Revealing the 3D nanostructure of extended colloidal networks in food emulsions using ptychographic X-ray computed tomography

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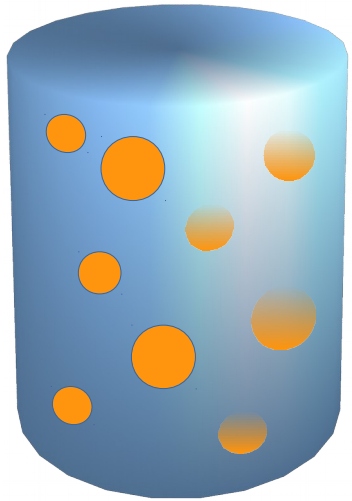
The structure of food emulsions

Water

Fat

Food emulsion



Liquid

(Semi)-solid

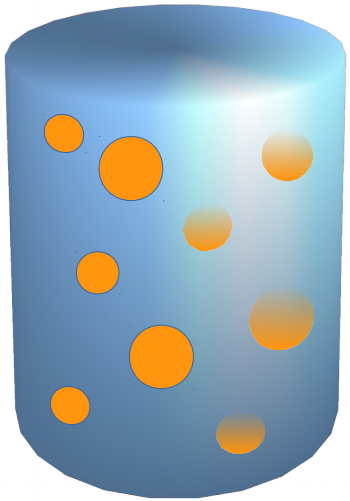
The structure of food emulsions

Water

Fat

Food emulsion

Picture: Bearas - Wikimedea Commons



Picture: Merete Bøgelund Munk

Liquid

(Semi)-solid

Effect of addition of emulsifier

Effect of addition of emulsifier

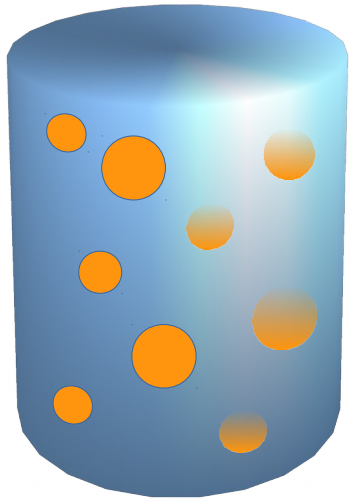
Product composition

~25 w% lipid phase:

- *25 w% Palm kernel oil*

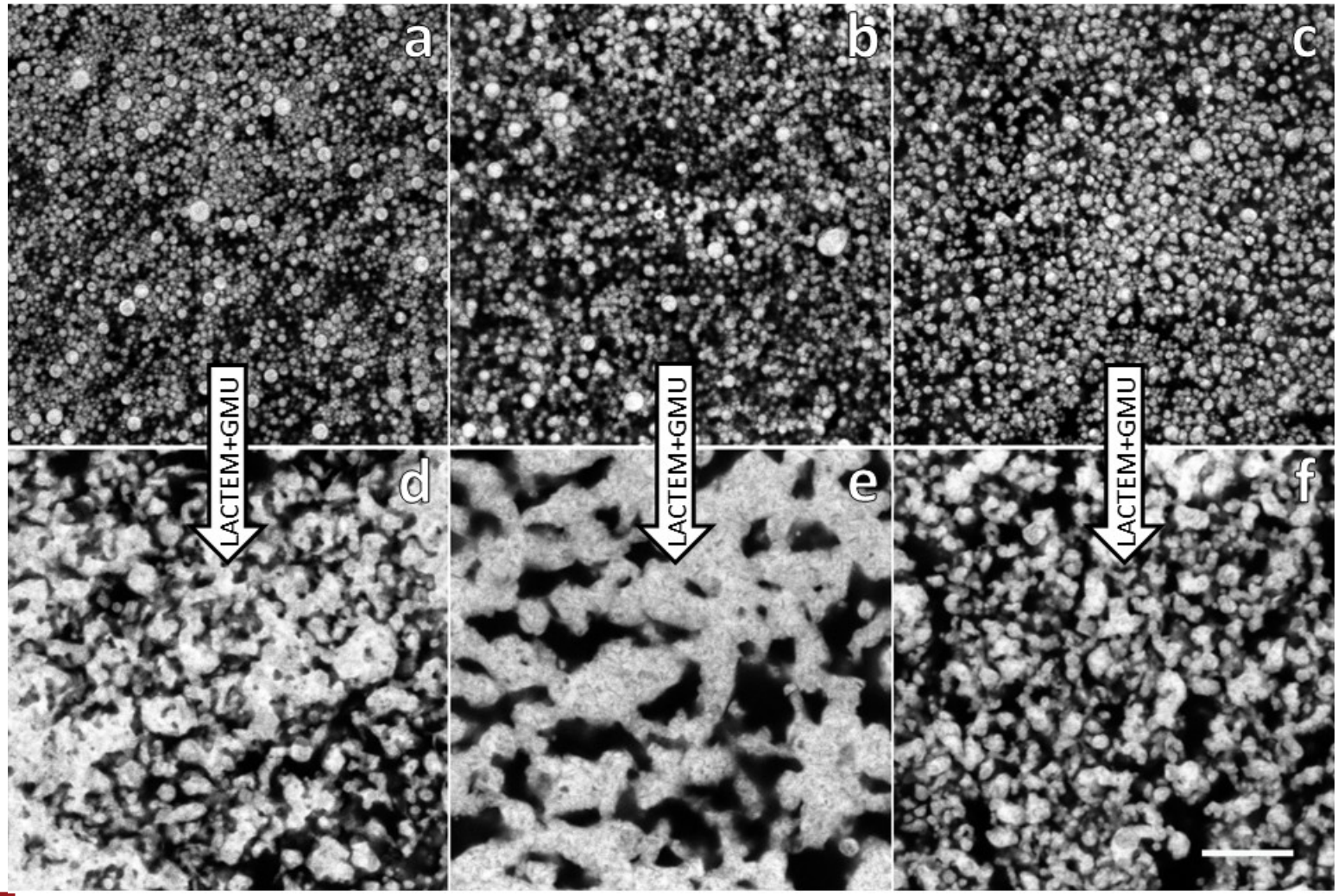
~75 w% water phase:

- *10 w% sugar (sucrose)*
- *62 w% water*
- *0.6 w% sodium caseinates*
- *0.6 w% stabilizers*
- *1 w% emulsifier*



Effect of addition of emulsifier

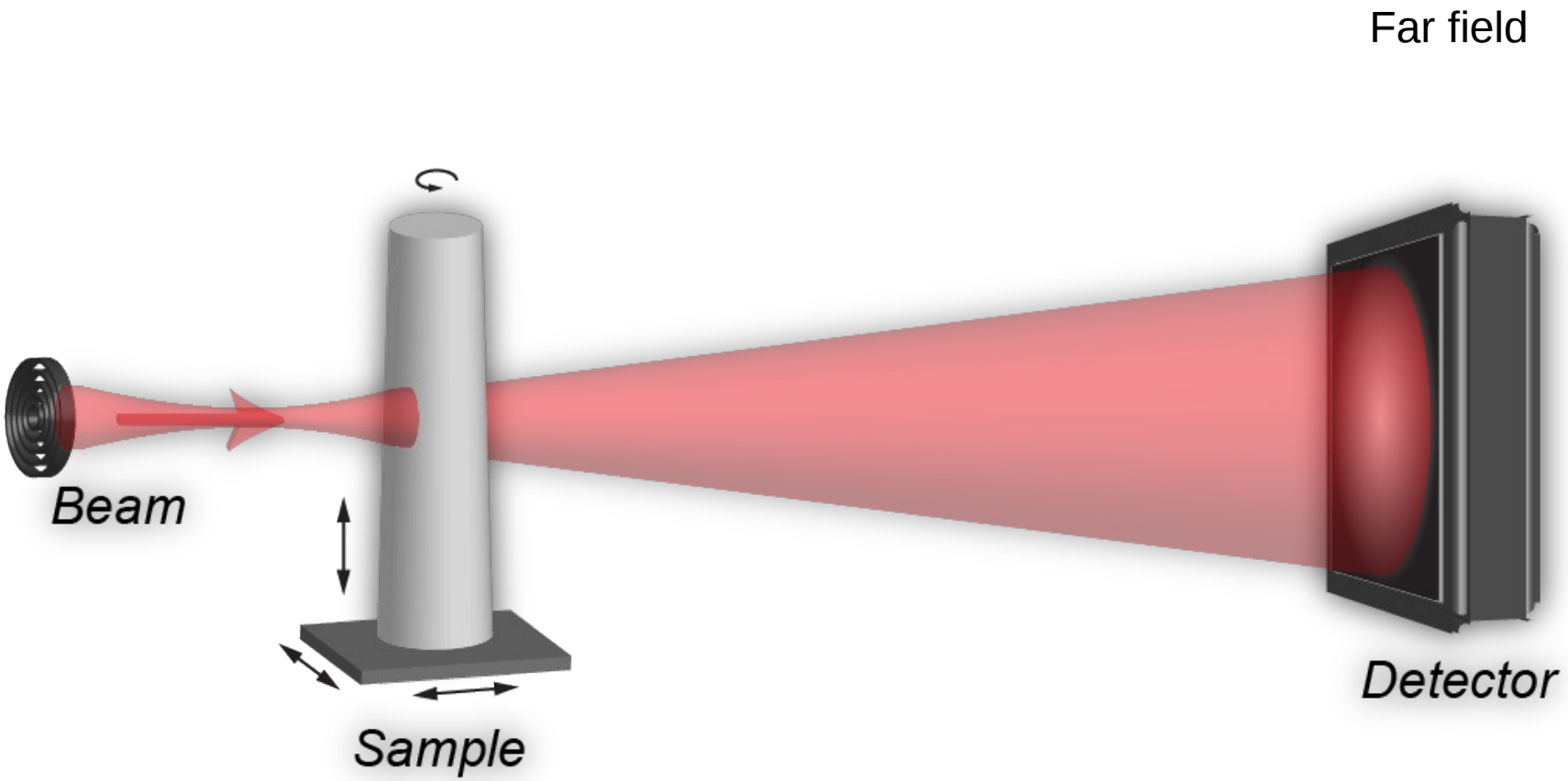
Confocal laser scanning microscopy



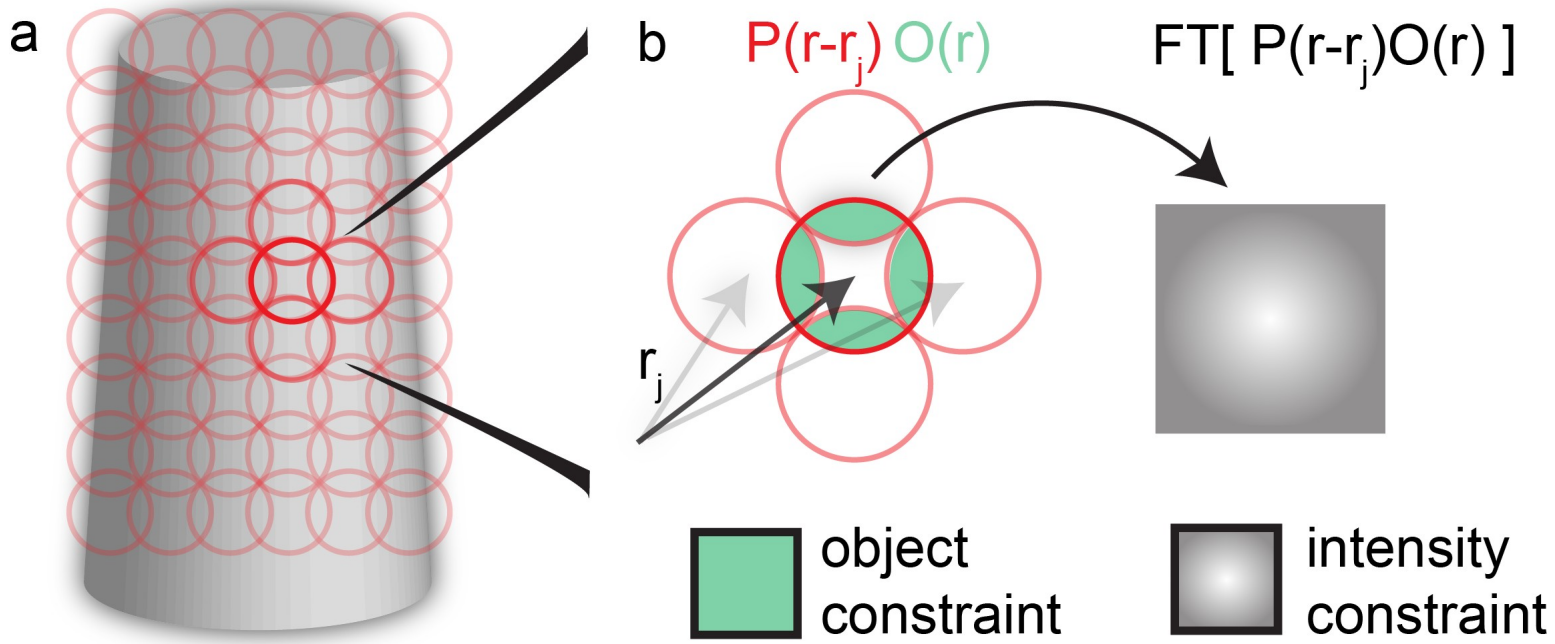
Scalebar: 10 microns

X-ray ptychography

X-ray ptychography

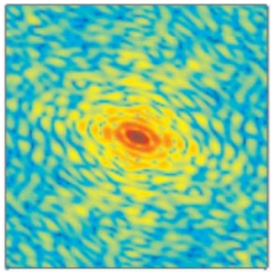


Ptychographic scan



From recorded patterns to an image

Recorded pattern
(Reciprocal space)

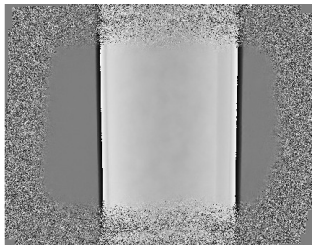


$\mathcal{FT}^{-1}$

Measured intensity

Go to new scan point

Reconstructed image
(Real space)



Intensity constraint

Overlap constraint

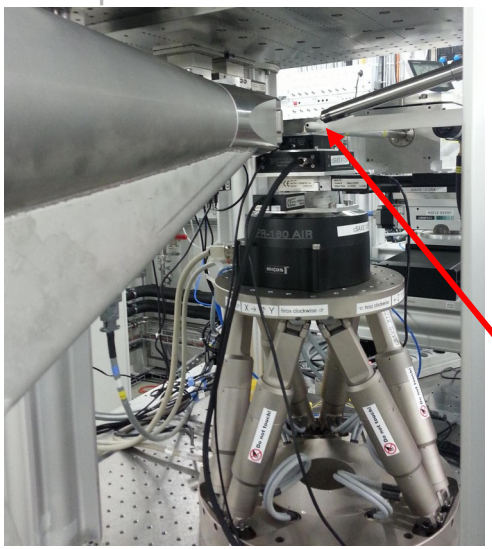
Pattern from updated image

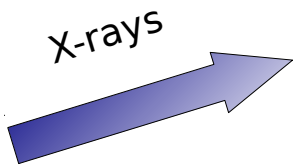
Updating image with overlap

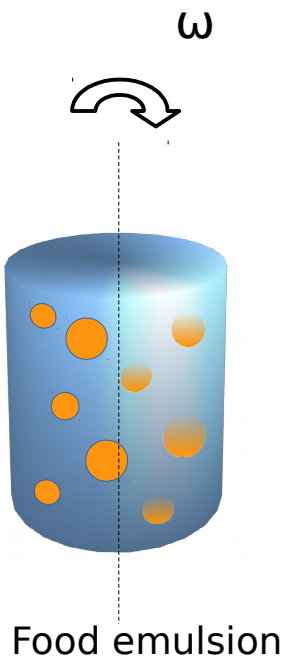
$\mathcal{FT}$

Experimental setup

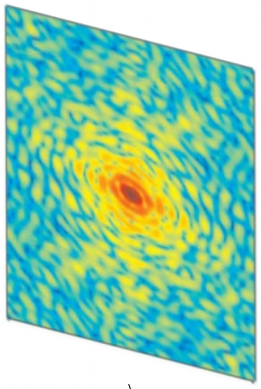
Setup at cSAXS beamline

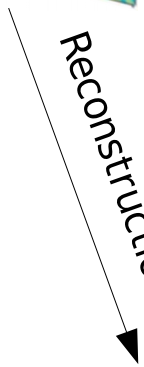


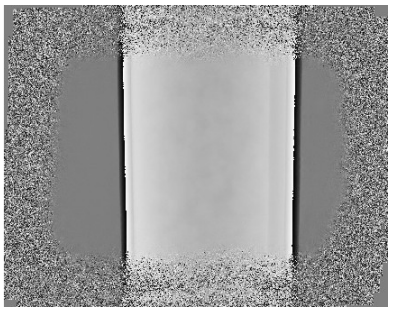




Ptychographic X-ray computed tomography

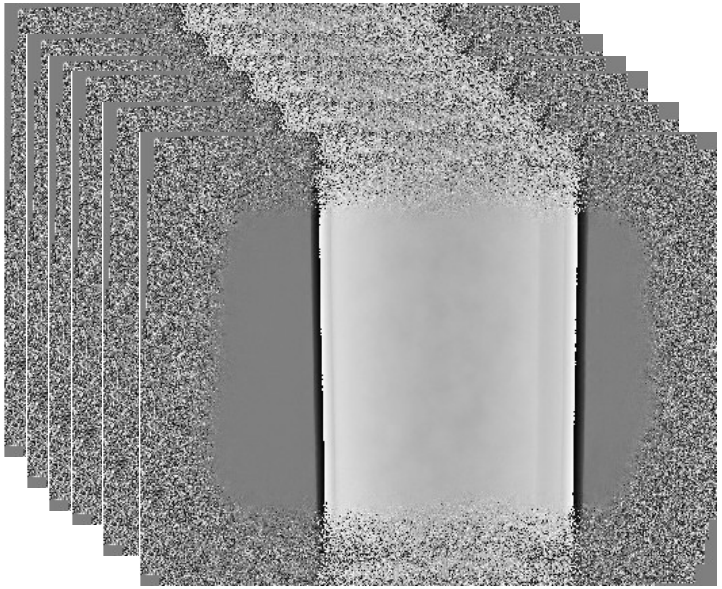






Tomographic reconstruction

Combining projections from rotation of sample



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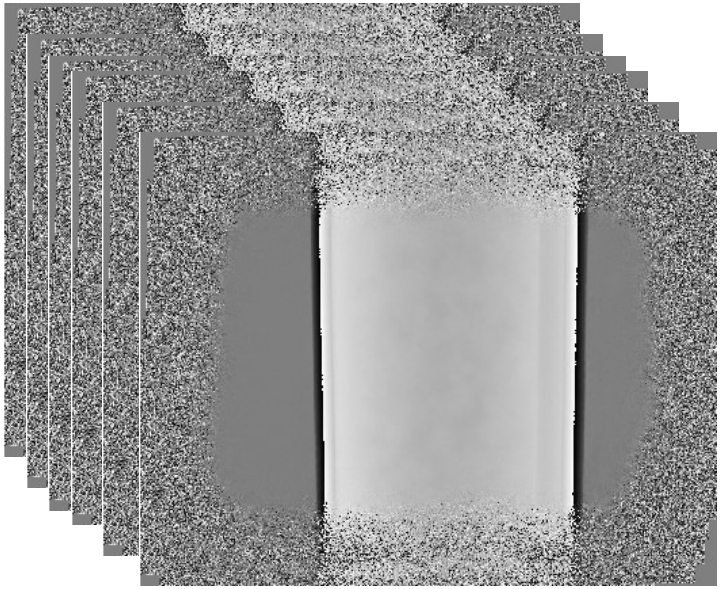
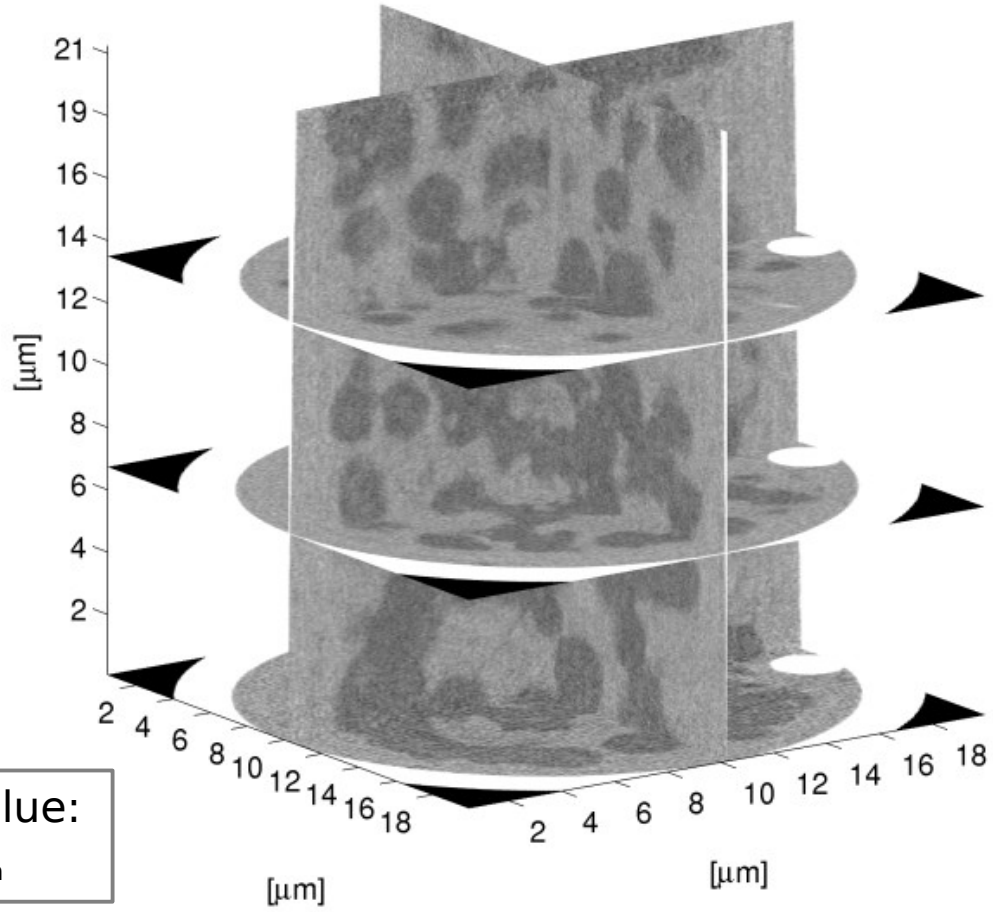




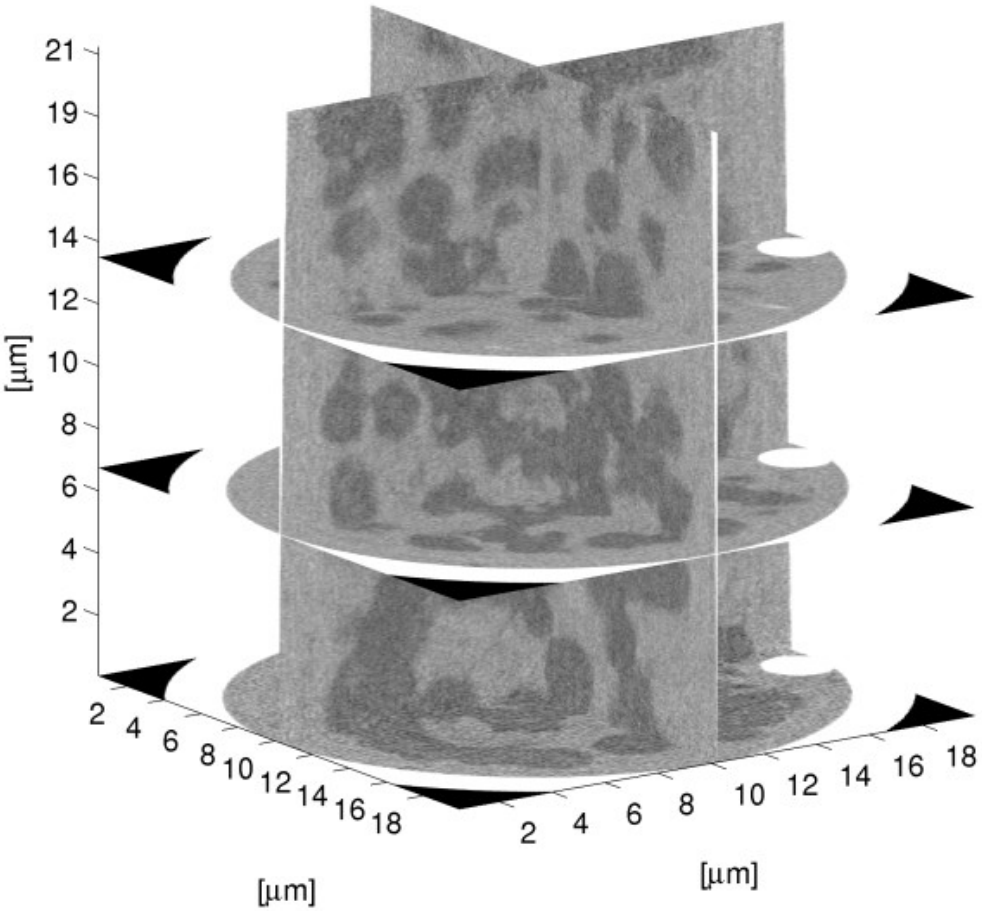
Bonus info box:

Reconstruction algorithm:
Filtered back-projection

Reconstructed value:
$\rho_e = N_A \cdot Z/M \cdot \rho_m$

Denosing

Removing noise without blurring features



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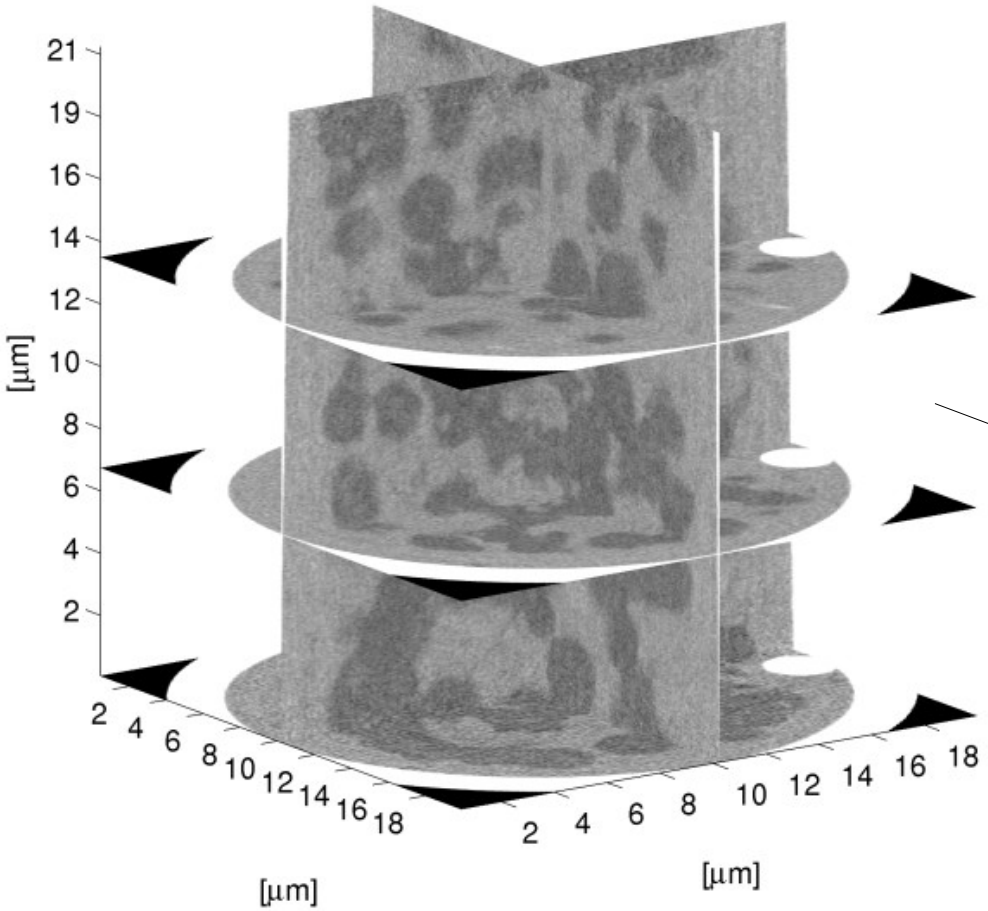
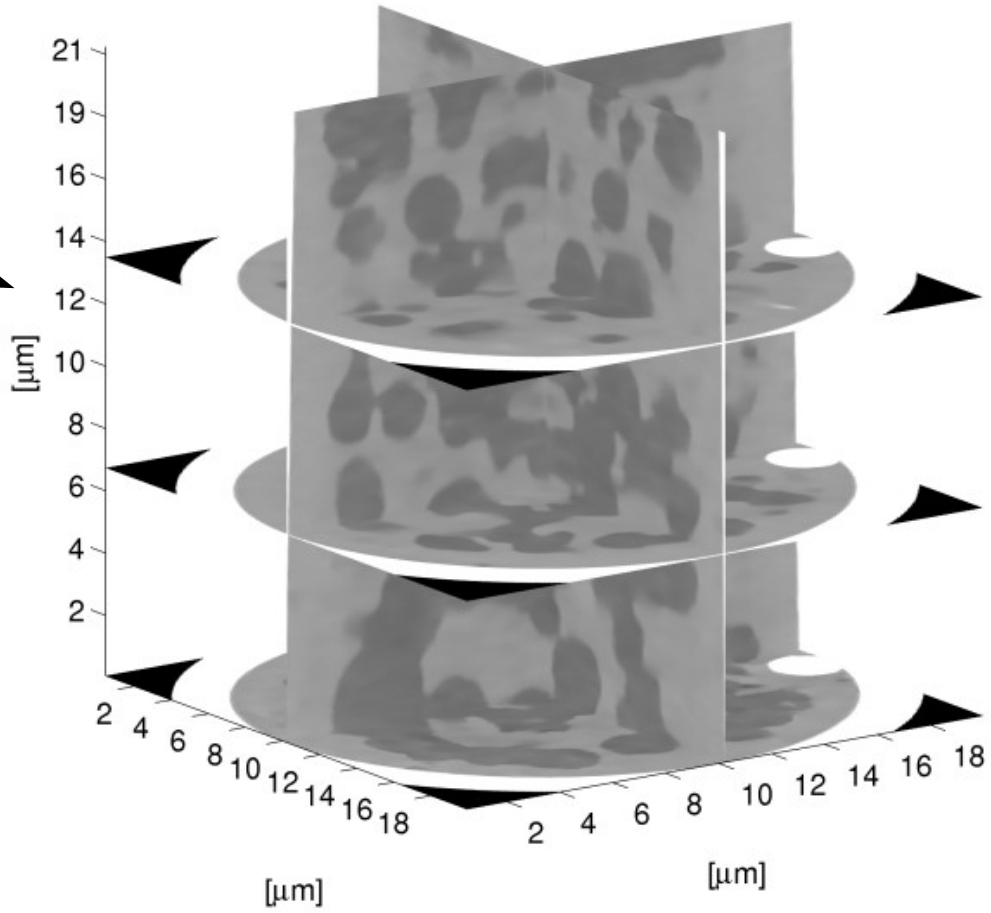


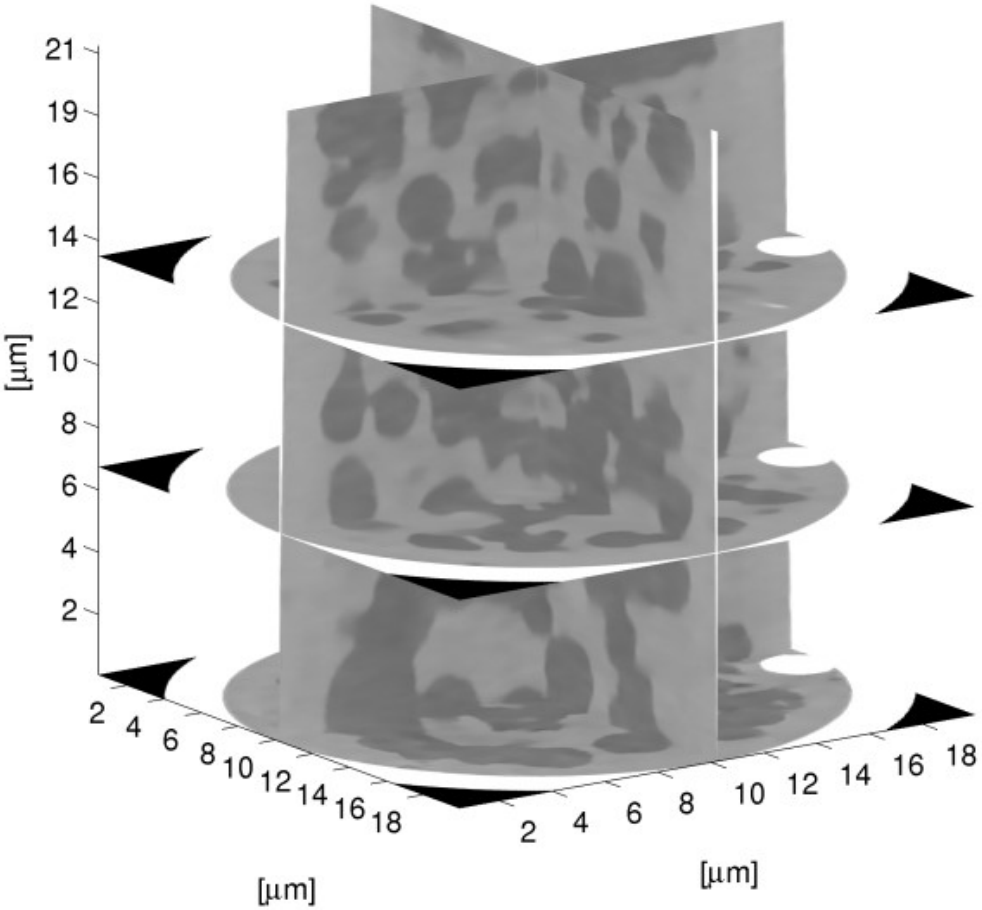


Bonus info box:

Denoising algorithm: Iterative non-local mean

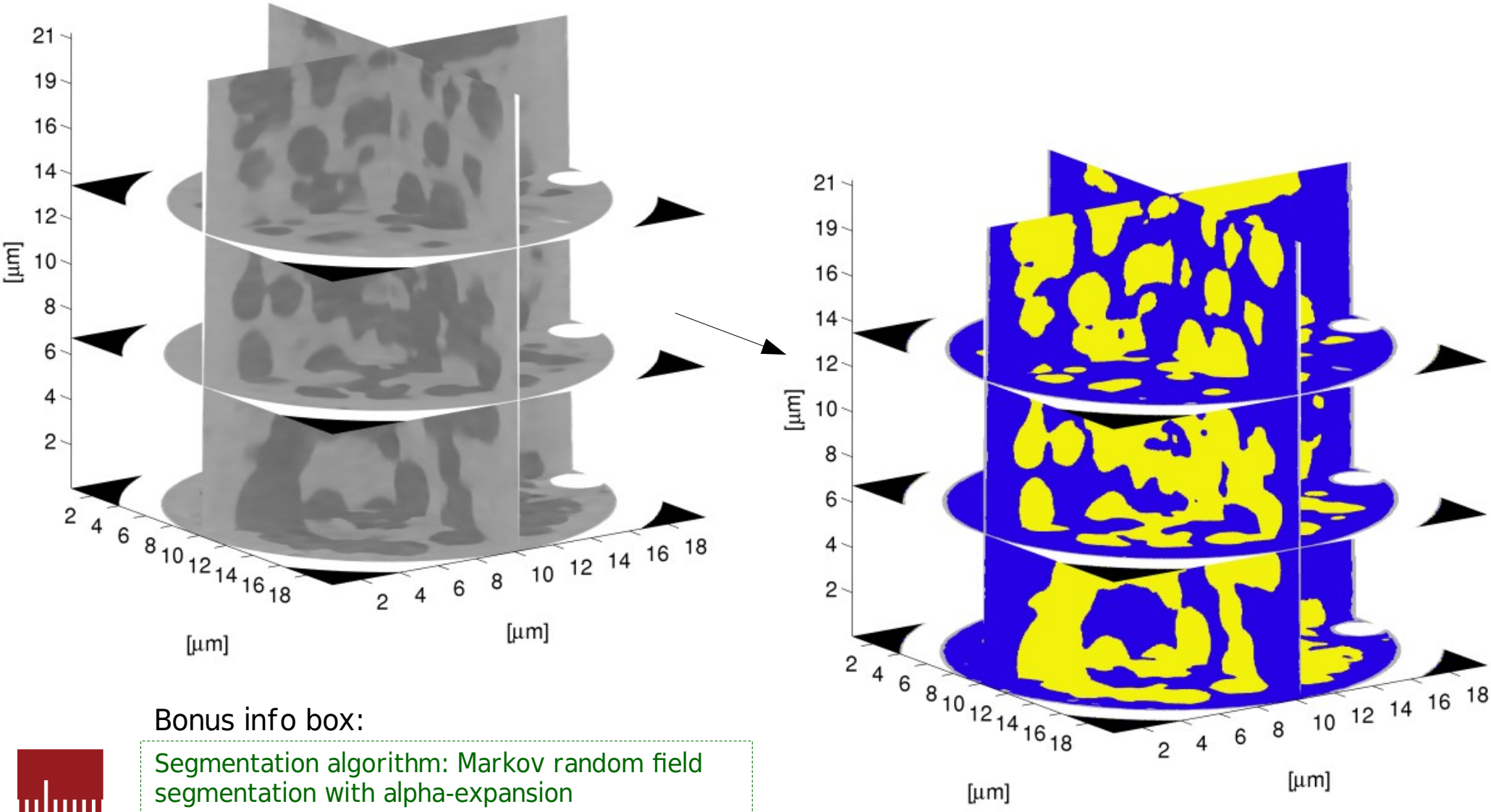
Segmentation

Segmentation of water and lipid phases



Segmentation

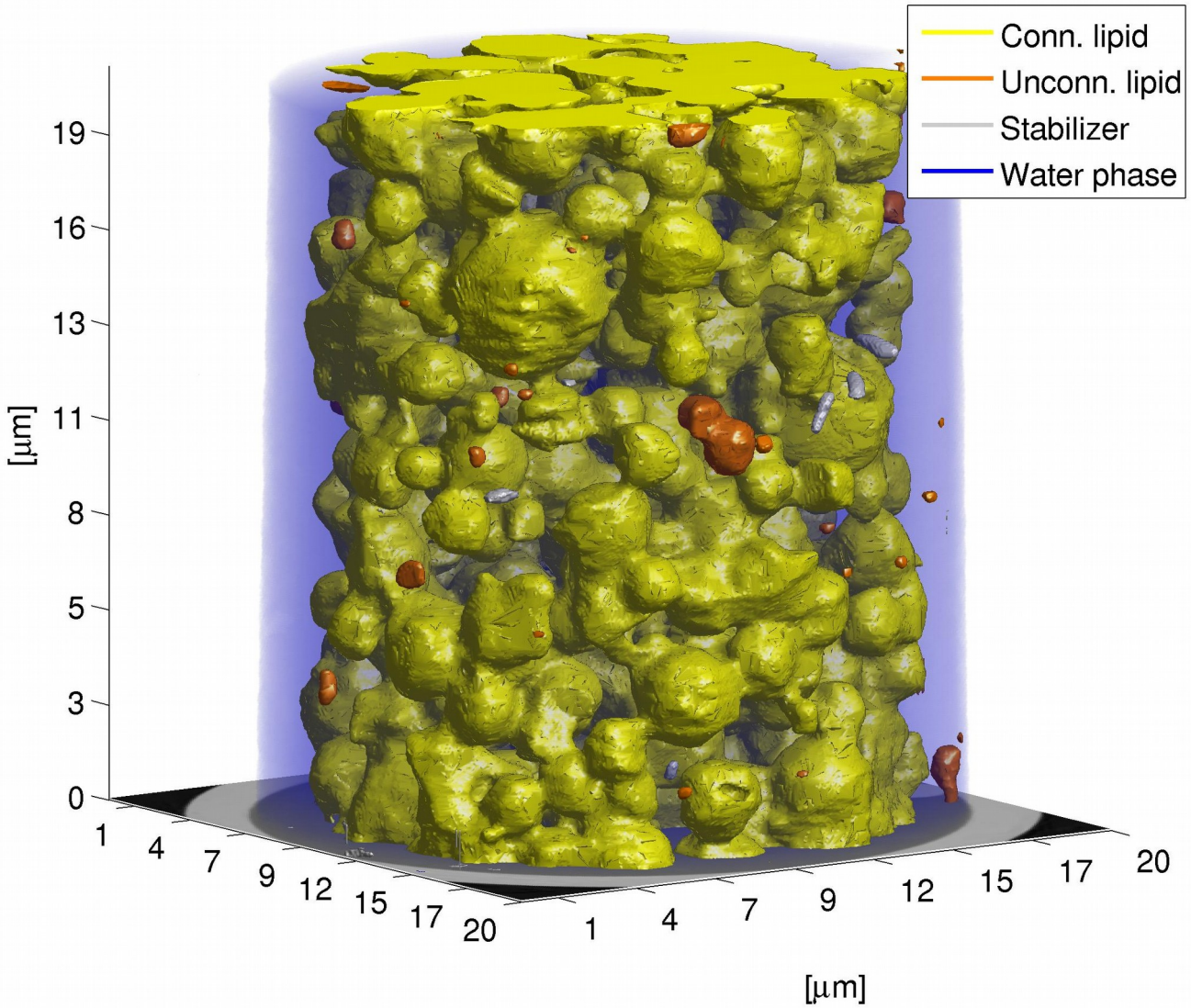
Segmentation of water and lipid phases



Bonus info box:

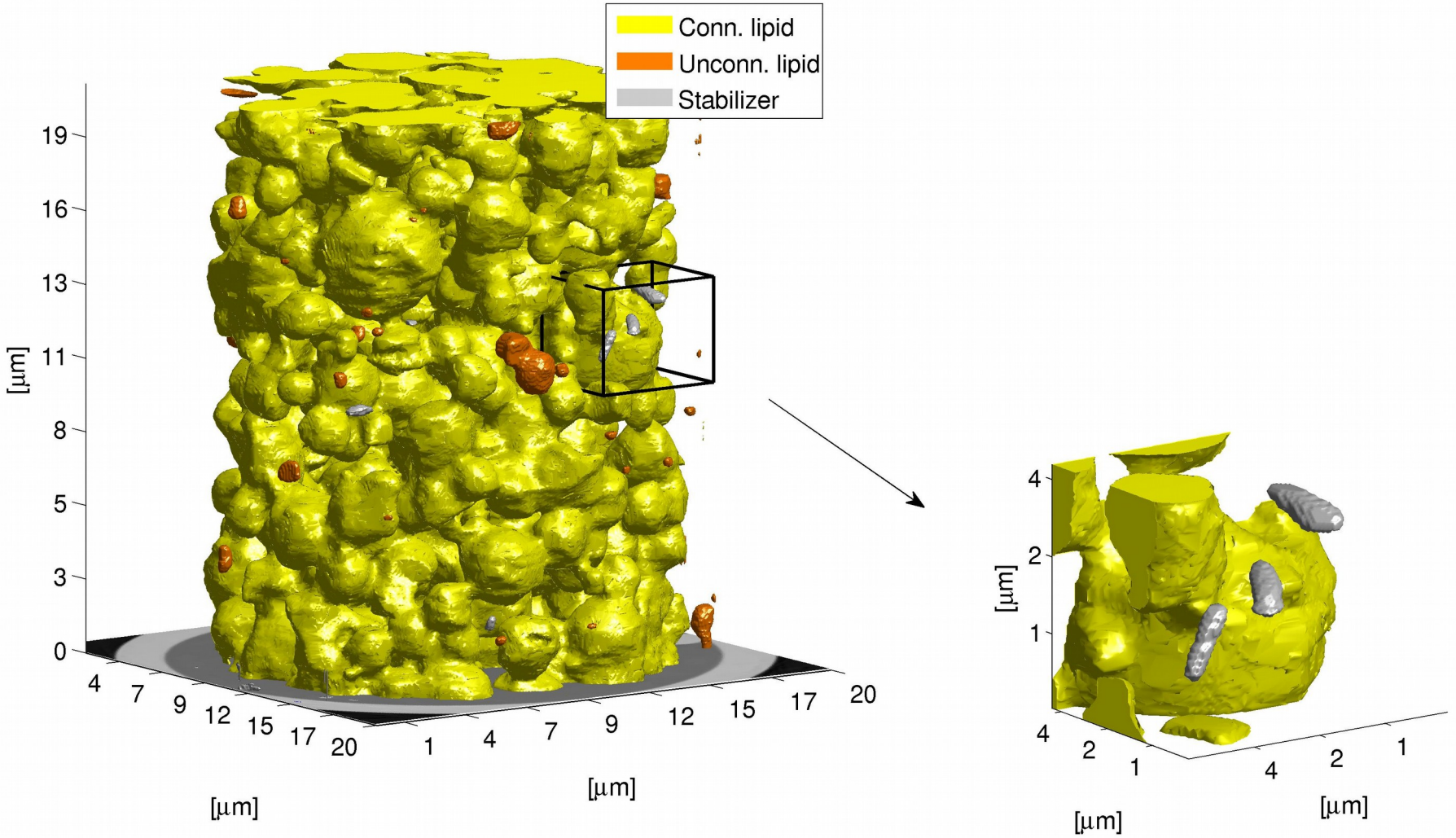
Segmentation algorithm: Markov random field segmentation with alpha-expansion

3d visualization of the emulsion



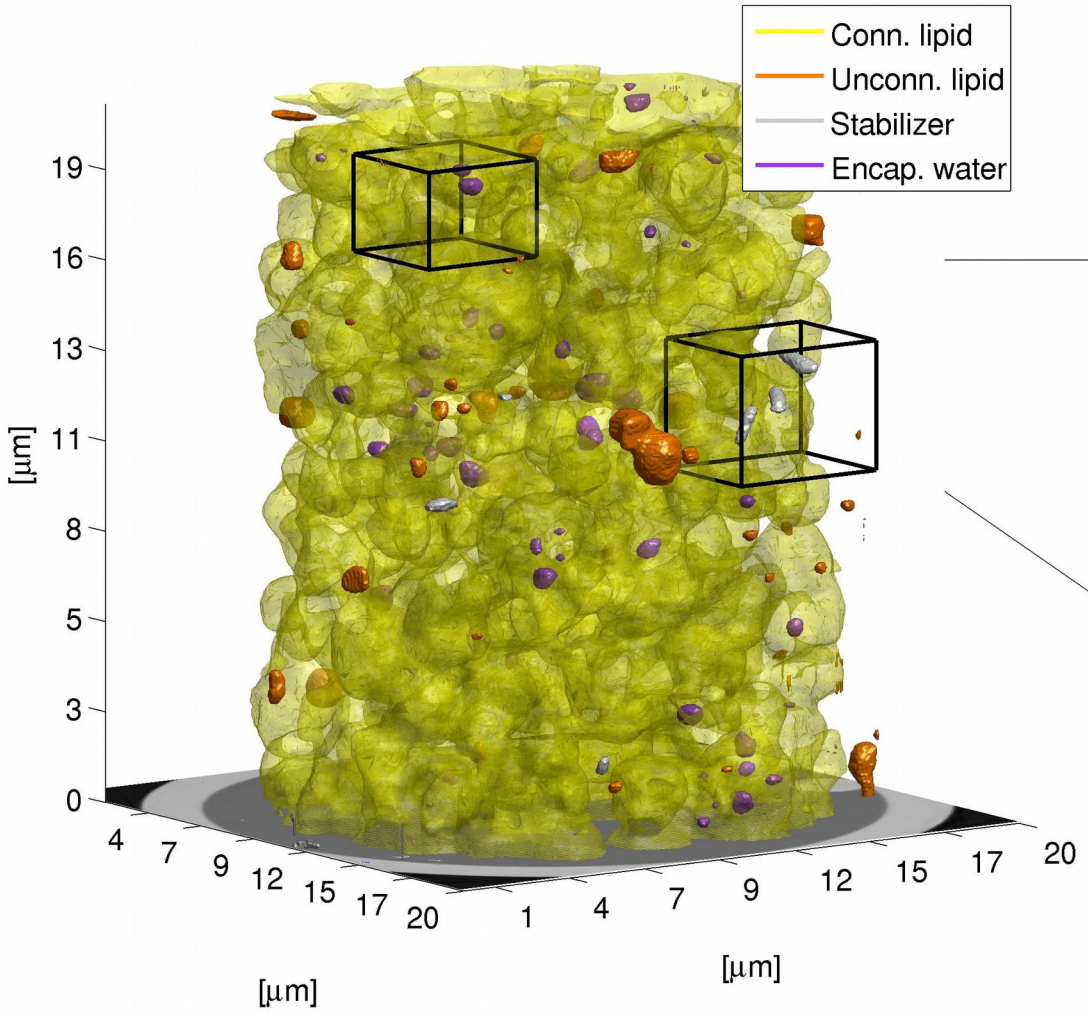
3d visualization of the emulsion

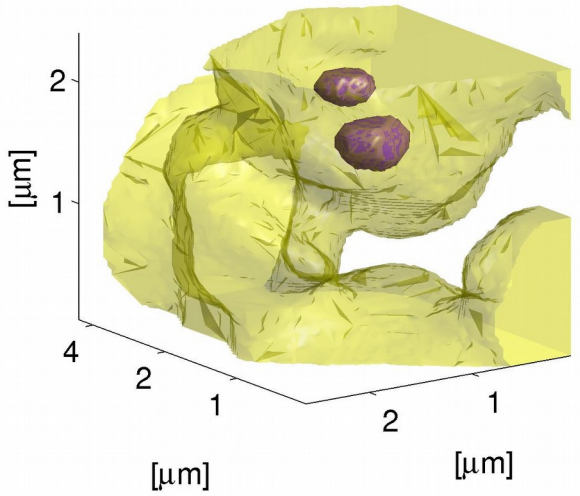
Micro-cellulose stabilizers

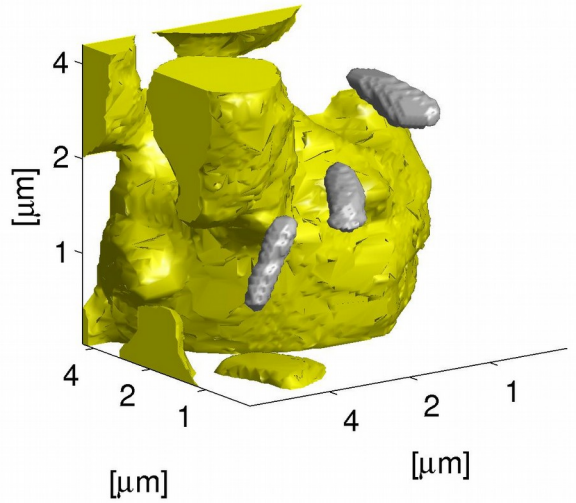


3d visualization of the emulsion

Encapsulated water in the lipid phase



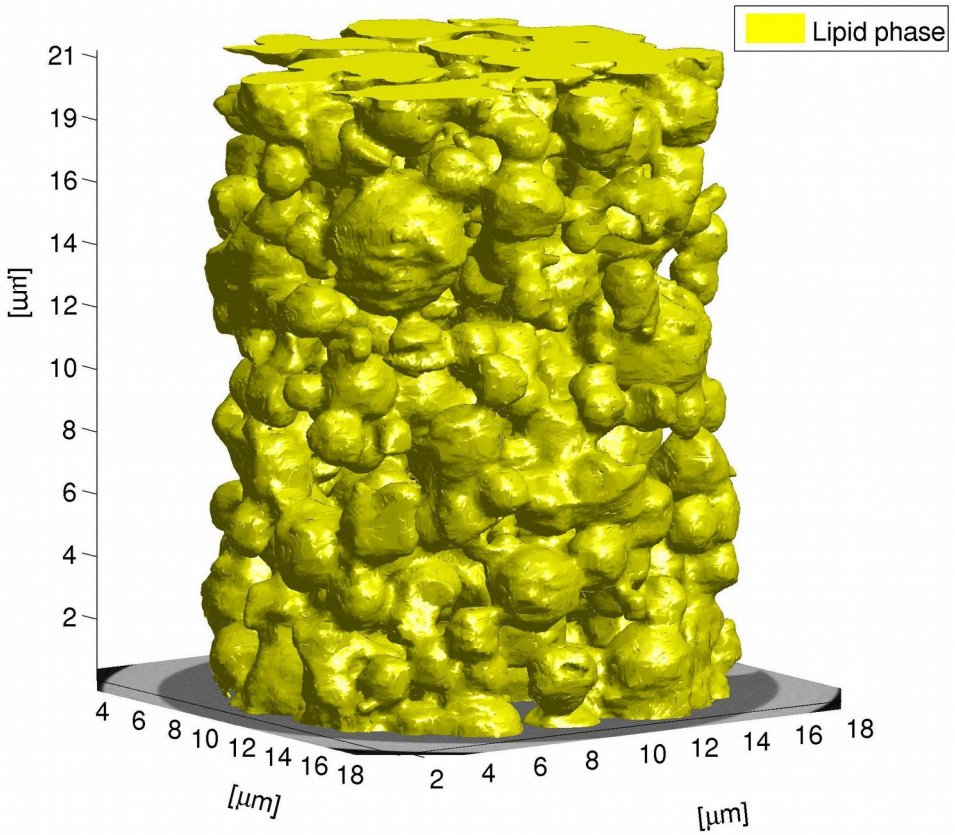




Lipid network

Lipid network

Partial coalescence of globules?



Lipid network

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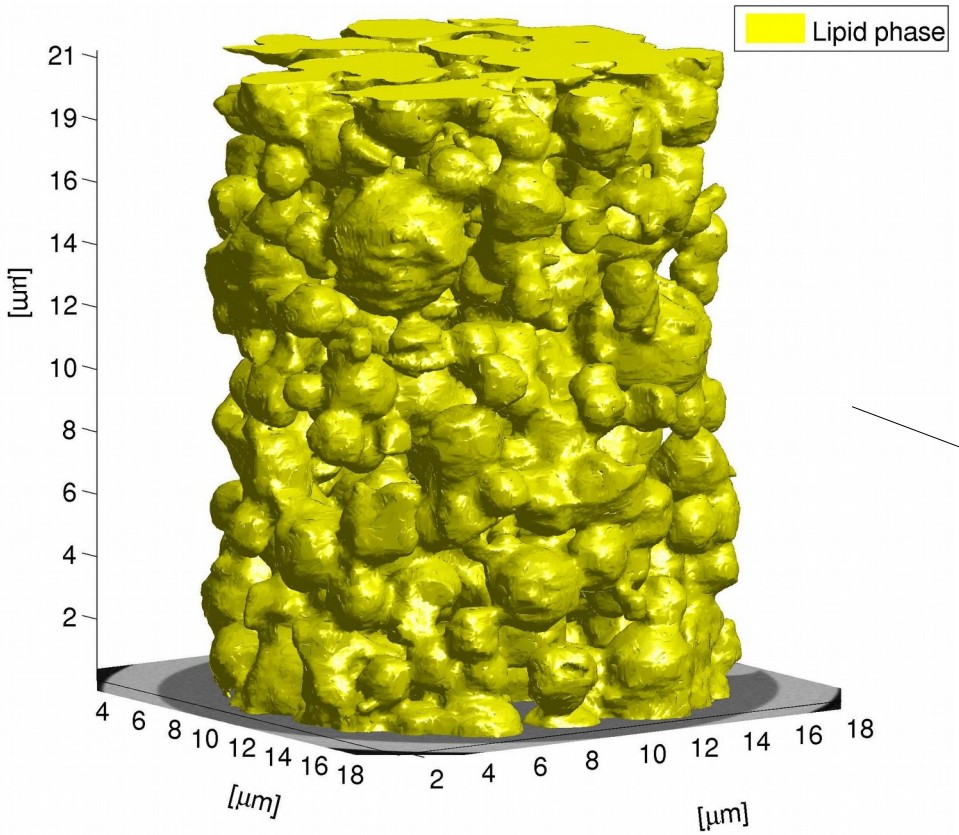
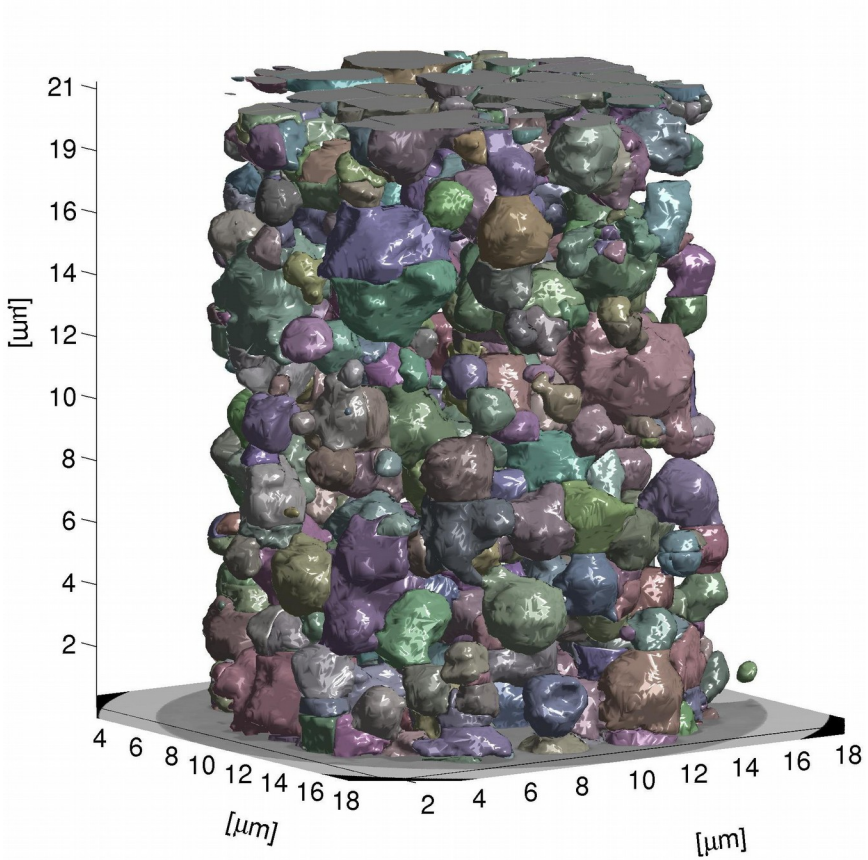
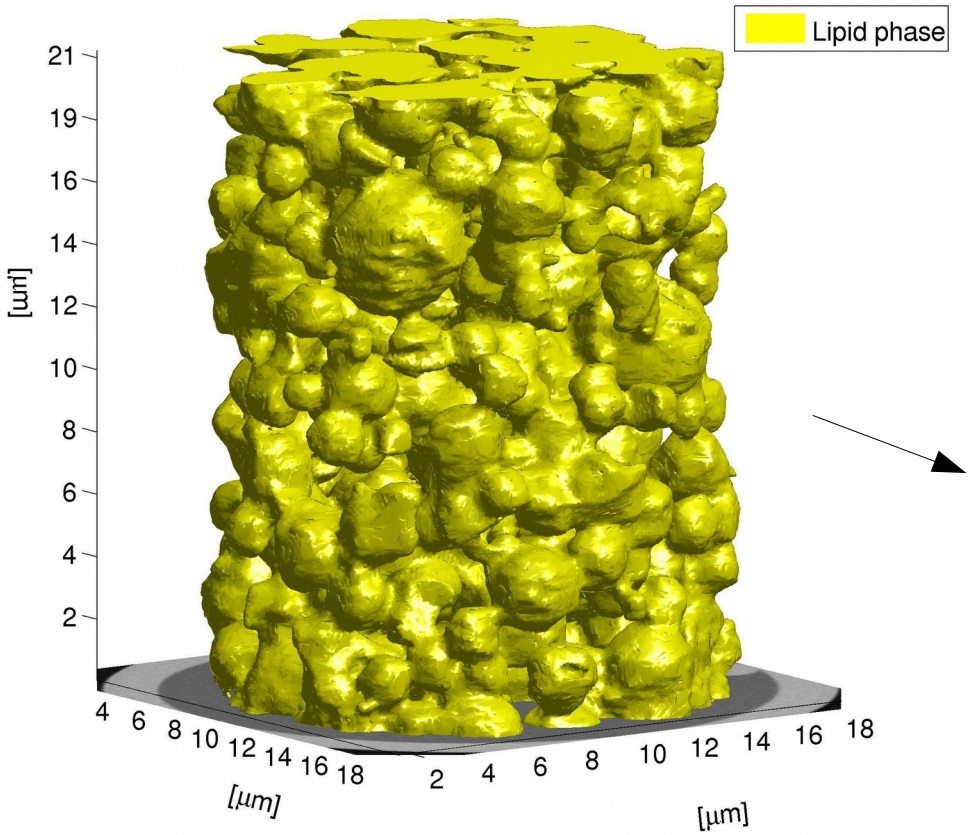


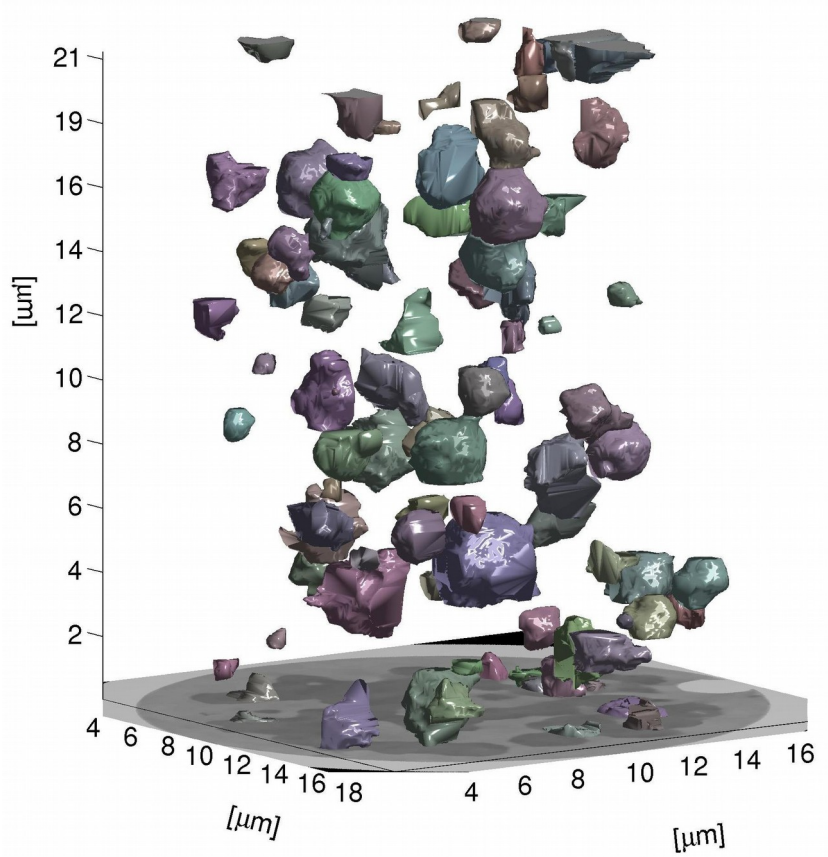


Watershed algorithm

Lipid network

Partial coalescence of globules?

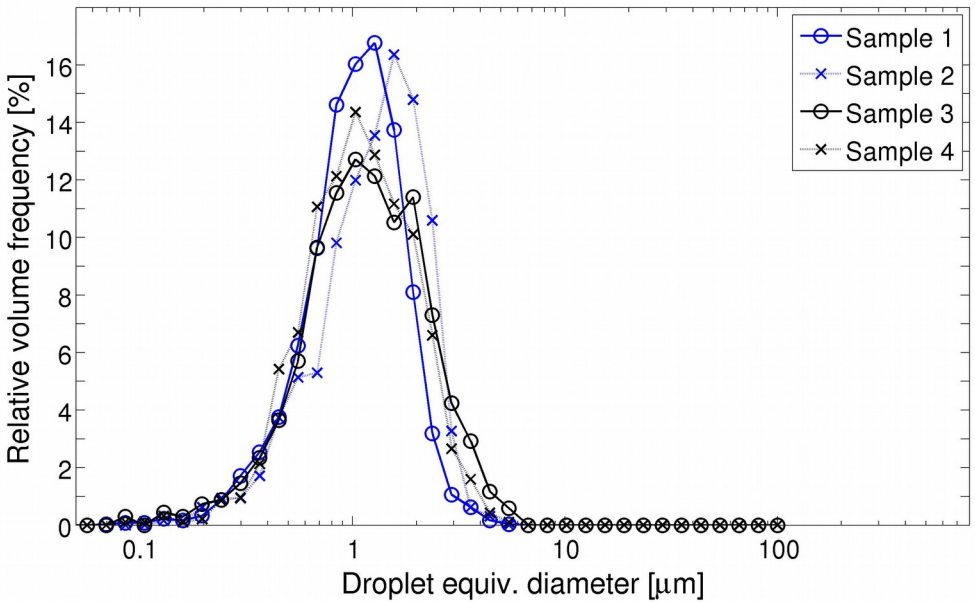




Lipid network

Lipid domain size distributions

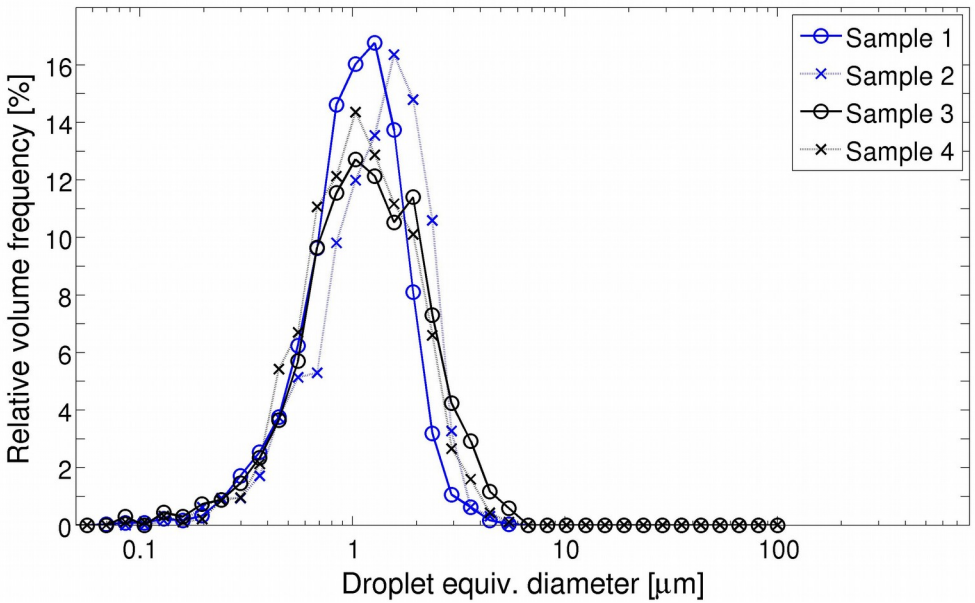
Ptychographic X-ray CT



Lipid network

Lipid domain size distributions

Ptychographic X-ray CT



Light scattering

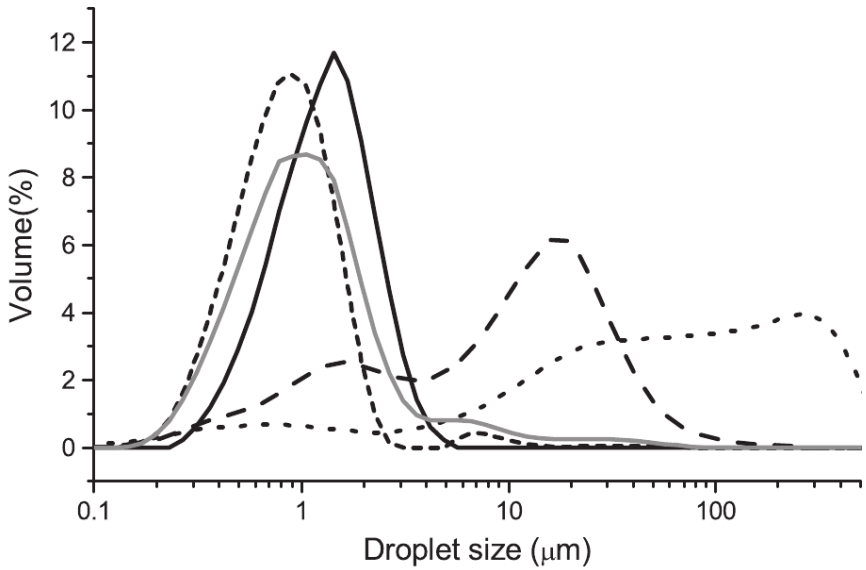


Fig. 2. The effect of monoglycerides on droplet size distribution in emulsions, — (solid black) control(solid black), LACTEM (long dash), The line style of "LACTEM + GMS" should be grey LACTEM + GMS (solid grey), – LACTEM + DATEM (short dash), ... LACTEM + GMU (dot).

Measure-ment	DLS control	Sam1	Sam2	Sam3	Sam4
Mean diameter	0.98	1.15	1.41	1.40	1.25

Network analysis

Fractal dimensions – a way forward?

Measurement	Pty-1	Pty-2	Pty-3	Pty-4
Fractal dimension	2.67	2.42	2.44	2.48

Network analysis

Fractal dimensions – a way forward?

Measurement	Pty-1	Pty-2	Pty-3	Pty-4
Fractal dimension	2.67	2.42	2.44	2.48

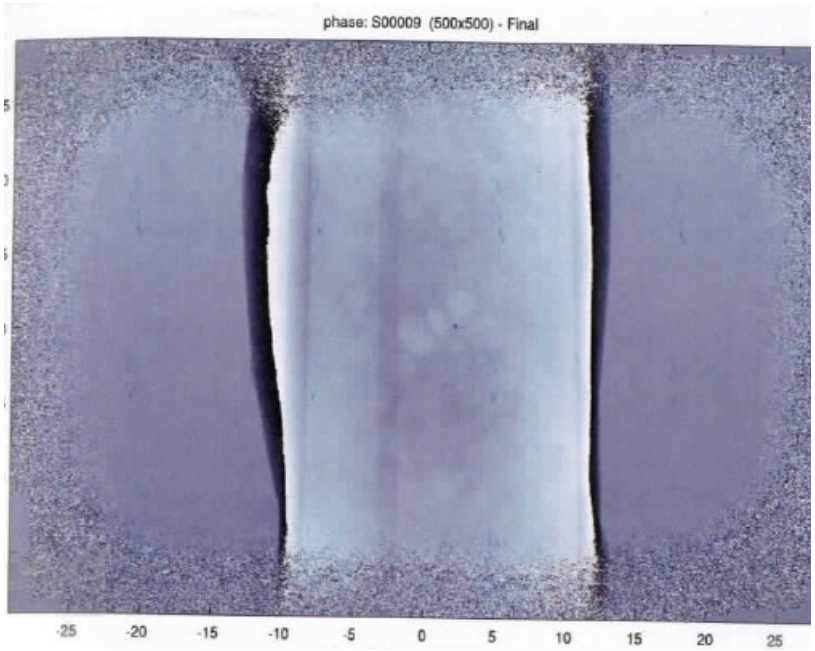
Table 2
Fractal dimension calculated via image analysis compared to fractal dimension calculated via rheology using the weak theory. Errors in D are standard errors of three replicates

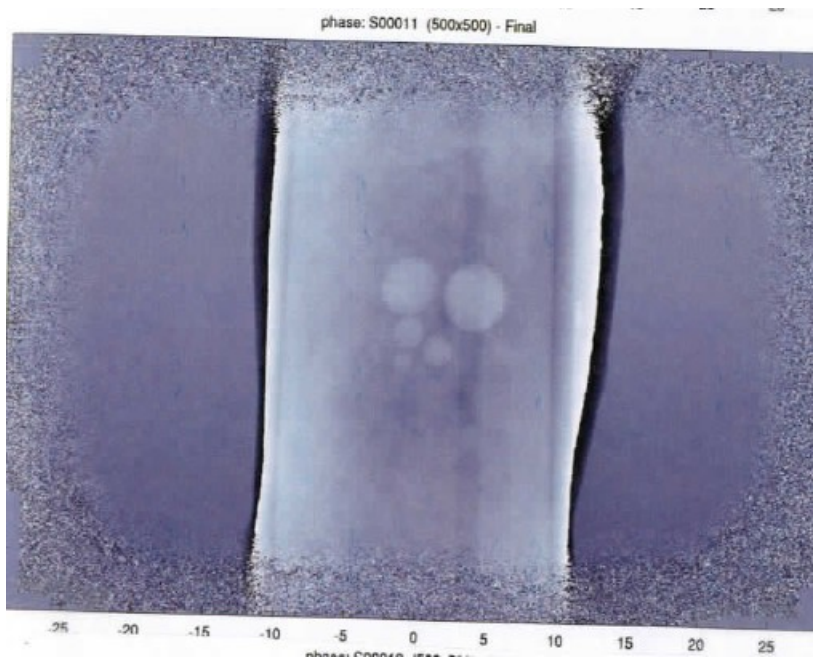
Fat system	Fractal dimension from image analysis	Fractal dimension from rheology (weak-link regime)	Percent deviation
Cocoa butter #1	2.31 ± 1.7%	2.37 ± 4.0%	2.5
NIE milkfat #4 (analysed using DMA)	2.02 ± 1.2%	2.01 ± 15.7%	1.5
Palm oil	2.82 ± 0.6%	2.82 ± 0.6%	0.0
Lard	2.86 ± 0.6%	2.88 ± 0.5%	1.0
Tallow	2.42 ± 1.2%	2.41 ± 6.4%	0.4

Discussion and conclusion

Discussion - radiation damage

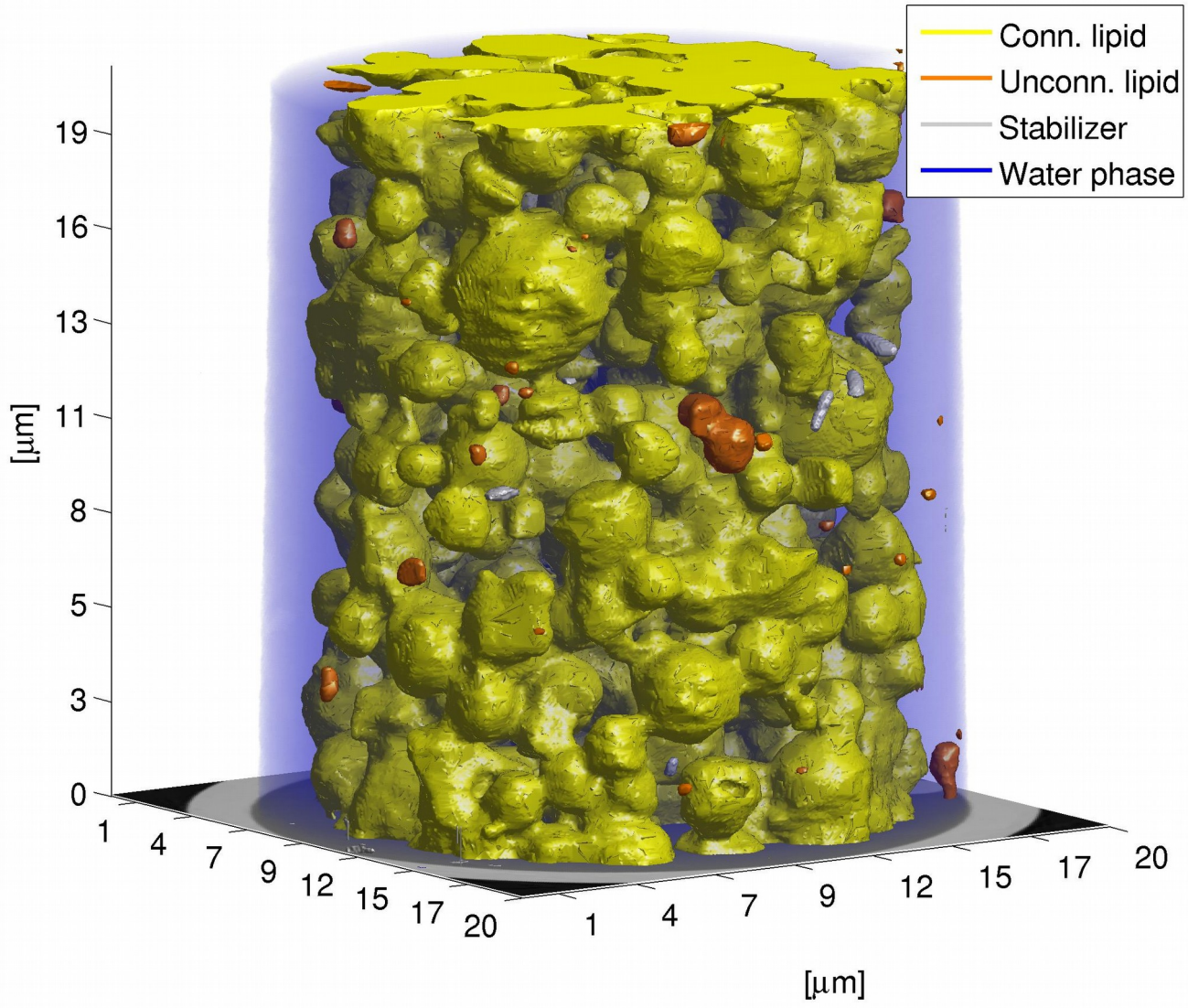
High intensity of initial beam causes bubble formation





Discussion – sample container

Small container effects the sample?



Conclusion and outlook

The 3D nanostructure of a dairy-like emulsion

Conclusion

- The nanostructure of the food emulsion was imaged using ptychographic X-ray CT.
- Lipid-phase forms 3D network
- Consistent with (extreme) partial coalescence.

Outlook

- From tomographic scans to viscoelastic properties - *Finite element modelling?*
- Increased avalability of method – MAX IV

Acknowledgements

University of Copenhagen
Merete B. Munk
Jens Risbo
Kell Mortensen
Stefan Bruns
Robert Feidenhans'l
Kristian Rix

Technical University of Denmark
Emil B.L. Pedersen
Jens W. Andreasen

Paul Scherrer Institute, Switzerland
Ana Diaz
Mirko Holler

Funding agencies
Danish council for strategic funding
The danish national advanced technology foundation

Thank you for your attention!

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