September 28, 2012: Cheiron School 2012 @ SPring-8

# Small-Angle X-ray Scattering
# Basics & Applications

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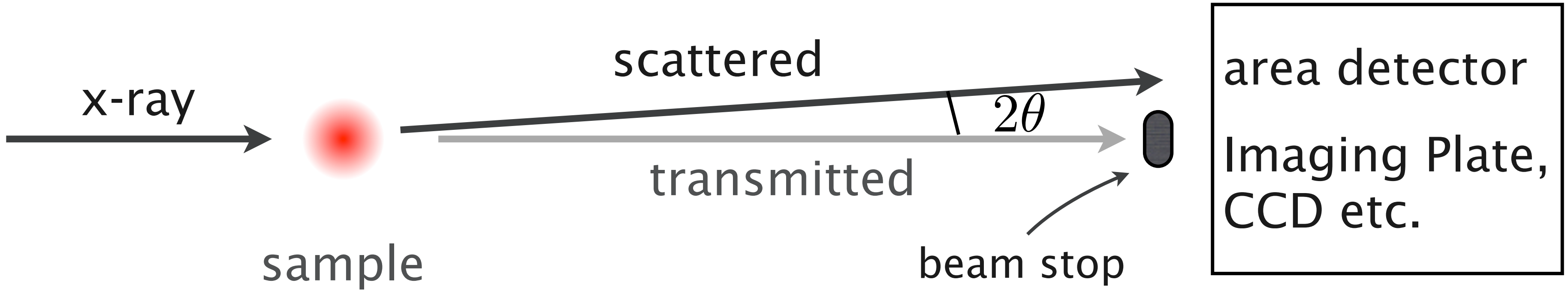
The University of Tokyo

# Table of Contents

# What's Small-Angle X-ray Scattering ?



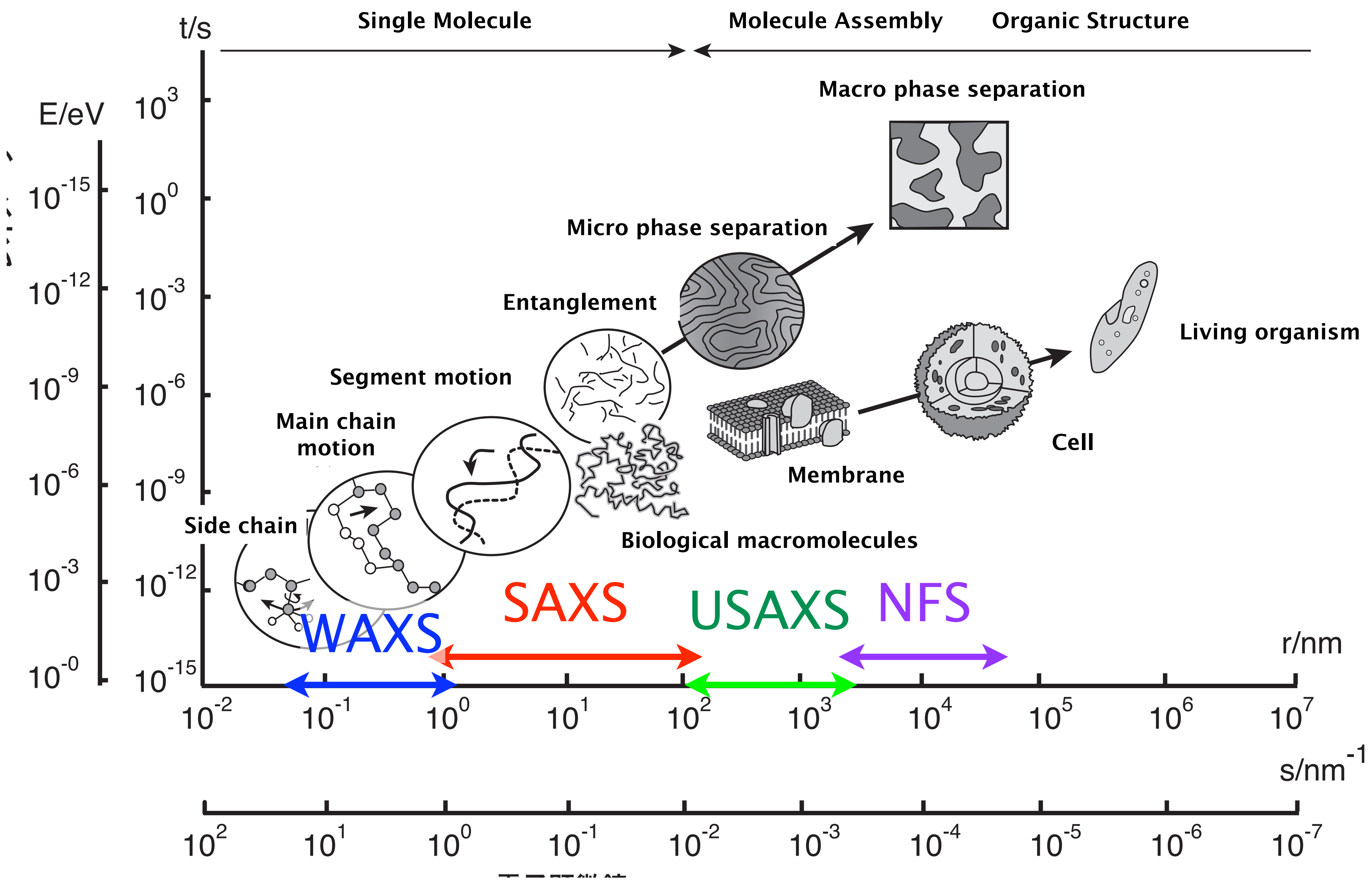

Bragg's law: $\lambda = 2d \sin\theta$

**small angle → large structure**
(1 – 100 nm)

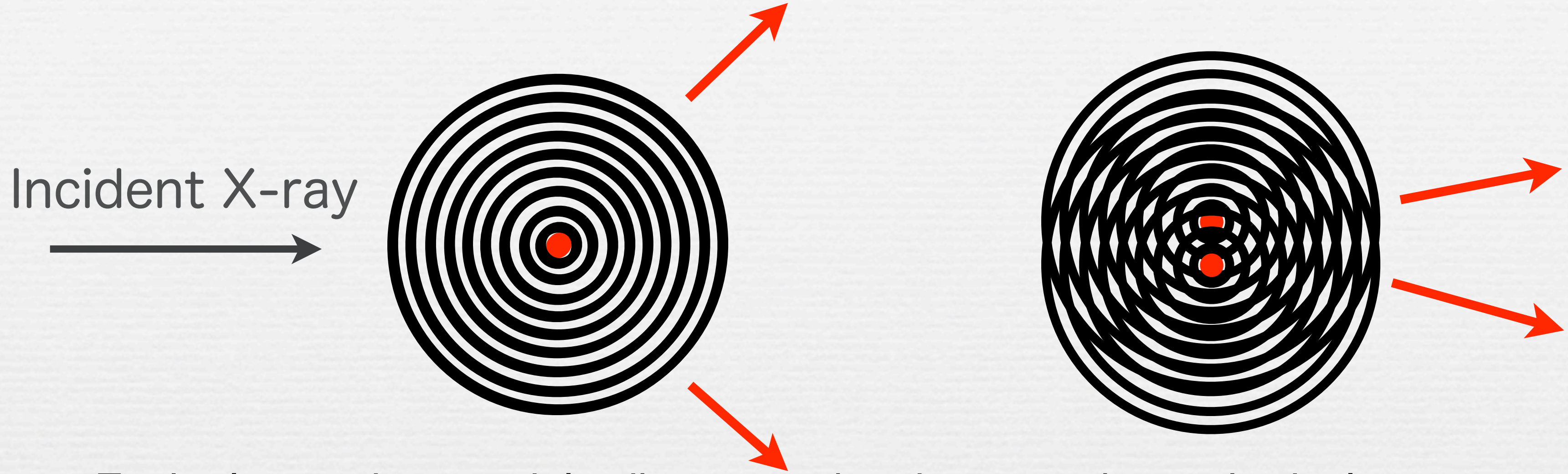
crystalline sample --> small-angle X-ray diffraction: SAXD

solution scattering / inhomogeneous structure --> SAXS

# Hierarchical Structure of Soft Matter



# Interference of secondary waves




Each electron in marerials vibrates and emits secondary spherical wave

When there are two electrons,

- interference between secondary waves from electrons
- when a distance between electrons is small

  --> scattering at large angle is intensified
- when a distance between electrons is large

  --> scattering at small angle is intensified --> SAXS

# History of SAXS (< 1936)

Krishnamurty (1930)

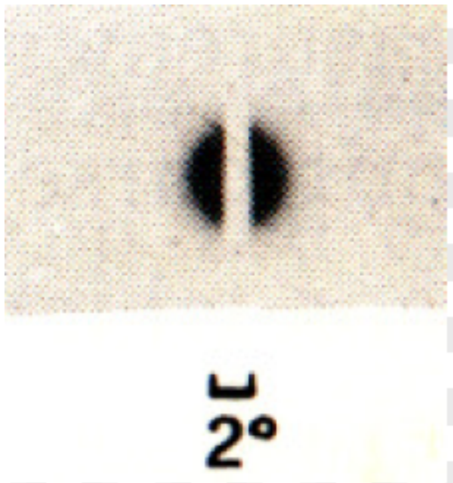
Hendricks (1932)

Mark (1932)

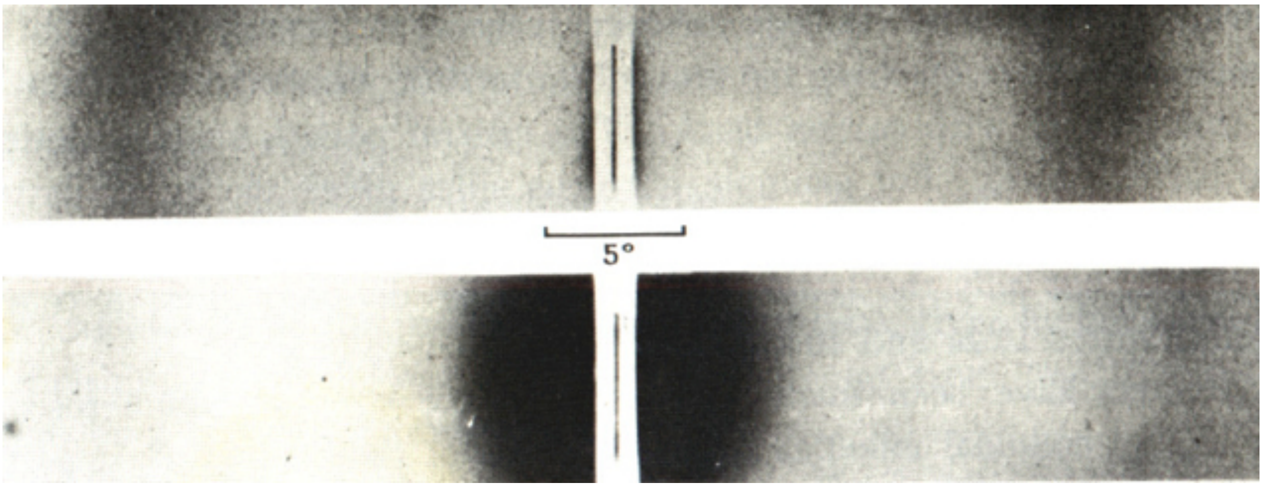
Warren (1936)

Observation of scattering

from powders, fibers, and colloidal dispersions



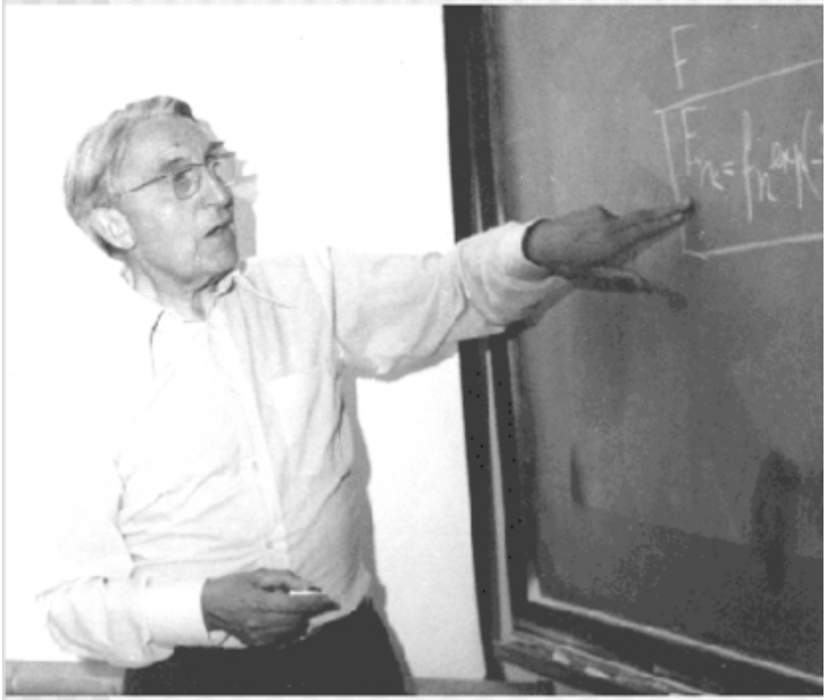

carbon black




Molten silica - silica gel
(above ) (below)

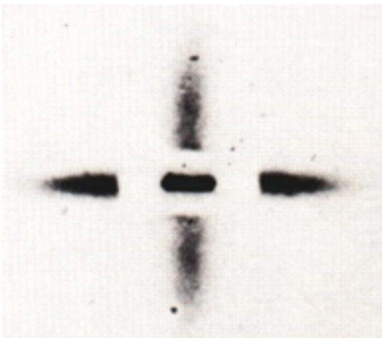
courtesy to Dr. I.L.Torriani

# History (> 1936)



A. Guinier (1937, 1939, 1943)

Interpretation of inhomogeneities in Al alloys "G-P zones", introducing the concept of "particle scattering" and formalism necessary to solve the problem of a diluted system of particles.



Single crystals of Al-Cu hardened alloy

O. Kratky (1938, 1942, 1962)

G. Porod (1942, 1960, 1961)

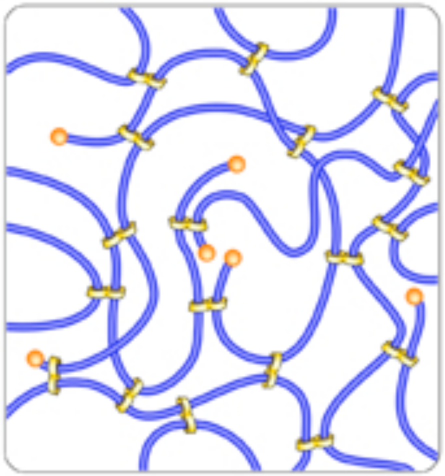
Description of dense systems of colloidal particles, micelles, and fibers.

Macromolecules in solution.

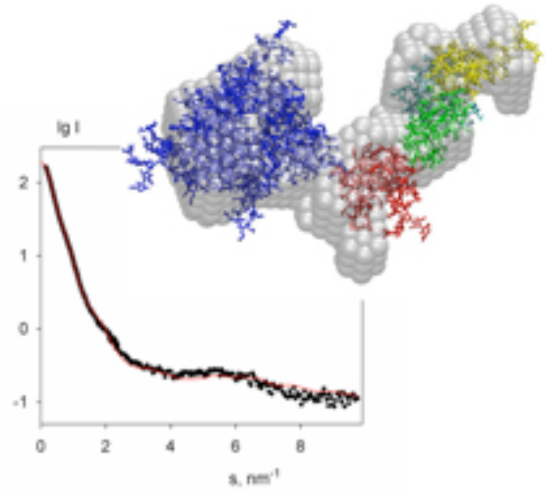

Hemoglobin

courtesy to Dr. I.L.Torriani

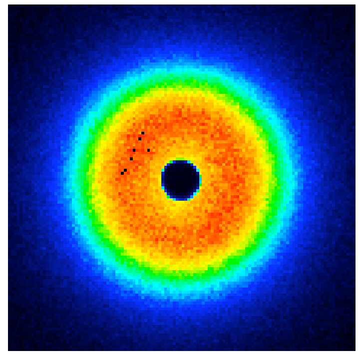
# Application of SAXS



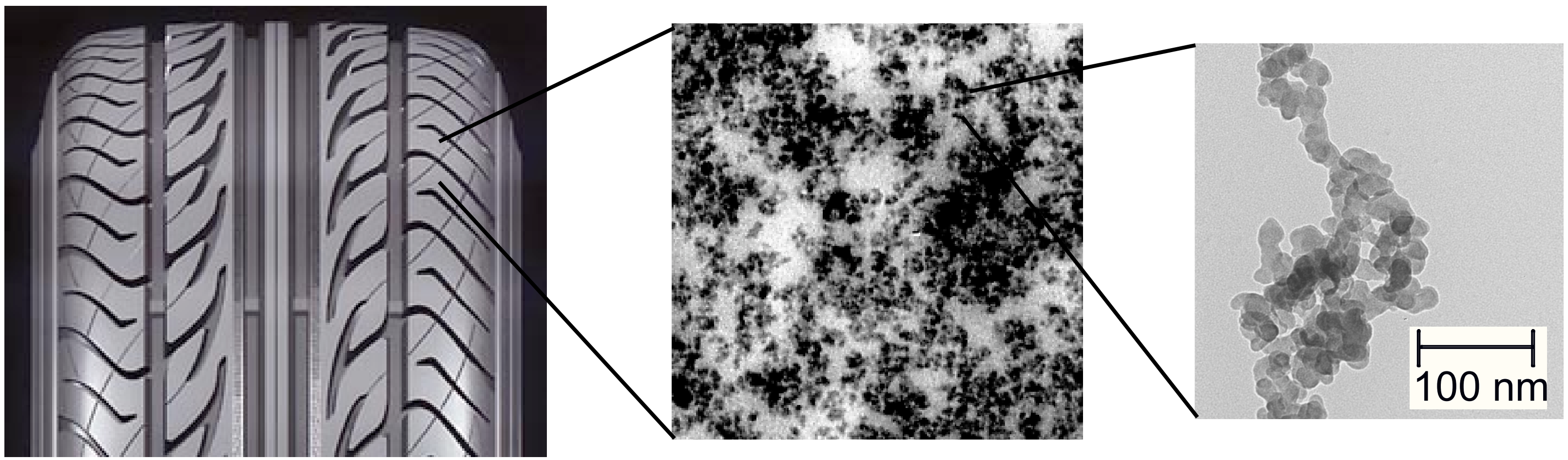
gel




Proteins in solution (Dr. Svergun, EMBL)



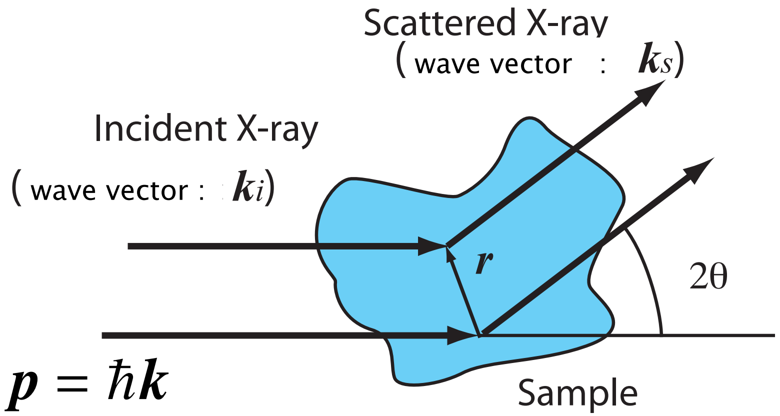
Typical SAXS image

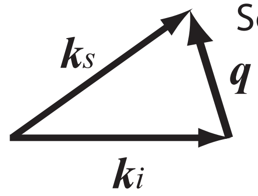



Nanocomposite

# Table of Contents

# Basic of X-ray scattering




Scattering vector
$\boldsymbol{q} = \boldsymbol{k}_s - \boldsymbol{k}_i$

$\rho(\boldsymbol{r})$ : electron density

$\boldsymbol{p} = \hbar \boldsymbol{k}$

momentum of a photon

$q = |\boldsymbol{q}| = 4\pi \sin\theta / \lambda$

Complex number

$\mathrm{d}\boldsymbol{r} = dxdydz$ around $\boldsymbol{r}$

Amplitude of scattered X-ray $A(\boldsymbol{q}) = \int_V \rho(\boldsymbol{r}) \exp(-\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r})\mathrm{d}\boldsymbol{r}$

Fourier transform of electron density

Intensity of scattered X-ray : $\mathrm{I}(\boldsymbol{q}) = \mathrm{A}(\boldsymbol{q})\mathrm{A}^*(\boldsymbol{q}) = |\mathrm{A}(\boldsymbol{q})|^2$

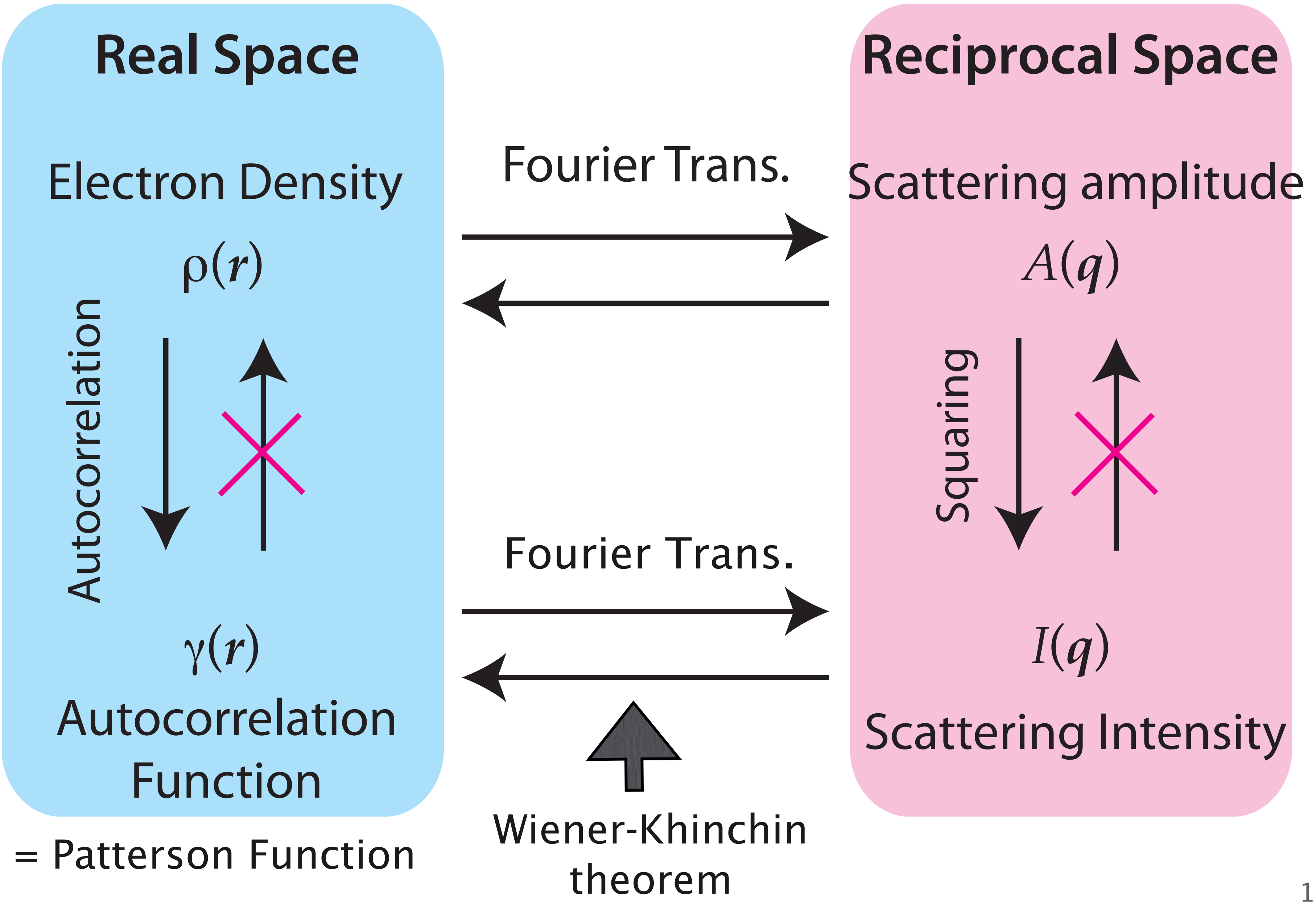
(Extensive variable)

Intensity of scattered X-ray per volume: $\mathrm{I}(\boldsymbol{q}) = \dfrac{\mathrm{A}(\boldsymbol{q})\mathrm{A}^*(\boldsymbol{q})}{V} = \dfrac{|\mathrm{A}(\boldsymbol{q})|^2}{V}$

(Intensive variable)

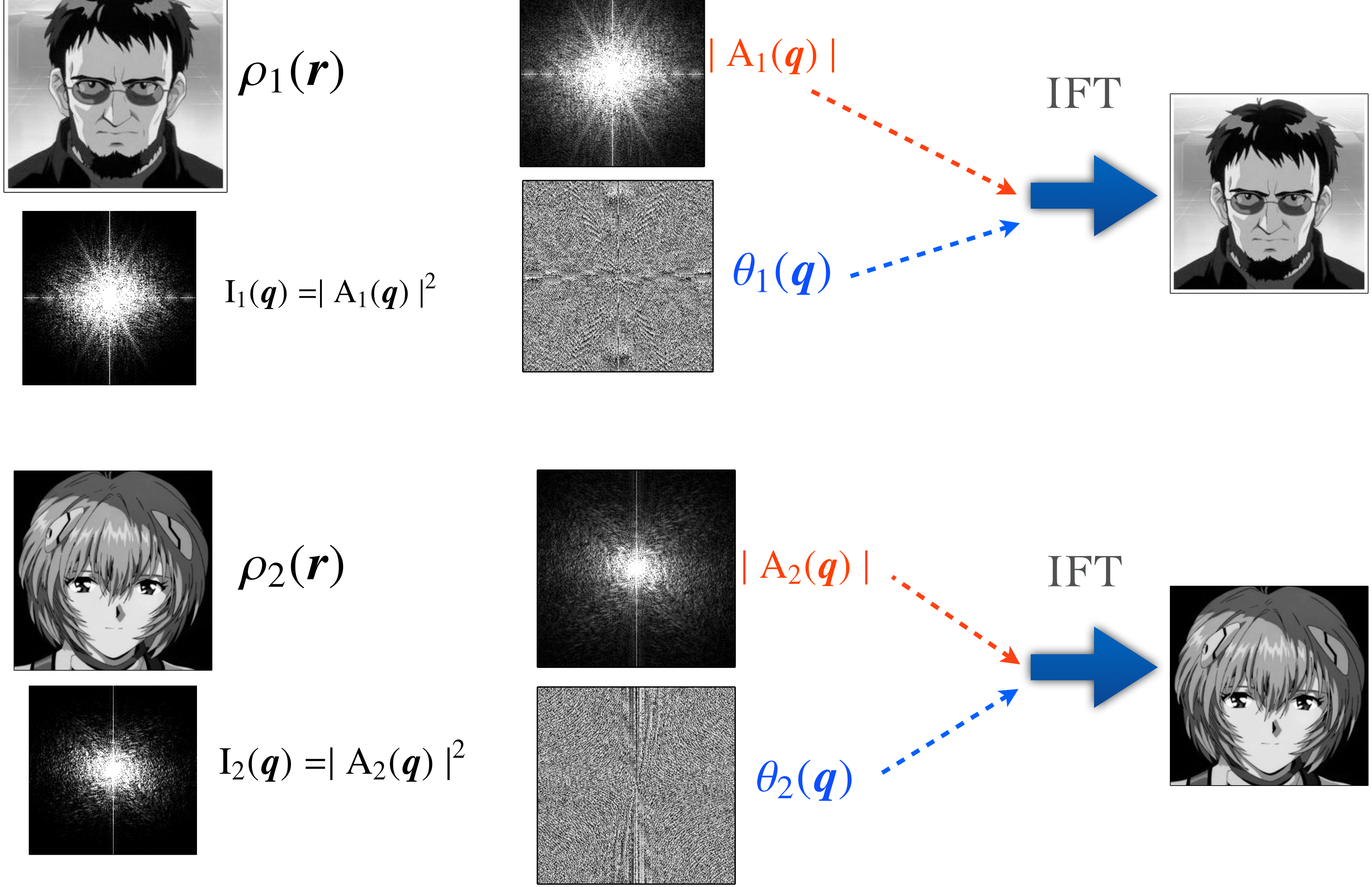
This doesn't depend on sample volume, and is used to obtain the absolute intensity

# Real space and Reciprocal Space



# Importance of phase, $\theta(\boldsymbol{q})$ of complex amplitude

$$A(\boldsymbol{q}) = |A(\boldsymbol{q})| \exp(-i\theta(\boldsymbol{q}))$$



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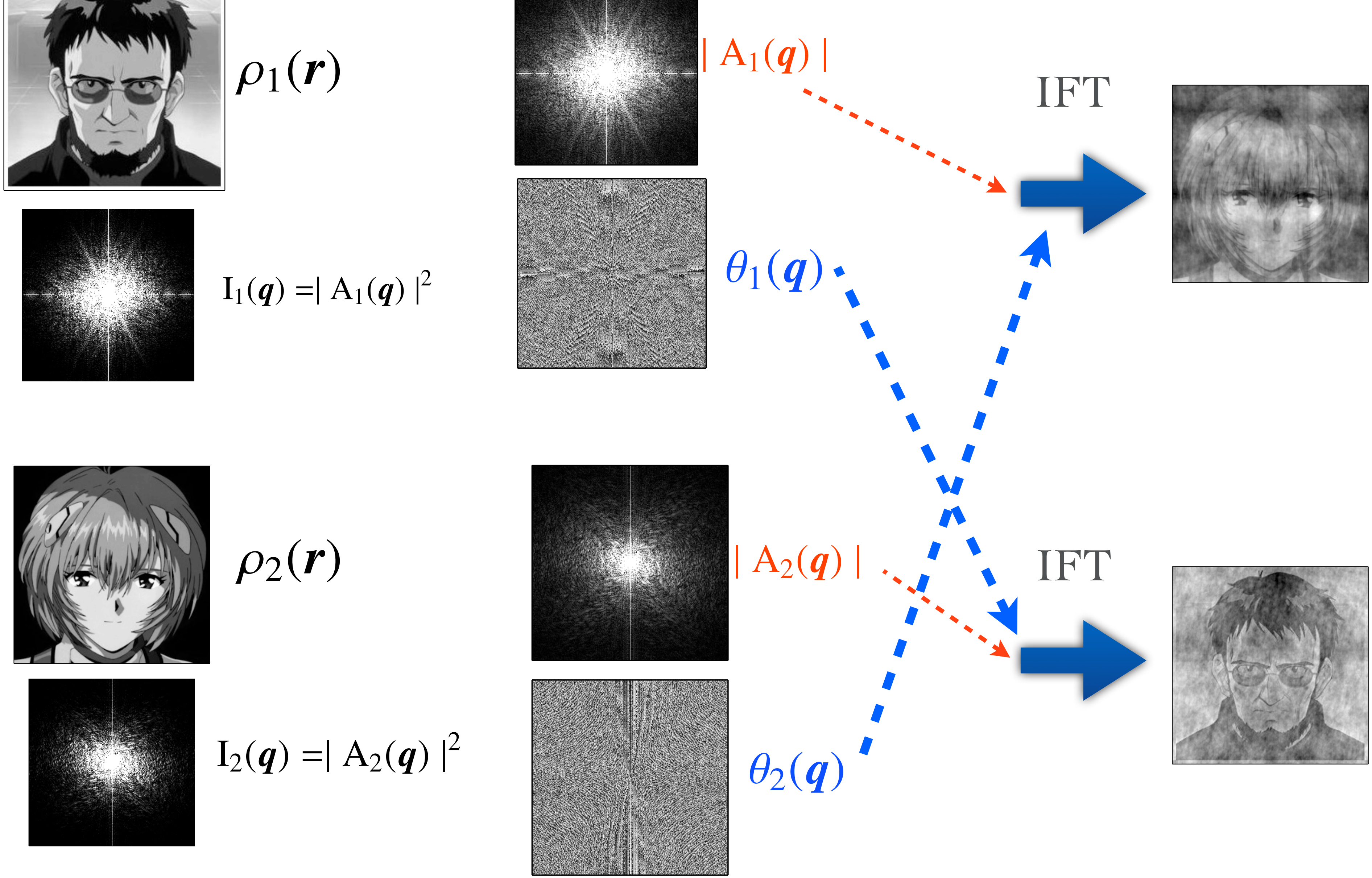


# Autocorrelation Function & Scattering Intensity

Autocorrelation function of electron density

$$\gamma(\boldsymbol{r}) = \frac{1}{V}\int_V \rho(\boldsymbol{r}')\rho(\boldsymbol{r}+\boldsymbol{r}')\mathrm{d}\boldsymbol{r}' = \frac{1}{V}\underline{P(\boldsymbol{r})}$$

Patterson Function

(Debye & Bueche 1949)

asymptotic behavior of the autocorrelation function

$$\gamma(0) = \langle\rho^2\rangle \qquad \gamma(\infty) = \langle\rho\rangle^2$$

Scattering Intensity : Fourier Transform of autocorrelation function

$$I(\boldsymbol{q}) = \int_V \gamma(\boldsymbol{r}) \exp(-\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r})\,\mathrm{d}\boldsymbol{r}$$

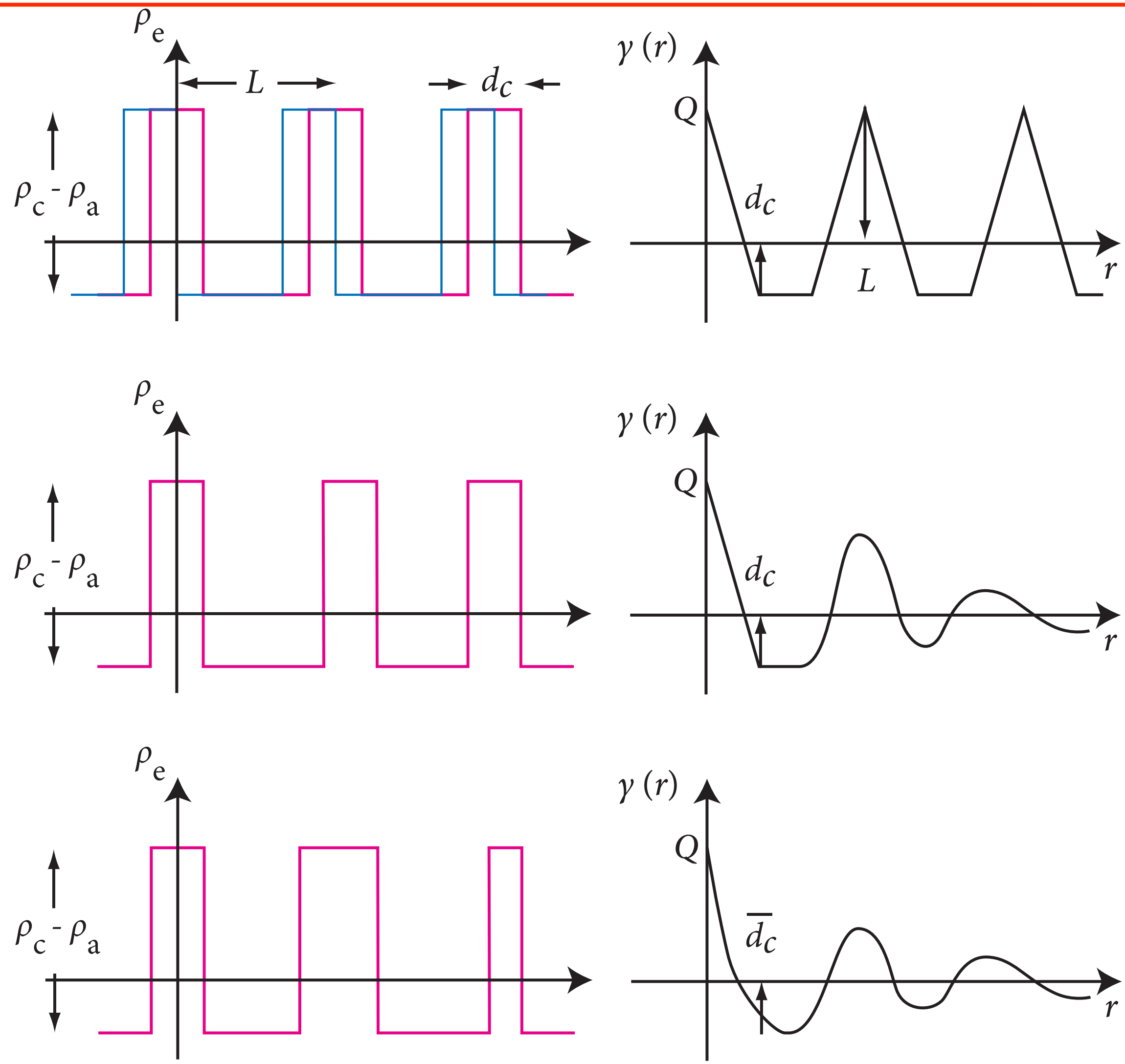
cf. Wiener-Khinchin theorem

# Example of ρ(r) & γ(r) : in case of lamellar

ideal ordering

Long period changes.

Thickness of crystal changes.




real space autocorrelation

# Normalized Autocorrelation Function:

Introducing the relative electron density, $\eta(\boldsymbol{r})$ , as

$$\eta(\boldsymbol{r}) = \rho(\boldsymbol{r}) - \langle\rho\rangle \longrightarrow \langle\eta^2\rangle = \langle(\rho(\boldsymbol{r}) - \langle\rho\rangle)^2\rangle = \langle\rho^2\rangle - \langle\rho\rangle^2$$

Introducing the normalized autocorrelation function, $\gamma_0(\boldsymbol{r})$ , as

$$\gamma_0(\boldsymbol{r}) = \frac{1}{\langle\eta^2\rangle}\frac{1}{V}\int_V \langle\eta(\boldsymbol{r}')\eta(\boldsymbol{r}+\boldsymbol{r}')d\boldsymbol{r}'$$

then, $$\gamma_0(\boldsymbol{r}) = \frac{\gamma(\boldsymbol{r}) - \langle\rho\rangle^2}{\langle\eta^2\rangle}$$ where $\gamma_0(0) = 1 \quad \gamma_0(\infty) = 0$

then, $$I(\boldsymbol{q}) = \underline{\langle\eta^2\rangle}\int_V \gamma_0(\boldsymbol{r})e^{-i\boldsymbol{q}\cdot\boldsymbol{r}}d\boldsymbol{r} + \underline{\langle\rho\rangle^2\delta(\boldsymbol{q})}$$

The average of the relative electron density fluctuations determines the magnitude of I(q). The normalized autocorrelation function $\gamma_0$(r) determines the shape of I(q).

Not observable.

# Invariant Q

Invariant: $\boldsymbol{Q} = \int_0^\infty \mathrm{I}(\boldsymbol{q})d\boldsymbol{q} \Rightarrow \int_0^\infty \mathrm{I}(q)4\pi q^2 dq$

(when isotropic)

$= (2\pi)^3 \langle \eta^2 \rangle$ ← It doesn't depend on the structure

$$(\because) \quad \boldsymbol{Q} = \int_0^\infty \mathrm{I}(\boldsymbol{q})d\boldsymbol{q} = \langle \eta^2 \rangle \int_0^\infty \int_V \gamma_0(\boldsymbol{r}) \mathrm{e}^{-\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r}} d\boldsymbol{r} d\boldsymbol{q}$$

$$= \langle \eta^2 \rangle \int_V \gamma_0(\boldsymbol{r}) \int_0^\infty \mathrm{e}^{-\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r}} d\boldsymbol{q} d\boldsymbol{r}$$

$$= (2\pi)^3 \langle \eta^2 \rangle \int_V \gamma_0(\boldsymbol{r}) \delta(0) d\boldsymbol{r} = (2\pi)^3 \langle \eta^2 \rangle \gamma_0(0) = (2\pi)^3 \langle \eta^2 \rangle$$

$$I(\boldsymbol{q}) = \langle \eta^2 \rangle \int_V \gamma_0(\boldsymbol{r}) \mathrm{e}^{-\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r}} \mathrm{d}\boldsymbol{r} + \underline{\langle \rho \rangle^2 \delta(\boldsymbol{q})}$$

Omitted.

**Parseval's theorem**

$$A(\boldsymbol{q}) \xleftrightarrow{\text{Fourier Trans.}} \eta(\boldsymbol{r})$$

$$\int |A(\boldsymbol{q})|^2 \mathrm{d}\boldsymbol{q} = (2\pi)^3 \int |\eta(\boldsymbol{r})|^2 \mathrm{d}\boldsymbol{r}$$

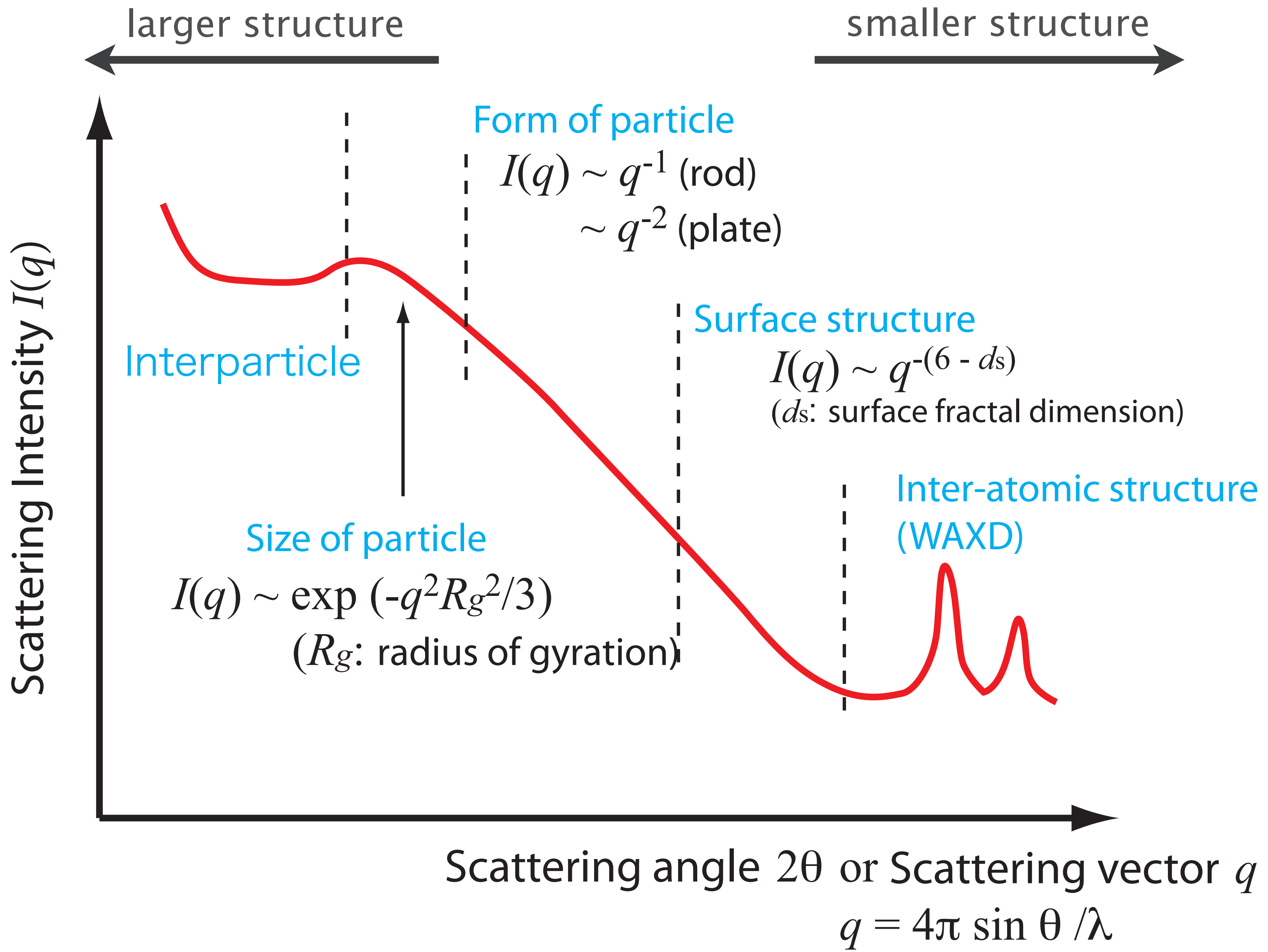
# Table of Contents

# Information obtained from SAXS

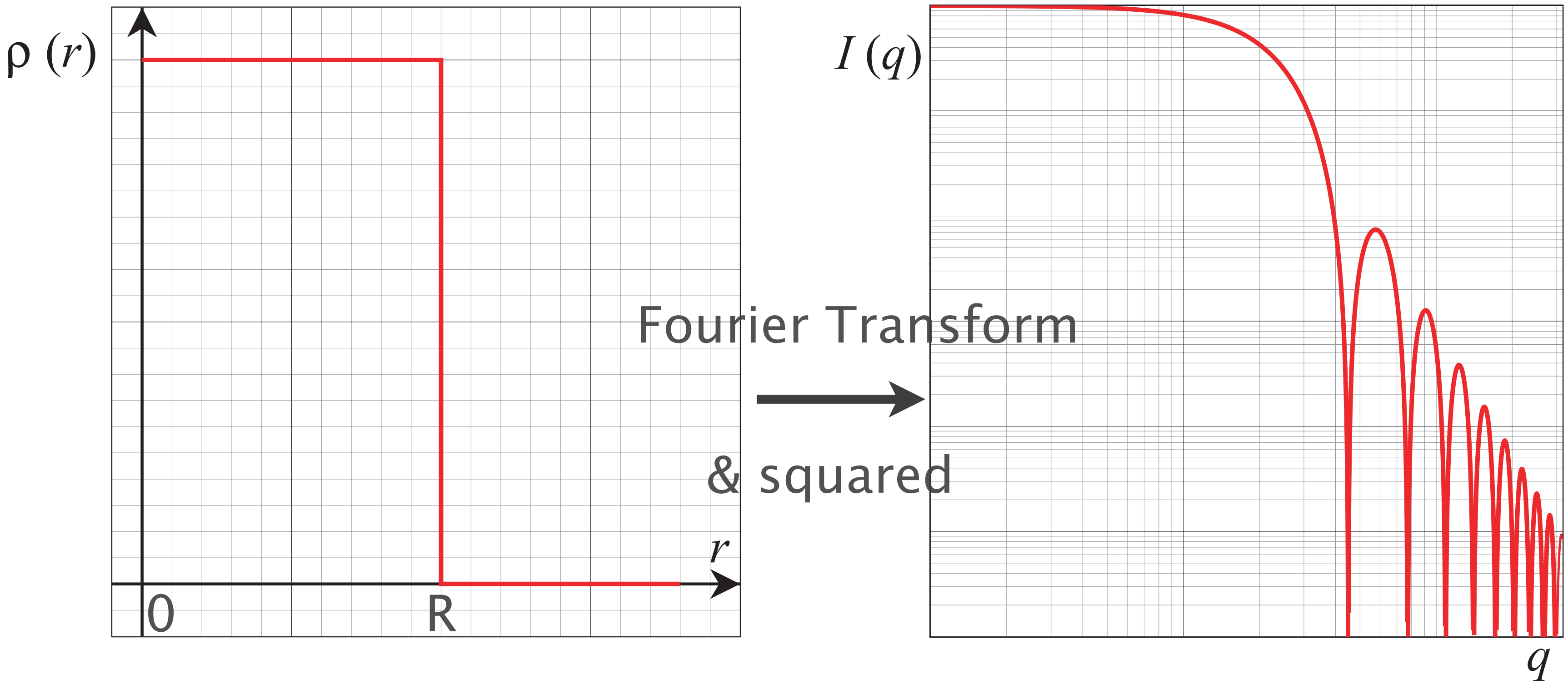
1. Size and form of particulate system
   - Colloids, Globular proteins, etc...
2. Correlation length of inhomogeneous structure
   - Polymer chain, two-phase system etc.
3. Lattice parameters of distorted crystals (para-crystal)
4. Degree of crystallinity, crystal size, crystal distortion
   - Crystalline polymer

# SAXS of particulate system

## Relation between SAXS pattern and Structural information



# Spherical sample

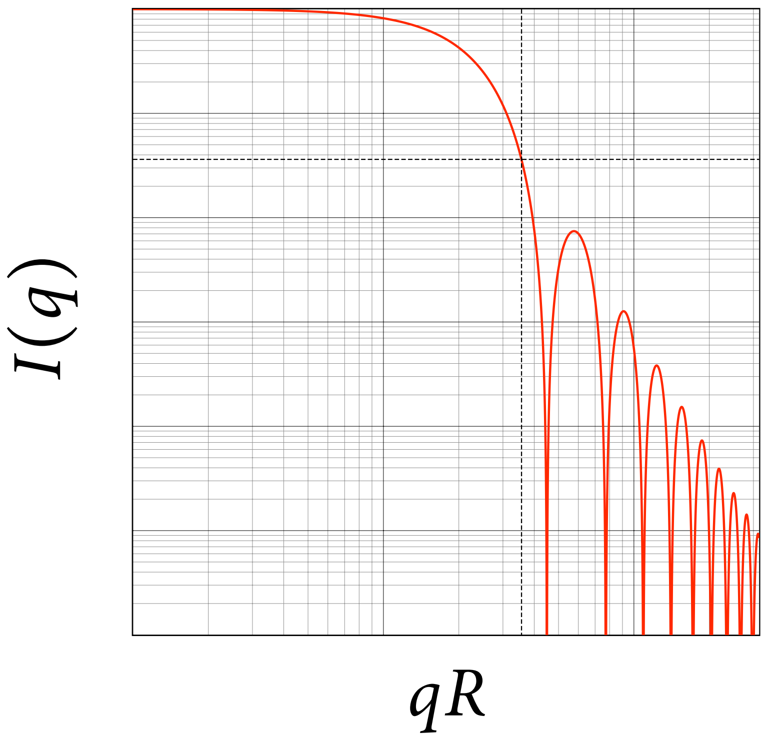


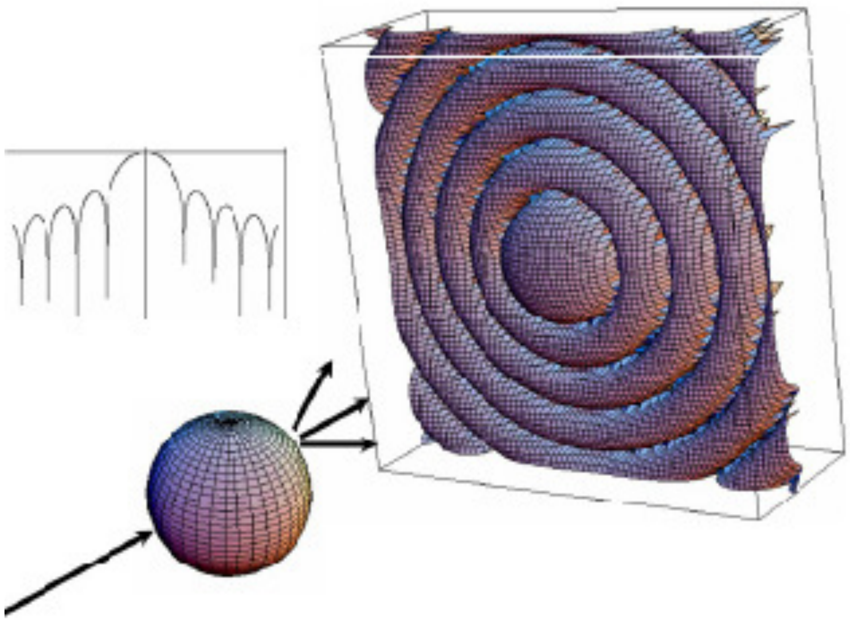

$$\rho(r) = \begin{cases} \Delta\rho & r < R \\ 0 & \text{else} \end{cases}$$

$$I(q) = \frac{(\Delta\rho)^2 V_{\text{particle}}{}^2}{V} \left[ 3 \frac{\sin qR - qR\cos qR}{(qR)^3} \right]^2$$

# Homogeneous sphere

$$I(q) = \frac{(\Delta\rho)^2 \, V_{\text{particle}}{}^2}{V} \left[ 3 \frac{\sin qR - qR \cos qR}{(qR)^3} \right]^2$$



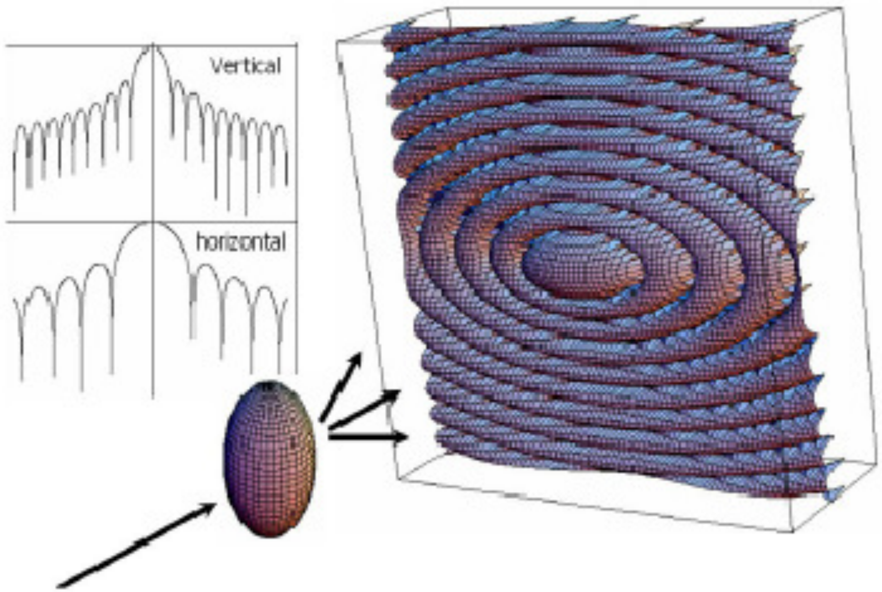
isotropic scattering

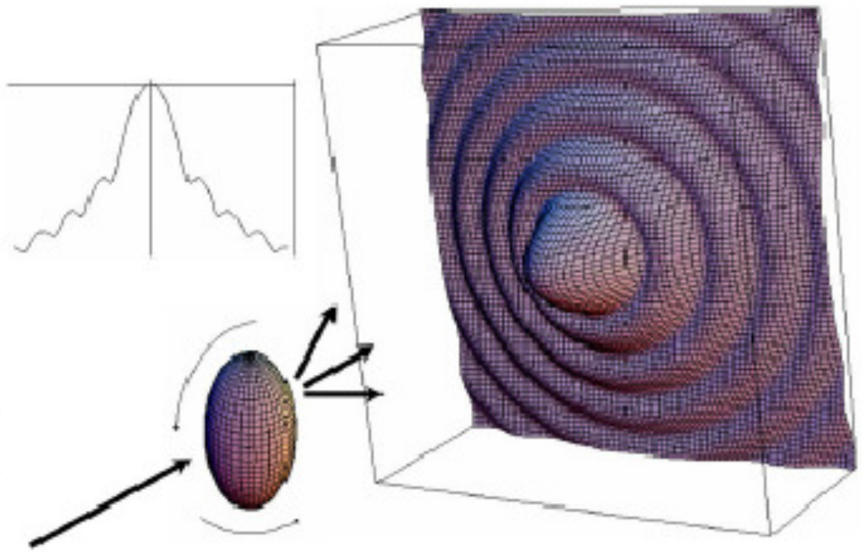
courtesy to Dr. I.L.Torriani

# Homogeneous elipsiod

Fixed particle

Random orientation



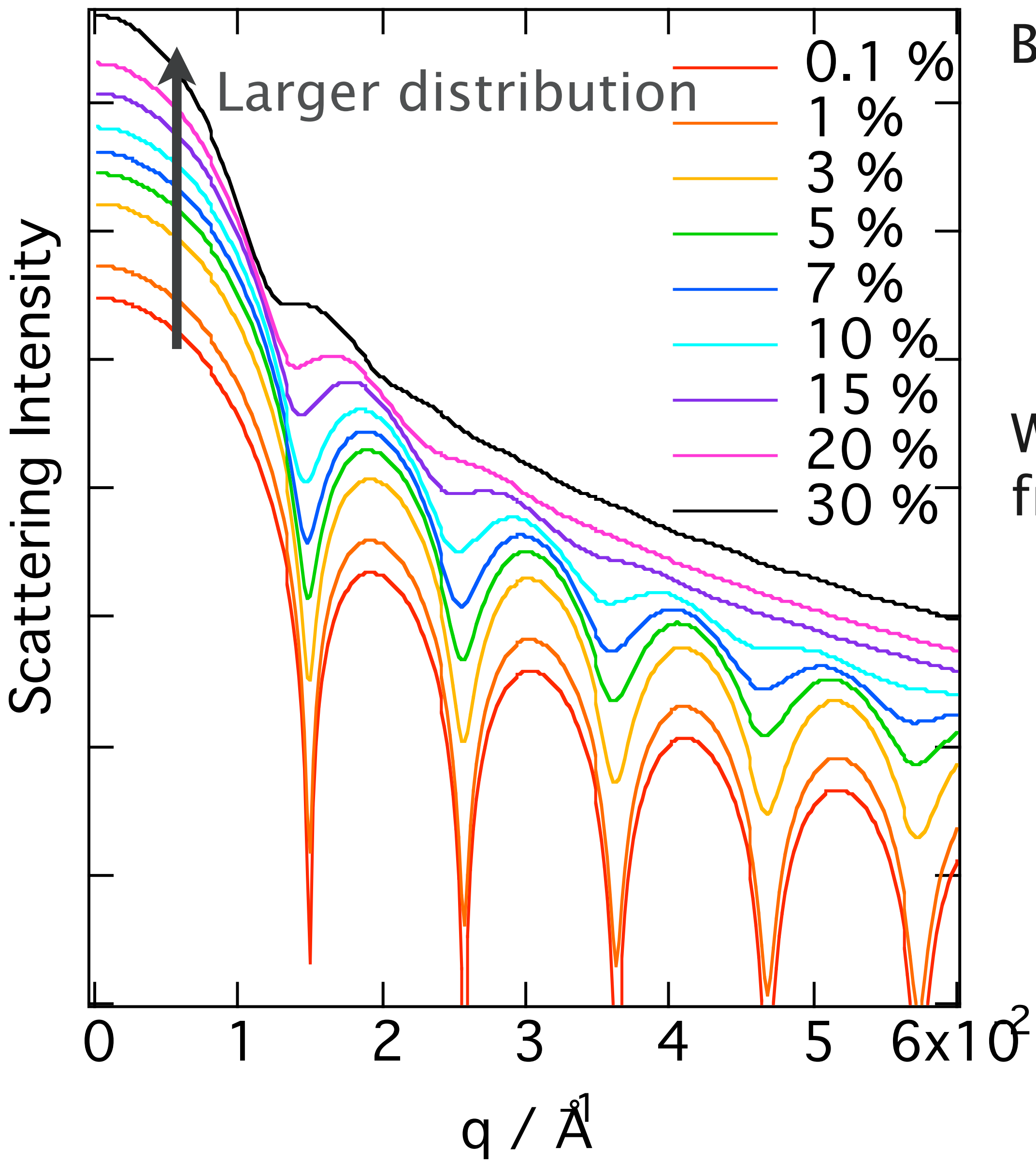



anisotropic scattering

isotropic scattering

courtesy to Dr. I.L.Torriani

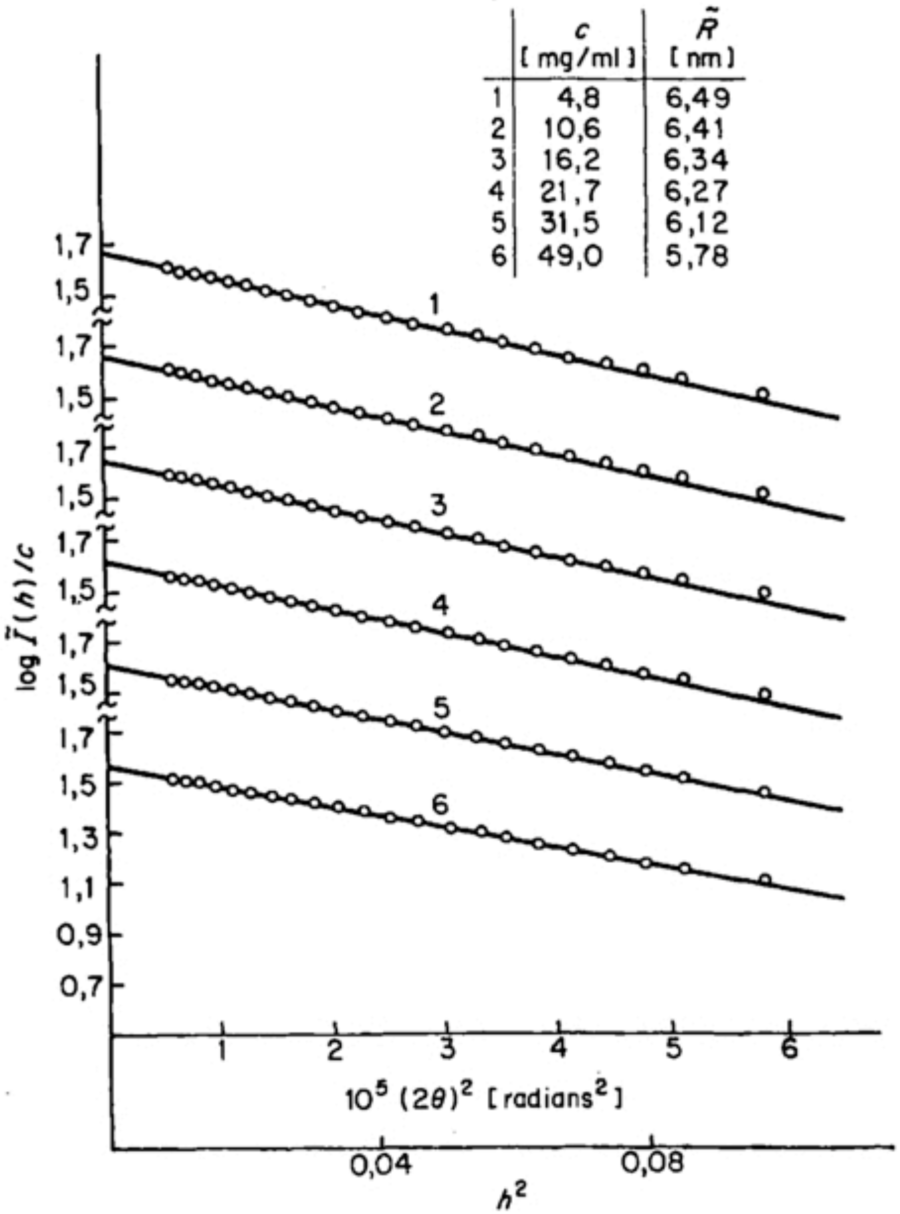
# Size distribution




Based on Gaussian distribution

When the form has distribution, fringes are missed.

# Radius of Gyration: $R_g$ ($R_g^2 = \frac{\int r^2 \rho(\mathbf{r}) d\mathbf{r}}{\int \rho(\mathbf{r}) d\mathbf{r}}$) ----- Guinier Plot




$$I(q) \sim \exp\left(-\frac{q^2 R_g{}^2}{3}\right)$$

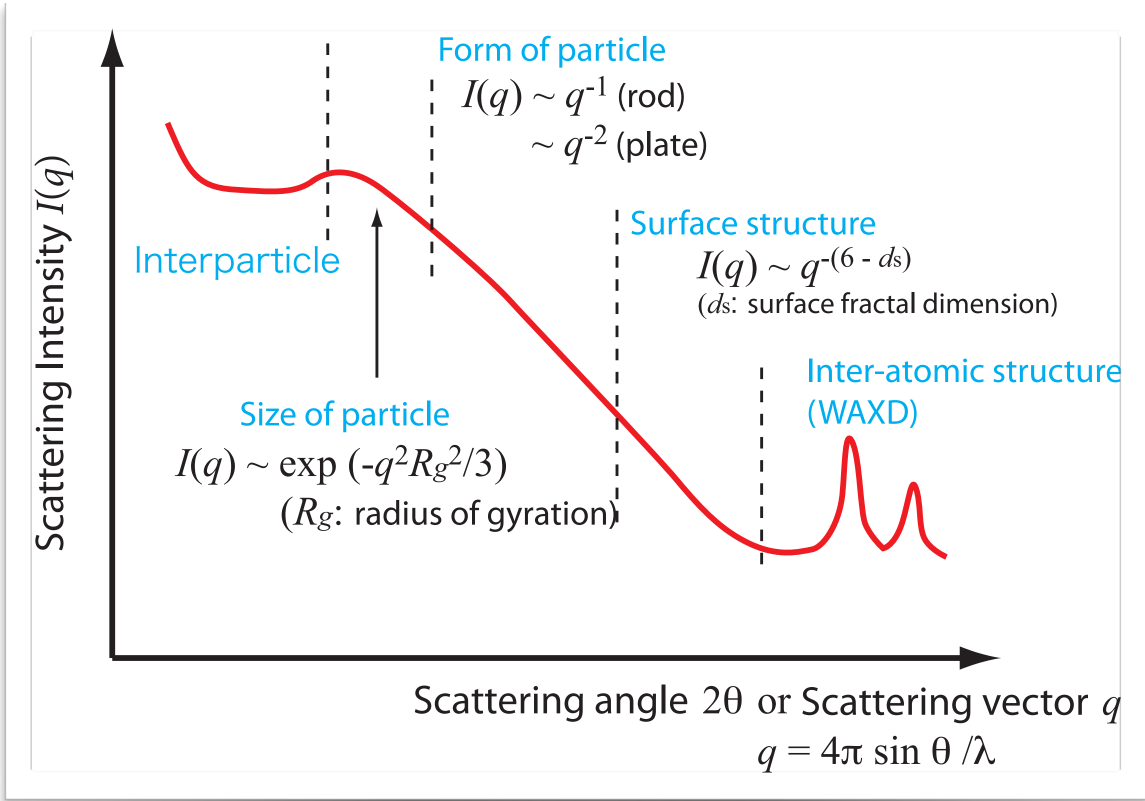
↓

$$\log\left(I(q)\right) = -\frac{q^2 R_g{}^2}{3}$$

Guinier plot: log ($I$($q$)) vs $q^2$

O. Glatter & O. Kratky ed., “Small Angle X-ray Scattering”, Academic Press (1982).

# Structure Factor & Form Factor




$$I(q) = \phi V_{\text{particle}} S(q) F(q)$$

Structure Factor → inter-particle structure

Form Factor → intra-particle structure

**Separation of S(q) & F(q)**

→ Everlasting issue

(especially, for non-crystalline sample)

**Proposed remedy:**

- GIFT (Generalized Inverse Fourier Trans.) by O. Glatter

# Scattering from Inhomogeneous Structure

**Electron Density** $\rho(r)$

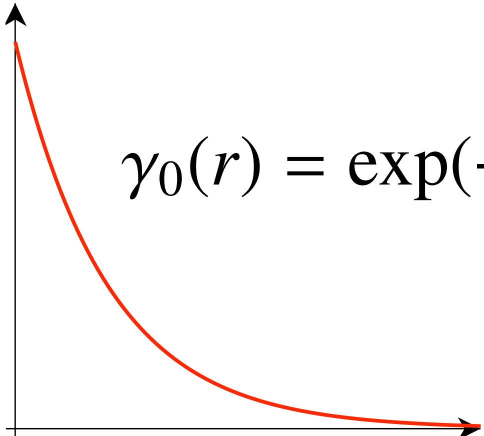
**Autocorrelation Function** $\gamma_0(r)$

**Scattering Intensity**

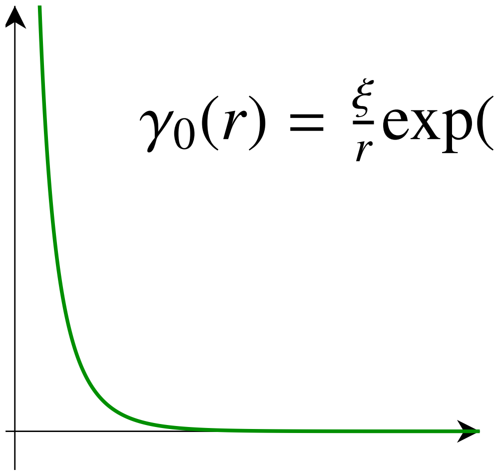
two phase system

polymer chain etc.

Autocorrelation →

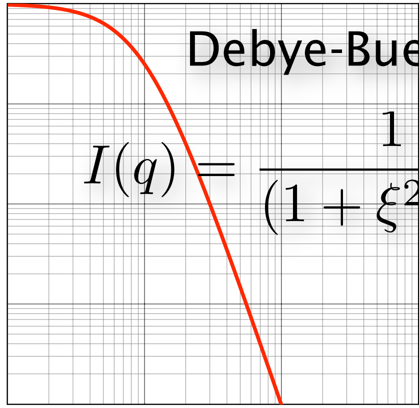


$$\gamma_0(r) = \exp(-\frac{r}{\xi})$$



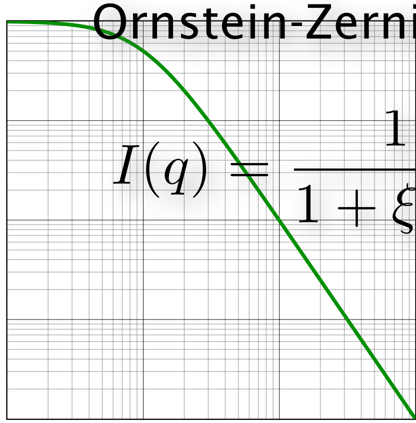
$$\gamma_0(r) = \frac{\xi}{r}\exp(-\frac{r}{\xi})$$

Fourier trans. →



Debye-Bueche

$$I(q) = \frac{1}{(1+\xi^2 q^2)^2}$$



Ornstein-Zernike

$$I(q) = \frac{1}{1+\xi^2 q^2}$$

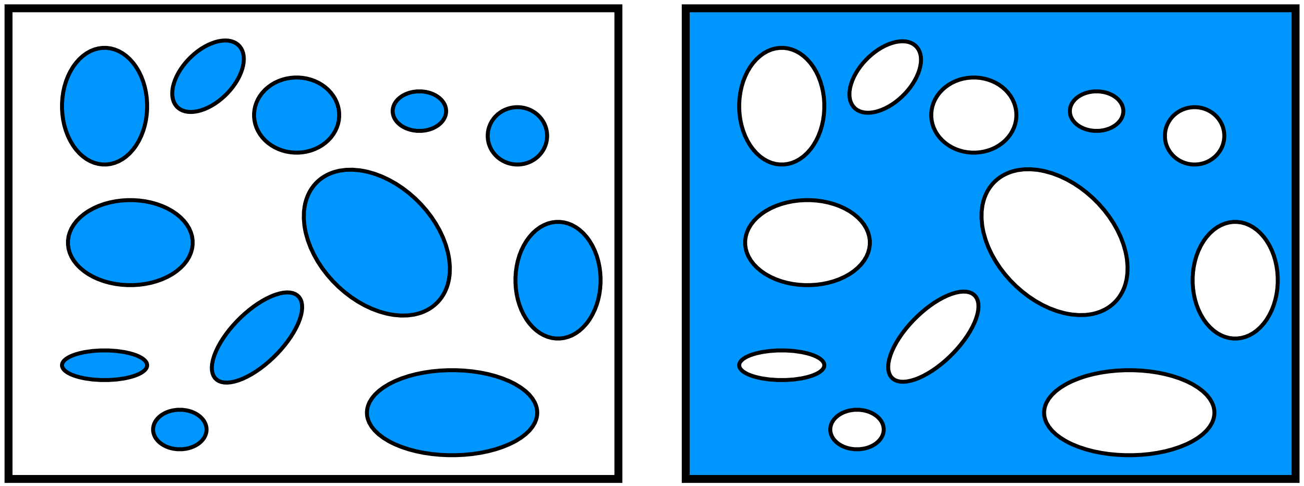
# Two-phase system

Phase 1: $\rho_1$, volume fraction $\phi$ Phase 2: $\rho_2$ volume fraction $1 - \phi$

$$A(\boldsymbol{q}) = \int_{\phi V} \rho_1 \mathrm{e}^{-\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r}} \mathrm{d}\boldsymbol{r} + \int_{(1-\phi)V} \rho_2 \mathrm{e}^{-\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r}} \mathrm{d}\boldsymbol{r}$$

$$= \int_{\phi V} (\rho_1 - \rho_2) \mathrm{e}^{-\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r}} \mathrm{d}\boldsymbol{r} + \rho_2 \int_V \mathrm{e}^{-\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r}} \mathrm{d}\boldsymbol{r}$$

$$A(\boldsymbol{q}) = \int_V \Delta\rho \, \mathrm{e}^{-\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r}} \mathrm{d}\boldsymbol{r} + \rho_2 \delta(\boldsymbol{q})$$



Babinet's principle

Two complementary structures produce the same scattering.

# Two-phase system -- cont.

Averaged square fluctuation of electron density

$$\langle \eta^2 \rangle = \phi(1-\phi)(\Delta\rho)^2 \qquad \text{where} \qquad \Delta\rho = \rho_1 - \rho_2$$

Φ : volume fraction

$$I(q) = 4\pi\langle \eta^2 \rangle \int_0^\infty \gamma_0(r) \frac{\sin(qr)}{qr} r^2 \mathrm{d}r$$

$$I(q) = 4\pi\phi(1-\phi)(\Delta\rho)^2 \int_0^\infty \gamma_0(r) \frac{\sin(qr)}{qr} r^2 \mathrm{d}r$$

$$Q = \int_0^\infty I(q) q^2 \mathrm{d}q = 2\pi^2 \phi(1-\phi)(\Delta\rho)^2$$

**Invariant**: does not depend on the structure of the two phases but only on the volume fractions and the contrast between the two phases.

# Porod's law

For a sharp interface, the scattered intensity decreases as $q^{-4}$.

$$I(q) \to (\Delta\rho)^2 \frac{2\pi}{q^4} S/V$$

internal surface area

Combination of Porod's law & Invariant Q

$$\pi \cdot \frac{\lim_{q\to\infty} I(q) q^4}{Q} = \boxed{\frac{S}{V}}$$

surface-volume ratio

important for the characterization of porous materials

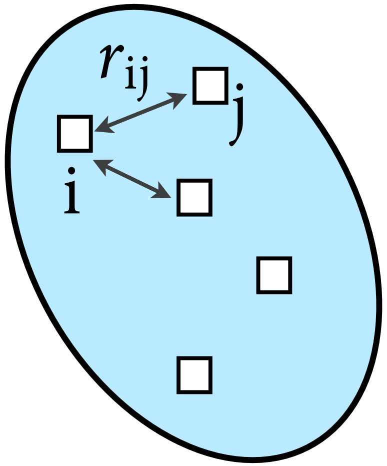
# Pair Distance Distribution Function: PDDF

Scattering intensity: $I(q) = 4\pi \int_0^\infty \gamma_0(r) \frac{\sin(qr)}{qr} r^2 \mathrm{d}r$
**(when isotropic)**

PDDF : $p(r) = r^2 \gamma_0(r)$

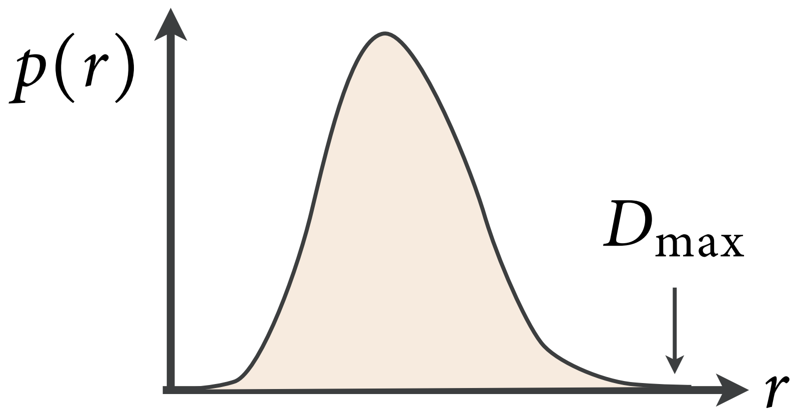
the set of distances joining the volume elements within a particle, including the case of non-uniform density distribution.

Particle's SHAPE and maximum DIMENSION.



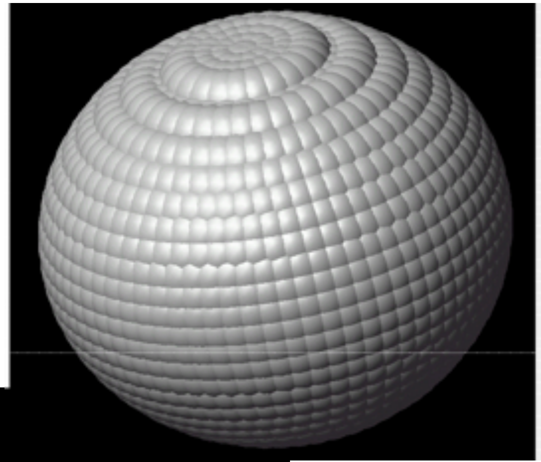

pairs of volume elements i-j

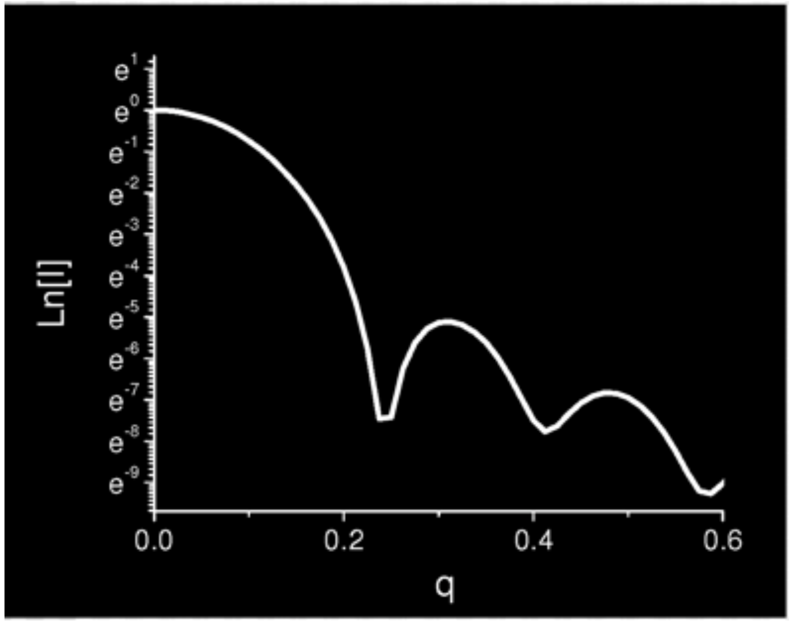
histogram of all intra-particle distances

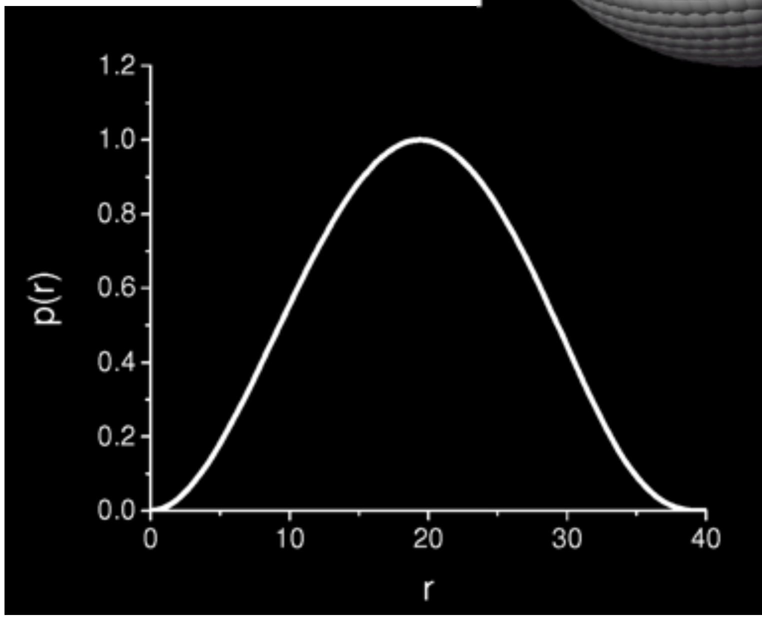



$$I(q) = 4\pi \int_0^\infty p(r) \frac{\sin(qr)}{qr} \mathrm{d}r$$

# I(q) & P(r) of Spherical particle

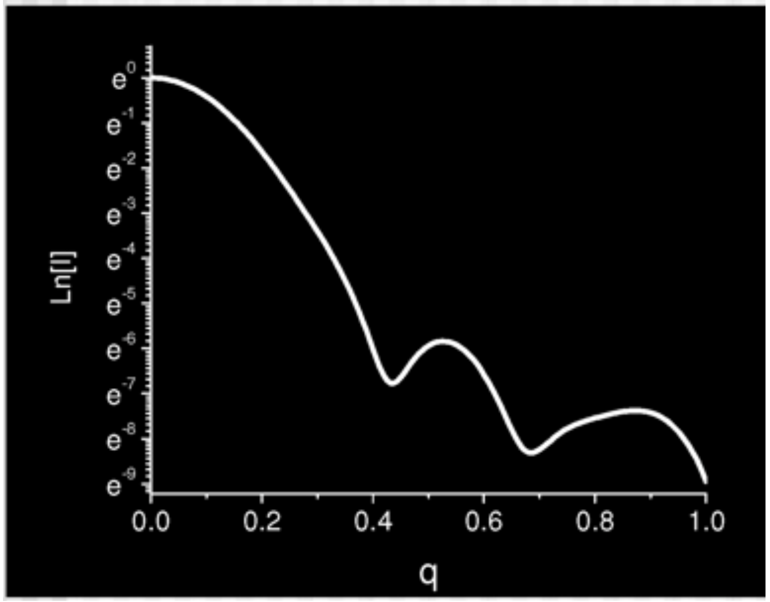


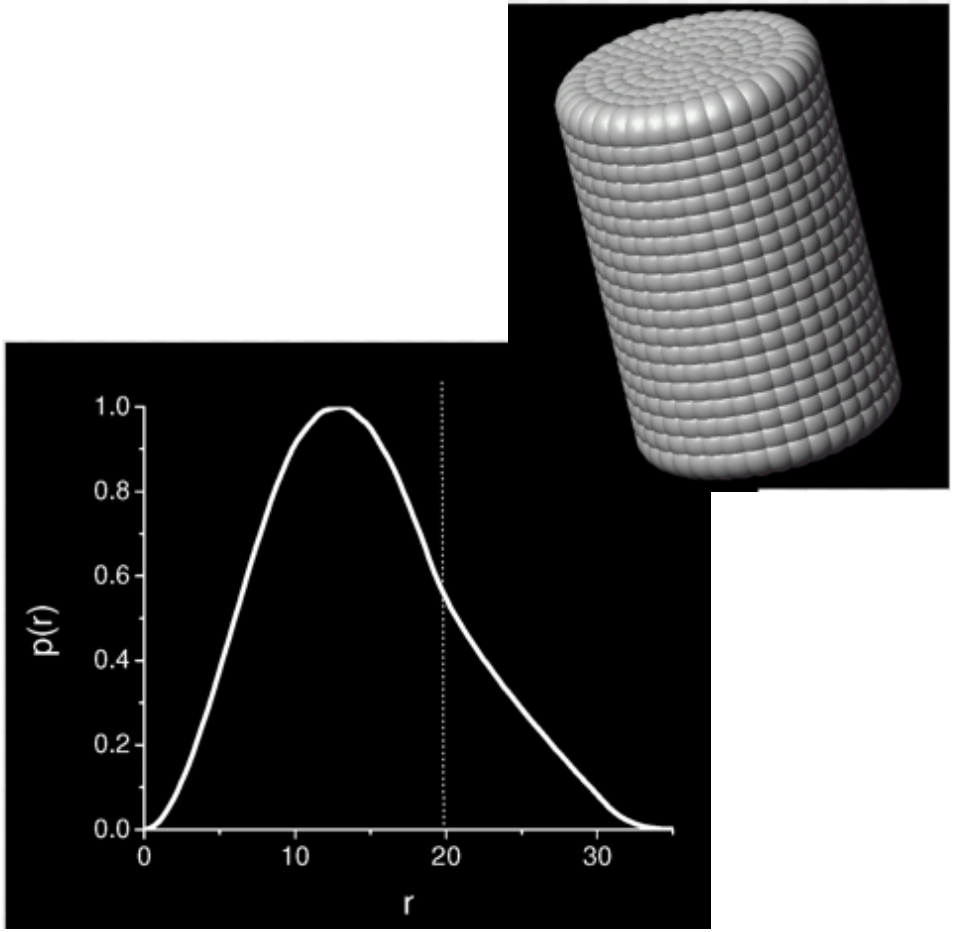



courtesy to Dr. I.L.Torriani

# I(q) & P(r) of Cylindrical particle

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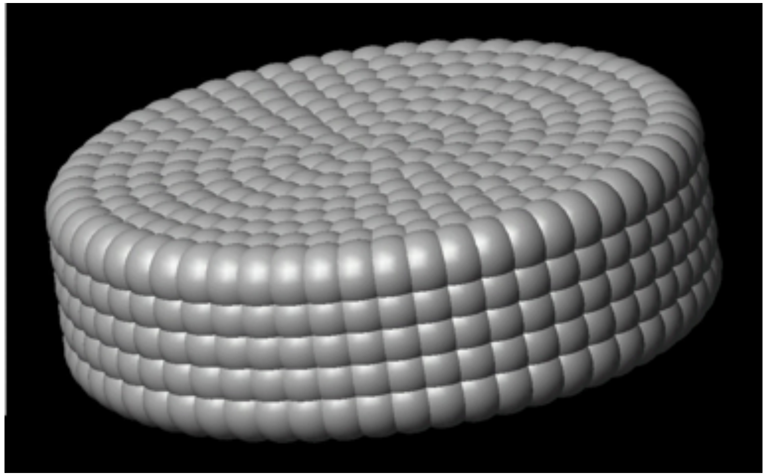
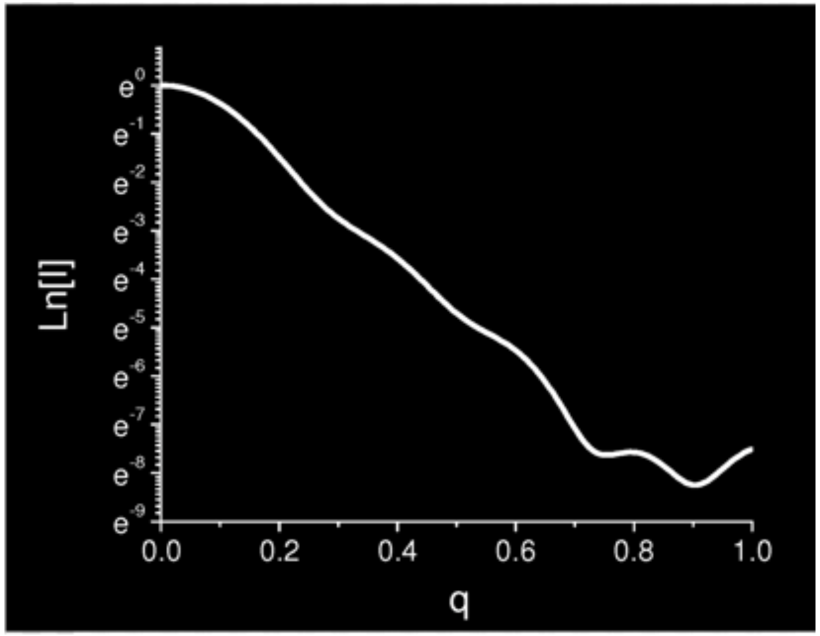
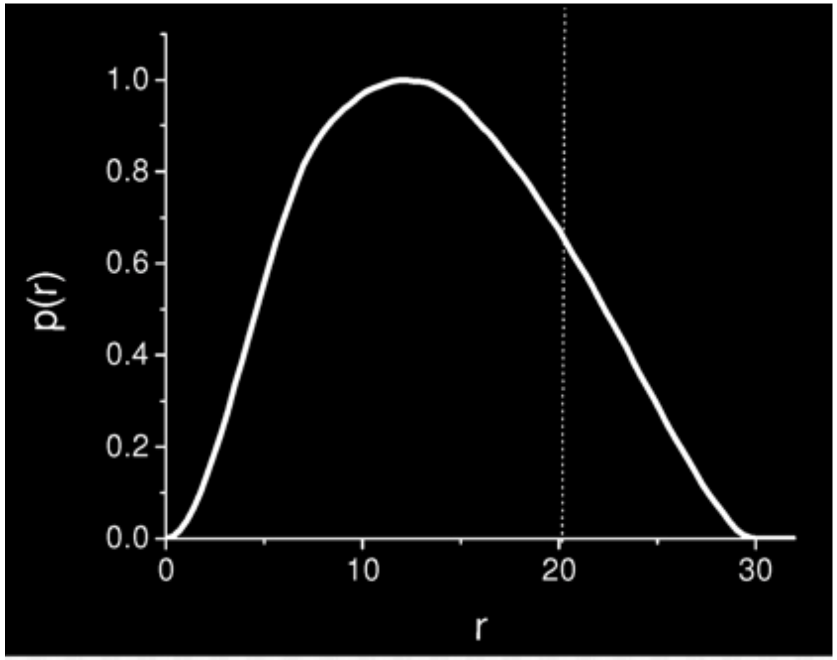
# I(q) & P(r) of Flat particle

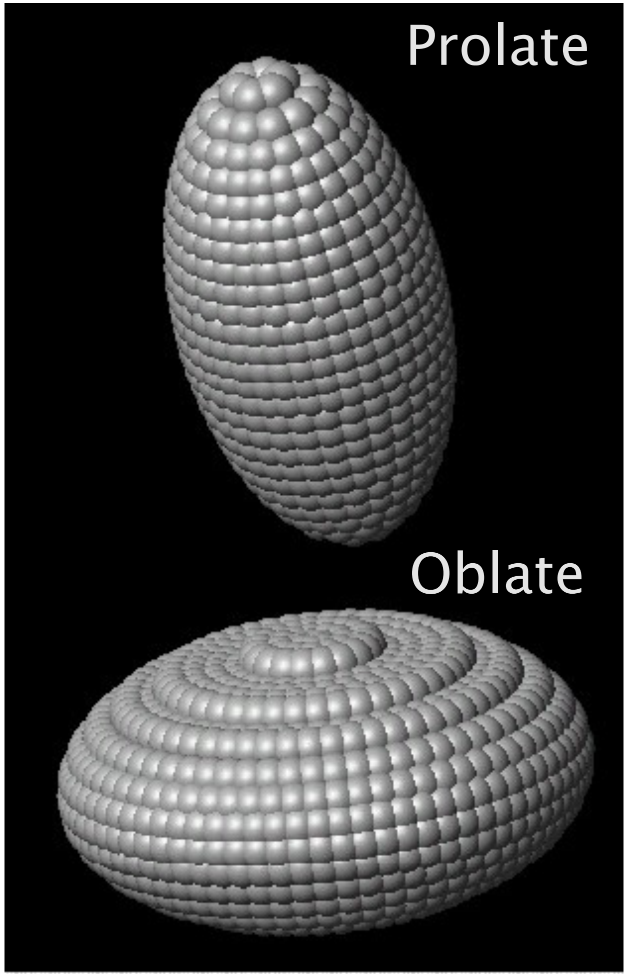


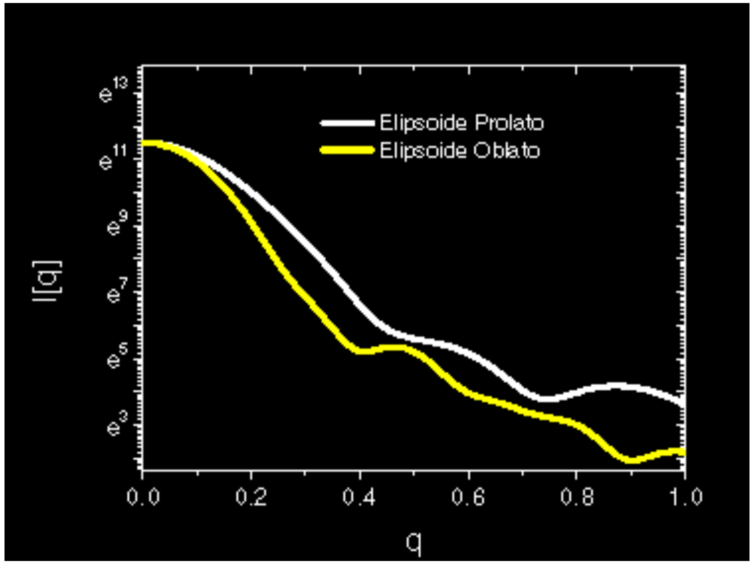


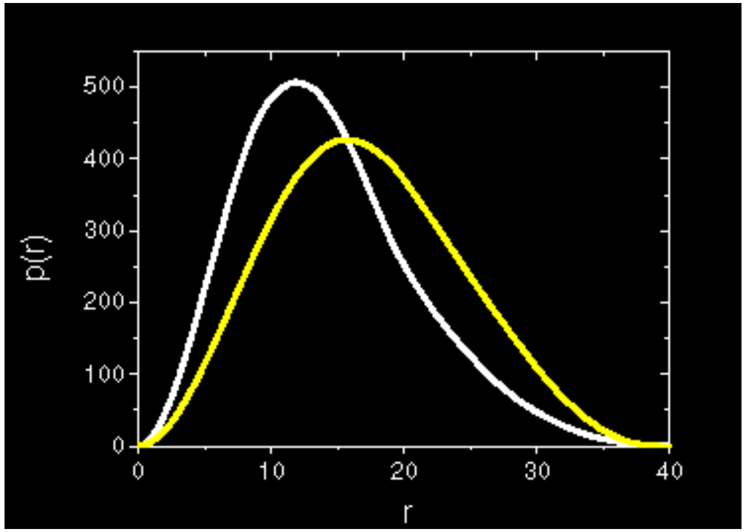




courtesy to Dr. I.L.Torriani

# I(q) & P(r) of Ellipsoids

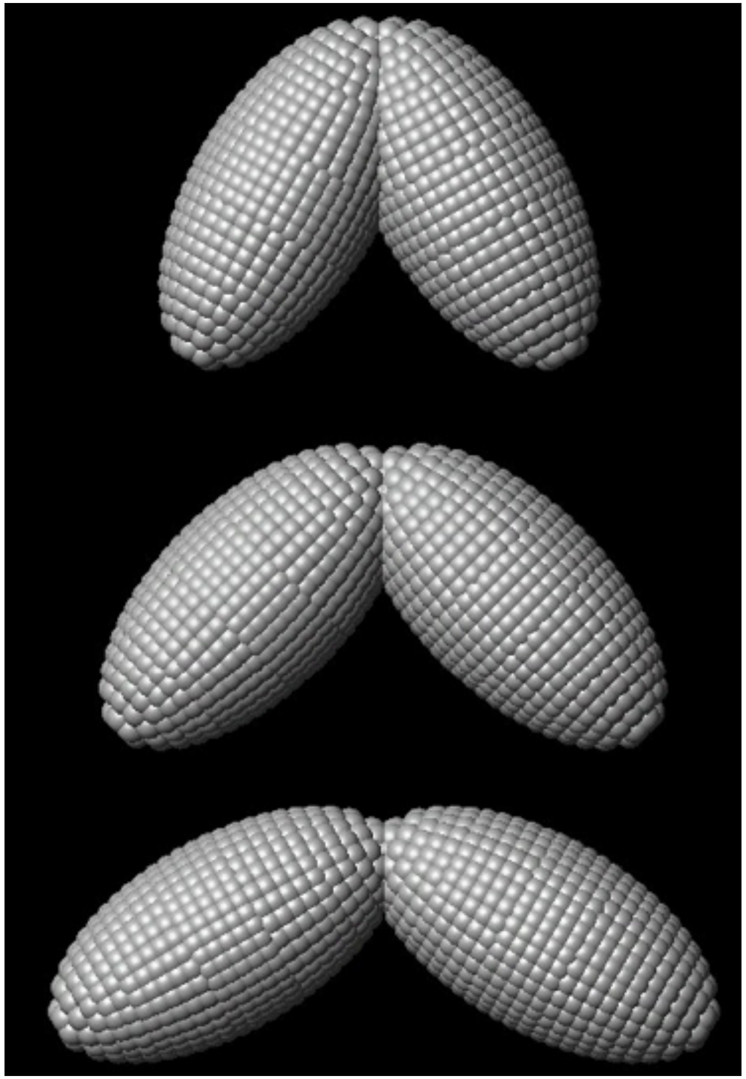


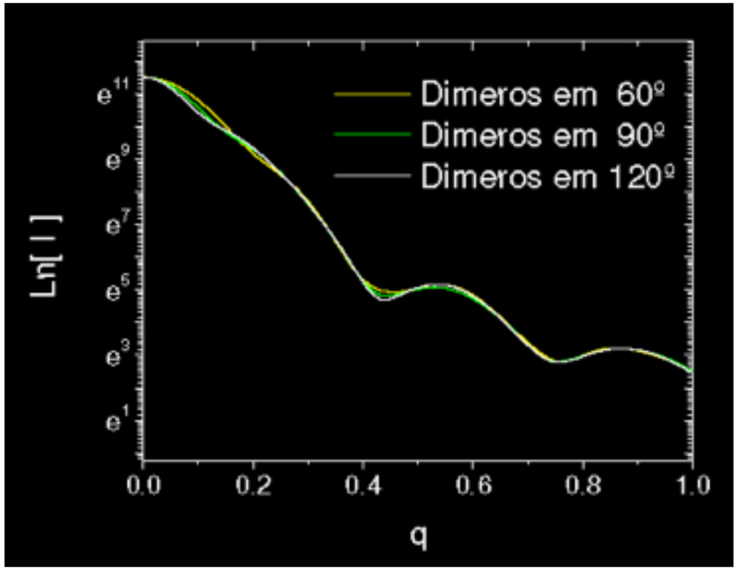



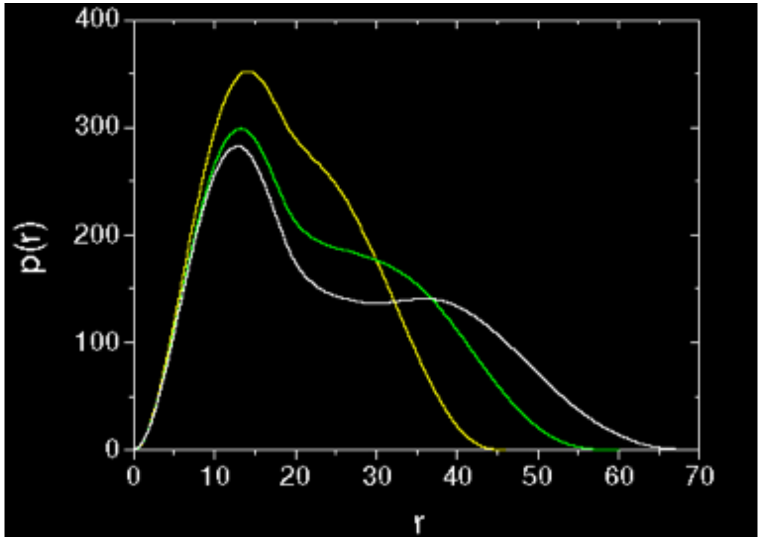




courtesy to Dr. I.L.Torriani

# I(q) & P(r) of Two ellipsoid = dimer

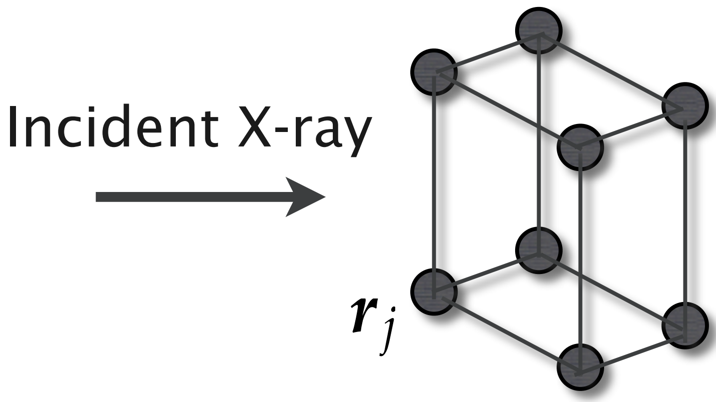





courtesy to Dr. I.L.Torriani

# Diffraction from Periodic Structure




Diffraction from Unit cell (Crystalline structure factor)

$$F(\boldsymbol{q}) = \sum_j f(\boldsymbol{q}) \exp(-\mathrm{i}\boldsymbol{q} \cdot \boldsymbol{r}_j)$$

$f(\boldsymbol{q})$ : Atomic Form Factor

Diffraction Intensity: $$I(\boldsymbol{q}) \sim G(\boldsymbol{q})^{2} \; F(\boldsymbol{q})^{2}$$

Laue function: $$\left|G(\boldsymbol{q})\right|^2 = \frac{\sin^2(\pi N \boldsymbol{q} \cdot \boldsymbol{r})}{\sin^2(\pi \boldsymbol{q} \cdot \boldsymbol{r})}$$

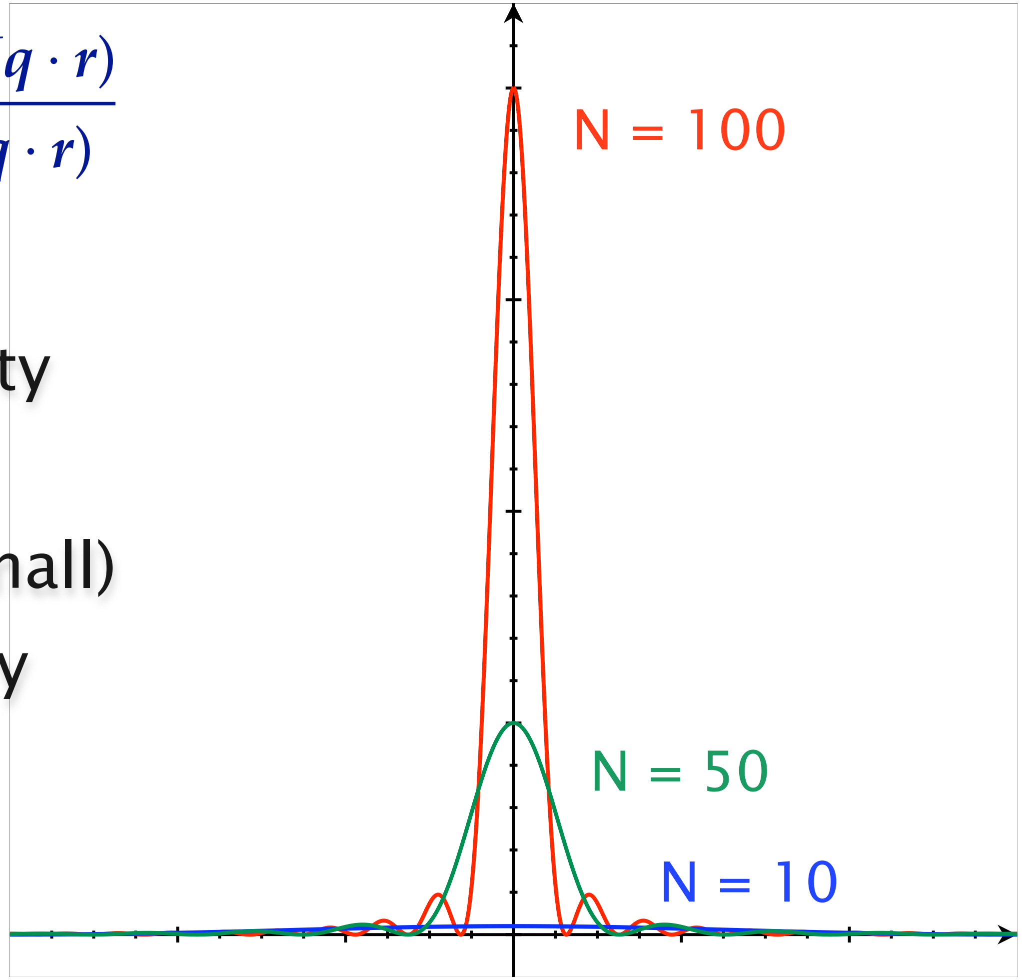
- Maximum ~ $N^2$
- FWHM ~ 2π/N
  - FWHM --> Size of crystal

# Laue Function

Laue function: $|G(\boldsymbol{q})|^2 = \dfrac{\sin^2(\pi N \boldsymbol{q}\cdot\boldsymbol{r})}{\sin^2(\pi \boldsymbol{q}\cdot\boldsymbol{r})}$

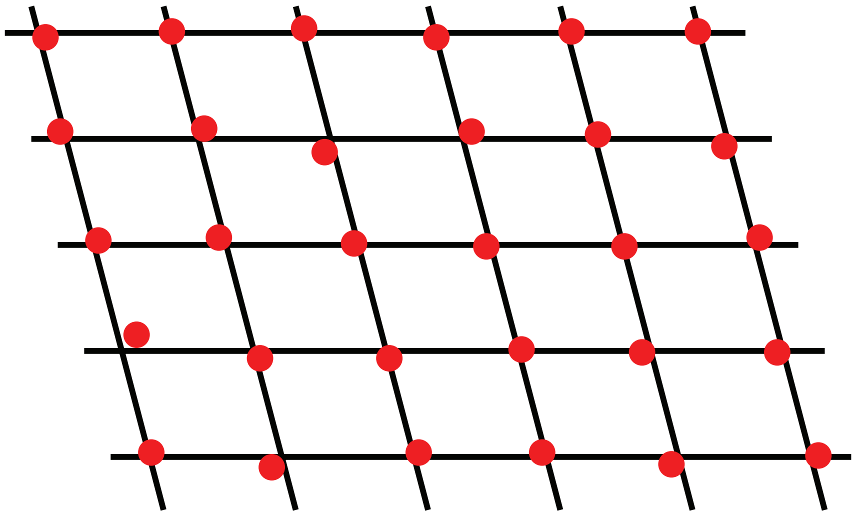
- Large crystal
  - High diffraction intensity
  - Narrow FWHM
- Soft matter (crystal size: small)
  - Low diffraction intensity
  - Wide FWHM

→ low S/N



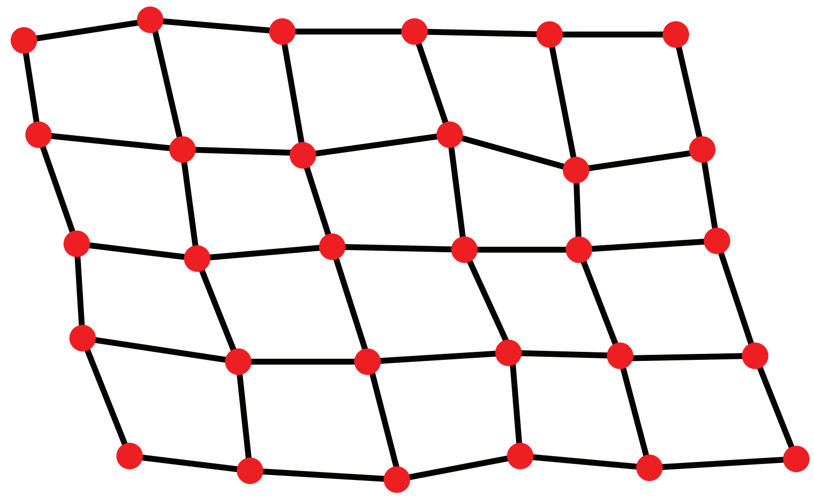

Crystal size --> Intensity & FWHM of diffraction

# Imperfection of crystal (2D)



**Imperfection of 1st kind**

Thermal fluctuation etc.



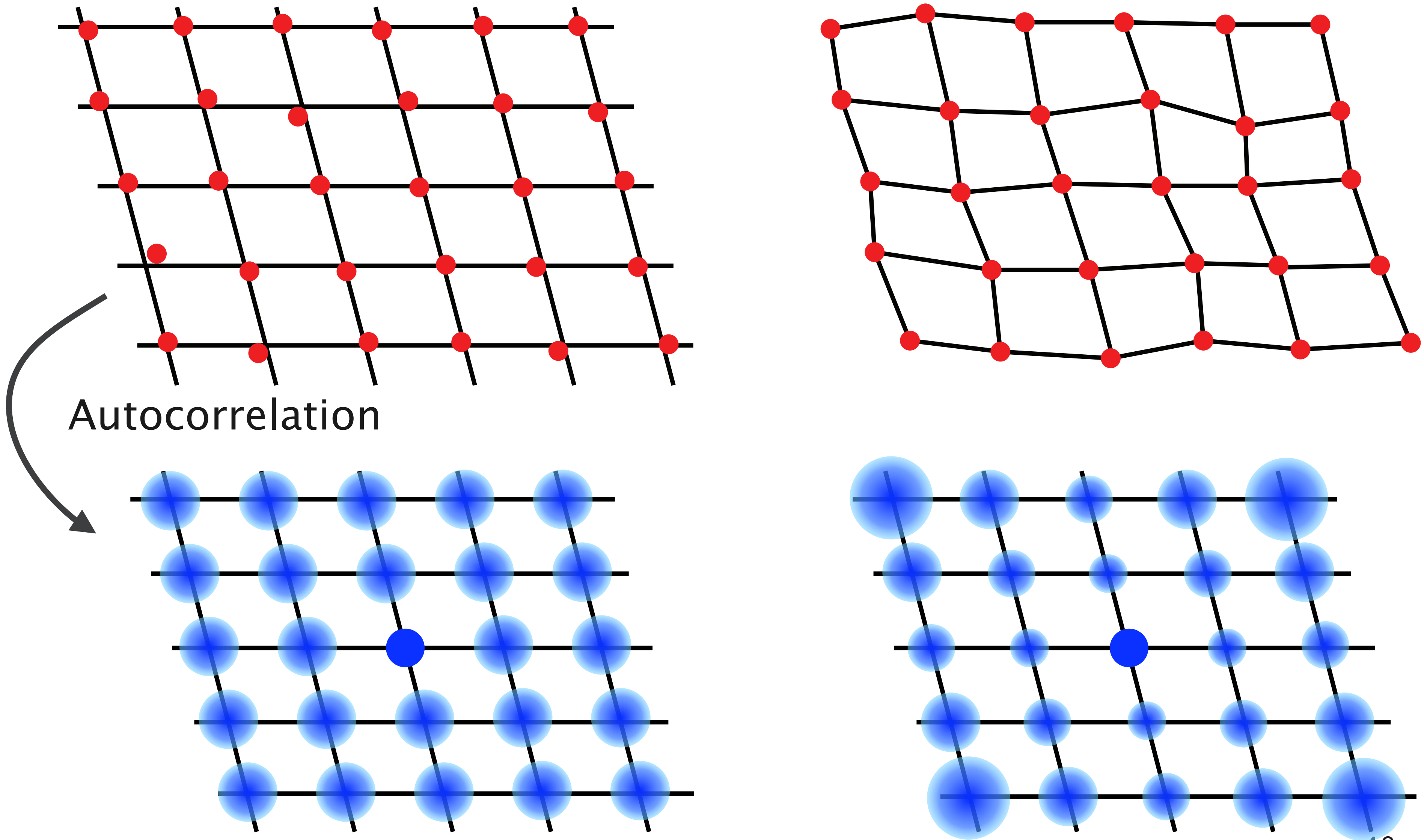
**Imperfection of 2nd kind**

in the case of soft matter

# Imperfection of crystal

**Imperfection of 1st kind**

**Imperfection of 2nd kind**



# Imperfection of lattice (1D)

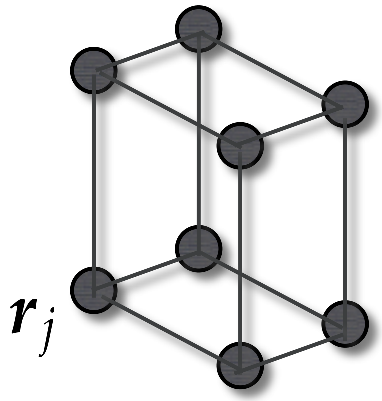
Perfect lattice

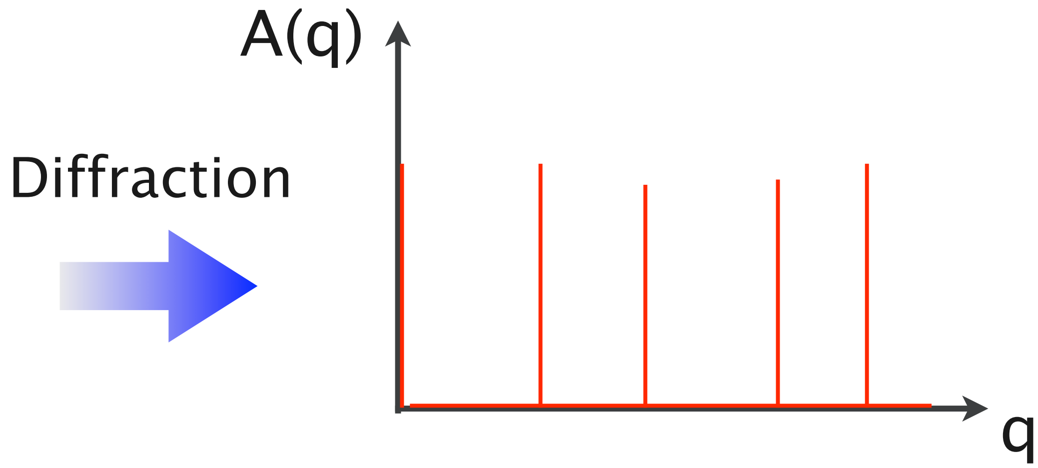
Imperfection of 1st kind

Imperfection of 2nd kind

❧ Effect of imperfections on diffraction ?

# Diffraction from lattice-structure




$$\rho(\boldsymbol{r}) = \rho_u(\boldsymbol{r}) * \underline{z(\boldsymbol{r})}$$

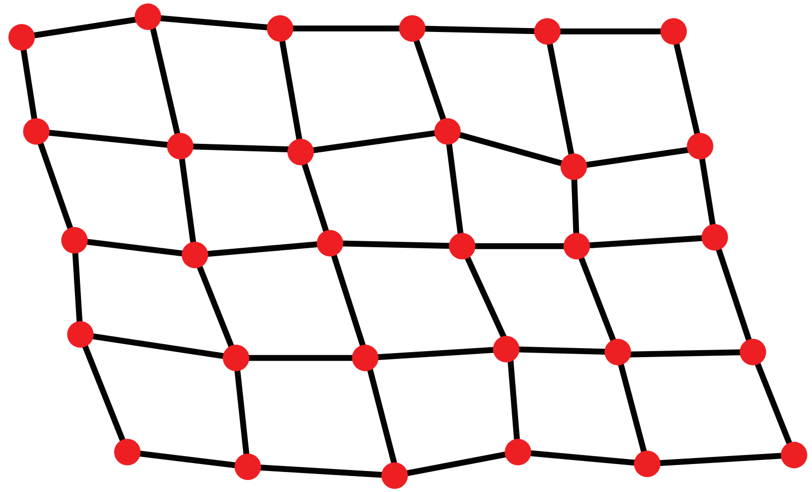
$$A(\boldsymbol{q}) = F(\boldsymbol{q}) \cdot \underline{Z(\boldsymbol{q})}$$

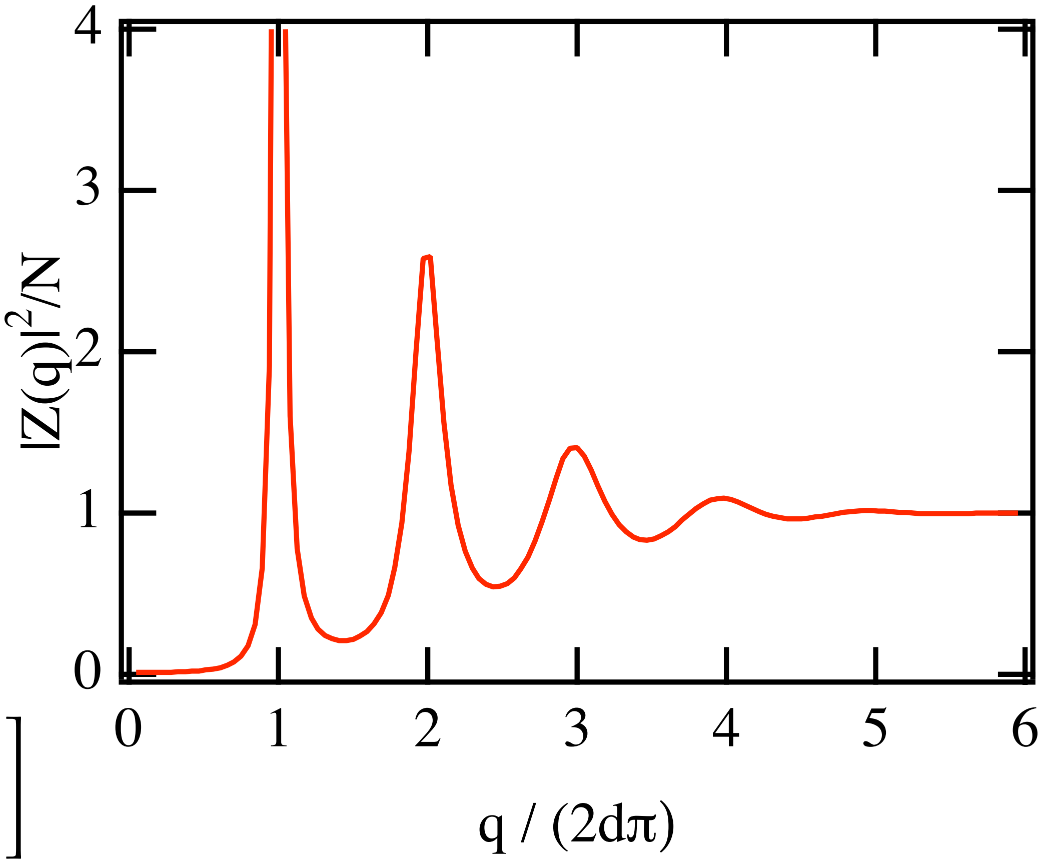
Form of lattice

convolution

z(**r**) with imperfection ---> calculate Z(**q**)

# Imperfection of 2nd kind






Paracrystal theory

$$\left|Z(q)\right|^2 = N\left[1 + \frac{P(q)}{1 - P(q)} + \frac{P^*(q)}{1 - P^*(q)}\right]$$

Decrease of diffraction intensity and Increase of FWHM

R. Hosemann, S. N. Bagchi, Direct Analysis of Diffraction by Matter, North-Holland, Amsterdam (1962).

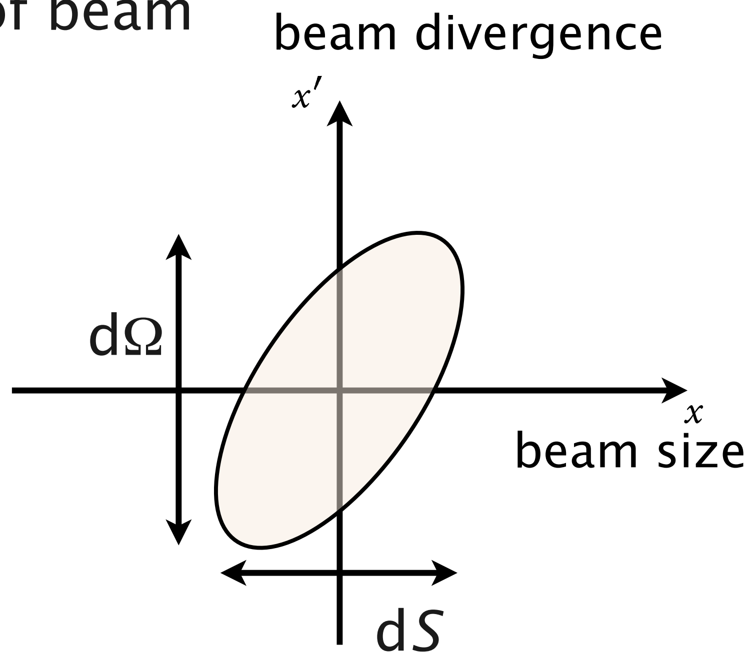
# Table of Contents

# X-ray Source for SAXS

Emittance -- Product of size and divergence of beam

$$\text{Brilliance} = \frac{\mathrm{d}^4 N}{\mathrm{d}t \cdot \mathrm{d}\Omega \cdot \mathrm{d}S \cdot \mathrm{d}\lambda/\lambda}$$

[photons/(s·mrad²·mm²·0.1% rel.bandwidth)]

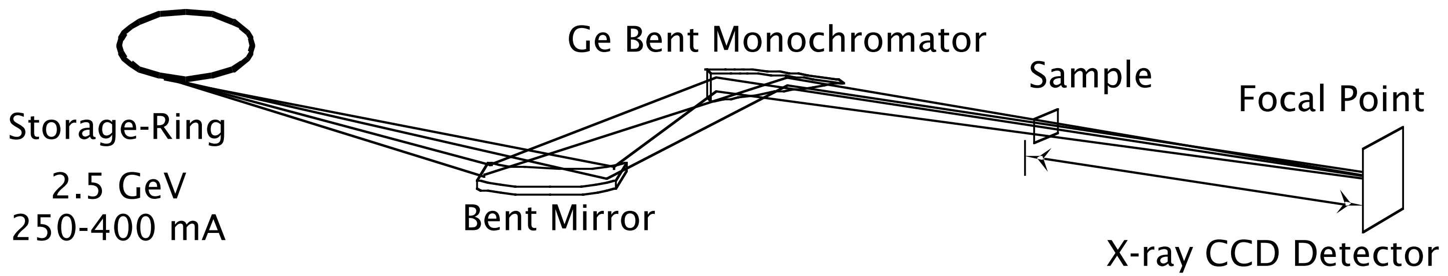



SAXS needs to use a low divergence and small beam

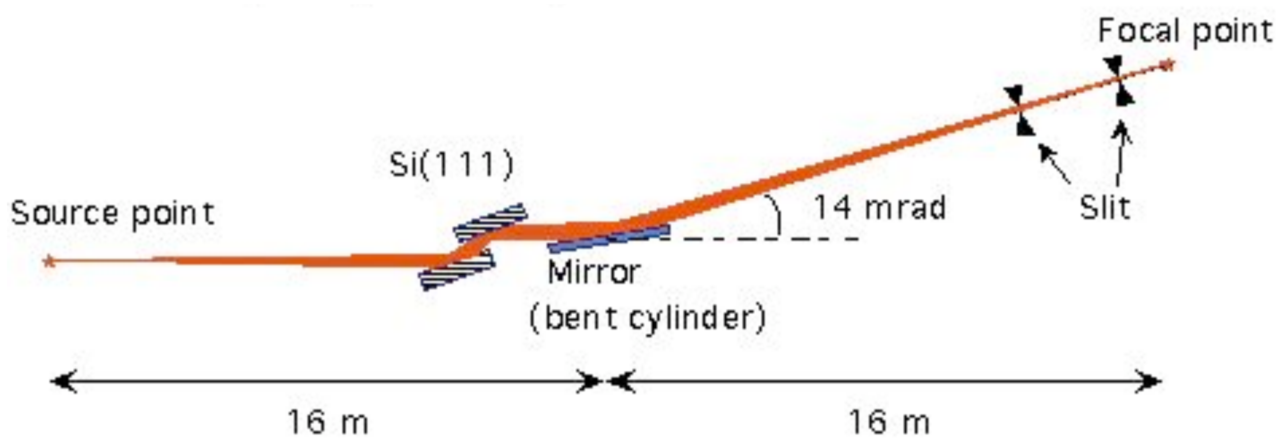
→ High brilliance beam is required !

# X-ray Optics for SAXS

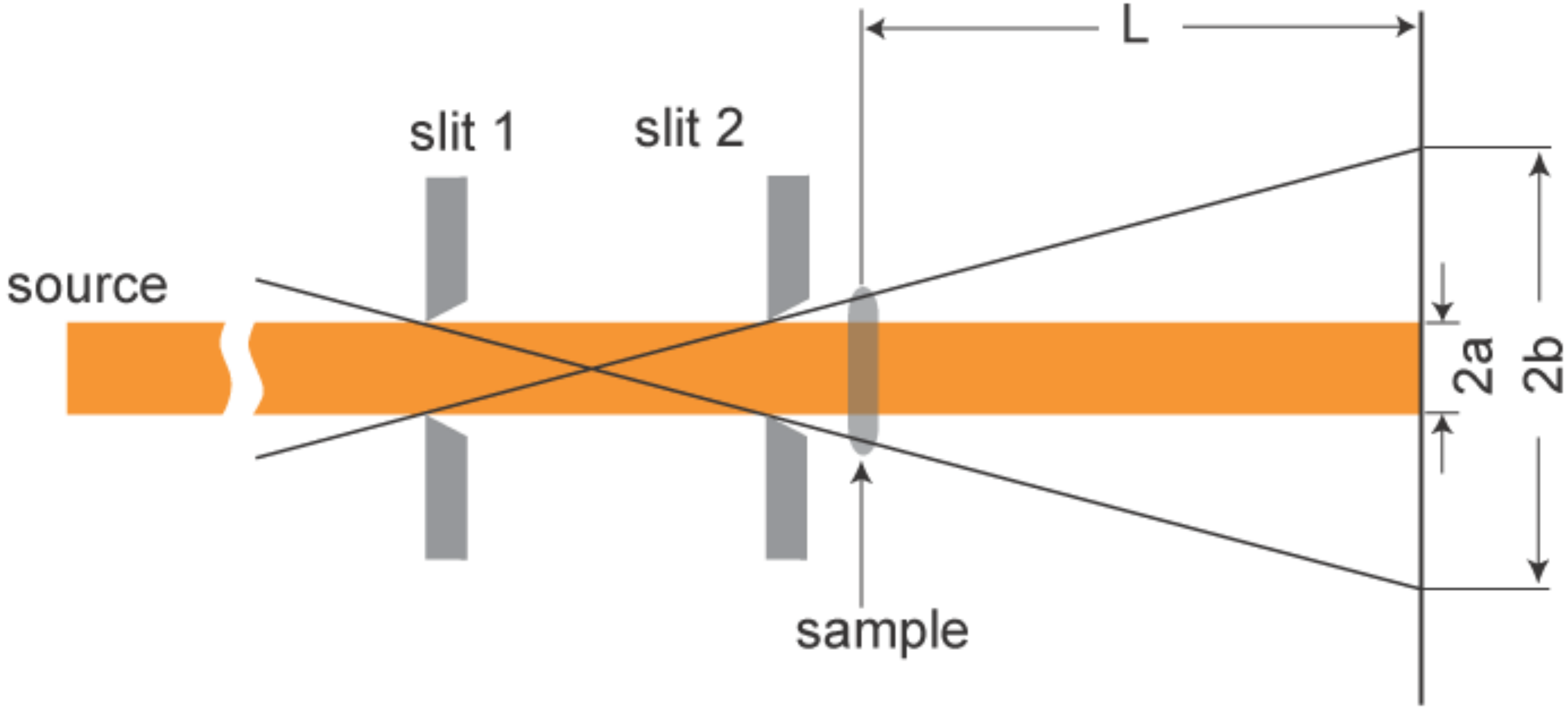
PF BL-15A




PF BL-10C



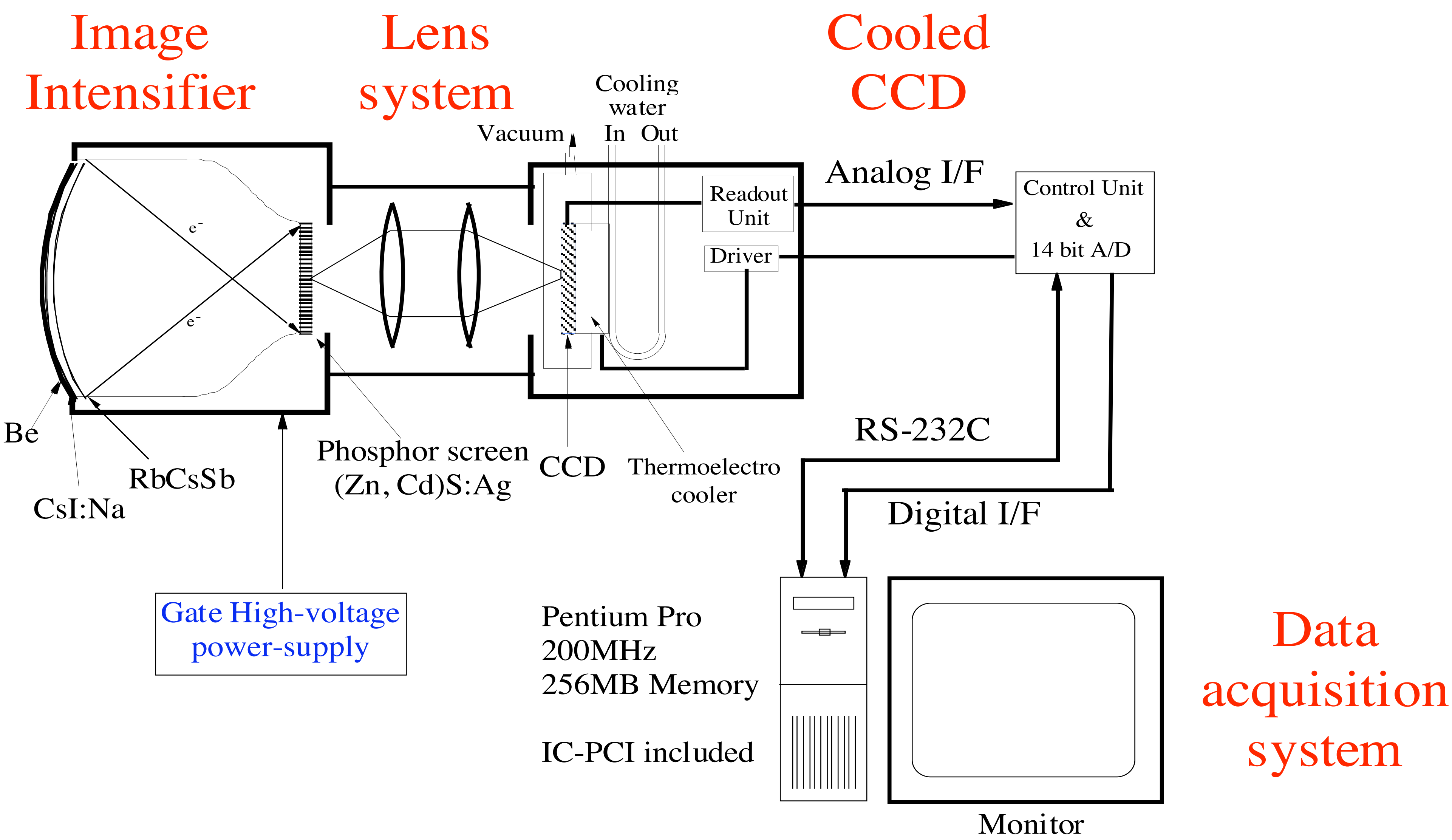
# Slits for SAXS



# Detectors for SAXS

| | Good Point | Drawback |
| --- | --- | --- |
| PSPC | • time-resolved<br>• photon-counting<br>• low noise | • counting-rate limitation |
| Imaging Plate | • wide dynamic range<br>• large active area | • slow read-out |
| CCD with Image Intensifier | • time-resolved<br>• high sensitivity | • image distortion<br>• low dynamic range |
| Fiber-tapered CCD | • fast read-out<br>• automated measurement | • not good for time-resolved |

# X-ray CCD detector with Image Intensifier



# Table of Contents

- Introduction
  - What's SAXS ?
  - History
- Theory
  - Basic of X-ray scattering
  - Structural Information obtained by SAXS
- Experimental Methods
  - X-ray Optics
  - X-ray Detectors
- Advanced SAXS
  - Microbeam, GI-SAXS, USAXS, XPCS etc...

# Advanced SAXS

## SAXS

### Microbeam X-ray
- Inhomogeneity of nano-structure
- local time evolution of structure

### Time-resolved
- time evolution of structure

### GI-SAXS
- surface, interface, thin films

### XPCS
- structural fluctuation
- dynamics

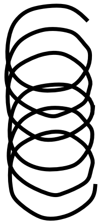
### Combined measurement with DSC, viscoelasticity

**wide-q** (USAXS-SAXS-WAXS)
- hierarchical structure

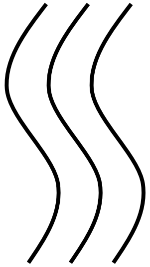
**2D measurement**
- anisotropic structure

# Application of paracrystal theory

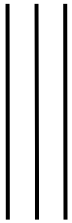
Collab. with Kao ltd.



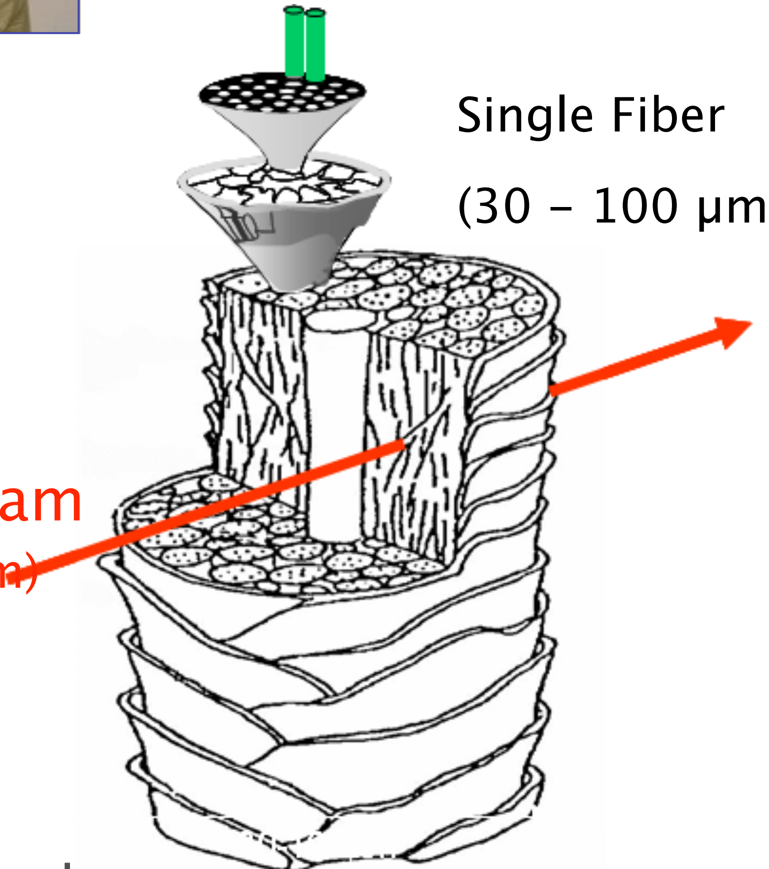
African



Caucasian



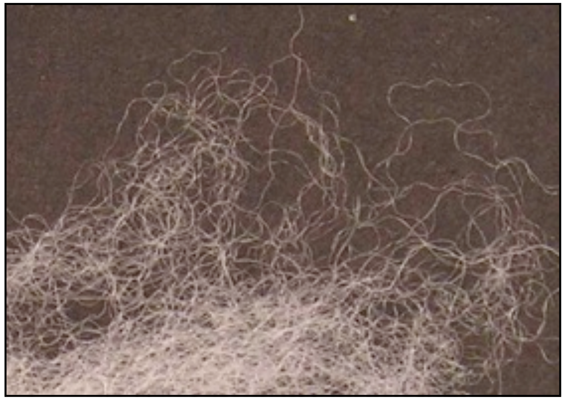
Asian



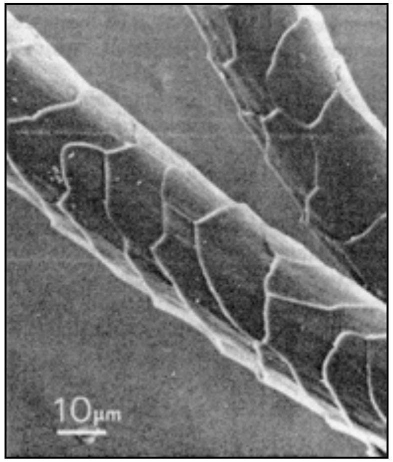

Relationship between macroscopic form and nano structure?

Local observation with an X-ray microbeam

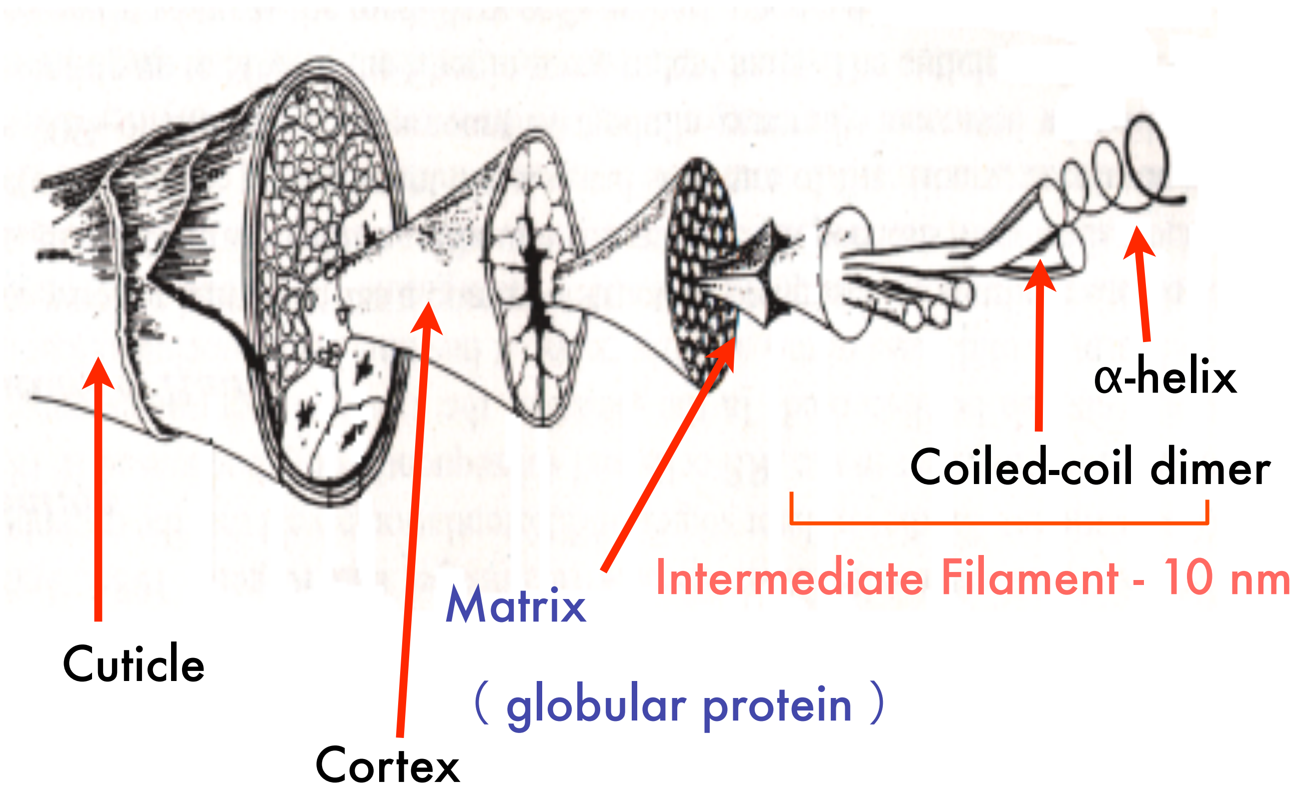
# Internal structure of wool



SEM 像



H. Ito et al., Textile Res. J. **54**, 397–402 (1986).

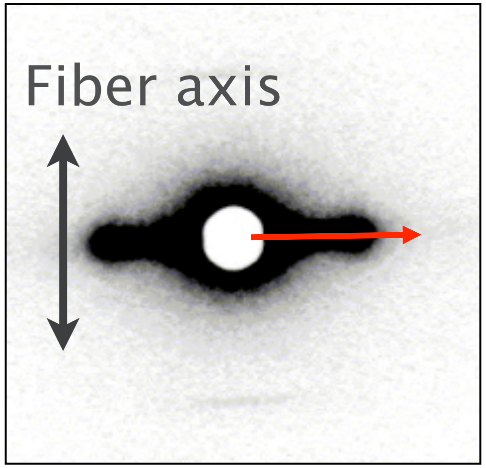


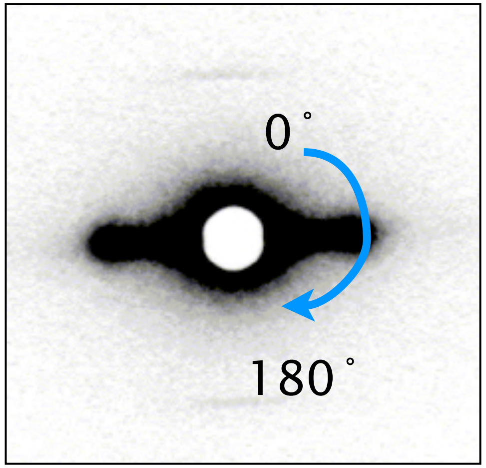

R. D. B. Fraser et al., Proc. Int. Wool Text. Res. Conf., Tokyo, II, **37**, (1985) partially changed.

**Relationship between IF distribution and hair curlness?**

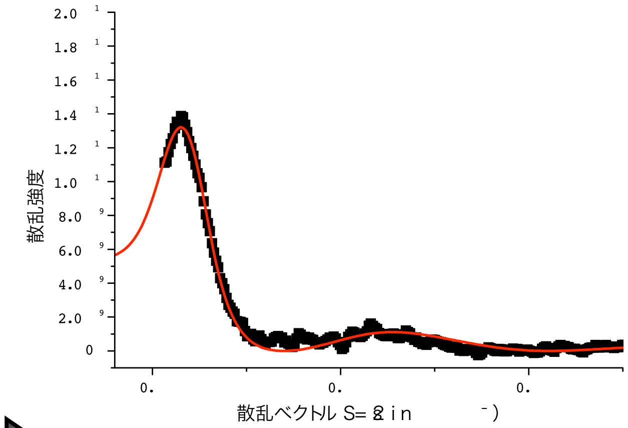
# Structure of Intermediate Filament

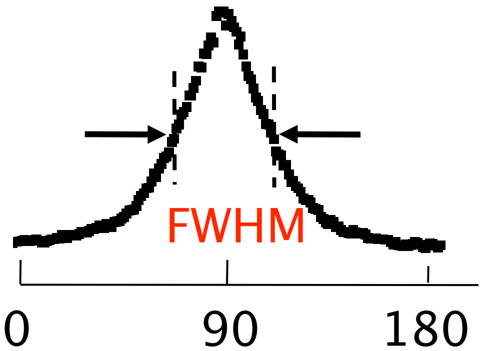
Scattering pattern



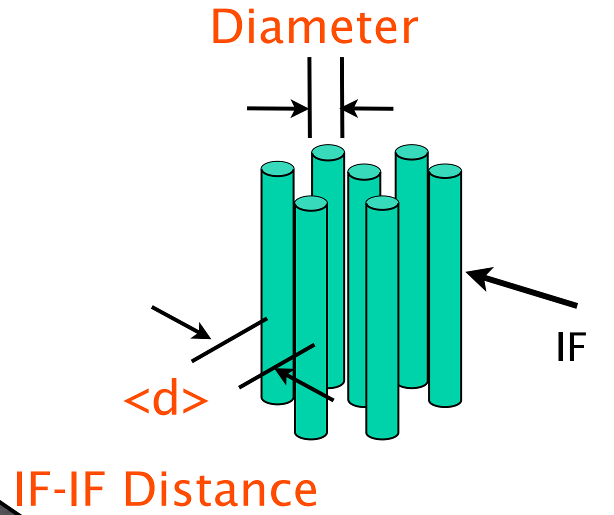



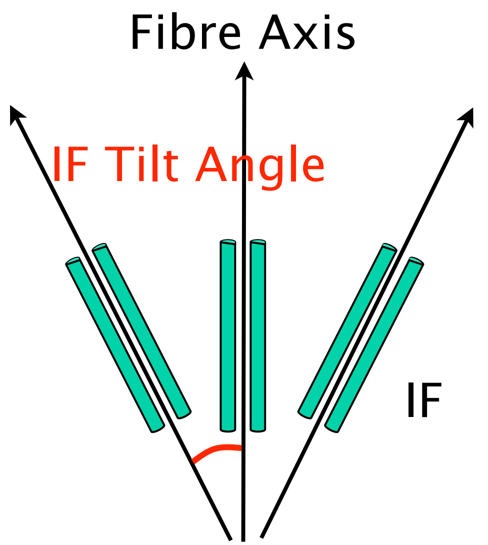

1D intensity profile



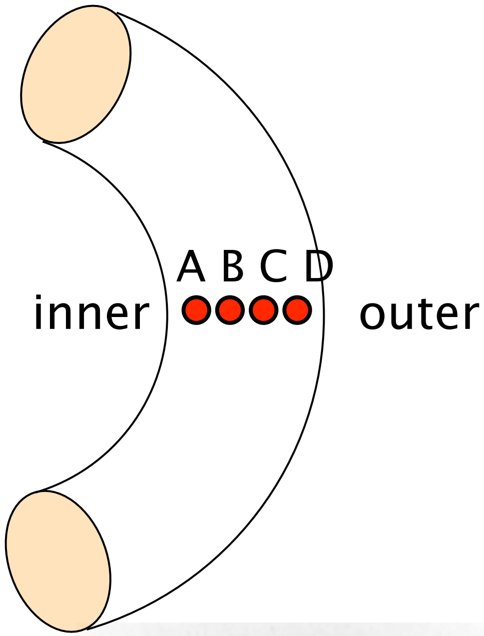



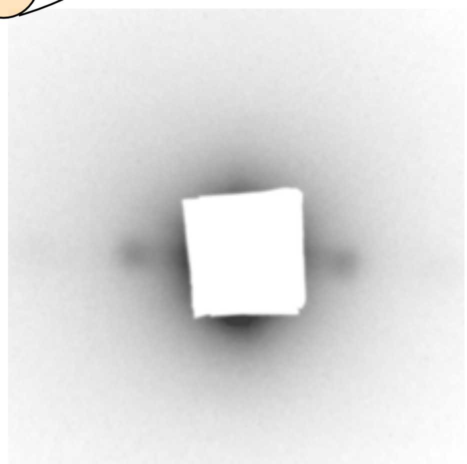

Real space structure

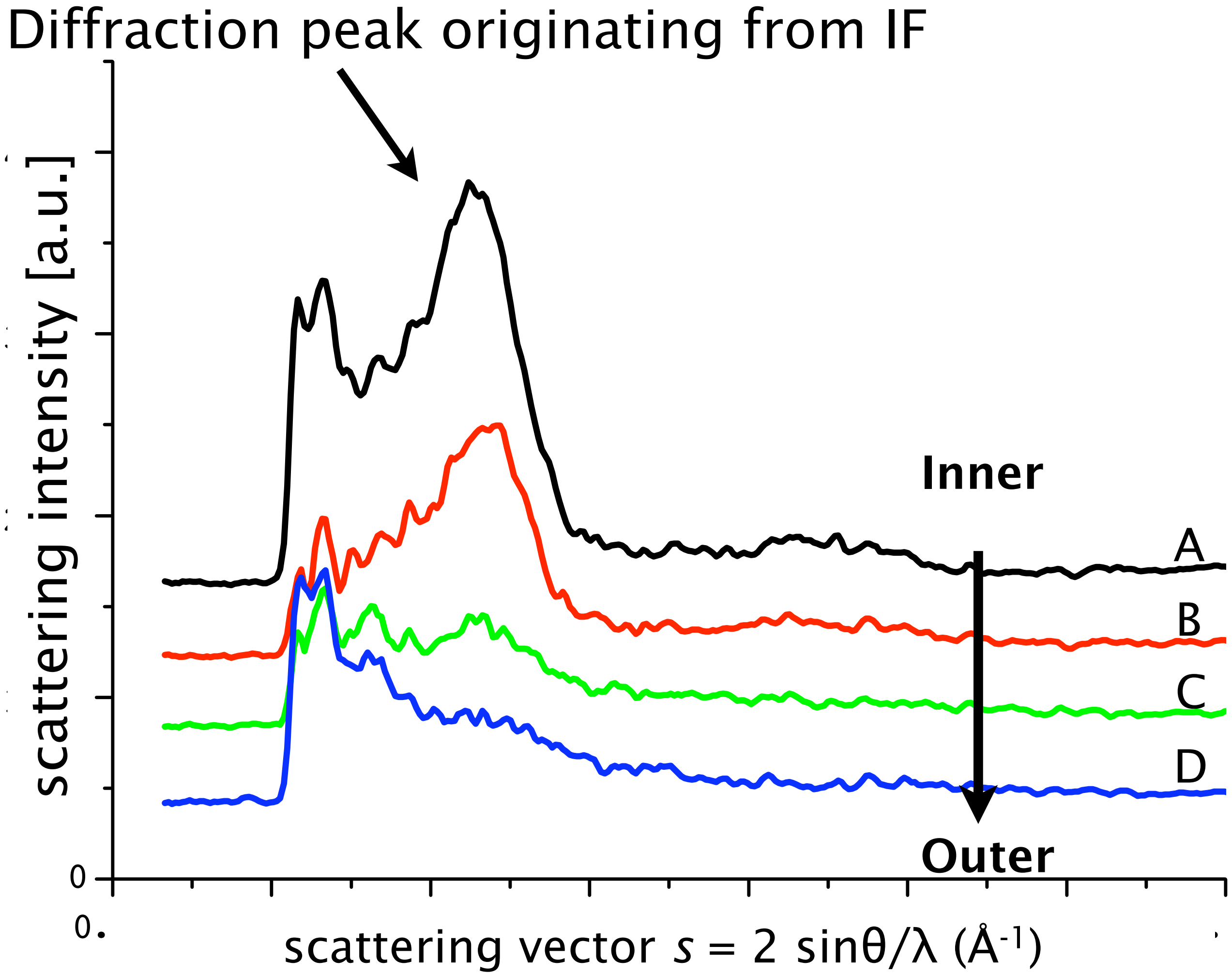


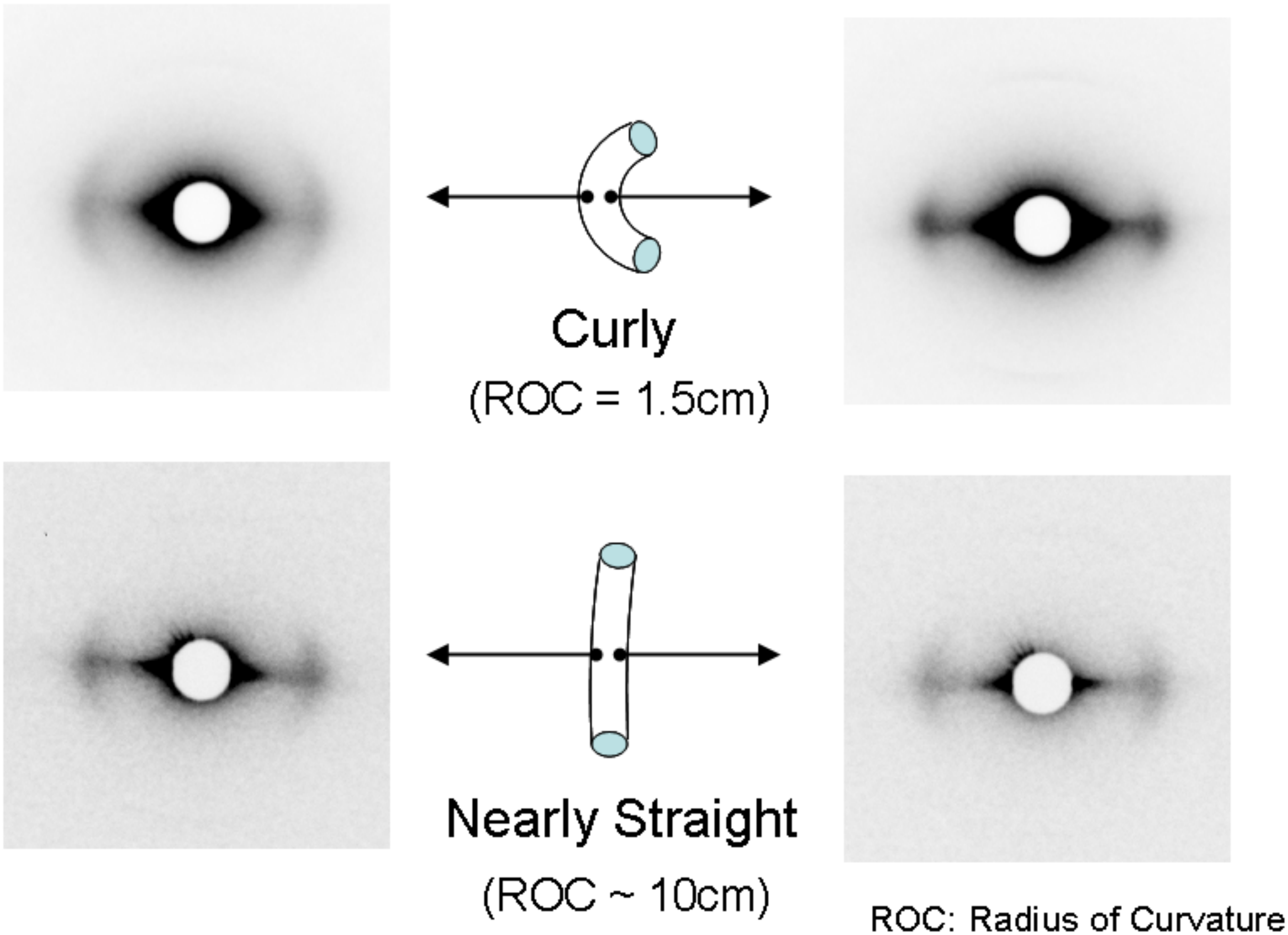
# Diffraction intensity profiles



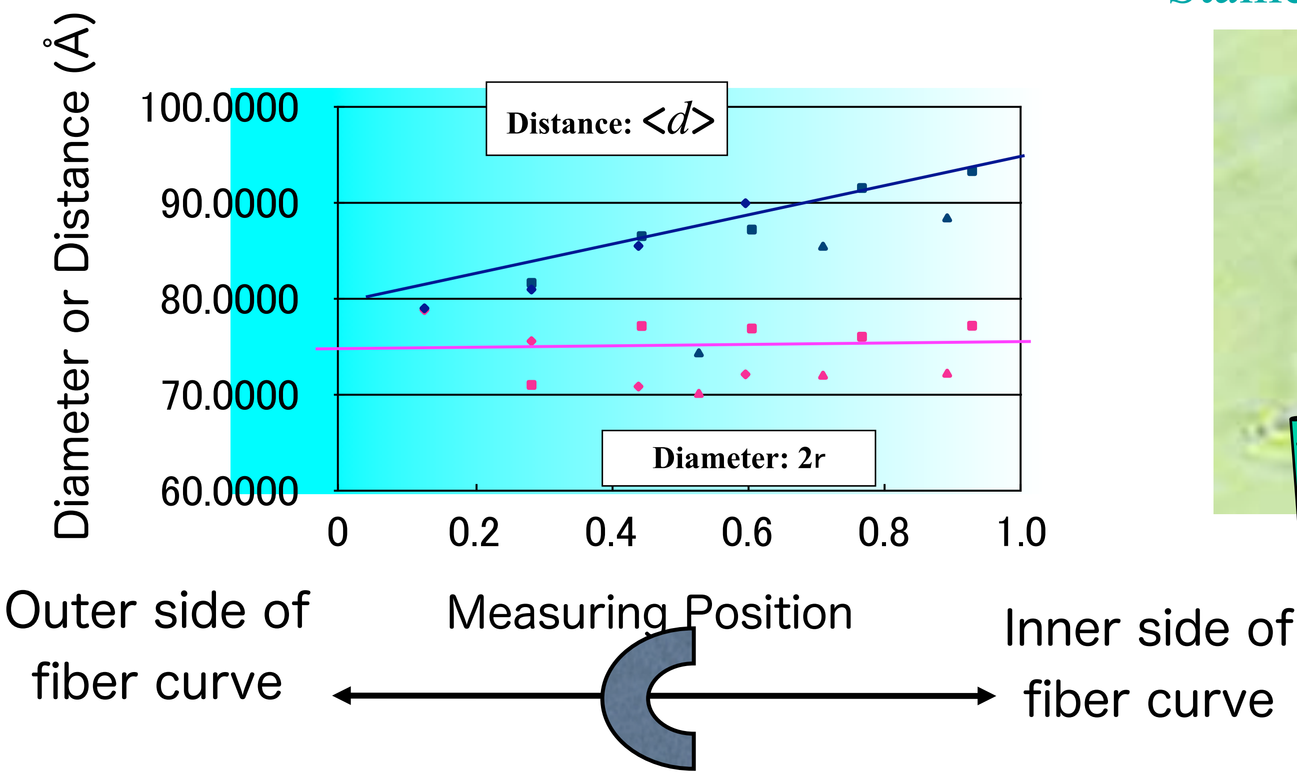





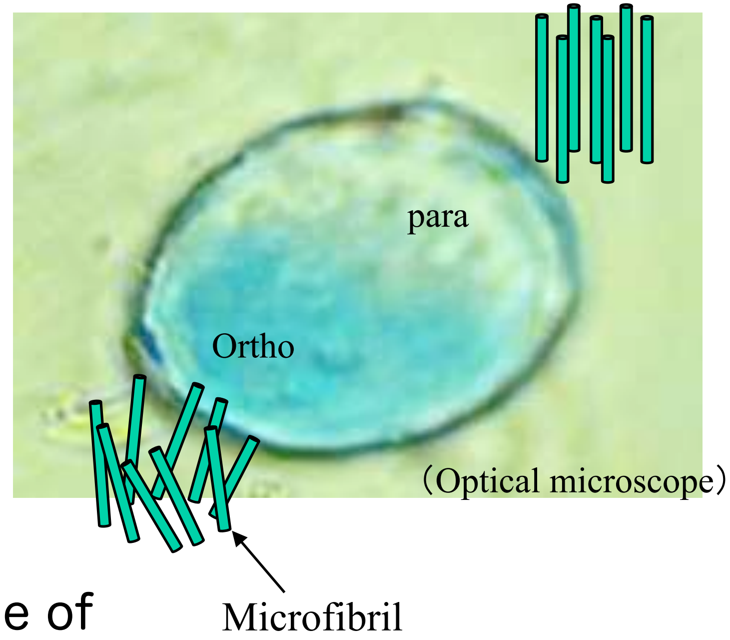

Difference in diffraction intensity
--> Structural difference in cortex.


Curly
(ROC = 1.5cm)
Nearly Straight
(ROC ~ 10cm)
ROC: Radius of Curvature

# Distribution of Intermediate Filament (IF)

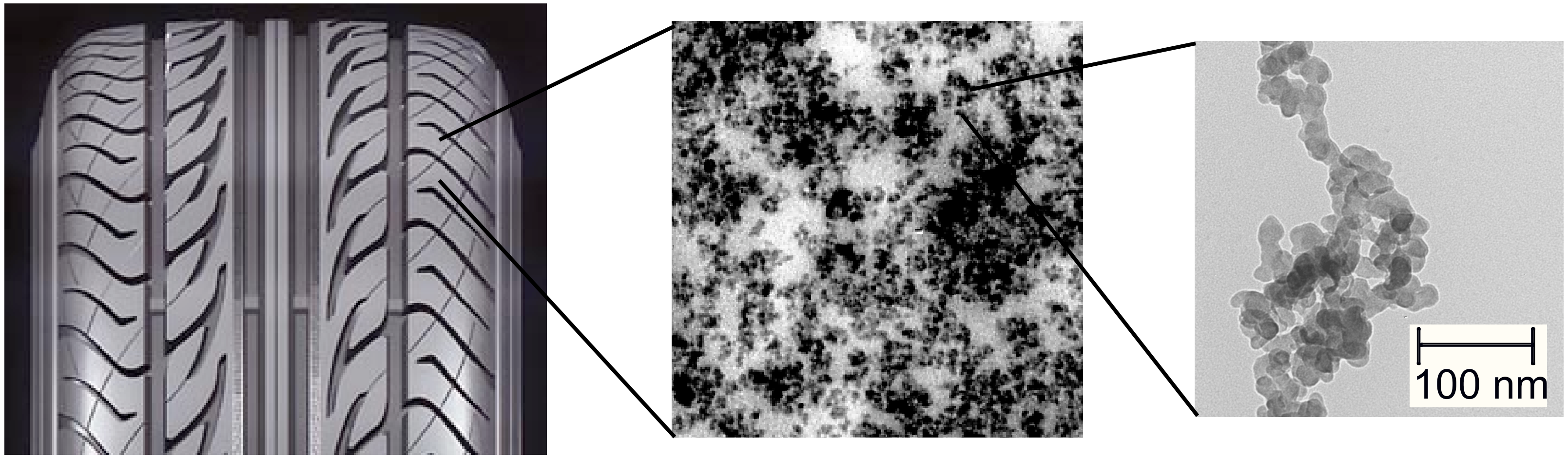



Stained with Methylene blue dye



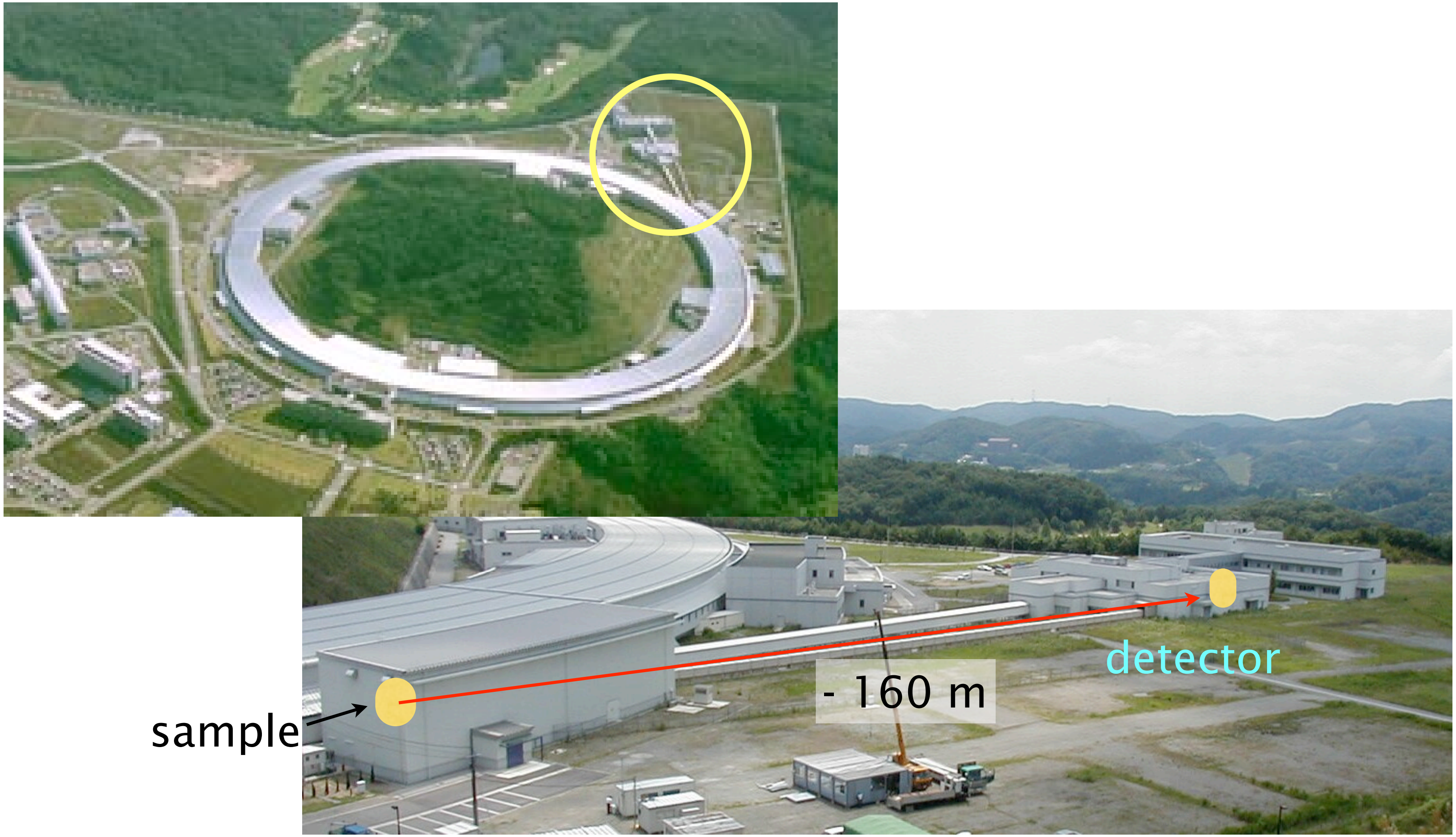

- Diameter of Intermediate filament (IF) is almost constant
- Distance between IFs increases from outer to inner sides.

# USAXS for nano-composite in rubber

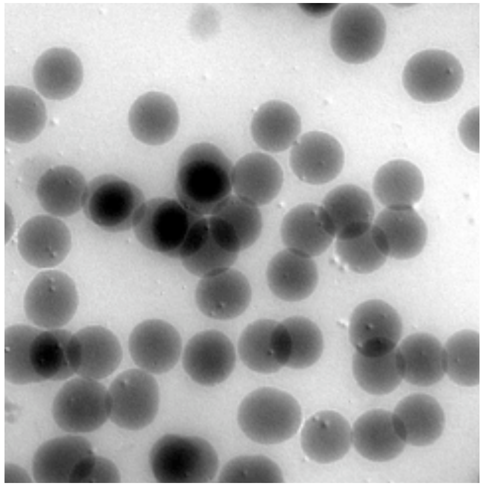



Nanocomposite

# USAXS using medium-length beamline

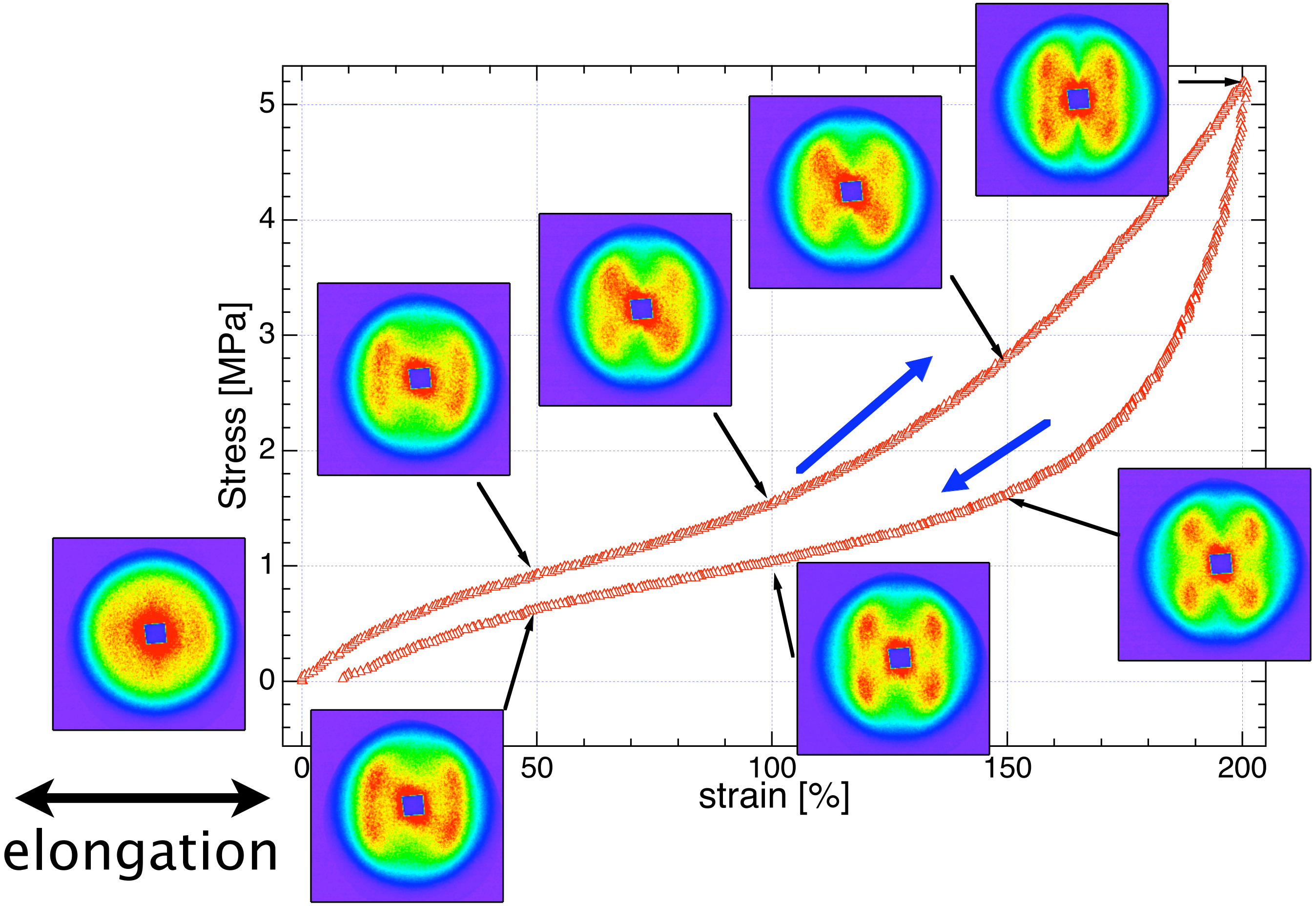


# USAXS patterns from elongated rubber



TEM image

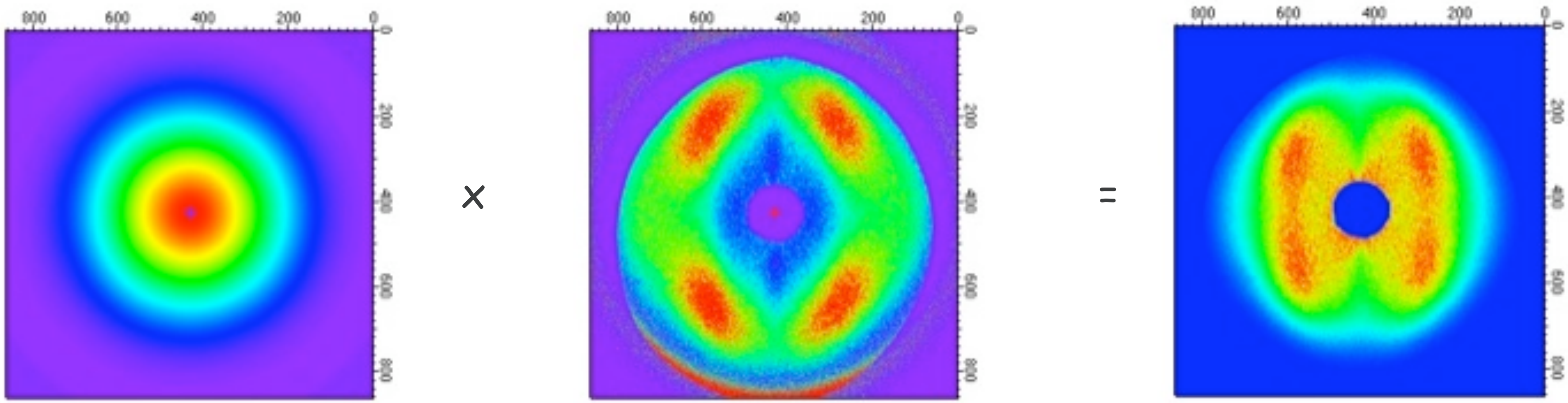
Rubber filled with spherical silica




Scattering pattern also shows hysteresis.

Y. Shinohara et al., J. Appl. Cryst., **40**, s397 (2007).

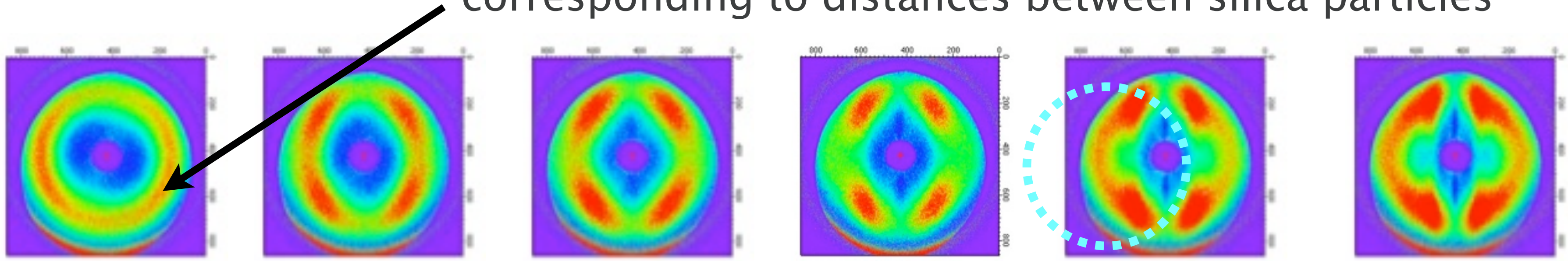
# Separation of Structure factor S(q)




F(q): form factor        S(q): structure factor        I(q): intensity

$D_{ave}$ = 282.9 nm

corresponding to distances between silica particles

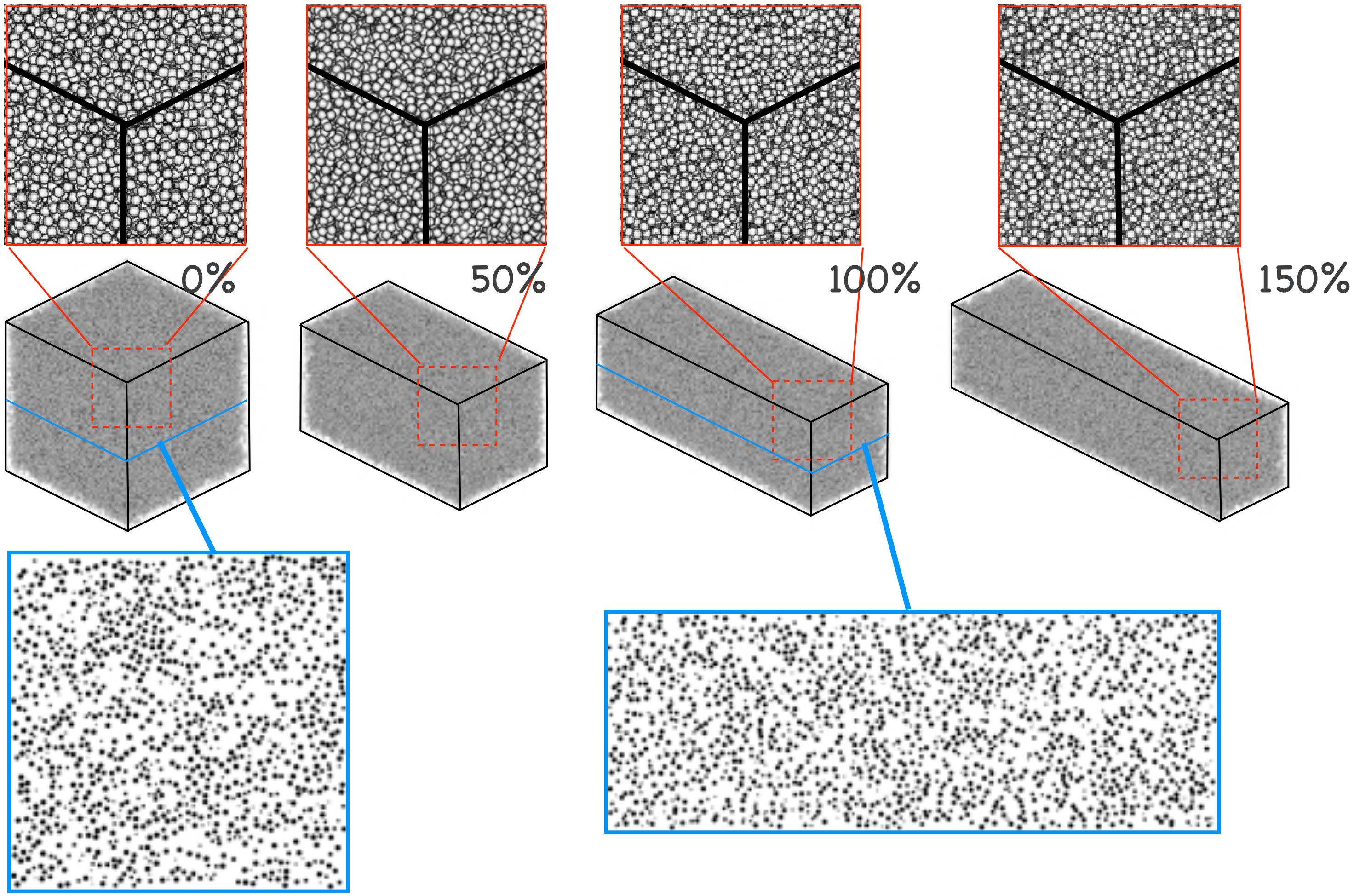


0 %        50 %        100 %        150 %        200 %        250 %

Y. Shinohara et al., J. Appl. Cryst., **40**, s397 (2007).

# Analysis by RMC (Reverse Monte Carlo)

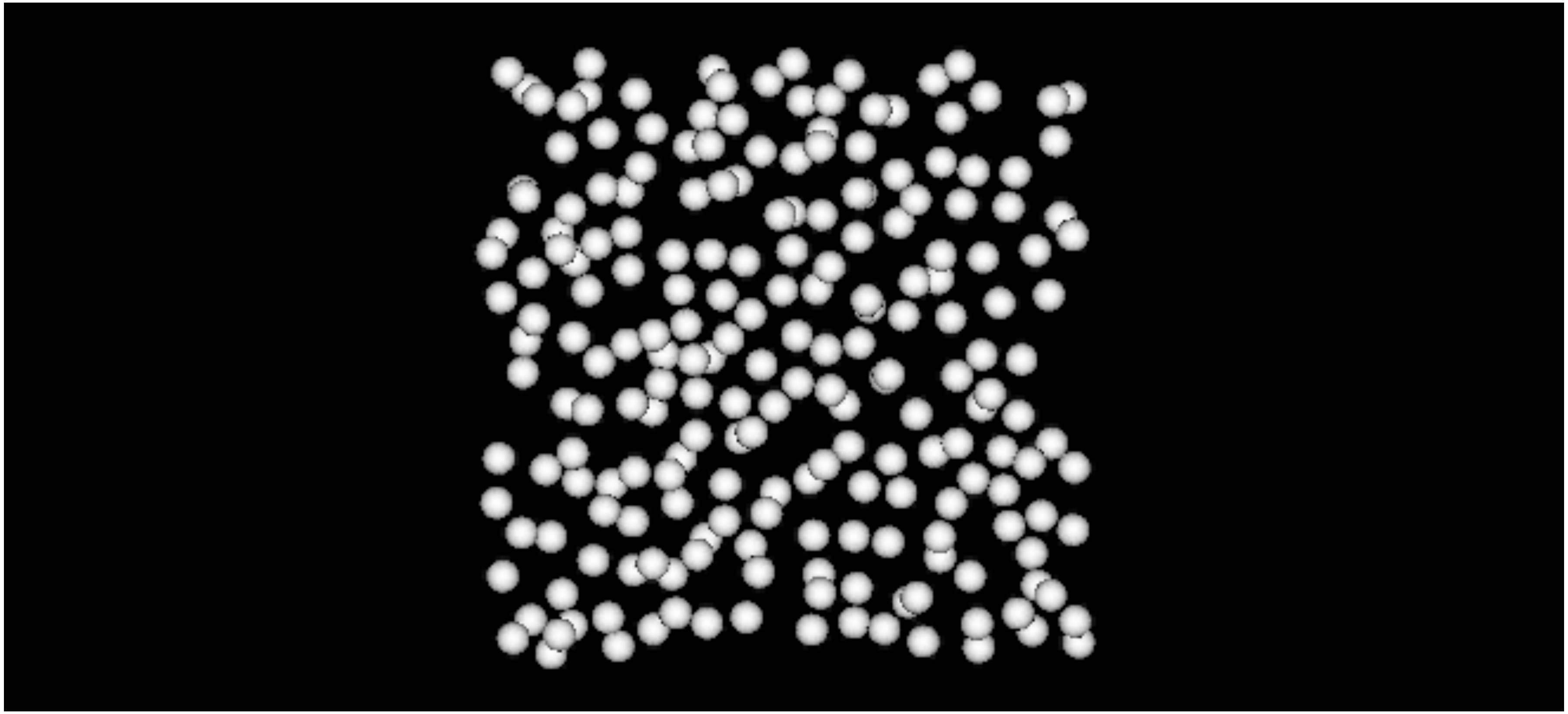
Sample : monodispersive silica spheres in rubber




Courtesy to Dr.Hagita & Prof. Arai

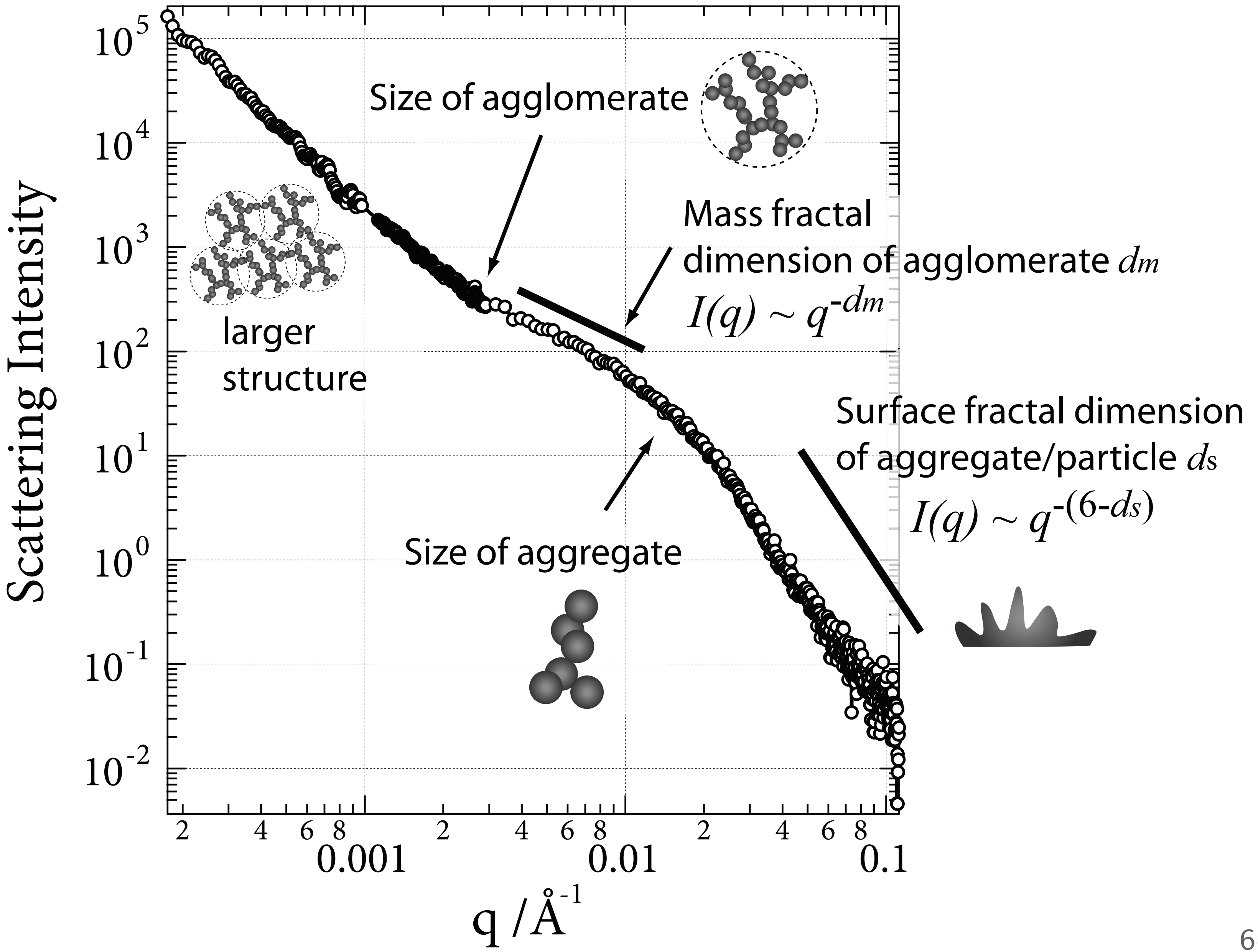
# Visualization of structure change of fillers during elongation of rubber by using SAXS and RMC

0→150% : elongation process



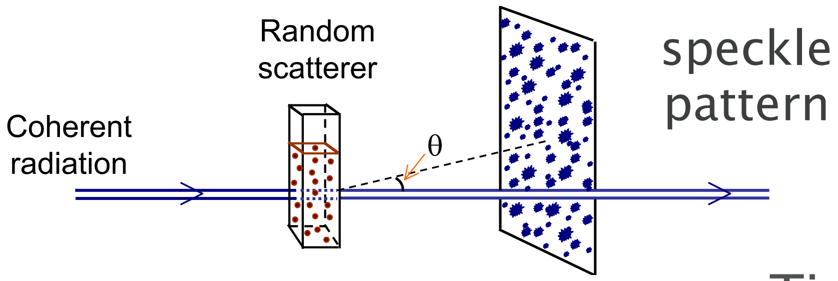
non-uniformity increases along the elongation direction.

# Structural information from USAXS



# X-ray Photon Correlation Spectroscopy: XPCS

- Measurement of fluctuation of X-ray scattering intensity
  --> Structural fluctuation in sample

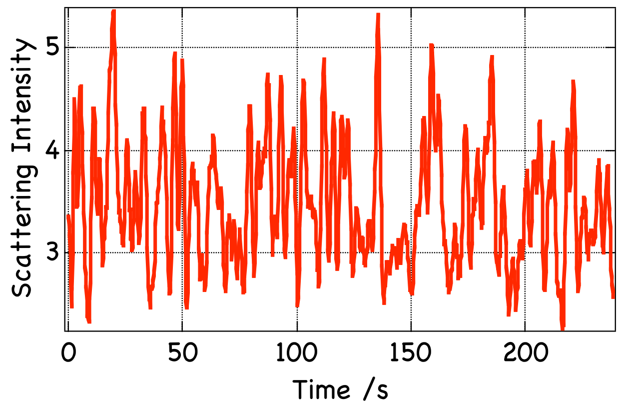



$$g^{(2)}(q,\tau) = \frac{\langle I(q,0)I^{*}(q,\tau)\rangle}{\langle I(q)\rangle^{2}}$$

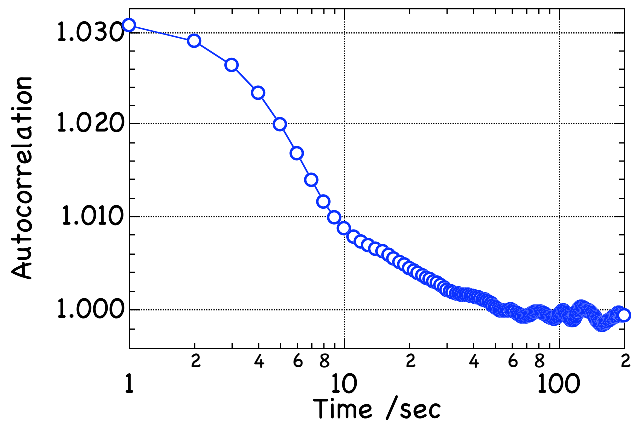
Time-resolved SAXS with coherent X-ray

Fluctuation of intensity

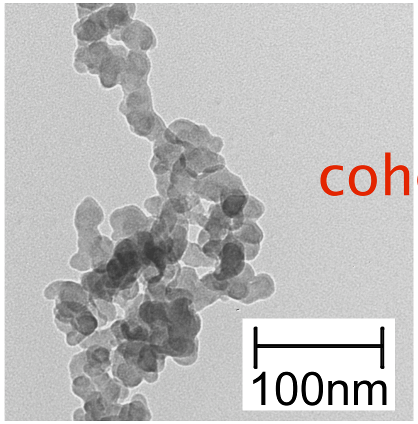
relaxation time in system



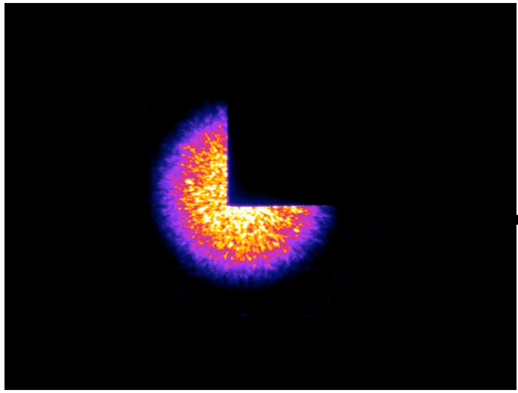

Autocorrelation →

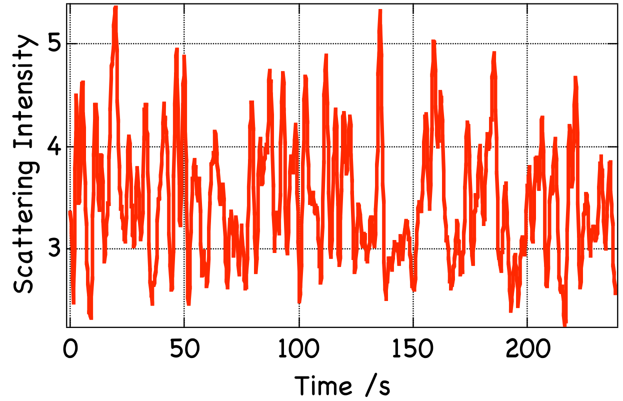


# Dynamics of nanoparticles observed with XPCS




coherent x-ray






nano-particles in rubber

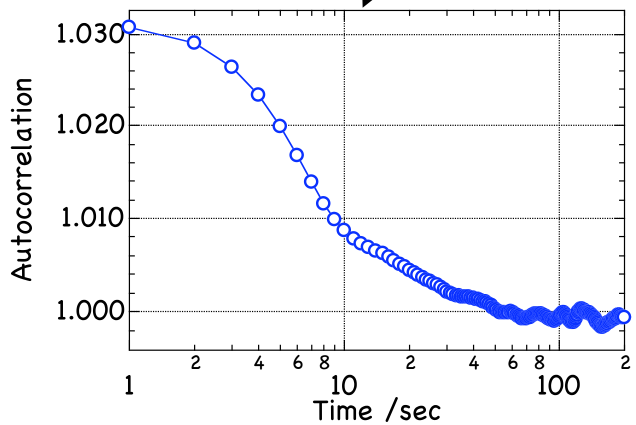
speckle pattern

fluctuation of scattering intensity

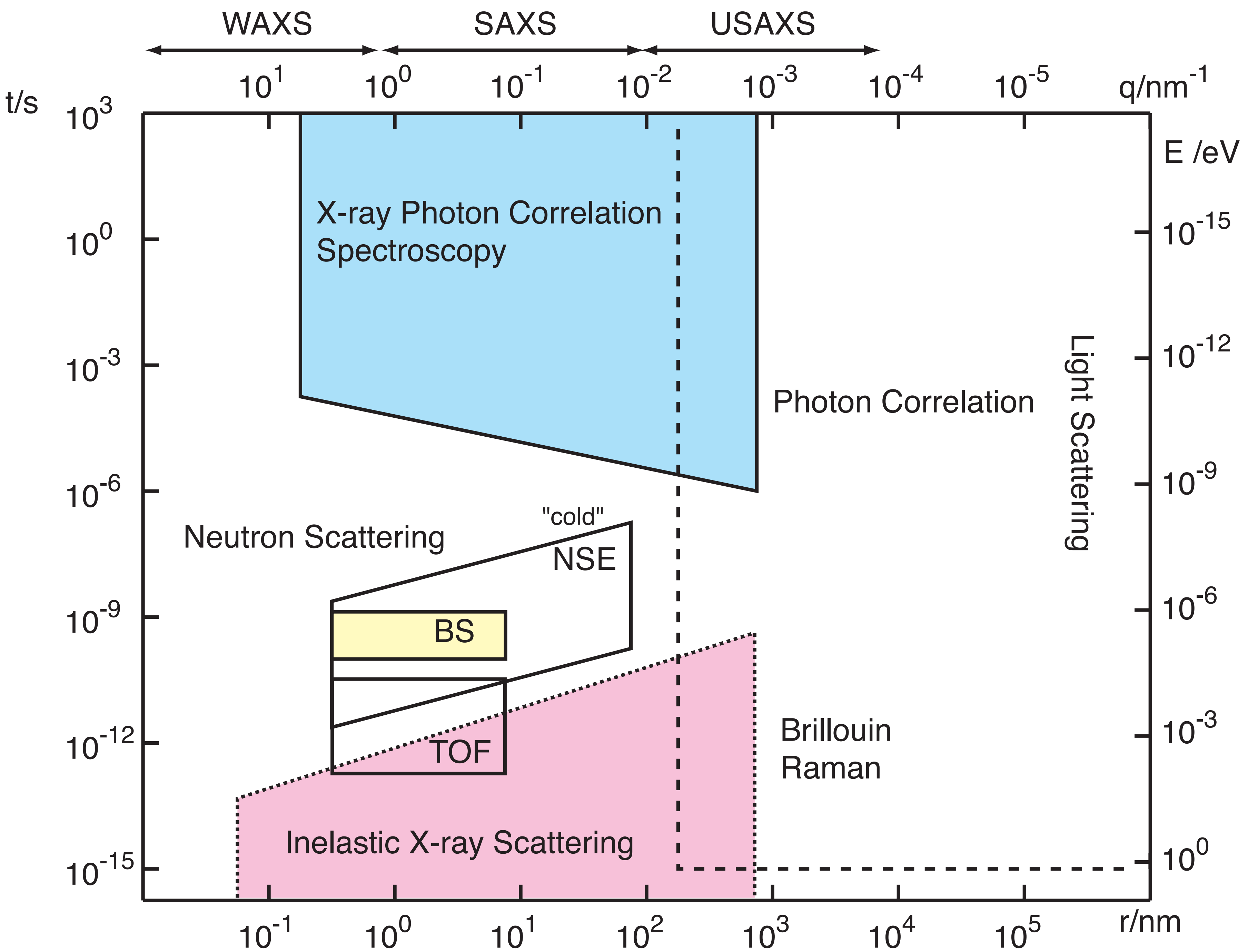
## Dependence of dynamics on...

- Volume fraction of nano-particles
- Vulcanization (cross-linking)
- Type of nano-particles
- Temperature

etc.




Dynamics of Filler in Rubber



WAXS
SAXS
USAXS
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
q/nm$^{-1}$
t/s
$10^3$
$10^0$
$10^{-3}$
$10^{-6}$
$10^{-9}$
$10^{-12}$
$10^{-15}$
E /eV
$10^{-15}$
$10^{-12}$
$10^{-9}$
$10^{-6}$
$10^{-3}$
$10^0$
X-ray Photon Correlation
Spectroscopy
Photon Correlation
Light Scattering
Neutron Scattering
"cold"
NSE
BS
TOF
Brillouin
Raman
Inelastic X-ray Scattering
$10^{-1}$
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$
r/nm

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