Evaporative Drying of Droplets and the Formation of Microstructured and Functional Particles and Films

"Drying Droplets"

EPSRC
Engineering and Physical Sciences Research Council

Durham University

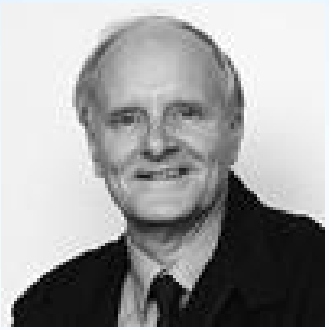
University of Leeds

University of Bristol

The Academic Team

Durham

Colin Bain



Phil Gaskell

Sergii Veremieiev

Leeds

Andrew Bayly

Mark Wilson

Bristol

Jonathan Reid

Aim of project

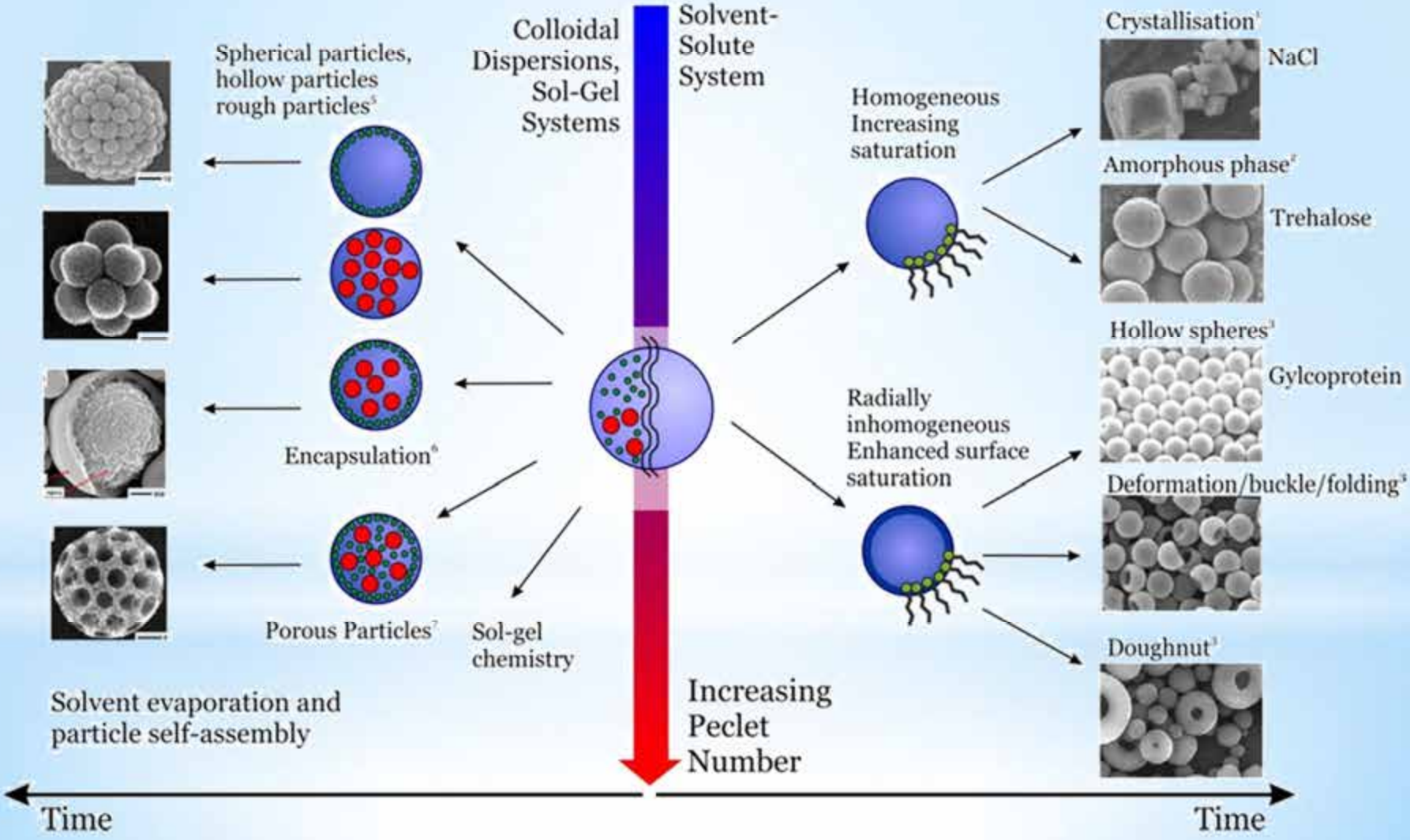
To develop a predictive understanding of droplet drying and how it can be used to produce microstructured particles and thin films both in manufacturing processes and in end-use applications.

Laundry **Agrochemicals**

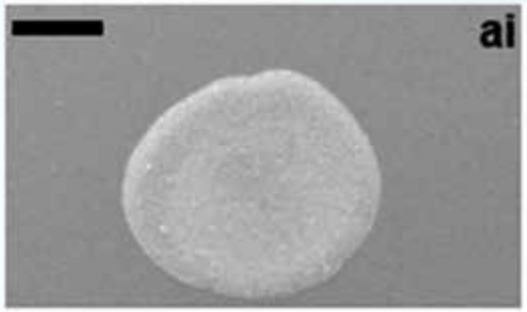
Printing **Coatings** **Pharmaceuticals**

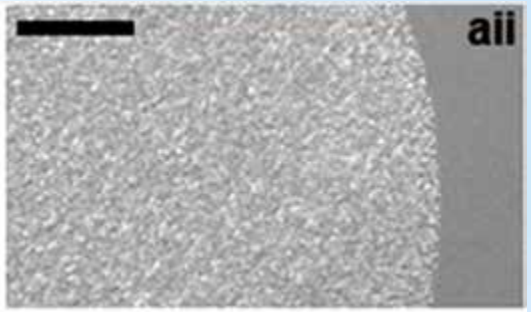
Food **Personal care**

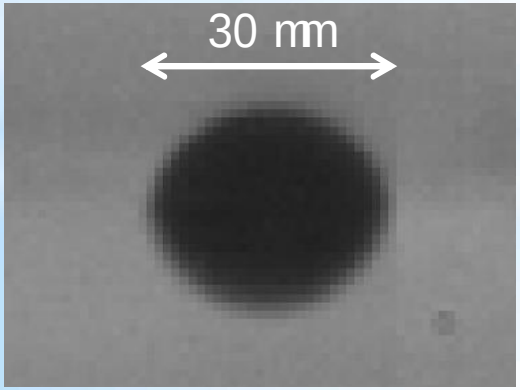
Single isolated drops

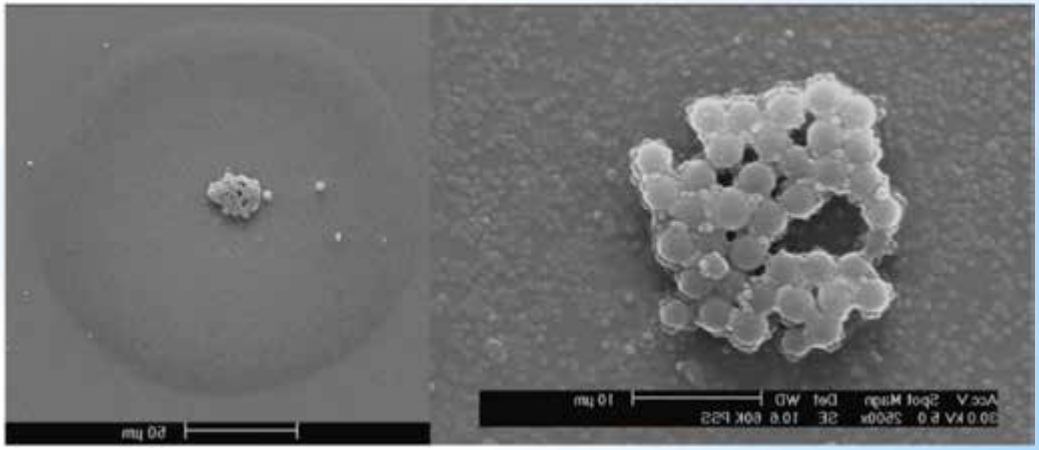


Sessile drops

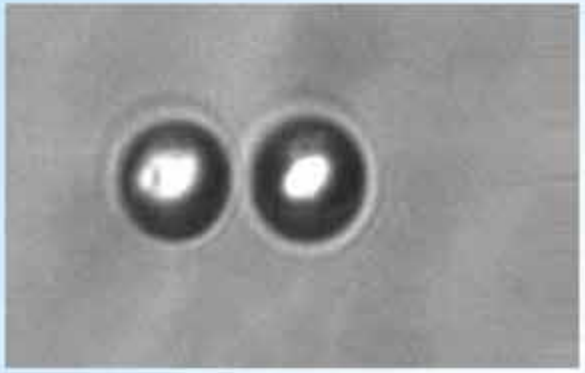




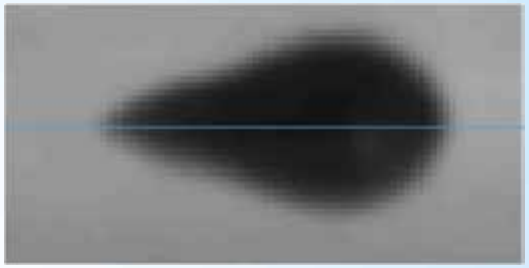




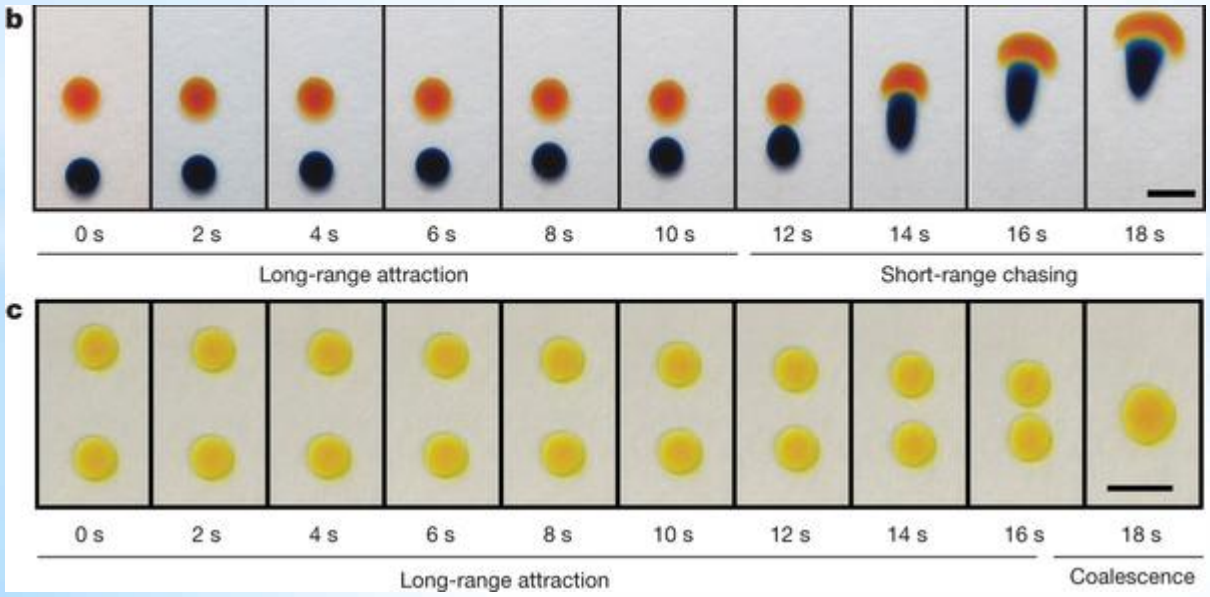
Binary drops



drops held in optical tweezers

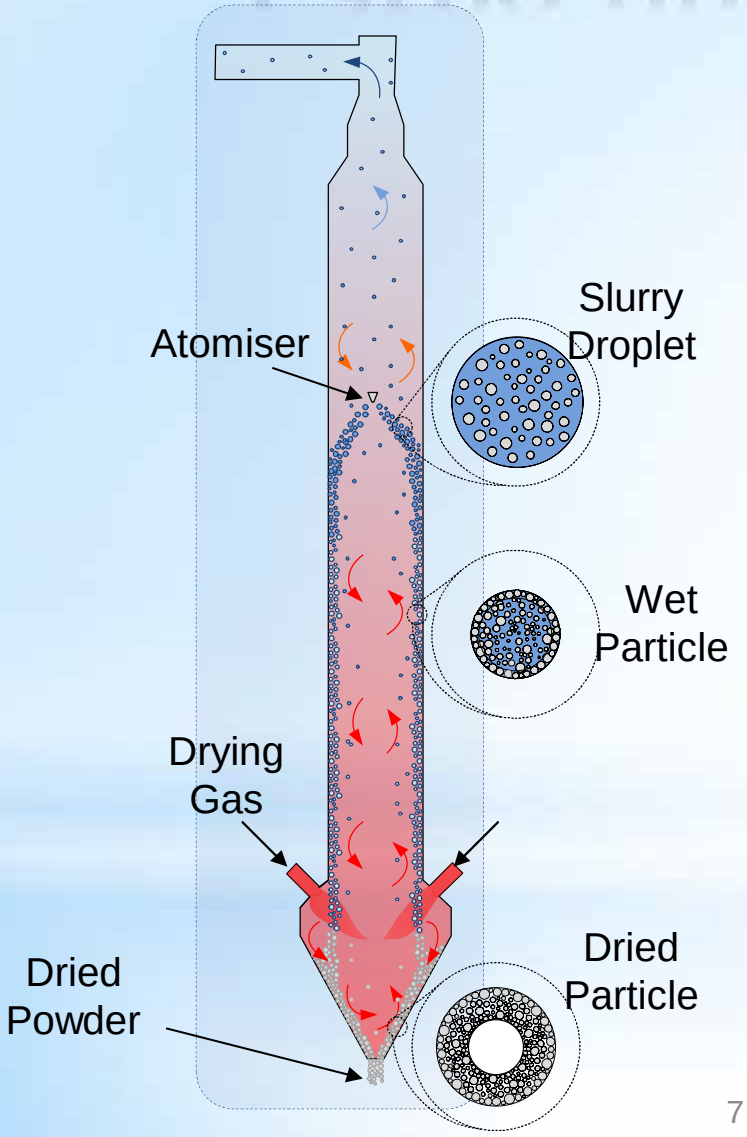


sequential printing of drops



Cira, Benusiglio & Prakash
Nature, *519*, 446 (2015)

Large numbers of drops



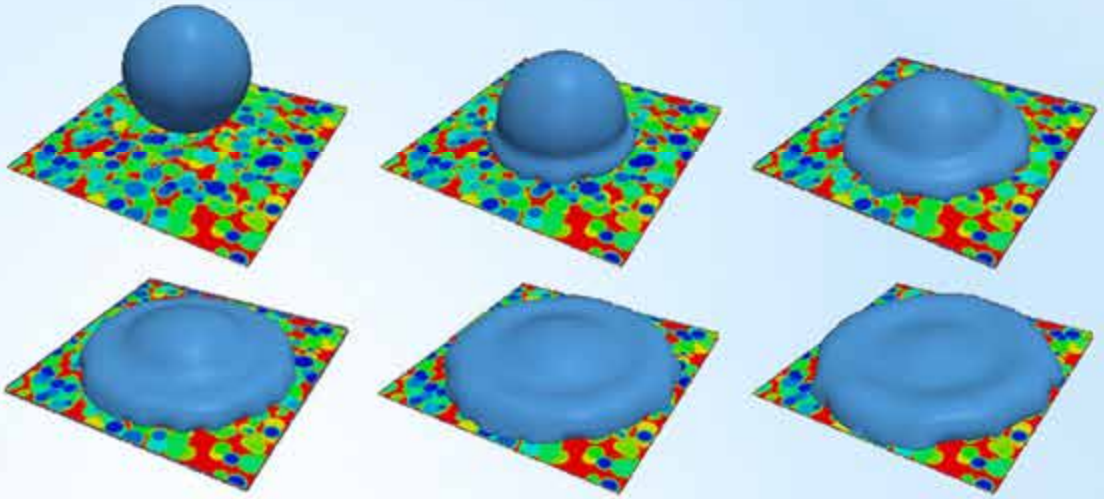
spray drying

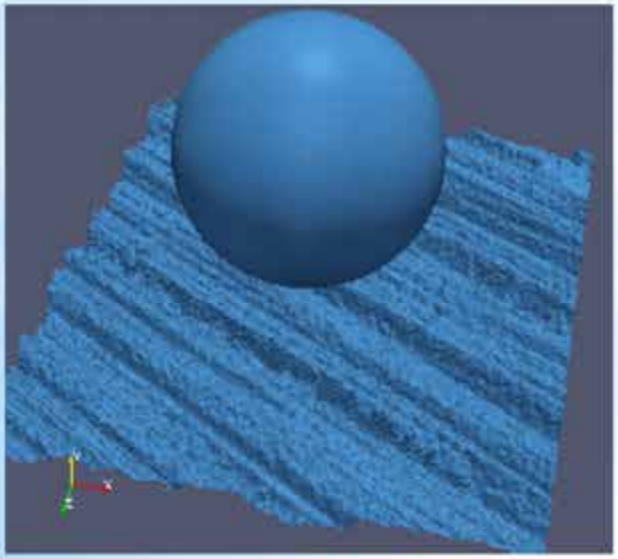
inkjet printing

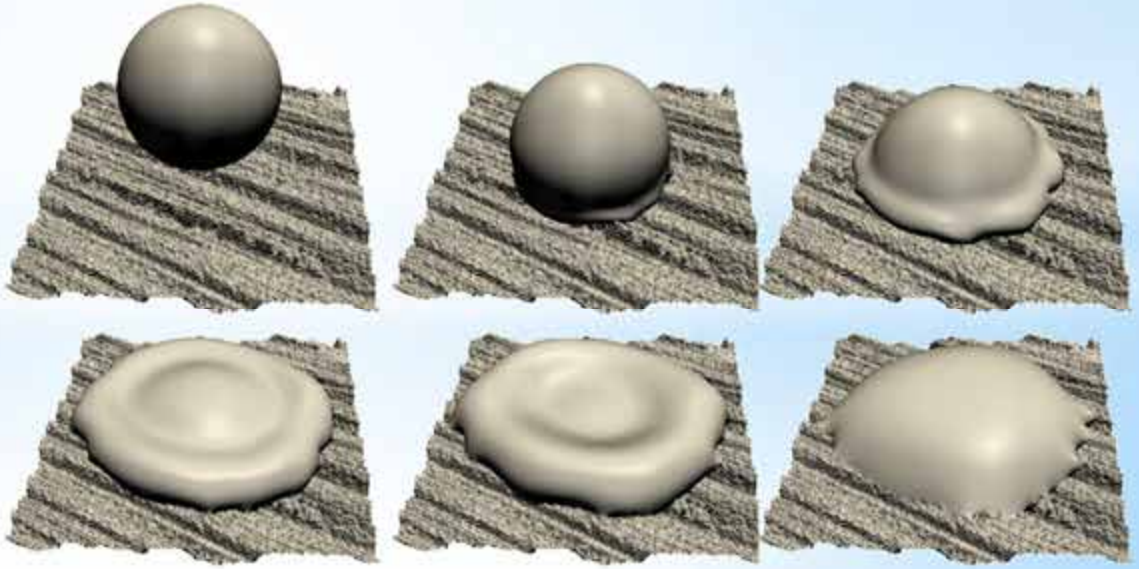
crop spraying

Lattice-Boltzmann models

Explore substrate heterogeneity

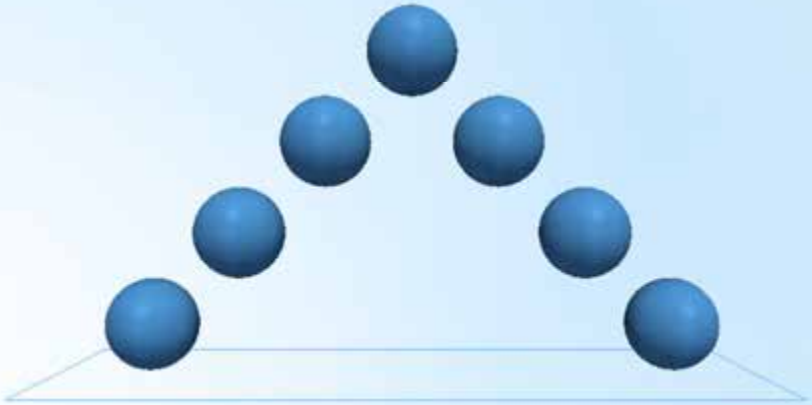


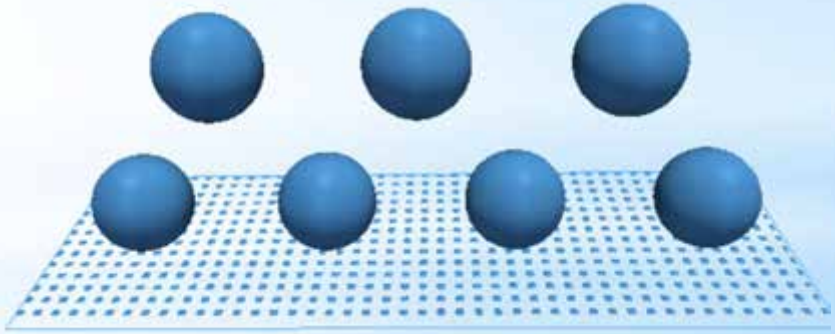




Mark Wilson

Coalescence

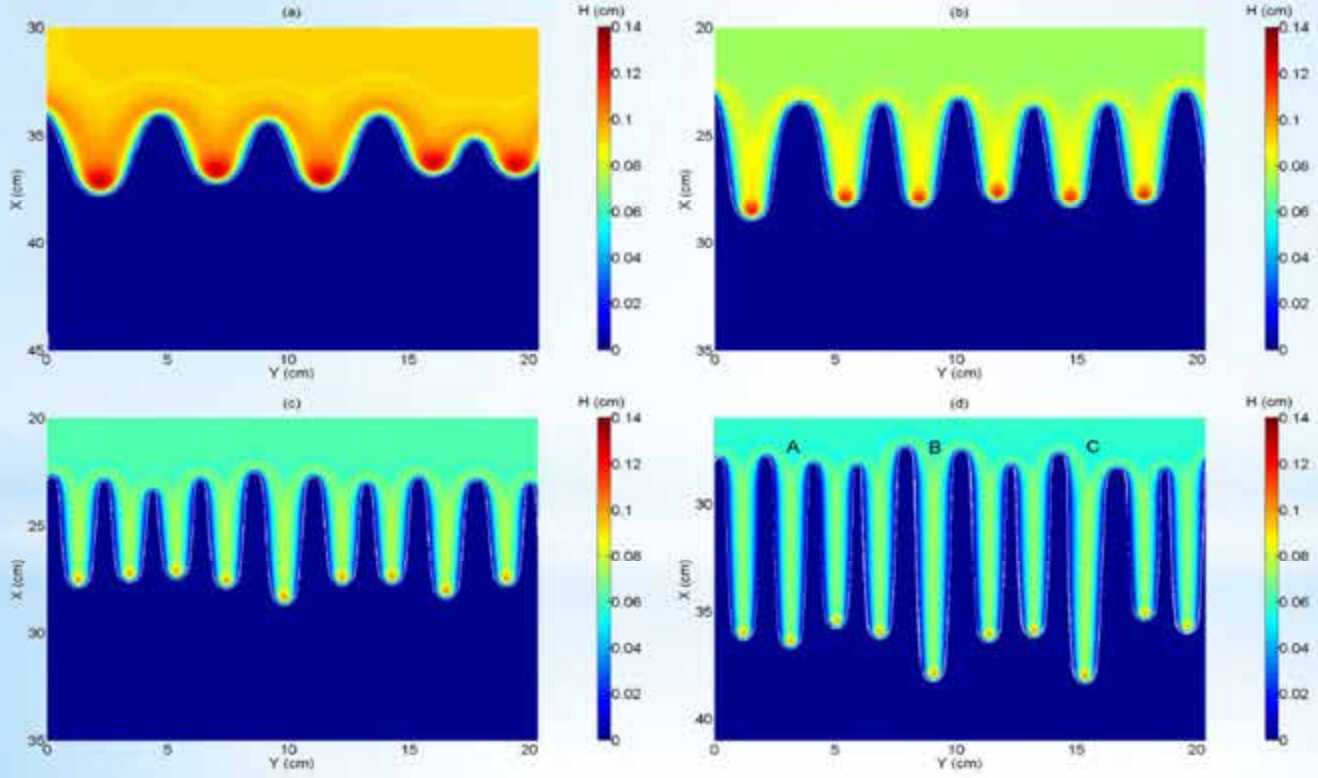


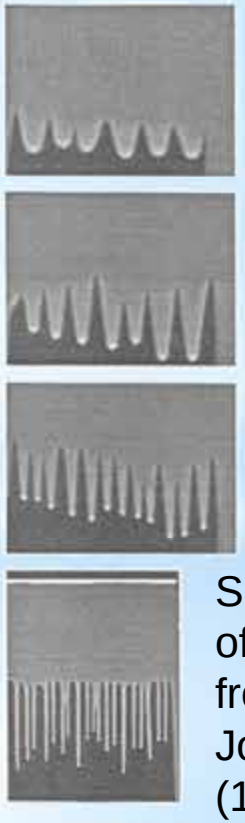


Compare predictions with experimental drop profiles and internal flows

Instabilities

Finite difference modelling of rivulet formation on inclined planes, in lubrication approximation

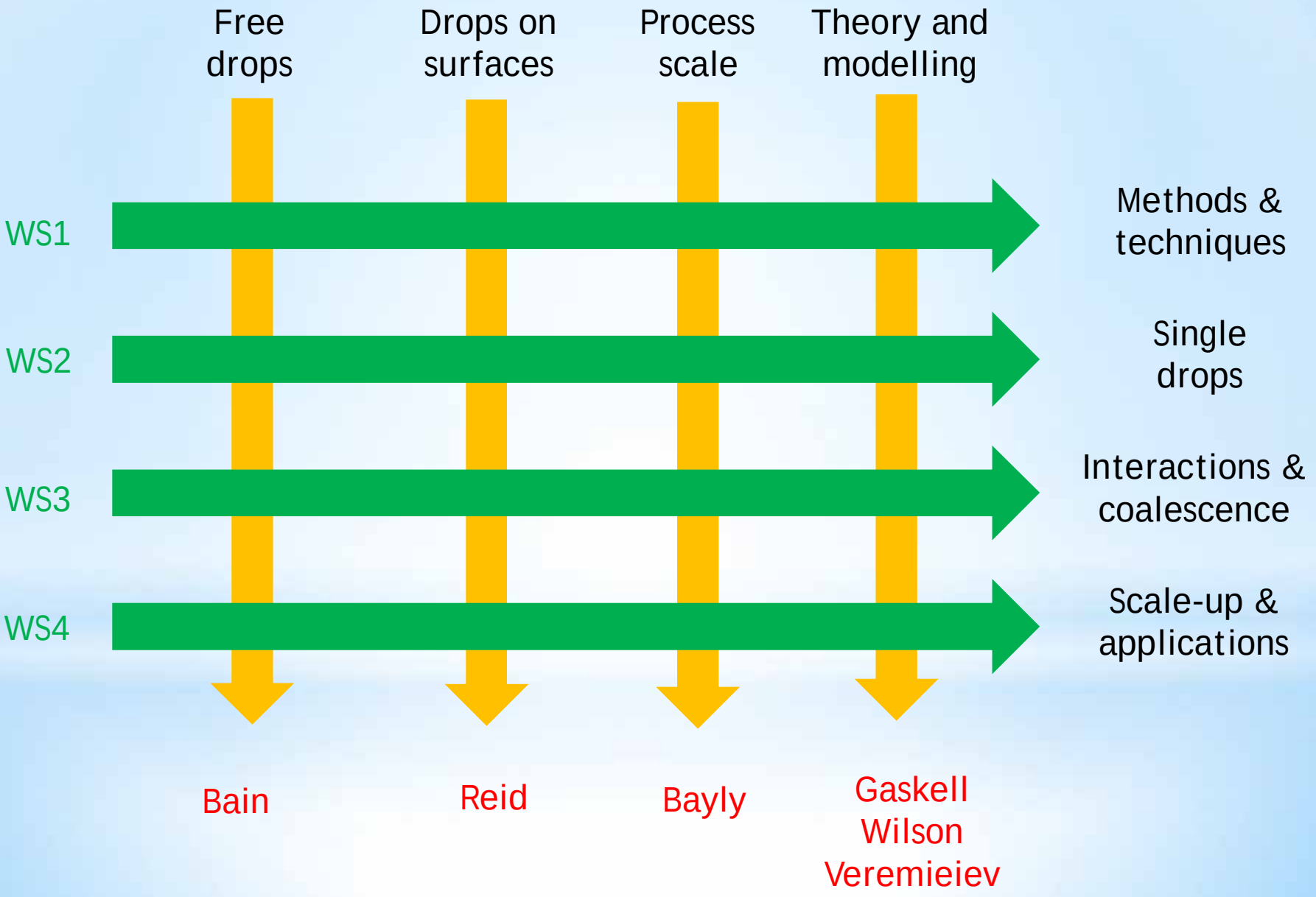




Sample of results from Johnson (1997)

Veremieiev

CAPABILITIES



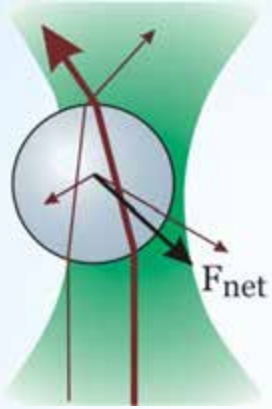
Industry Club

* Centre for Process Innovation
* Procter and Gamble
* AkzoNobel
* Bristol Myers Squibb
* Merck
* Chiesi
* Aptuit
* Croda
* Syngenta
* Sun Chemical
* Inca Digital
* Nutricia
* Nestlé
* + accession mechanism for new companies

Manipulating Droplets with Light....

Optical Tweezers

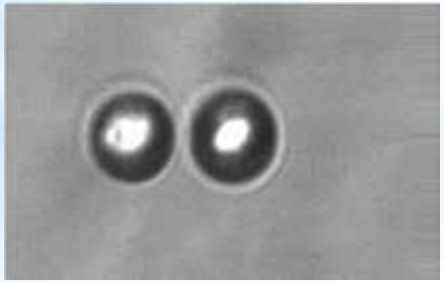
Gradient force:
Pulling particles



• Indefinite trapping of droplets >1 mm radius.

• Manipulation of arrays.

• Characterisation of water content and transport kinetics, viscosity, surface tension,...

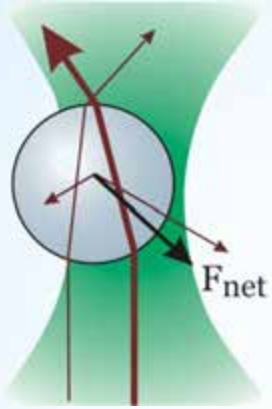


U.K. Krieger, C. Marcolli and J.P. Reid, 'Exploring the Complexity of Aerosol Particle Properties and Processes using Single Particle Techniques', Chem. Soc. Rev. 41 (19) (2012) 6631 - 6662.

...and charge

Optical Tweezers

Gradient force:
Pulling particles



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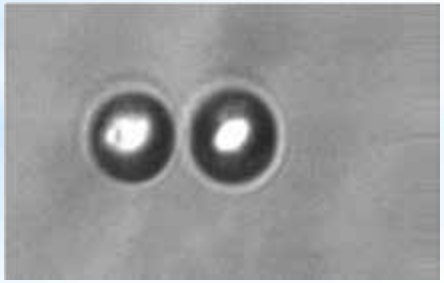
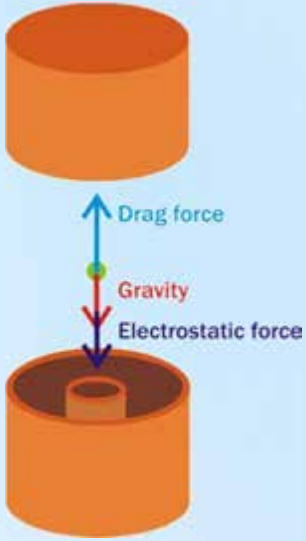
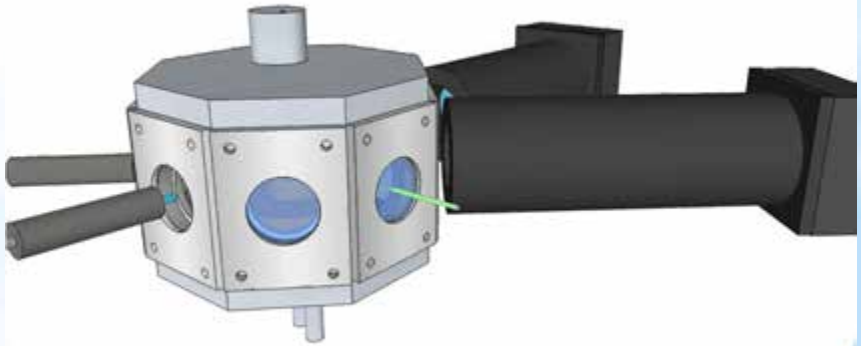


Electrodynamic Balance (EDB)

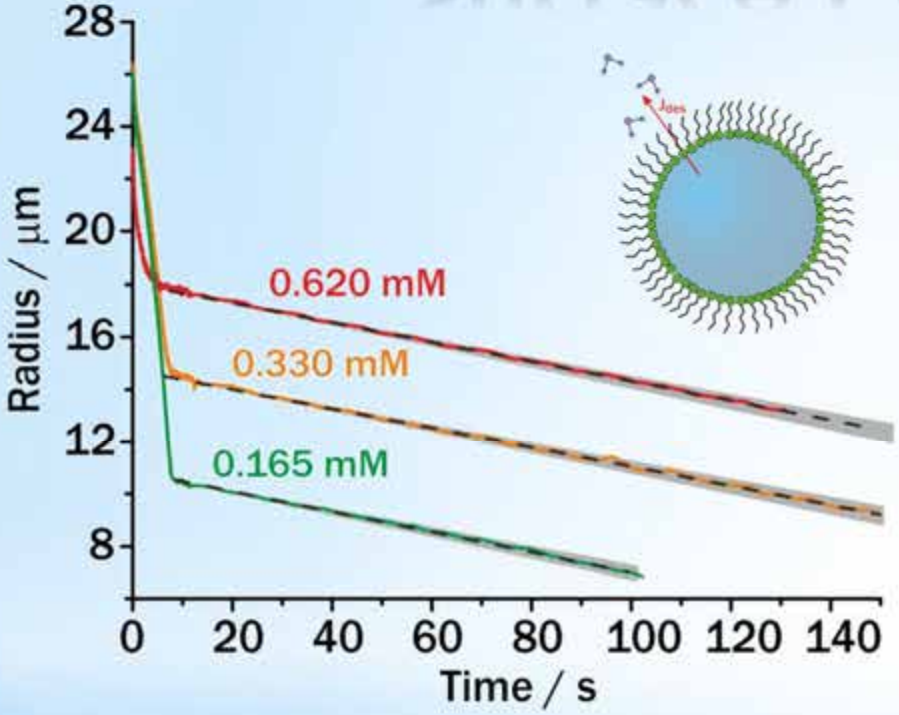


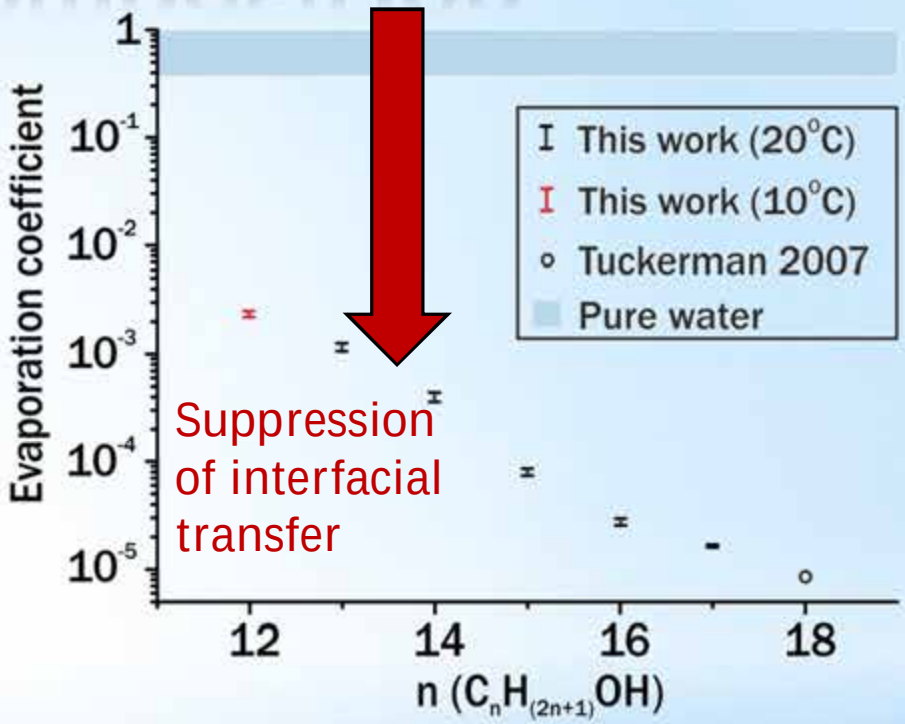
- >4 mm radius liquid droplets and solid particles.
- Droplet size from elastic light scattering with 10 ms time-resolution.



U.K. Krieger, C. Marcolli and J.P. Reid, 'Exploring the Complexity of Aerosol Particle Properties and Processes using Single Particle Techniques', Chem. Soc. Rev. 41 (19) (2012) 6631 - 6662.

Dependence of Timescale on Surface Composition

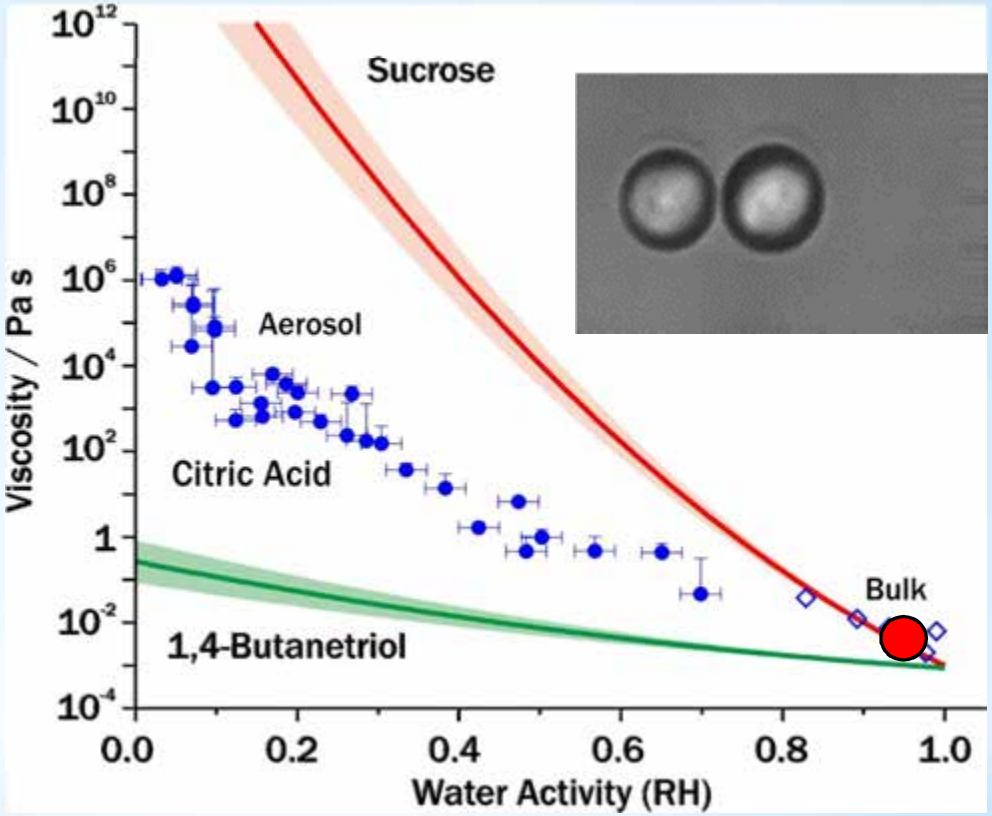




- The evaporation coefficient falls below 1×10^{-4} when cetyl alcohol forms a complete compact solid monolayer around the droplet surface.
- The evaporation coefficient increases with decreasing carbon chain length and increase in temperature.

Davies, Miles, Haddrell and Reid, 'Influence of organic films on the evaporation and condensation of water in aerosol', PNAS 110 (2013) 8807-88212.

Coalescence relaxation

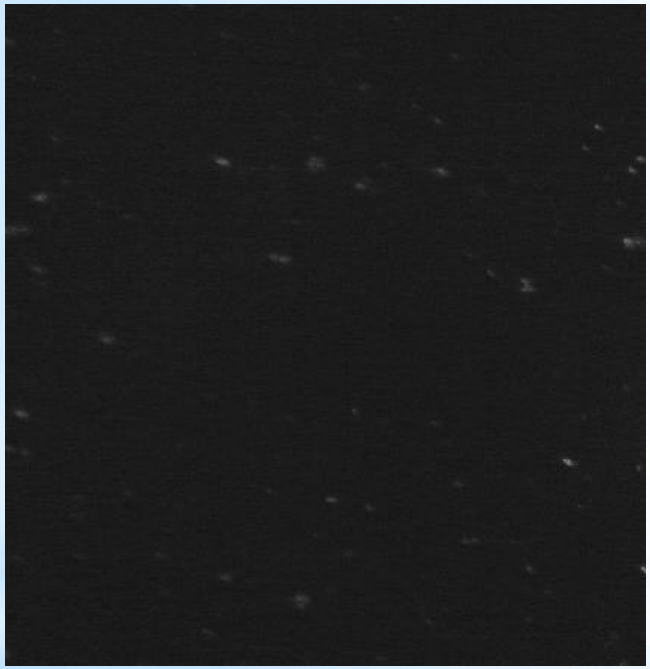


- Viscosity can be measured over more than 11 orders of magnitude (11 orders of magnitude in relaxation times) as a function of relative humidity/water activity.
- Droplet and bulk measurements are consistent although bulk measurements cannot access supersaturated states.

R. M. Power, S. H. Simpson, J. P. Reid* and A. J. Hudson 'The Transition from Liquid to Solid-Like Behaviour in Ultrahigh Viscosity Aerosol Particles', Chemical Science 4(6) (2013) 2597 - 2604

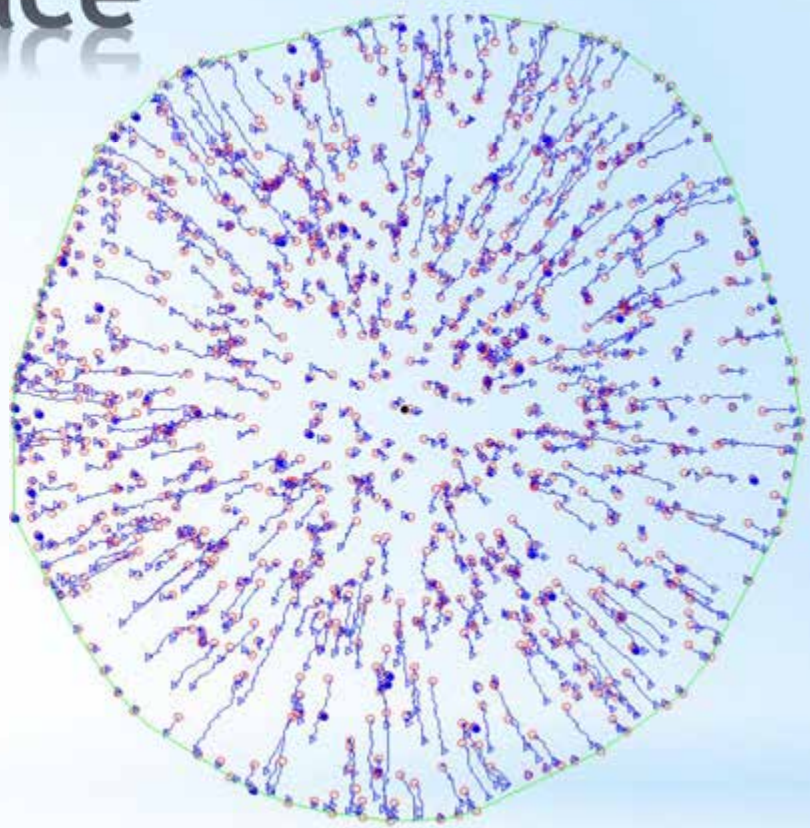
Evaporation of water on surface

~ 50 μm diameter droplet
Impact velocity ~ 1 ms^{-1}
Ambient temperature and humidity



20 μm

Water + 0.05%v 600-nm polystyrene spheres, glass
Video speed x1/8

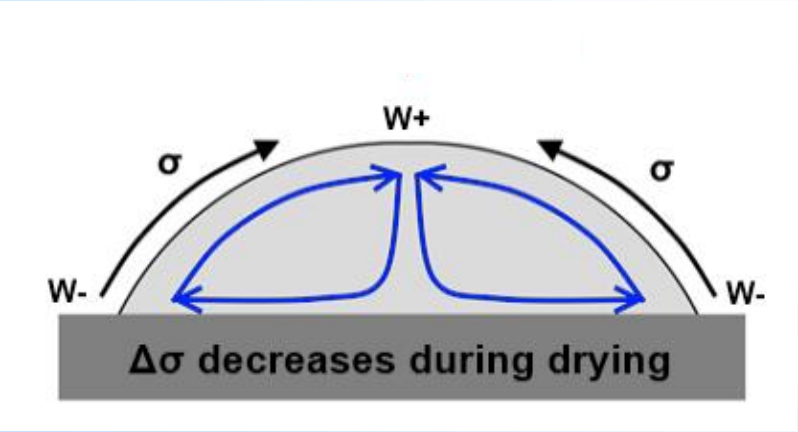


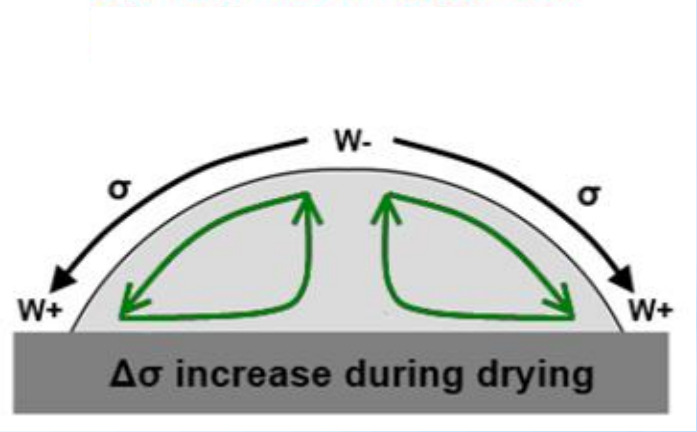
Particle tracks 2 – 3 s after impact

○ initial particle position
▲ final particle position

Binary solvent mixtures

Fluid	σ / mNm^{-1} @ 20°C	p / kPa @ 20°C
Ethanol	22.4	5.9
Isopropanol (IPA)	21.3	4.4
Methoxypropanol (PM)	27.7 @ 25°C	1.2
Water	72.9	2.3

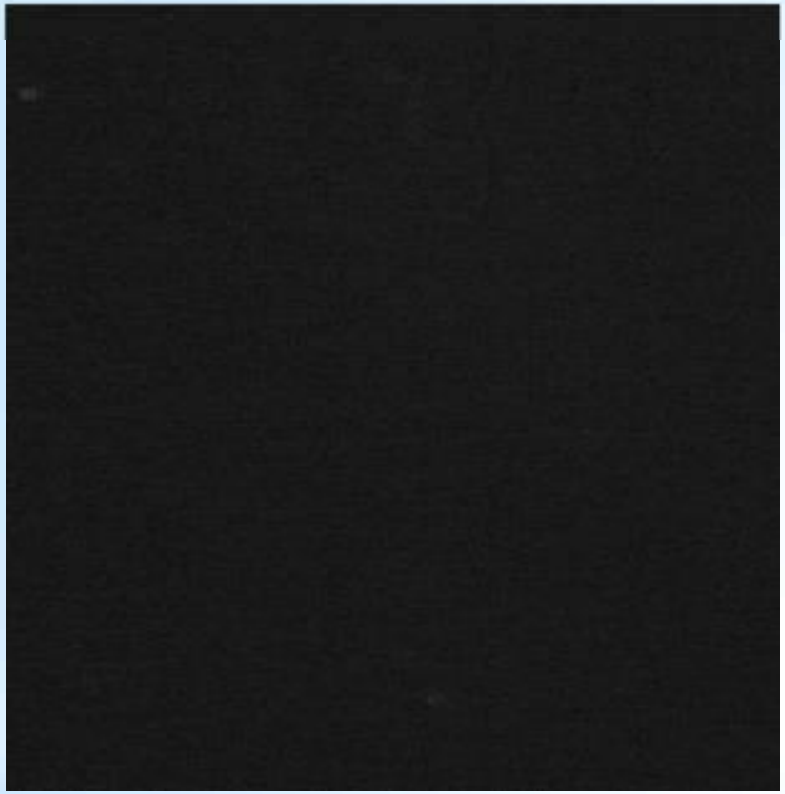




Marangoni stresses drive internal flows

$$\frac{\partial s}{\partial t} = -h\frac{\partial u_t}{\partial n}$$

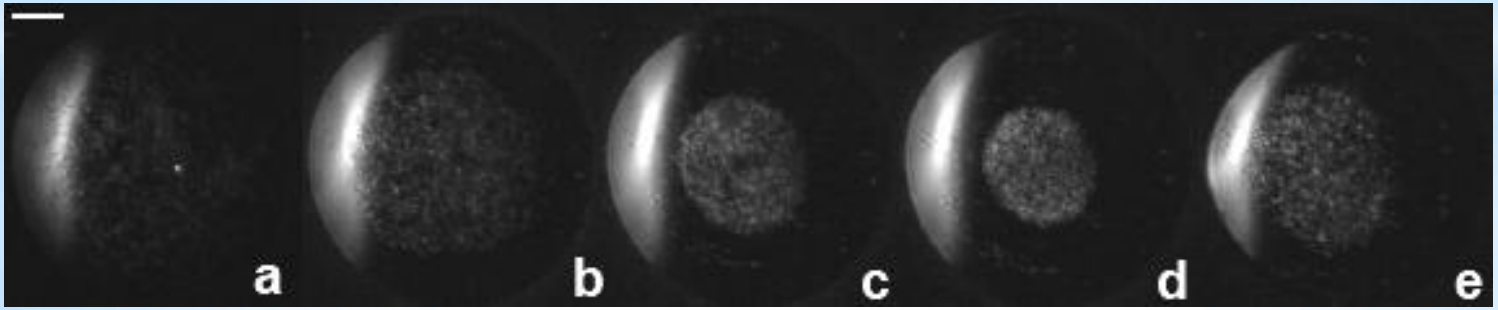
Evaporation of IPA/water drops



30%v IPA/water 0.1%v 600 nm PS, T = 20°C, RH 0.65

i. Particles uniformly dispersed
ii. Marangoni circulation
iii. Particles migrate across streamlines
iv. Minimum radius of particle group
v. Marangoni flows stop and radial flow carries particle to contact line

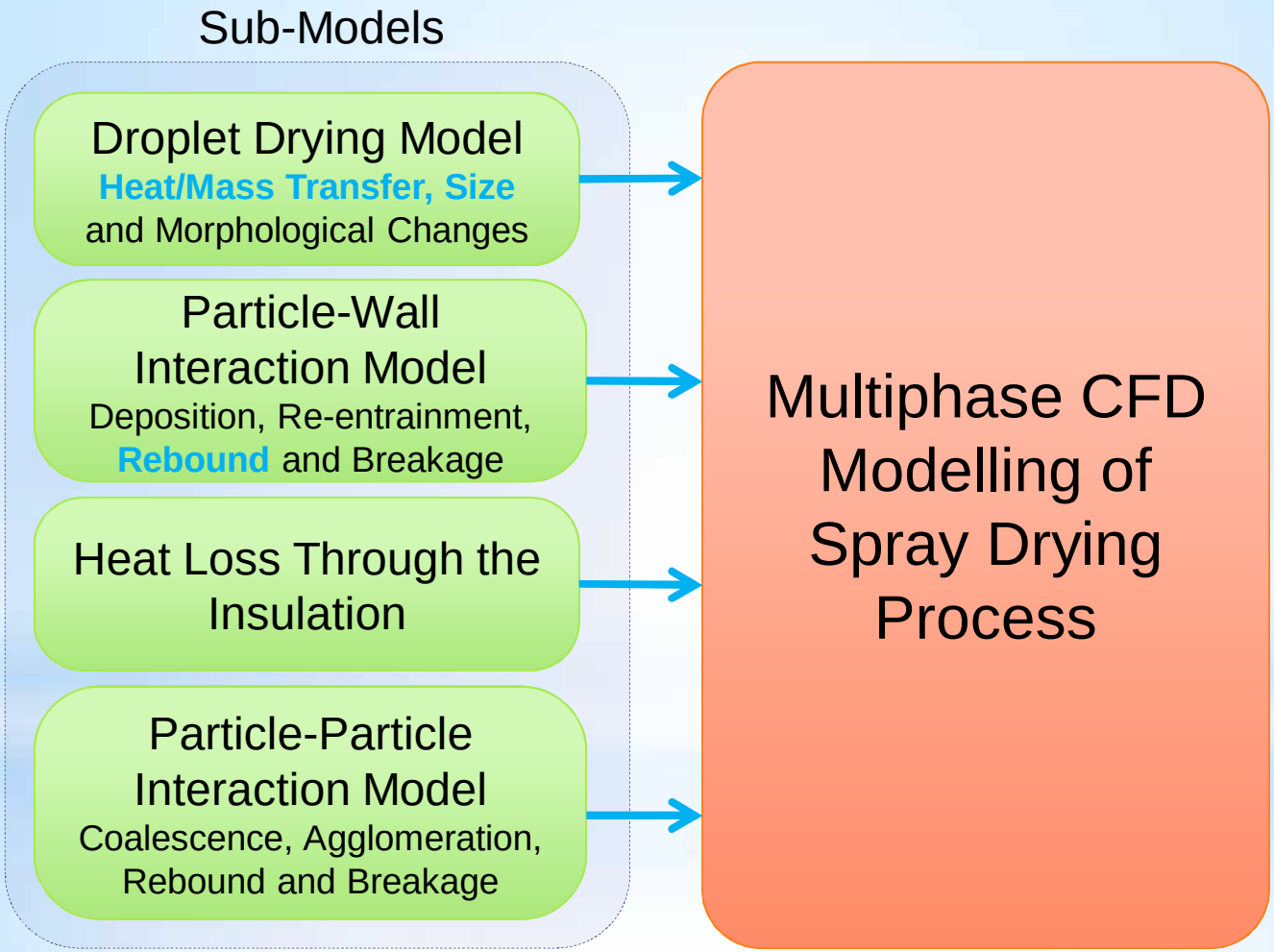
Video x 1/20



Scale 20 μm

0.002 s 0.40 s 0.80 s 1.00 s 2.76 s

Modelling of Spray Drying Process



Trajectories coloured by moisture fraction