Making amorphous solids with proteins, a scattering perspective.

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Small Brownian particles, such as colloids or proteins dispersed in solvent, can be viewed as giant atoms exhibiting a wide range of interactions from repulsive to attractive. In this talk, I will explore the formation, from a scattering point of view, of three types of colloidal amorphous solids, shaped by their concentration and interaction potentials:

1- Alpha cristallin and hard sphere glasses.
2- Lysozyme and arrested phase separations.
3- Casein micelles and fractal gels.

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27/28 Nov. 2024
SAXS/SANS, Saclay

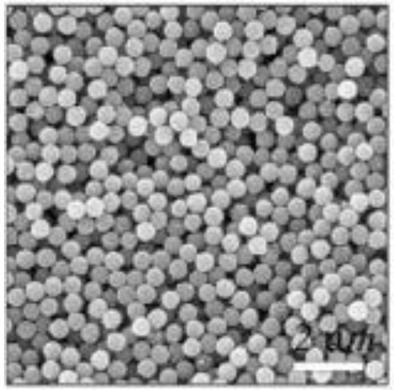
1- Colloids/proteins as giant atoms
2- α-cristallin and hard sphere glasses
3- Casein micelles and fractal gels
4- Lysozyme and arrested phase separations

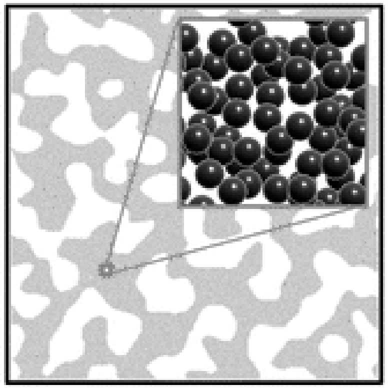
Structure
SAXS/SANS
microscopy

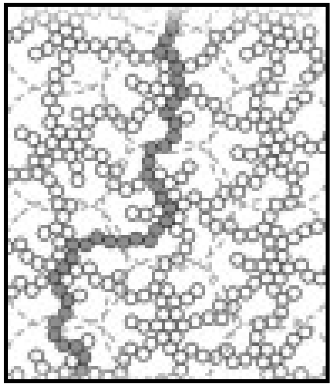
Mechanical properties
Rheology

State diagram
of the dispersion

Dynamics
DLS, XPCS





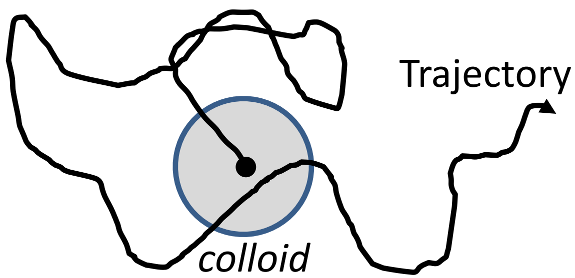


Colloids as big atoms

W Poon, Science 304, 830 (2004)

Dynamics

Thermal energy k_BT induces Brownian motion

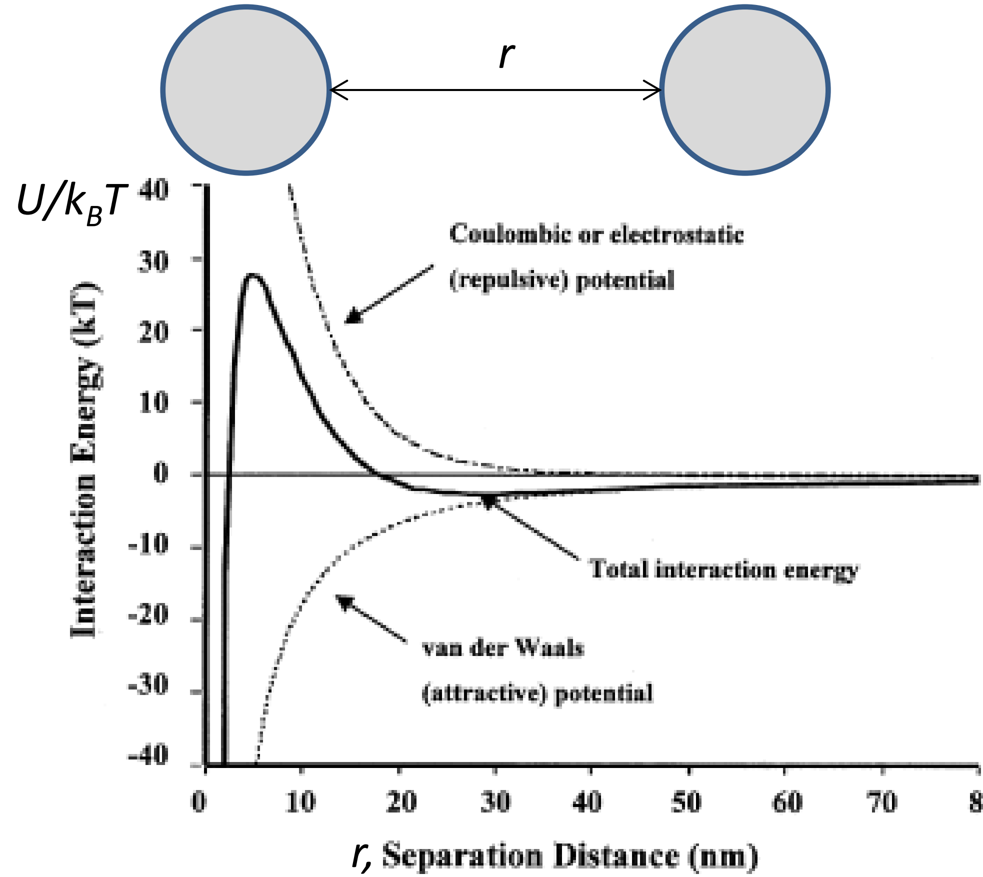


Proteins = Colloids?

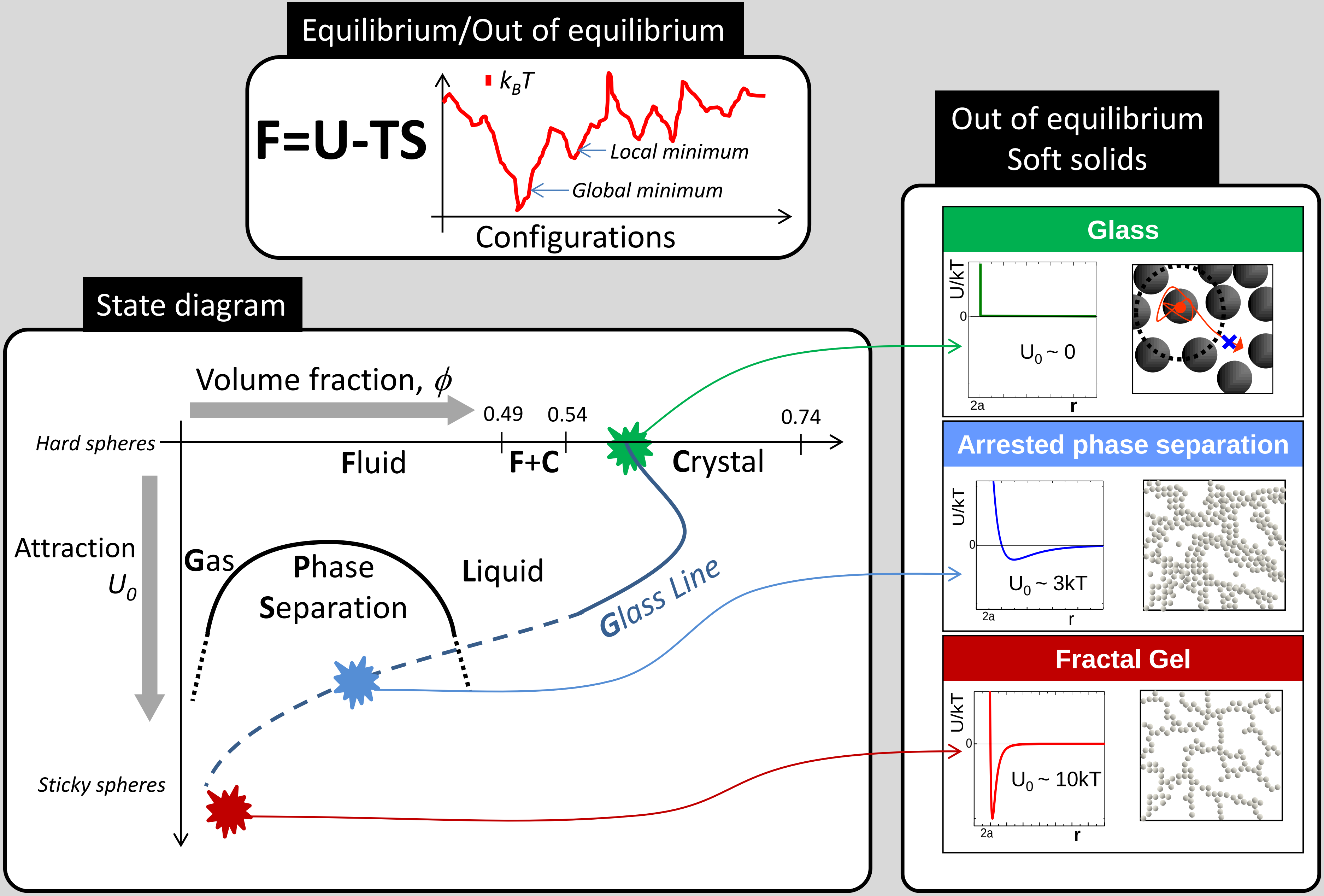
Potential and limits of a colloid approach to protein solutions. A Stradner, P Schurtenberger. Soft Matter 16, 307 (2020)

Engineering Interaction potential

Ex: DLVO



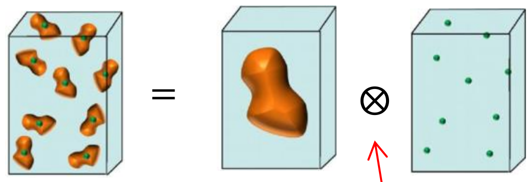
Colloids state diagram



Scattering to probe the structure in colloidal science

Real Space

$$\Delta\rho(r) = \Delta\rho_{colloid}(r) \otimes \sum \delta r_i$$



Convolution

As long as the colloids are undeformable

Scattering with colloids is simple!

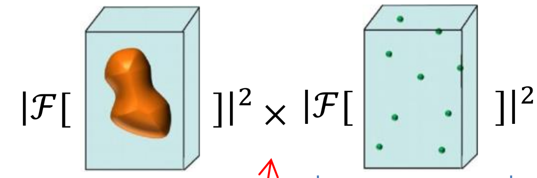
Fourrier Space

$$I(q) \propto |\mathcal{F}[\Delta\rho(r)]|^2$$

$$I(q) \propto |\mathcal{F}[\Delta\rho_{colloid}(r) \otimes \sum \delta r_i]|^2$$

$$I(q) \propto |\mathcal{F}[\Delta\rho_{colloid}(r)]|^2 \times |\mathcal{F}[\sum \delta r_i]|^2$$

Wiener–Khinchin theorem



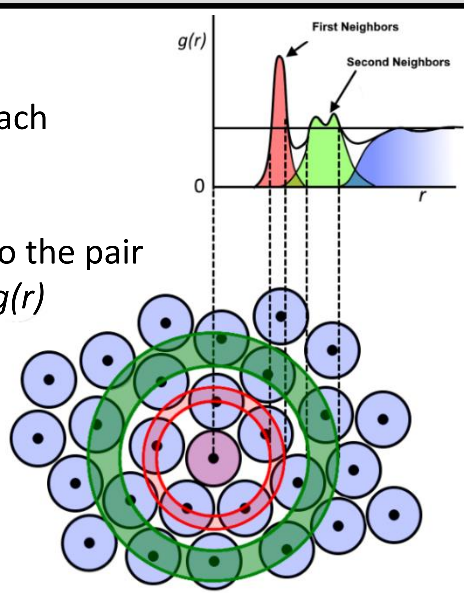
P(q)
Form Factor

S(q)
Structure Factor

Product

Yes, but …

- The phase between each colloids is lost
- We are **only** sensitiv to the pair distribution function *g(r)*



Many real space configurations have the same *g(r)*

Structure factor

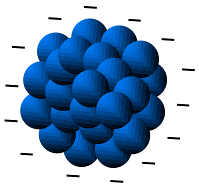
$$S(\mathbf{q}) = 1 + \rho \int_V \mathrm{d}\mathbf{r}\, \mathrm{e}^{-i\mathbf{q}\mathbf{r}} g(\mathbf{r})$$

"Small angle neutron scattering." F Cousin. EPJ web of conferences. 104. EDP Sciences, 2015

α-crystallin

= chaperon protein in the eye lens

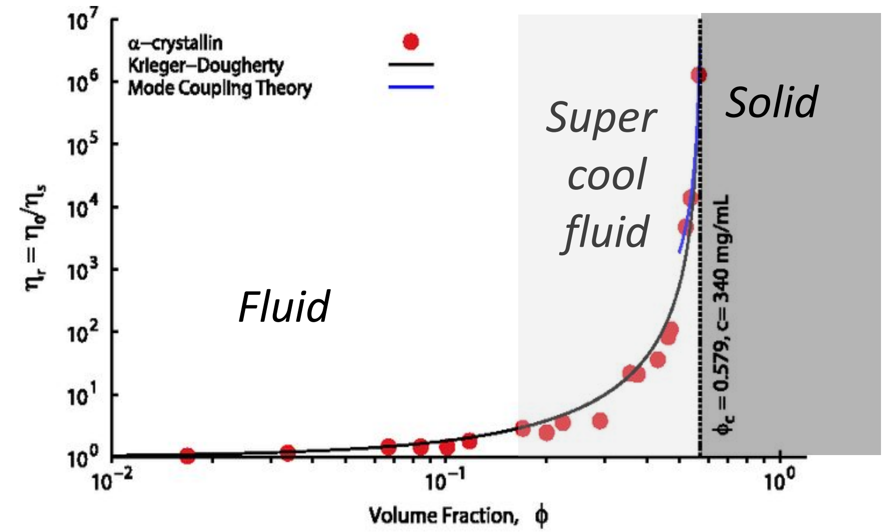
Globular Proteins
α-crystallin



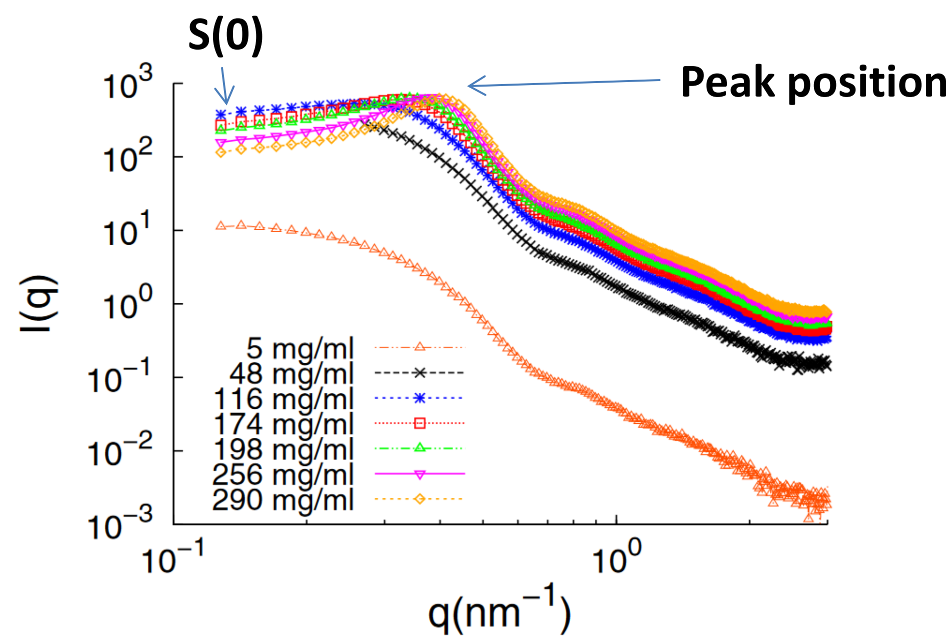
~ 800 kDa
multisubunit protein
polydisperse
repulsive interactions

Hard sphere-like glass transition in eye lens α-crystallin solutions. G Foffi, G Savin, S Bucciarelli, N Dorsaz, GM Thurston, A Stradner, P Schurtenberger. PNAS 111 16748 (2014)

Viscosity

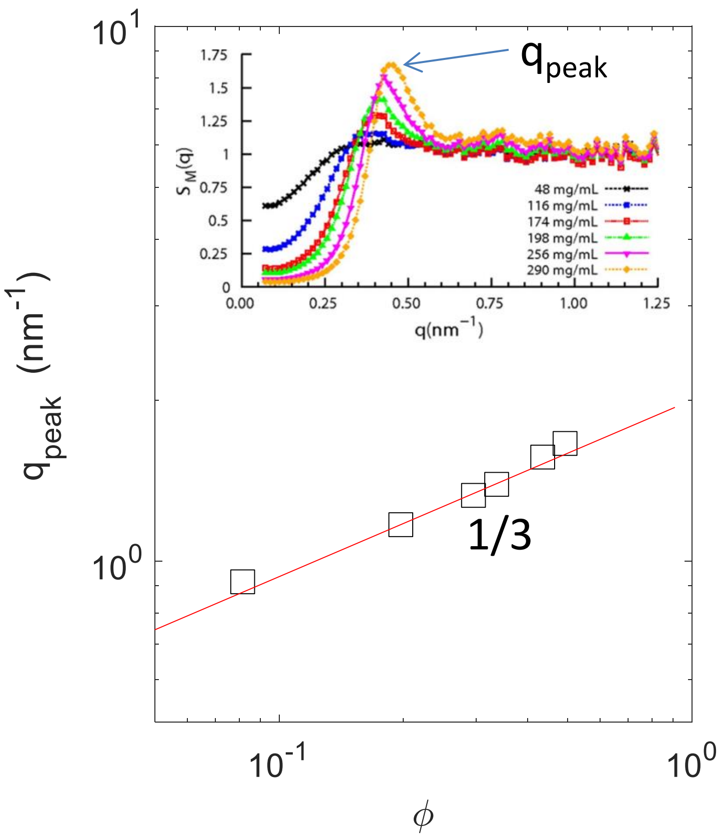


Scattering

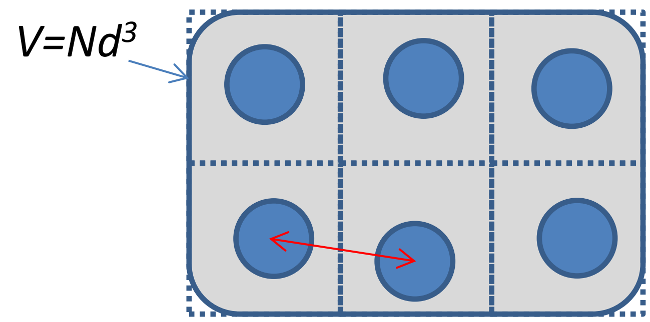


α-crystallin, interparticle distance

Structure factor:
$S(q)=[I(q,c)*c_0]/[I(q,c_0)*c]$



Particle on average tend to maximize their distance from one another



$d=2\pi/q_{peak}$

$\phi \sim c = m/V \sim 1/d^3$

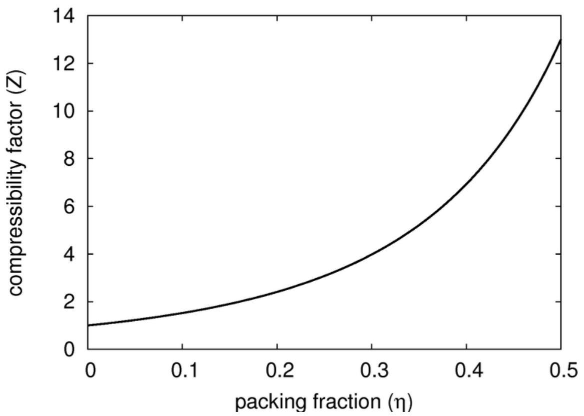
$q_{peak} \sim \phi^{1/3}$

Typical of repulsive systems

S(0) and the compressibility

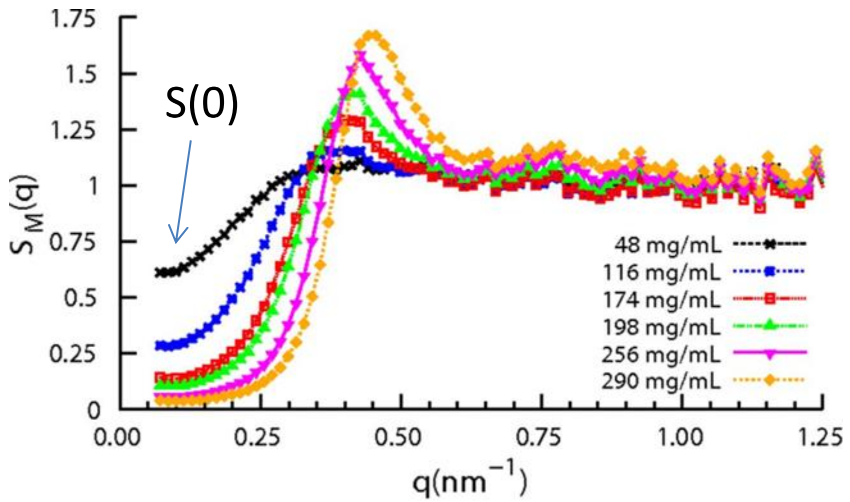
Carnahan–Starling:
Equation Of State for hard spheres

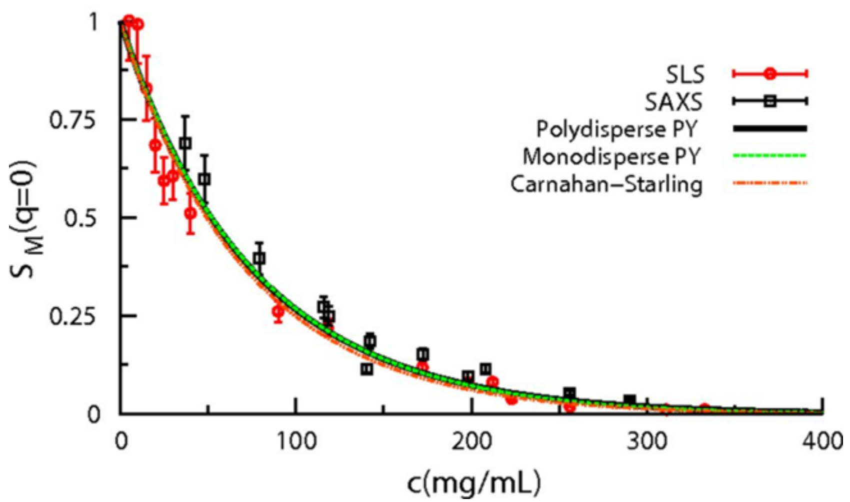
$$Z = \frac{pV}{Nk_BT} = \frac{1+\eta+\eta^2-\eta^3}{(1-\eta)^3}.$$



$$\lim_{q\to 0} S(q) = \rho\, k_\mathrm{B} T\, \chi_T = k_\mathrm{B} T \left(\frac{\partial \rho}{\partial p}\right).$$

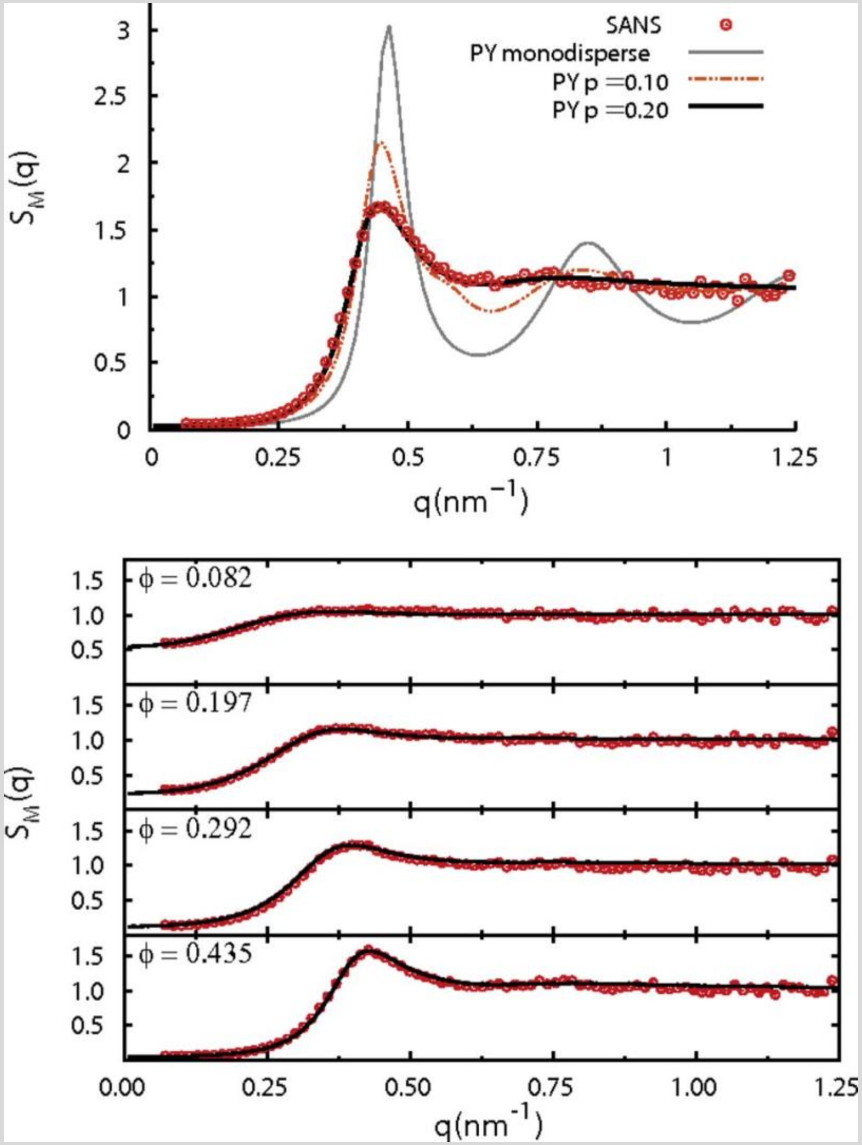
$$S_\mathrm{CS}(0) = \frac{(1-\phi)^4}{(1+2\phi)^2+\phi^3(\phi-4)}$$





Scattering gives acces to the osmotic pressure and the EOS

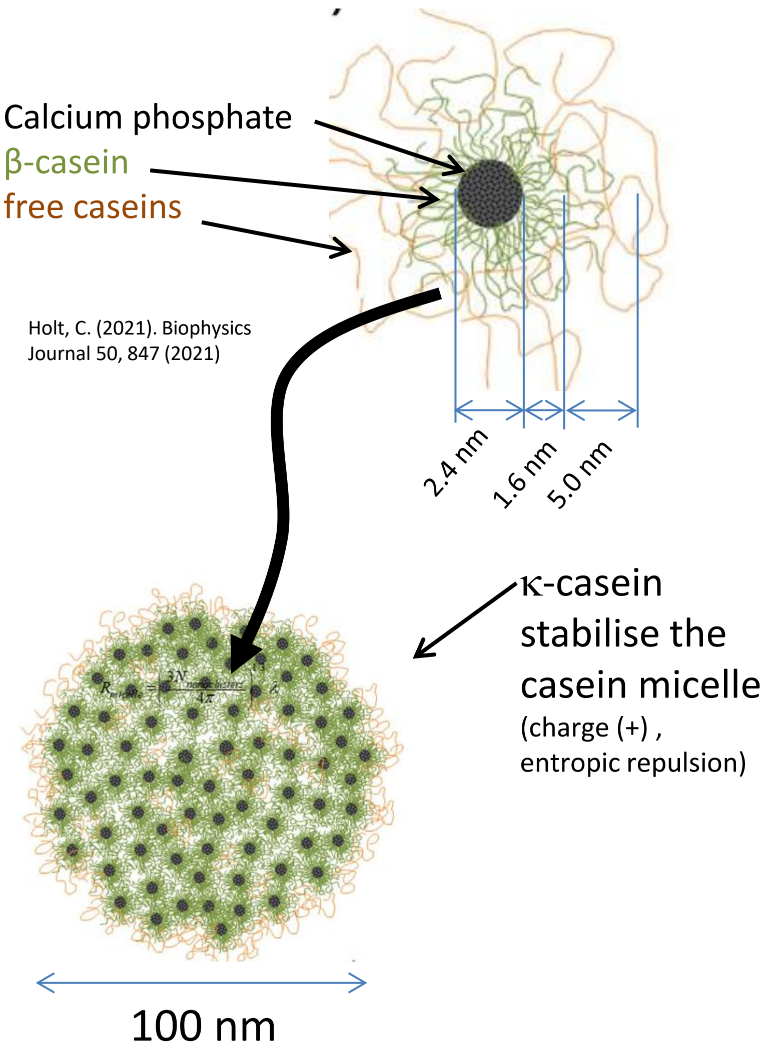
α-crystallin, full model



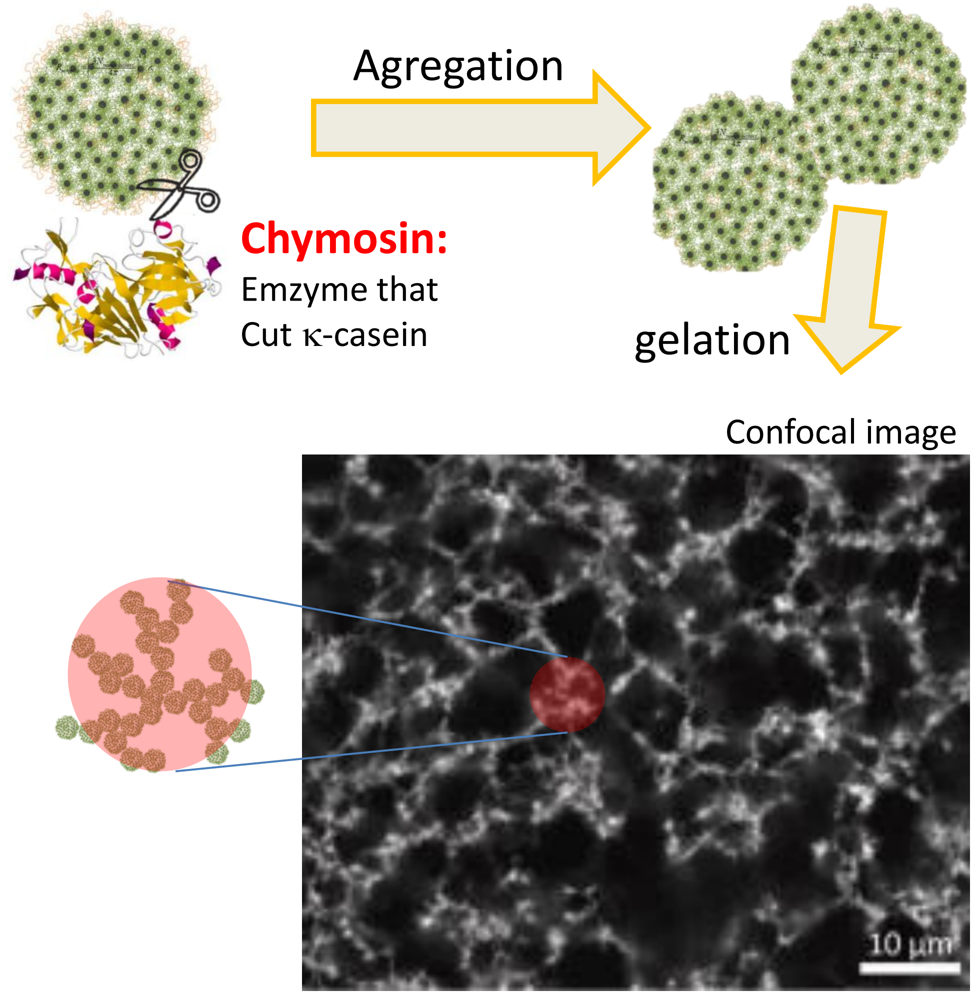
To do Integral theory …

Casein micelles

= carrier for of proteins and salts with low solubilities



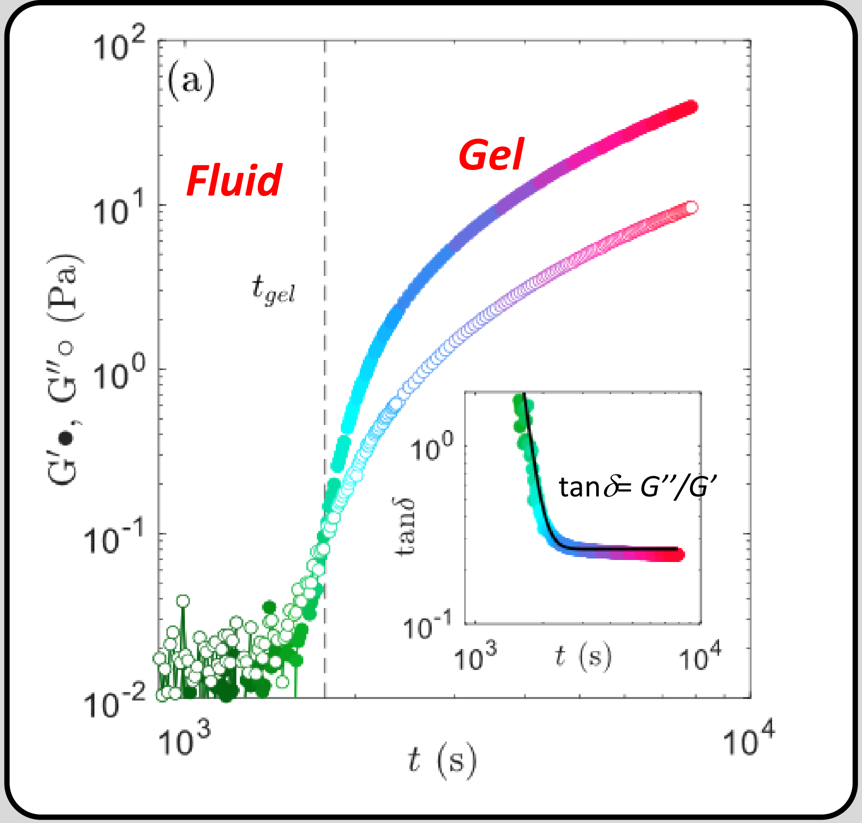
Gelation



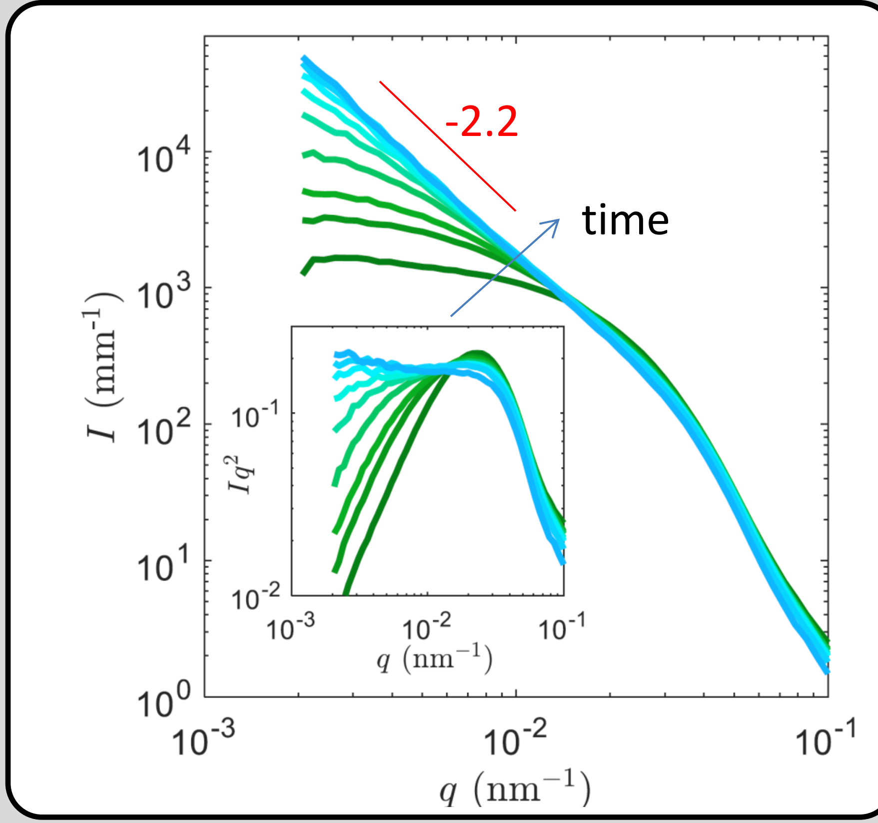
Gel = Network of particles
Can we be more specific?

Casein micelles and fractal gels

Rheology



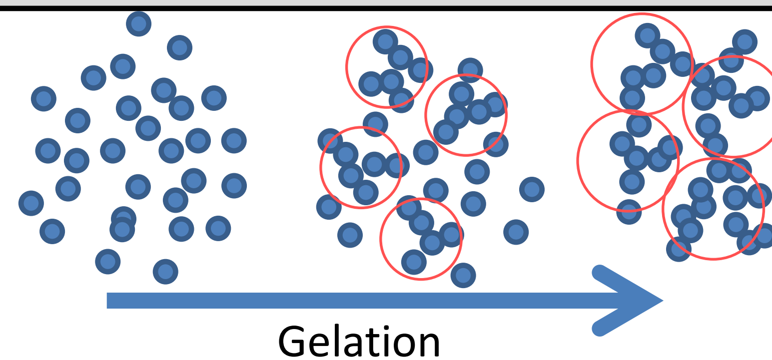
SAXS



Interpretation

How do you form a solid with a volume fraction of 10%?

fractal cluster of size ξ and fractal dimension d_f



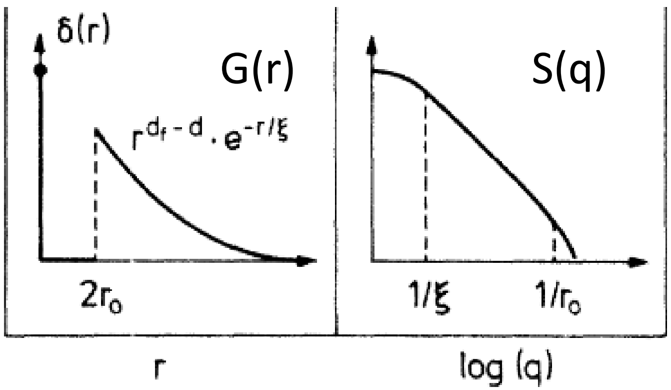
Model for fractal gels

Geometric model: mass fractal

$$S(\mathbf{q}) = N \int G(\mathbf{r}) e^{-i\mathbf{q}\cdot\mathbf{r}} d\mathbf{r} \, ,$$

$$G(\mathbf{r}) = \delta(\mathbf{r}) + G_{\mathrm{diff}}(\mathbf{r}) \, .$$

$$G_{\mathrm{diff}}(r) = (A / r^{d-d_f}) \exp(-r/\xi)$$



$$S(Q) = 1 + \frac{D}{r_0^D} \int_0^\infty r^{D-1} \exp(-r/\xi) \frac{\sin(Qr)}{Qr} \, dr$$

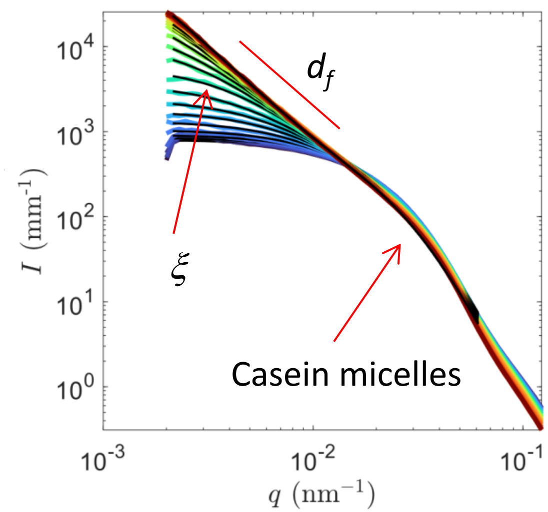
$$= 1 + \frac{1}{(Qr_0)^D} \frac{D\Gamma(D-1)}{[1 + 1/(Q^2\xi^2)]^{(D-1)/2}}$$

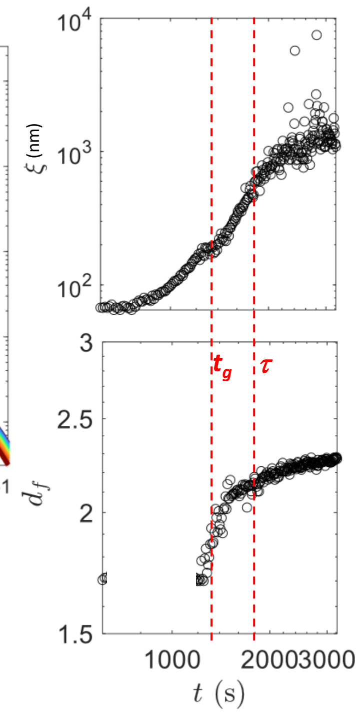
$$\times \sin[(D-1)\tan^{-1}(Q\xi)]$$

Power-law correlations and finite-size effects in silica particle aggregates studied by small-angle neutron scattering. T. Freltoft, J. K. Kjems, and S. K. Sinha. Phys. Rev. B 33, 269 (1986)

Small-angle scattering by fractal systems. J Teixeira. Applied Crystallography (1988)

Casein gel





Model:

- Clusters = mass fractal
- Casein micelles = polydisperse spheres

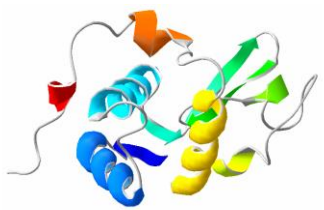
To do Plot phieff versus time

Two-step aging dynamics in enzymatic milk gels. J Bauland, G Manna, T Divoux, T Gibaud. Physical Review Materials 8, L072601 (2024)

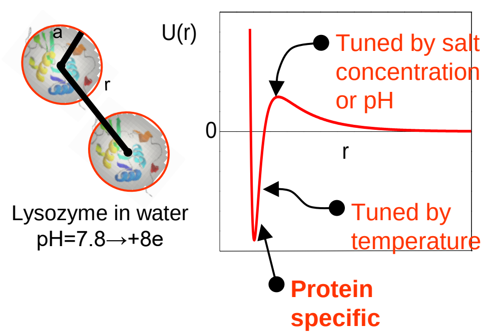
Lysozyme

= enzyme (glycoside hydrolase)

Interaction potential

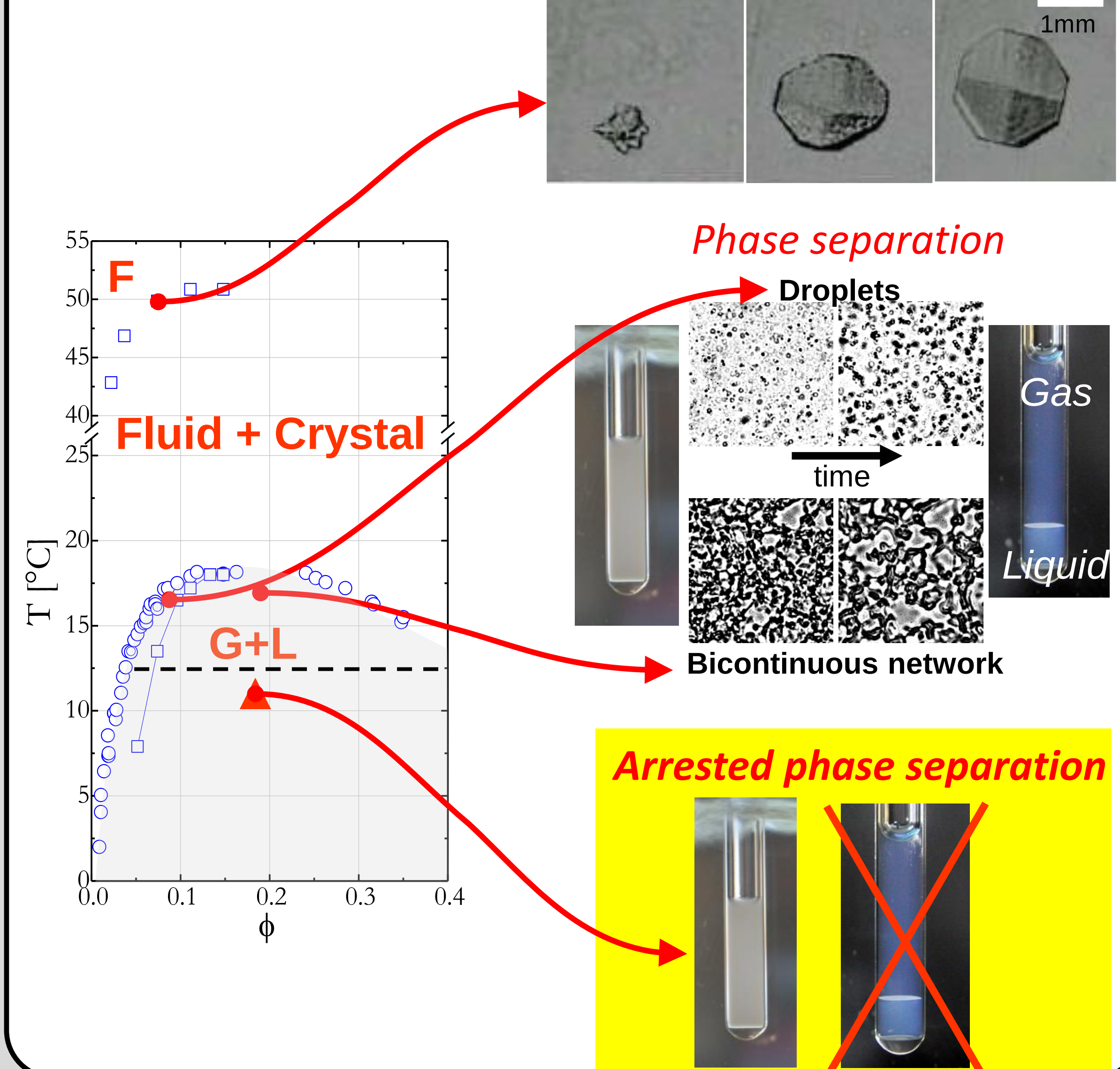


Globular protein
4.5x3x3nm monodisperse
Charged: pH=7.8→+8e



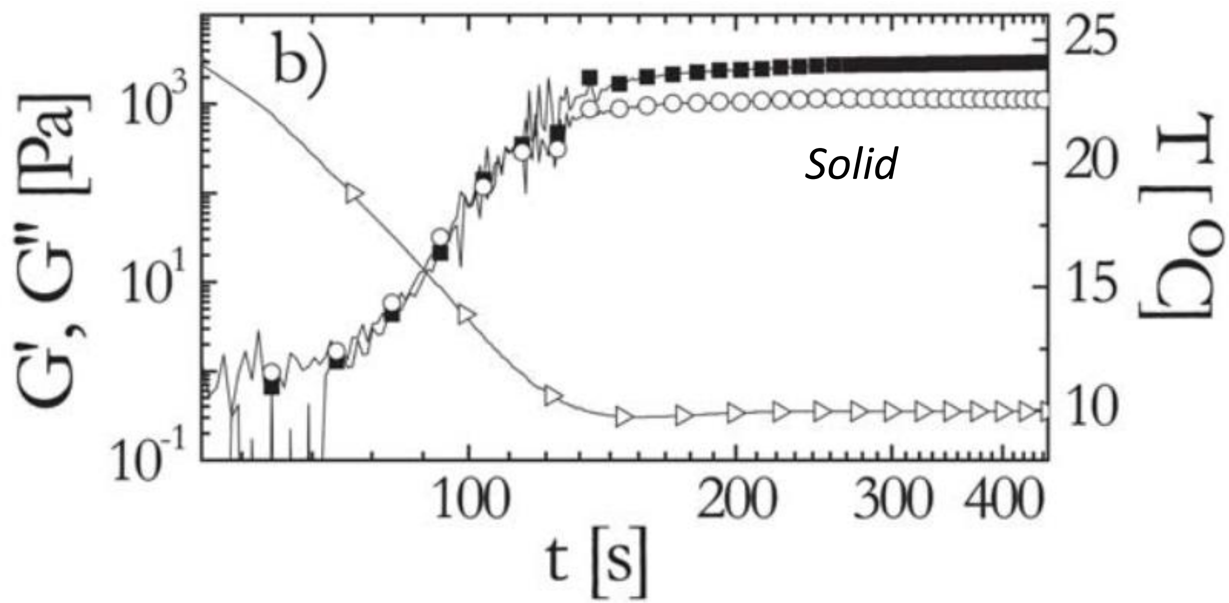
Interplay between Spinodal Decomposition and Glass Formation in Proteins Exhibiting Short-Range Attractions. F Cardinaux, T Gibaud, A Stradner, P Schurtenberger
PRL 99 (11), 118301 (2007)

State diagram



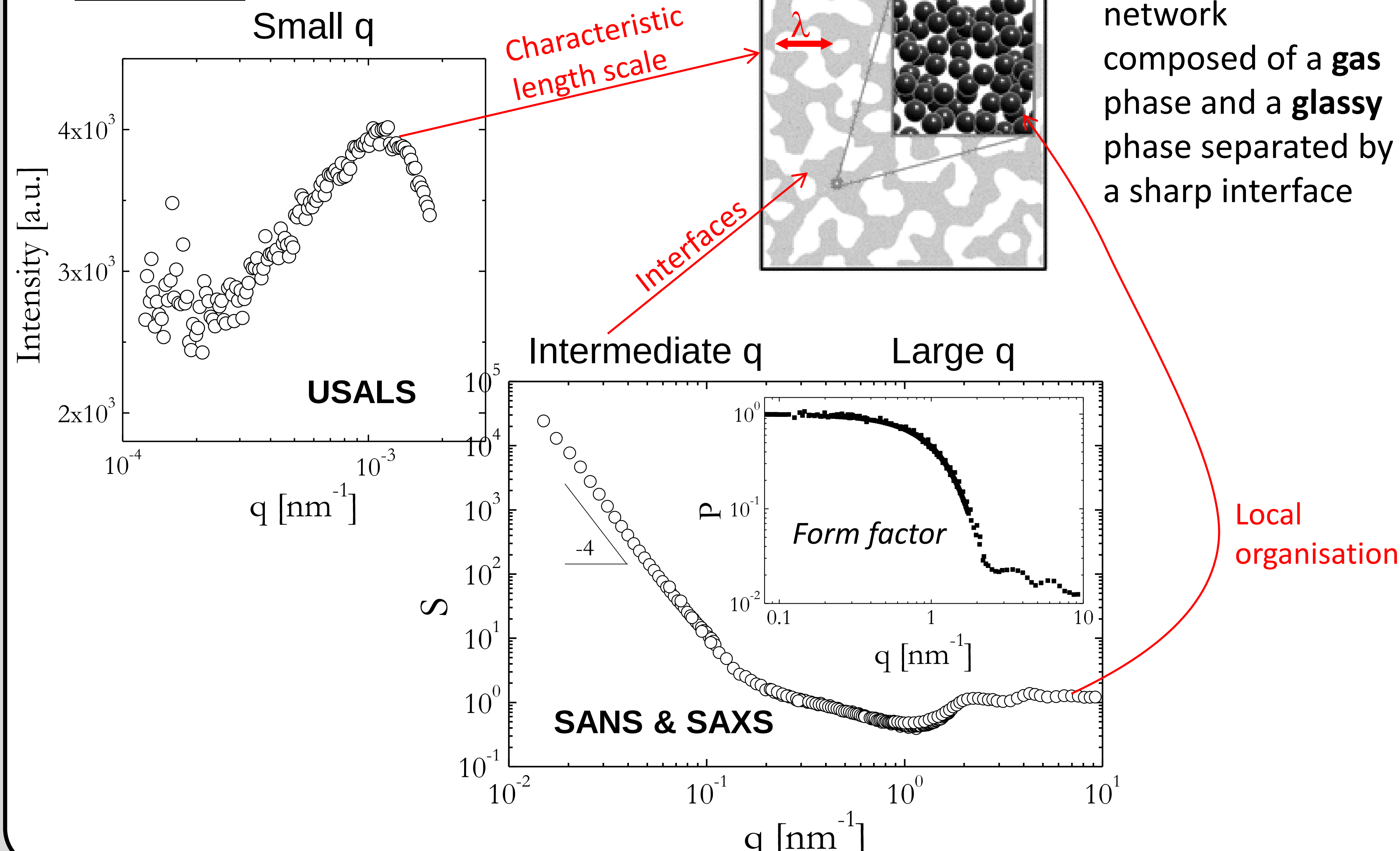
Lysozyme, arrested phase separation

Rheology



Lysozyme and arrested phase separation

Structure



Bicontinuous network composed of a **gas** phase and a **glassy** phase separated by a sharp interface

Model for arrested phase separation

Intermediate q

$$I_{\text{Porod}}(q) = \frac{2\pi\Delta\rho^2}{q^4}\frac{S}{V}$$

$$\Delta\rho = [\rho_L\phi_2 + (1-\phi_2)\rho_W] - [\rho_L\phi_1 + (1-\phi_1)\rho_W]$$

T_f [°C]	13	10	5
ϕ_0	0.148	0.148	0.148
ϕ_1	0.048	0.041	0.026
ϕ_2	0.344	0.329	0.270
h	0.342	0.381	0.520
ξ [μm]	~3.5	~2.5	~1.9
S/V [nm^{-1}]	76	186	331

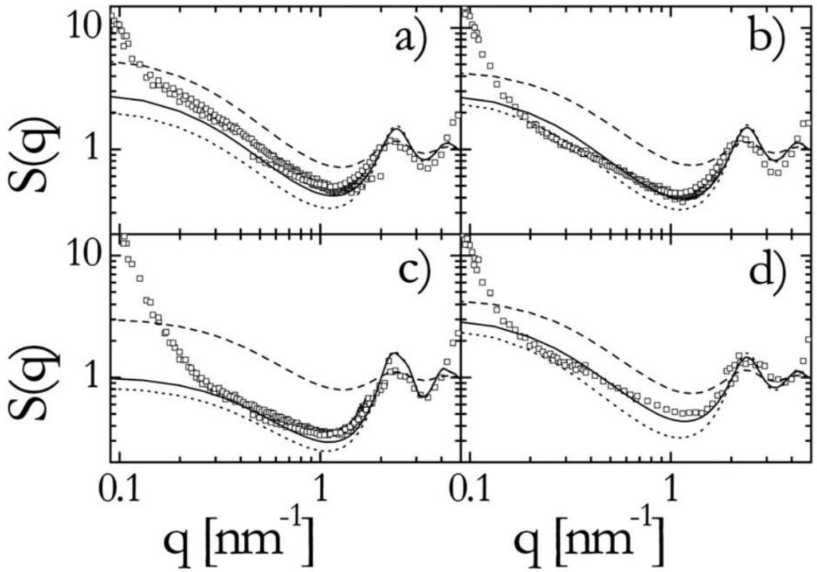
Large q

Square well potential

$$U_{SW}(r) = \begin{cases} \infty & 0 < r < 2a_{\text{eff}} \\ -\varepsilon & 2a_{\text{eff}} < r < 2a_{\text{eff}}(1+\lambda) \\ 0 & r > 2a_{\text{eff}}(1+\lambda) \end{cases}$$

$$S_{\text{cal}}(q,\phi_0,T_f) = \left[\frac{(1-h)\phi_1}{\phi_0}S_1(q,\phi_1,\varepsilon) + \frac{h\phi_2}{\phi_0}S_2(q,\phi_2,\varepsilon)\right]$$

Gas Liquid



Conclusion

Thank you for your time and attention
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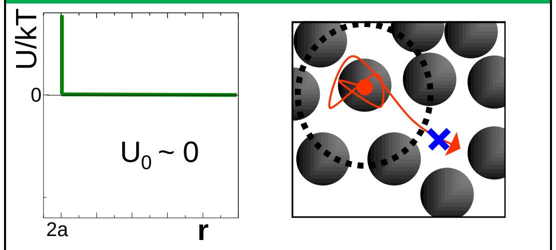
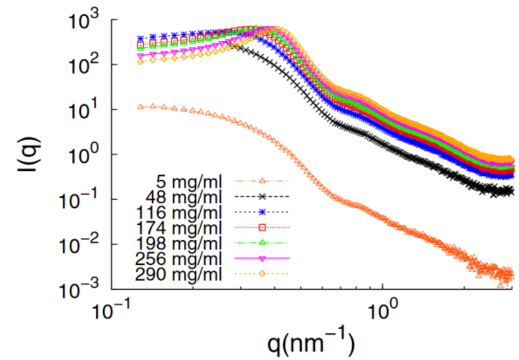
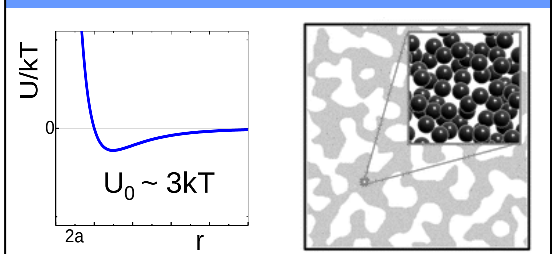
Glass



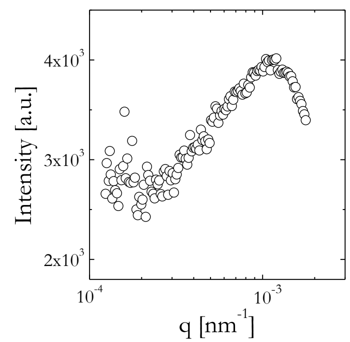
Dense Fluid like structure

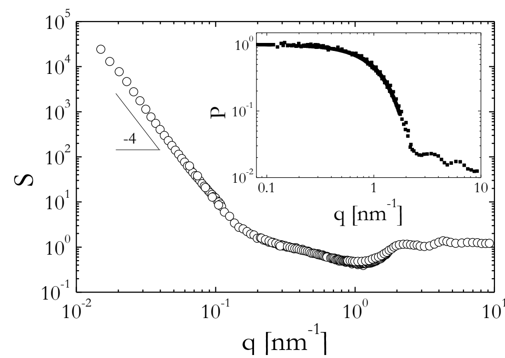


Arrested phase separation

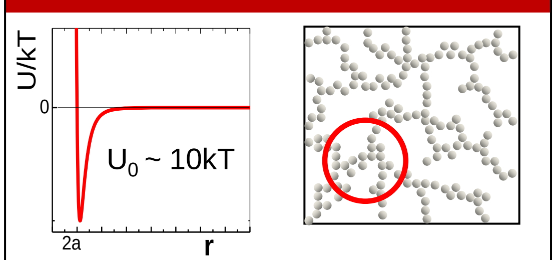


Bi-continuous network





Fractal Gel



Network=
Dense packing of fractal clusters