

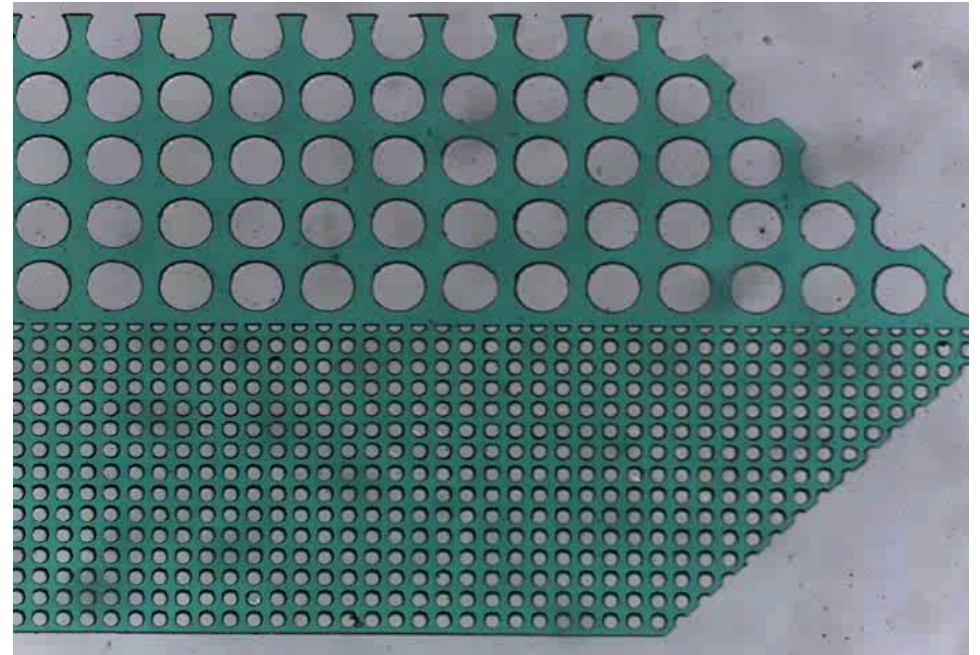
Analysis of Foam Stability Using Microfluidic Channels

Kun Ma, Rachel Liontas, Charles Conn, George Hirasaki, and
Sibani Lisa Biswal

Chemical and Biomolecular Engineering
Rice University



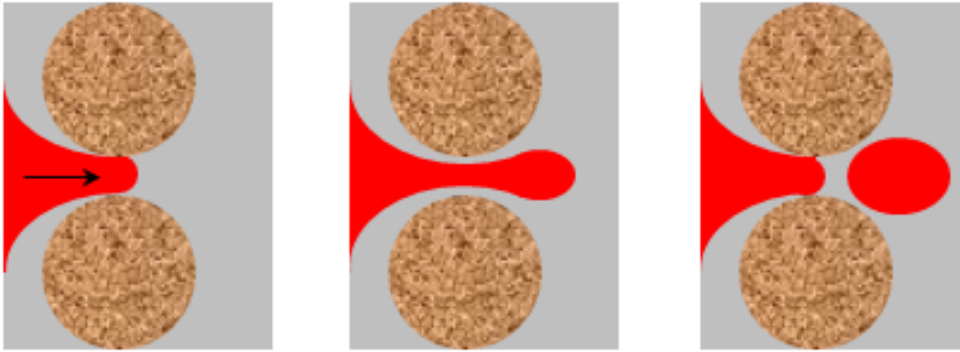
Foam for Enhanced Oil Recovery



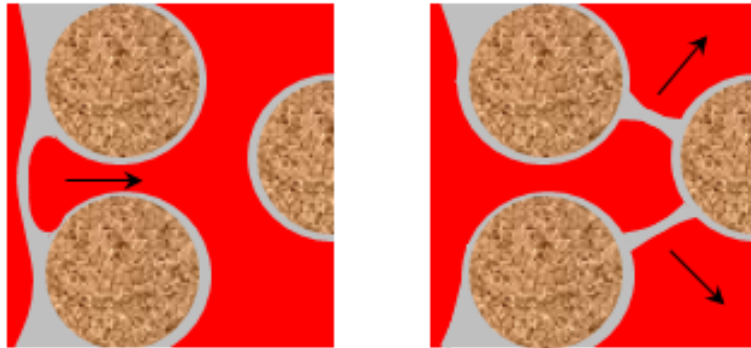
Gas mobility visualized in a micromodel with contrasting permeability

Foam mobility visualized in a micromodel with contrasting permeability

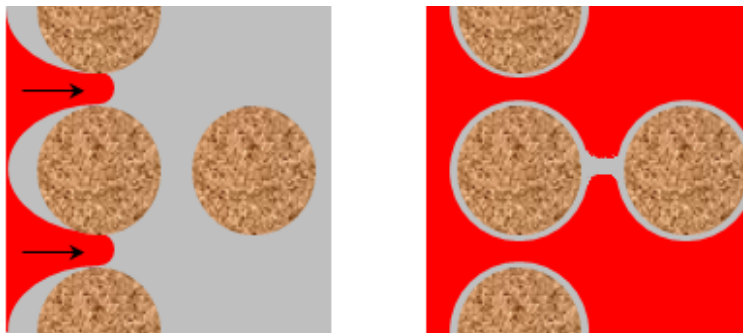
Classic Mechanisms for Foam Generation



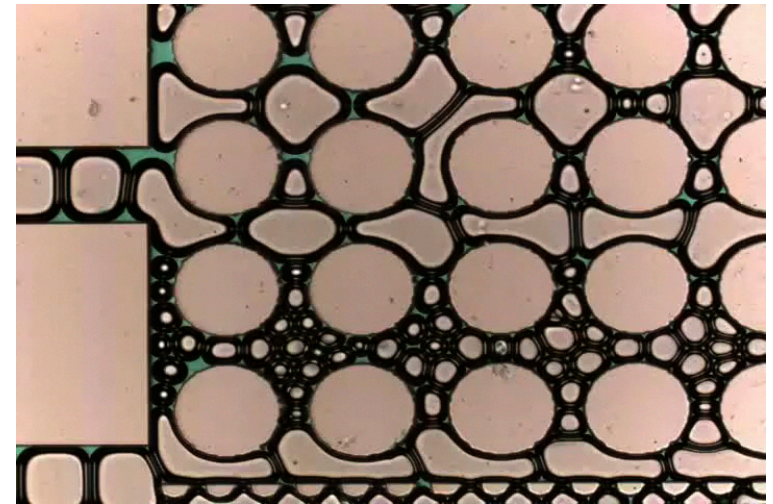
Snap -off



Lamella
Division



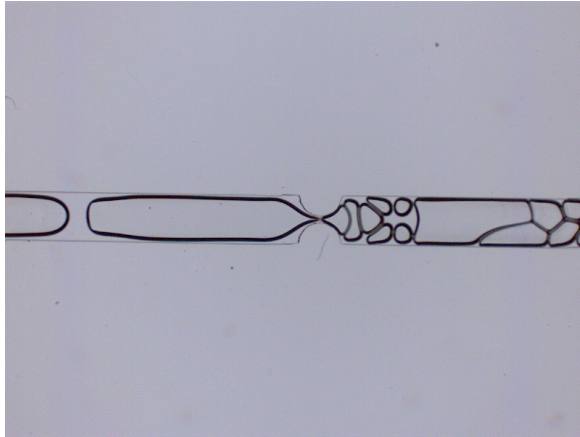
Leave-behind



Ref: Hiraskai, Kovscek and Radke

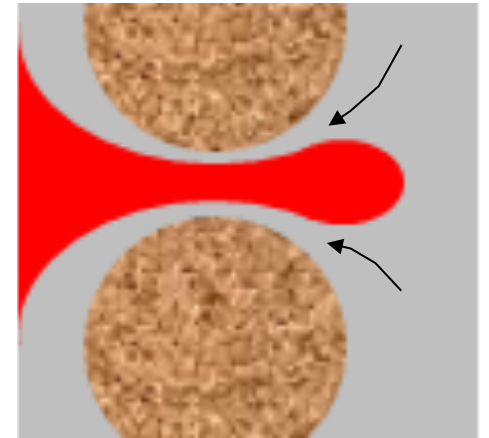
Foam Snap-Off

- Snap off is observed for
 - Wet Foam with large bubbles relative to constriction

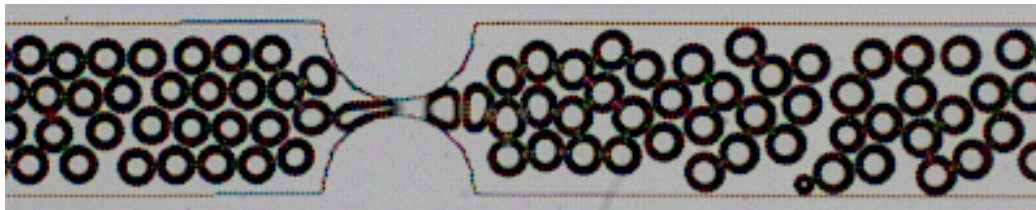


Young-Laplace:

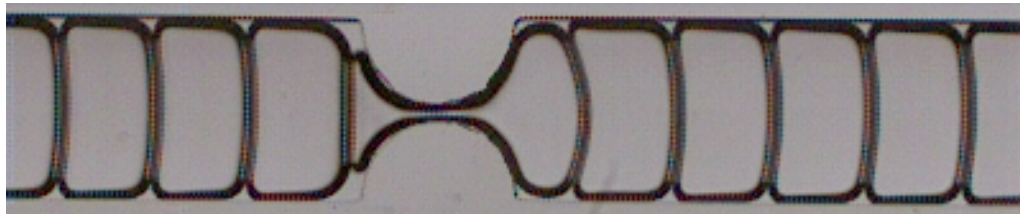
$$\Delta p = \sigma \left(\frac{1}{r_1} + \frac{1}{r_2} \right) = P_c$$



- No snap-off

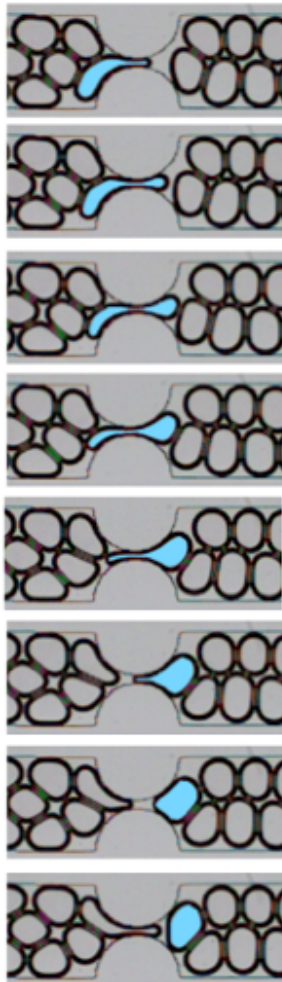
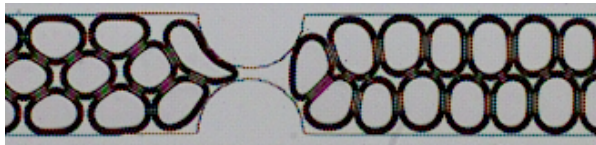


$$P_c = P_d(h) + 2C_m\sigma$$



Reorientation

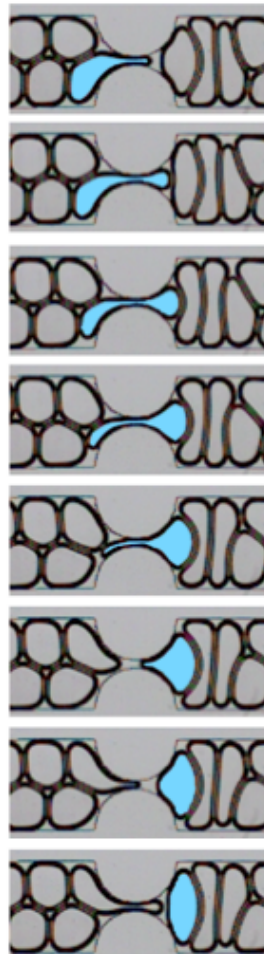
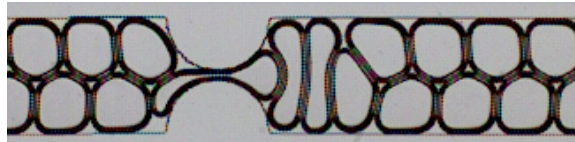
3-bubble: reorientation



time



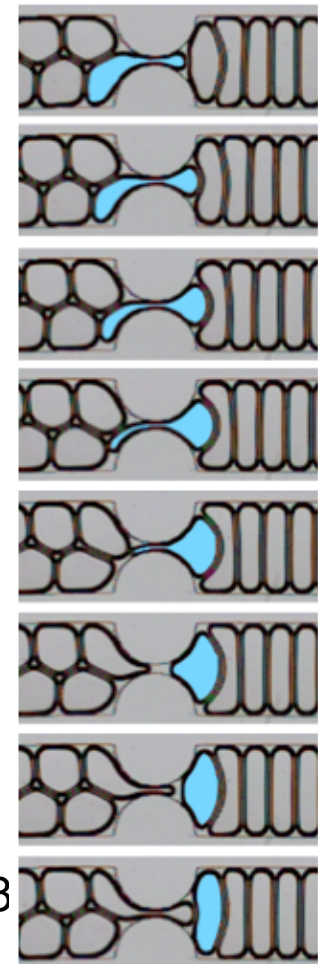
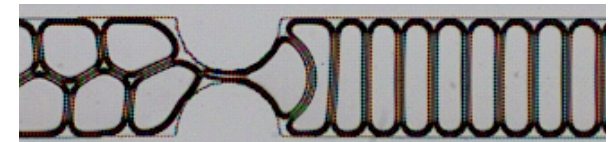
2-bubble: incomplete reorientation



time

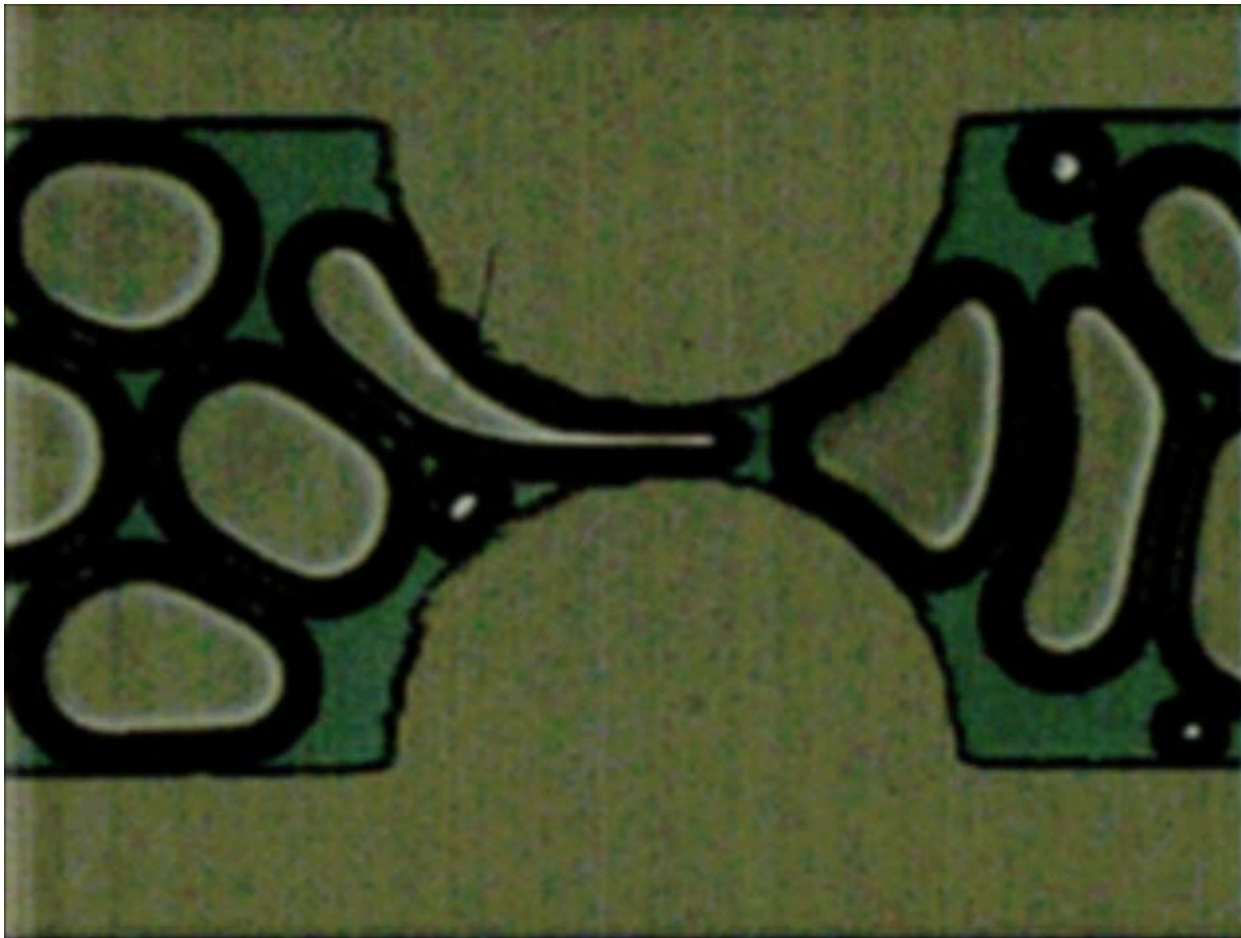


2-bubble: complete reorientation



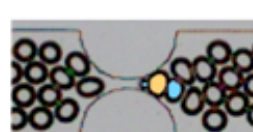
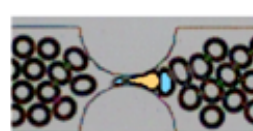
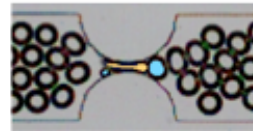
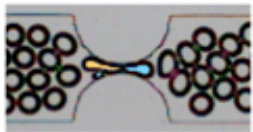
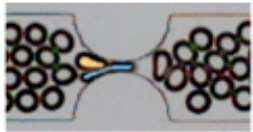
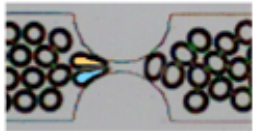
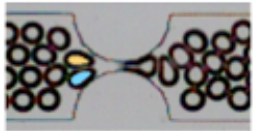
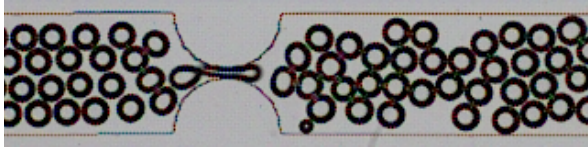
Pinch-Off

When multiple bubbles enter a constriction, foam lamella is generated via a pinch-off mechanism



Neighbor-Wall Pinch-off

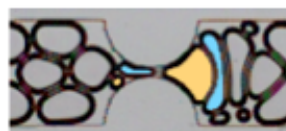
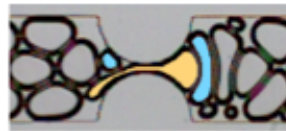
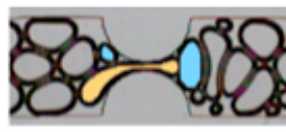
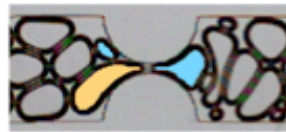
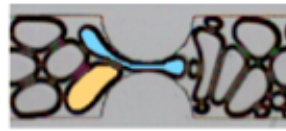
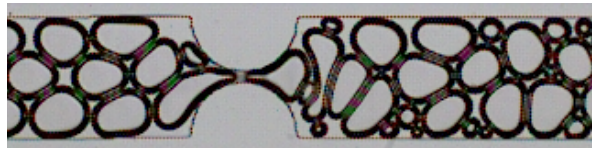
> 3-bubble



time



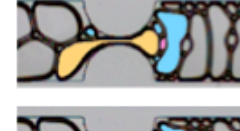
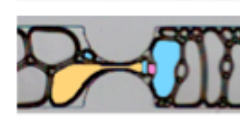
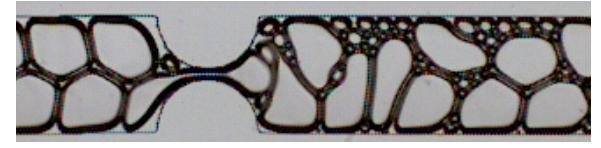
3-bubble



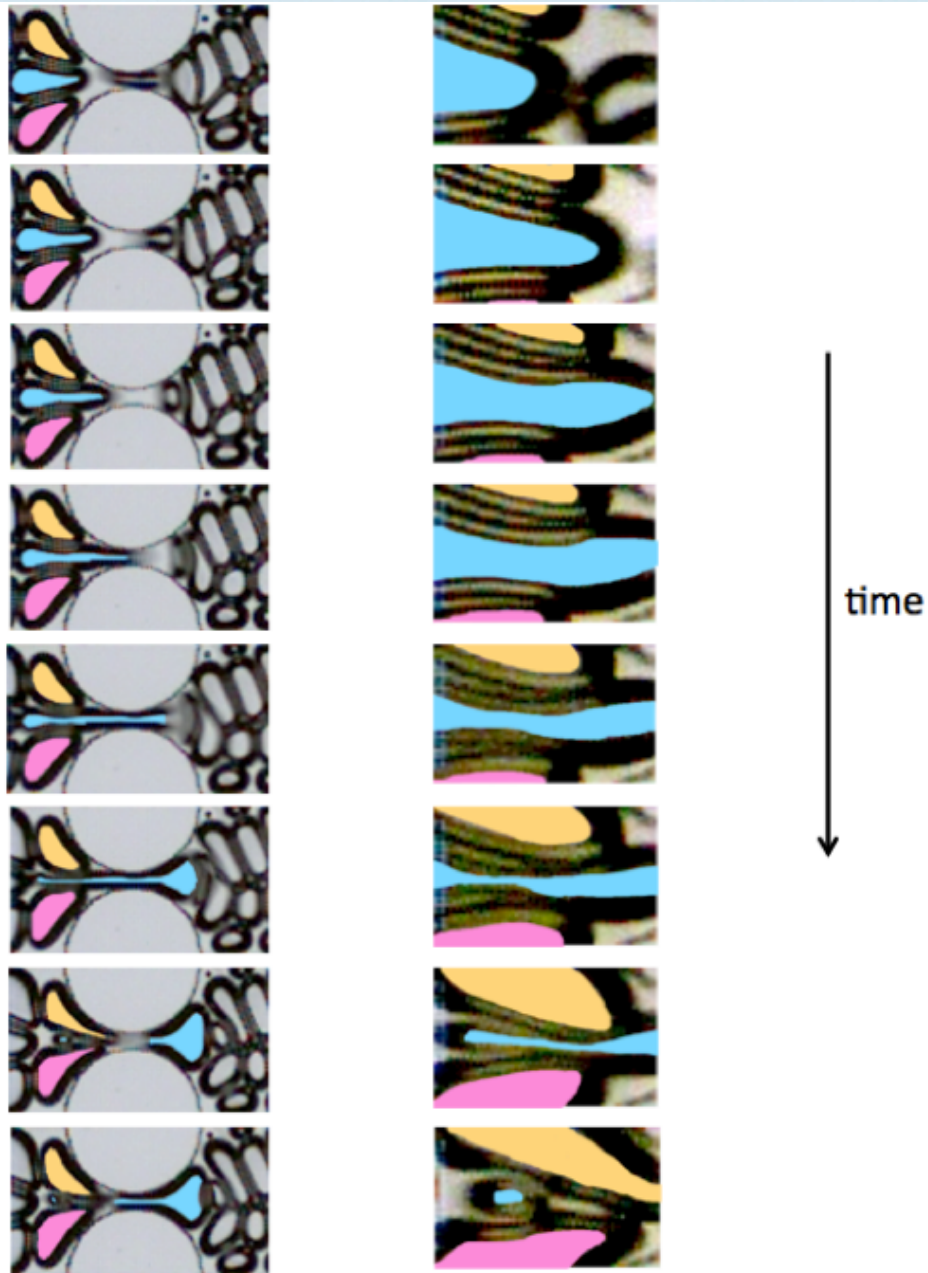
time



2-bubble



Neighbor-Neighbor Pinch-Off



Constructing Foam Transport Phase Diagram

- Bubble Volume^[1]

$$V_{sphere} = \frac{\pi D^3}{6}$$

$$V_{pancake} = \frac{\pi h^3}{6}$$

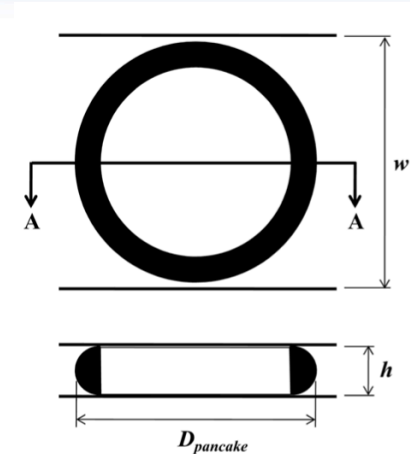
- Dimensionless Bubble Volume^[1]

$$V^* = \frac{V_b}{w^2 h}$$

- Capillary Number^[2]

$$Ca = \frac{\eta_{liq} J}{\gamma}$$

$$J = \frac{Q_{liq} + Q_{gas}}{D_h^2}$$

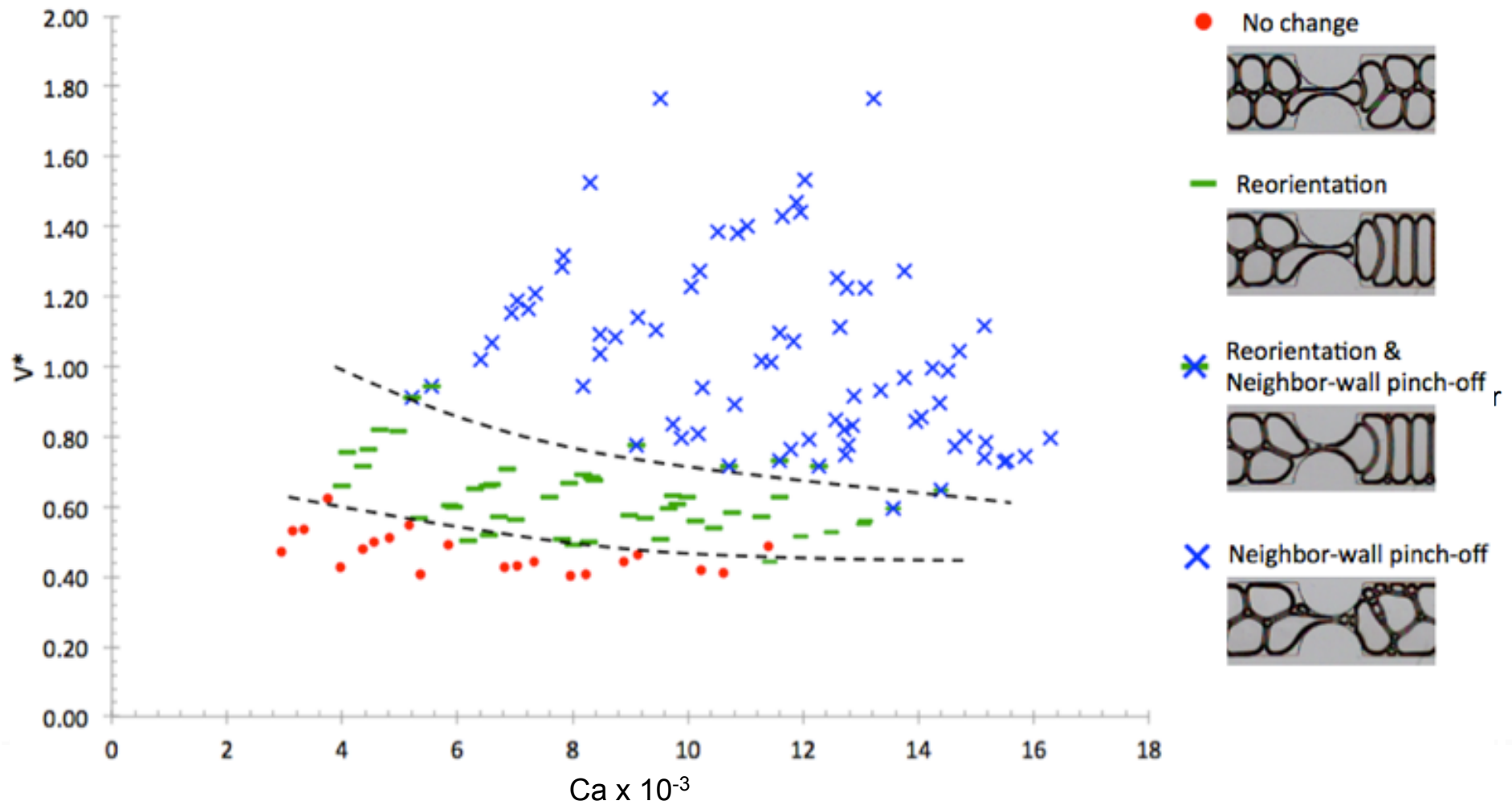


[1] Vuong, S. M., Anna, S. L. (2012). "Tuning bubbly structures in microchannels." Biomicrofluidics. 6: 022004.

[2] Darvishi, S., Cubaud, T., (2012). "Formation of capillary structures with highly viscous fluids in plane microchannels." Soft Matter.

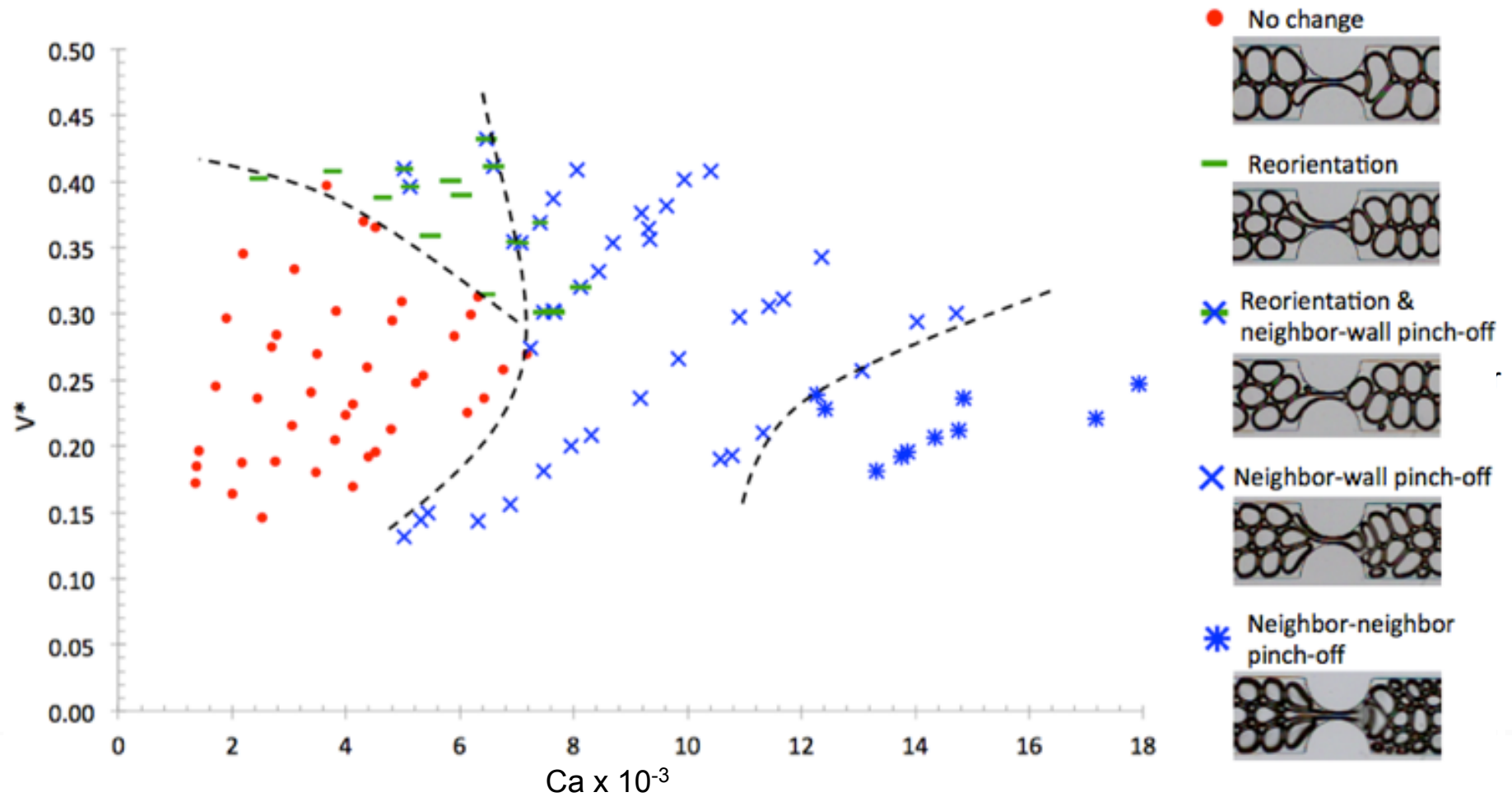
Phase Diagram for 2-Bubble Foam

Behavior dependent on capillary number and bubble volume.



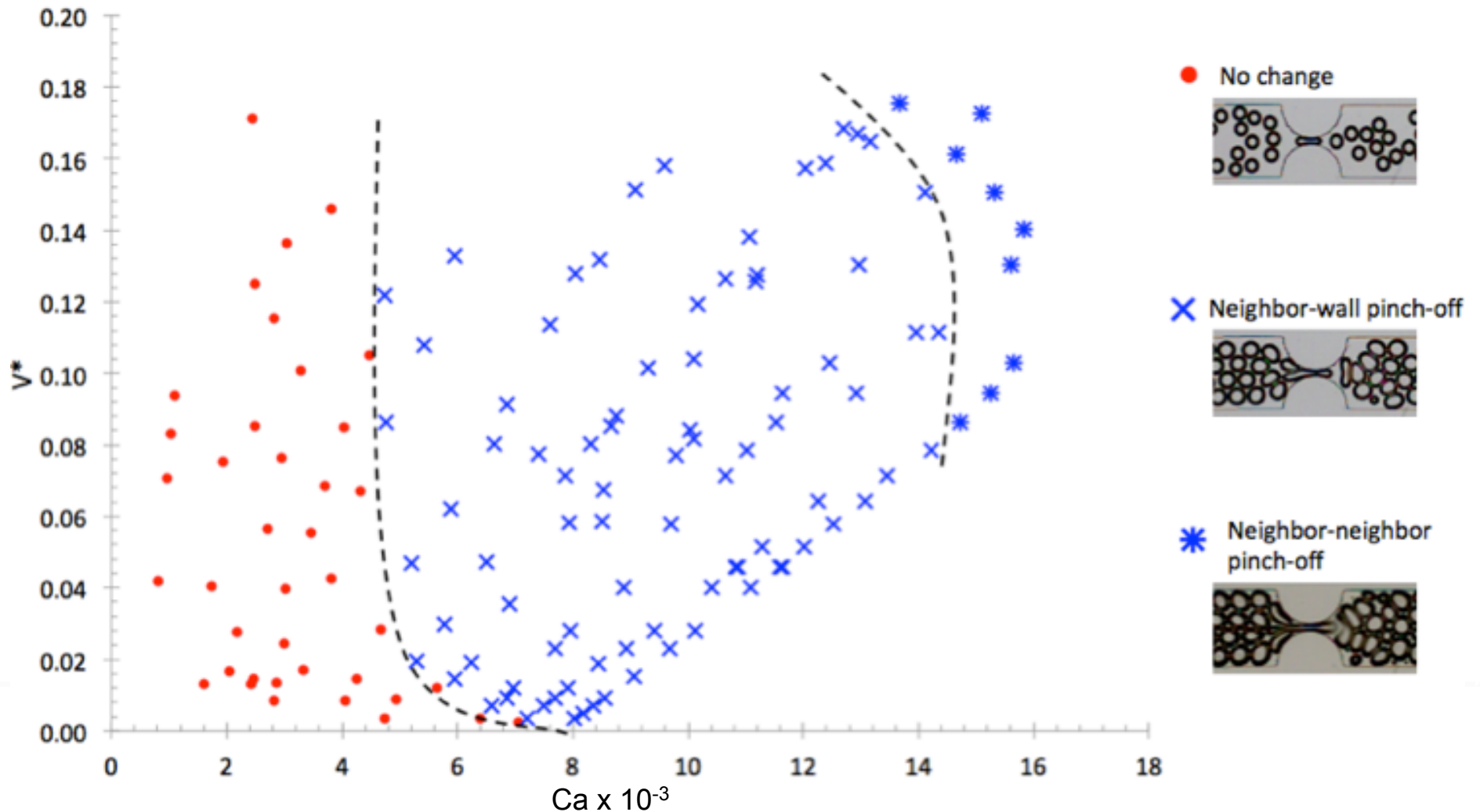
Phase Diagram for 3-Bubble Foam

Behavior dependent on capillary number and bubble volume.

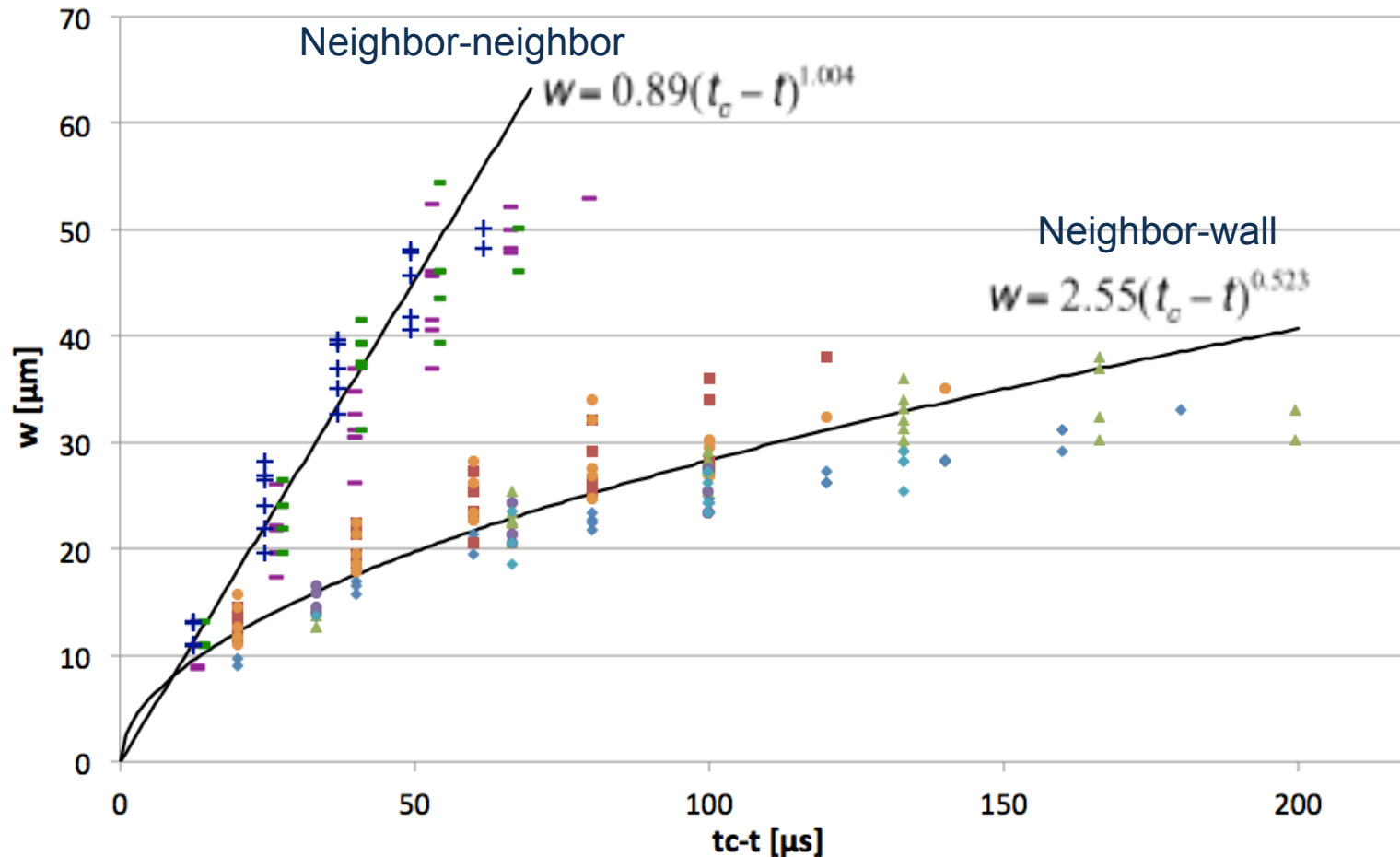


Phase Diagram for >3-Bubble Foam

Behavior dependent on capillary number and bubble volume.



Analysis of Bubble Widths Before Pinch-Off



Neighbor-neighbor pinch-off

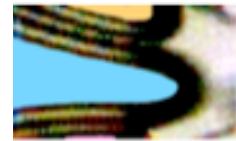
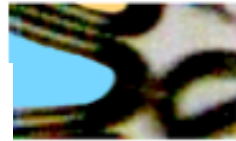
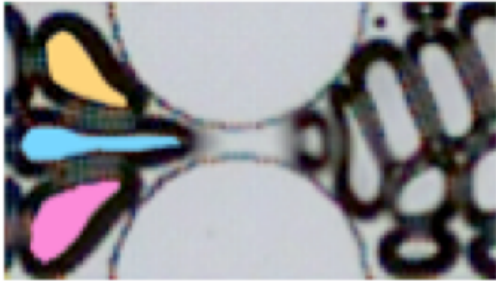
- Coefficient = 0.89 ± 0.19
- Exponent = 1.004 ± 0.048

Neighbor-wall pinch-off

- Coefficient = 2.55 ± 0.52
- Exponent = 0.523 ± 0.063

Analysis of Bubble Widths Before Pinch-Off

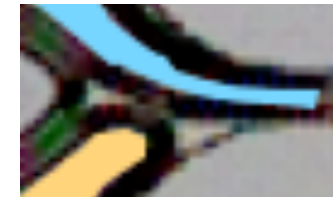
Neighbor-neighbor pinch-off



Exponent =
 1.004 ± 0.048

Exponent ~ 1.0
matches scaling
behavior of gas in a
high viscosity
external phase^[1]

Neighbor-wall pinch-off



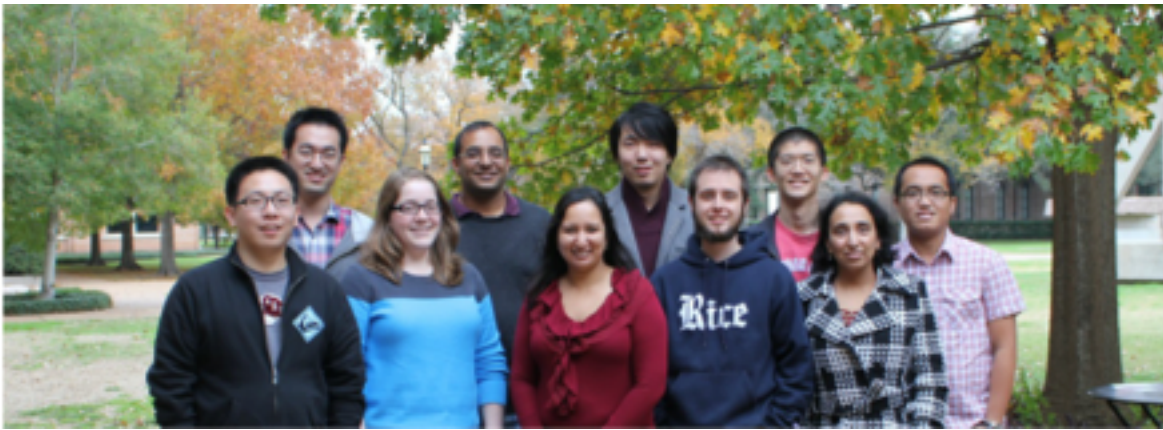
Exponent =
 0.523 ± 0.063

Exponent $\sim 1/2$
matches scaling
behavior of gas in a
low viscosity external
phase found by
Rayleigh-Plesset
theory^[1]

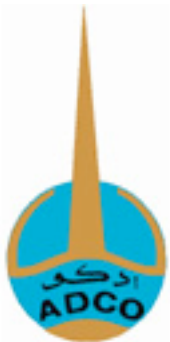
[1] Burton, J.C., Waldrep, R., Taborek, P., (2005). "Scaling and Instability in Bubble Pinch-Off." [Physical Review Letters](#) 94: 184502.

Conclusions and Acknowledgements

- Two novel foam mechanisms have been found: neighbor-wall pinch off and neighbor-neighbor-neighbor pinch off.
- Shear and capillary forces dictate pinch off mechanisms



Kun Ma
Charles Conn
Rachel Liontas



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