Methoden moderner Röntgenphysik: Streuung und Abbildung

Lecture 17	Vorlesung zum Haupt- oder Masterstudiengang Physik, SoSe 2021
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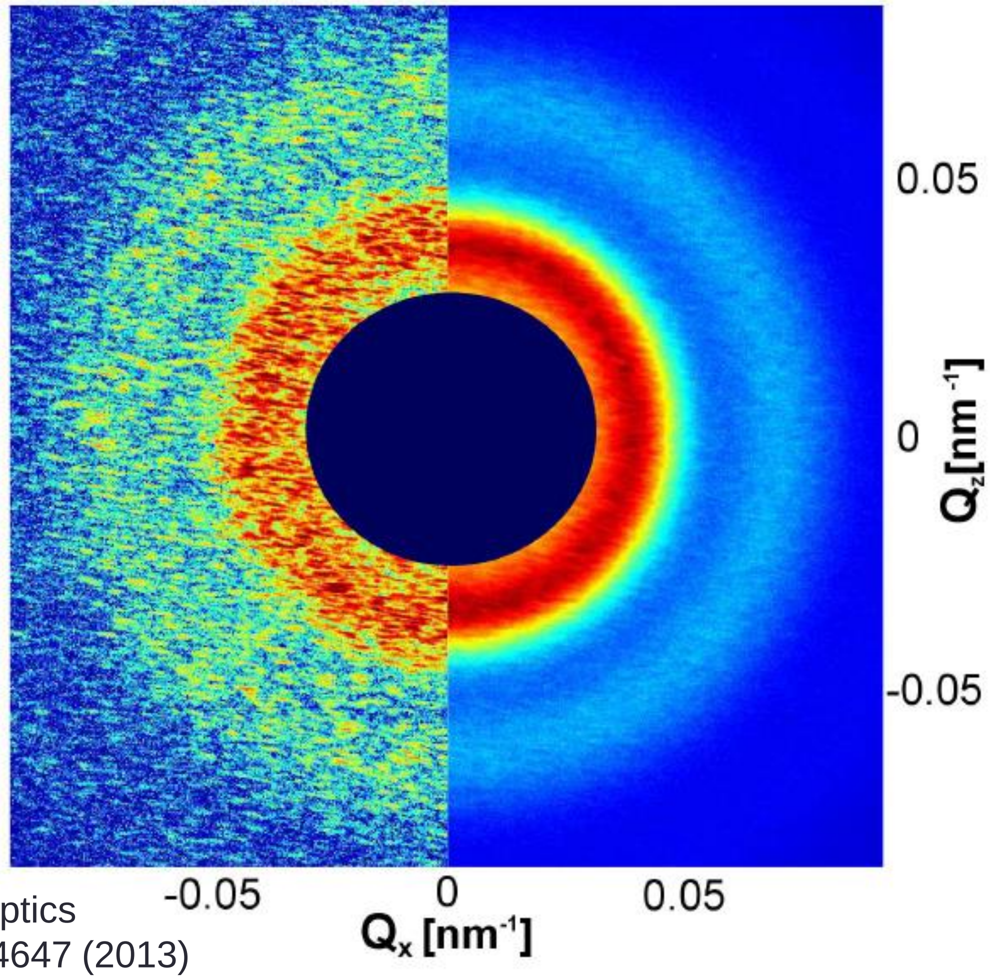
Location	online
Date	Tuesday 12:30 - 14:00 (starting 6.4.)
	Thursday 8:30 - 10:00 (until 8.7.)

Soft Matter – Timeline

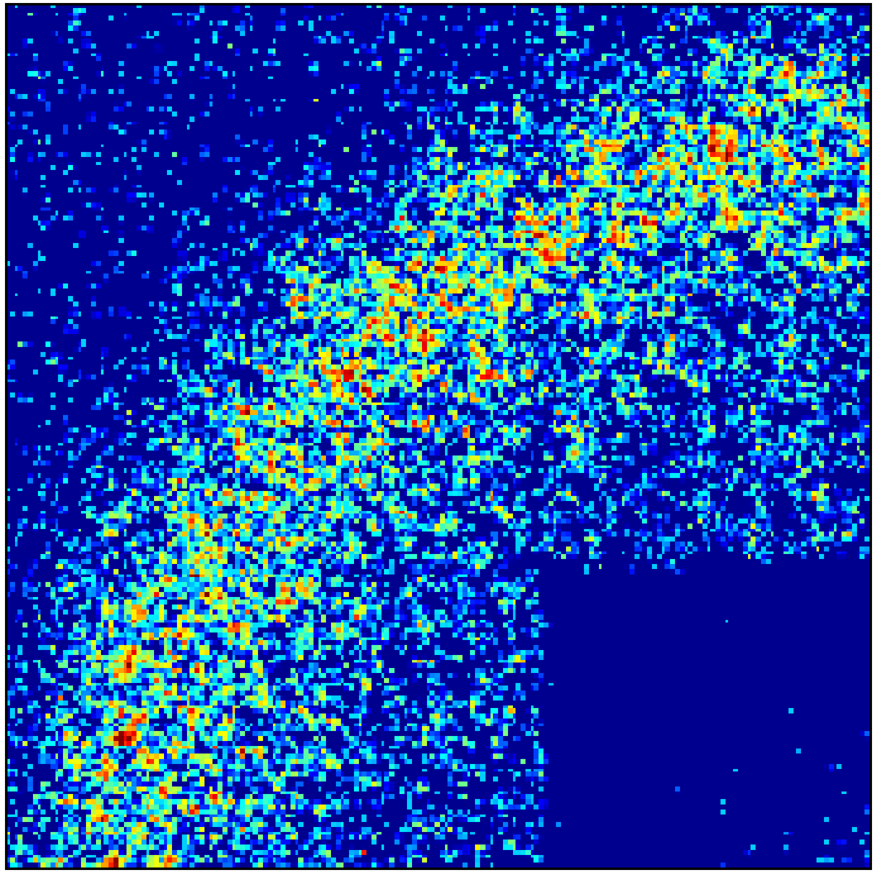
- Do 27.05.2021 Soft Matter studies I: Methods & experiments
  Definitions, complex liquids, colloids, storage ring and FEL experiments, setups, liquid jets, **…**
- Di 01.06.2021 Soft Matter studies II: Structure
  SAXS & WAXS applications, X-ray cross correlations, **…**
- Do 03.06.2021 Soft Matter studies III: Dynamics
  XPCS applications, diffusion, dynamical heterogeneities, ...
- Di 08.06.2021 XPCS & XCCA simulations and modelling
- Do 10.06.2021 Case study I: Glass transition
  Supercooled liquids, glasses vs. crystals, glass transition concepts, structure-dynamics relations, ...
- Di 15.05.2021 Case study II: Water
  Phase diagram, anomalies, crystalline and glassy forms, FEL studies, ...
- Do 17.06.2021 Outlook: Opportunities at new facilities

Probing dynamics with coherent X-rays: X-ray photon correlation spectroscopy (XPCS)

X-ray scattering from disordered samples: speckles → structure decoded

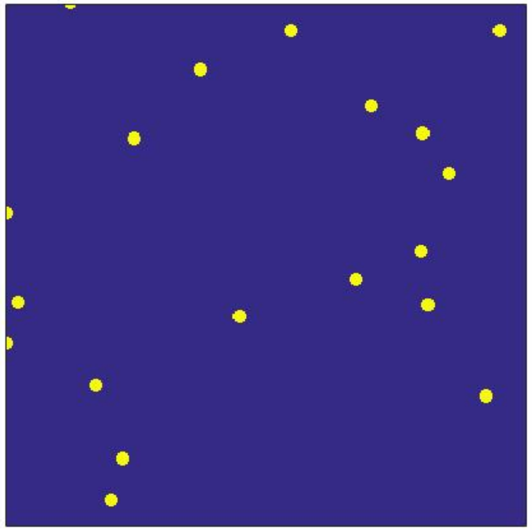


S. Lee et al. Optics Express 21, 24647 (2013)

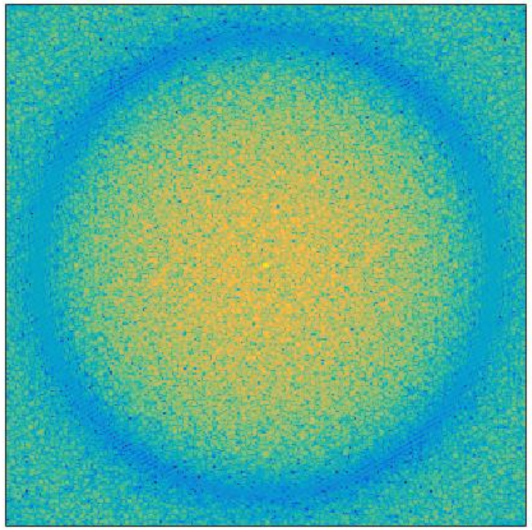


XPCS

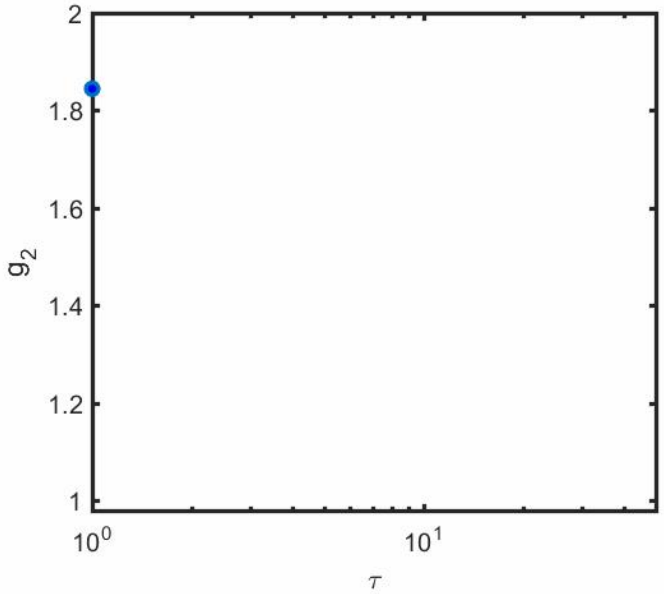
- **Time domain**: changing sample structure → change of speckle pattern
- Correlation function $g_2(q,\tau) = \frac{\langle I(q,t)I(q,t+\tau)\rangle_t}{\langle I(q,t)\rangle_t^2} = 1 + \beta^2|f(q,\tau)|^2$, speckle contrast $\beta = \mathrm{std}(I)/\langle I\rangle$
- Intermediate scattering function $f(q,\tau) = S(q,\tau)/S(q,0)$



Diffusing particles



Speckle pattern



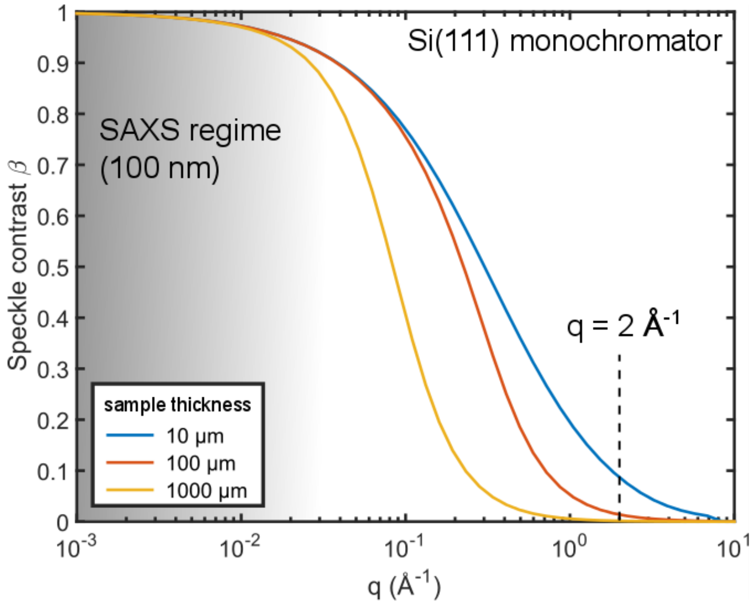
g_2 function

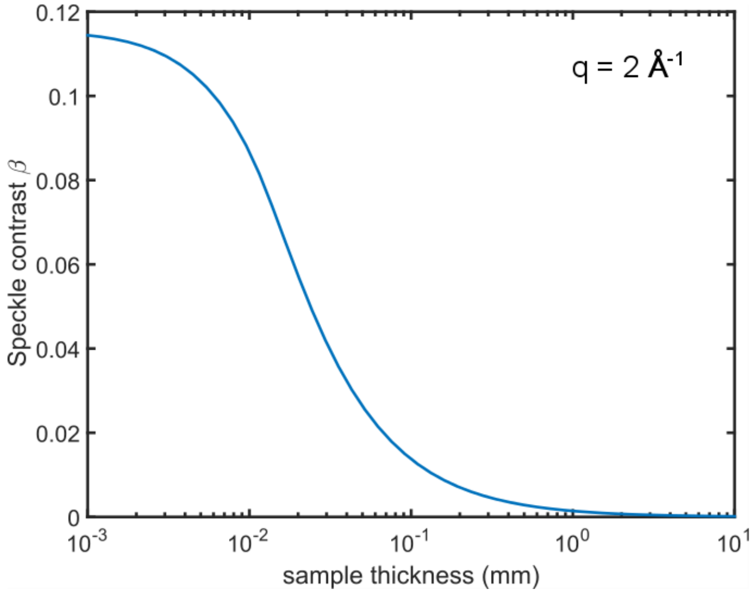
XPCS experiments – requirements

- Degree of coherence → speckle contrast
- Need to resolve speckles
  - speckle size $s \approx \frac{\lambda D}{b}$
  - using hard X-rays ($\lambda \sim 10^{-10}$ m)

  → $\frac{bs}{D} = 10^{-10}$ m

  → $bs \sim 10^{-10}$ m² for $D \sim 1$ m
- Statistics and q-dependence: 2D detectors (e.g. CCD)
  - Typical pixel sizes of $\sim 10 - 100$ µm
  - Consequently beam sizes in the µm regime
- Limit of time scales by detector read-out
  - CCD: ~ seconds
  - Photon counting: >kHz

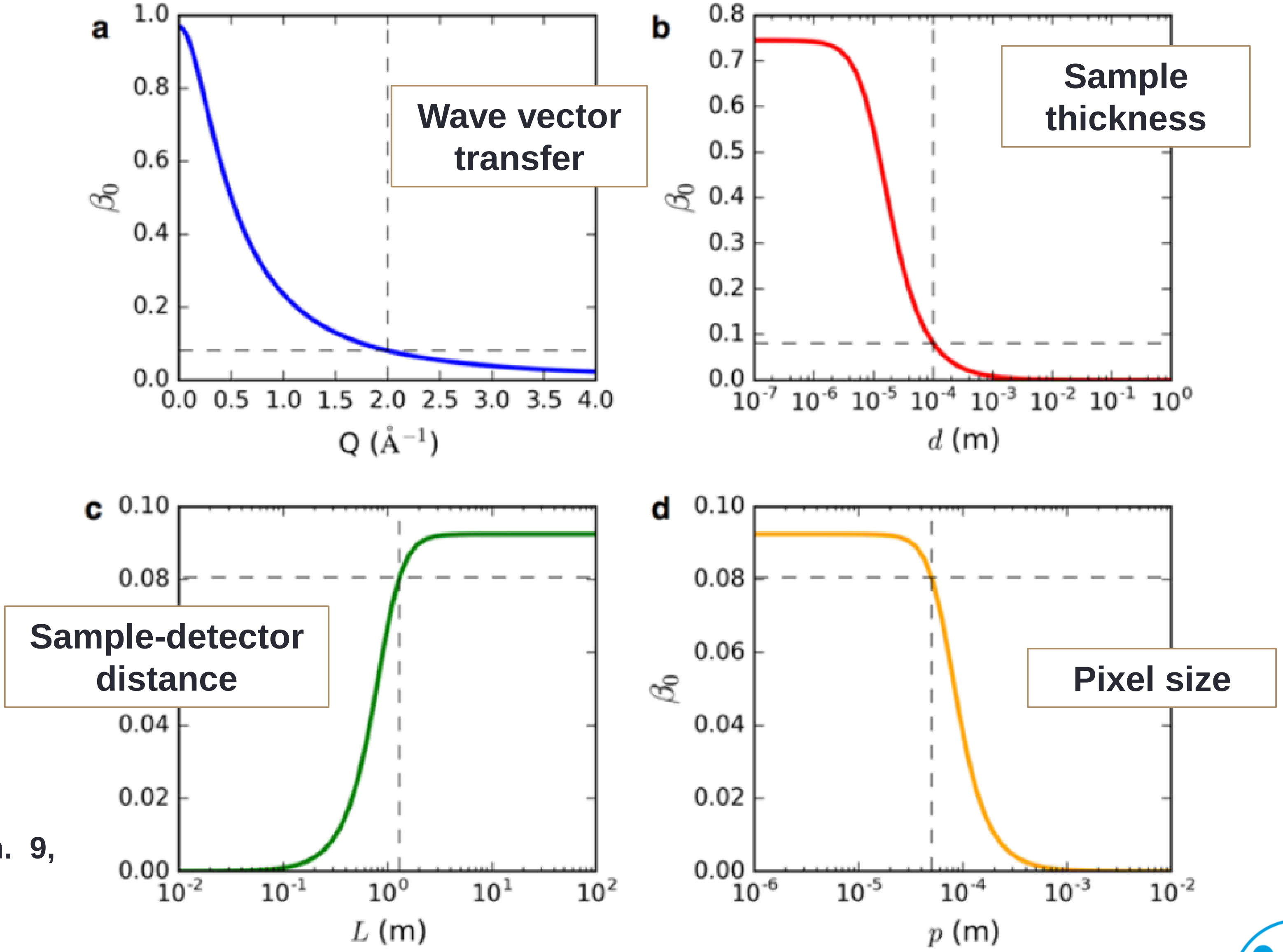




Large q
→ molecular lengths

XPCS experiments – requirements

Speckle contrast as a function of various parameters



Nature Comm. 9, 1917 (2018).

Diffusion in Soft Matter

- Brownian motion: random movement of particles (pollen collision with water molecules (Einstein 1905))
- Omnipresent in soft matter systems
- Derivation (after Langevin, here only one direction x):

$$m\frac{d^2x}{dt^2} = F - f\frac{dx}{dt}$$

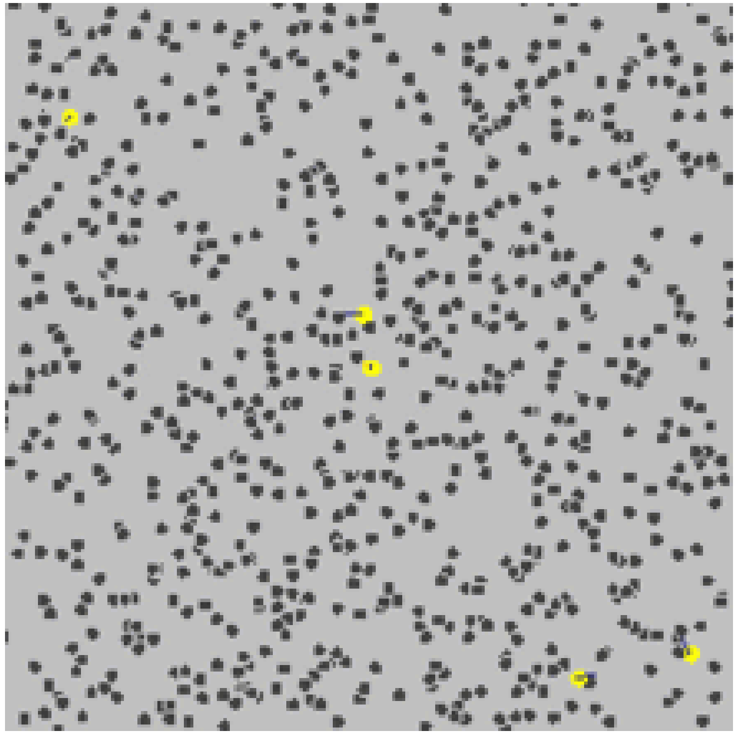
(with force F and viscous friction $F_R = -f\frac{dx}{dt}$)

$$\Leftrightarrow m\frac{d}{dt}\langle v\rangle = \langle F\rangle - f\langle v\rangle \qquad \text{(Averaging)}$$

$\langle F\rangle = 0$ for random particle collisons

$$\frac{d}{dt}\langle v\rangle = -\frac{f}{m}\langle v\rangle$$

$$\Rightarrow \langle v(t)\rangle = v(0)\exp\left(-\frac{m}{f}t\right)$$



Diffusion of particles

Diffusion in Soft Matter

→ Mean drift velocity $\langle v \rangle$ decays with time. Back to $m\frac{d}{dt}v = F - fv$. Multiply by instantaneous position r of an particle and average yields:

$$\frac{d^2}{dt^2}\langle r^2 \rangle + \frac{f}{m}\frac{d}{dt}\langle r^2 \rangle = 2\,\langle v^2 \rangle$$

Following the equipartition theorem ($\langle v^2 \rangle = \frac{3k_BT}{m}$) the equation can be solved with the result

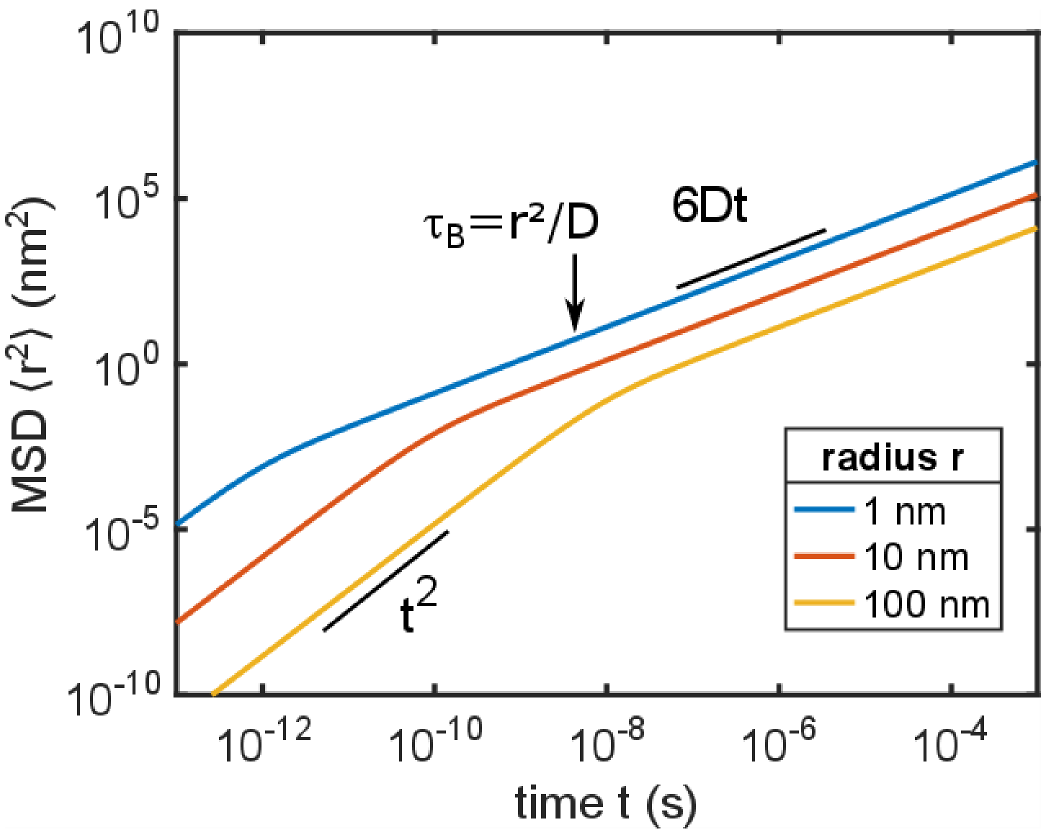
$$\langle r^2 \rangle = \frac{6k_BTm}{f^2}\left(\frac{f}{m}t\; - \left[1 - \exp\left(-\frac{f}{m}t\right)\right]\right)$$

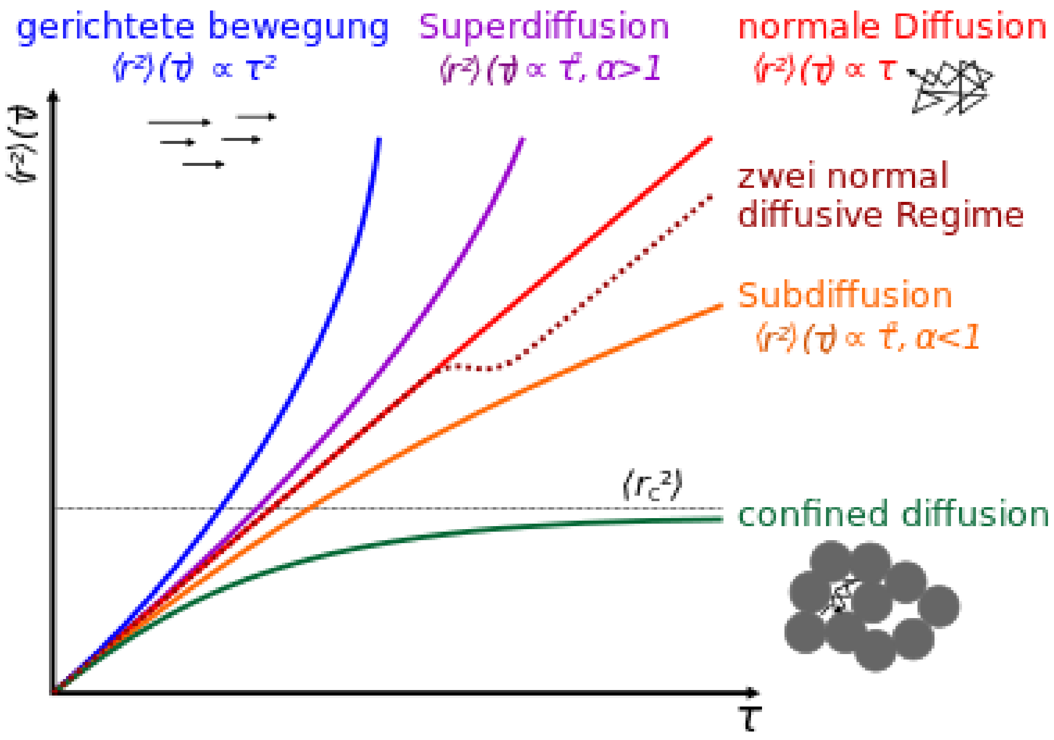
For $t \gg \frac{m}{f}$ we obtain with Stoke's law (friction of spheres, $f\, = 6\pi R\eta$)

$\langle r^2 \rangle = \left(\frac{k_BT}{\pi R\eta}\right)\, t\, = 6Dt$ with diffusion coefficient $D\, = \frac{k_BT}{6\pi\eta R}$

Diffusion in Soft Matter

Mean squared displacement $\langle r^2 \rangle$ – particles in water





Characteristic time $\tau_B = \frac{R^2}{D}$ to move by one radius (here $4.5 \cdot 10^{-9}$ s for $\mathrm{R} = 1$ nm)

Diffusion in Soft Matter – XPCS

Intermediate scattering function $f(q,\tau) = S(q,\tau)/S(q,0)$ with

$$f(q,\tau) = \frac{1}{N}\left\langle \sum_{i=1}^{N}\sum_{j=1}^{N} \exp(i\mathbf{q}\cdot[\mathbf{r_i}(0) - \mathbf{r_j}(\tau)]) \right\rangle$$

For diffusion, only single particle properties are probed → cross terms $i \neq j$ average out and $S(q) = 1$ → we obtain

$$f(q,\tau) = \frac{1}{N}\left\langle \sum_{i=1}^{N} \exp(i\mathbf{q}\cdot[\mathbf{r_i}(0) - \mathbf{r}_{\boldsymbol{i}}(\tau)]) \right\rangle$$

And finally (cf. Physica 32, 415 (1966)) the result for diffusion

$$f(q,\tau) = \exp(-Dq^2\tau)$$

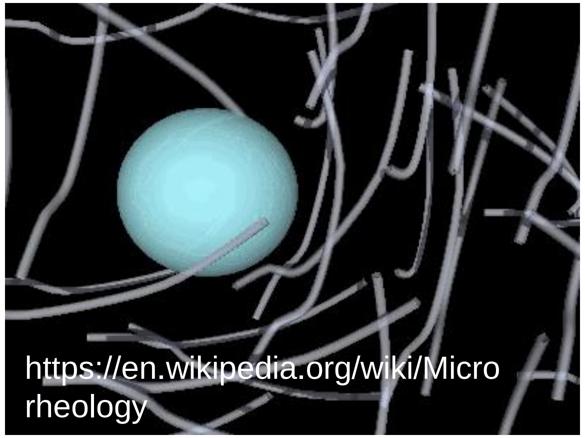
Diffusion by XPCS – Notes

- In XPCS, correlation function for diffusion:
$$g_2(q,\tau) = 1 + \beta^2 |f(q,\tau)|^2 = 1 + \beta^2 \exp(-2Dq^2\tau)$$

- Relaxation time $\tau_0 = \frac{1}{\Gamma} = \frac{1}{Dq^2}$ → characteristic $\tau_0 \propto q^{-2}$

- Measuring g_2 allows to obtain particle size $R = \frac{k_B T \tau_0 q^2}{6\pi\eta}$ when solvent properties are known → Dynamical light scattering

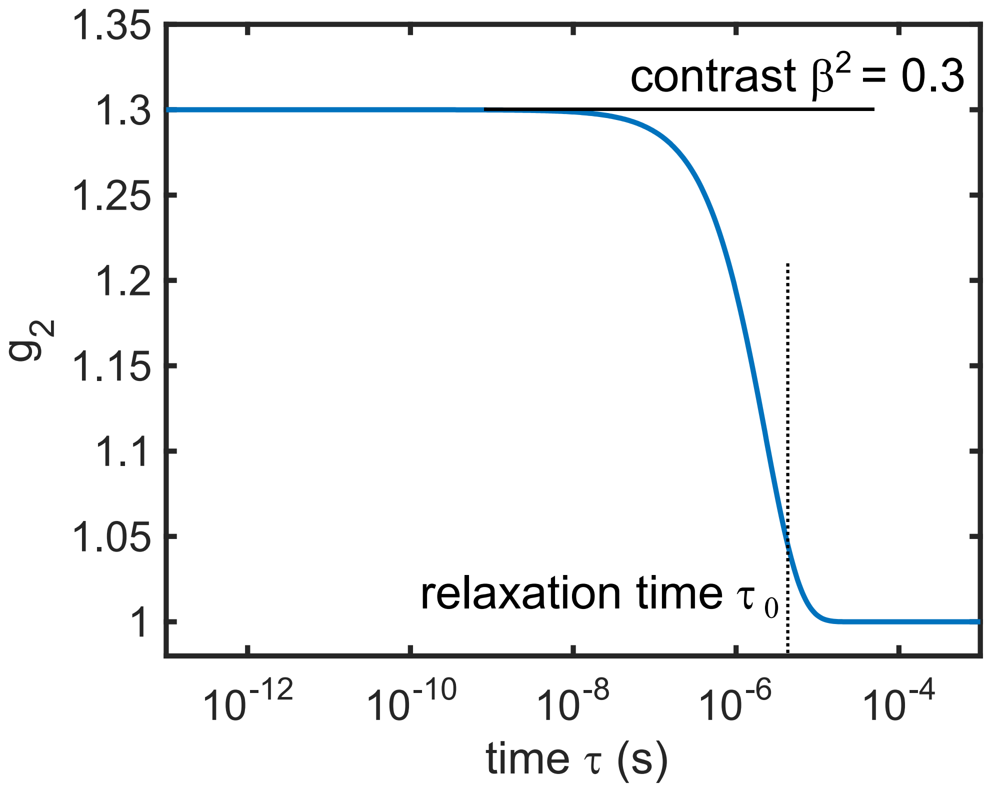
- On the other hand, known particles can be used to probe solvent properties, in particular viscosity η → microrheology

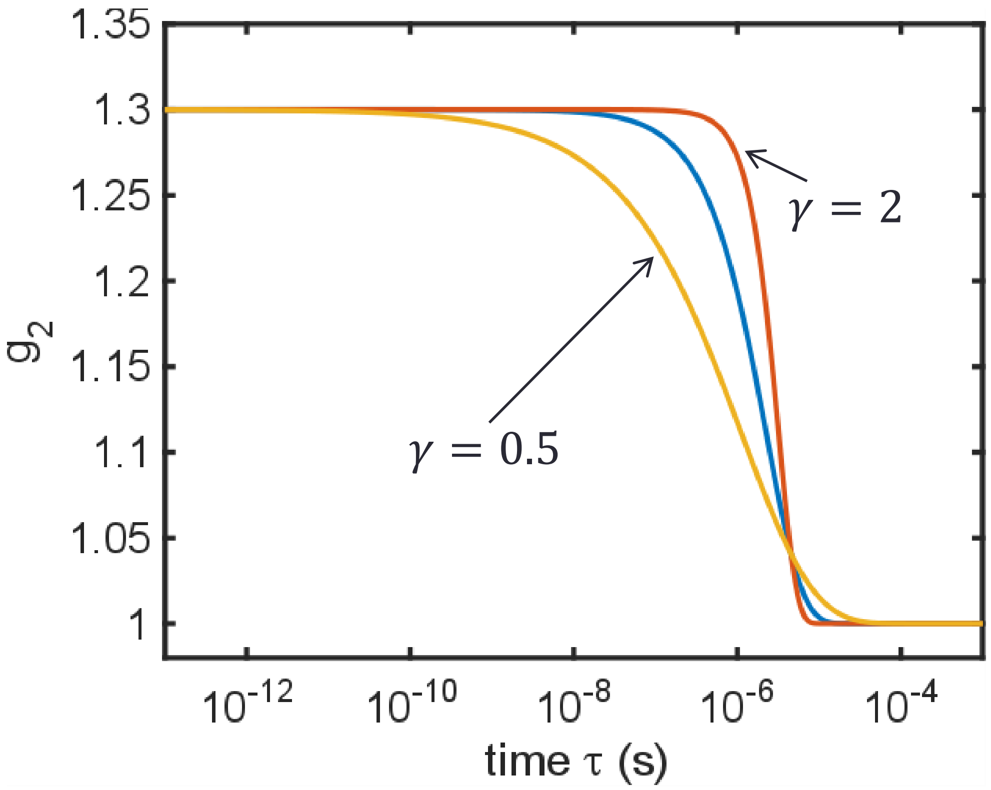


https://en.wikipedia.org/wiki/Microrheology

XPCS – correlation functions

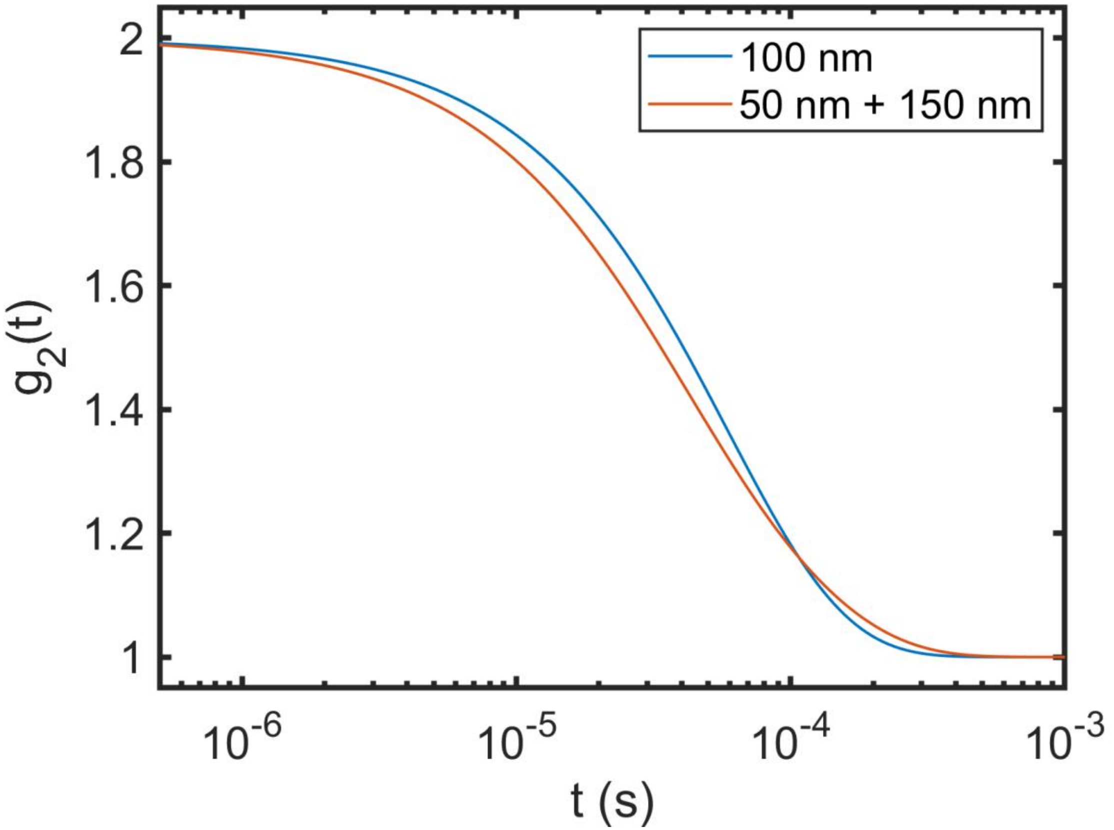
Spherical particles with $\mathrm{R} = 10$ nm in water





- Stretched and compressed correlation functions: Kohlrausch-Williams-Watts function $f(q,\tau) = \exp(-(\Gamma\tau)^{\gamma})$
- Measure of width of distribution of (local) relaxation times

XPCS – correlation functions



Example: heterogeneous dynamics

- Diffusive dynamics of 100 nm particles
- Compared to average of 50 nm and 150 nm particles (Note: scattering strength different in reality!)
- Correlation function appears stretched, here: $\gamma = 0.89$

→ disperse particles

→ dynamic heterogeneities, e.g. for glass transition (see lecture 19)

XPCS – correlation functions

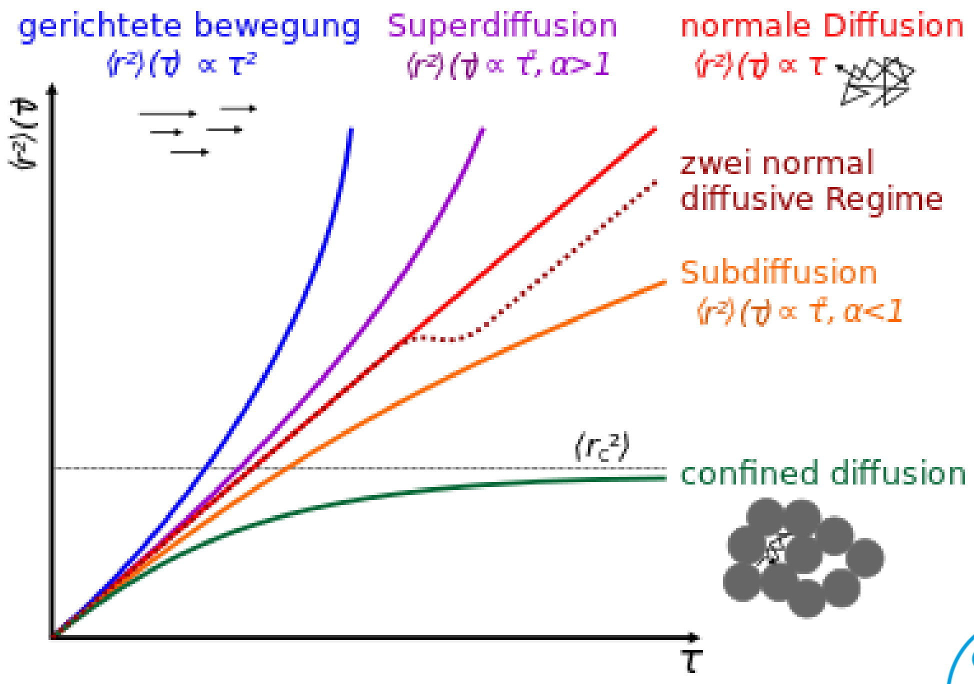
Q-dependencies

- Diffusion: $\tau_0 \propto q^{-2}$, $\langle r^2 \rangle \propto \tau$

- More general ($\tau_0 \propto q^{-\delta}$): $\langle r^2 \rangle \propto \tau^{\alpha} \rightsquigarrow \; r \propto \tau^{\frac{\alpha}{2}} \rightsquigarrow \tau \propto q^{\frac{2}{\alpha}} \quad \Rightarrow \quad \alpha\delta = -2$

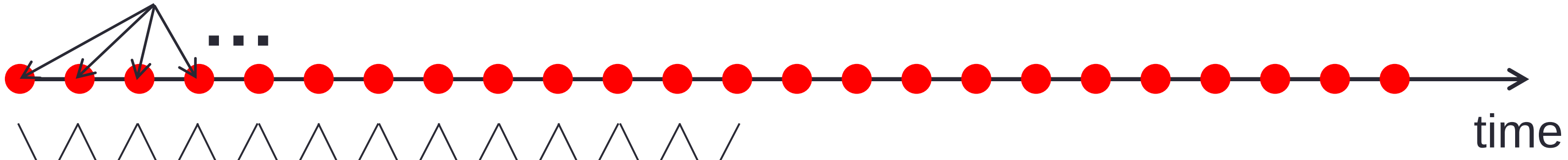
- Diffusion: $\delta = 2$
- Subdiffusion: $\delta > 2$
- Superdiffusion: $\delta < 2$
- Balistic motion: $\delta = 1$

→ The analysis of both exponents γ and δ provides information on the type of dynamics



XPCS – instantaneous correlation function

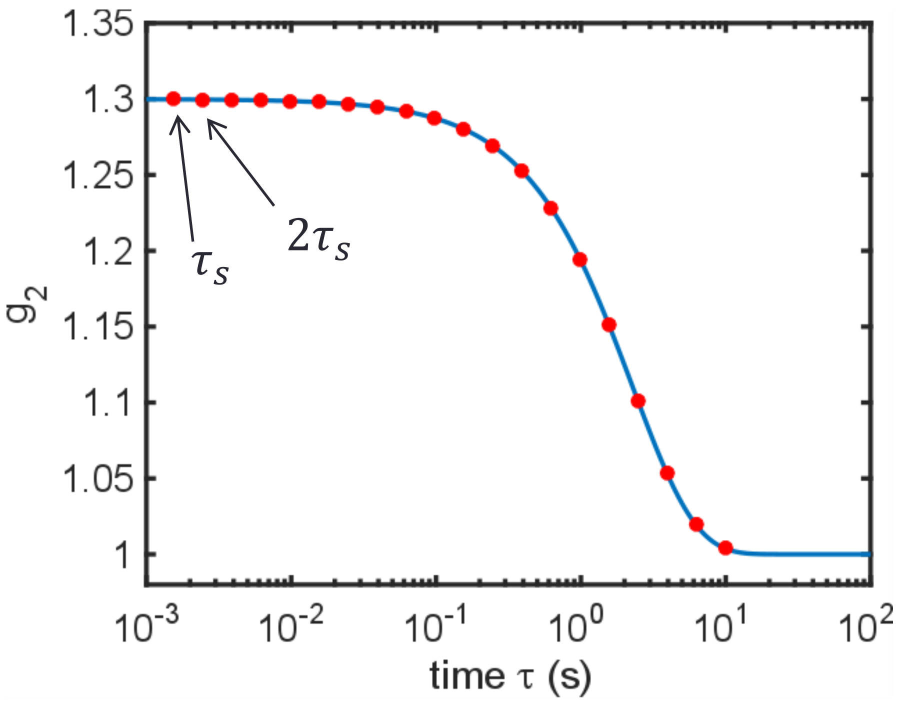
Measured speckle patterns



Correlate & average → Shortest lag time τ_s

Correlate & average → 2nd shortest lag time $2\tau_s$

⋮



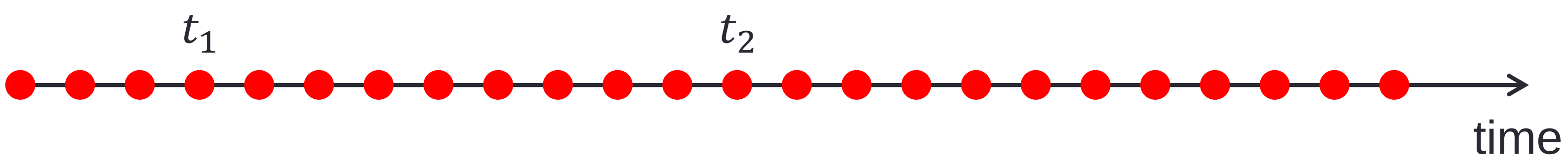
Standard procedure → $g_2(q,\tau)$ averaged over pairs of same lag time τ (…**and** pixels!) taken during the experimental run

XPCS – instantaneous correlation function

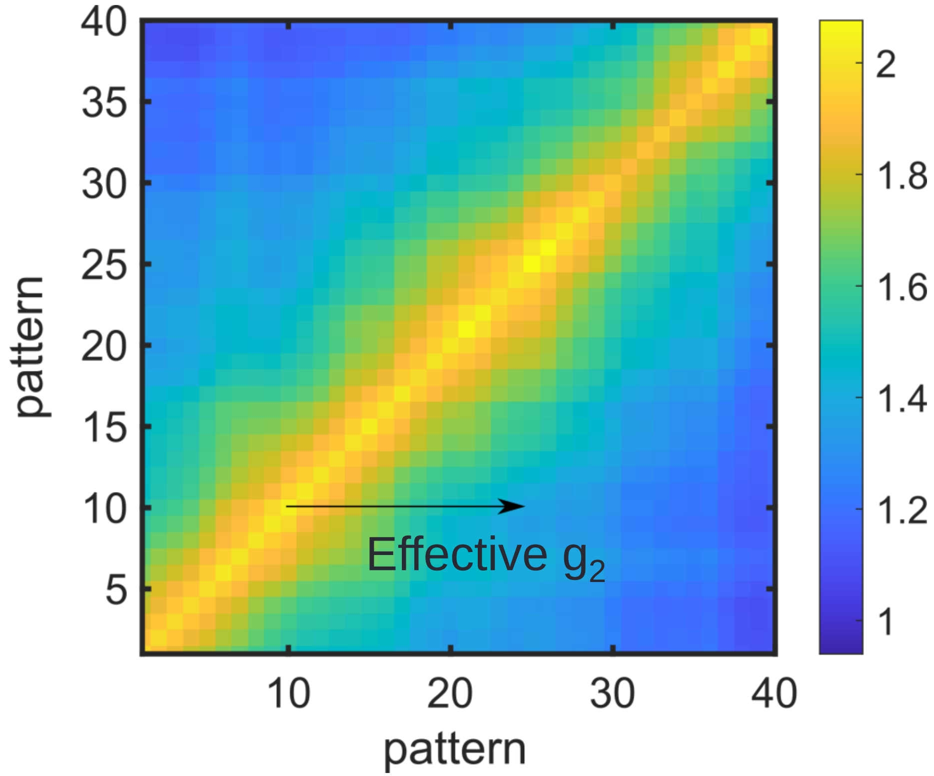
But: sample may change during the measurement

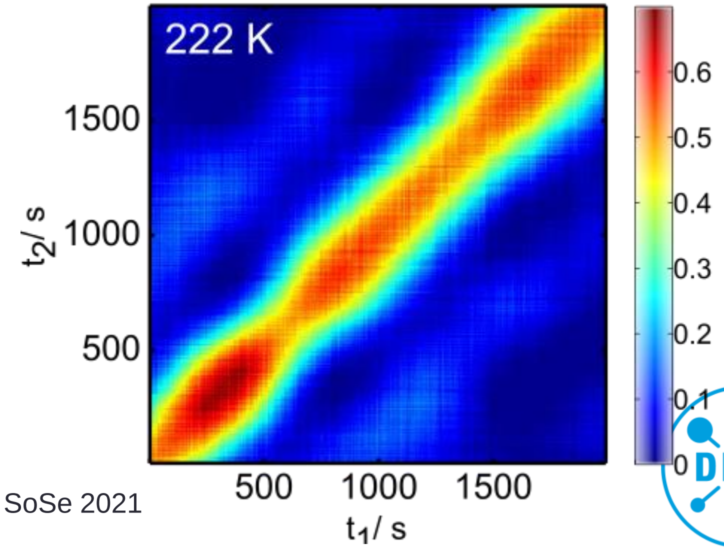
→ Two-time correlation function $C_I(q, t_1, t_2) = \frac{\langle I(q,t_1) I(q,t_2) \rangle}{\langle I(q,t_1) \rangle \langle I(q,t_2) \rangle}$

- t_1, t_2 are points in experiment time, e.g.:



- Example: t_1, t_2 = pattern number
- Sample ages along $t_1 = t_2$ diagonal $t_{age} = \frac{t_2 - t_1}{2}$
- Lag time $\tau = |t_2 - t_1|$
- Effective g_2 for each waiting time, e.g. $g_2(q, \tau) = C_I(q, t_1 - t_2, t_2 = const.)$

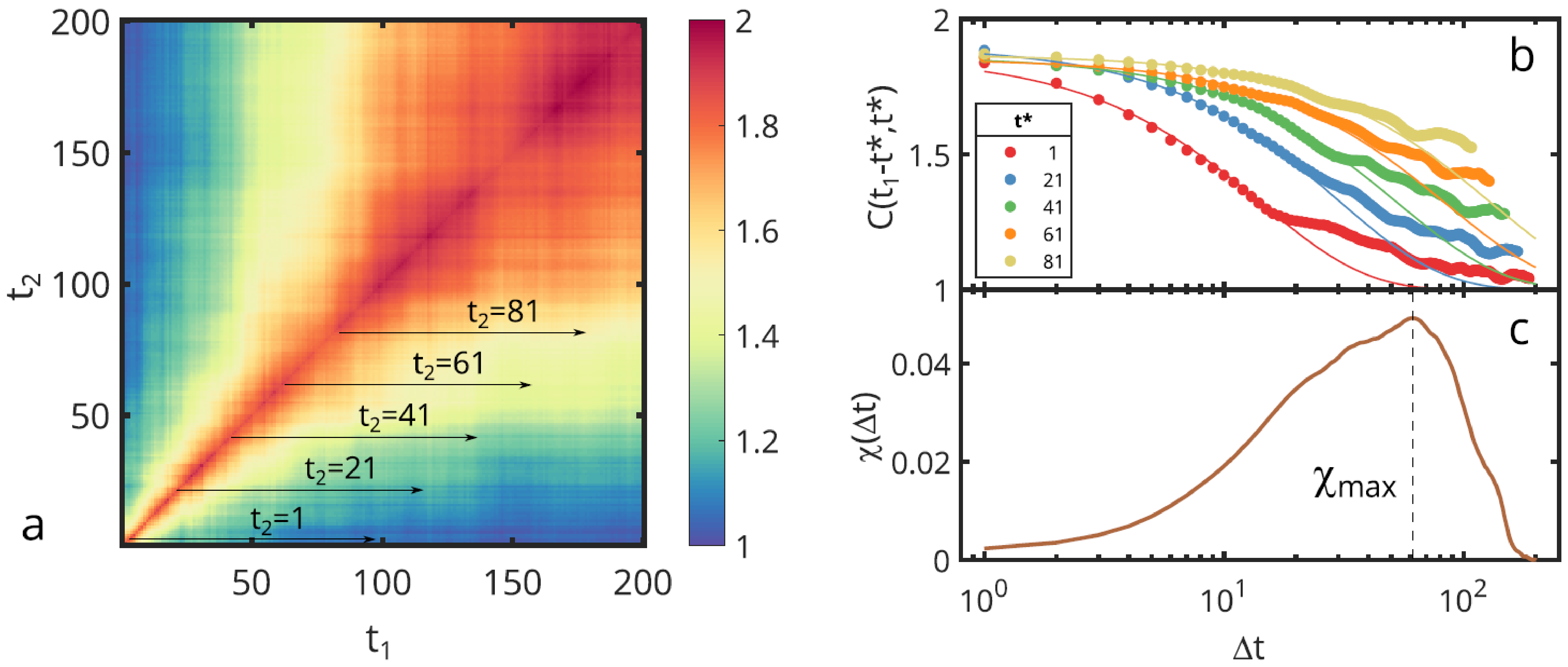




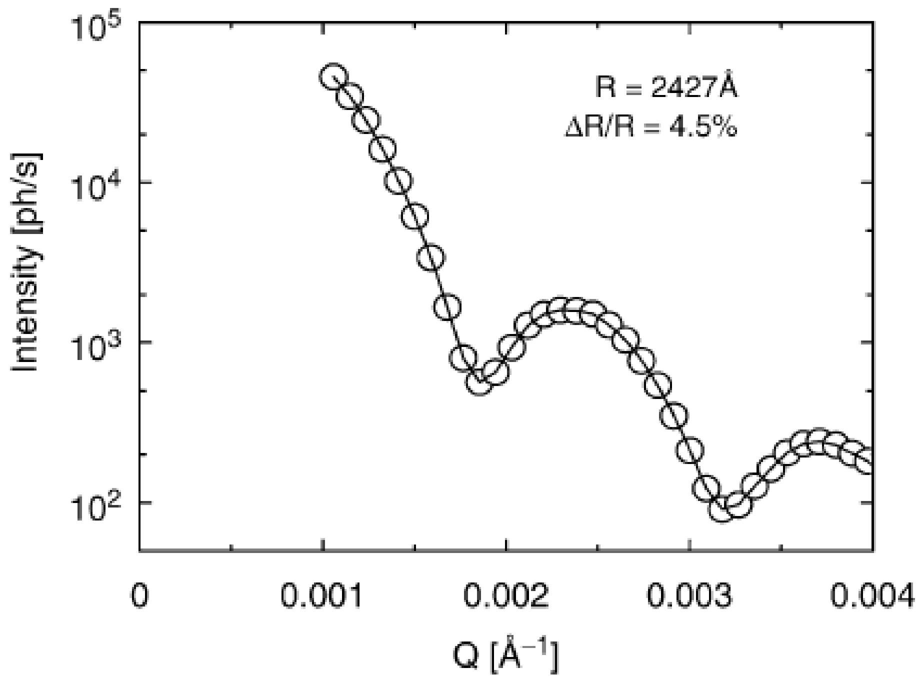
Experiment → Dynamical heterogeneities!

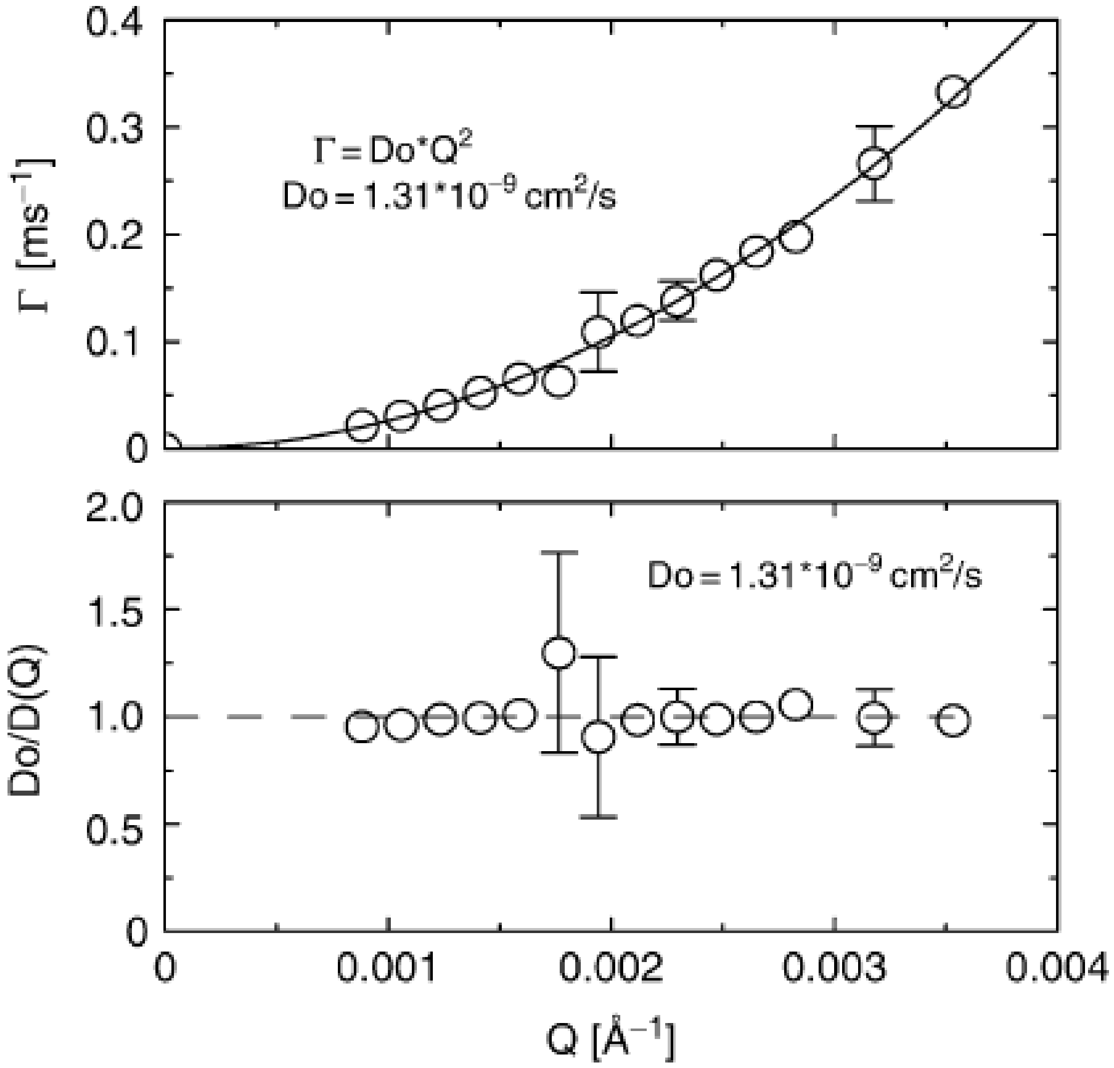
DESY.

Example for an aging sample



XPCS example 1 – dynamics in colloidal systems





G. Grübel et al. In "Soft Matter Characterization", Springer (2008)

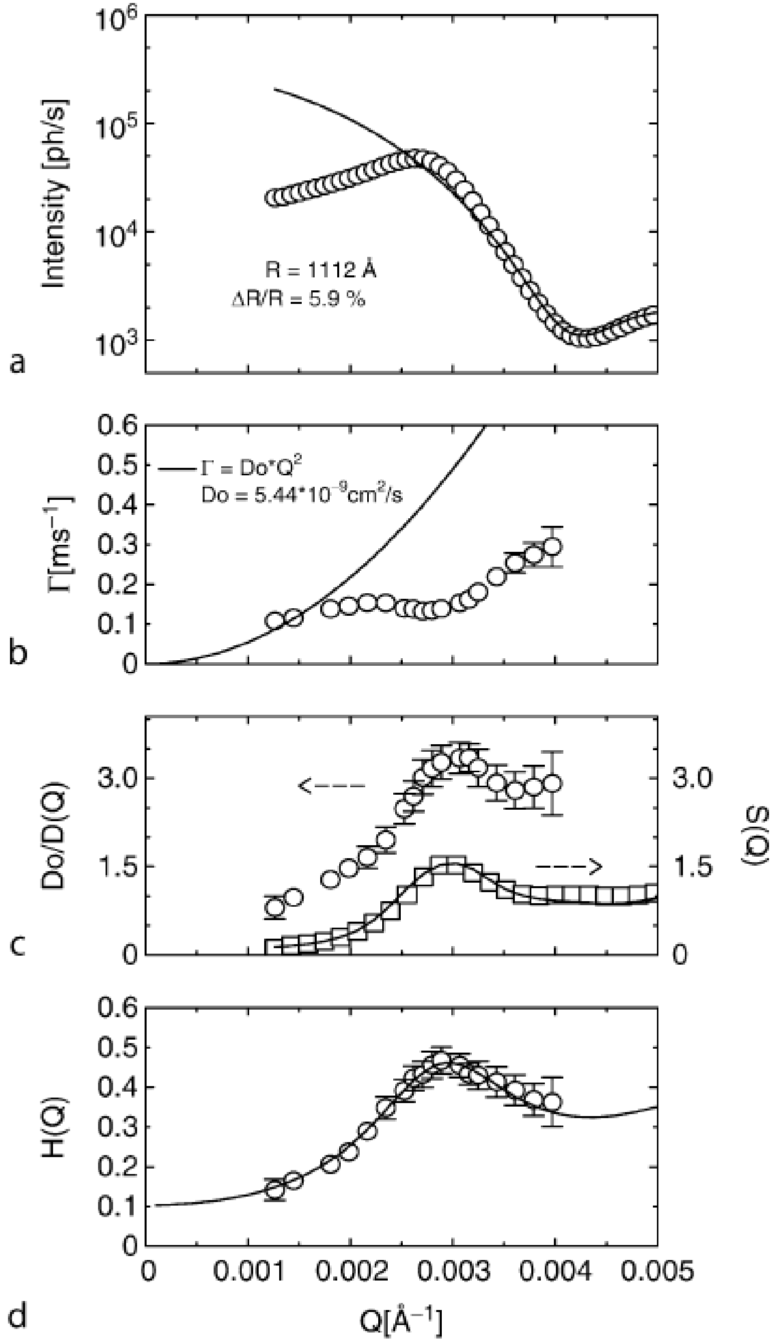
SiO_2 colloidal spheres in glycerol/water

- Low concentration: volume fraction 1%
- SAXS: Formfactor
- XPCS: diffusion with $\Gamma \propto q^2$

XPCS example 1 – dynamics in colloidal systems

PMMA particles in decalin

- High concentration: volume fraction 37%
- SAXS: Structure factor
- XPCS results deviate from $\Gamma \propto q^2$
- Effective diffusion constant $D(q) = D_0 H(q)/S(q)$ for short times, hydrodynamic function $H(q)$
- $H(q) = 1 \Rightarrow D(q) = D_0/S(q)$: de Gennes narrowing, i.e. slowing down around next-neighbour distances.



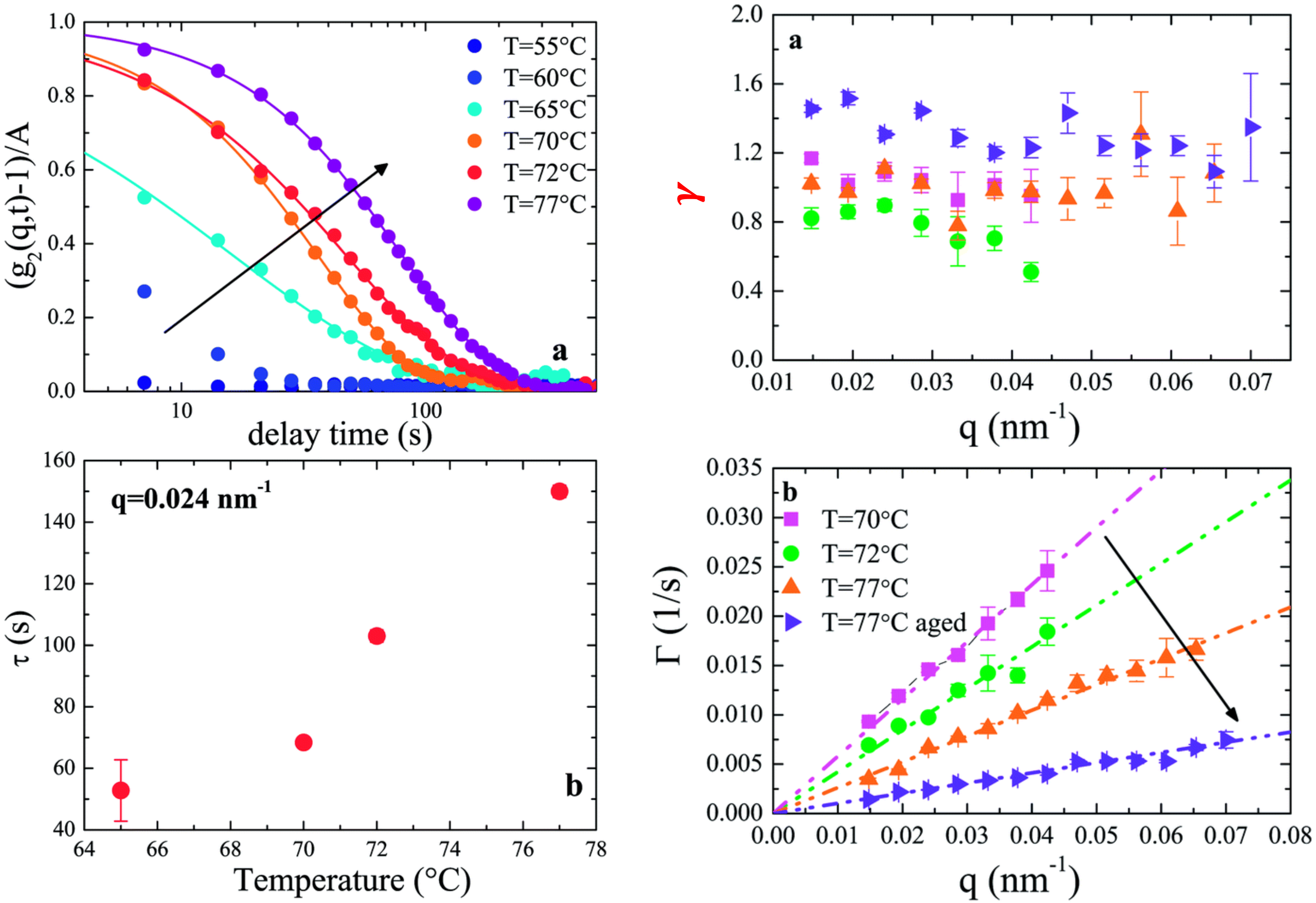
G. Grübel et al. In "Soft Matter Characterization", Springer (2008)

XPCS example 2 – microrheology

Tracer particles to measure solvent properties

- Weak scattering signal from solvent
- Large q-region has to be probed (low speckle contrast)
- Slower dynamics in SAXS regime
- Indirect access to solvent properties only
- Length scale of several 10 nm given by the tracer particle size
- Low tracer particle concentrations, so that $S(q) = 1$ for the particles → avoid any particle-solvent interactions

XPCS example 2 – microrheology

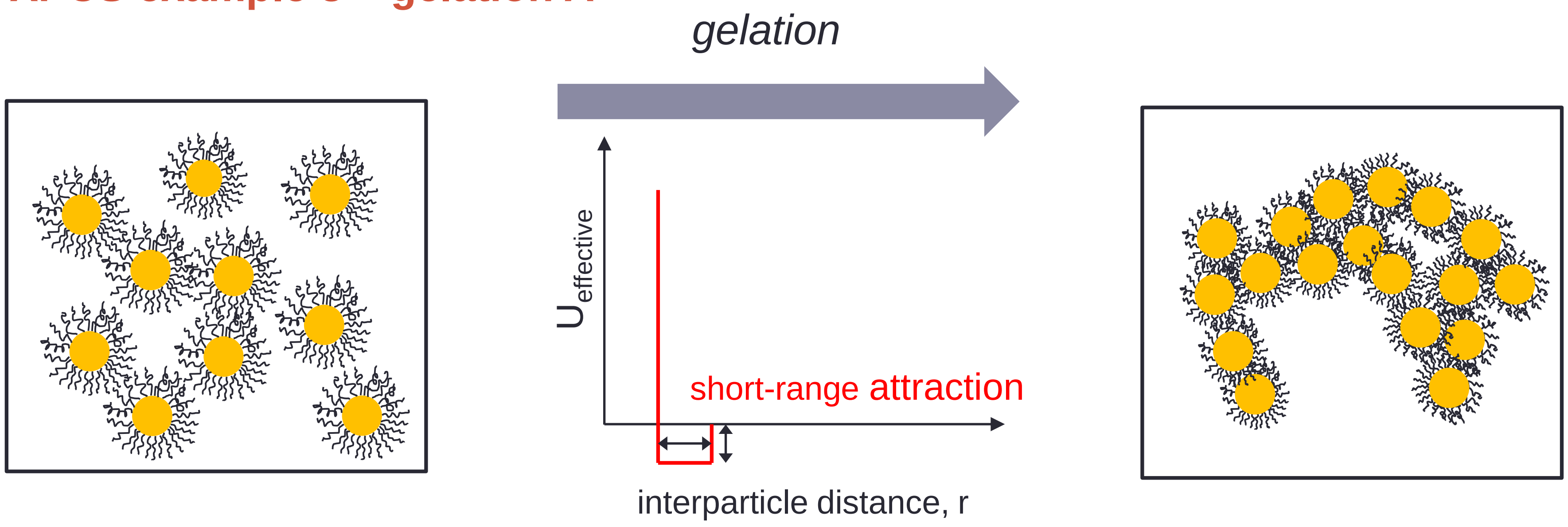


- SiO_2 particles as tracer for gelation of methylcellulose in water
- Gel-gel-transition: Turbid gel for $T \geq 60$ °C
- Stretched ($\gamma < 1$) to compressed ($\gamma > 1$) transition (KWW exponent!)
- Hyper-diffusive & compressed at high temperatures → stress-dominated

Glass transition studies: →Lecture 19

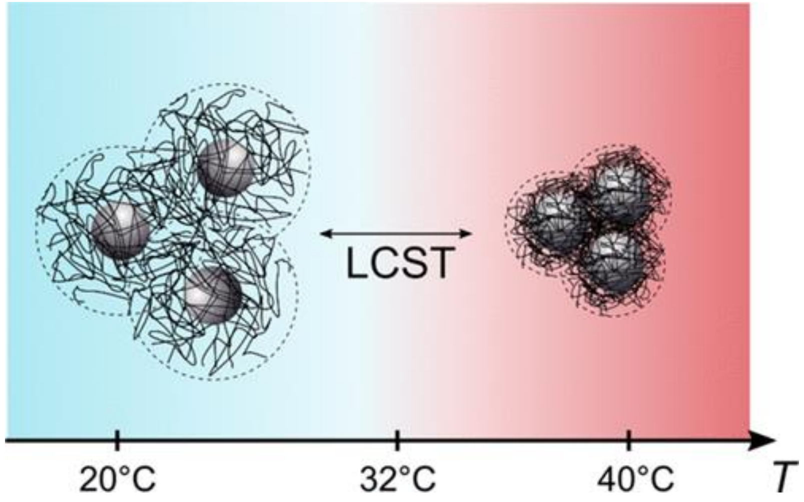
B. Ruta et al. Soft Matter 10, 4547 (2014)

XPCS example 3 – gelation A

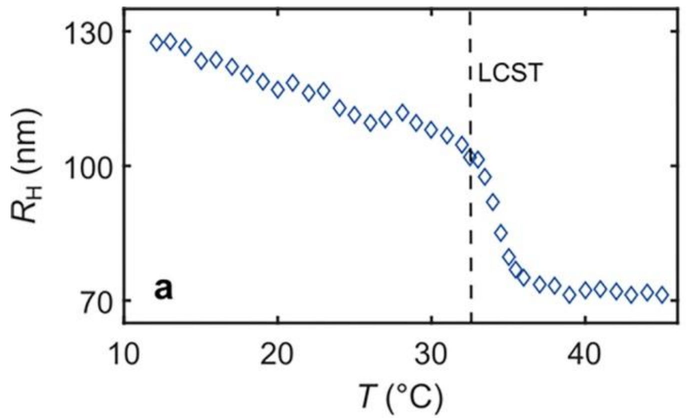


networked structure gives rise to arrested dynamics

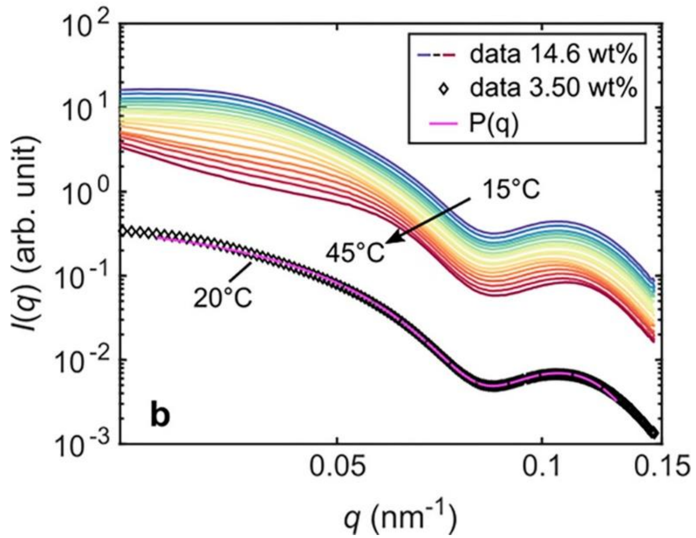
- Poly(N-isopropylacrylamide) (PNIPAM) particles (here: core-shell particles)
- Temperature-responsive: volume phase transition at ~32°C (LCST, lower critical solution temperature)
- Change of interaction potential: from repulsive to attractive upon heating → gelation



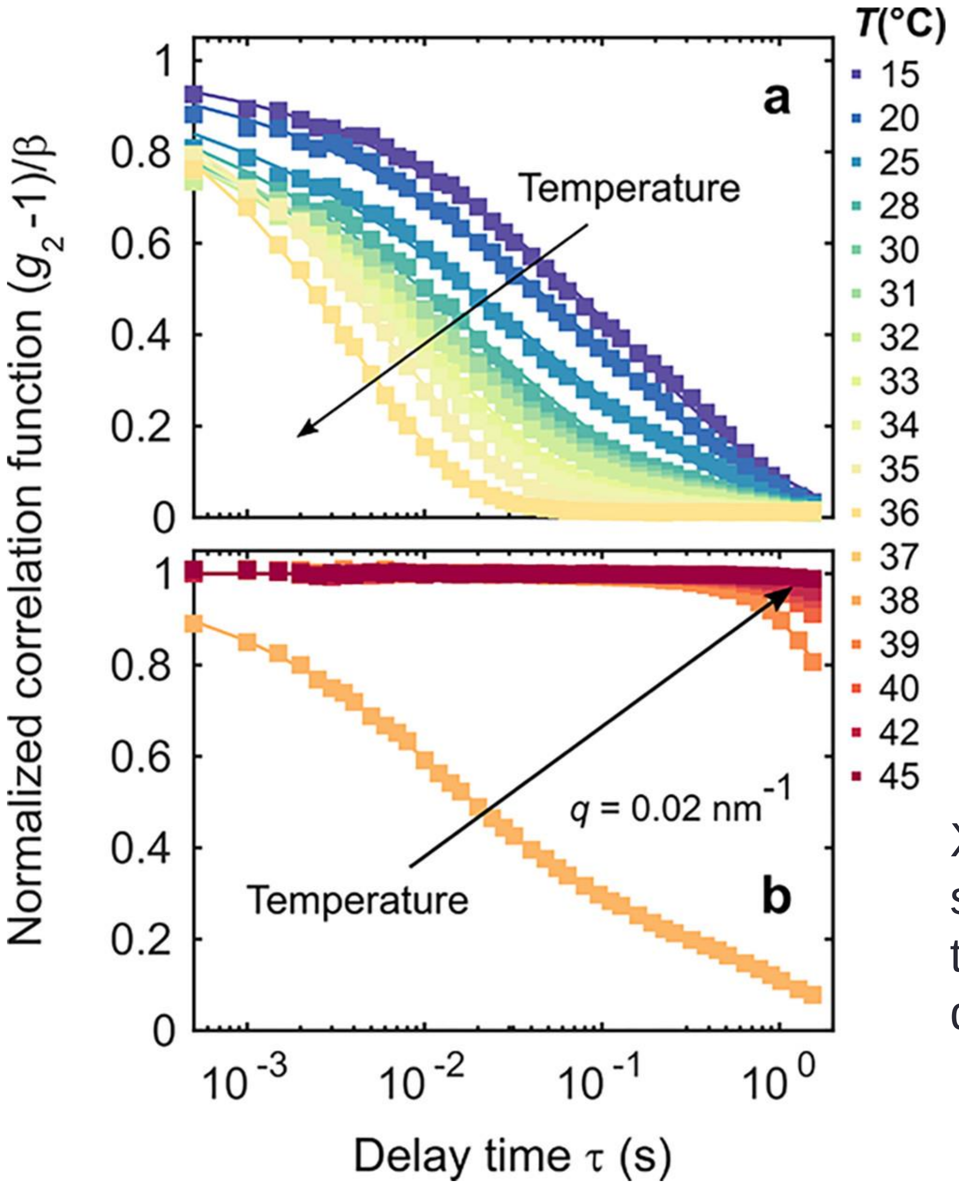
XPCS example 3 – gelation B



Particle radius



I(q) shows upturn for $q \rightarrow 0$ → indication of attractive interaction



XPCS: first speed up, then slow down

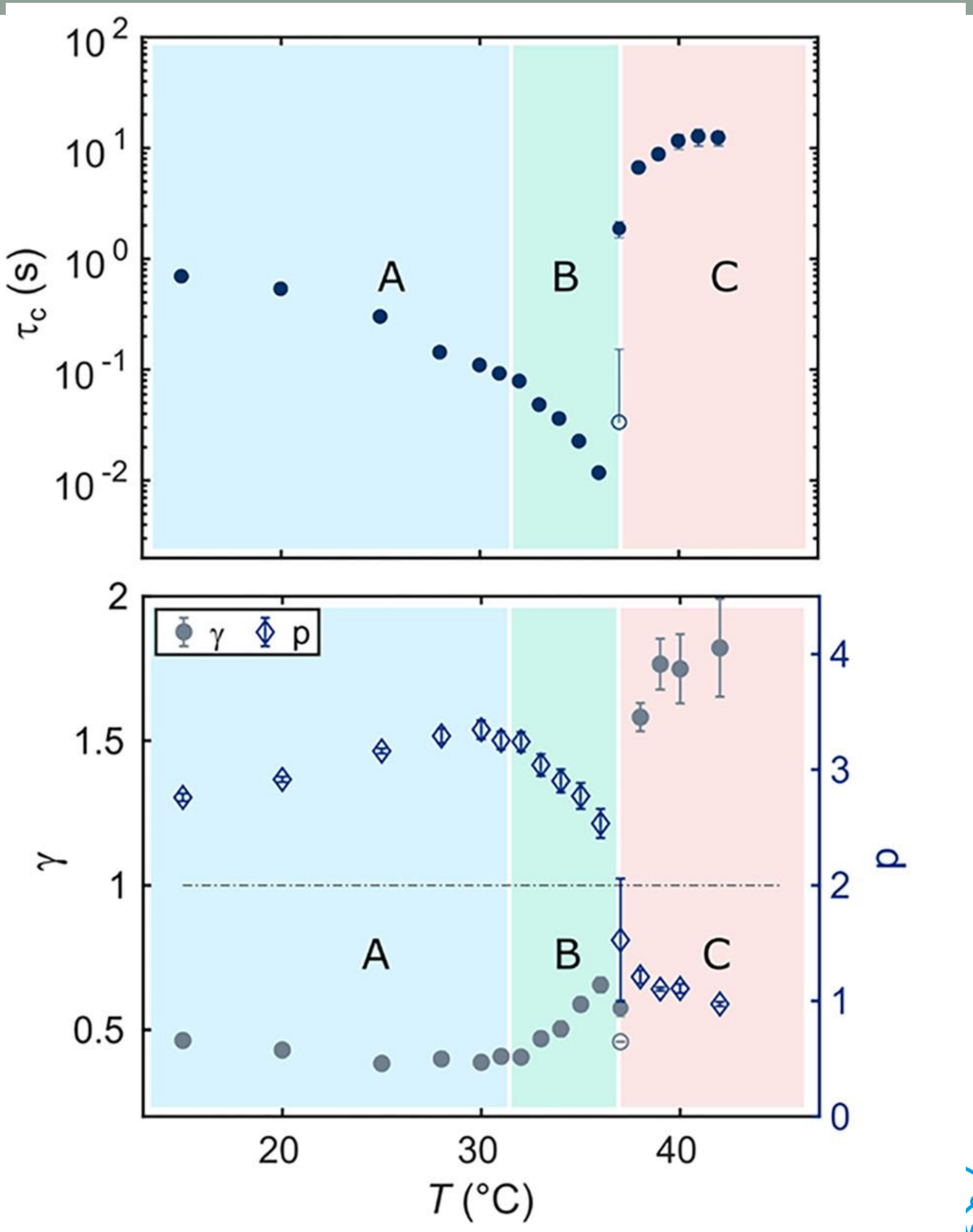
XPCS example 3 – gelation B

Correlation functions

- KWW model $g_2(q,\tau) = 1 + \beta \exp(-2(\tau/\tau_c)^\gamma)$
- Q-dependency: $\tau_c \propto q^{-p}$
- Three regimes
  a. Subdiffusive dynamics with $p \approx 3, \gamma \approx 0.5$
  b. Speed up with $p > 2, \gamma < 1$ & second decay
  c. Sudden slow-down with $p \approx 1, \gamma \approx 2$

Results

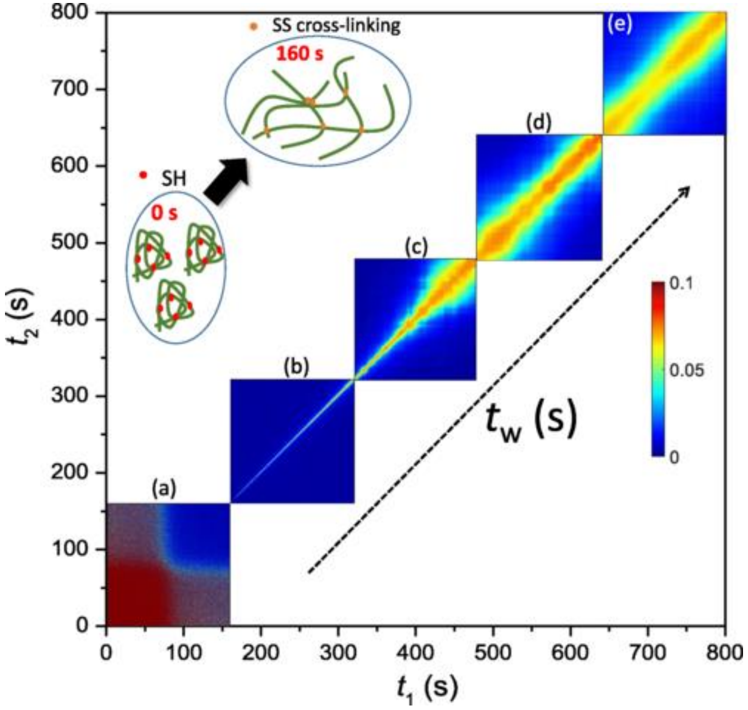
- Polymer-driven dynamics below LCST
- Colloidal gel above ~37°C, well above LCST

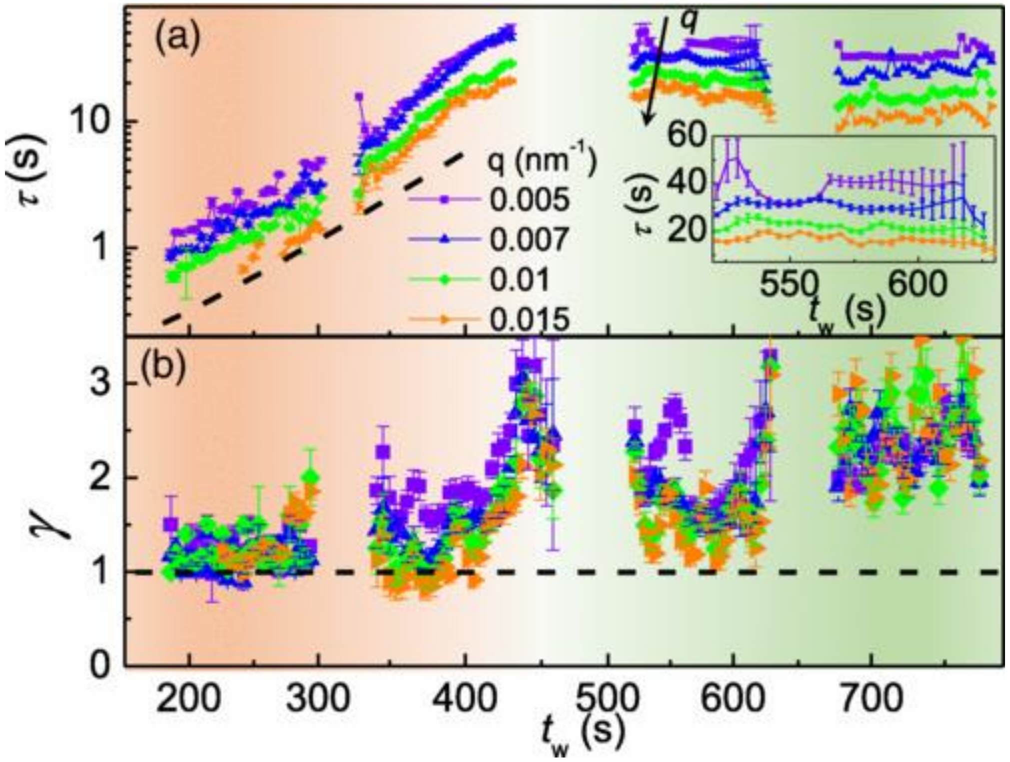


L. Frenzel et al. J. Phys. Chem. Lett. 10, 5231 (2019)

XPCS example 4 – Network formation and heterogeneous dynamcis in egg cooking

Time evolution of the dynamics of egg white after heating to 80 °C





Network formation after 400 s

→ „perfect“ egg takes about 6.5 min

N. Begam et al. Phys. Rev. Lett. 126, 098001 (2021)

XPCS example 5 – directed motion

Sample undergoes (shear) flow

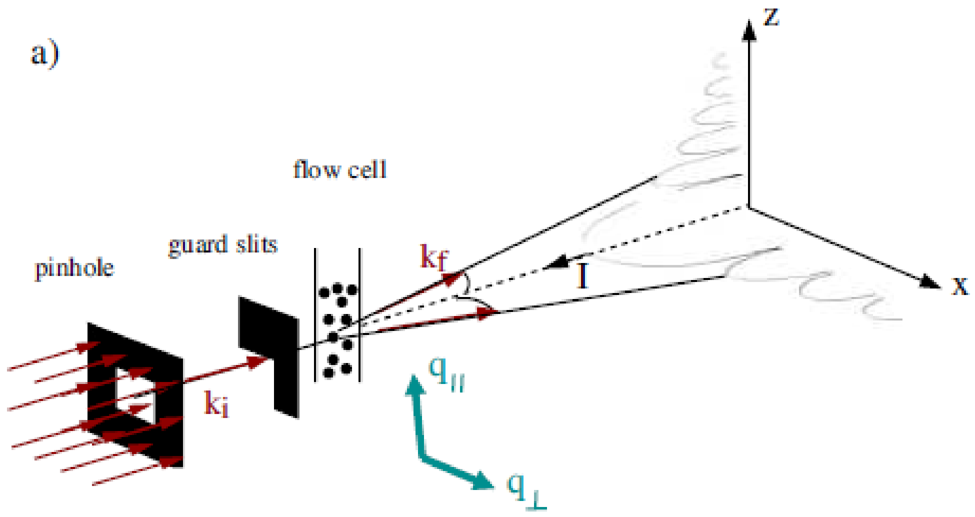
- Flowing sample to avoid radiation damage
- Sedimentation of particles

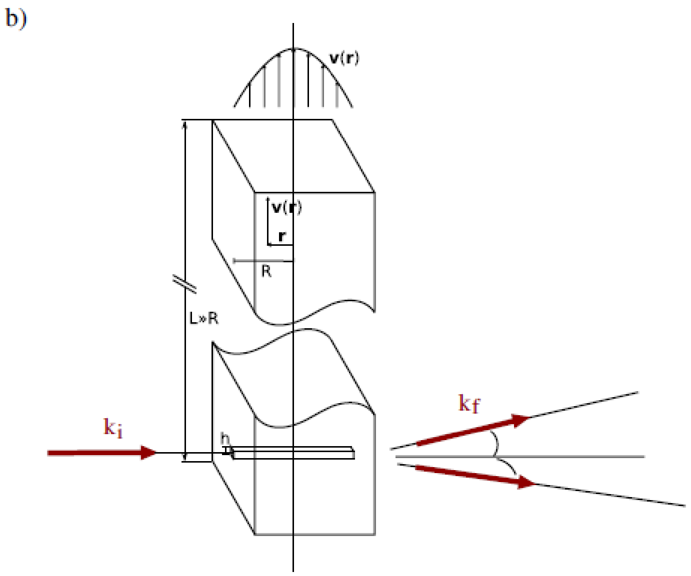
- $f(q,\tau)$: product of diffusive and advective contributions
  $f(q,\tau) = f_d(q,\tau) \cdot f_a(q,\tau) = \exp(-\Gamma t) \cdot f_a(q,\tau)$

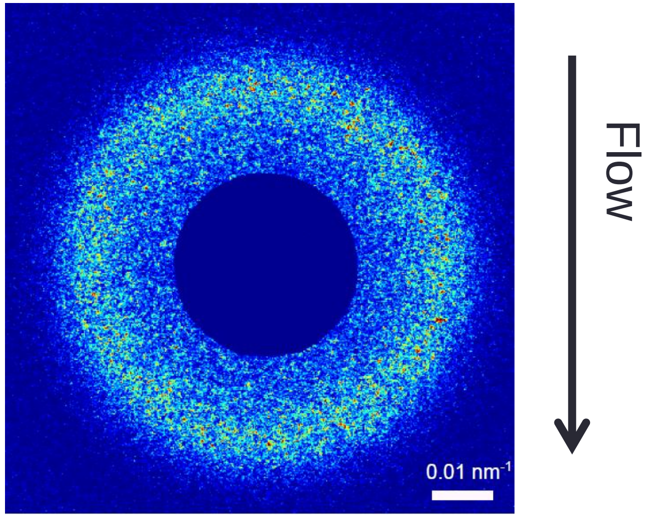
- $f_a(q,\tau)$ can become complicated

Perpendicular to flow it simplifies to
$g_{2,\perp}(q,\tau) = 1 + \beta^2 \exp(-2\Gamma\tau) \exp(-(\nu_{tr} t)^2)$,
transit-induced frequency ν_{tr}

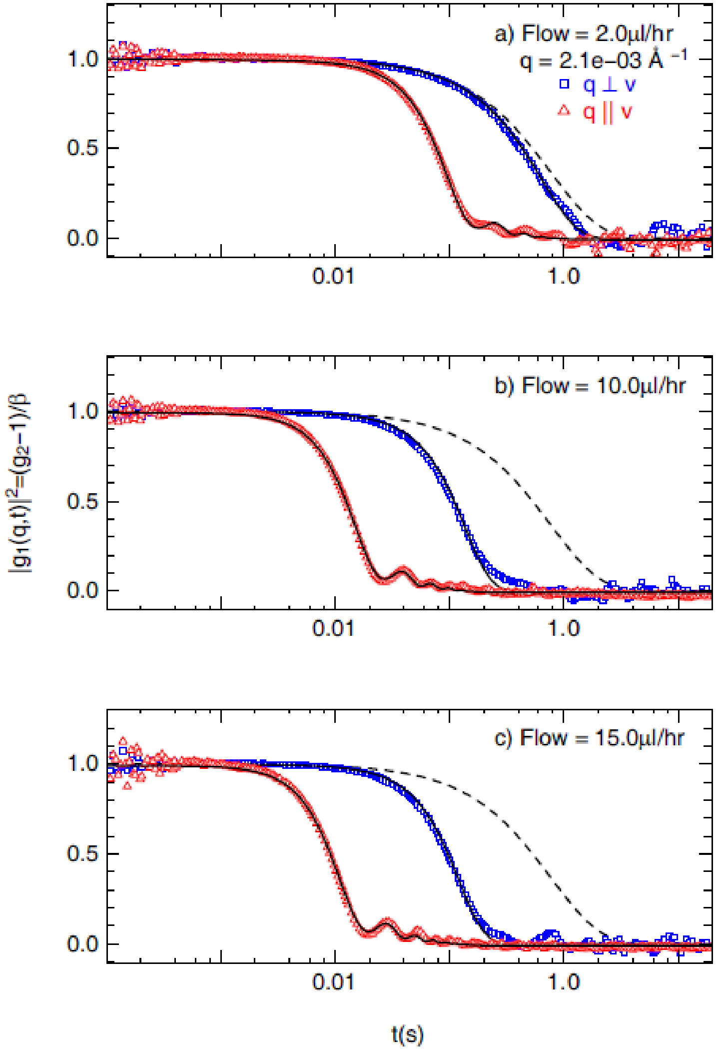
In flow direction: oscillating behaviour



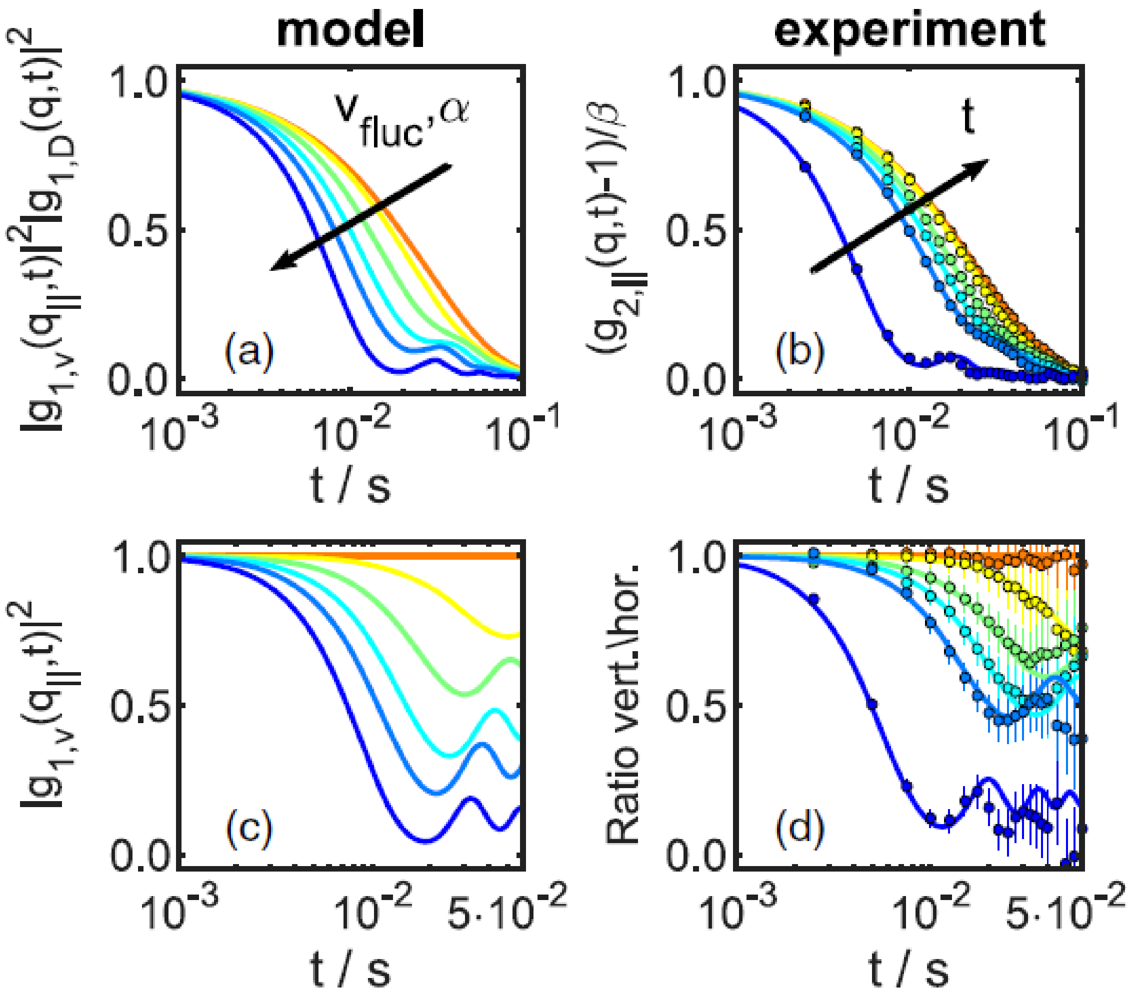




XPCS example 5 – directed motion



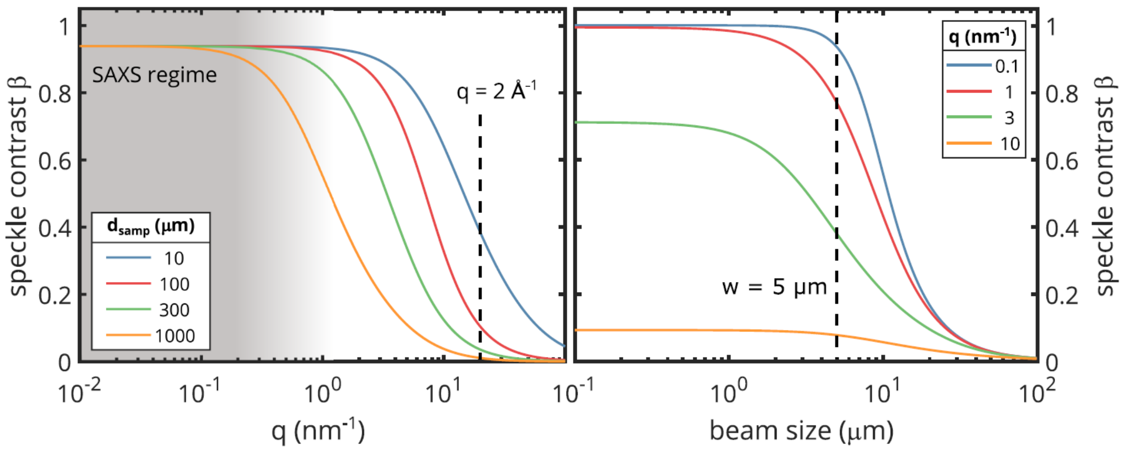
S. Busch et al. Eur. Phys. J. E 26, 55 (2008)

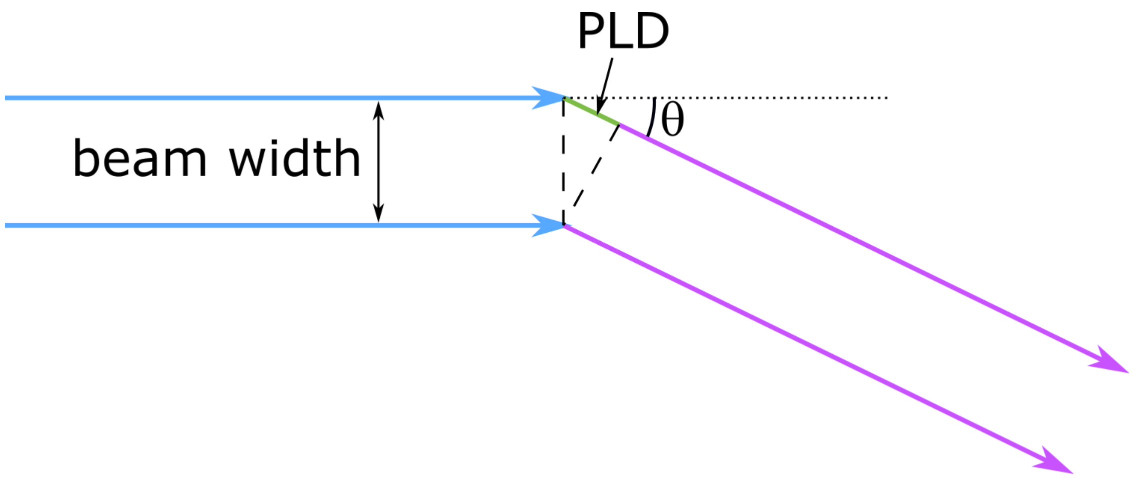


Particle sedimentation

J. Möller et al. PRL 118, 198001 (2017)

XPCS example 6 – Large q





Reduced speckle contrast at large q (molecular length scales) because of longitudinal coherence length → path length differences

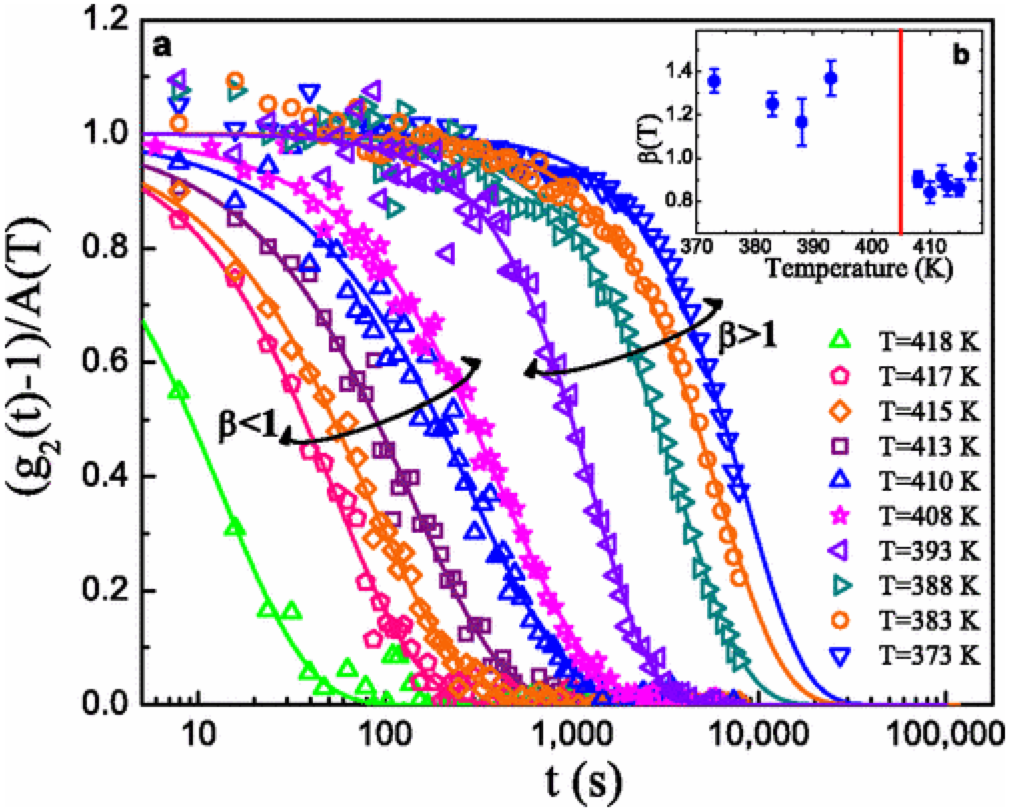
Mainly dependent on energy bandwidth, beam size, sample thickness → small beams and thin samples

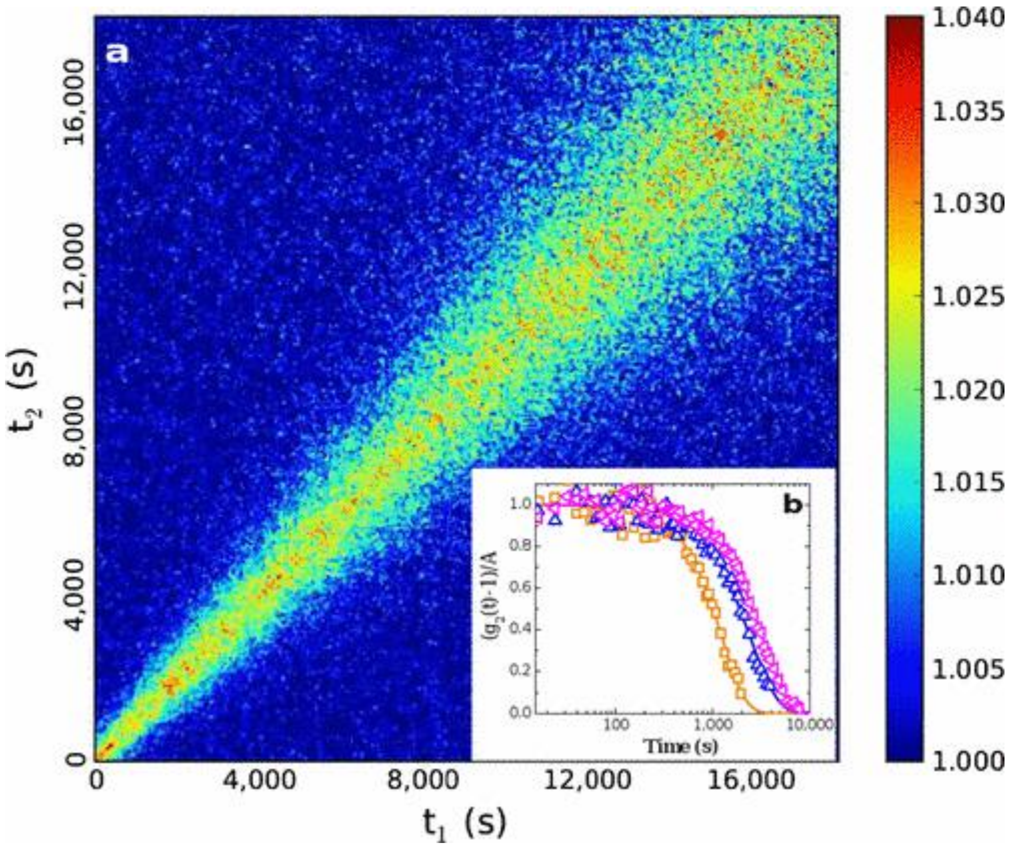
SAXS: $\theta \approx 0.1°$ → PLD < 0.02 µm

WAXS: $\theta = 25°$ → PLD = 4.2 µm
(beam width 10 µm)

Compare to longitudinal coherence length of few µm

XPCS example 6 – Large q



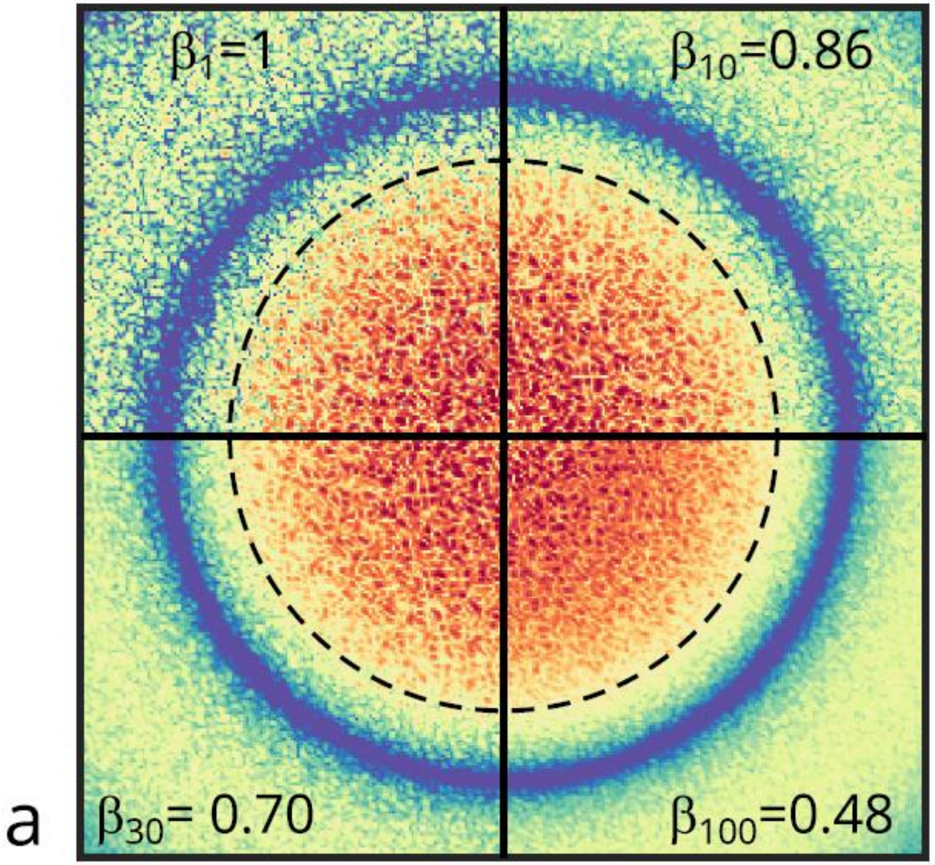


Atomic scale dynamics from metallic glasses

Here: $q \approx 2.56$ Å^{-1} → length scale of $\frac{2\pi}{q} \approx 2.5$ Å

→ More details in upcoming lectures

XPCS example 7 – X-ray speckle visibility spectroscopy



Dynamics via change of exposure times

- Contrast as function of exposure ($\beta^2 = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1$)
- $\beta^2(q, t_e) = \frac{2\beta_0^2}{t_e} \int_0^{t_e} \left(1 - \frac{\tau}{t_e}\right) |f(q,\tau)|^2 d\tau$
- For diffusion, this can be solved analytically (→ Exercise!)
- Limited by accessible exposure times
  - Pulse lengths (FEL)
  - Detector read out & flux (storage rings)
- FEL: pulse lengths variations & split-pulse applications
- Examples: Lecture 21

XPCS: further examples

- Glass dynamics and glass transition (→ lecture 19)

- In general, large q experiments
    - Water (→ lecture 20)
    - Hard condensed matter
    - Atomic diffusion
    - Domain wall dynamics
    - Network glasses (SiO_2, …)
    - …

- Liquid surfaces: capillary waves → oscillating ISF

- Outlook for new X-ray sources → Lecture 21

- …

- Relation to neutron spin echo and dynamic light scattering