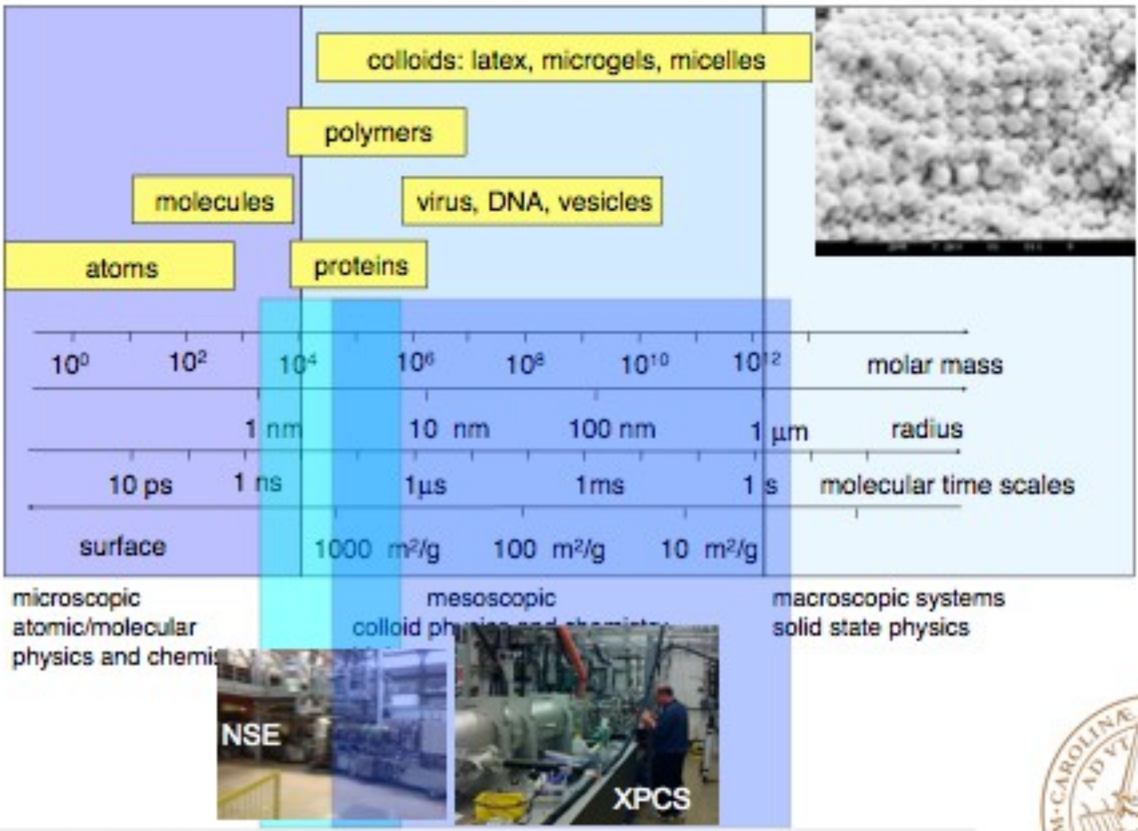
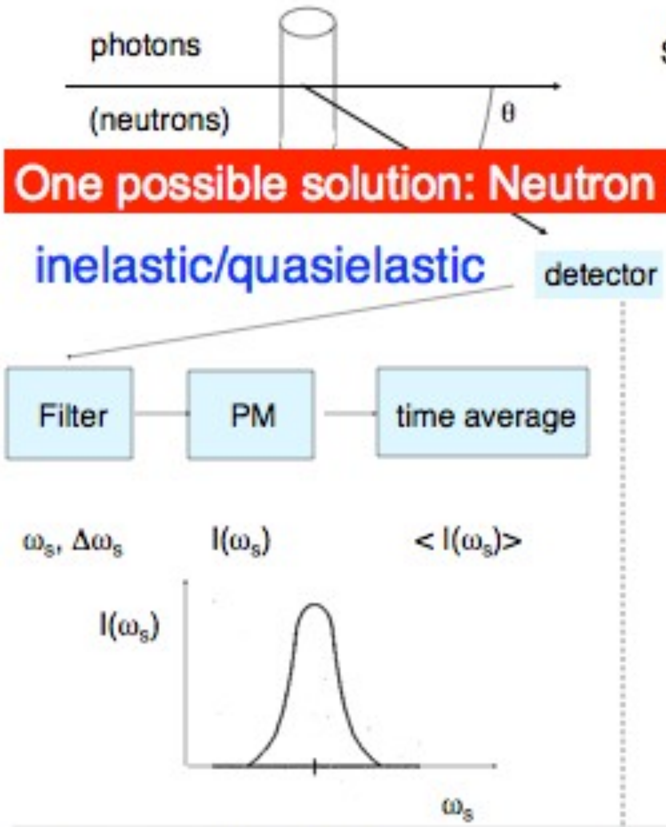
Characteristic length and time scales



Two generic experiments for dynamic information



One possible solution: Neutron spin echo experiments

Scattering vector $q = (4\pi/\lambda)\sin(\theta/2)$

spatial resolution ~ $1/q$

Problems:

- Line width for soft matter samples

$\Gamma = Dq^2$

Example: nanoparticle, R = 10 nm
$D = 2.5 \times 10^{-11}$ m²/s
for q = 0.6 nm^{-1} -> $\Gamma = 9 \times 10^6$ s^{-1}

- Intensity

The neutron spin

Is there any information the neutron carries with itself?
— Yes:

Spin Direction

Neutron spin in magnetic field described by

Bloch equation:

$$\frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = \frac{g_n \mu_N}{h} (\mathbf{P} \times \mathbf{B})$$

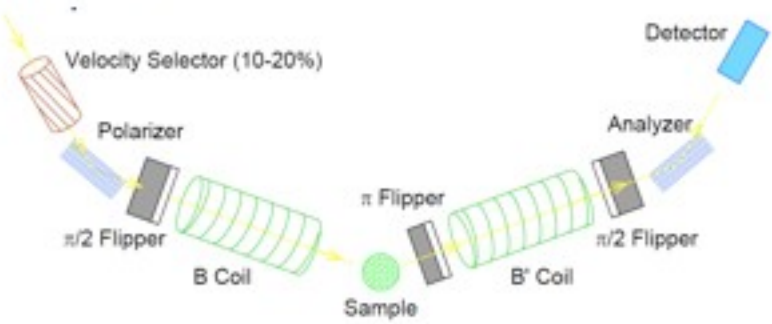
Larmor precession in constant field:

$$\omega_L = \frac{g_n \mu_N}{h} B \leftrightarrow 2900 \frac{\text{rot/s}}{\text{Gauss}}$$

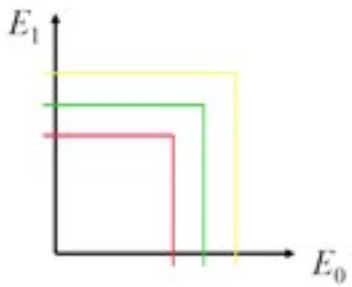
... used as individual stop-watch

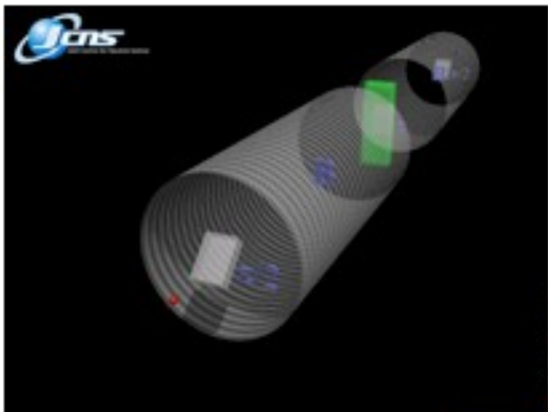
(courtesy R. Zorn, Bombannes-Lectures)

Neutron Spin Echo



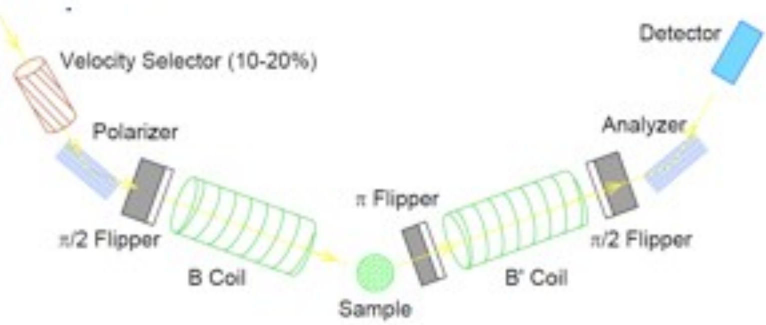
Spin development, elastic:



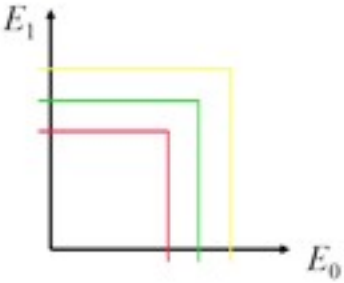


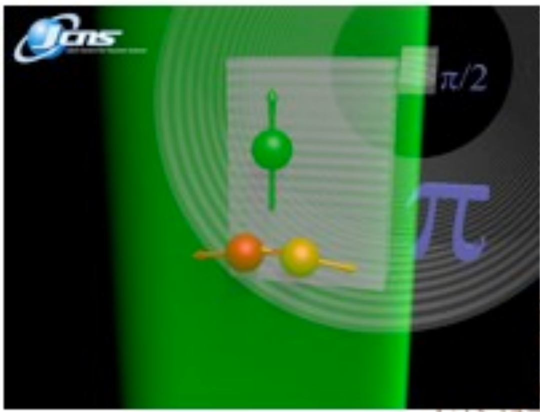
(courtesy R. Zorn, Bombannes-Lectures)

Neutron Spin Echo



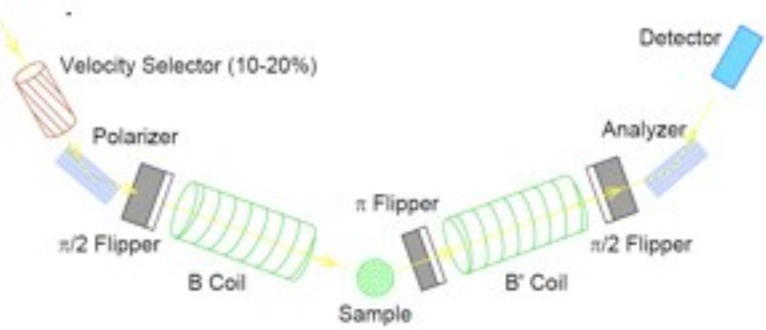
Spin development, elastic:



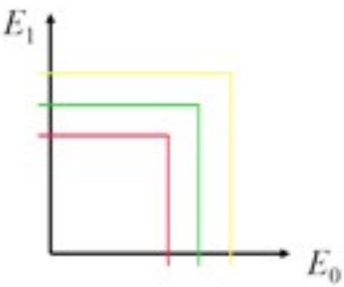


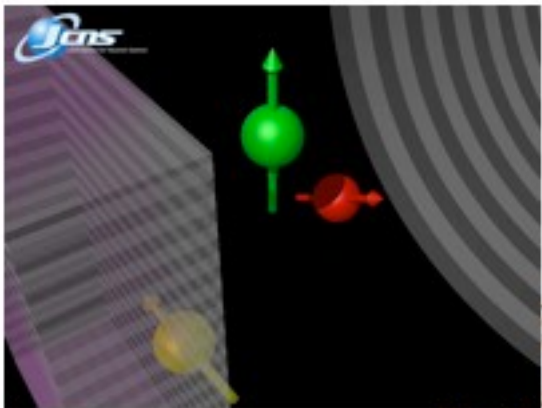
(courtesy R. Zorn, Bombannes-Lectures)

Neutron Spin Echo



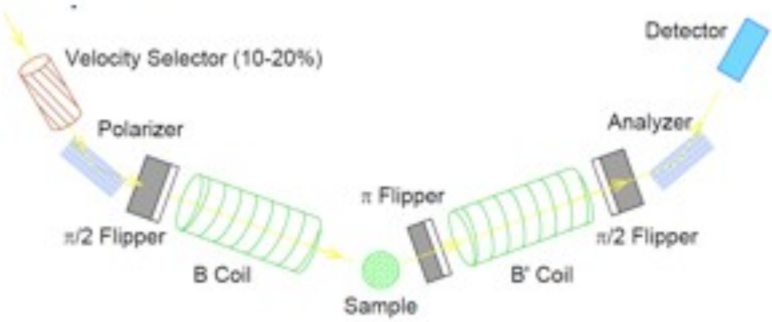
Spin development, elastic:



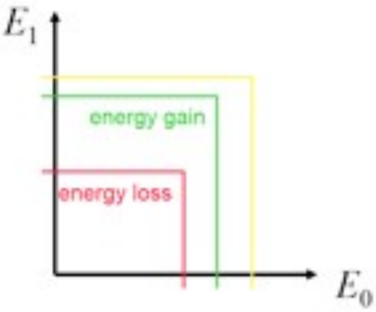


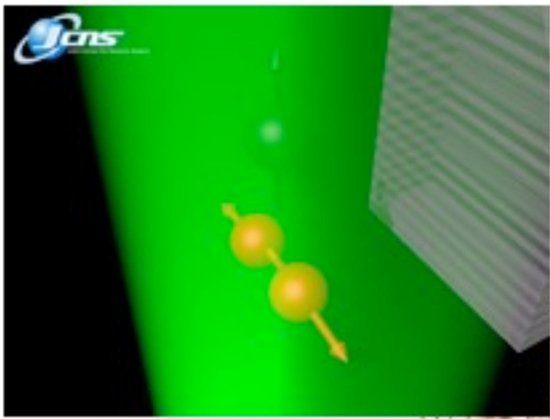
(courtesy R. Zorn, Bombannes-Lectures)

Neutron Spin Echo



Spin development, inelastic:





(courtesy R. Zorn, Bombannes-Lectures)

NSE Theory

Precession angle mismatch:

sensitivity proportional to λ^3

$$\Delta\phi = \left(\frac{2\pi |g_n| \mu_N m_n}{h^2}\right) Bl\,(\lambda_f - \lambda_i) \approx \underbrace{\frac{|g_n| \mu_N m_n \lambda^3 Bl}{h^3}}_{t_{NSE}(B)}\,\omega$$

time parameter proportional to B and current

$\Rightarrow$ Loss of polarization:

$$P = \cos\Delta\phi$$

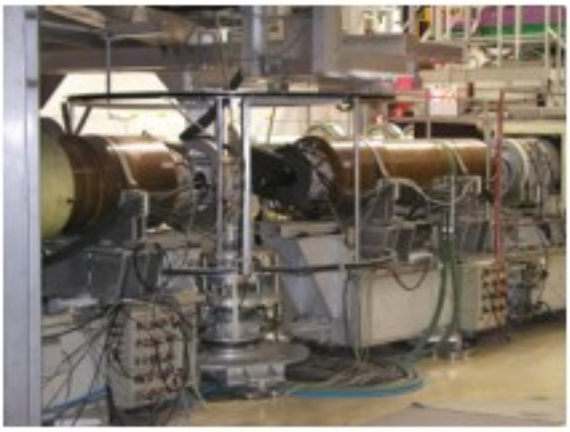
... averaged over all scattered neutrons:

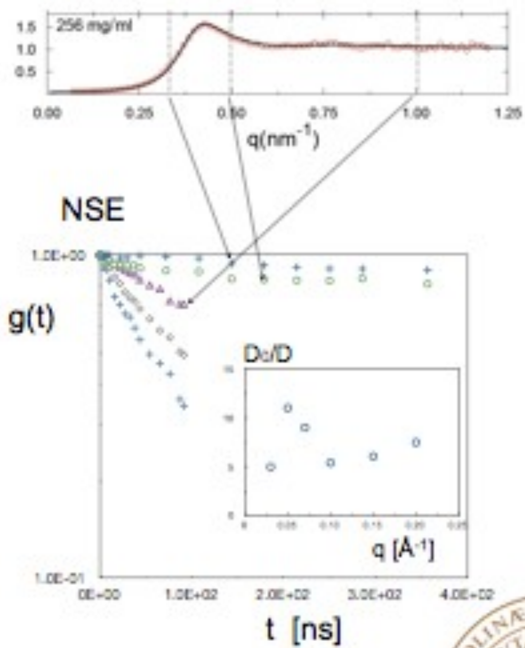
$$P(Q, t_{NSE}) = \frac{\int_{-\infty}^{\infty} S(Q,\omega)\cos(\omega t_{NSE})\,d\omega}{\int_{-\infty}^{\infty} S(Q,\omega)\,d\omega} = \frac{I(Q, t_{NSE})}{I(Q,0)}$$

Neutron Spin Echo measures directly the normalized intermediate scattering function!

(courtesy R. Zorn, Bombannes-Lectures)

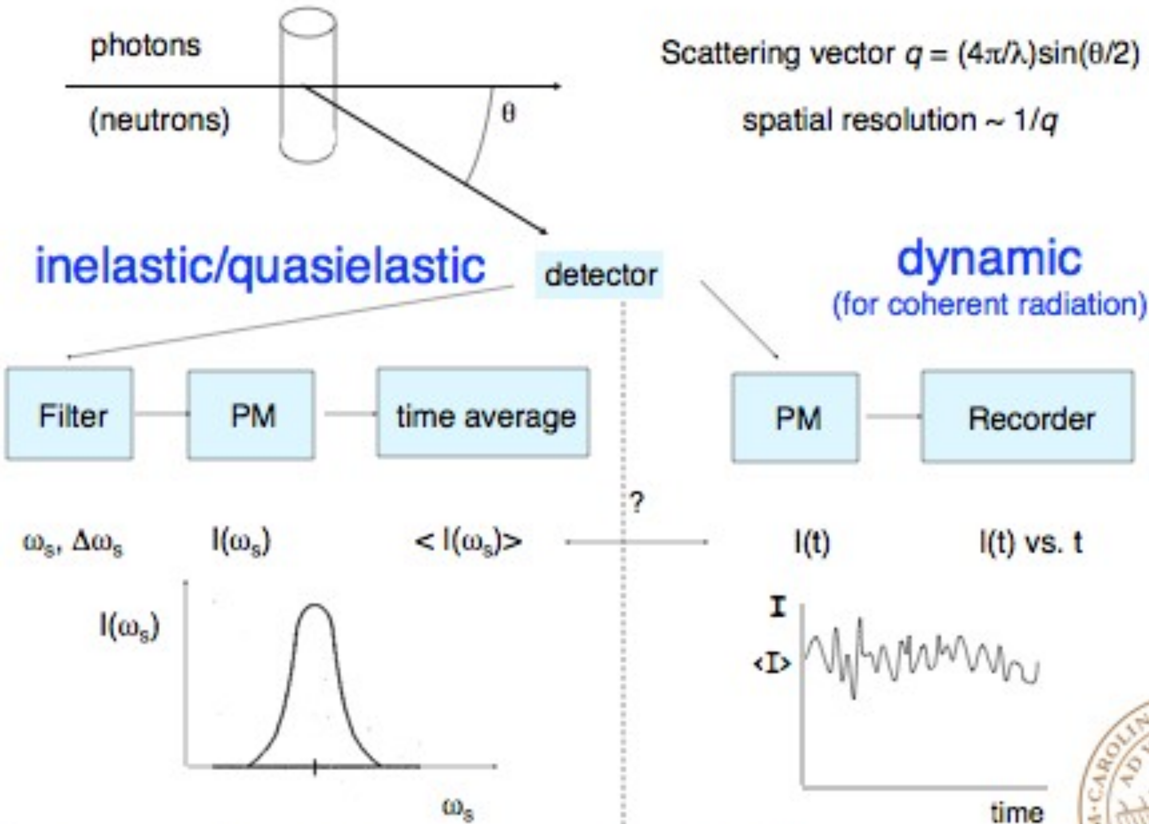
Example: Diffusion of concentrated proteins



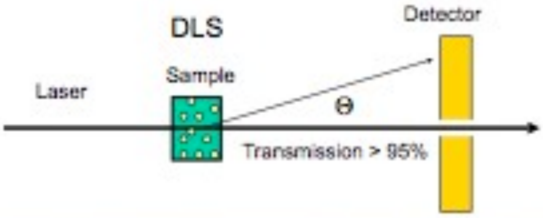


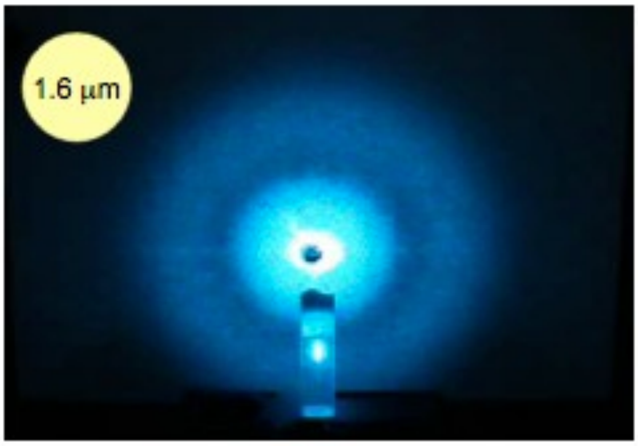
measurement of S(q,t) for concentrated protein solutions, covering the appropriate length and time scales

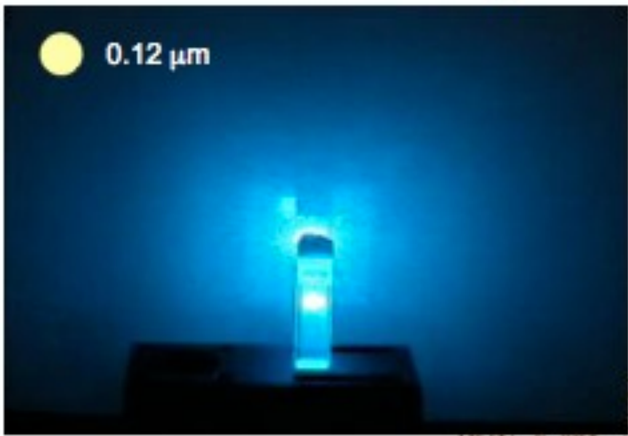
Two generic experiments for dynamic information



A short introduction to dynamic light scattering

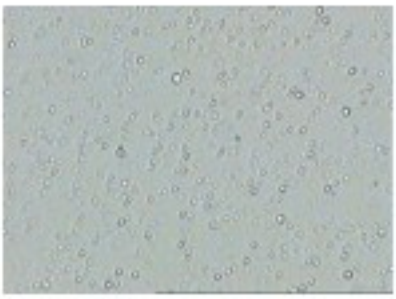


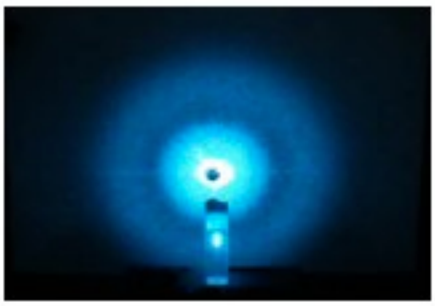




Interlude: Particle dynamics in real and reciprocal space

Particle tracking with a microscope

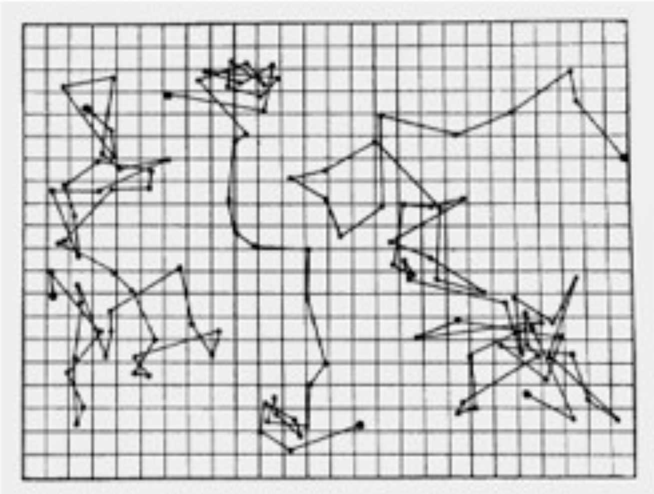




Dynamics in reciprocal (Fourier) space

Interlude: Particle dynamics in real and reciprocal space

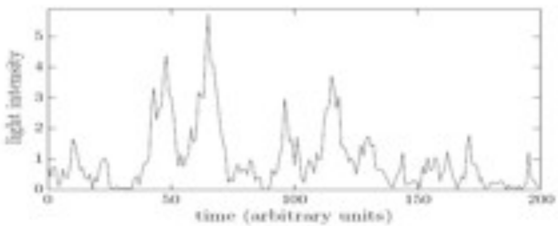
Particle tracking with a microscope

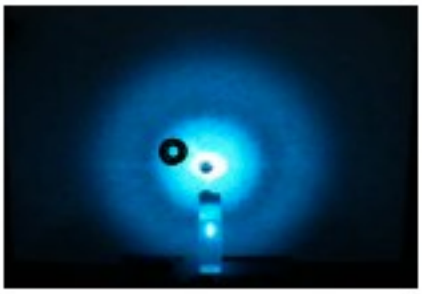


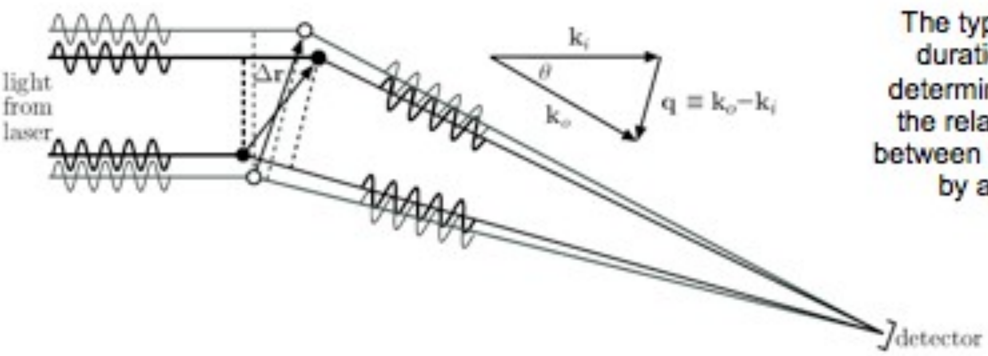
J. B. Perrin, "Mouvement brownien et réalité moléculaire," Ann. de Chimie et de Physique (VIII) 18, 5-114 (1909)

Interlude: Particle dynamics in real and reciprocal space

Dynamics in reciprocal (Fourier) space:



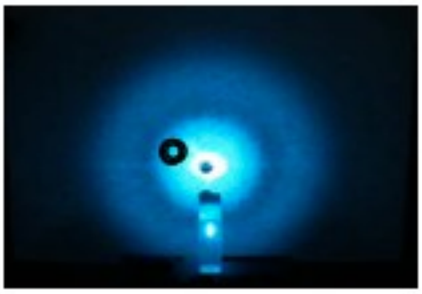


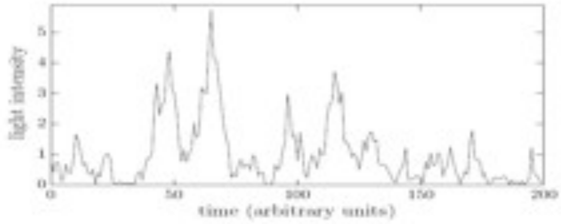


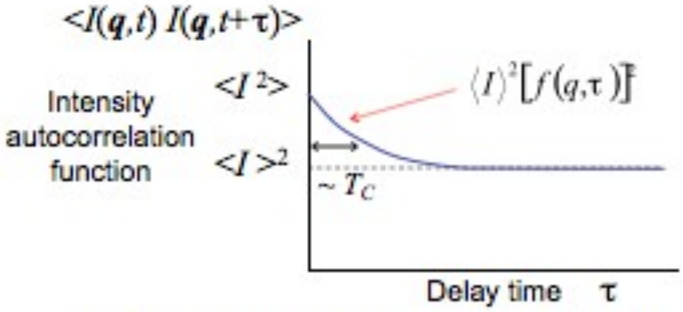
The typical time scale for the duration of a fluctuation is determined by the time it takes the relative phase differences between the two paths to change by approximately unity.

Interlude: Particle dynamics in real and reciprocal space

Dynamics in reciprocal (Fourier) space:

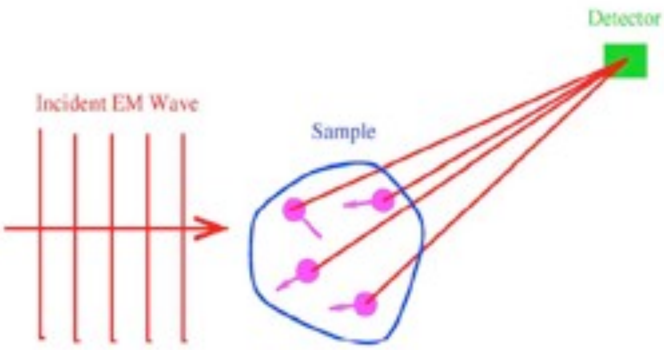


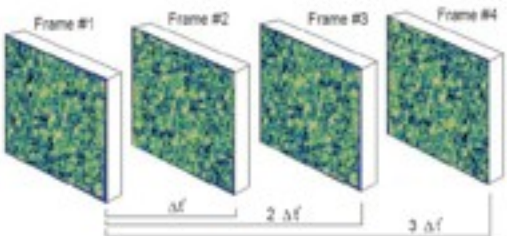




Structure of *intermediate scattering function*, $f(q,\tau)$, gives information on scatterer dynamics

Measuring dynamics





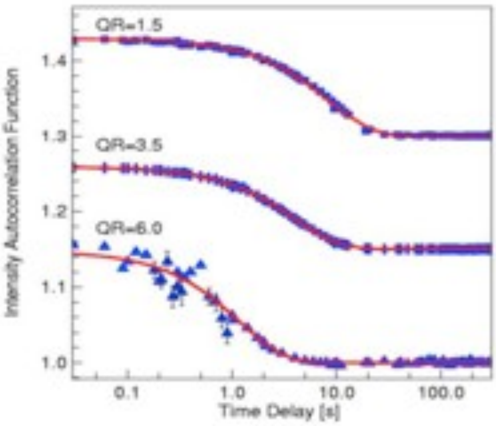
$$g_2(q,t) = \frac{\langle I(q,t')I(q,t'+t)\rangle}{\langle I(q,t')\rangle^2}$$

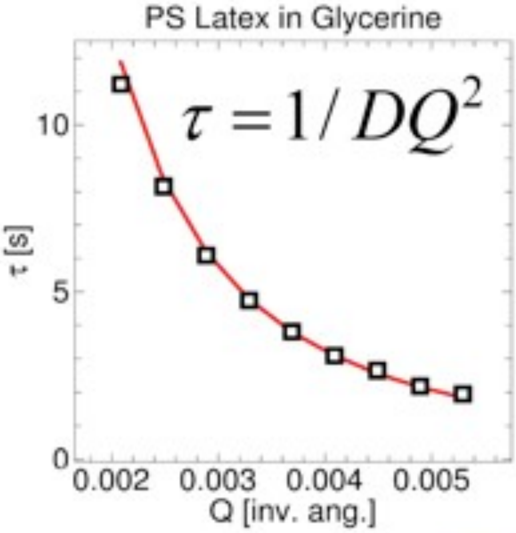
$$g_2(q,t) \sim e^{-2\Gamma t}$$

$$\Gamma = Dq^2$$

Correlation functions for a dilute colloidal suspension

PS, 71 nm in glycerol



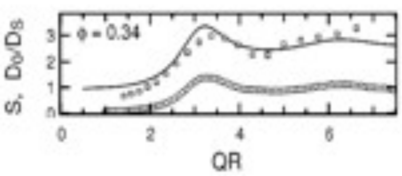


(L. Lurio)

Other examples:

concentrated particle suspensions

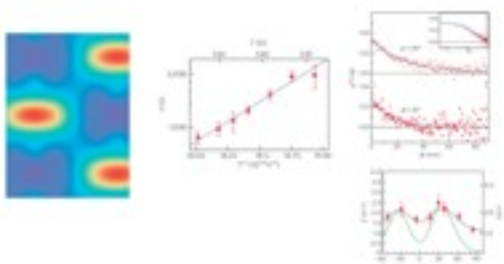
Deviations for Stokes-Einstein Diffusion



$$D(Q) = D_0 H(Q) / S(Q)$$

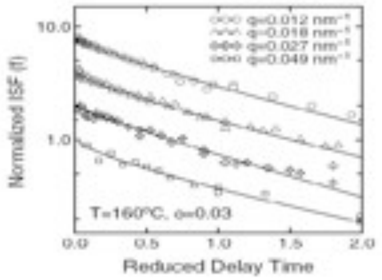
Atomic Diffusion in Metal Alloys

Leitner et. al. Nature Materials, 2009



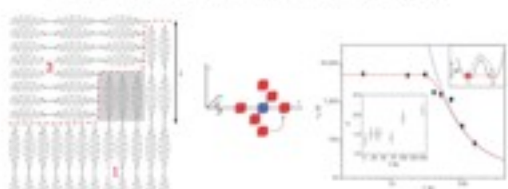
Concentrated Block Copolymer Vesicles

Falus et. al. PRL 94, 16105, 2005



Antiferromagnetic Domain Fluctuations

- O. G. Shpyrko *et al.*, *Nature* ***447, 68 (2007).***



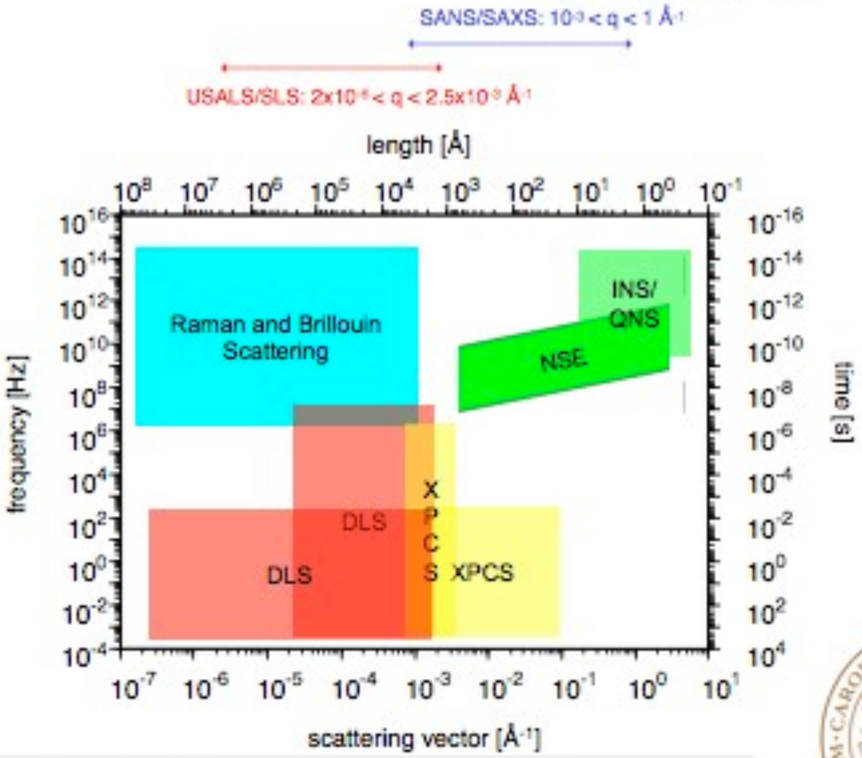
Note that although the length scale of the fluctuations is large (>10 nm) they require x-rays with wavelengths ~0.1 nm in order to be visible.

Scattering techniques, length and time scales

Structure SANS: $10^{-3} < q < 1$ Å^{-1} SAXS: $10^{-3} < q < 1$ Å^{-1} ESRF

$10^{-2} < q < 1$ Å^{-1} Lab.

Dynamics



Advantages and disadvantages

NSE

- \+ no beam damage
- \+ isotope-selective
- \+ large q-range
- \- limited time window (< 1 μs)

XPCS

- \+ large q-range
- \+ in principle large time window, but currently limited because of detectors
- \- beam damage
- \- limited signal (low coherence of x-rays)