Stretching colloidal suspensions: from flow to fracture

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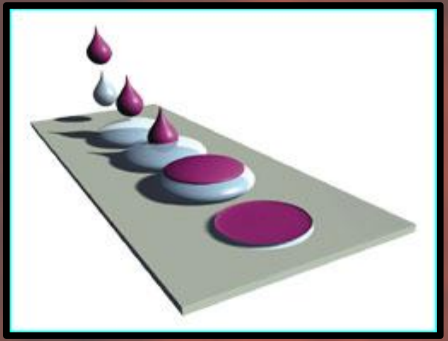
Concentrated colloidal suspensions

Concentrated suspensions of particles (CS) are common every day fluids

CS can exhibit pronounced increases in viscosity with strain rate (shear thickening)

Under certain conditions fluids may even jam solid



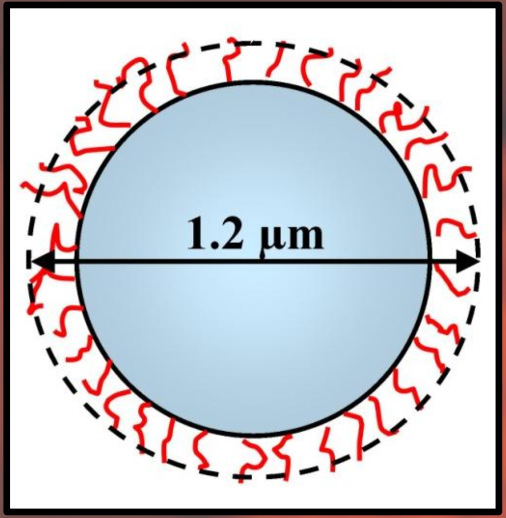
Model Hard Sphere Colloids

Hard spheres are commonly used as a model system.

This simplifies the interactions present:

- *Geometry rather than energetics*
- *Hydrodynamic interactions*

Insights gained from hard spheres, provide insight into more complicated systems (e.g emulsions)



<u>Our Colloids</u>

Poly-methyl methacrylate particles (D ~ 1.2 μm)

Sterically stabilised with 10nm
Poly-12- hydroxystearic acid chains

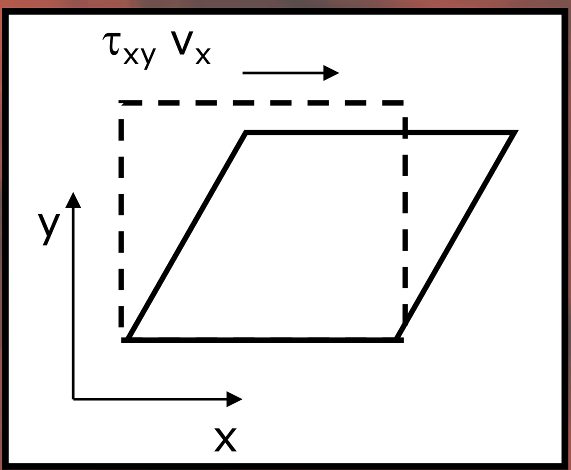
Shear and extensional flows

Concentrated suspensions are generally studied in shear flows

Very little research has examined extensional geometries.

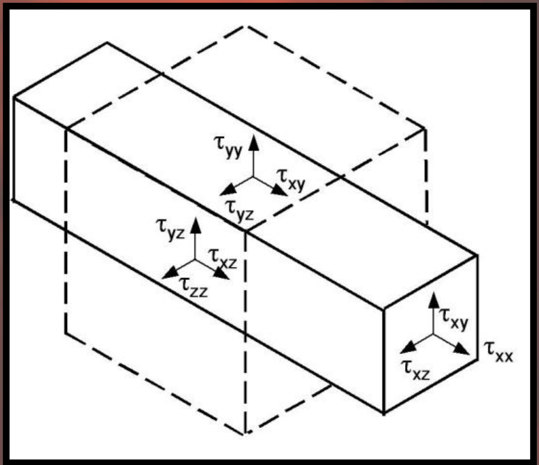
However, many practical flows are extensional or mixed.
e.g nozzle flows

Shear flow:



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

Extensional flow:



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

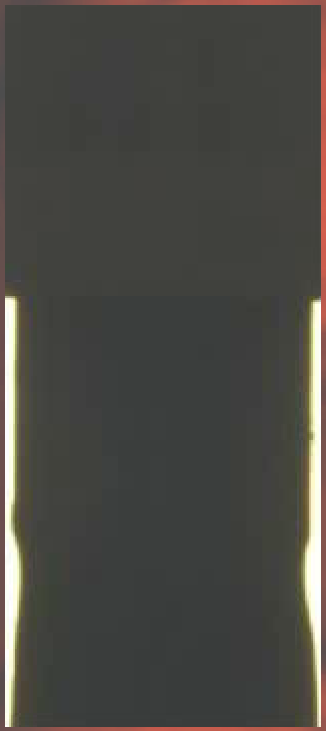
Extensional Rheometer

Sample placed between two cylindrical plates (example using Glycerol)

Top plate is moved upwards at a constant velocity

The dynamics of the liquid are imaged using a high speed camera

Strain-rate dependent behaviour of Concentrated Suspensions of Colloids (φ~0.603)

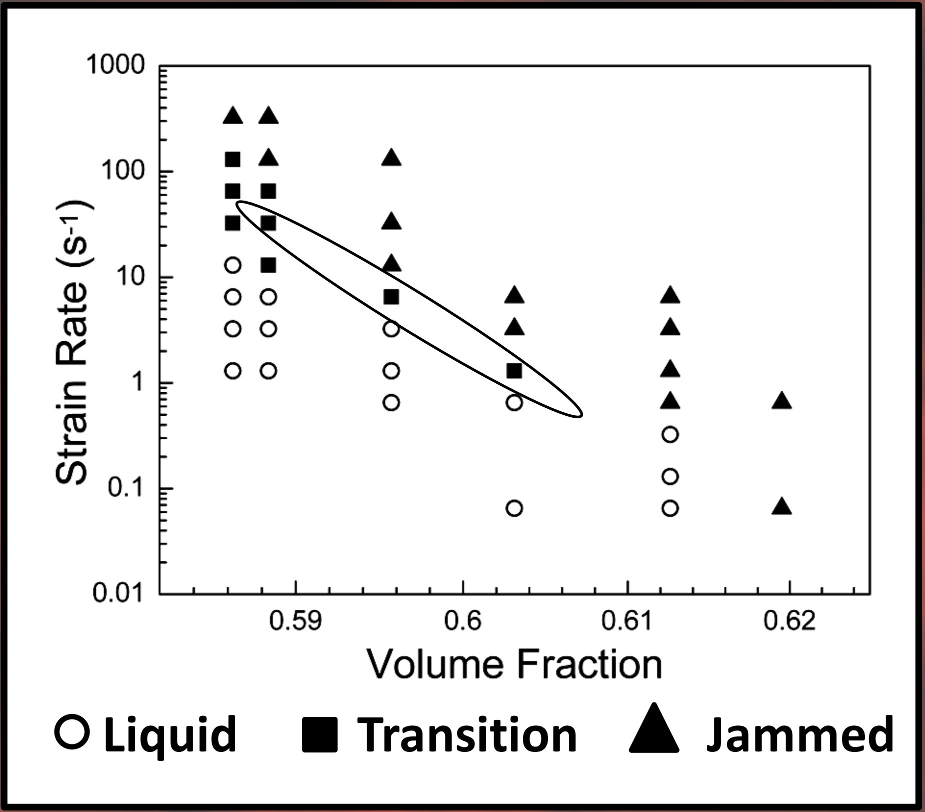


Liquid
(ε = 0.65 s^{-1})

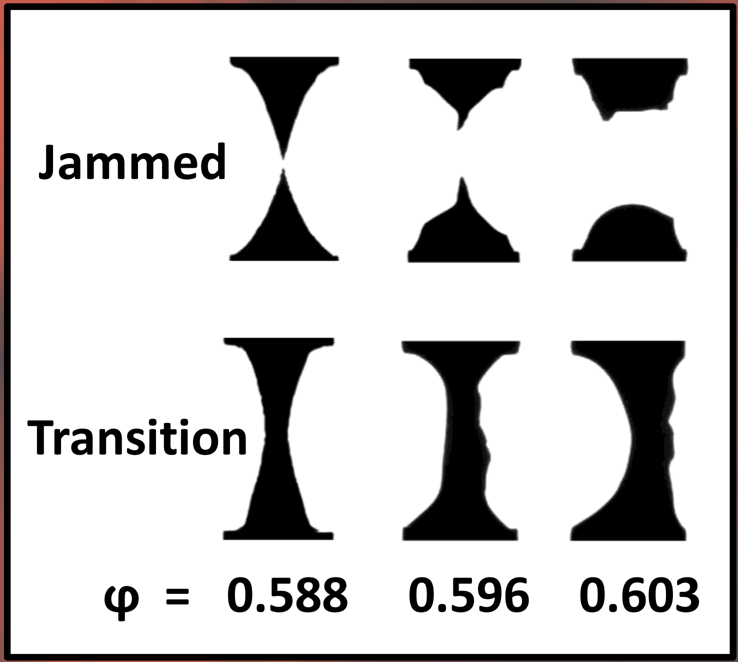
Transition
(ε = 1.3 s^{-1})

Jammed
(ε = 3.25 s^{-1})

Volume Fraction Dependence



A 2% change in volume fraction alters critical strain rate by ~2 orders of magnitude



With increasing volume fraction we see increasing asymmetry and larger granules

Understanding the jamming mechanism

Relationship to Shear Rheology

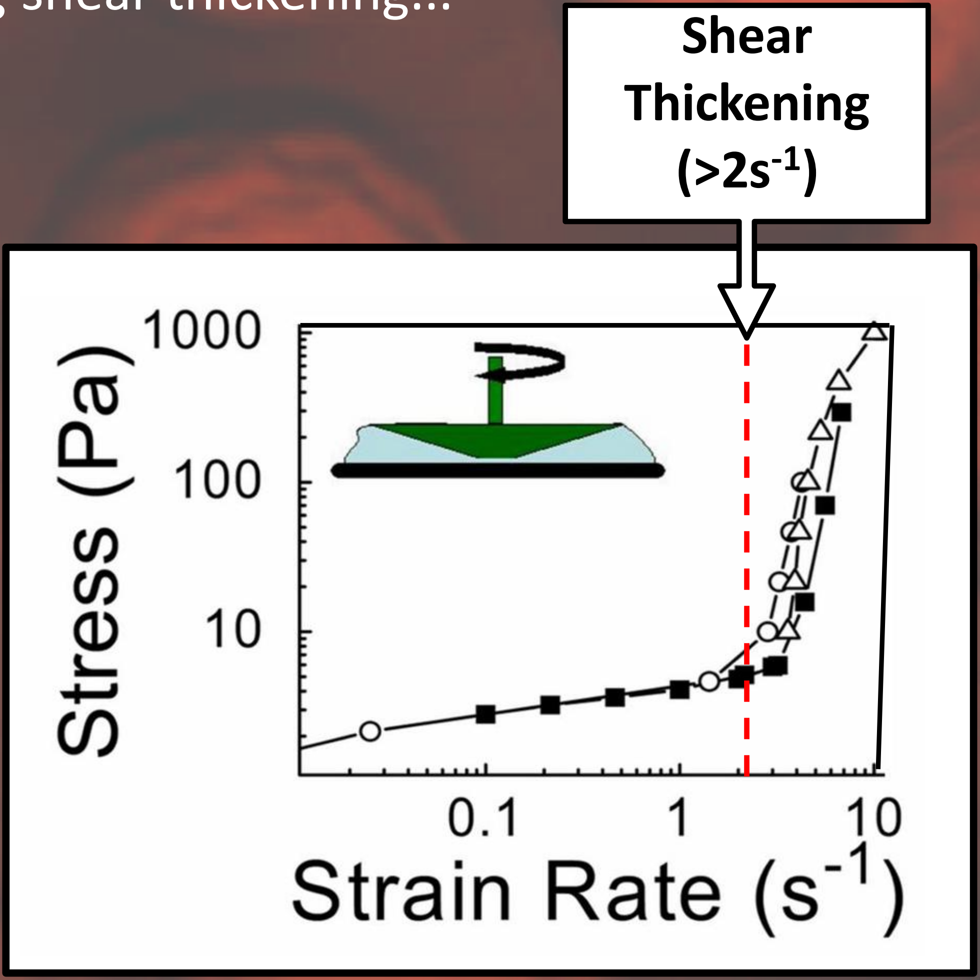
For φ ~ 0.603 we observe strong shear thickening...

...but **not** jamming

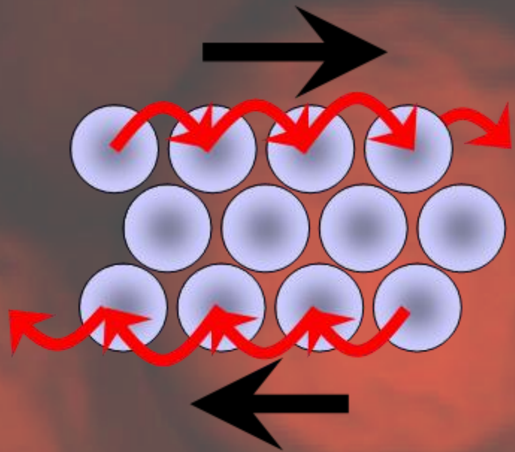
Timescale for the onset of shear thickening closely matches the 'transition'

In extension the plate separation initially results in a mixed flow of shear and extension

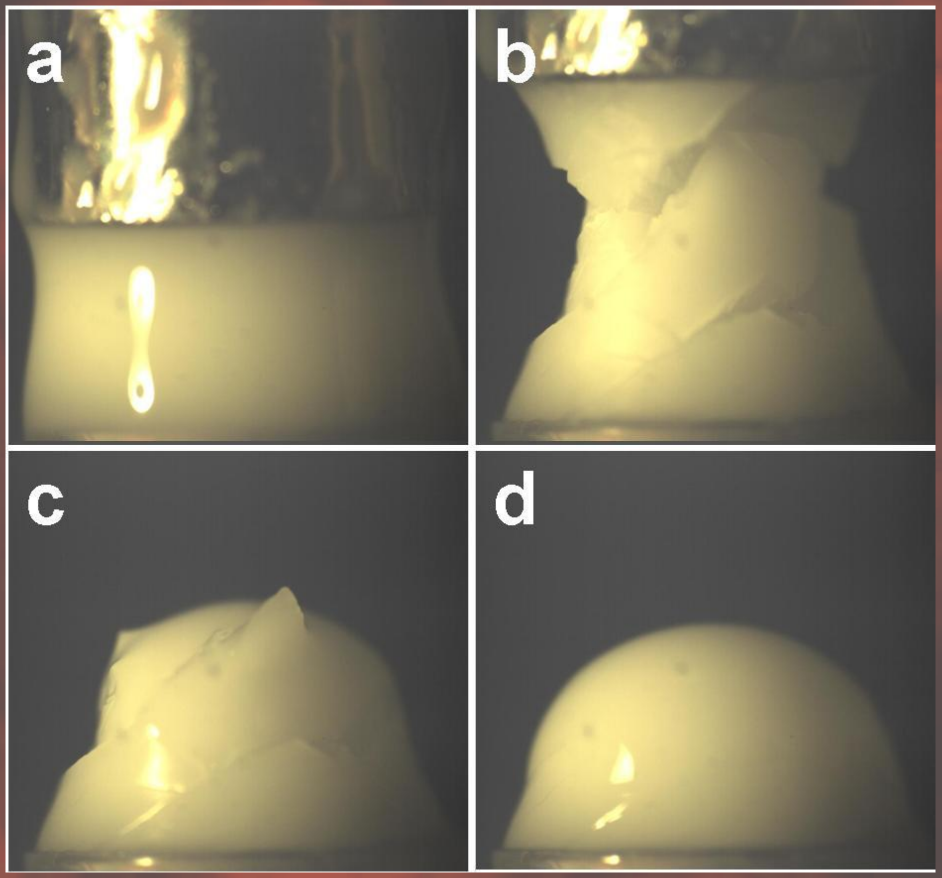
So what causes the dramatic jamming and granulation in the extensional geometry?



Dilatancy



In order for a packed bed of particles to flow the volume must increase.

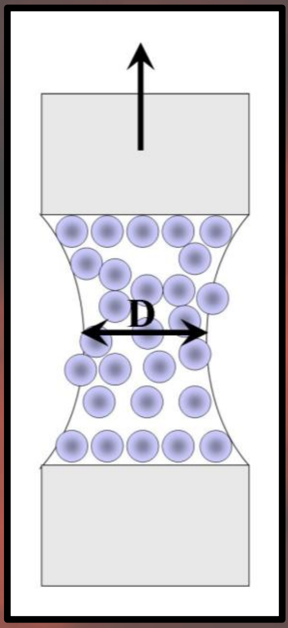


Particles poke through the liquid surface resulting in scattering

→ Surface appears dry and matt

Dilatancy appears to correlate with the onset of granulation

Jamming



As volume filled by the particles expands, particles will poke through the air-liquid interface .

Dilatancy would be enhanced by Shear Thickening due to cluster formation

Capillary forces generated between exposed particles confine and arrest flow of suspension.

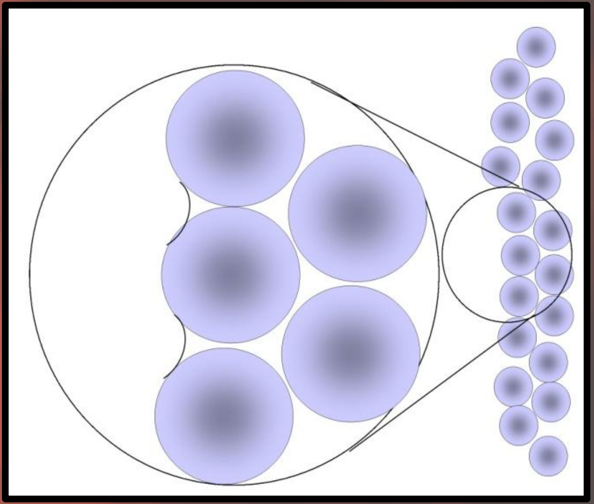
→ jamming and granulation

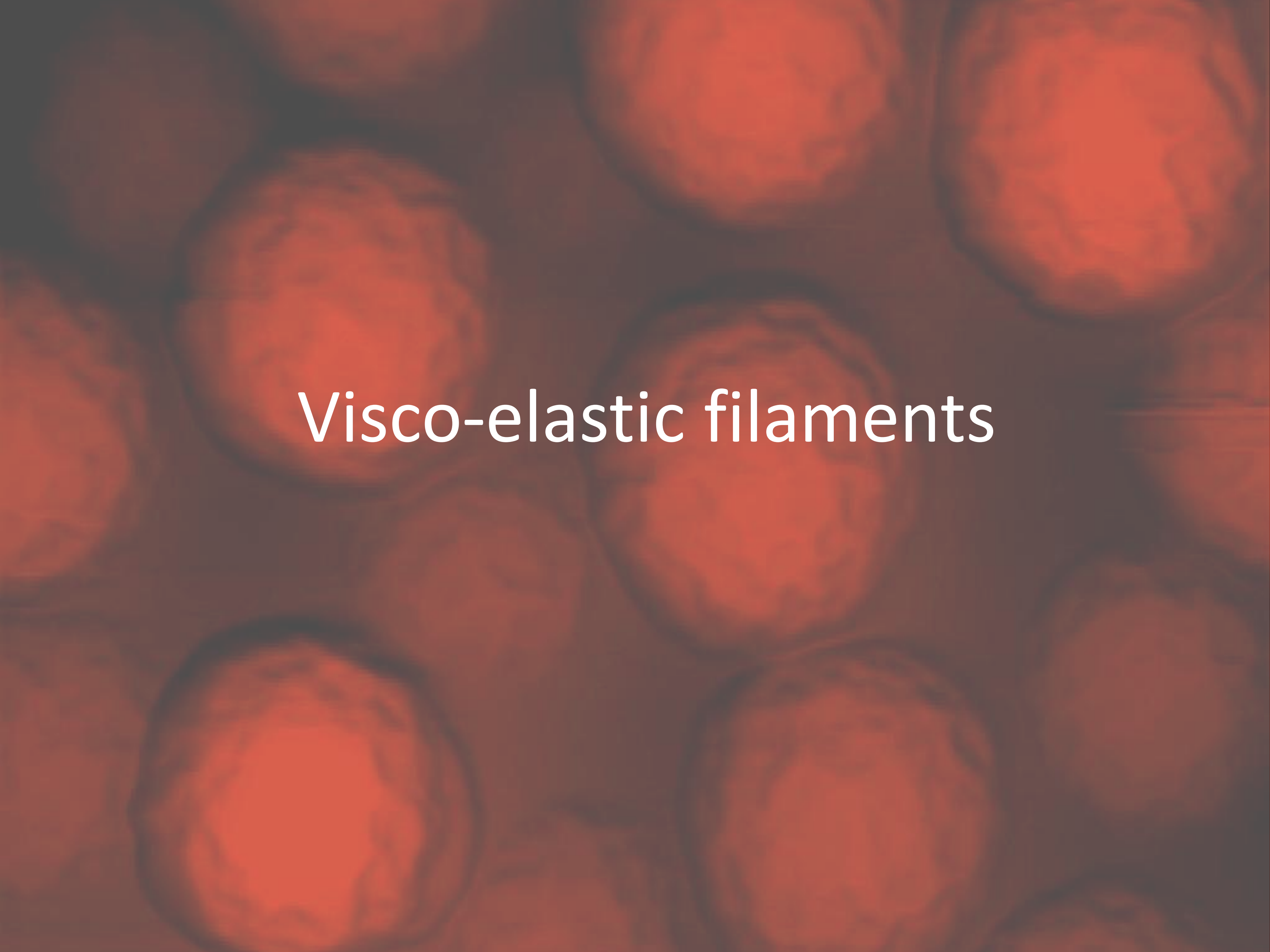
<u>Simple estimate:</u>

$P_{osmotic} = \eta\dot{\varepsilon}/(1-(\varphi/\varphi_0))^2 \sim P_{LaPlace} = \gamma/D$

→ $\dot{\varepsilon}_{Critical} \sim 10s^{-1}$ for $\varphi \sim 0.6$

Compares well with experimental value of ~ $4s^{-1}$





Visco-elastic filaments

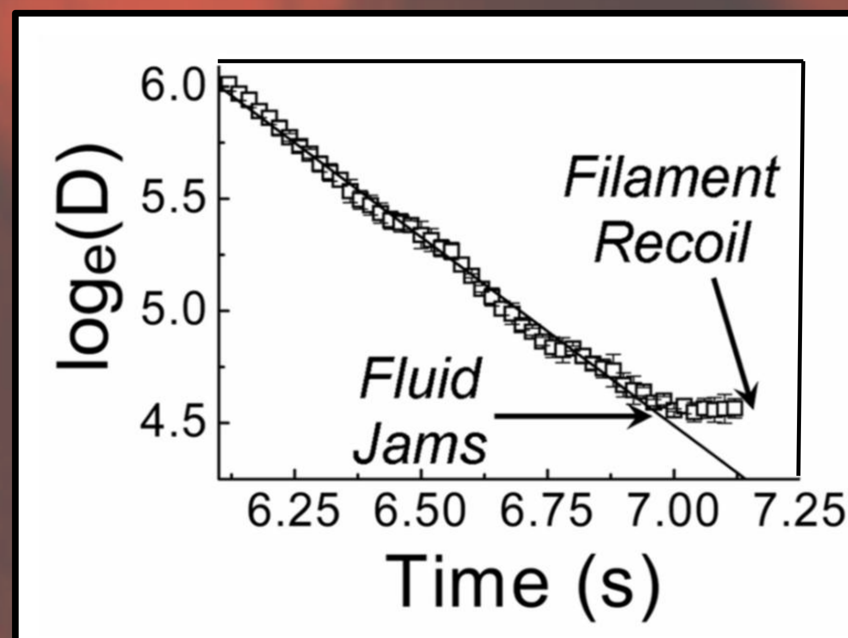
Viscoelastic filament

We observe visco-elastic recoil of filaments

Two stages:
1) Rapid elastic recoil after filament ruptures
2) Slow viscous movement on timescale of fluid relaxation.

Diameter of filament narrows exponentially with time

Prior to recoil, filament diameter stops thinning → Jamming



Viscoelastic filament

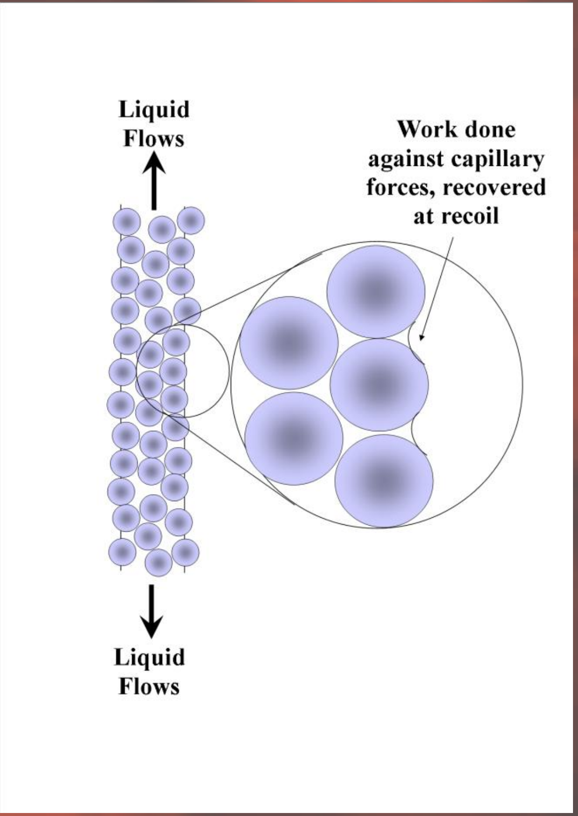
- Jamming may be due to self-filtration

  - filament ~100x particle diameter

  $-u \sim (\sigma/D^2)ka^2/\eta$ → few % change in volume fraction

- Upon jamming the rheometer continues to stretch the filament

- This performs work against capillary forces which is recoverable upon rupture (ie elastic)



Conclusions

- Above a critical strain rate hard sphere colloidal suspensions undergo dilatancy induced jamming and granulation.
- Colloidal filaments can display visco-elastic recoil.

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Pioneering research and skills