Optical techniques to probe internal dynamics of soft materials

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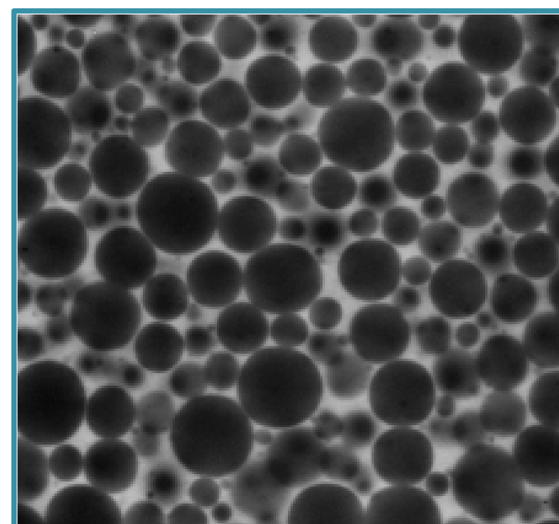
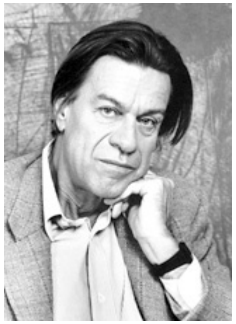


Outline

- Soft materials – a new class of materials?
- Foam, the quintessential soft material
  - Major questions
  - Crash course on foam physics
- Optical techniques for foam research
  - Confocal microscopy
  - Optical Axial Tomography
- Summary

Soft Materials



A class of materials that share in common two unifying characteristics:

- Complexity
  - Soft Matter possess a variety of *internal structures* in a broad range of length scales
- Flexibility
  - Soft Matter display remarkable *fluid* and *mechanical* properties that emerges from its internal dynamics

Pierre-Gilles de Gennes, Nobel laureate 1991

Soft Materials

Foams

Pastes

Liquid crystals

Emulsions

Colloids

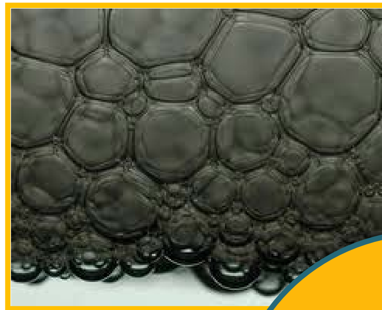
Cells

Grains

Vesicles

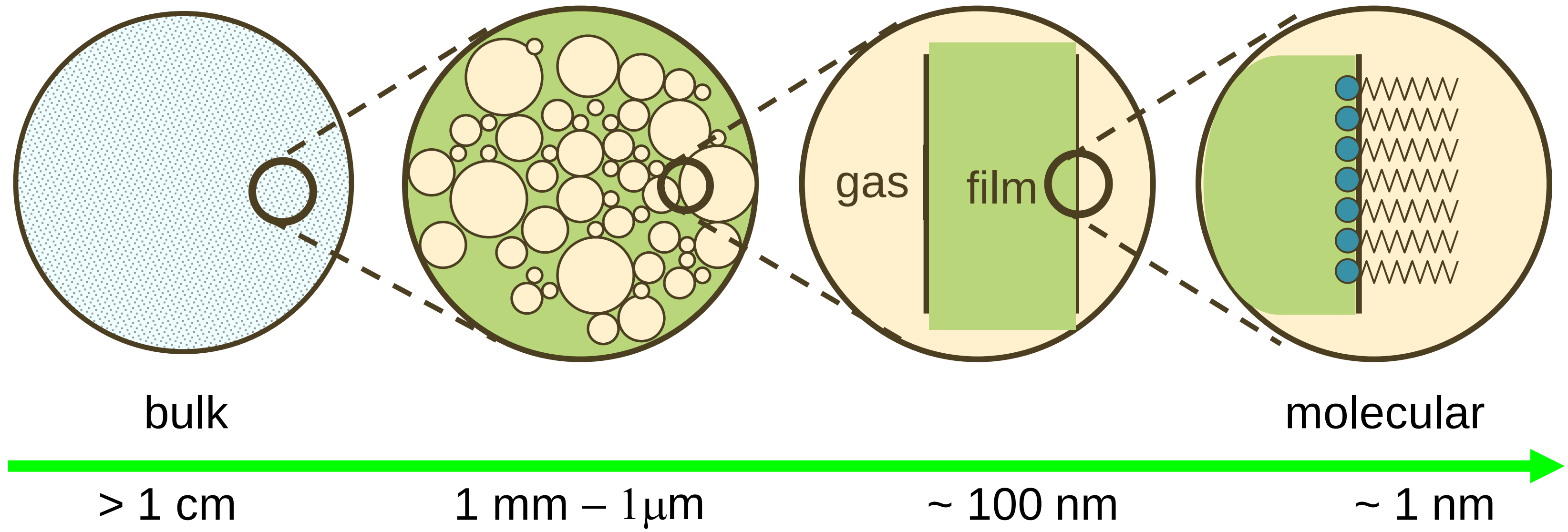
Gels

Soft Materials



- Foams
- Pastes
- Liquid crystals
- Emulsions
- Colloids
- Cells
- Grains
- Vesicles
- Gels

Complexity: structure & microscopic processes



- Microscopic processes
  - Gas diffusion, liquid flow, film rupture

Evolution and Meta-stability

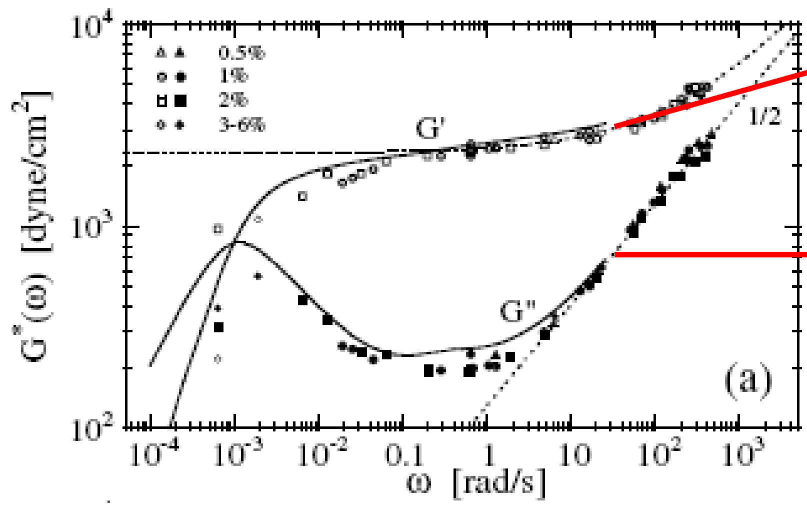
Flexibility:
foams: a solid or a fluid?

- **Fluid:** flow above an yield stress

- **Solid:** withstand small deformations

- **Aging:** memory loss caused by bubble rearrangements

Viscoelasticity: complex combination of elastic and viscous behavior



[Gopal & Durian, PRL (2003)]

Storage modulus: (elasticity) weak frequency dependence

Loss modulus: (viscosity) anomalous behavior

Frequency dependence of storage modulus $\rightarrow$ broad distribution of <u>relaxation rates</u>

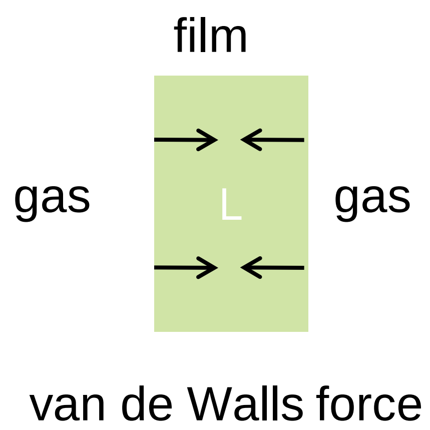
Important questions:

- Which are the **length and time scales** that dominate the viscoelastic behavior of foams?
- What is the role played by the **structure** in bubble rearrangements and flow?
- How can we explain the broad range of **relaxation rates**?

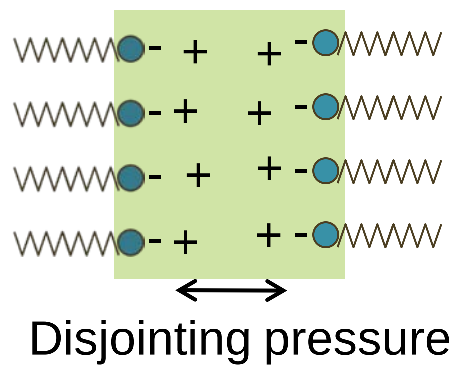
Access to the <u>internal structure</u> of the foam and its dynamics is essential to answer these questions

What keeps foams stable?

- Pure water → bubbles attract and coalesce easily

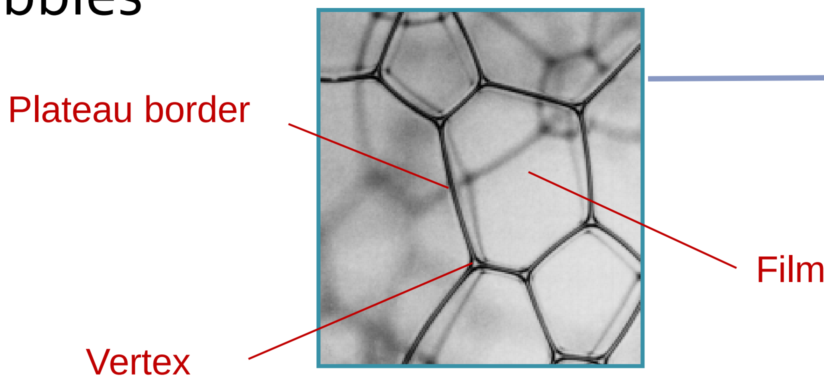


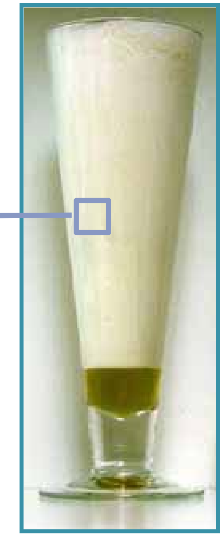
- Effect of surfactants
  - Disjointing pressure
  - Reduce surface tension



Structure and Meta-stability

Structure: random packing of bubbles





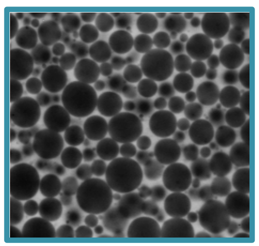
Dynamics: evolution driven by

- Liquid drainage (through Plateau borders)
- Gas diffusion (through films)
- Film rupture

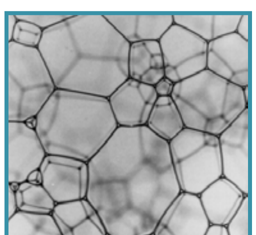
Major challenge

- Foam is typically opaque $\rightarrow$ it is difficult to visualize its internal structure and dynamics

Can we overcome this obstacle?



Wet foam: confocal microscopy

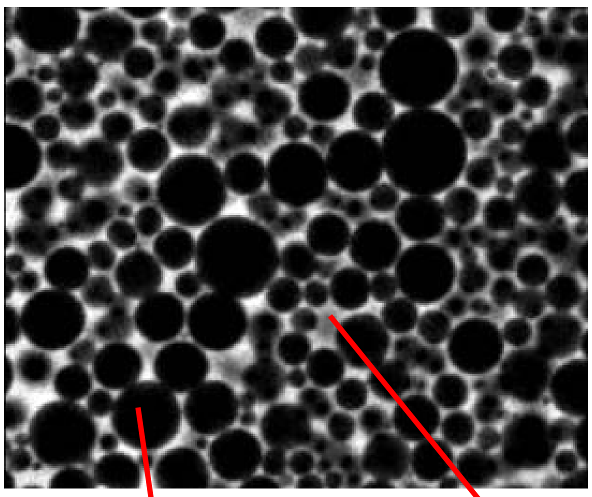


Dry foam: optical axial tomography

Wet foam: confocal microscopy

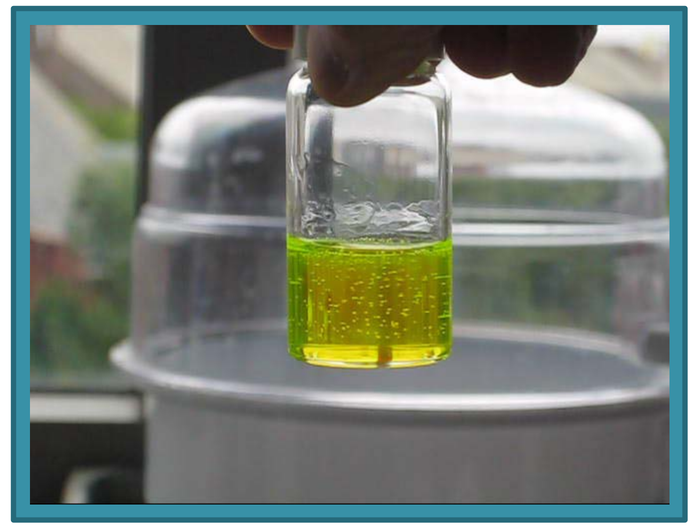
- Mix 4 components + surfactant → **optically clear** and **neutrally buoyant** emulsion

Foam-like structure & dynamics



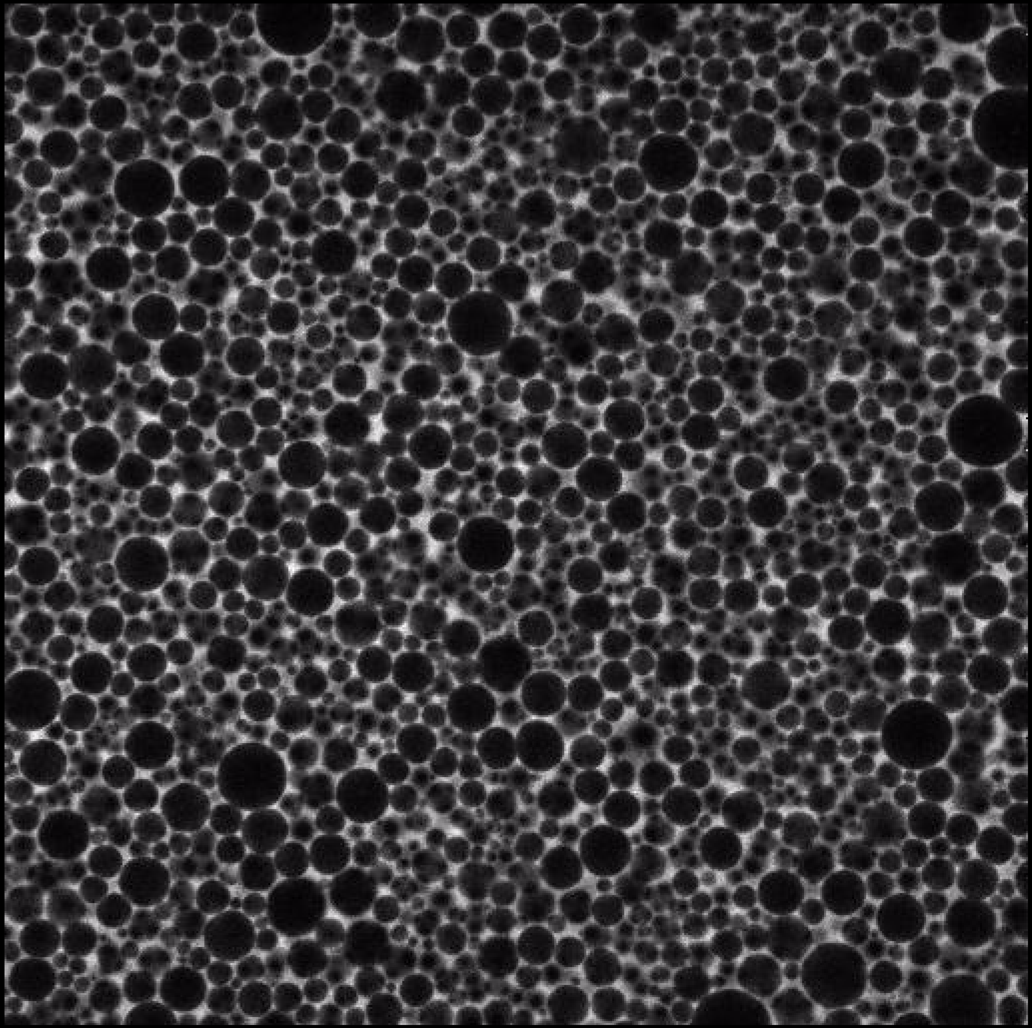
Dispersed phase:
Bromohexane + isooctane (6.3%)

Continuous phase
Formamide + water (5%)



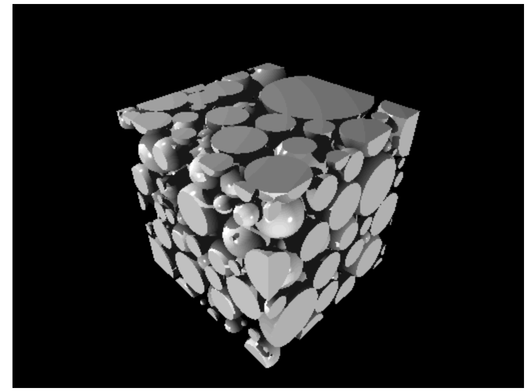
- Stabilized by non-ionic surfactant
- Fluorescent dye added to the continuous phase for visualization

Visualization: confocal microscope



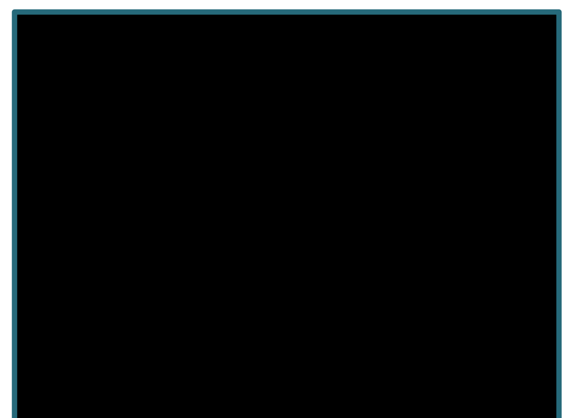
Tracking rearrangements

- Localization of droplets using image analysis



3D reconstruction

- Tracking of droplet displacements in time



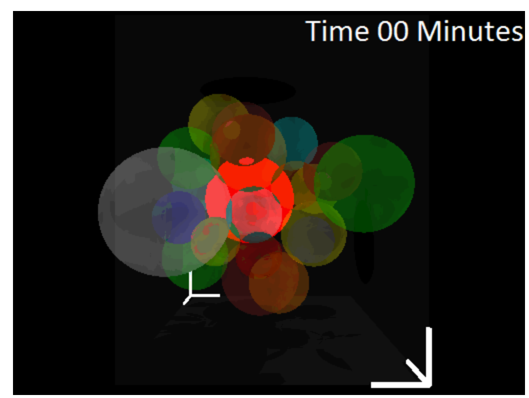
Droplet gliding and rearrangement

Tracking rearrangements

- 3D Localization of droplets using image analysis

3D reconstruction

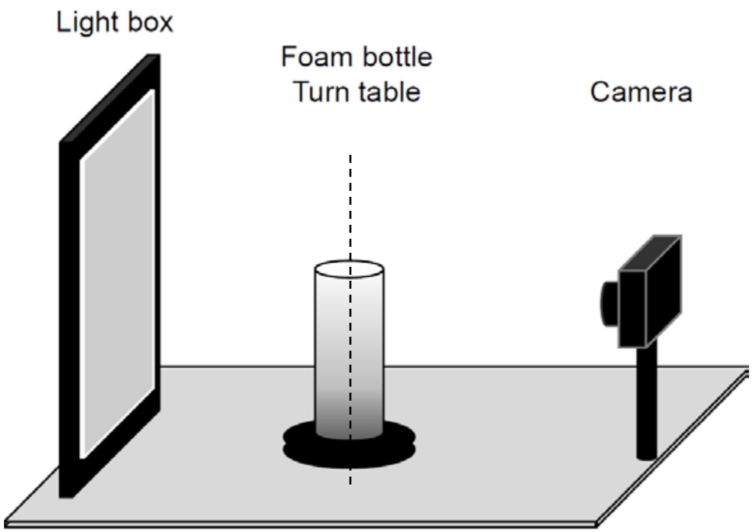
- Tracking of droplet displacements in real time



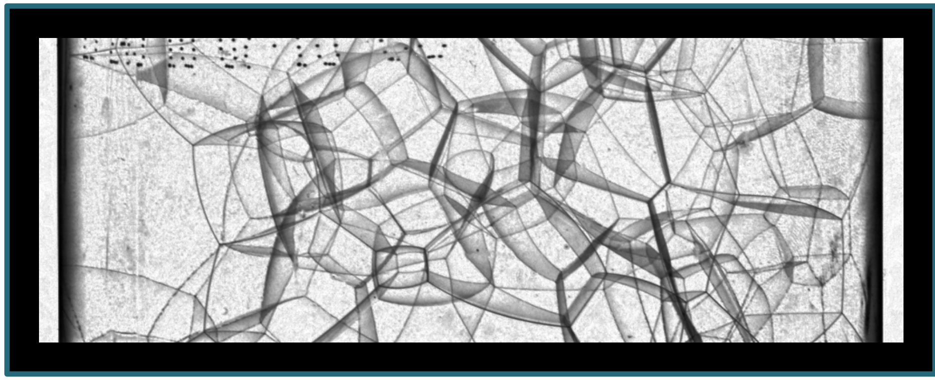
Droplet gliding and rearrangement

Dry foam: optical axial tomography

- Foam
  - de-ionized water (90.5%)
  - glycerol (4.75%)
  - detergent (4.75%)
  - aged for 24 hrs

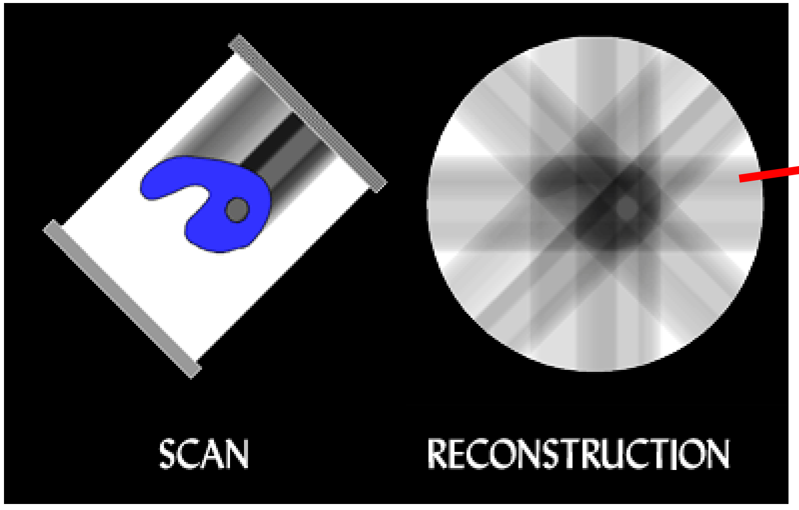


- Photographs
  - Nikon D70 camera
  - 300mm lens
  - uniform white background
  - 360 pictures ($\Delta\theta = 0.5°$)



How does axial tomography work?

- Take a photograph of the "shadow" of the specimen
- **Dark shadow** = light scattered or absorbed by specimen
- The sum of projections from all angles produces an image of the cross section of the specimen

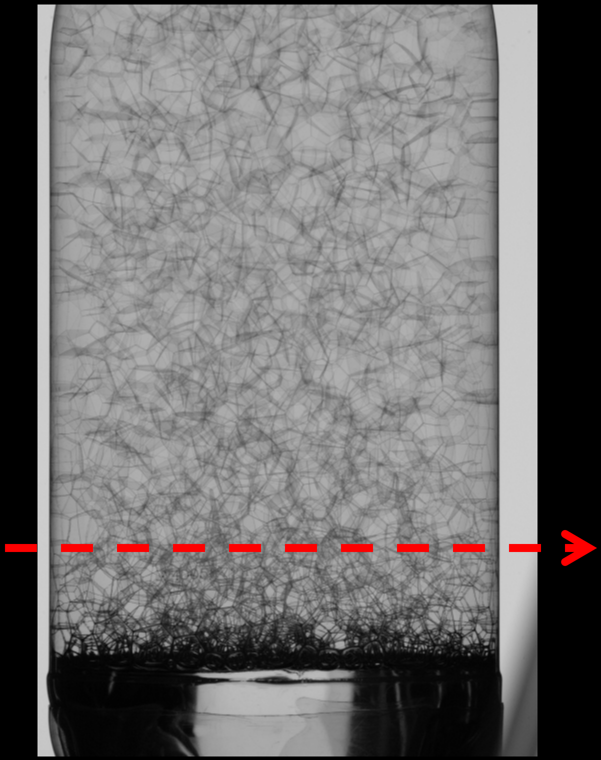


Back projection

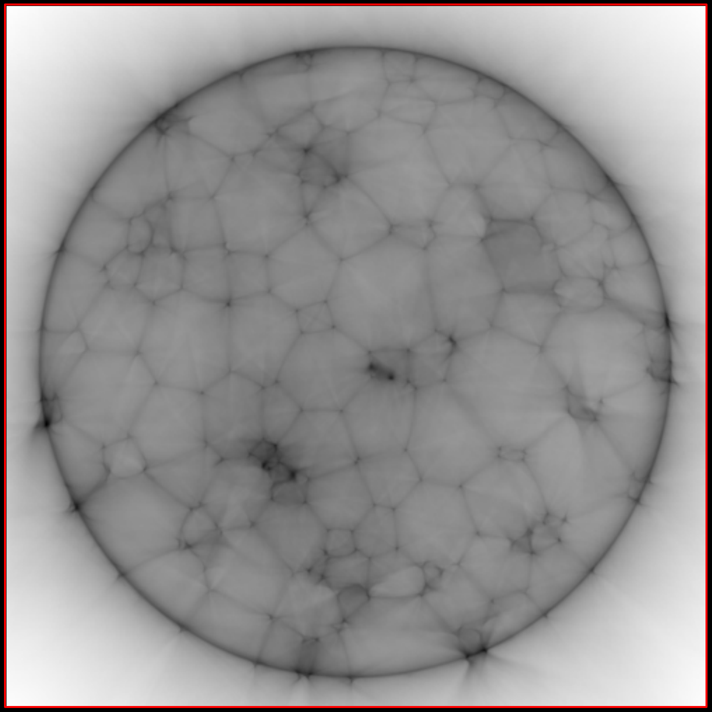
http://genex.hgu.mrc.ac.uk/OPT_Microscopy/optwebsite/how_it_works/hiwtheory.htm

Tomographic reconstruction of foam cross section

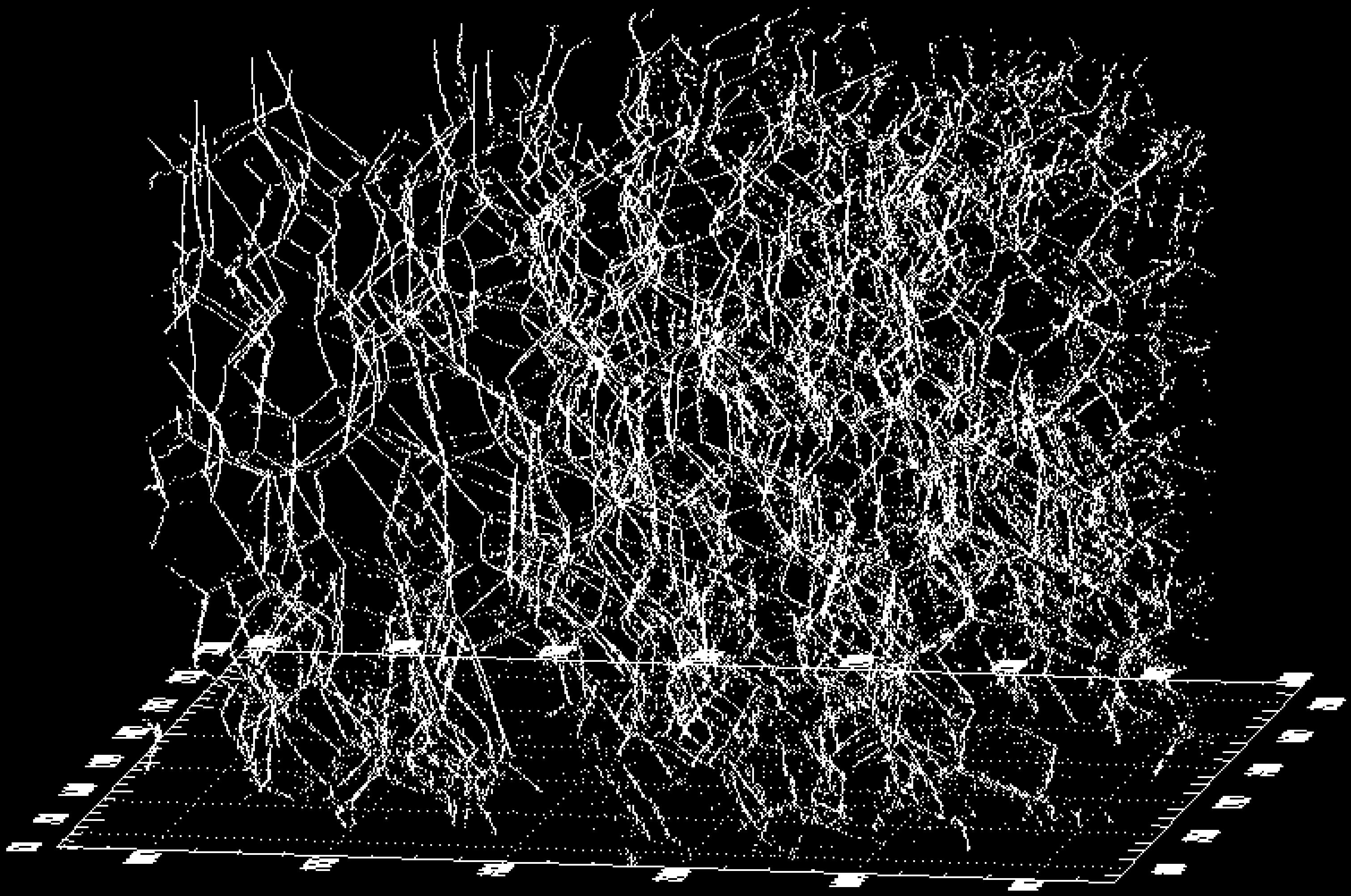
Dry foam



Slice Reconstruction

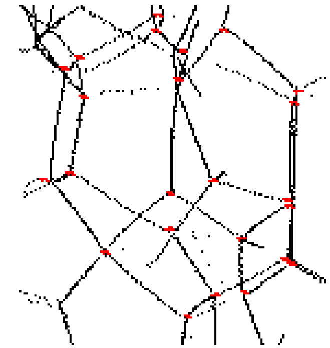


3D reconstruction of the internal

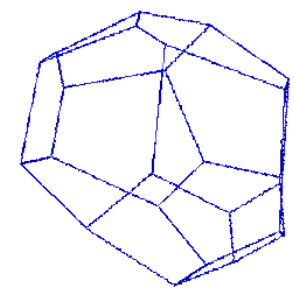


Identifying individual bubbles

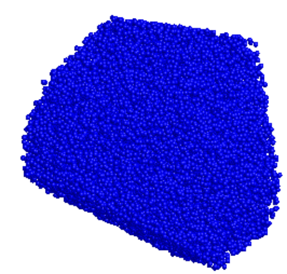
- Localization of vertices



- Geometrical calculation of faces using vector algebra



- Volume calculation by Monte Carlo methods



Summary

- We have implemented two powerful techniques for imaging internal structure and dynamics of foam
  - Confocal microscopy – high liquid fraction
  - Optical axial tomography – low liquid fraction

- These techniques provides opportunity to connect microscopic interactions with bulk properties of aqueous foam.

Acknowledgments

JAMES MADISON UNIVERSITY

JAMES MADISON UNIVERSITY PHYSICS AND ASTRONOMY

National Science Foundation
WHERE DISCOVERIES BEGIN

DEPARTMENT OF DEFENSE UNITED STATES OF AMERICA

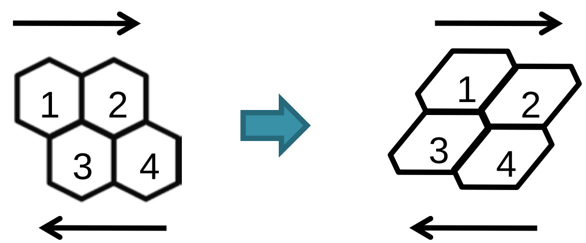
Nick, Anthony, Jon, Harry

Joice

Robbie

Source of elasticity

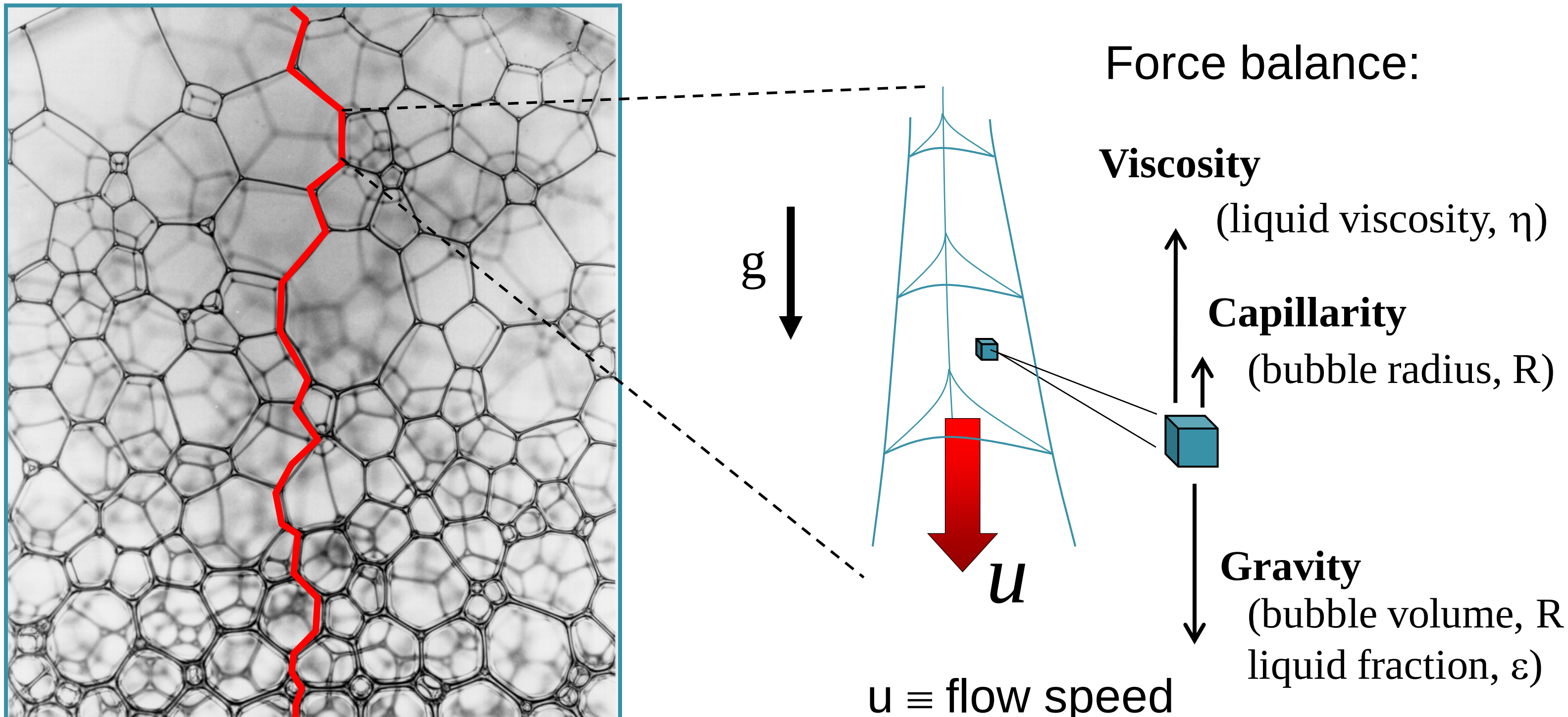
- Small deformations: energy is stored in the films; deformation increases area



$G' \sim \gamma / d$ [Princen, JCIS (1983)]

- Beyond a threshold, bubbles rearrange and the foam flows

Liquid drains through plateau borders

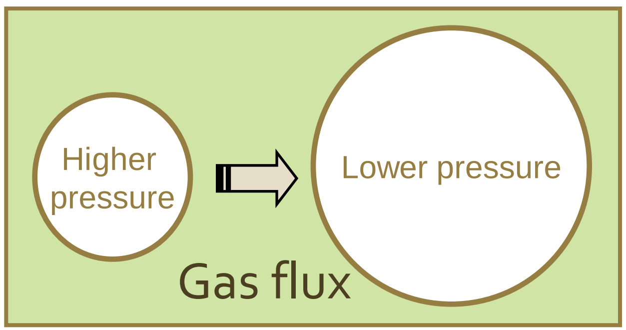


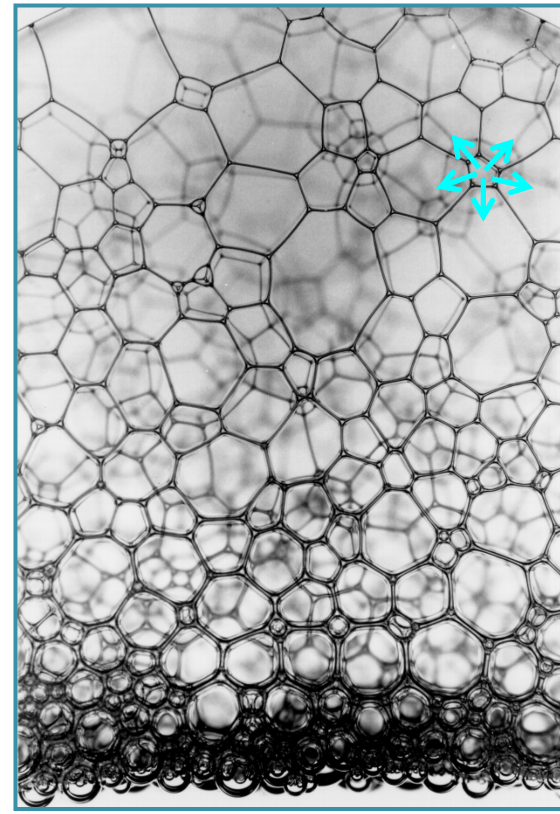
$$u \sim \frac{R^2 \varepsilon^{1/2}}{\eta},$$

[Koehler, et al., PRE (1998)]

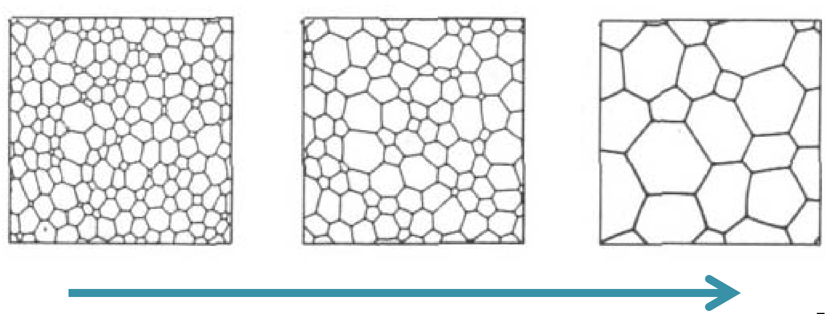
Gas diffusion makes bubbles grow

- Laplace pressure: $\Delta p \sim \dfrac{\gamma}{r}$ (Surface tension) (Bubble radius)
- Soluble gas





- Foam coarsening, scaling behavior,

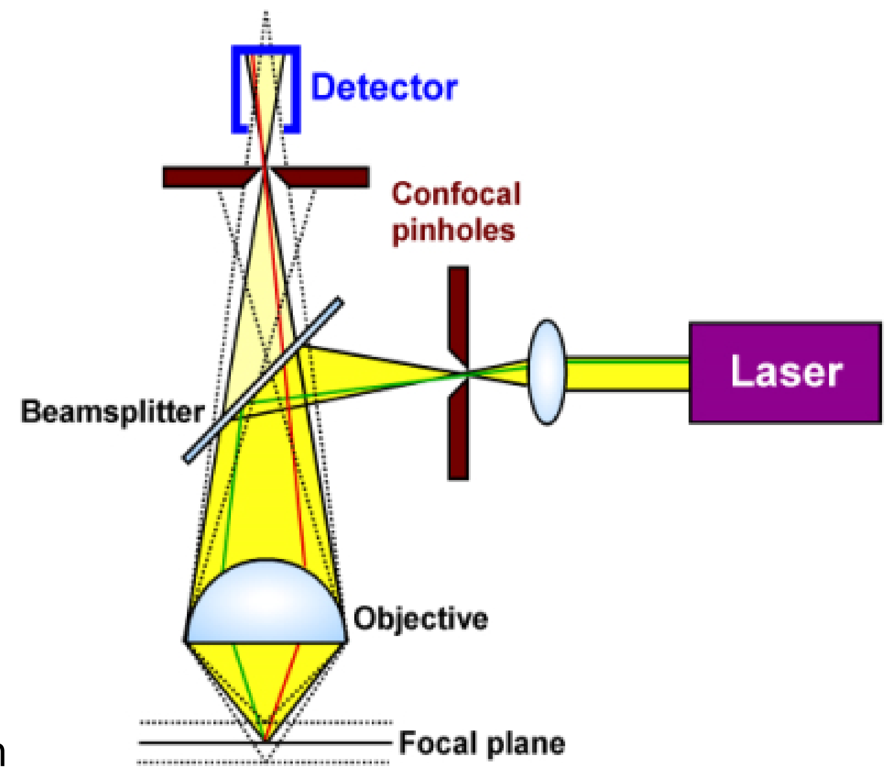


$$\frac{\partial R}{\partial t} \sim \frac{1}{R} \Rightarrow \boxed{R \sim t^{1/2}}$$

[Glazier and Weaire, J. Phys.: Condens. Matter (1992)]

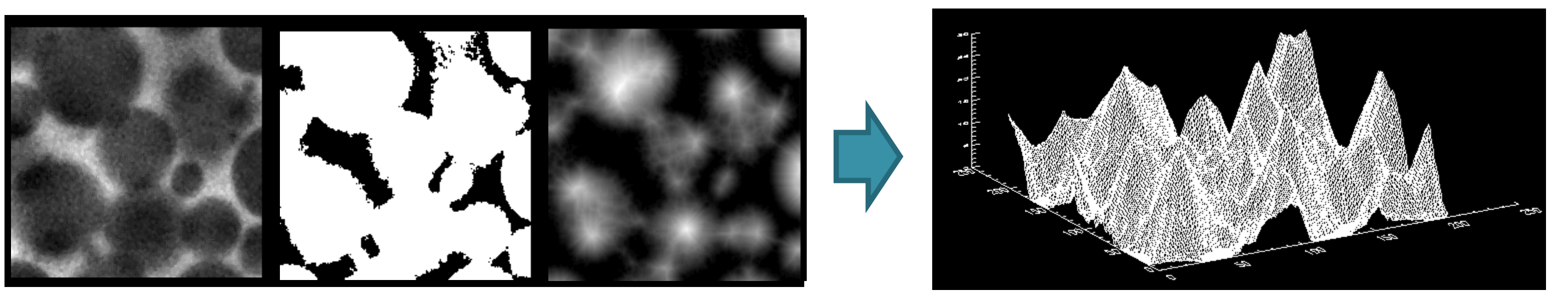
How a confocal microscope works

- A laser beam is focused on the sample through a pinhole
- Light reflected from the sample crosses a beam splitter and hits the second conjugated pinhole
- Light coming from the focal plane goes through the second pinhole while any other is rejected.
- An image of the sample is constructed point by point in the detector (photomultiplier)



Vectorizing the emulsion

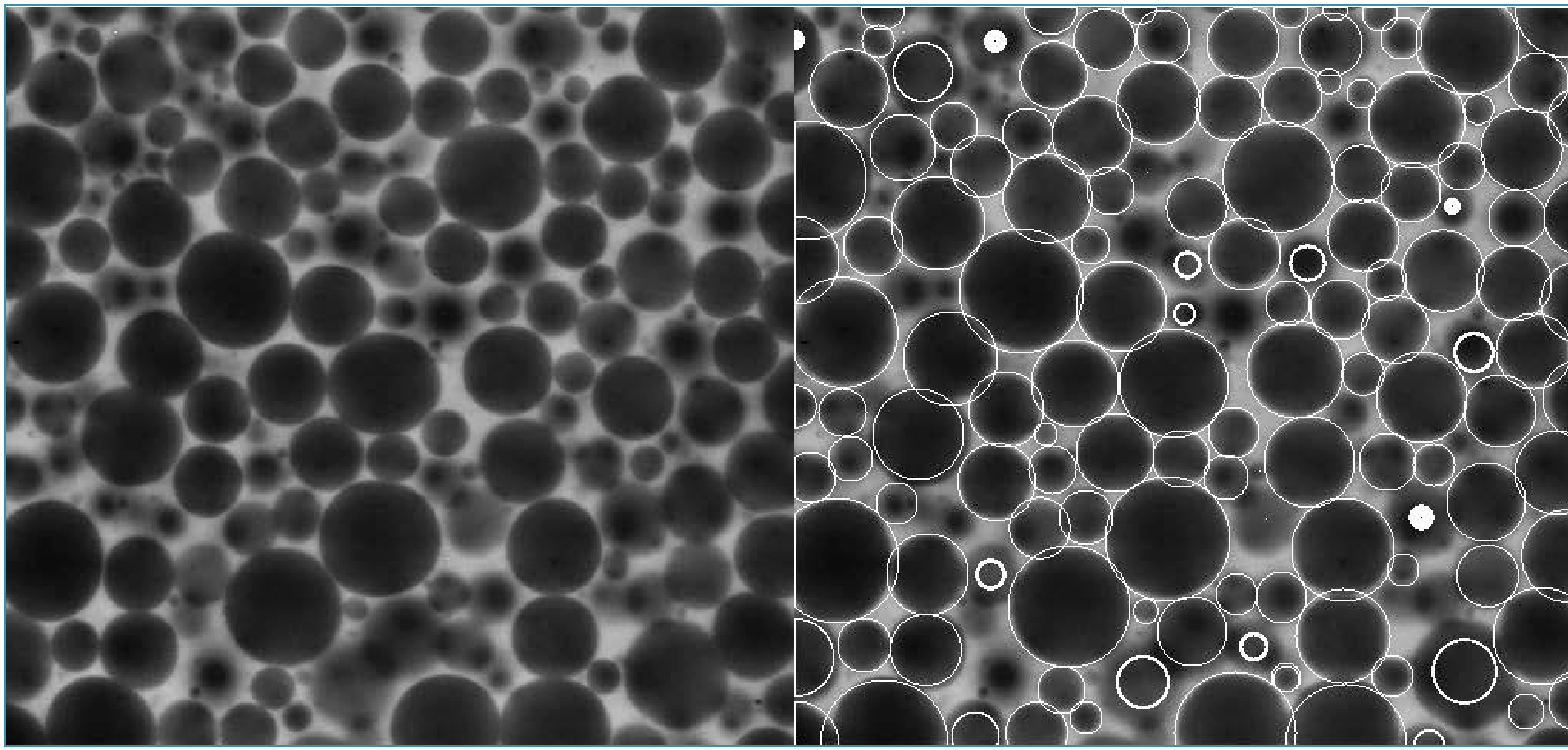
- Morphological distance operation
  - Generate a thresholded image
  - Assign Euclidian distance to nearest ‘background’ voxel



- Result
  - Landscape where dark voids (droplets) become cones
  - Peaks → centers; Height → effective radius
  - Process cones to obtain droplets coordinates and radii

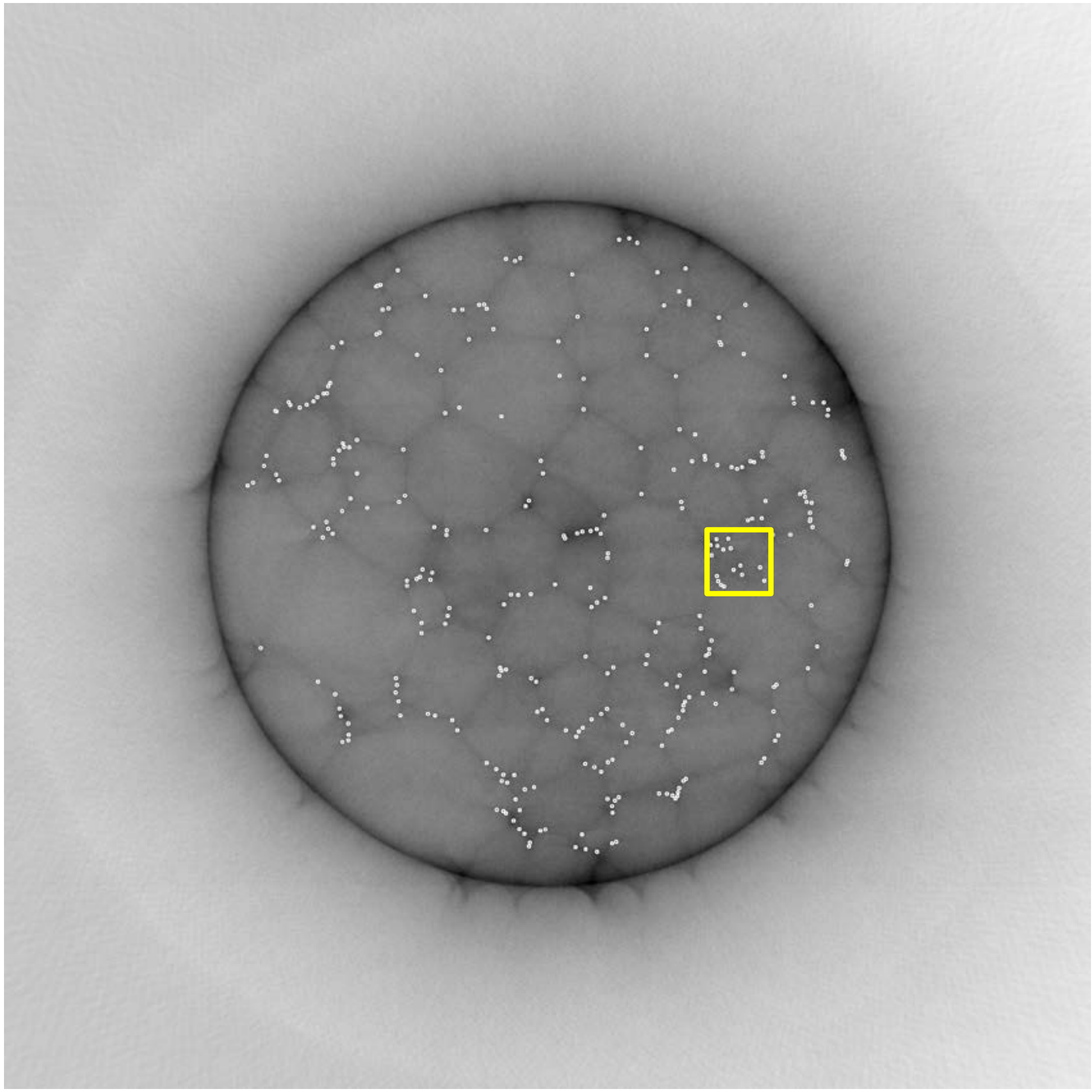
*Similar to method described by Penfold, et.al., ***Langmuir*** 2005*

Flying through the “foam”

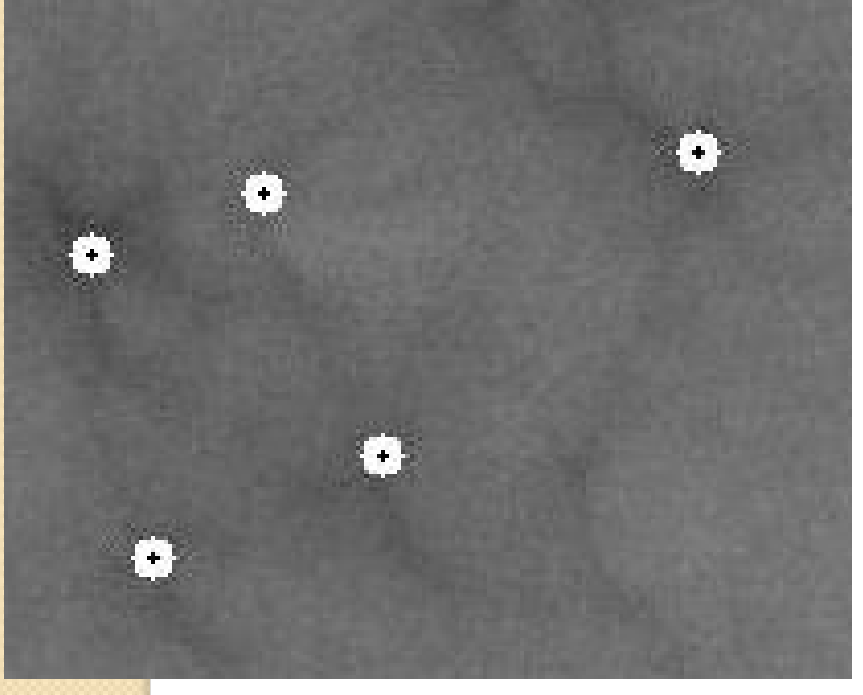
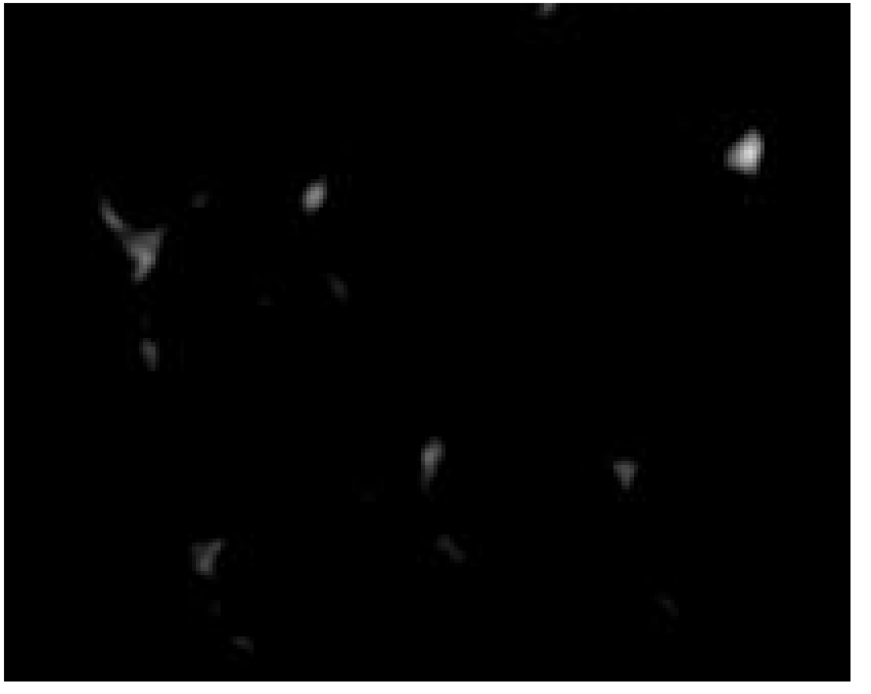


Step 2

Tracking Plateau Borders

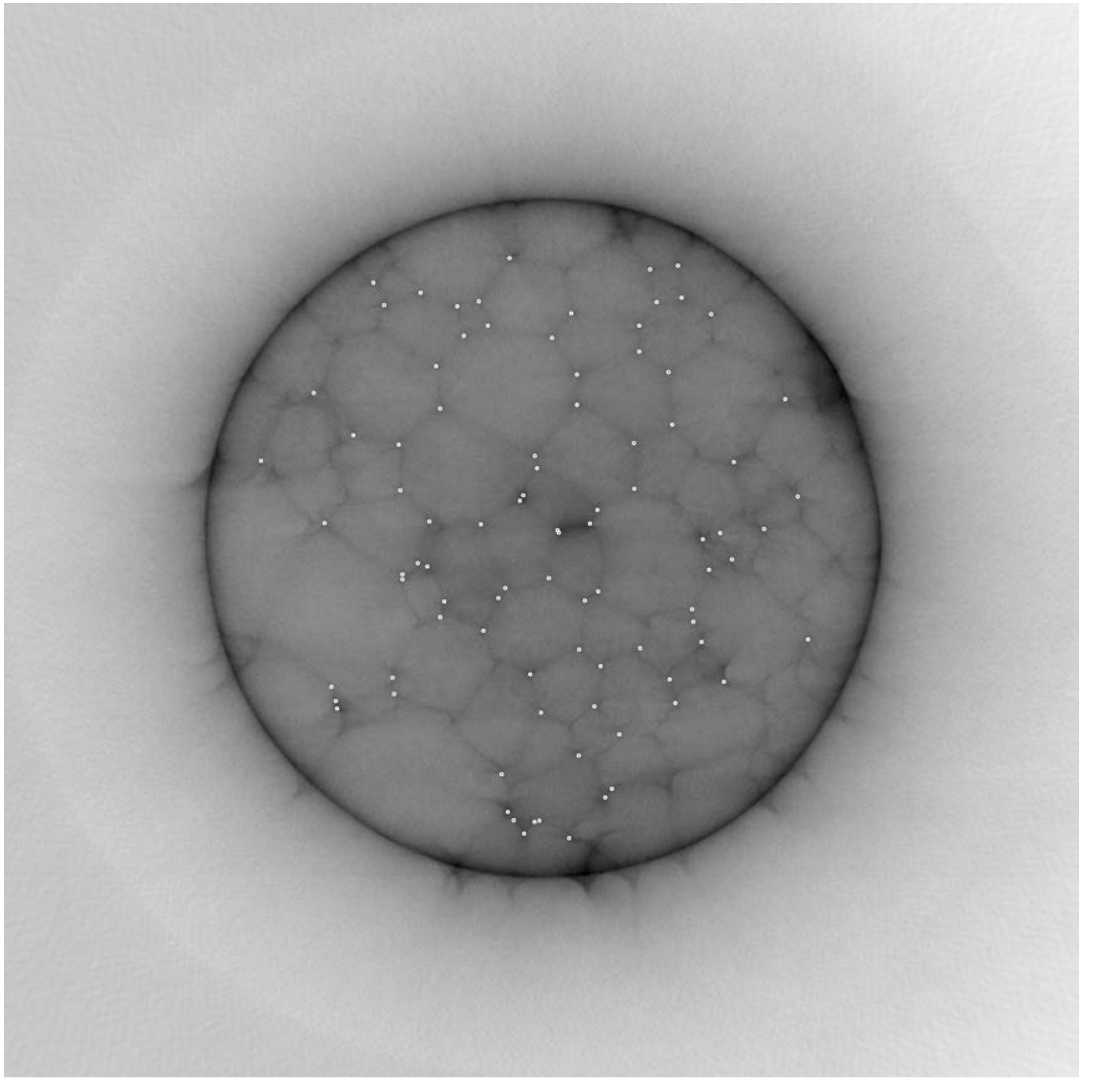


Deciding What is a Plateau Border

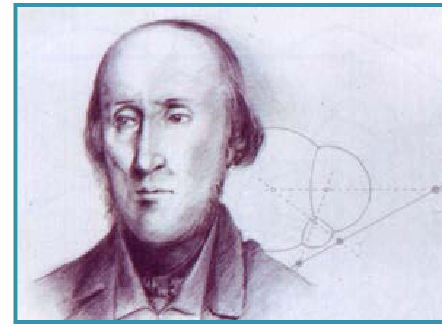
 

Step 2

New Plateau Borders

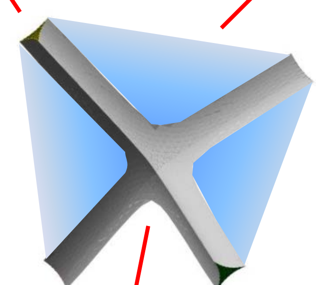


A recognizable network

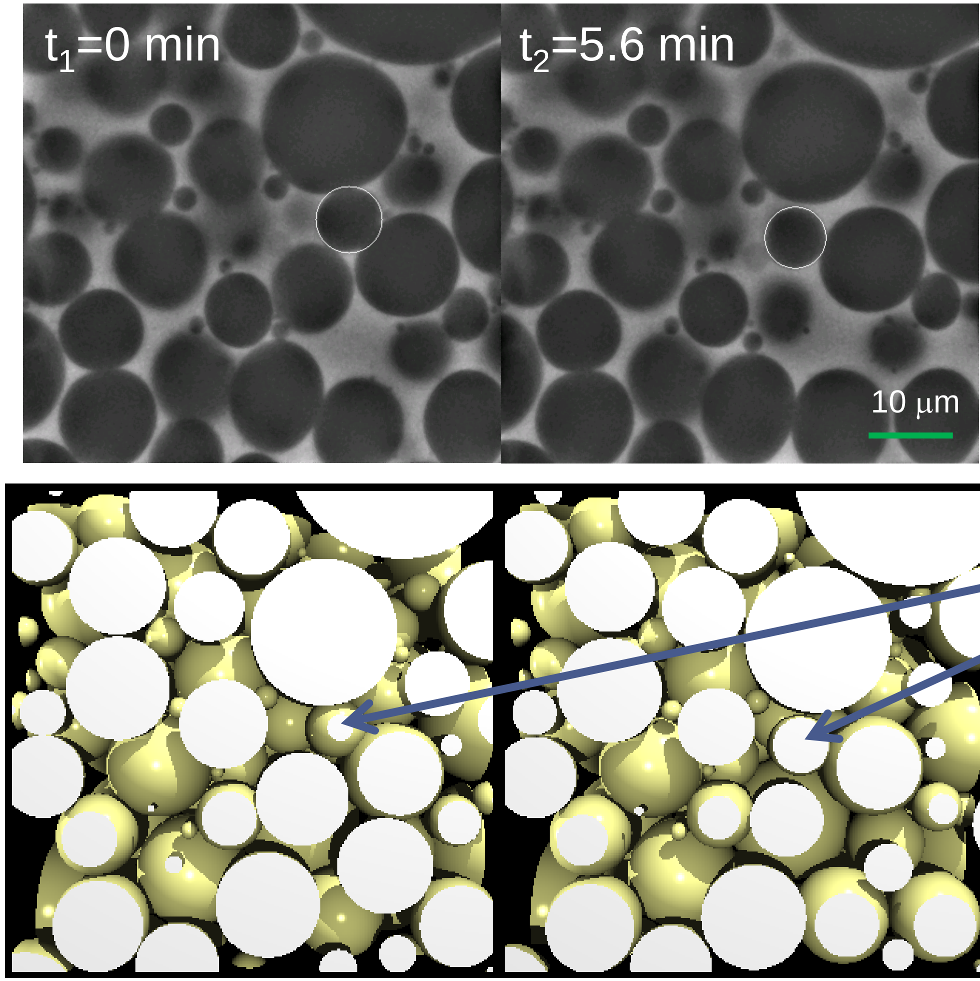

Joseph Plateau

Plateau's rules for mechanical equilibrium (dry foam)

- Films have constant curvature and meet three at a time at 120º
- Borders intersect four at a time at 109.47º



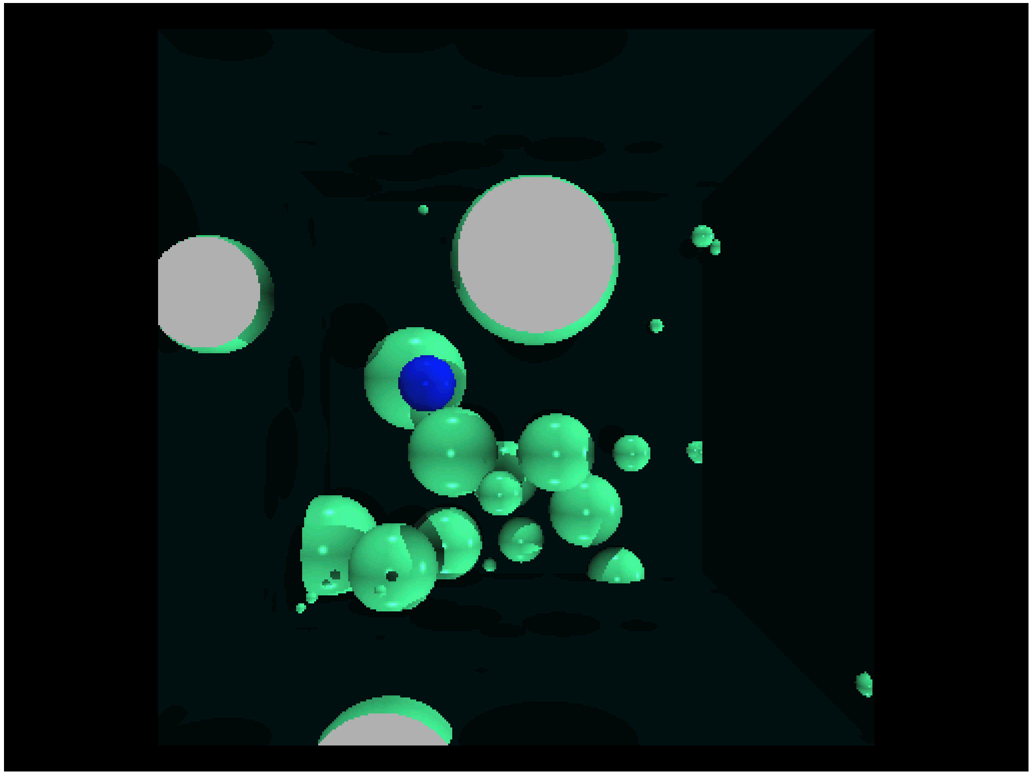
Investigate rearrangements in 3D



Droplet marked in the micrograph

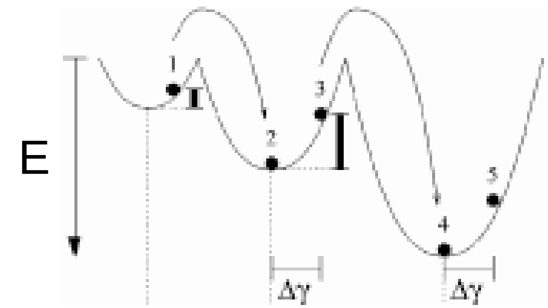
And painted blue in the next slide

Investigate rearrangements in 3D



Soft glass rheology model

- The elements of the system are trapped in potential wells of energy E
- They escape their traps via an activation process



In foams, disorder provides the energy barriers, and coarsening/rearrangements the activation process

Self-organized criticality

- The system arranges itself near a critical point
- Small disturbances produce avalanche-like collective rearrangements

In foam, coarsening could be the mechanism of self organization

A dynamic conspiracy

In foams **coarsening** and **drainage** occur **simultaneously**.

...bubble growth squeezes the Plateau borders, enhancing drainage which increase gas diffusion intensifying bubble growth...

Leads to an interdependent rate of coarsening and drainage!

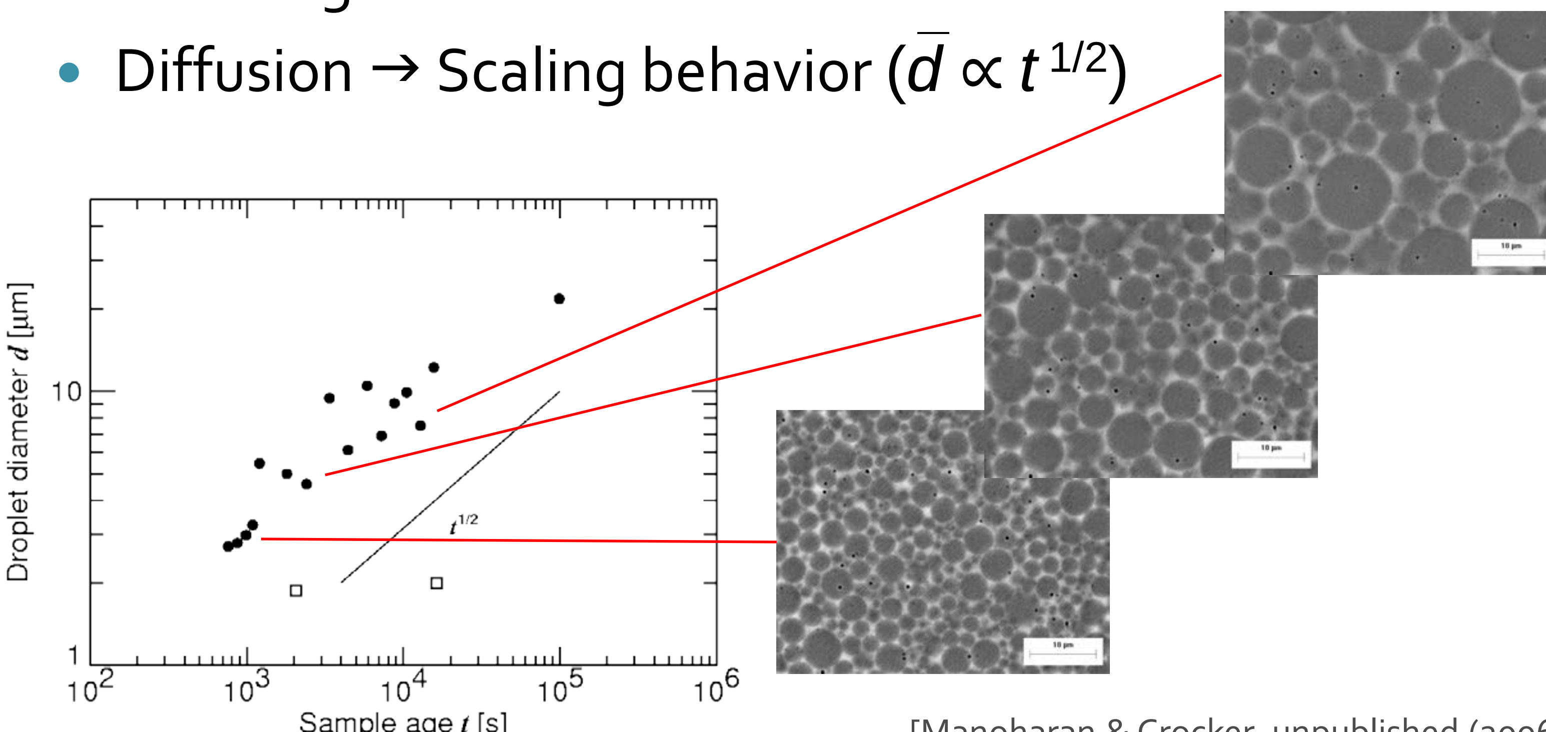
Challenge:

Understand the mutual interplay of these dynamical processes to predict and control foam evolution

Coarsening is common to other systems

Coarsening emulsion

- Diffusion → Scaling behavior ($\bar{d} \propto t^{1/2}$)



[Manoharan & Crocker, unpublished (2006)]

- Also domain growth in solid-liquid coexistence, binary alloys, proteins, etc