DTU

Imaging Foams

Rajmund Mokso
DTU Physics, Denmark
Lund University, Sweden

Outline

- Flow of liquid foam
  - around an obstacle
  - in constriction

- Dynamic tomography for various foams

- The tomographic workflow

Foams are all around

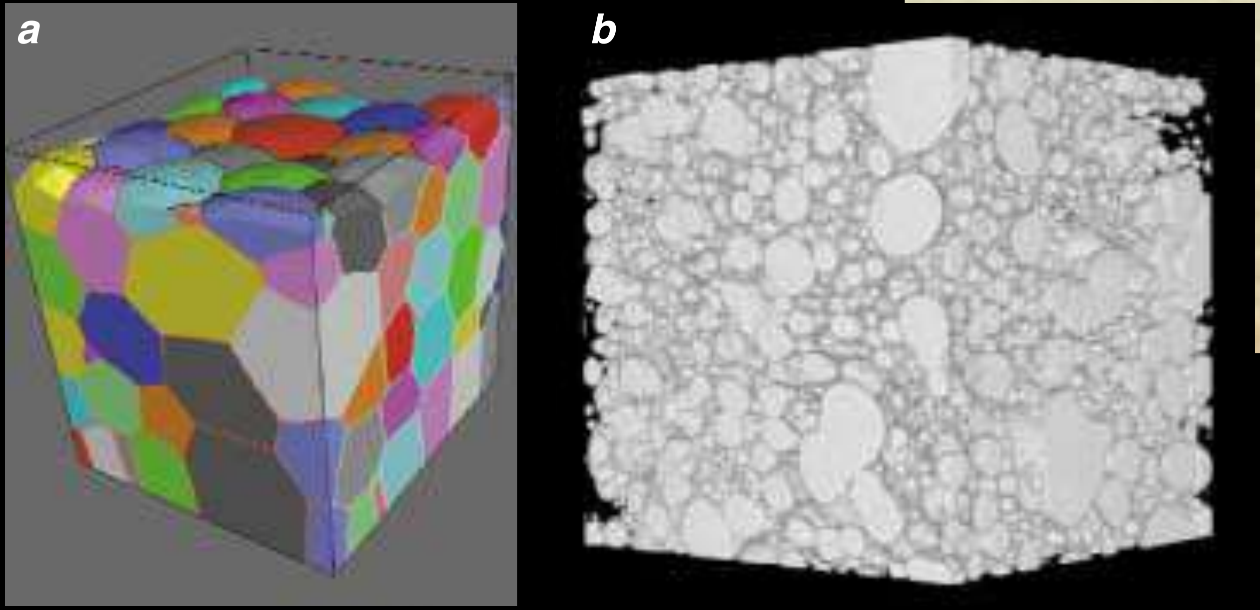
Food /drinks

Fire fighting

Ore / oil extraction

Nature

The first synchrotron tomography of a foam



chocolate

La vie éphémère

MICHÈLE VIGNES-ADLER · FRANÇOIS GRANER

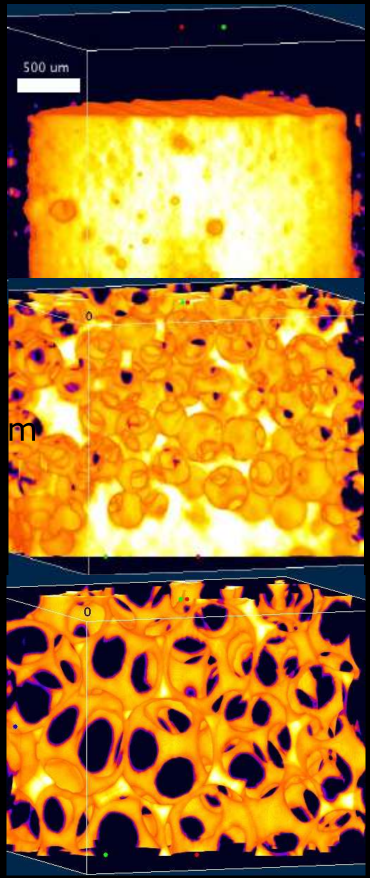
La mousse du champagne disparaît rapidement. Celle de la bière persiste davantage. Les physiciens découvrent les mécanismes responsables de la fugacité des mousses.

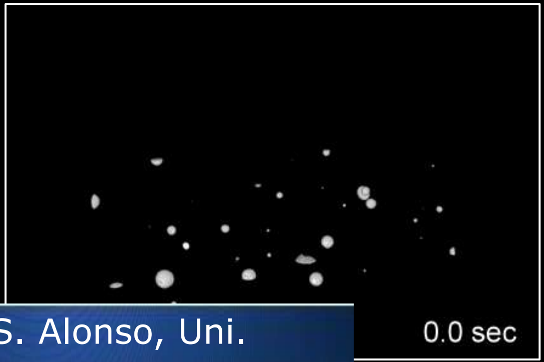
ID19, ESRF Grenoble, France

Adler, Graner, Pour la Science 2002

In-situ foaming

PU foams





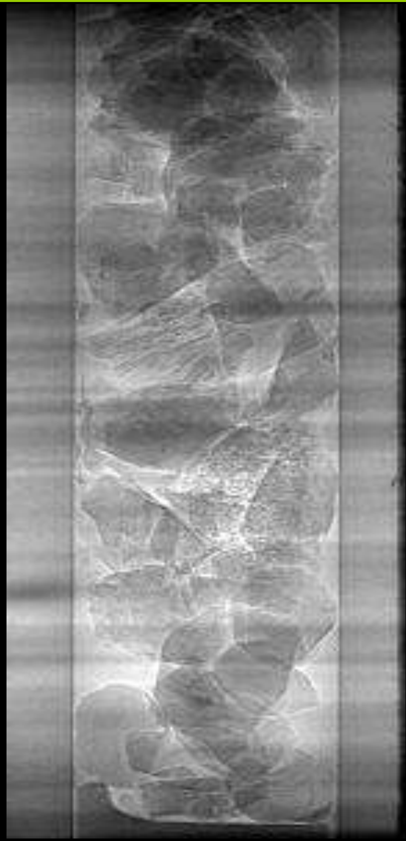
E. Solorzano, S. Alonso, Uni. Valladolid

Fast tomogrpahy: motion artifact

Localised events in foam during tomographic acquisition

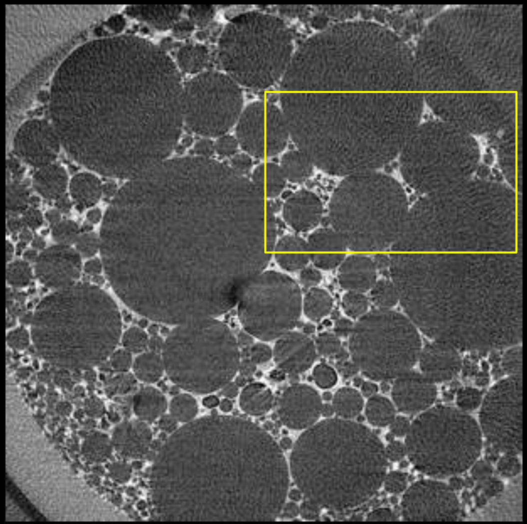
Angular projections

Projections are modified during scan



Tomographic slice

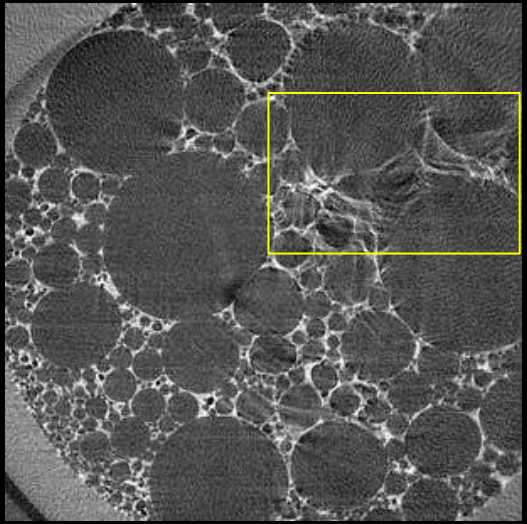
$t_{SCAN} < \delta R / V_{EVOL}$



t_0

Tomographic slice

$t_{SCAN} > \delta R / V_{EVOL}$



$t_0 + 2.t_{SCAN}$

Mokso et al, J. Phys 2013

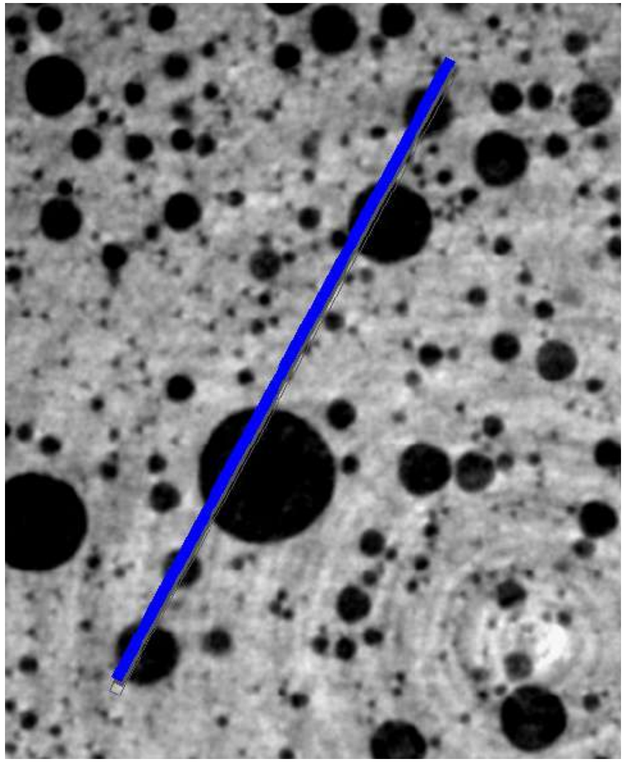
Tomographic microscopy: Why phase?

PU foam, 20 Hz tomography

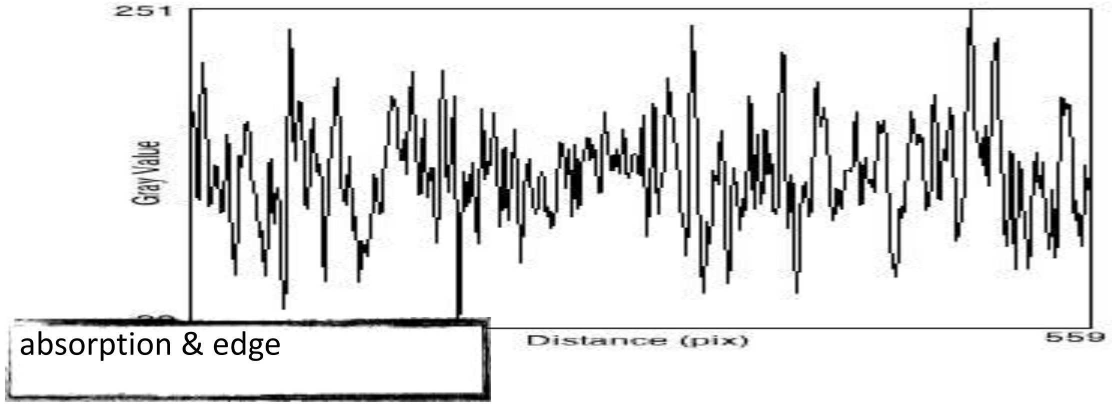
- Refractive index n

$$\boxed{n = 1 - \delta + i\,\beta}$$

$$\delta \gg \beta$$



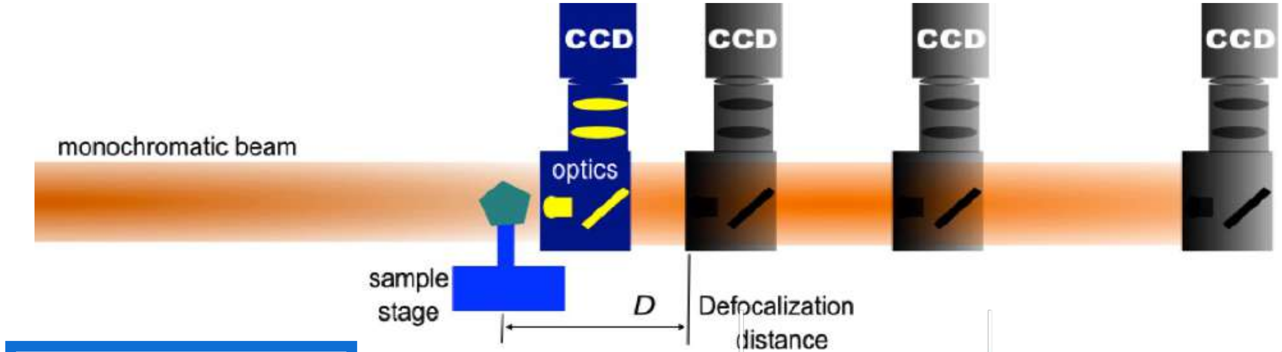
Windhab, SLS experiment, May 2014



Phase contrast tomography

Mokso et al., J. Phys. D, 2013

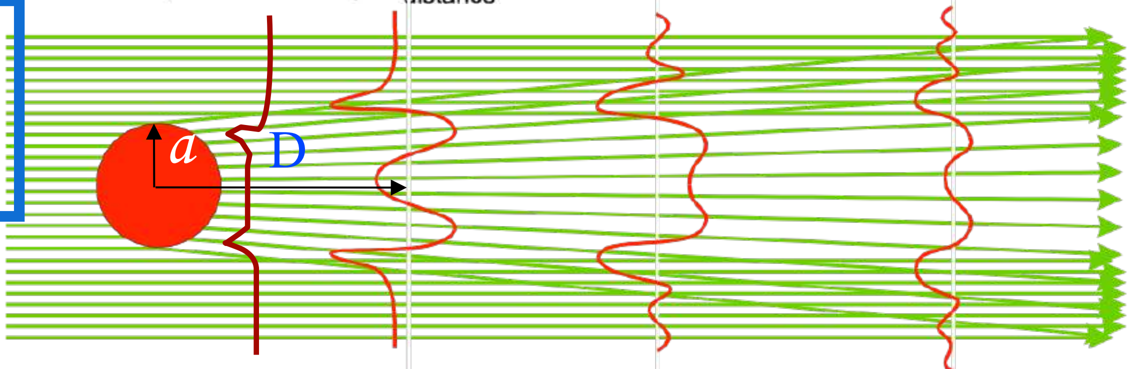
Phase contrast in free space propagation



$$U_D(x) = U_0(x) \otimes \boxed{\sqrt{\frac{-i\pi}{\lambda . D}} . e^{\frac{i\pi}{\lambda . D} . x^2}}$$

propagator

Born, M., and E. Wolf, 1990, Principles of Optics

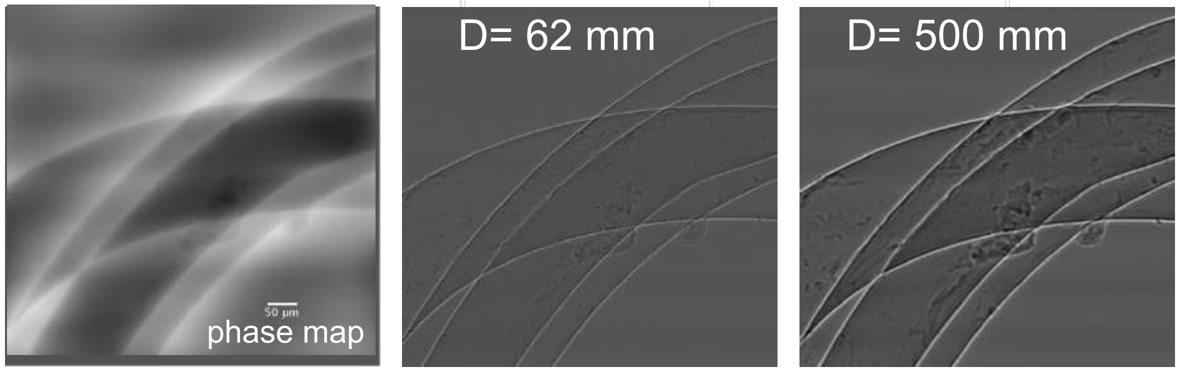


Three phase fibers

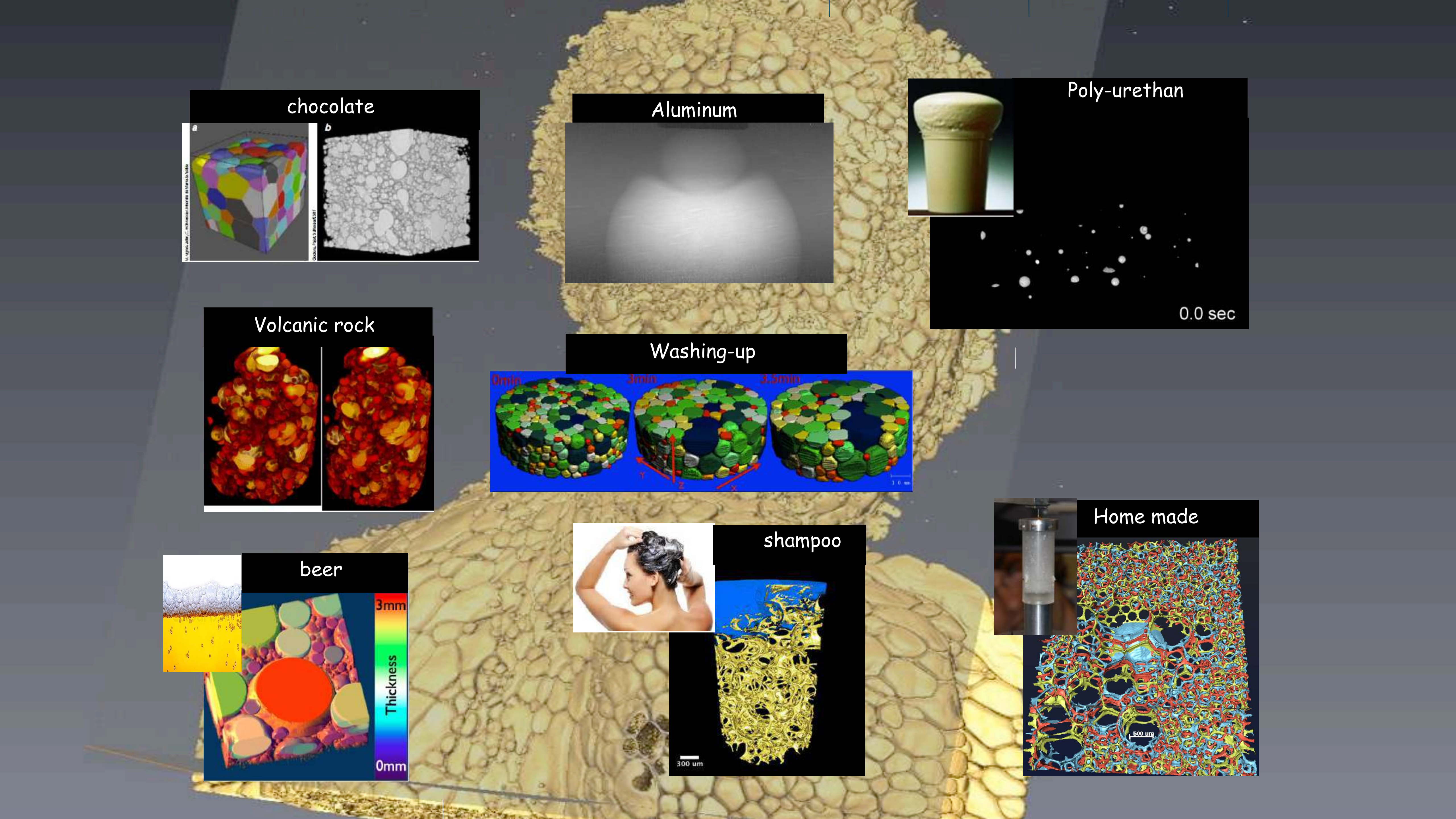
Fresnel diffraction

Partially coherent illumination

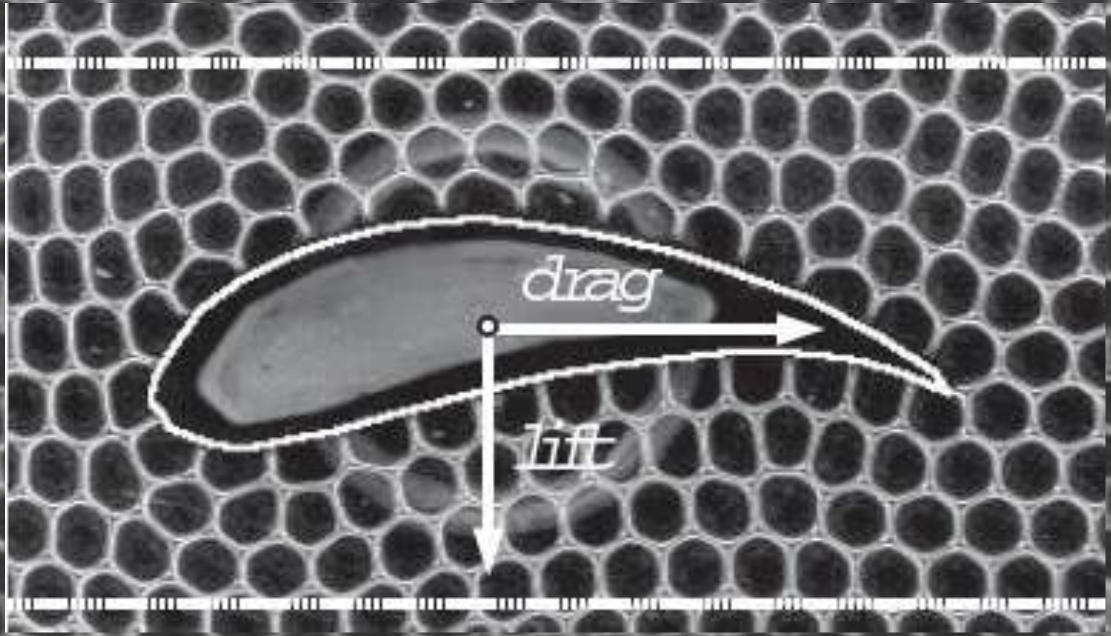
$$\varphi(f) = \frac{\sum_m \sin(\pi \lambda D_m f^2) I_m(f)}{\sum_m 2\sin^2(\pi \lambda D_m f^2)}$$



Cloetens et al. J. Phys. 1999


chocolate
Aluminum
Poly-urethan
0.0 sec
Volcanic rock
Washing-up
0min
3min
3.5min
Home made
500 um
shampoo
300 um
beer
3mm
Thickness
0mm

Flow around a wing

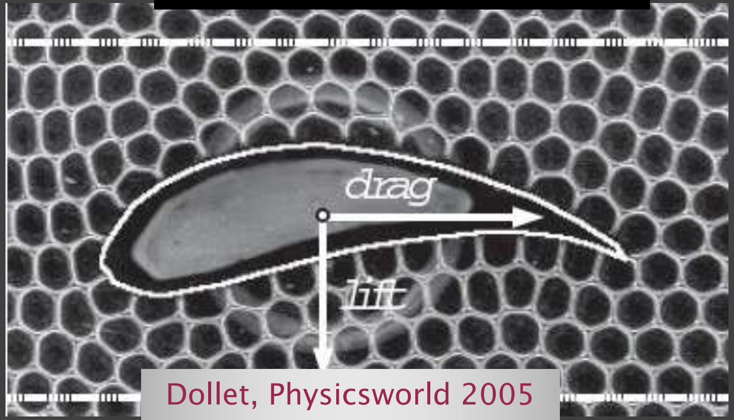


Dollet, Physicsworld 2005

What would we like to know about foams

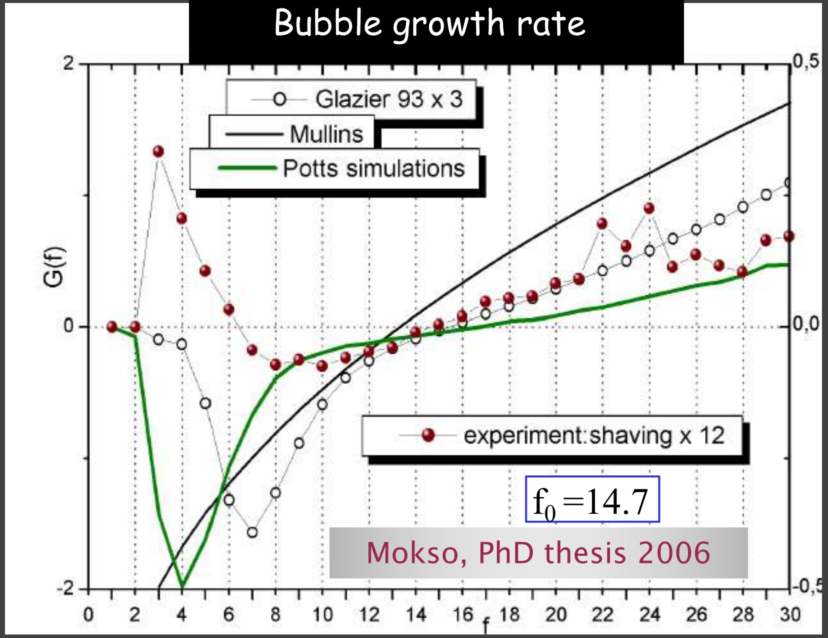
- How do individual bubbles grow and shrink?
- Foam stability?
- Do the Bubble Size Distribution and Bubble Topology Distribution reach a time invariant *scaling* state?
- How do Correlations evolve in time?
- Foams Under stress? Behavior in the presence of external forces?
- Drainage and redistribution of fluid
- How do individual bubbles change shape?
- How do macroscopic properties depend on Quantifiers?

Flow around a wing



Dollet, Physicsworld 2005

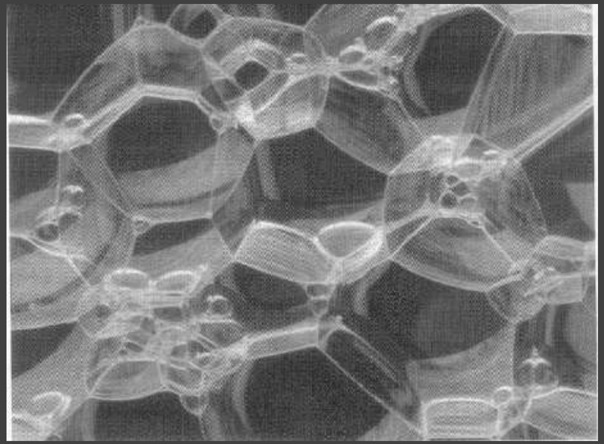
Bubble growth rate



Mokso, PhD thesis 2006

In-situ foaming

Liquid foam:



dispersion of a gaseous phase

inside a continuous liquid phase.

Interfaces stabilized by surfactants.

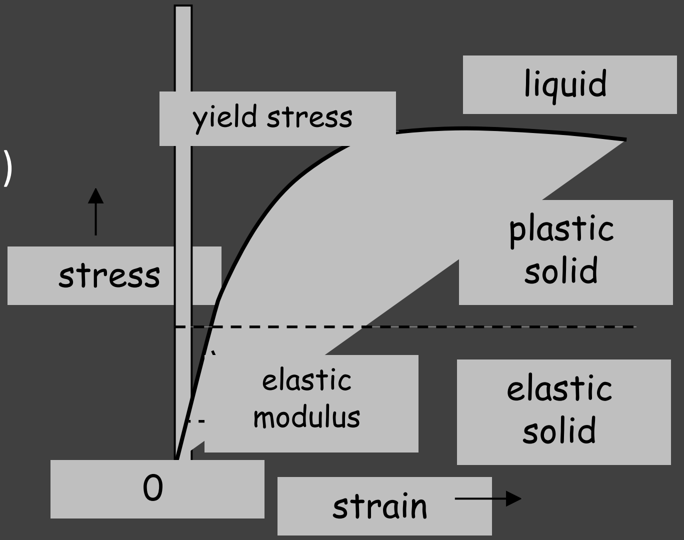
- Multiscale structure : films (micro) – bubbles (meso) – foam (macro)

  (1) elastic solid at low strain

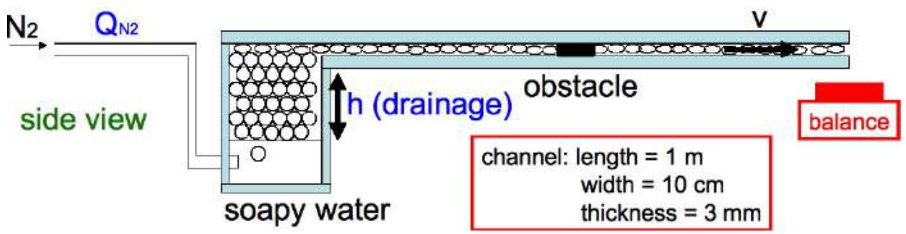
  (2) plastic solids as strain increases

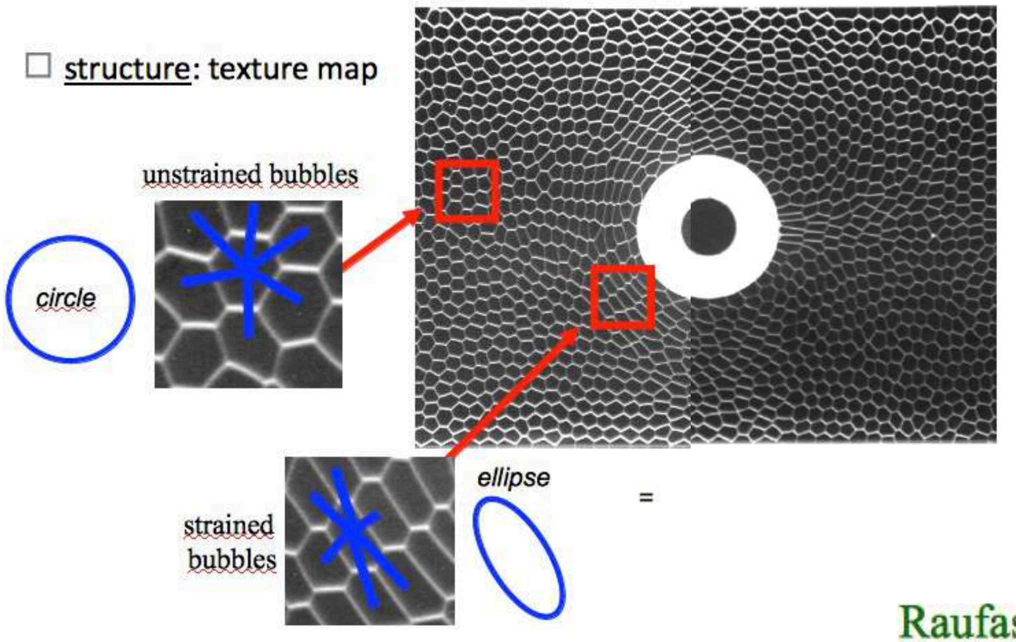
  (3) liquid-like at very high strain

- Original mechanical properties!



Foam rheology: the 3D case



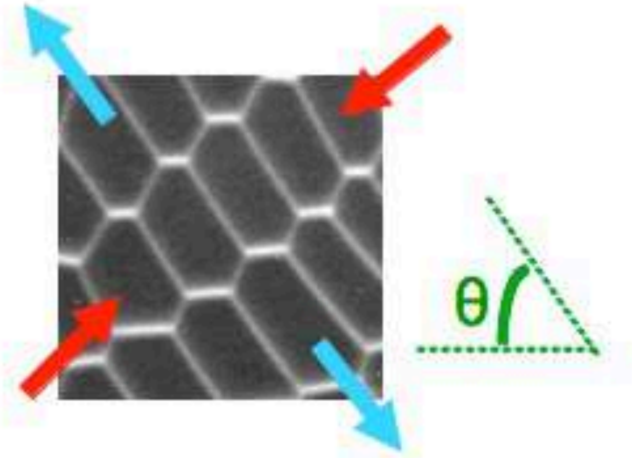


Raufaste & al, Phys. fluids 2009

Graner et l, EPJE 2008

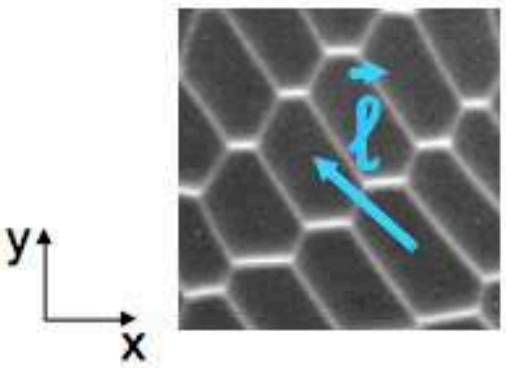
Foam rheology: 2D tensor analysis

- ☐ structure: need for tensorial tools



Necessits more than 2 informations:
elongation, compression, direction

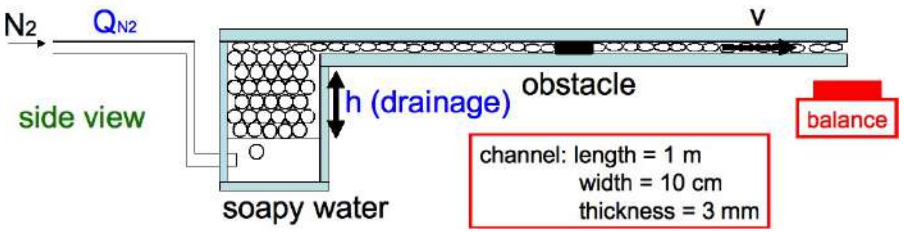
~~vector~~ tensor

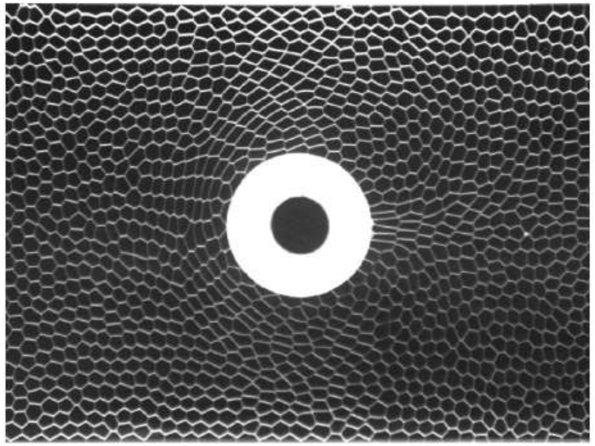


$\vec{\ell}$: link between two neighbors

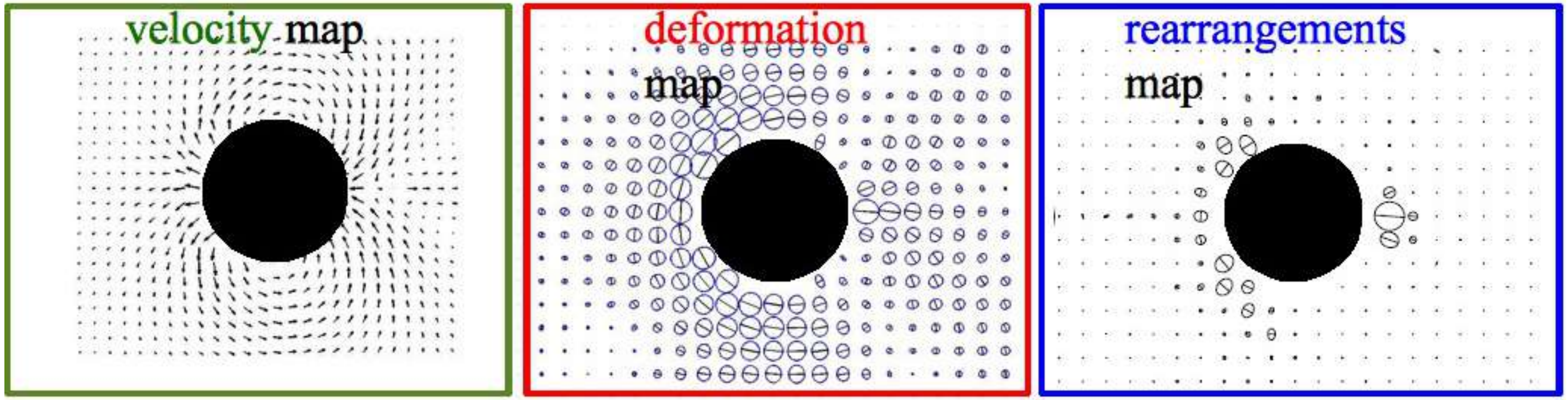
$$\bar{\bar{M}}_\ell = \begin{pmatrix} \ell_x\ell_x & \ell_x\ell_y \\ \ell_y\ell_x & \ell_y\ell_y \end{pmatrix}$$

Foam rheology: 2D tensor analysis





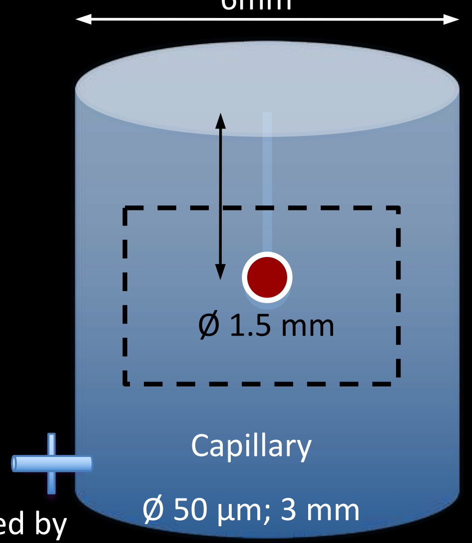
Raufaste & al, Phys. fluids 2009



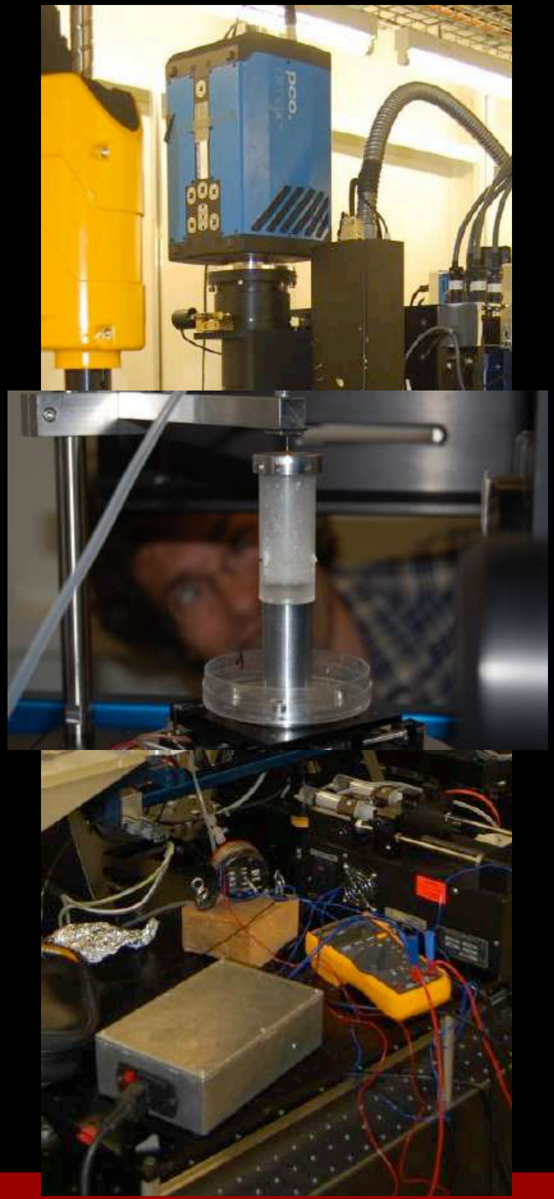
Graner et l, EPJE 2008

Foam rheology: the 3D case

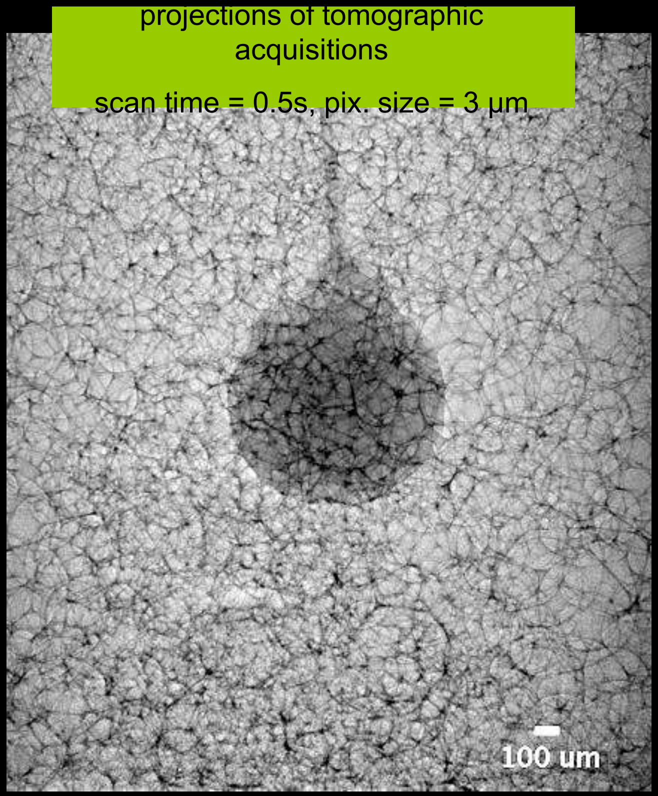
Foam flow around an obstacle



Flow induced by gravity (opening at bottom of the cell)

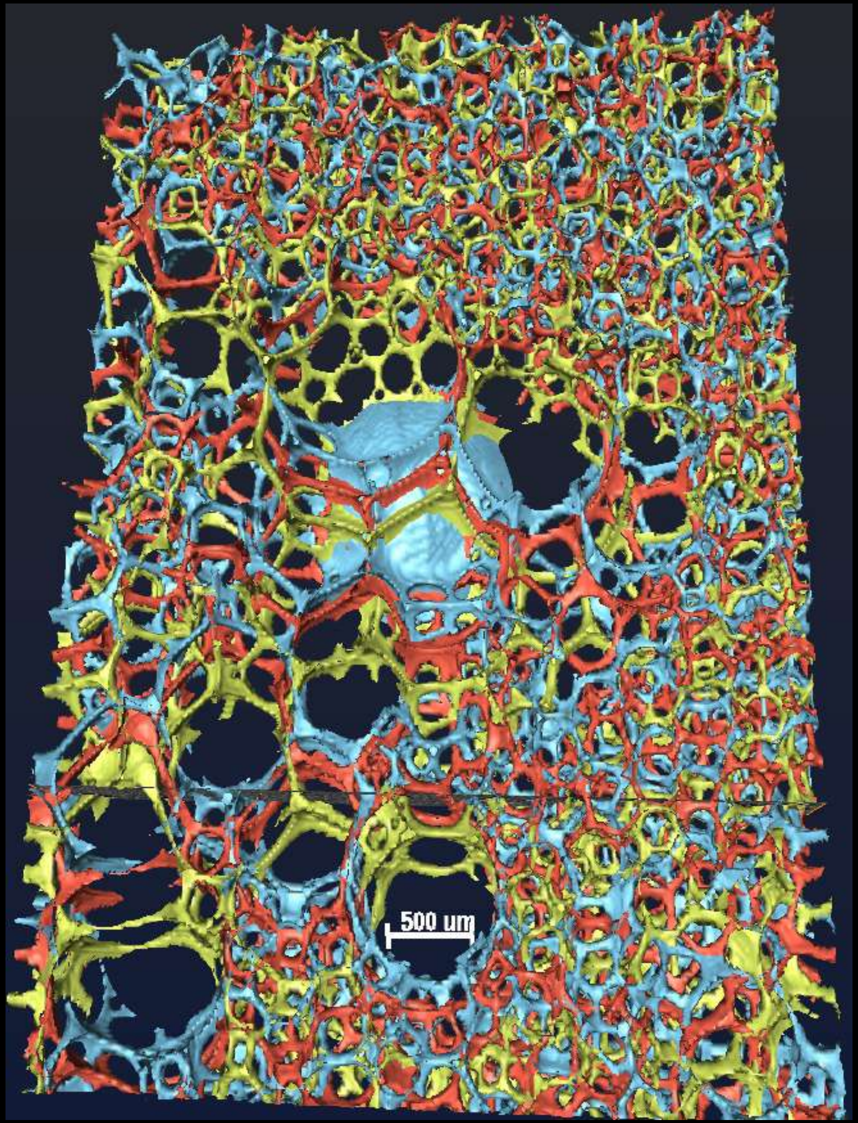


Obstacle size: 1.5 mm

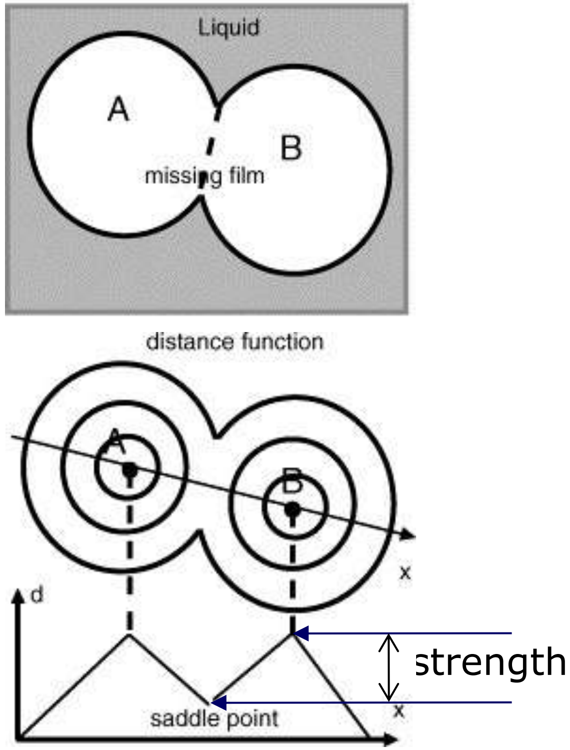


C. Raufaste, Nice
B. Dollet, Rennes
S. Santucci, Lyon

3D rendering of the foal flow

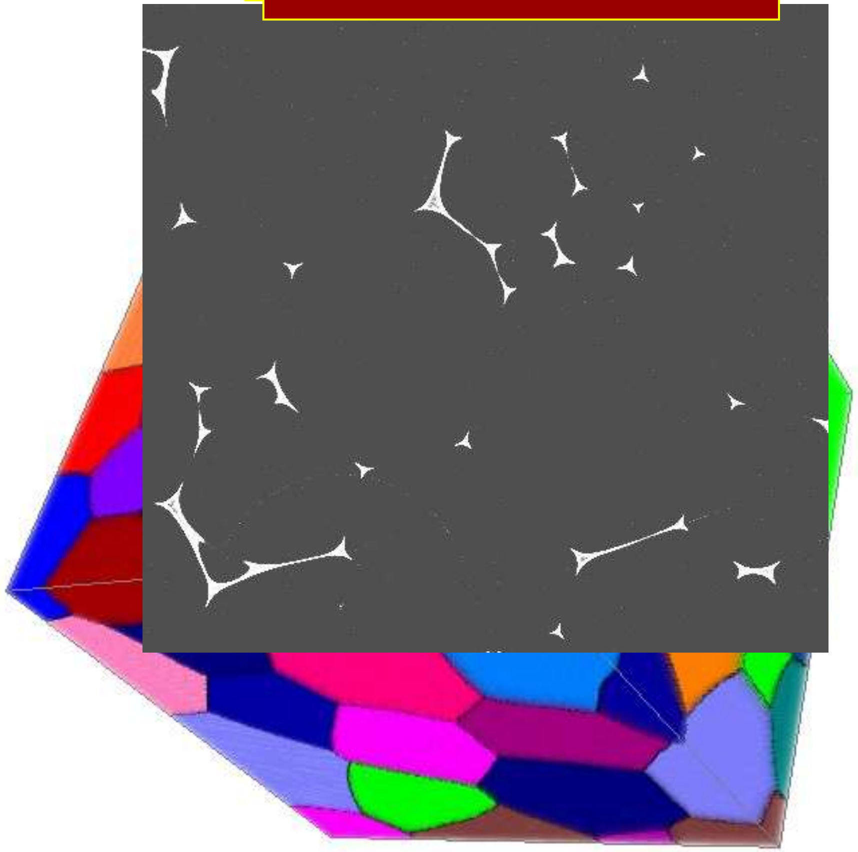


Quantitative analysis of complex cellular systems



film thickness in dry foams beyond the spatial resolution (~3-11 μm) of the setup

labeled volume

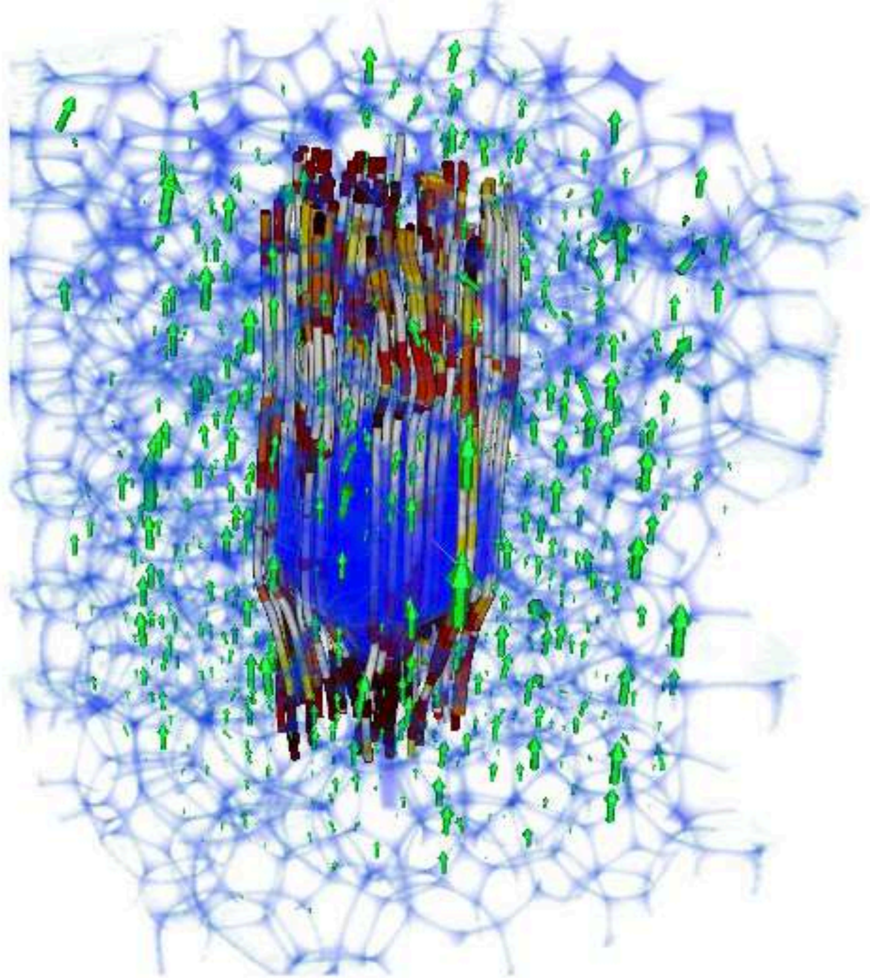


Dreft foam, liquid fraction <2%

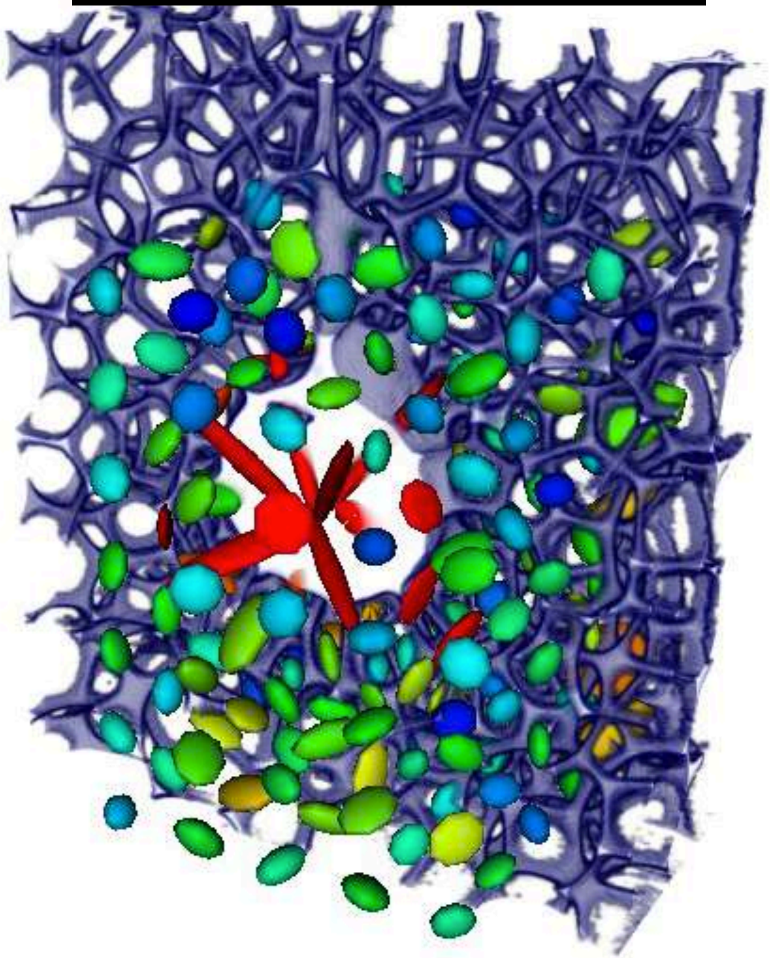
J. Lambert et al., APL (2005), Mader et al. Coloids & Surfaces (2012)

Flow around obstacle in 3D

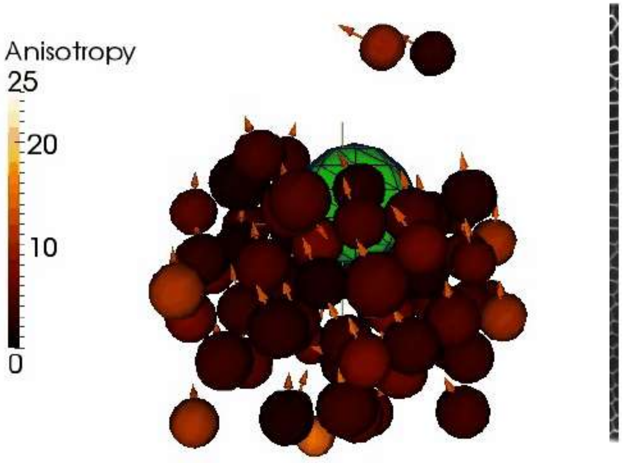
Velocity field

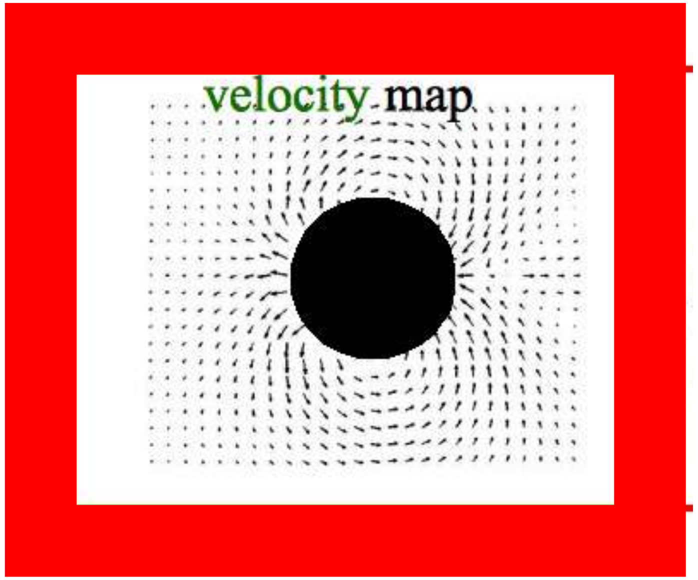


Deformation field

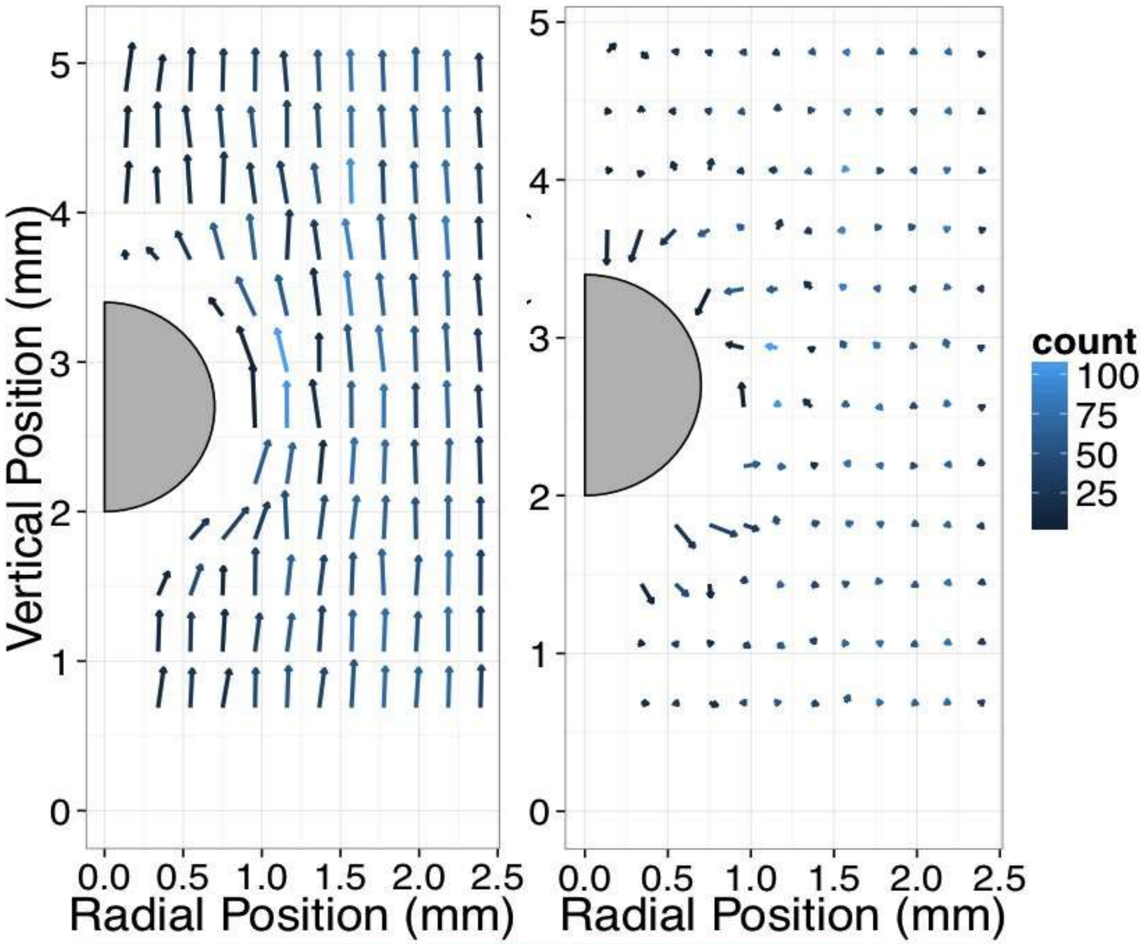


Flow around obstacle in 3D





- -Flow field more localized
- -recirculation as 2D

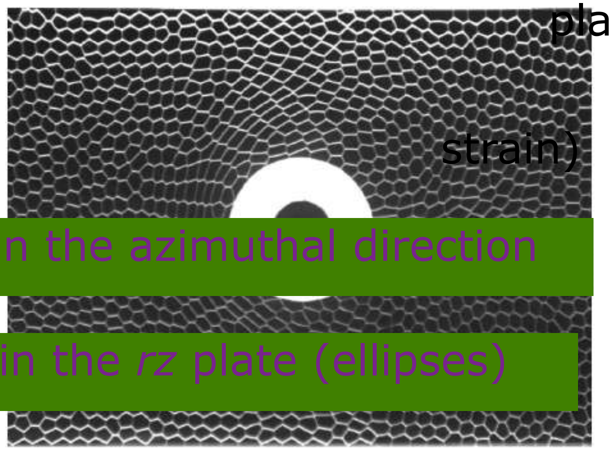


Raufaste, Mader, Dollet, Santucci & Mokso, APL 2014

Flow around obstacle in 3D

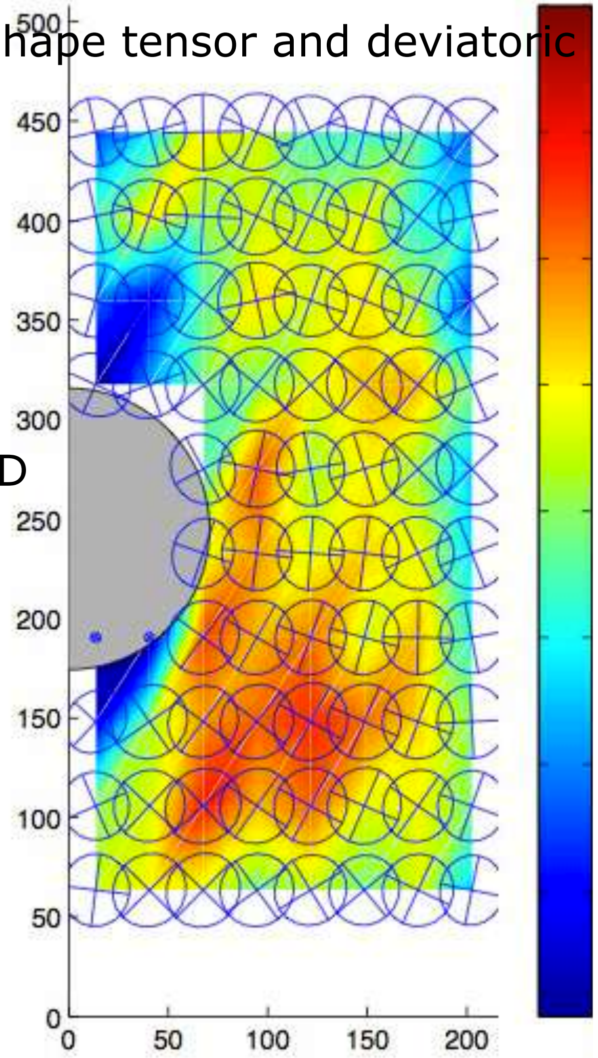
I. The deformation field in the *rz* plane

(shape tensor and deviatoric strain)

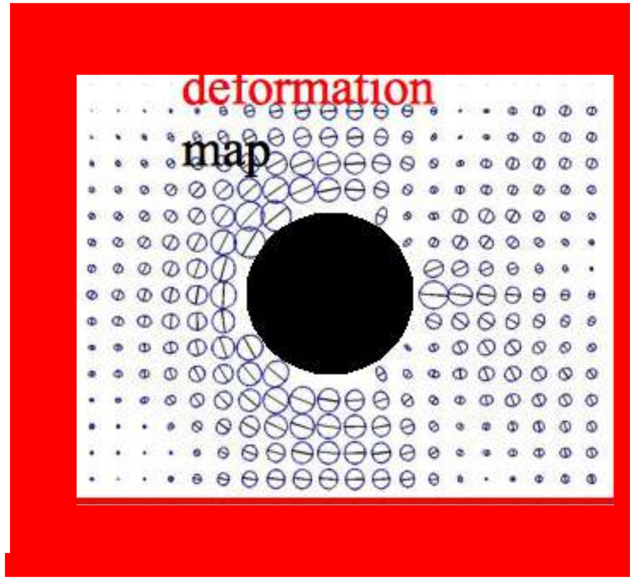


$(S_{\Theta}-R_{eff})/R_{eff}$: Deformation in the azimuthal direction (colormap)

$(S_{rz}^{+}-S_{rz}^{-})/R_{eff}$: Deformation in the *rz* plate (ellipses)

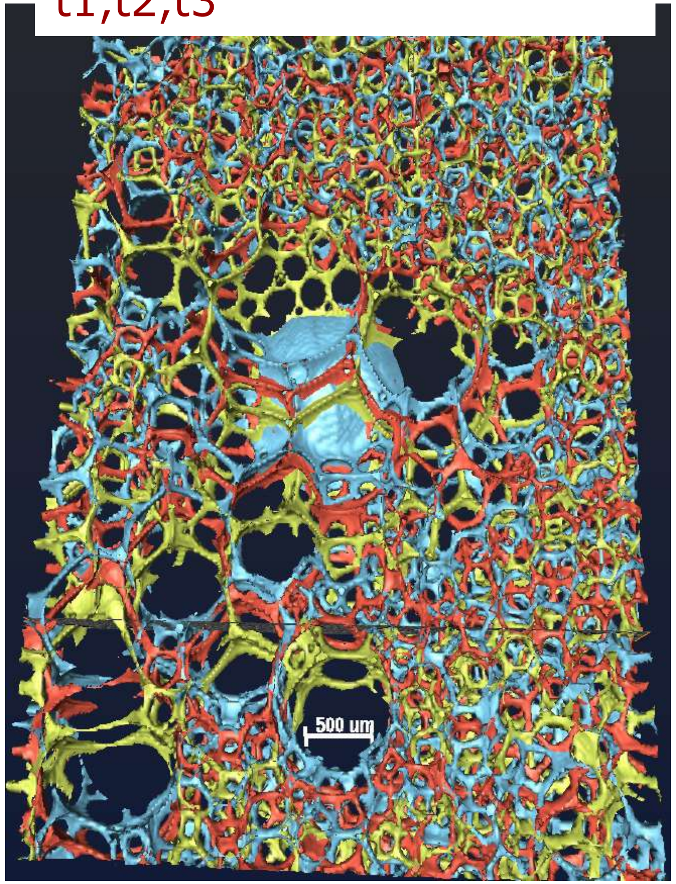


Deformation is smaller than in 2D



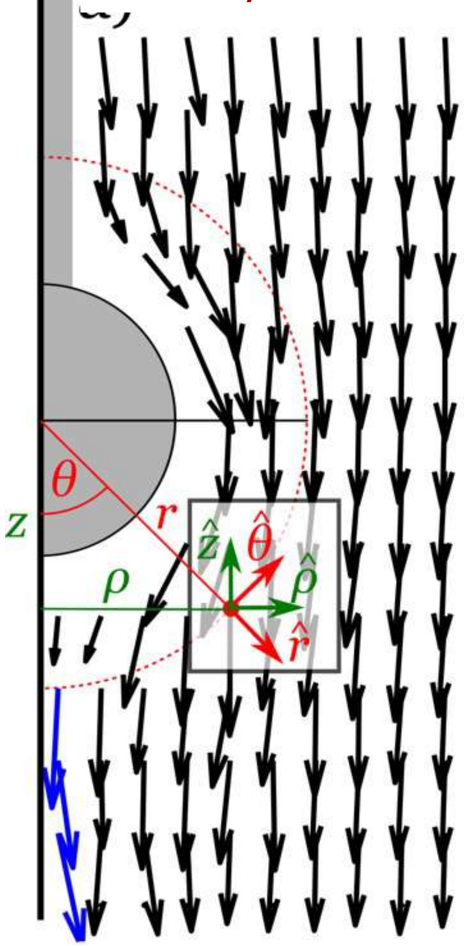
Liquid foam rheology in 3D

Isosurfaces at times t1,t2,t3

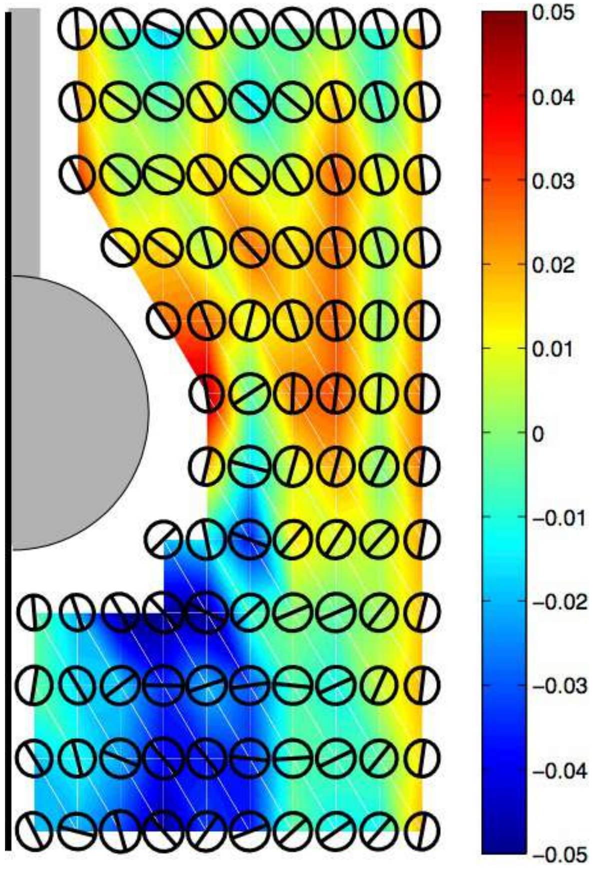


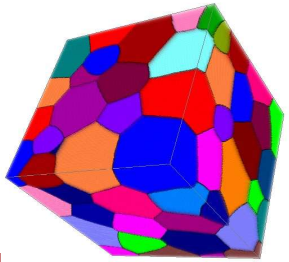
3 time instances in the flow experiment
T0=0 (blue), T1=10 s (red), T2=20 s (yellow)

Velocity field

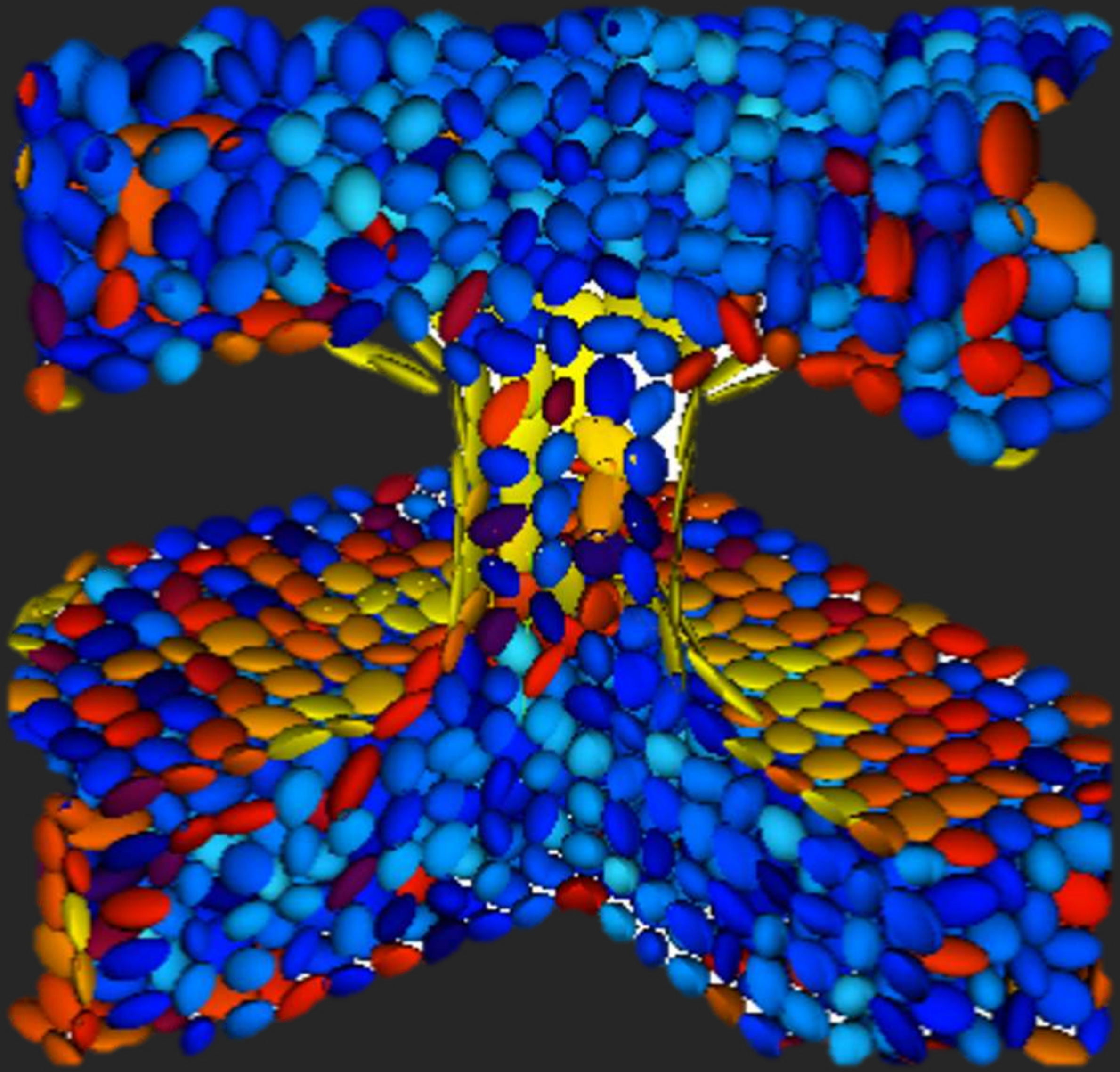


deformation field



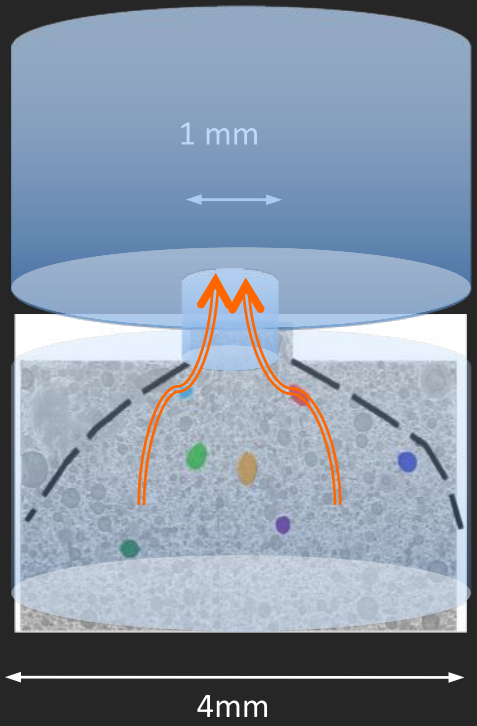


Straight constriction



Foam rheology in food science

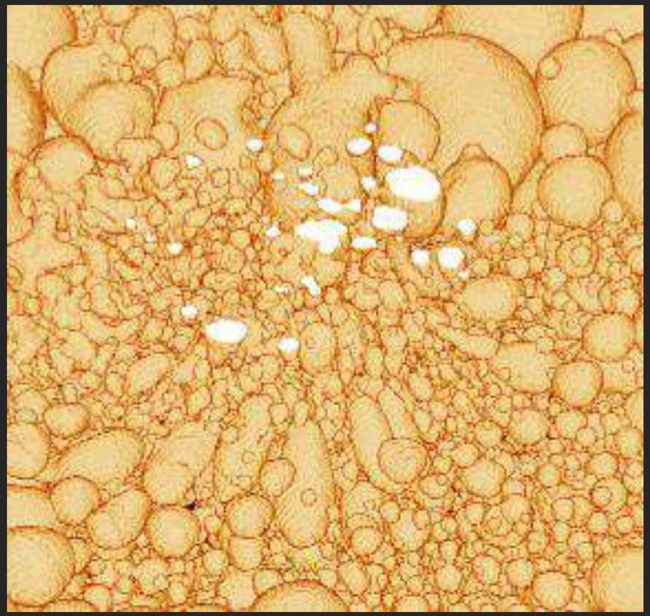
constriction (4:1:4)



20 HZ tomo

E= 20 keV, scan time = 50 ms, pix. size = 3 um

Concentrated glucose sirup

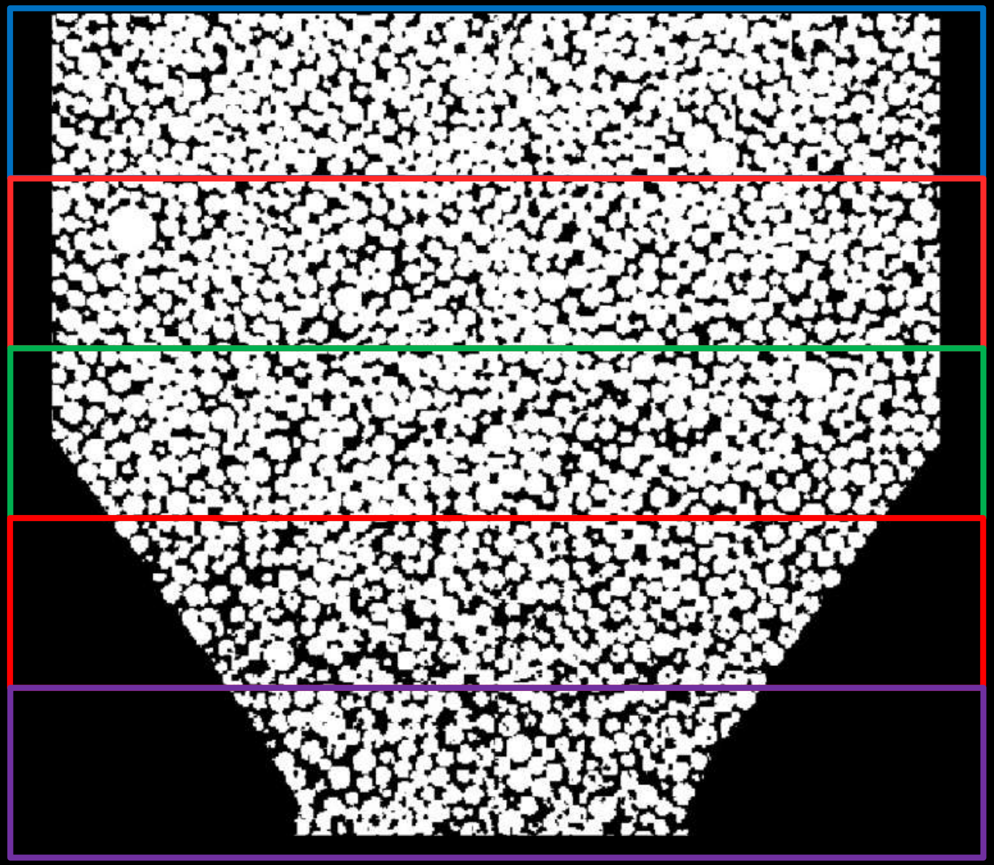


Birbaum, experiment at TOMCAT, SLS 2015

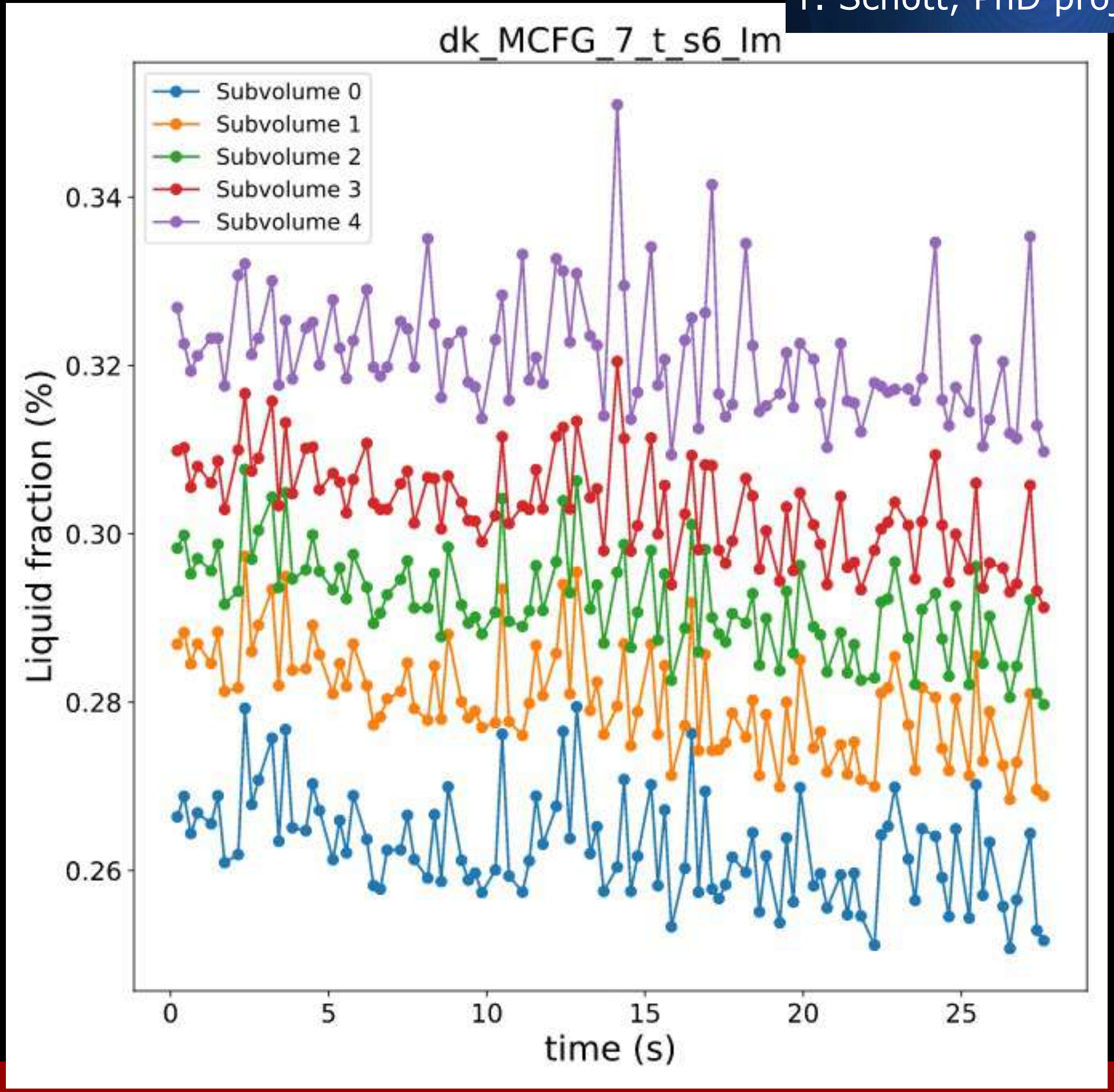
- Optimize extrusion processing and extrudor design
- Quantify the stability of foam lamellae in food production
- Elongation contraction flow of non-Newtonian fluids

Foam flow in a constriction

F. Schott, PhD project, LTH



Liquid fraction

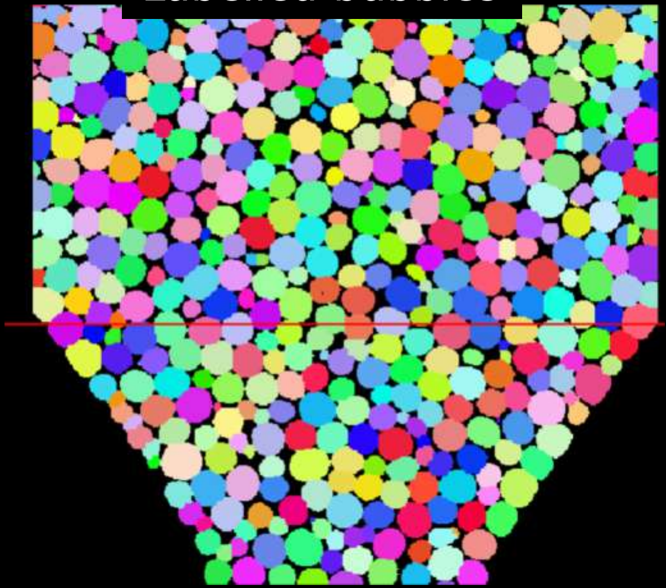


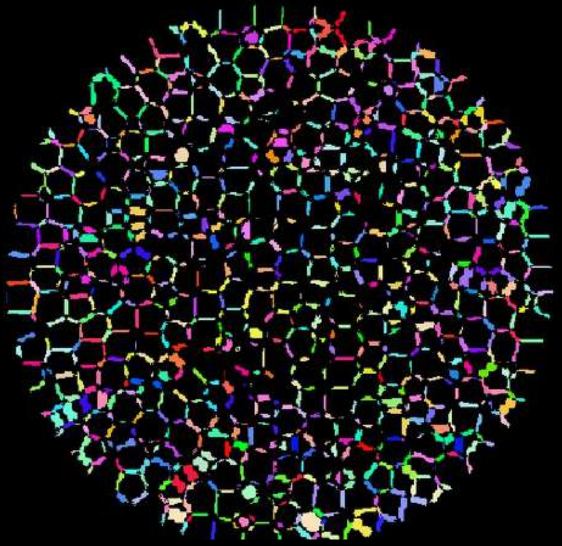
Foam flow in constriction: faces

iFoam python toolbox

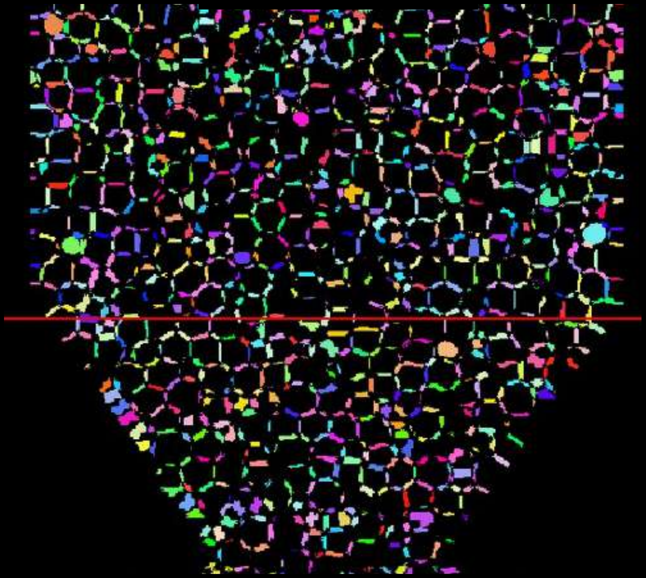
soon available

Labelled bubbles

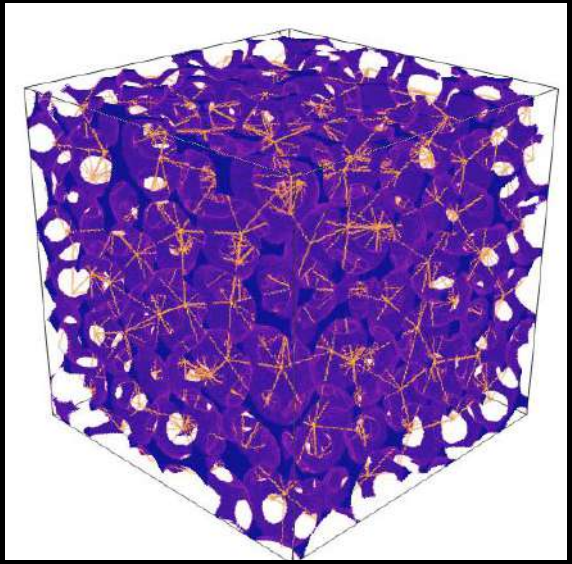




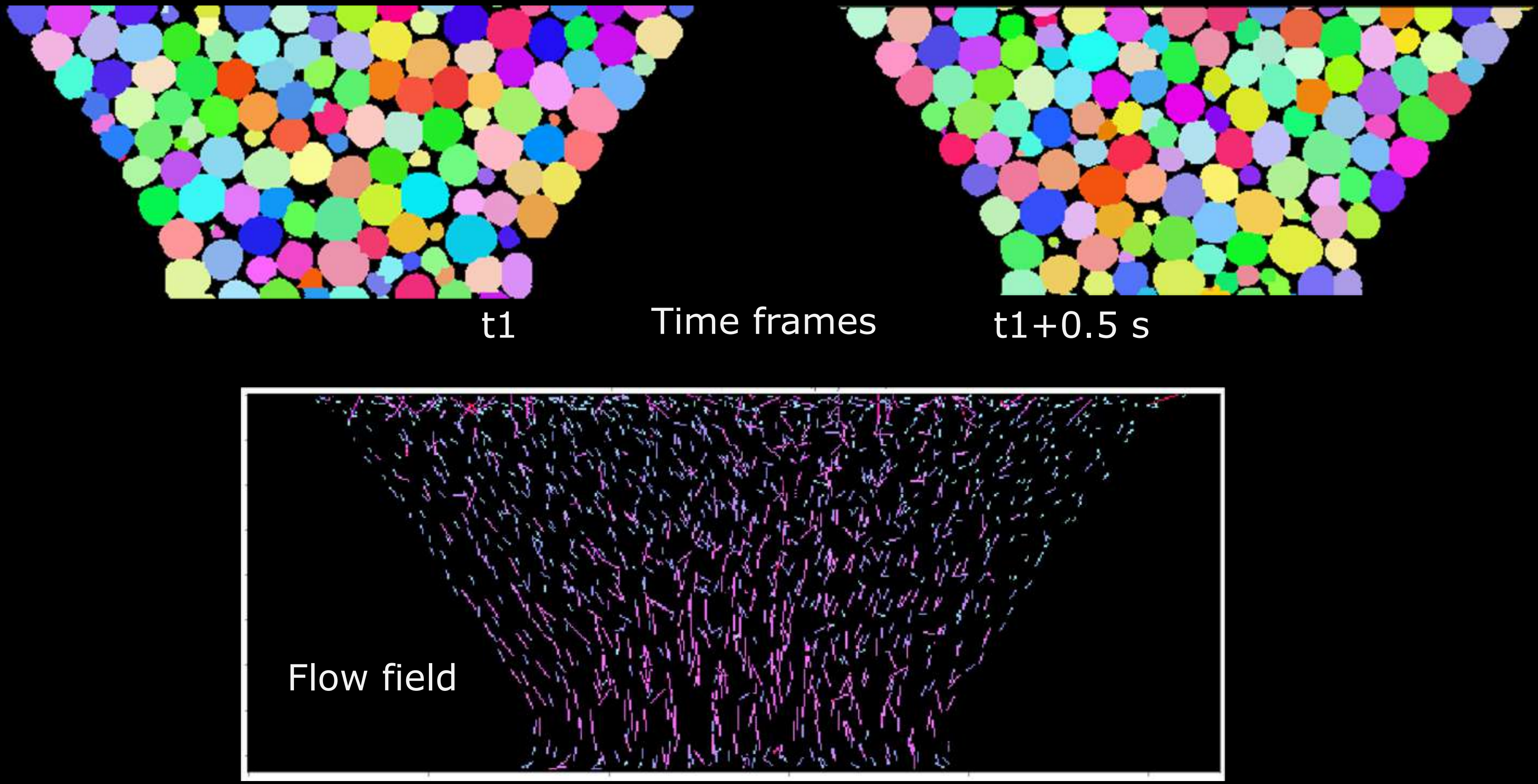
neighbours



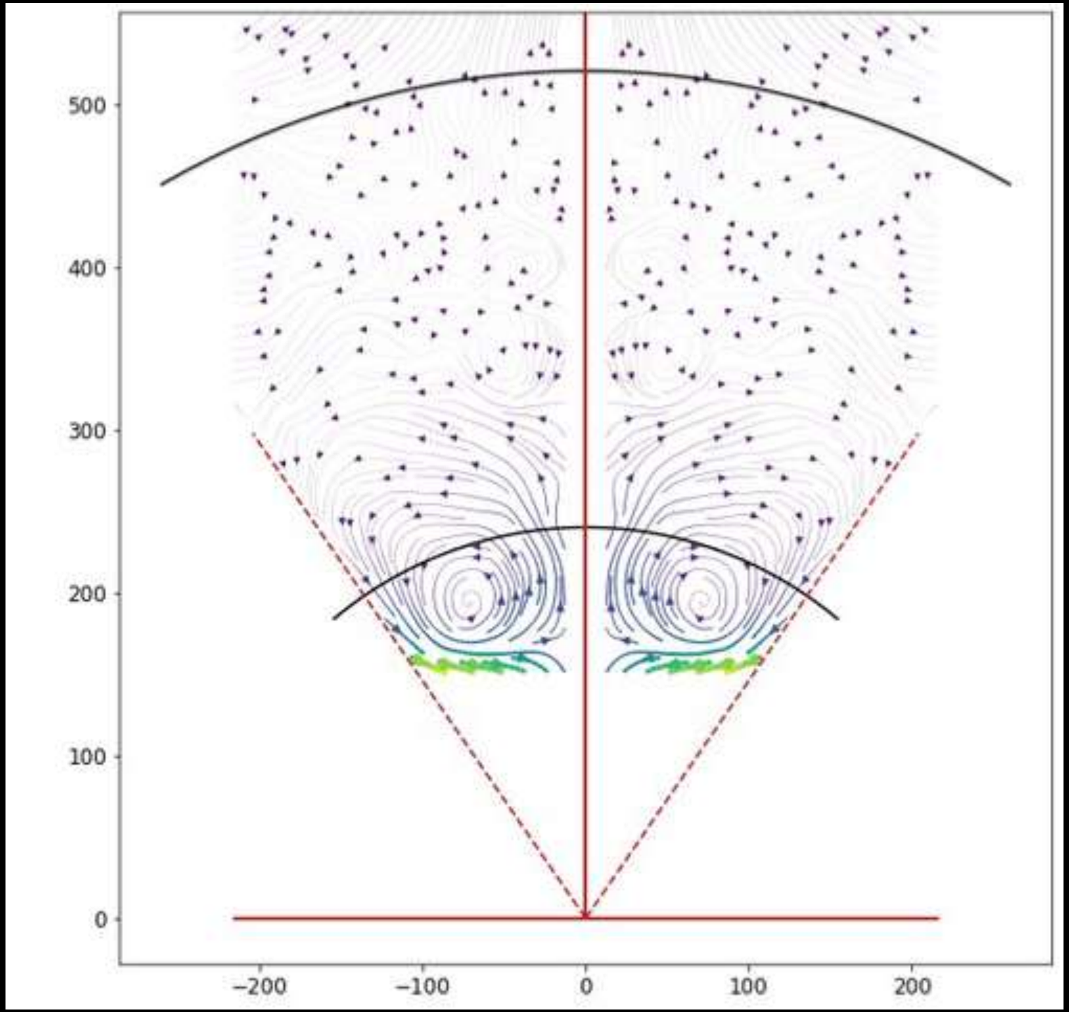
Centroid connections



Foam flow in constriction: trajectories



Flow field



Florian Schott, PhD project – unpublished data

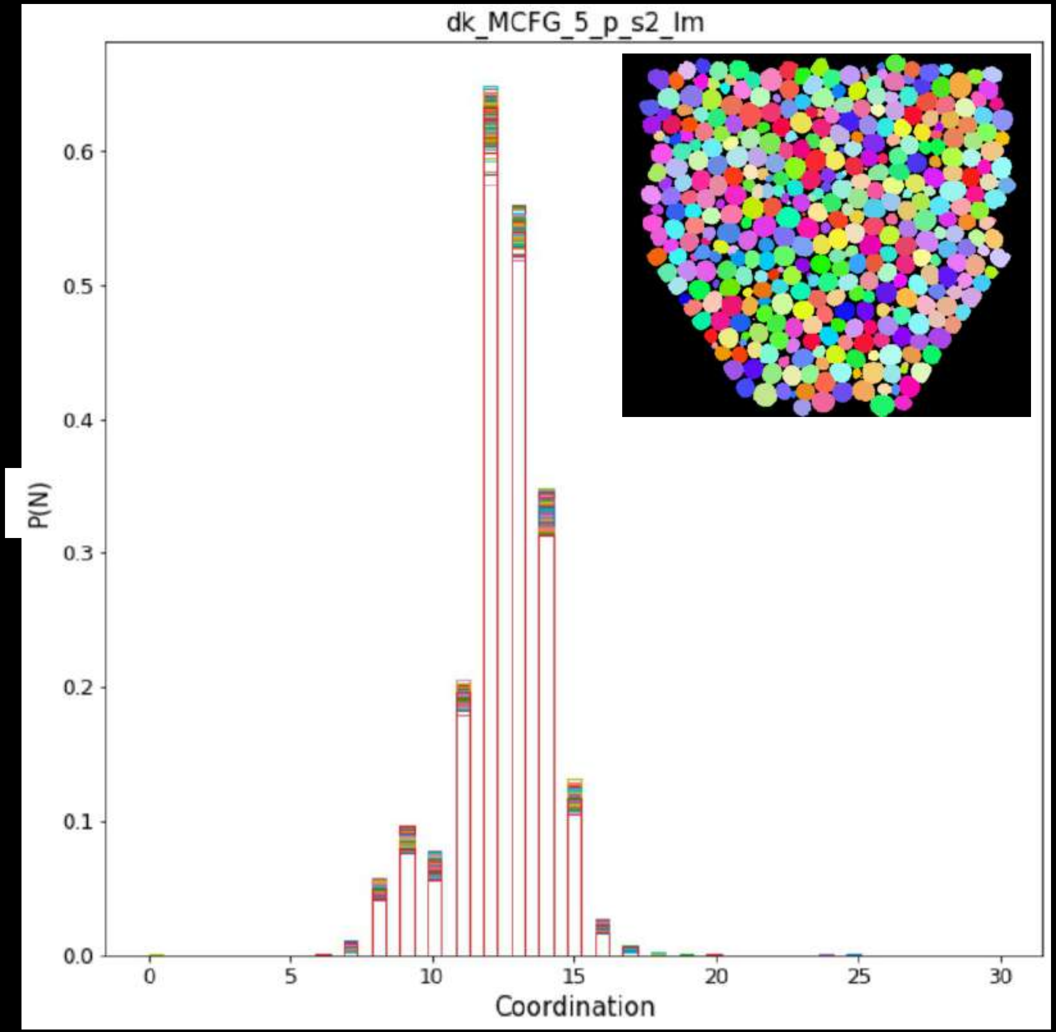
- Optimize extrusion processing and extrudor design
- Quantify the stability of foam lamellae in food productio
- Elongation contraction flow of non-Newtonian fluids

20 HZ tomo

E= 20 keV, scan time = 50 ms, pix. size = 3 um

Image: Florian Schott

Liquid foam topology: number of faces



Vetenskapsrådet

F. Schott, PhD project, LTH

Discovery of the Weaire-Phelan structure
(the true story)

3D foam simulations

PRL **111,** 138301 (2013) PHYSICAL REVIEW LETTERS week ending 27 SEPTEMBER 2013

Networklike Propagation of Cell-Level Stress in Sheared Random Foams

Myfanwy E. Evans,[1,*] Andrew M. Kraynik,[1] Douglas A. Reinelt,[2] Klaus Mecke,[1] and Gerd E. Schröder-Turk[1]

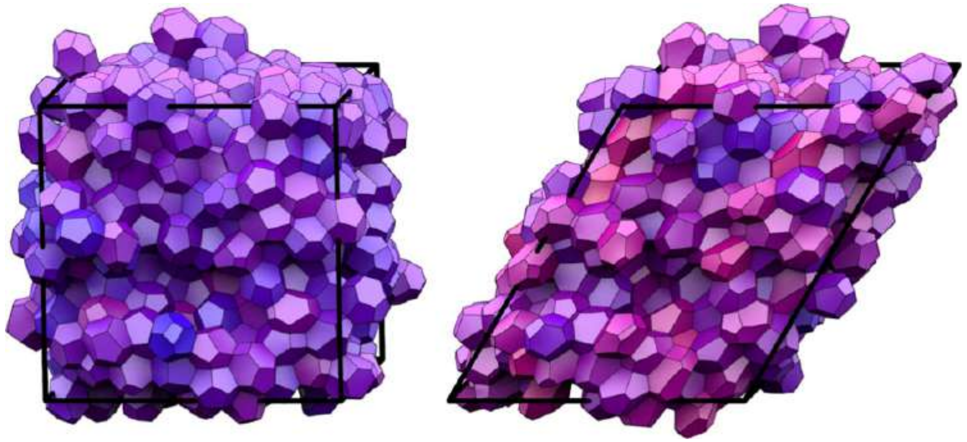


FIG. 1 (color online). A dry liquid foam with 512 cells in a unit cell at strains of 0 and 0.6, respectively. The cells are colored by Q, a scalar measure of cell distortion, where blue through red symbolizes values 0 through 1. The average Q values over all cells are 0.244 and 0.425, respectively.

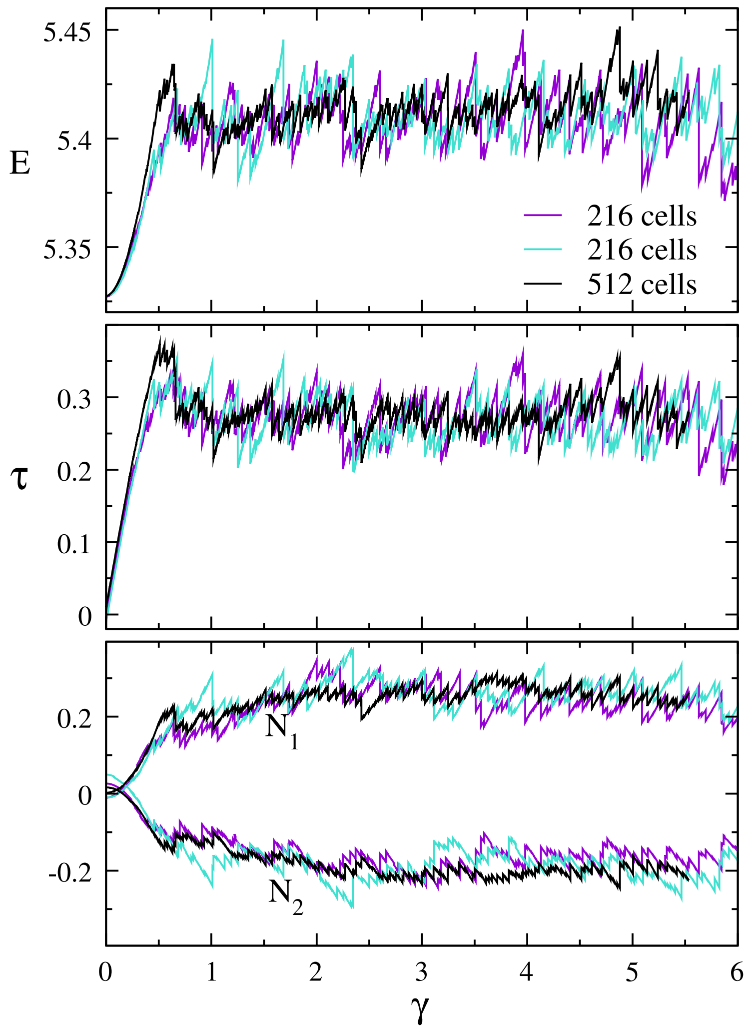
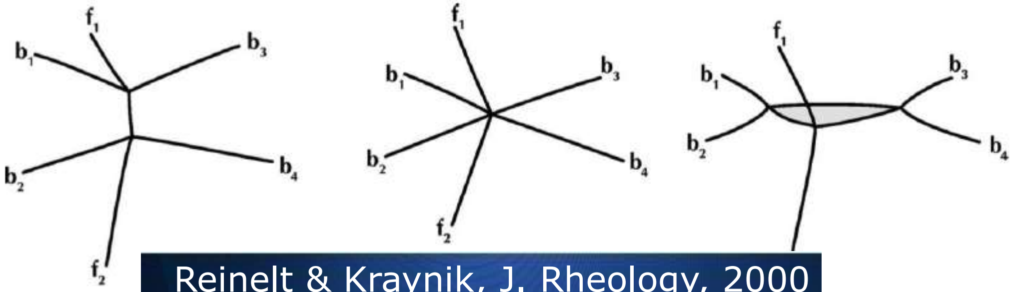
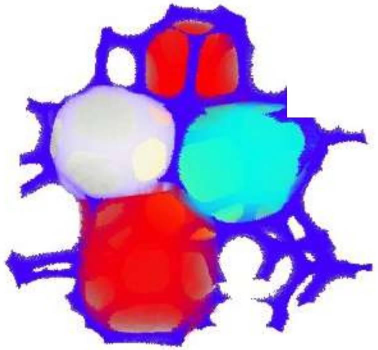


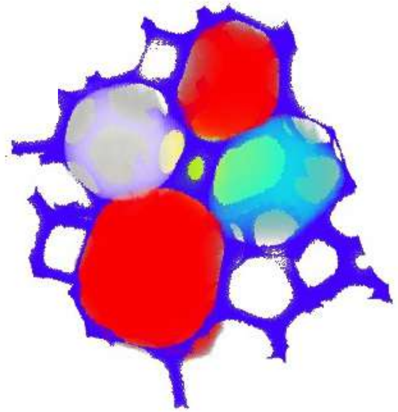
FIG. 3 (color online). The foam energy E (top), shear stress τ (middle), and normal stress differences N_1 and N_2 (bottom), normalized by surface tension and average cell volume $\sigma V^{-(1/3)}$,

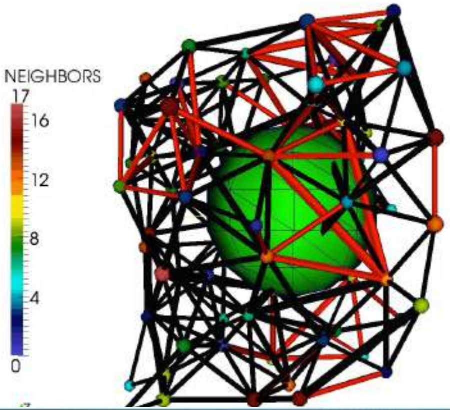
The fundamental topological transitions



Reinelt & Kraynik, J. Rheology, 2000







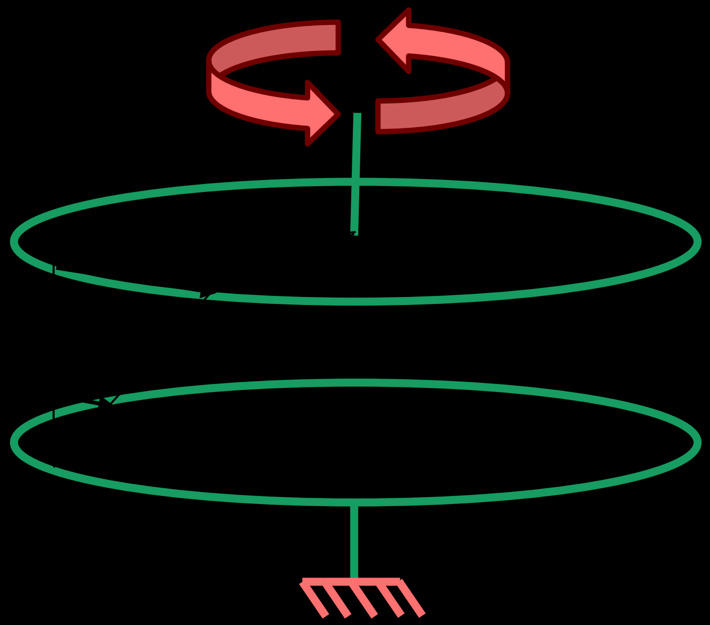
Raufaste, Dollet, Santucci, Mader, Mokso. E

- We have the labeling tool, but the neighborhood relations are not yet reliable

Rheo-tomoscopy

Vetenskapsrådet

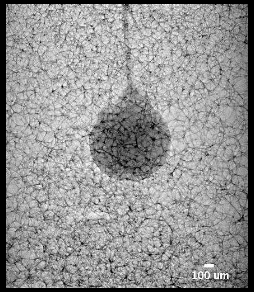
F. Schott, PhD project, LTH

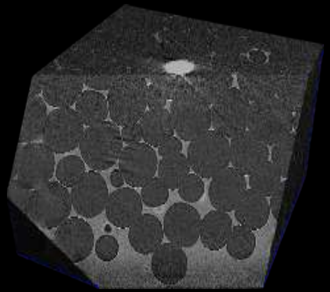


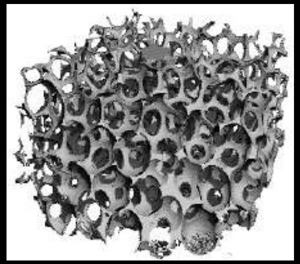
Upcoming Rheometer experiments (Dec 2021 @ TOMCAT)

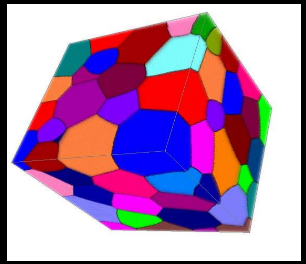
- Complete control of the deformation
- Simultaneous macroscopic torque measurement with tomograpl

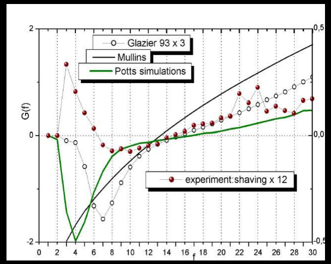
Tomography workflow

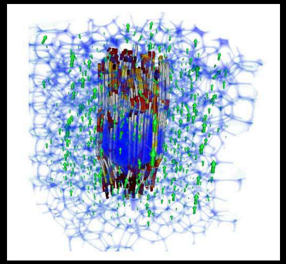












acquisition → reconstruction → Inspection & binarization → labeling → quantification → visualization

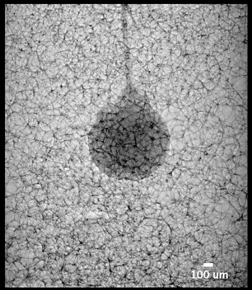
tomopy

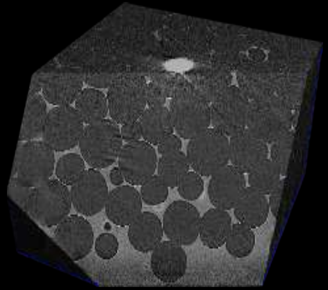
Tomographic reconstruction methods

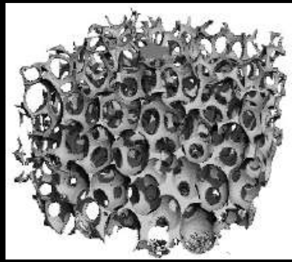
- FBP : the classical method — The golden standard
  - requires perfect geometry
- GRIDREC: fourier based
  + fast
- ART (algebraic reconstruction):
  - slow,
  + can deal with low number of projections
- SIRT (simultaneous iterative reconstruction):
  - slow
  + low number of projections
- DART(discrete algebraic rec.):
  - Local tomography
  + phases are directly binarized

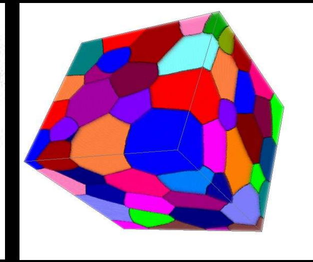
tomopy.readthedocs.io

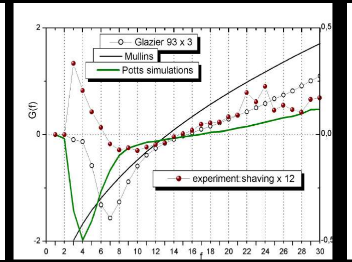
The workflow

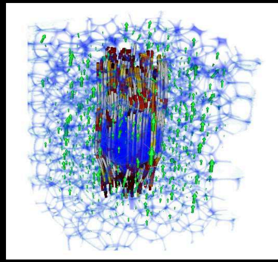












acquisition → reconstructio → Inspection & binarization → labeling → quantificatio → visualization

tomopy

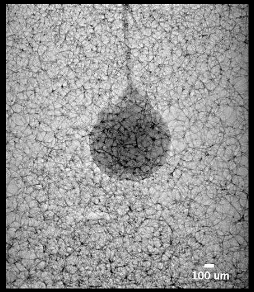
ImageJ, scikit

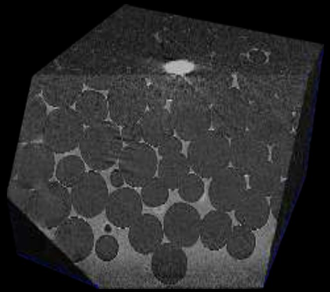
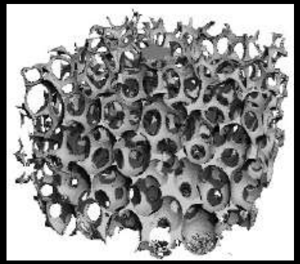
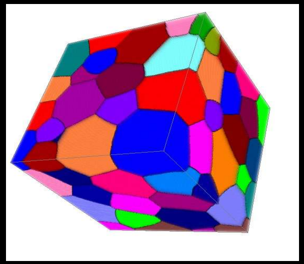
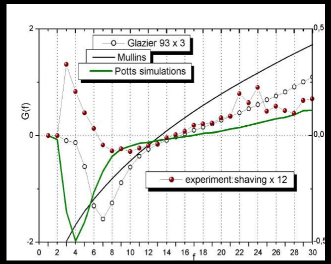
Binarization of gray-scale images

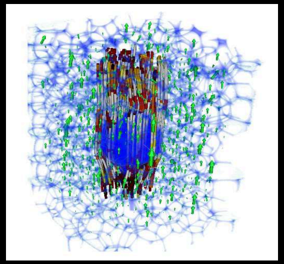
- First step is usually the data inspection. For this I often use ImageJ
- ImageJ and almost all other image viewers / processing tools have algorithms for binarization / segmentation

- For large / multiple datasets I use the scikit-image library in python

Tomographic workflow





acquisition → reconstruction → Inspection & binarization → labeling → quantification → visualization

tomopy

ImageJ
scikit

Scikit
sdk

Scikit
matlab

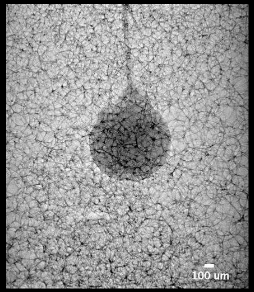
Labelling and quantification

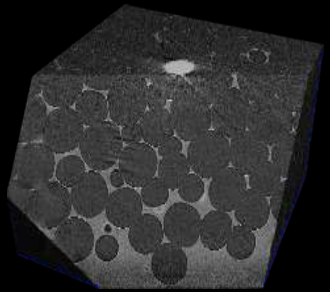
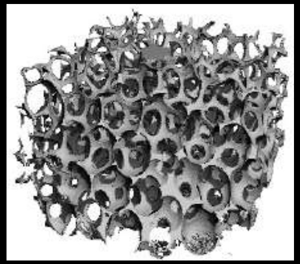
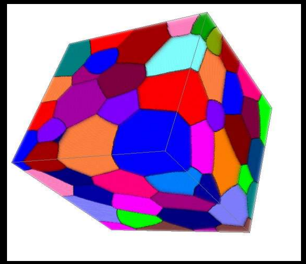
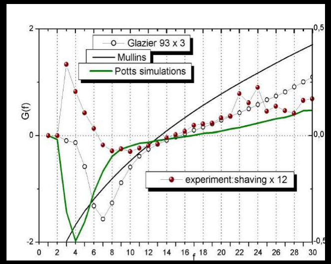
- A number of proprietary software exists: AVIZO, VG STUDIO
- Even more free toolboxes: PARAVIEW, MEVISLAB

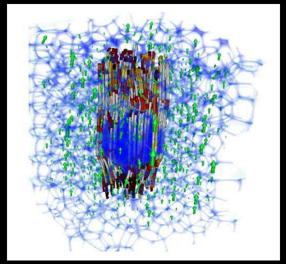
- I use the scikit-image library in python. See link below for an example notebook

kaggle.com/rajmund

The full workflow





acquisition

reconstructio

Inspection &

binarization

labeling

quantificatio

visualization

tomopy

ImageJ
scikit

Scikit

sdk

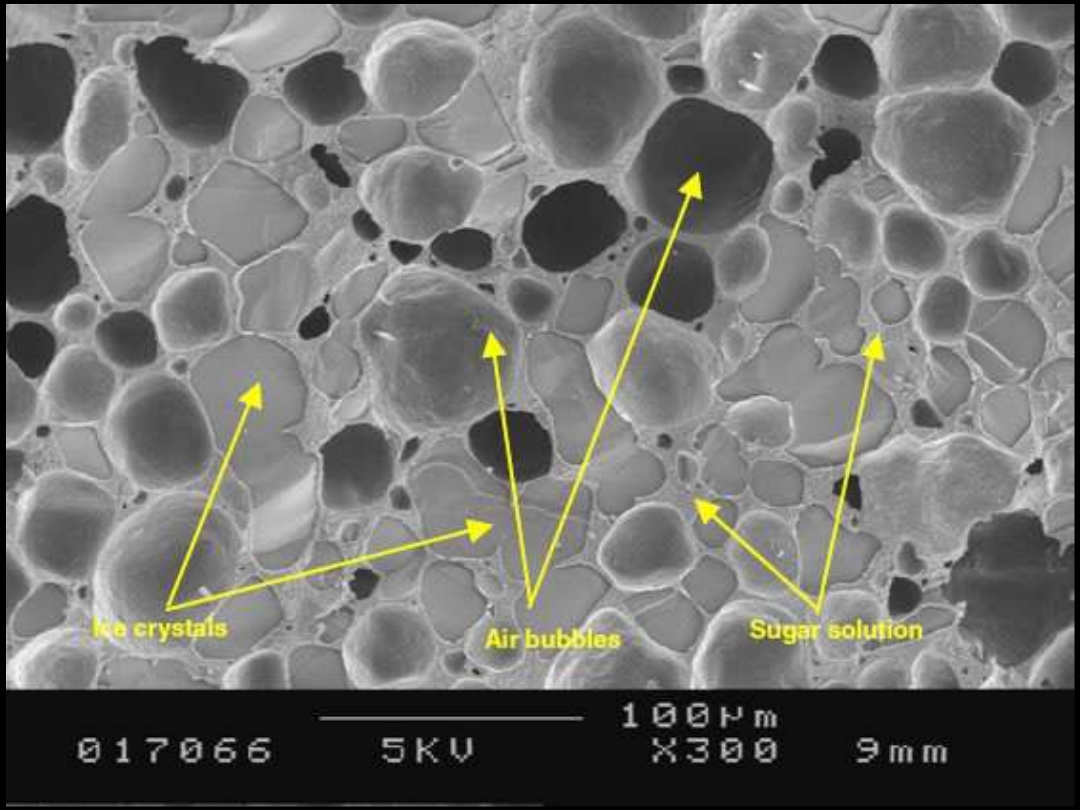
Scikit
matlab

Tomviz

Paraview

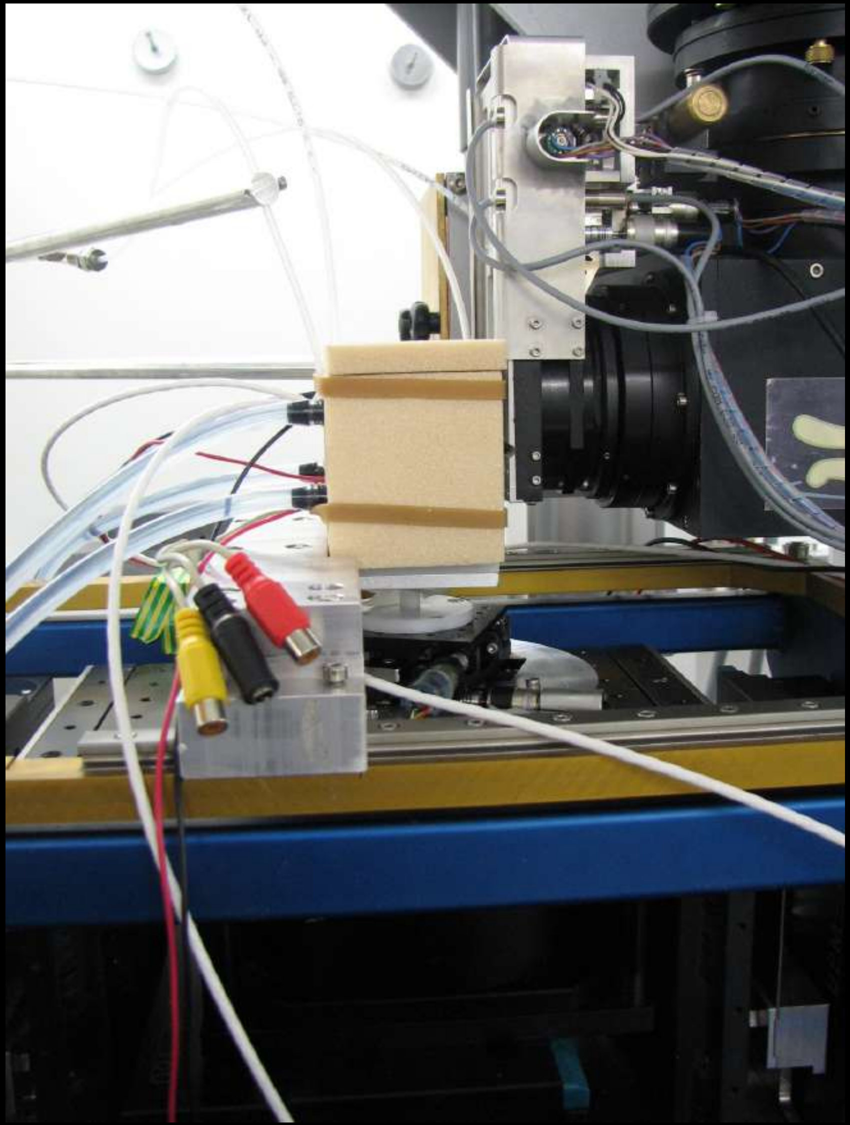
Ice cream: the swiss quest for a better taste

- Study micro structure of frozen food and its response to varying external conditions
- Needs / Boundary conditions
  - non-destructive, high-res, 3D
  - Cryo conditions
  - No contrast agents!



In-situ cryo experiment on ice cream

- Temperature range + 5° to - 45° C
- High stability (± 0.05K)
- Suitable for frozen samples, e.g. snow, ice-cream, etc…

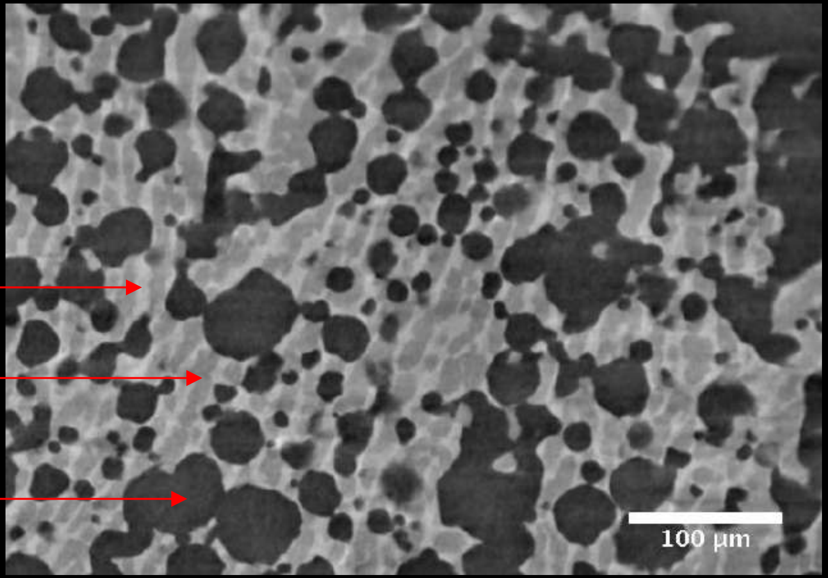


TOMCAT, Swiss Light Source

Sugar solution

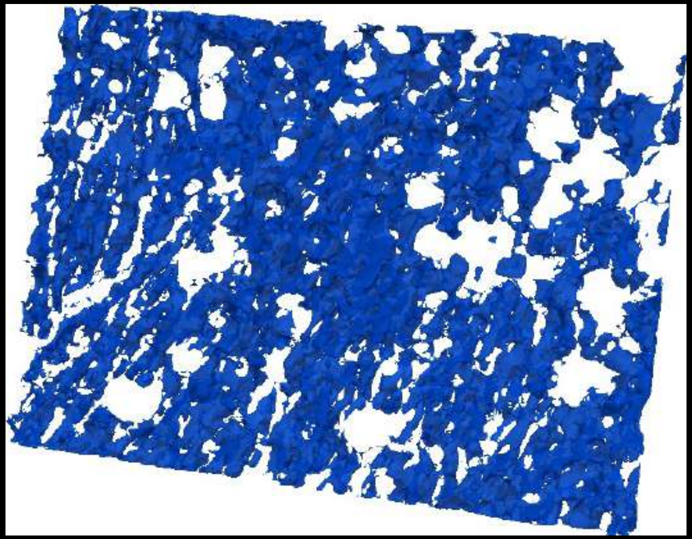
Ice crystals

Air bubbles

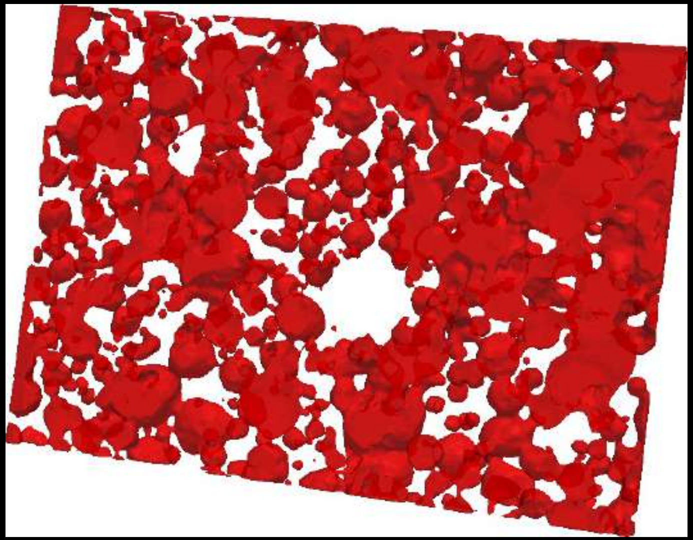


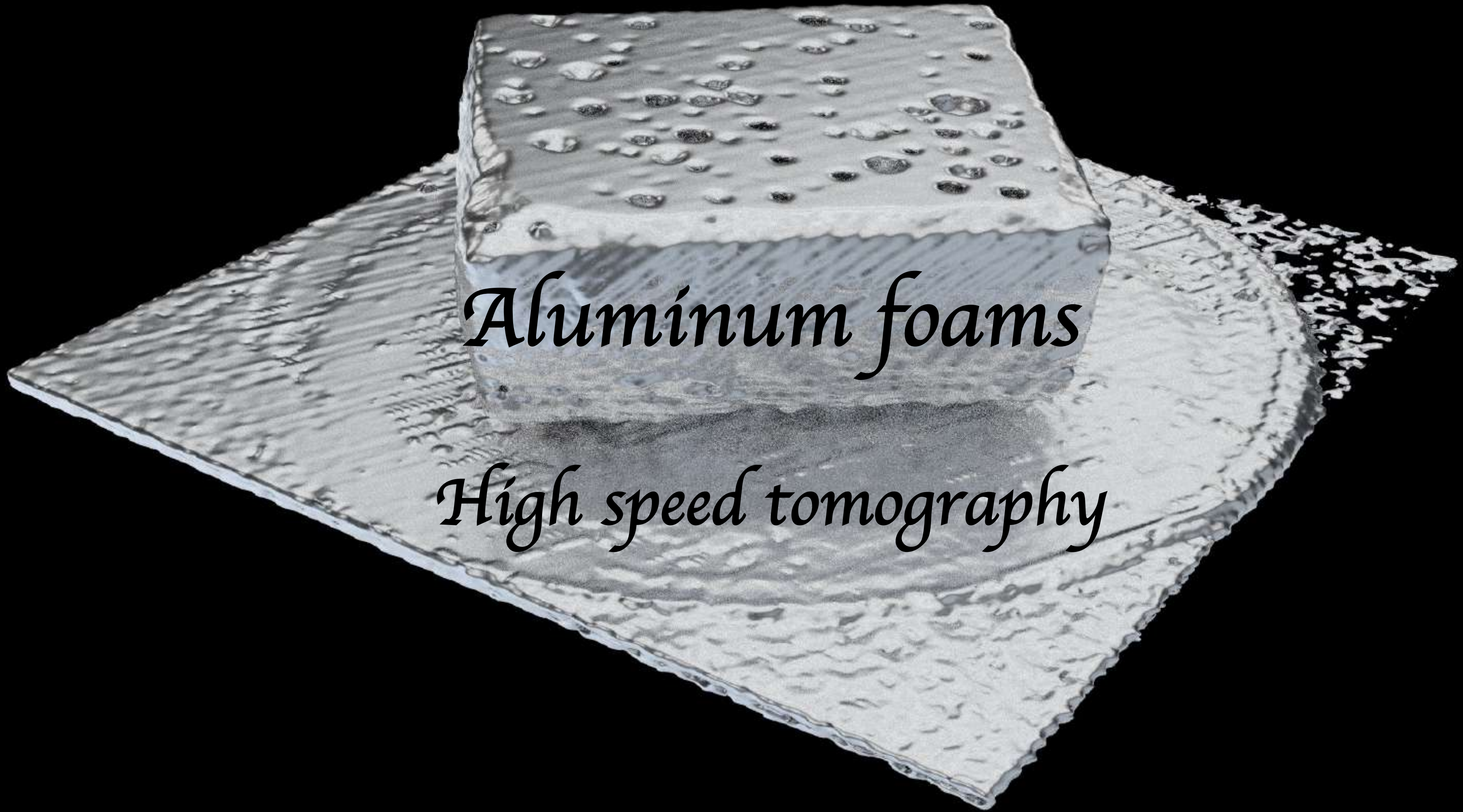
TOMCAT, Swiss Light Source

Ice crystals



Air cells





Aluminum foams
High speed tomography

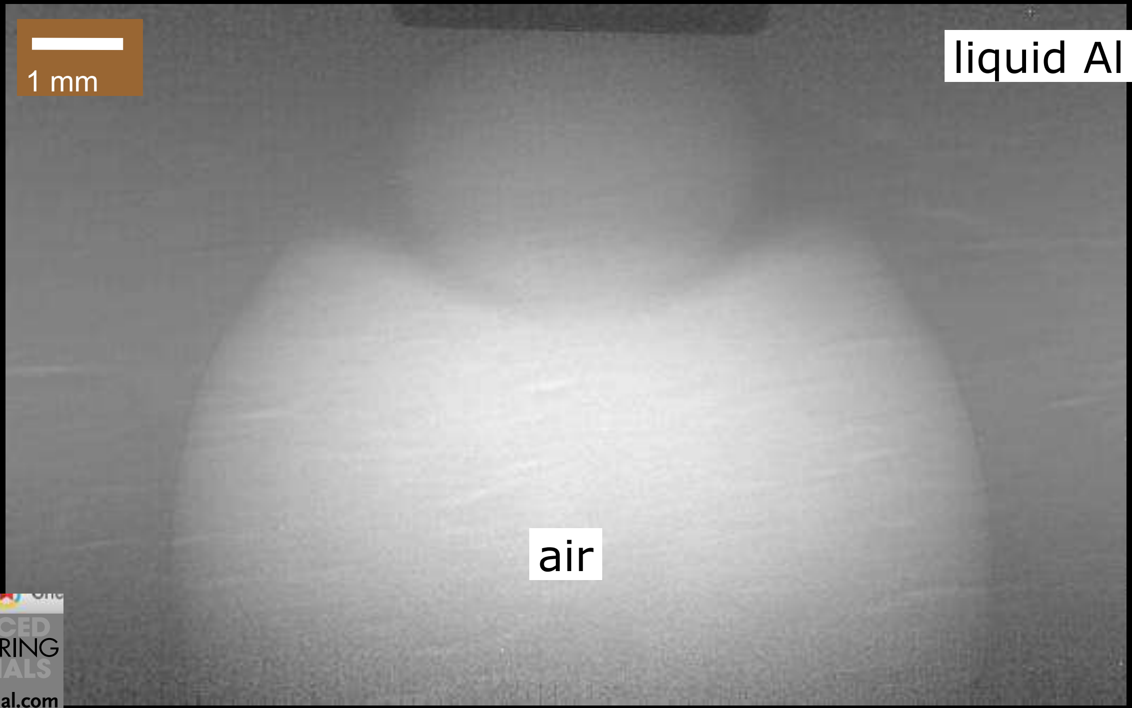
Acoustic-pressure-assisted engineering of Aluminum foams

RESEARCH ARTICLE

ADVANCED ENGINEERING MATERIALS
www.aem-journal.com

Acoustic-Pressure-Assisted Engineering of Aluminum Foams

Xavier Mettan, Edoardo Martino, Lidia Rossi, Jaćim Jaćimović, Juraj Krsnik, Osor S. Barišić, Norbert Babcsán, Sándor Beke, Rajmund Mokso, George Kaptay, and László Forró**

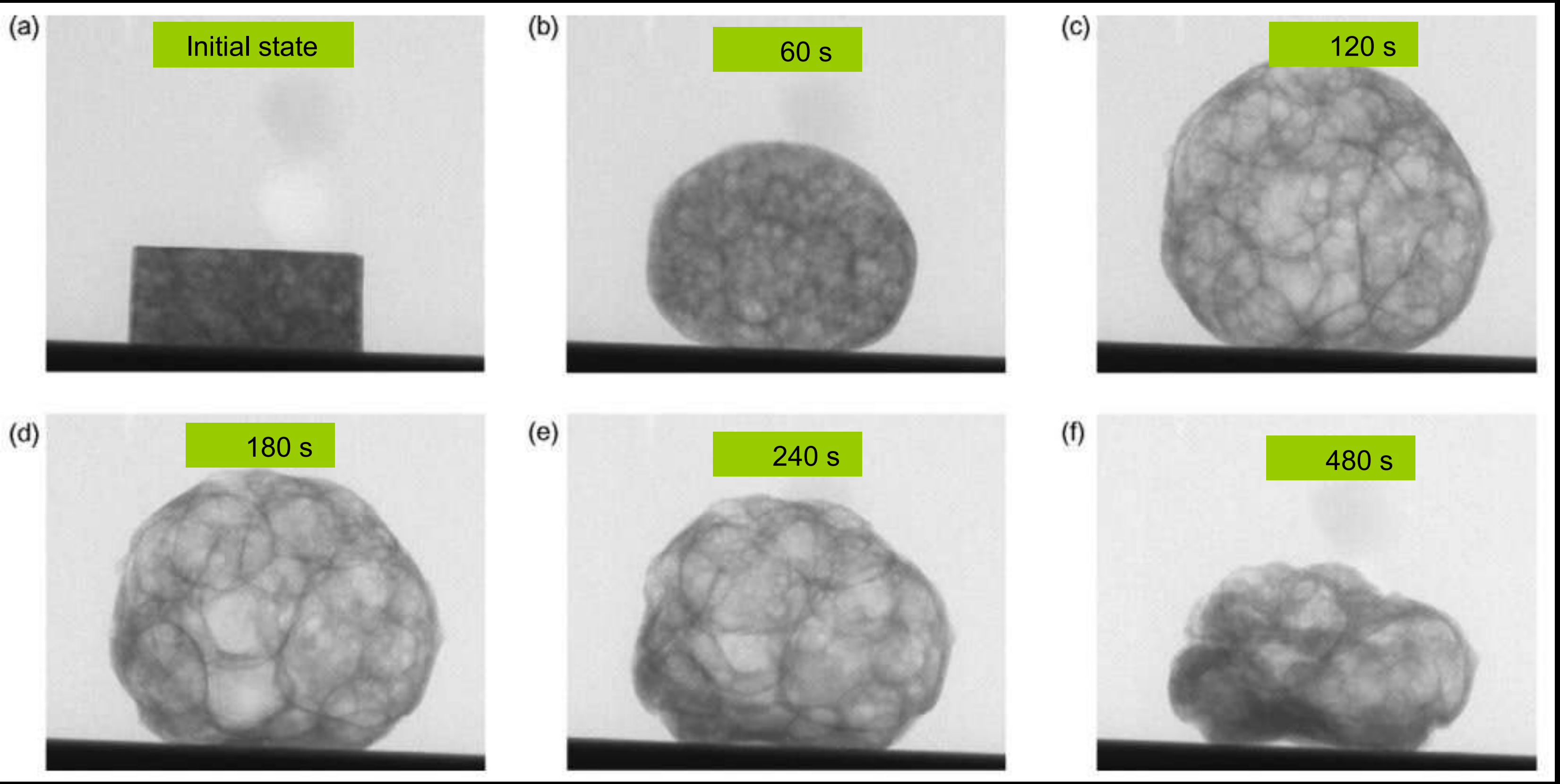


Bubbling gas into liquid aluminum

Radiography at 10-20'000 fps
Pixel size = 5 µm
Acquisition time= 3 s

Producing Al foams with small and monodisperse cell sizes

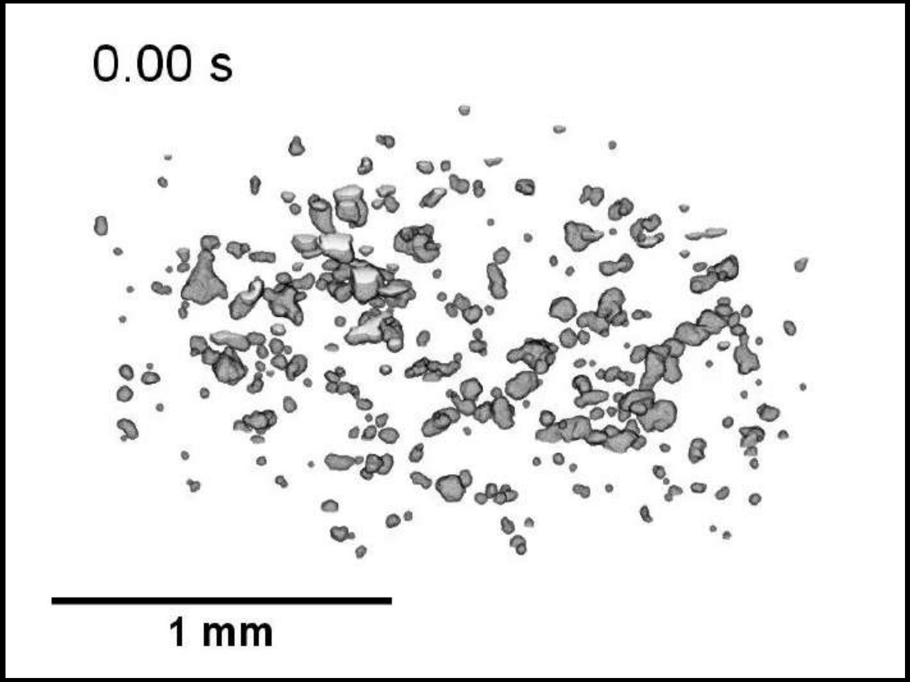
Nanoparticle stabilization for industrial Al foam production

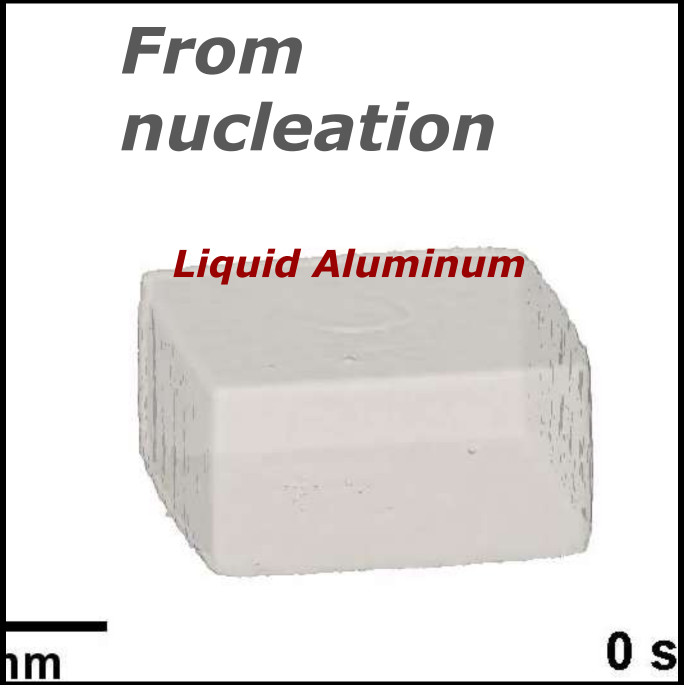


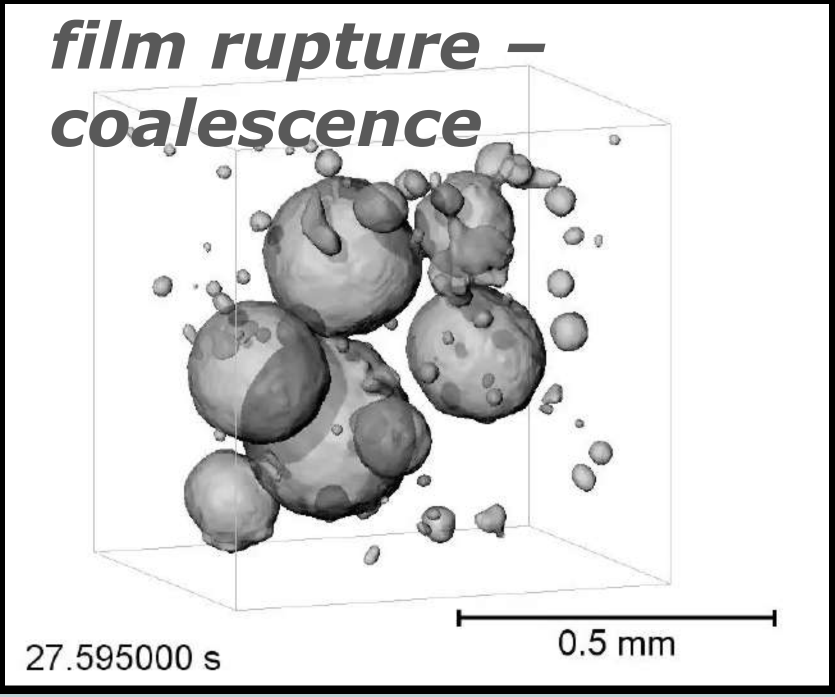
Babcsan, Moreno, Banhart, Colloinds & Surfces A 2007

Precursor made from oxidised melt heated slightly above the melting point.

The rise and collapse of Al foam







TOMCAT, Swiss Light Source (2018)

Acquisition speed: 208 tomo/s

nature COMMUNICATIONS

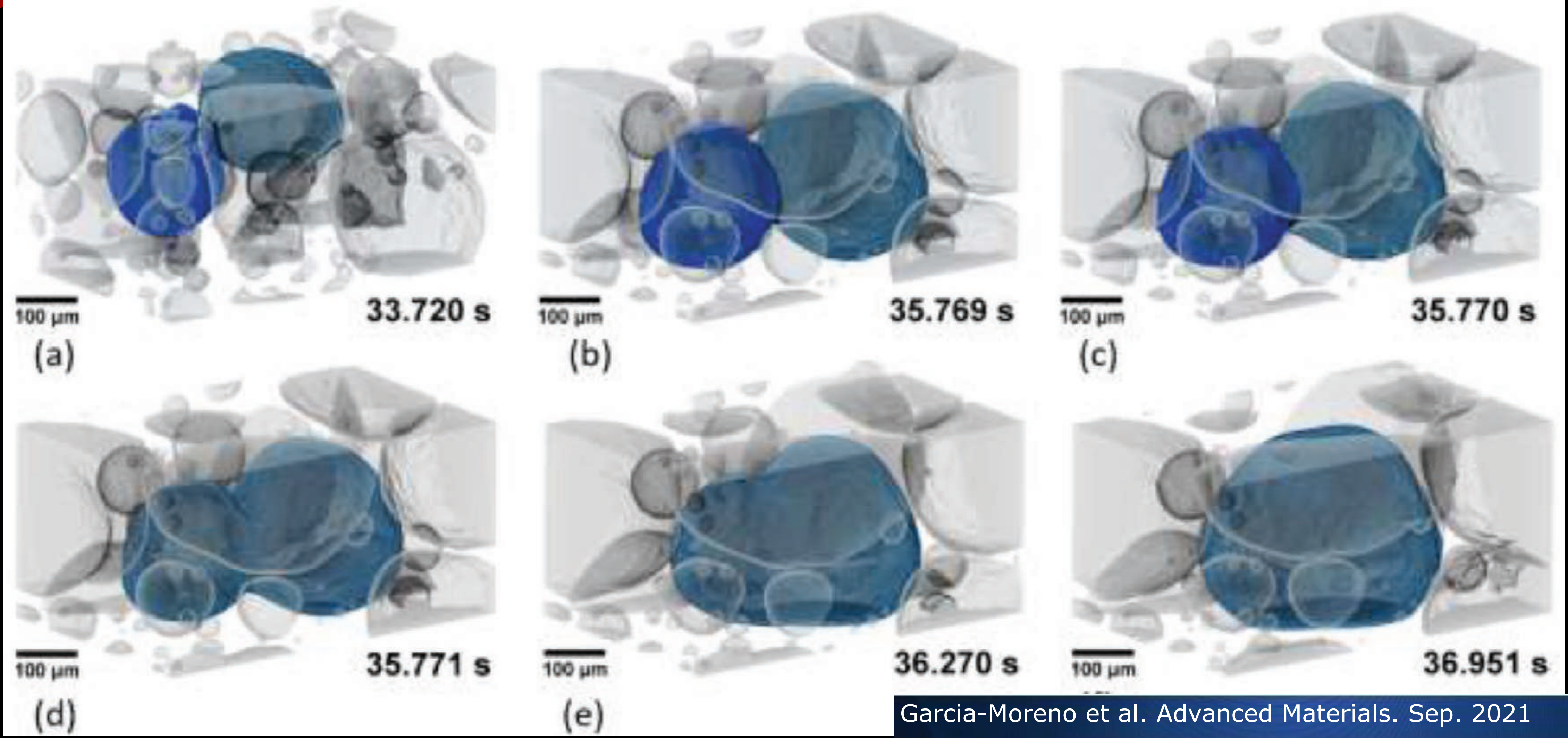
ARTICLE 2019

https://doi.org/10.1038/s41467-019-11521-1 OPEN

Using X-ray tomoscopy to explore the dynamics of foaming metal

Francisco García-Moreno [1,2], Paul Hans Kamm [1,2], Tillmann Robert Neu[1,2], Felix Bülk[1,2], Rajmund Mokso[3], Christian Matthias Schlepütz [4], Marco Stampanoni[4,5] & John Banhart[1,2]

Coalescence of Bubbles in AlSi8Mg4 Alloy



Garcia-Moreno et al. Advanced Materials. Sep. 2021

Coalescence of two cells in an Aluminum foam. Acquisition speed: 1000 tomo/s

Tomographic scan time improvements over time

What is the rate of acquisition speed increase of synchrotron microtomography?

(a)doubles every 5 years

(b)triples every 3 years

(c)ten fold every 3 years


Thank you

Spider Silk