Pinch-off and Coalescence in Liquid/Liquid Mixtures with Surface Tension

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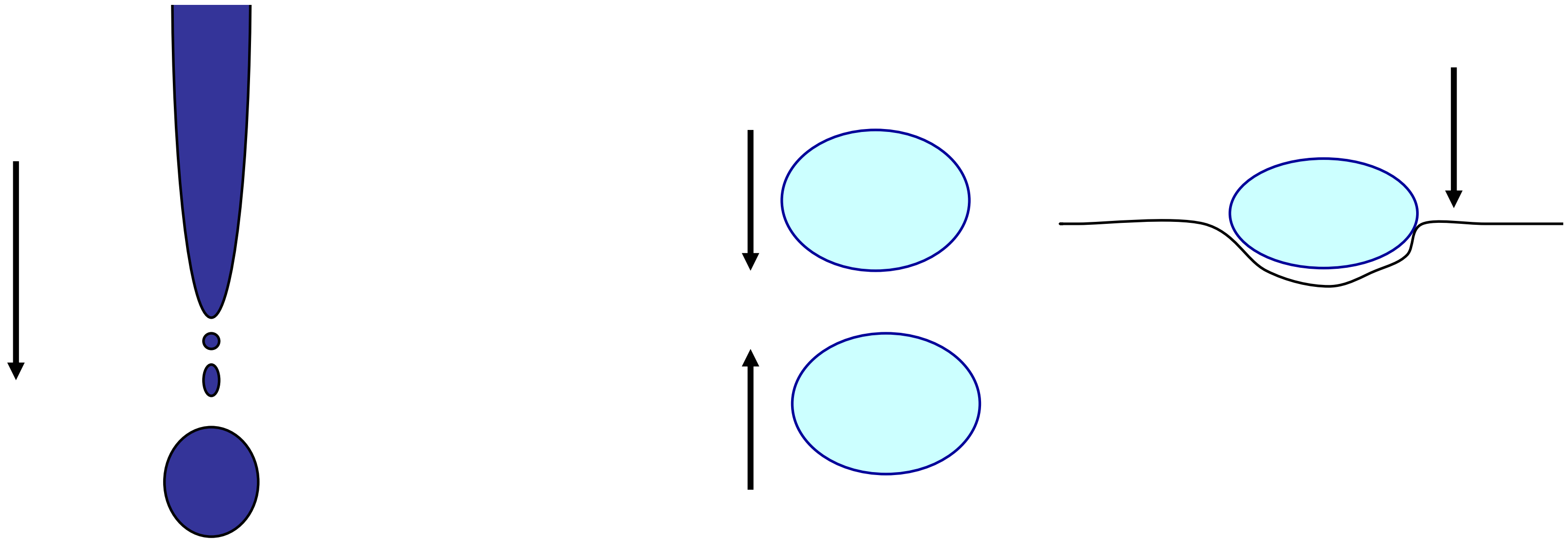
Motivation:

Develop accurate engineering-level models for **transitions** in multi-fluid flows with surface tension



Molecules at the interfaces must rearrange.

Difficulties:

Transitions difficult to observe and model !

Applications:

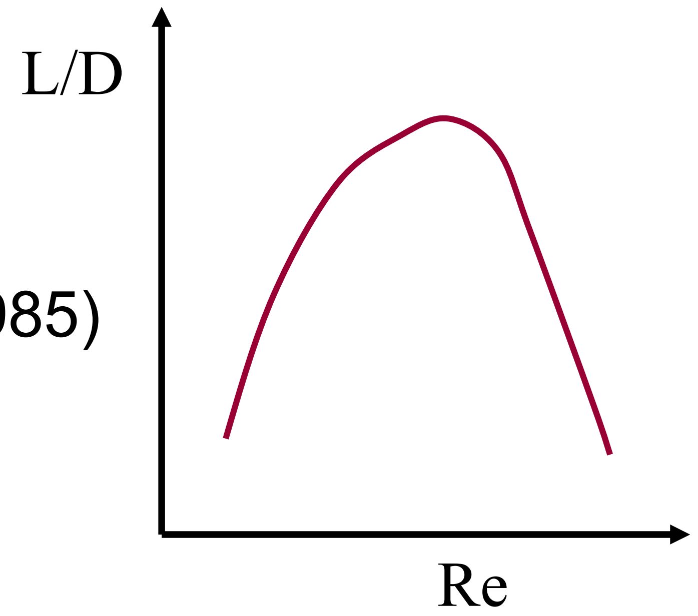
Transport, mixing, and separation of petroleum, chemical, food, and waste products

Issues: complex flow geometries

large range of scales

transition details affect process!

Previous Work (pinch off):



Jets:

Scheele and co-workers (1969-1985)

Skelland and Johnson (1974)

Kitamura et al (1982)

Tadrist et al (1991)

Determination of instability modes, jet length before pinch off

Straining and Dripping Flows:

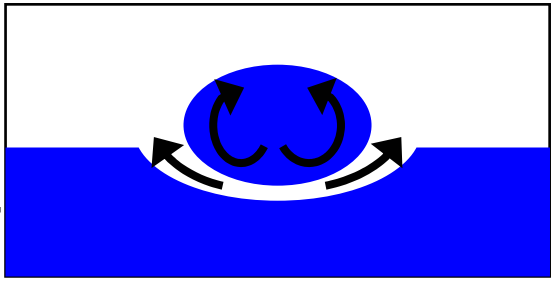
Tjahjadi, Stone, Ottino (1992)

Cohen et al. (1999, 2001)

Zhang and Lister (1999)

Does flow become ‘self similar’ near pinch off locations?

Previous Work:



Drop coalescence at an interface

Hartland and co-workers (1967)

film shape and drainage rate, rupture characteristics, Re << 1

Chi & Leal (1989), Manga & Stone (1995)

boundary integral methods, axisymmetric flow

Drop/drop coalescence:

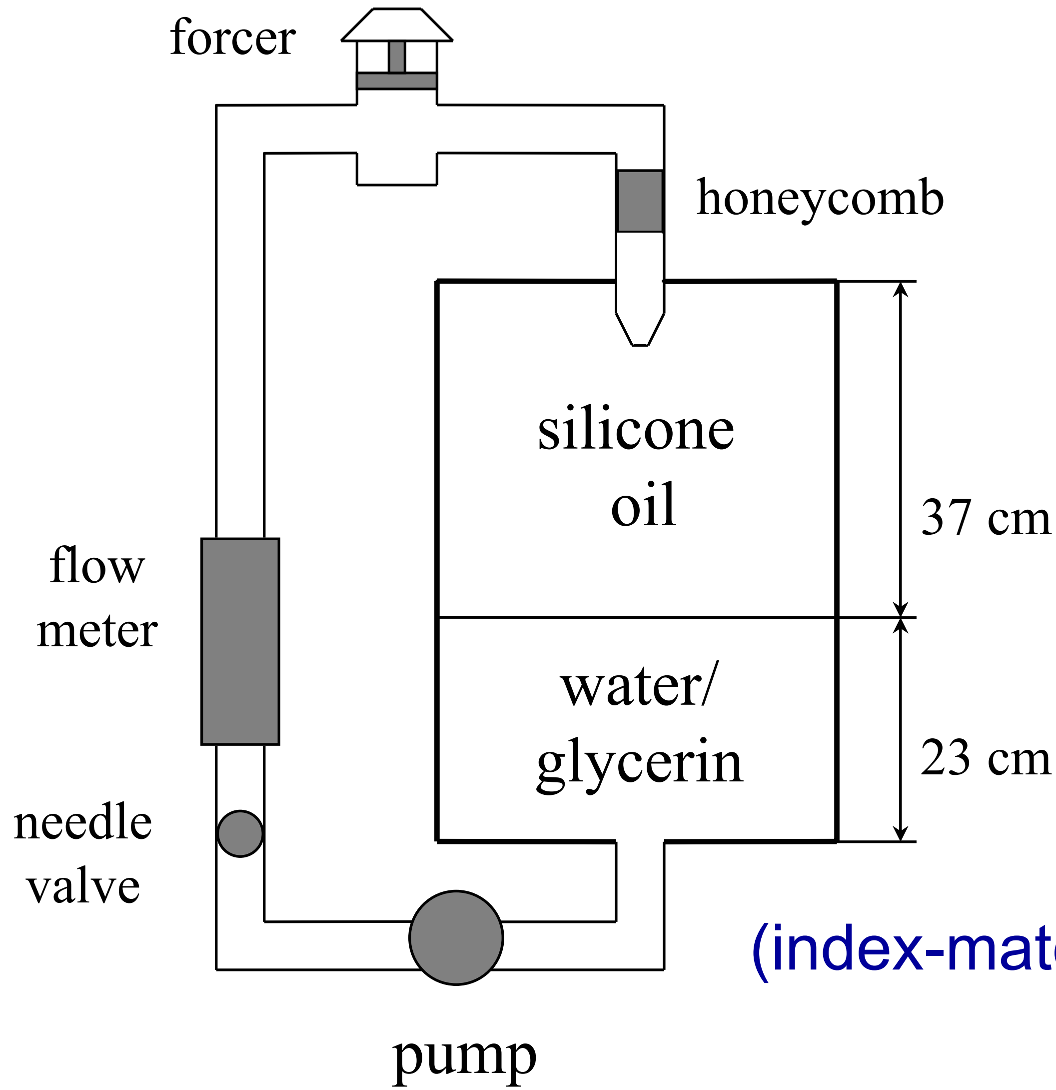
Leal and co-workers (2000, 2001, 2003)

Experiments in shearing flows at Re, We << 1

Objectives:

- Quantify transition dynamics in fundamental flows with significant inertia
- Compare with computations that include transition models
- Develop ‘physically-justified’ reconnection conditions for engineering-level codes

Jet Facility



TiO_2

TiO_2 + dye

(index-matched fluids)

Flow Parameters:

Glycerin/Water (50% by volume): $\mu_i = 8.3$ cp, $\rho_i = 1.14$ g/cc

Silicone Oil (Dow Corning 200): $\mu_o = 4.8$ cp, $\rho_o = 0.96$ g/cc

D = 1 cm, $\sigma = 0.0296$ N/m

$$Bo = \frac{\Delta\rho \cdot g \cdot D_e^2}{\sigma} = 7.3$$

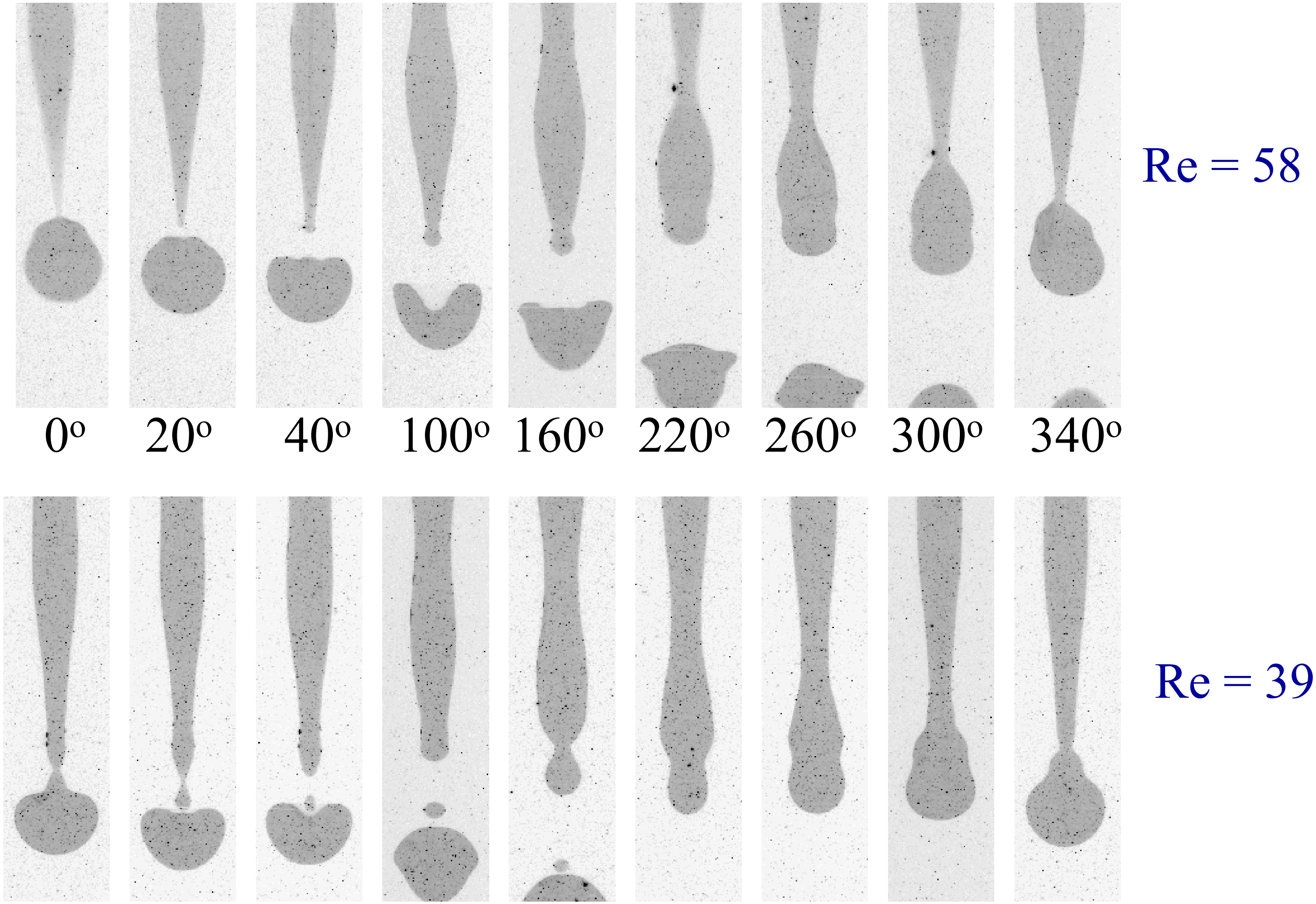
$$Oh = \frac{\mu_i}{\sqrt{\rho_i \cdot D_e \cdot \sigma}} = 0.015$$

$$\lambda = \frac{\mu_i}{\mu_o} = 1.6$$

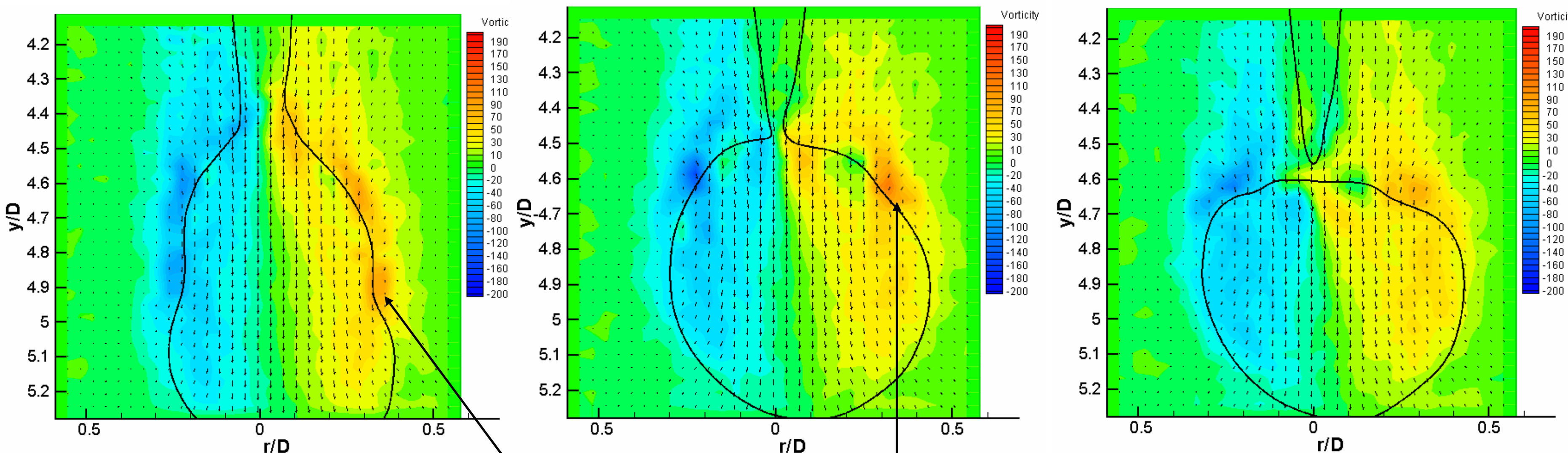
$$Re = \frac{\rho_i \cdot U_e \cdot D_e}{\mu_i} = 35 - 70$$

$$St = \frac{f \cdot D_e}{U_e} = 1.4 - 5.2$$

LIF of Phase-locked flow: St = 3.5, λ = 1.6



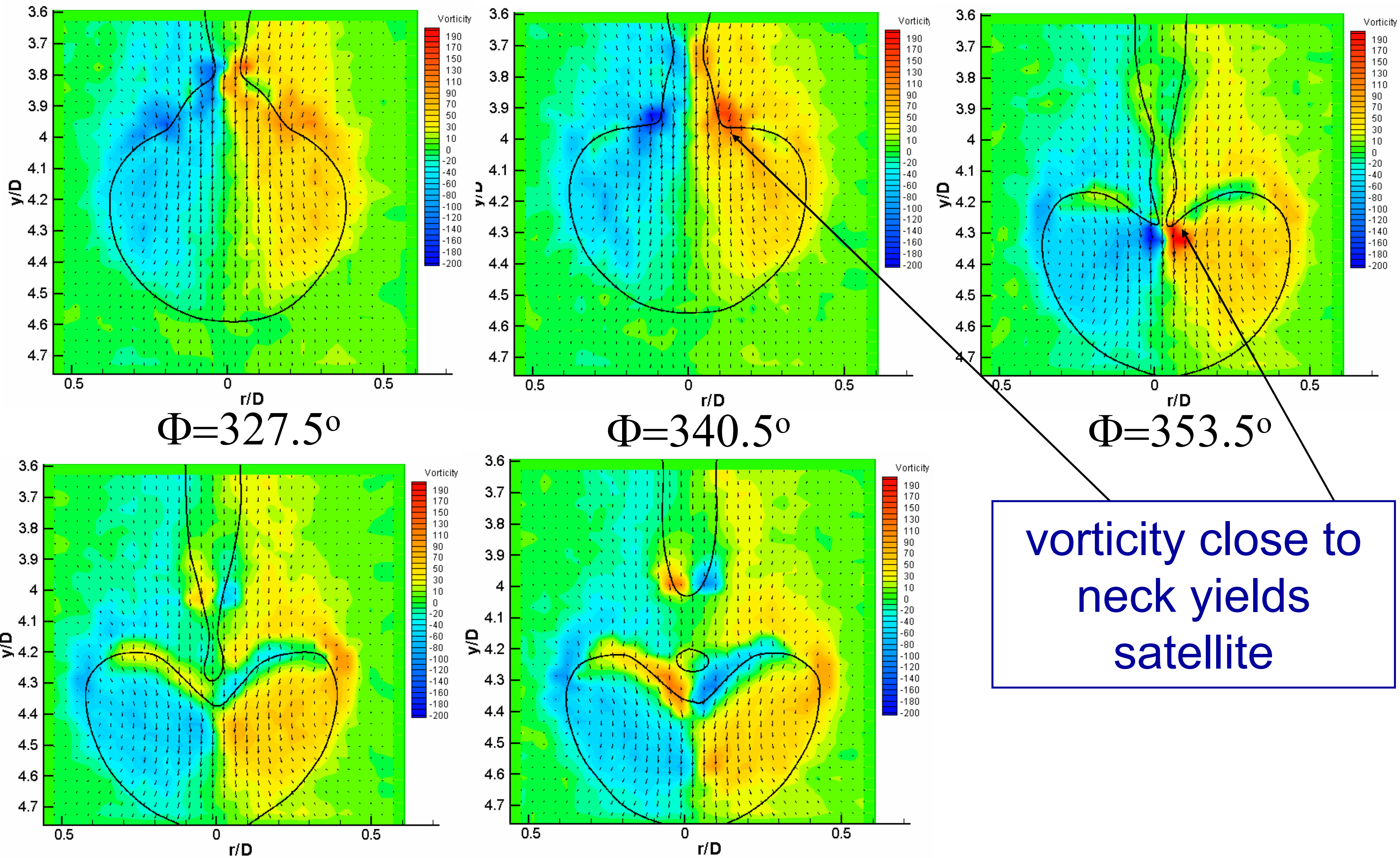
Vorticity Contours: Re = 58, St = 3.5



$\Phi=313^{o}$ $\Phi=350.6^{o}$ $\Phi=9.4^{o}$

vorticity away from neck: no satellite

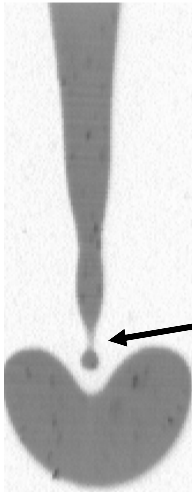
Vorticity Contours: Re = 39, St = 3.5



Φ=327.5° Φ=340.5° Φ=353.5°

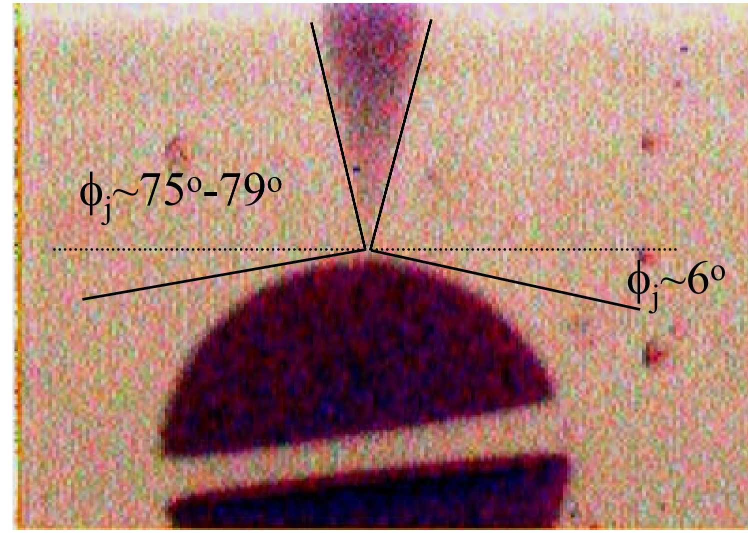
Φ=6.5° Φ=13°

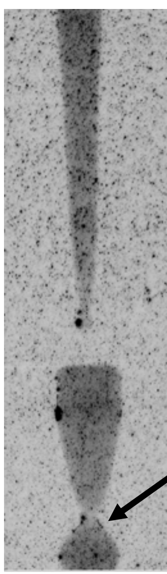
Close-ups of pinch-off modes, $\lambda = 1.6$



Re = 39
St = 3.5

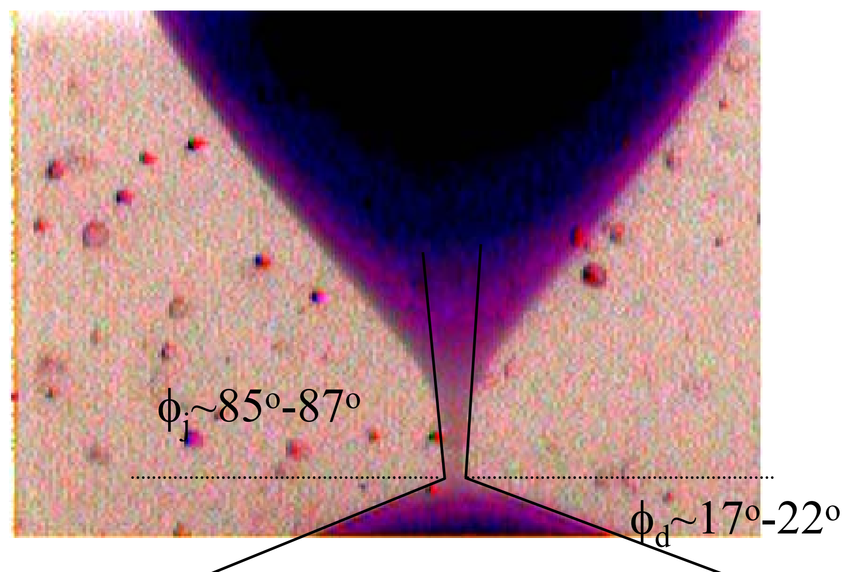
jet/drop break





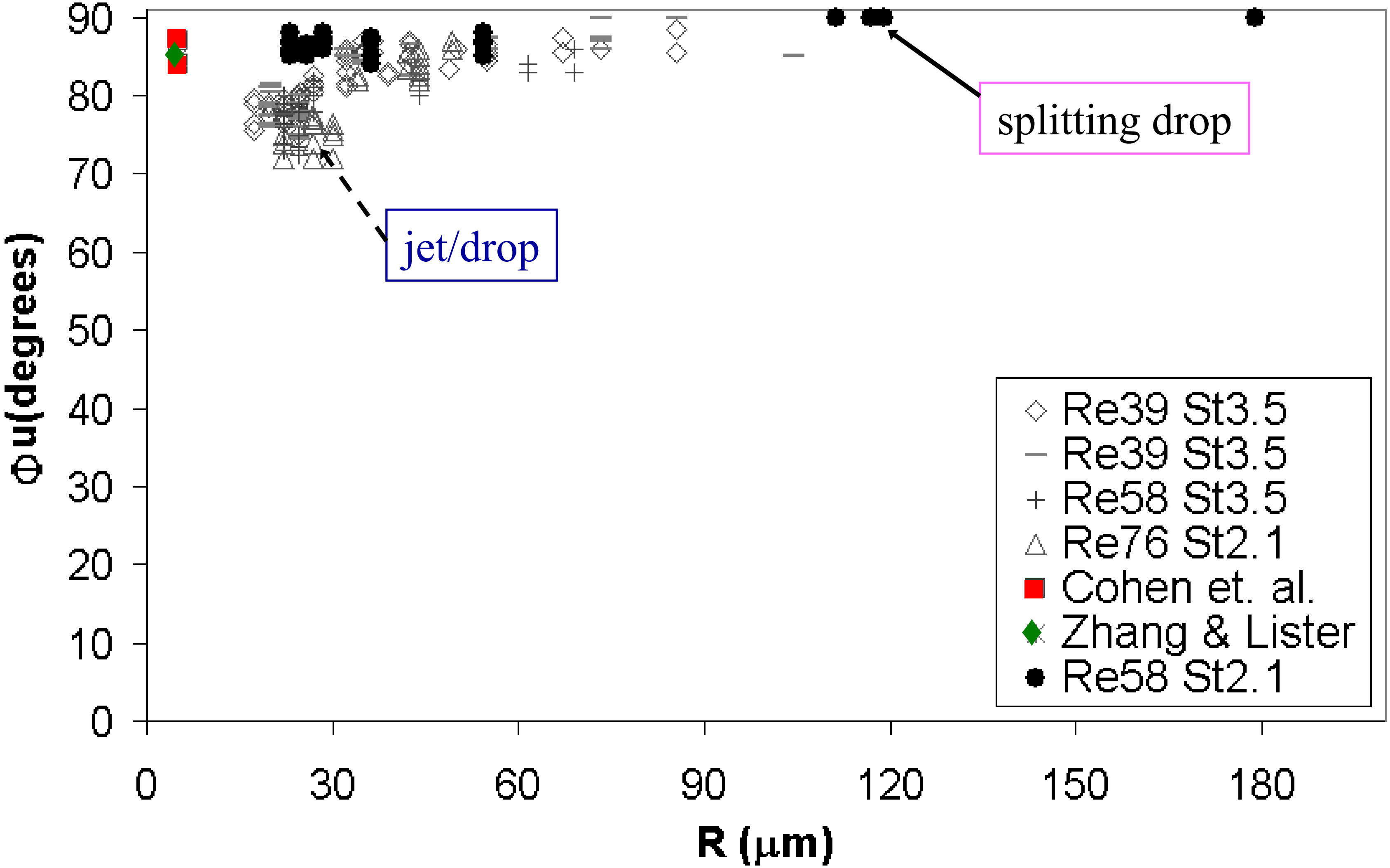
Re = 58
St = 2.1

splitting drop

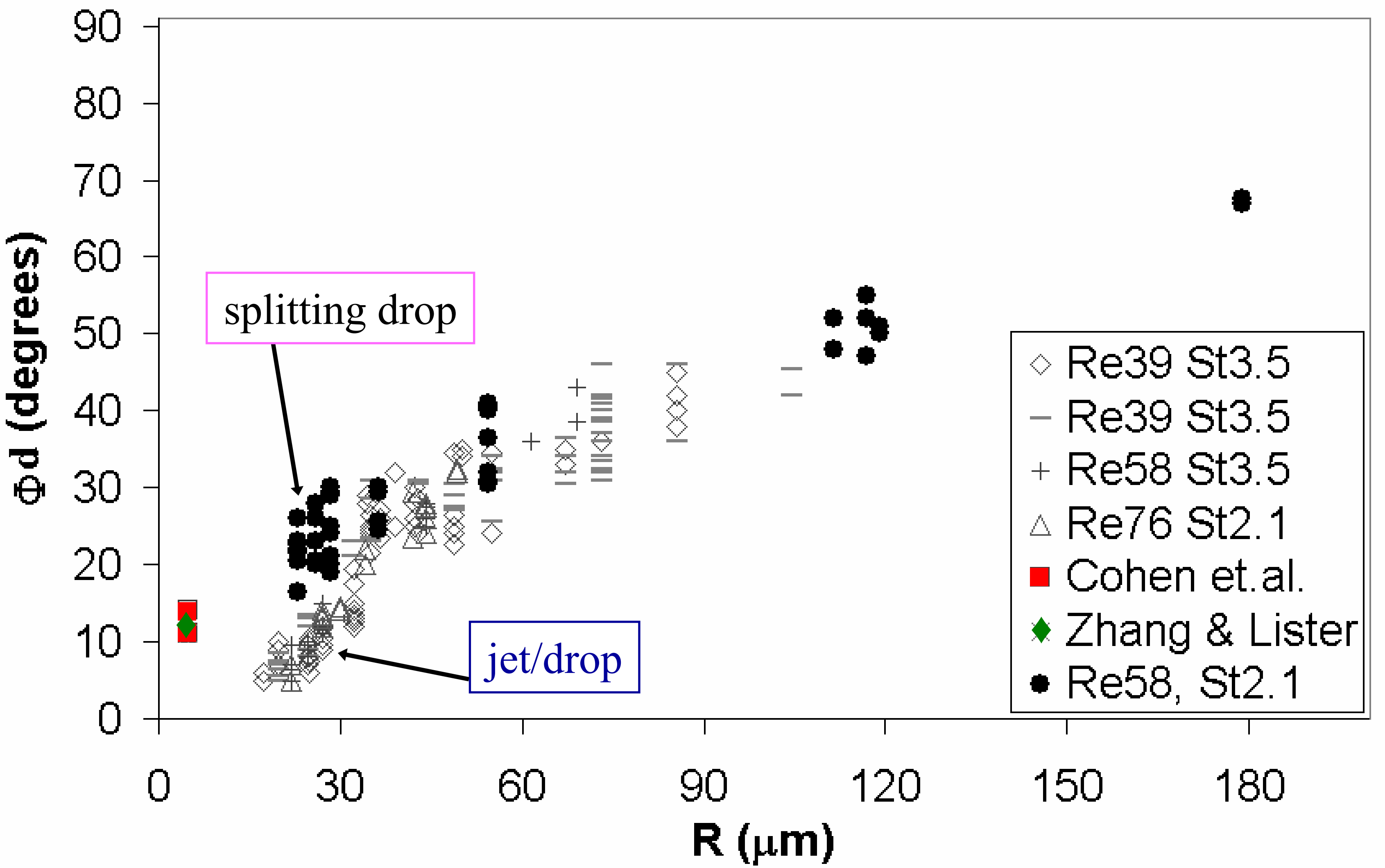


Do angles depend on λ only?

Upper pinch-off angles



Lower pinch-off angles

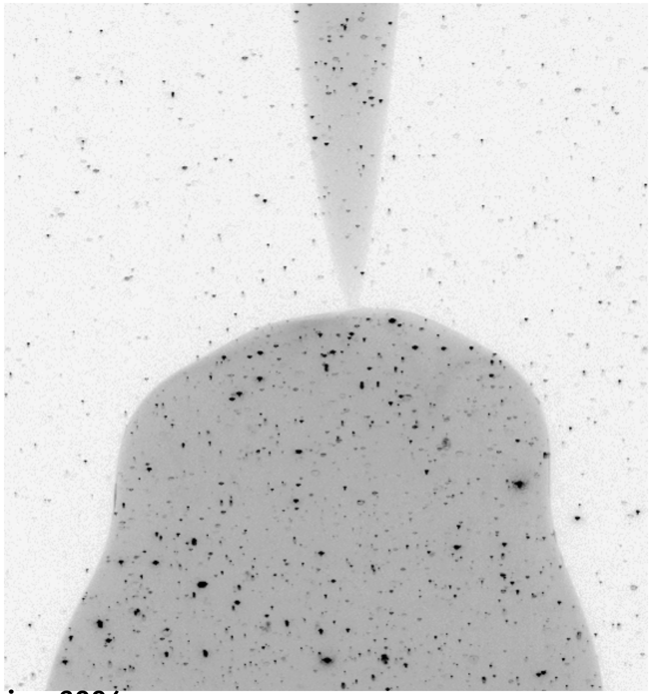


Similarity Question:

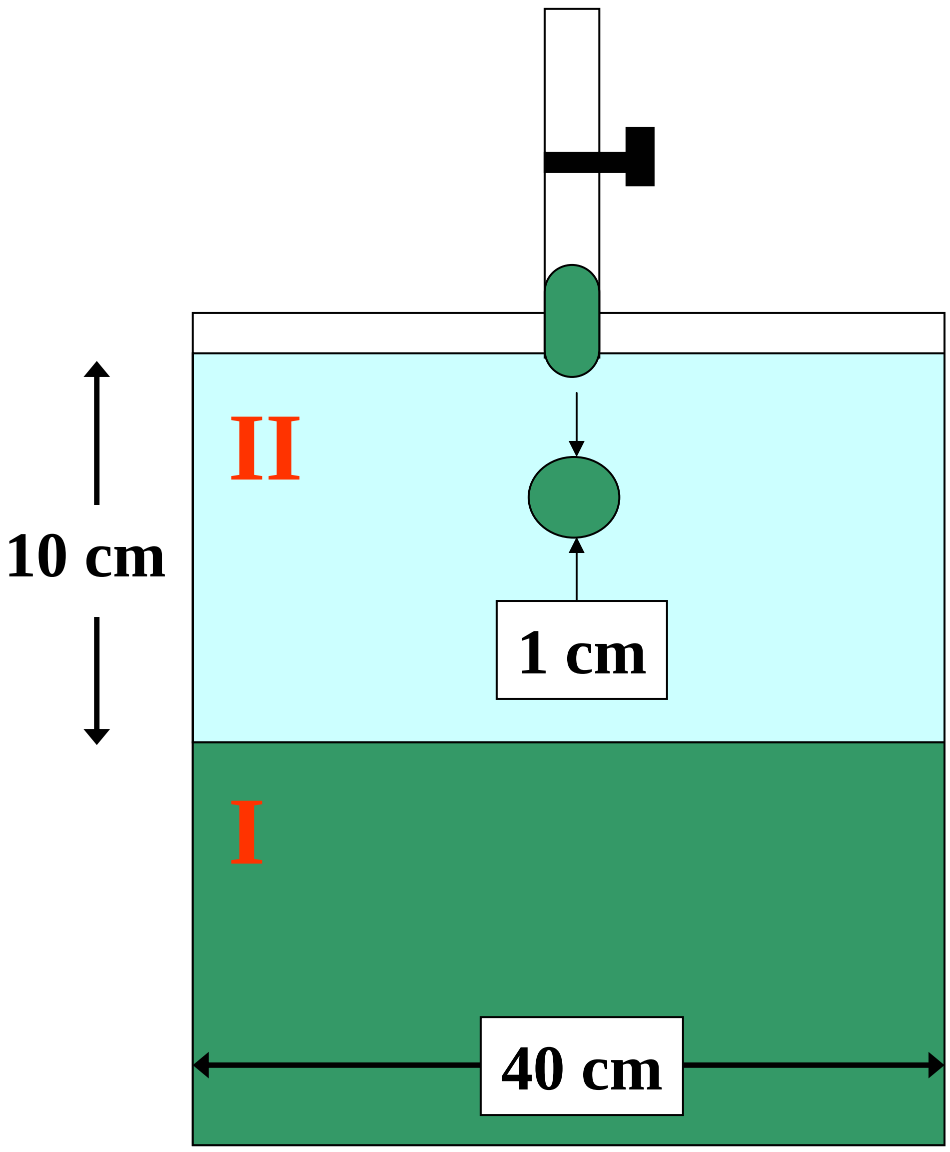
- For scales ~ 15 μm:
  splitting drop mode converges toward similarity values
  jet/drop modes do not

- Stokes scaling valid for neck < 5 μm

Does flow ever reach Stokes scaling??



Coalescence Facility



II Silicone oil (50 & 5 cs)

I Water/glycerin mixture

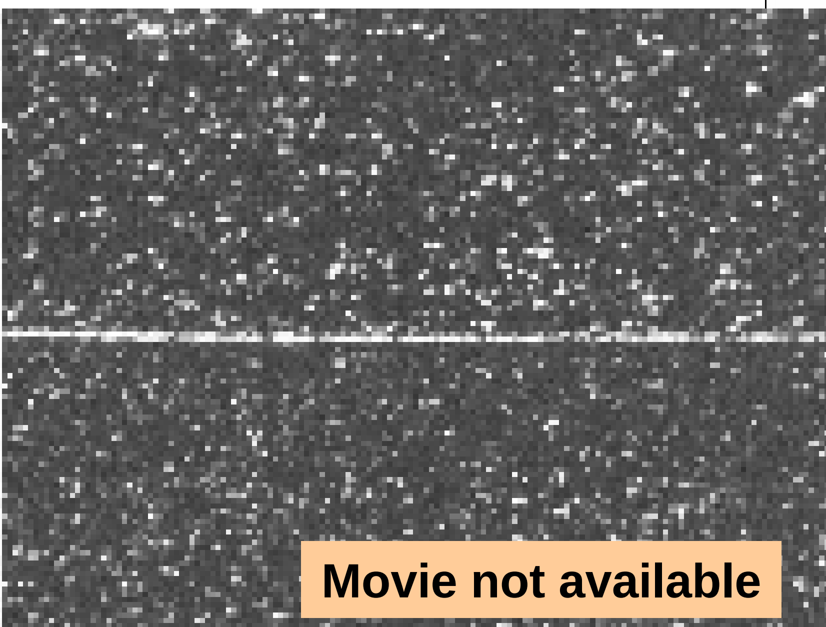
$$\frac{\rho_I}{\rho_{II}} = 1.18$$

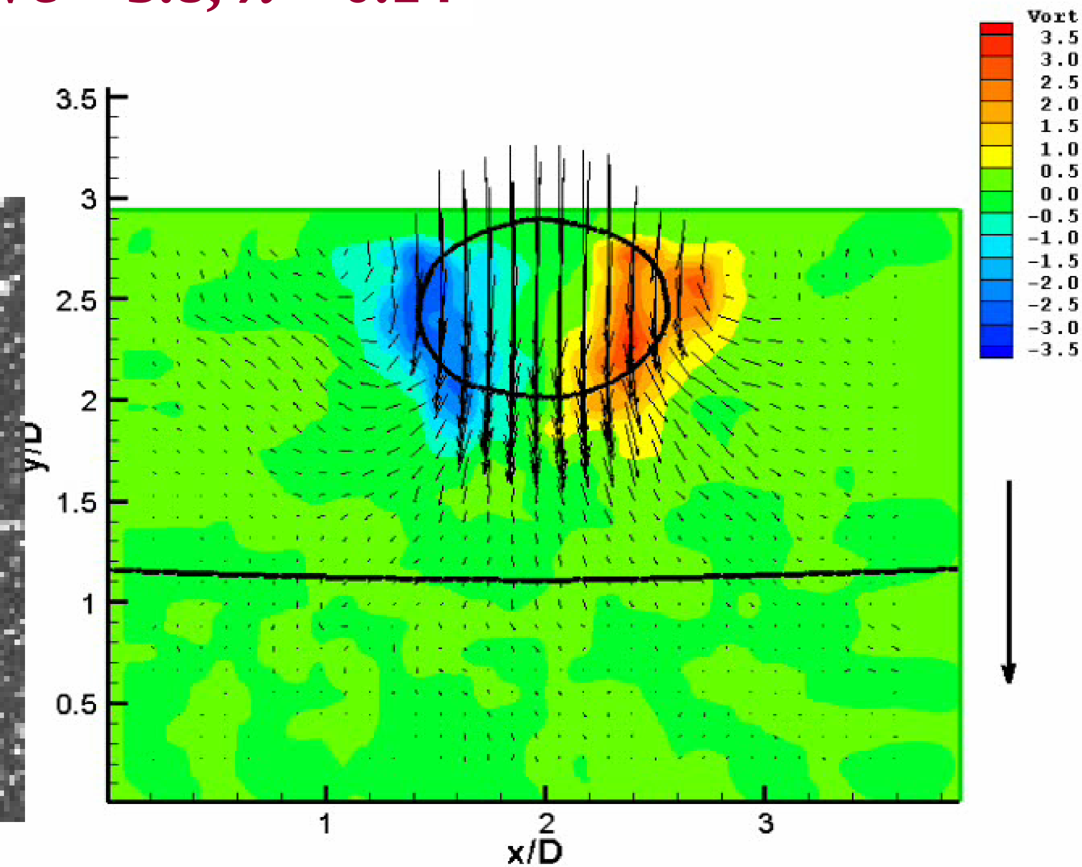
$$\lambda = \frac{\mu_I}{\mu_{II}} = 0.14, 0.33, 1.8$$

PIV image sequences acquired at 500 Hz

Drop Impact

Re = 20, We = 3.8, λ = 0.14





1/30 of real speed

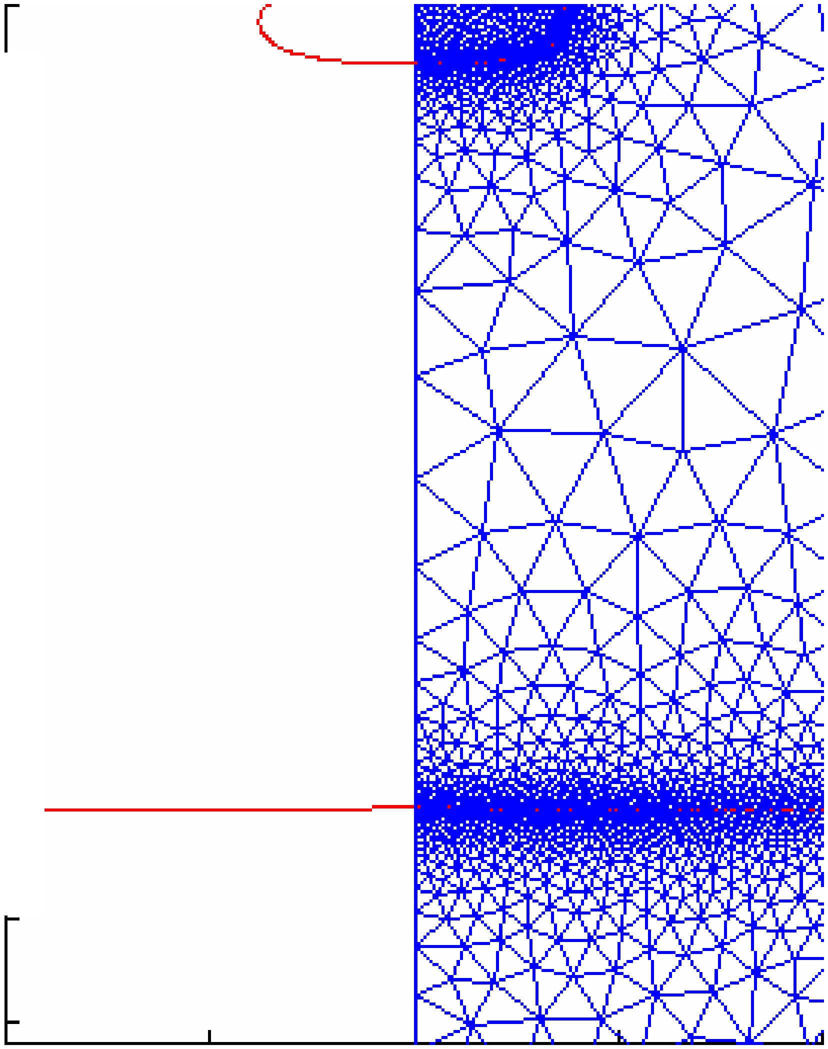
Axisymmetric Simulation, Adaptive Grid

Finite Element Projection Method

Interface modeled as level set

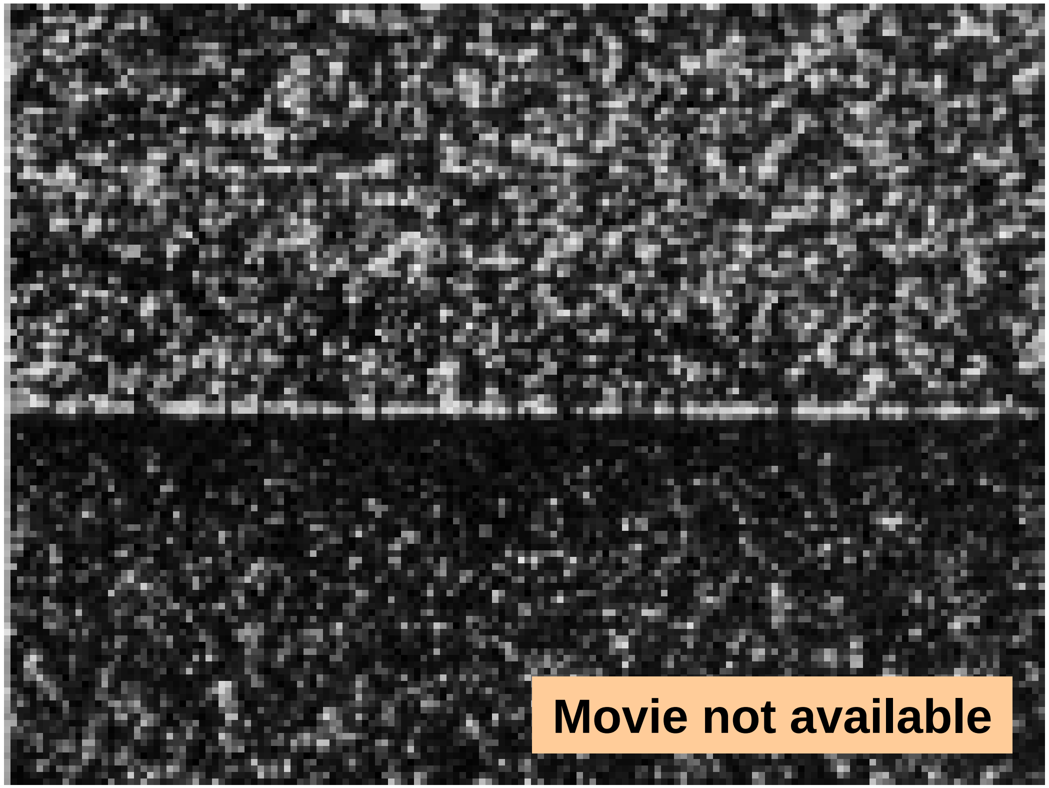
Surface tension is continuum surface force in momentum equation

Mesh size scales with distance from interface

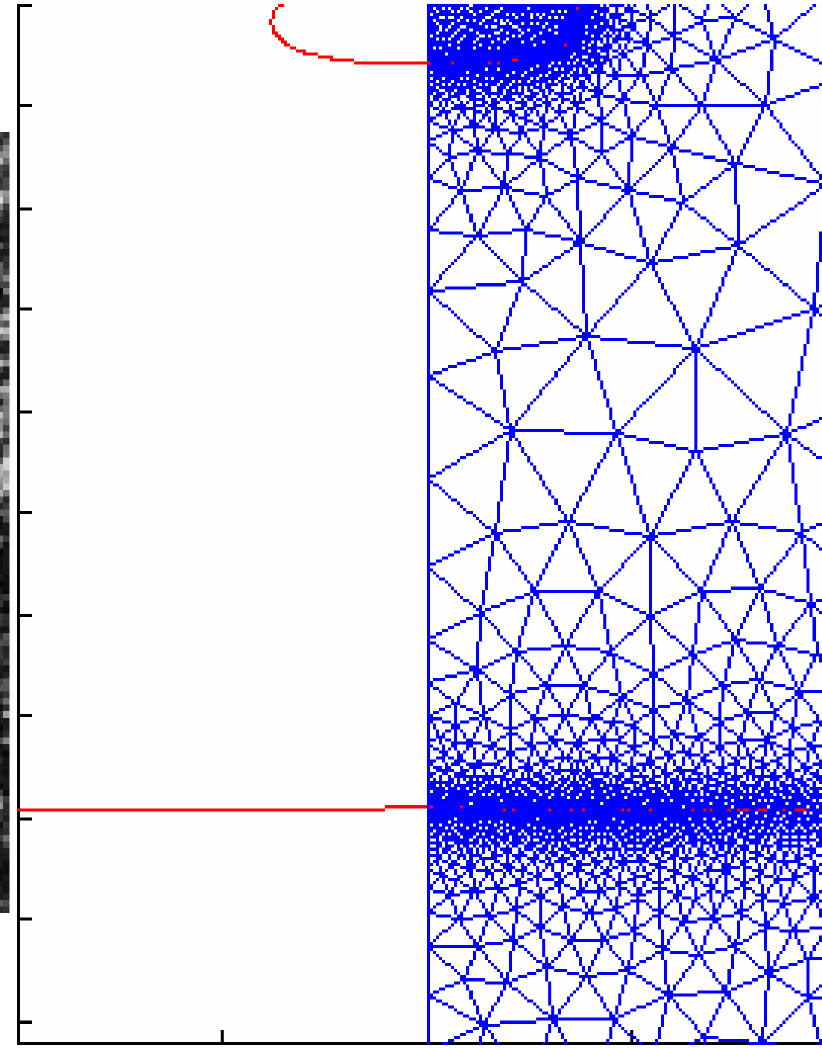


Zheng, Lowengrub, Cristini
Talk NB4 on Tuesday

Axisymmetric Simulation, Adaptive Grid

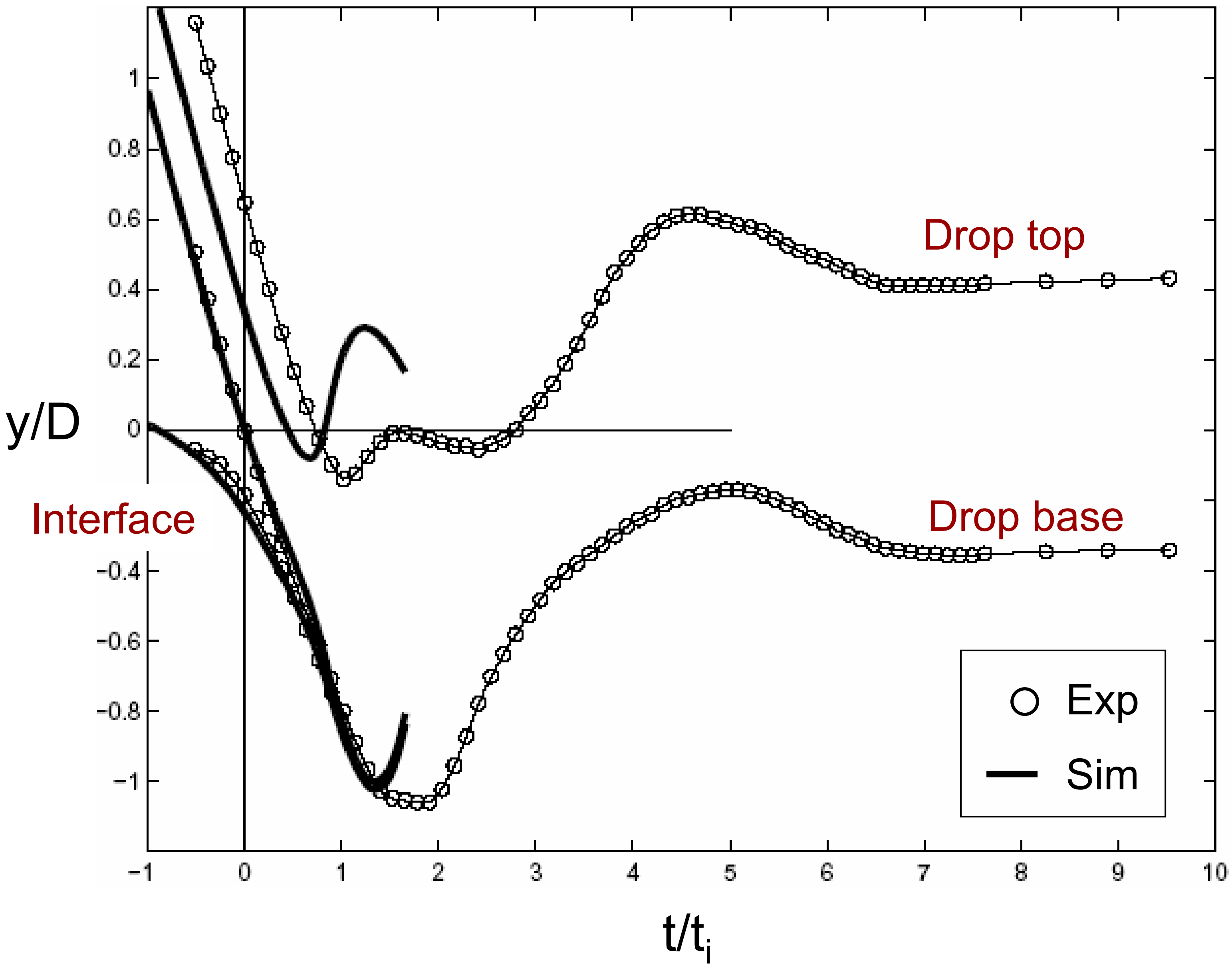


Re = 68, We = 7, λ = 0.33

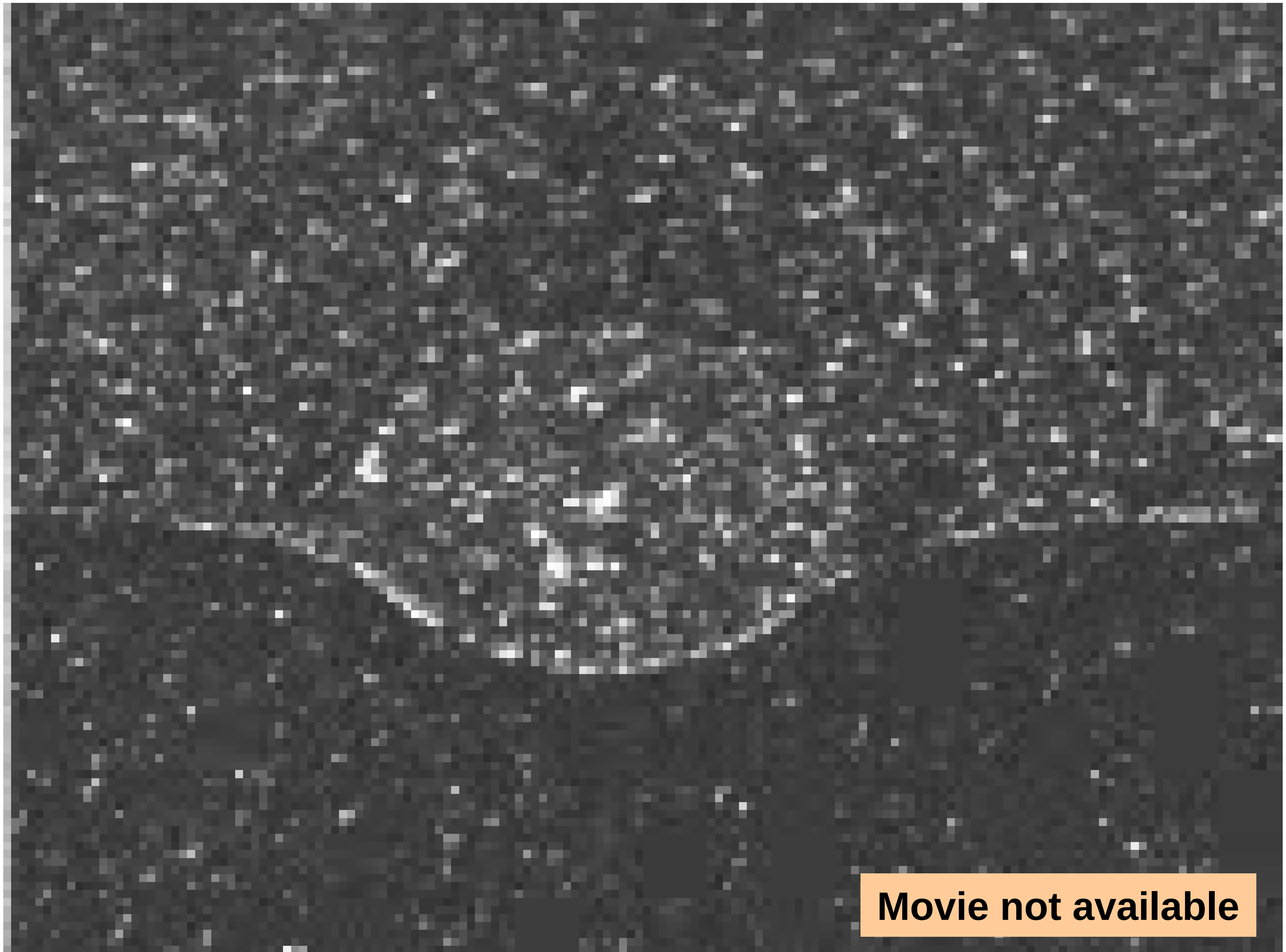


Zheng, Lowengrub, Cristini
Talk NB4 on Tuesday

Vertical Interface Locations on Drop Axis



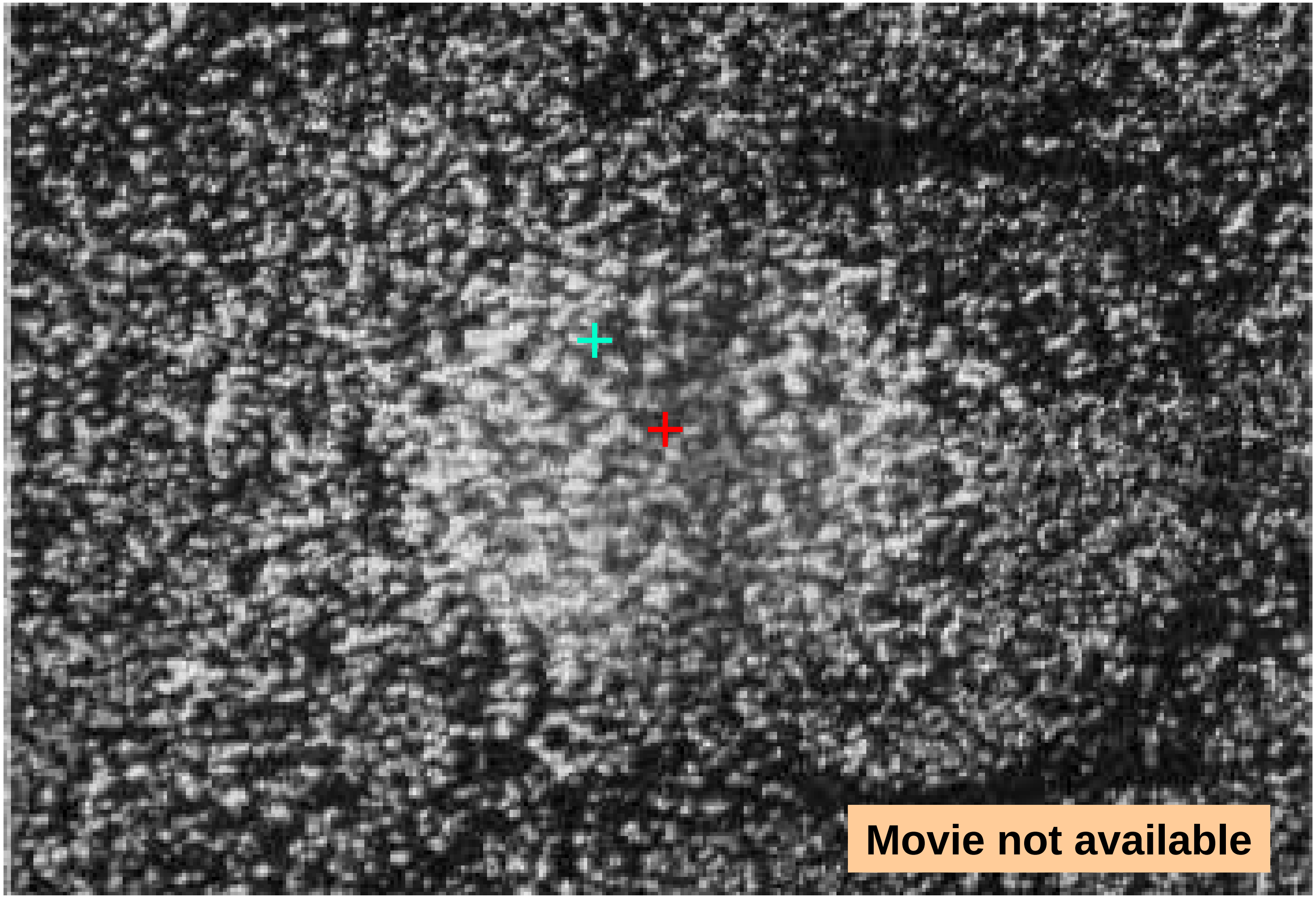
Drop Coalescence



λ= **0.14**
Ca = 0.09
Bo = 6

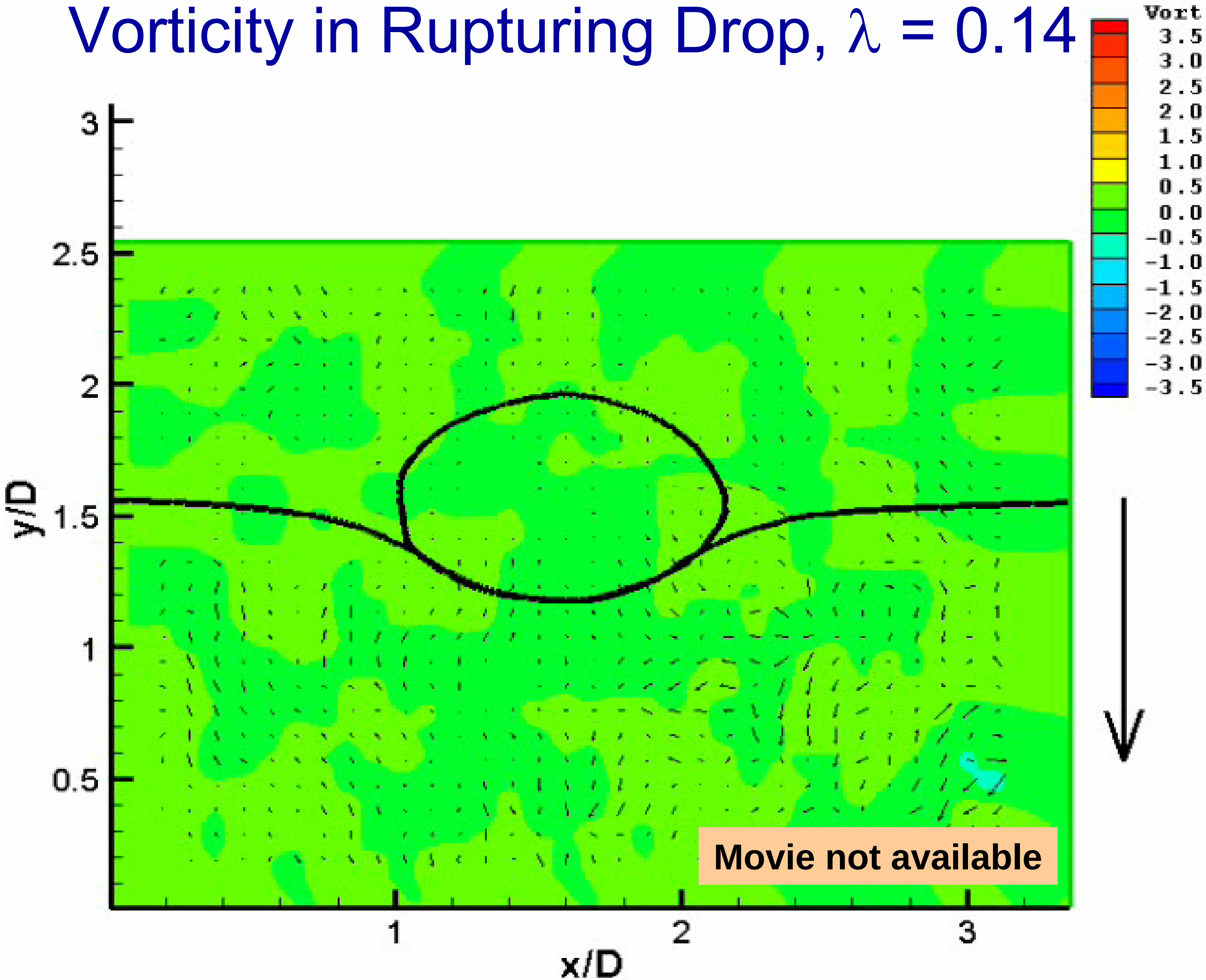
1/30 of real speed

Interface Rupture (horizontal plane)

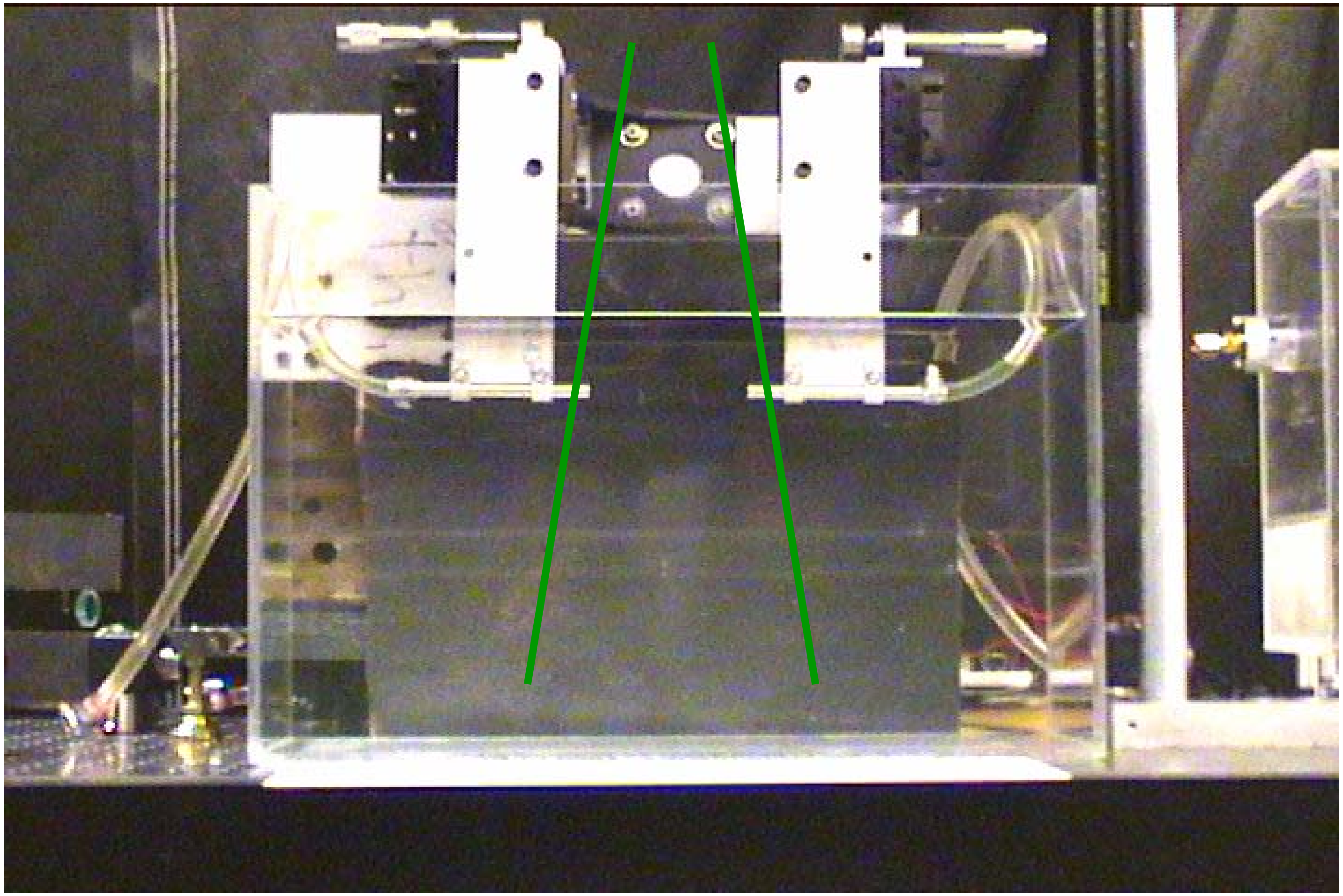


+ = rupture point   + = drop centerline

Vorticity in Rupturing Drop, λ = 0.14

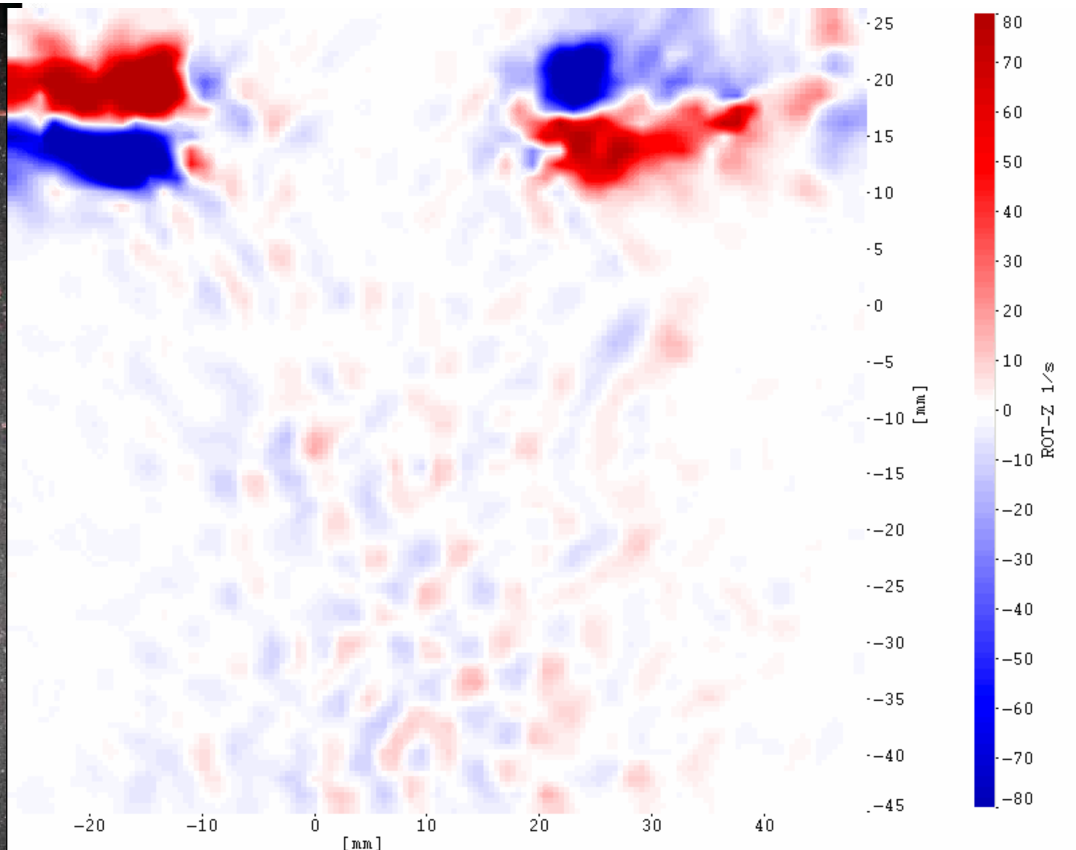


Colliding Drop Pairs



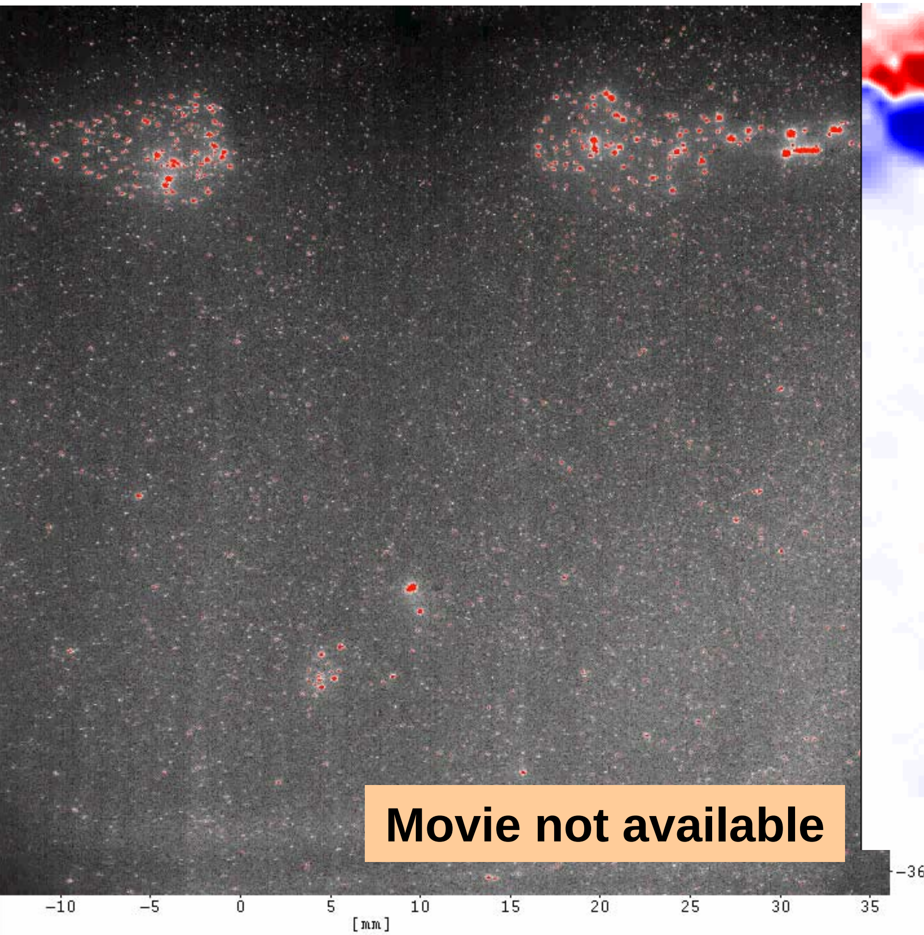
High speed stereo PIV

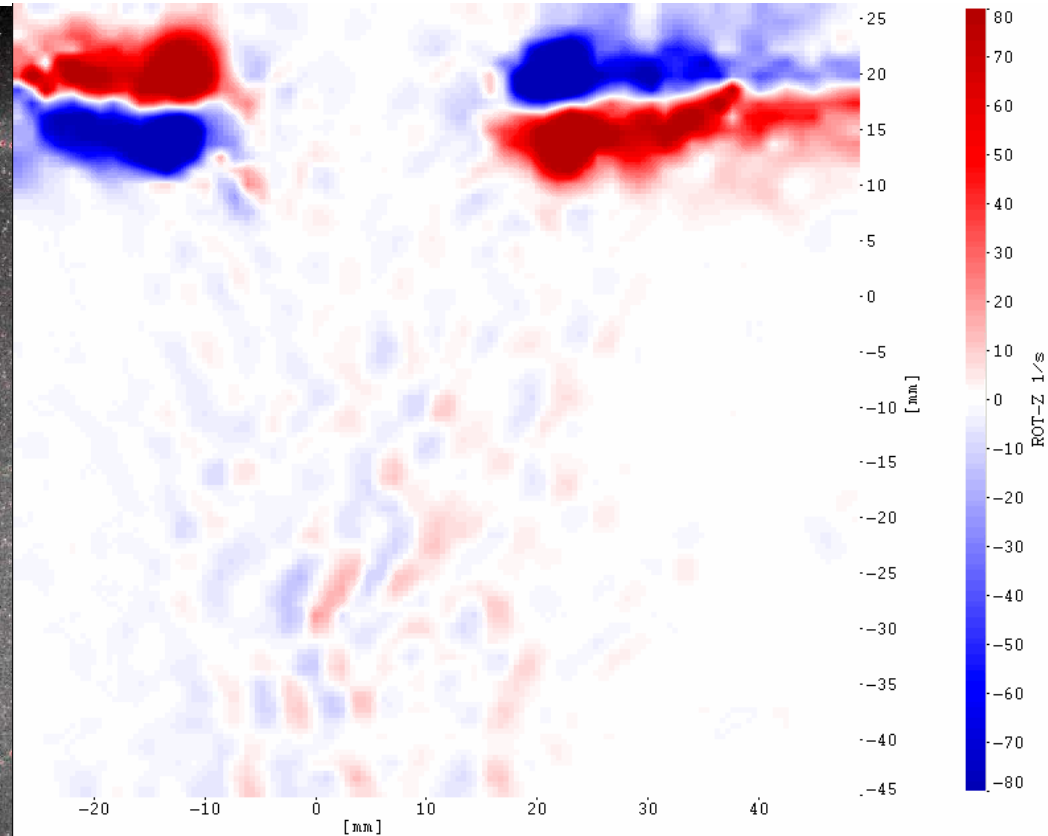
Rebounding Drops



Re = 16, We = 4.5, λ = 0.14

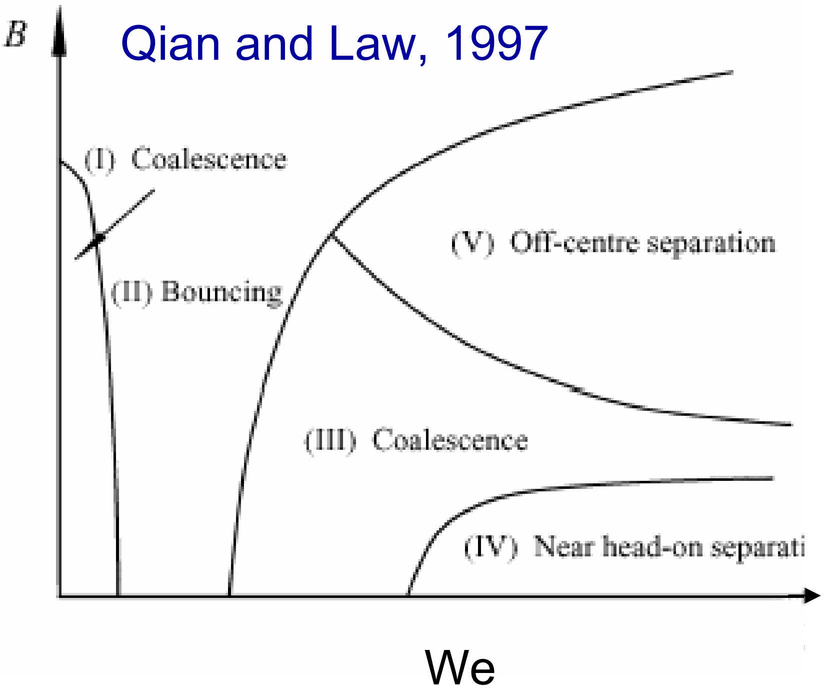
Coalescing Drops

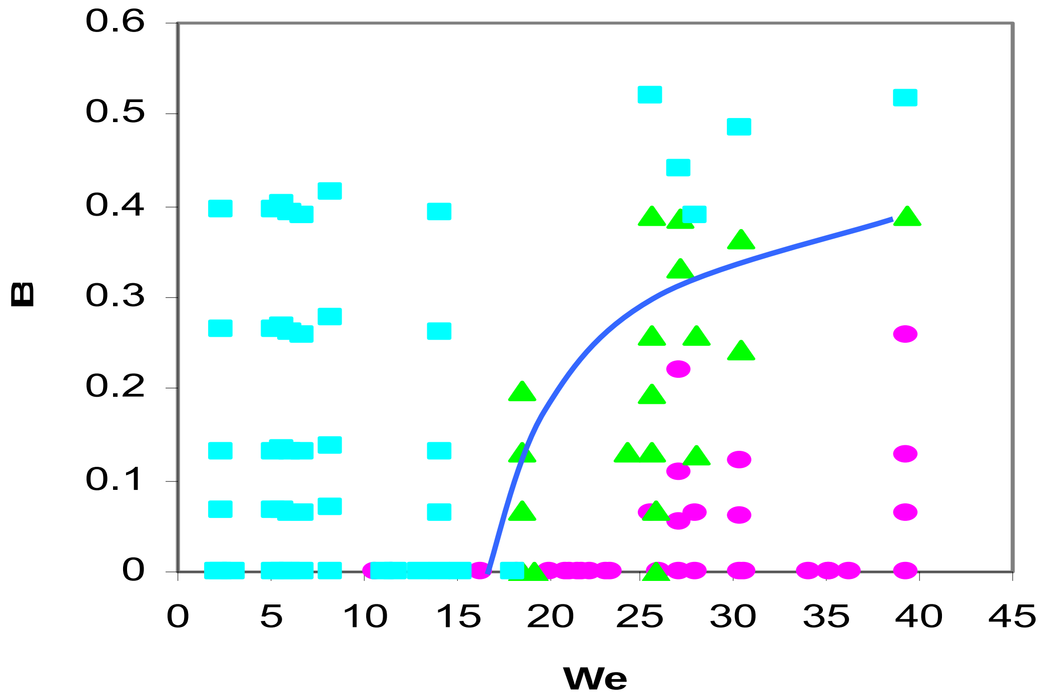




Re = 29, We = 17, λ = 0.14

Comparison to Drop Collisions in Gases





- Rebound/coalescence boundary has similar We for drops in gases and liquids
- 'Separation' at higher We also observed for drops in liquid

Conclusions

Jet:

Satellite formation encouraged by lower Re, outer viscosity

Pinch-off angles not always consistent with similarity theory ?

Drop/Interface:

Impact decoupled from coalescence:

$0.3 < Re < 300$ ($0.001 < Ca < 1$)

Drop vortex dissipates during and after impact

Coalescence occurs off axis yielding 3D flow

Small scale behavior initiates large scale behavior

Drop/Drop:

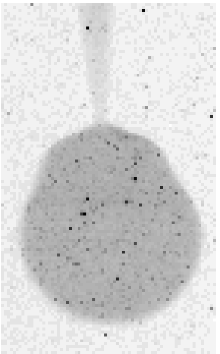
trends consistent with drop collisions in gases

including We at rebounding-coalescence boundary

Future Work

Jet:

Resolve jet neck to ~2 micron to answer similarity question



Drops:

Find parametric effects on coalescence time/topology

Resolve larger and smaller scales simultaneously to examine behavior near thin films