Controlling drop impact by polymer additives

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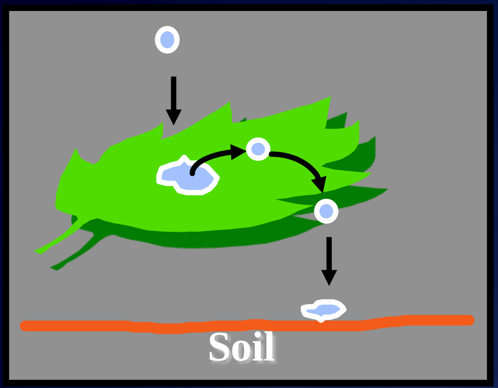
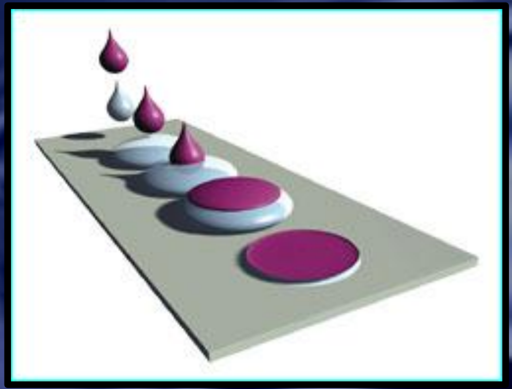
Why study droplet Impact?



Agrochemicals



Inkjet printing

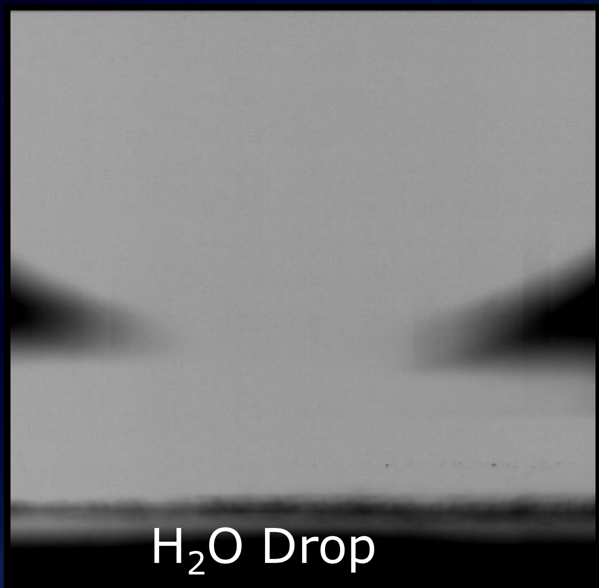
- Wetting /dewetting

- Controlling droplet deposition is important in a number of commercial applications:

    -Inkjet printing
    -Agrochemical industry
    -Spray cooling
    -Soldering of microelectronics

- Suppressing droplet rebound is advantageous

Dynamics of drop impact



- Droplets spread on impact forming a “lamella” (~5ms)
- On hydrophobic surfaces, retraction leads to drop rebound
- Addition of tiny amounts of a flexible homopolymer completely suppresses rebound

Impact / expansion:

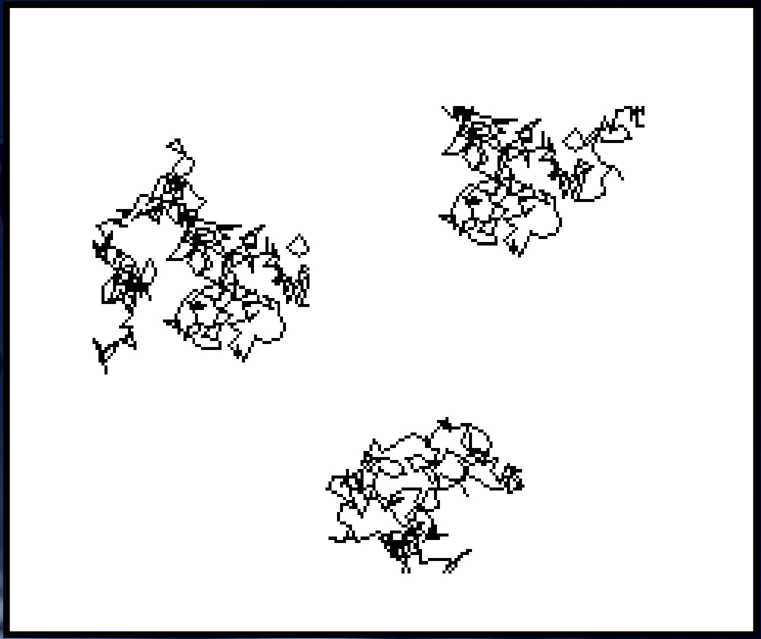
$$\text{Weber \#,}\quad We = \frac{\text{inertia}}{\text{capillarity}} = \frac{\rho V_i^2 D_o}{\sigma}$$

$$\text{Reynolds \#,}\quad Re = \frac{\text{inertia}}{\text{viscosity}} = \frac{\rho V_i D_o}{\eta}$$

Retraction:

$$\text{Capillary \#,}\ Ca = \frac{\text{viscosity}}{\text{capillarity}} = \frac{We}{Re} = \frac{V_{ret}\,\eta}{\sigma}$$

Flexible polymers



- In solution polymer molecules adopt random coil
- Dilute regime: polymer molecules do not overlap
- No significant differences in shear viscosity or surface tension

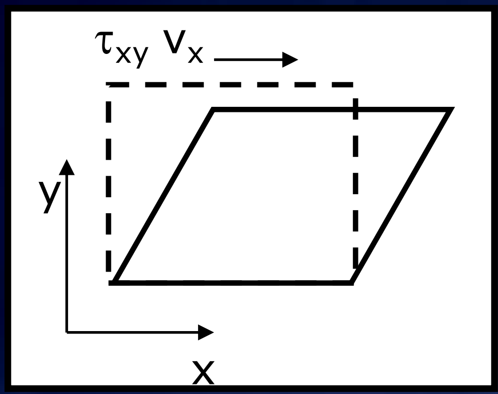
Typical concentration:
10-200 p.p.m. (0.001-0.02%)

H_2O → $\sigma \approx 72$ mN/m, $\eta \approx 1$ mPa s
PEO_{200ppm} → $\sigma \approx 70$ mN/m, $\eta \approx 1.23$ mPa s

→ **Same parameters, different behaviour!**

Elongational viscosity

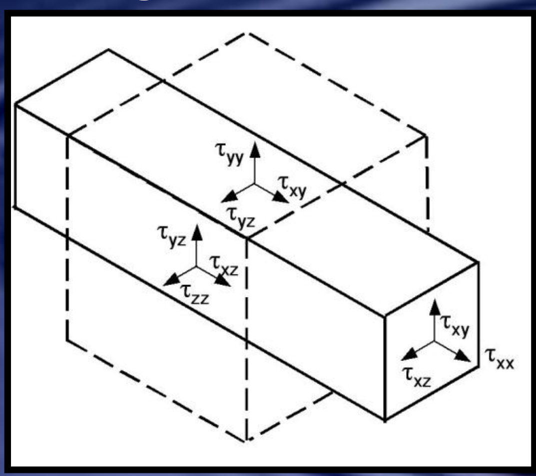
Shear flow:



Shear Viscosity

$$\eta = \frac{\tau_{xy}}{\dot{\gamma}_{xy}} \qquad \dot{\gamma}_{xy} = \frac{dv_x}{dy}$$

Elongational flow:



Elongational Viscosity

$$\eta_e = \frac{\tau_{xx}-\tau_{yy}}{\dot{\varepsilon}_{xx}} \qquad \dot{\varepsilon}_{xx} = \frac{dv_x}{dx}$$

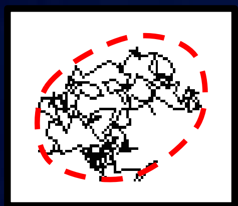
$\eta_e = T\eta$

(Trouton, 1906)

$T = 3$ (Newtonian)

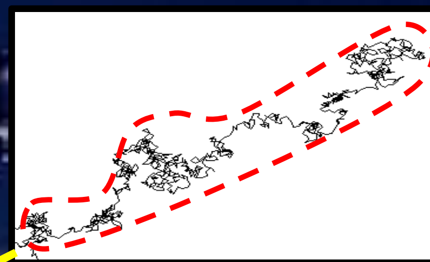
$T \approx 10^3$ (non-Newtonian)

Coil-stretch transition (De Gennes, 1974)



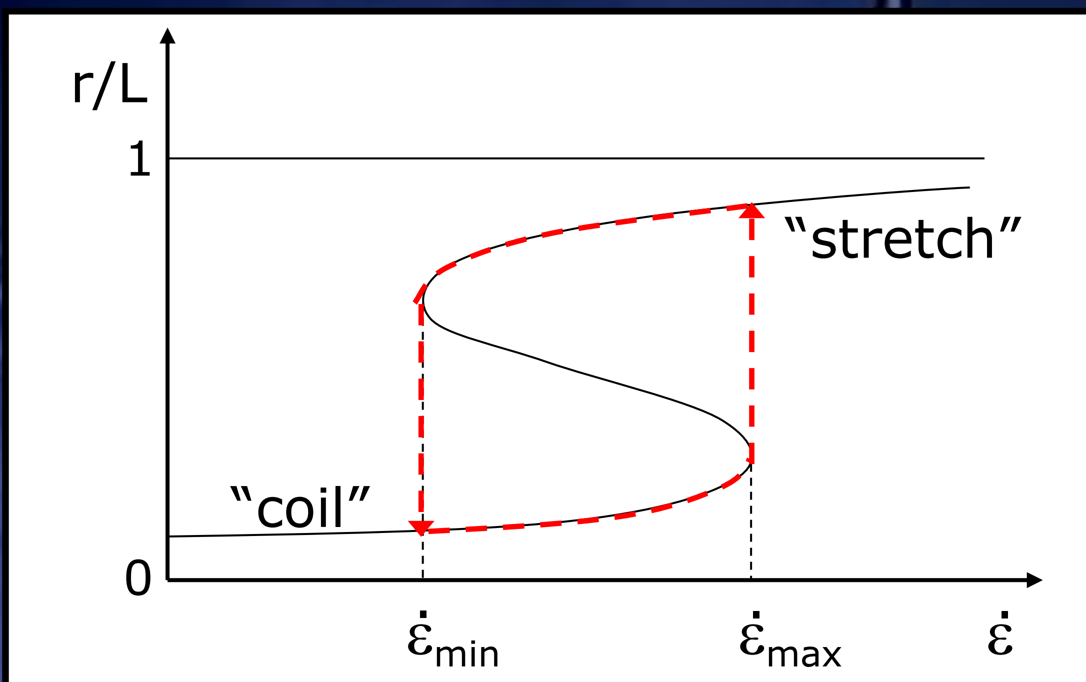
Hydrodynamic interaction with external monomers only

Coil



Hydrodynamic interaction with all monomers

Stretch

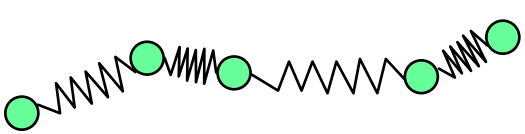


$$\dot{\varepsilon}_{max} \approx \frac{1}{\tau_{Zimm}} \approx \frac{k_B T}{\eta_s R^3}$$

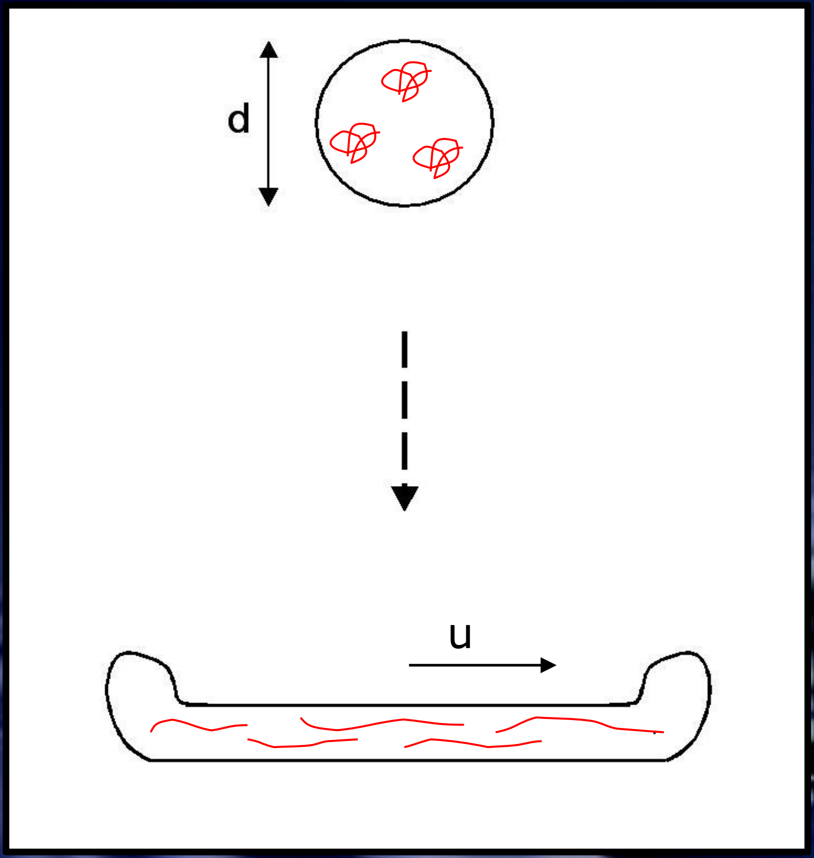
(hard sphere)

$$\dot{\varepsilon}_{min} \approx \frac{1}{\tau_{Rouse}} \approx \frac{k_B T}{\xi R^2}$$

(spring-bead)



Anti-rebound phenomenon



Proposed mechanism:

•Inertia causes drop to spread

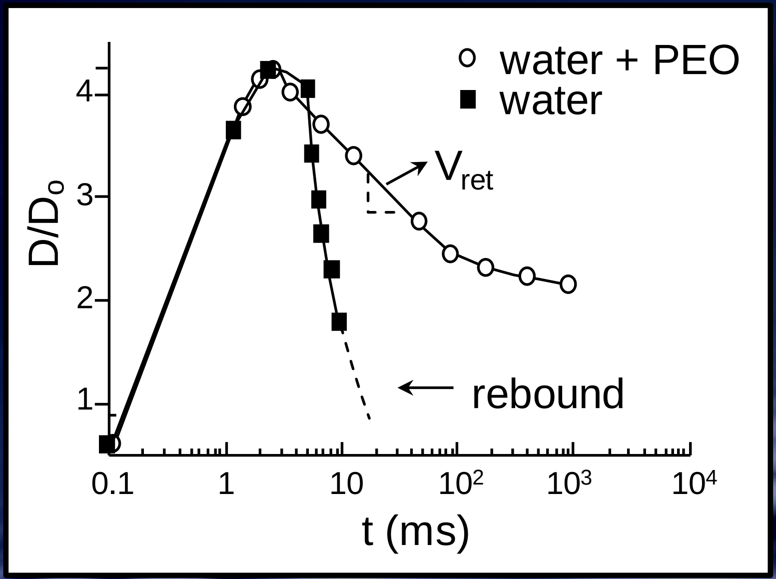
•Polymers stretch in the fluid's velocity gradient

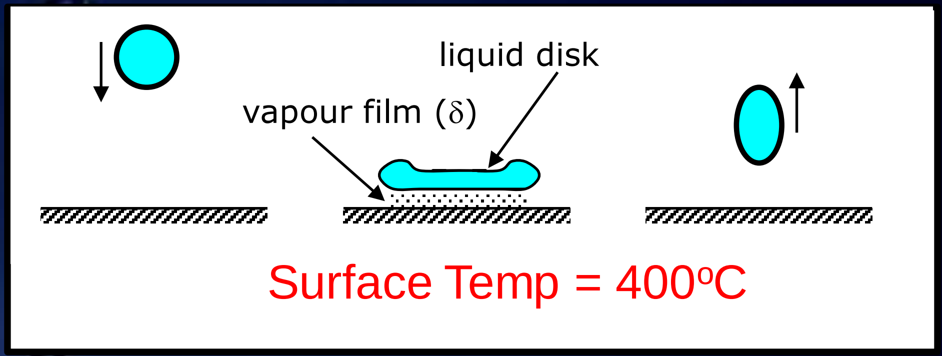
•Leads to increased extensional Viscosity

•Sufficient energy dissipated to prevent rebound

Dissipation of mechanical energy during expansion and retraction
(Bergeron, 2003)

Problems with proposed mechanism





- The polymer does NOT change the maximum spreading diameter

- Only retraction of drop is affected

Interfacial effects are important

Is elongational viscosity responsible for the anti-rebound phenomenon?

Particle Imaging Velocimetry

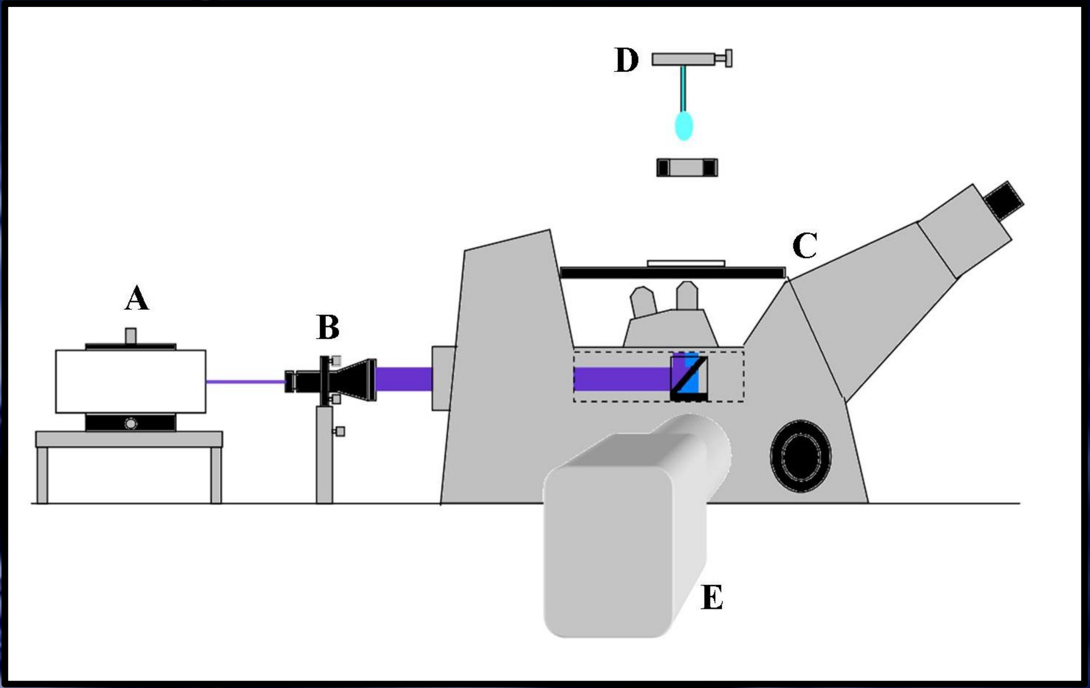
Map fluid velocity profile in the impacting drop

- Fluid contains 2μm fluorescent particles (<0.001wt%)

- Drop illuminated with pulsed UV laser (A), frequency ~8kHz

- High speed camera (E) with image intensifier views flow inside drop through a x40 microscope objective (2000fps)

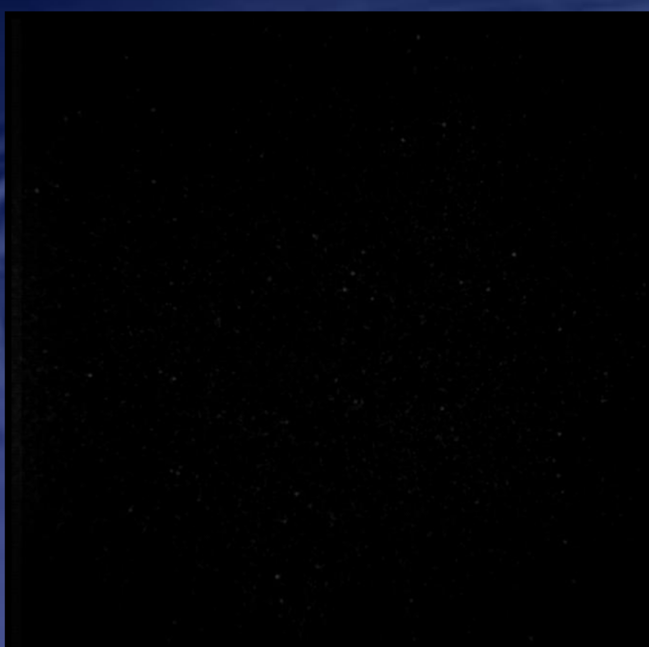
- Movies captured at different radial positions in the spreading drop

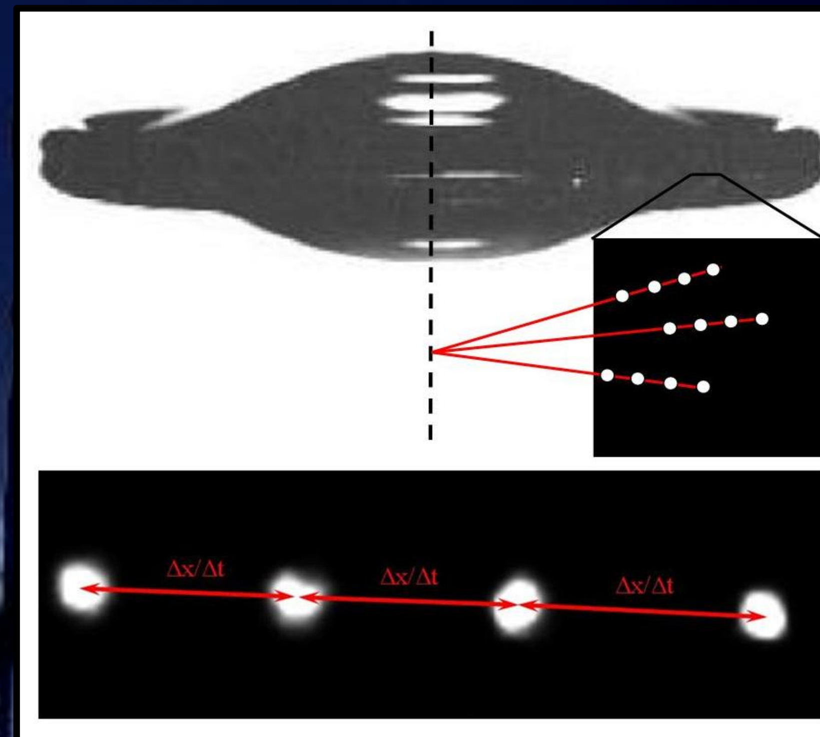


Smith, M.I. Bertola, V., Expts Fluids, (2010)
"Particle Velocimetry inside Newtonian and non-Newtonian droplets impacting a hydrophobic surface"

Measuring fluid velocity with fluorescent colloids

- Particles travel radially during spreading
- Each colloid exposed 4x in each frame





Intersection of particle paths enables radial distance to be measured.

$$\text{Fluid Velocity} = \Delta x.\ f_{Laser}$$

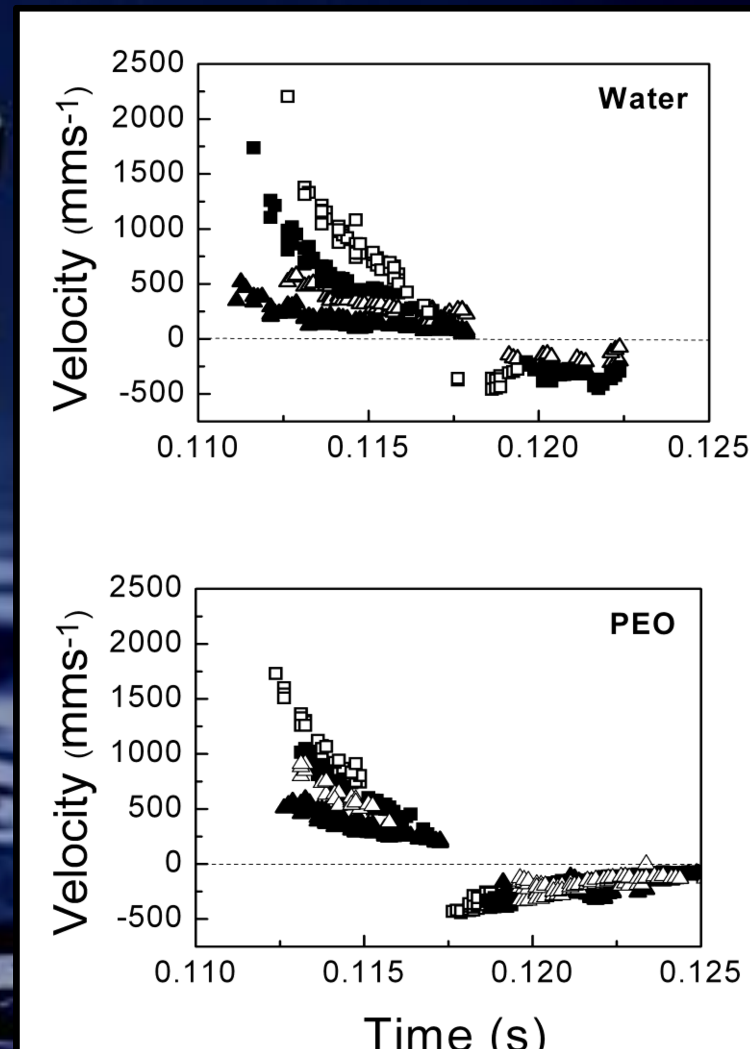
Particle Image Velocimetry

Fluid velocity as a function of time
at different radial positions

Drop spreads faster at the edge

Spreading slows as interfacial energy increases

Estimate initial retraction velocity of the fluid in the drop at different radial positions



Smith, M.I., Bertola, V., Phys Rev Letts, 104 (2010) 154502
"Effect of Polymer Additives on the Wetting of Impacting Drops"

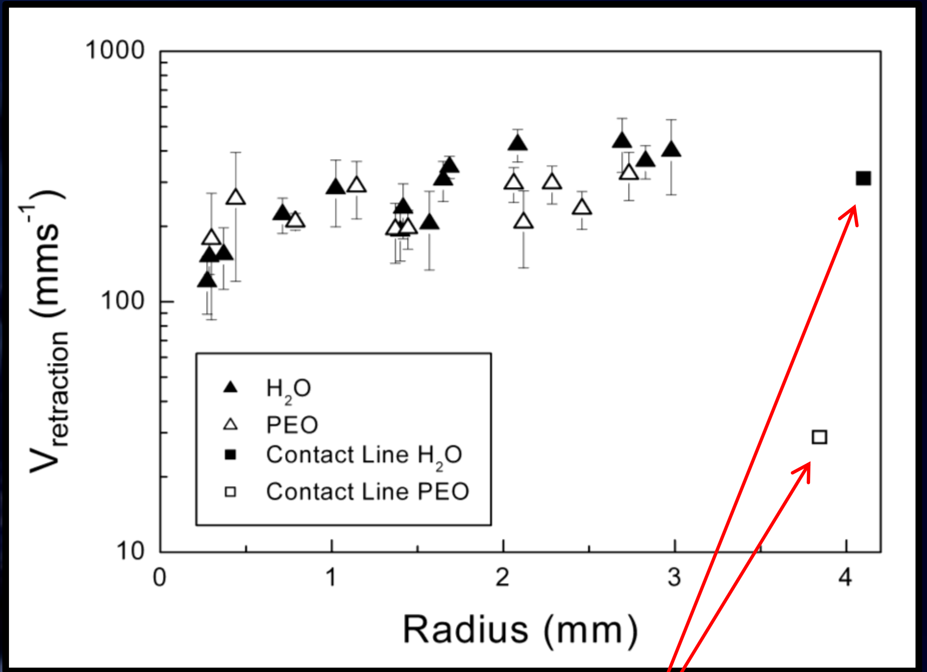
Retraction Velocity

•Retraction velocities are similar in the bulk of the drop

-Retraction Velocity is controlled by surface tension and viscosity

→Both drops have similar elongational viscosity

→Elongational viscosity is *<u>not</u>* responsible for anti-rebound effect



Comparison with drop edge suggests anti-rebound phenomenon is a contact line effect

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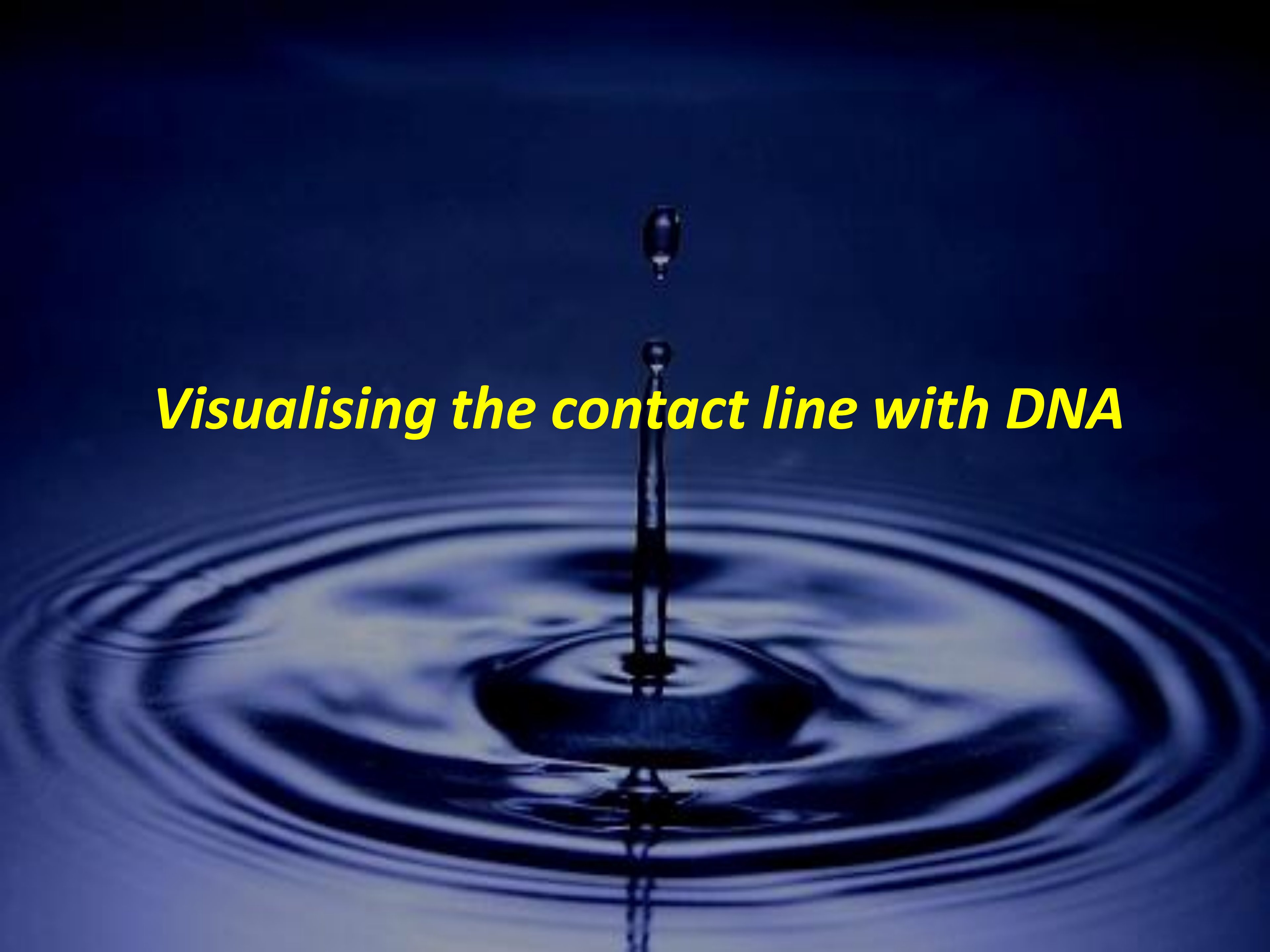
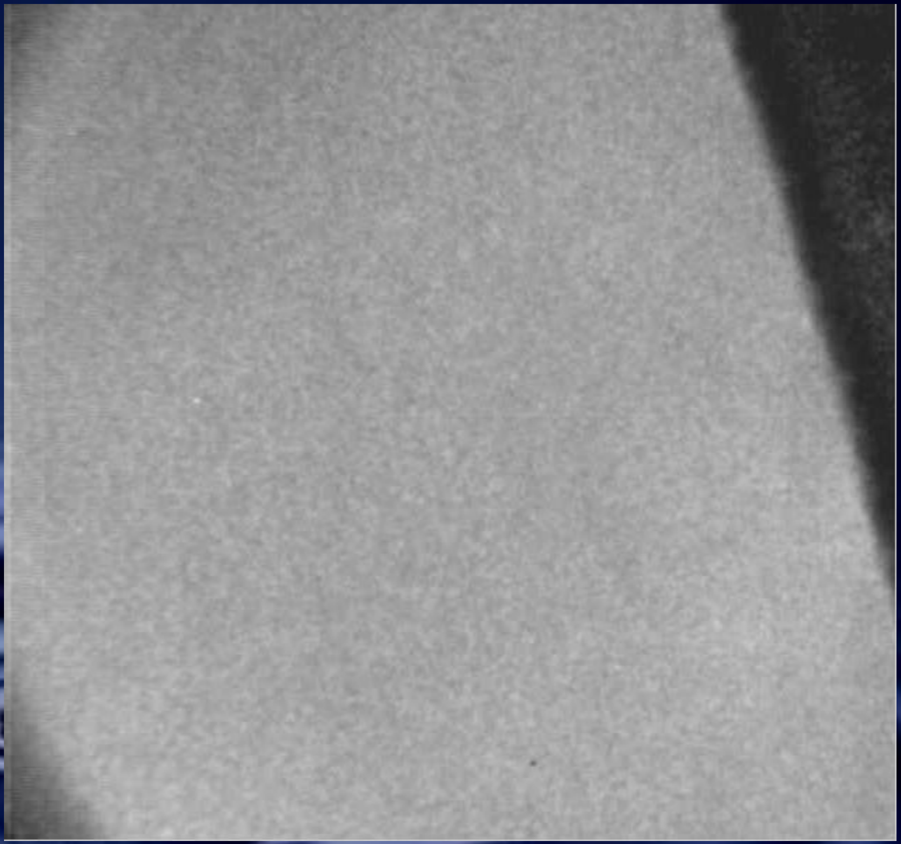
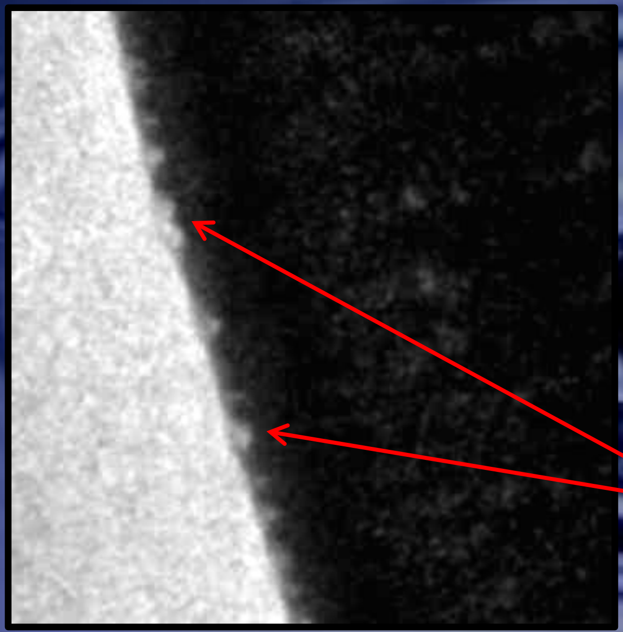
Visualising the contact line with DNA



Direct Visualisation of contact line with DNA

- Prepare 200ppm PEO solution
- Add 0.2ppm fluorescently stained λ-DNA
- Using a continuous wave laser and 20mm drop height



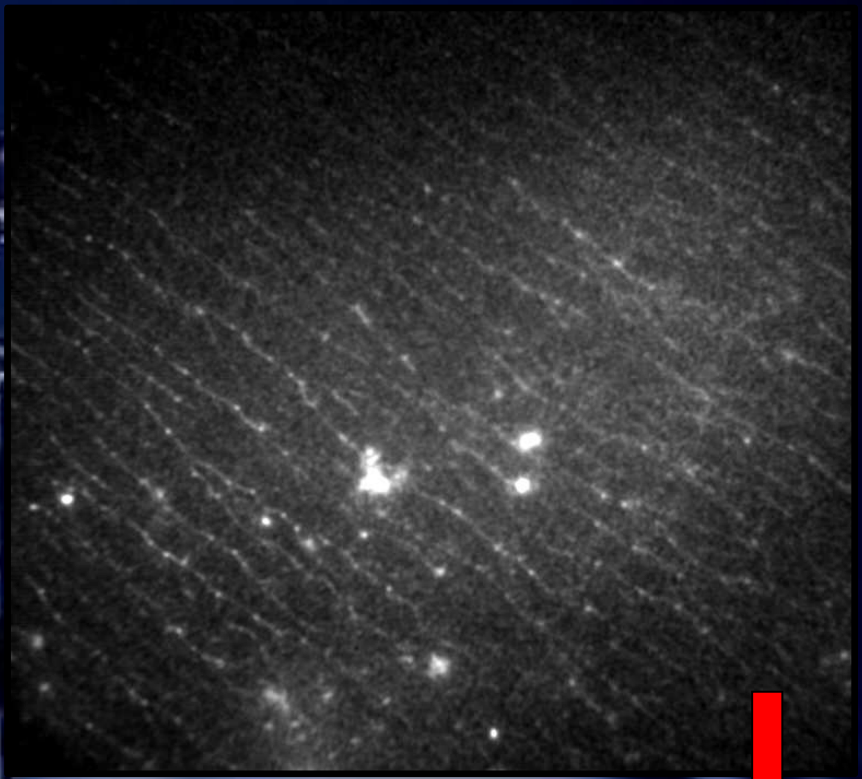


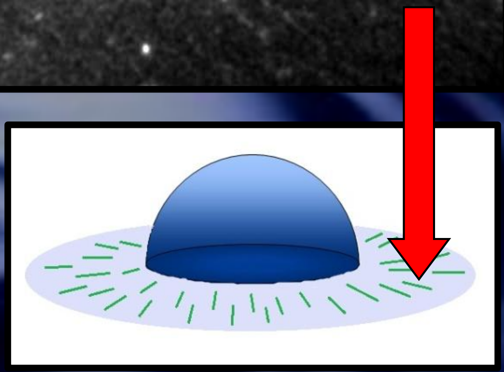
DNA stretching at contact line as drop edge recedes

"Molecular Combing"

•Retracting drop leaves molecules stretched out on substrate

•Molecules are aligned radially, lying end to end





What causes the anti-rebound effect?

→Molecules Interact with the substrate, dissipating energy at the contact line

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Conclusions

- Extensional viscosity cannot be responsible for suppressing droplet rebound
- Anti-rebound phenomenon is a contact line effect
- Stretching of polymers at the contact line by the receding drop edge prevents rebound

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•Smith, M.I., Bertola, V., Phys Rev Letts, 104 (2010) 154502
"Effect of Polymer Additives on the Wetting of Impacting Drops"
•Smith, M.I. Bertola, V., Expts Fluids, 50 (2010) 1385
"Particle Velocimetry inside Newtonian and non-Newtonian droplets impacting a hydrophobic surface"