Imperial College London

Neutrons in soft matter

Lecture 1 - Structure

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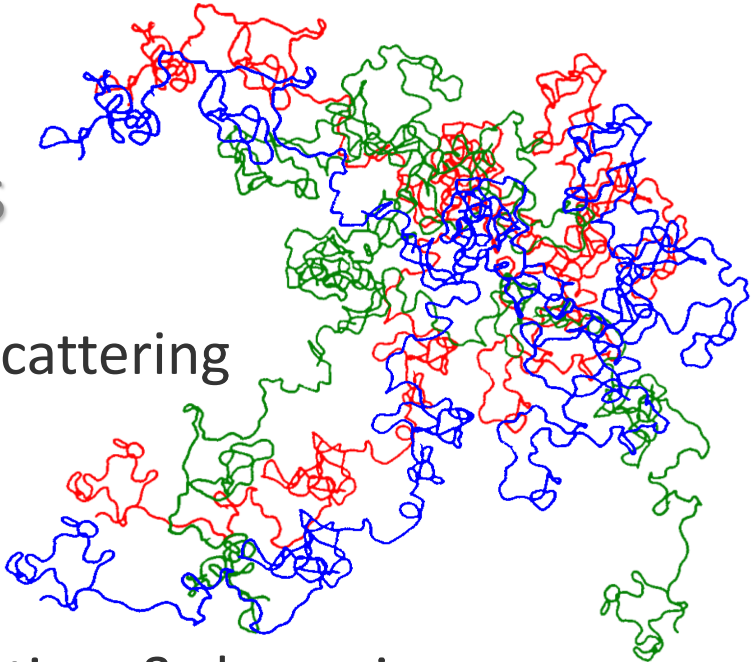
14th Oxford School on Neutron Scattering, 16 September 2015

Outline



Lecture 1 – Structure & kinetics – SANS

Introduction

soft matter & relevance of neutron scattering

Single objects: spheres, coils, rods...

Single chain polymer conformation

(solution and blends)

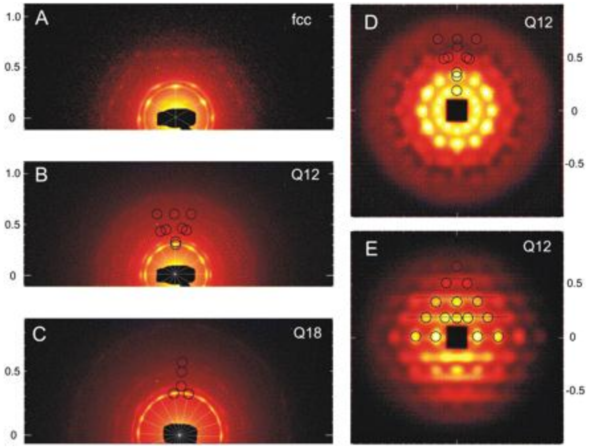
Polymer blends: interactions, conformation & dynamics

(equilibrium and phase separation)

Lecture 2 – Interfaces and dynamics

Reflectivity and diffusion

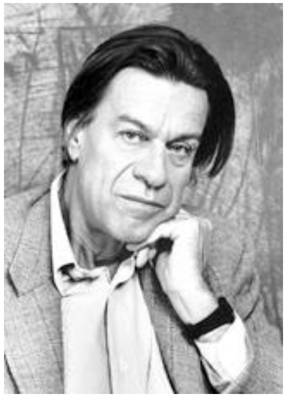
Dynamics in soft matter, QENS, BS, Spin-echo



Forster et al (2011)

Soft Matter

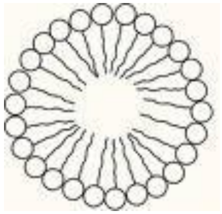
“molecular systems giving a strong response to very weak command signal”

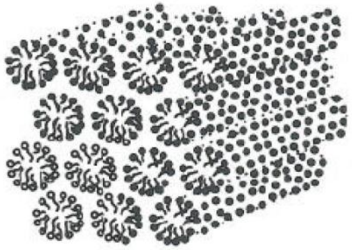


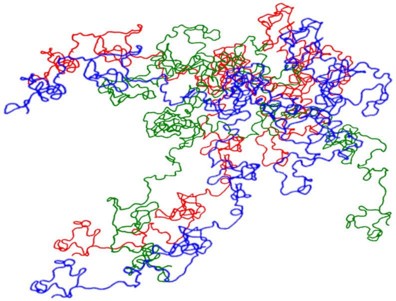
deGennes (1991)

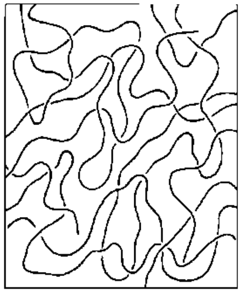
Condensed matter: states are easily deformed by small external fields, including thermal stresses and thermal fluctuations.

Relevant energy scale comparable with room temperature thermal energy.









Sir Sam Edwards (-2015)

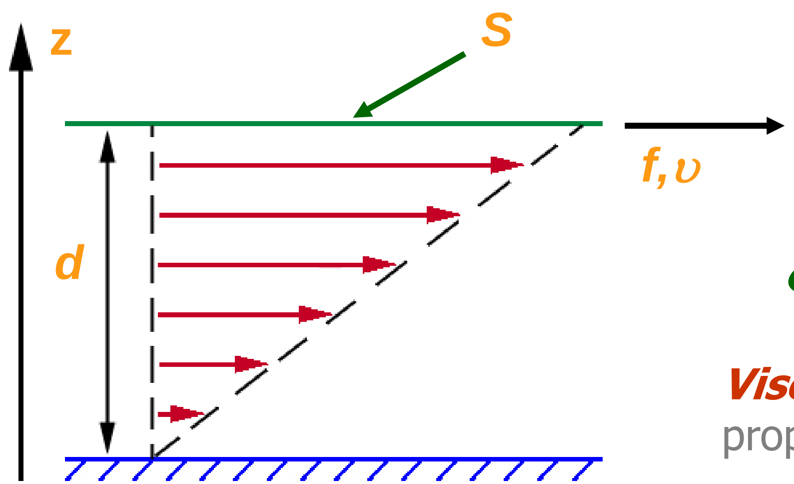
Complex fluids: including colloids, polymers, surfactants, foams, gels, liquid crystals, granular and biological materials.

shear

Movie: complex fluids are generally non-Newtonian... and structured

Viscosity

Simplest setup to measure viscosity

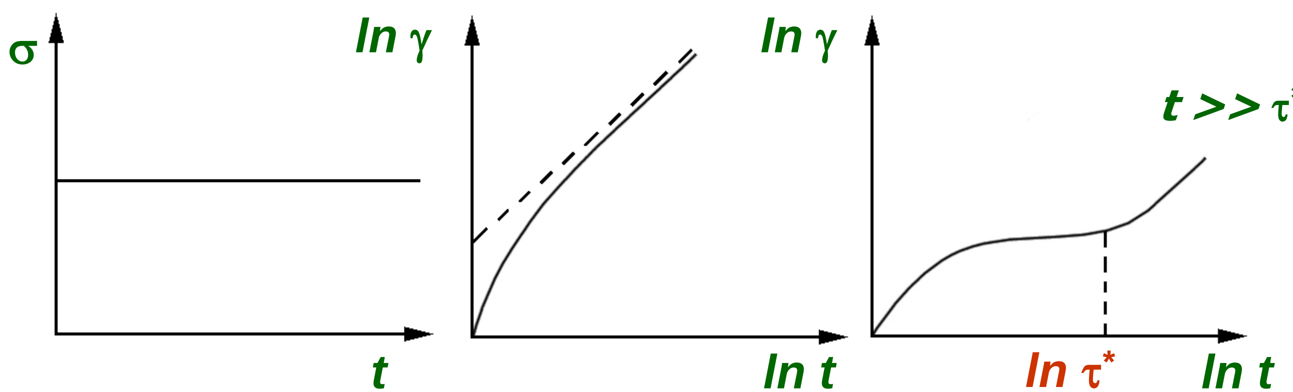


$$f = \eta \frac{S\upsilon}{d}$$

$$\sigma = \frac{f}{S} = \eta \frac{d\upsilon}{dz}$$

Viscosity:
proportionality coefficient η

Viscoelasticity?



Step-wise stress starting at *t* =0

normal liquid

polymer

t **<<** τ^* **:** ***elastic*** **response**

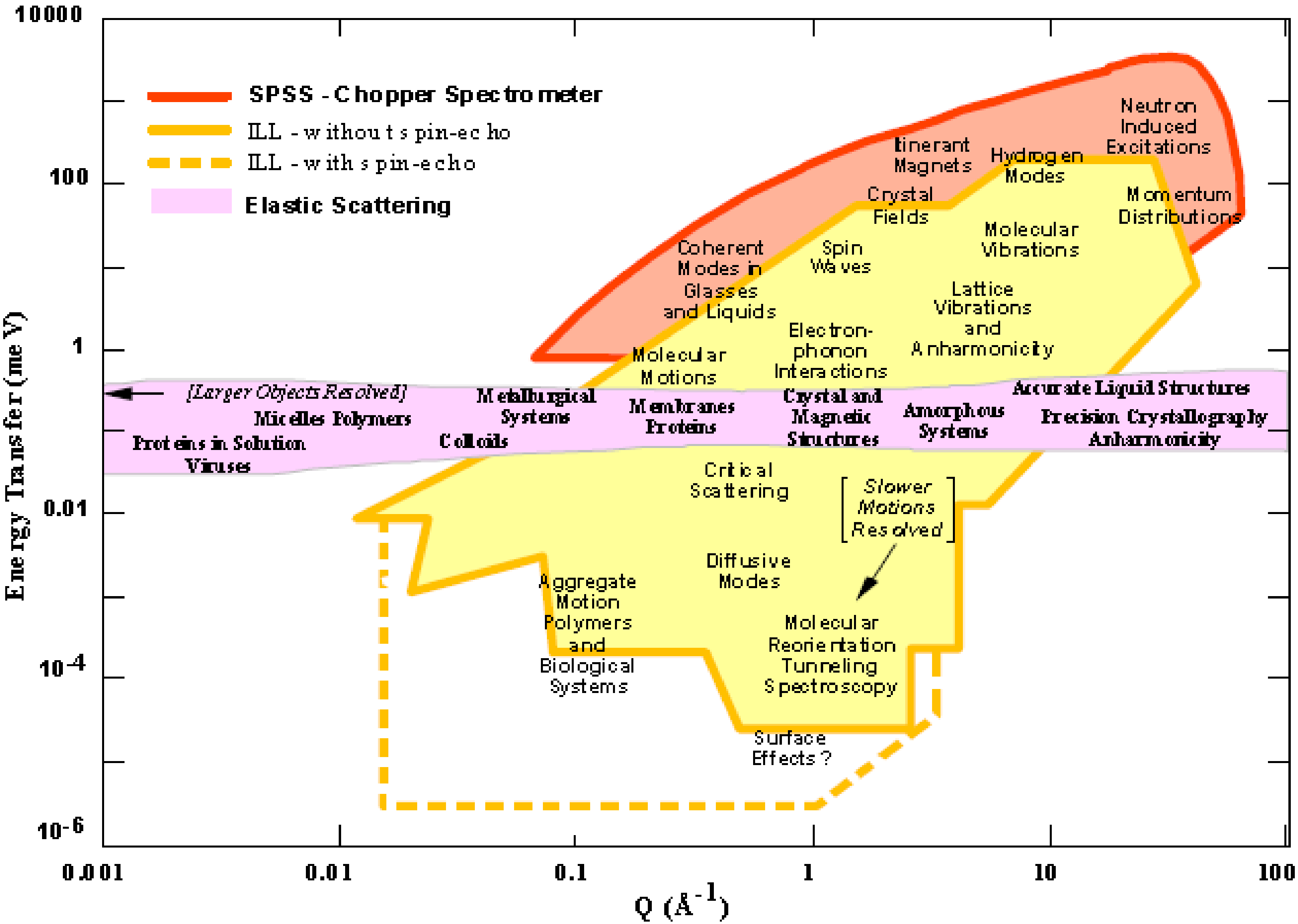
$$\gamma \approx \sigma / E$$

t **>>** τ^* **:** ***viscous*** **response**

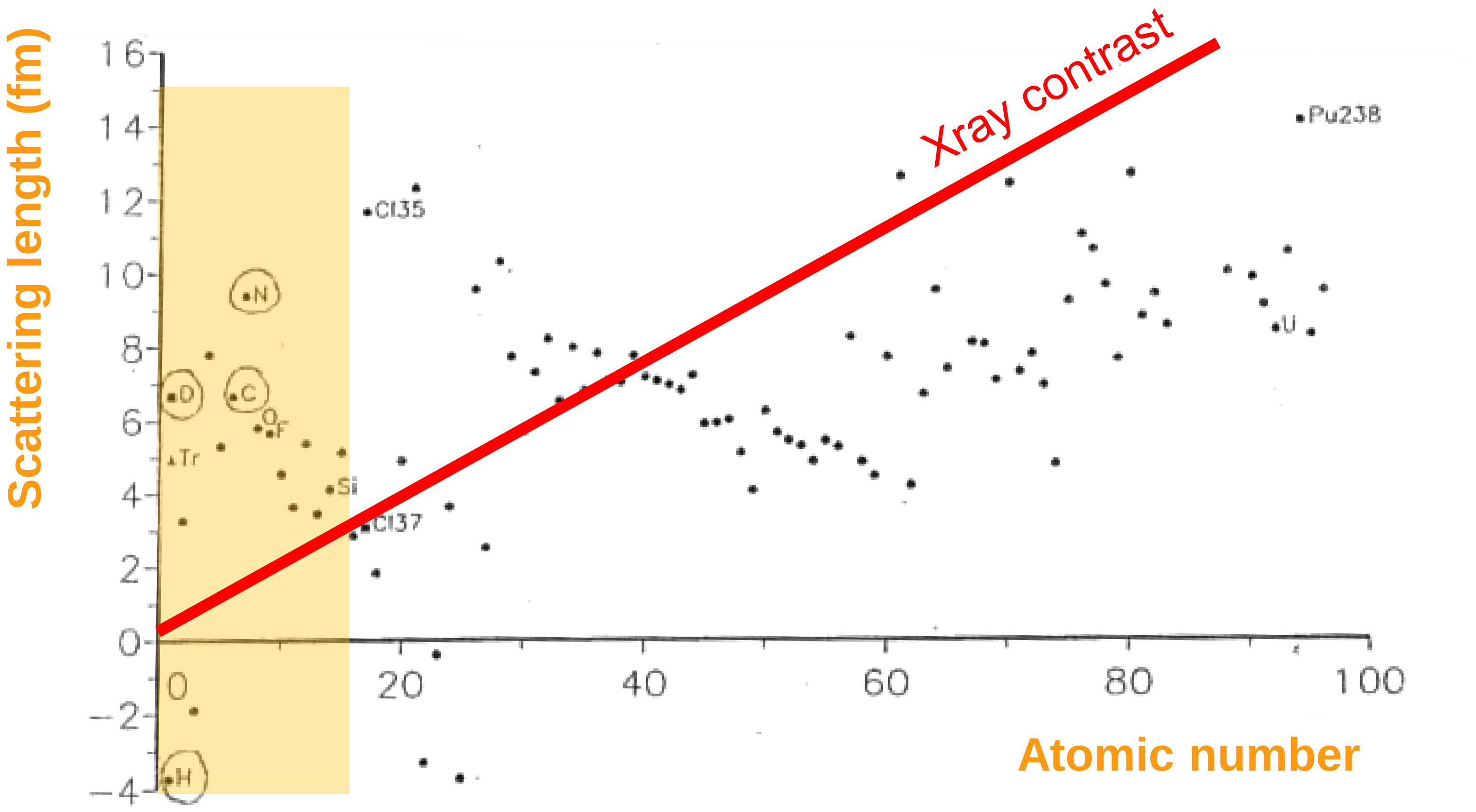
$$\gamma \propto \sigma \cdot t / \eta$$

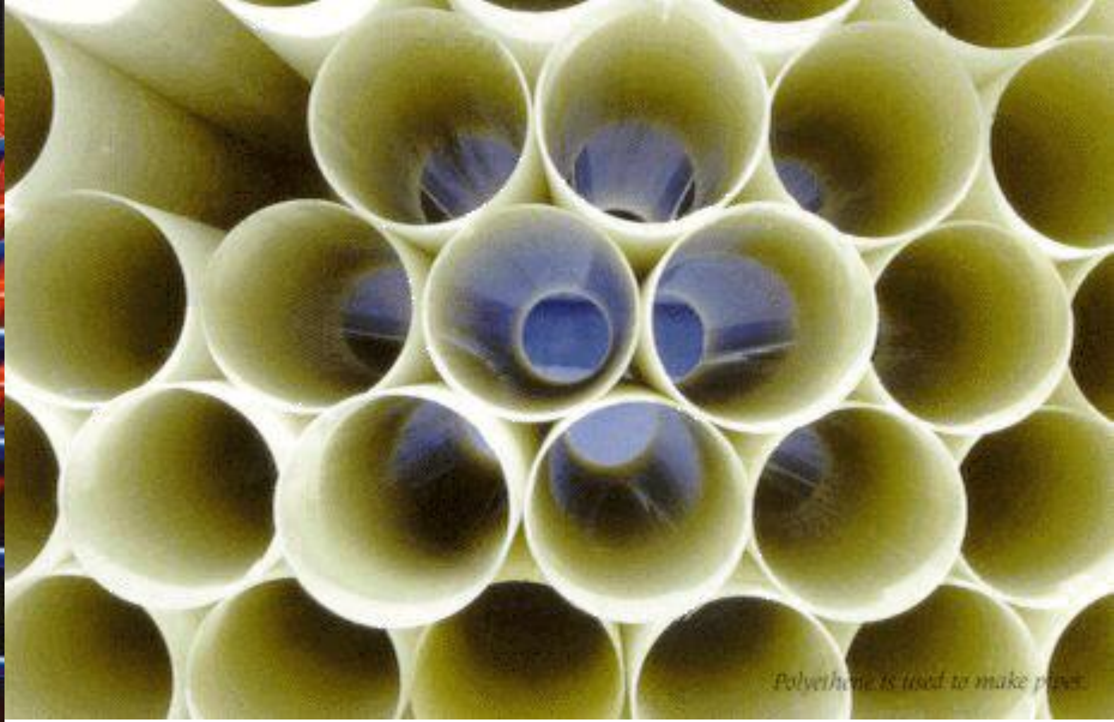
γ shear angle

Neutron scattering is *key* in soft condensed matter

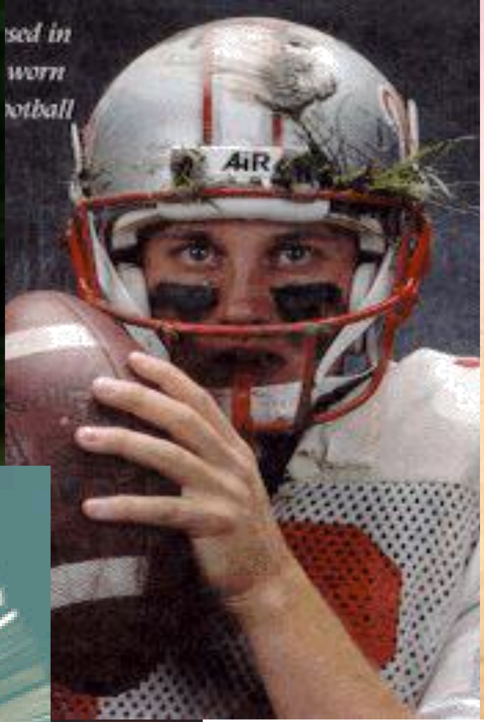


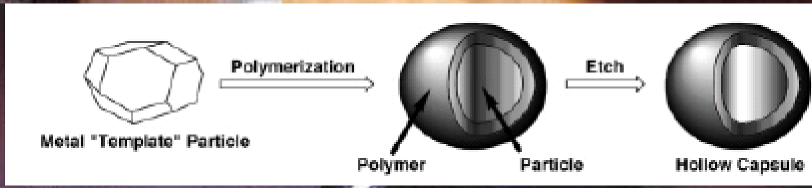
Neutron scattering is *key* in soft condensed matter

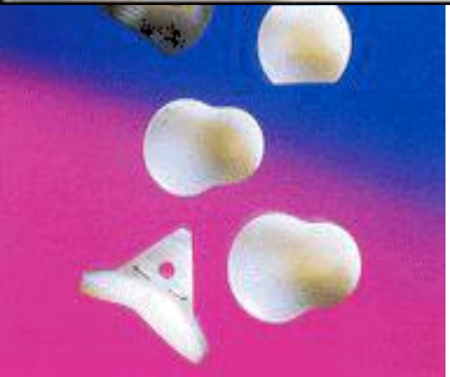




Common soft matter



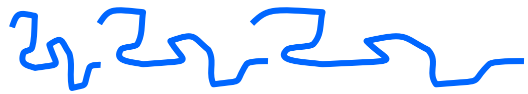




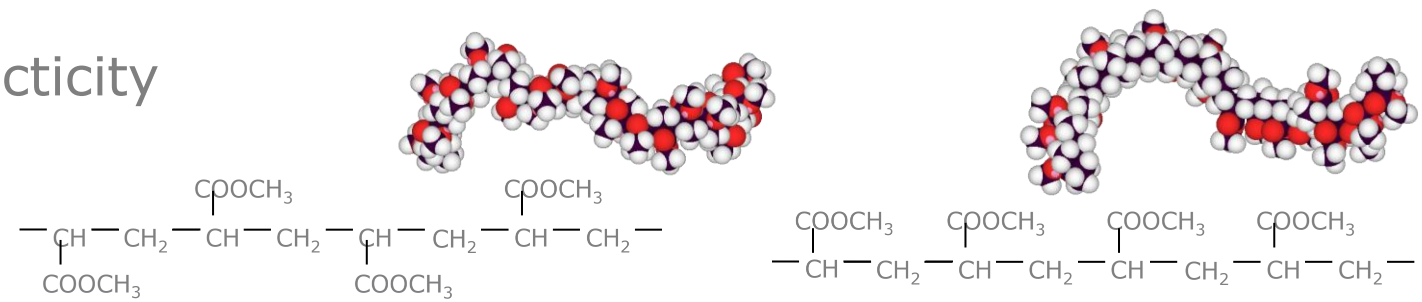
Speciality polymers

Polymer key properties

Molecular weight, N  (size)

Polydispersity  (distribution of sizes)

Tacticity

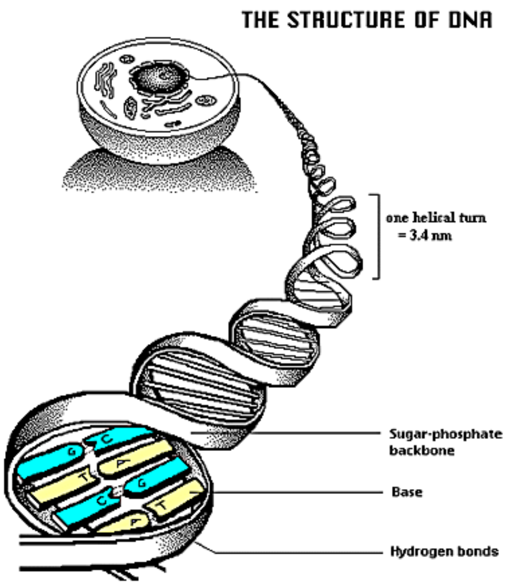


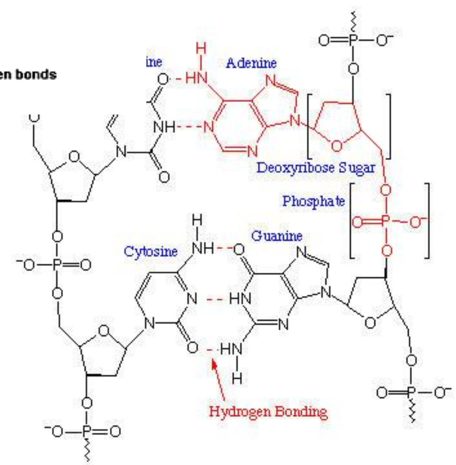
Glass transition (solid-liquid)

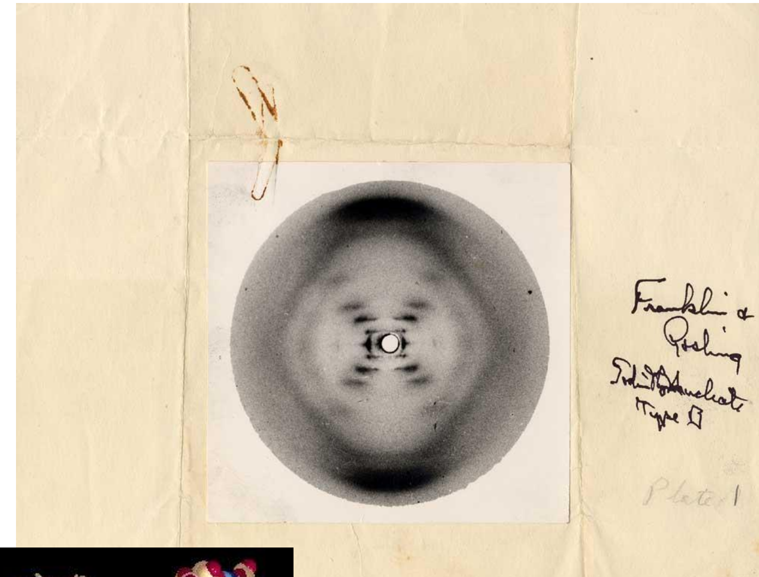
Crystallinity

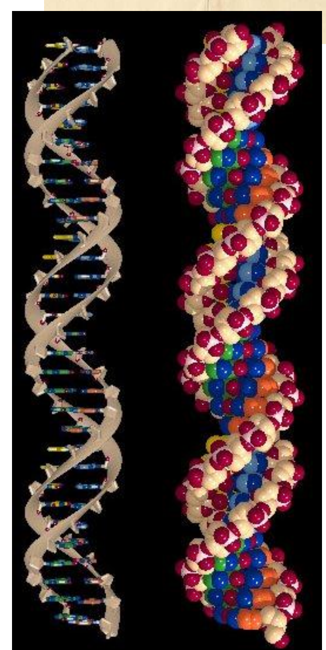
Interaction parameter χ → Combine properties to make new materials!

Soft matter: DNA

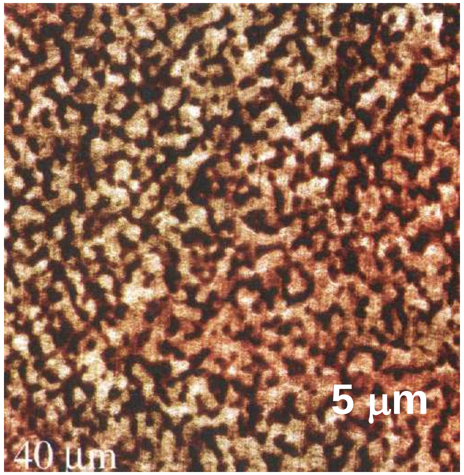




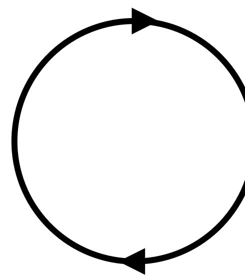


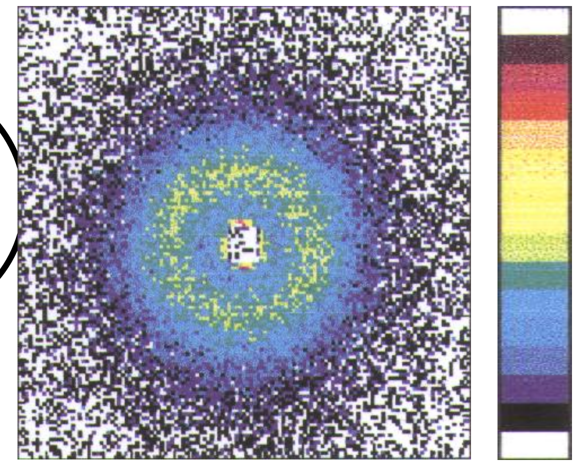


Soft Matter: membranes, photovoltaics (BHJ)

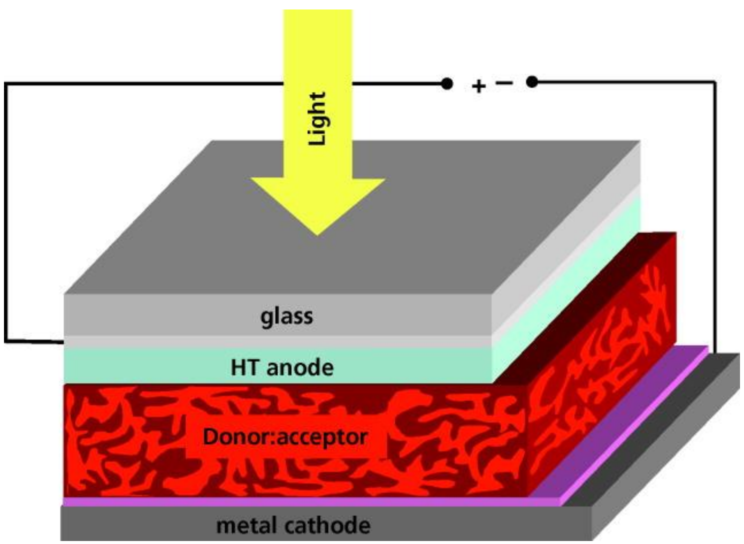


Real space

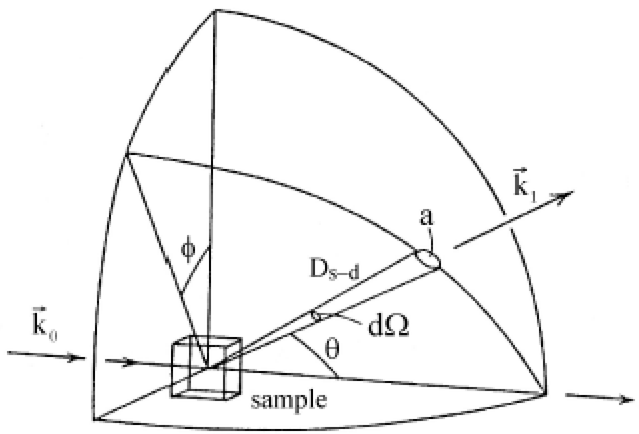




Reciprocal space



Scattering theory reminder



Scattering cross section

$$\frac{d^2\sigma}{d\Omega dE} = \left(\frac{d^2\sigma}{d\Omega dE}\right)_{coh} + \left(\frac{d^2\sigma}{d\Omega dE}\right)_{inc}$$

coherent *incoherent*

$$\left(\frac{d^2\sigma}{d\Omega dE}\right)_{coh} = \frac{1}{2\pi\hbar}\frac{k_1}{k_0}\frac{\sigma_{coh}}{4\pi}\int_{-\infty}^{+\infty}\sum_{i,j}\left\langle e^{-i\mathbf{q}\cdot\mathbf{R}_i(0)}e^{i\mathbf{q}\cdot\mathbf{R}_j(t)}\right\rangle e^{-i\omega t}dt$$

$$\left(\frac{d^2\sigma}{d\Omega dE}\right)_{inc} = \frac{1}{2\pi\hbar}\frac{k_1}{k_0}\frac{\sigma_{inc}}{4\pi}\int_{-\infty}^{+\infty}\sum_{i}\left\langle e^{-i\mathbf{q}\cdot\mathbf{R}_i(0)}e^{i\mathbf{q}\cdot\mathbf{R}_i(t)}\right\rangle e^{-i\omega t}dt$$

Dynamic structure factor

FT (*t*,*ω*)

$$S(\mathbf{q},\omega) = \frac{1}{2\pi\hbar}\int_{-\infty}^{+\infty} I(\mathbf{q},t)e^{-i\omega t}dt.$$

$\int d\omega$

Elastic structure factor

$$\int_{-\infty}^{+\infty} S(\mathbf{q},\omega)|_{\mathbf{q}=Const.}\, d\omega = S(\mathbf{q})$$

Intermediate scattering function

FT (*r*,*q*)

$$I_s(\mathbf{q},t) = \frac{1}{N}\sum_i \left\langle e^{-i\mathbf{q}\cdot\mathbf{R}_i(0)}e^{i\mathbf{q}\cdot\mathbf{R}_i(t)}\right\rangle e^{-i\omega t}.$$

Pair correlation function

$$G(\mathbf{r},t) = \frac{1}{(2\pi)^3}\int I(\mathbf{q},t)e^{-i\mathbf{q}\cdot\mathbf{r}}d\mathbf{q}.$$

S(q)

$$S(q) = Nz^2P(q) + N^2z^2Q(q)$$

Form factor

$$P(q) = \frac{1}{z^2}\sum_{i=1}^{z}\sum_{j=1}^{z}\langle e^{-i\mathbf{q}\cdot\mathbf{r}_{ij}}\rangle$$

Structure factor

$$Q(q) = \frac{1}{z^2}\sum_{i_p=1}^{z}\sum_{j_q=1}^{z}\langle e^{-i\mathbf{q}\cdot\mathbf{r}_{i_p j_q}}\rangle$$

Reminder: Fourier Transforms

$$H(f) = \int_{-\infty}^{\infty} h(t)\, e^{2\pi i f t}\, dt$$

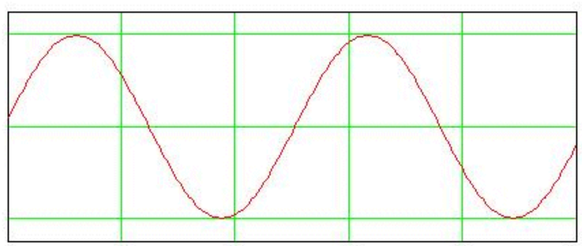
$$h(t) = \int_{-\infty} H(t)\, e^{-2\pi i f t}\, df$$

Fourier transform:

$\Phi(H(f),t) = h(t)$

$\Phi^{-1}(h(t),f) = H(f)$

h(t)

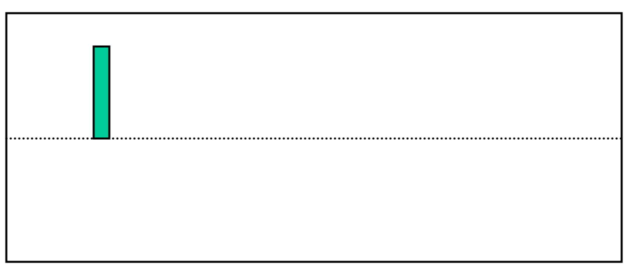


t

$$h(t) = Ae^{i(t+\phi)}$$

$$H(f) = \int_{-\infty}^{\infty} h(t)\, e^{2\pi i f t}\, dt$$

H(f)



f

$H(f) = 0$ if $(ft \neq 1)$

$H(f) = A\, e^{i\phi}$ if $(ft = 1)$

Reminder: Fourier Transforms

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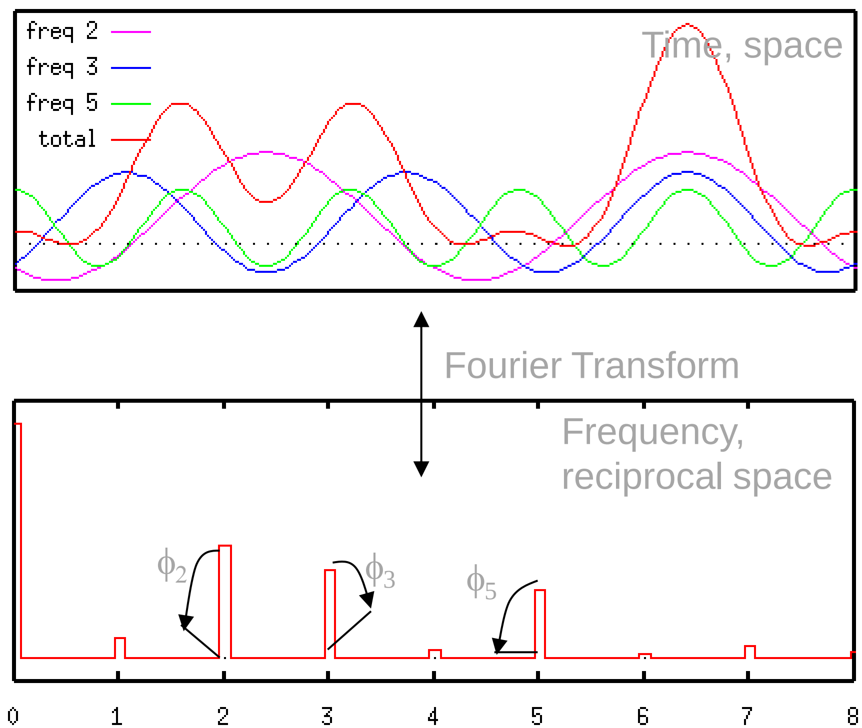
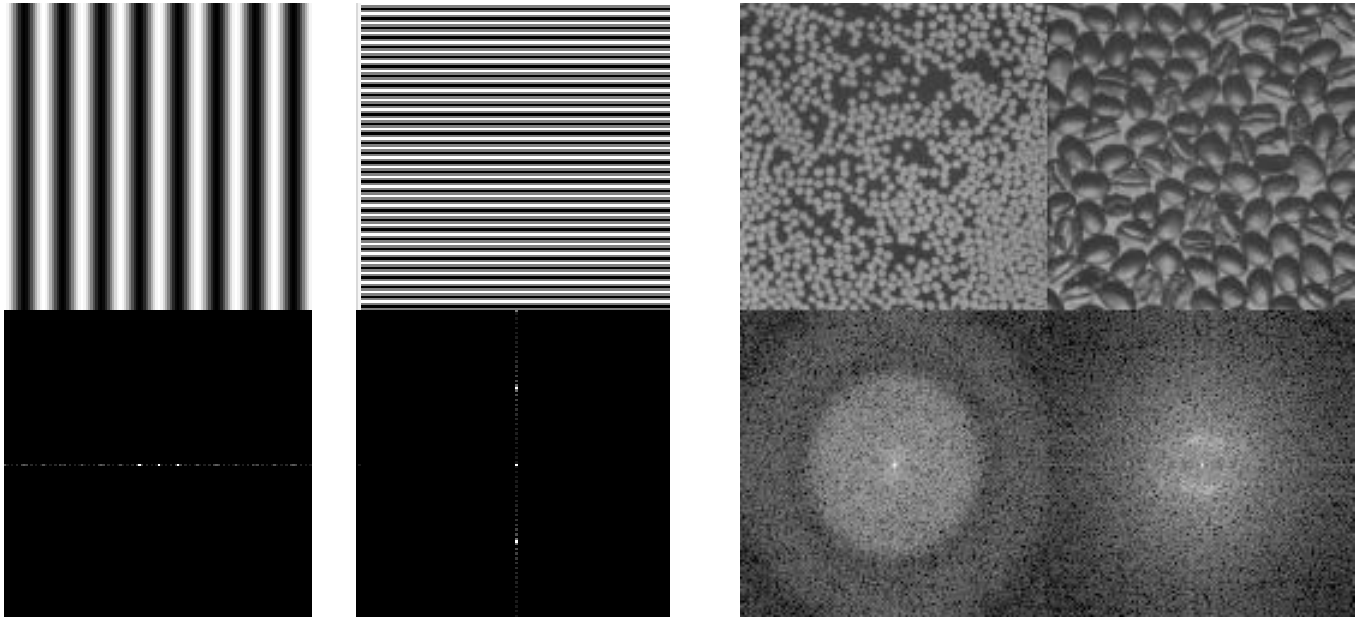


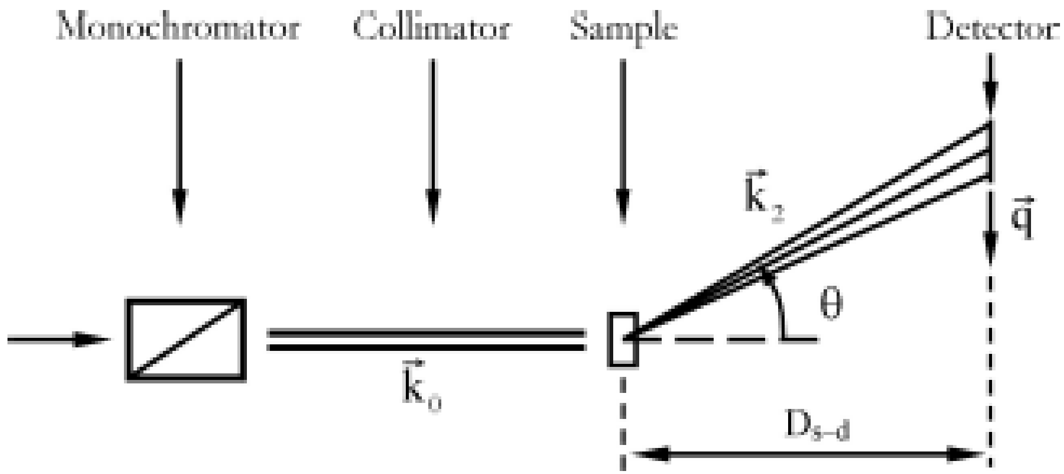
Reminder: Fourier Transforms

Real space



Reciprocal space

SMALL-ANGLE NEUTRON SCATTERING



$$q = \frac{4\pi}{\lambda}\sin\left(\frac{\theta}{2}\right)$$

$$q \approx \frac{2\pi}{\lambda}\theta$$

$$q \approx \frac{2\pi}{\lambda}\frac{R}{D_{s-d}}$$

Absolute scattering intensity [cm^{-1}]

$$\frac{\partial\sigma}{\partial\Omega}(Q) = N_p\, V_p^2\, (\Delta\delta)^2\, P(Q)\, S(Q) + B_{inc}$$

incoherent background

structure factor

volume

form factor

number density

contrast

Scattering length density

$$\delta = \sum_i b_i \cdot \frac{D\, N_A}{M_w}$$

Relationship between *q* *λ* *θ* and *d*

$$q = \frac{4\pi}{\lambda}\sin(\theta/2)$$

$$d = \frac{2\pi}{q}$$

small q ~ large d [large q ~ small d]

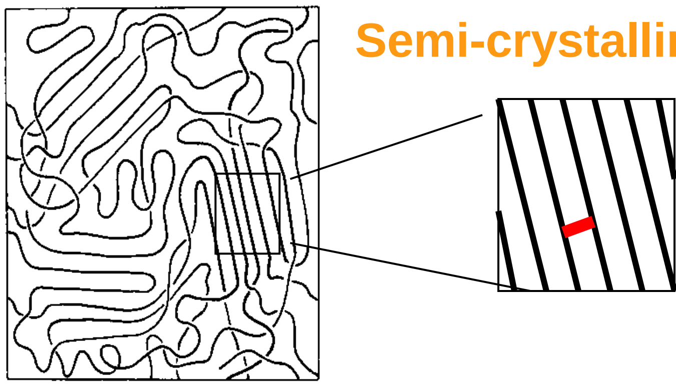
small λ ~ large q ~ small d
[large λ ~ small q ~ large d]

Radiation	Wavelength
light	~ 500 nm
X-rays	~ 1 Å
neutrons	~ 5 Å

Ångstrom:
1 Å = 10^{-10} m
1 nm = 10 Å

Bottom line:
radiation of small wavelength λ can 'see' smaller sample features d (provided that contrast is sufficient).

Example: crystalline structure of polymer



Semi-crystalline poly(ethylene) PE

lamella spacing is **d ~ 20 nm**

$q = 2\pi/d \sim 0.3\ nm^{-1}$

$$q = \frac{4\pi}{\lambda}\sin(\theta/2)$$

Radiation	Wavelength	Scattering angle
X-rays	~ 1 Å	$\theta \sim 0.27$ degrees
neutrons	~ 5 Å	$\sin(\theta/2) \sim 0.013$, $\theta \sim 0.7$ degrees
light	~ 500 nm	$\sin(\theta/2) > 1$ **impossible!**

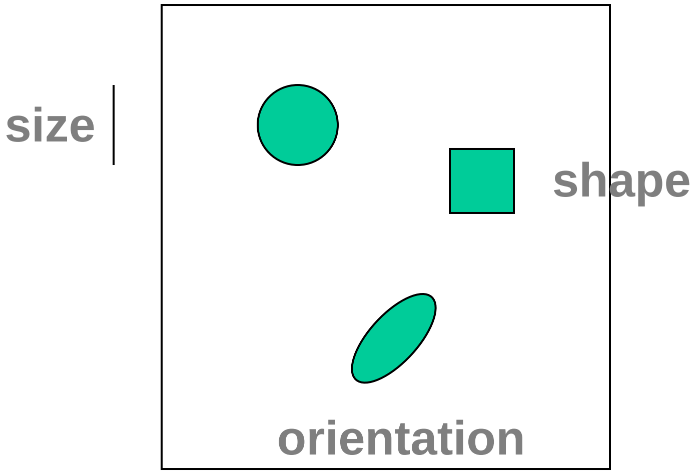
the smallest dimension probed by wavelength λ corresponds to largest angle θ=180 degrees (backscattering). For light d_{min}~ 0.25 μm, for X-rays or neutrons d_{min}~ 0.5 to 2.5 Å.

In typical experiments, scattering angles range from $0.1 < \theta < 70$ degrees

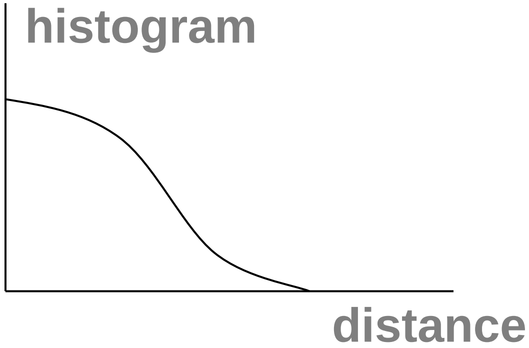
Form factor: P

Self-correlations

Form factor *P*



‘sample’

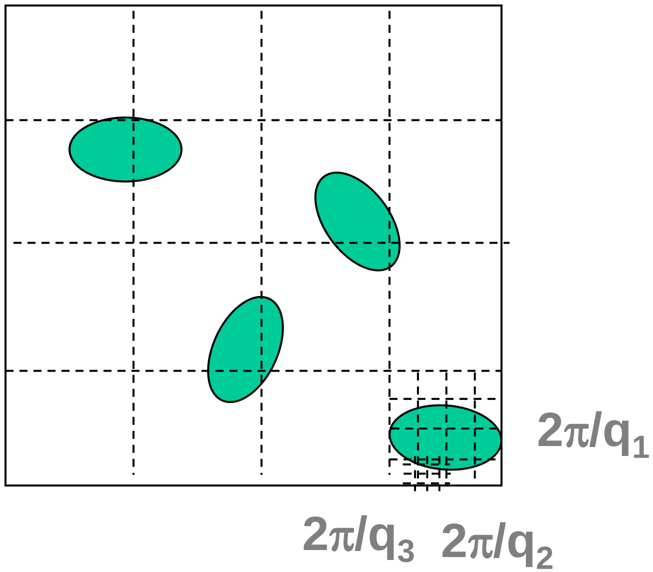


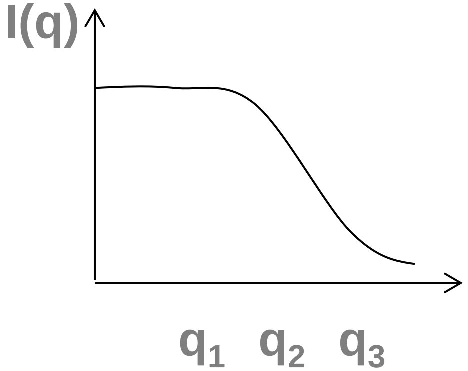
$$P(Q) = \frac{1}{V_p^2} \left| \int_0^{V_p} \exp\left[i \, f(Q\,\alpha)\right] \, dV_p \right|$$

Interference between scattered radiation from different parts of the same object

(analytical solutions for common shapes)

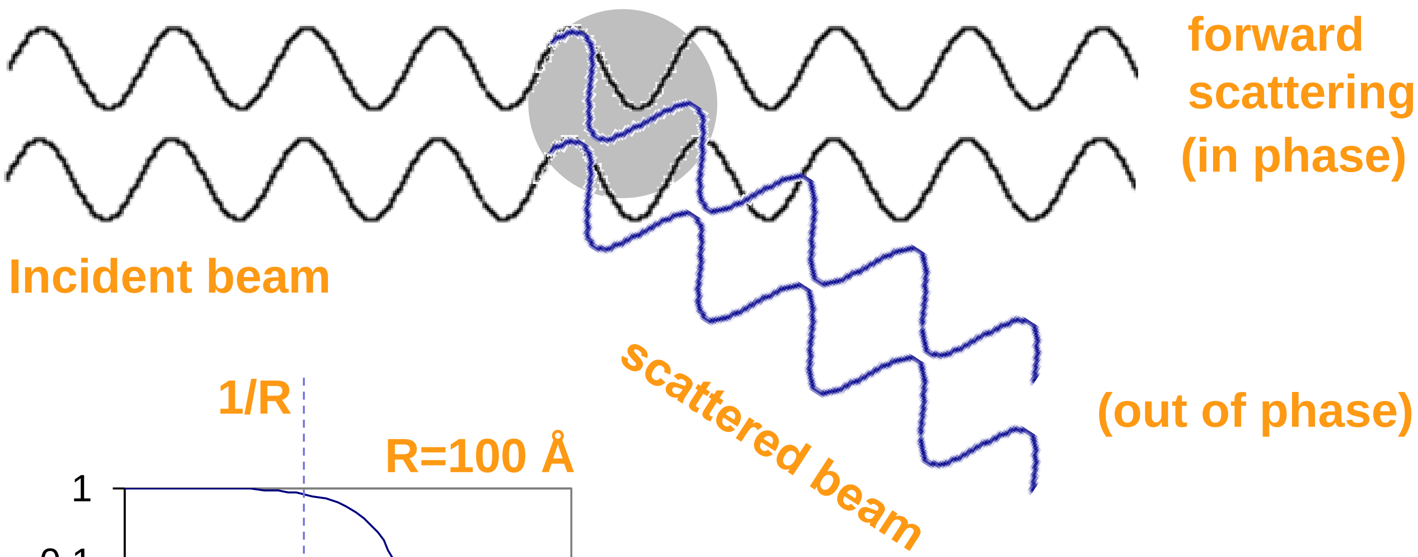
Multiple lengthscales

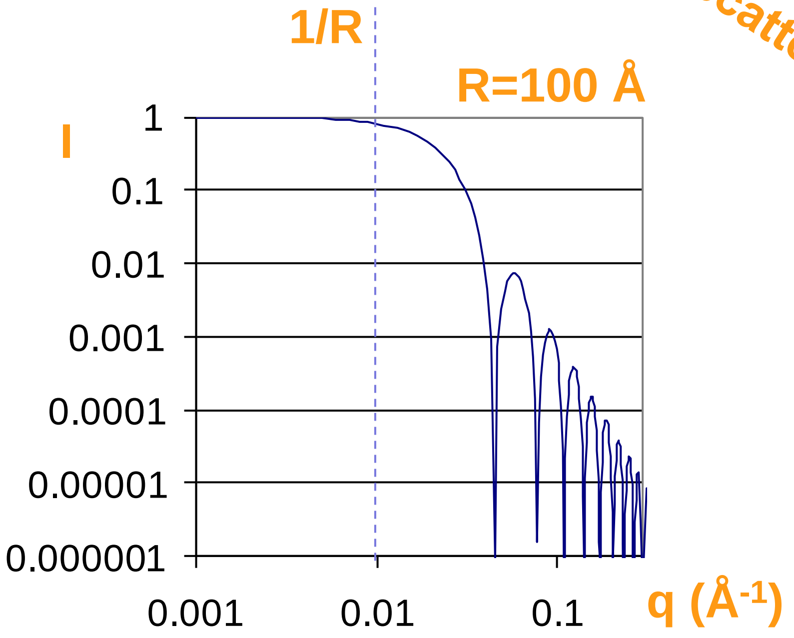




scattering spectrum corresponds to different "magnifications", thus several approximations may be relevant

Scattering from a sphere

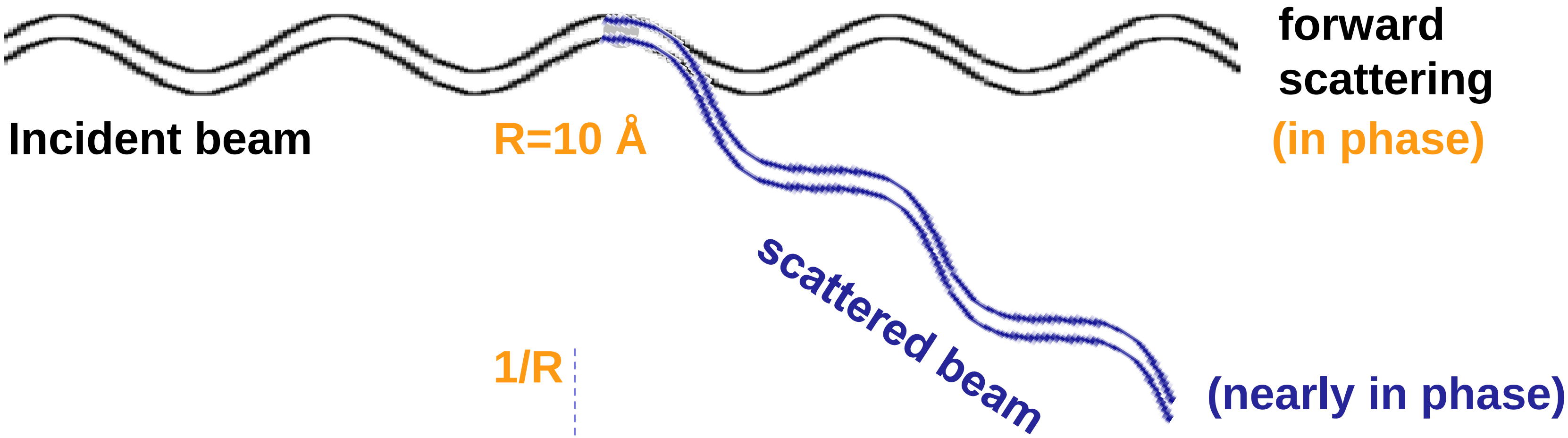


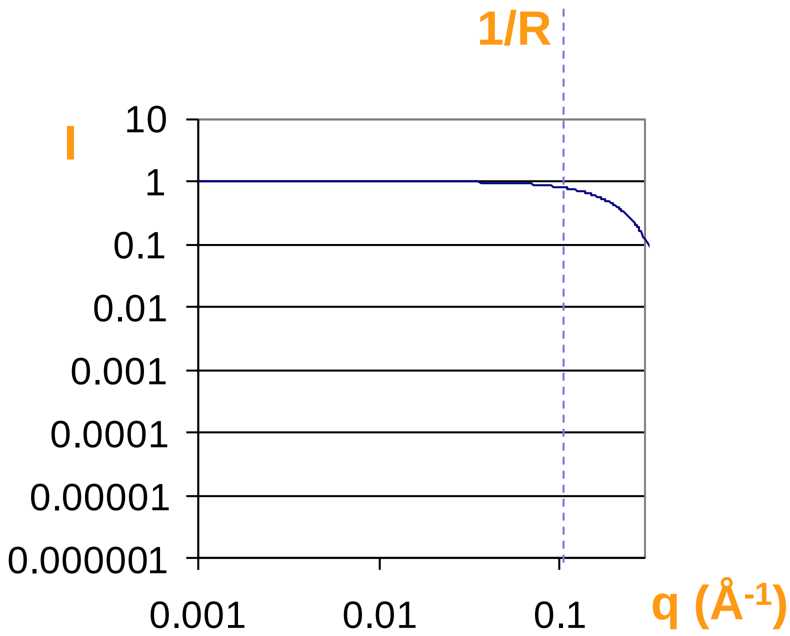


$$P(q) = \frac{9\left(\sin qR - qR\cos qR\right)^2}{\left(qR\right)^6}$$

$$R_g^2 = \frac{3}{5}r^2$$

Scattering from a (tiny) sphere





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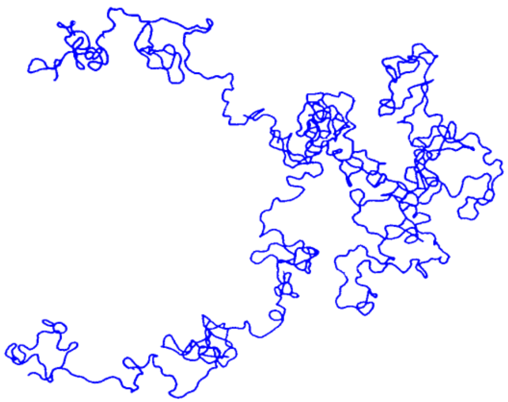
Scattering from a random coil



Debye form factor

$$g_D(x) = \frac{2}{x^2}\left(x - 1 + e^{-x}\right)$$

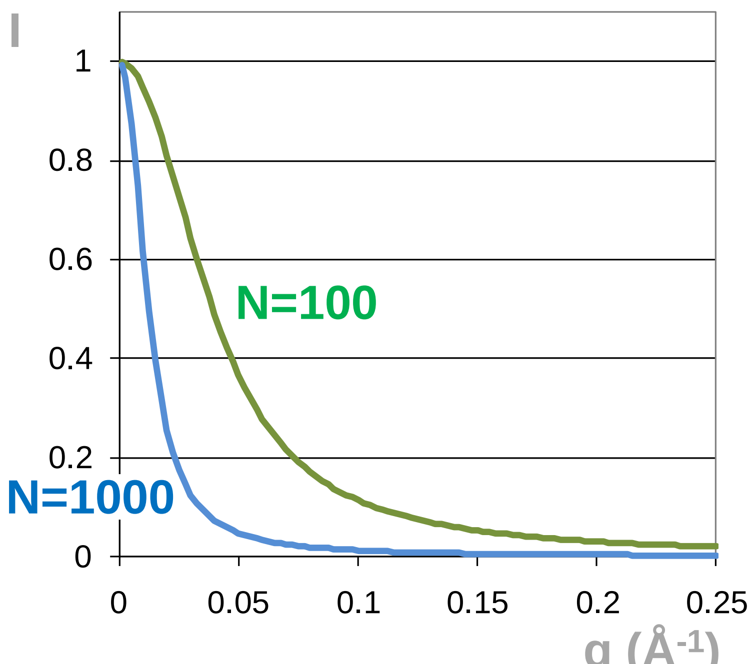
$$x \equiv q^2 R_g^2$$

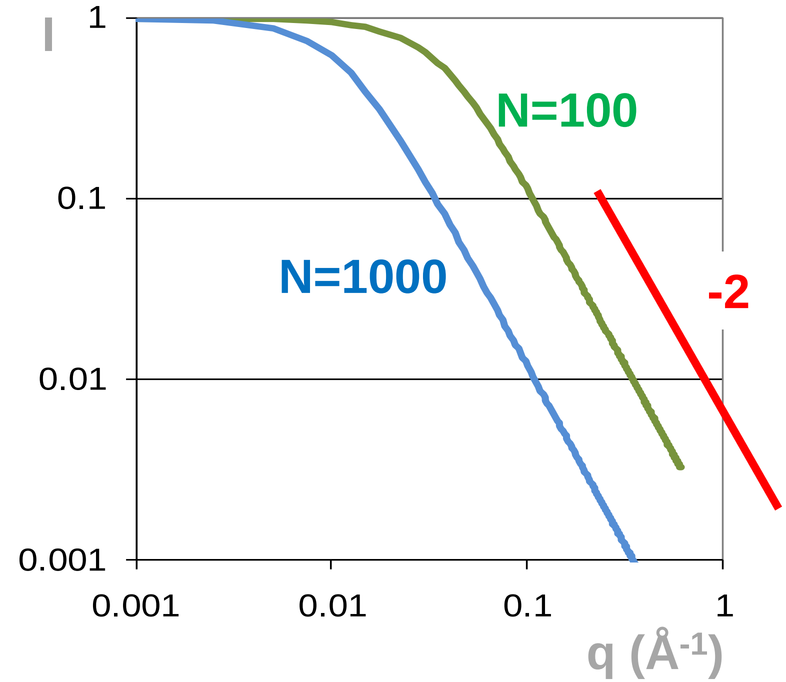
$$R_g^2 = \frac{Na^2}{6}$$

a=10 Å

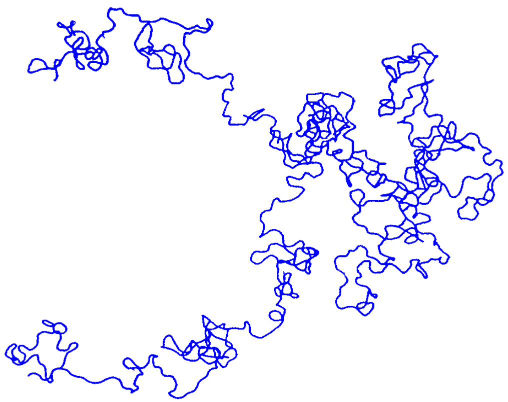
N=100 → Rg≈4nm

N=1000 → Rg≈13nm





Scattering from a random coil



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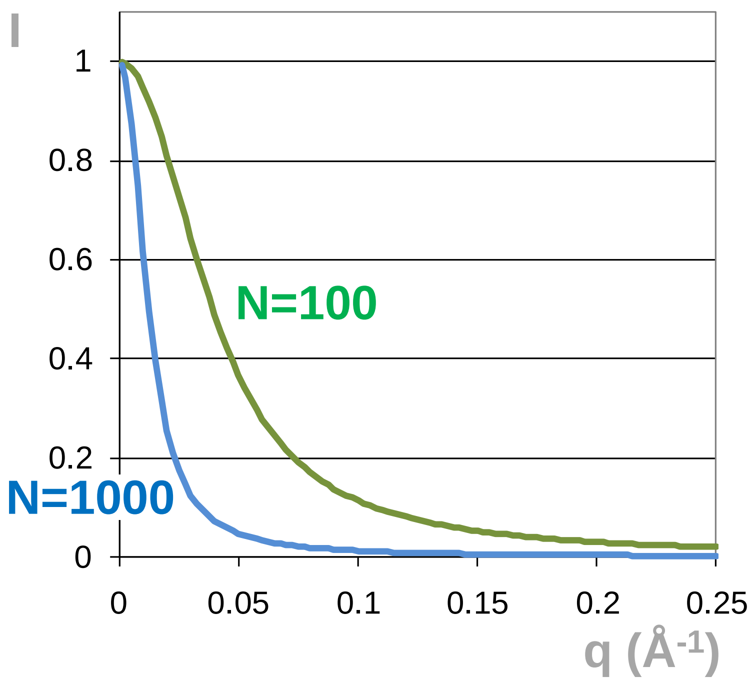
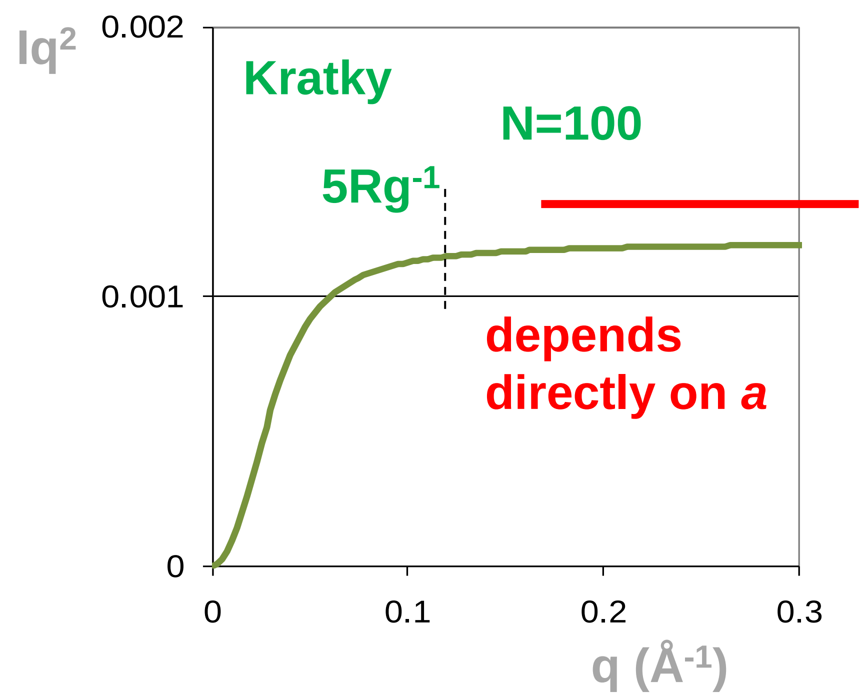
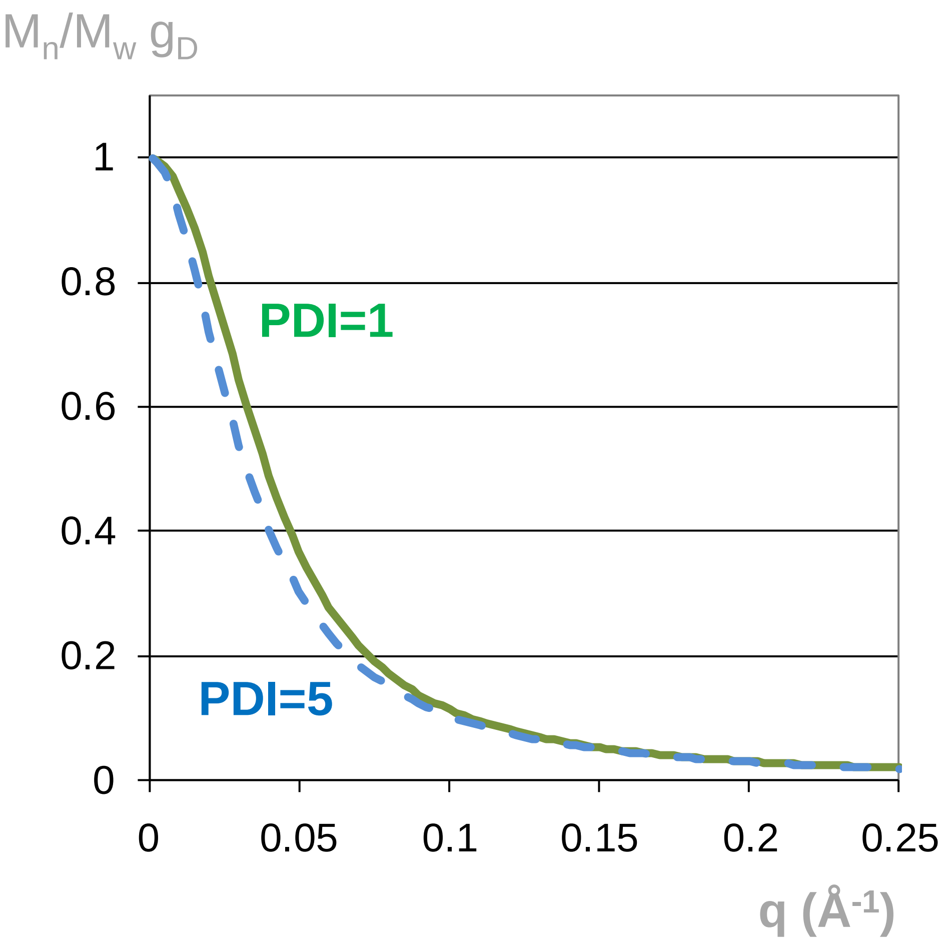




Polydisperse random coils



Polydisperse debye form factor

$$g_D(x) = \frac{2}{(1+1/h)x^2}\left[\left(1+\frac{x}{h}\right)^{-h} - 1 + x\right]$$

$$x \equiv q^2\langle R_g^2\rangle_n \equiv \frac{q^2\langle R_g^2\rangle_z}{1+2/h}$$

$$h = \left(\frac{M_w}{M_n} - 1\right)^{-1}$$

(normalised to PDI)

a=10 Å

N=100 → Rg≈4nm

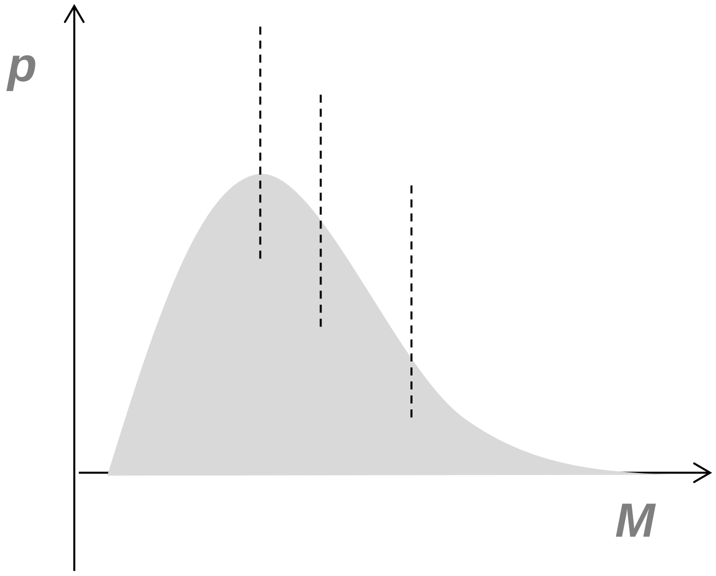
N_w=100, N_w/N_n=5

A polydispersity model

(Schultz-Zimm)

$$p(M) = \frac{h^h}{\Gamma(h)}\left(\frac{M}{M_n}\right)^h e^{-h\left(\frac{M}{M_n}\right)}$$

$$h = \left(\frac{M_w}{M_n} - 1\right)^{-1}$$

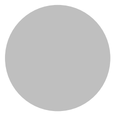


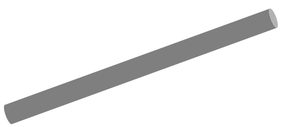
Number average $M_n = \int p(M) M\, dM$

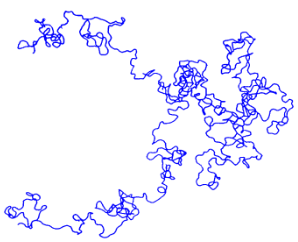
Weight average $M_w = \frac{\int p(M) M^2 dM}{\int p(M) M\, dM} \equiv \frac{\langle M \rangle_2}{\langle M \rangle_1}$

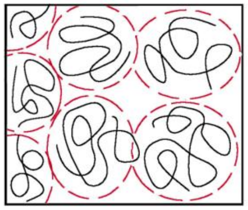
$\mathrm{z} -$ average $M_z = \frac{\int p(M) M^3 dM}{\int p(M) M^2 dM} \equiv \frac{\langle M \rangle_3}{\langle M \rangle_2}$

Useful form factors







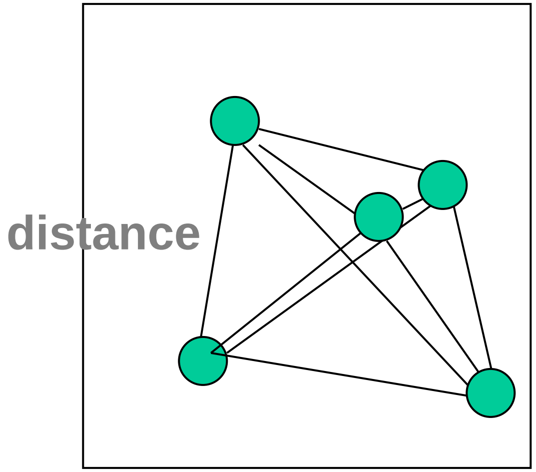


Sphere of radius R_p	$P(Q) = \left[\frac{3\,(\,Sin\,(QR_p) - QR_p\;Cos\,(QR_p)\,)}{(QR_p)^3}\right]^2$
Disc of negligible thickness and radius R_p (J_1 is a first-order Bessel function)	$P(Q) = \frac{2}{(QR_p)^2}\left[1 - \frac{J_1(2QR_p)}{QR_p}\right]$
Rod of negligible cross-section and length L (S_i is the Sine integral function)	$P(Q) = \frac{2S_i(QL)}{QL} - \frac{Sin^2\,(QL/2)}{(QL/2)}$
Gaussian random coil with z-average radius of gyration R_g, polydispersity $(Y+1)$ and $U = \frac{(QR_g)^2}{(1+2Y)}$	$P(Q) = \frac{2\left[(1+UY)^{-1/Y} + U - 1\right]}{(1+Y)\,U^2}$
Concentrated polymer solution with screening length x where $\xi = R_g\left(\frac{\phi}{\phi^*}\right)^{\frac{\nu}{(1-3\nu)}}$	$P(Q) = P(0)\left[\frac{1}{1+(Q\xi)^2}\right]$

S King

http://www.ncnr.nist.gov/resources/

Structure factor: S

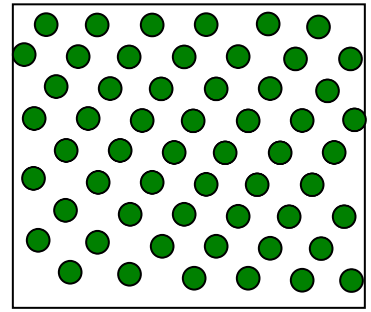


Interference between radiation scattered by distinct objects

$$S(Q) = 1 + \frac{4\pi N_p}{QV} \int_0^\infty [g(r) - 1]\, r \,\mathrm{Sin}\,(Qr)\, dr$$

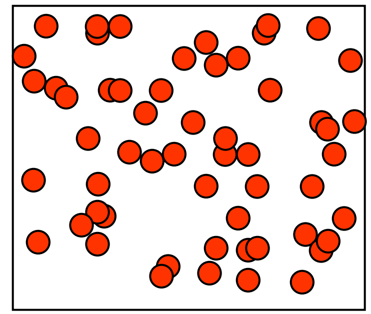
$$G(r) = \frac{4\pi N_p r^2}{V} g(r)$$

Radial distribution function, provides information about their relative position

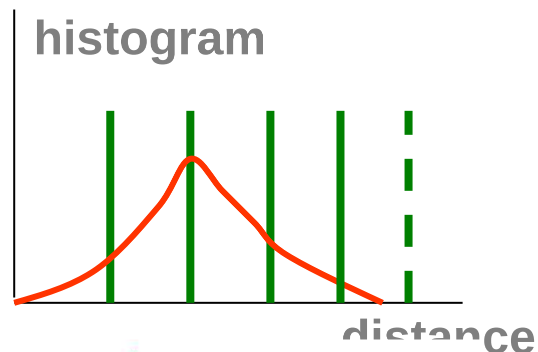


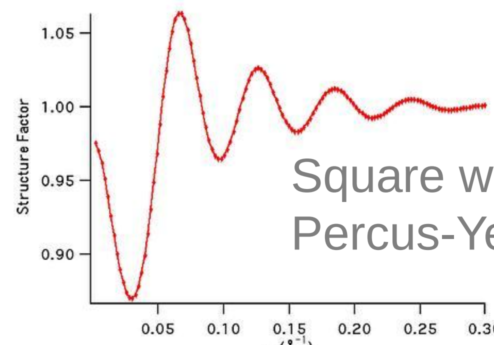
Ordered structure

'crystal'



Disordered structure

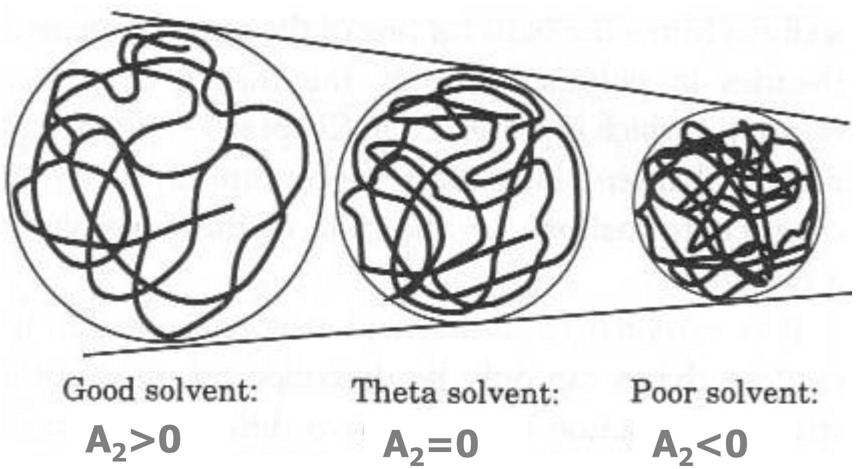


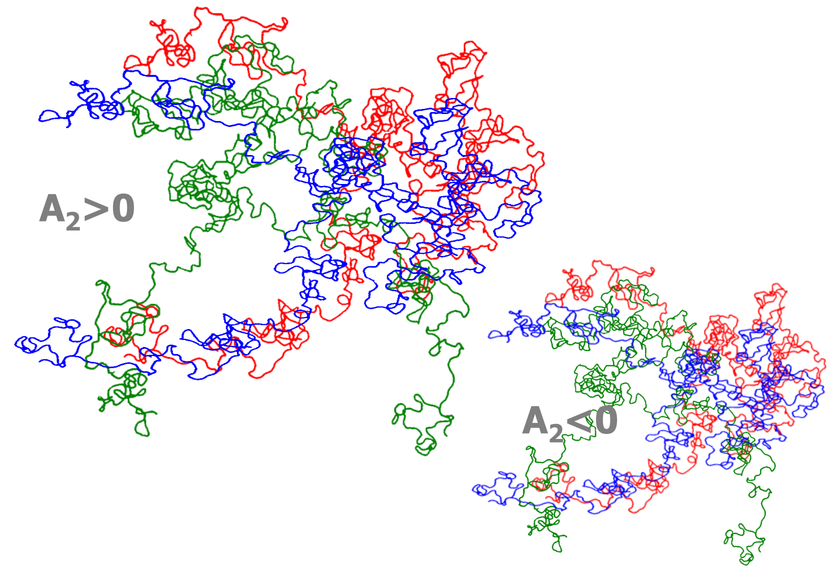


Square well, Percus-Yevick...

Interactions: Polymers in solution and melt

<u>1953</u> Flory described the shape and size of individual polymer molecules in solutions and melts.



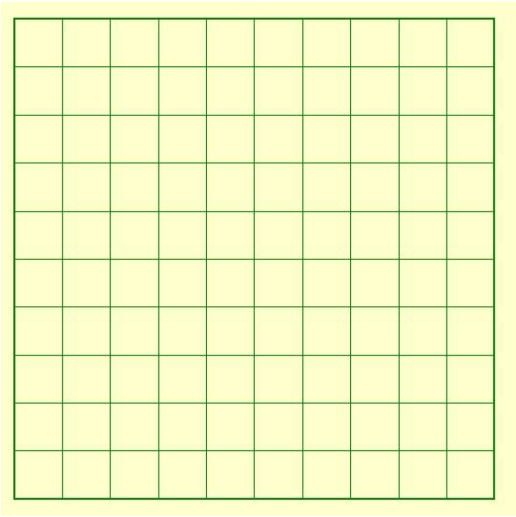


Ideal chains occur in θ-solutions (ie, neutral solvent, $A_2=0$) or in melt. Chains expand or contract depending on interactions: A_2 (Second Virial coeff, for solutions) or χ (for polymer mixtures)

Polymer miscibility (1)

Thermodynamics $\Delta G_m = \Delta H_m - T\Delta S_m$

Flory-Huggins
lattice



Binary mixture

Combinatorial entropy

$$-\frac{\Delta S}{R} = n_A \ln \phi_A + n_B \ln \phi_B$$

Ω Boltzmann law

Enthalpy $\Delta H_m = K_B T \phi_A \phi_B \chi_{AB}$

$$\frac{\Delta G_m}{K_B T} = \frac{\phi_A}{N_A} \ln \phi_A + \frac{\phi_B}{N_B} \ln \phi_B + \phi_A \phi_B \chi_{AB}$$

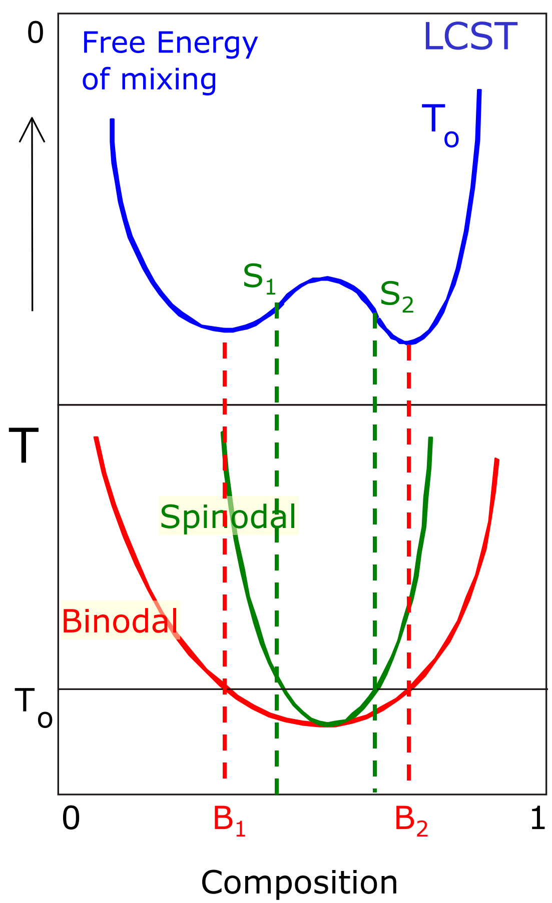
Combinatorial entropy

Enthalpy

$\chi < 0$ mixing occurs $\forall T, \phi$

$\chi > 0$ $\Delta G_m = \Delta H_m - T\Delta S_m$ only at high T

Polymer miscibility (2)



Thermodynamics $\Delta G_m = \Delta H_m - T\Delta S_m$

$$\frac{\Delta G_m}{k_B T} = \frac{\phi}{v_A N_A}\ln\phi + \frac{(1-\phi)}{v_B N_B}\ln(1-\phi) + \frac{\phi(1-\phi)}{v}\chi$$

Combinatorial entropy

Enthalpy

Phase boundaries?

Binodal

$$\begin{cases} \dfrac{\partial \Delta G_m}{\partial \phi_{B1}} = \dfrac{\partial \Delta G_m}{\partial \phi_{B2}} \equiv \mu \\ \Delta G_m(\phi_{B1}) + \Delta G_m(\phi_{B2}) = \min \end{cases}$$

'minima'

Spinodal

$$\frac{\partial^2 \Delta G_m}{\partial \phi^2} = 0$$

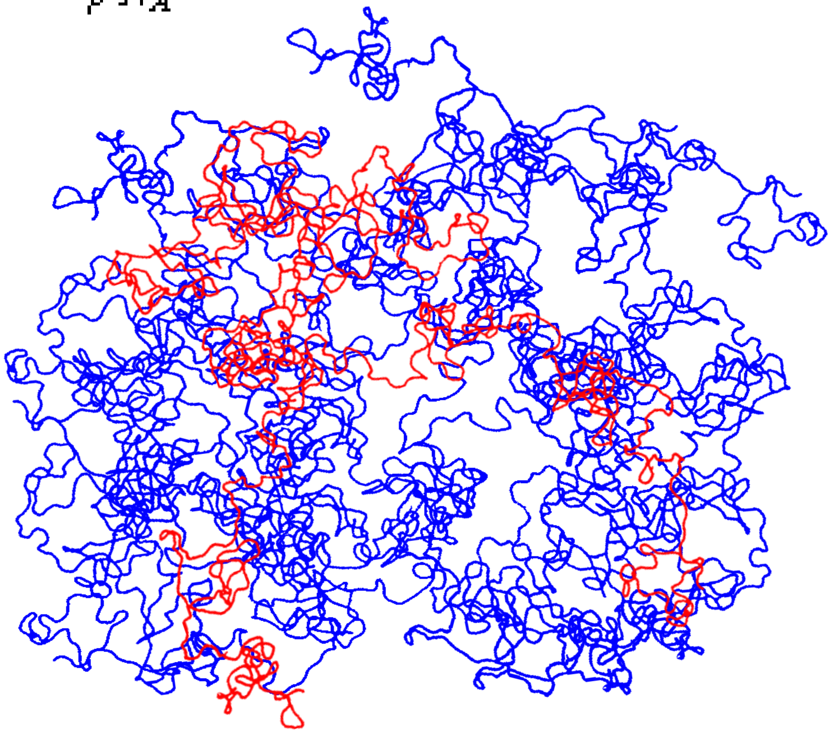
inflection points

Isotopic polymer mixture

$$\frac{\partial\sigma}{\partial\Omega}(q) = (b_D - b_H)^2 S_{DD}(q) = (b_D - b_H)^2\, \phi(1-\phi) N z^2 P(q)$$

$$\left.\frac{1}{V}\,\frac{d\sigma}{d\Omega}(q)\right|_{cm^{-1}} = (b_D - b_H)^2\, \phi(1-\phi)\, \langle M\rangle_w\, \frac{\rho\, N_A}{m^2}\, P(q)$$

$$= (b_D - b_H)^2\, \phi(1-\phi)\, \langle M\rangle_w\, \frac{(\Delta\varrho)^2}{\rho\, N_A}\, P(q)$$



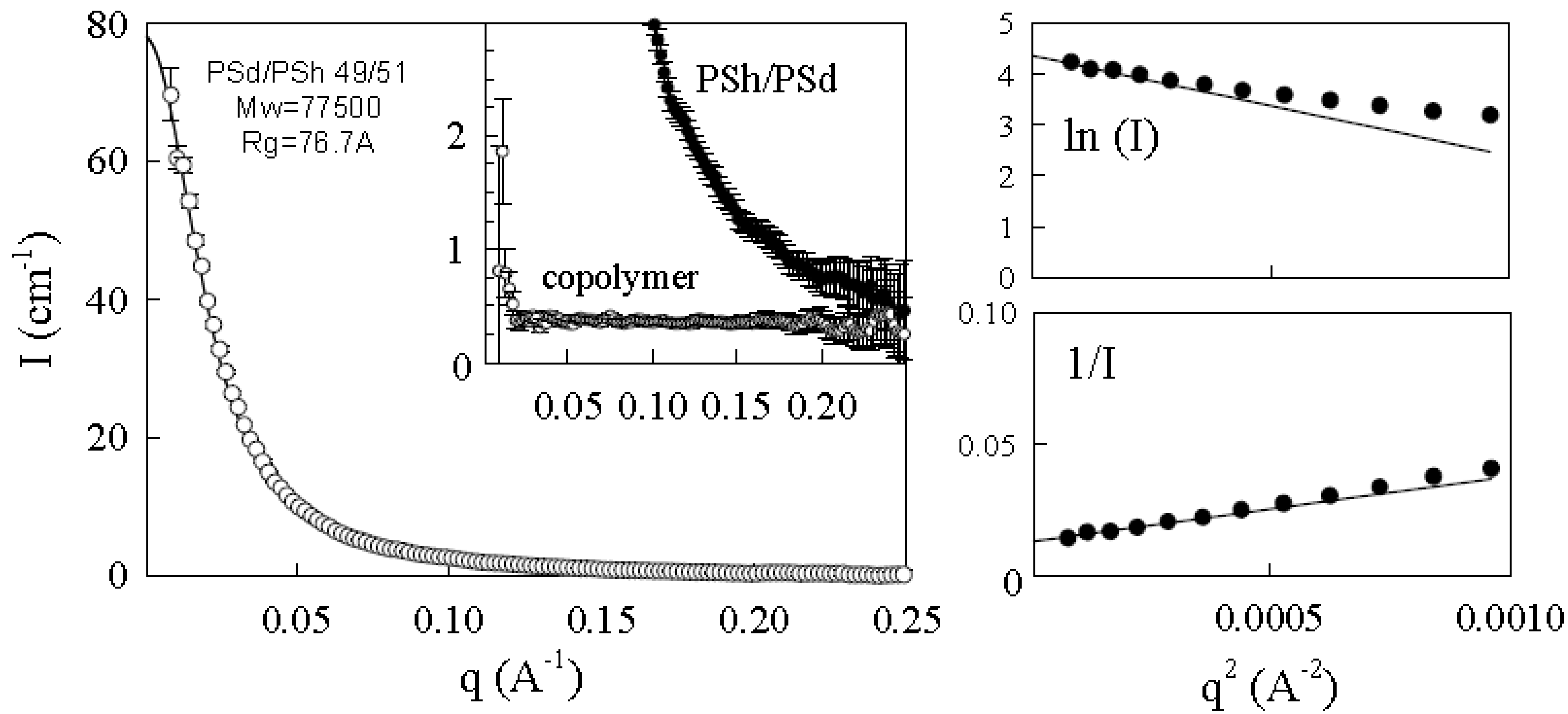
Approximations: Guinier & Zimm

$$\text{Guinier}: \quad \frac{d\Sigma(q)}{d\Omega} \approx \frac{d\Sigma(0)}{d\Omega} \left(-\frac{(qR_g)^2}{3}\right)$$

$$\text{Zimm}: \quad \left[\frac{d\Sigma(q)}{d\Omega}\right]^{-1} \approx \left[\frac{d\Sigma(0)}{d\Omega}\right]^{-1} \left[1 + \frac{(qR_g)^2}{3}\right]$$

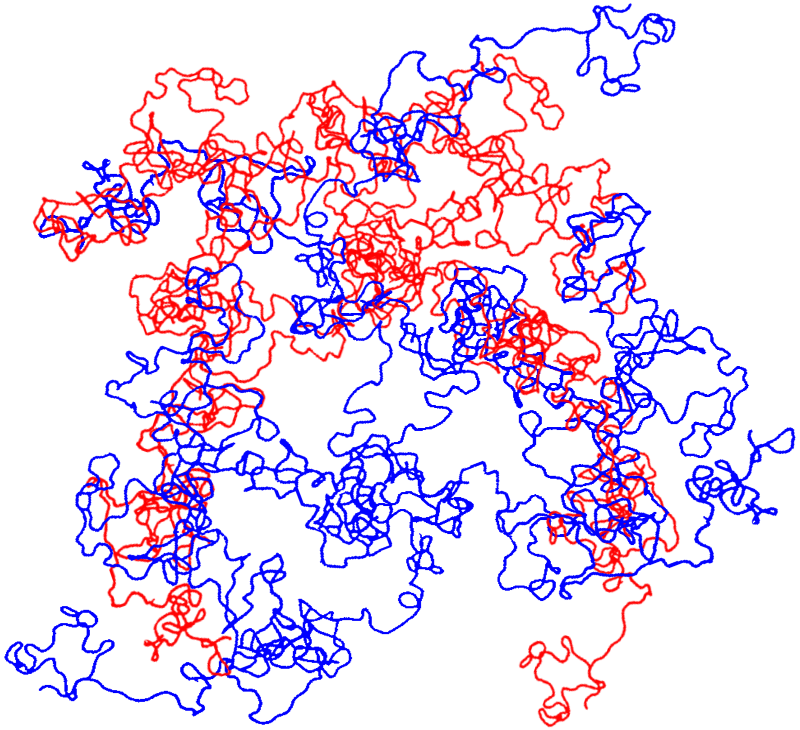
where $$\frac{d\Sigma(0)}{d\Omega} = \frac{\phi(1-\phi)\ M_w\ (\Delta\varrho)^2}{N_A\ \rho}$$

for a polymer coil



Interacting polymer mixtures

$$\frac{1}{V}\frac{d\sigma}{d\Omega}(q)\bigg|_{cm^{-1}} = N_A\left(\frac{b_1}{v_1}-\frac{b_2}{v_2}\right)^2 S(q)$$



$$\frac{1}{S(q)} = \frac{1}{S_1(q)}+\frac{1}{S_2(q)} - 2\frac{\tilde{\chi}_{12}}{v_0}$$

$$S_i(q) = \phi_i\, v_i\, \langle N_i\rangle_n\, \langle g_D(R_{gi}^2 q^2)\rangle_w$$

Zimm $$S_i(q) \approx \phi_i\, v_i\, \langle N_i\rangle_w \left(1-\frac{1}{3}\langle R_{gi}^2\rangle_z q^2\right)$$

$$\frac{1}{S(q)} = \frac{1}{S(0)}\left[1+\frac{1}{3}R_{app}^2 q^2\right]$$

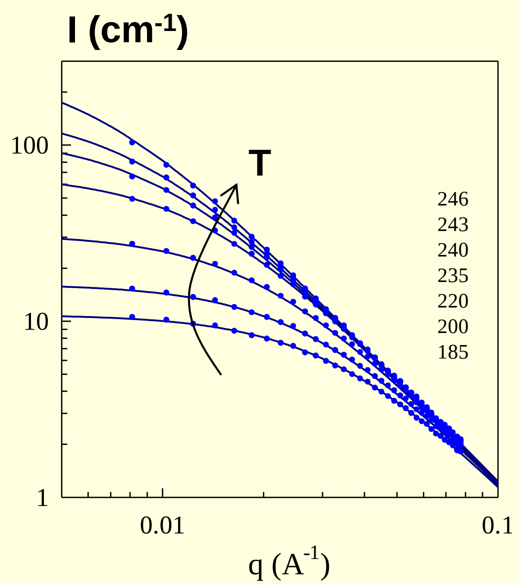
where $$R_{app}^2 = \left(\frac{\langle R_{g1}^2\rangle_z}{\phi_1 v_1\langle N_1\rangle_w}+\frac{\langle R_{g2}^2\rangle_z}{\phi_2 v_2\langle N_2\rangle_w}\right)S(0)$$

$$\frac{1}{S(0)} = \frac{1}{\phi_1 v_1\langle N_1\rangle_w}+\frac{1}{\phi_2 v_2\langle N_2\rangle_w} - 2\frac{\tilde{\chi}_{12}}{v_0}$$

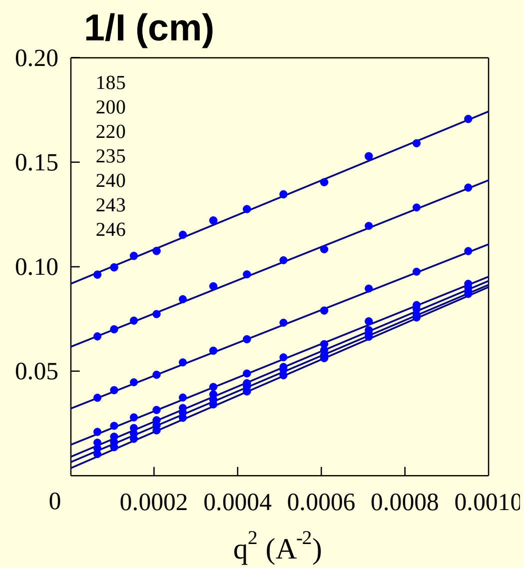
Equilibrium: SANS

TMPC/PSd 50/50

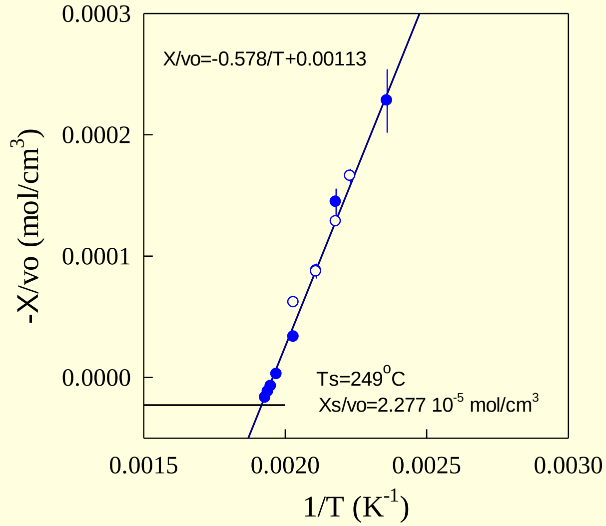
1-phase scattering



Orstein-Zernike



Interaction χFH



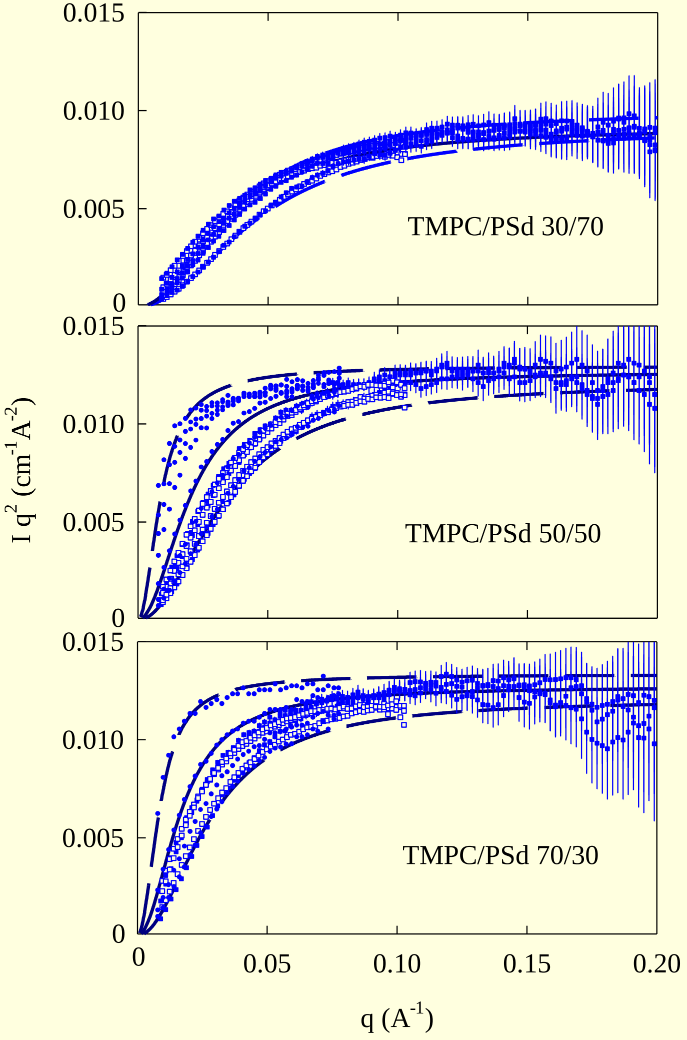
Random Phase Approximation

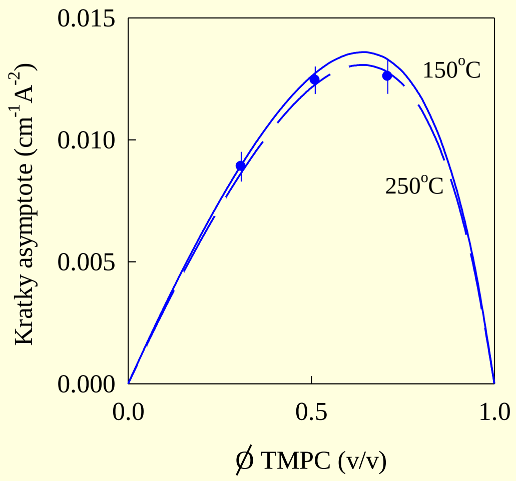
$$\frac{1}{S_{AB}(q)} = \frac{1}{\phi_A v_A \langle N_A \rangle_n \langle g_D(q)_A \rangle_w} + \frac{1}{\phi_B v_B \langle N_B \rangle_n \langle g_D(q)_B \rangle_w} - 2\frac{\tilde{\chi}_{AB}}{v_o}$$

$$\frac{1}{S(q)} = 2(\chi_S - \chi_F) + \frac{\xi^2}{S(0)} q^2$$

$$\xi^2 = \frac{v_0}{36(\tilde{\chi}_S - \tilde{\chi}_{AB})} \left(\frac{\langle N_A \rangle_z}{\langle N_A \rangle_w} \frac{a_A{}^2}{\phi_A v_A} + \frac{\langle N_B \rangle_z}{\langle N_B \rangle_w} \frac{a_B{}^2}{\phi_B v_B} \right)$$

Equilibrium: Kratky asymptote



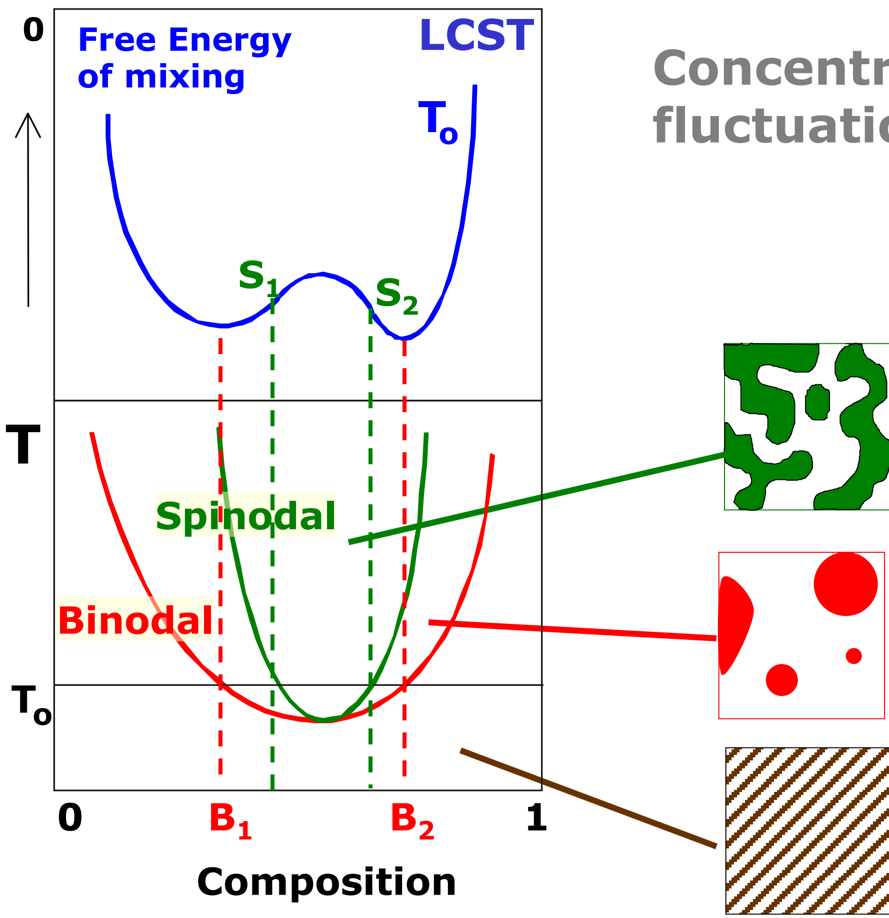


Kratky asymptote and segment length

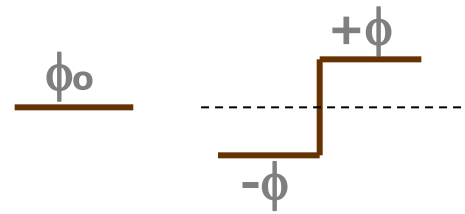
$$S(q) \approx \frac{12\phi_1\phi_2}{q^2}\frac{v_o}{\hat{a}^2}$$

$$\frac{\hat{a}^2}{v_0} \equiv \phi 1 \phi 2\left(\frac{a_1{}^2}{\phi_1 v_1} + \frac{a_2{}^2}{\phi_2 v_2}\right)$$

Non-equilibrium: Fluctuations & Phase separation



Concentration fluctuations

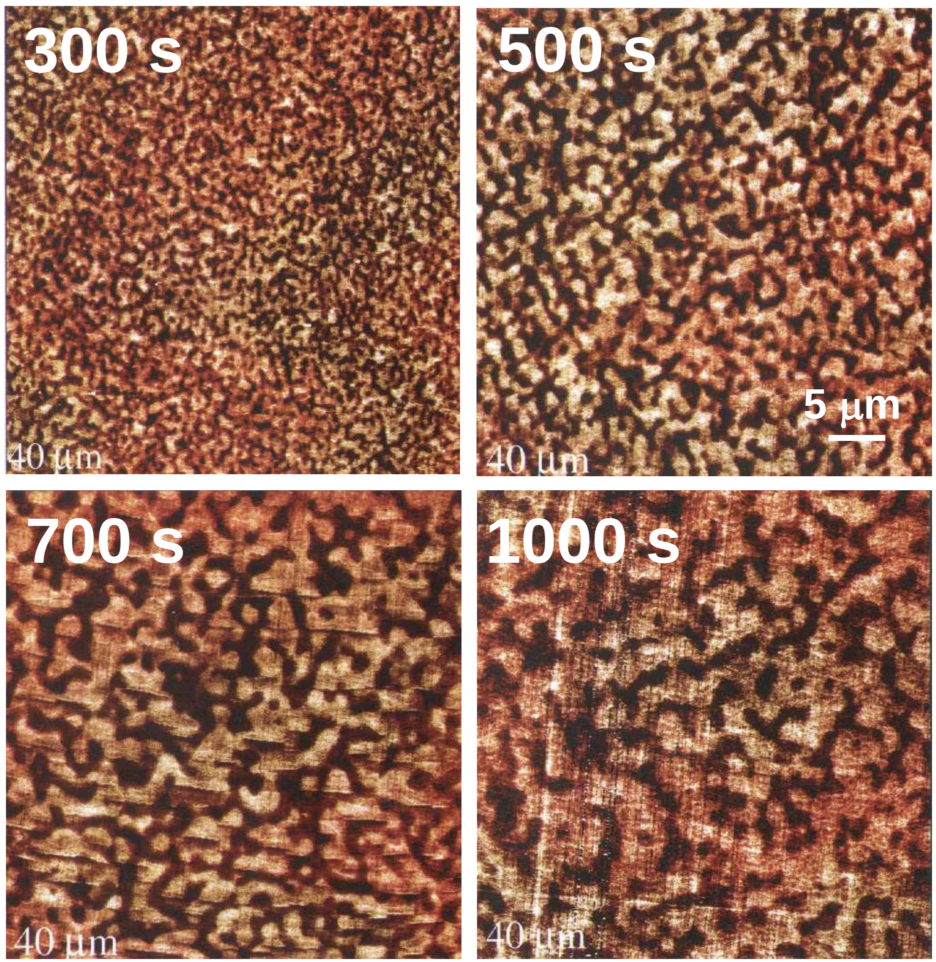


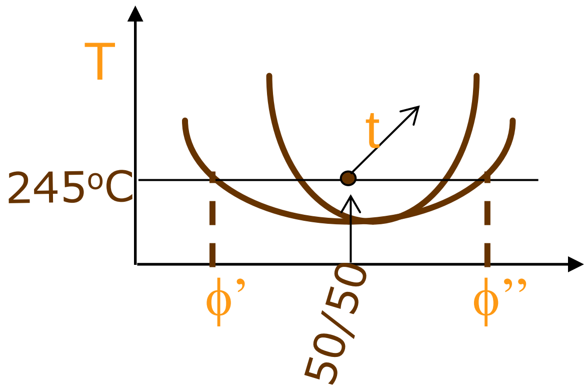
Unstable: $G'' < 0$
spinodal decomposition

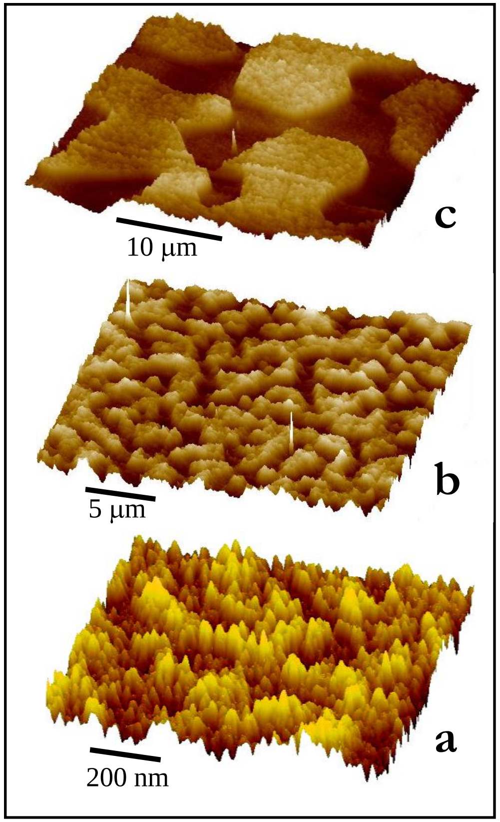
Metastable:
nucleation & growth

Stable:
equilibrium

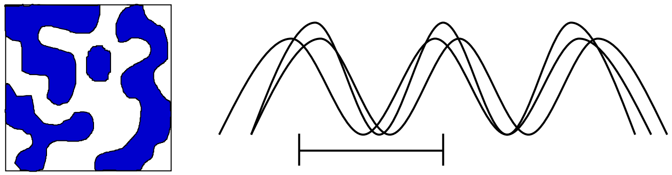
Phase separation: spinodal decomposition



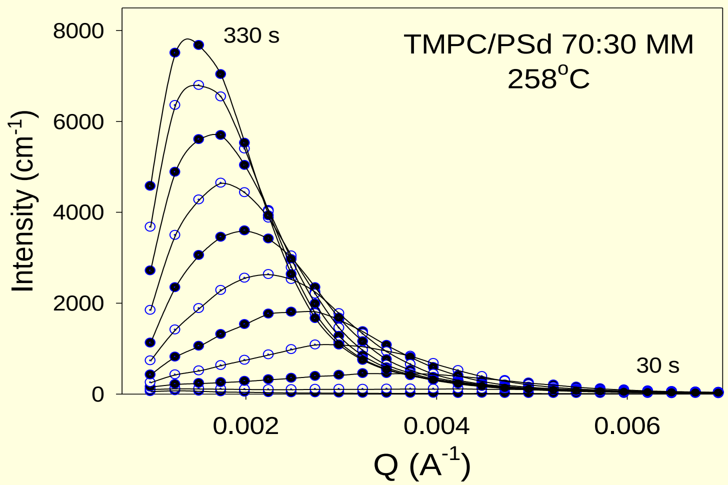


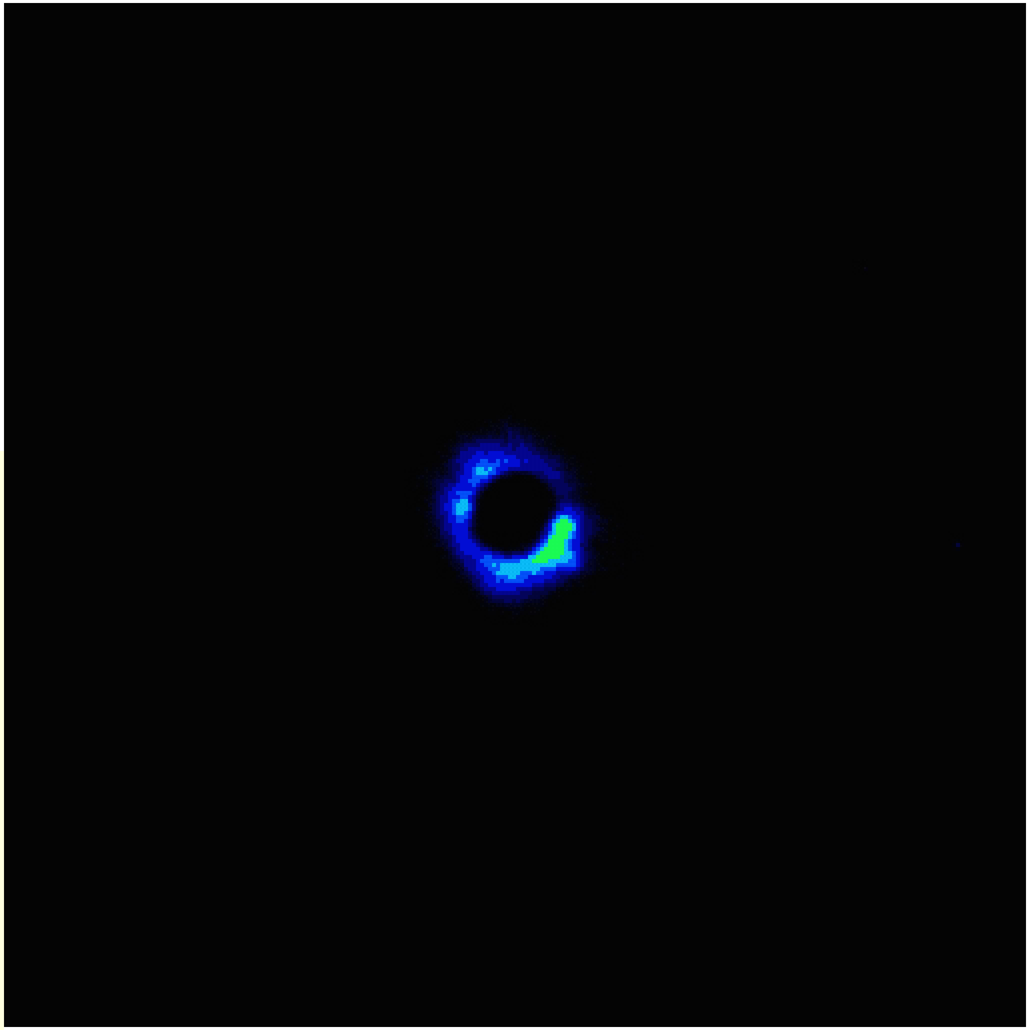


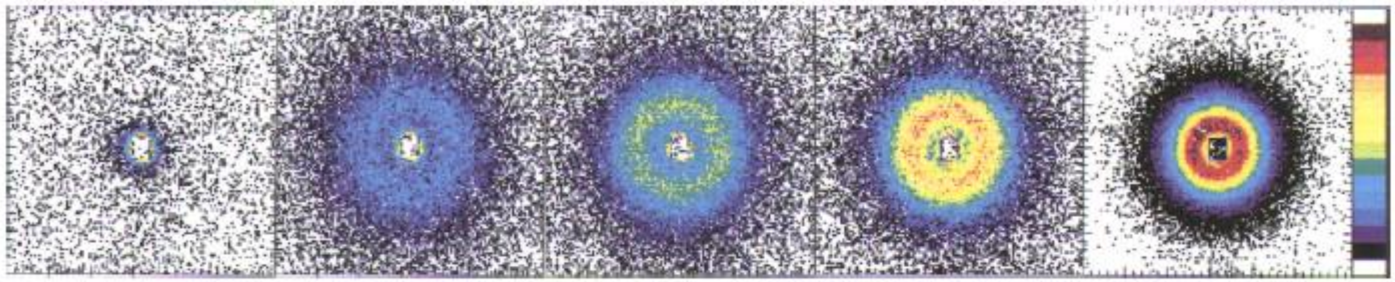
Phase separation

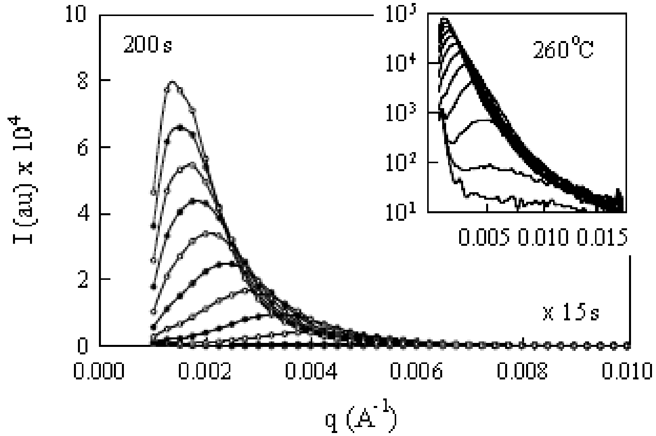


Λ_m: characteristic length of phase separation ~10s-100s nm

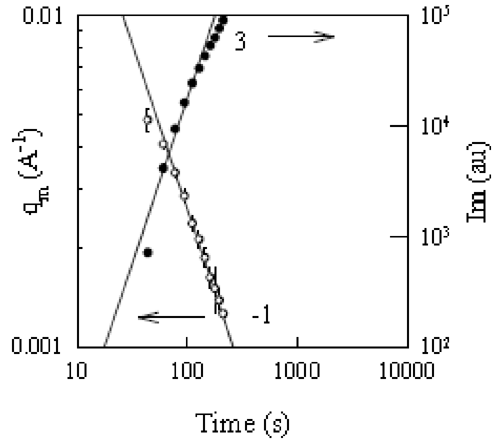




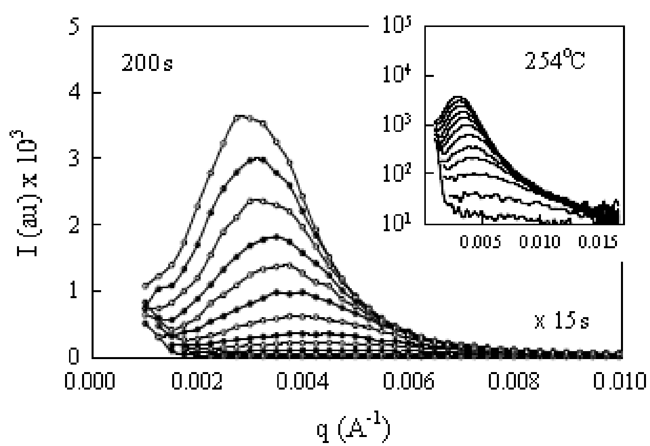




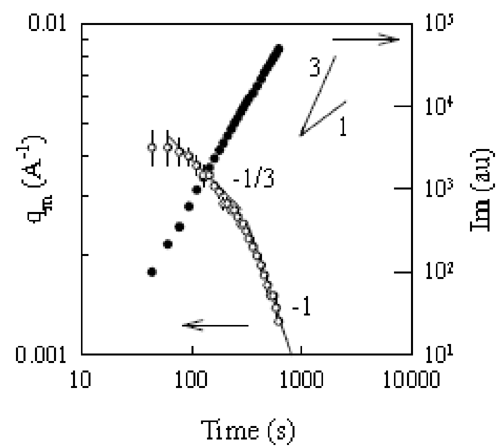
200 s
260°C
x 15 s
I (au) x 10^4
q (A^-1)
0.000 0.002 0.004 0.006 0.008 0.010
0.005 0.010 0.015



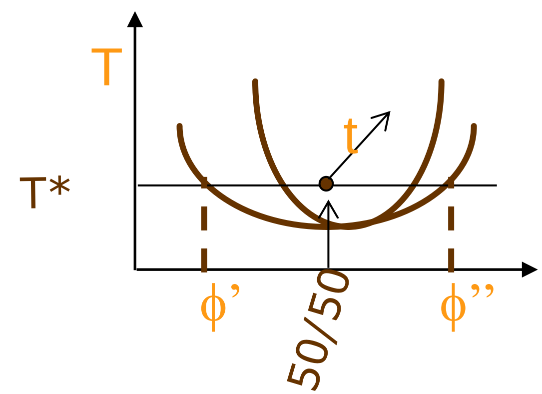
3
-1
q_m (A^-1)
Im (au)
Time (s)
10 100 1000 10000



200 s
254°C
x 15 s
I (au) x 10^3
q (A^-1)
0.000 0.002 0.004 0.006 0.008 0.010
0.005 0.010 0.015



3
1
-1/3
-1
q_m (A^-1)
Im (au)
Time (s)
10 100 1000 10000

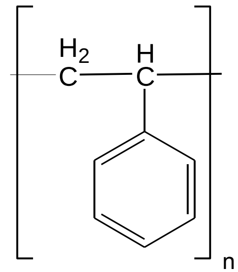


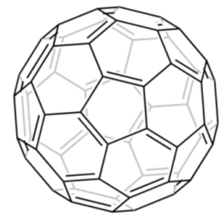
T
T*
t
φ'
50/50
φ''

Opportunities & recent developments

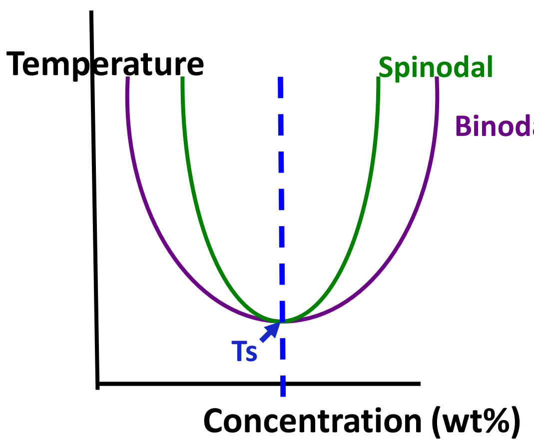
nano*composites*

structure



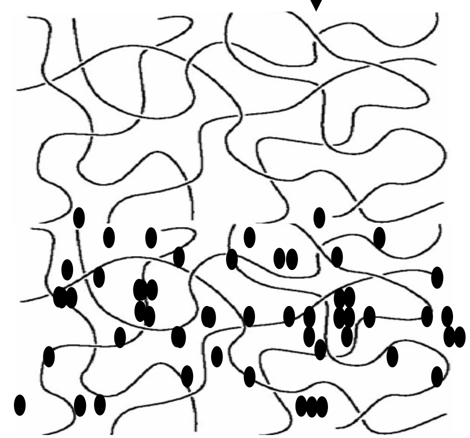


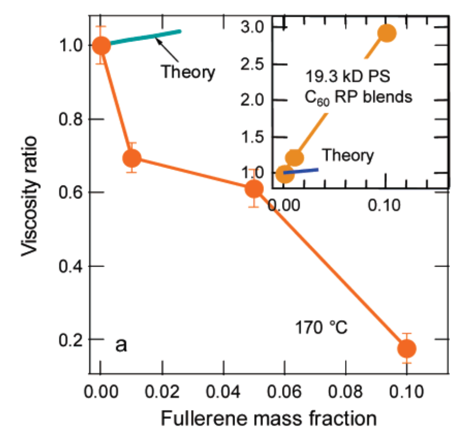
dynamics



Bulk

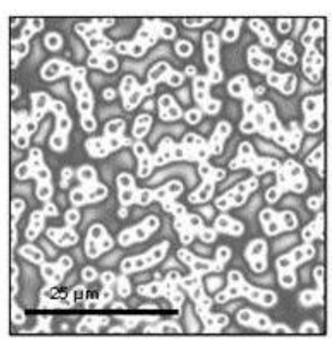
Thermodynamics & phase separation





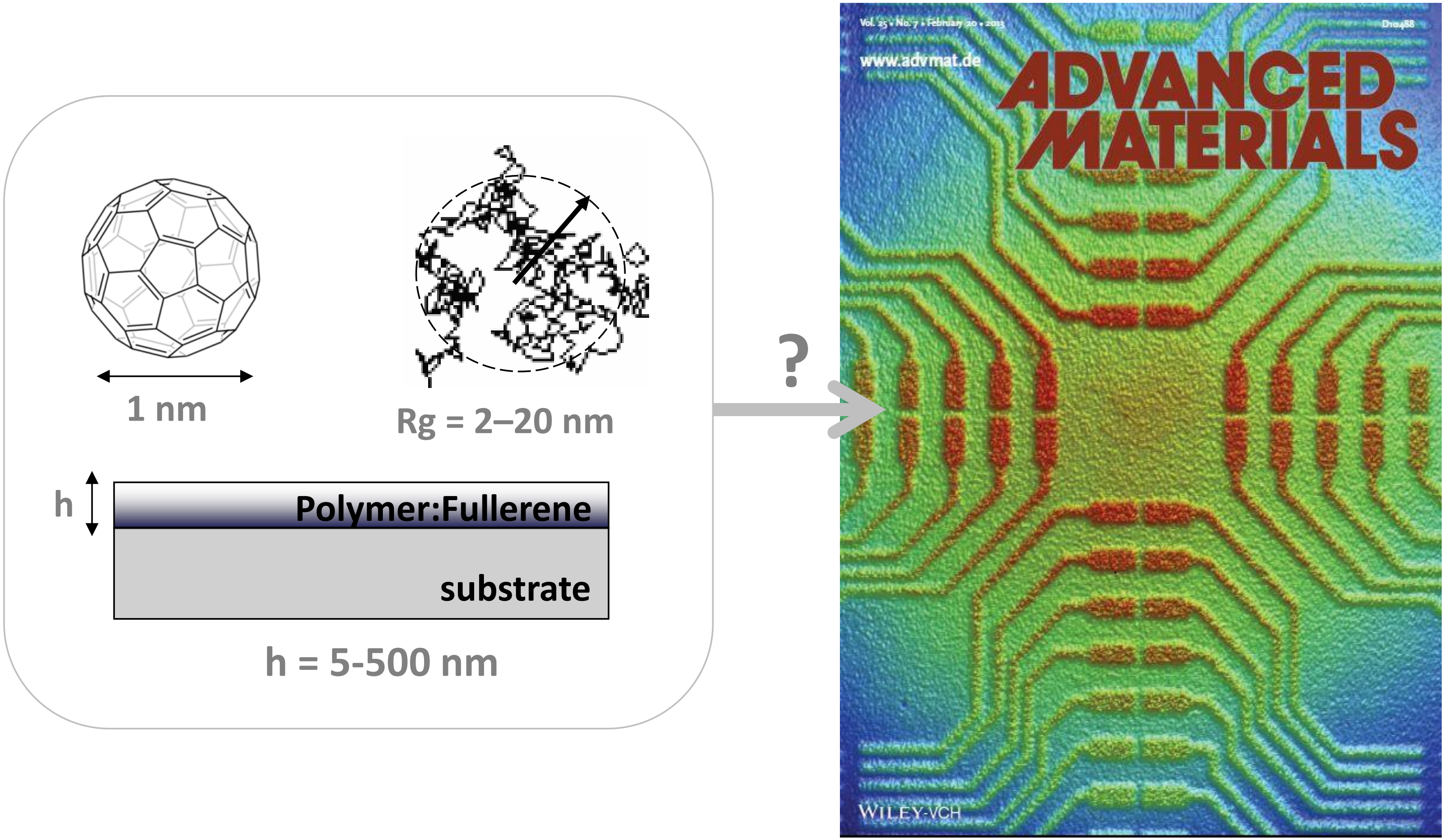
Thin Films

Morphology



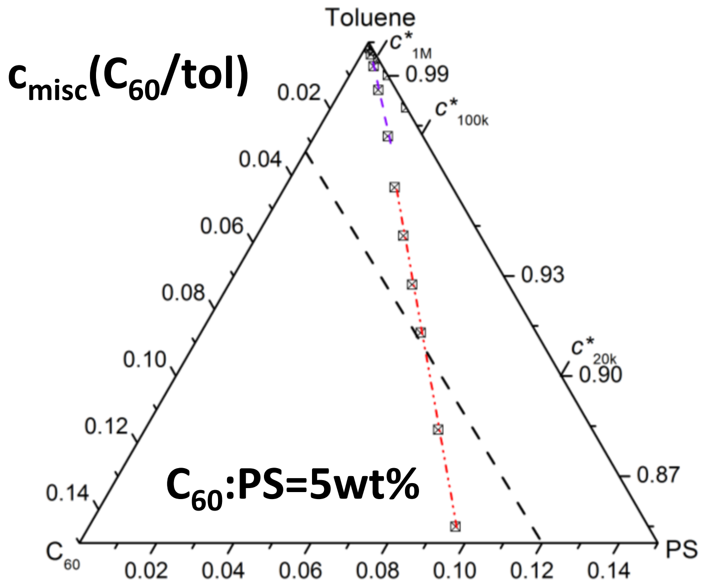
Tuteja et al. Nat. Mat. (2003) 2, 762

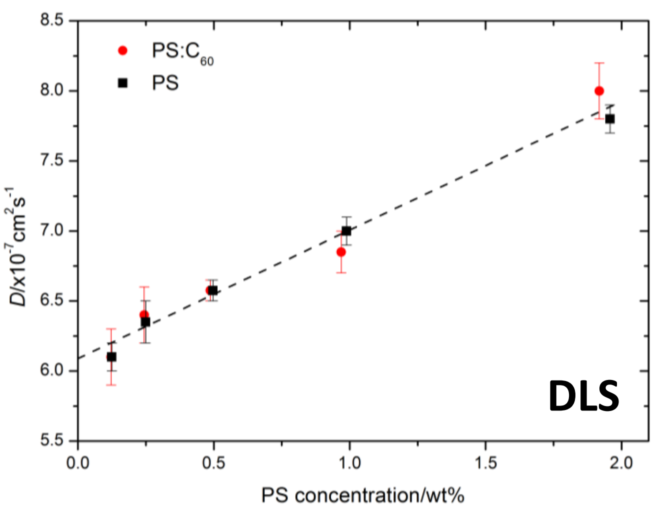
Polymer-fullerene blends



Adv. Mater. **25** 985-991 (2013)

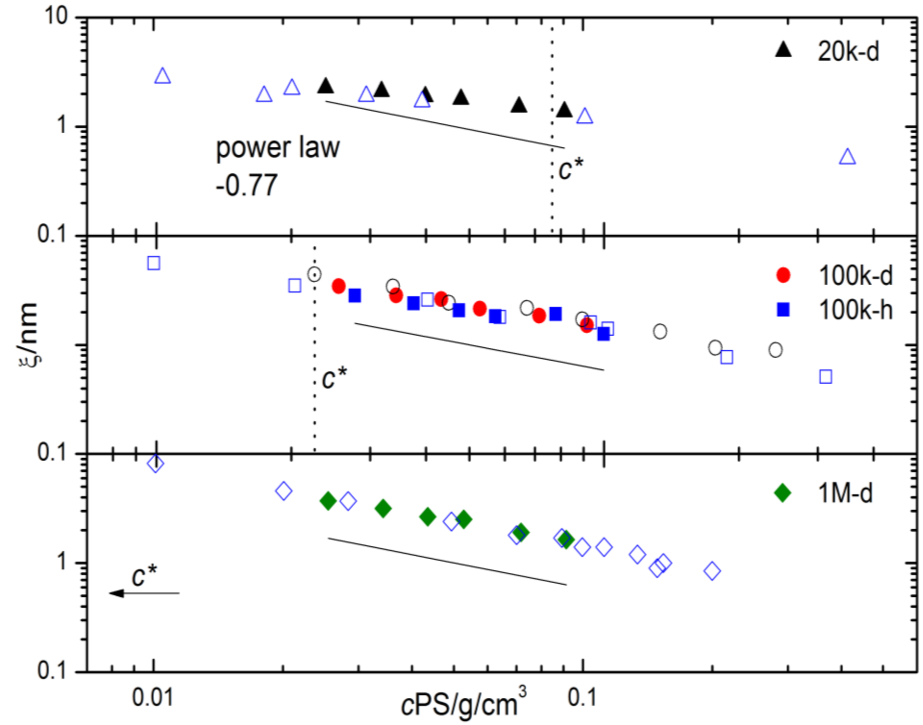
Polymer solution conformation + fullerenes





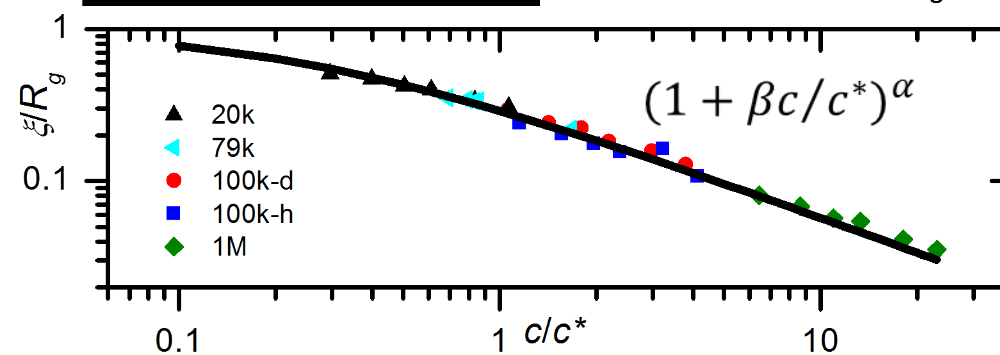
Macromolecules 47, 6113–6120 (2014)

SANS

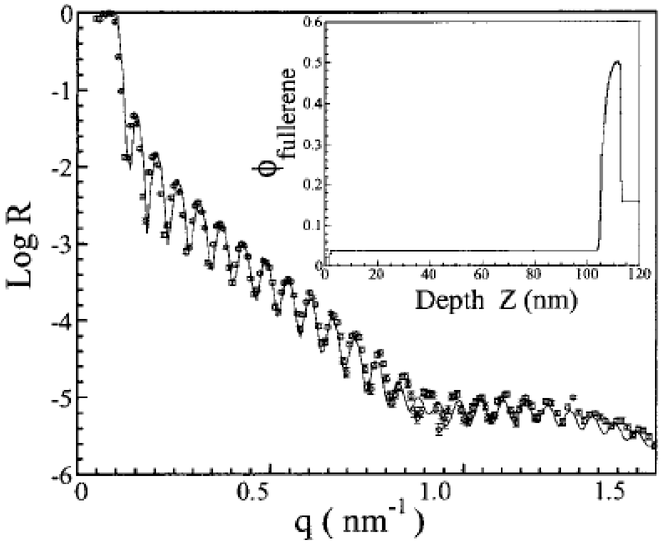


Dimensions unchanged

c^*: $3M/4\pi N_A R_g^3$

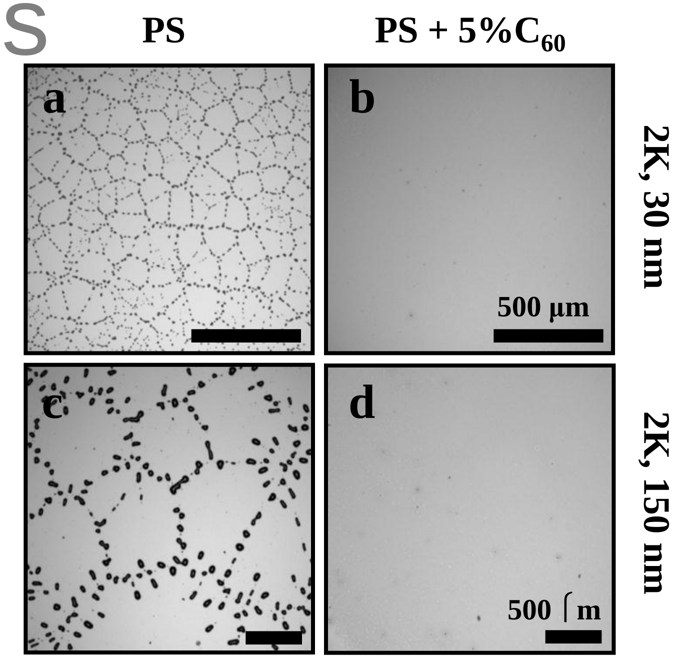


Design 3D composites



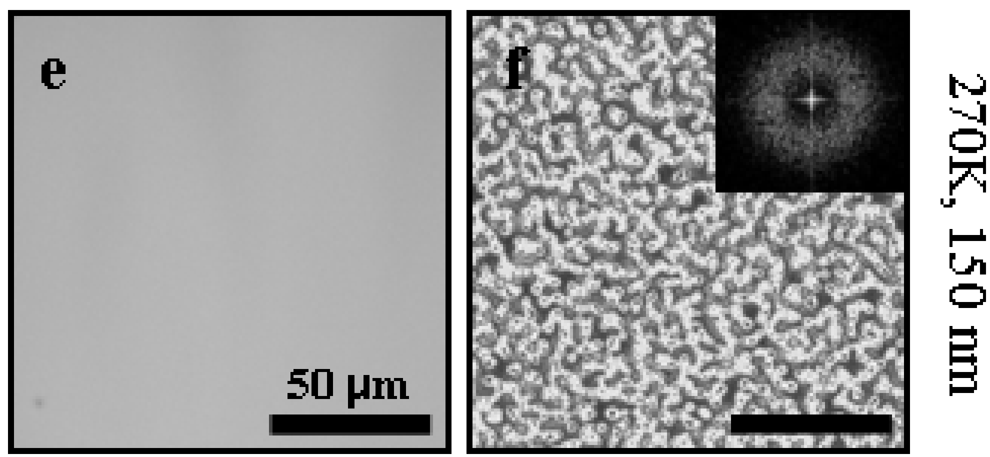
PS+5% C60 h = 100nm

GISANS & reflectometry



140ºC

180ºC



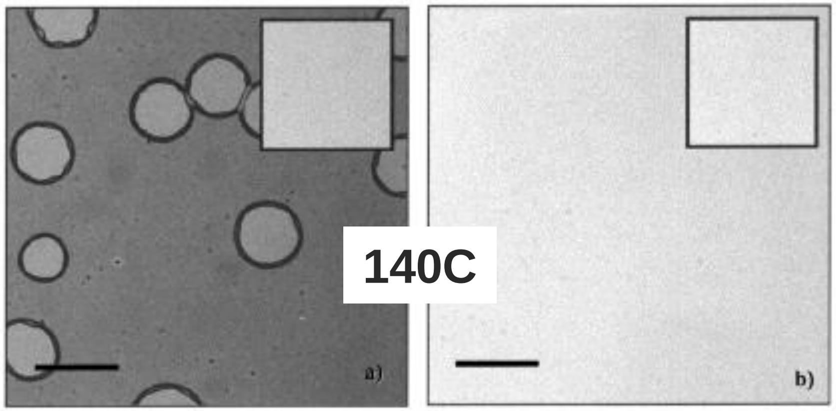
180ºC

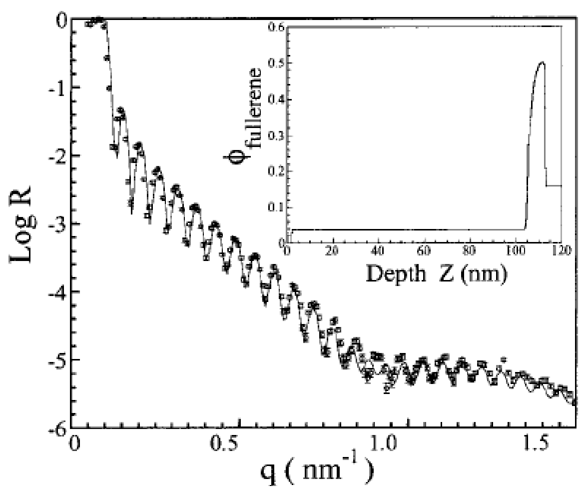
'Spinodal Clustering'

PRL 2010

Thin films

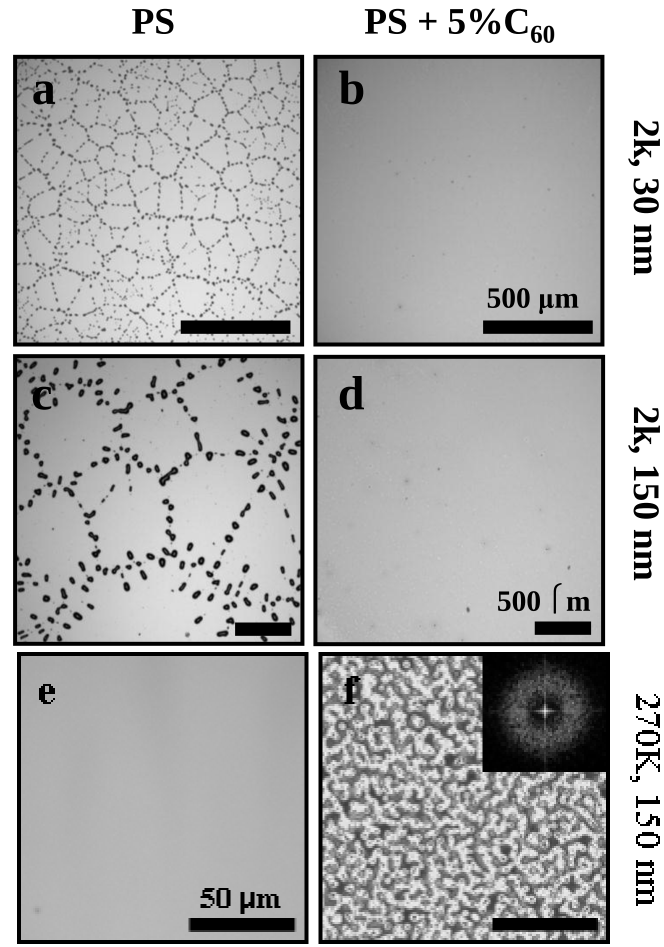
PS (2k), 30 nm | **1% C60, 30 nm**





PS+5% C60 h = 100nm

GISANS & reflectometry



140^{o}C

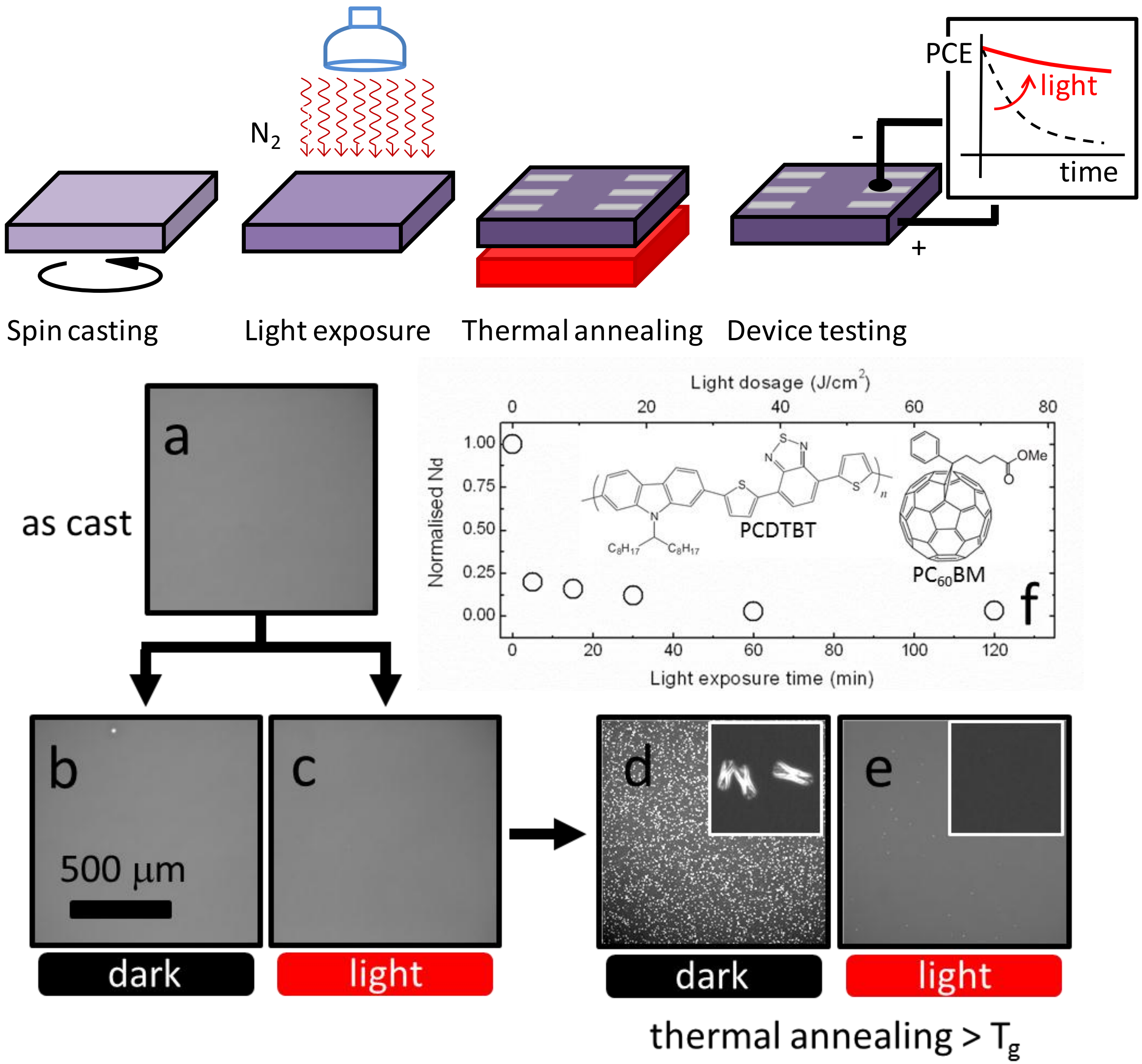
180^{o}C

180^{o}C

‘Spinodal nucleation’

Phys. Rev. Lett. **105**, 038301 (2010)
Macromolecules **44**, 4530-4537 (2011)

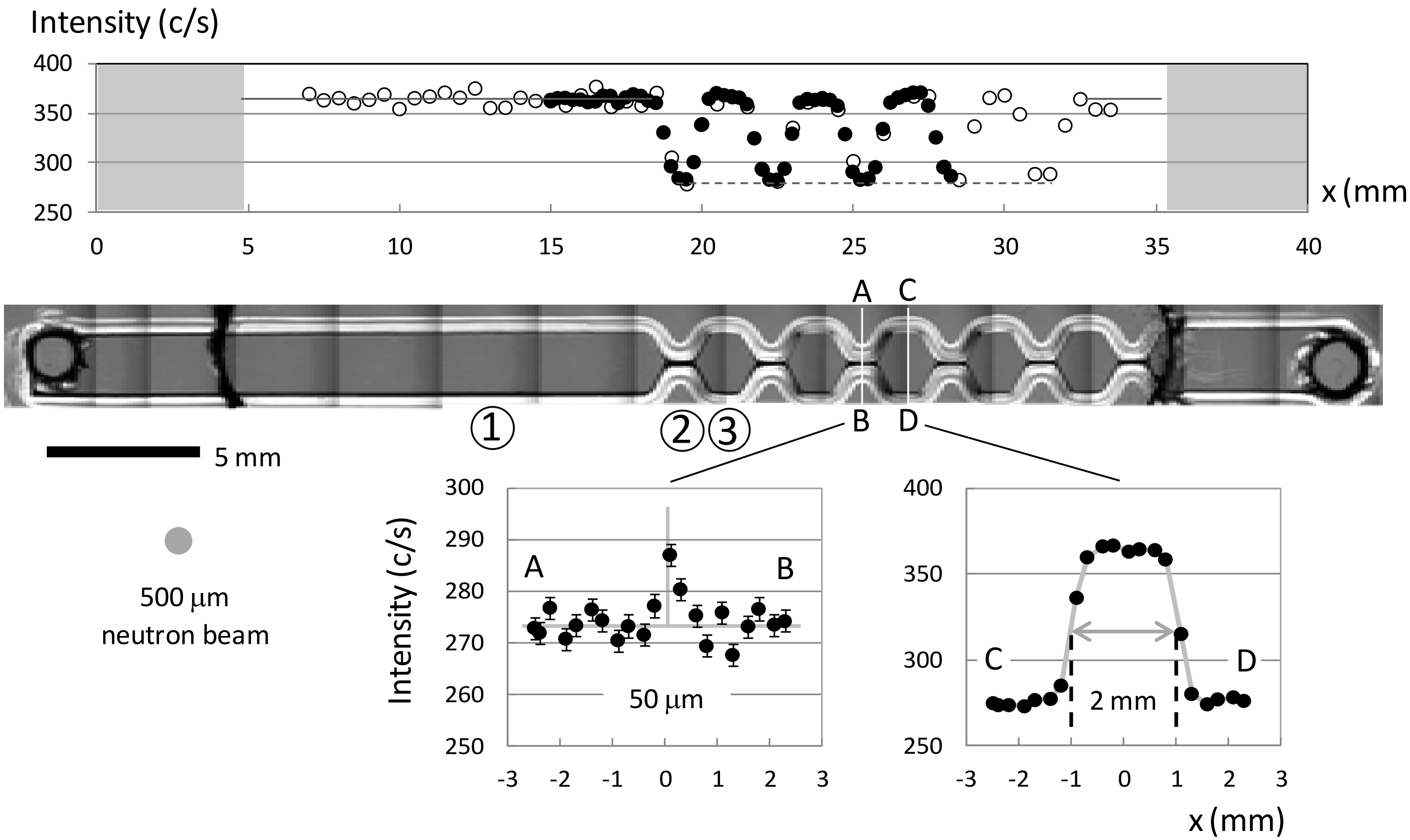
Organic Solar Cell lifetime?

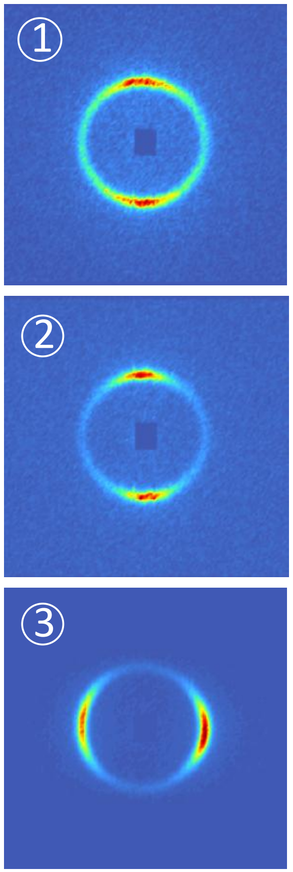


Angew. Chem. Int. Ed. 53, 12870-12875 (2014)

Nature Communications 4, 2227 (2013)

MicroSANS: microprocessing

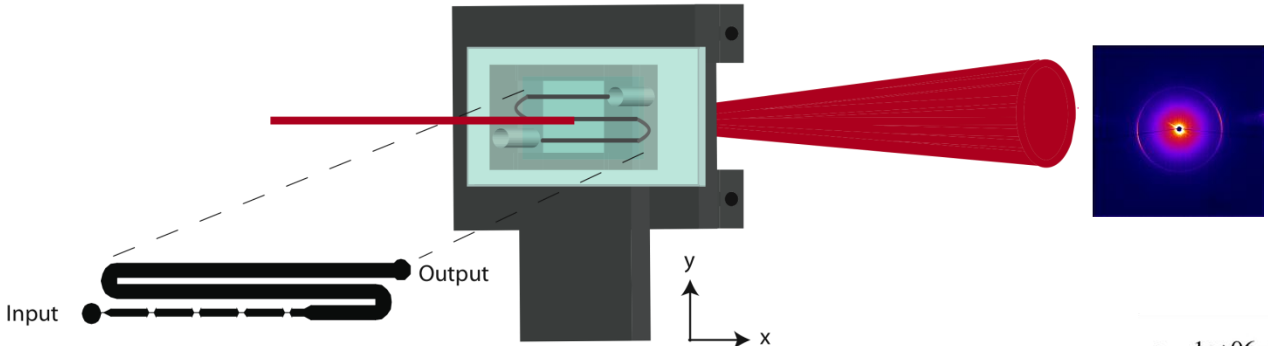


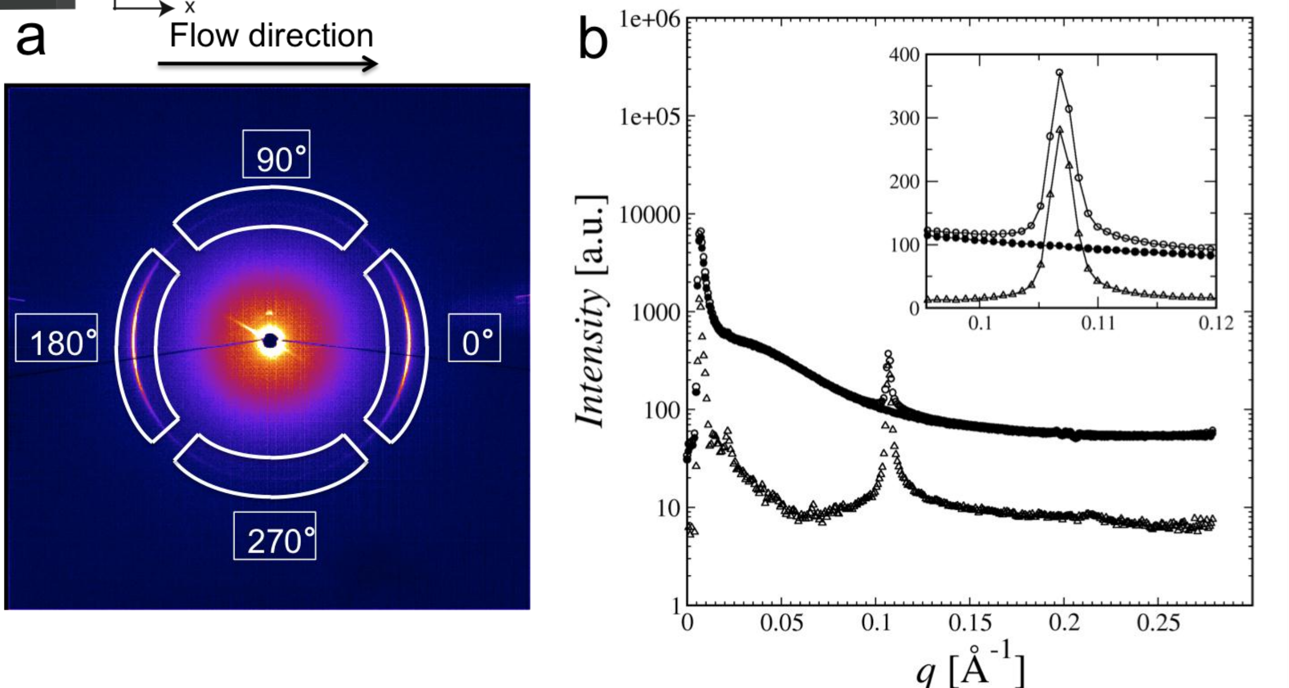


CTAC/pentanol/water

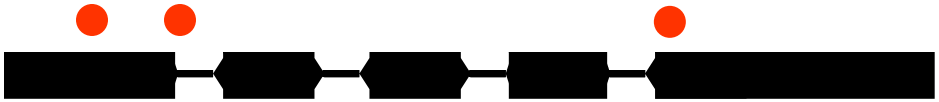
Flow fields (and microfluidics?)

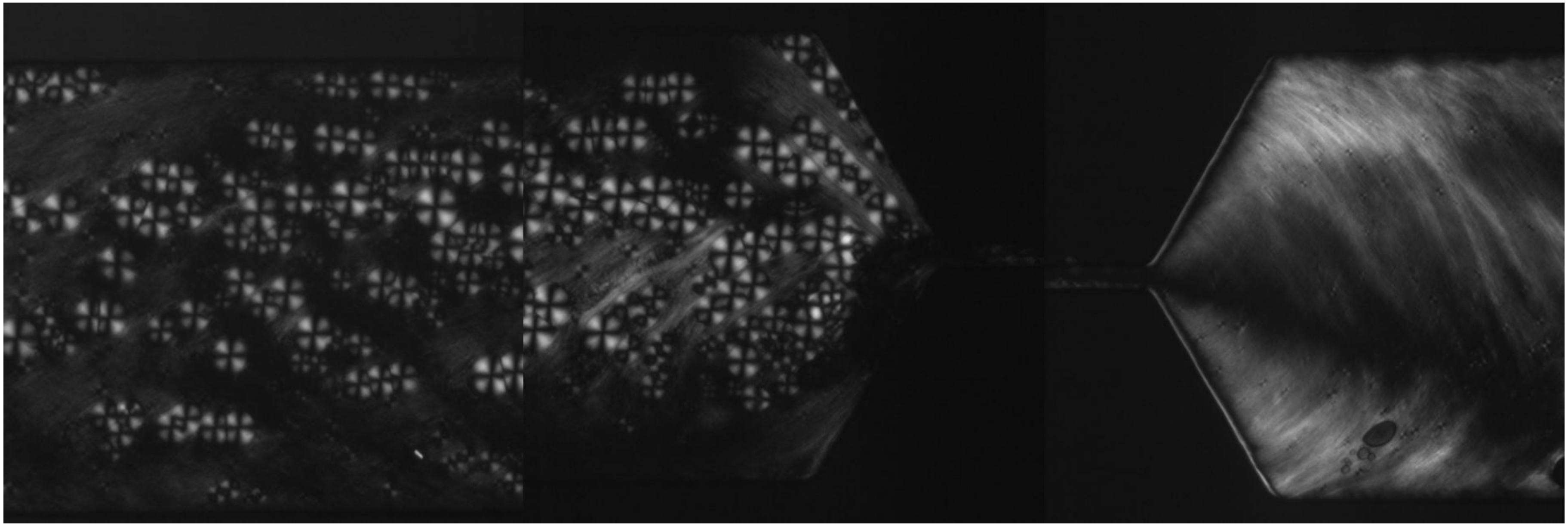
CTAC/ Pentanol/Water



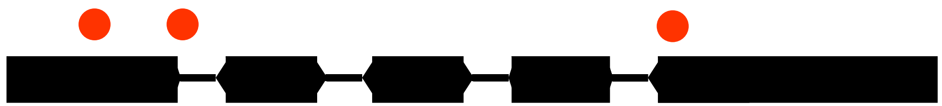


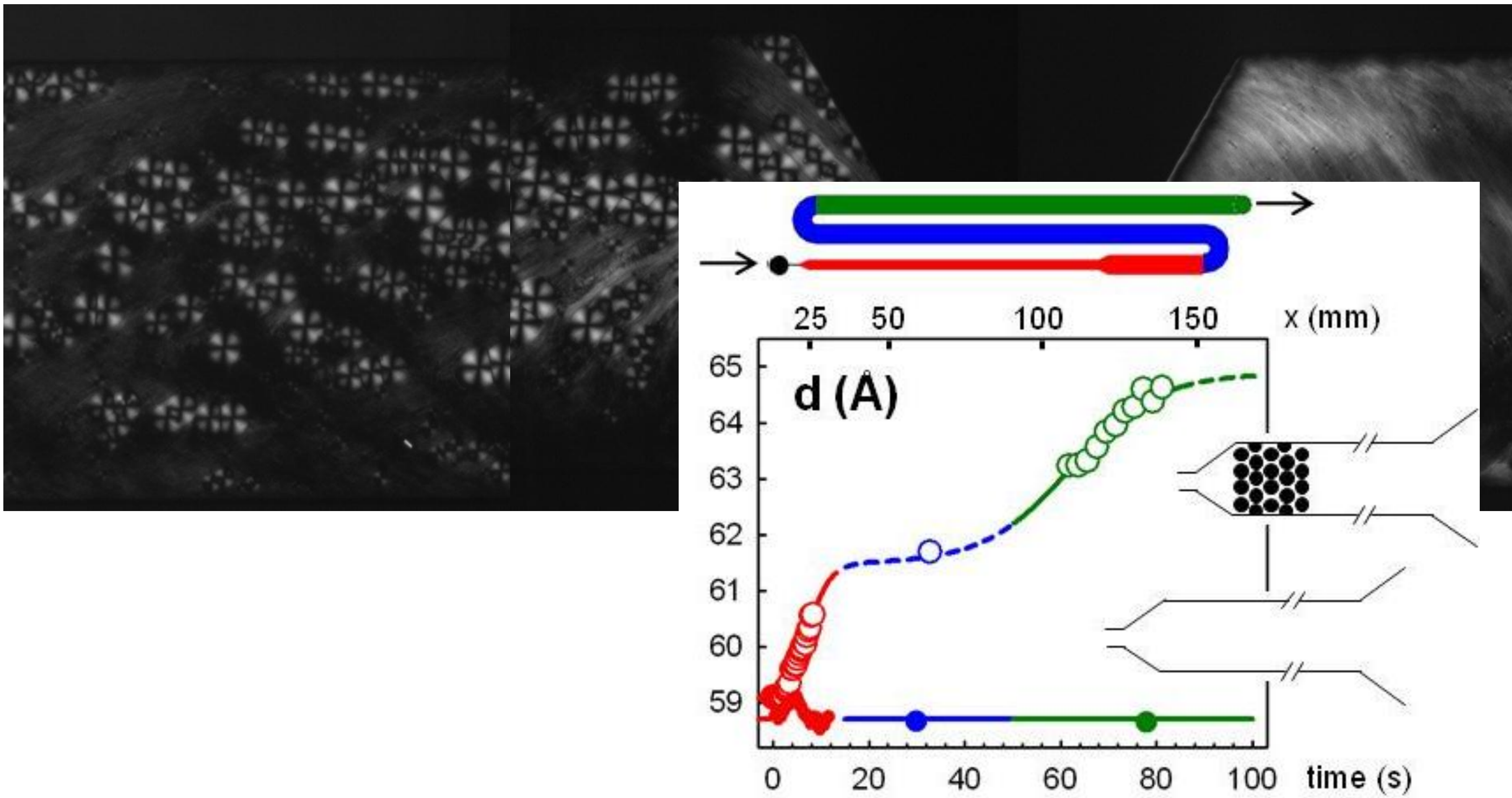
Microflow complex fluids



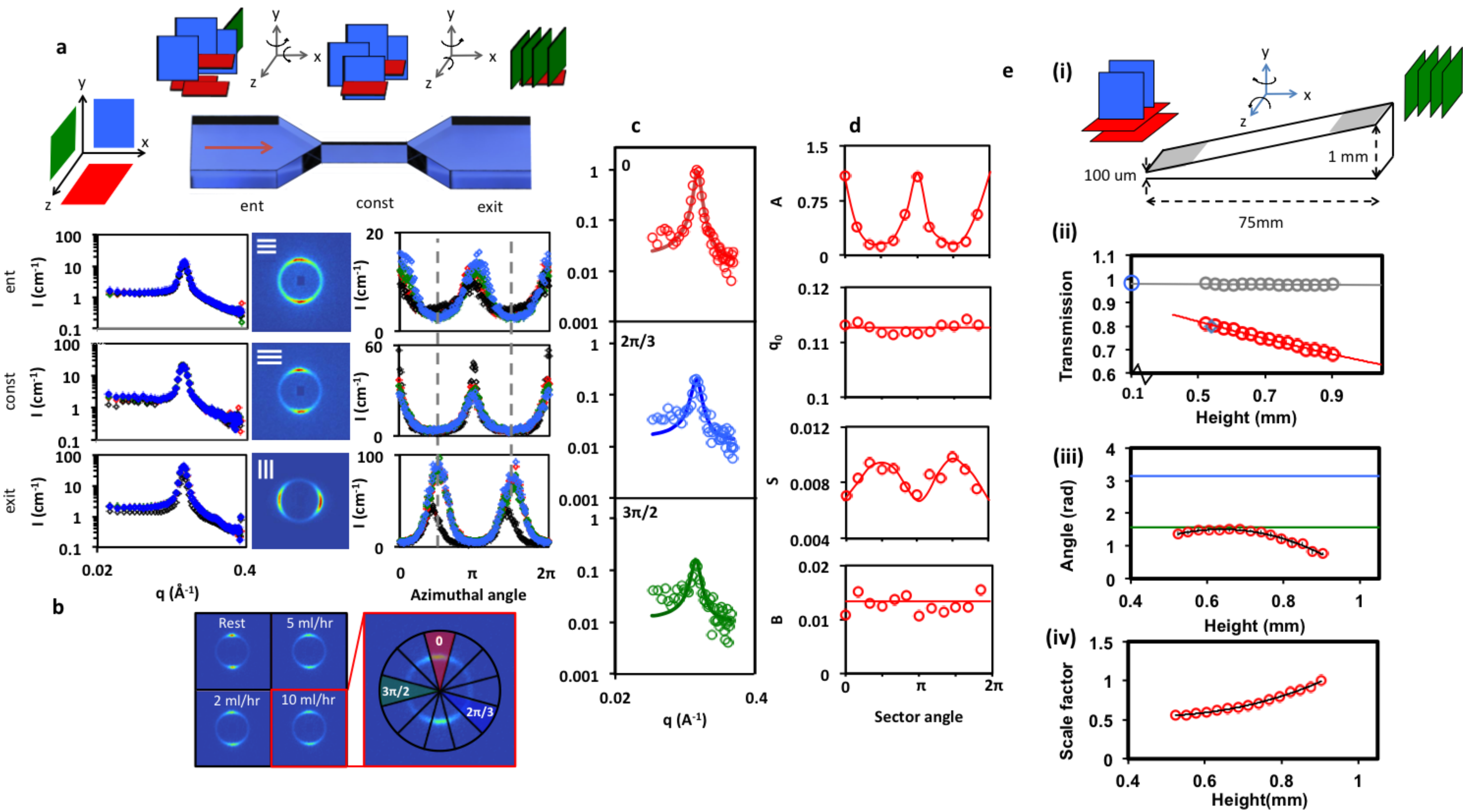


Microflow complex fluids





Mechanistic molecular insight SANS/XS

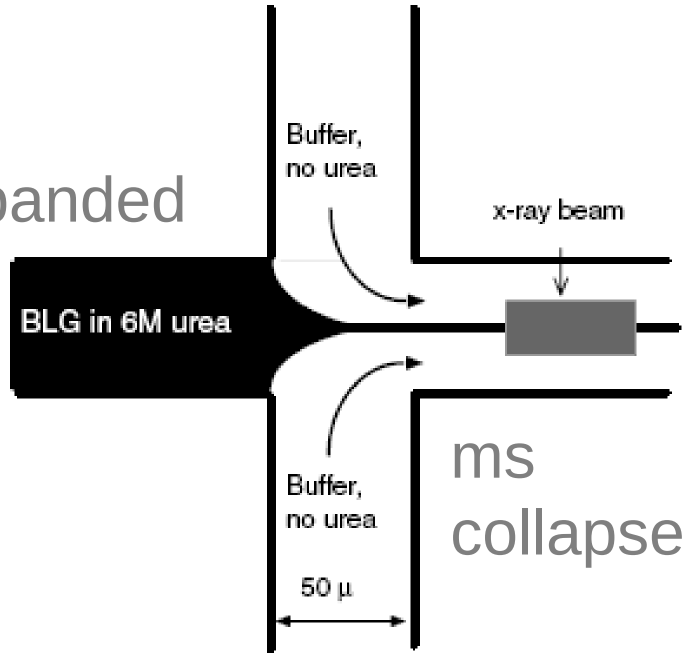


Scientific Reports 5, 7727 (2015)

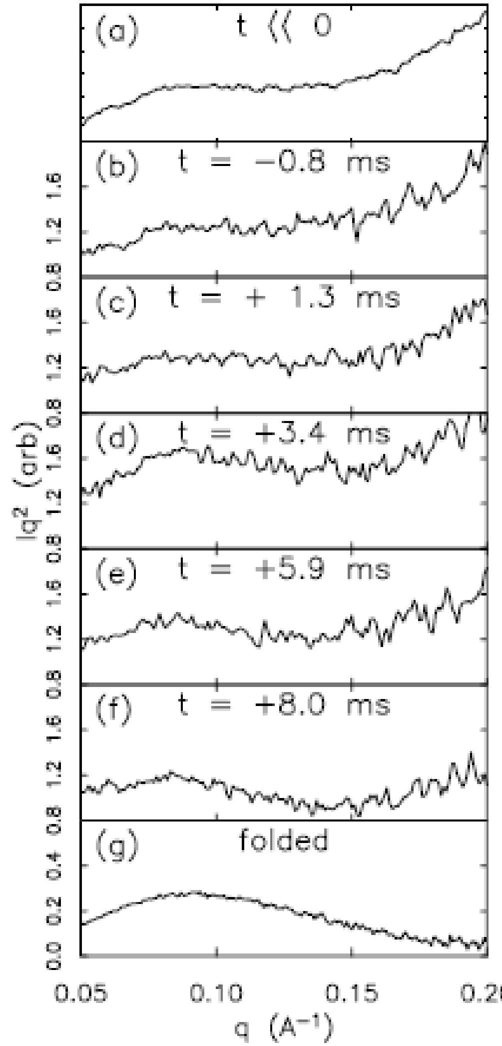
Spatio-temporal mapping:

Coil-to-globule transition

expanded

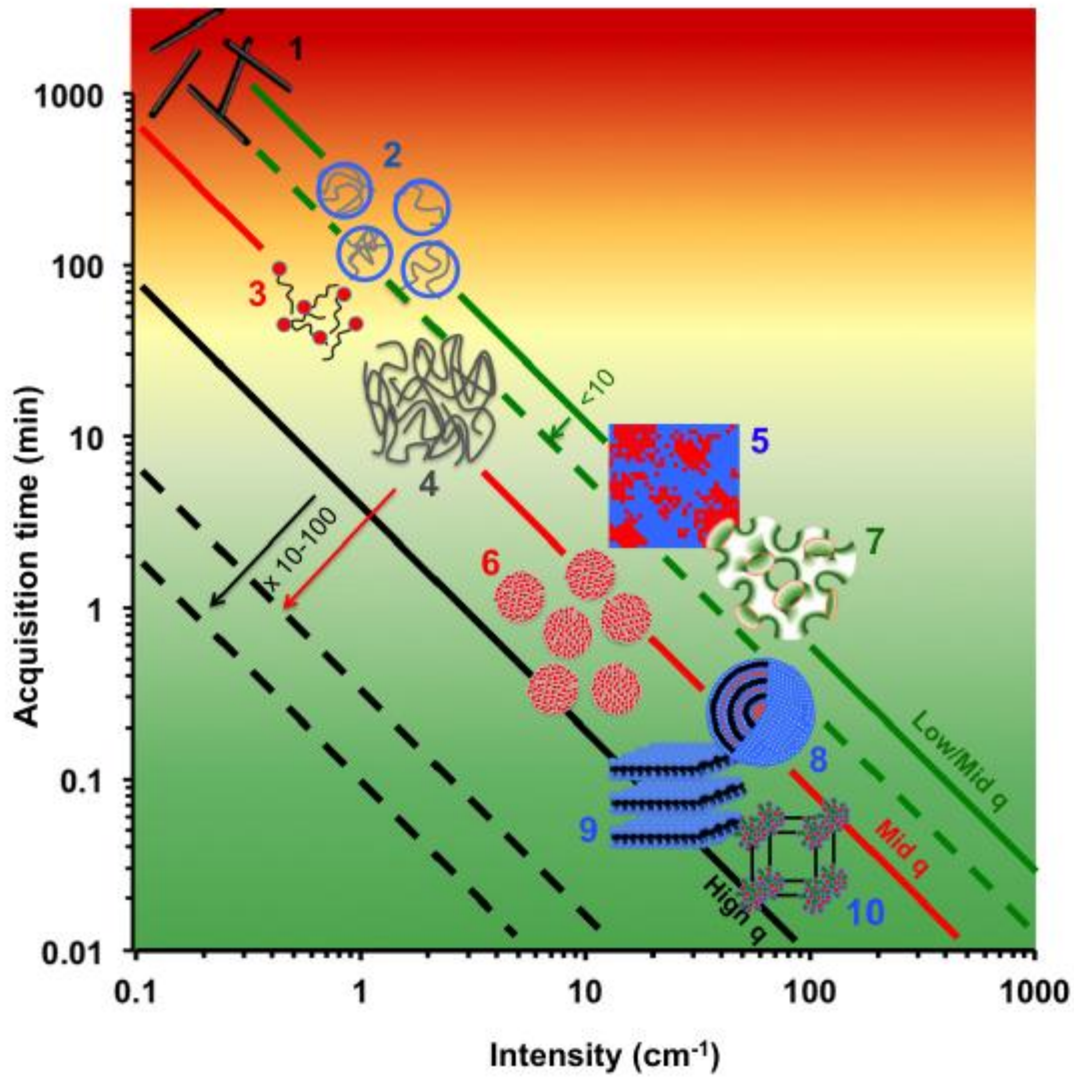


ms collapse



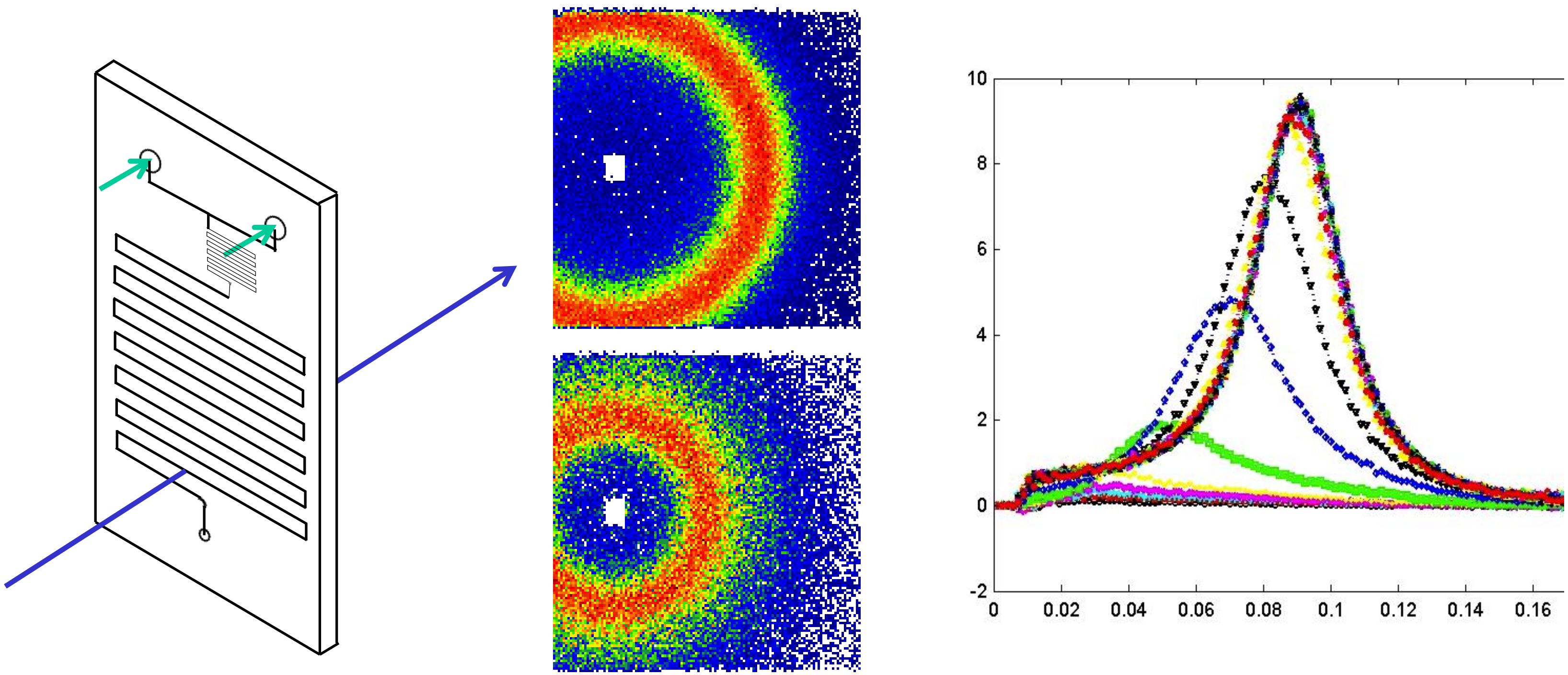
β-lactoglobulin (BLG)

(Pollack, Austin, etc)

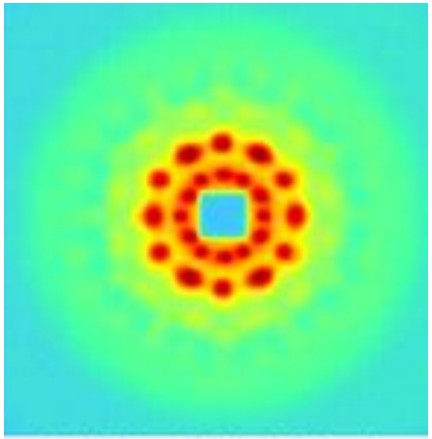


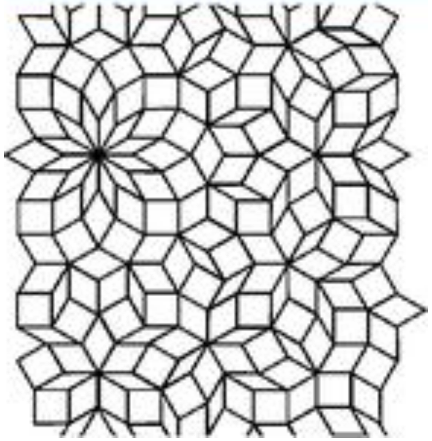
Scientific Reports 5, 7727 (2015)

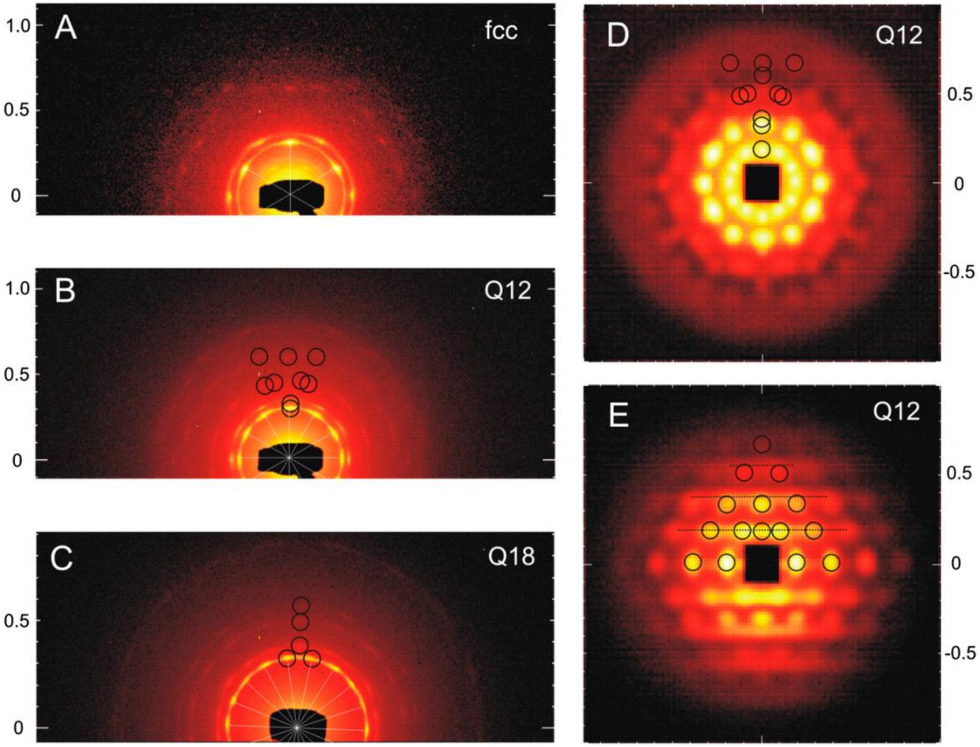
MicroSANS: High throughput



Soft colloids under flow







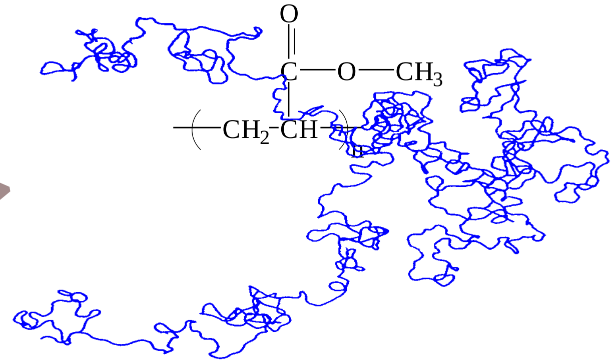
Forster et al. PNAS 2011

Summary

① **Intro**

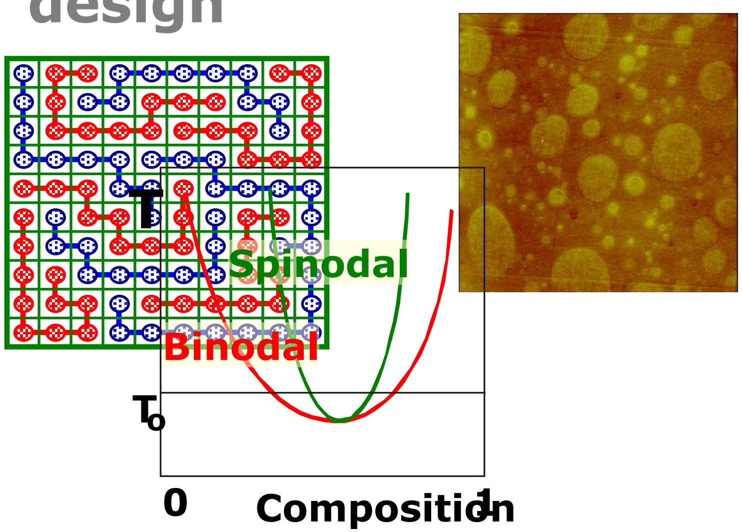
History

② Soft matter



③ Form and structure

④ Mixtures & design



⑤ Outlook