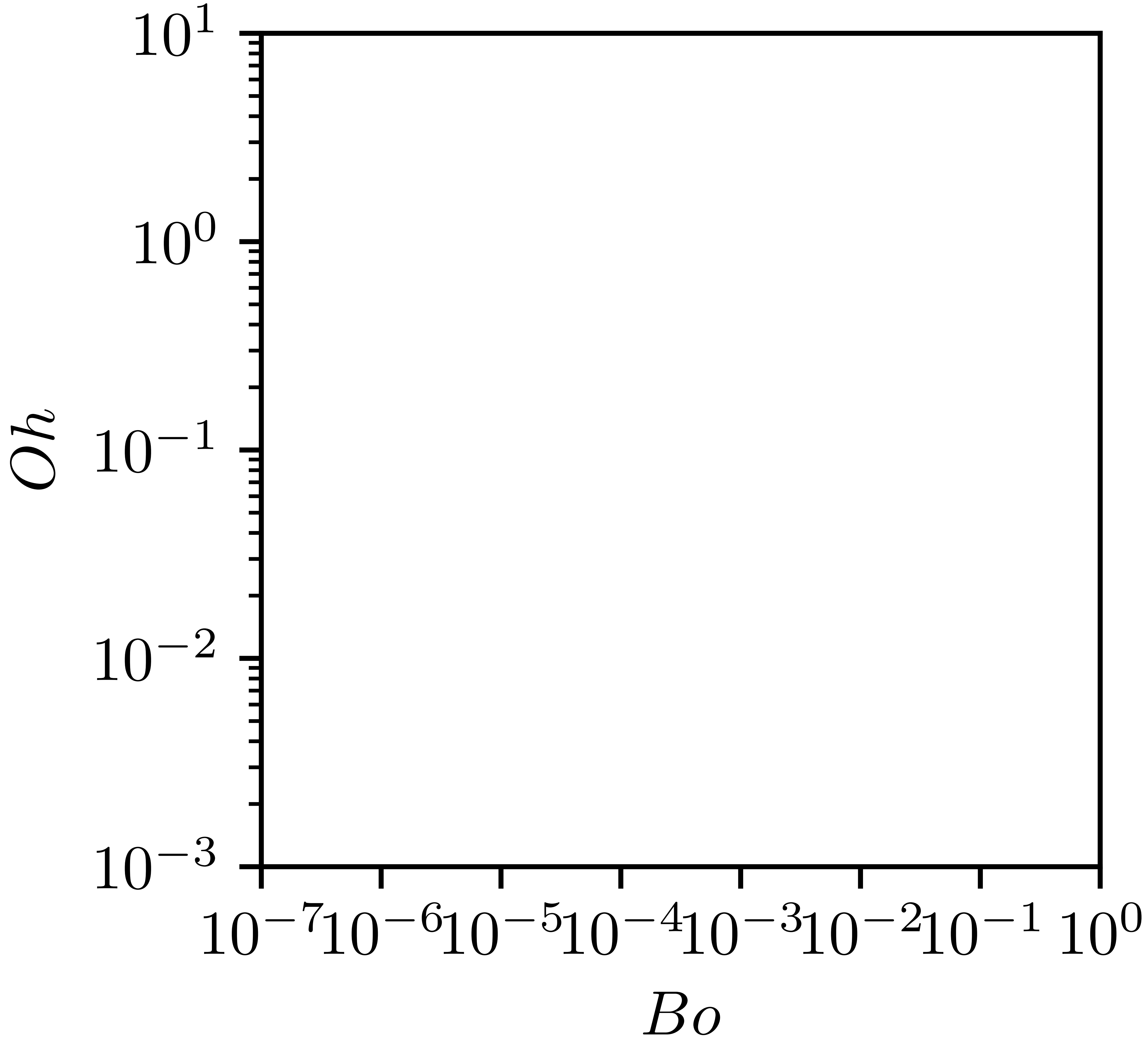




$$Bo = \frac{\rho \omega^2 R_0^3}{\gamma} \quad Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}}$$

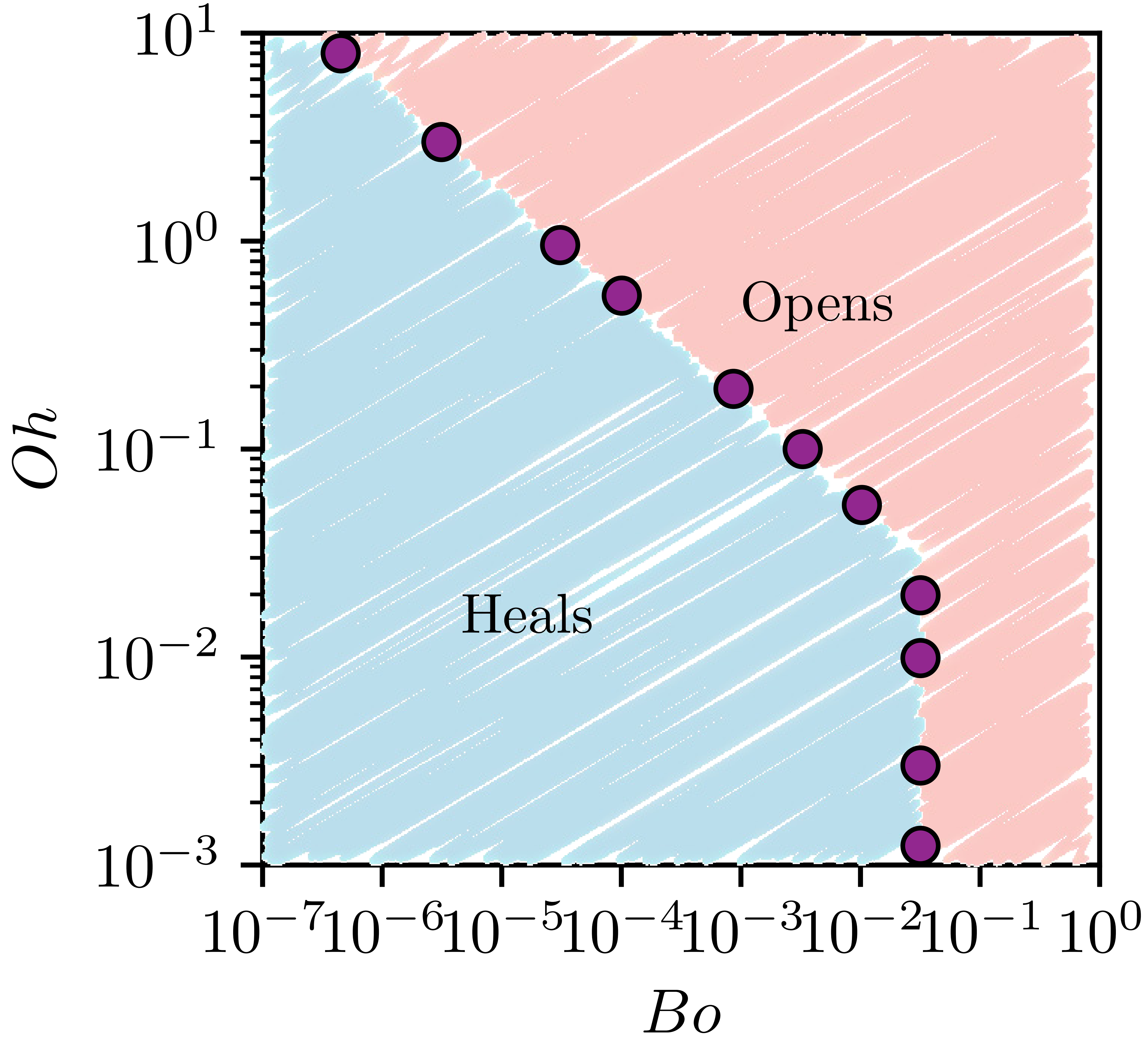
Gong & Kang Pest Manag. Sci. 78, 12 (2022)

Oh-Bo parameter space



$$Bo = \frac{\rho \omega^2 R_0^3}{\gamma} \quad Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}}$$

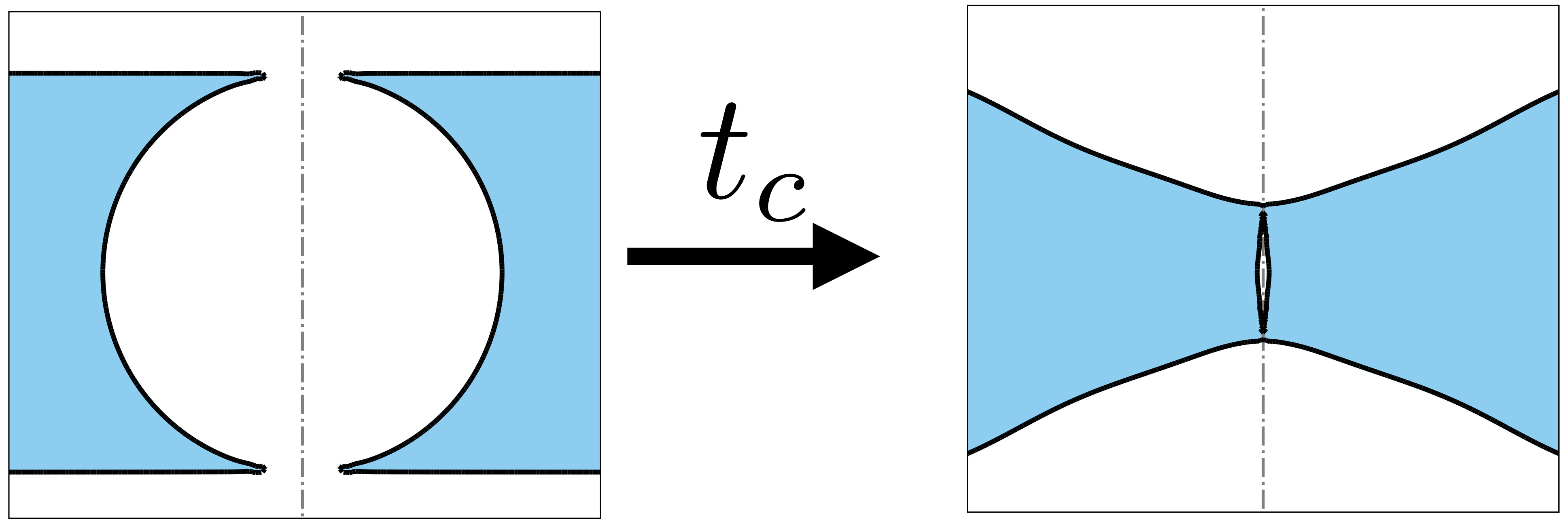
Oh-Bo parameter space: 300 simulations

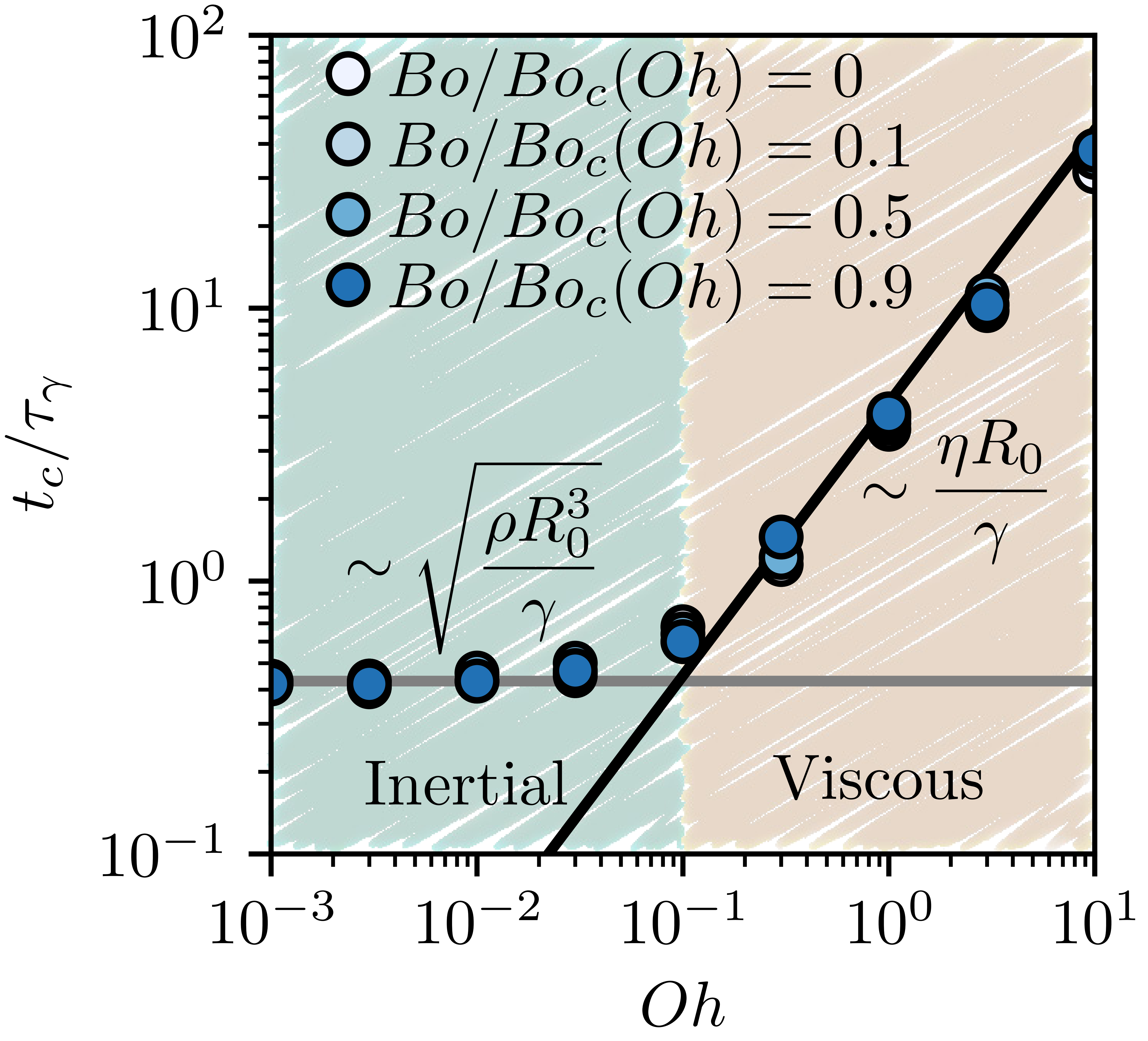


$$Bo = \frac{\rho\omega^2 R_0^3}{\gamma} \quad Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}}$$

What sets the transitions?

Collision time scale

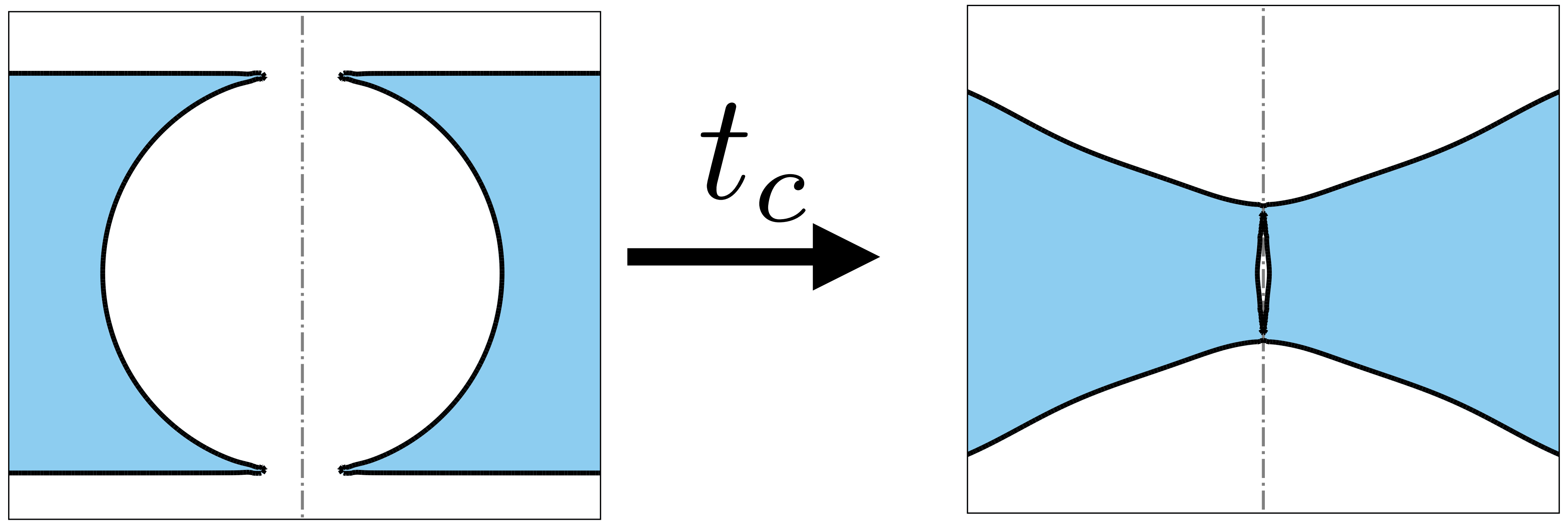




Small Oh: $\frac{\gamma}{R_0} \sim \rho U_0^2 \qquad t_c \sim \sqrt{\frac{\rho R_0^3}{\gamma}}$

Large Oh: $\frac{\gamma}{R_0} \sim \frac{\eta U_0}{R_0} \qquad t_c \sim \frac{\eta R_0}{\gamma}$

Collision vs retraction at small Oh



Collision time scale $\sim$ Retraction time scale of tip

$$\sqrt{\frac{\rho R_0^3}{\gamma}} \sim \frac{1}{\omega}$$

$$\frac{\rho \omega^2 R_0^3}{\gamma} = \text{constant}$$

$$Bo = \text{constant}$$

$Bo = \frac{\rho \omega^2 R_0^3}{\gamma}$ $\quad Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}}$

Collision vs retraction at high Oh

Collision time scale $\sim$ Retraction time scale of tip

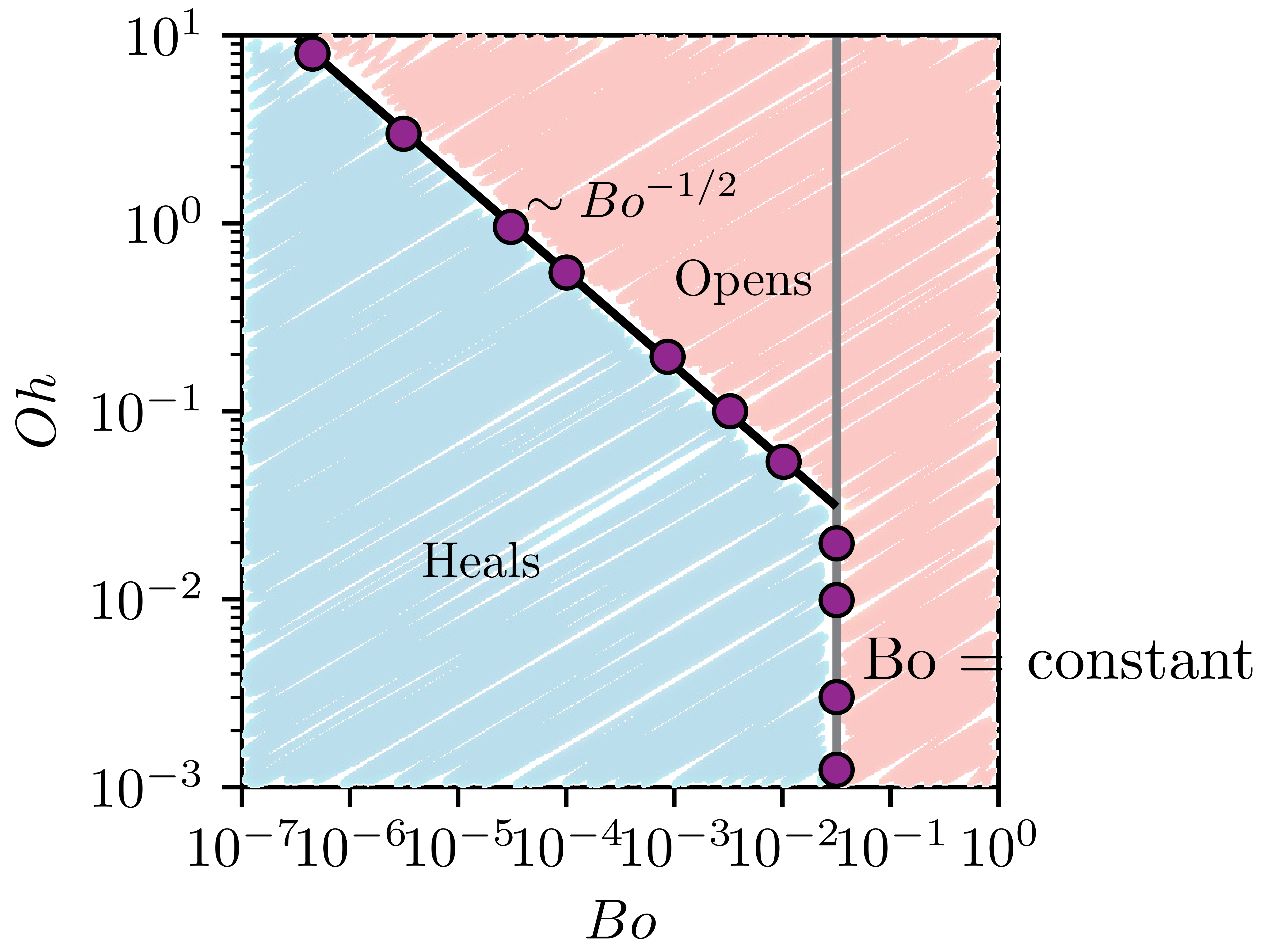
$$\frac{\eta R_0}{\gamma} \sim \frac{1}{\omega}$$

$$\frac{\eta R_0 \omega}{\gamma} \sim 1 \qquad Oh \sim Bo^{-1/2}$$

$$Oh\, Bo^{1/2} = \text{constant}$$

$Bo = \frac{\rho \omega^2 R_0^3}{\gamma}$ $\quad Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}}$

Oh-Bo parameter space

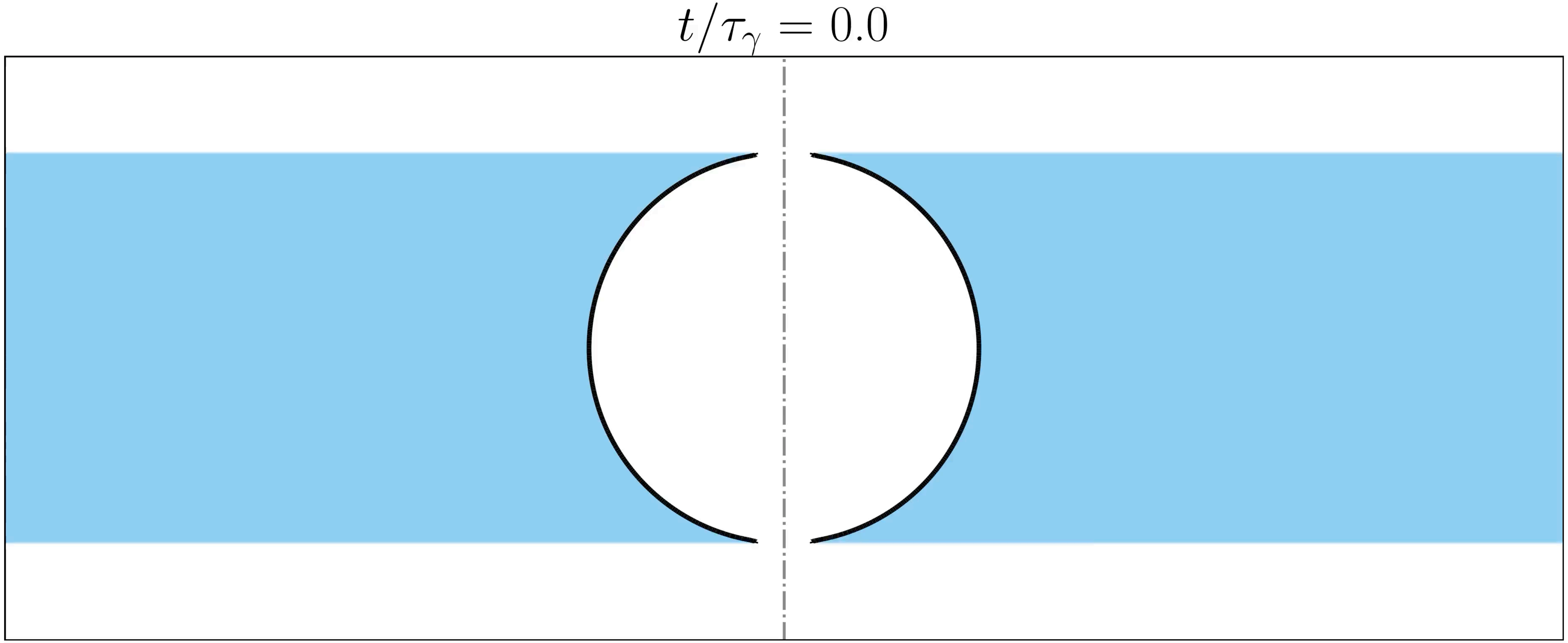


$Bo = \frac{\rho \omega^2 R_0^3}{\gamma} \quad Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}}$

$$Oh_c \sim 1/\sqrt{Bo}$$

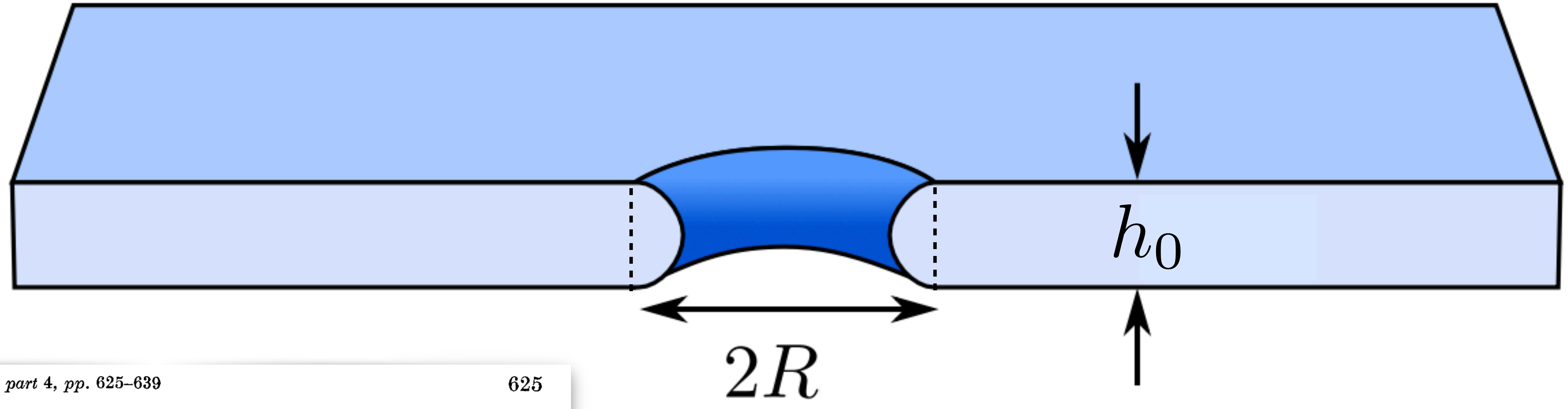
What happens for vanishing driving?

Holes always heal at $Bo = 0$



$$Bo = \frac{\rho\omega^2 R_0^3}{\gamma} \quad Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}}$$

Taylor & Michael's geometric condition for hole opening



J. Fluid Mech. (1973), *vol.* 58, *part* 4, *pp.* 625–639 625
Printed in Great Britain

On making holes in a sheet of fluid

By G. I. TAYLOR
Trinity College, Cambridge
AND D. H. MICHAEL
Department of Mathematics, University College London

(Received 12 October 1972)

It is suggested in this paper that axisymmetric holes in thin sheets of fluid in which surface tension forces predominate will open out if they are initially large in relation to the thickness of the sheet; but that small holes will close up. No exact criterion has been found for the critical hole size in a free falling sheet, but the behaviour of the sheet may be closely simulated by the suspension of a soap film between coaxial circular rings. Theoretical results and experimental observations on catenoid films so formed are described.

$$\frac{\Delta G}{\gamma h_0^2} = -\pi + \pi^2 \left(\frac{R}{h_0}\right) - 2\pi \left(\frac{R}{h_0}\right)^2$$

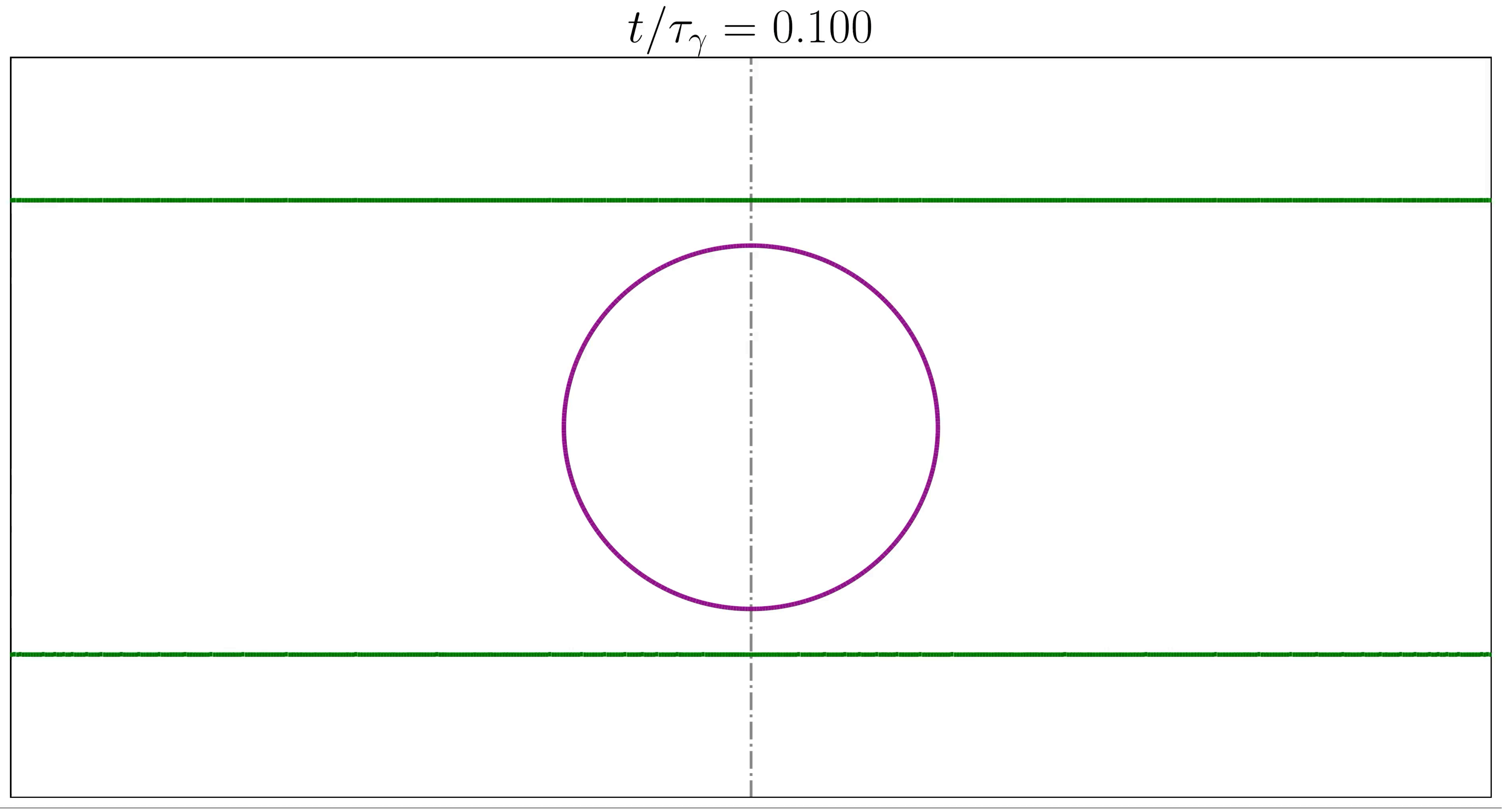
$$\frac{R}{h_0} \gg \frac{\pi}{4} - \frac{1}{2}$$

Not included: dynamic effects

What if the hole geometry changes?

If there is delayed breakup!

$Oh = 0.1 \qquad Bo = 0.1$

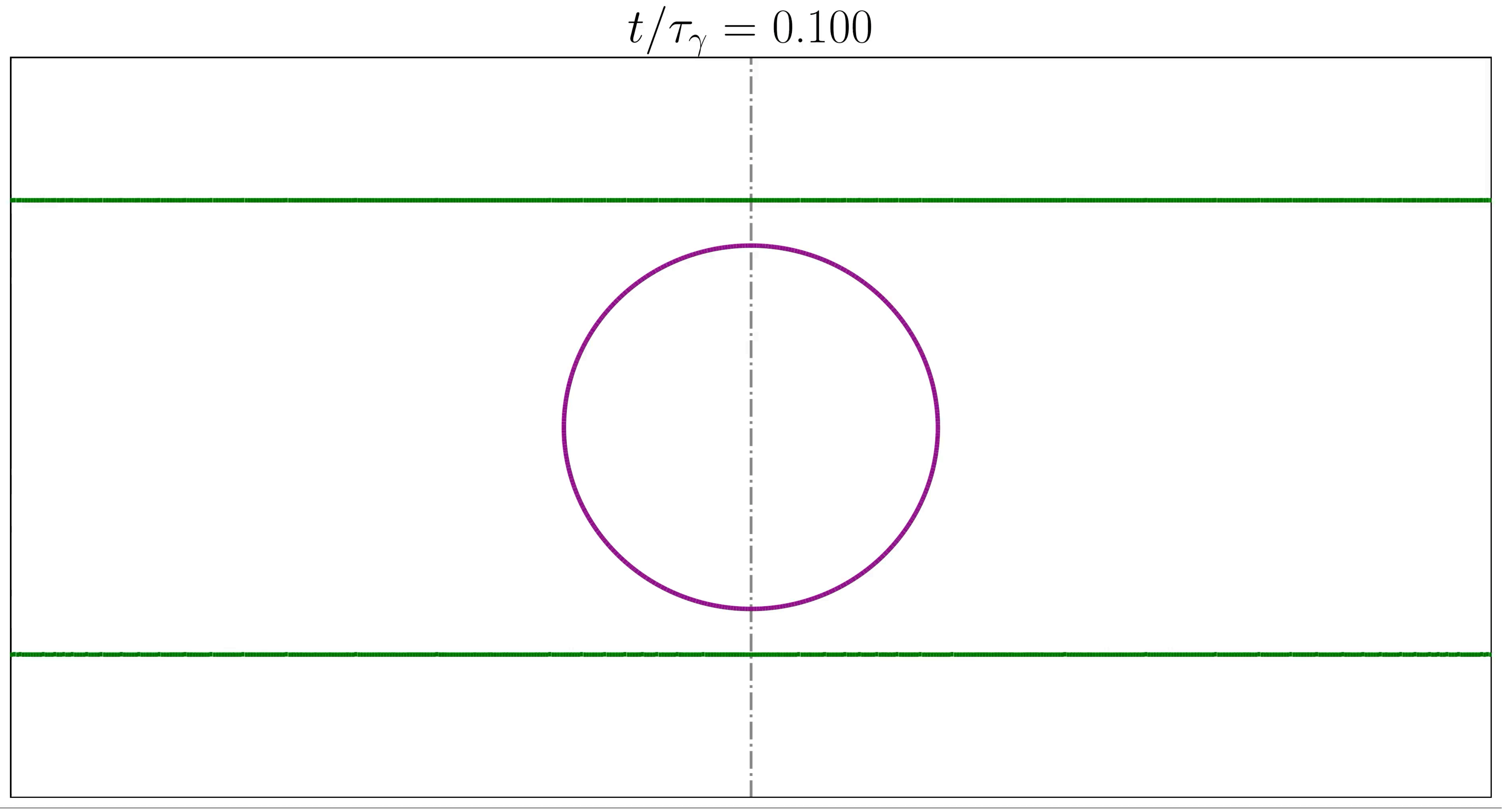


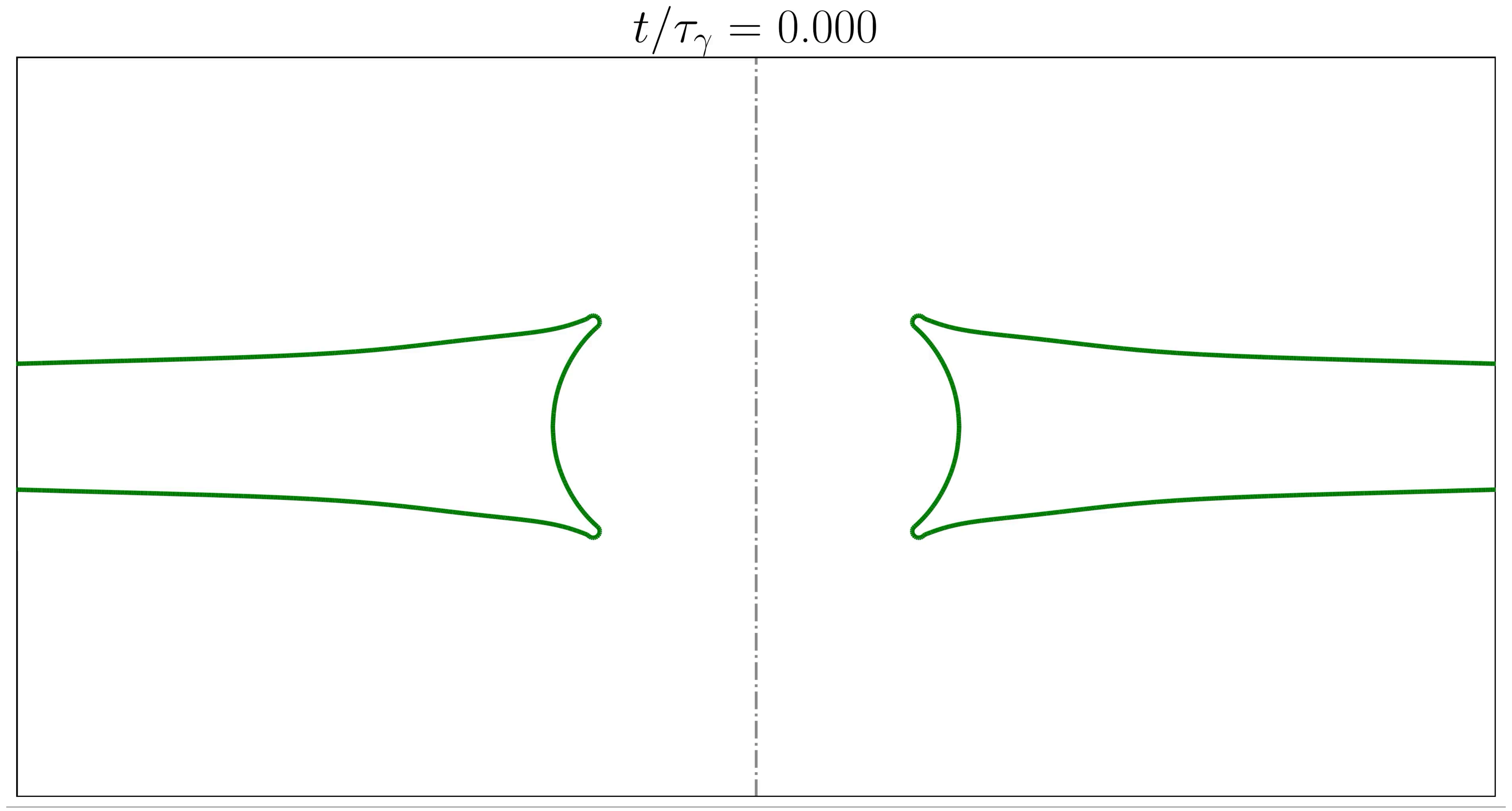
$$Bo = \frac{\rho\omega^2 R_0^3}{\gamma} \quad Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}}$$

Time-controlled rupture

$Oh = 0.1 \quad Bo = 0.1$

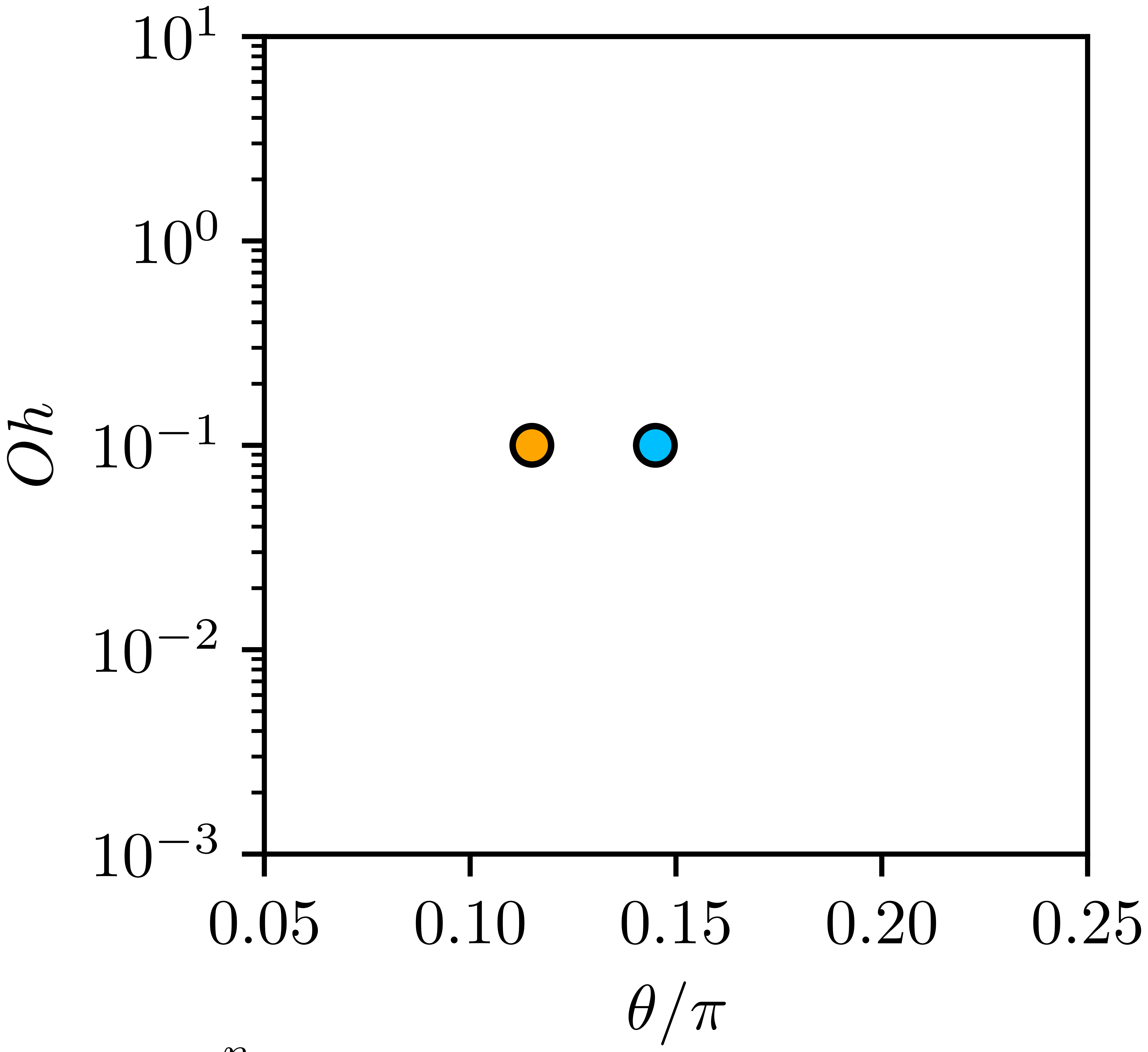
$t_r/\tau_\gamma = 6$

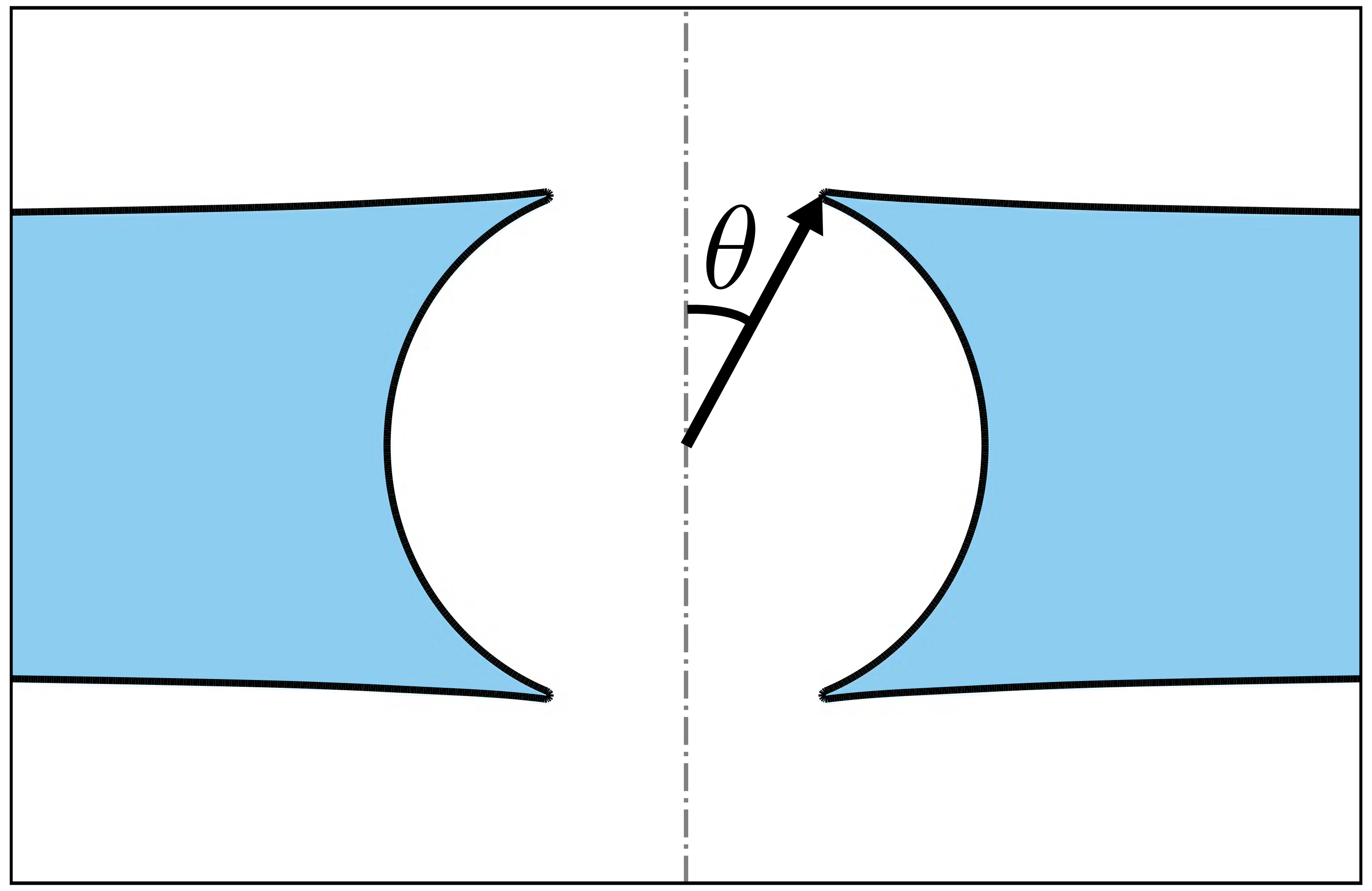




$$Bo = \frac{\rho\omega^2 R_0^3}{\gamma} \quad Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}}$$

Initial shape effects at $Bo = 0$





$Bo = \frac{\rho\omega^2 R_0^3}{\gamma}$ $\quad Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}}$

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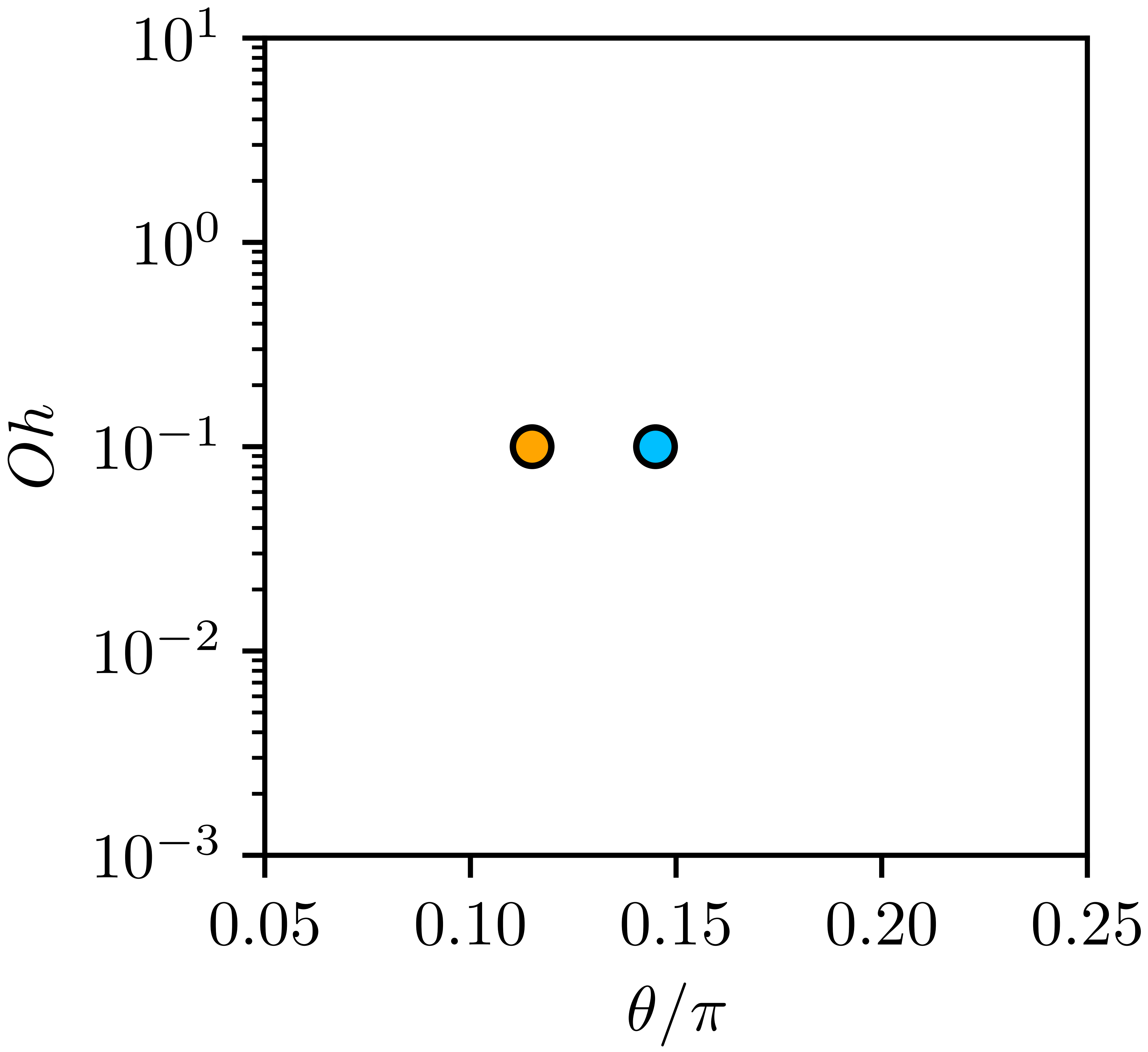
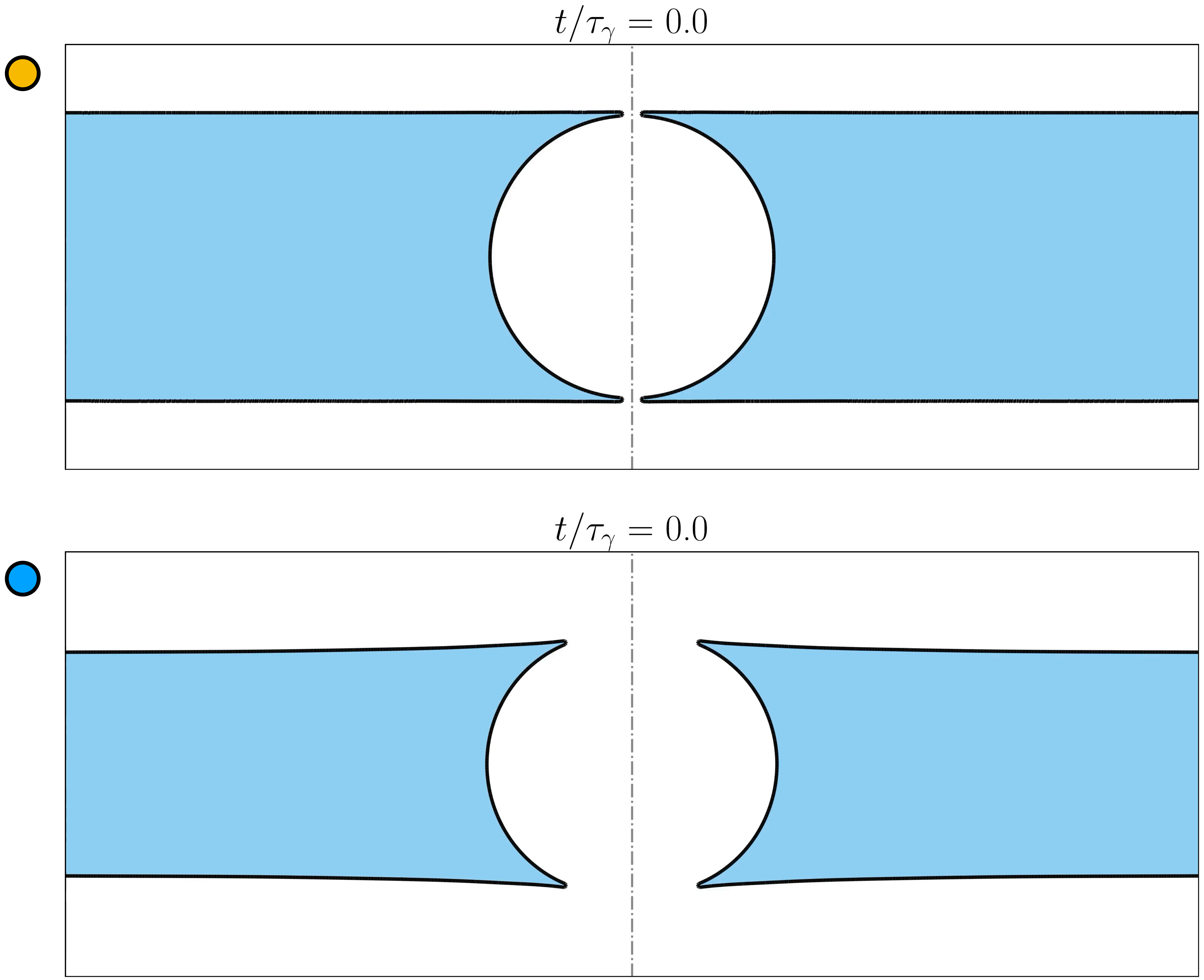
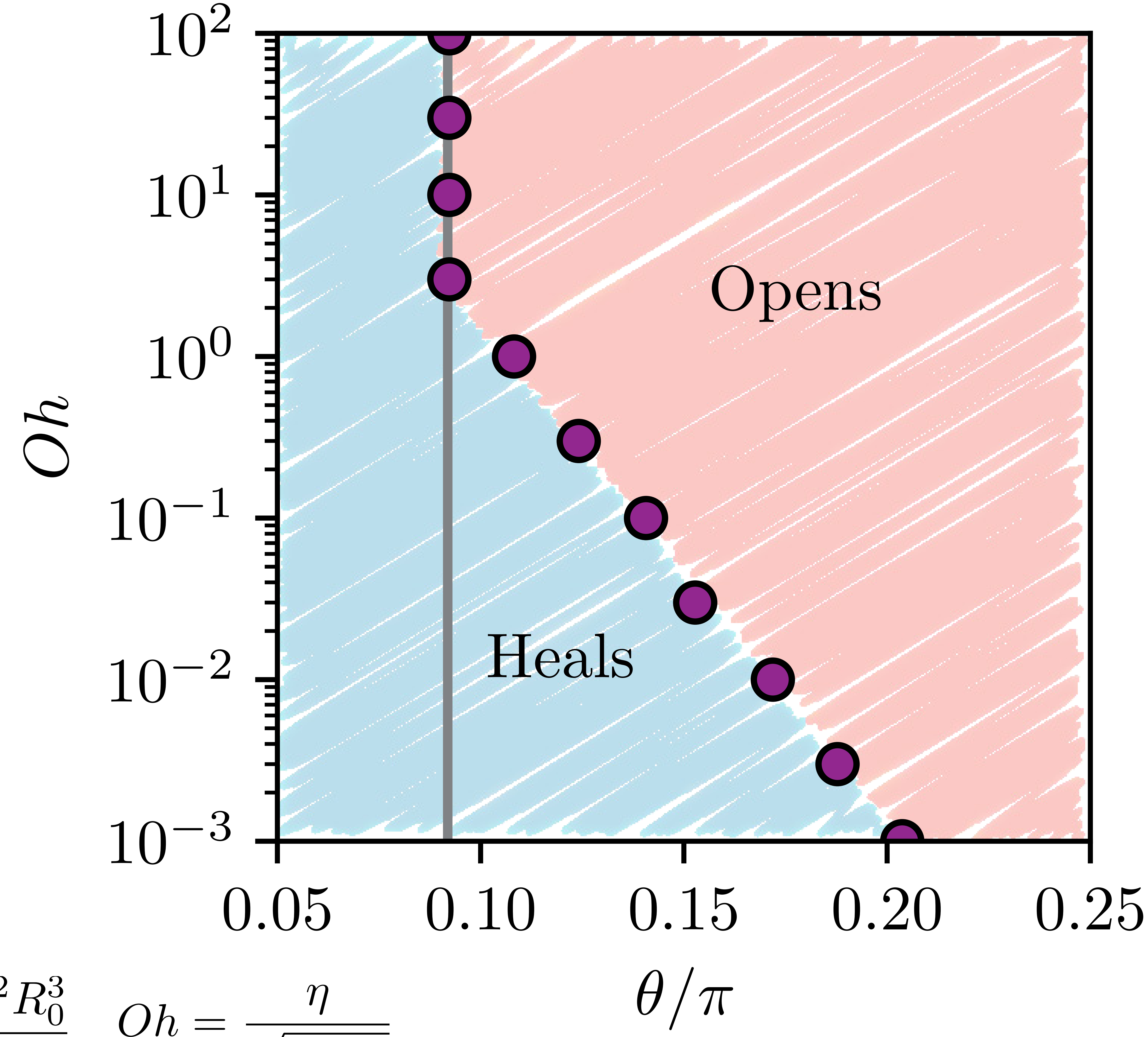


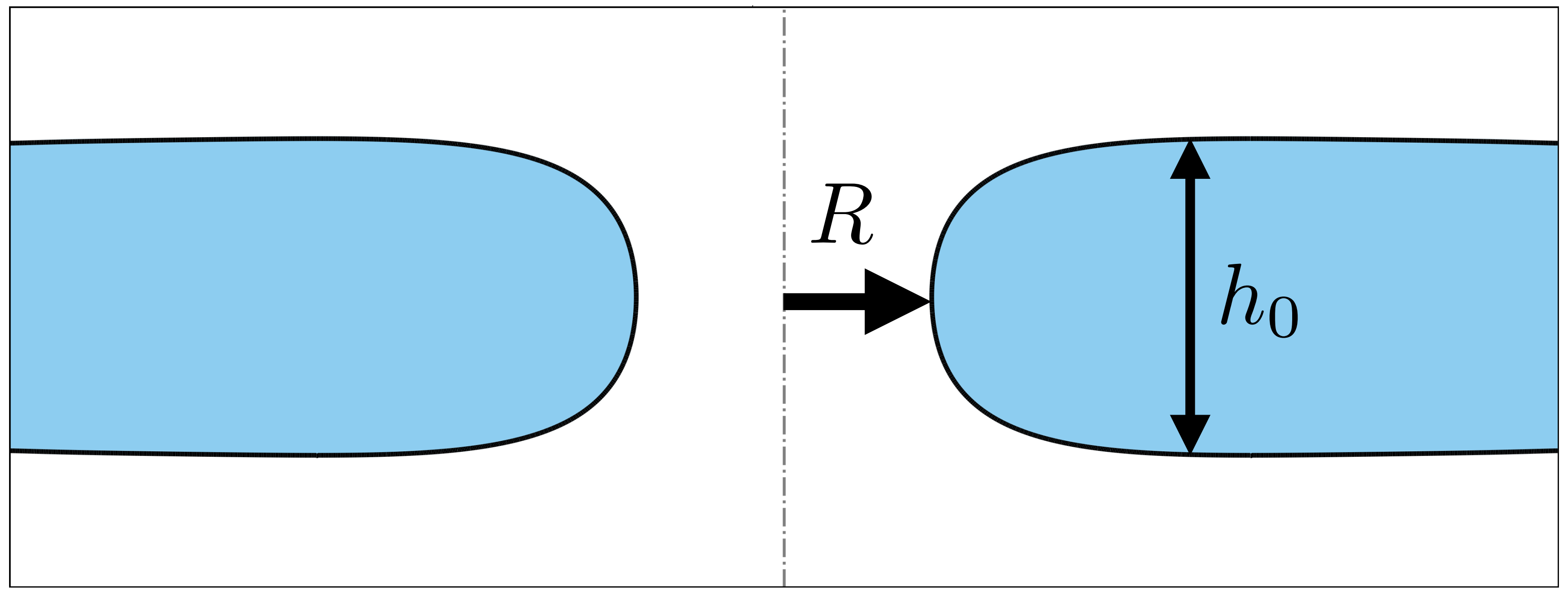


$$Bo = \frac{\rho\omega^2 R_0^3}{\gamma} \quad Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}}$$

Regime map (Oh-Bo)



Near transition high Oh cases



Taylor and Michael's criterion

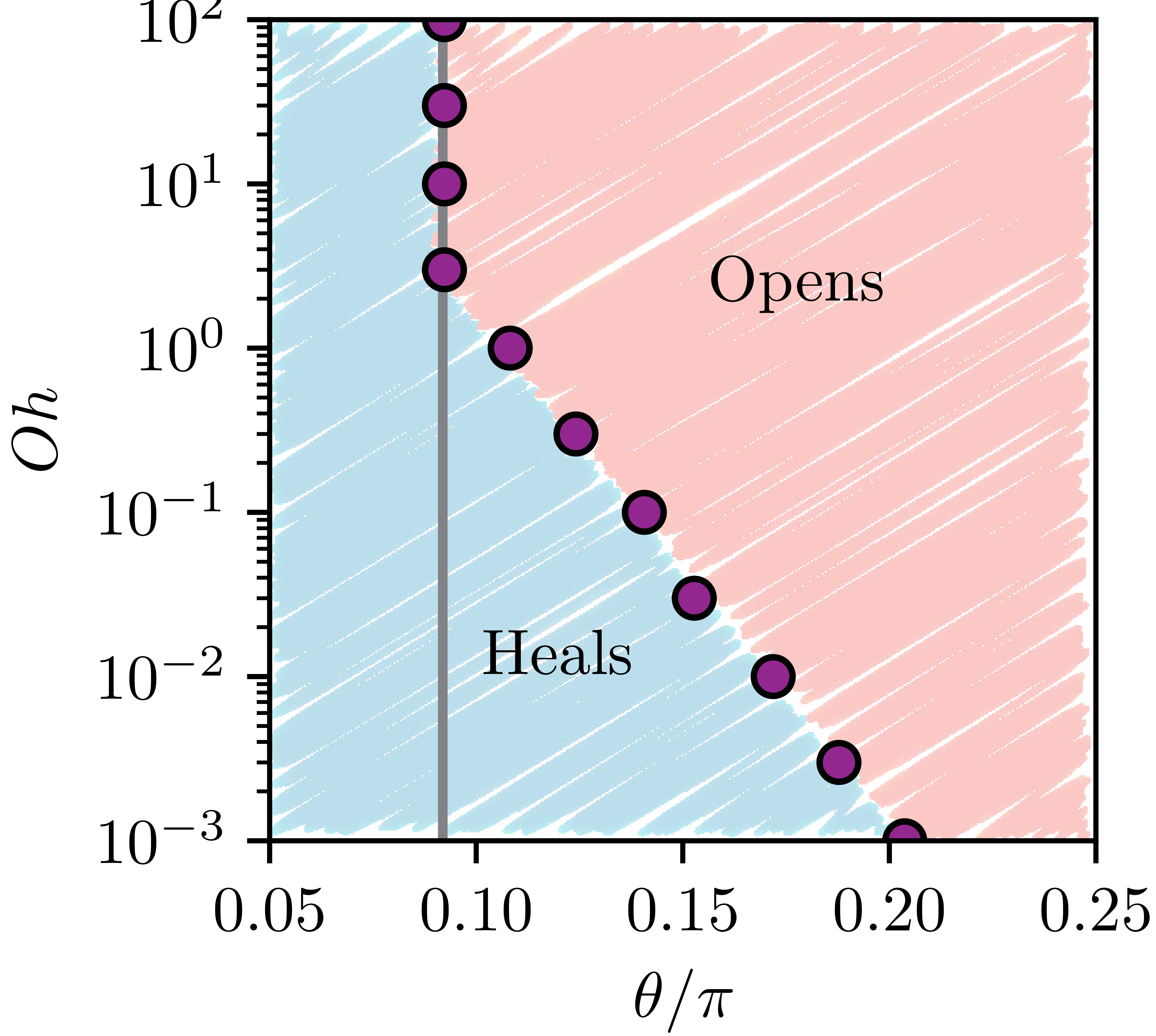
$$\frac{R}{h_0} > 0.28$$

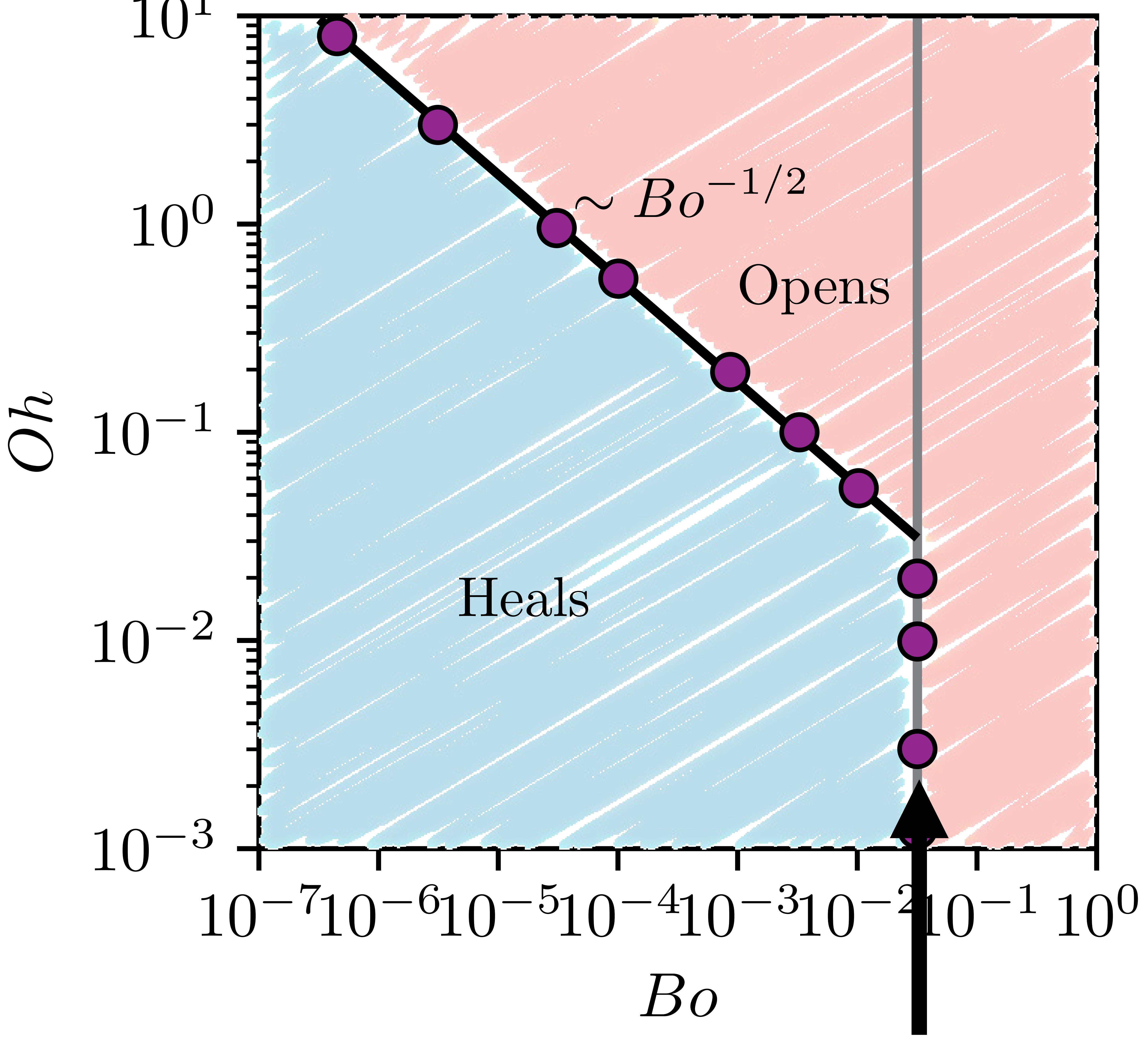
For vanishing inertia ($Oh >> 1$)

$Bo = \frac{\rho \omega^2 R_0^3}{\gamma}$ $\quad Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}}$

Summary

Vanishing driving





Vanishing viscosity

$Bo = \frac{\rho \omega^2 R_0^3}{\gamma} \quad Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}}$

COMMENTARY

Proc. Natl. Acad. Sci. 117, 32 (2020)

Double threshold behavior for breakup of liquid sheets

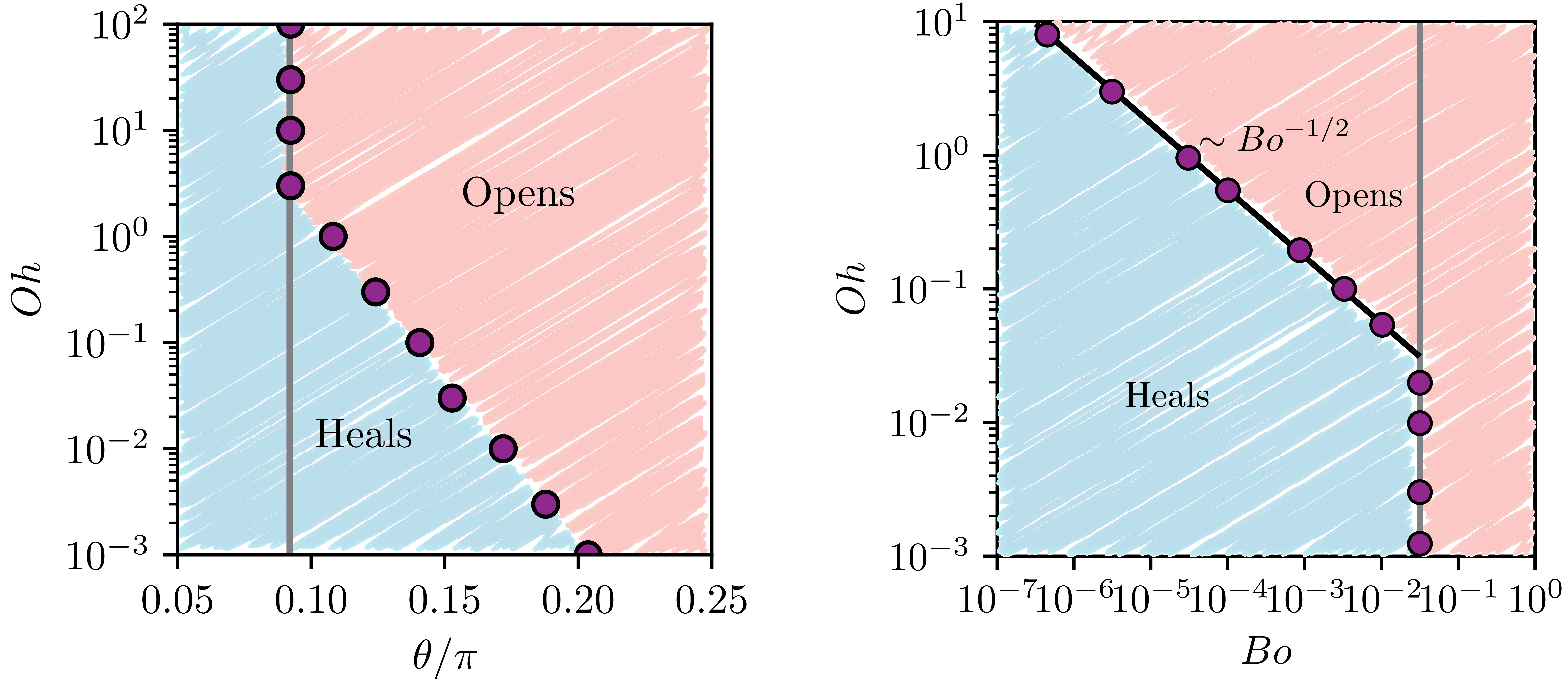
Detlef Lohse[a,1] and Emmanuel Villermaux[b]

1. Strong enough driving

2. Large enough distortions

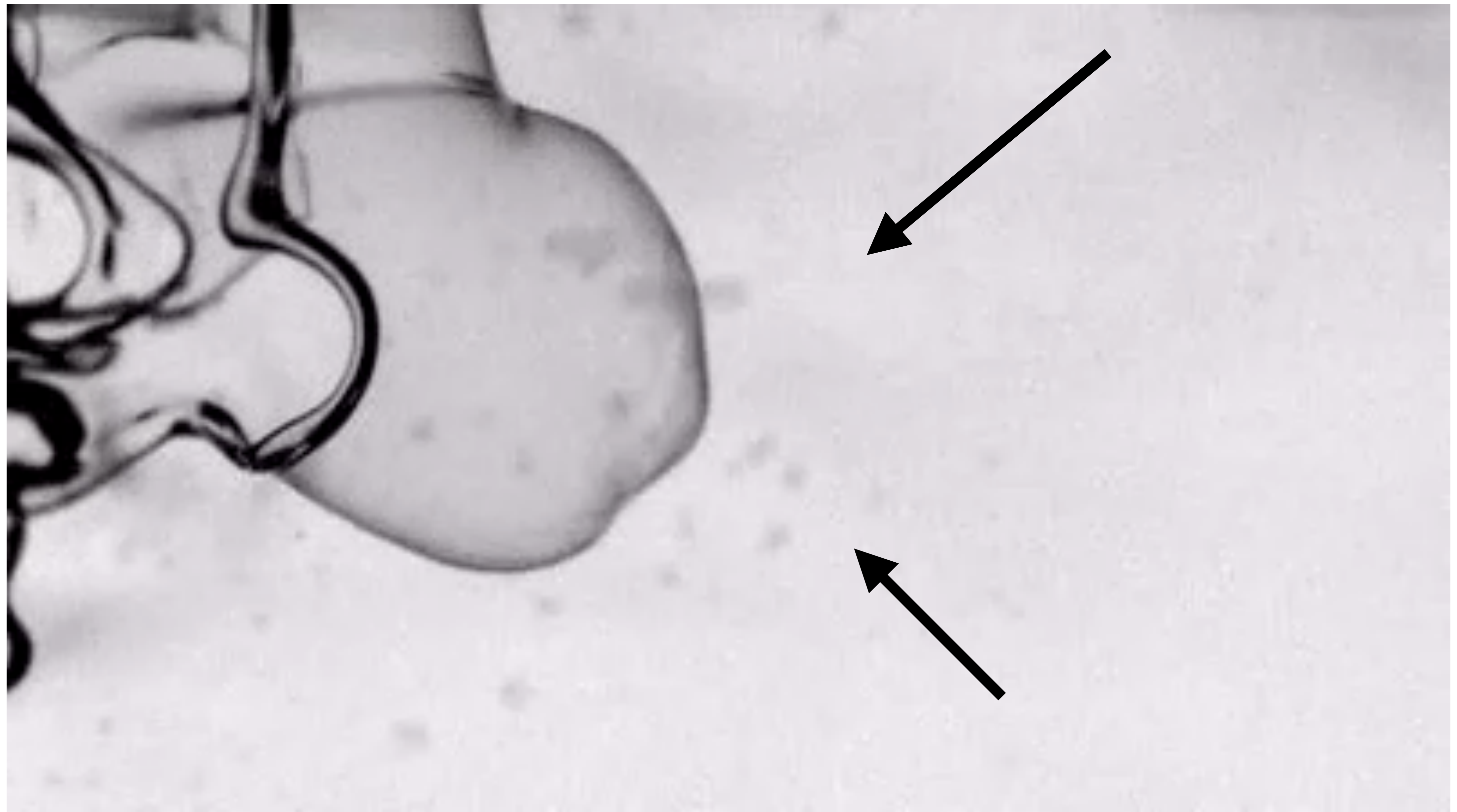
$$Bo = \frac{\rho\omega^2 R_0^3}{\gamma} \quad Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}}$$

Summary



$Bo = \frac{\rho \omega^2 R_0^3}{\gamma} \quad Oh = \frac{\eta}{\sqrt{\rho R_0 \gamma}}$

How do holes nucleate in sheets?

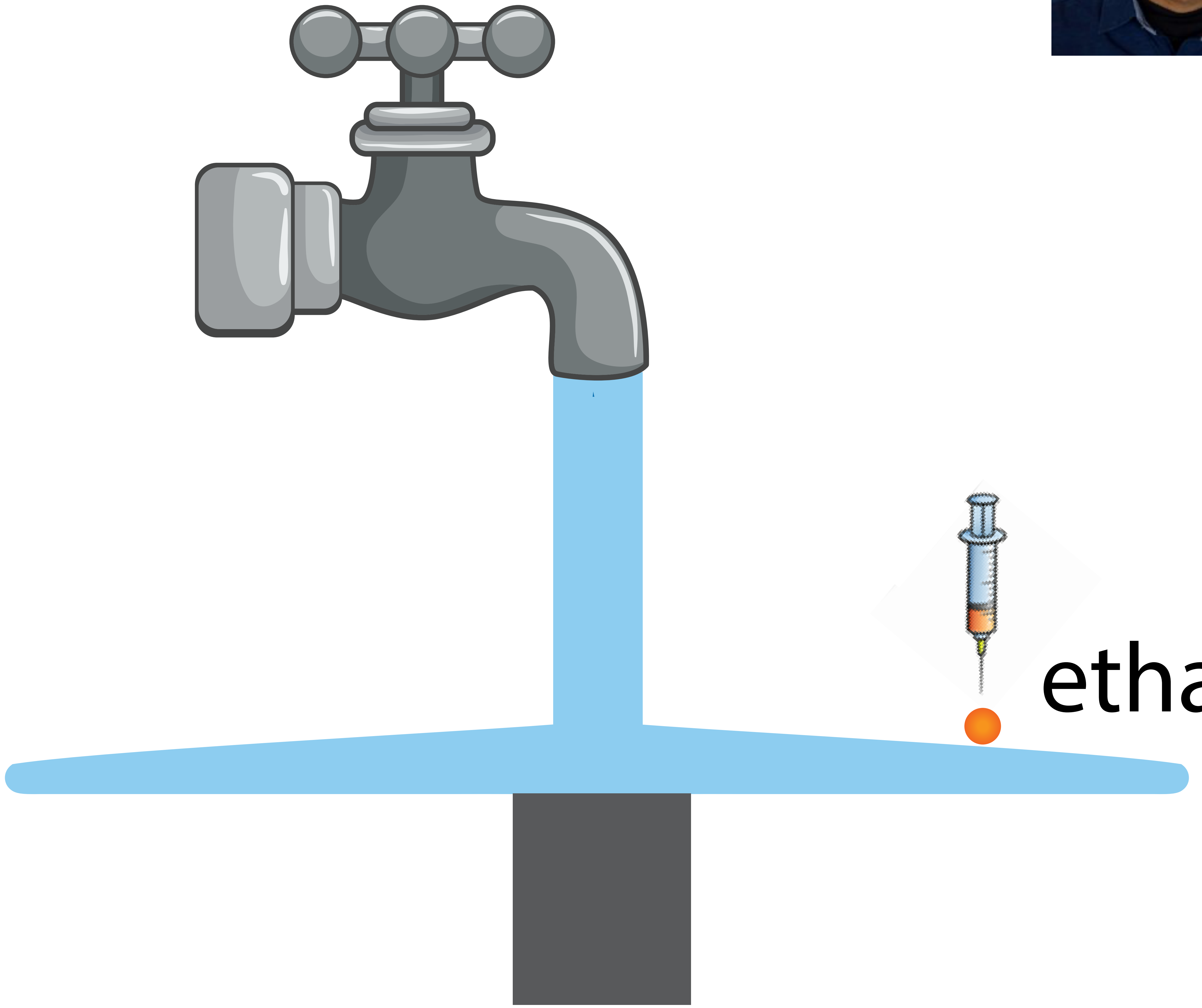


- Thermal fluctuations
- Van der Waal forces
- By hydrophobic particles or bubbles
- Chemical and temperature inhomogeneities

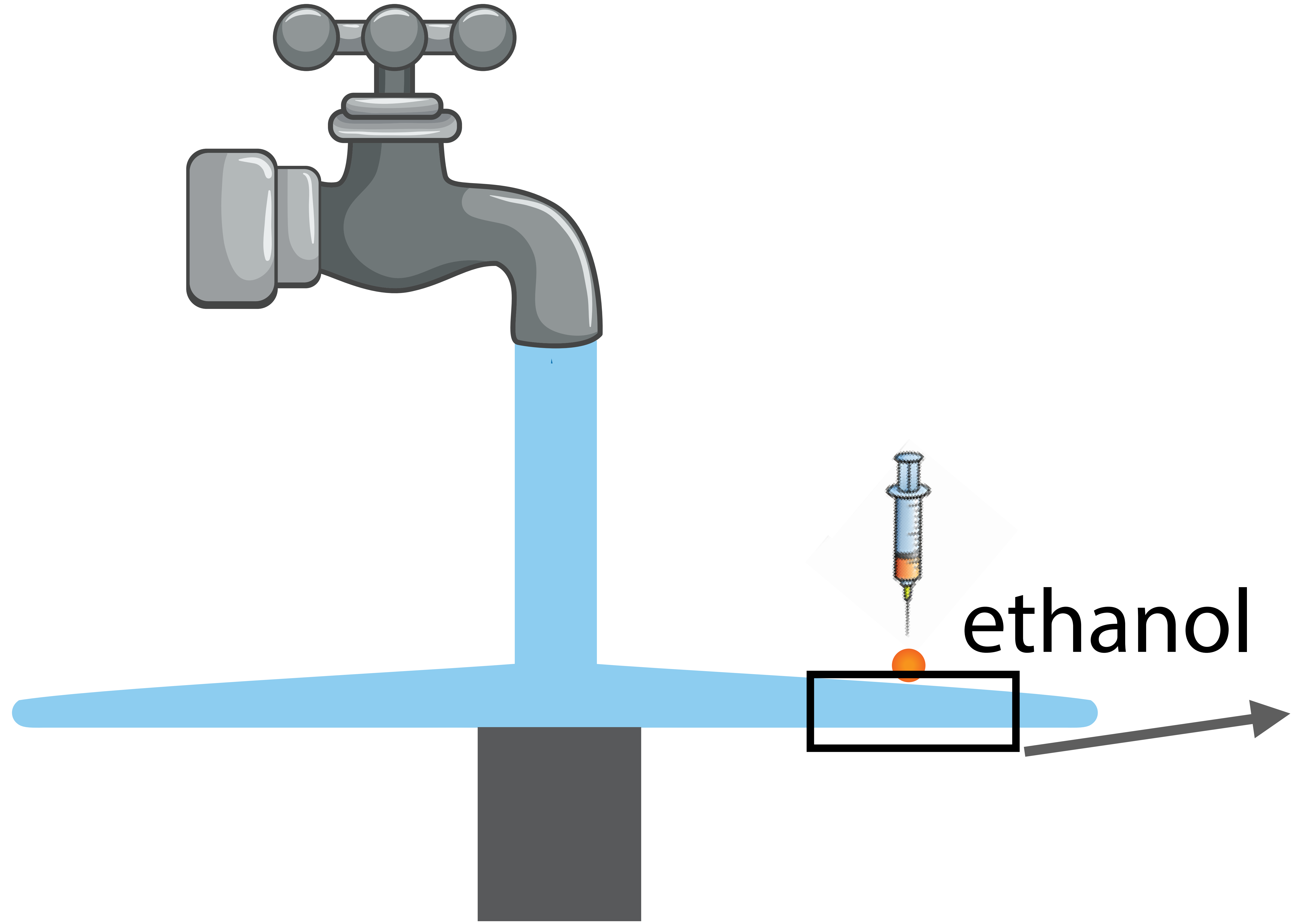
Lohse & Villermaux Proc. Natl. Acad. Sci. 117, 32 (2020)

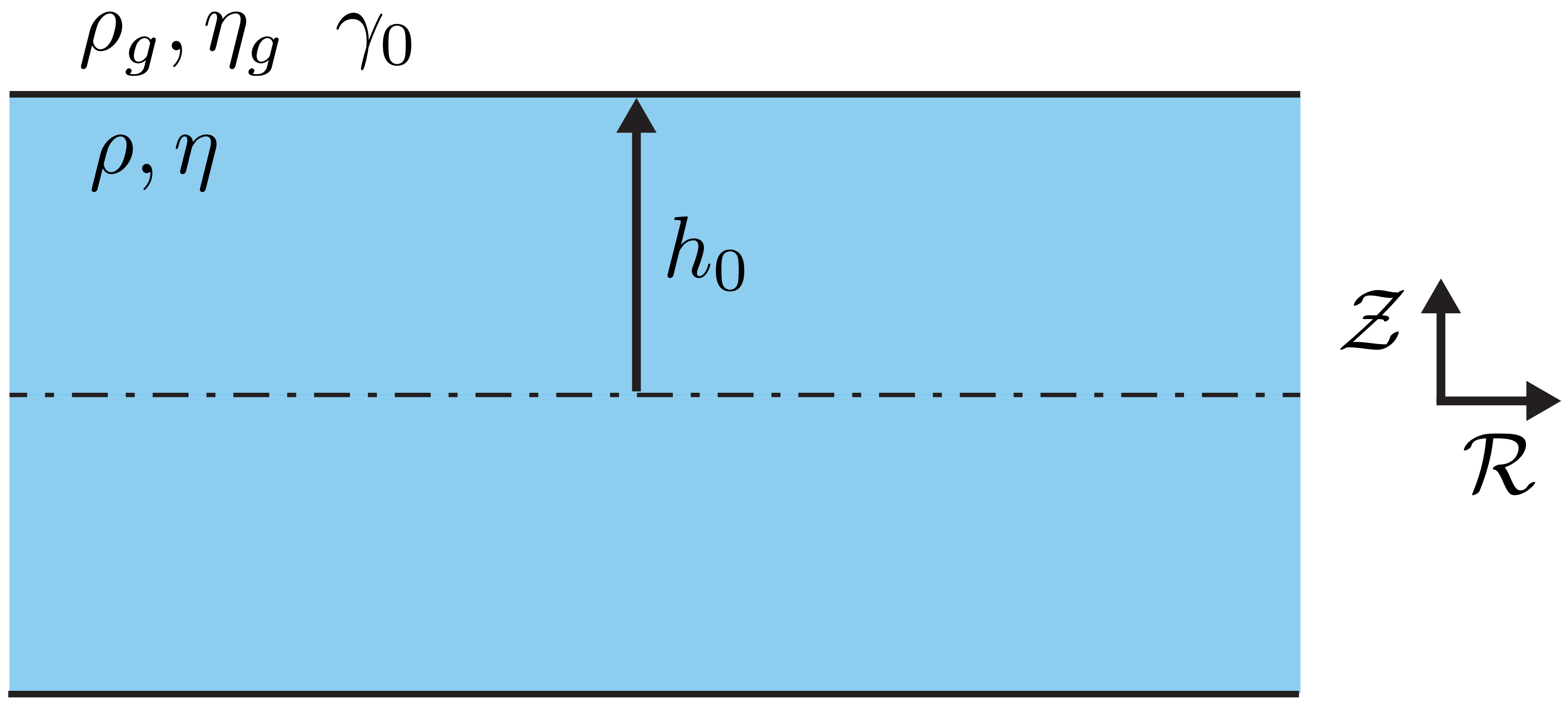
Open tap on a spoon

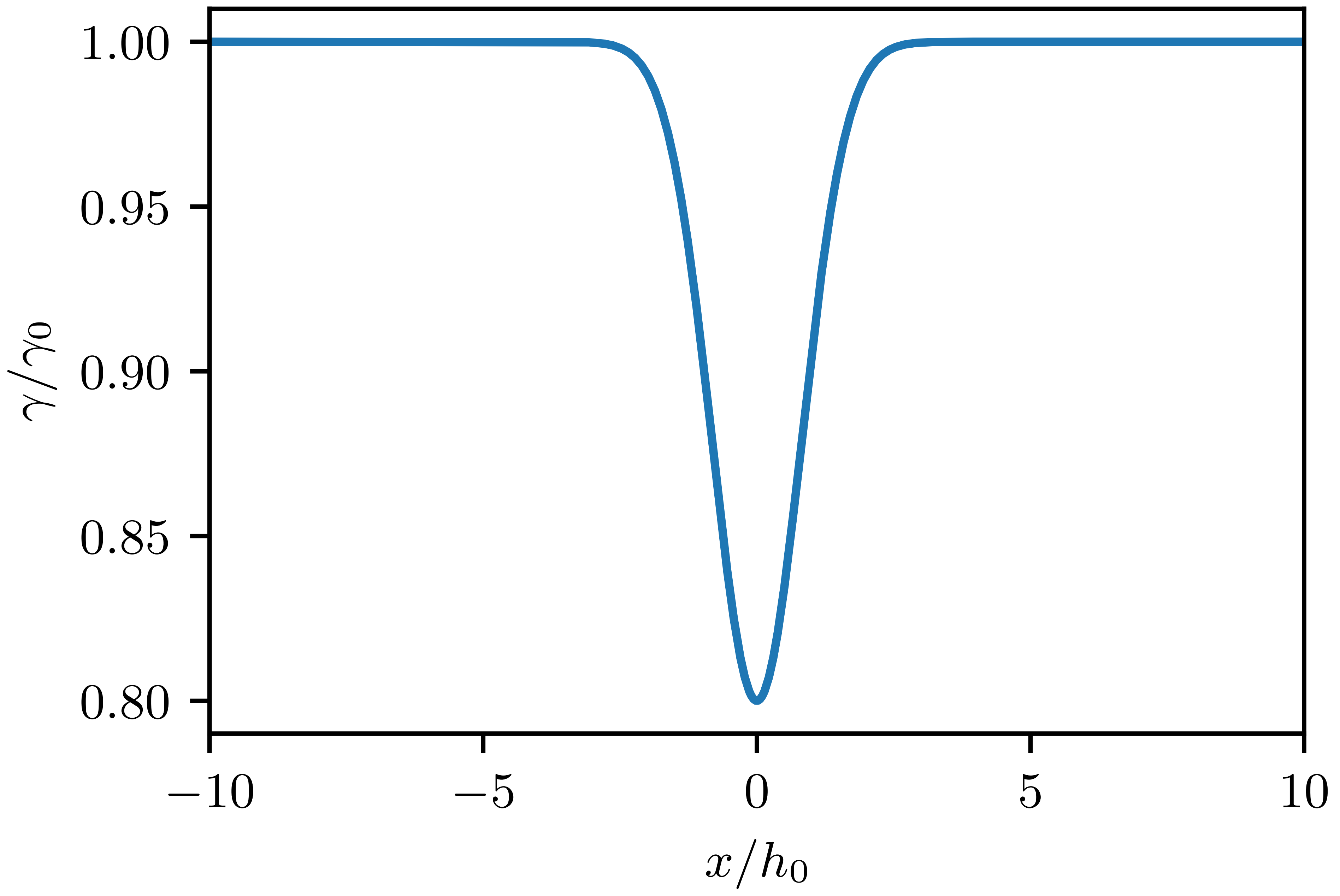

@r/WtWFotMJaJtRAtCaB



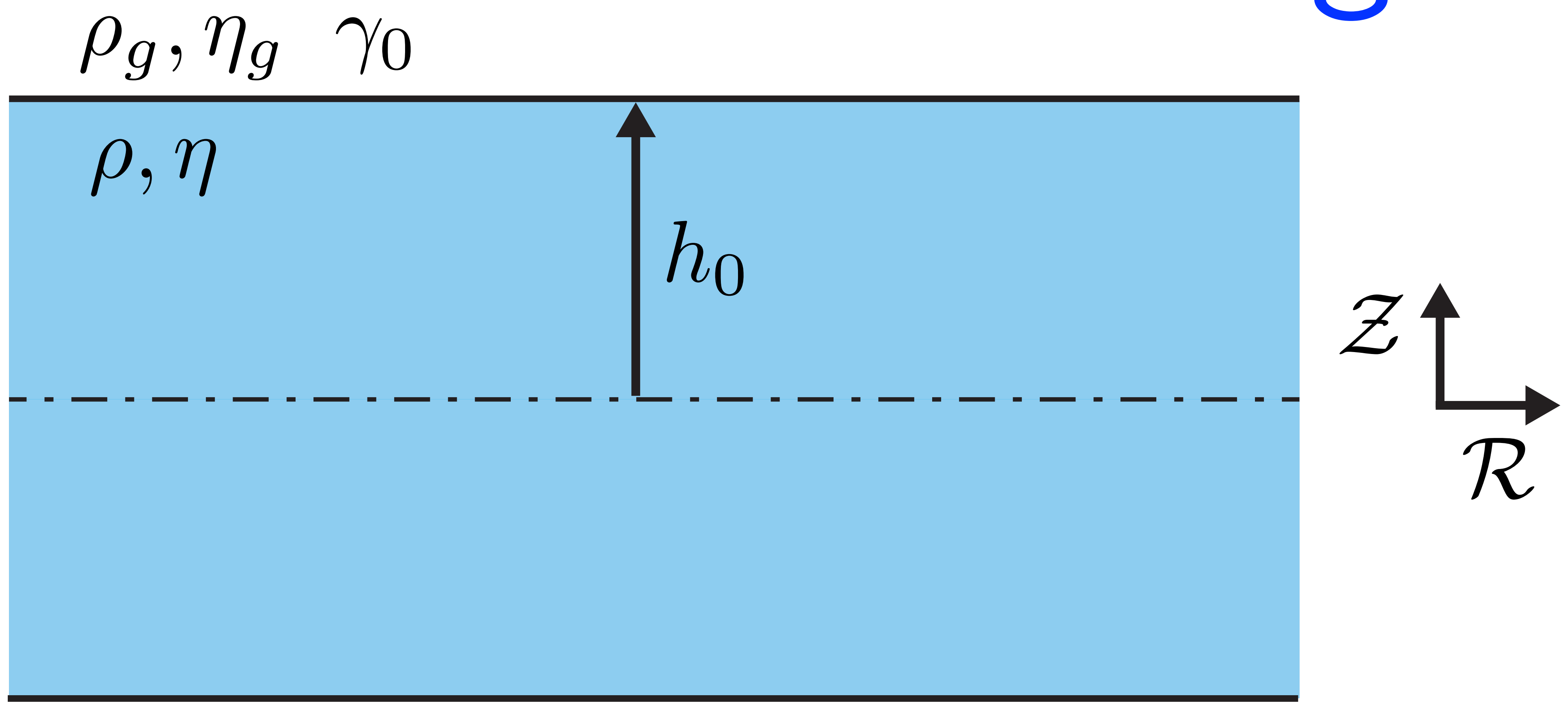
Open tap on a spoon

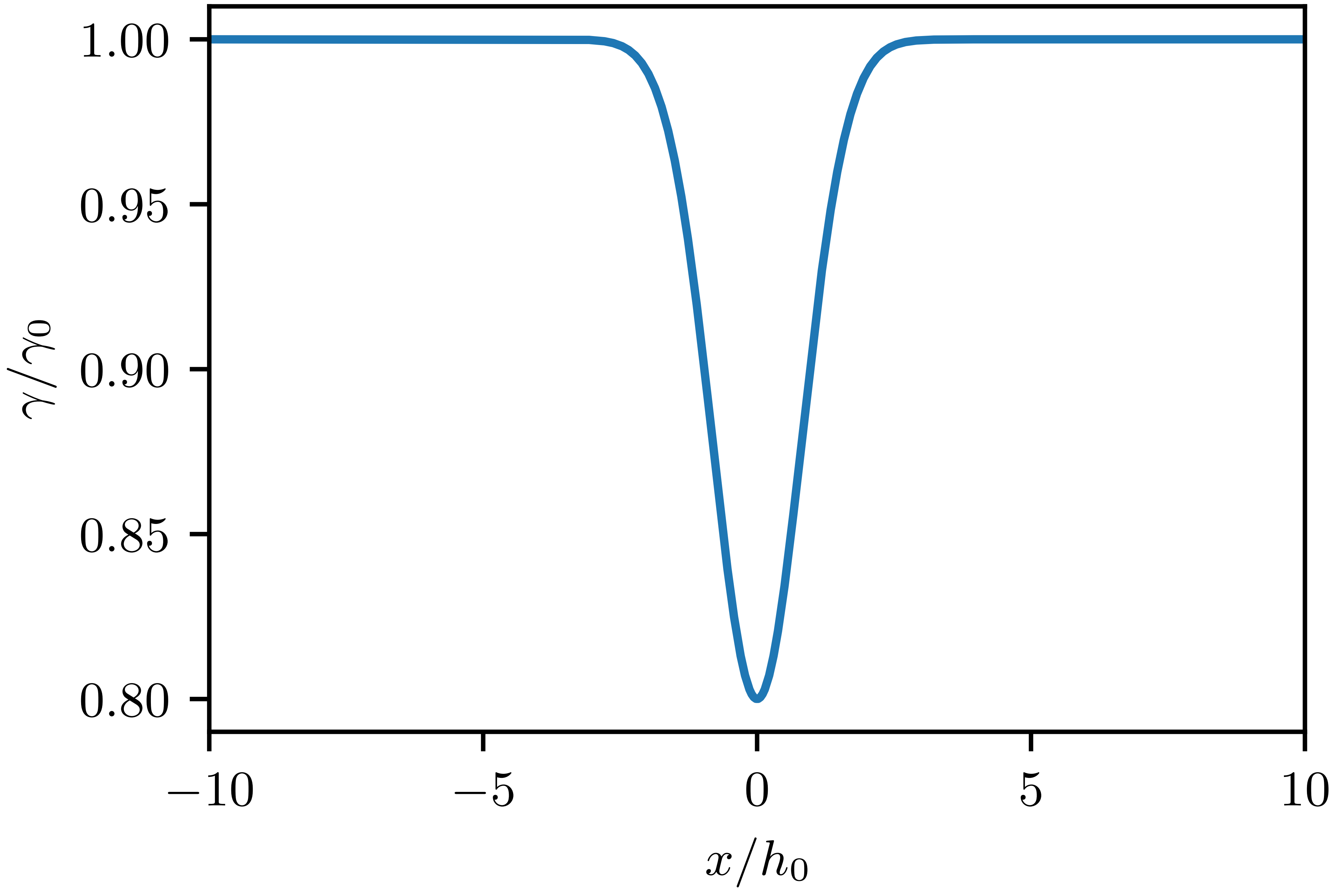




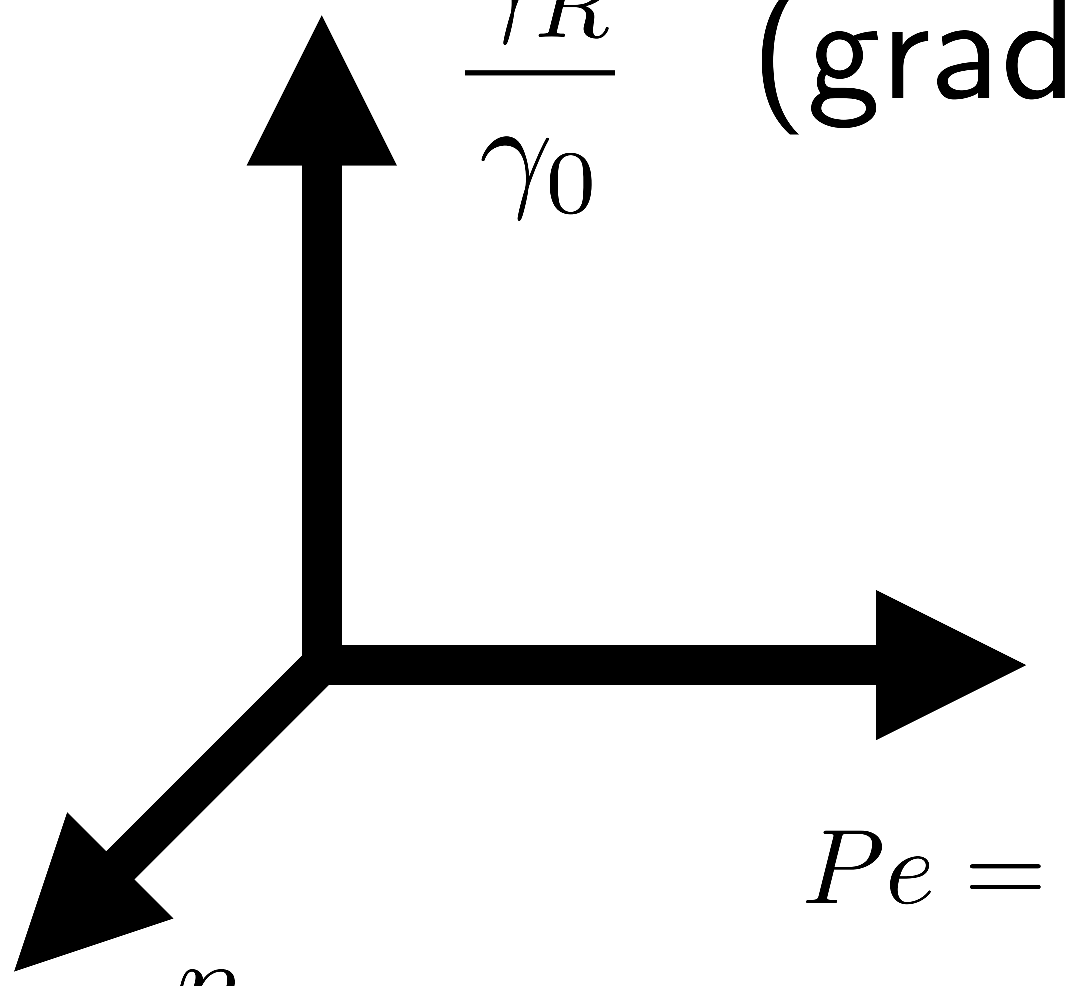


Marangoni driven sheet





Finite D: $\gamma = \gamma_0 - \gamma_R c$



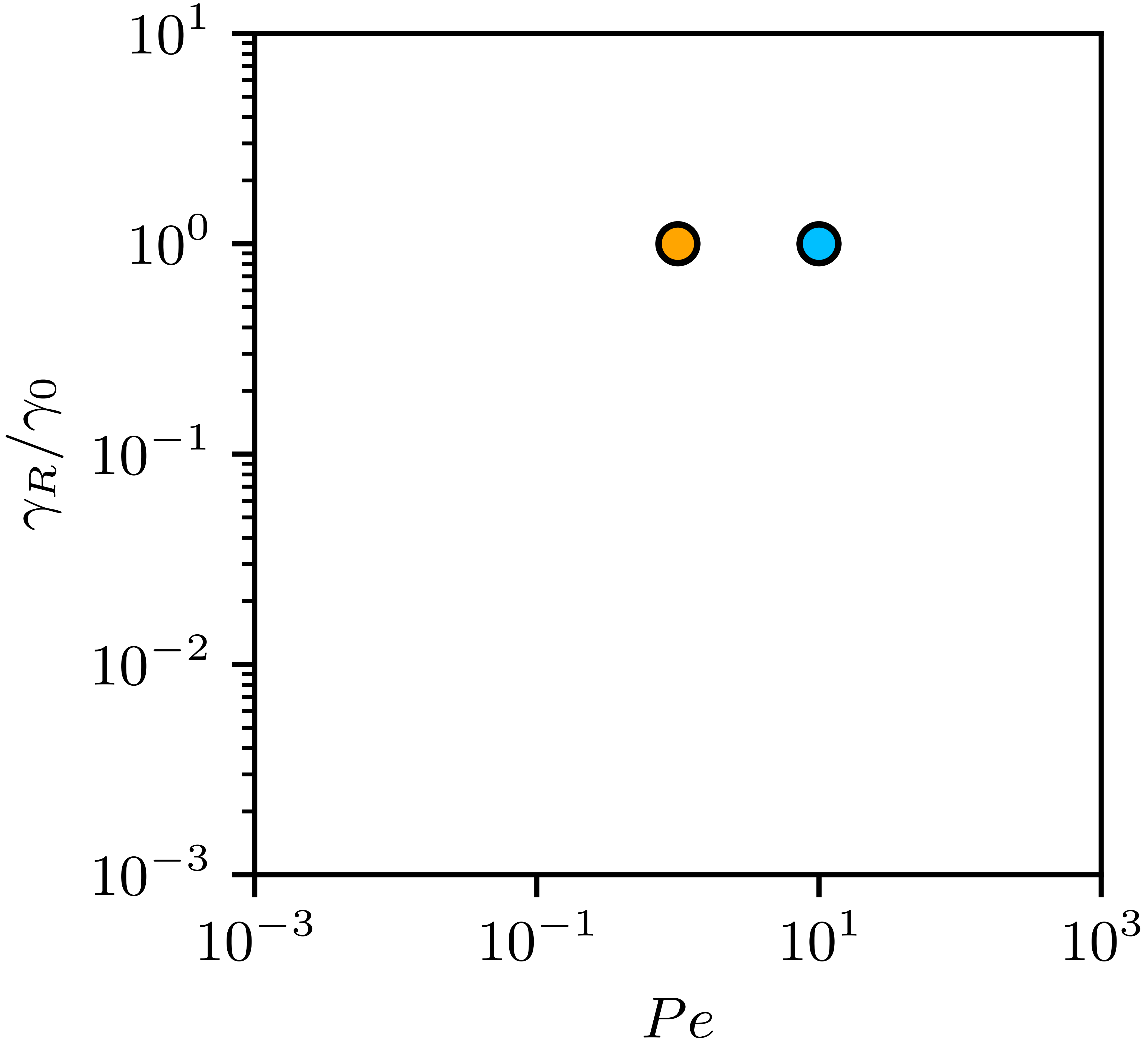
$\dfrac{\gamma_R}{\gamma_0}$ (gradient)

$Pe = \dfrac{1}{D}\sqrt{\dfrac{\gamma_0 h_0}{\rho}}$ (diffusion time)

$Oh = \dfrac{\eta}{\sqrt{\rho \gamma_0 h_0}}$ (viscosity)

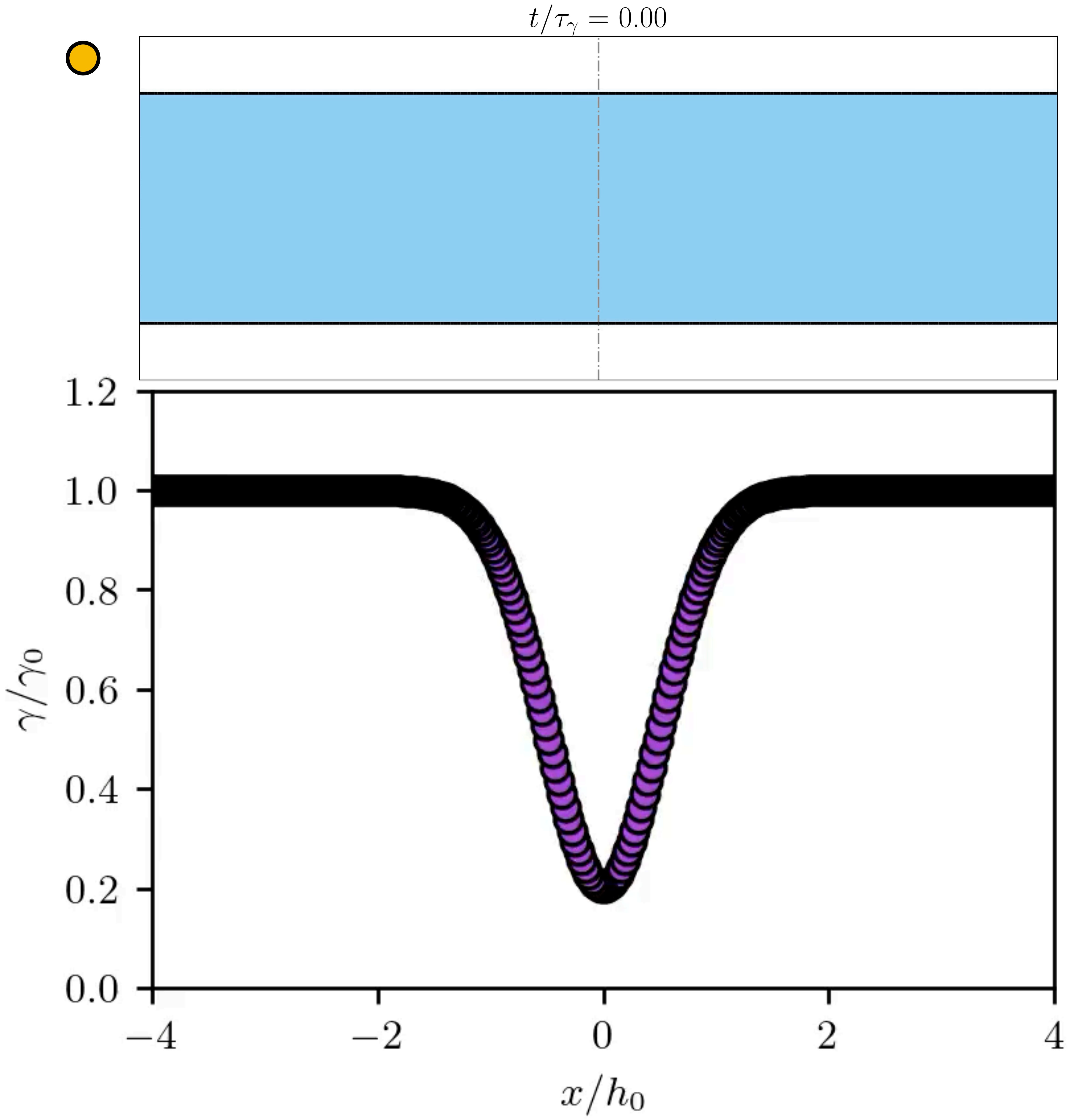
Parameter space

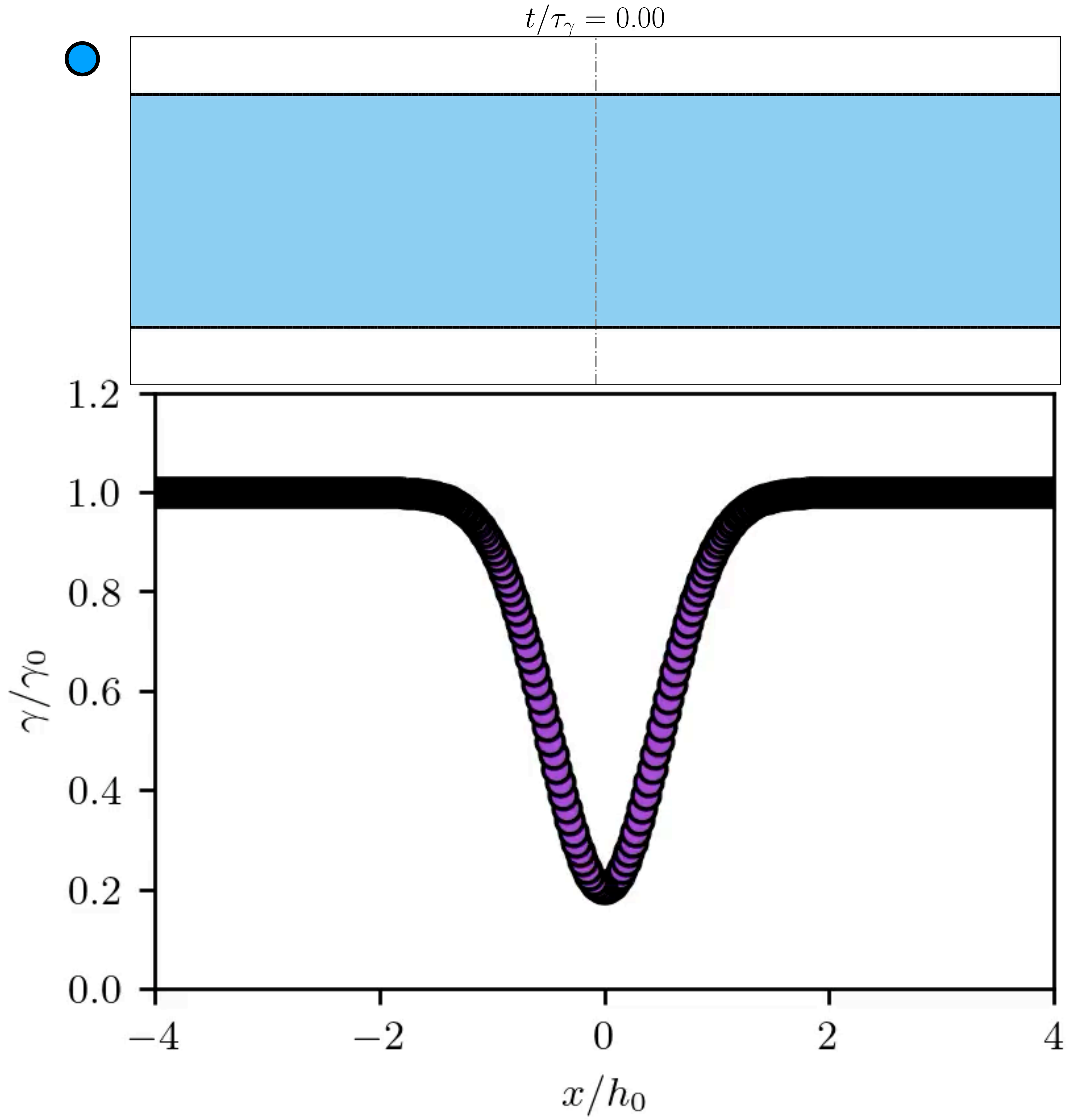
(gradient)



(diffusion time)

Effect of Péclet number





Thank you for your attention! Questions?