Complex coacervation in heteroprotein systems: formation mechanism, rheology, and potential applications.

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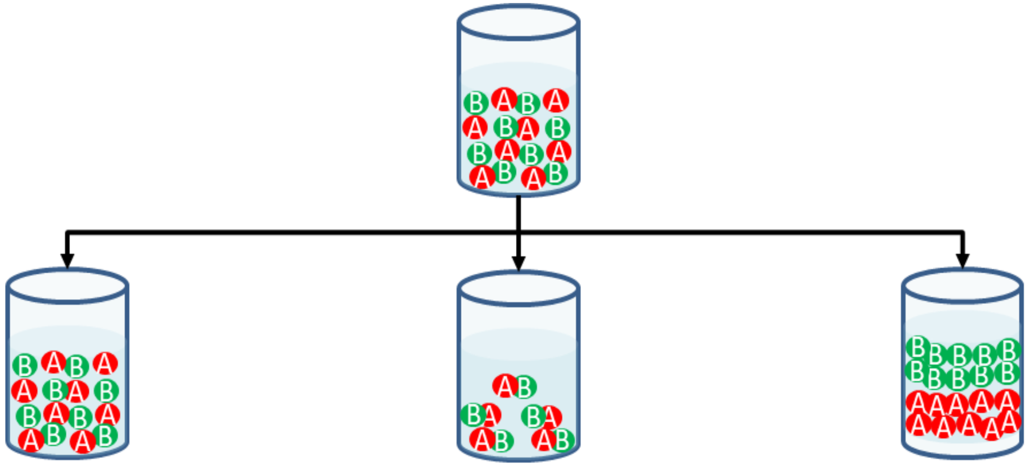
Introduction

- Food matrix: complex systems (Mixture of macro- and micro-nutriments)

PHASE BEHAVIOR OF TERNARY SYSTEM: (BIO)POLYMER A / (BIO)POLYMER B / SOLVANT



Co-solubility

Associative phase separation
Liquid-liquid (complex coacervation)
or Solid-liquid

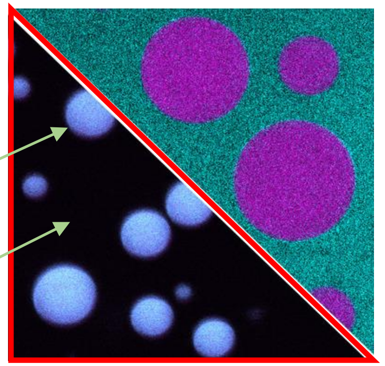
Segregative phase
separation

Associative liquid-liquid phase separation

Segregative liquid-liquid phase separation

(Bio)polymers rich phase

(Bio)polymers poor phase



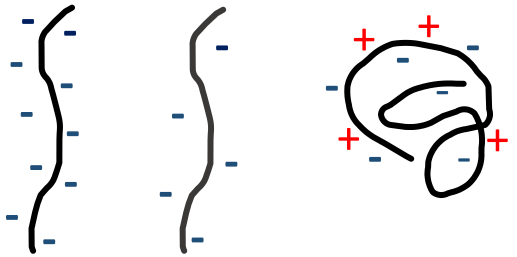
(Bio)polymer A rich-phase

(Bio)polymer B rich-phase

COMPLEX COACERVATION

Polyelectrolytes

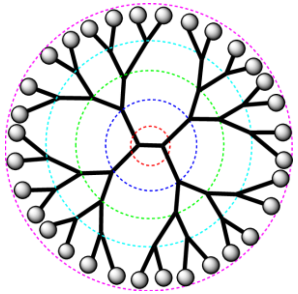
Strong ***Weak*** ***Polyampholyte***



Schlenoff et al., Macromolecules., 2019

Colloids

Dendrimers

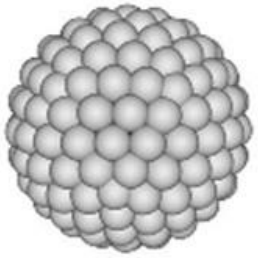


Kaup et al., ACS Nano, 2021

Globular proteins

Croguennec et al., Adv. Coll. Int. Sci., 2017

Micelles



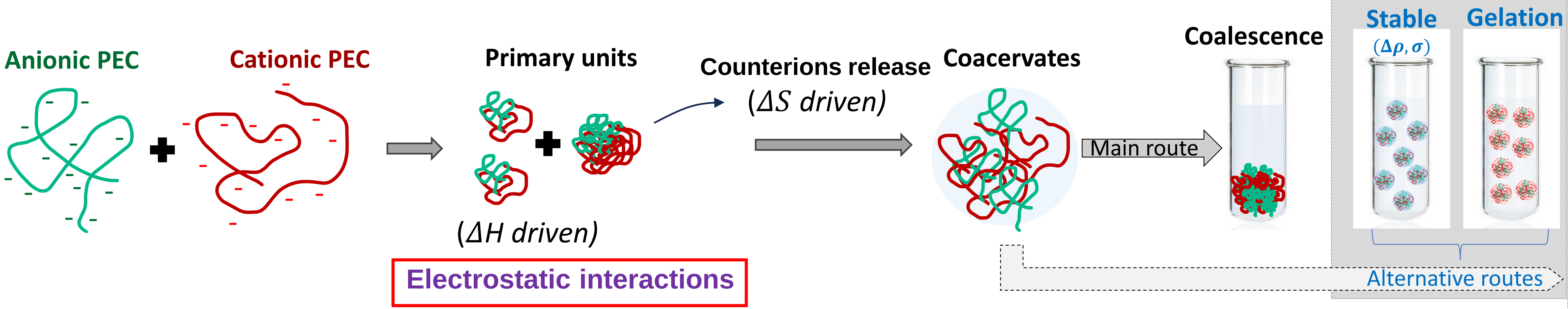
G. Ben Messaoud et al., *Green Chem*, 2018

Inorganic macroions

Polyoxometalate

Jing et al., *Soft Matter*, 2017

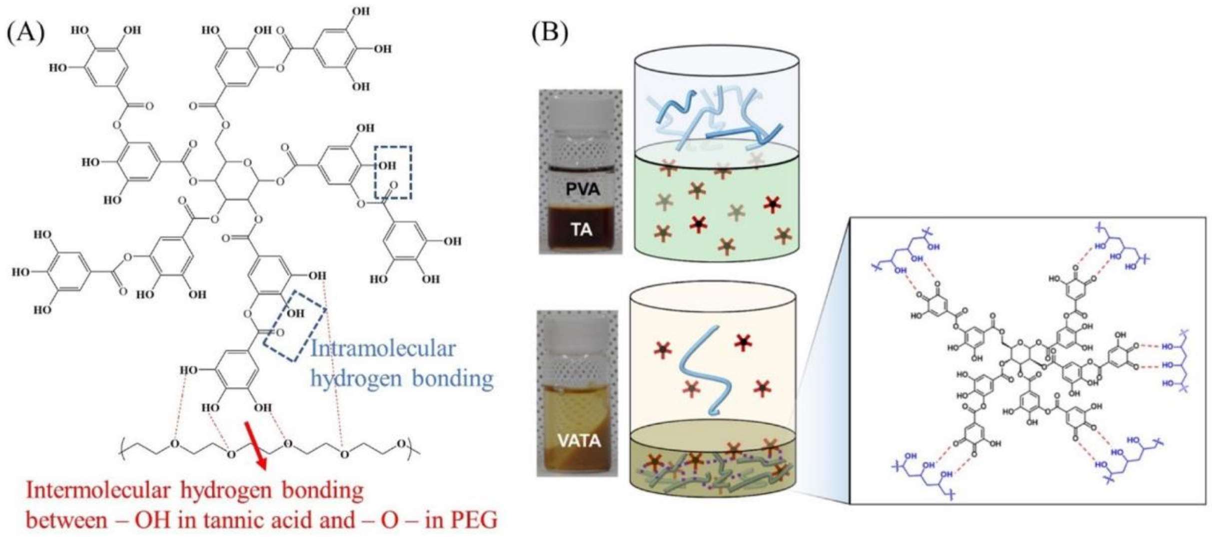
Complex coacervation…a generic process



Electrostatic interactions

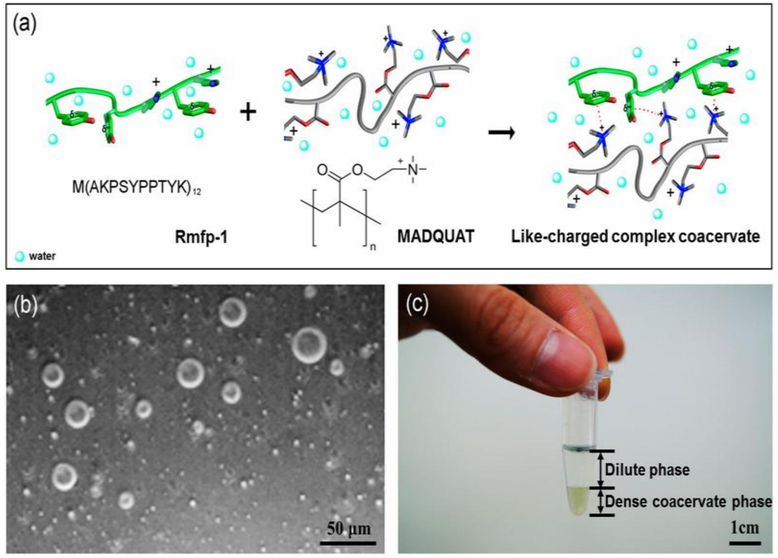
Often…but not only!

Hydrogen bonding



Kim et al., *Adv Funct Mater*, 25 (2015)
Lee et al., *ACS Appl Mater Interfaces*, 12 (2020)

$\pi - \pi$ Stacking

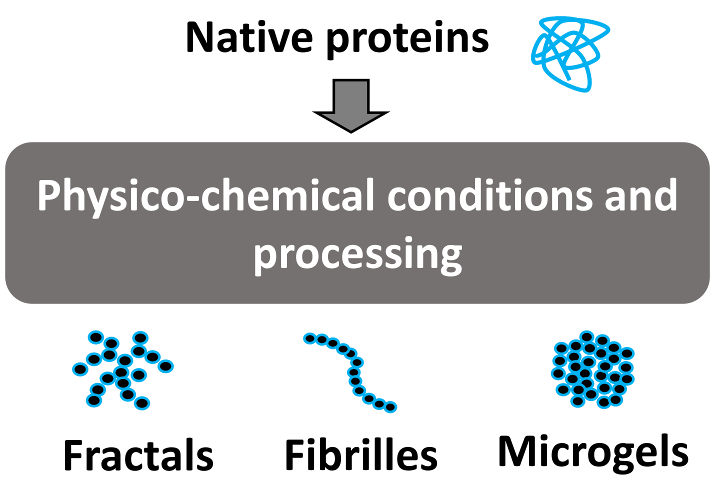


Kim, et al., *PNAS*, 113(7), 2016.

Heteroprotein Complex coacervation (HPCC) in food science

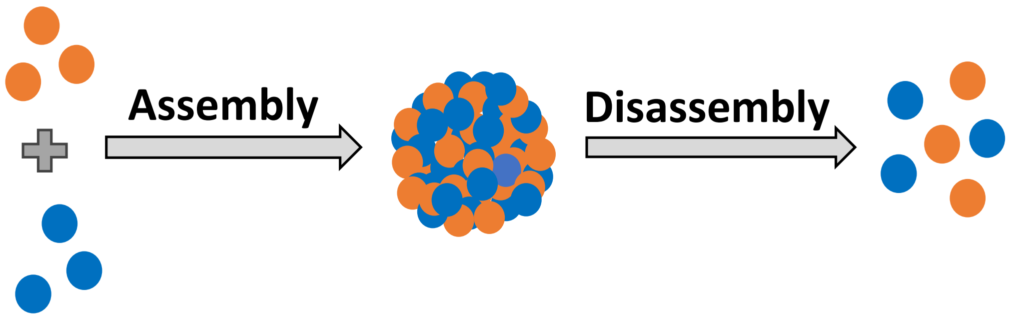
Food protein interactions & assemblies

- Formed after protein denaturation (heat, pressure, drying)
- Irreversible association reactions (non-covalent and covalent bounds)
- Inactive structures (biologically speaking) but relevant on a techno-functional point of view (Texturization, Stabilization of interfaces,..)

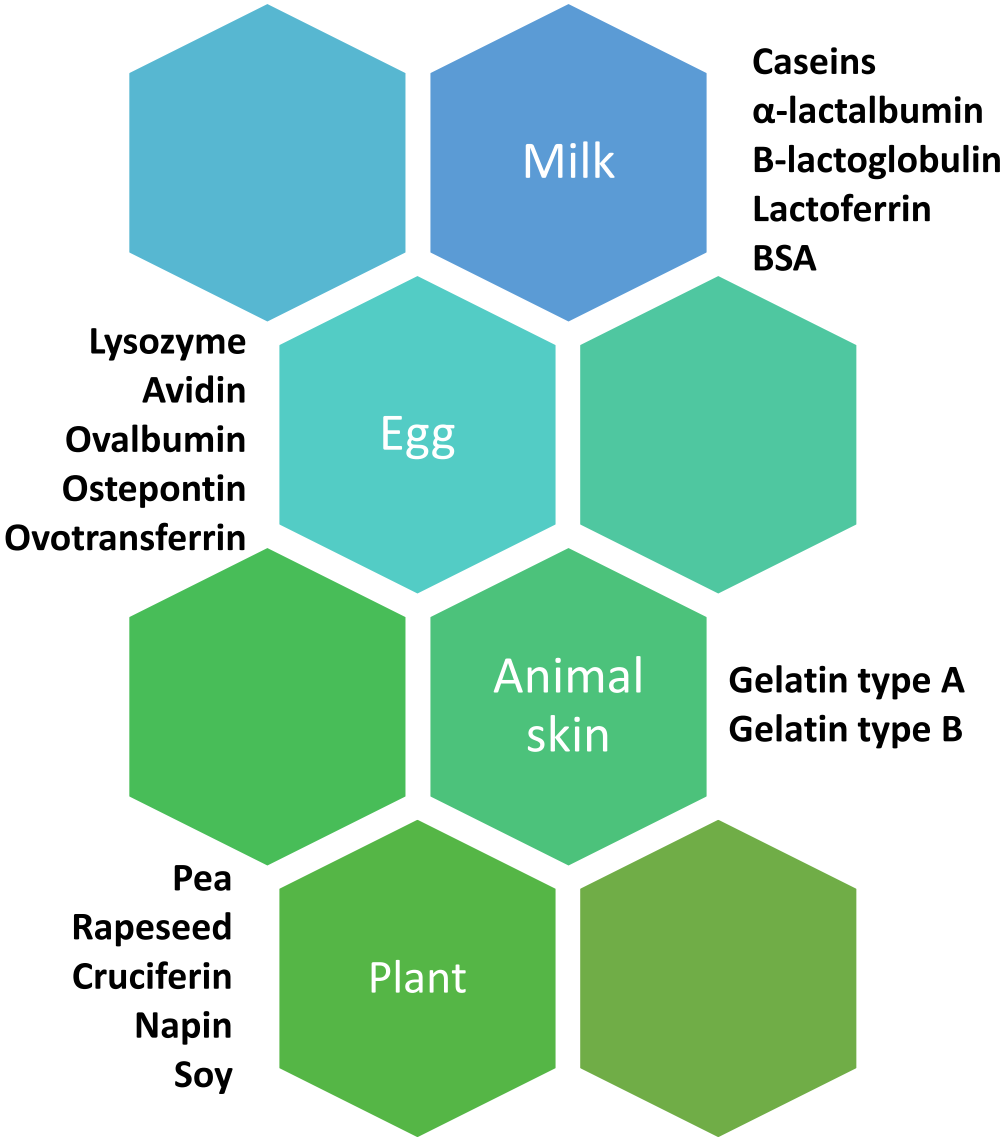


HPCC

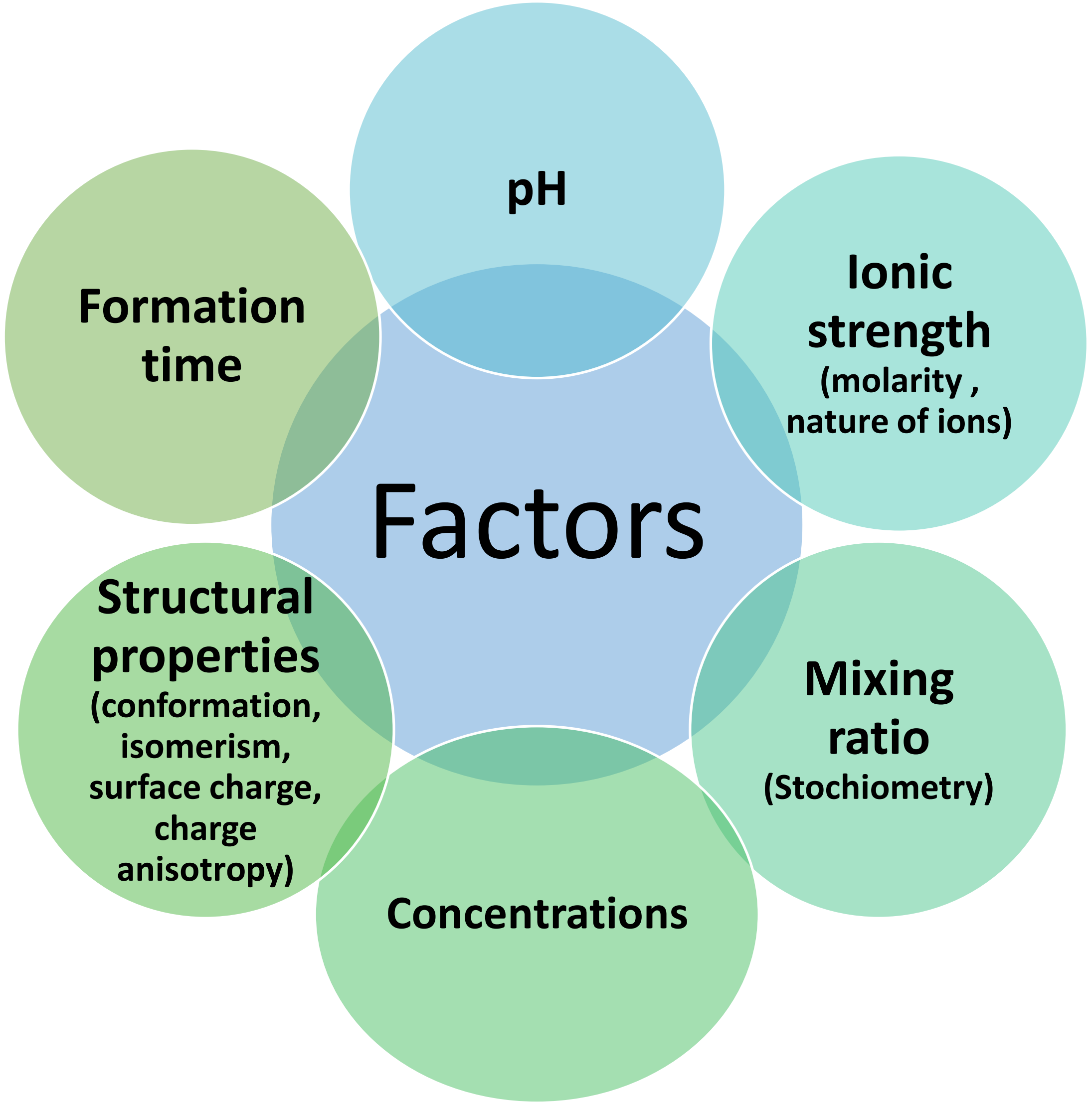
- Self- or co-assembly under “mild” conditions:
- Reversible associations between proteins (non-covalent interactions)
- Flexible design (microscale, bulk, assembly-disassembly of food products, functional and nutritional properties)



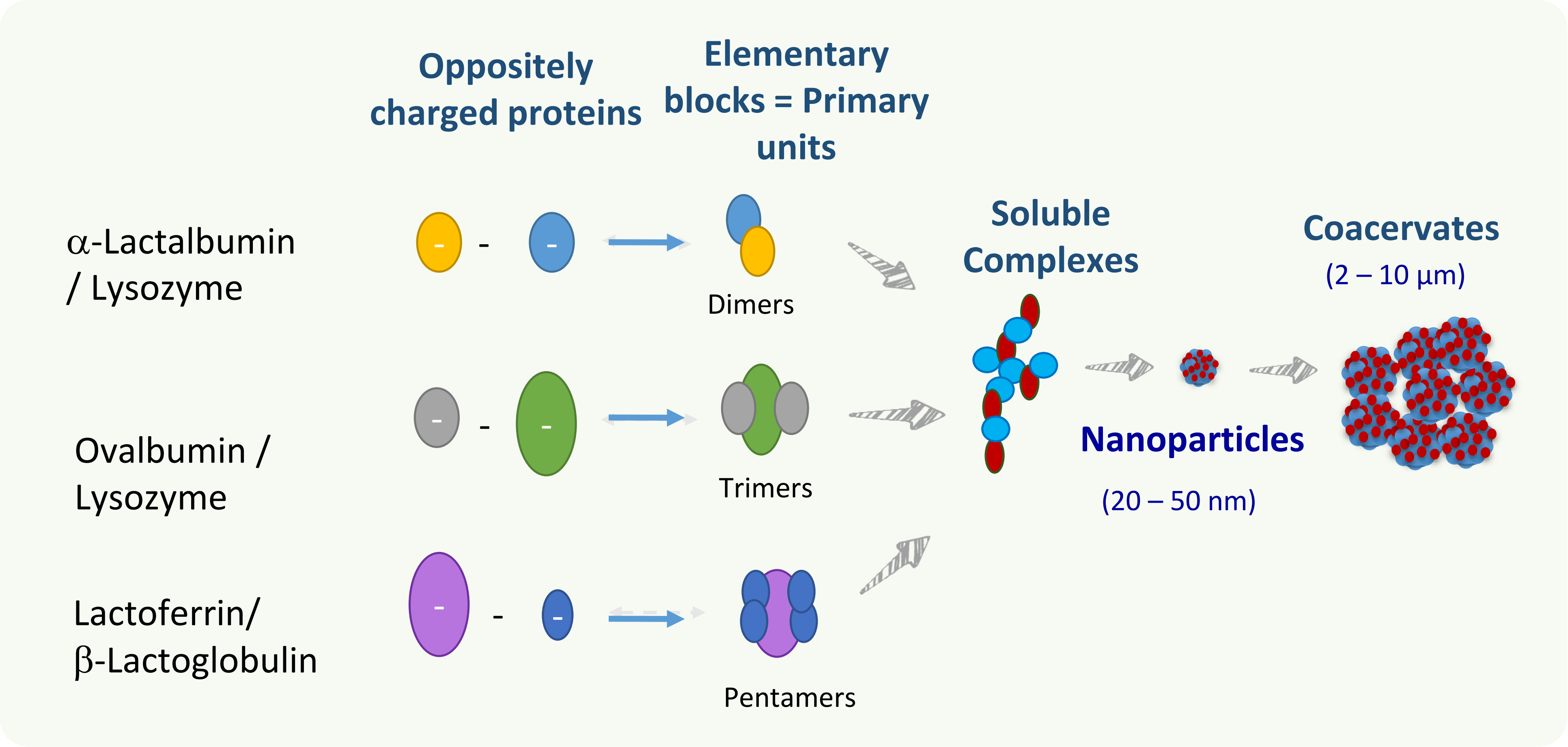
Studied food heteroprotein systems



Influencing factors



Formation dynamic

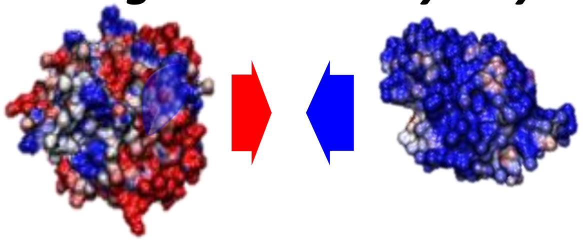


Croguennec et al., Adv. Coll. Int. Sci., 2017
Salvatore et al. Biomacromolecules, 2011
Dubin et al., Biomacromolecules, 2014

Specificity over other macromolecular systems….Charge patchines

LYS and NAP with similar charge but:

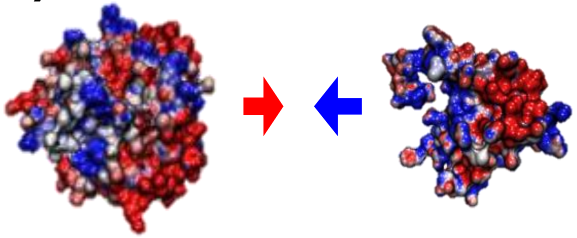
***β*-lactoglobulin** **Lysozyme**



Potentiel Zeta = - 50 mV *Potentiel Zeta = + 20 mV*

Phase separation: > µm

***β*-lactoglobulin** **Napin**

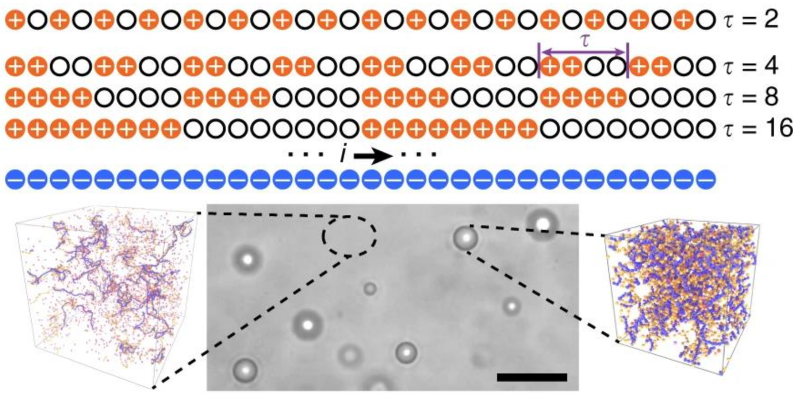


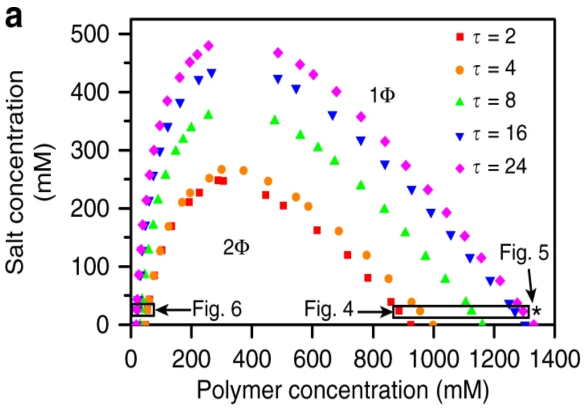
Potentiel Zeta = - 50 mV *Potentiel Zeta = + 20 mV*

Soluble complexes: < 20 nm

Ainis et al., Langmuir, 2019

Specific to proteins… but in a good agreement with…

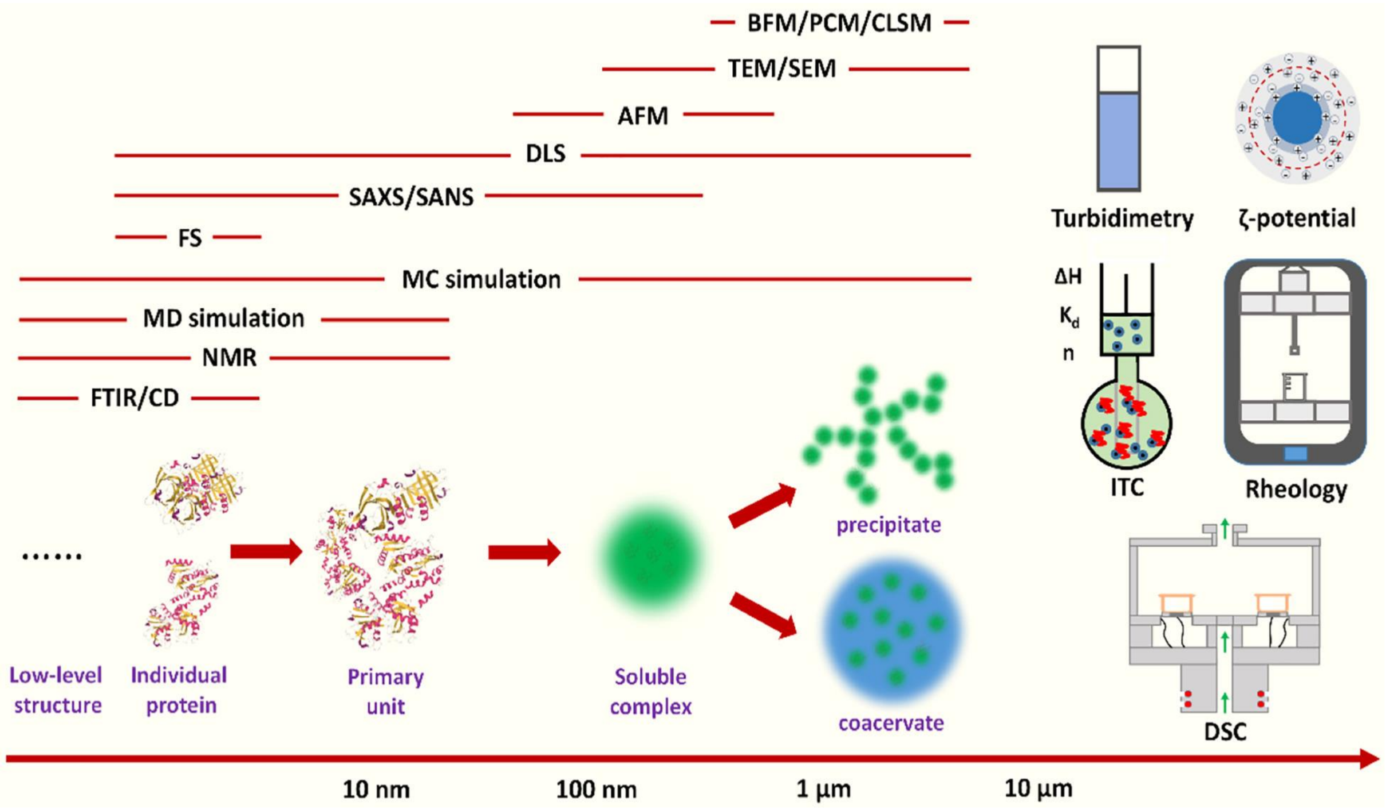




Chang et al., *Nat Commun* 8, 1273, 2017.

Experimental techniques

Length Scale



Aspects

Formation
- Turbidimetry (Qualitative formation analysis)
- Dynamic light scattering (Particle size and polydispersity)
- Laser Doppler electrophoresis (Surface charge)
- Isothermal titration calorimetry (Thermodynamic driving force)
- Molecular dynamics simulation (Formation process and assembly structure)
- Molecular docking (Binding sites and assembly structure)

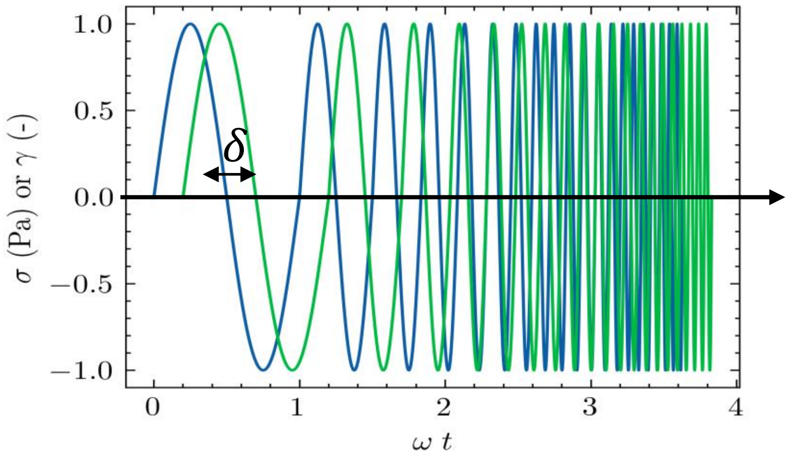
Structure
- Fourier transform infrared spectroscopy (Secondary structure, hydrogen bond, and electrostatic interaction)
- Far-UV circular dichroism (Secondary structure)
- Fluorescence spectrum (Molecular conformation)
- Differential scanning calorimetry (Molecular conformation and bonding water)
- Small angle x-ray scattering (Multiscale assembly structure)
- Small angle neutron scattering (Multiscale assembly structure and single component structure)
- Nuclear magnetic resonance (Interacting amino acid residues, hydrodynamic radius, and relative abundance)
- Scanning electron microscopy (Network structure)
- Transmission electron microscopy (Morphologic structure)
- Atomic force microscopy (Morphologic structure)
- Laser confocal scanning microscopy (Structural co-localization)

Properties
- Bright-field microscopy (Phase behavior)
- Phase-contrast microscopy (Phase behavior)
- Monte Carlo simulation (Assembly and phase boundary)
- Rheology (Viscoelasticity and macroscopic properties of interactions)

Zheng et al., *Adv in Coll & Inter Sci*, 2020

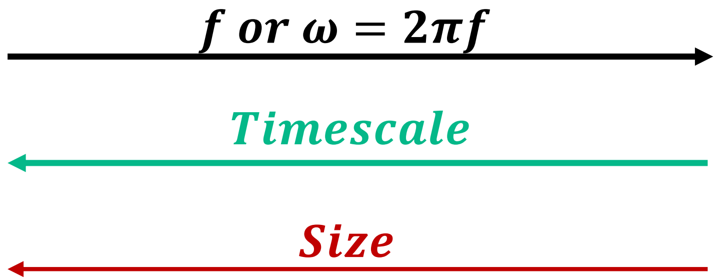
Rheology

Linear viscoelasticity (SAOS, SR...)



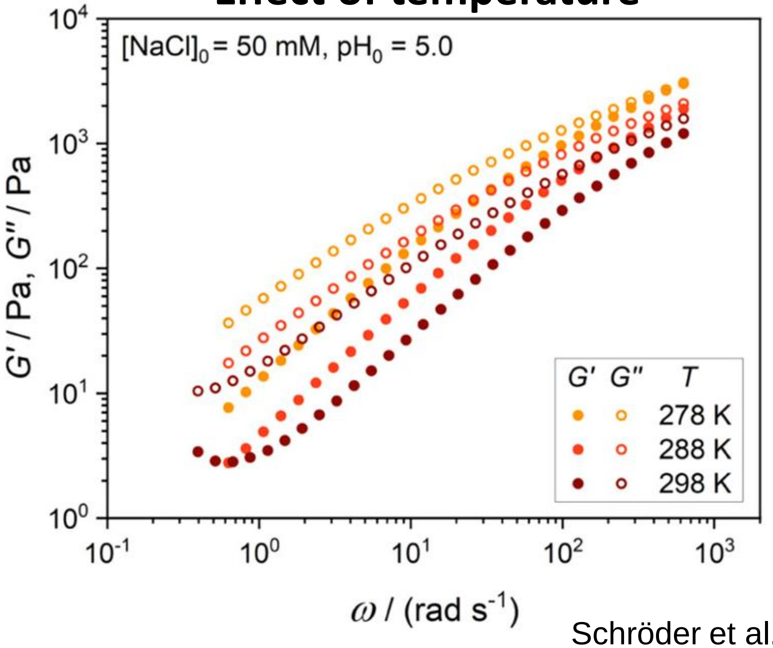
$$\gamma(t) = \gamma_0 \sin(\omega t)$$
$$\sigma(t) = \sigma_0 \sin(\omega t + \delta)$$
$$0° < \delta < 90°$$

$$G' = \sigma_{0/\gamma_0} \cos(\delta)$$
$$G'' = \sigma_{0/\gamma_0} \sin(\delta)$$

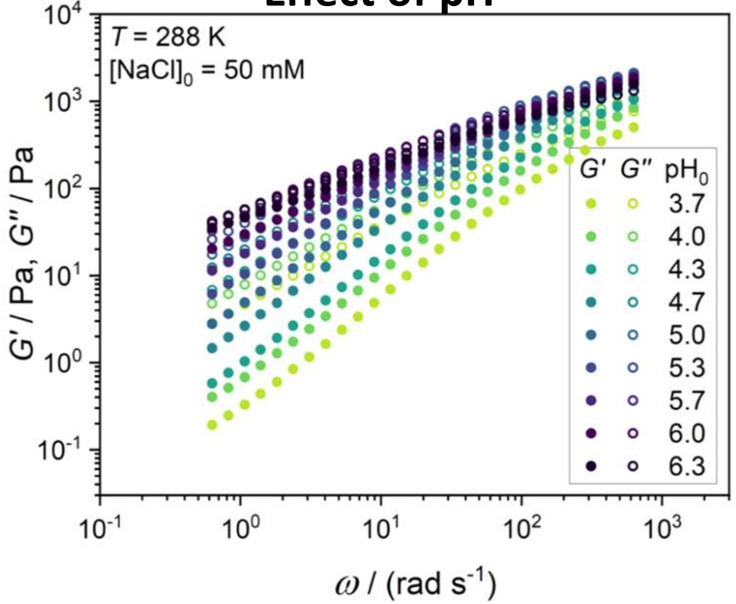


Chitosan–Gum Arabic

Effect of temperature



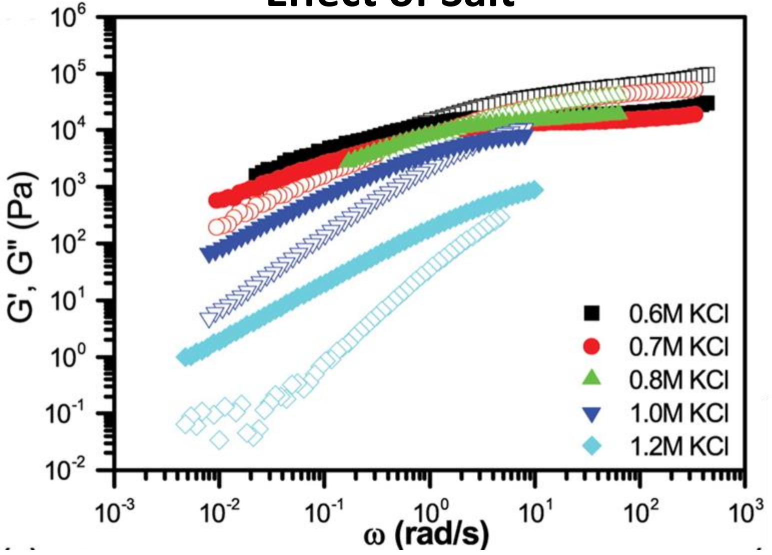
Effect of pH



Schröder et al., *Macromolecules* 2023

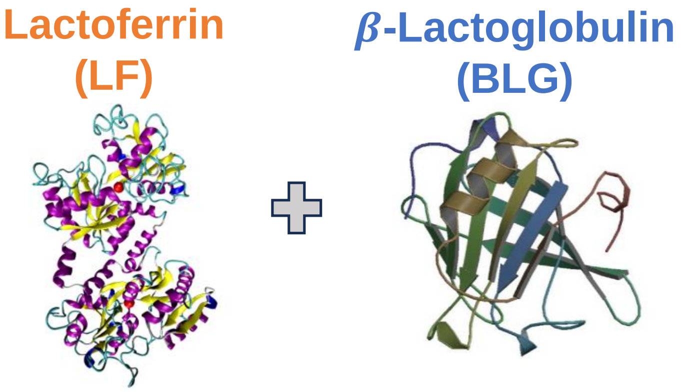
PDMAEMA - PAA

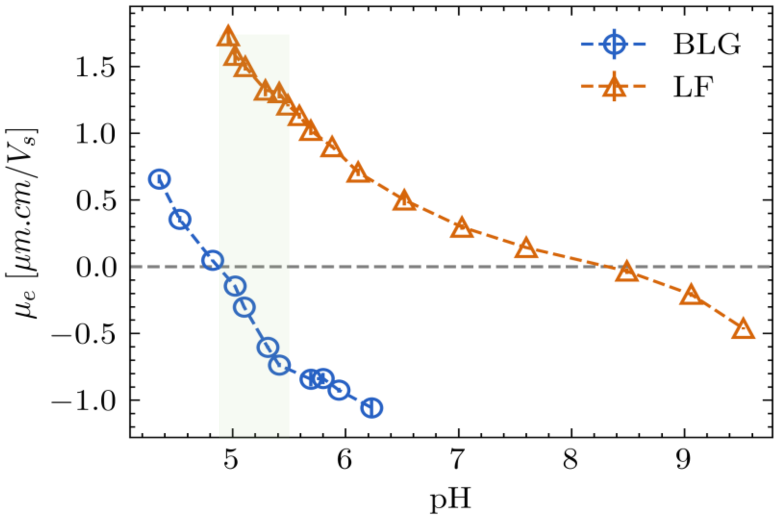
Effect of Salt

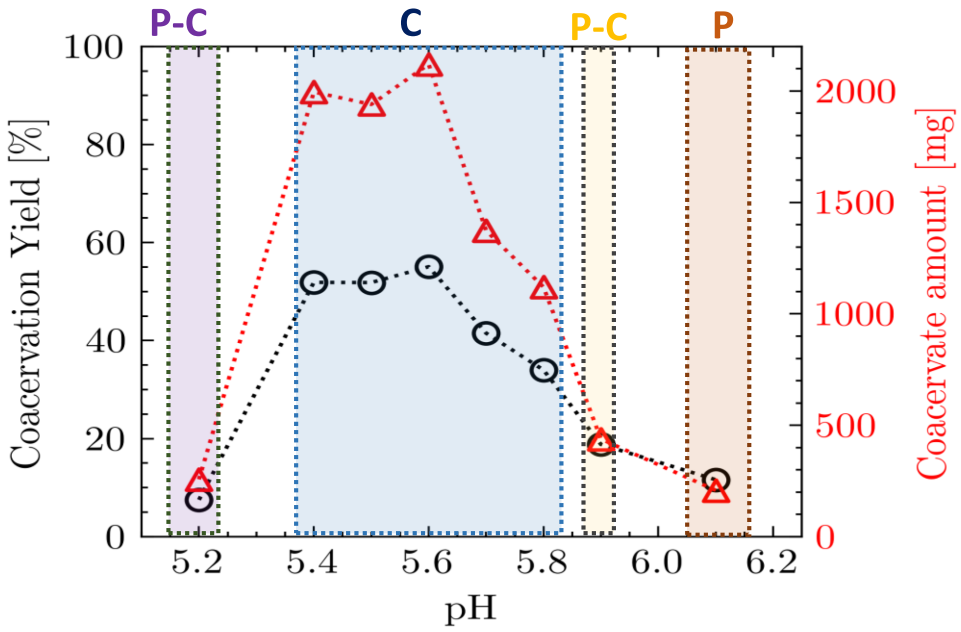


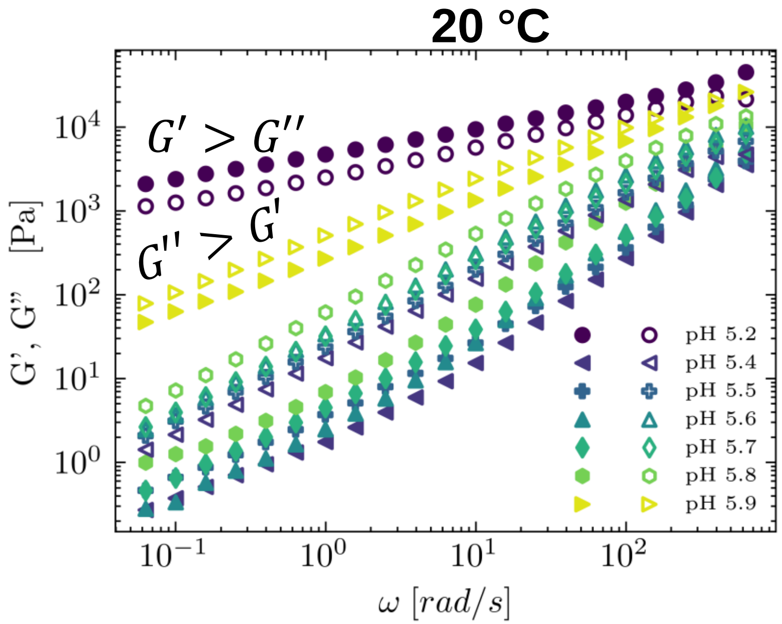
E. Spruijt, *Macromolecules*, 2013

HPCC



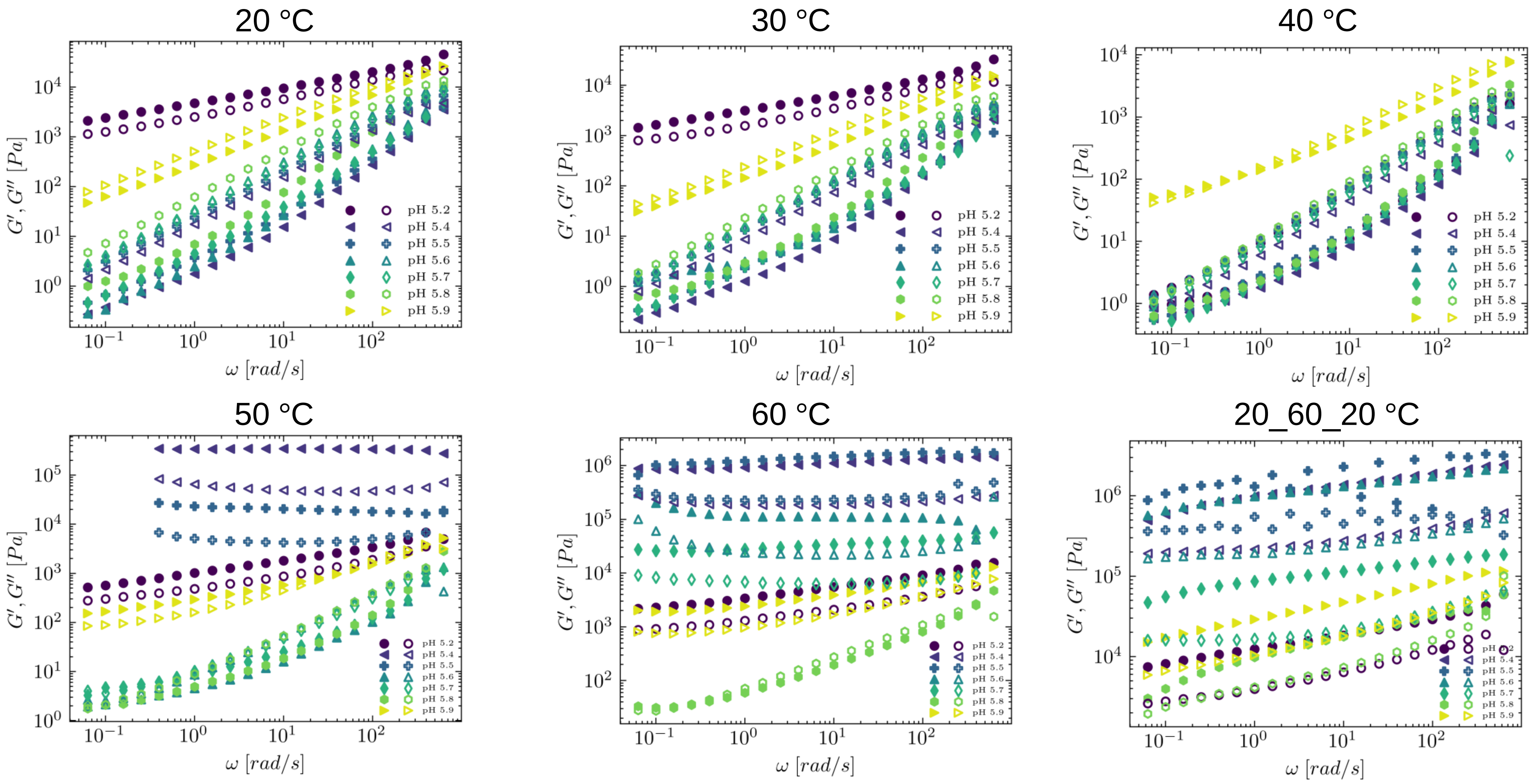






- High sensitivity of the system towards slight change of pH (0.1 unit).
- pH 5.2: Precipitate-coacervates: BLG precipitation close to the isoelectric point ($pH \sim 5$)
- pH5.9 and pH 6.1: precipitation due to strong electrostatic interaction between BLG and LF

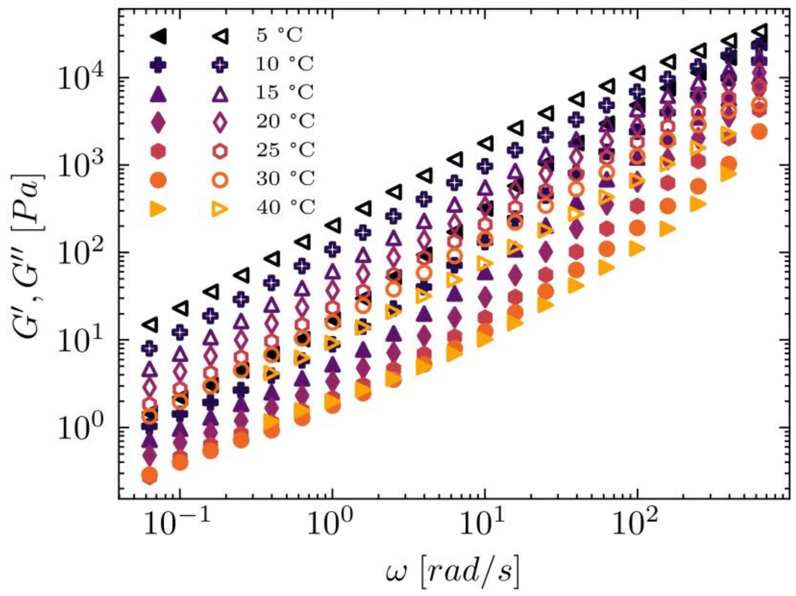
Influence of temperature for different pH-values



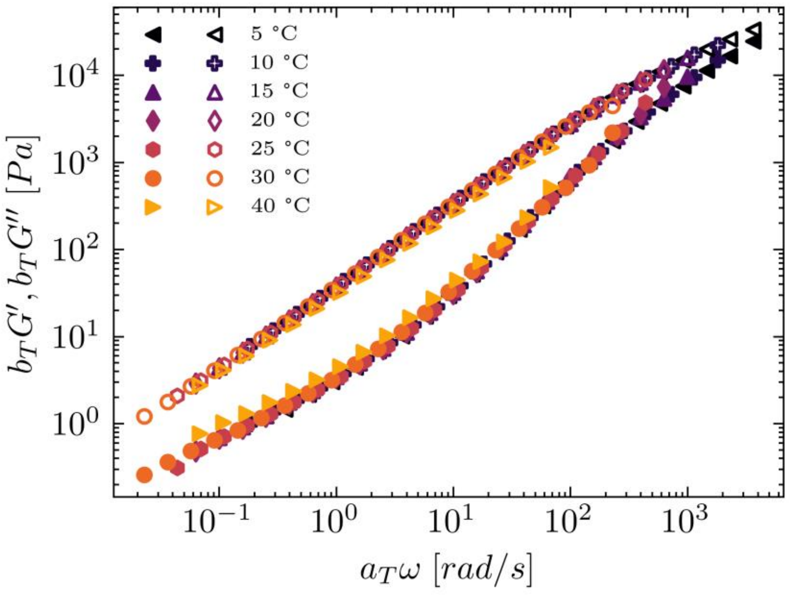
- Absence of thermal gelation at pH5.2
- Thermal behavior: Softening from 20 to 40 (or 50 °C as a function of pH) followed by irreversible gelation at 60 °C (or 50°C).
- Gelation of the coacervate phase lead to stiff materials (1 KPa < G’ < 1 MPa)

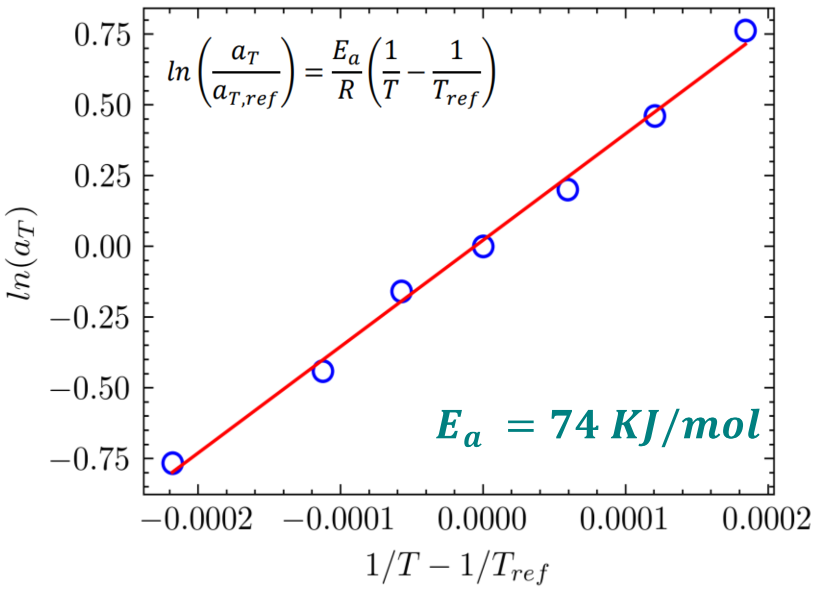
Time temperature superposition

pH5.6



TTS

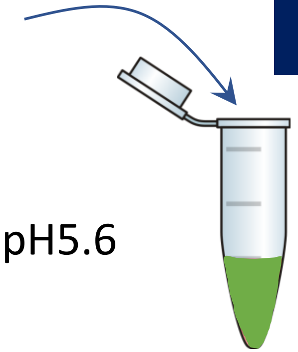




- Heating: accelerate the coacervates dynamics
- TTS principle applies in the limited range of T°C ($5 \leq T < 50$ °C):
  - Both proteins show the same *T*-dependent monomer friction
  - The dynamics of the coacervate is dominated by BLG/LF interactions
  - The dynamics of the two proteins are strongly coupled.

Time salt superposition

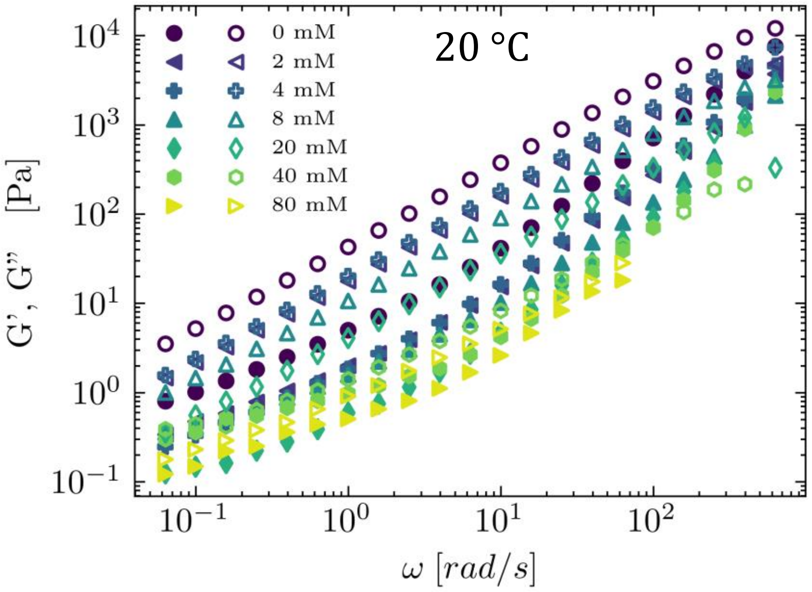
Effect of added NaCl
0 – 80 mM

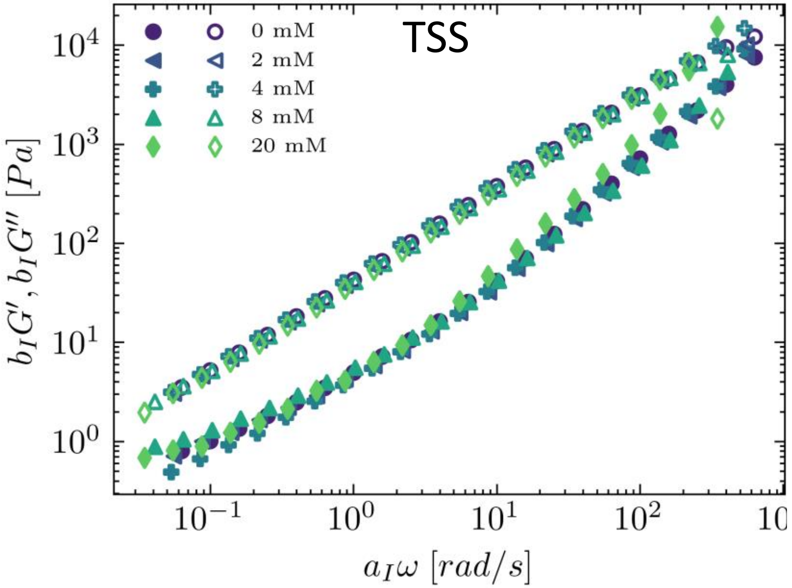


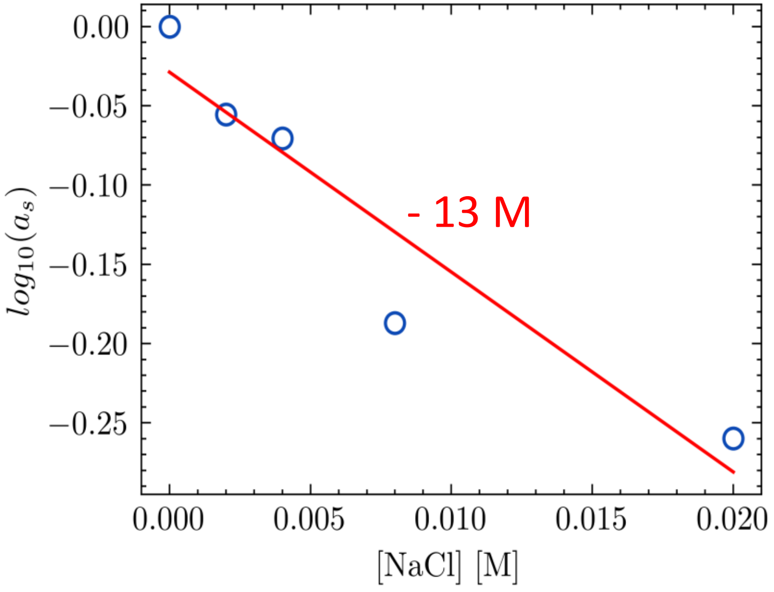
pH5.6

0 - 80 mM

Added [NaCl] (mM)





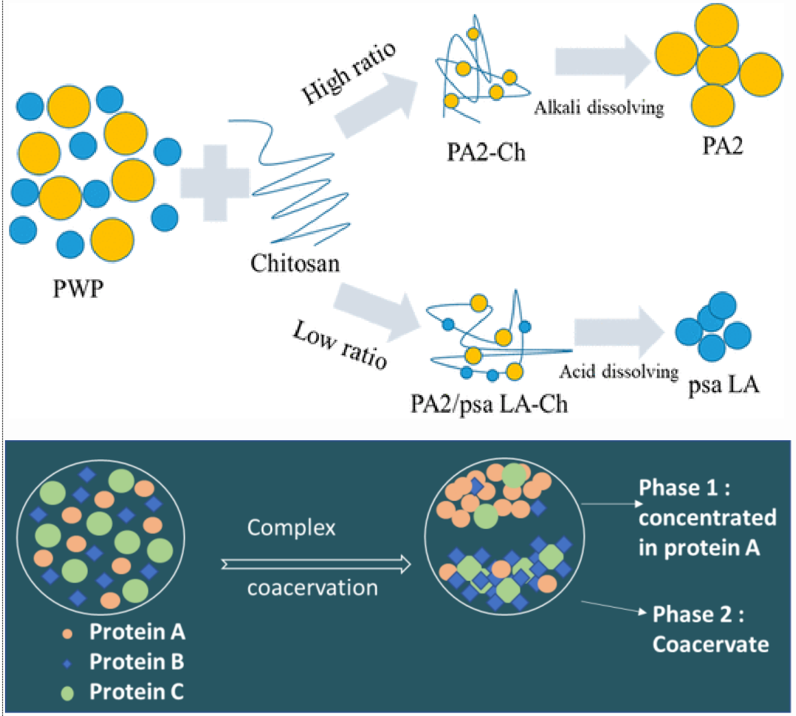


- **Accelerates the coacervates dynamics of the system.**
  - Decrease of the number of intrinsic ion pairs
  - Decrease of the energy of their dissociation (E_a)
  - Reduced local friction

Potential applications

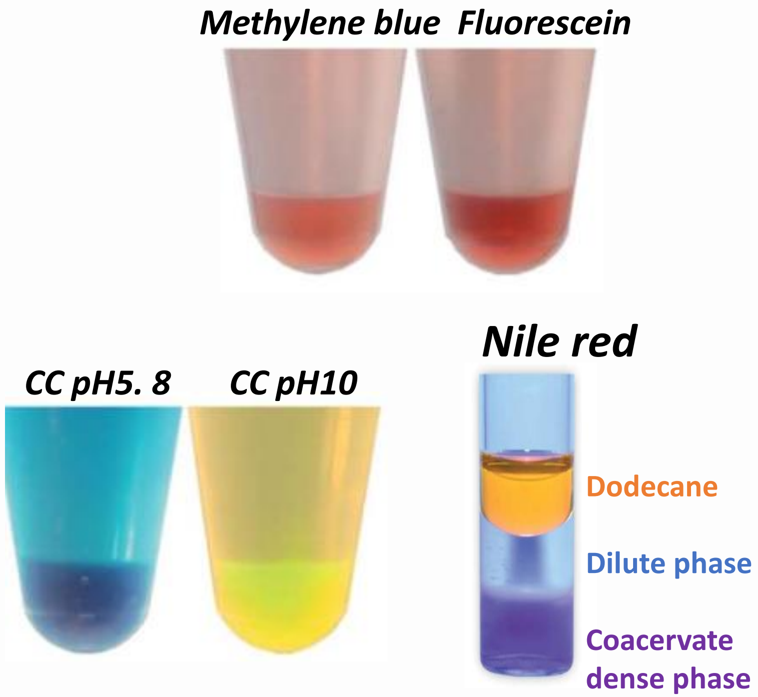
Purification & Encapsulation

Selective Complex Coacervation



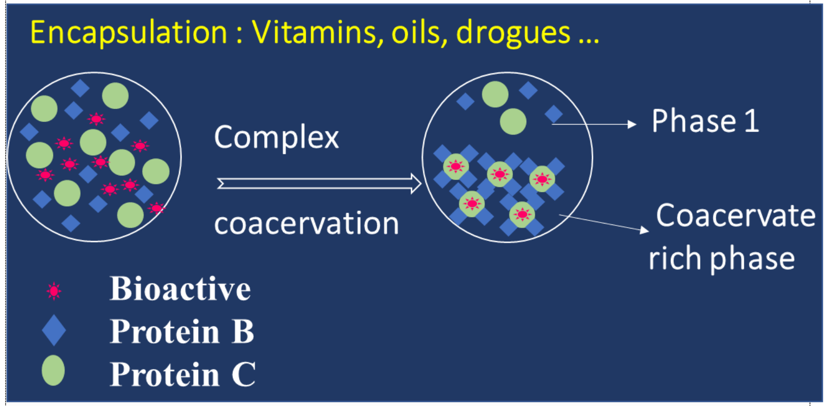
Yang et al., J. Agric. Food Chem. 2020

Sequestration properties (preferntial partionning)



Williams et al., Soft Matter, 2012

Weak attractive interactions

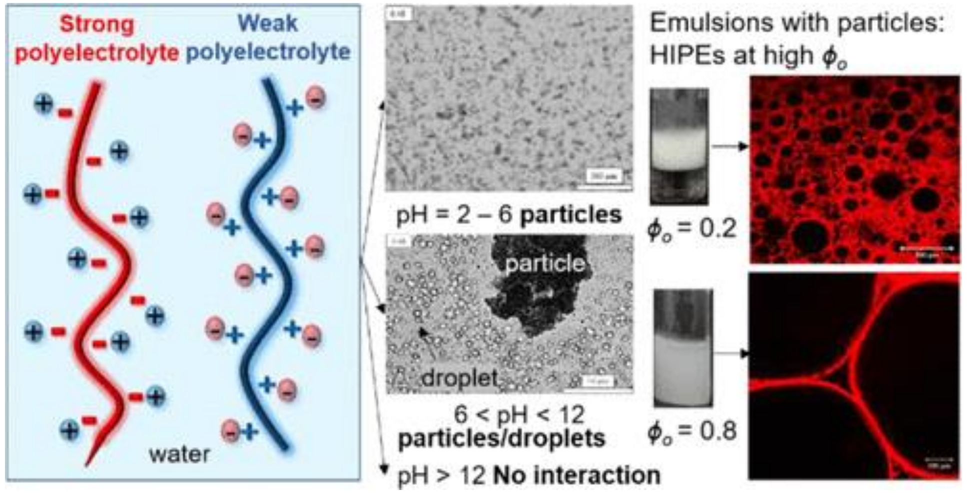


Chapeau et al., Food Hydrocolloids, 2016
McTigue et al., Soft Matter, 2019

III. Emulsion stabilization

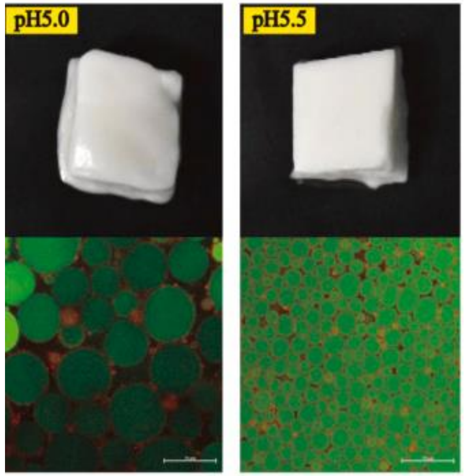
Up to date synthetic PEC/PEC or polysaccharide/proteins coacervates…

PSS / PAH



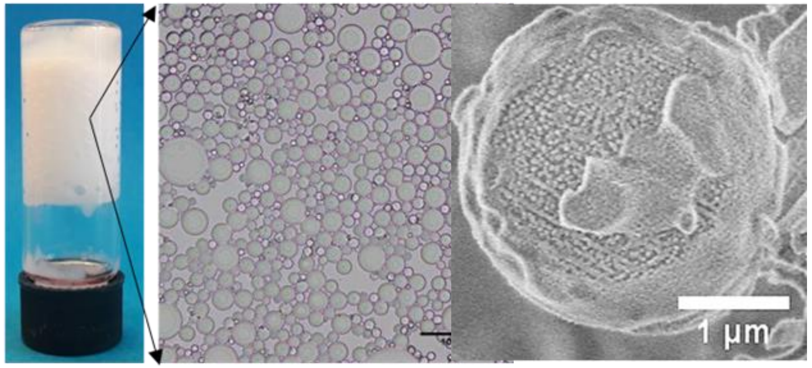
Bago et al., *Langmuir*, 2019

Soy protein isolate / κ-Carrageenan



Meng et al., *Food Hydrocolloids*, 2024

Biosurfactant / PEC



Laquerbe et al., *JCIS*, 2021

✓ **Successful stabilization of oil/water emulsion and High internal phase emulsion (HIPE)**

However…

Stabilization mechanism is still poorly understood: A pickering effect or a continuous layer around the dorplets?

Evolution of coacervate structures from bulk solution to the interfaces: crowding at the interface, nature of oil/water interface?

Conclusion

- Complex coacervation: Generic process
- Optimal conditions: specific for each mixture (Patchiness, Charge anisotropy…)
- “High” Sensitivity to: pH, Ionic strength, concentrations, stoichiometry
- Possible variability in the same system (isomerism, oligomerization)
- Rheology – structure relationship: still to be elucidated
- Promising applications in food industry (thickening agent, stabilizer…): Fondamental aspects still to be understood (stabilization mechanism of biphasic systems, preferential partitioning of active molecules,…)

Acknowledgements

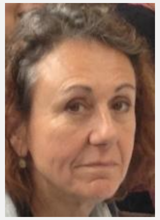
S. Bouhallab

F. Rousseau

P. Hamon

M. Ganne

M.F. Famelart

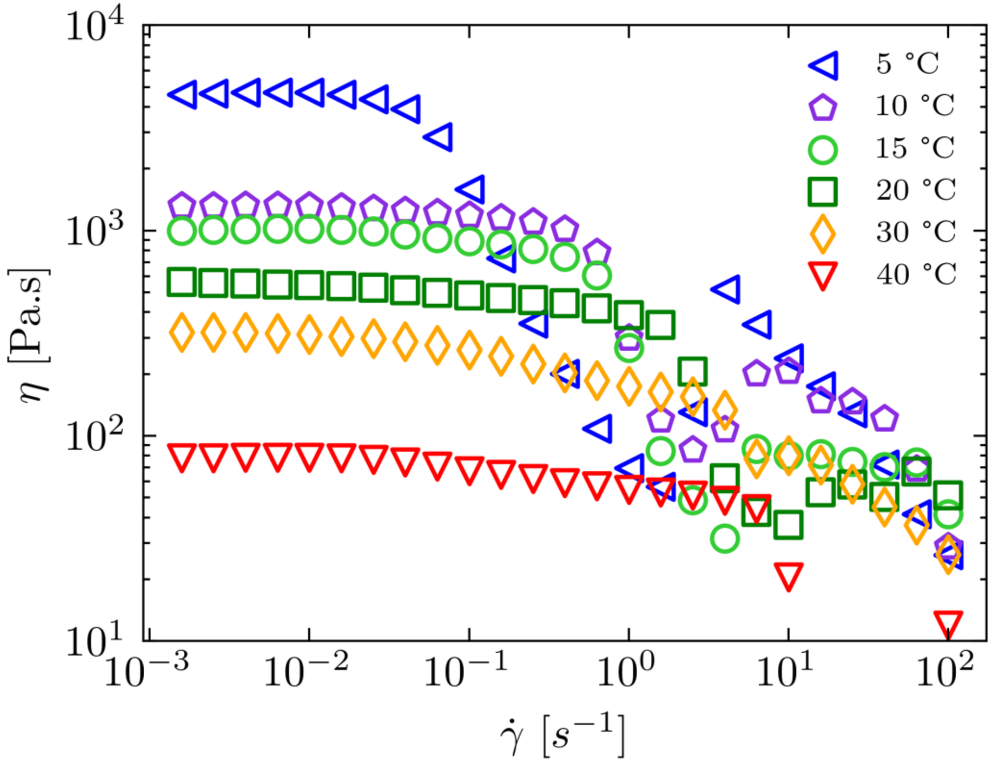


R. Soussi

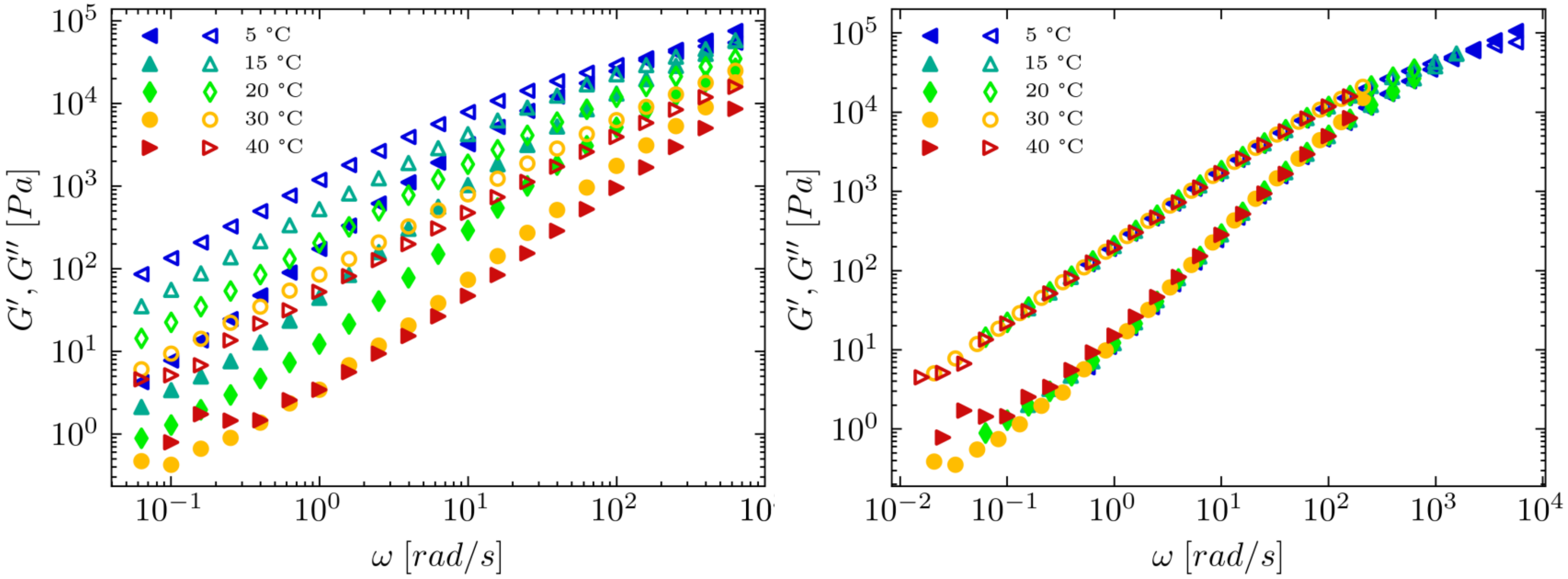
Thank you for your attention

Additional Slides

New Sample Ghazi



New sample Ghazi



New sample Ghazi