High-speed imaging of drops and bubbles

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- **How fast do free-surface flows move?**
  - Drop and bubble oscillations
  - Coalescence Cascade of a drop
- **Imaging and high-speed camera types**
  - Rotating mirror cameras
  - Image converter cameras
  - Very fastest cameras
  - CCD and CMOS high-speed video cameras
- **The pinch-off of a drop or a bubble from a nozzle**
  - Relevant forces
  - Low viscosity pinch-off
  - Effect of higher viscosity
- **Coalescence of two drops or two bubbles**
  - Similarity solutions
  - Experimental considerations
  - Simple dynamical models
  - Interface shape and capillary waves
  - Miscible drops

Outline

- 1. **How fast do free-surface flows move?**

  why 1,000,000 fps?
- 2. **Imaging and high-speed camera types**

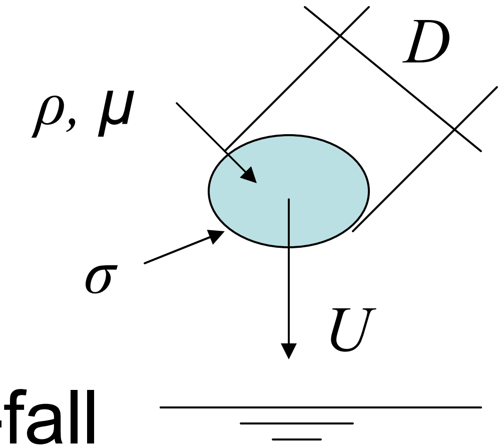
  high-speed CCD video cameras
- 3. **The pinch-off of a drop or a bubble from a nozzle**

  Different dynamics!
- 4. **Coalescence of two drops or two bubbles**

  Miscible drops

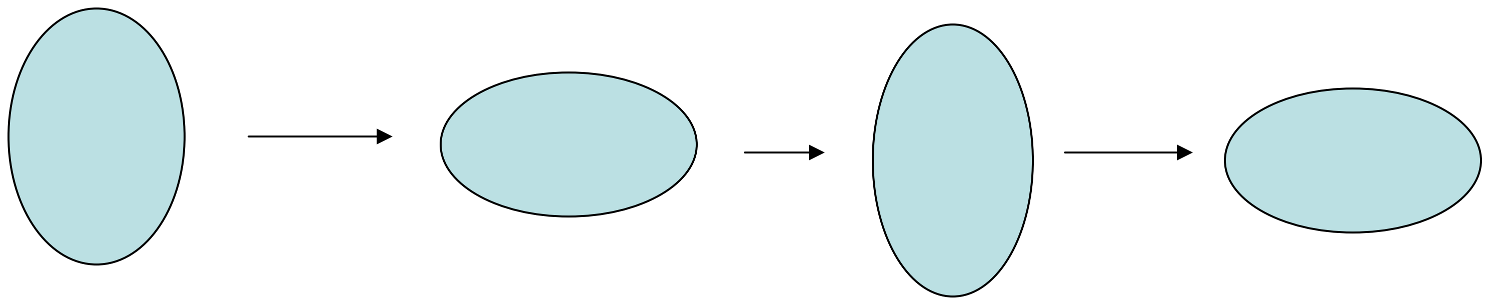
Parameter Space

- **Relevant forces:**
  1. Surface tension, σ
  2. Inertia
  3. Viscous forces



- Ignore Gravity, $dx = \frac{1}{2}\, g\, t^2$
  in $t = 1\ ms$, $dx = 5\ \mu m$ in free-fall
- $Re = \rho U D / \mu$
- $We = \rho D U^2 / \sigma$ **kinetic / surface energies**
- $Ca = \mu U / \sigma$
- Dynamic air pressure!
- Drop shape

1. How fast do free-surface flows move?



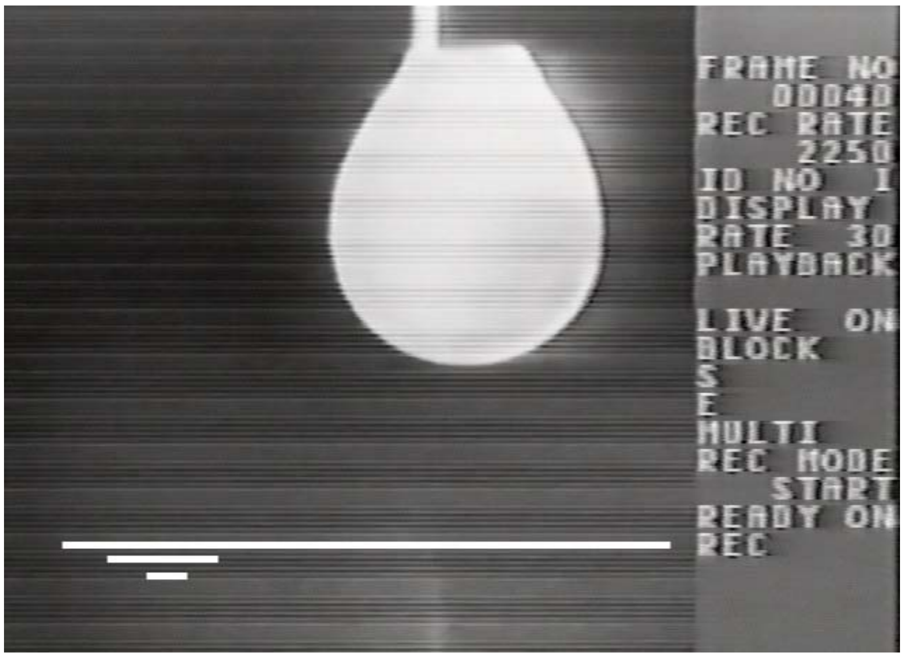
$$\omega_n = \sqrt{\frac{\sigma}{\rho R_i^3}\, n(n-1)(n+2)}$$

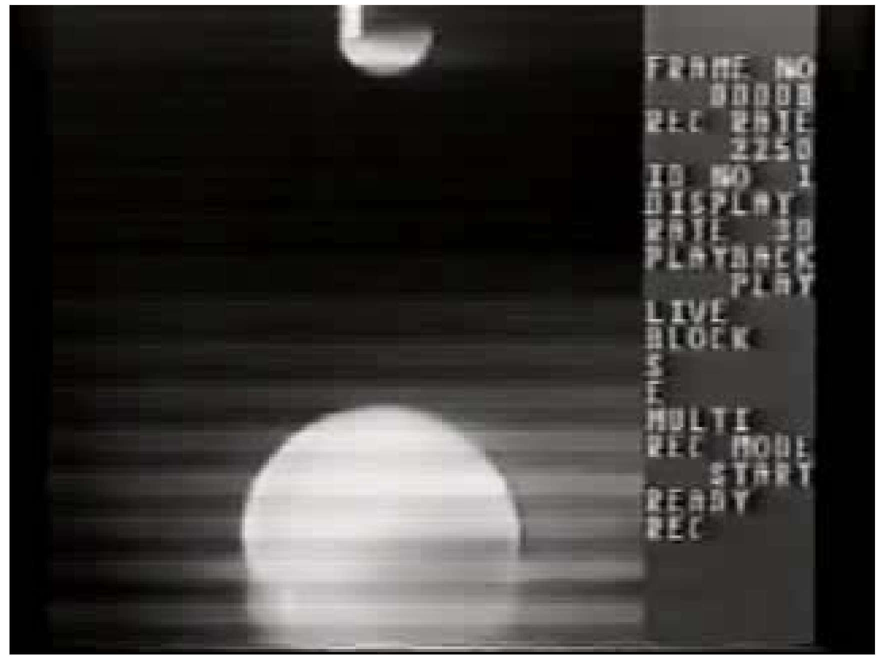
$$\omega_2 = \sqrt{\frac{\sigma}{\rho R_i^3}\, 8}$$

R = 100, 10, 1 μm

ω_2 = 3.8, 120, 3800 kHz

Small impact velocity
Drop rests on pool surface

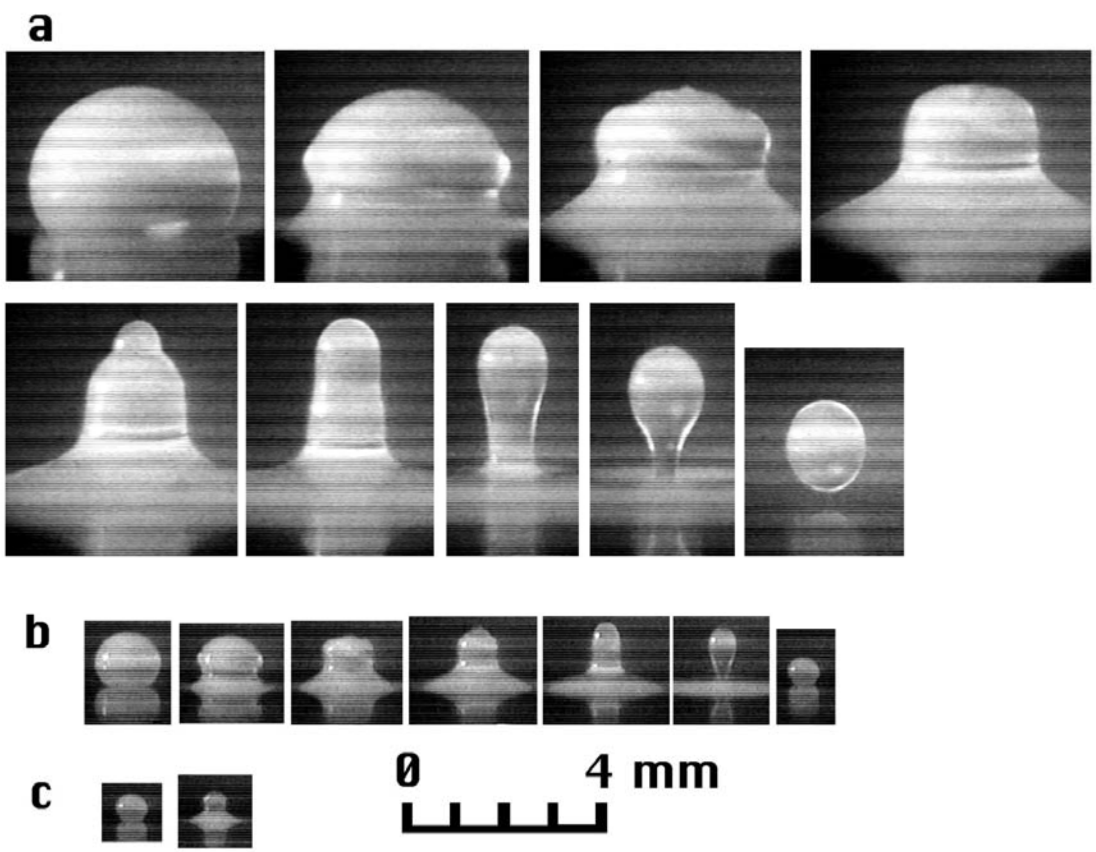




Real time

2250 frames/s

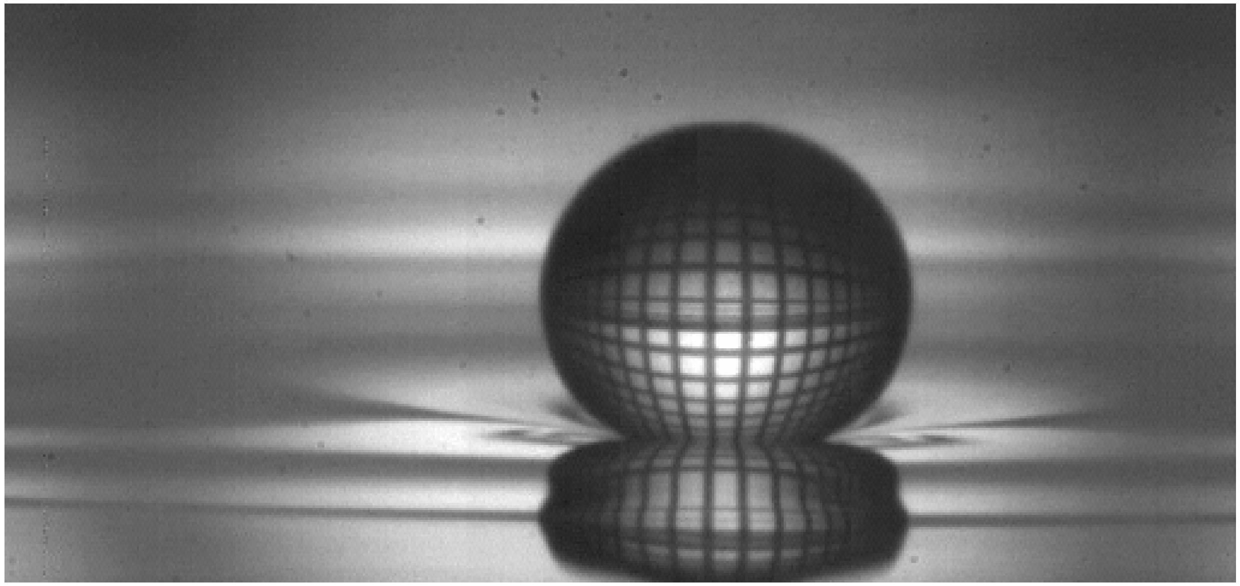
Coalescence Cascade



Six steps

In cascade!

Thoroddsen & Takehara (2000) *Phys. Fluids*, **12**, p. 1265
Liquid-Liquid case → Charles & Mason (1960) *J. Colloid Sci.* **15**, 105

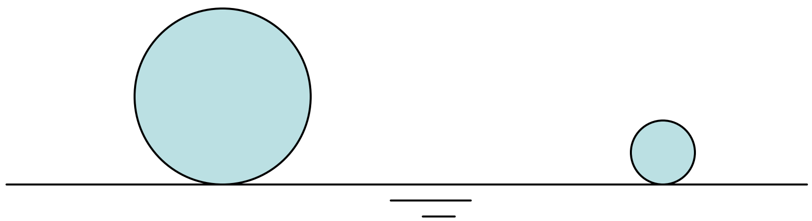


Time-scale of each step T_s

Time between first contact → daughter drop pinch-off

Capillary-inertial Scaling

- Geometric similarity:



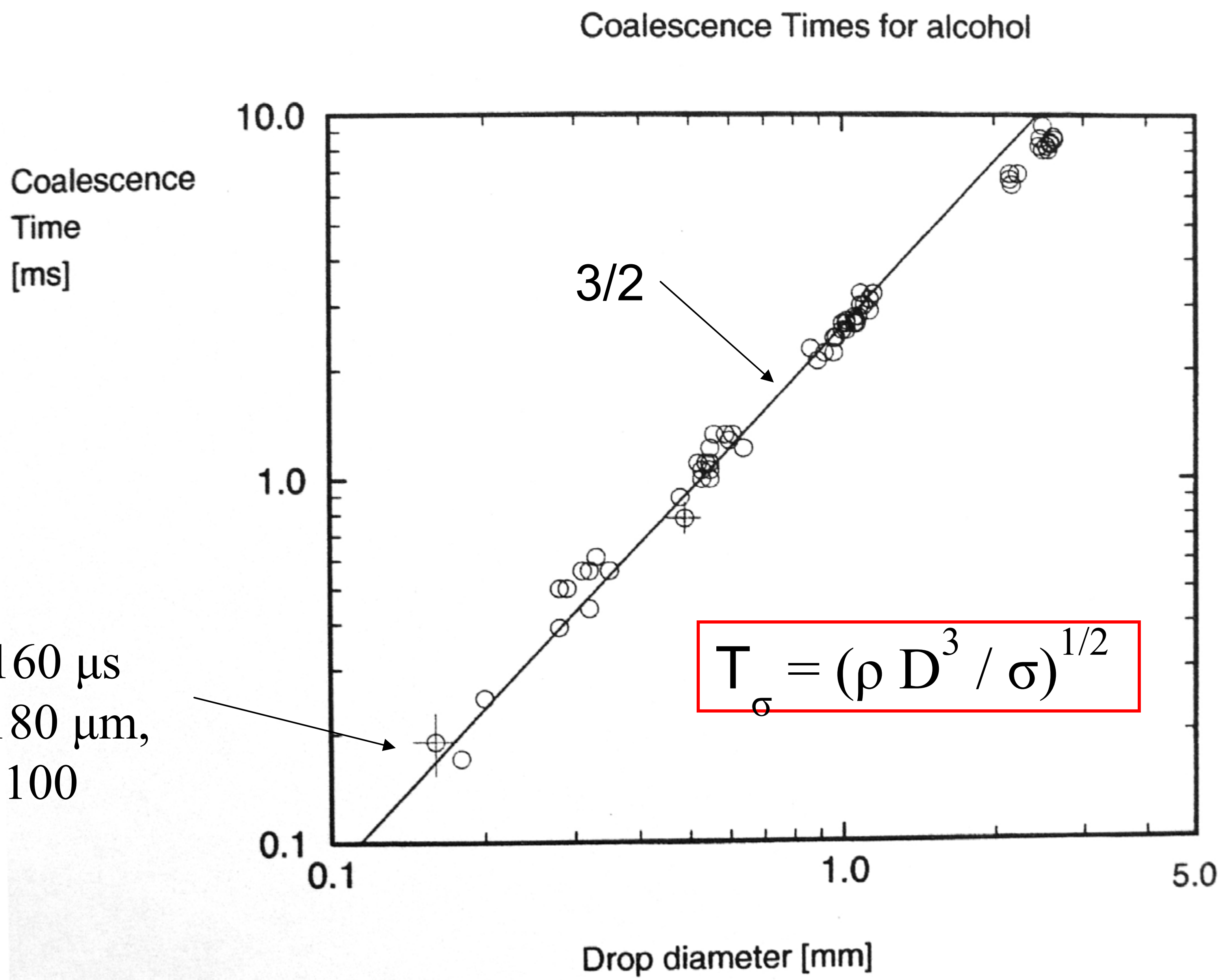
- Dynamic similarity:

$$T_\sigma = (\rho\, D^3 / \sigma)^{1/2} \qquad \Rightarrow \quad U = D / T_\sigma$$

$$We = \rho\, DU^2/\sigma = \rho\, D\, (\, D/\, (\rho\, D^3 \,/\, \sigma\,)^{1/2}\,)^2 \,/\, \sigma$$

$$= \rho D\, D^2/\, (\rho\, D^3 \,/\, \sigma\,)\,/\sigma \;=\; 1$$

How small?



$$T_\sigma = (\rho D^3 / \sigma)^{1/2}$$

$T_\sigma \sim 160\ \mu s$
$D \sim 180\ \mu m$,
$Re \sim 100$

$U = D / T_\sigma$

Viscosity?

$$Re = \rho\, D U / \mu = \rho\, D \left(D / (\rho\, D^3 / \sigma)^{1/2} \right) / \mu$$

$$= (\rho D \sigma)^{1/2} / \mu \sim D^{1/2}$$

$$weak \neq D$$

Smallest drop, $D \sim 180\ \mu m \Rightarrow Re = 60$

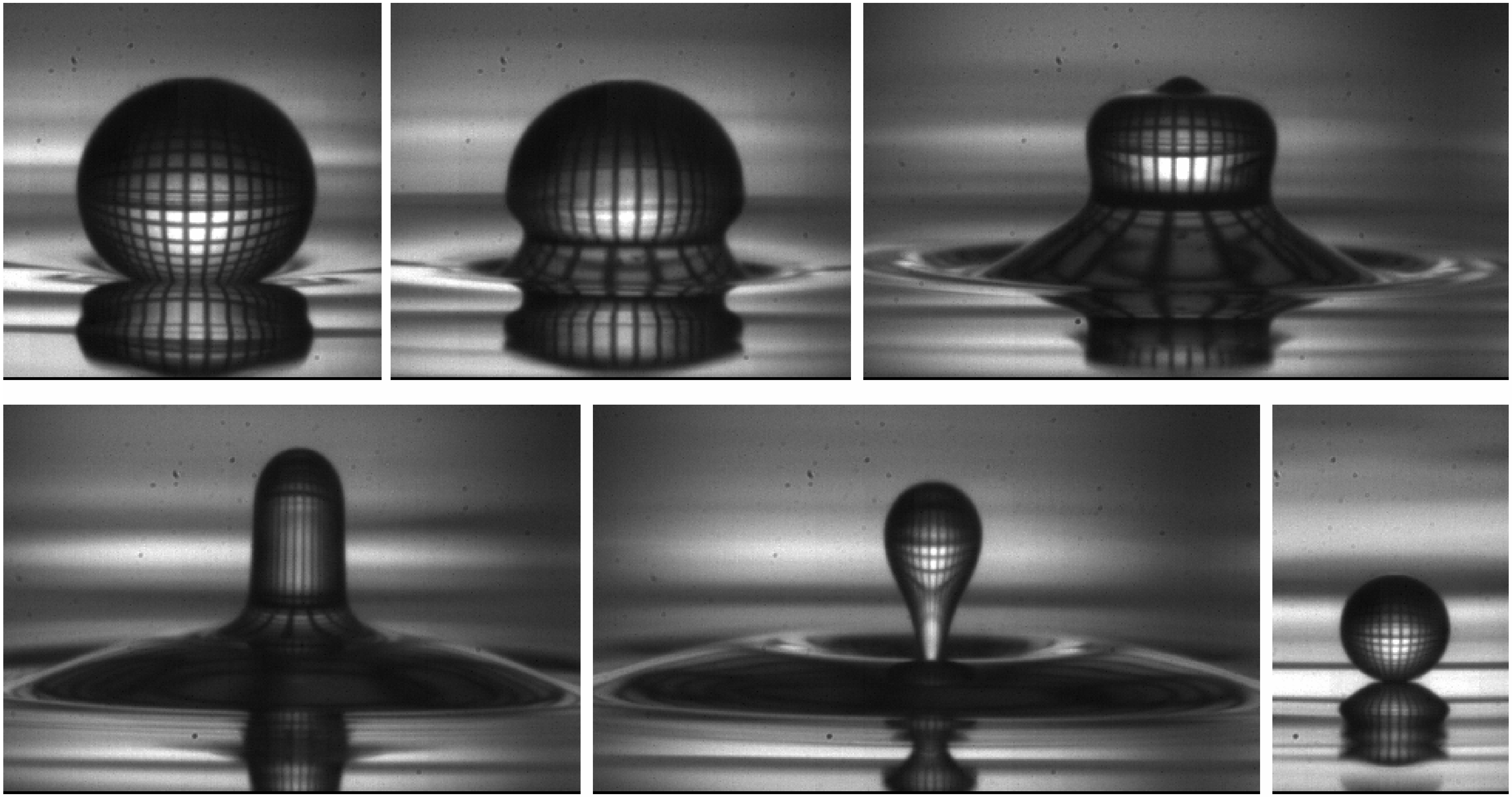
$$Re = \rho DU/\mu$$

$$Oh = \mu / (\rho D\sigma)^{1/2} < 0.026$$

Blanchette & Bigioni (2006) *Nature Phys.* **2**, 254-257

For water, smallest mother drop R = 22 μm

Mercury, R = 0.5 μm.



Thoroddsen & Li

Thoroddsen (2006) *Nature Phys.*, **2**, 223-224
Blanchette & Bigioni (2006) *Nature Phys.*, **2**, 254-257

Mercury, smallest mother drop ≈ 0.5 μm.
Time of phenomenon ≈ 0.1 μs

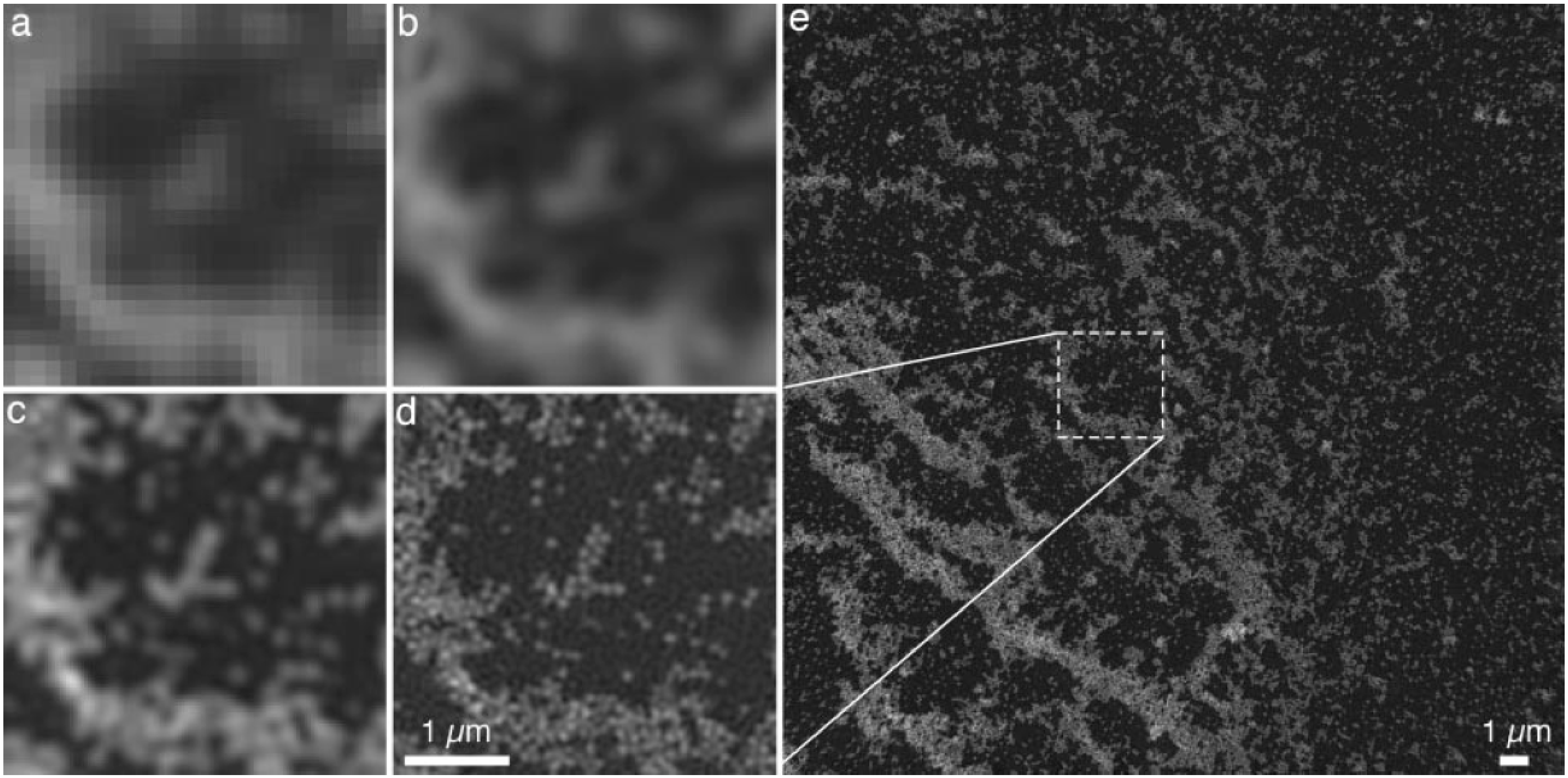
Optical magnification

- Microscopic observations
- Velocity of 1 m/s => 1 μm in 1 μs
- Diffraction limit ~ 0.5 μm

➔TEM ?

Transmission Electron Microscopes

Structured illumination



Gustafsson (2005) *PNAS*, **102**, pp. 13081-86

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- **1. How fast do free-surface flows move?**

  why 1,000,000 fps?
- **2. Imaging and high-speed camera types**

  high-speed CCD video cameras
- **3. The pinch-off of a drop or a bubble from a nozzle**

  Different dynamics!
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2. Imaging and high-speed camera types

–Rotating mirror cameras

–Image converter cameras

–Very fastest cameras

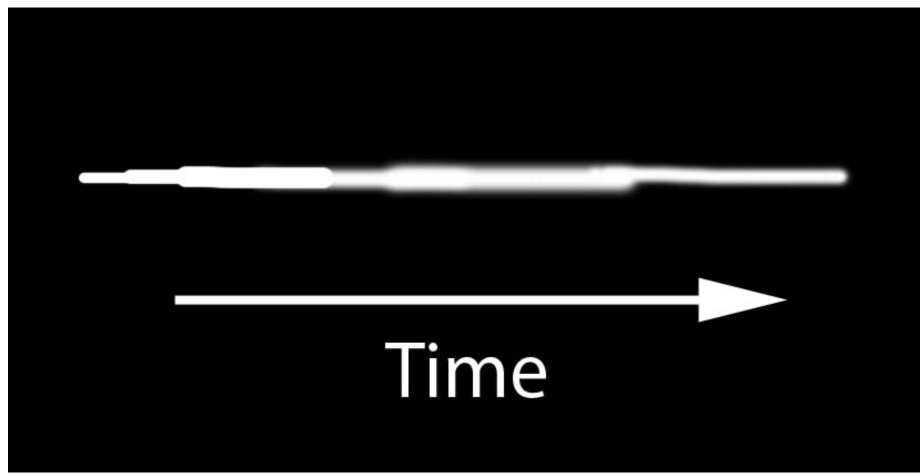
–CCD and CMOS high-speed video cameras

Streak cameras

Move the image point

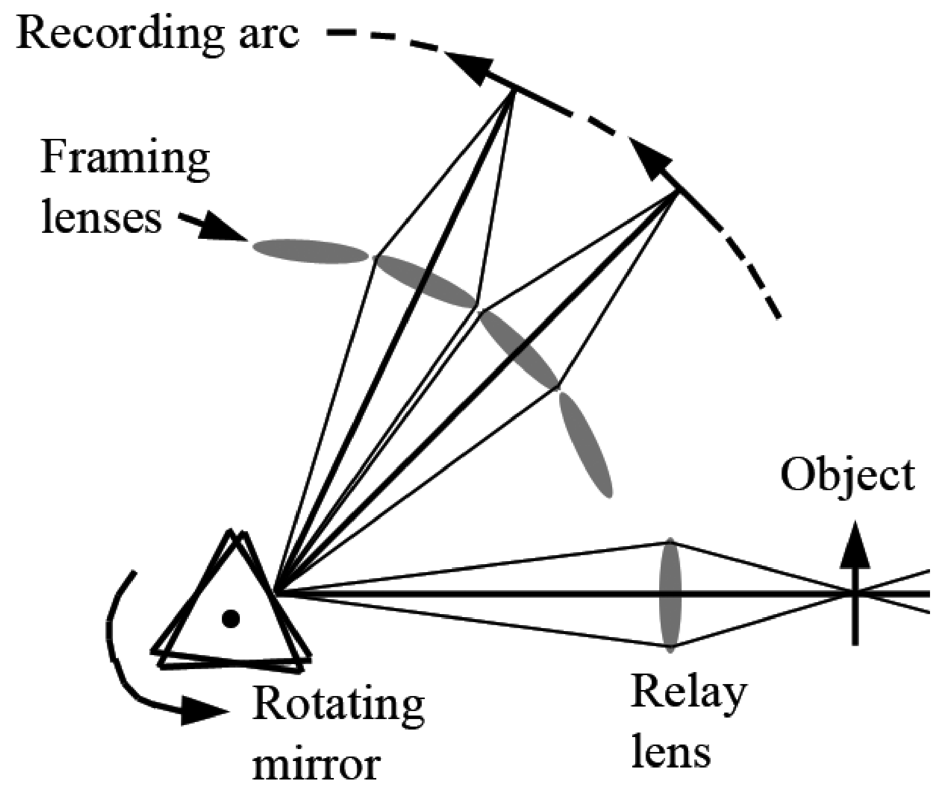
Rapidly across the recording medium

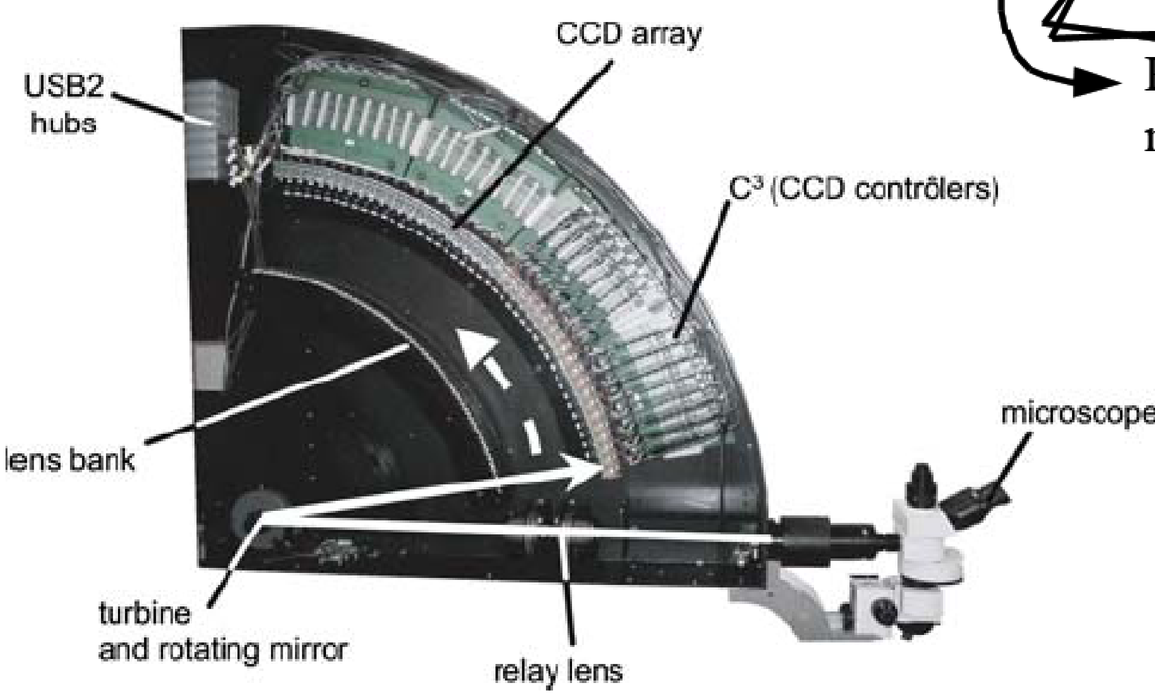
Convert time into space coordinate on the ‘film’



Rotating Mirror

Streak / Framing cameras



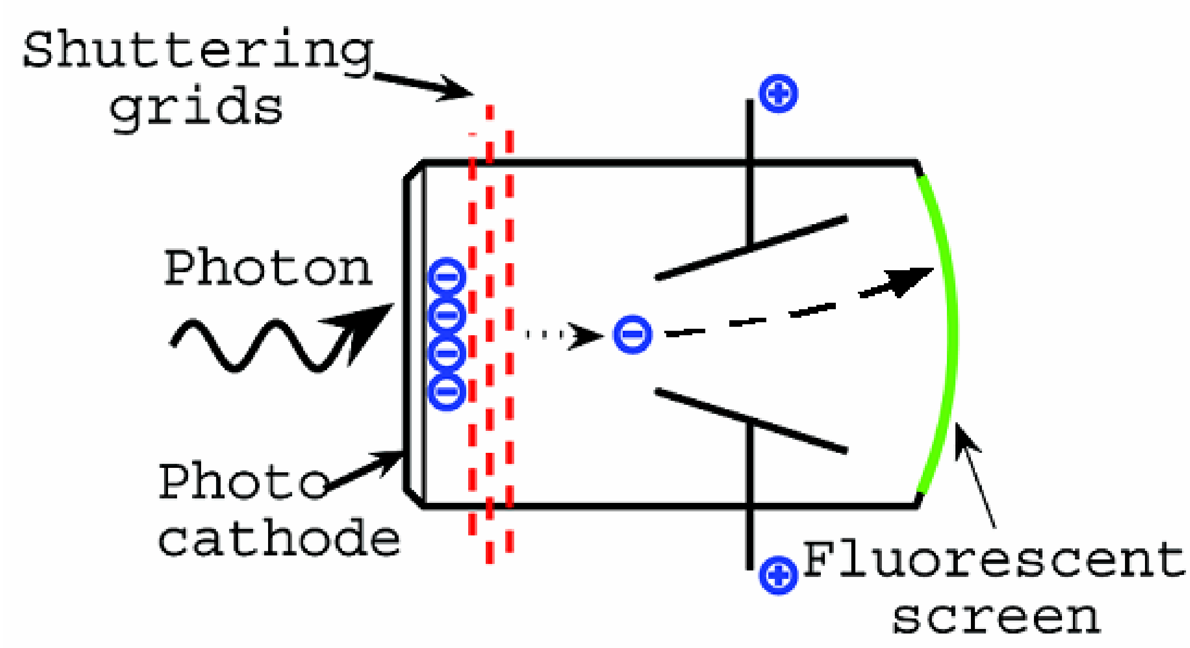


Brandaris 128

Lohse, Versluis, De Jong

Twente University

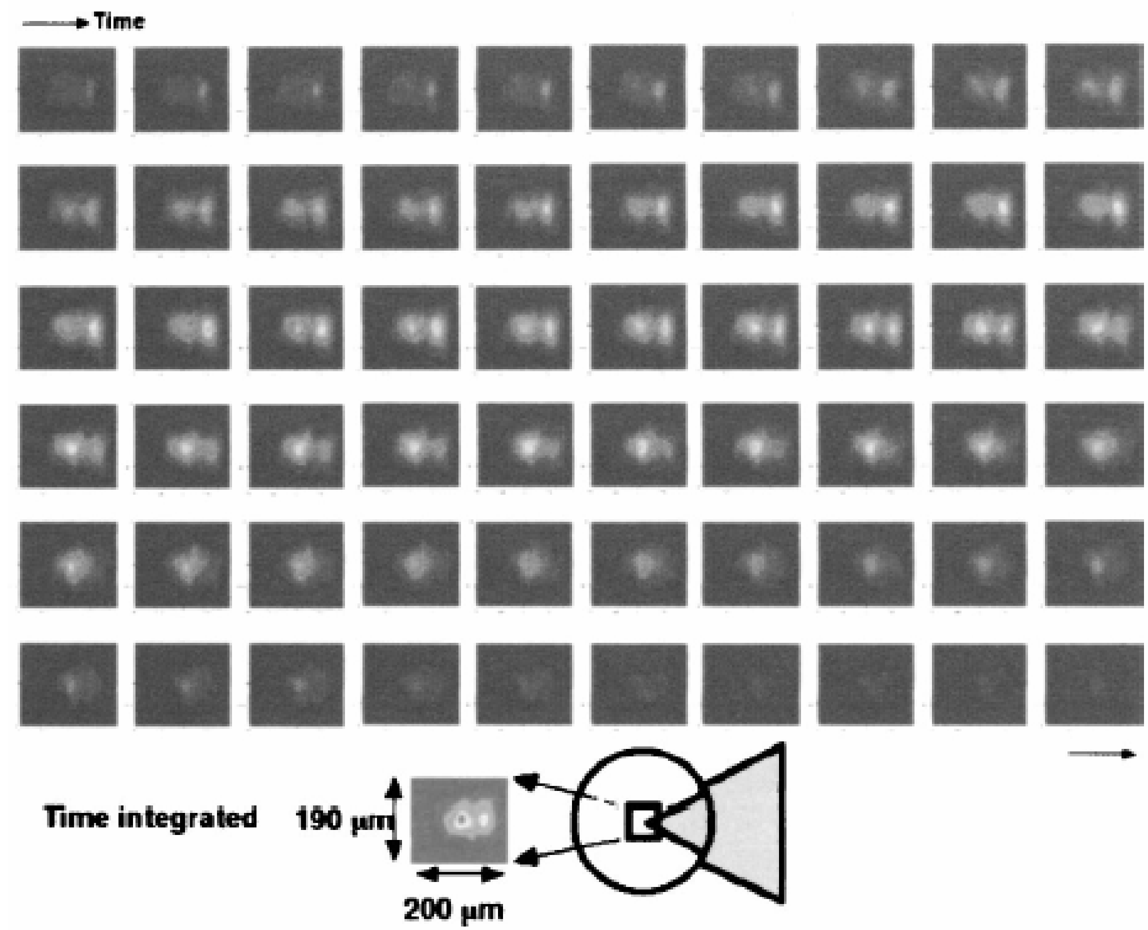
Image-converter cameras



Drawbacks:

Few frames, poor image quality

The very fastest cameras

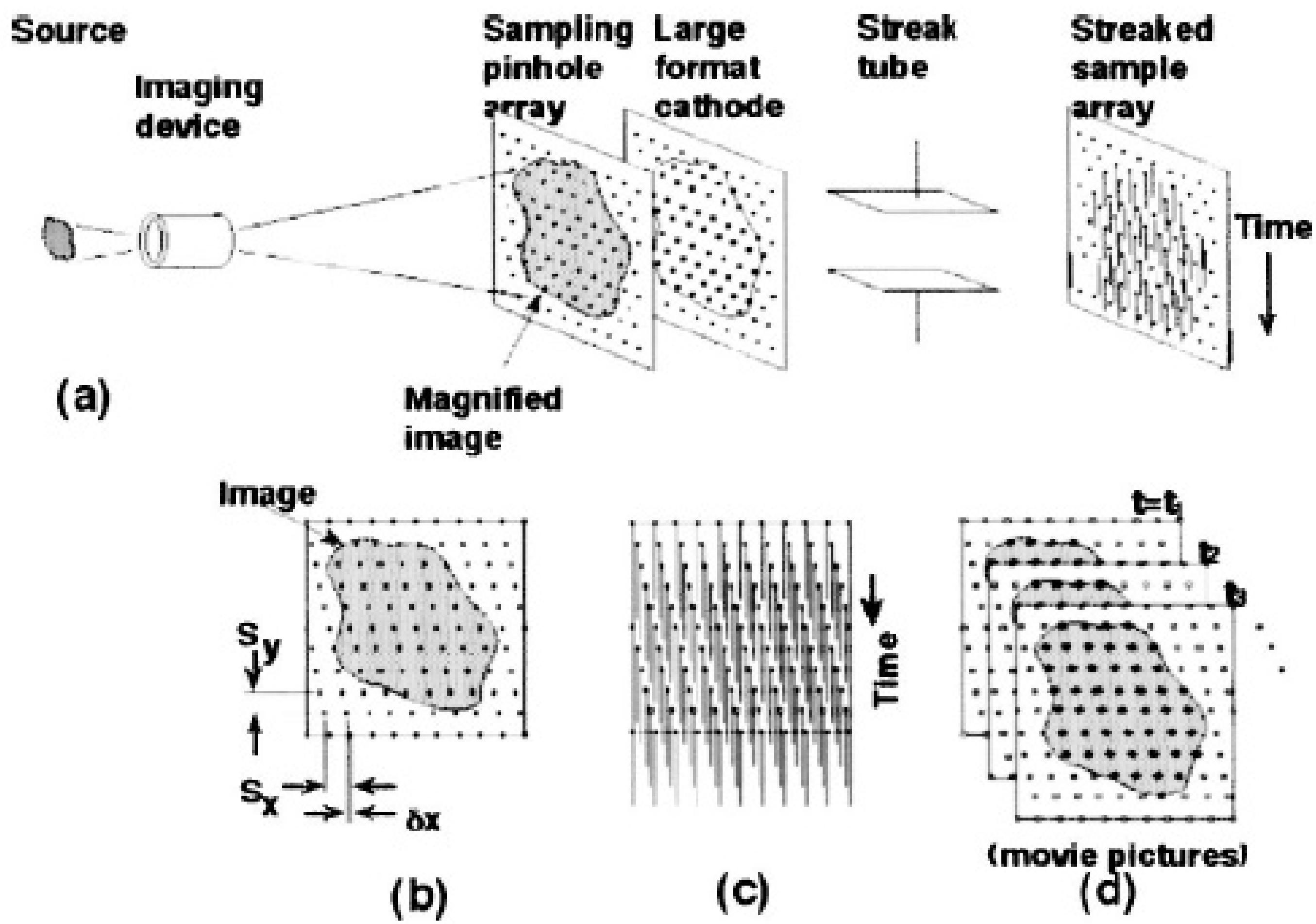


dt = 10 ps

pico-s = 10^{-12} s

Laser Implosion of pellet, Inertial Confined Fusion

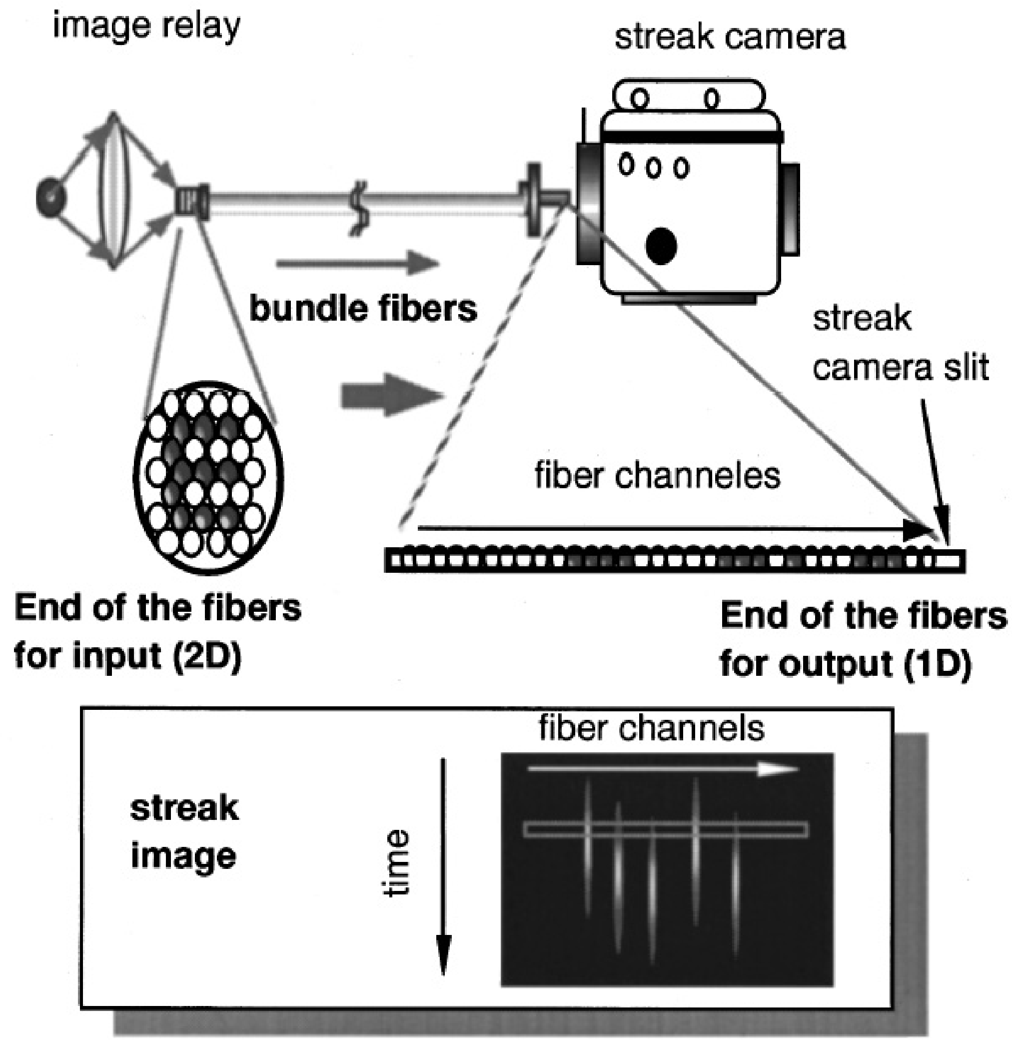
X-rays



Shiraga et al. (2004)

Rev. Sci. Instrum. **75**, 3921-25

Using UV light



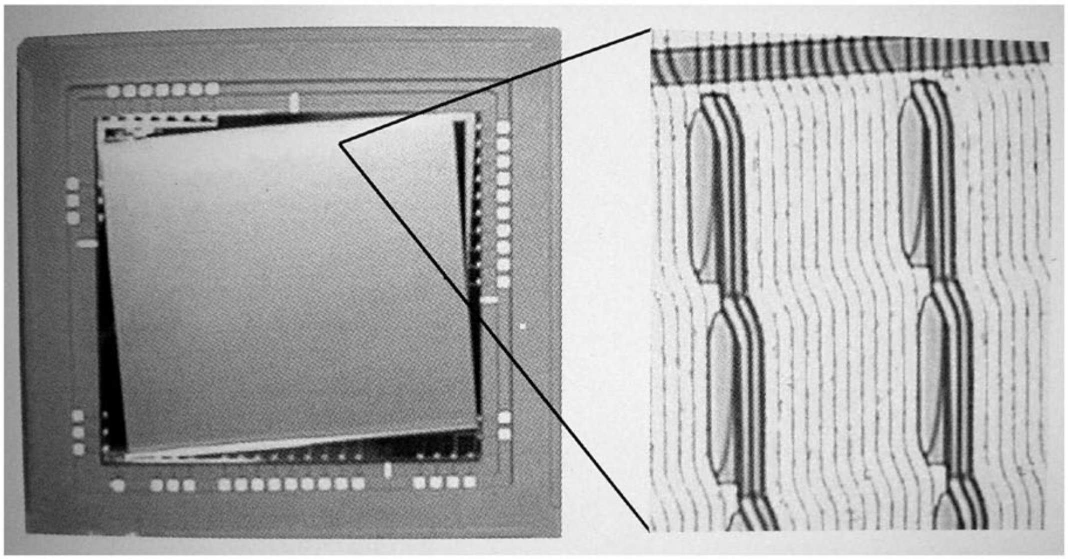
Kodama et al. (1999)

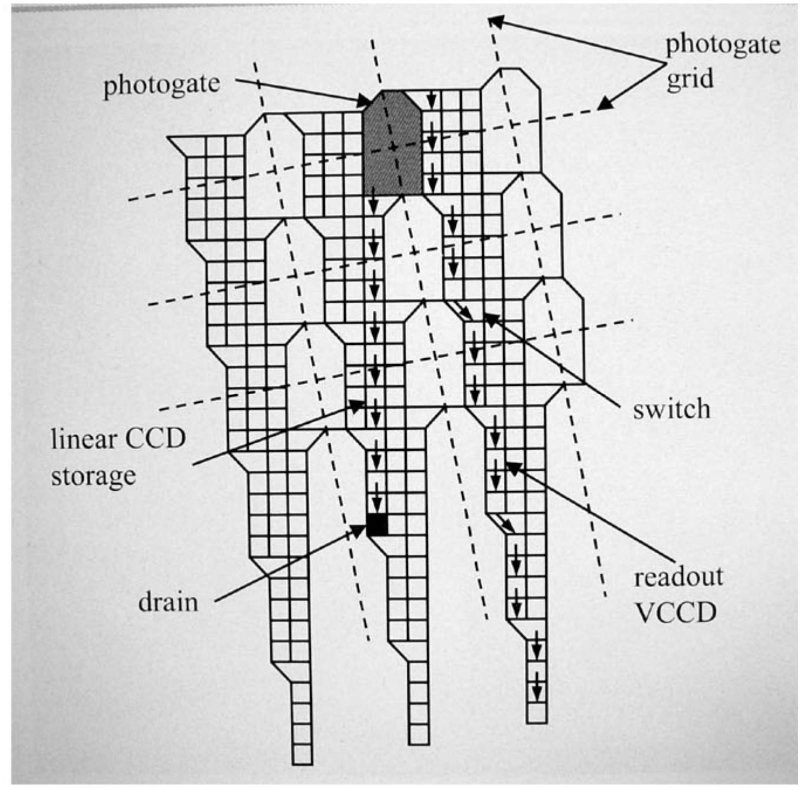
Rev. Sci. Instrum. **70**, 625 - 628

CCD vs CMOS sensors

- Both based on
  Metal Oxide Semiconductors
  using the *Photo-electric* effect
- Differences:
  Transfer of electron packages
  between registers

Ultra-High-Speed ISIS Video CCD Sensor





260 x 312 pixels, 103 frames

Triggering

Shimadzu Corp. $ 250 k

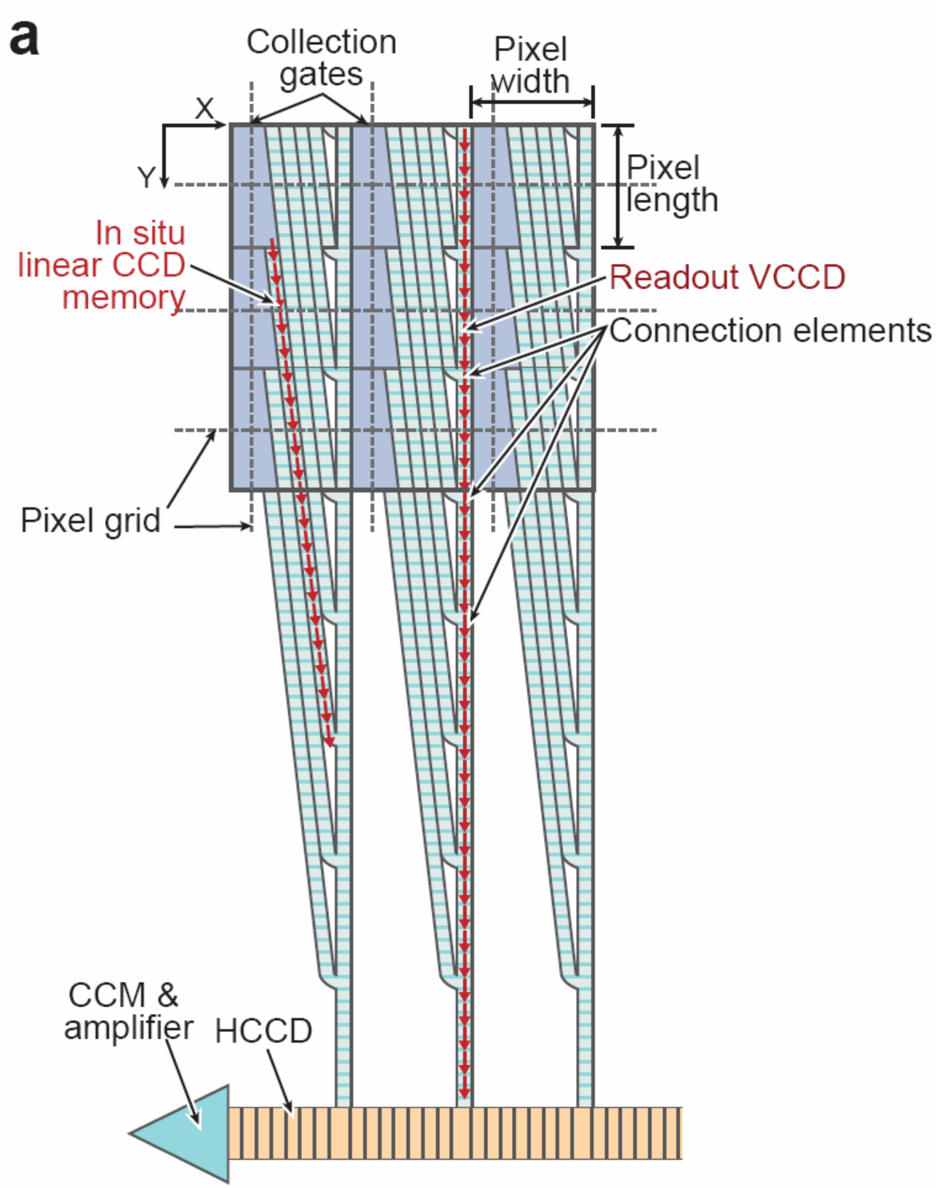
Etoh, Poggemann, Kreider *et al.* (2003)
IEEE Trans. on Electron Dev. **50**, 144--151.
"An image sensor which captures 100 consecutive framesat 1000,000 frames/s"

160 Gb / sec

Challenges

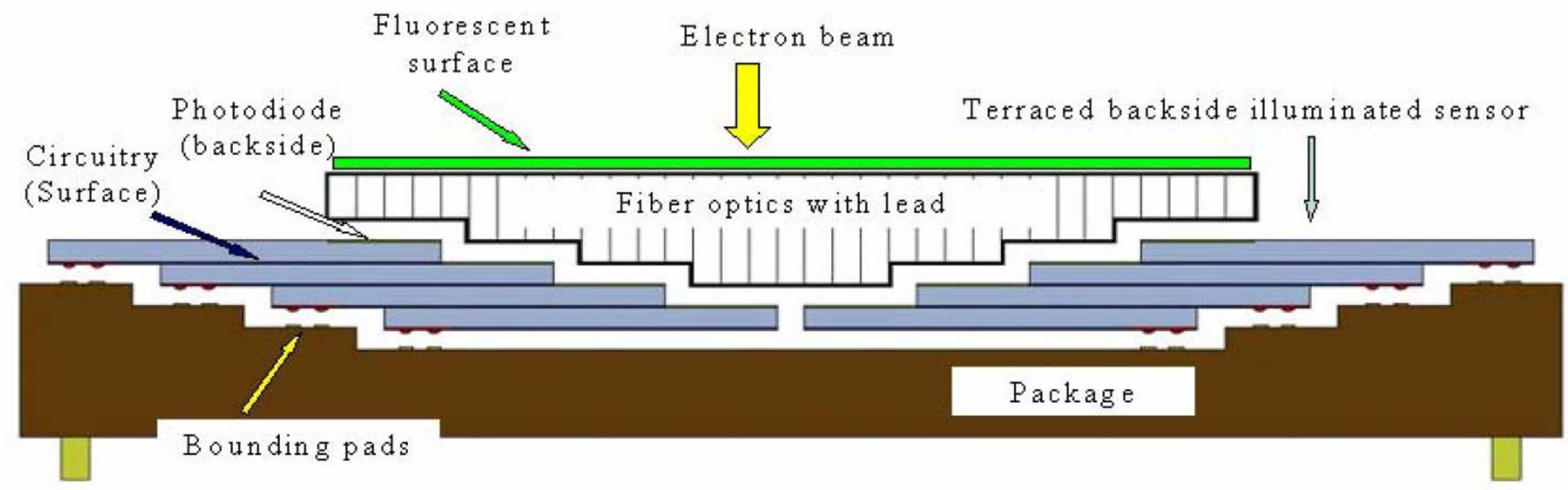
- Higher frame-rates
  - Drive signal damping
- Larger number of pixels
- Total number of frames
  - Space for the storage element
    Terraced sensors

Latest Sensor: High-Definition



410 x 720 pixels

Terraced sensor



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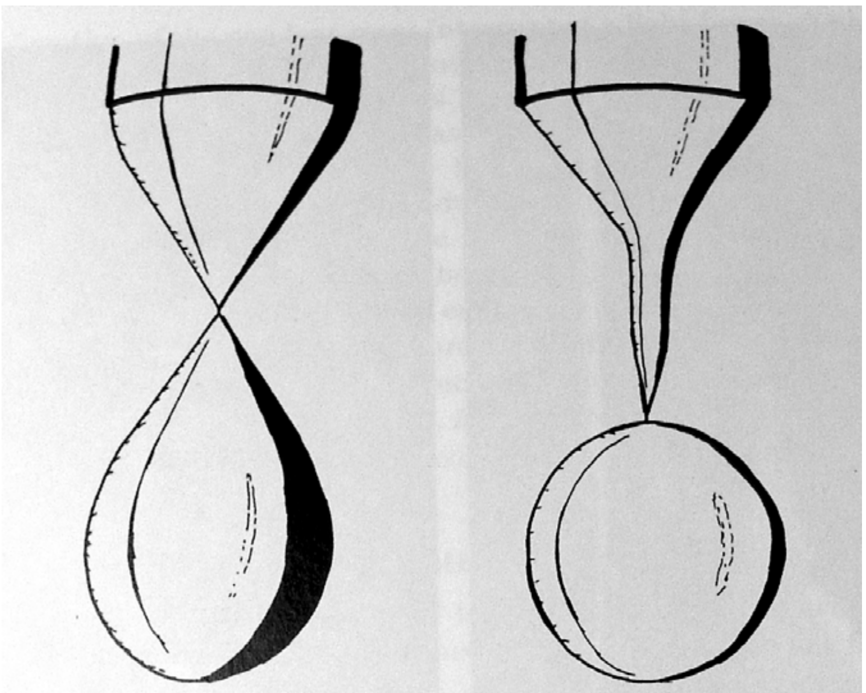
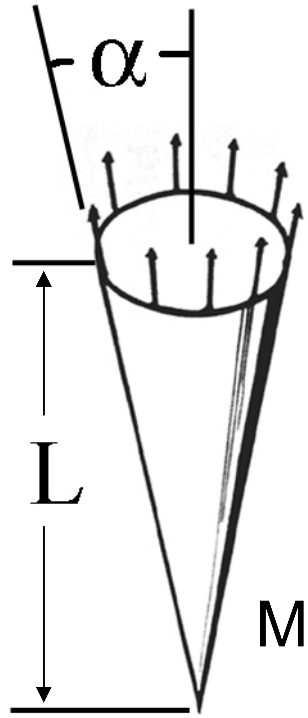
  Miscible drops

3.a Pinch-off of a drop from a nozzle

Peregrine et al. *JFM* (1991)
& Keller & Miksis (1983)





$F_\sigma = \mathbf{L}\,\sigma\,(2\pi \sin\alpha)$

$M = \mathbf{L}^{3}\,(\rho\pi \sin^{2}\alpha \cos\alpha)/4$

$\text{acceleration} \sim F_\sigma / M \sim 1 / \mathbf{L}^{2}$

acceleration tends to infinity for small L !

Drop pinch-off: driven by capillary-inertial dynamics

$$R \sim t^{2/3}$$

Eggers J. (1997)
Non-linear dynamics and breakup of free-surface flows.
Rev. Mod. Phys. **69**, 865 - 929

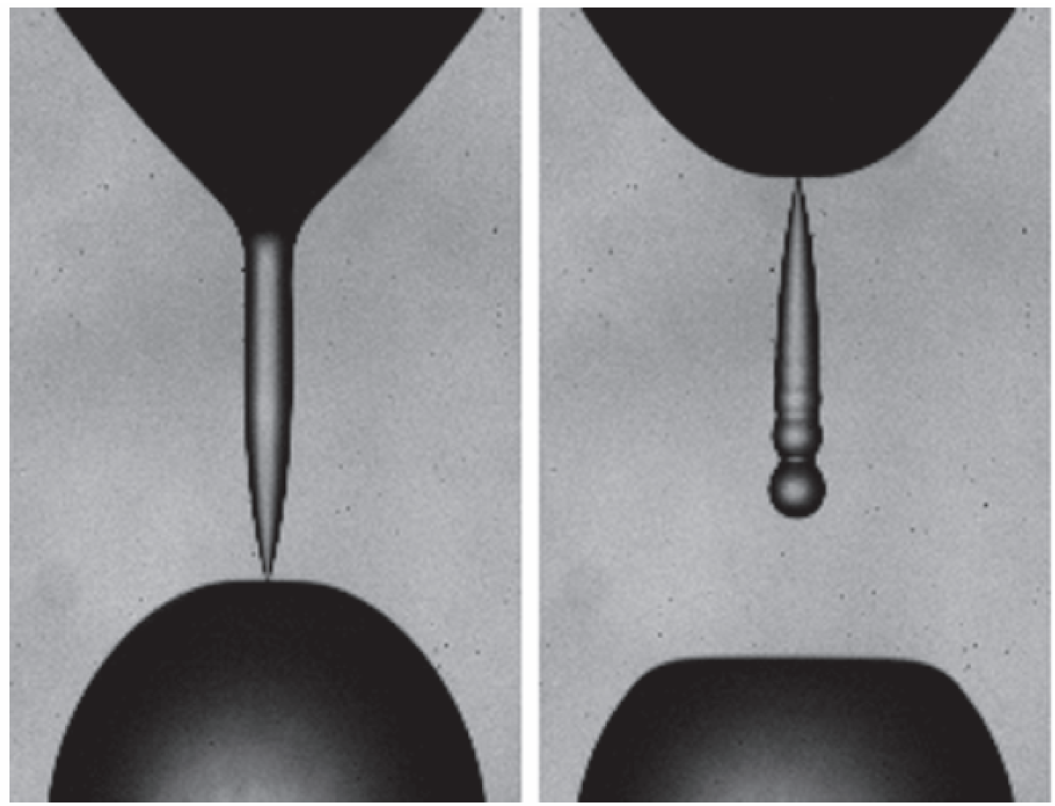
Bubble pinch-off:

Surface tension becomes irrelevant

$$R \sim t^{0.57}$$

Pinch-off of a water drop

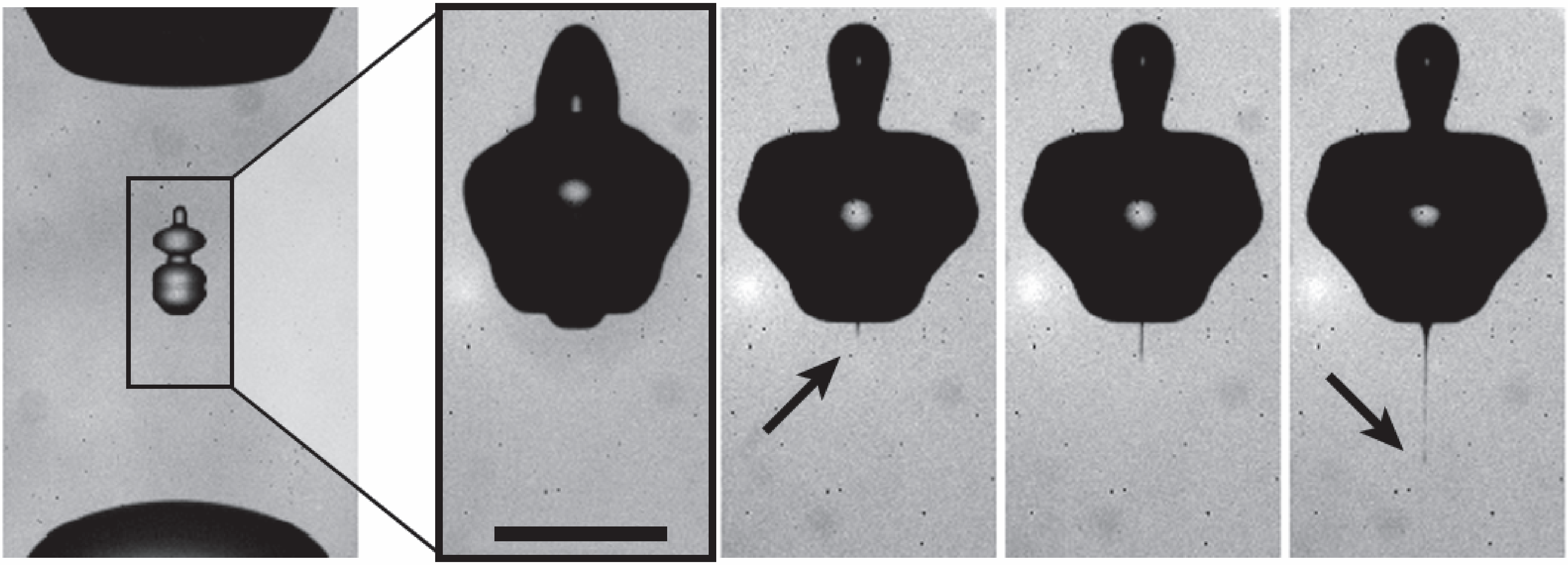
Formation of a satellite thread



Oscillations of the satellite

Formation of a bottom jet

Speed and size of jet?

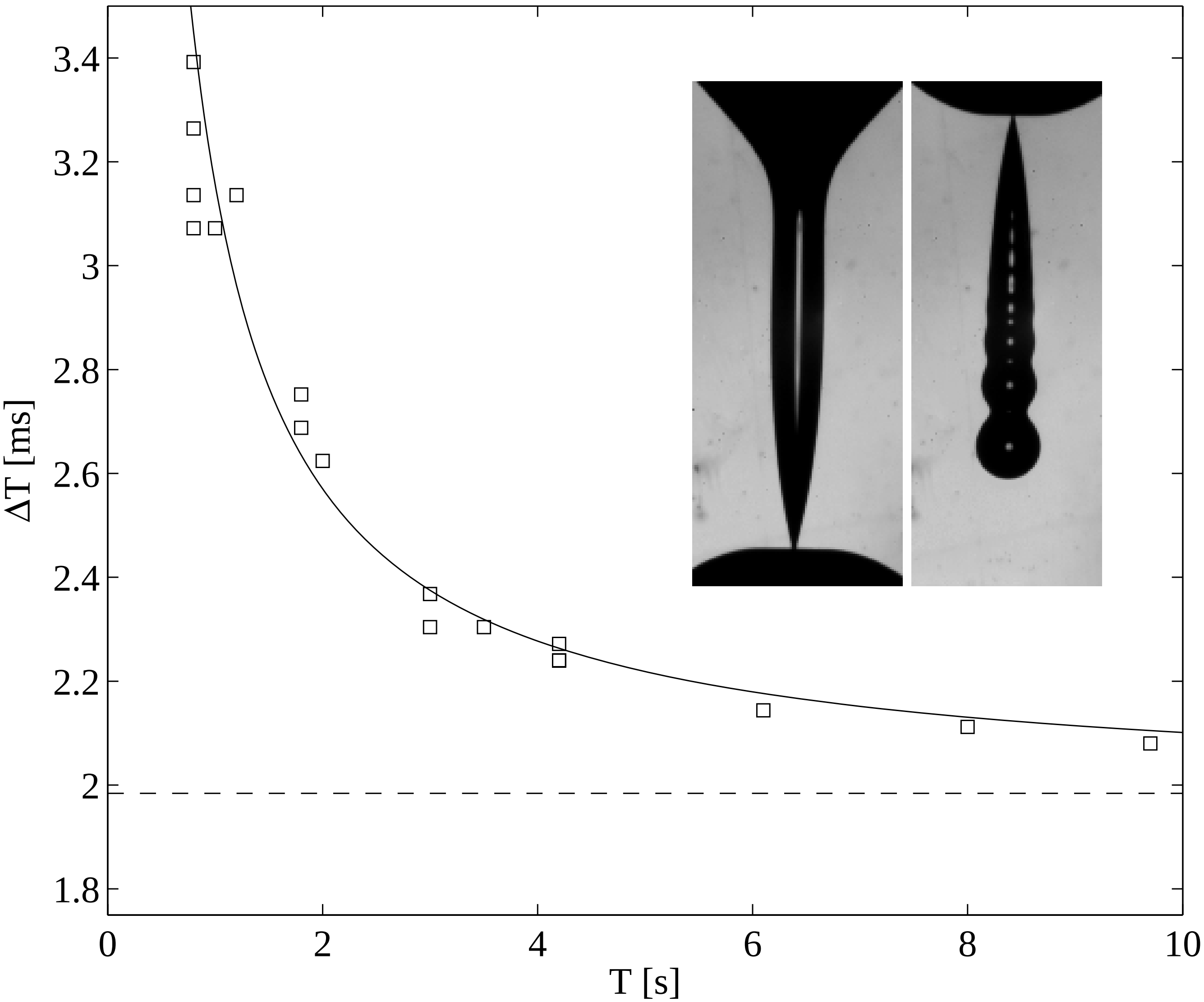


Thoroddsen, Etoh & Takehara (2007) Micro-jetting from wave focusing on oscillating drops. *Phys. Fluids* **19**, 052101

Satellite controls

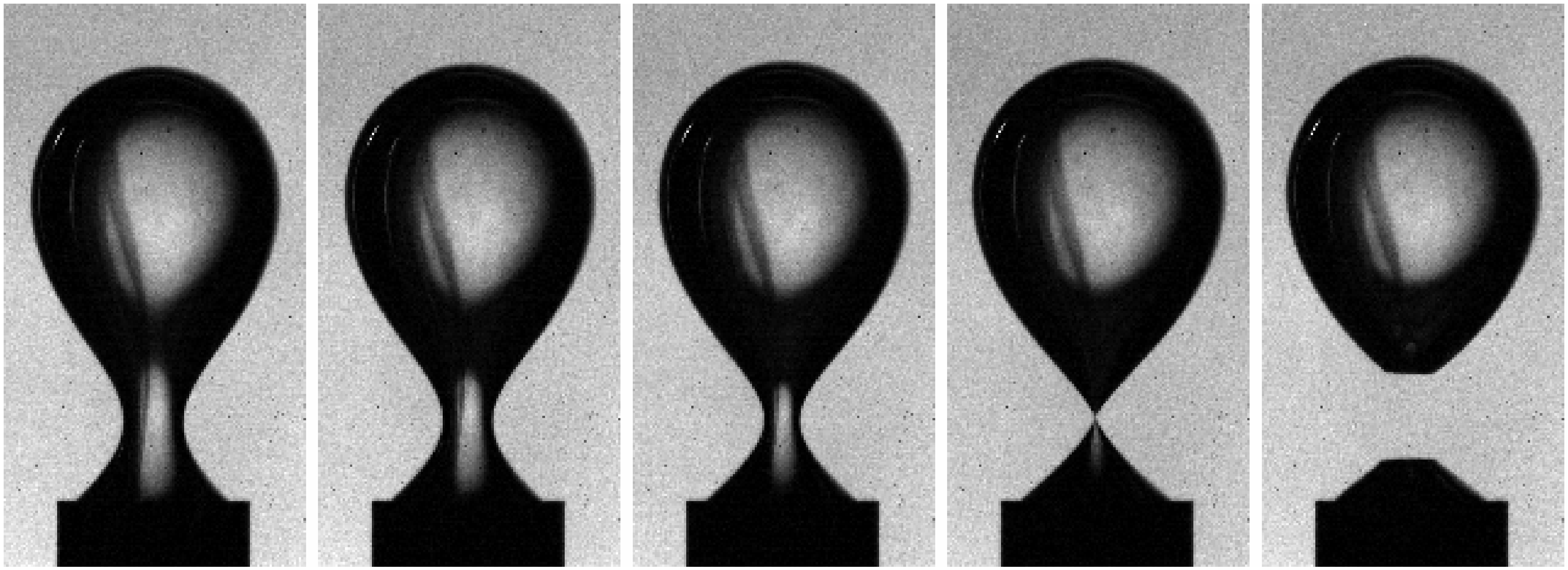
- Nozzle size
- Surface tension
- Liquid density
- Air density
- Liquid viscosity
- *Flow-rate into the drop*

Time between top and bottom pinch-off



Time between subsequent drop pinch-off

3.b The pinch-off of a bubble



dt = 0.5 ms
OD = 2.7 mm

Recent references on bubble pinch-off

- Burton, Waldrep & Taborek (2005)

  Scaling and instabilities in bubble pinch-off.

  Phys. Rev. Lett. **94**, 184502
- Keim, Møller, Zhang & Nagel (2006)

  Breakup of air bubbles in water: breakdown of cylindrical symmetry. *Phys. Rev. Lett.* **97**, 144503
- Thoroddsen, Etoh & Takehara (2007) Experiments on bubble pinch-off. *Phys.Fluids* **19**, 042101

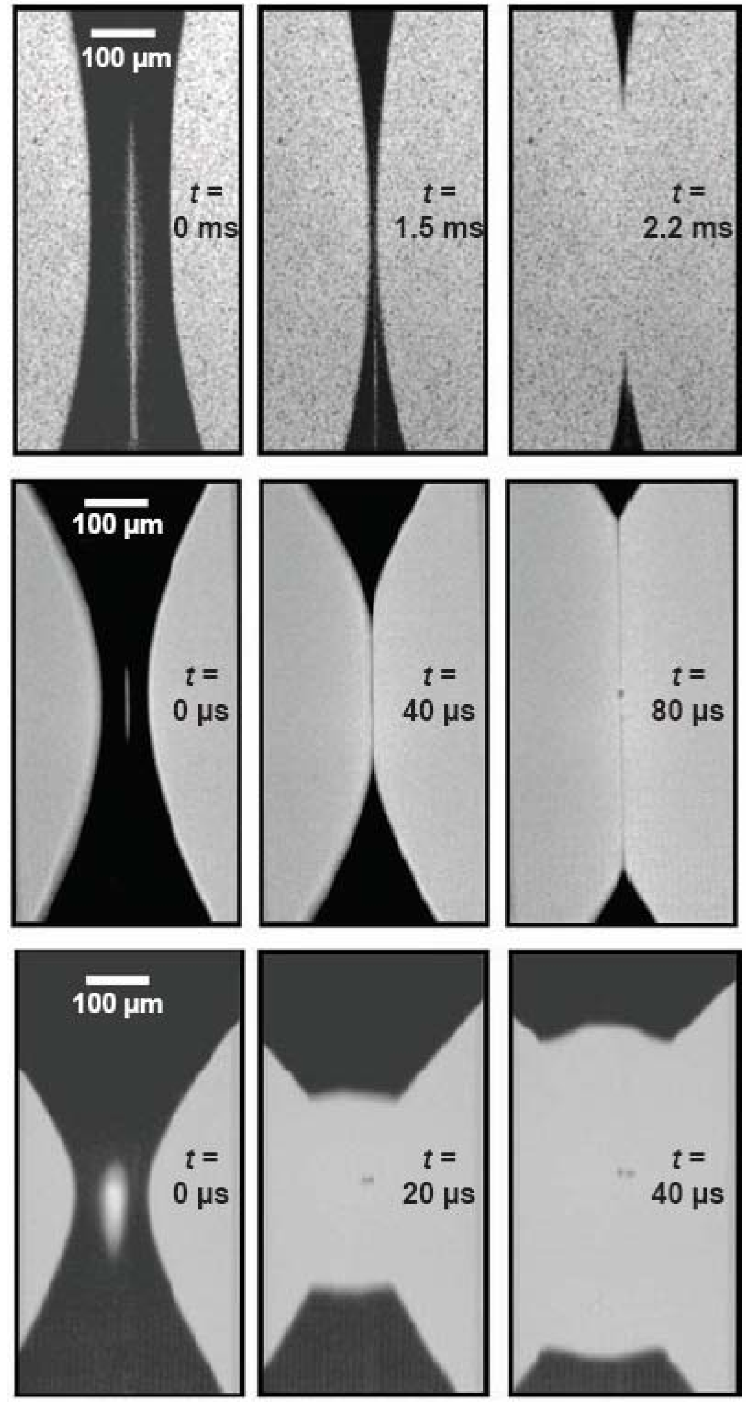
Burton, Waldrep & Taborek (2005)

Very viscous liquid

Intermediate viscosity

air thread!

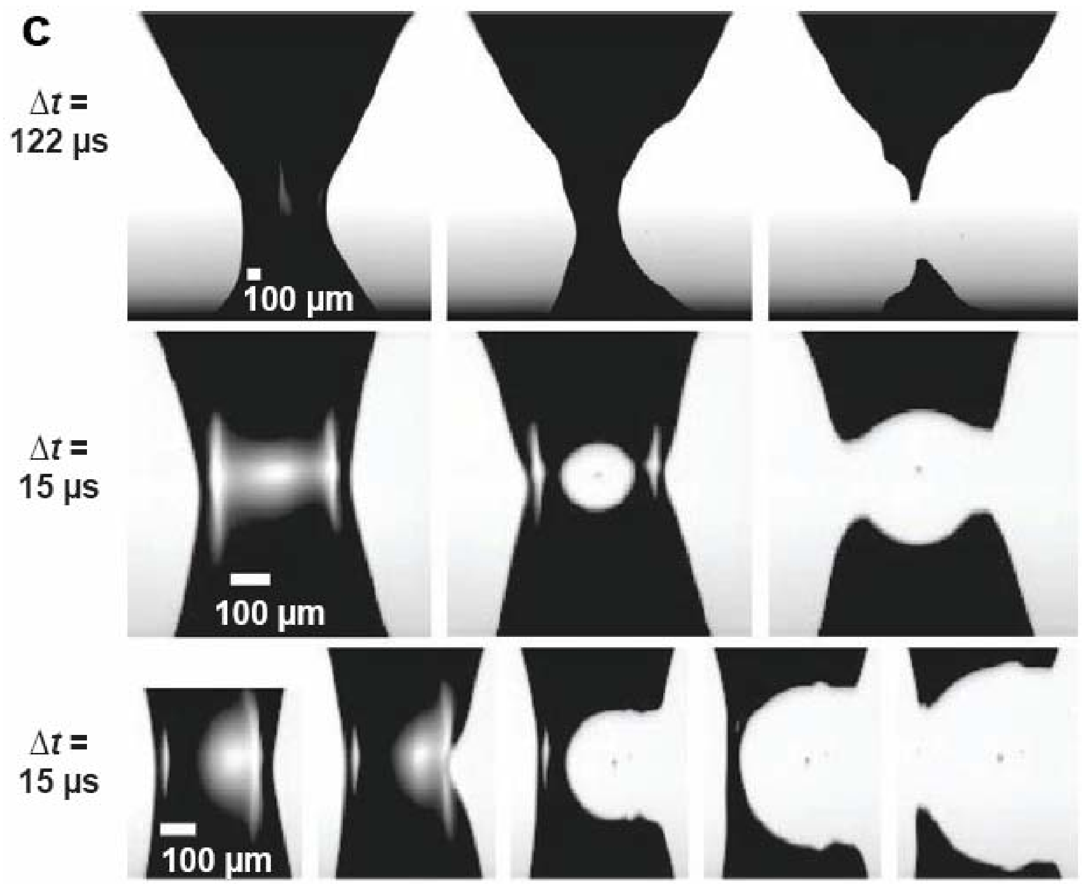
Water



Keim, Møller, Zhang & Nagel (2006)

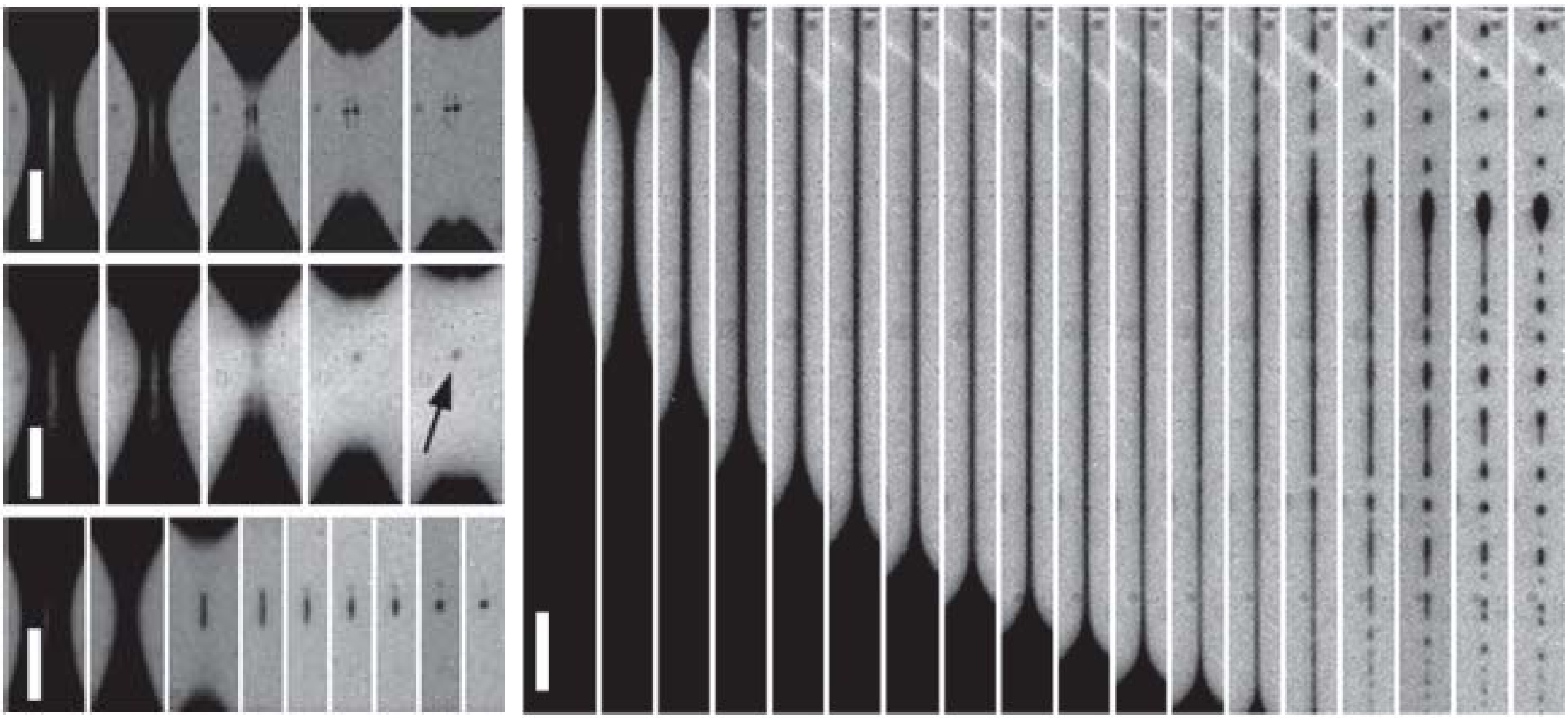
Air pinch-off

from an asymmetric nozzle



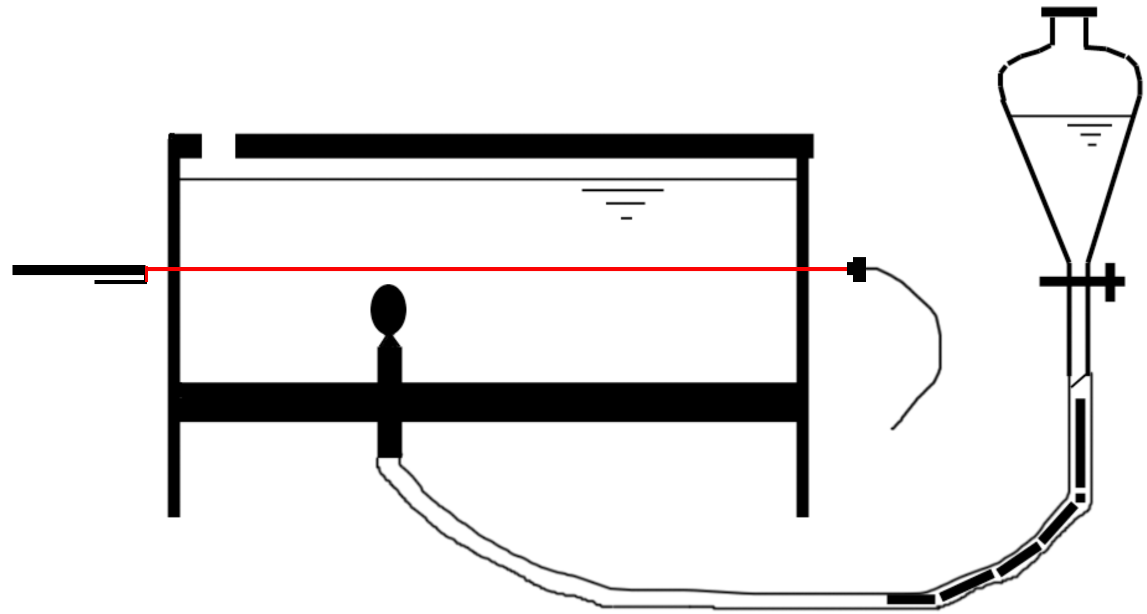
Intermediate viscosity

Time-resolved break-up of air thread

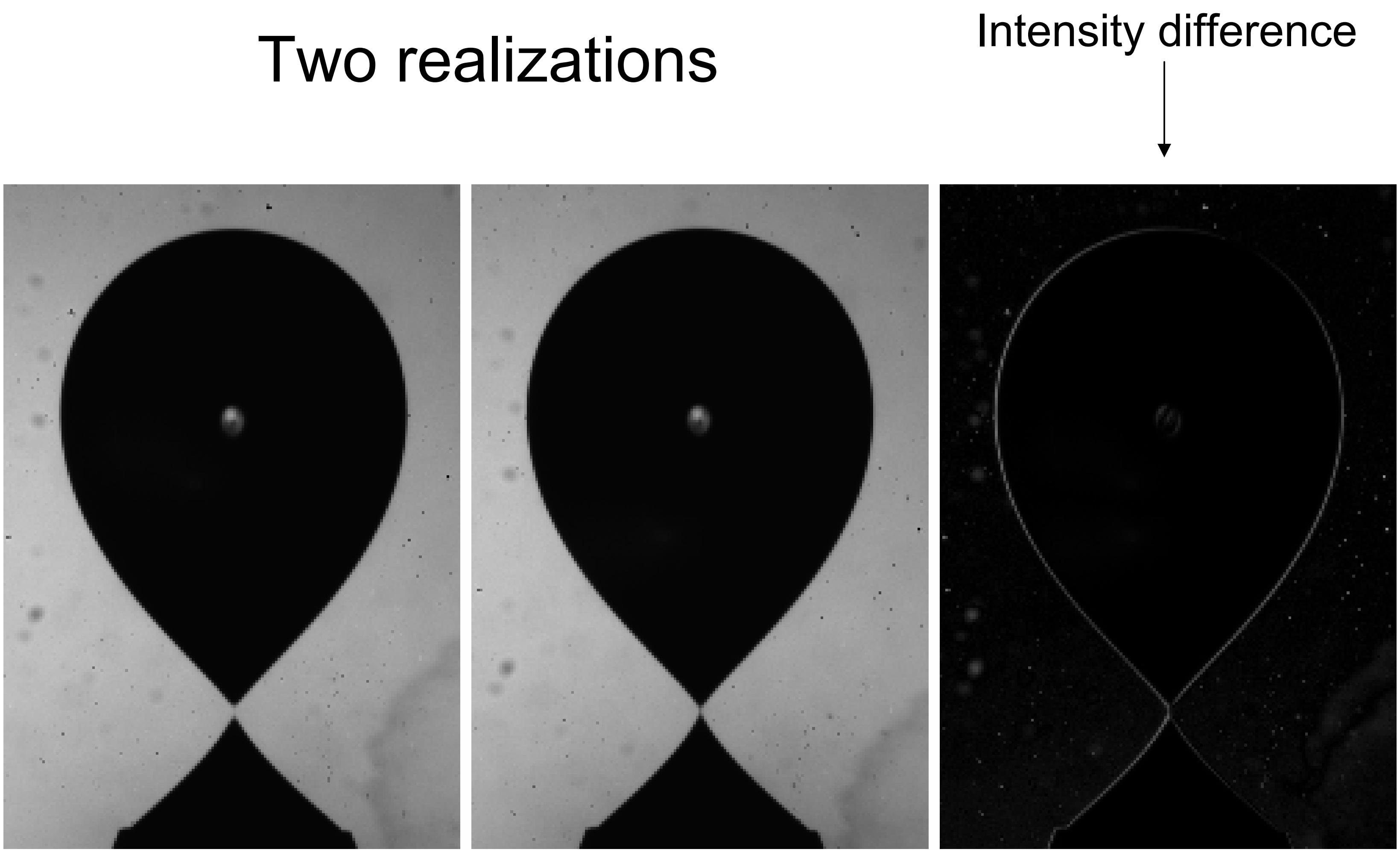


1 M fps

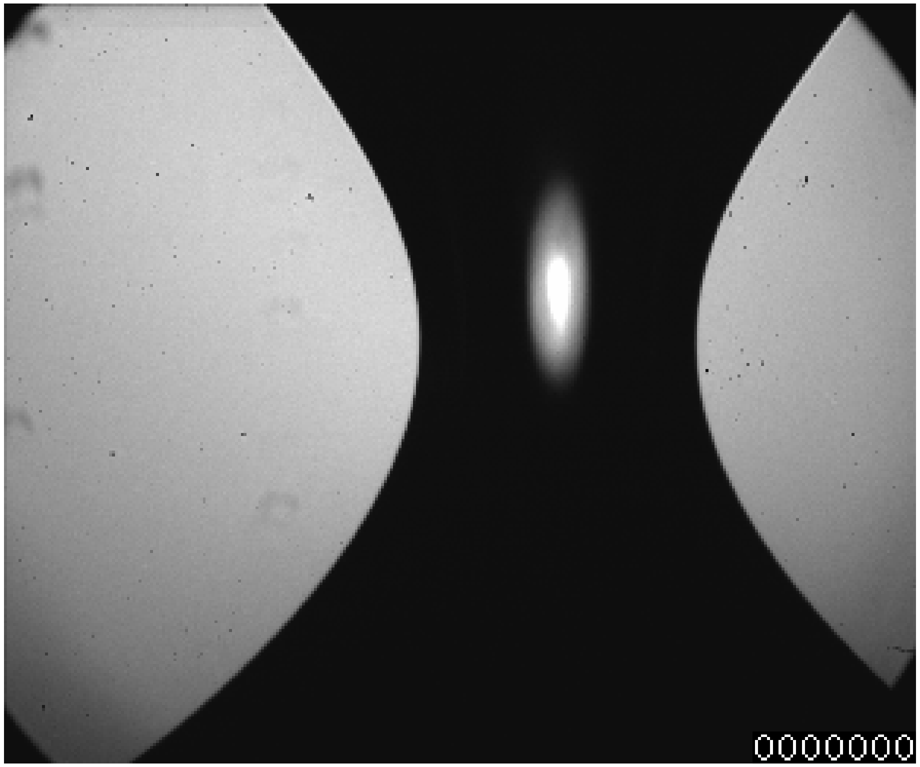
Experimental Setup

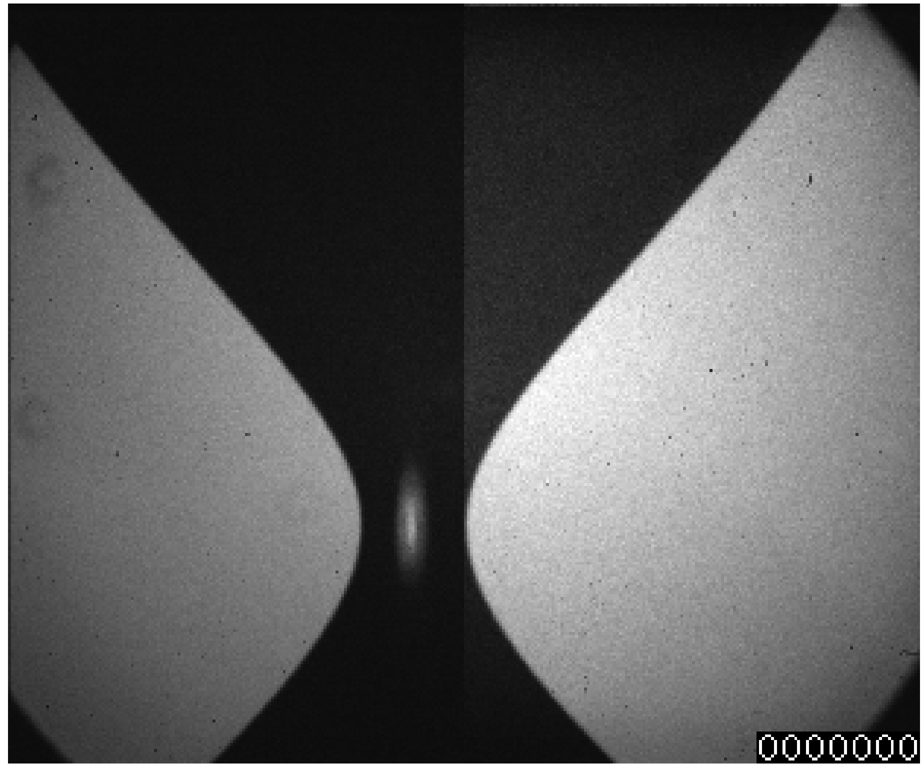


- Slowly growing bubbles, T ~ 10 s
- ‘Vertical’ tube
- Gravity feed through gate valve
- Highly repeatable


Two realizations
Intensity difference

Typical clips, air in water



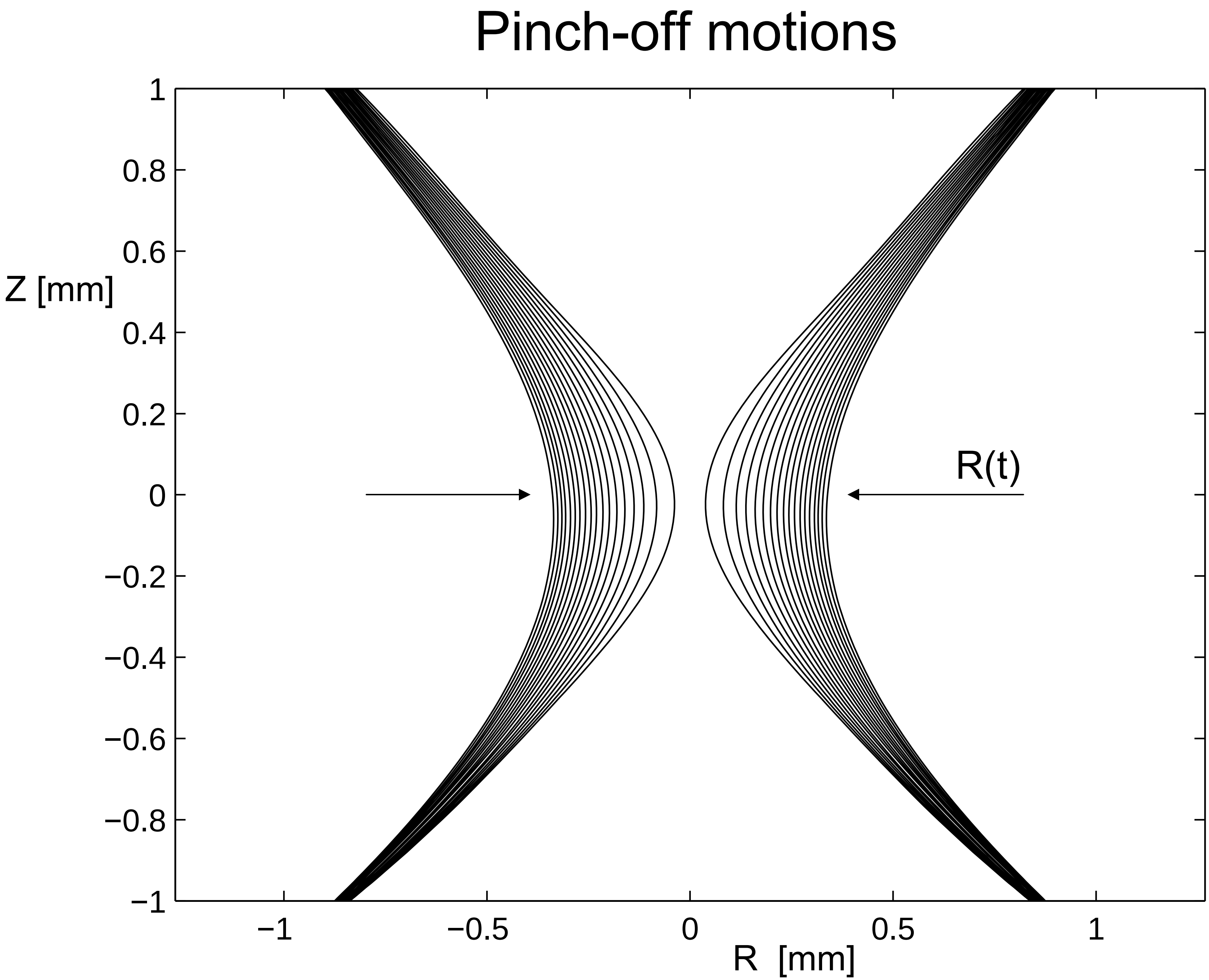


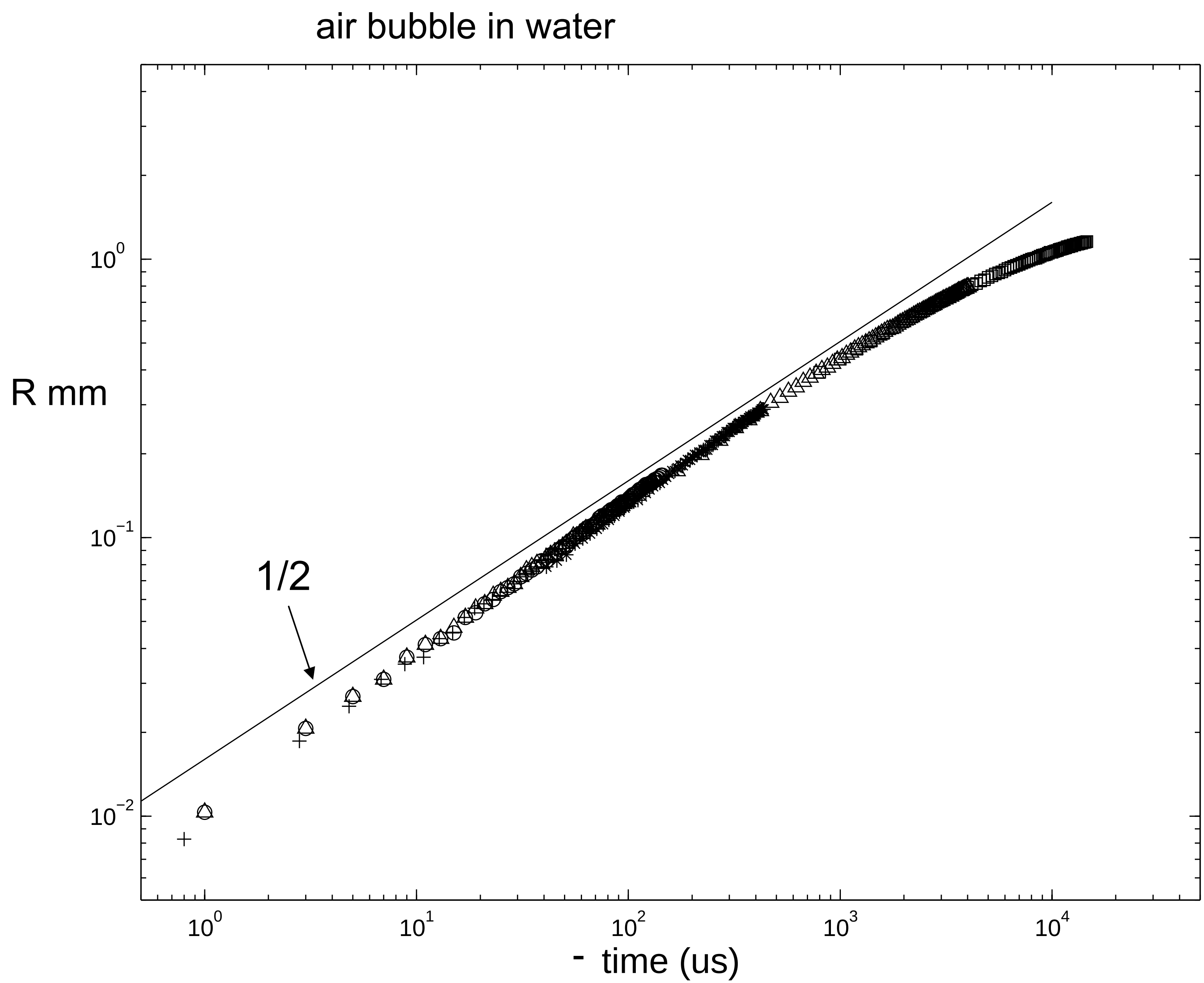
100 000 fps

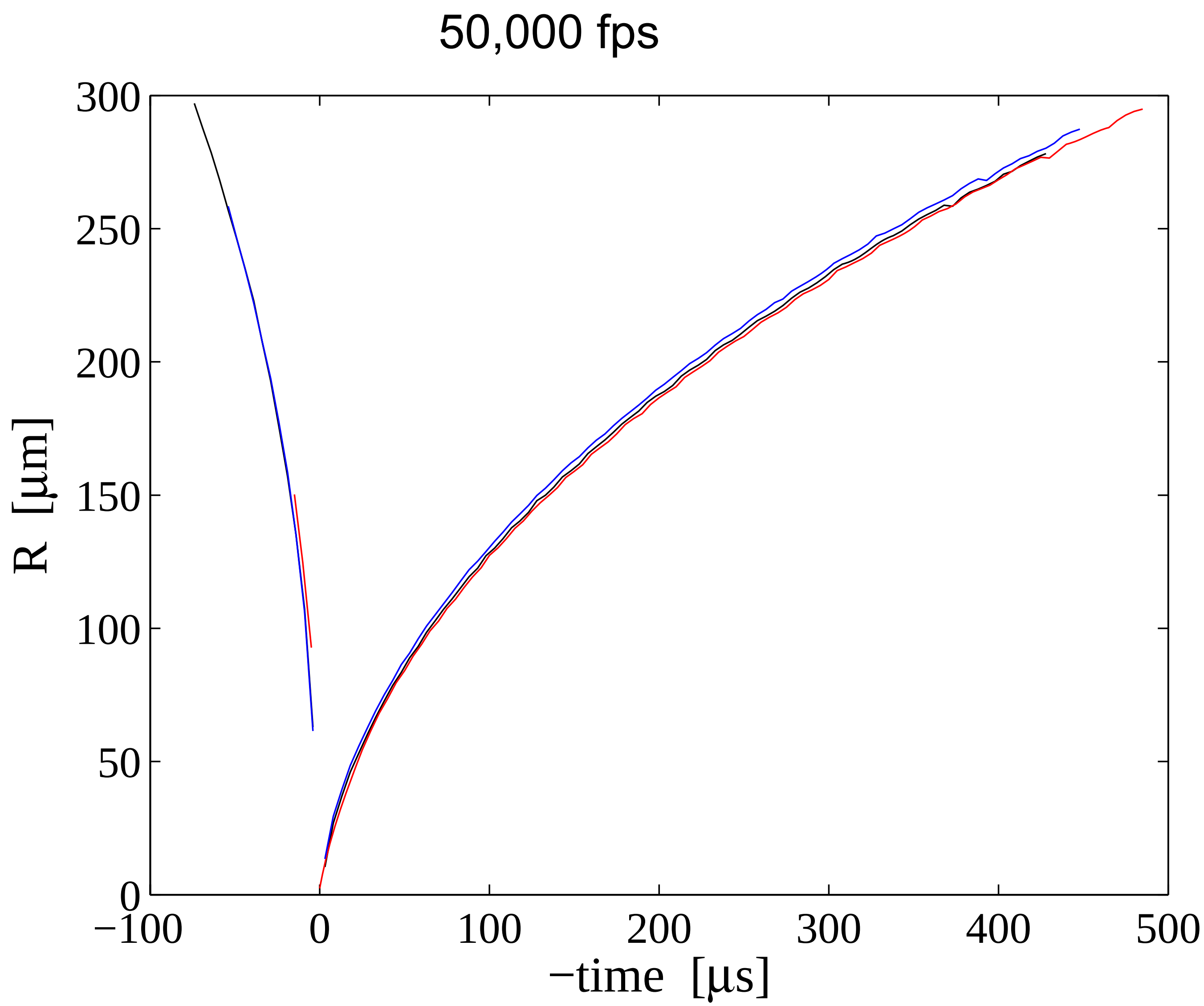
3-4 μm / px

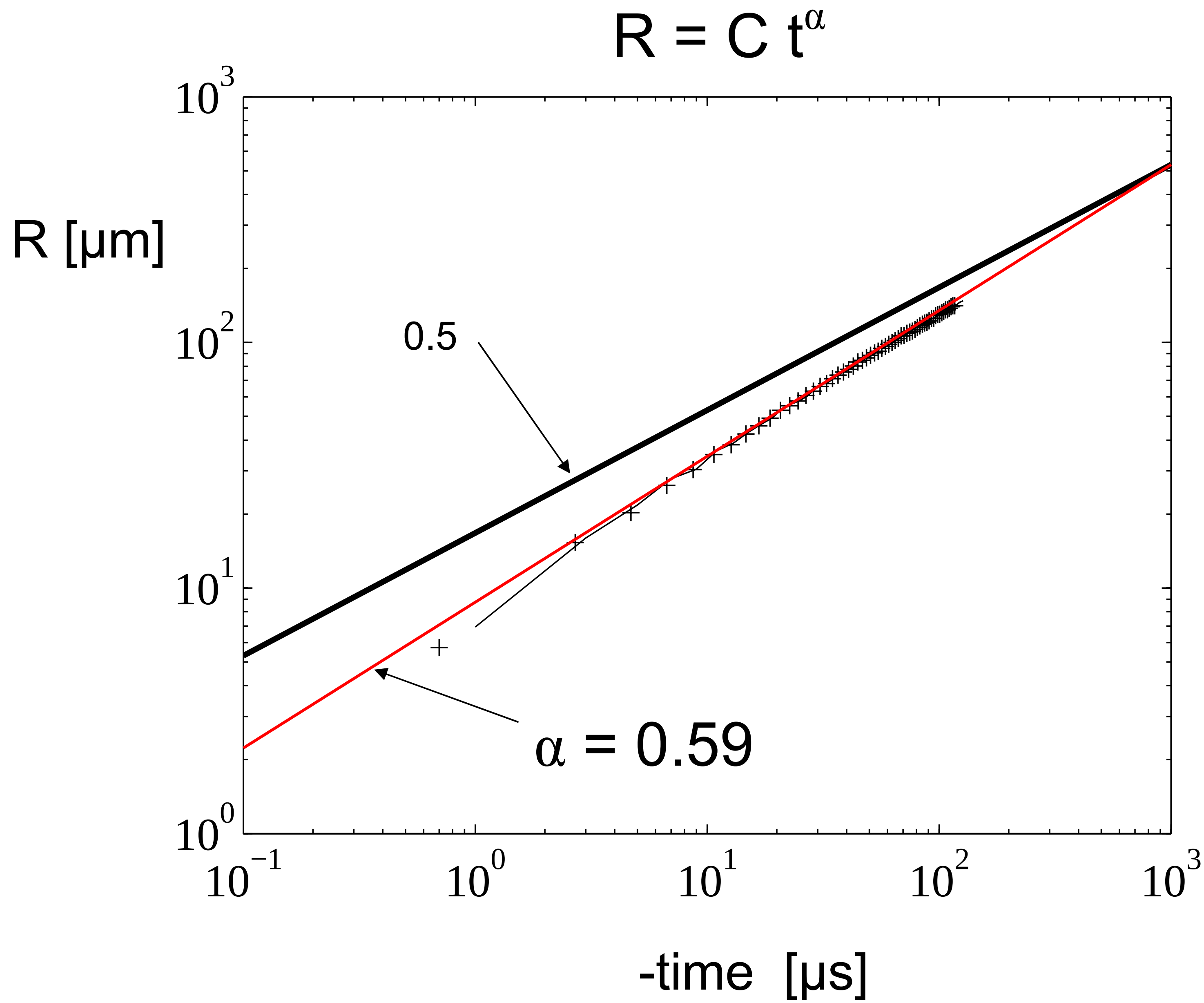
500 000 fps

8-10 μm / px


Pinch-off motions
Z [mm]
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1
−0.5
0
0.5
1
R [mm]
R(t)

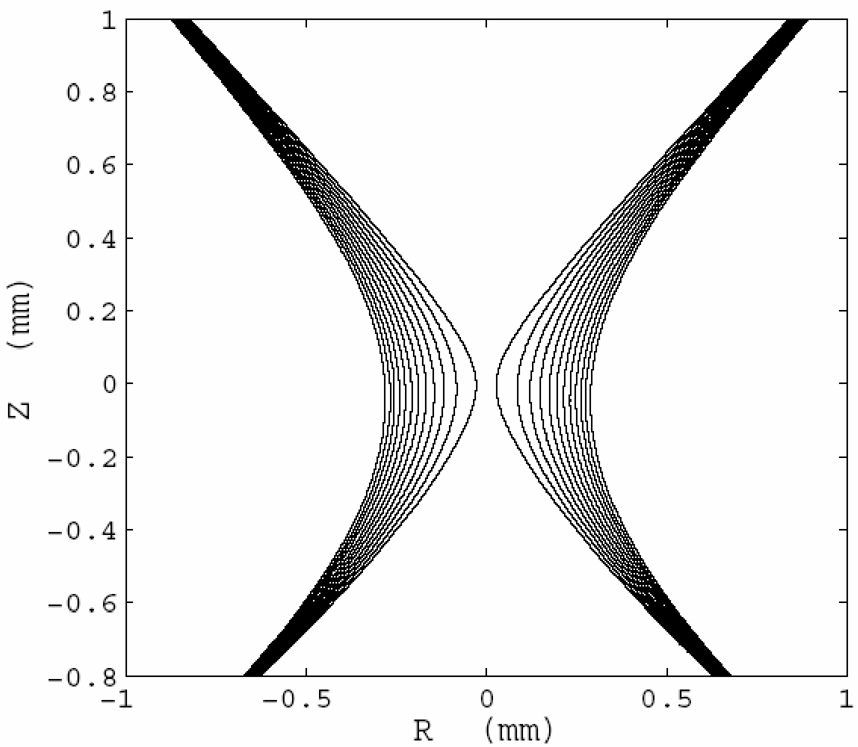

air bubble in water
R mm
10^{0}
10^{-1}
10^{-2}
1/2
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
- time (us)

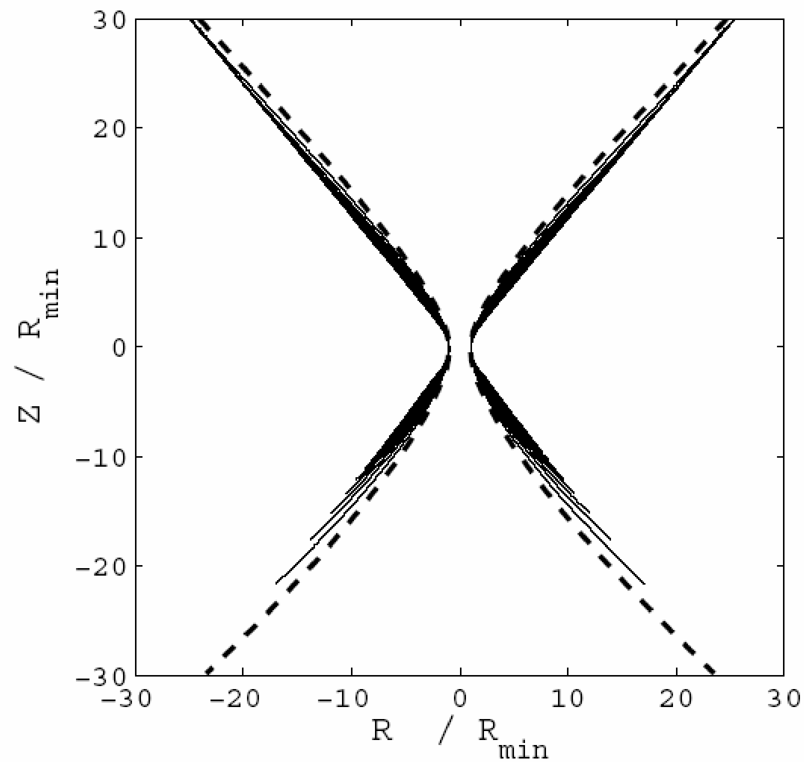

50,000 fps
R [μm]
300
250
200
150
100
50
0
−100
0
100
200
300
400
500
−time [μs]


R = C t^α
R [μm]
0.5
α = 0.59
10^3
10^2
10^1
10^0
10^−1
10^0
10^1
10^2
10^3
-time [μs]

Shapes not self-similar

Air bubble in water

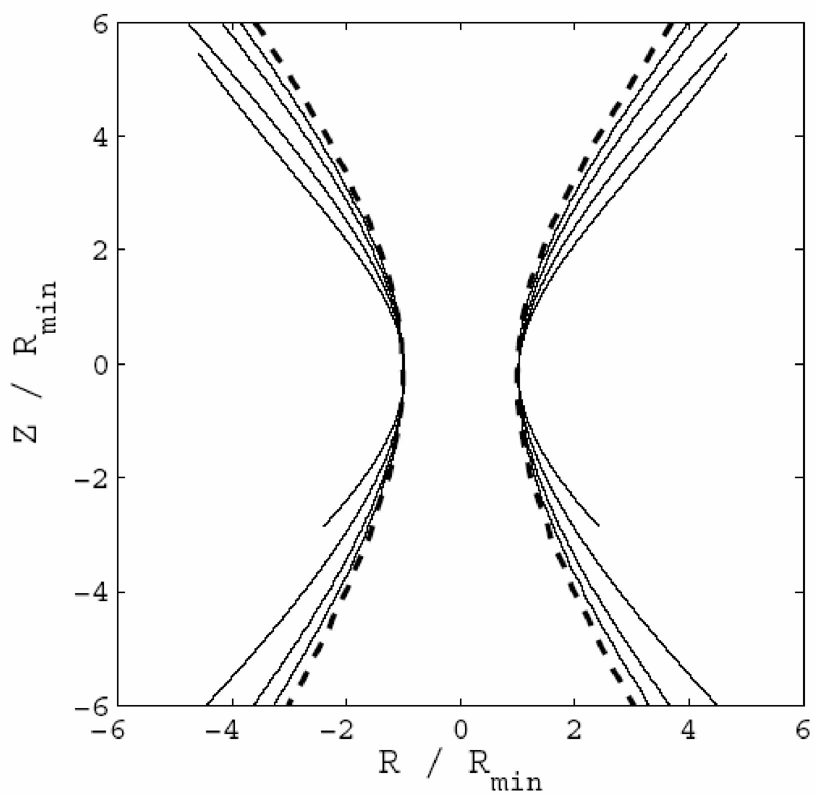


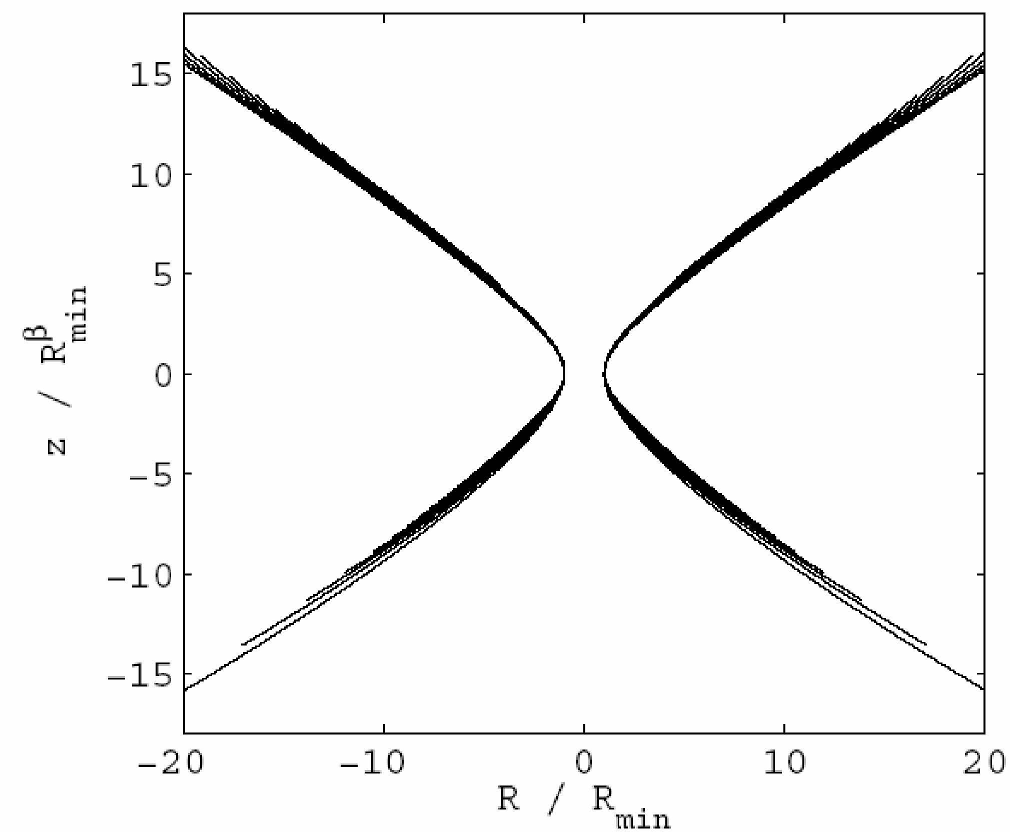


Need two length-scales,

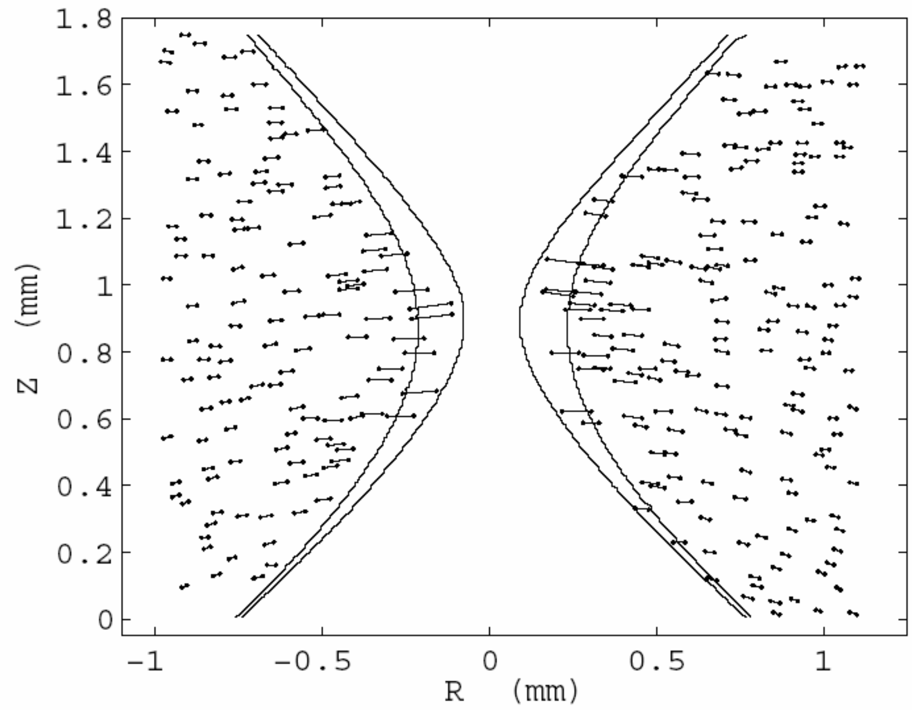
R and L_z

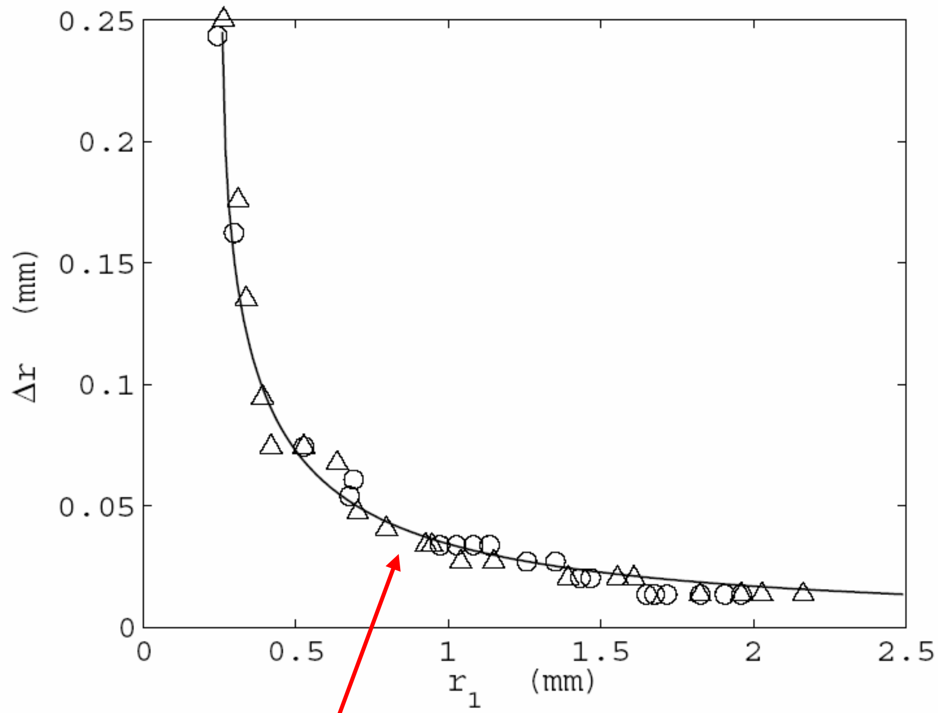
$$L_z \sim R_{min}^{\beta} \sim (t^{\alpha})^{\beta} \sim t^{\alpha\beta} \sim t^{\gamma}.$$





Particle paths inside liquid, follow potential theory



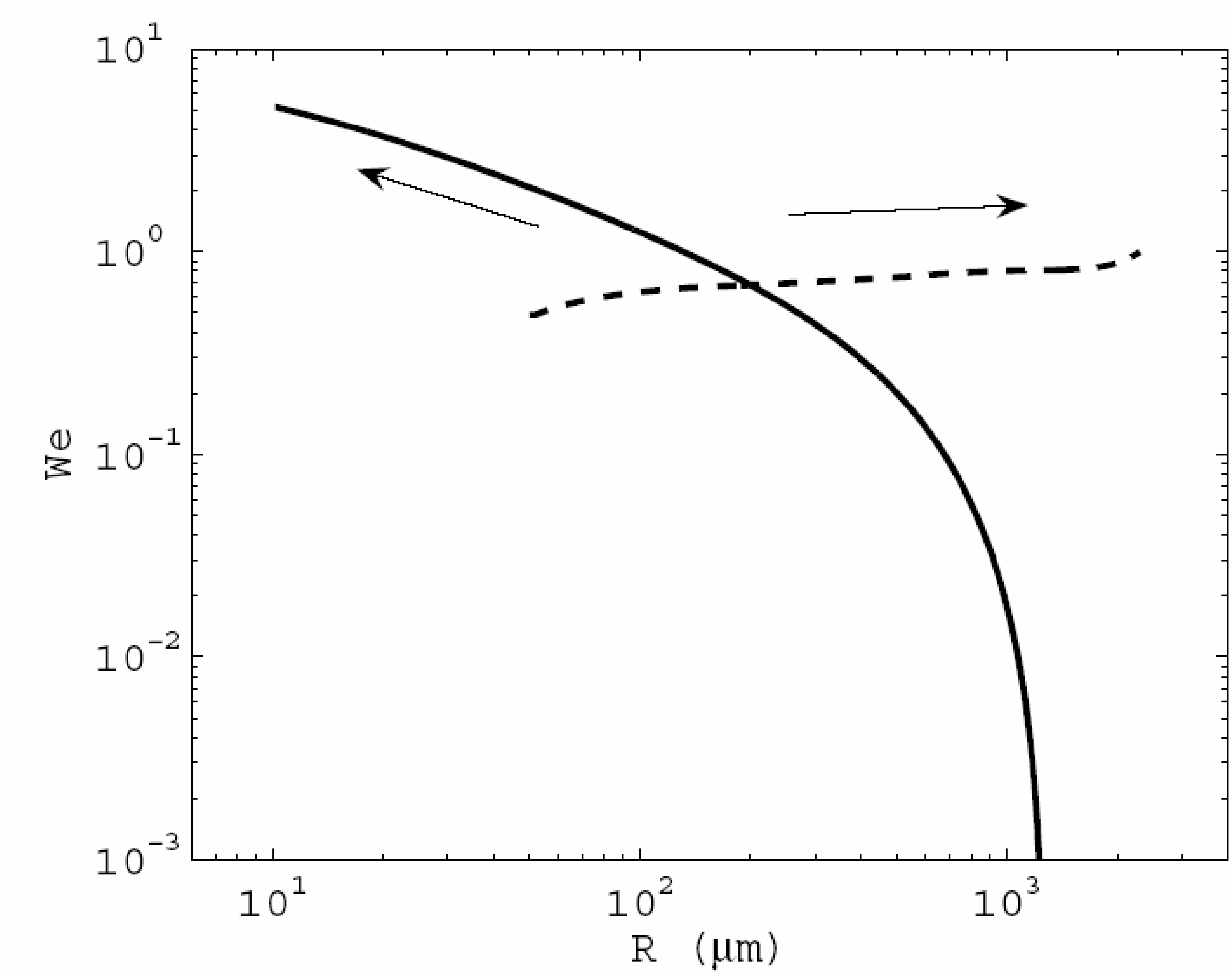


$$\frac{dr}{dt} = u(r) = -\frac{R\,R'}{r} \longrightarrow \frac{dr}{dt} = \frac{\alpha\, C^2\, t^{2\alpha-1}}{r} \longrightarrow r = \sqrt{C^2\, t^{2\alpha} + D}$$

$$R(t) = C(t_o - t)^{\alpha}$$

$$\Delta r(t, t_1, R_1, r_1) = r_1 - \sqrt{r_1^2 - R_1^2\,[\,1 - (t/t_1)^{2\alpha}\,]}.$$

Can surface tension be ignored?



Finite neck length at pinch-off ?