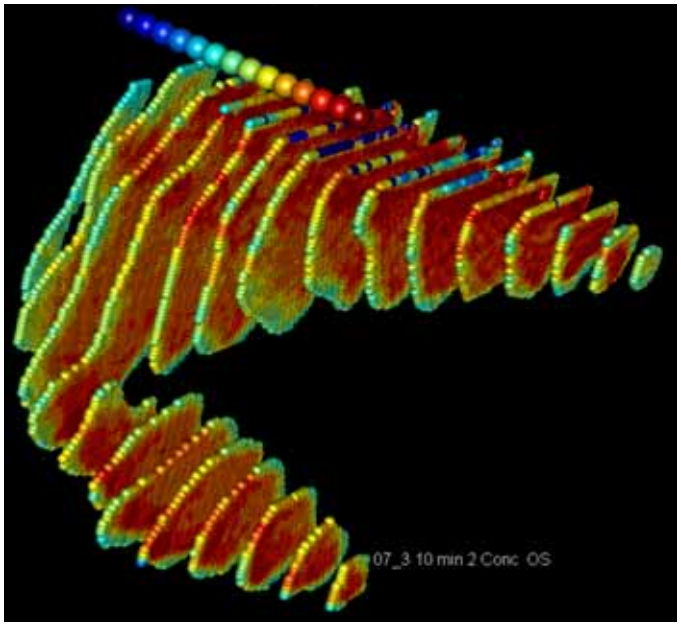
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Structure and rheology of stimuli responsive nanocellulose interfacial layers



Nordic Lights on Foods, 10.6.2021

Peter Fischer

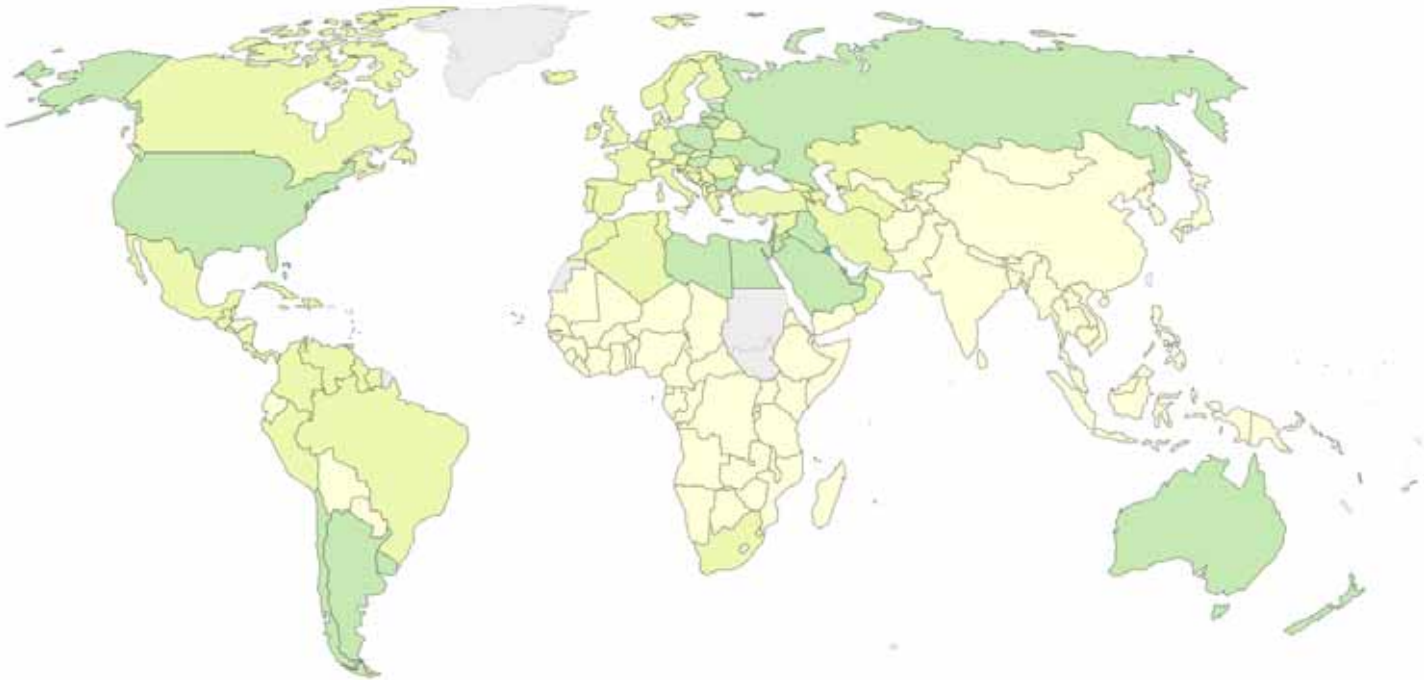
Institute of Food, Nutrition and Health, ETH Zürich, Switzerland

A bit(e) of motivation: Global obesity and malnutrition

Share of adults defined as obese, 1975

Our World in Data

Percentage of adults aged 18+ years old who are defined as obese based on their body-mass index (BMI). BMI is a person's weight in kilograms (kg) divided by his or her height in metres squared. A BMI greater than or equal to 30 is defined as obese.



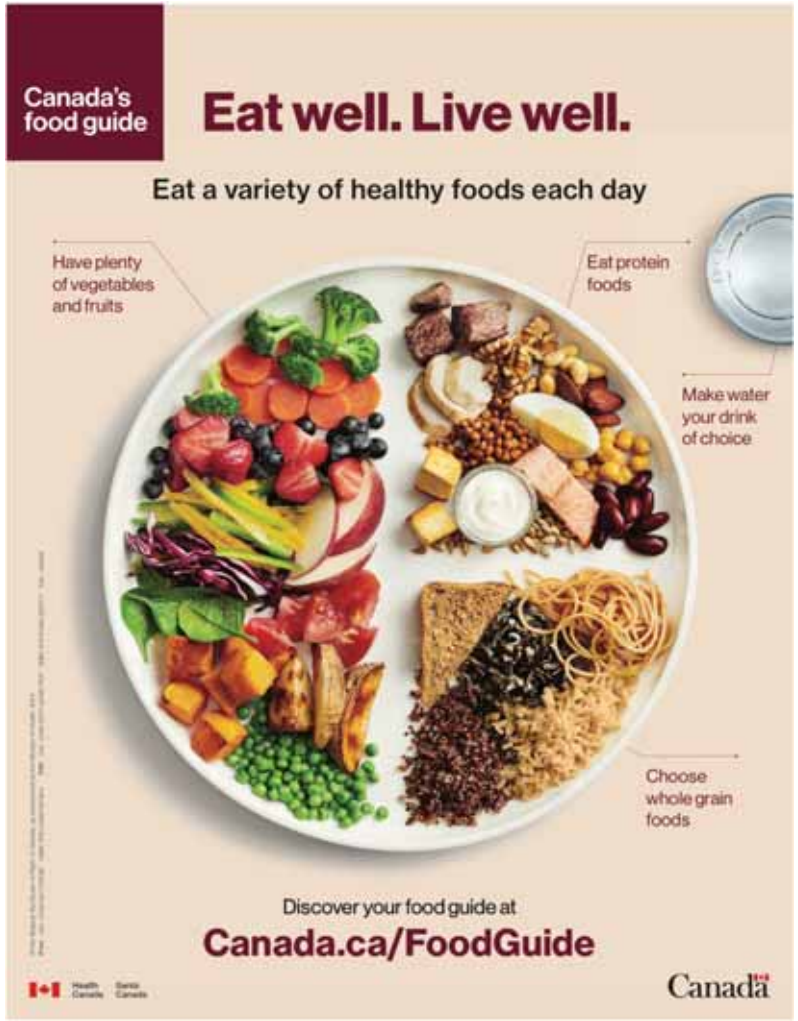
No data 0% 5% 10% 15% 20% 25% 30% 35% >40%

Source: WHO, Global Health Observatory

How to reduce overweight and obesity

General consensus

- Achieve energy balance
- Limit intake of total fat
- Shift from saturated to unsaturated fats
- Fruit, vegetables, whole grains, nuts
- Limit intake of sugars
- Increase physical activity



Some proposals from food science

- The 'Great Fat Ban'
- Artificial sweeteners
- Fibers and fullness
- Controlling nutrient/mucus/biofilm interaction
- **Rethinking the role of fat*:* Controlling lipid digestion and uptake**

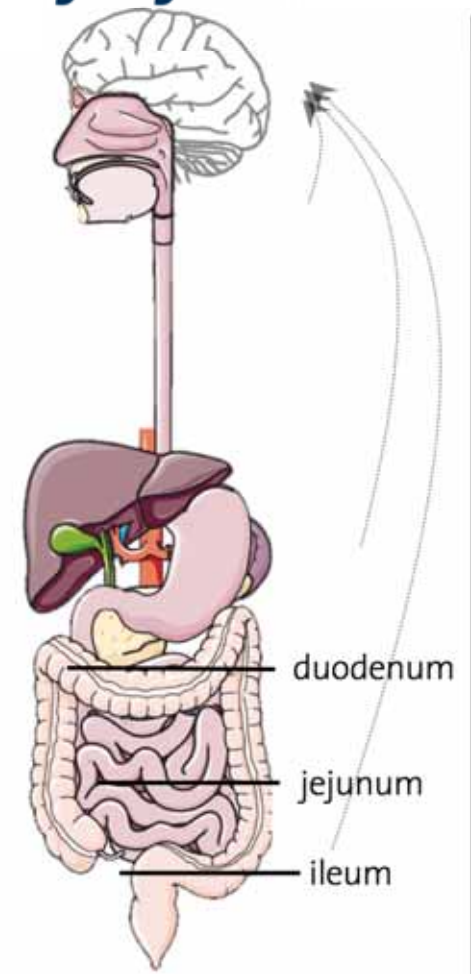
Golding M, Wooster TJ: COCIS 15 (2010) 90

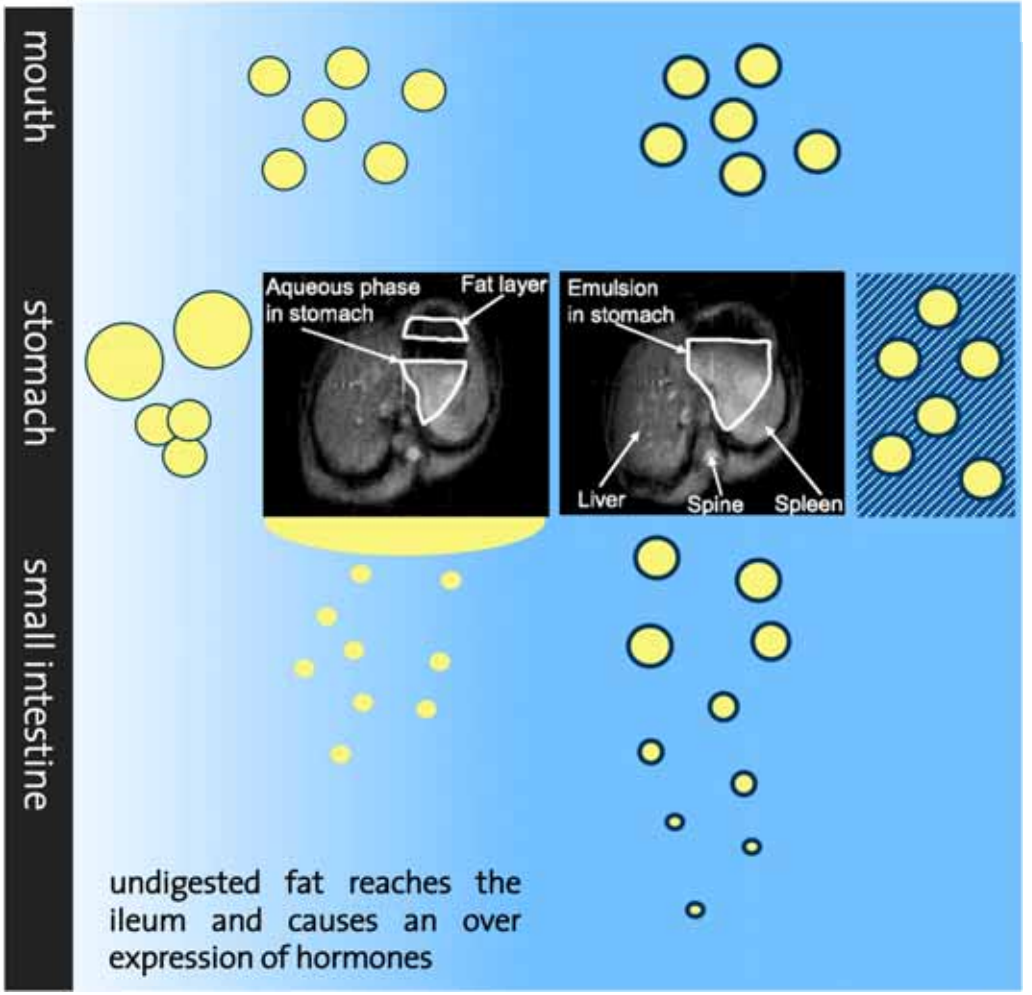
Increase satiety by defined hormone release

Fat & lipid uptake

Structural changes in stomach and small intestine

Ileal brake: Lipids in the small intestine will trigger satiety hormones (CCK, GV, TAG)





Idea: Get lipid emulsios as fast as possible into small intestine

Problem: Lipid emulsions have to survive stomach

Golding M, Wooster TJ: COCIS 15 (2010) 90

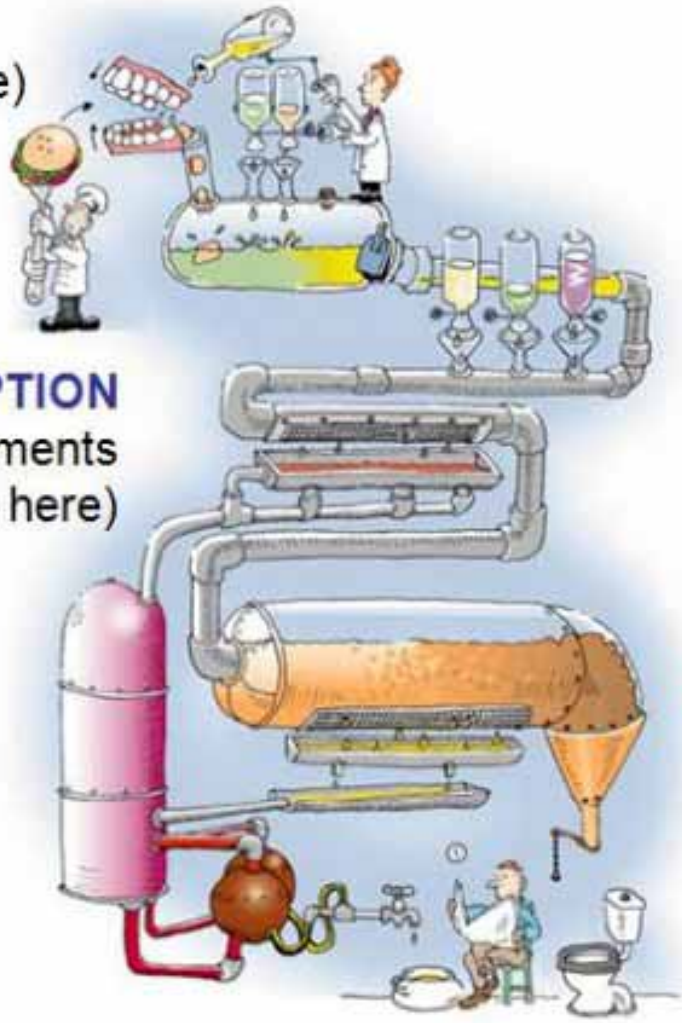
Boundary conditions in GI environment

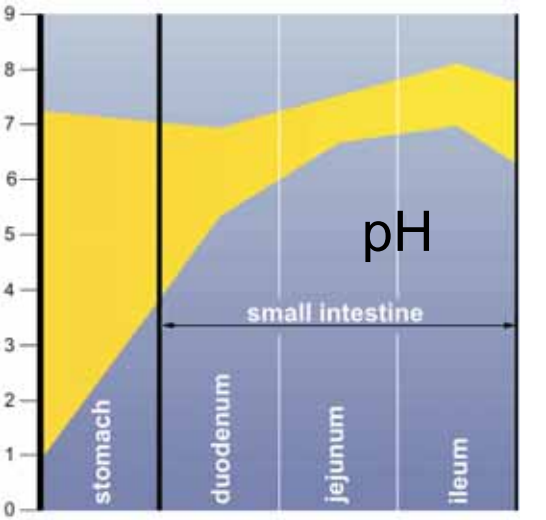
INGESTION
(Nutrition starts here)

ABSORPTION
(Supplements help here)

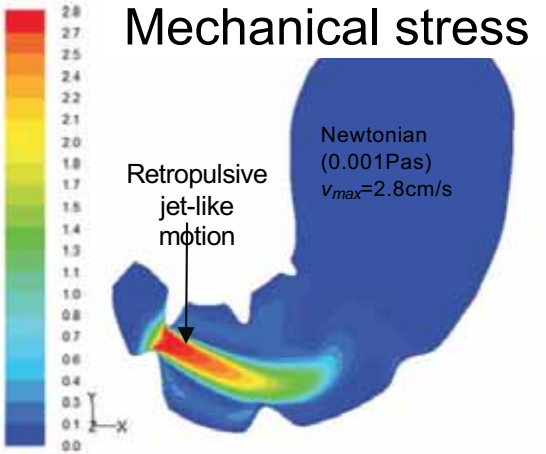
DIGESTION
(Enzymes work here)

GUT HEALTH
(Probiotics live here)





Mechanical stress



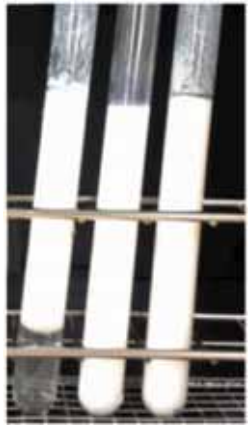
Mucus
Ionic strength
Temperature

Approach: Stable but responsive lipid emulsions

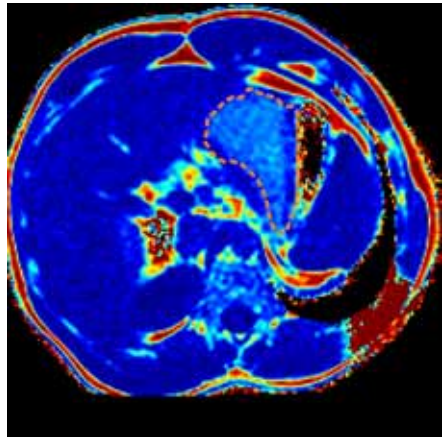
- Step 1: Emulsion design (interfacial rheology, neutron reflectivity)
- Step 2: In-vitro survival of emulsion droplets
- Step 3: In-vivo gastrointestinal response

Emulsion design

Microfluidic analysis



Bulk phase structuring



In vivo studies (rats, humans)

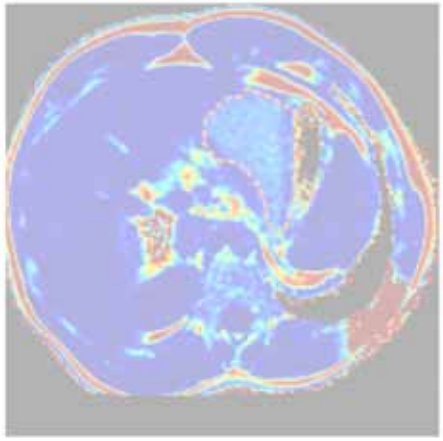
Step 1: Emulsion and interfacial layer design

Emuslion design

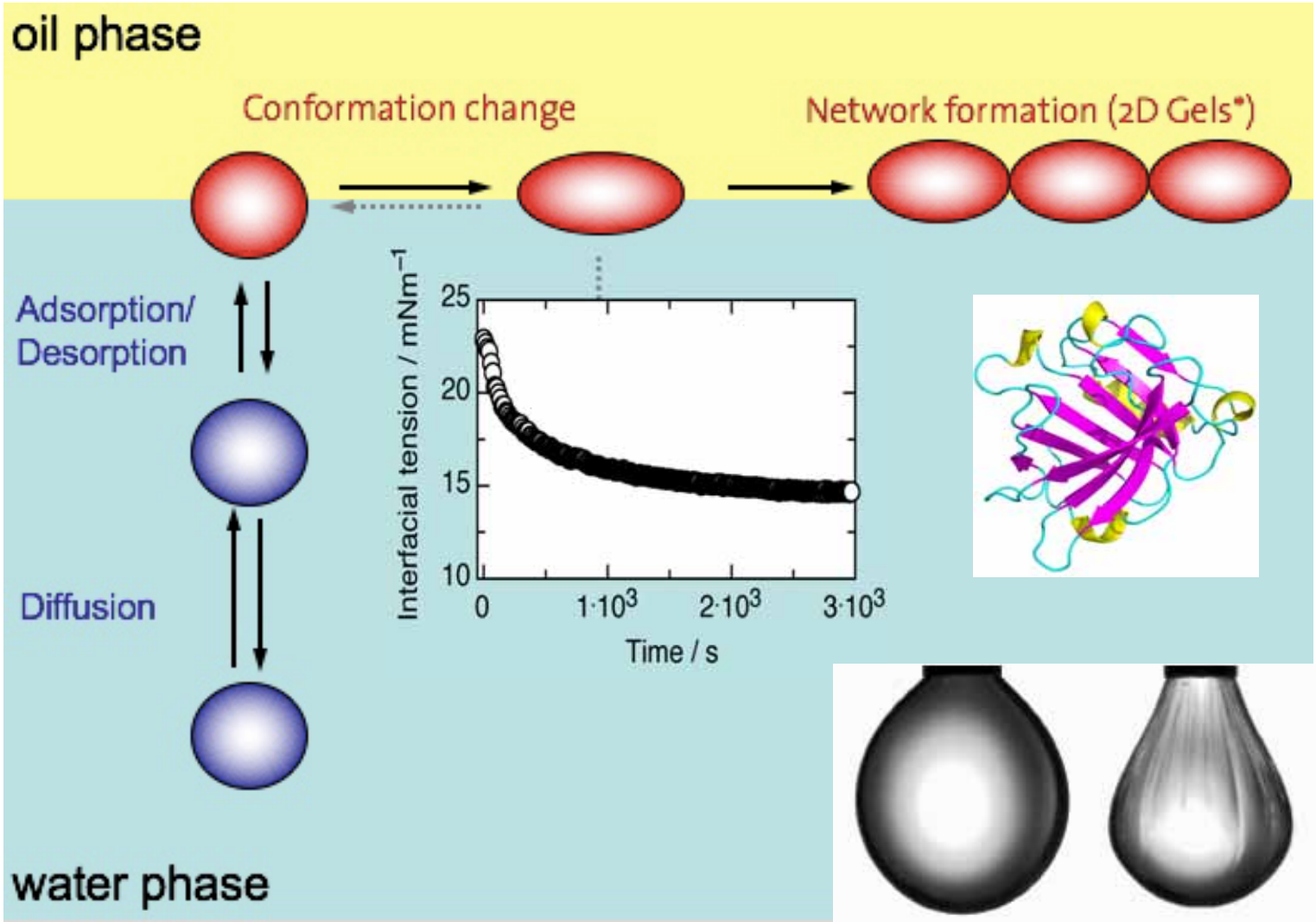
Microfluidic analysis

Bulk phase structuring

In vivo studies



Adsorption layers: Proteins, surfactants, particles, …



β-lactoglobulin
(bovine milk)
pI 5.4
$M_r \cong 18300$

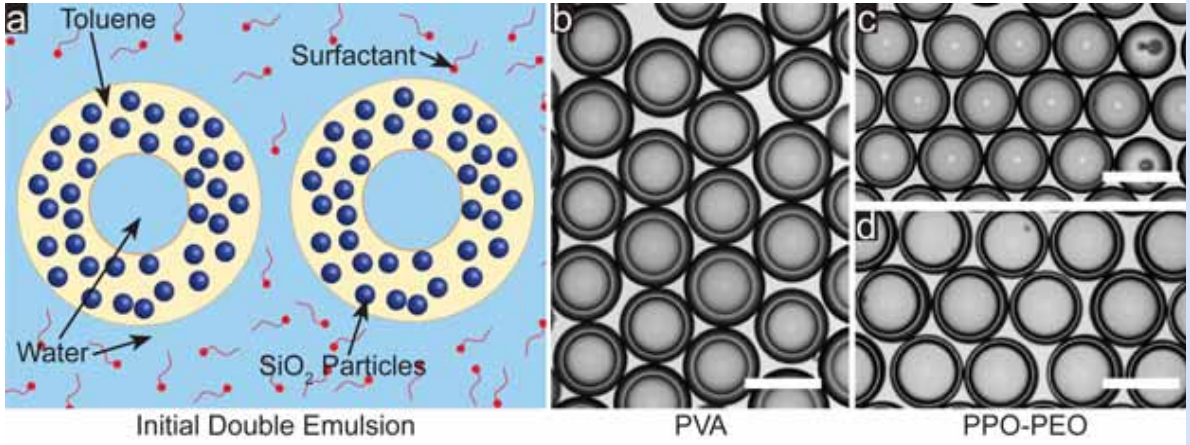
Mezzenga R, Fischer P: Rev. Prog. Phys. 76 (2013) 046601

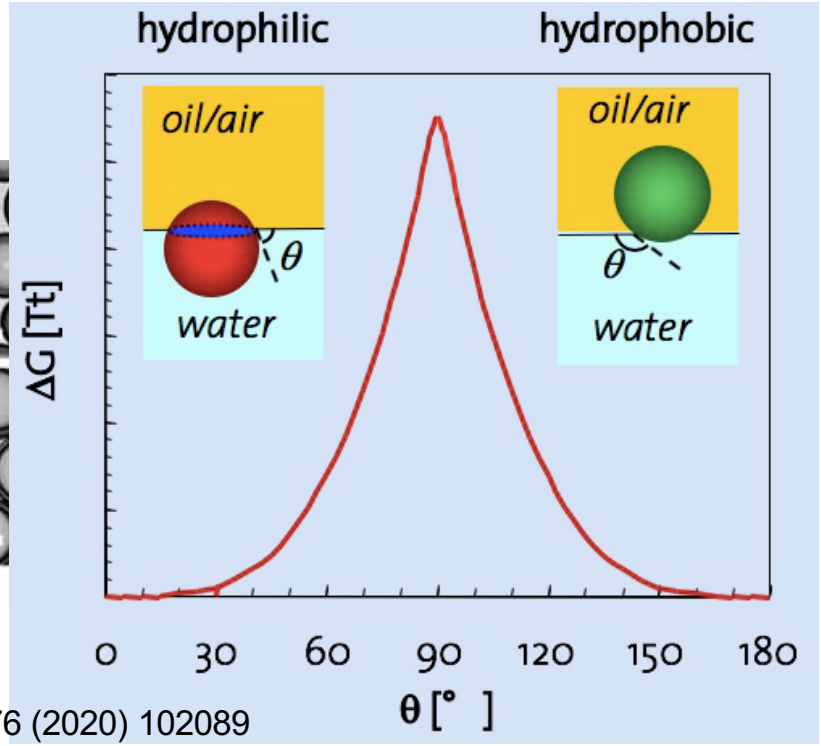
Benjamins J (2002) Dissertation, Wageningen University
Dickinson E (1998) J Chem Soc, Faraday Trans 94:1657

Adsorption layers: Proteins, surfactants, **particles**, …

Nanoparticles for food-grade **oil-in-water**

- Chemically modified **starch** particles (Tan et al., 2012)
- **Cellulose** nanocrystals (Kalashnikova et al., 2011)
- Solid **lipid** particles (Gupta and Rousseau, 2012)
- **Flavonoid** particles (Luo et al., 2011, 2012)
- **Chitin** nanocrystals (Tzoumaki et al., 2011)
- **Zein** particles (de Folter et al. 2012)





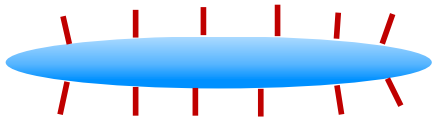
Review food grade particles: Sarkar & Dickinson: COCIS 49 (2020) 49
Review cellulose particles: Bertsch & Fischer, Adv. Colloid Interface Sci. 276 (2020) 102089

CNC: Modifications and adsorption isotherms

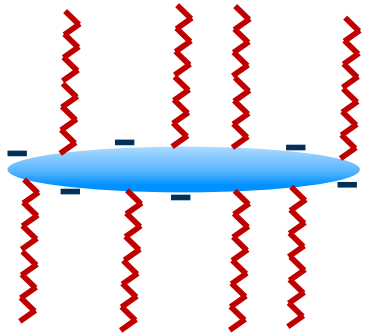
Hydrophobicity

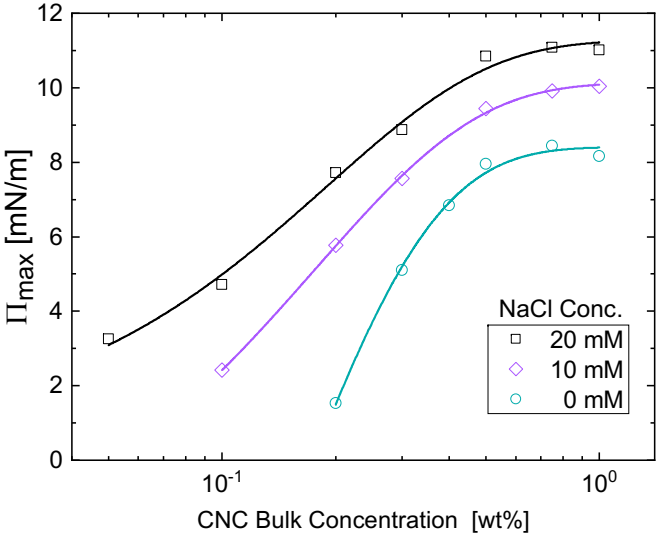
Unmodified

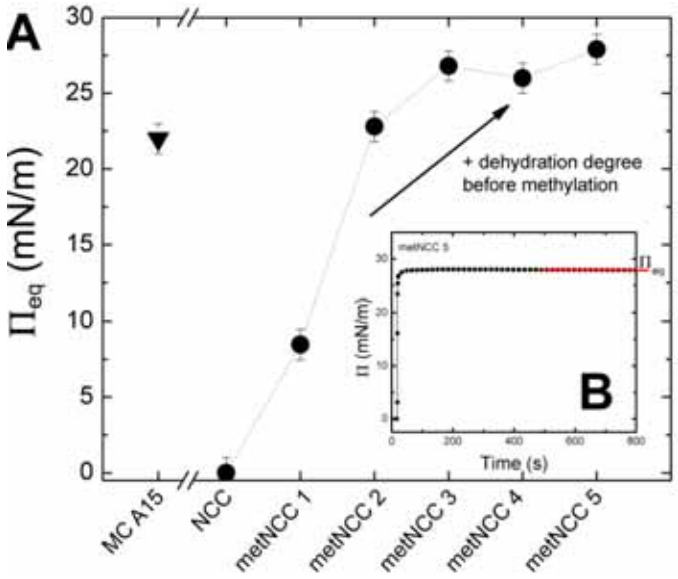
Methylated

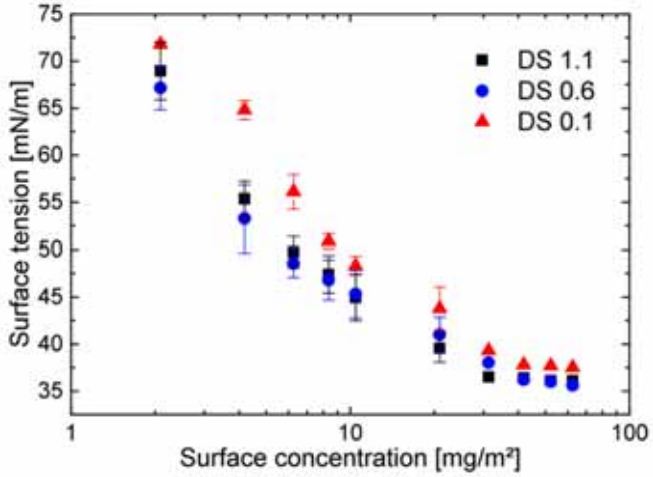


Esterified







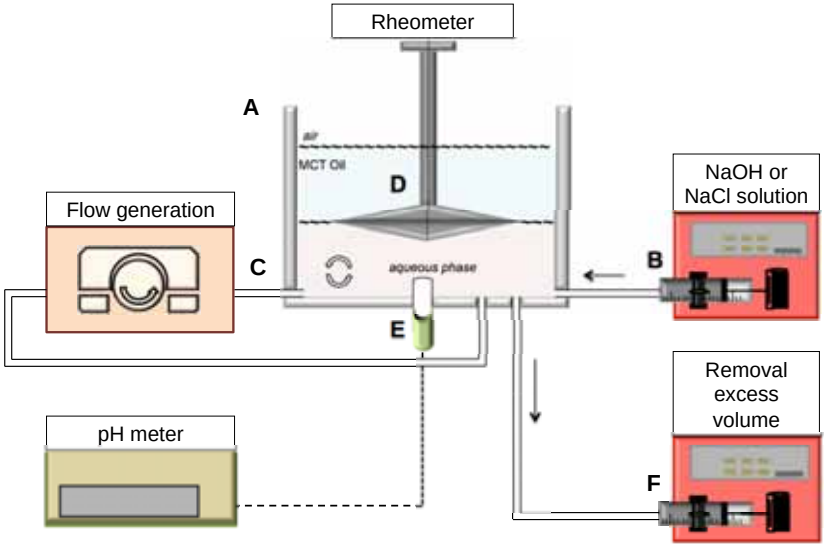


Langmuir 34 (2018) 15195

Langmuir 32 (2016) 1396

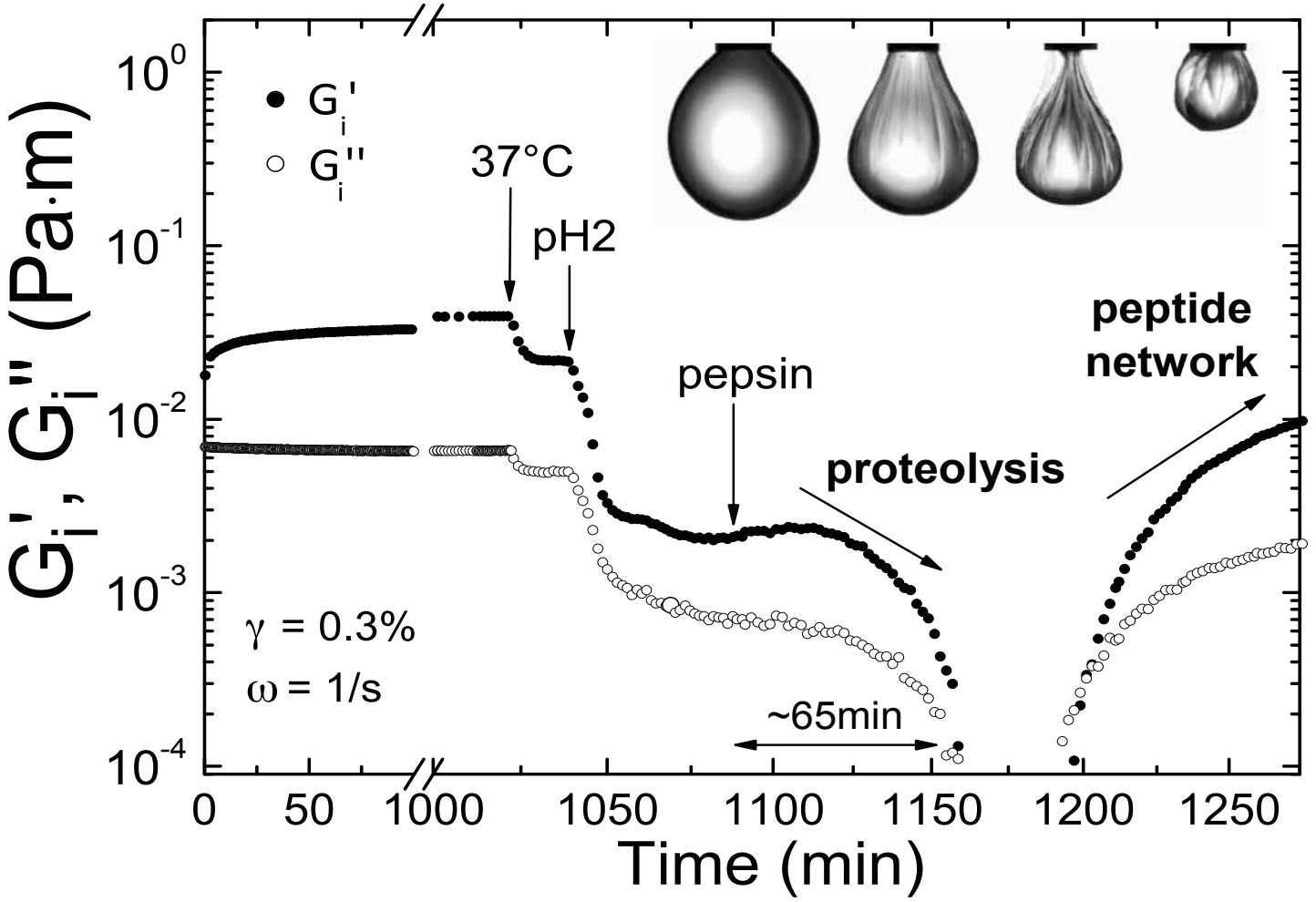
Langmuir 34 (2018) 10932

Using interfacial rheology for digestion



Rühs PA et al.: Langmuir 28 (2012) 12536
Erni P et al.: Rev. Sci. Instrum. 74 (2003) 4916

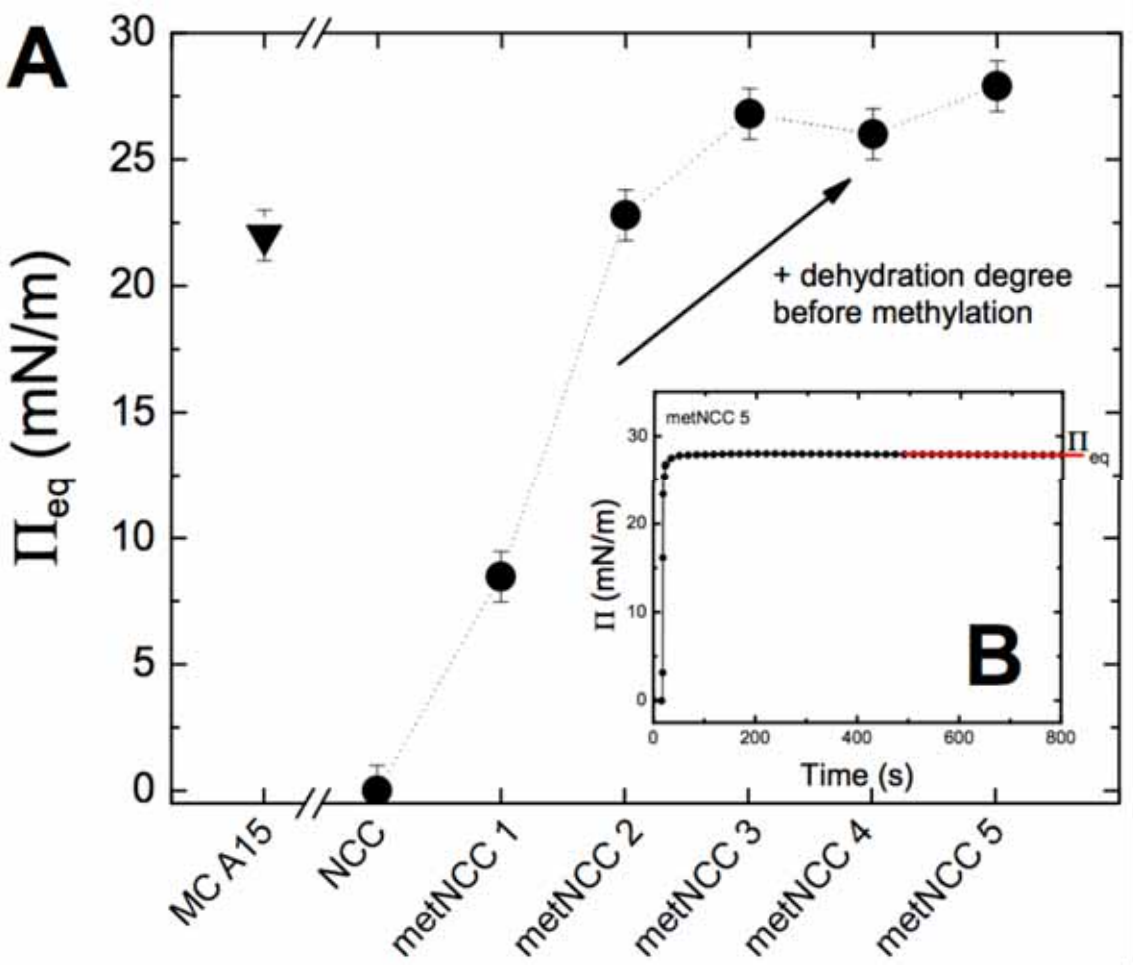
β-lg under gastric conditions



β-lg: 0.1mg/ml
water phase: pH4, 10mM phosphate buffer

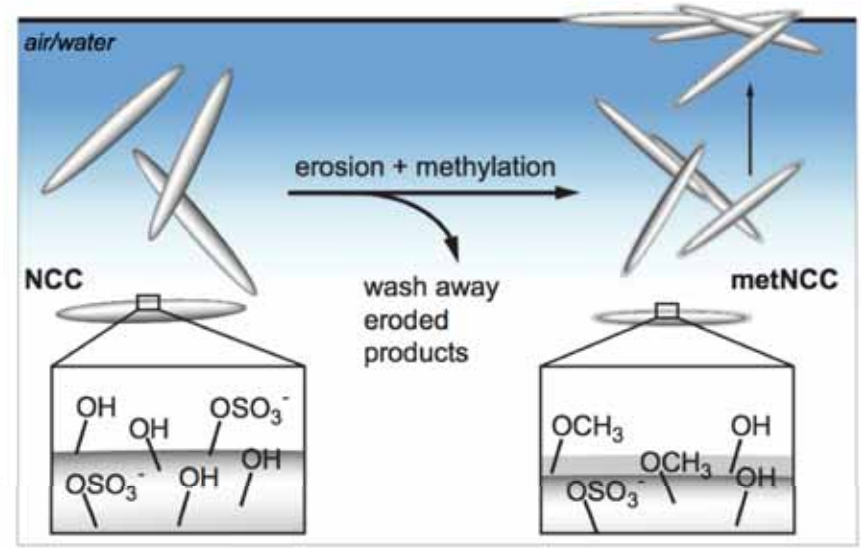
Scheuble N et al.: Biomacromolecules 15 (2014) 3139

Design of composite layers: Interfacial activity



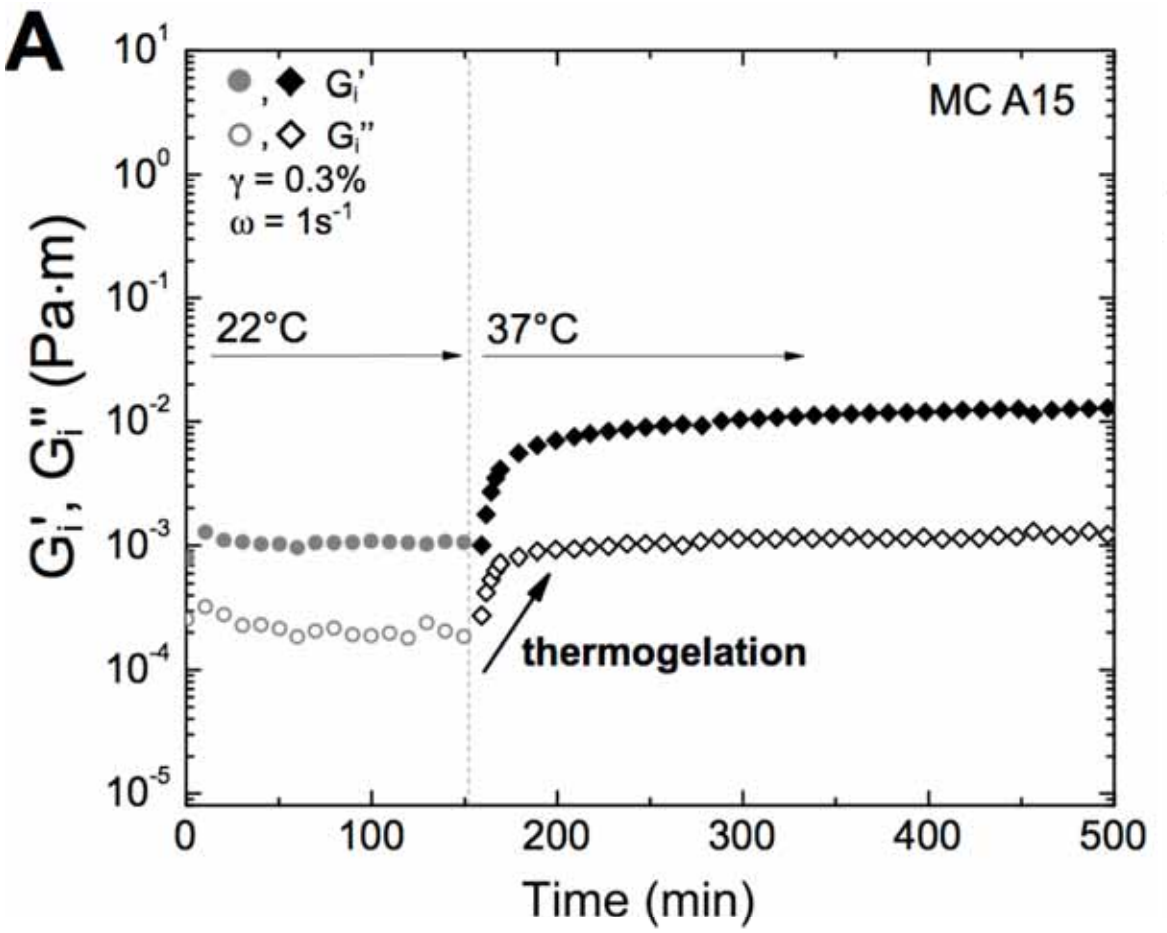
Methylcellulose (MC A15)
Nano Crystalline Cellulose (NCC)
Methylated NCC (metNCC)

2 to 10 nm width
80−150 nm length



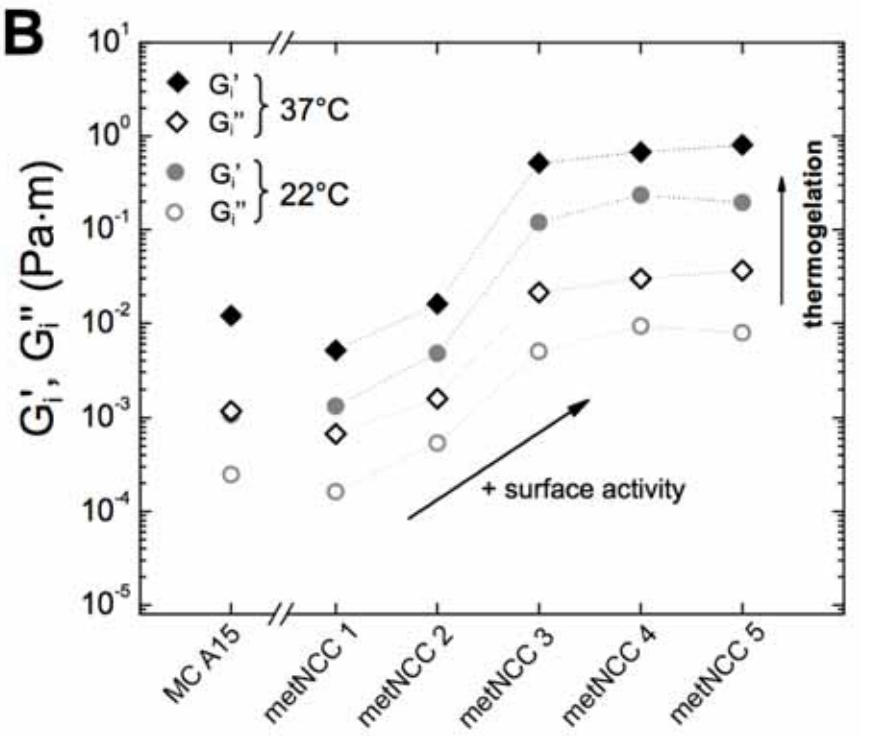
BTW: **NCC is surface active**, but only one guy waited long enough to see it: Bertsch et al.: Langmuir 34 (2018)15195

Design of composite layers: Thermogelation



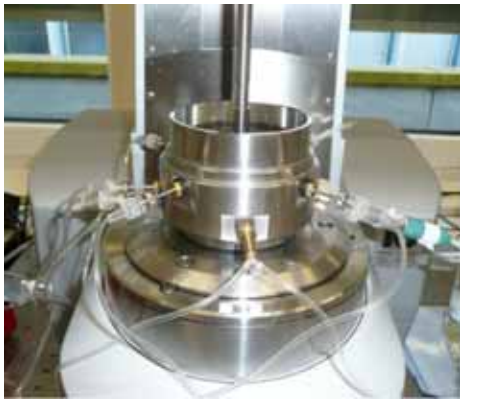
MC & metNCC

- Bulk gelation at 48° C
- Interfacial gelation at 22° C

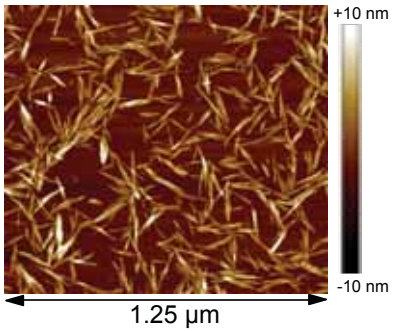


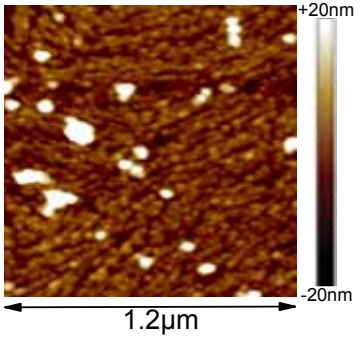
Scheuble N et al.: Langmuir 32 (2016) 1396
Scheuble N et al.: Biomacromolecules 17 (2016) 3328

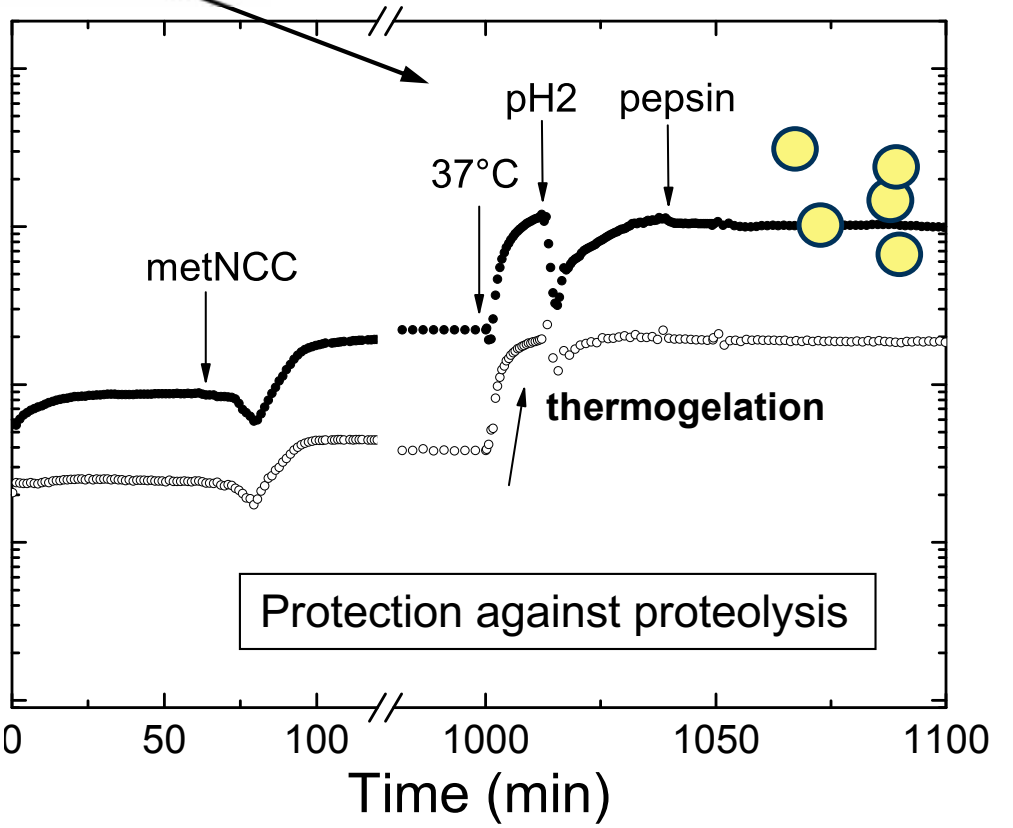
metNCC & β-lg under gastric conditions



β-lg + metNCC

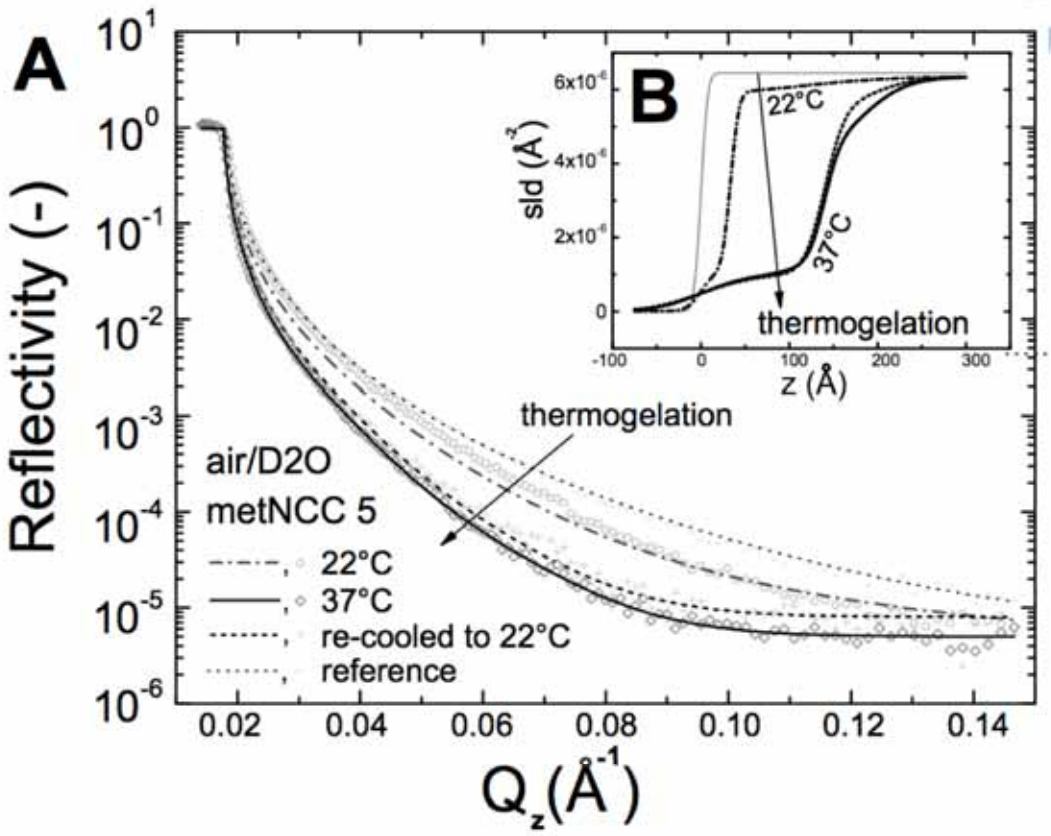


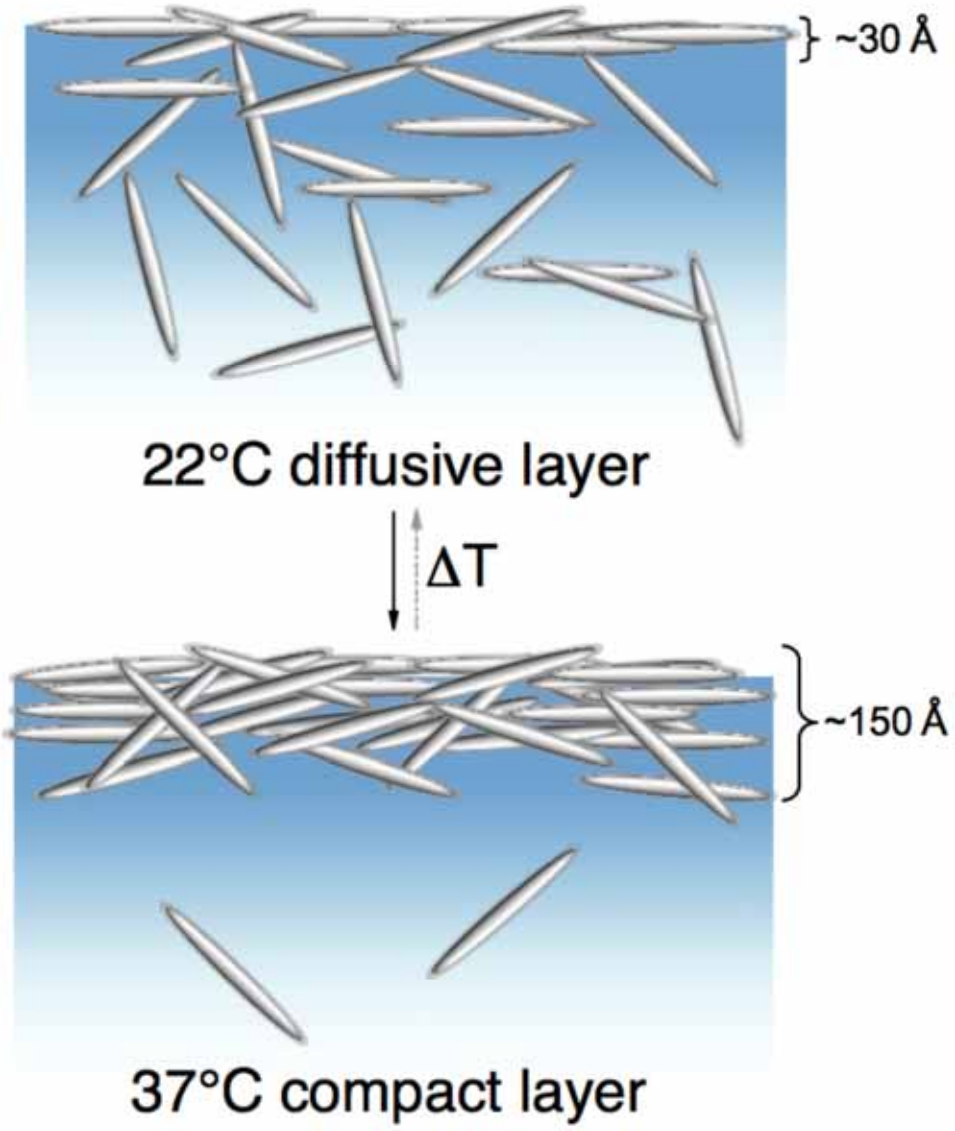




Scheuble N et al.: Biomacromolecules 15 (2014) 3139

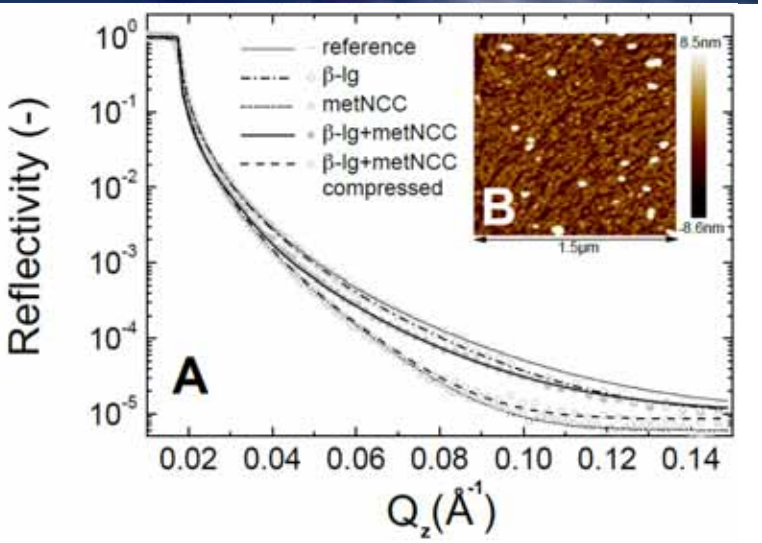
Interfacial structure tested by neutron reflectometry: Thermogelation

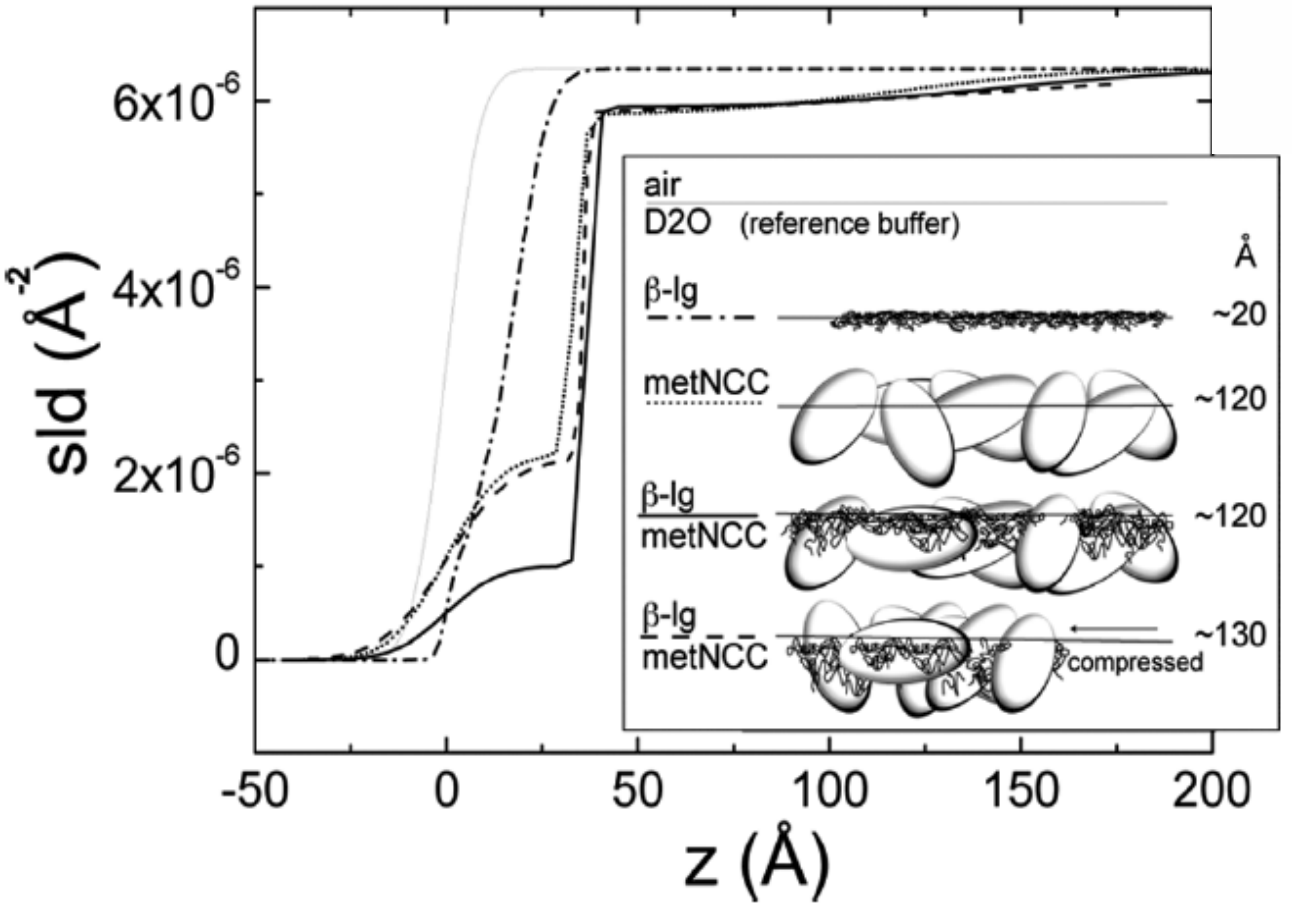




Scheuble N et al.: Langmuir 32 (2016) 1396
Scheuble N et al.: Biomacromolecules 17 (2016) 3328

Interfacial structure tested by neutron reflectrometry: Composite structure



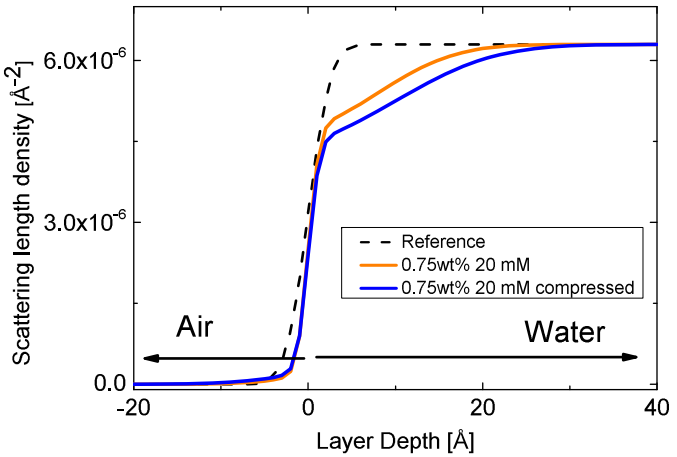


Composite structure:

- Thickness by NCC
- Glue by β-lg
- Indifferent to area changes (strong flow)

CNC: Interface structure

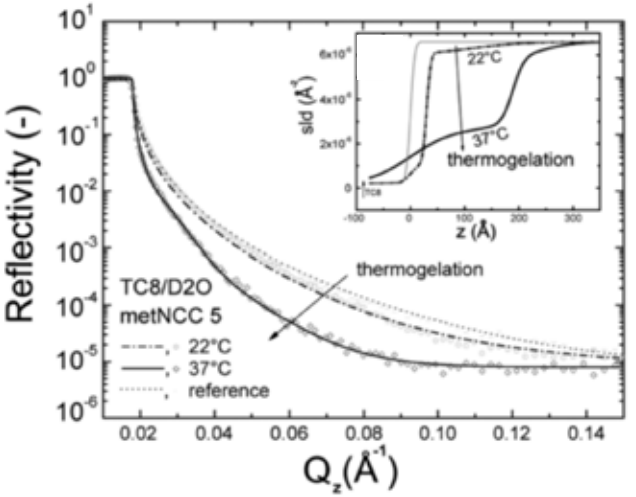
Unmodified



Slow adsorption
10 Å discontinuous monolayer
Coverage ≈ 20 %
π_{max} = 11 mN/m
Contact angle θ << 90°
Salt-induced elasticity

Langmuir 34 (2018) 15195

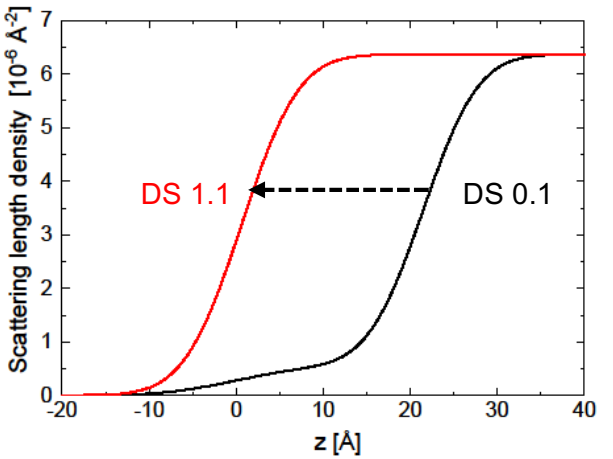
Methylated



30 Å monolayer
Thermogelation at 37ºC
150 Å multilayer
π_{max} = 28 mN/m
Contact angle θ < 90°
CNC - β-IG composite

Langmuir 32 (2016) 1396
Biomacromolecules 17 (2016) 3328

Esterified

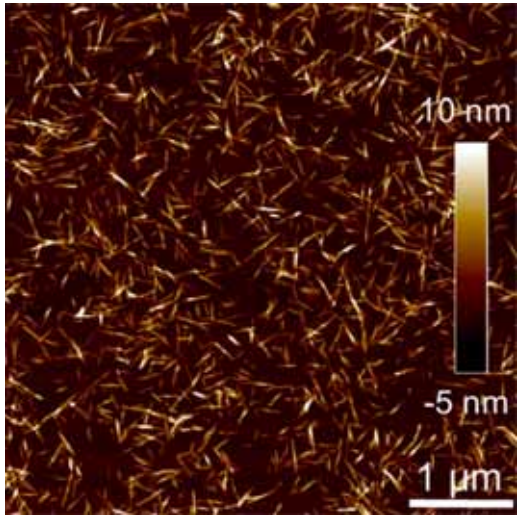


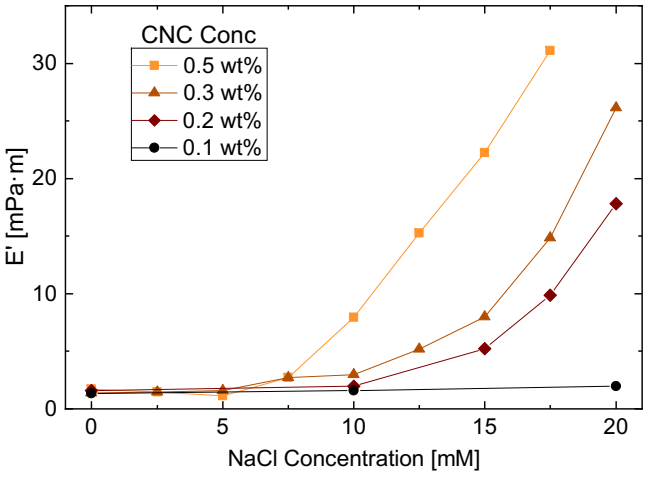
Solvent spreading
Aggregated clusters
π_{max} = 35 mN/m
DS affects θ
DS 0.1 ≈ 126°
DS 1.1 ≈ 156°

Langmuir 34 (2018) 10932

CNC: Interface structure and rheology

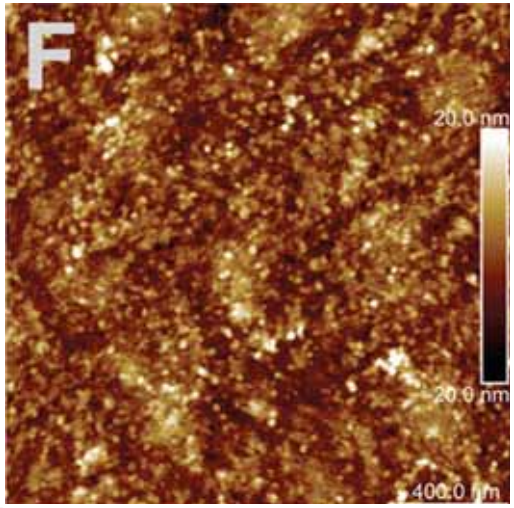
Unmodified

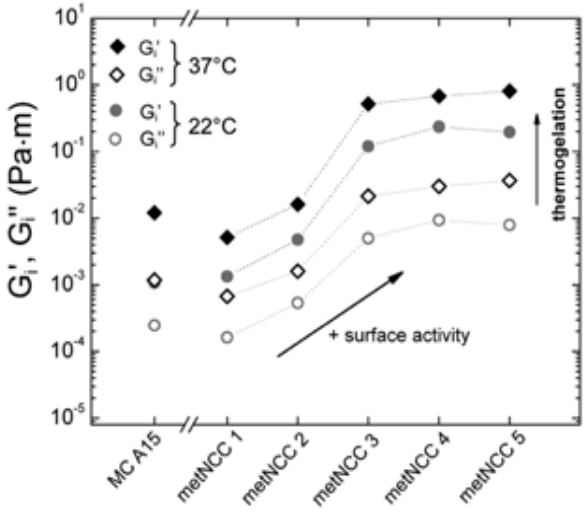




Langmuir 34 (2018) 15195

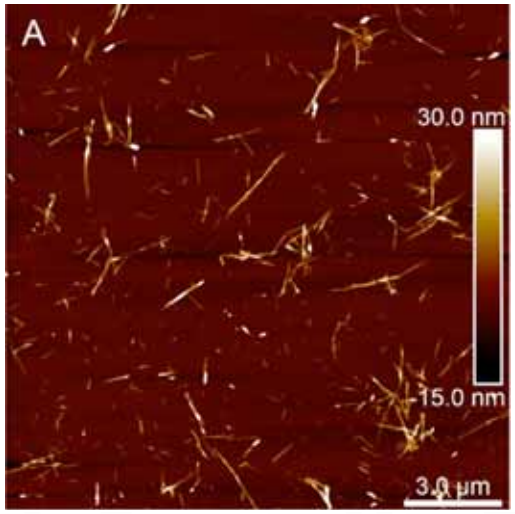
Methylated

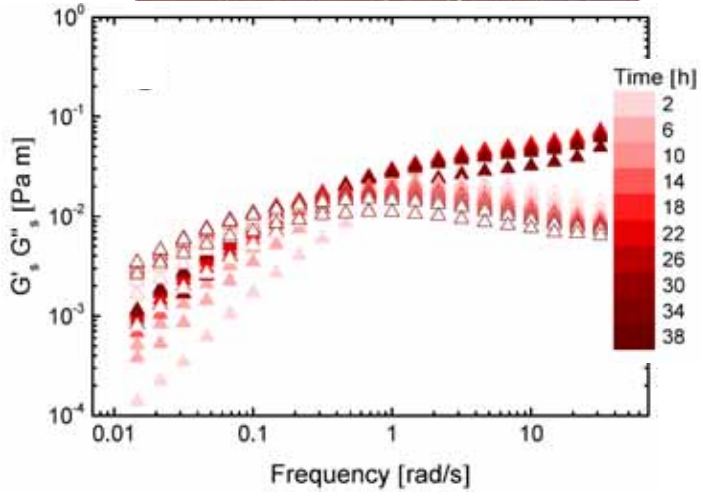




Langmuir 32 (2016) 1396
Biomacromolecules 17 (2016) 3328

Esterified

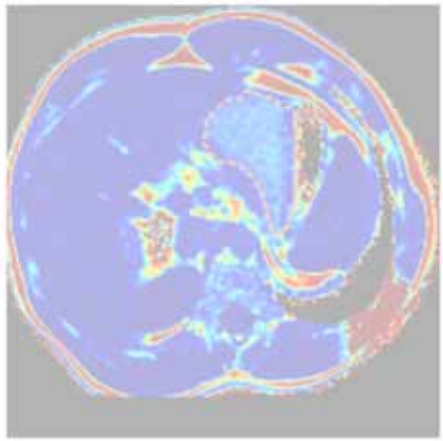




Langmuir 34 (2018) 10932
Phys. Fluids 30 (2018) 072103

Step 2: In vitro survival of droplets: Gastric and pancreatic lipolysis

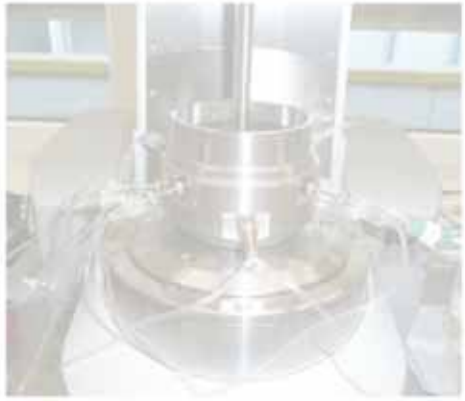
In vivo studies



Bulk phase structuring

Microfluidic analysis

Interfacial layer design

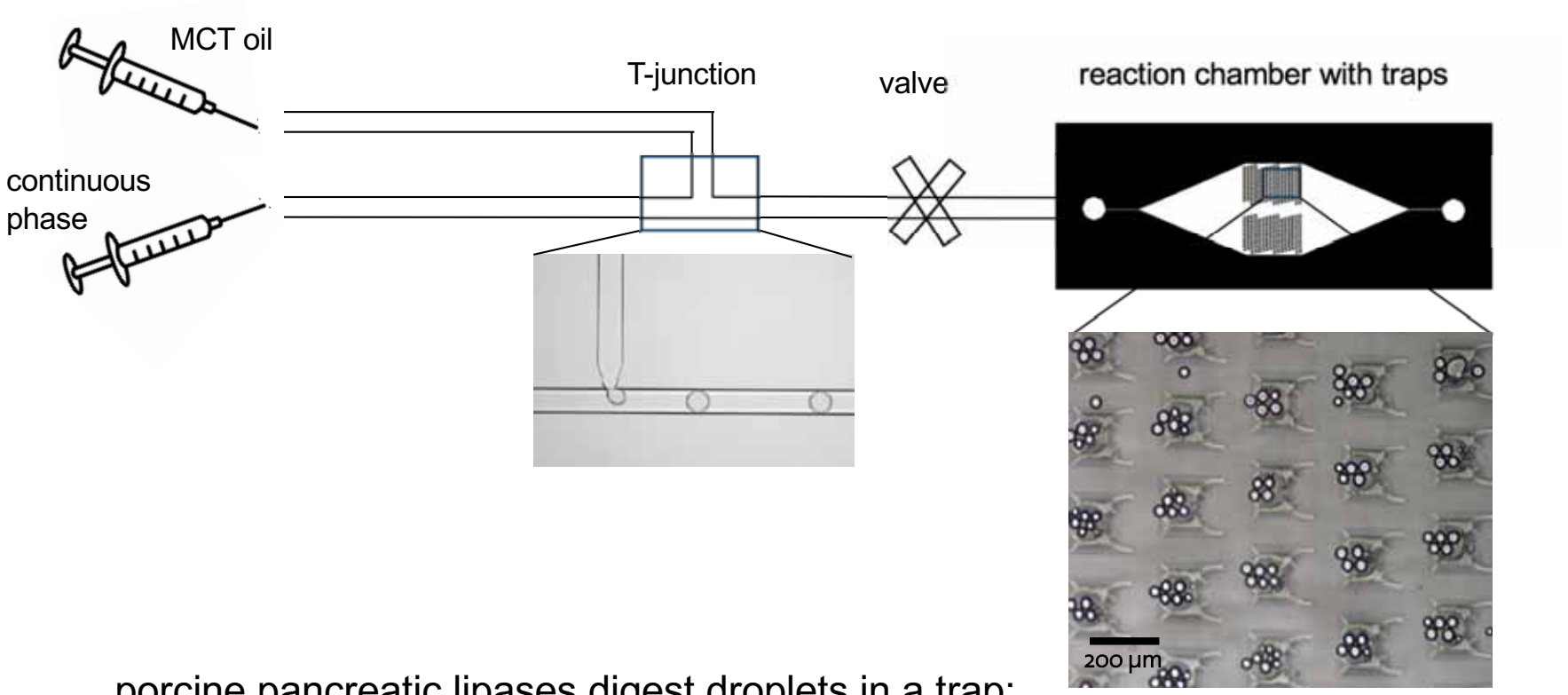


***in-vitro* studies** classically lack:

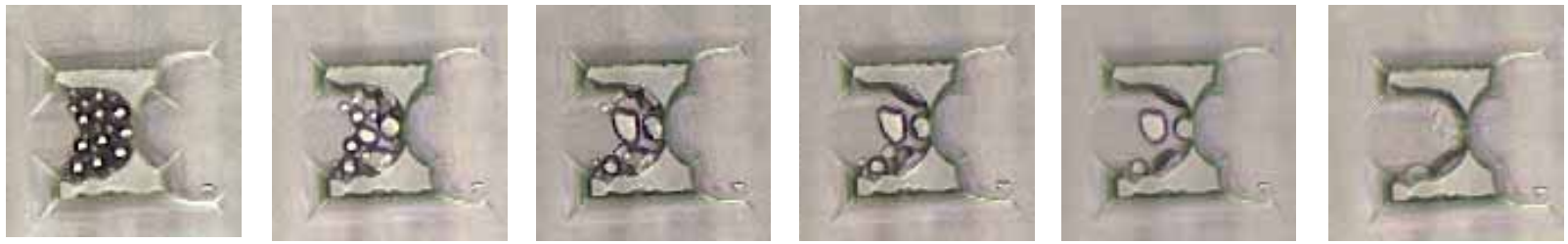
- **Lipase** (not commercial available)
- Influence of **mucus**
- **Food structuring** during digestion

MCT-oil/water interface, rDGL: recombinant dog gastric lipase

Gastric and pancreatic lipolysis by microfluidics *in situ*



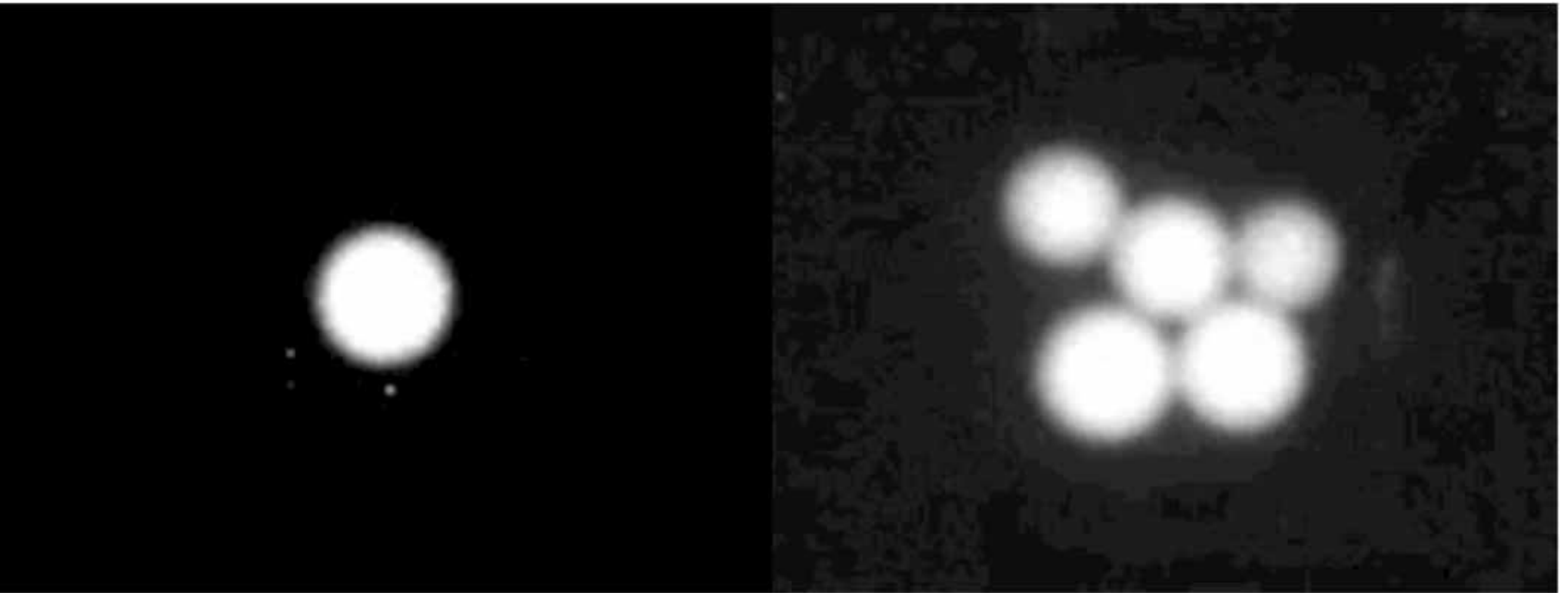
porcine pancreatic lipases digest droplets in a trap:



Coalescence and lipolysis *in microfluidics* II

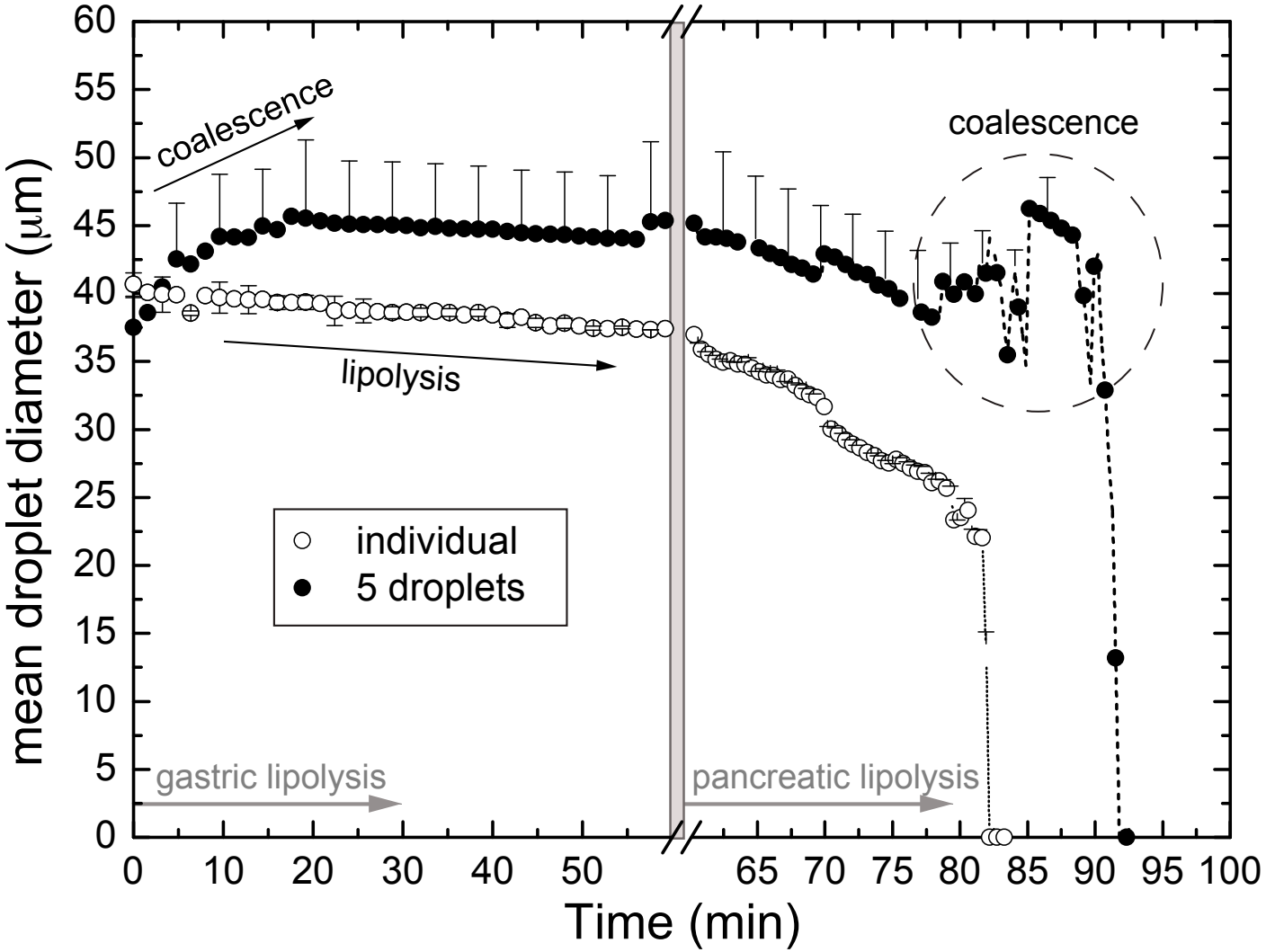
One droplet in trap

Five droplets in trap



Scheuble N et al.: Analytical Chemistry 89 (2017) 9116

Coalescence and lipolysis *in microfluidics* II



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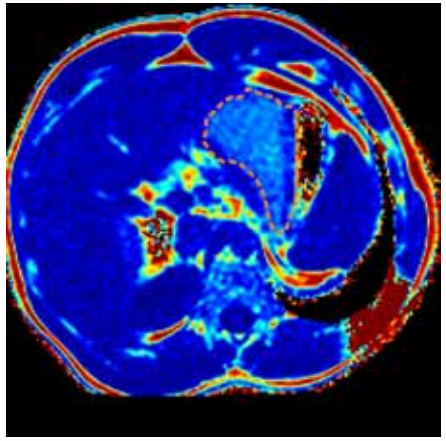
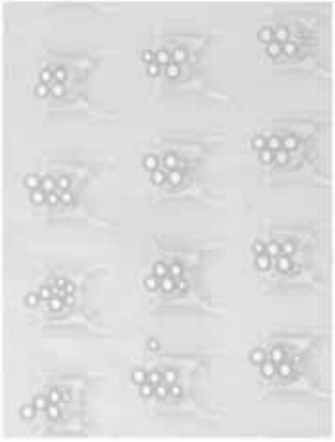
Step 3: Human in vivo digestion studies

In vivo studies

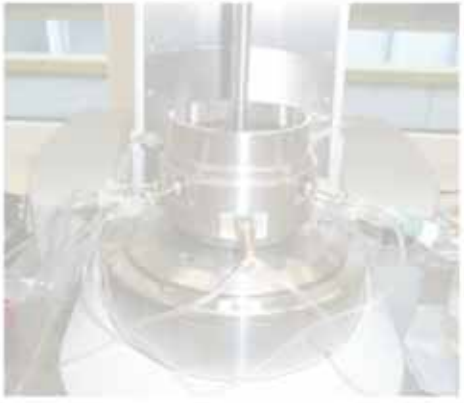


Bulk phase structuring

Microfluidic analysis



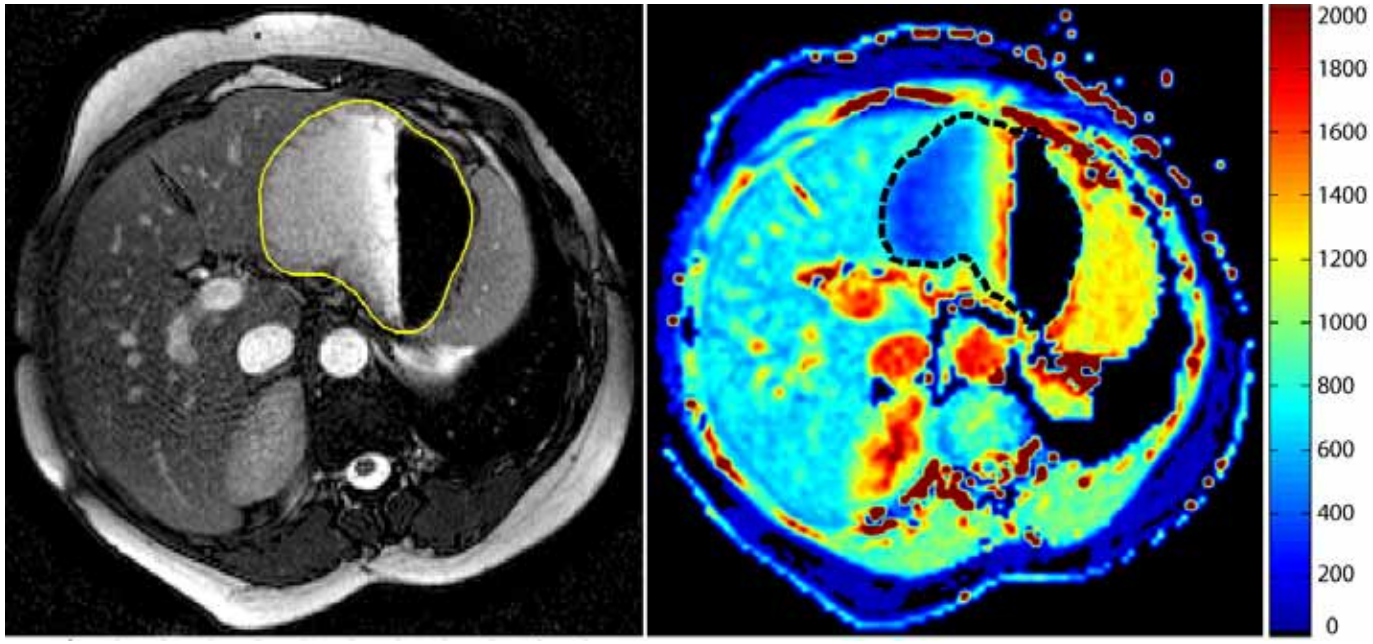
Interfacial layer design

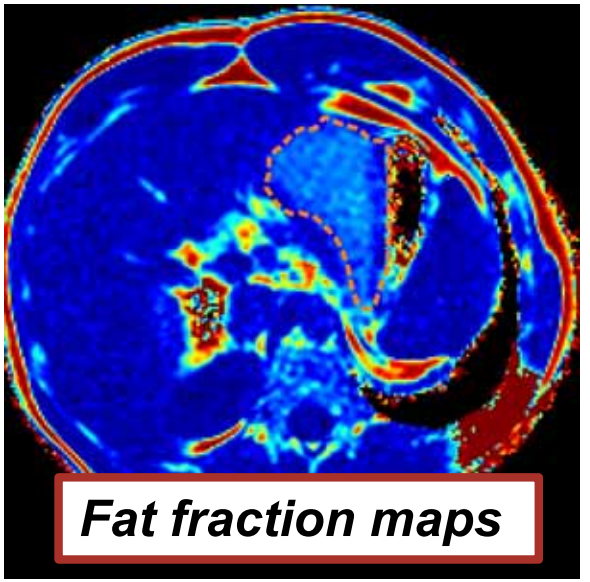


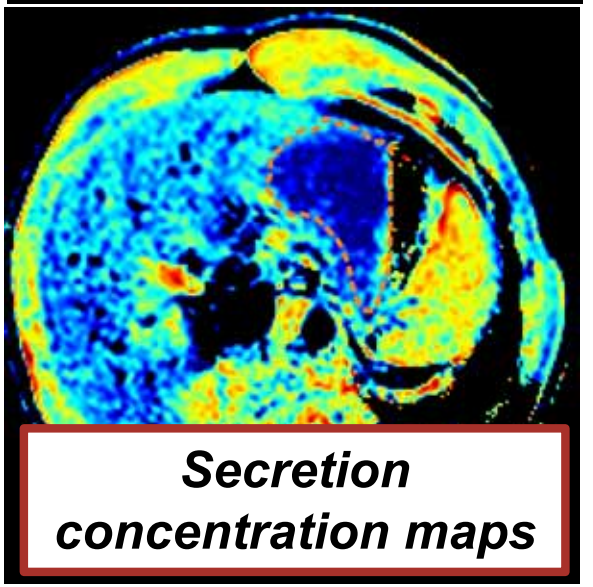
Quantitative MRI: From signal to physical measure

Standard MRI image with arbitrary signal intensity

Corresponding T_1 map





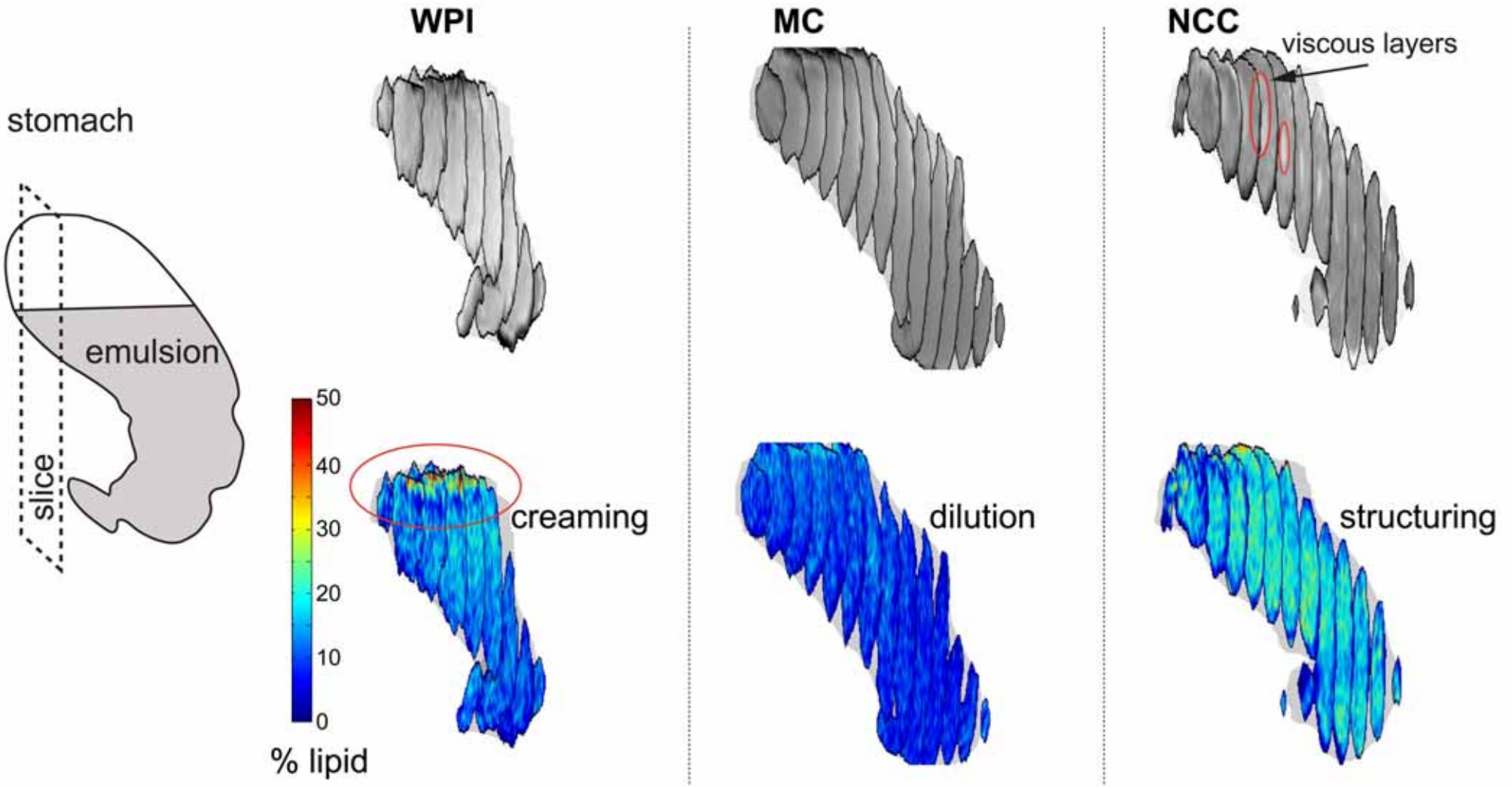


Detection of **Water-fat separation** [1]

Quantification of **intragastric secretion** concentration [2, 3]

[1] Liu D et al.: Br. J. Nutr. 2016
[2] Treier R et al.: JMRI 2008
[3] Nehrke K et al.: MRM 2012

In vivo gastric behavior



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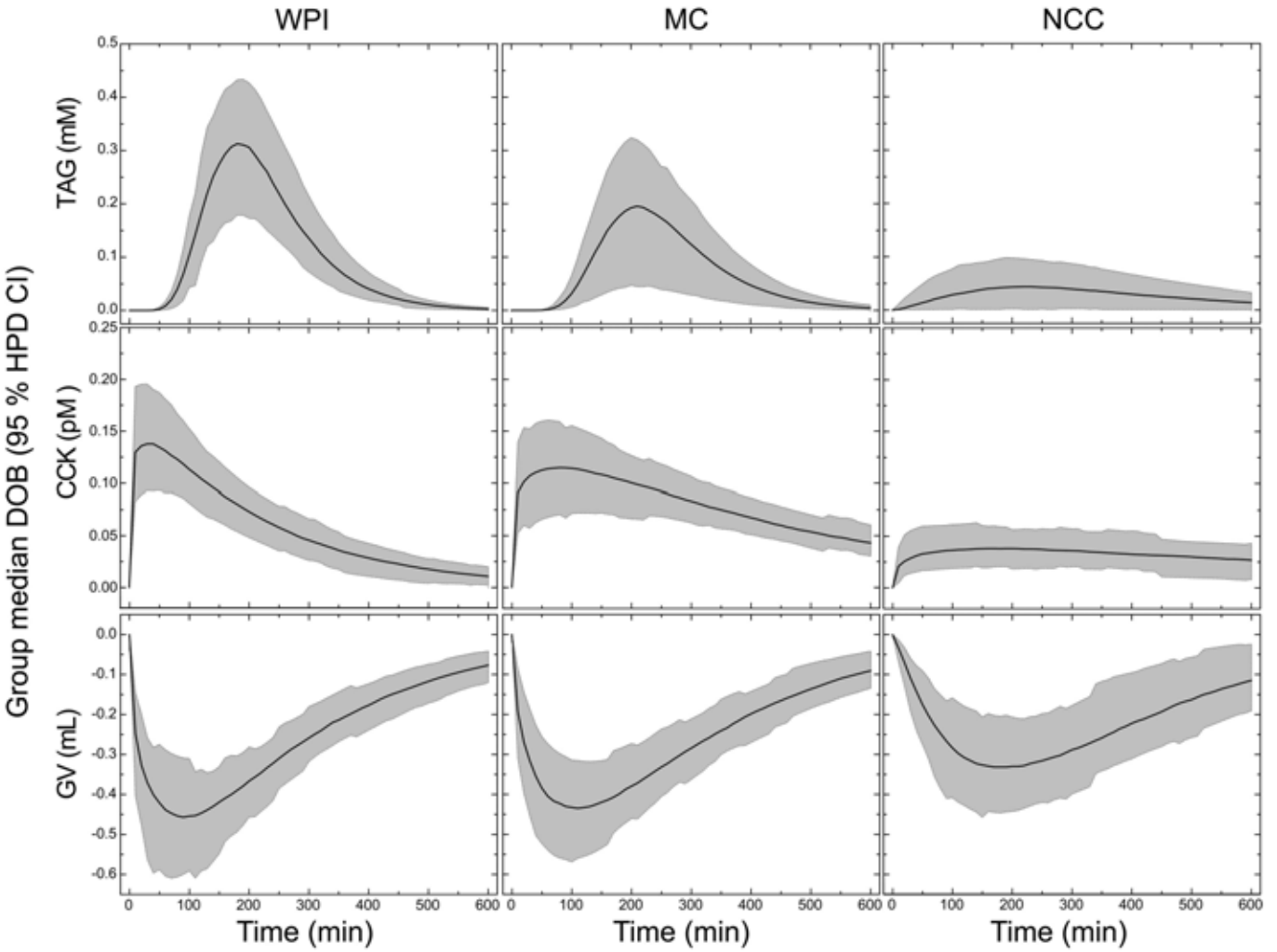
Postprandial gastrointestinal response

TAG = Triglycerides
CCK = plasma cholecystokinin
GV = Galebladder volume



TAG same dynamics at very different amplitude

CCK and GV delayed for NCC

Almost no metabolite & hormone response for NCC

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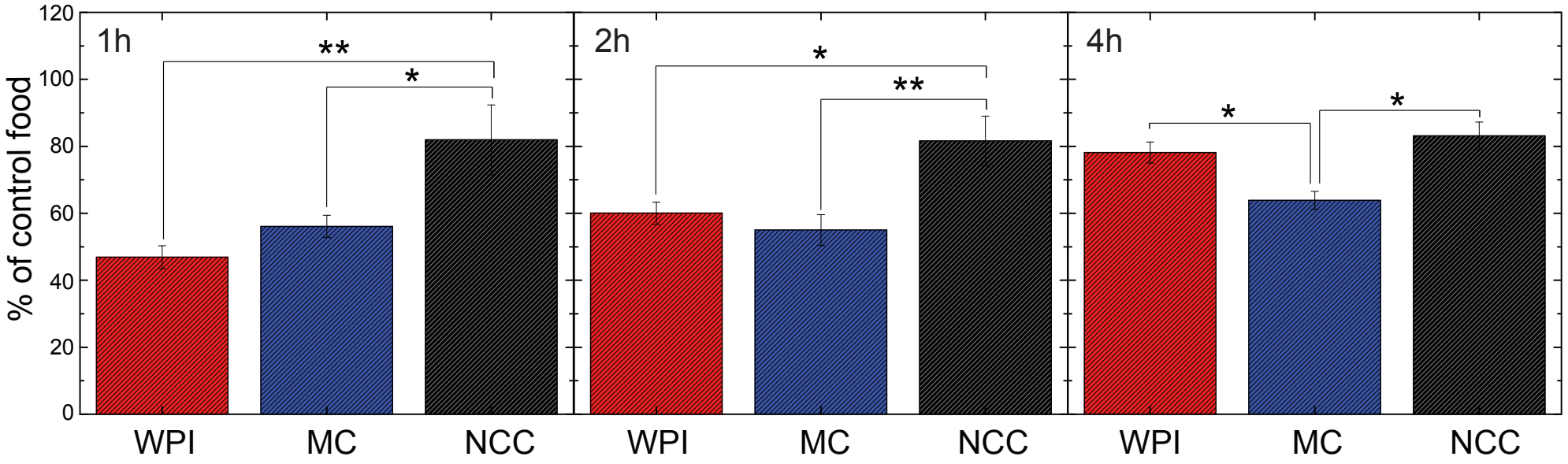
Cumulative food intake in rats



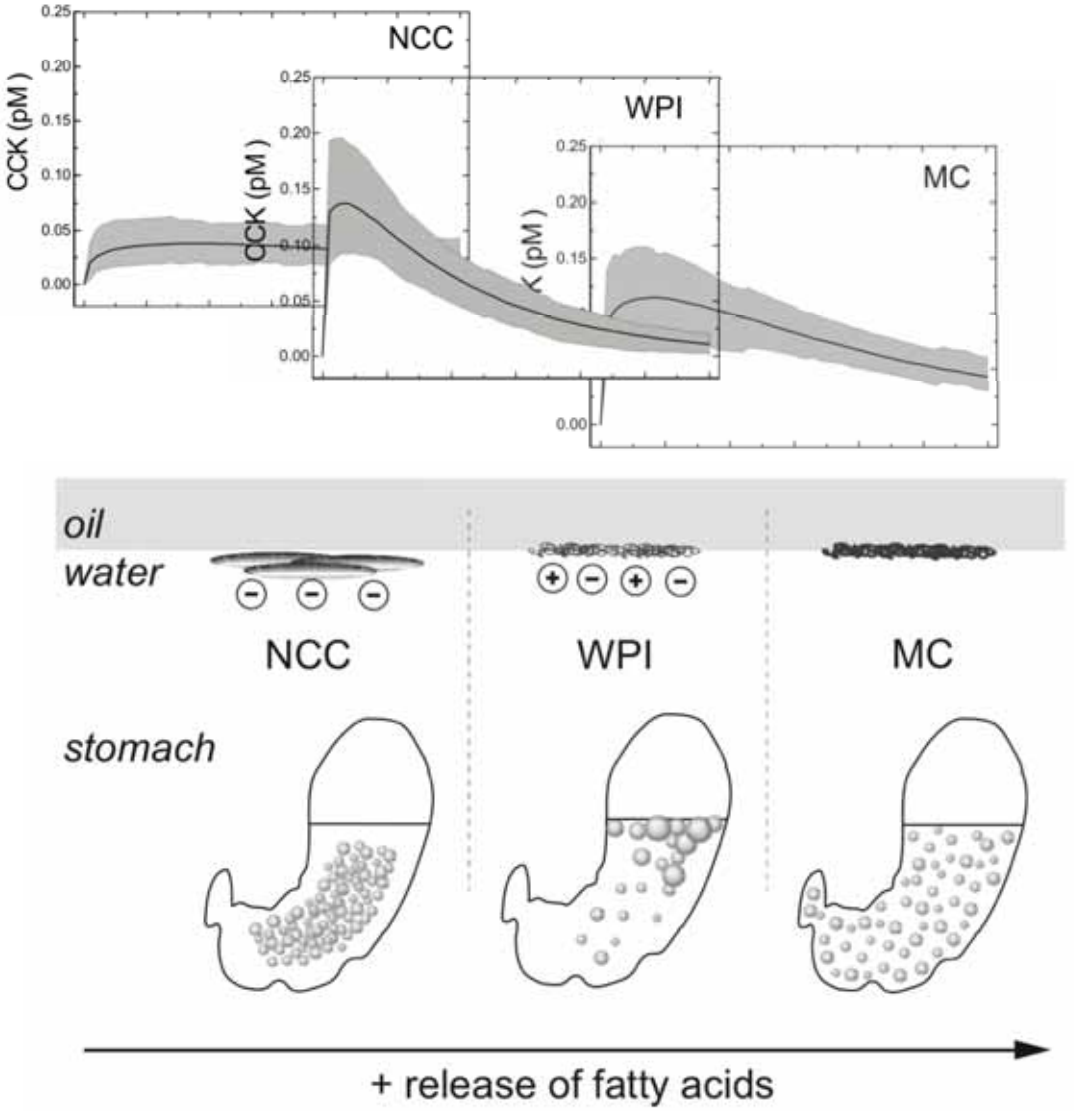
gastric lipolysis, emulsion instabilities, intermediate pancreatic lipolysis

IT IS ALL ABOUT NUTRIENT SENSING

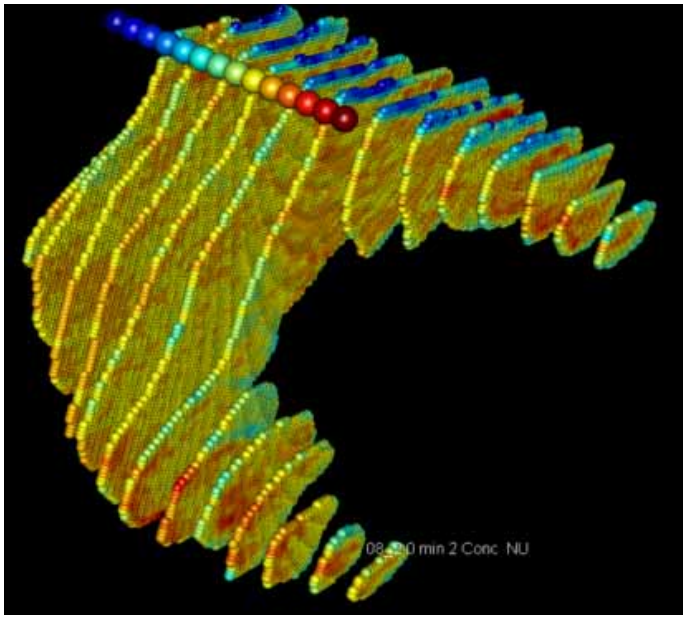
low gastric structuring, constant lipid release, fast pancreatic lipolysis

high gastric structuring slowest lipolysis

Summary: *In vitro – in vivo* correlation



- Interfacial layer design
- In-vitro lipase activity
- Gastric stability in-vivo
- Gastrointestinal response



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Acknowledgments

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